SESSION 2: EMERGING TECHNOLOGIES

Chair: Bernie James, Energy, Mines & Resources Canada

1993 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

EXPERIENCE WITH LNG AND LNG - CNG

V. Jayaraman
Consolidated Natural Gas Company

ISSUES TO BE COVERED

- What is LNG?
- Why should we consider using LNG as a transportation fuel?
- What is LNG's availability/price?
- Is LNG safe?
- Who are all experimenting with LNG at this time?
- What has been their experience to date?
- What are the technical/commercial/regulatory obstacles?
- Is there a role for LNG in fueling CNG vehicles?

VJ/1130

LNG (LIQUID METHANE) PROPERTIES

■ Temperature @ Atmos. Press	-259°F
■ Density	3.54 lb/gal
■ 1 Gallon LNG	83.6 cu ft of gas
■ LHV of Methane (CH_4)	911 Btu/cu ft
■ LHV of LNG (CH_4)	76,160 Btu/gal
■ LHV of Gasoline (C_4-C_{10})	114,132 Btu/gal
■ LHV of Diesel (C_{12} - C_{20})	129,400 Btu/gal

■ 1 gal Gasoline $= \frac{114,132}{76,160} =$ 1.5 gal LNG

■ 1 gal Diesel $= \frac{129,400}{76,160} =$ 1.7 gal LNG

VJ/1130

WHY LNG?

- @ 3000 PSI, 250 cu ft Natural Gas in 1 cu ft of space

  @ LNG, 625 cu ft Natural Gas in 1 cu ft of space

  ∴ With LNG, we can pack 2 1/2 times as much fuel in a given space.

- LNG offers the possibility of being able to control the fuel composition within close limits.

- LNG offers the possibility of being able to serve areas not covered by pipeline gas.

- LNG fuel tanks could cost only about half that of compressed gas tanks.

- LNG fueling stations could cost only about a third of compressed gas fueling stations.

- Delivered cost of LNG on vehicles could be less than that of compressed gas.

LNG SAFETY

- Cryogenic liquid; possibility of severe burns on contact.
- Vapor heavier than air below - 170°F, thereafter lighter than air.
- More difficult to ignite and sustain ignition than gasoline/diesel.
- In accident situations, probably safer than gasoline/diesel if no ignition; if ignited, probably less intense fire than gasoline/diesel.
- No odorant; need to depend on methane sensors.

GENERAL INFORMATION ON CRYOGENIC LIQUIDS

LIQUID	TEMP. AT ATMOS. PRESS.	LB/GAL
Helium	-452°F	1.04
Hydrogen	-423°F	0.59
Nitrogen	-320°F	6.75
Argon	-303°F	11.63
Oxygen	-297°F	9.52
Methane	-259°F	3.54

VJ/1130

PRESENT & FUTURE LNG PROJECTS IN THE U.S.

Present	Roadway Express	-	3 trucks running; 4 more planned
	Houston Metro	-	80 buses running; hundreds more planned
	Greater Austin Transp.	-	26 vehicles running
	Burlington Northern Railroad	-	2 locomotives running
	Others		
Future	Chambers Development	-	7 refuse haulers
	Dallas Area Rapid Transit	-	30 buses
	Los Angeles Airport	-	12 coaches
	Union Pacific Railroad	-	6 locomotives
	Others		

TECHNICAL OBSTACLES

■ Vapor Generation	-	Recovery, Disposal
	-	Effect on Economics
■ Ease of Fueling	-	Intermittent Operations
	-	Priming, Cool-down, Cavitation
	-	Heat Pickup
■ Metering	-	Liquid/Vapor
■ Sensors	-	Cool-down
	-	Vehicle Filling
■ Weathering	-	Pure Methane
	-	Pipeline LNG
■ Odorant		

LNG HARDWARE PRICES

■ 100-gallon fuel tank	$ 4,000
■ 10,000-gallon storage tank	100,000
■ Submerged transfer pump	20,000
■ LNG dispenser	75,000
■ LNG fueling connector	5,000

VJ/1158

REGULATORY STATUS

- NFPA 57 under preparation
- Local authorities have cooperated
- Tunnels
- Roof-mounted tanks

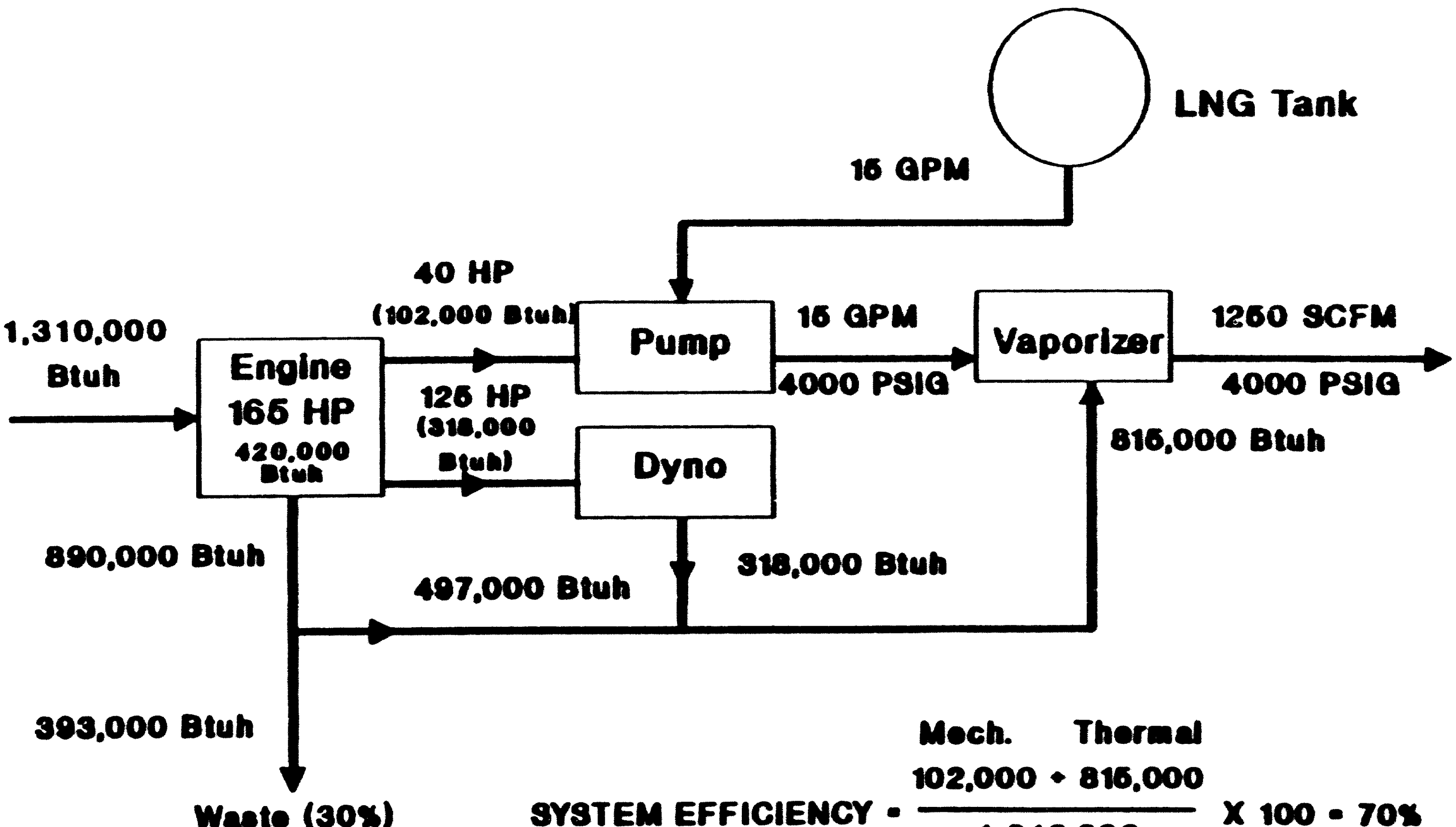
COST OF COMPRESSED GAS SYSTEMS

		1	2	3
Capacity, SCFM		50	240	700
Inlet Pressure, PSIG		15	100	50
Outlet Pressure, PSIG		3600	3600	3800
HP		30	100	300
Storage, SCF		44,000	?	22,000
Costs	- Compressor	40,000		364,000
	- Storage	55,000		39,000
	- Dryer	25,000	380,000	69,000
	- Dispenser	32,000		28,000
	- Site Prep, Install, Misc.	98,000	90,000	150,000
	- Total	$ 250,000	470,000	650,000
Cost $/SCFM		5,000	2,000	1,000

Variables: Inlet Pressure
Storage
Site Prep

VJ/1134

LNG Fast Fill System



$$\text{SYSTEM EFFICIENCY} = \frac{\overset{\text{Mech.}}{102{,}000} + \overset{\text{Thermal}}{815{,}000}}{1{,}310{,}000} \times 100 = 70\%$$

COST OF LNG - CNG SYSTEM

*LNG Tank (10,000 gallons)	100,000
LNG Pumping/Vaporizing System (15 GPM or 1250 SCFM, @ 4000 PSIG)	150,000
Site Prep, Install, Misc.	50,000
Storage	35,000
Dispenser	40,000
Total	**$ 375,000**
Cost $/SCFM	300

**Can serve 100 vehicles/day at the rate of 100 gallons/vehicle.*

VJ/1134

LNG - CNG SYSTEM

ADVANTAGES

- Much lower cost than compressed gas systems.
- No moisture in gas.
- Can control gas temperature to compensate for temperature rise during fast fill.
- Mobile fueling stations possible.

DISADVANTAGES

- Need supply of LNG.
- Cost of LNG could vary from competitive to non-competitive, depending on hauling distance.

VJ/1134

1993 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

EMERGING TECHNOLOGIES FROM SwRI

J. Cole, D. Meyers, K. Guglielmo
Southwest Research Institute

Emerging Technologies From SwRI

Abstract

SwRI has been working to reduce emissions from powerplants burning many types of fuels. A hybrid rich-burn/lean-burn engine concept has been developed to take advantage of the high hydrogen-to-carbon ratio of natural gas. Rich-burn operation using natural gas produces high amounts of hydrogen and carbon monoxide in the exhaust. This exhaust can then be routed through a watershift catalyst where additional hydrogen is produced. The hydrogenated exhaust from rich-burn cylinders can then be supplemented to remaining lean-burn cylinders to extend the lean limit and further reduce NOx emissions.

In addition to the unique low emissions engine concept discussed above, SwRI has been developing advanced engine control technology for alternative fueled engines. A custom PC-based universal engine controller has been developed to enable researchers to fully optimize engines for performance and emissions. SwRI has also aided in the development of an advanced lean-burn control system for heavy-duty natural gas engines and a natural gas conversion system for light-duty vehicles. The details of these control systems including recent test data will be presented.

OUTLINE

- Hybrid Rich-Burn/Lean-Burn Engine Concept

- Advanced Engine Control Technology

HYBRID RICH-BURN/LEAN-BURN ENGINE CONCEPT

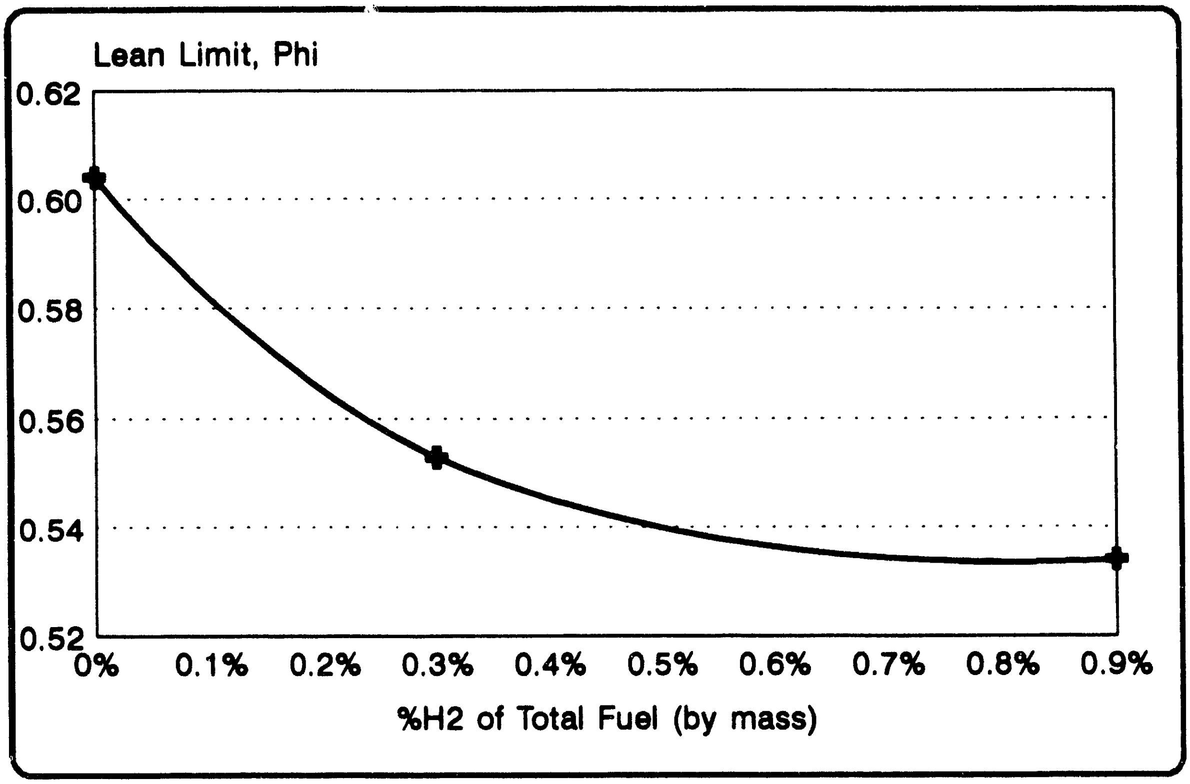
OBJECTIVE

- Demonstrate New Engine Concept
- 5 ppm NOx @ 15% Oxygen Stationary Engine
- Retain Thermal Efficiency of Base Engine

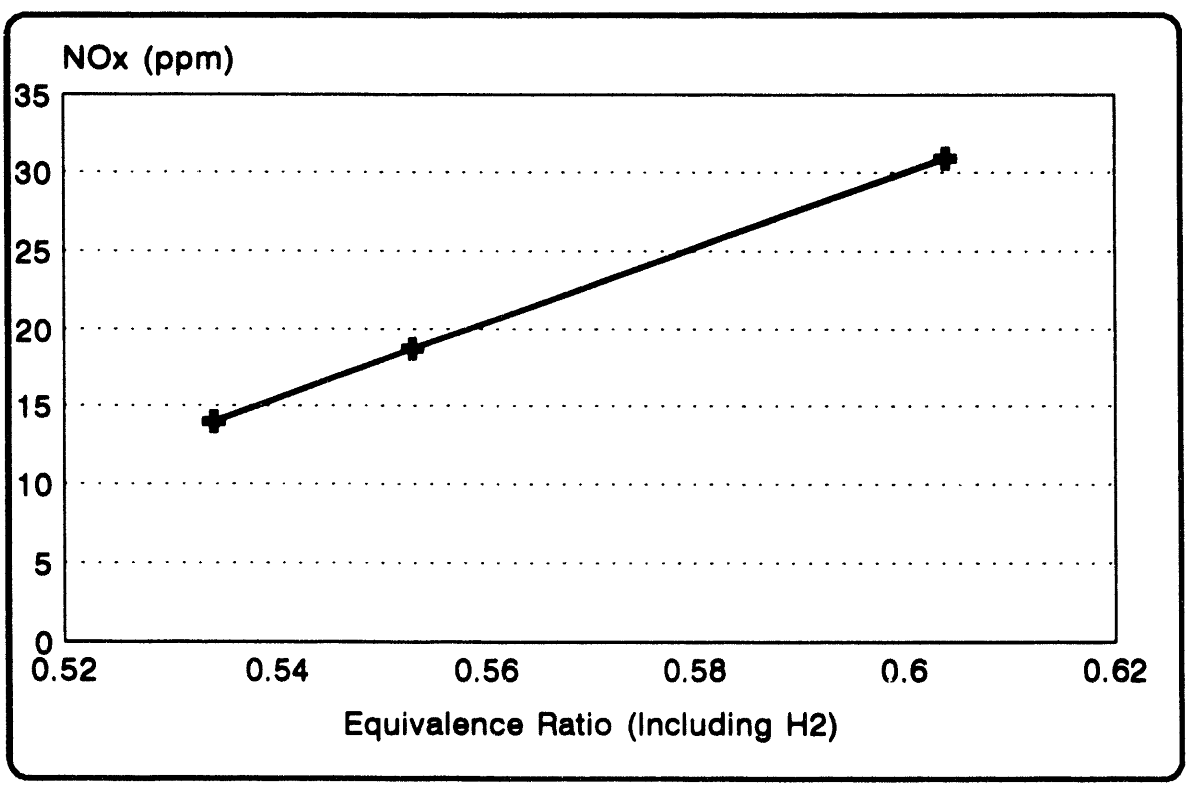
LEAN-BURN COMBUSTION

- NOx Decreases Phi<0.9
- NOx Level Limited by Misfire Limit
- Hydrogen Extends Misfire Limit of NG

HYDROGEN EFFECT ON LEAN LIMIT



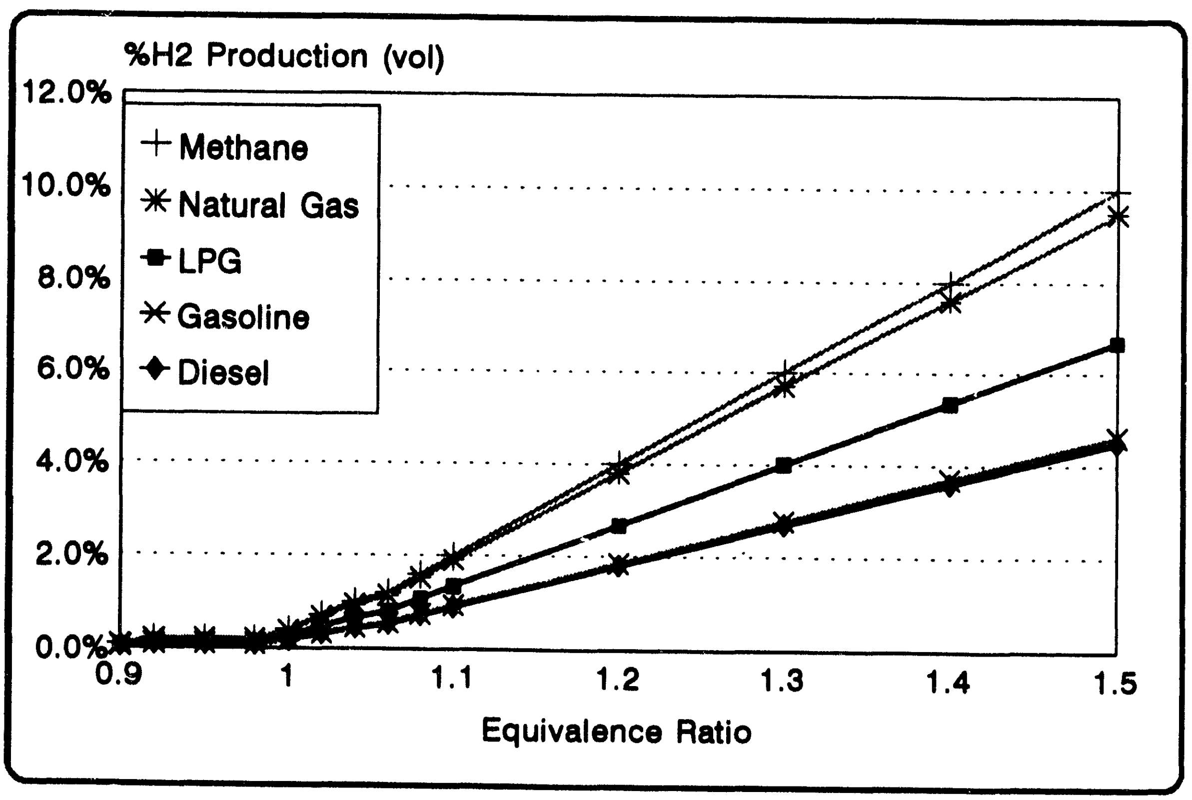
EQUIVALENCE RATIO EFFECT ON NOx



RICH-BURN COMBUSTION

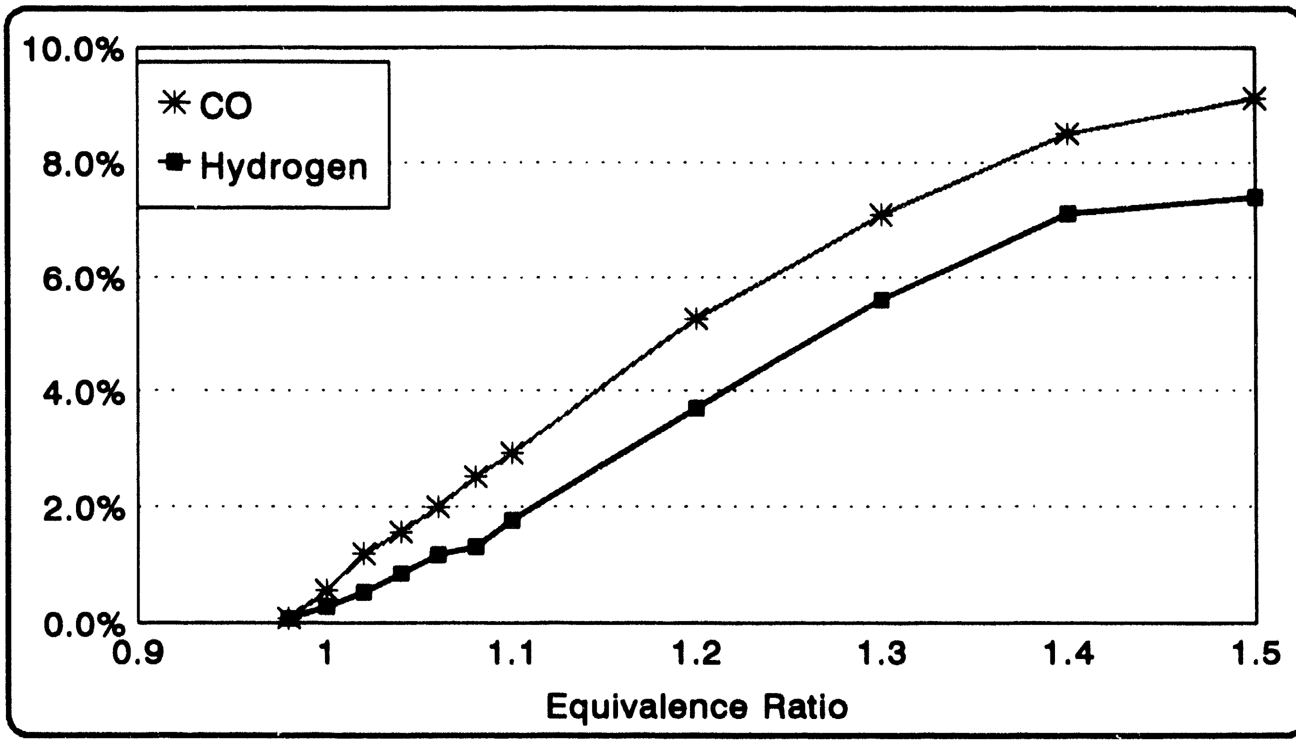
- NOx Decreases Phi>1.0
- NOx Level Limited by High CO and HC
- Excessive Hydrogen and CO Produced
- Hydrogen Production= f(H/C,Phi)

H/C EFFECTS ON HYDROGEN PRODUCTION



H2 & CO EMISSIONS

Labeco CLR Test Engine

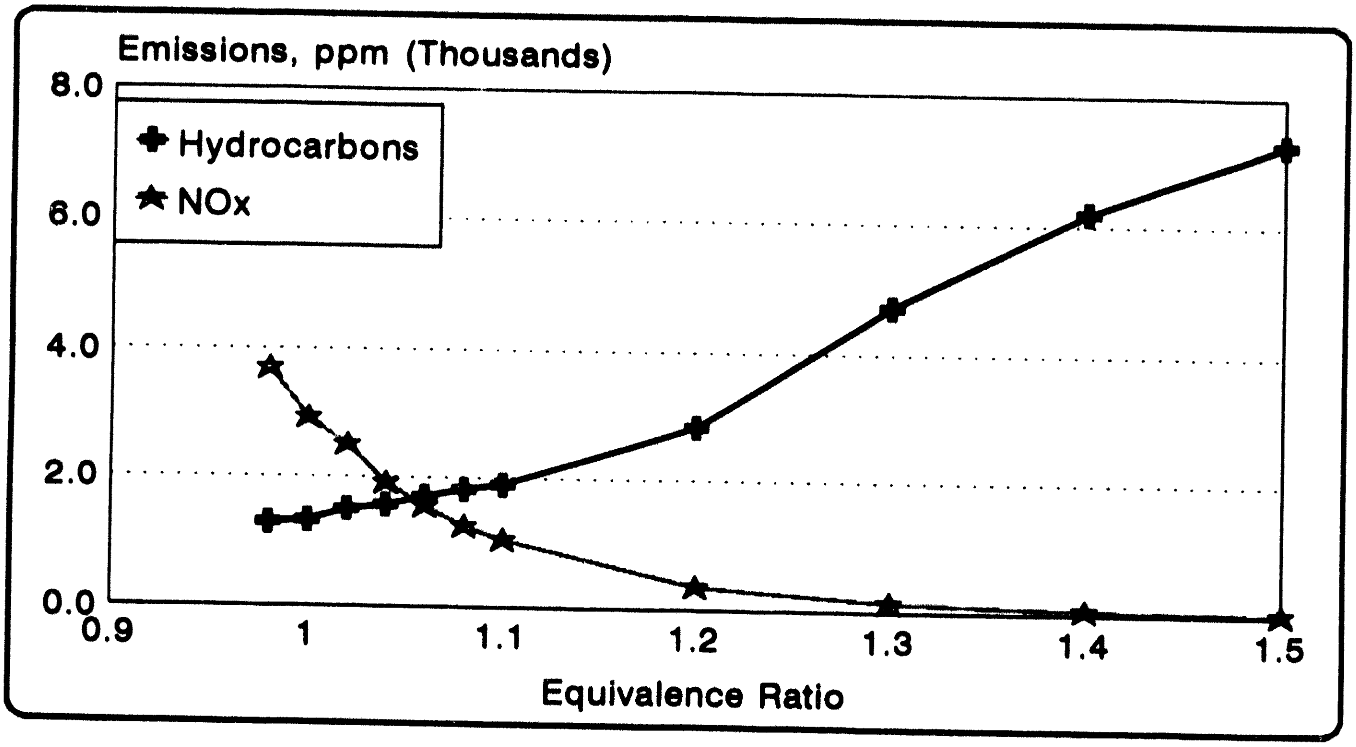


WATER-SHIFT CATALYST

- Converts CO and Water from Rich-Burn Exhaust into Hydrogen and CO2

$$CO + H20 \rightarrow CO2 + H2$$

HC & NOx EMISSIONS
Labeco CLR Test Engine



HYBRID RICH-BURN/LEAN-BURN ENGINE CONCEPT

- Operate 1 Cylinder Phi>1.4
- Rich Exhaust Through Watershift Catalyst
- Supplement Remaining Lean Cylinders w/ Hydrogen and EGR

PROJECT TASKS

1. Modeling
2. Rich-Burn Experiments
3. Combined Rich/Lean Experiments (Two Single Cylinder Engines)
4. Full-Size Engine Demonstration
5. Retrofit Package For Field Demonstration

ACCOMPLISHMENTS TO DATE

- Minimal Modeling Completed
- Rich-Burn Completed- 10:1 Diesel Piston (Burn Rate Too Slow at Phi=1.45)
- High-Turbulence Piston Design Completed
- Twin Engine Set-Up Completed

BENEFITS

- Extremely Low Emissions w/o Exhaust Aftertreatment
- Lean-Limit Extension Increases Efficiency-Reduced Throttling
- Ultra Rich/Lean Burn Allows Increased Compression Ratio

ADVANCED ENGINE CONTROL TECNOLOGY

ADVANCED CONTROL TECHNOLOGY OUTLINE

- Custom Engine Control System
- PRO-LEAN Engine Control System
- TRANSLATOR Conversion System

FEATURES CUSTOM CONTROL SYSTEM

- Fuel Neutral
- TBI/SMPI
- Adaptive Spark Control
- Advanced Adaptive Fuel Control
- Mass Air Flow or Speed-Density Open-Loop Fuel Metering
- Advanced Transient Compensation

FUEL DELIVERY
CUSTOM CONTROL SYSTEM

- Interface Circuitry for Driving:
  - Gasoline PWM Injectors
  - NG PWM Injectors
  - CNG Proportional Metering Valves
  - Diesel Electrically Actuated Injectors

FUEL DELIVERY
CUSTOM CONTROL SYSTEM

- Additional Interface Circuitry for Driving:
  - EGR Valves
  - Idle Bypass Valves
  - Wastegate Actuators
  - Drive-by-wire Throttle

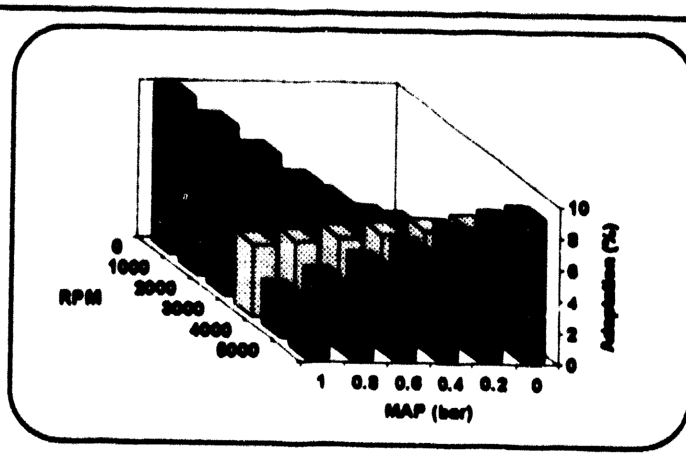
ADAPTIVE SPARK CONTROL CUSTOM CONTROL SYSTEM

- Possible Spark Adjustment Inputs:
  - Cylinder Pressure
  - Force Sensors
  - Ionization Probes
- Adaptive Learn of Optimum Spark Map
- Misfire Detection and Diagnostics

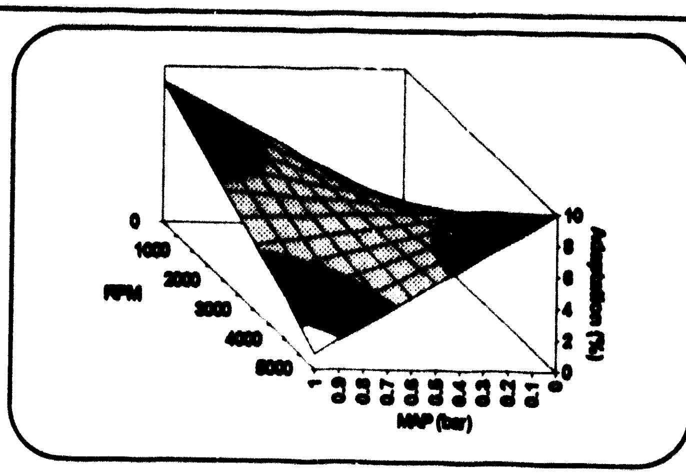
ADAPTIVE FUEL CONTROL CUSTOM CONTROL SYSTEM

- Non-Discontinuous Multi-Dimensional Adaptive Learn Scheme:
  - Injector Miscalibration/Aging
  - Volumetric Efficiency Changes
  - Drift in Sensors Used for Open Loop
  - Faster Fuel Metering Adaptation
- Computationally Efficient
- Small Memory Requirements

DISCONTINUOUS ADAPTATION



CONTINUOUS ADAPTATION SURFACE



OPEN-LOOP METERING CUSTOM CONTROL SYSTEM

- Mass Air Flow Sensor Measurement
- Speed-Density Based Calculation
- Advanced Manifold Filling/Emptying Model for Throttle Transients

EQUIVALENCE RATIO CONTROL CUSTOM CONTROL SYSTEM

- Ability to Use Feedback From:
  - Stoichiometric EGO
  - Wide-Range EGO Sensors
  - Multiple EGO Sensors
- Custom Circuitry for UEGO Sensor

PRO-LEAN NATURAL GAS FOR FUEL CONTROL SYSTEM

- Heavy-Duty Diesel and Gasoline Conversions
- Based on Ford EEC-IV Hardware
- Applied to Hercules GTA3.7L and Mack E7
- Teaming Partners:
  GRI
  DAI Technologies
  Southbend Controls

FEATURES PRO-LEAN CONTROL SYSTEM

- Mass Air Flow Measurement
- Closed Loop Control w/UEGO Sensor
- Direct-Fire Spark Coil Control
- Electronic Wastegate Control
- Engine Speed Governing
- Diagnostic Link

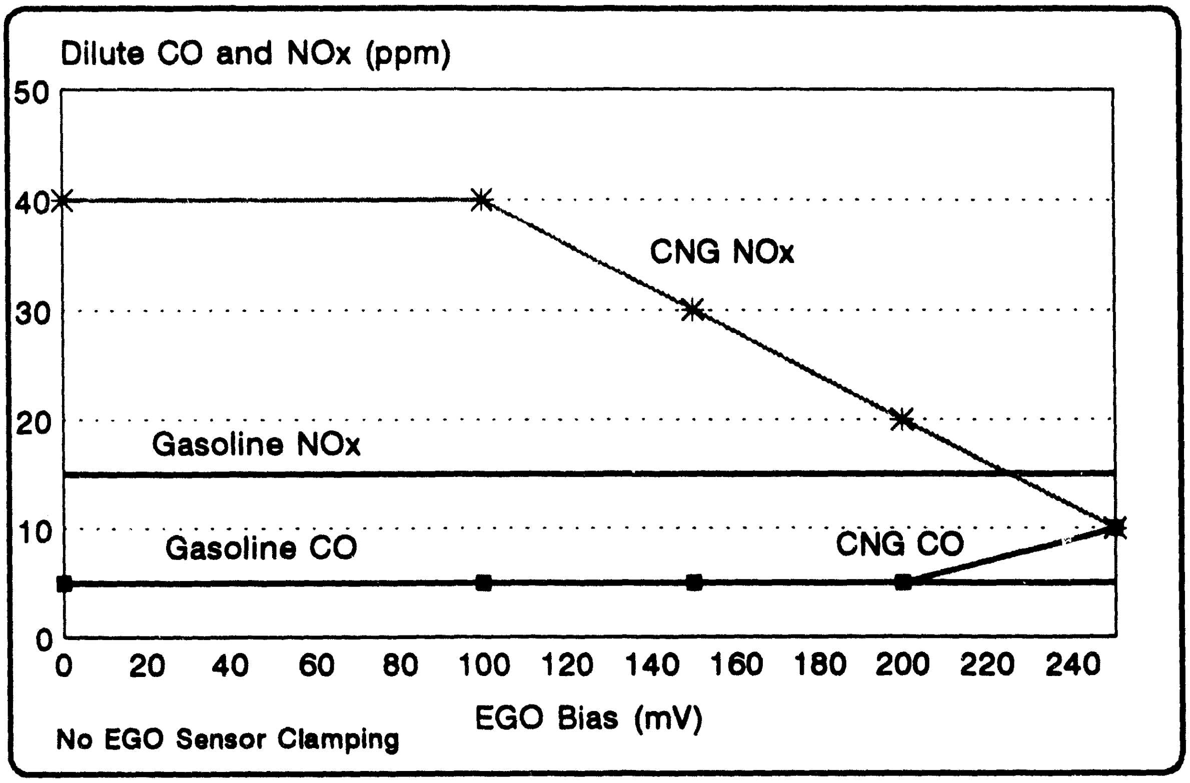
TRANSLATOR CONVERSION SYSTEM

- Simple Bi-fuel Conversion System
- EFI Closed-Loop Gasoline Vehicles
- Teaming Partners:
  GRI
  DAI Technologies

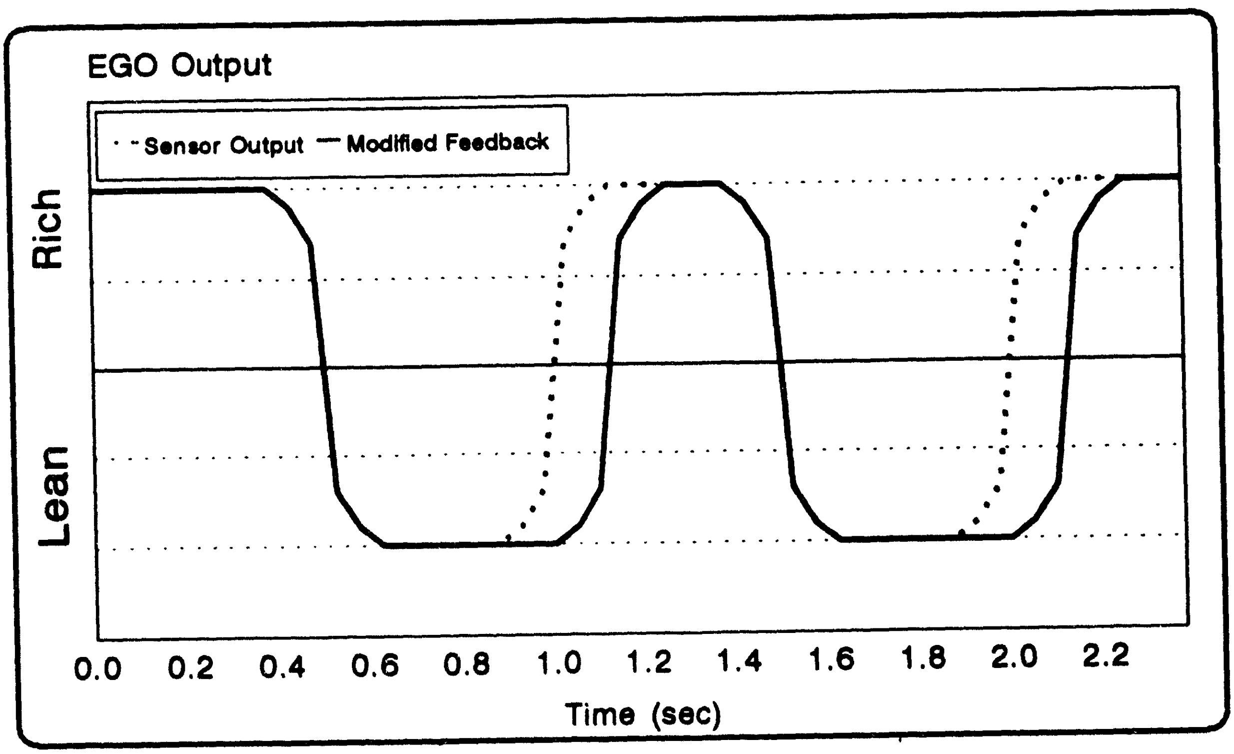
FEATURES
TRANSLATOR CONVERSION SYSTEM

- OEM Diagnostics
- OEM Adaptive Learn
- Elimination of Cold Enrichment
- Spark Advance
- Rich Bias for Low Emissions

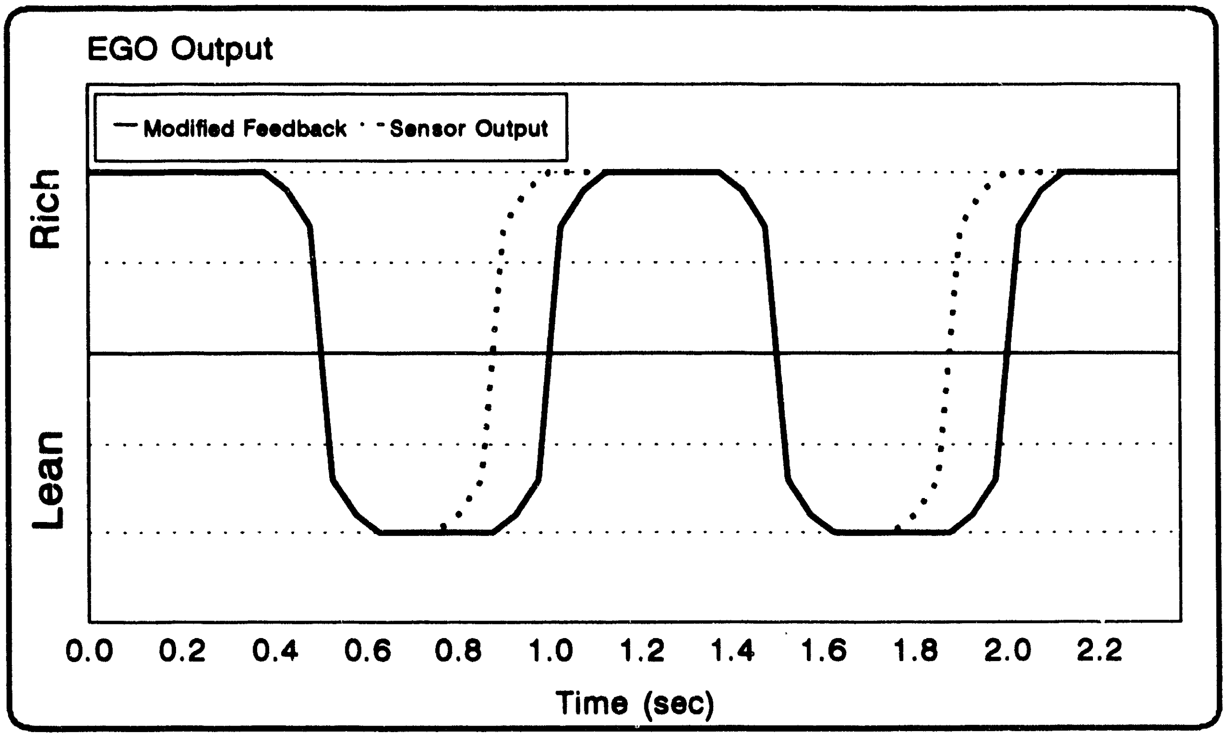
STEADY STATE NOx/CO TRADEOFF



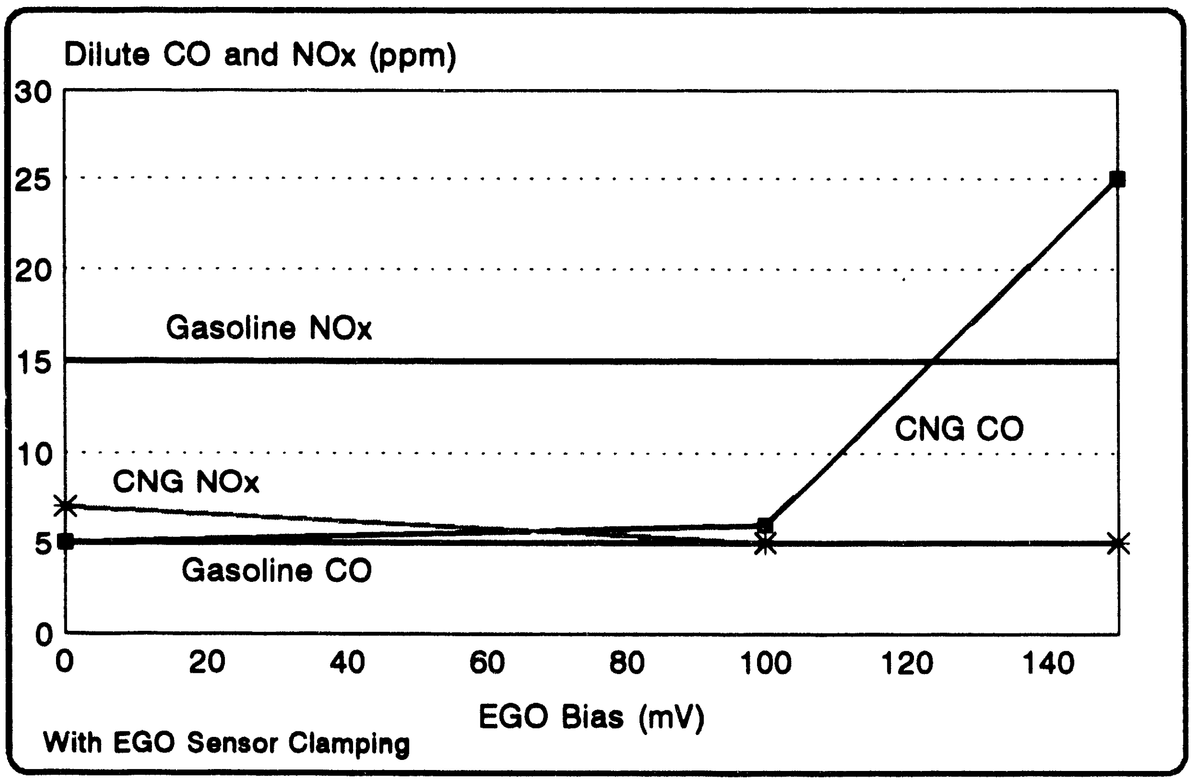
INITIAL LEAN CLAMPING RESPONSE



STABILIZED LEAN CLAMPING RESPONSE

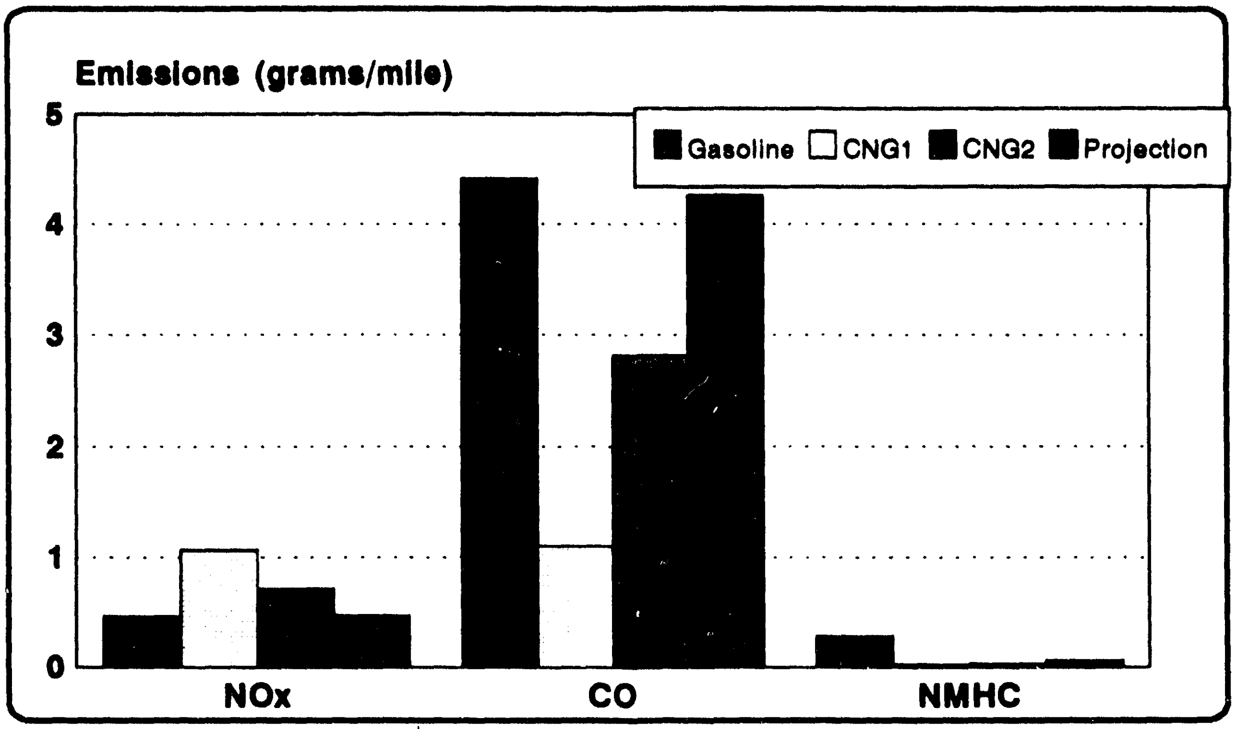


STEADY STATE NOx/CO TRADEOFF



3-BAG FTP EMISSIONS

5.2L TRANSLATOR-EQUIPPED DODGE



ACKNOWLEDGEMENTS

- South Coast Air Quality Management District
- Southern California Gas Company
- Gas Research Institute

SUMMARY OF VERBAL COMMENTS OR QUESTIONS AND SPEAKER RESPONSES

EMERGING TECHNOLOGIES FROM SwRI
J. Cole, Southwest Research Institute

Q. Vinod Duggal, Cummins Engine Co.: As a suggestion, could you mix hydrogen with natural gas for the lean-burn operation?

A. That would be a good idea for laboratory tests, but hydrogen is not generally available for blending with natural gas. Also, the plan is to return the unburned and unconverted hydrocarbons from the rich cylinder to the engine so that these materials contribute to the overall efficiency.

Q. Anonymous: In the adaptive loop control system, what happens if the fuel is changed from gasoline to natural gas and back to gasoline?

A. If the loop is on calibration, not much change occurs, and the control loop adjusts to fit the new fuel.

1993 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

CUMMINS B6G: AN ADVANCED TECHNOLOGY NATURAL GAS ENGINE

M.M. Kamel
Cummins Engine Co. Inc.

CUMMINS B6G N.G. ENGINE
OUTLINE

* OBJECTIVE

* TECHNICAL PROFILE

* TECHNOLOGY CONCEPTS

  - DESIGN FEATURES
  - ELECTRONIC CONTROLS

* DEVELOPMENT SCHEDULE

* DEVELOPMENT STATUS

  - PERFORMANCE
  - EMISSIONS
  - MECHANICAL
  - FIELD TEST

* SUMMARY

(MMK,6/1/93,TO-2)

B6G OVERVIEW
OBJECTIVE

* OBJECTIVE

DEVELOP THE B6 ENGINE FOR OPERATION WITH NATURAL GAS FOR URBAN AUTOMOTIVE APPLICATION

* ENVIRONMENT

= LEGISLATIONS FOR LOWER EMISSIONS
= POLITICAL PRESSURES FOR CLEAN AIR
= ENERGY SECURITY
= ECONOMICS

(MMK,6/10/93,TO-5)

B6G TECHNICAL PROFILE

PERFORMANCE:

* 195 HP @2800 RPM
* 420 FT.LB. PEAK TORQUE @1600 RPM
* 285 FT.LB. CLUTCH ENGAGEMENT TORQUE @FULL THROTTLE
* UPTO 8500 FT ALTITUDE CAPABILITY

EMISSIONS:

* 1998 CARB ULEV LEVELS
  2.5 (NOx + NMHC) & 0.05 PART

NOISE:

* US AND EEC DRIVE-BY LEGISLATED LIMITS

B6G TECHNICAL PROFILE (Con't.d)

HEAT REJECTION:
* LESS THAN OR EQUAL TO 94B-230 DIESEL

RELIABILITY:
* APPROACHES DIESEL RELIABILITY AT MATURITY

DURABILITY:
* EQUIVALENT TO DIESEL

ELECTRONICS:
* ENGINE MOUNTED

(MMK,6/1/93,TO-1)

TECHNOLOGY CONCEPTS
DESIGN FEATURES

* LEAN BURN / SPARK IGNITED
  = DIESEL LIKE THERMAL LOADING
  = HIGH BMEP CAPABILITY (IMPROVE EFFICIENCY)
  = LOW ENGINE OUT NOX EMISSION

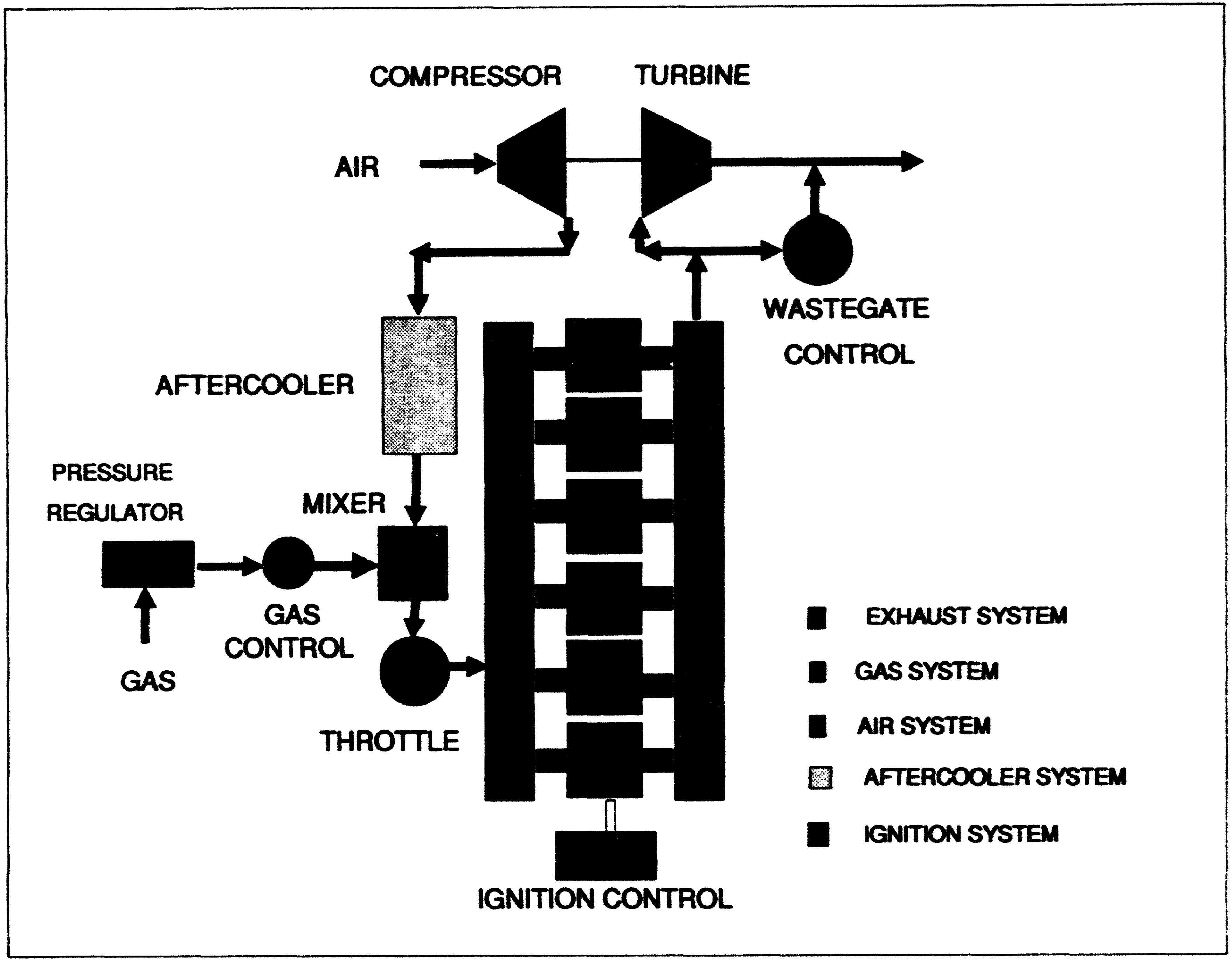
* WASTEGATED TURBOCHARGER
  = TORQUE CURVE SHAPING
  = ENGINE OUTPUT LIMITING
  = DROOP CURVE LIMITING
  = ALTITUDE COMPENSATION

* AIR-TO-AIR AFTERCOOLING
  = MATCHES '94 DIESEL CONFIGURATION (COMMONALITY)

* OXIDATION CATALYST
  = NMHC CONTROL

* ENHANCED DURABILITY
  = NEW CYLINDER HEAD WITH INSERTS
  = WATERCOOLED BEARING HOUSING TURBOCHARGER

(MMK,6/10/,TO-8)


COMPRESSOR
TURBINE
AIR
WASTEGATE
CONTROL
AFTERCOOLER
PRESSURE
REGULATOR
MIXER
GAS
CONTROL
GAS
THROTTLE
IGNITION CONTROL
EXHAUST SYSTEM
GAS SYSTEM
AIR SYSTEM
AFTERCOOLER SYSTEM
IGNITION SYSTEM

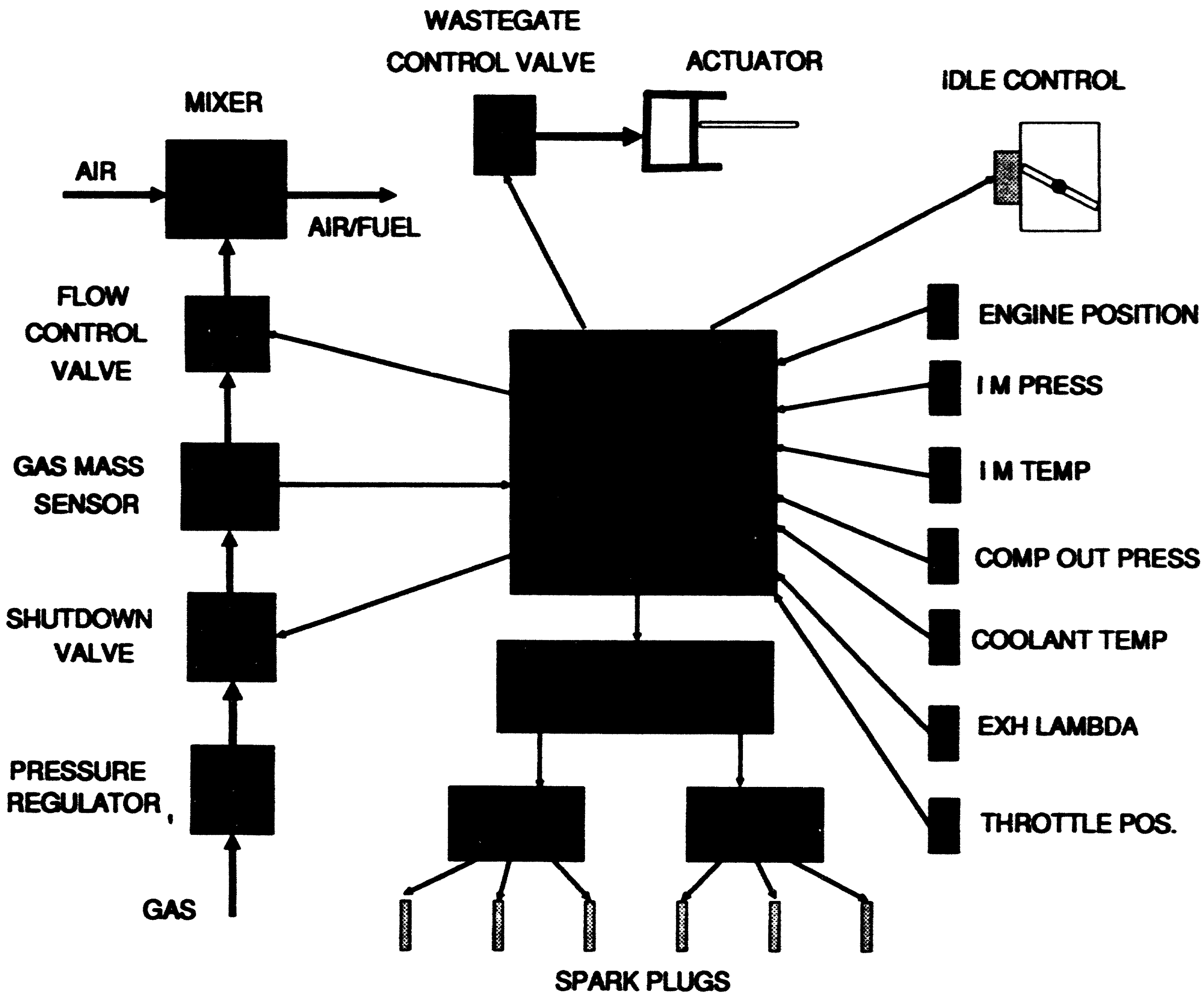
TECHNOLOGY CONCEPTS
ELECTRONIC CONTROLS

* ENGINE MOUNTED ELECTRONICS
  = MINIMIZE CUSTOMER INSTALLATION IMPACT
  = MAXIMIZE PRODUCT CONTROL

* ELECTRONIC CONTROL OF
  = IGNITION SYSTEM
  = GAS SYSTEM
  = MIN/MAX ENGINE SPEEDS
  = BOOST PRESSURE

* ENHANCE DIAGNOSTICS AND TROUBLESHOOTING

(MMK,6/10/93,TO-9)


WASTEGATE
CONTROL VALVE
ACTUATOR
IDLE CONTROL
MIXER
AIR
AIR/FUEL
FLOW
CONTROL
VALVE
GAS MASS
SENSOR
SHUTDOWN
VALVE
PRESSURE
REGULATOR
GAS
ENGINE POSITION
I M PRESS
I M TEMP
COMP OUT PRESS
COOLANT TEMP
EXH LAMBDA
THROTTLE POS.
SPARK PLUGS

DEVELOPMENT STATUS
PERFORMANCE

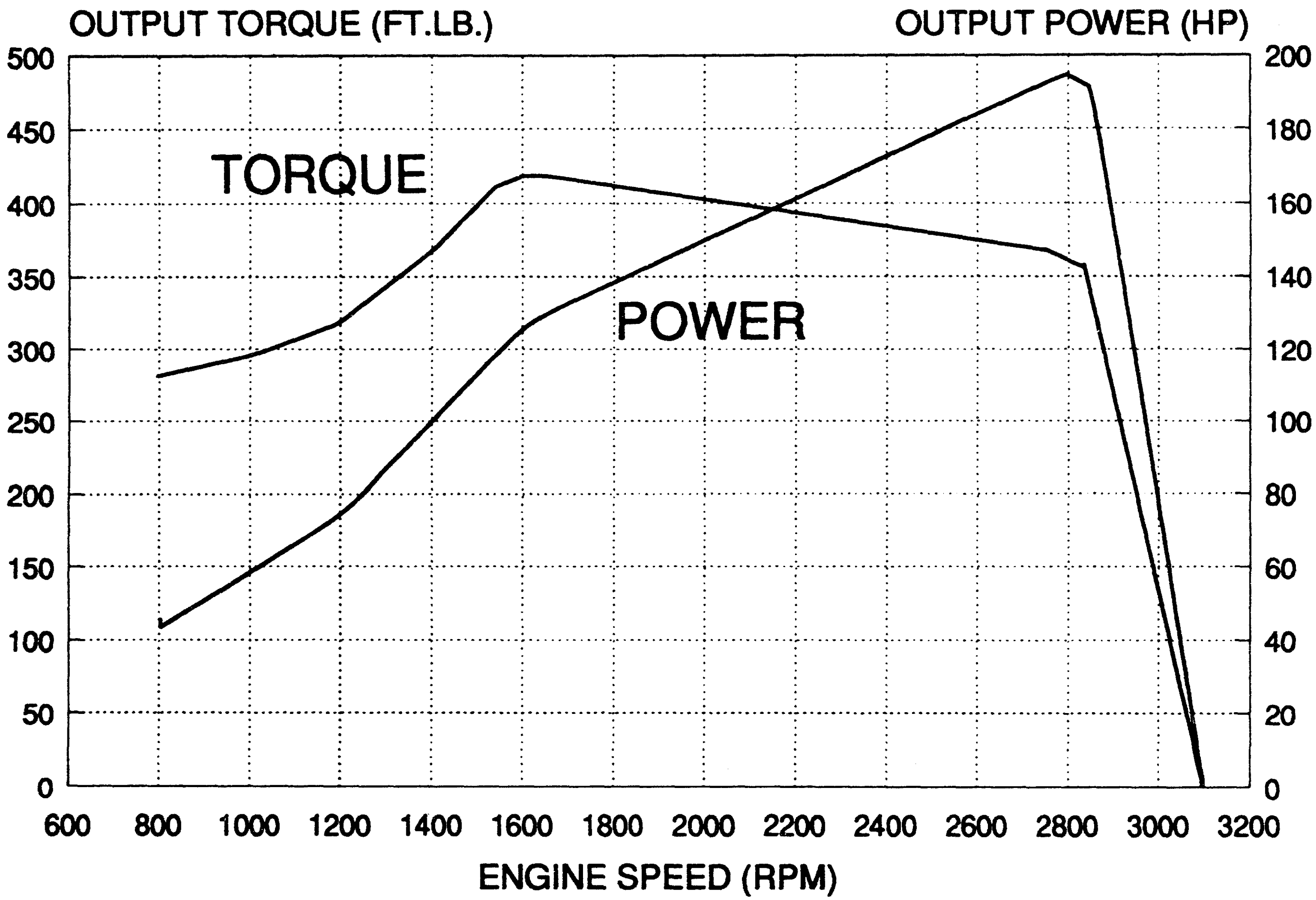
* HAVE DEMONSTRATED THE CAPABILITY TO ACHIEVE THE GOALS

= POWER
= TORQUE CURVE SHAPING
= WASTEGATE CONTROL
= MIN/MAX ENGINE SPEED CONTROL
= GAS SYSTEM CONTROL

* HAVE DEMONSTRATED REPEATED PERFORMANCE ON 9 ENGINES

(MMK,6/10/93,TO-6)

B6G NATURAL GAS ENGINE
TORQUE / POWER CURVES



(MMK,5/25/93,TRQ)

DEVELOPEMENT STATUS
EMISSIONS

		NOx	HC	NMHC	PART.
NO CATALYST					
	MIN	1.81	4.40	0.00	0.054
	MAX	2.16	5.59	0.93	0.067
WITH CATALYST					
	MIN	1.73	0.59	0.00	0.009
	MAX	2.28	3.03	0.27	0.019

(MMK,6/10/93,TO-7)

DEVELOPMENT STATUS
MECHANICAL DEVELOPMENT

* ENGINE TESTS

= LAB ENGINE TESTS (OVERSTRESS/ENDURANCE)
= FIELD TEST ENGINES TESTS

* RIG TESTS

= GAS SYSTEM COMPONENTS
= IGNITION SYSTEM COMPONENTS
= VIBRATION TESTING

* QUALIFICATION TESTS

= SENSORS
= ACTUATORS
= CONTROLLER

(MMK,6/10/93,TO-11)

DEVELOPMENT STATUS
FIELD TEST

* PLANNED FIELD TEST ENGINE IN THE FOLLOWING APPLICATIONS

  = SCHOOL BUS
  = SHUTTLE BUS
  = PICKUP/DELIVERY TRUCK

* HAVE ALREADY SHIPPED FOUR FIELD TEST ENGINES

(MMK,6/10/93,TO-10)

B6G TECHNICAL PROGRESS SUMMARY

* PROJECT IS ON SCHEDULE

* HAVE DEMONSTRATED THE PERFORMANCE AND EMISSIONS CAPABILITIES OF THE ENGINE

* MECHANICAL DEVELOPMENT PHASE IS UNDERWAY

  - ENGINE RELIABILITY IS ON TARGET TO ACHIEVE DESIGN GOAL

* ACCUMULATED 3000 HRS OF ENGINE TEST EXPERIENCE

  - BUILT AND TESTED 9 ENGINES

* SHIPPED FOUR FIELD TEST ENGINES

  - SHUTTLE BUS
  - SCHOOL BUS

(MMK,5/31/93,M2-12)

ACKNOWLEDGEMENT

WE ACKNOWLEDGE:

GRI AND SOCAL FOR THEIR PARTICIPATION IN FUNDING THIS PROGRAM.

(MMK,5/29/93,TX-10)

SUMMARY OF VERBAL COMMENTS OR QUESTIONS AND SPEAKER RESPONSES

CUMMINS B6G: AN ADVANCED TECHNOLOGY NATURAL GAS ENGINE
M.M. Kamel, Cummins Engine Co. Inc.

Q. Anonymous: Can Cummins provide conversion of existing engines?

A. No, the hardware could be purchased, but it would be expensive and there would be no certification.

1993 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

DEVELOPMENT OF A STOICHIOMETRIC NATURAL GAS ENGINE FOR USE IN HEAVY DUTY TRUCKS

(unavailable at time of printing)

L. Gettel, G.C. Perry
BC Research

D.H. Smith
IMPCO Technologies

SUMMARY OF VERBAL COMMENTS OR QUESTIONS AND SPEAKER RESPONSES

DEVELOPMENT OF A STOICHIOMETRIC NG ENGINE FOR USE IN HEAVY DUTY TRUCKS
G.C. Perry, and L.E. Gettel, B.C. Research Corporation

Q. Bernard James, Energy, Mines & Resources Canada: What range is obtained by the truck?

A. The range is 200-250 kilometers.

Q. Bryan Wilson, Colorado State University: Do you have emissions data?

A. No, emissions have not been measured yet on the vehicle.

1993 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

DEVELOPMENT STATUS FOR TWO DEDICATED METHANOL ENGINE COMBUSTION TECHNOLOGIES: DI HOT SURFACE IGNITION AND DI SPARK IGNITED STRATIFIED CHARGE

R. Last
FEV of America

B. Bartunek, N. Schorn, R. Schmidt
FEV Motorentechnik GmbH & Co. KG

Development Status for Two Dedicated Methanol Engine Combustion Technologies: DI Hot Surface Ignition and DI Spark Ignited Stratified Charge

Presented by:
Robert J. Last
FEV Engine Technology, Inc.

At the SAE Fuels and Lubricants Meeting in San Francisco last August, I presented the Phase 1 program results for two engine development programs that FEV has conducted with the support of funding by the U.S. Environmental Protection Agency and co-sponsorship by Volkswagen.

[SLIDES 1 through 3]

The direct injected, hot surface ignition system uses a shielded glow element that is heated at all times during the engine operating cycle. A single spray from a multi-hole nozzle is directed at the shielded cover of the glow plug. The fuel from the ignition spray enters the cover through perforations in its surface and ignites. This results in a torch-like ignition of the main injection quantity.

[SLIDES 2 through 6]

The DI, spark ignition combustion process is characterized by peripheral injection in a relatively deep, compact combustion chamber and the nearly simultaneous provision of a spark ignition source near the wall of the bowl. The fuel injection is accomplished with a two-spring injection nozzle holder. Mixture formation is supported by a relatively high swirl (4.0). Through adaptation of the two injector stages, a certain rate-shaping effect is possible, allowing control of the injection duration and the position of the spray cone relative to the spark plug. In comparison with traditional Otto engines, the higher compression ratio with this concept requires that a sufficiently large number of multiple sparks occur over a period of approximately 0.8 to 1.0 ms. Consequently, smaller electrode gaps are necessary to avoid "blow-off" or quenching effects. Because of the deep, slightly reentrant bowl shape, the spark plug protrusion must be relatively deep, requiring a long electrode length.

The Phase 1 results for the DI hot surface ignition concept reported near ULEV emissions levels as well as cold startability at -29°C with excellent driveaway characteristics and diesel-like fuel economy. The potential for very low emissions from the DI Spark Ignited, stratified charge concept was also demonstrated.

In addition to the very encouraging results that came out of Phase 1, the need for a number of improvments was also recognized, if the true potential of these concepts was to be realized. Most of the recommendations were related to the desire to dynamically adjust the engine for low emissions and to control the fuel system. The motivation for considering electronic control of the engines included the following considerations:

[SLIDE 7]
[SLIDE 8]

With these goals in mind, FEV commenced a Phase 2 effort with funding support by the U.S. Environmental Protection Agency and the assistance of Volkswagen.

Additionally, Robert Bosch provided limited technical support and allowed the use of some of their componentry in the design and development of the controller. I would be remiss in not acknowledging the support of these organizations.

Phase 2 was directed at adapting and developing an electronically controlled injection pump, EGR system and integration of a separate electronic ignition system, in the case of the DI SI engine. As a result of these efforts, the first fully electronic dedicated methanol engine concept for direct injection has been developed. Today, I would like to provide a brief overview of the control system concept and identify areas in which we feel additional development is necessary to ultimately provide a competitive methanol engine design concept.

The primary functions of the controller include:

[SLIDE 9]

1. <u>INJECTION QUANTITY CONTROL</u>

The primary function of an electronic engine controller for DI engines is, of course, the governing of the injection quantity. In the FEV IEEC controller, the fuel injection quantity is controlled in the following manner.

[SLIDE 10]

Based upon the requested engine operational point (foot pedal input), the controller performs any modifcations of the request that might be necessary due to the operating state of the engine (such as idle, full load, startup and/or need for temperature compensation) and requests a certain injection quantity. This is referred to in the figure as FQ_SOLL. The difference between the requested fuel quantity and the reported fuel rack position is then determined and a calculation takes place, as indicated in the figure. Depending upon whether the requested injection quantity is less than or greater than the reported quantity, a signal is output to a rotary torque motor which, in turn, drives the fuel rack to either higher or lower fuel delivery positions.

The initial development testing with the electronic controller has indicated a need for better temperature compensation of the fuel rack position feedback sensor. Typically, such sensors have non-linear voltage characteristics and exhibit a certain drift as a function of the temperature in the vicinity of the sensor. This temperature effect has a more significant influence on the engine operating characteristics than originally anticipated. FEV has, therefore, recommended that this problem be addressed in future development efforts with the controller.

In addition to temperature compensation, FEV has recommended the use of a self-calibration circuit in the controller. This circuit would compare the output of the fuel rack position sensor at a known angular position (such as the full load mechanical stop) with a calibration value which is stored in a EPROM. When the sensor deviates from the correct value, this "self calibration" circuit would apply a scalar correction factor to the sensor output, in an attempt to return it to the correct calibration.

2. <u>BEGINNING OF INJECTION</u>

During the course of development for both of the passenger car methanol engine concepts which are being developed by FEV, the need has been demonstrated for an injection timing strategy which is both load and speed dependent.

[SLIDE 11]

Under low load conditions, advanced timing is necessary to ensure good ignition quality as well as low HC and CO emissions. Under high, part load conditions where high temperatures prevent increased HC emissions, retarded timing is employed to reduce NOx emissions and to ensure good fuel economy. However, under high load, high speed conditions, it becomes necessary to re-advance timing because of the length of the injection event. Clearly, these considerations call for a flexible timing strategy that can only be acheived with electronic timing control.

The AMBAC Model 100 methanol compatible, electronic fuel injection pump is being used in both of these programs. The beginning of injection is controlled in closed loop through an evaluation of the output sigals from two vane sensors mounted inside the pump housing One sensor is located on the pump cam shaft and the other on the driven shaft which rotates the hydraulic head of the injection pump. The controller calculates a phase difference between the two sensors which is related to the BOI and then provides an appropriate driver signal to a linear magnet which, in turn, positions a helical spline gear to adjust the timing. In this manner, the timing for the fuel delivery from the injection pump is controlled in closed loop. However, our recent evaluations with the electronic control system indicate that this control strategy may not be adequate. While the start of fuel delivery is related to BOI, the hydrodynamics in the injection line and nozzle influence the actual BOI to a considerable extent, dependent upon injection pressure and the point in the operating map. Therefore, future efforts are planned to incorporate a needle lift sensor based BOI feedback signal.

3. EXHAUST GAS RECIRCULATION

One of the critical needs that was demonstrated during the Phase 1 vehicle evaluation was the need for closed loop control of the EGR system.

[SLIDE 12]

Under low speed, part load conditions, very high EGR rates are possible, resulting in a substantial reduction in NOx emissions. Under medium speed, part load conditions, most of the NOx reduction is acheived within the first 10% of EGR fraction and more sensitivity is observed with regard to higher EGR rates, therefore the EGR rate drops off more rapidly. Under high speed conditions, the sensitivity of the combustion process to higher EGR rates increases substantially and, therefore, EGR must be limited under these conditions.

[SLIDE 13]

However, despite EGR sensitivity (due to misfiring) in both engine concepts, a substantial reduction in NOx is possible with hot EGR. In general, under low load conditions, the application of hot EGR leads to a slight parallel improvement in HC emissions, since the intake air is preheated by the EGR. At higher EGR rates, the lower O_2 content results in a deterioration in flame speed and ignition characteristics, and HC concentration increases. However, this higher concentration is offset at part load by the fact that the exhaust gas mass flow is signficantly lower.

[SLIDE 14]

By properly "tailoring" the EGR and BOI strategy, it is possible to reduce NOx without a significant penalty in HC or BSFC. However, this ability requires flexible, electronic, closed loop control of both EGR and timing.

This approach is possible with both the HSI engine as well as the DI SI stratified charge engine. Although the spark ignited engine is somewhat more sensitive to EGR, as indicated here in the EGR map for the engine.

[SLIDE 15]

Flexible, dynamic EGR control capability was built into the electronic control system during the development of the electronic controller. A duty cycle signal from the IEEC unit, defining the desired EGR valve lift is provided to a solenoid, which modulates between vacuum pump and ambient pressure as necessary to actuate the EGR valve. An air mass flow sensor provides a feedback signal, indicating the actual air mass flow to the controller. The maximum air mass flow for this particular operating point occurs under conditions of no EGR. This value is stored in an EPROM. The controller then compares the actual air mass flow value with the maximum value, stored in EPROM. An actual EGR rate can, thus, be calculated and adjusted, resulting in closed loop control of the EGR.

4. IGNITION TIMING CONTROL

Although the controller architecture was designed to include it, the current controller concept does not include the capability for spark timing control. Currently, this remains a rather critical limitation for the DI SI stratified charge engine in terms of realization of the true potential engine performance.

[SLIDE 16]

The time difference between BOI and ignition defines the degree of in-cylinder homogenization of the air/fuel mixture. Ignition must occur during the period corresponding to the injection duration. Under part load conditions, very early injection timing (about 21°BTDC) and a (max) 2 - 3° later spark timing is necessary to acheive a good combination of low HC emissions and acceptable BSFC. However, under high load conditions, more homogenization is necessary for good air utilization and good BSFC. Therefore, the ignition timing should be very late in comparison with the injection timing to acheive the best characteristics. Clearly, flexible, independent control of both injection and ignition timing are necessary.

Unfortunately, the desired injection/ignition timing strategy is currently not possible with the ignition system that is being utilized on the vehicle. The ignition timing device that is currently available uses an engine speed dependent timing control function. After a signal for dynamic BOI has been registered, a programmed delay time occurs before spark ignition takes place. The time delay calibration is a function of engine speed and is controlled between 1° crank angle at low speed and 6° crank angle at rated speed. This system, while adequate, represents a compromise from the ideal ignition timing flexiblity.

The injection timing for the DI SI engine is shown here and represents the typical compromise between best timing at discrete steady-state points and a smooth transition for good electronic control system function.

[SLIDE 17]

The corresponding ignition timing here. Clearly, it is not currently possible to provide the desired residence time under all load and speed conditions and, consequently, the full potential of the in-cylinder homogenization concept cannot be taken advantage of.

[SLIDE 18]

FEV has recommended the incorporation of this feature into future direct injected, spark ignited vehicle development activities.

5. DRIVEABILITY/ACCELERATION

Numerous points exist in the engine map, from which accelerations typically begin during the FTP-75 cycle. These points are of particular concern due to the heavily weighted contribution of emissions peaks that occur during accelerations to the overall engine emissions characterization. In diesel applications, electronic controllers typically provide a smoke limitation feature that prevents localized overfuelling during accelerations by limiting the rate of increase of the fuel injection quantity. This is done as a function of the available air mass flow. In the methanol engine, where smoke is not a problem, this type of control feature can be utilized for a different purpose. The FEV engine controller uses this capability as an indirect Lambda control under acceleration conditions. The rate of injection quantity increase is limited, through the use of a special look up table that interacts with the EGR and BOI control systems. Hence, the EGR and BOI characteristics can be fine-tuned to reduce or eliminate acceleration induced emissions peaks.

6. IDLE SPEED CONTROL

The FEV controller also features a sophisticated P,I,D governor for idle speed and an integrated glow plug controller for the HSI engine. The glow plug controller feature allows special cold start and warm-up strategies as well as flexible, dyanamic control of the hot surface ignition system energy supply during engine operation.

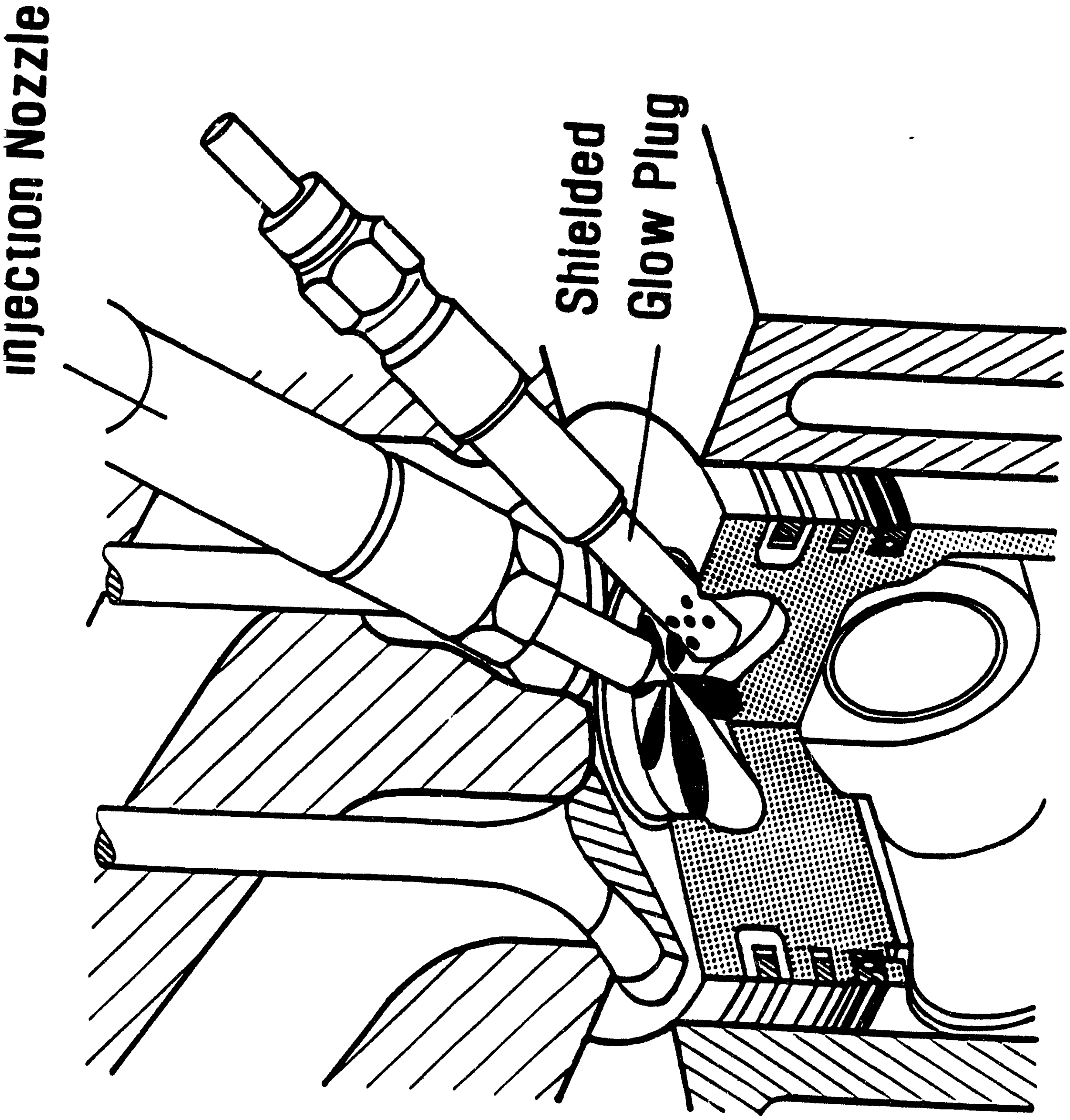
The controller was designed with the intent of upgradeability, including the future potential for spark timing control and variable geometry turbocharger control. However, these features have not yet been incorporated into the design.

7. SUMMARY AND CONCLUSIONS

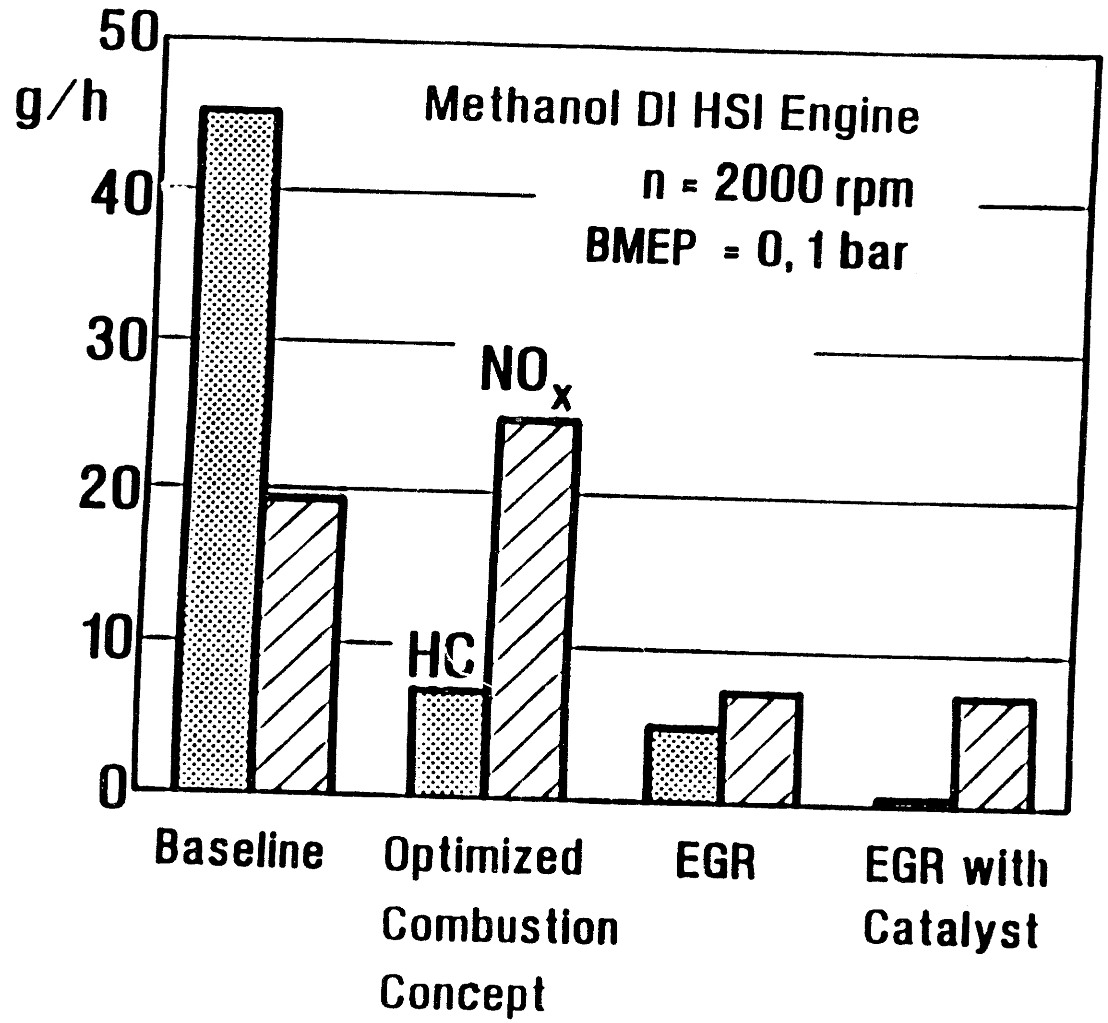
In addition to the basic consideration of incorporating independent spark timing control, the development steps which should be considered in the near term include the following:

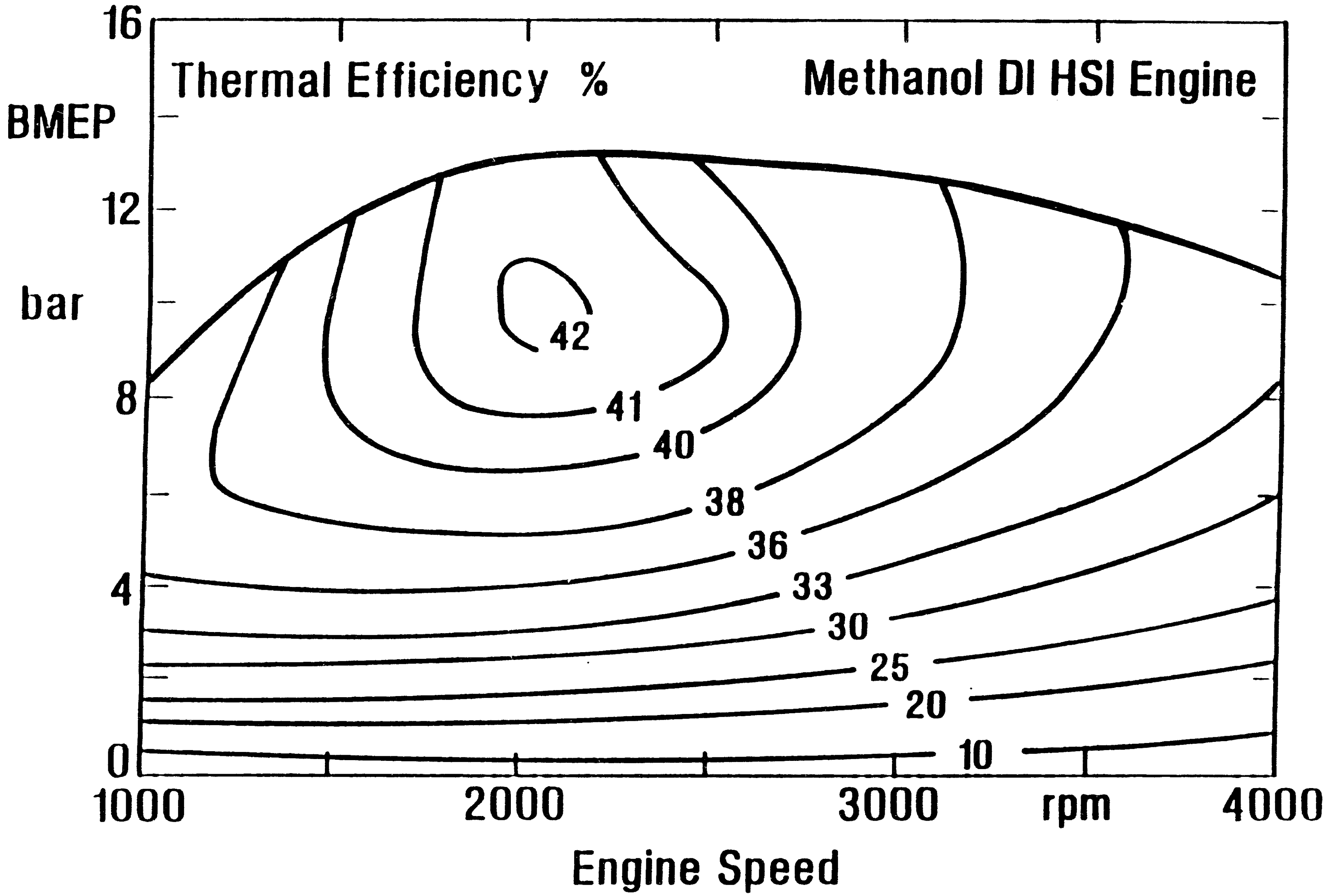
[READ SLIDE 19]

Although recent testing has indicated a need for improvements in the control concept, the FEV IEEC represents a significant development from the standpoint of dynamic control of a methanol engine. When fully developed, FEV believes that extremely low emissions values will be possible with both of these methanol engine concepts. Although the development of these engines on a steady-state basis is nearly complete, a considerable effort is still necessary to dynamically optimize the engine/controller system in a vehicle. Accordingly, these efforts represent FEV's recommendations for near term development goals for these technologies.

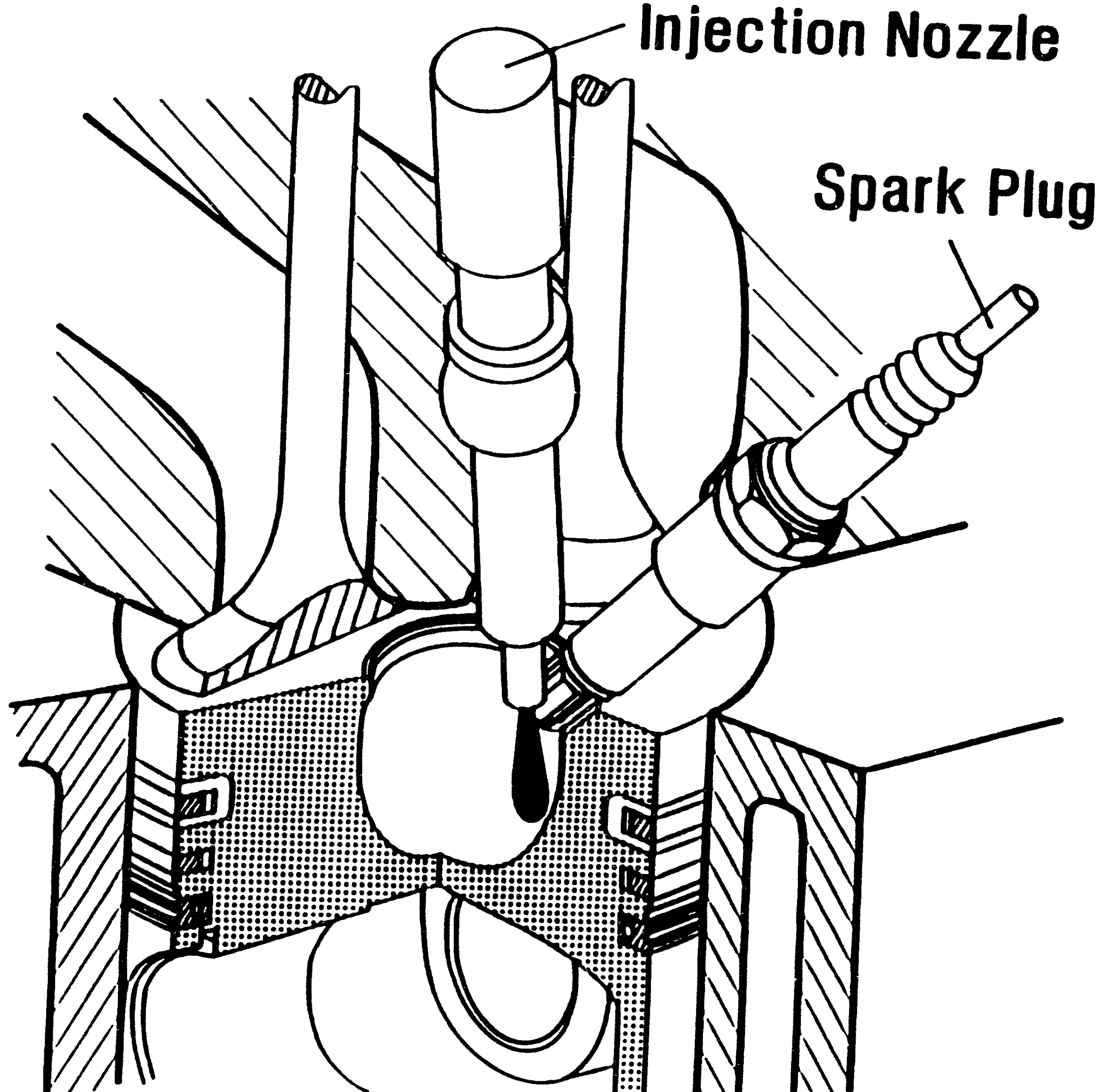


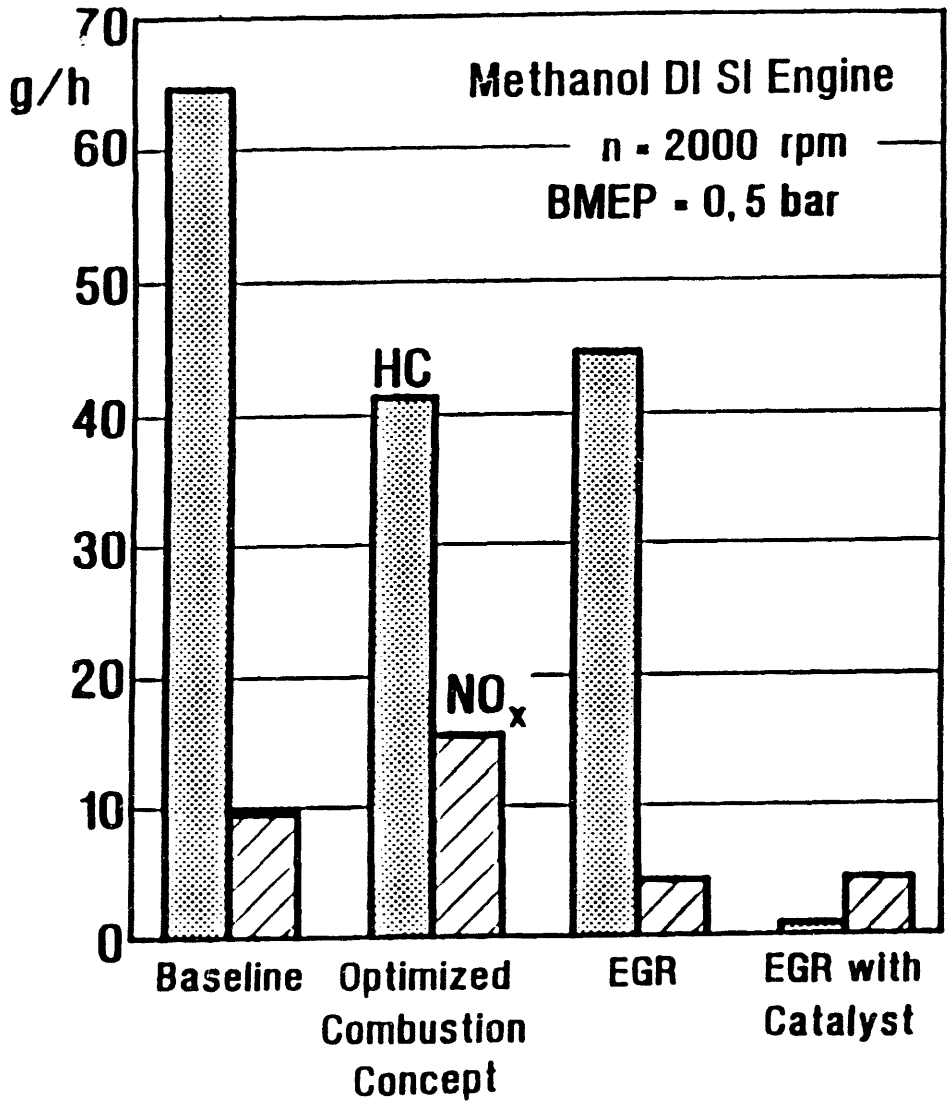
Injection Nozzle
Shielded
Glow Plug


50
g/h
40
30
20
10
0
Methanol DI HSI Engine
n = 2000 rpm
BMEP = 0,1 bar
NO$_x$
HC
Baseline
Optimized Combustion Concept
EGR
EGR with Catalyst

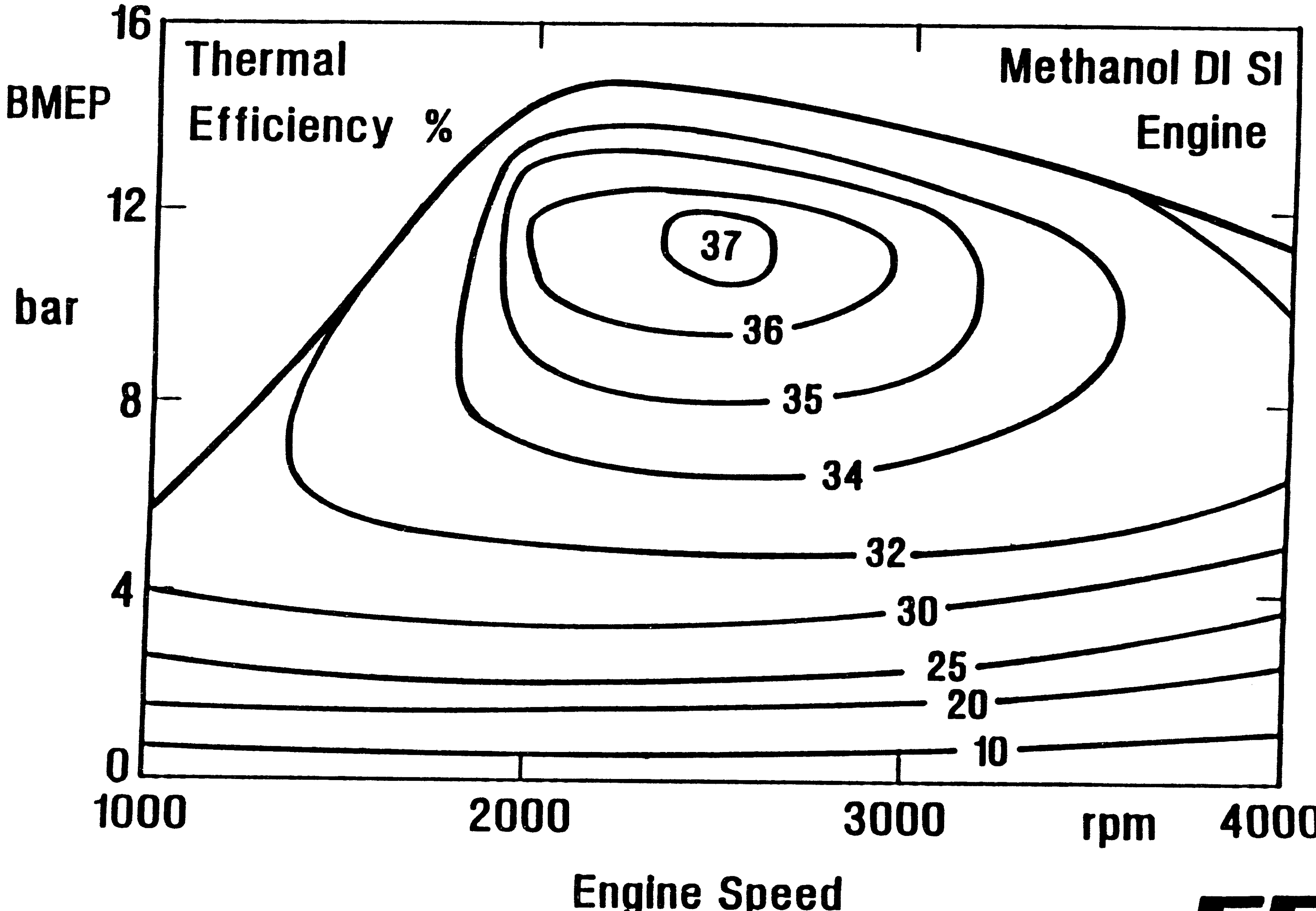


Thermal Efficiency %
Methanol DI HSI Engine
BMEP
bar
16
12
8
4
0
42
41
40
38
36
33
30
25
20
10
1000
2000
3000
rpm
4000
Engine Speed


Injection Nozzle
Spark Plug



70
g/h
60
50
40
30
20
10
0
Methanol DI SI Engine
n = 2000 rpm
BMEP = 0,5 bar
HC
NO_x
Baseline
Optimized Combustion Concept
EGR
EGR with Catalyst


Thermal
Efficiency %
Methanol DI SI
Engine
BMEP
bar
16
12
8
4
0
37
36
35
34
32
30
25
20
10
1000
2000
3000
rpm
4000
Engine Speed

FEV

Reasons for Electronic Injection System Control

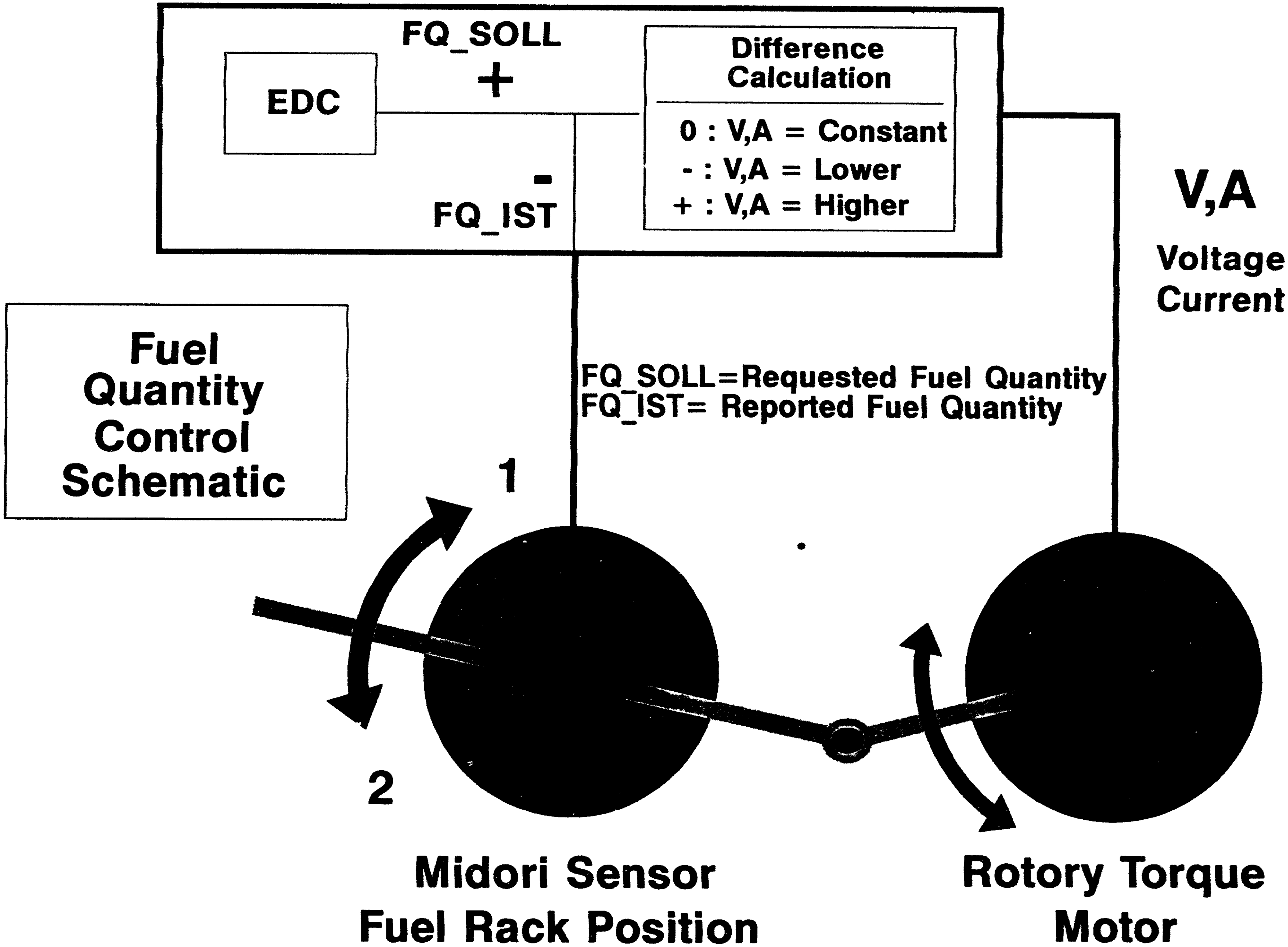
- Control of injection timing as a function of load and speed can only be achieved through complicated and inexact mechanical means (plunger helices and speed advance devices).
- Temperature compensation is not possible with the mechanical system.
- Rate of injection quantity increase cannot be directly controlled in a mechanical system as a means of avoiding transient HC peaks.
- A mechanical system is, in principal, more subject to hysteresis and accuracy problems and requires frequent readjustment and calibration.

Reasons for Electronic Injection System Control

- In-line injection pumps generate a significant level of operating noise (one plunger for each cylinder) in addition to the combustion noise from the engine.
- Due to the number of pumping elements and generally high pressure levels, in-line pumps are generally more expensive than rotary pumps.
- Use of a mechanical system requires separate controllers for EGR, glow plug power and spark timing control. The use of an electronic engine controller allows integration of the pump timing and quantity control with these separate control systems.
- Closed loop control of EGR is not possible with the mechanical system.

FEV IEEC Controller Primary Functions

- Injection Quantity Control
- Beginning of Injection
- Exhaust Gas Recirculation
- Cold Start and Warm-Up
- Driveability and Acceleration
- Idle Speed Control
- Glow Plug Power Control


EDC
FQ_SOLL
+
-
FQ_IST
Difference Calculation
0 : V,A = Constant
- : V,A = Lower
+ : V,A = Higher
V,A
Voltage
Current
Fuel Quantity Control Schematic
FQ_SOLL=Requested Fuel Quantity
FQ_IST= Reported Fuel Quantity
1
2
Midori Sensor
Fuel Rack Position
Rotory Torque
Motor

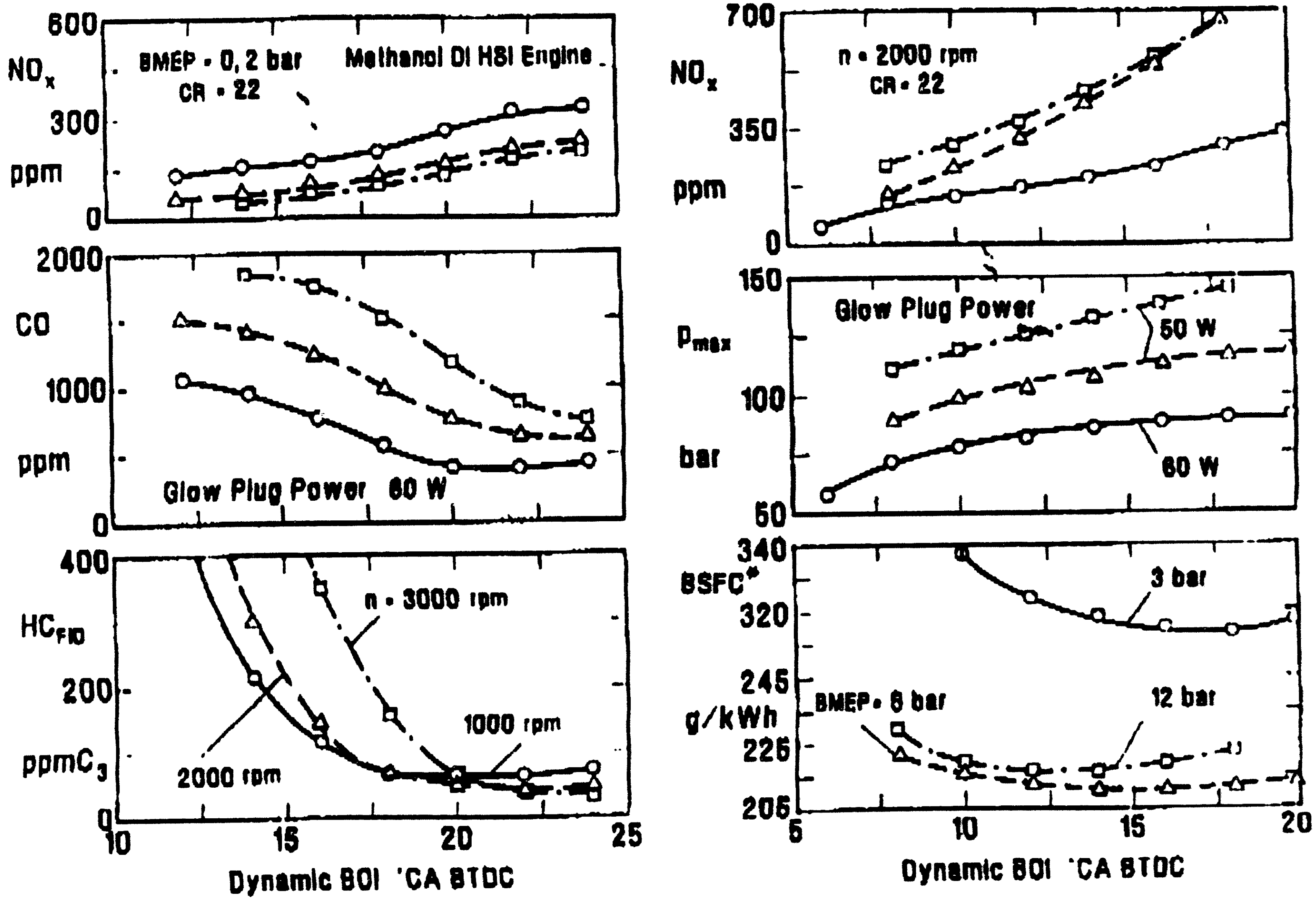
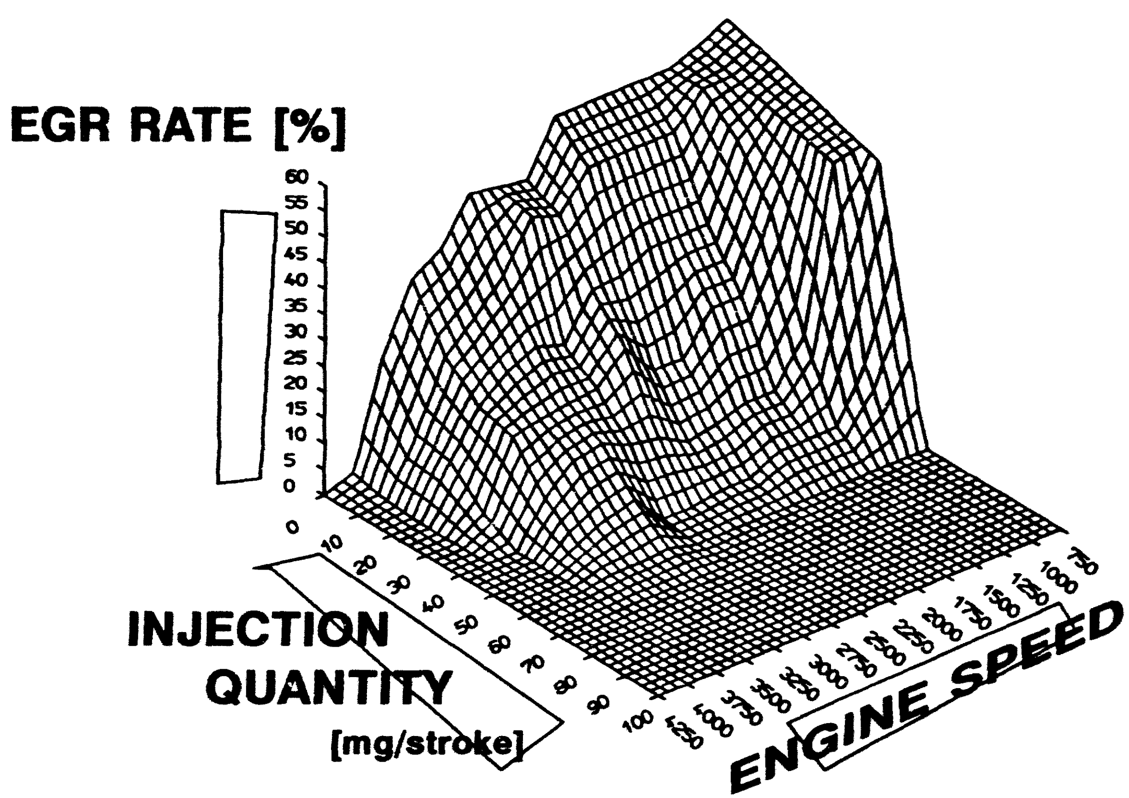
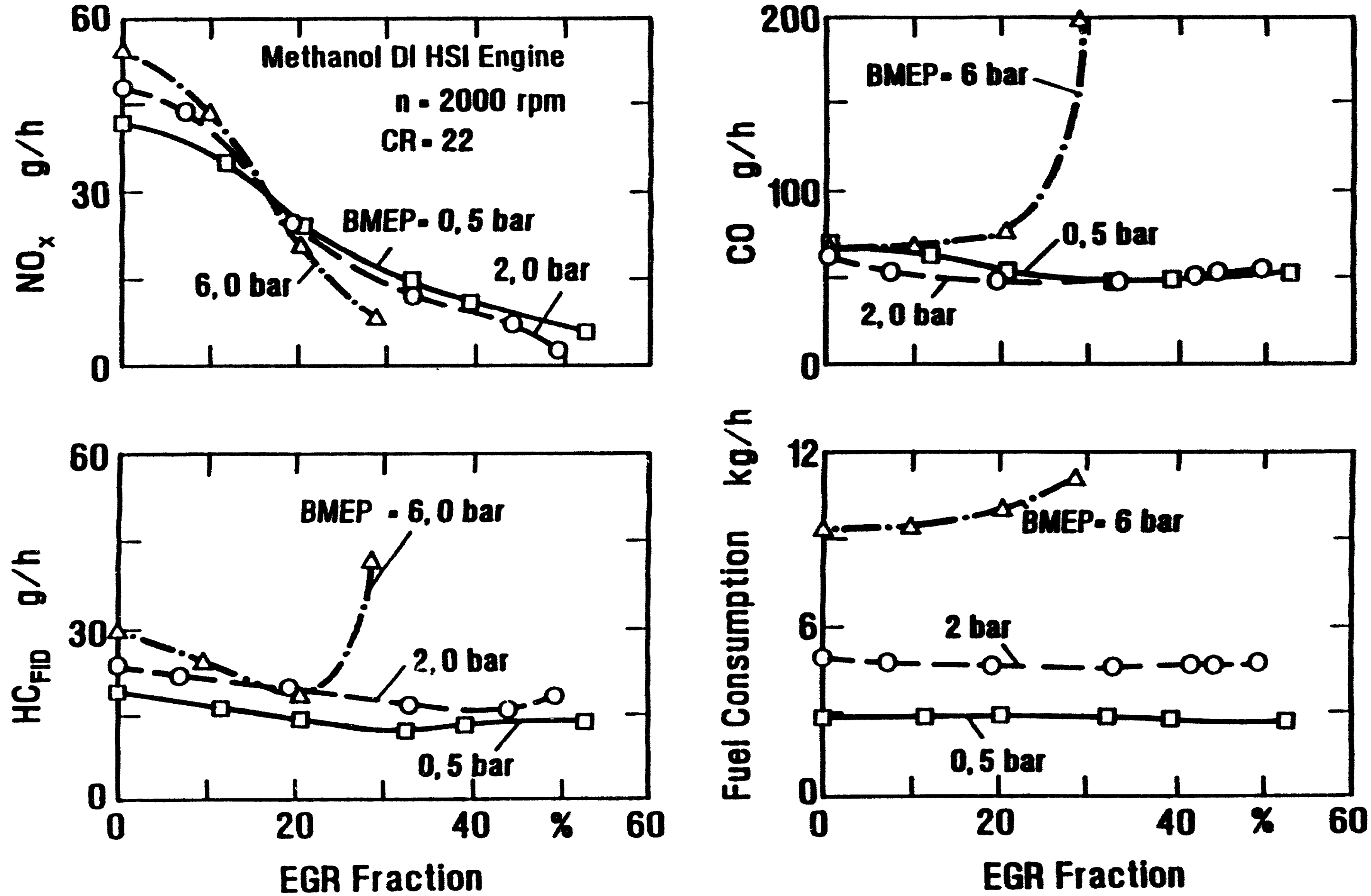


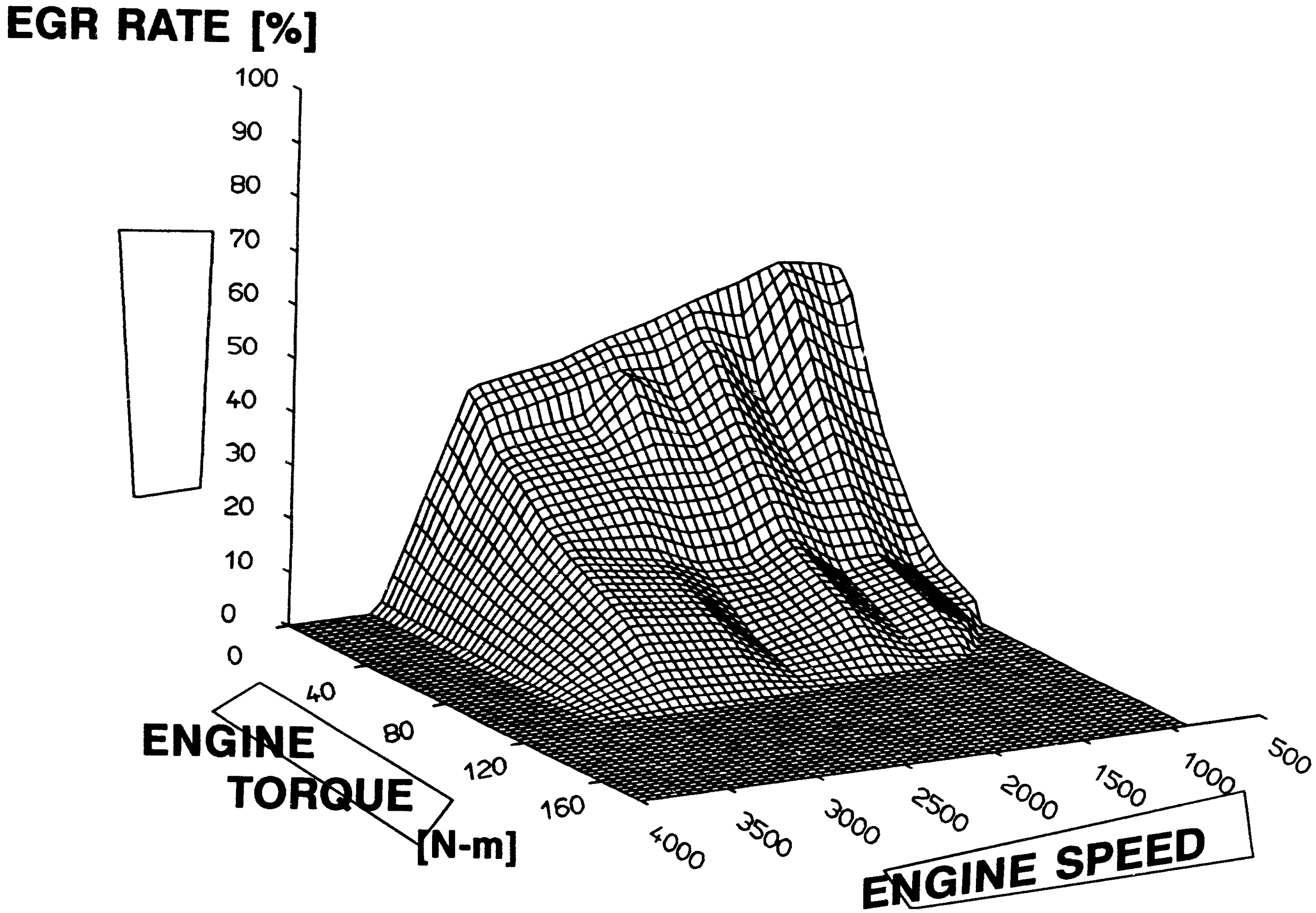
Figure 8[1] : Influence of Dynamic Injection Timing on the Operational Behavior of the DI HSI Methanol Engine

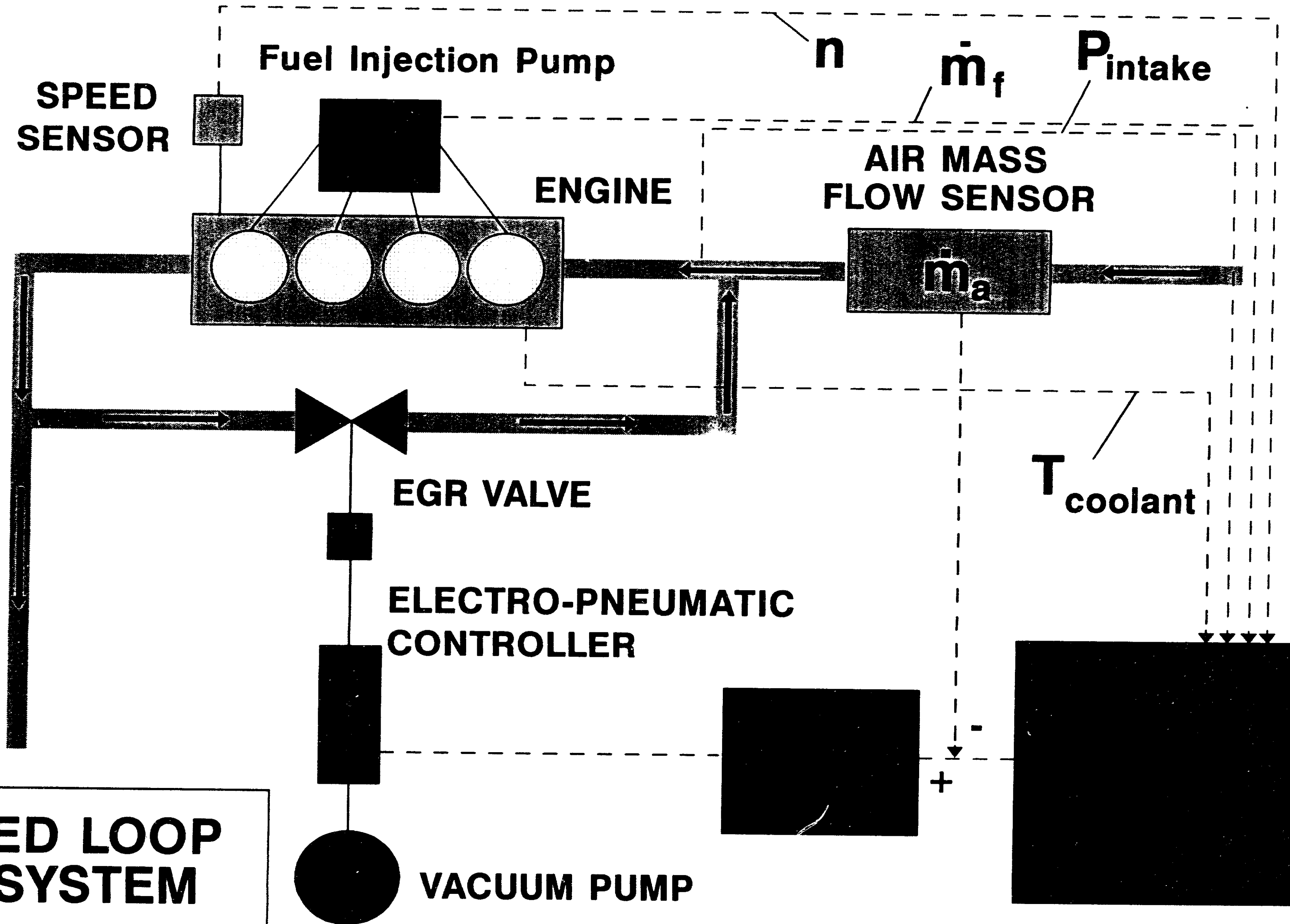
VW 1.9L DI HSI METHANOL ENGINE
EGR RATE [%]




Methanol DI HSI Engine
n = 2000 rpm
CR = 22
BMEP = 0,5 bar
6,0 bar
2,0 bar
NO_x g/h
60
30
0
200
100
0
CO g/h
BMEP = 6 bar
0,5 bar
2,0 bar
60
30
0
HC_{FID} g/h
BMEP = 6,0 bar
2,0 bar
0,5 bar
12
6
0
Fuel Consumption kg/h
BMEP = 6 bar
2 bar
0,5 bar
0
20
40
%
60
EGR Fraction
EGR Fraction

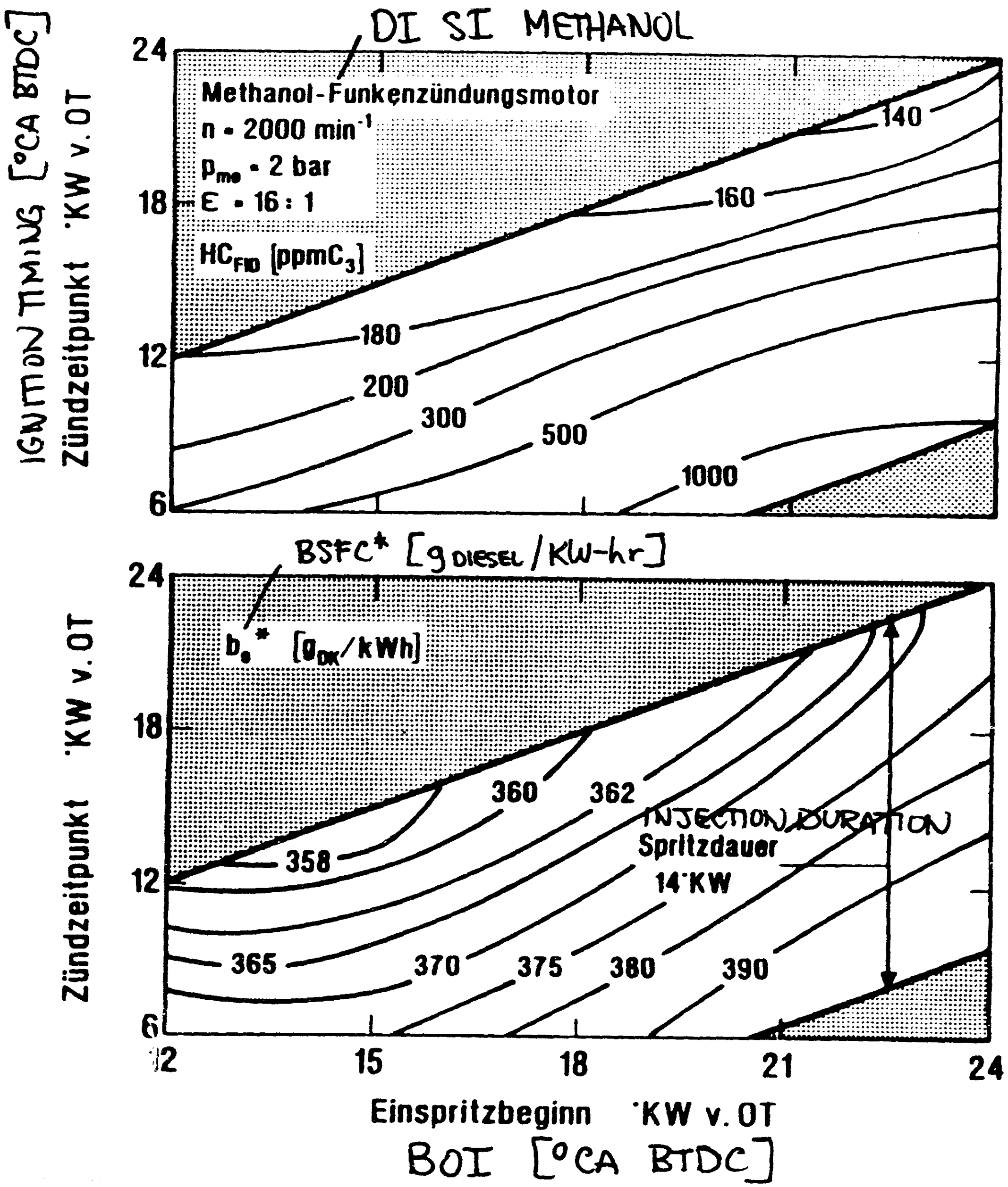
VW 1.7L DI SI METHANOL ENGINE

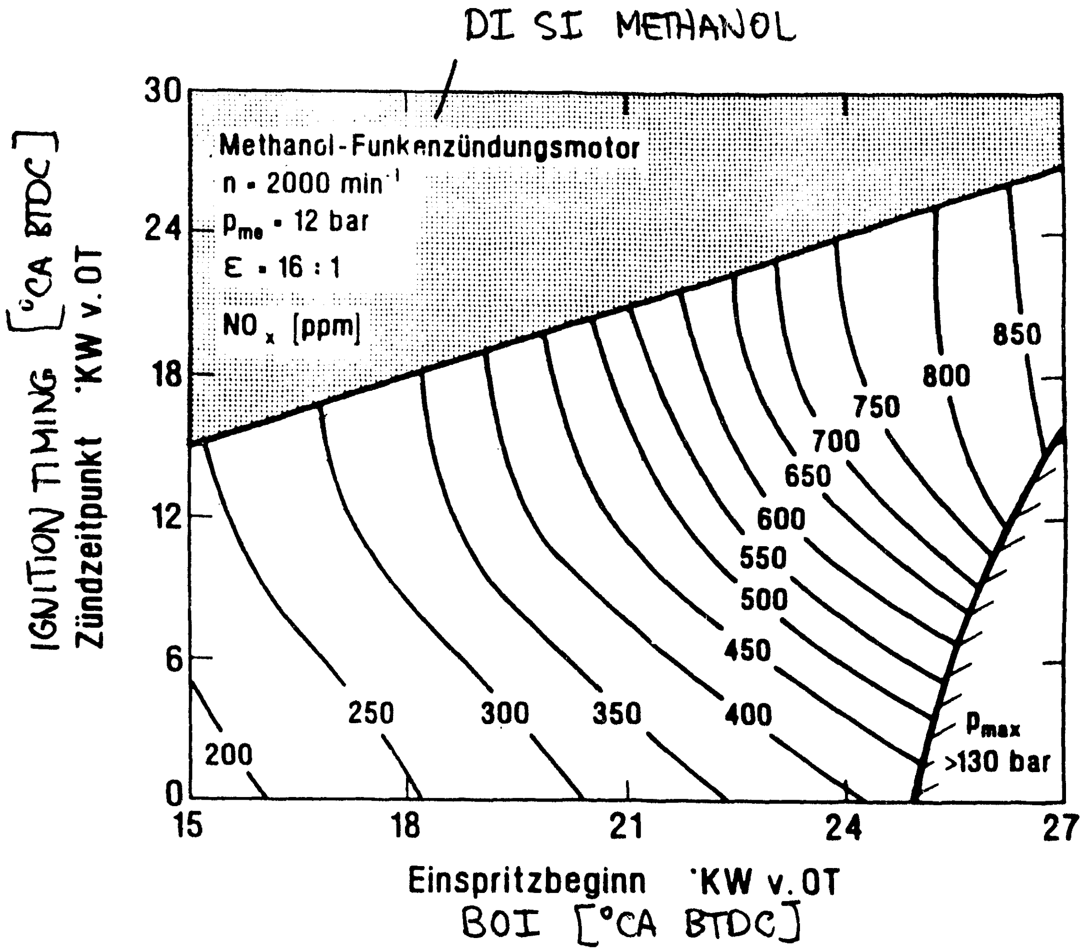


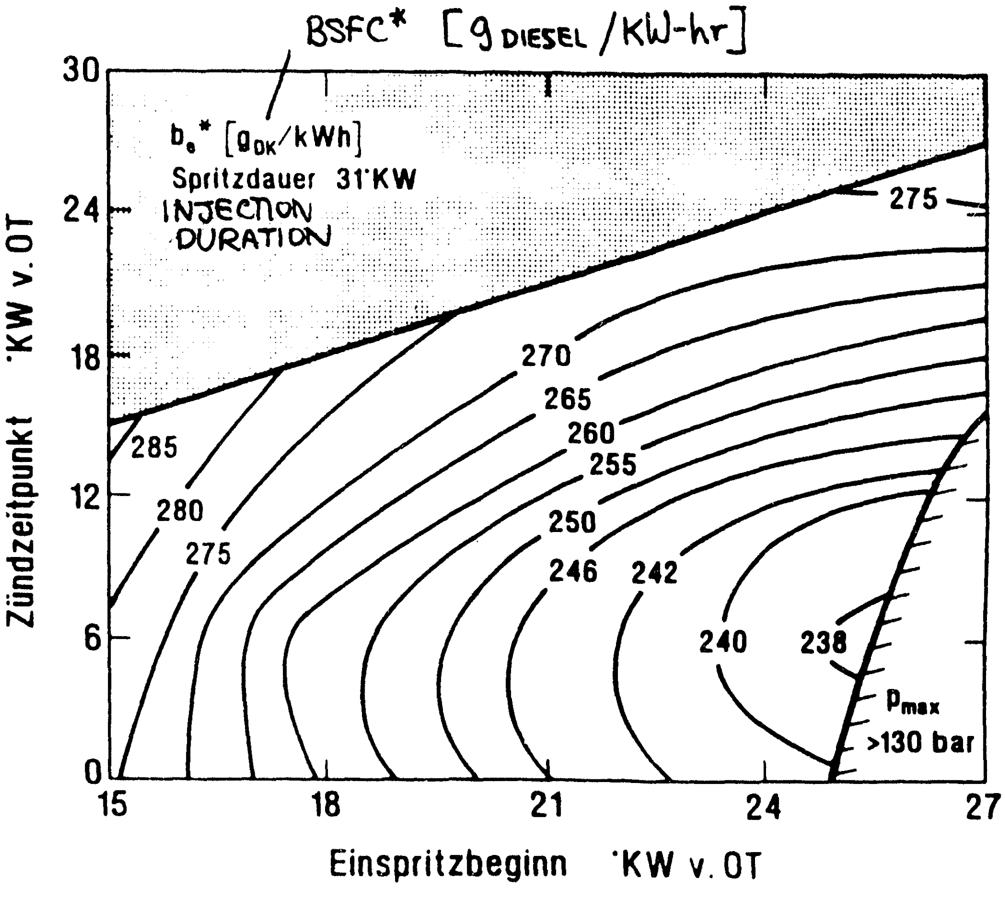


CLOSED LOOP EGR SYSTEM

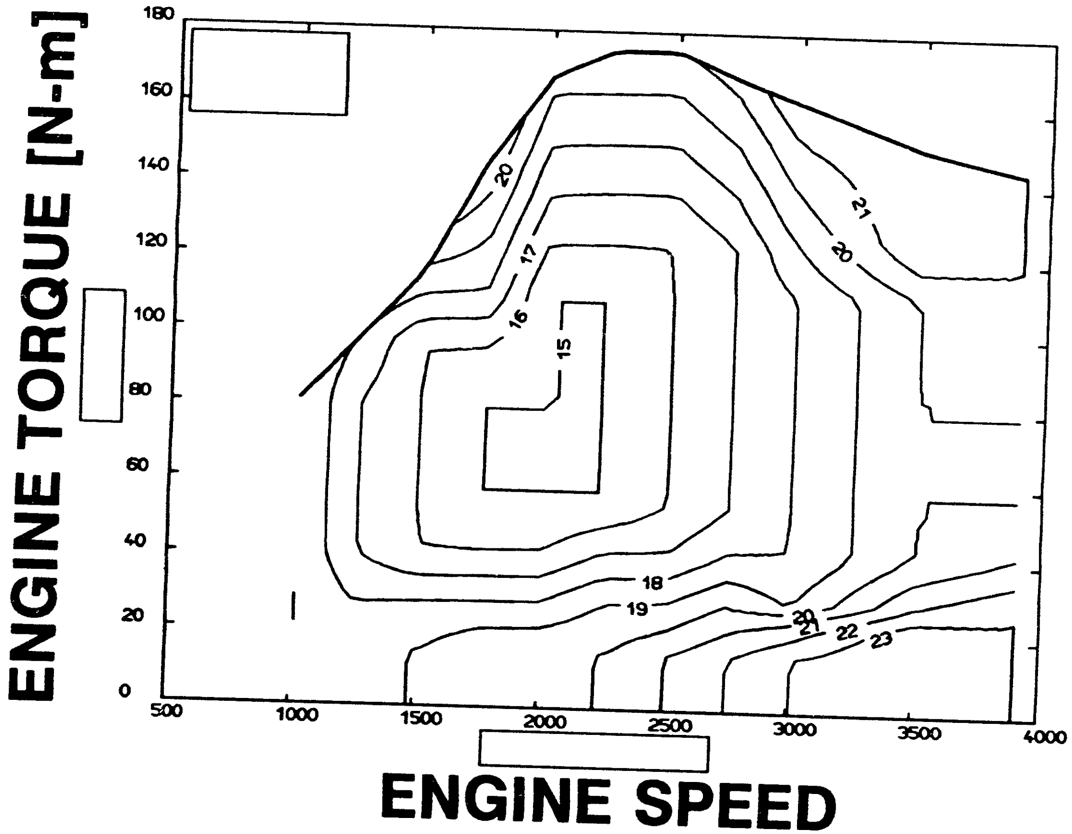
DI, UNTHROTTLED METHANOL ENGINE


DI SI METHANOL
Methanol-Funkenzündungsmotor
n = 2000 min⁻¹
p_me = 2 bar
ε = 16 : 1
HC_FID [ppmC_3]
140
160
180
200
300
500
1000
IGNITION TIMING [°CA BTDC]
Zündzeitpunkt °KW v. OT
24
18
12
6
BSFC* [g DIESEL / KW-hr]
b_e* [g_DK/kWh]
358
360
362
365
370
375
380
390
INJECTION DURATION
Spritzdauer
14°KW
Zündzeitpunkt °KW v. OT
12
15
18
21
24
Einspritzbeginn °KW v. OT
BOI [°CA BTDC]

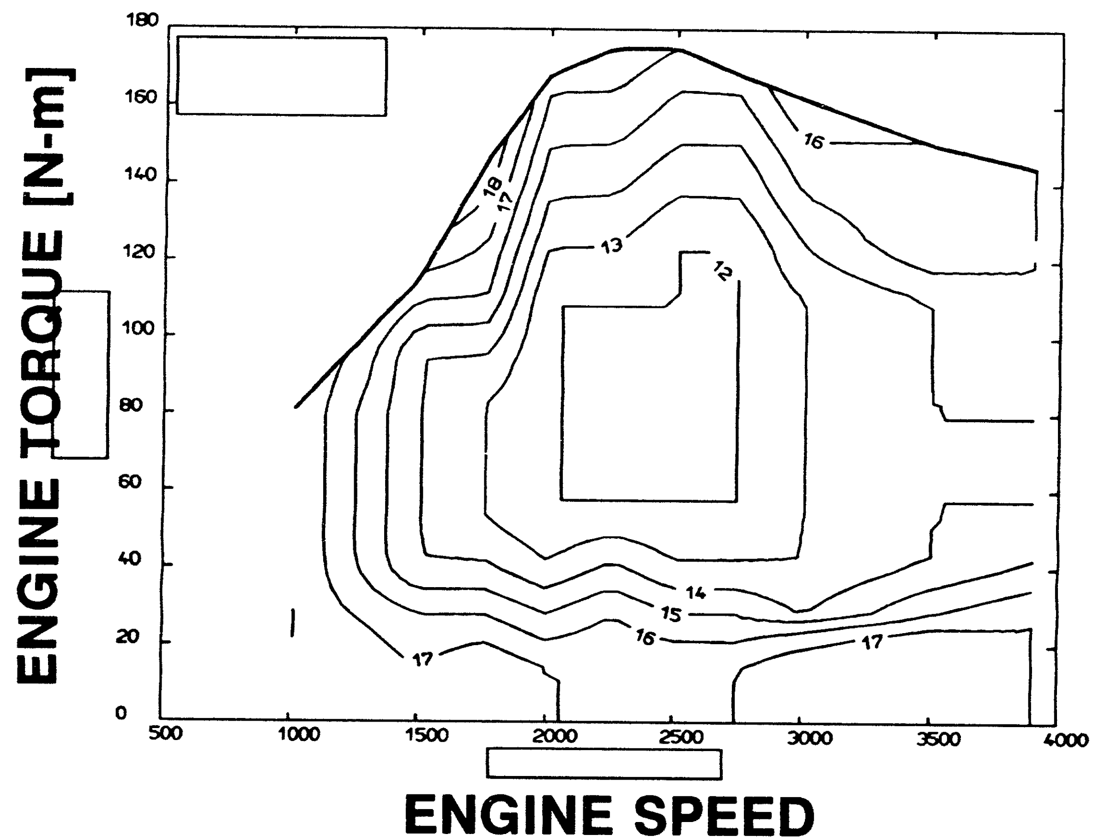

DI SI METHANOL
Methanol-Funkenzündungsmotor
n = 2000 min⁻¹
p_{me} = 12 bar
ε = 16 : 1
NO_x [ppm]
200
250
300
350
400
450
500
550
600
650
700
750
800
850
p_{max} >130 bar
IGNITION TIMING [°CA BTDC]
Zündzeitpunkt °KW v. OT
Einspritzbeginn °KW v. OT
BOI [°CA BTDC]


BSFC* [g DIESEL /KW-hr]
b_e* [g_{DK}/kWh]
Spritzdauer 31°KW
INJECTION DURATION
285
280
275
270
265
260
255
250
246
242
240
238
275
p_{max} >130 bar
Zündzeitpunkt °KW v. OT
Einspritzbeginn °KW v. OT

VW 1.7L DI SI Methanol Engine
Injection Timing



VW 1.7L DI SI METHANOL ENGINE IGNITION TIMING



Future Development Efforts
Electronic Engine Control System

- Further development is necessary with regard to the stability of the injection pump feedback signals as well as the interaction between the controller and the pump.
- Temperature compensation for the Midori sensor must be integrated into the control system concept.
- Closed loop control of the start of fuel delivery is not sufficient. A needle lift based, closed loop control of the actual BOI event should be incorporated.
- Nearly all mechanical position sensors are subject to hysteresis, accuracy and drift problems. A self calibration circuit should be incorporated into the control system.
- The fuel rack position feedback signal is critical to nearly every engine control system. The reliability of this position sensor must be improved.

SUMMARY OF VERBAL COMMENTS OR QUESTIONS AND SPEAKER RESPONSES

DEVELOPMENT STATUS FOR TWO DEDICATED METHANOL ENGINE COMBUSTION TECHNOLOGIES: DI HOT SURFACE IGNITION AND DI SPARK IGNITED STRATIFIED CHARGE
R.J. Last, FEV Engine Technology Inc.

Q. Robert Siewert, General Motors: One of your slides showed a large reduction in NOx emissions.

A. Yes, that was showing the influence of exhaust gas recirculation (EGR).

Q. What was the variation in EGR?

A. Under low load conditions, EGR rates were up to 50 percent. As the load was increased, percent EGR decreased sharply. The first 10 percent EGR normally gives the largest amount of NOx reduction.

1993 WINDSOR WORKSHOP ON ALTERNATIVE FUELS

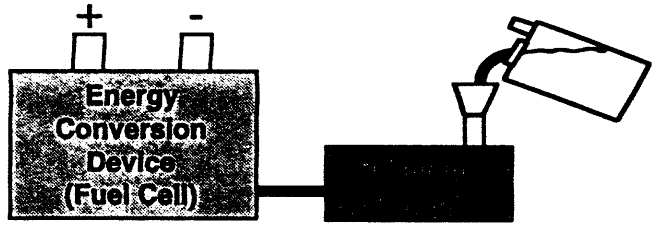
FUEL CELL POWERED ZEV BUS

P. Howard
Ballard Power Systems

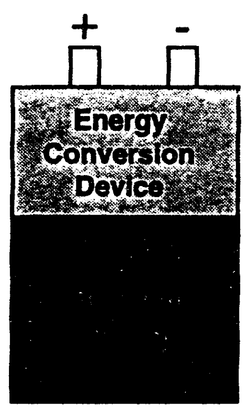
Outline

- Introduction
  - Technology
  - Company
  - Marketing Approach
  - Transit Bus Market
- Demonstration Program - 32′ ZEV PEM Fuel Cell / Electric Bus
  - Purpose
  - Organization
  - Scope
  - Performance
  - Technical Approach
  - Achievements/Results
- Commercialization Plan - 40′ ZEV PEM Fuel Cell / Electric Transit Bus
  - Overall Plan
  - Commercial Prototype
  - Motive Stack Development
- Alliances
- Benefits
- Acknowledgements

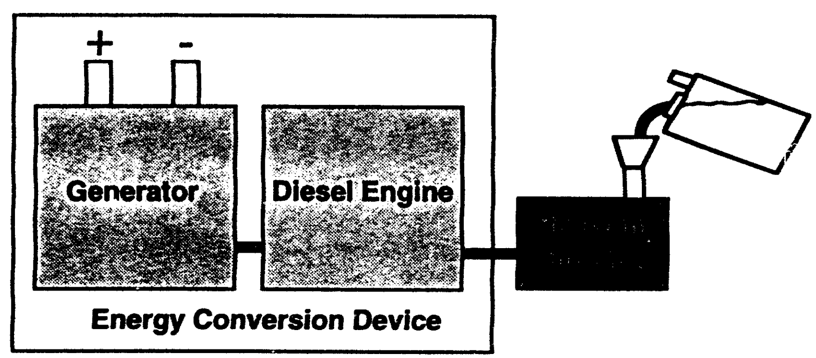
Fuel Cell Technology



Fuel Cell System



Battery



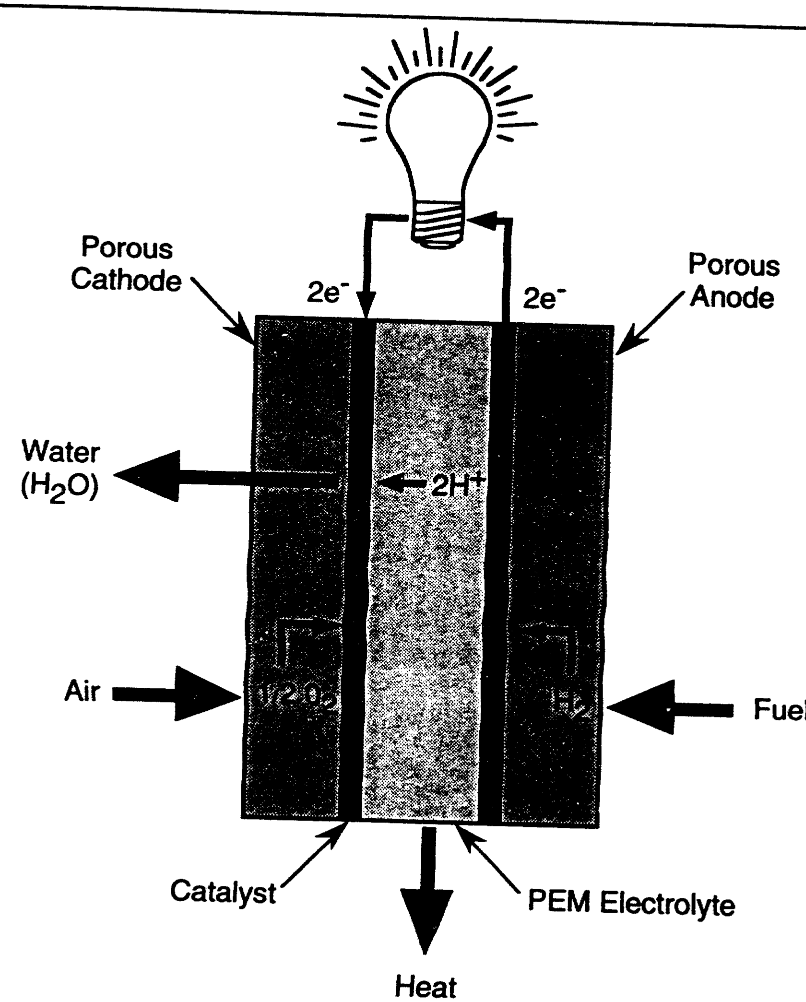
Diesel/Generator Set

Advantages

- Electricity Without Combustion
- Continuous Production of Electricity as Long as Fuel Supplied
- Environmentally Clean
- High Efficiency
- Low Noise
- Modular and Compact

Ballard

Proton Exchange Membrane Fuel Cell



Ballard

Company

- Business - Develop/Manufacture/Market PEM Fuel Cell Systems
- Incorporated 1979
  - Began PEM Fuel Cell Development in 1984
  - Membrane Research (BAM)
  - Battery Manufacturing (BBS)
- Employees - 150
- 60,000 ft^2 in North Vancouver, British Columbia

Marketing Approach

- Market "Push/Pull"
- OEM "Push" - OEMs Adapt Ballard Fuel Cell Systems
- End User "Pull" - Demonstration Programs
  - Secure Programs in Motive/Utilities/Military Sectors
  - End Users Motivate OEMs
  - Government Funding Assistance
- Bus Program - End User is BC Transit

Market Creation

		Air Quality Regulations (Emissions, gm/mile)			Implementation Schedule									
		HC	NOx	CO	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
	Tier 1 Standard	0.250	0.4	3.4	80%	85%	80%	73%	48%	23%				
TLEV	Transitional Low Emission Vehicle	0.250	0.4	3.4	10%	15%	20%							
LEV	Low Emission Vehicle	0.075	0.2	3.4				25%	48%	73%	96%	90%	85%	75%
ULEV	Ultra Low Emission Vehicle	0.040	0.2	1.7				2%	2%	2%	2%	5%	10%	15%
ZEV	Zero Emission Vehicle	0.000	0.0	0.0					2%	2%	2%	5%	5%	10%

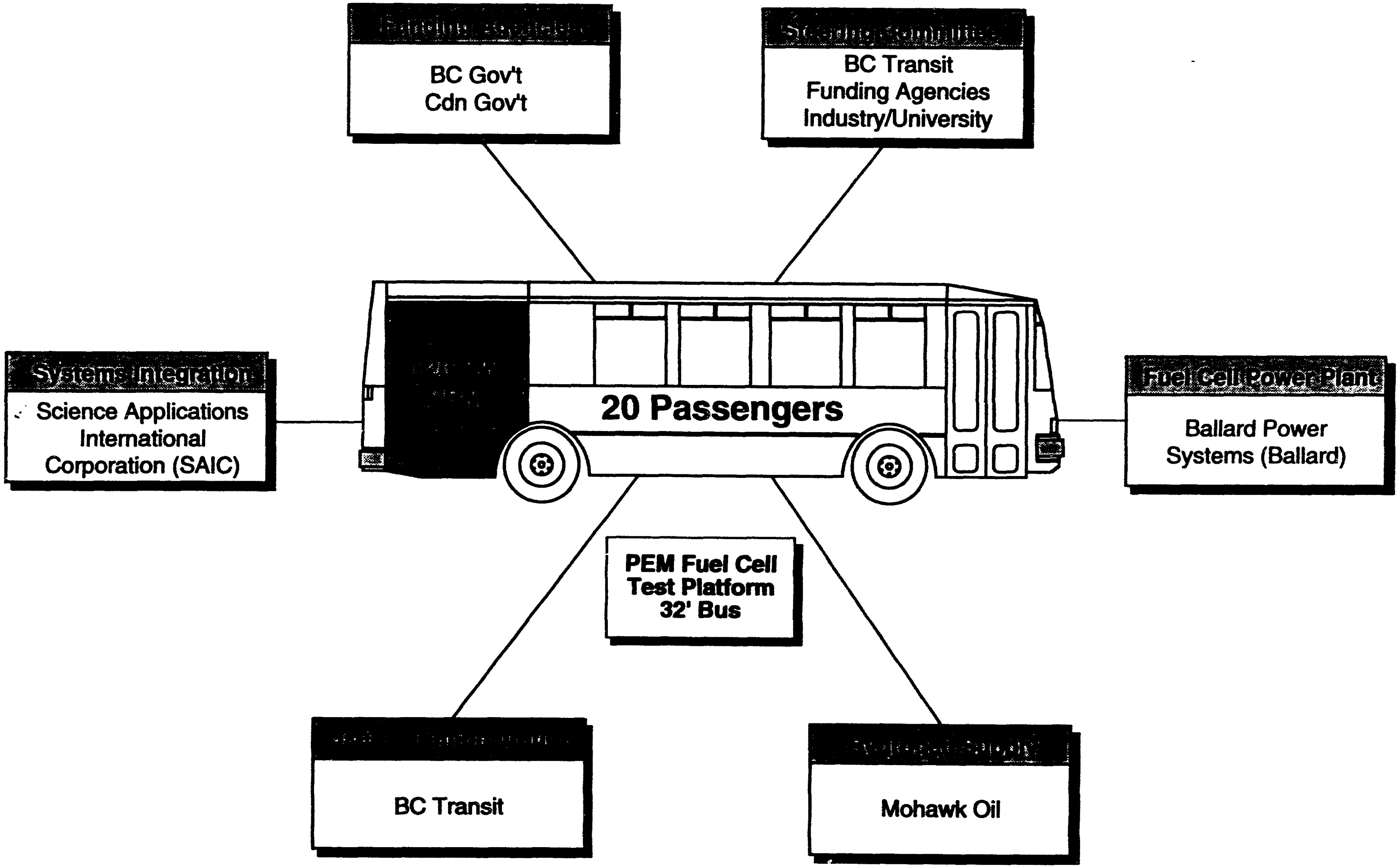
- California Legislation
  - 2% ZEV Cars in 1998
  - Bus / Locomotive / Truck in Draft
- ICE ***cannot*** meet ZEV — Electric Vehicle Market Created
- Credit Market — CARB Mobile Source Emission Credit

Transit Bus Choices

- Electrified Line - Trolley / Third Rail
- Battery
- Fuel Cell

Demonstration Program - Purpose

- Show PEM Fuel Cell Transportation Capability
- Advance Market Acceptance
  - OEMs
  - End Users
- Accelerate Commercialization
  - Market Entry Bus in 1996
  - Commercial Bus in 1998



Demonstration Program Organization

Ballard

Demonstration Program - Scope

- Transit Bus - Powered by Ballard PEM Fuel Cells
- Zero Emission Vehicle (ZEV) - Hydrogen
- Performance $\geq$ Diesel "Driver Acceptability"
- October 1990 to March 1993 - 30 Months
- $4.84 Million Assistance
- Demonstrate with a Transit Authority

Ballard

Demonstration Program - Performance

- White Book Requirements (UMTA)

Top Speed	60 mph (95 km/h)
Gradability	Maintain 44 mph (70 km/h) on 2.5% grade
	Maintain 7 mph (11 km/h) on 16% grade
Acceleration	0 to 30 mph (50 km/h) in 19 seconds
Range	350 miles (560 km)

- Meets or Exceeds White Book Performance
- Range to be met in Commercial Prototype

Ballard

Demonstration Program - Technical Approach

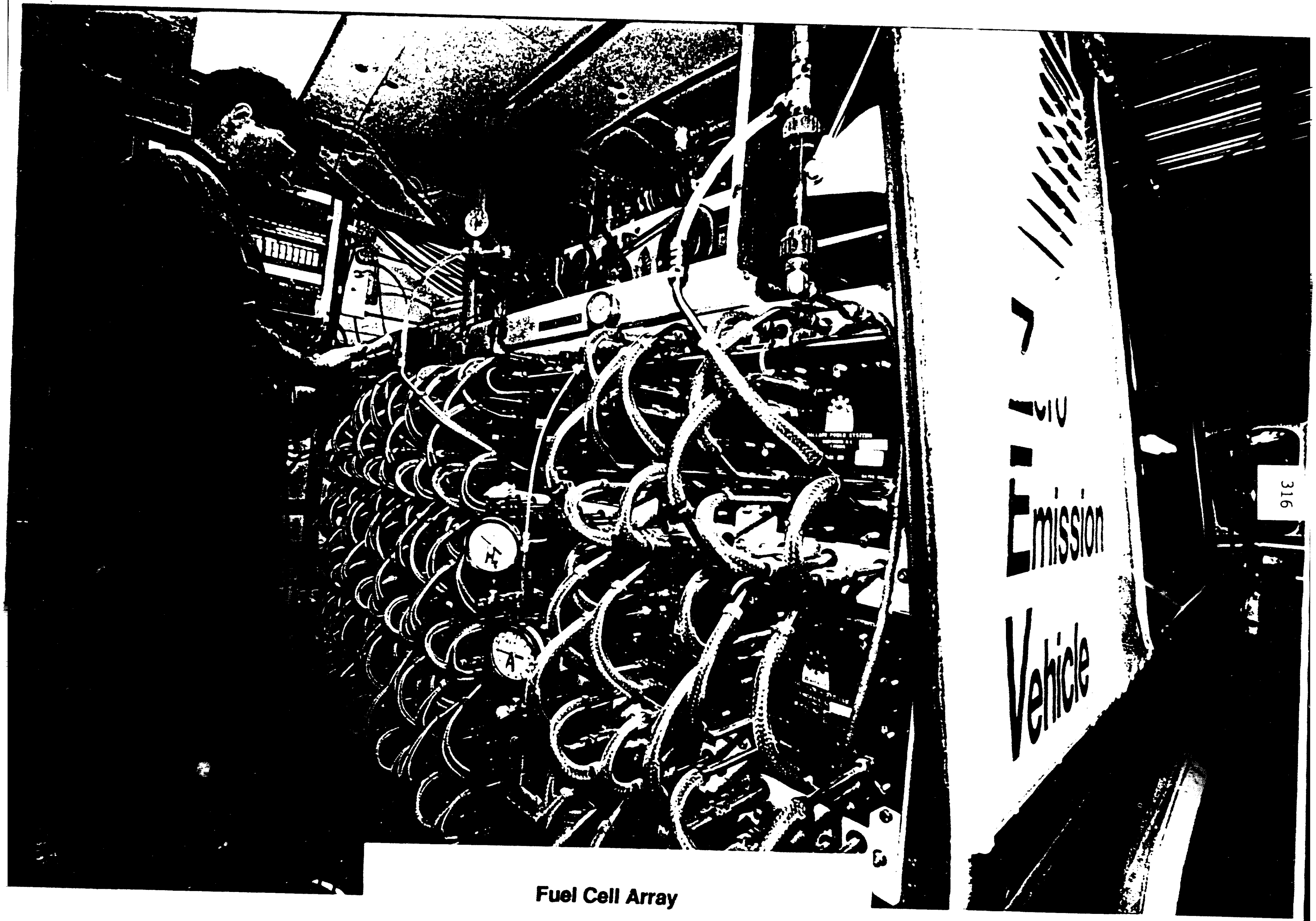
- Ballard MK5 Stack - 20 Vdc/5kW
- Hydrogen Fuel Storage @ 3000 psi
- 32′ Light-duty Transit Bus
- Commercial Components for Ancillaries
- Automotive Compressor/Turbocharger for Air Pressurization
- Conventional, Reliable DC Motor and Control
- Weight Tradeoff
  - Range - 100 miles (160 km)
  - Passengers - 20

Ballard

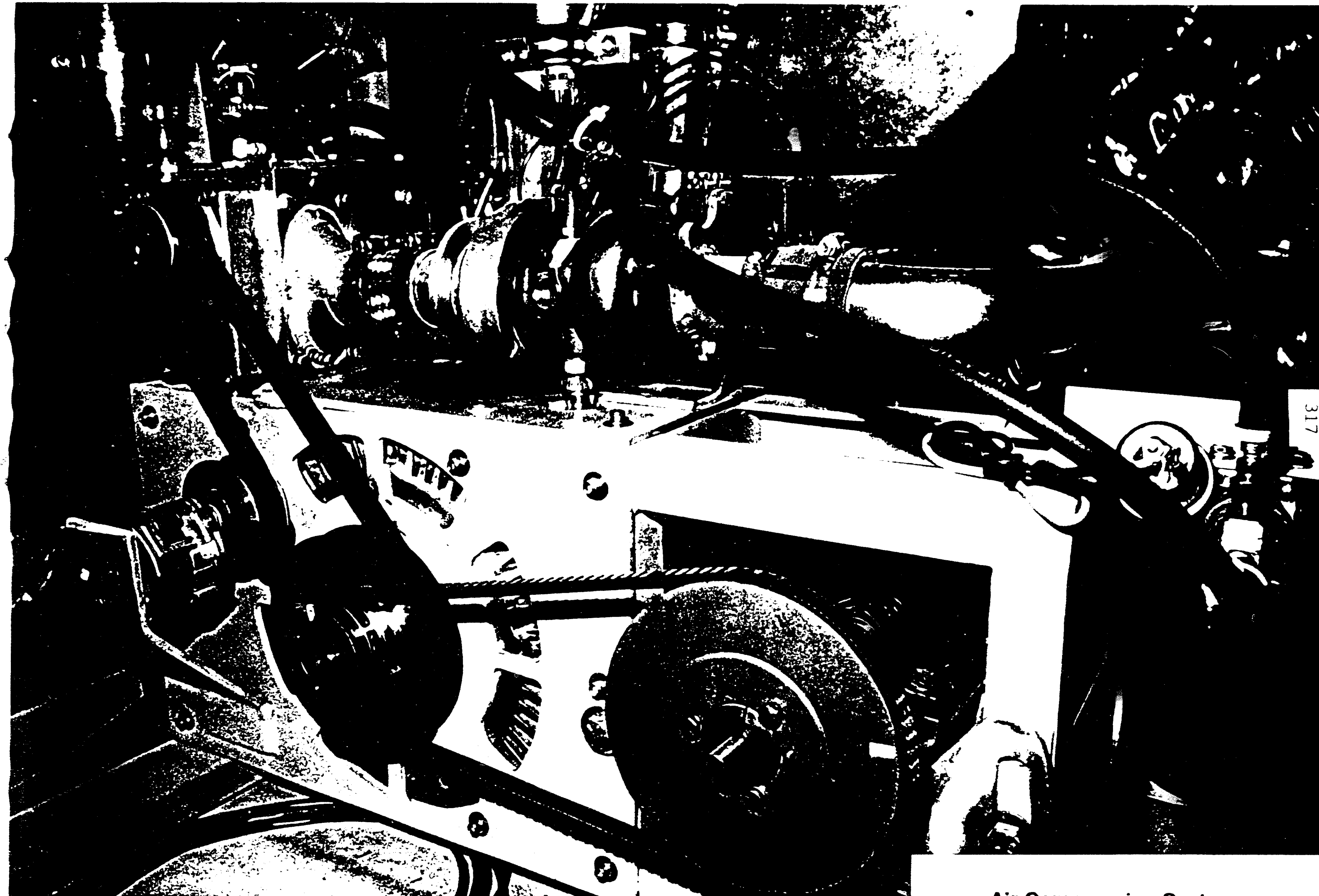
PEM Fuel Cell Powered Transit Bus

Zero Emission Vehicle (ZEV)

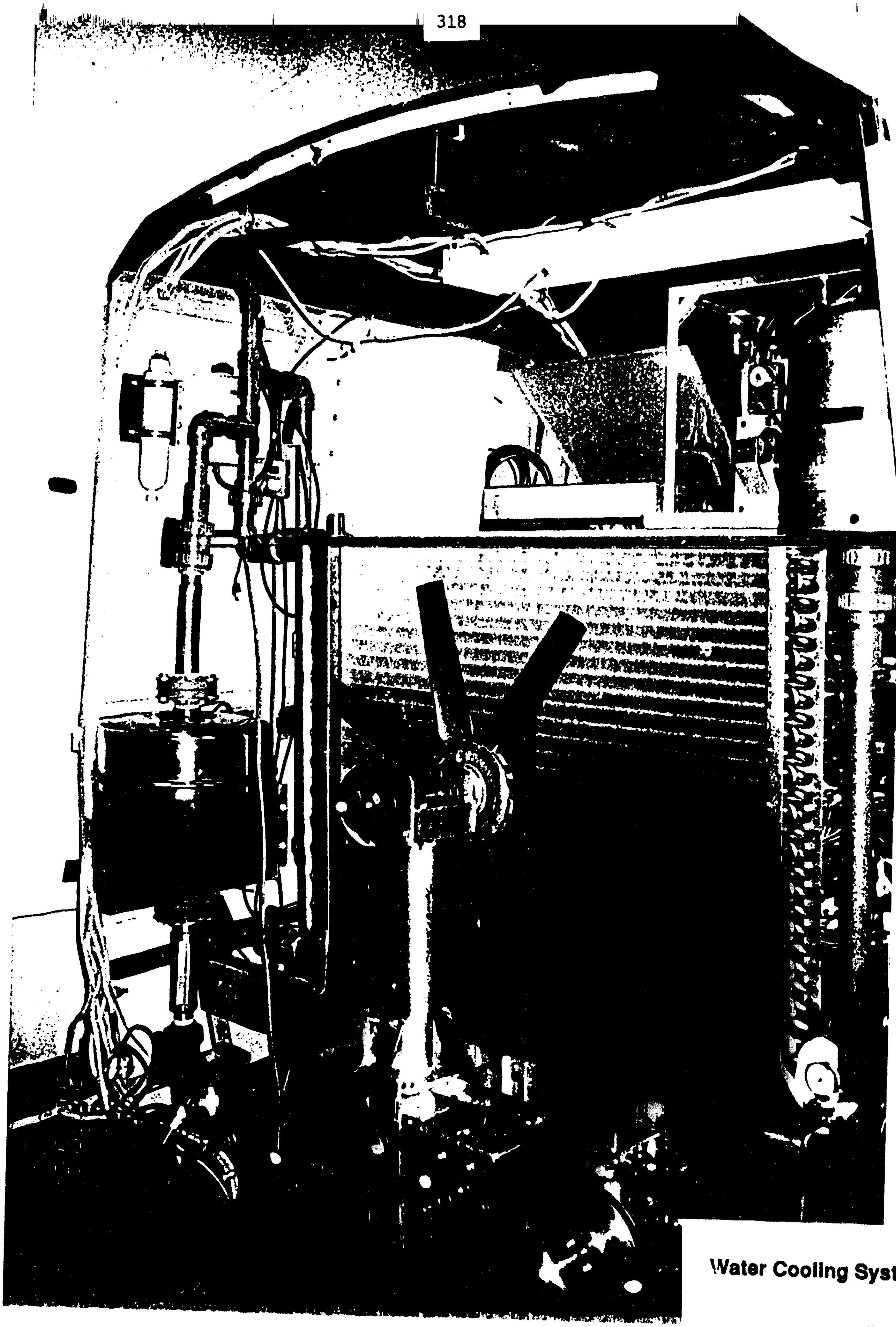
Bus Illustration



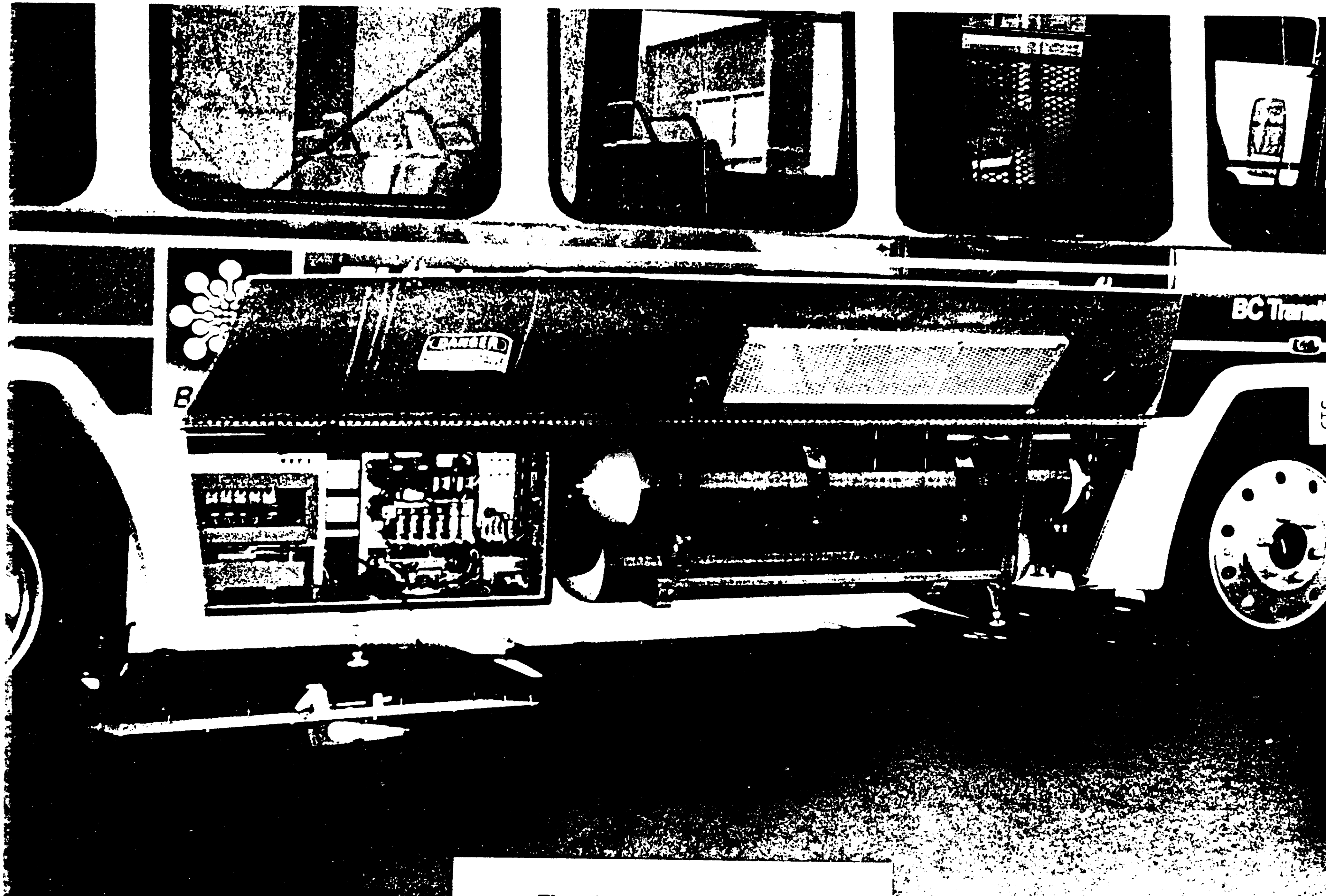
Fuel Cell Array



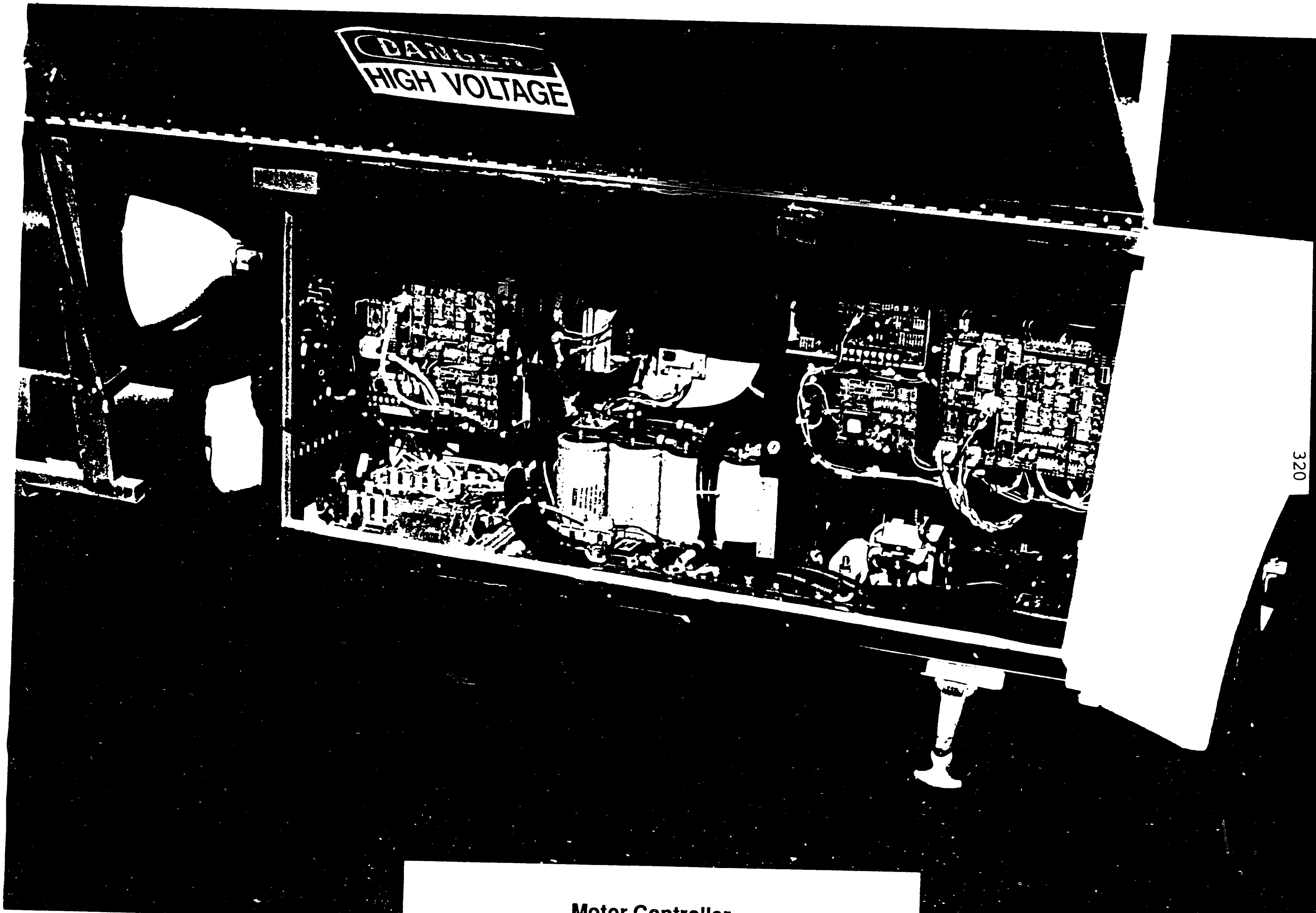
Air Compression System



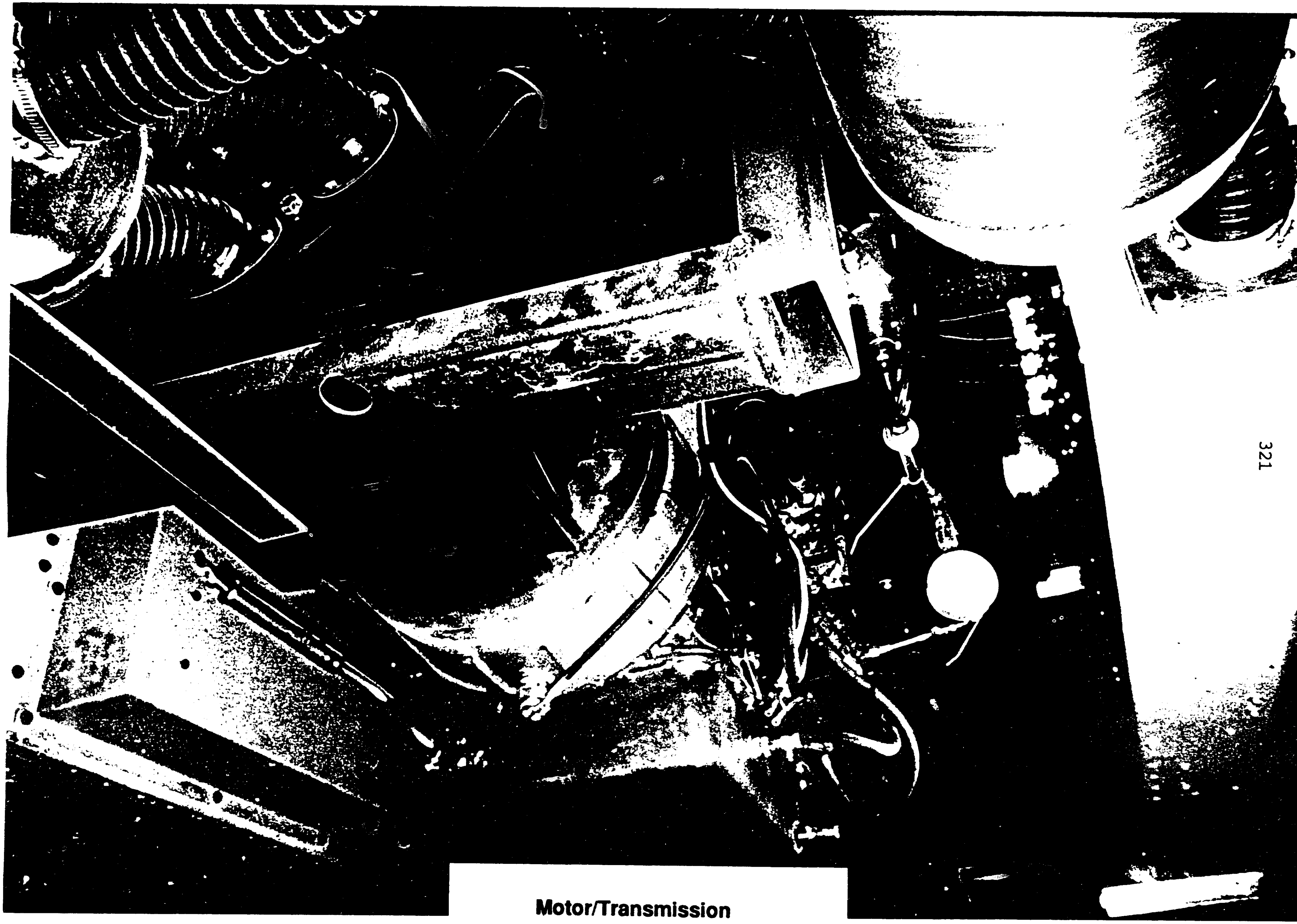
Water Cooling System

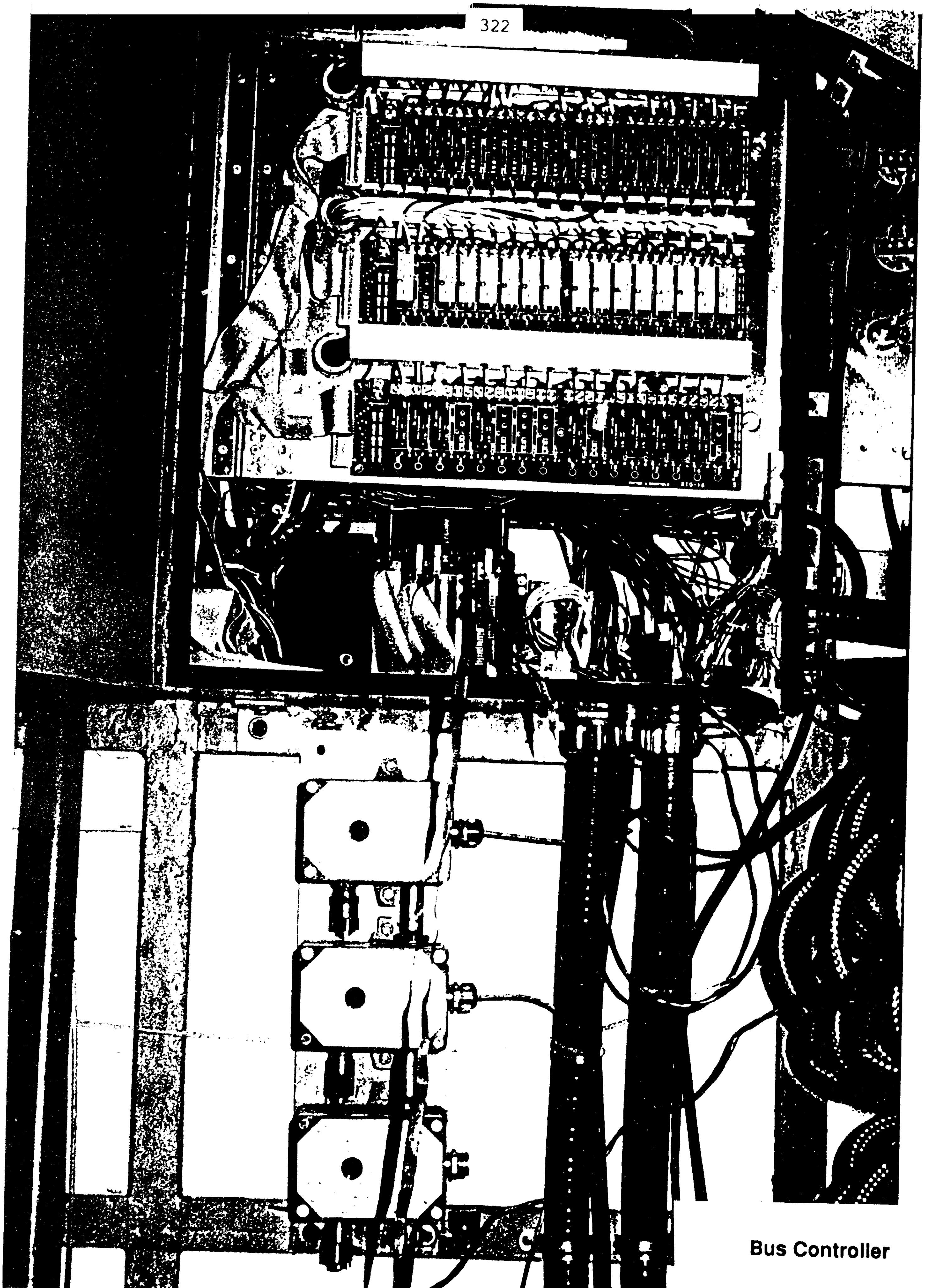


Electrical Distribution Panel

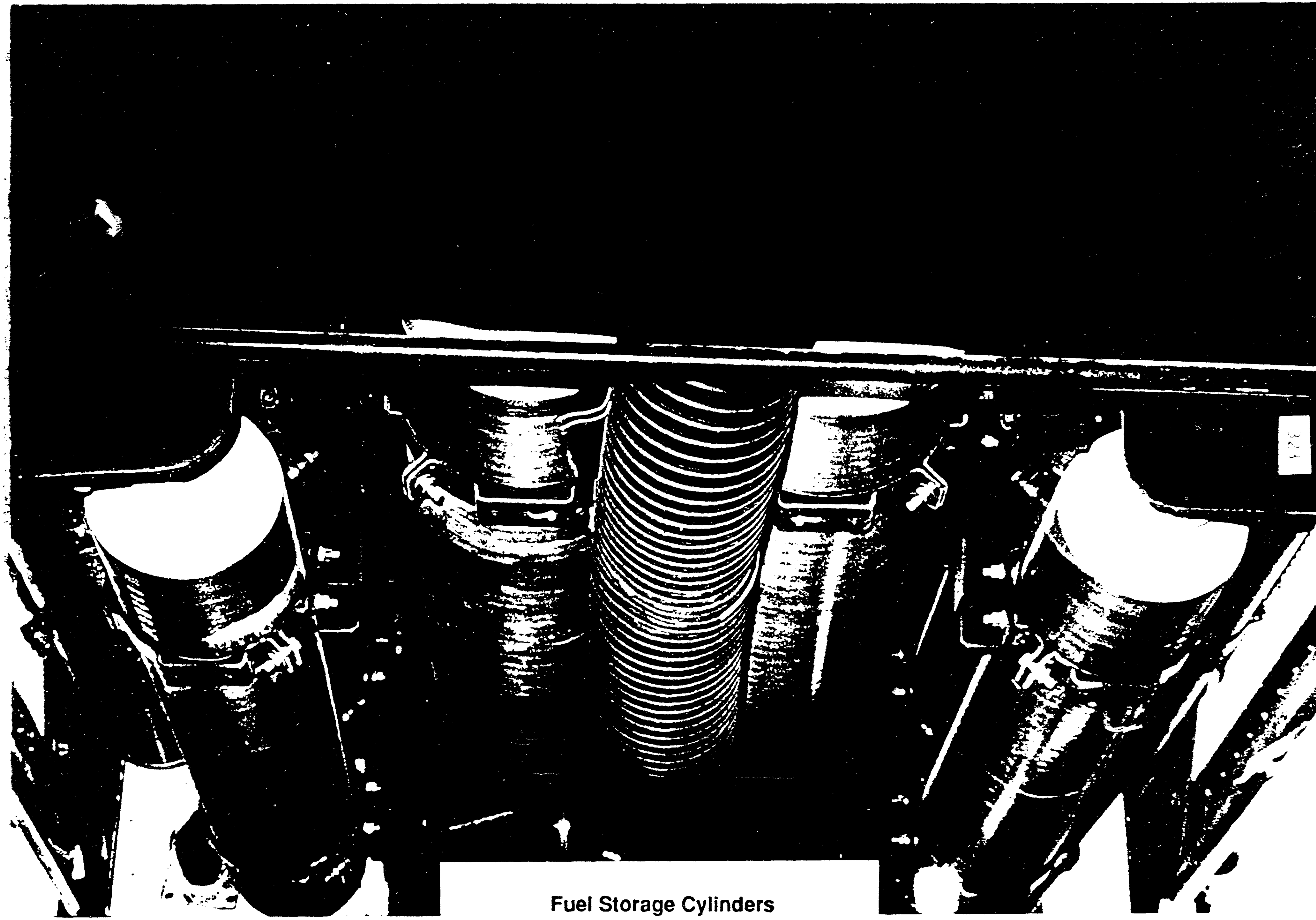


Motor Controller


Motor/Transmission



Bus Controller

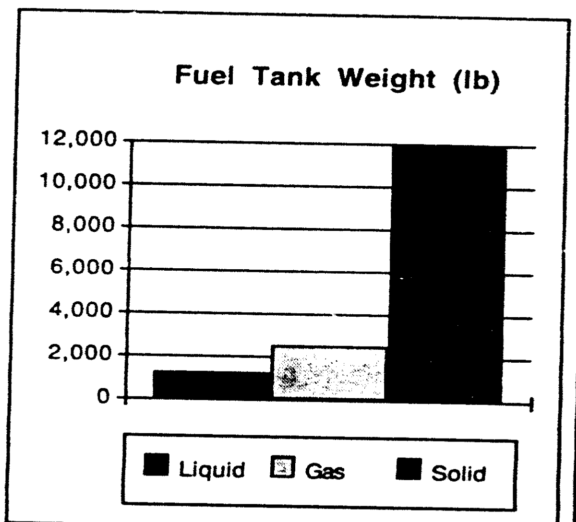


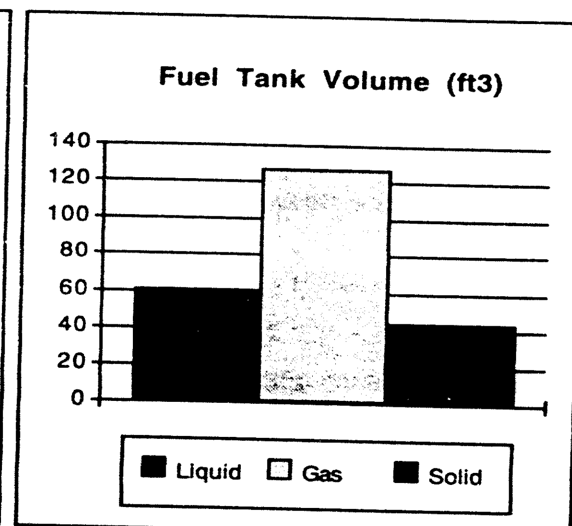
Fuel Storage Cylinders

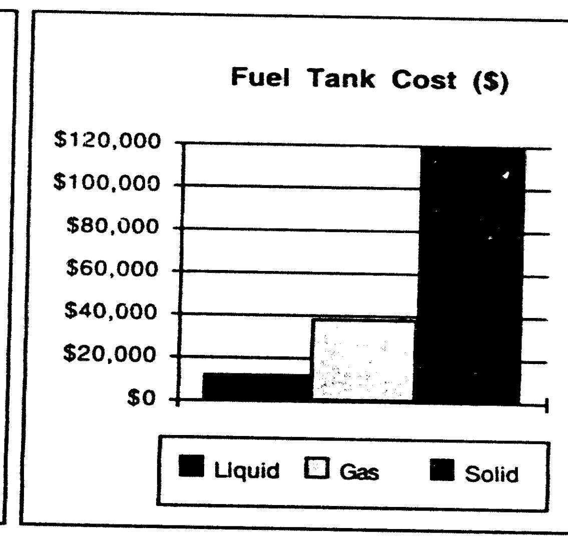
Ballard

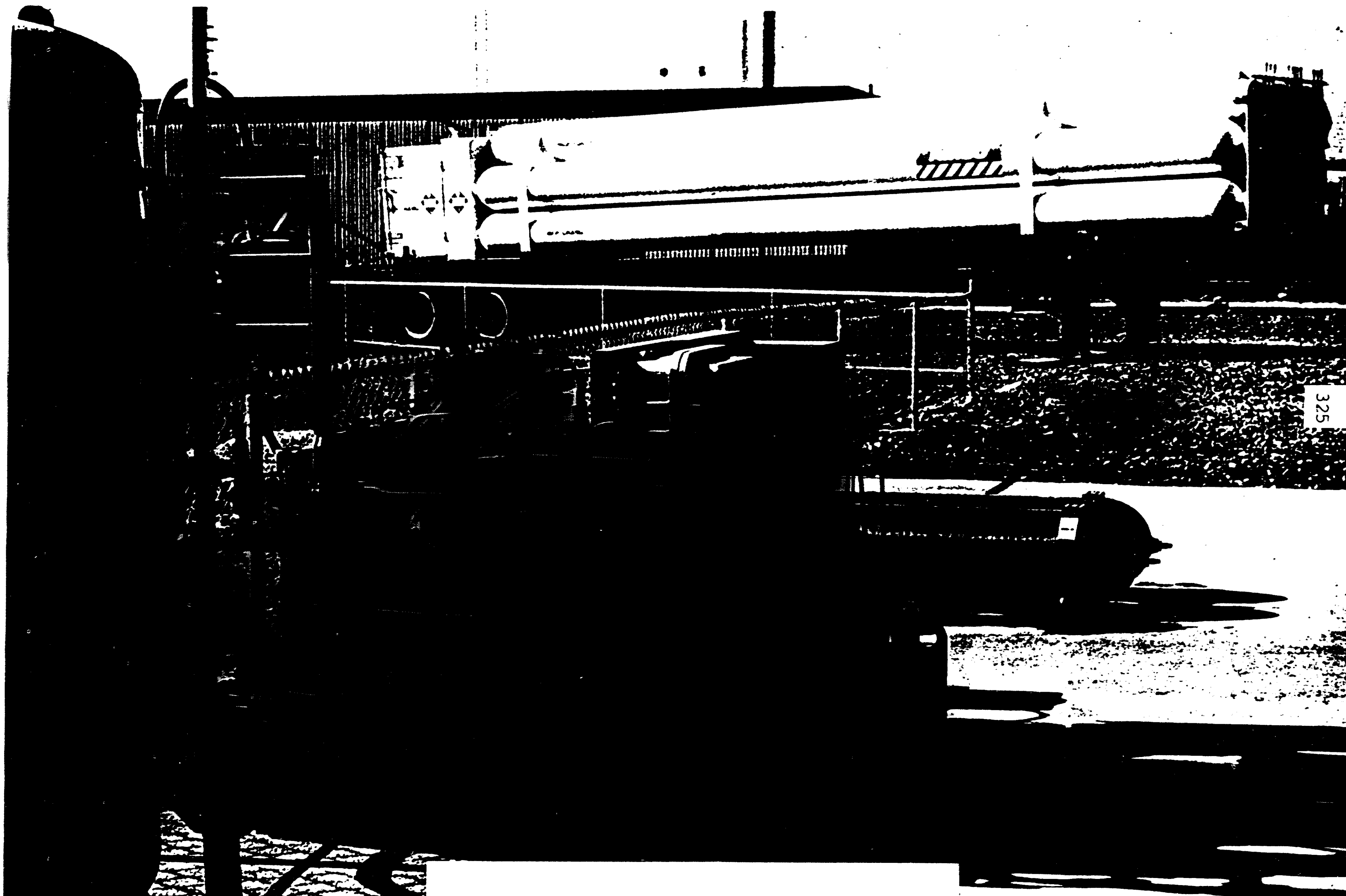
Fuel Storage/Range

- Hydrogen is Required to Meet ZEV Requirement
- Method must be Demonstratable Today — Liquid at -253°C / Gas at 5000 psi
- Bus Range of 350 miles - 180 lb/300 gallons Hydrogen









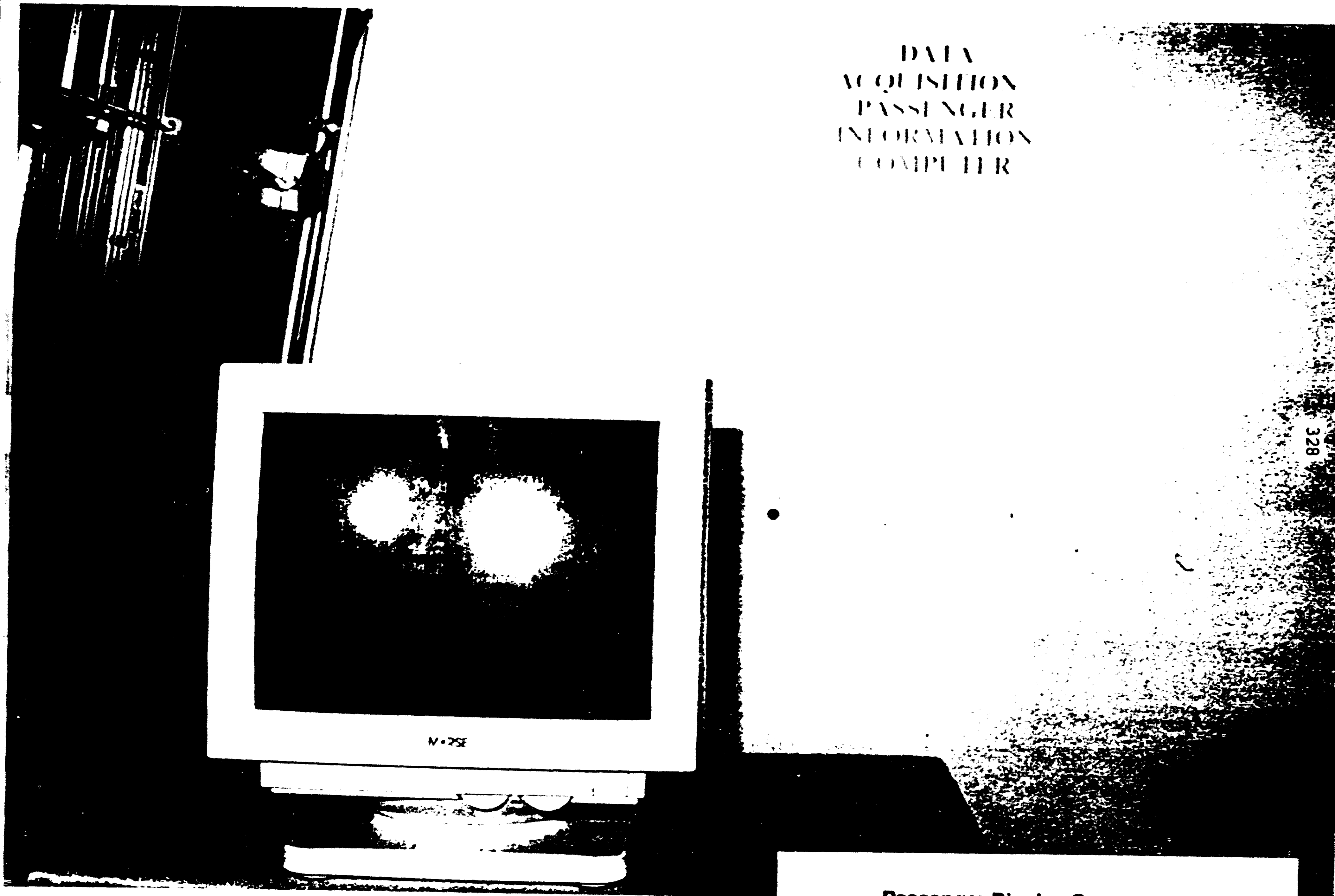
Refuelling Facility

Ballard

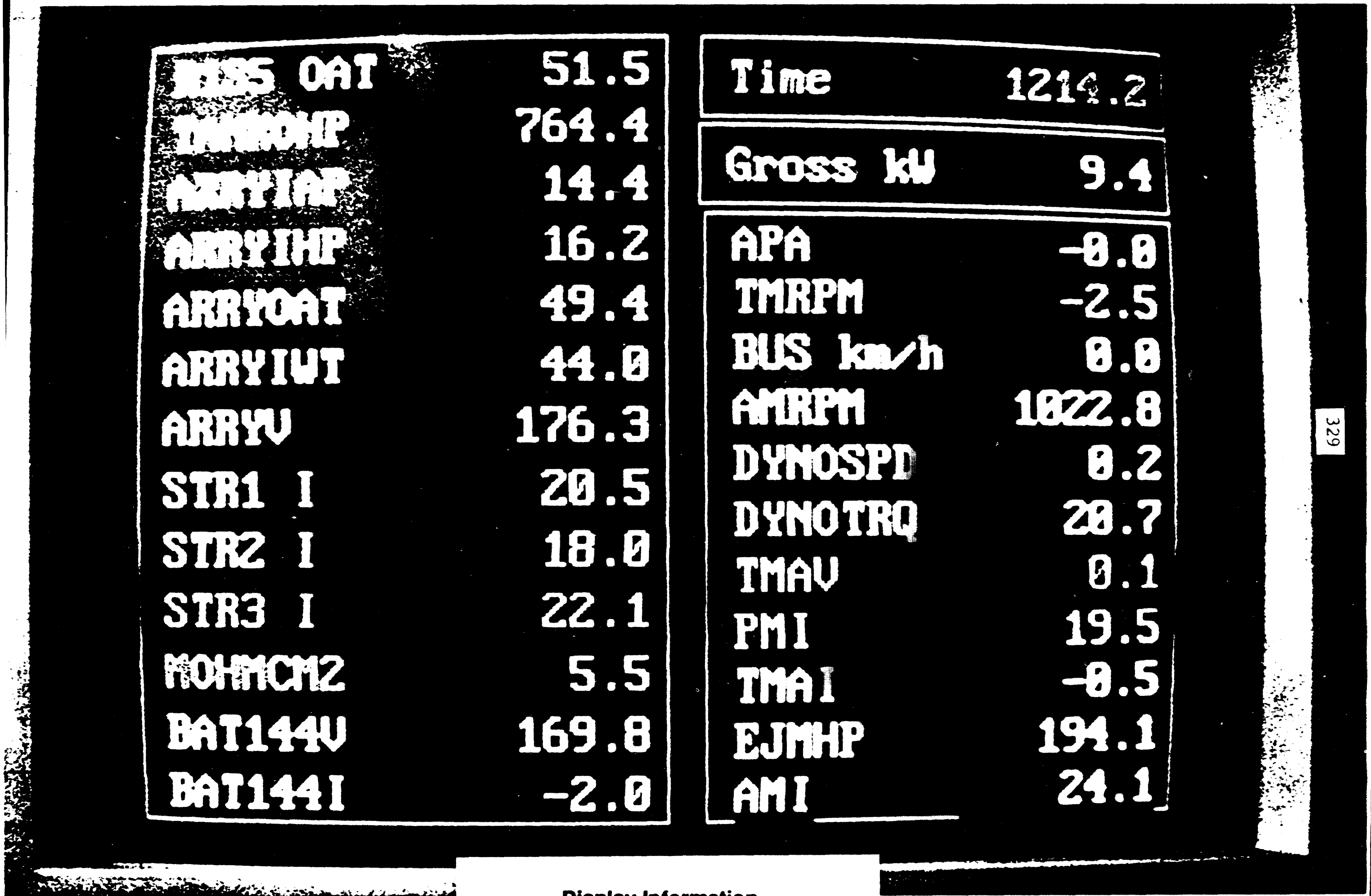
Refuelling/Cost

- Point Source Production
  - Natural Gas Reforming
  - Water Electrolysis
- Well Developed Commercial Technology - Suited for a Bus Depot
- Hydrogen Fuel Cost ~ $0.75/lb ($0.45/gallon)
- Fuel Cost/Mile - Comparable to ICE with Diesel

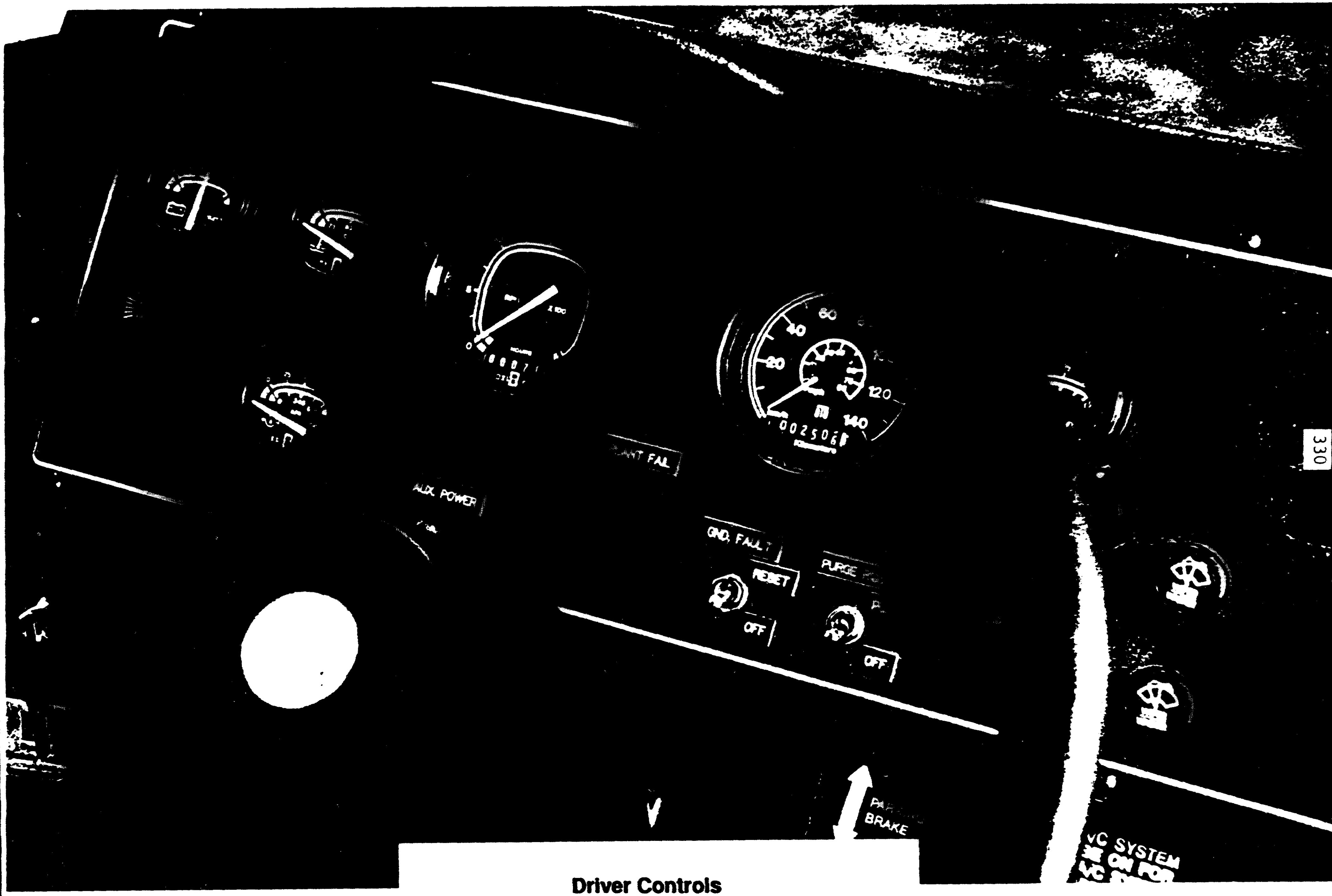
Bus Interior



Passenger Display Computer



Display Information



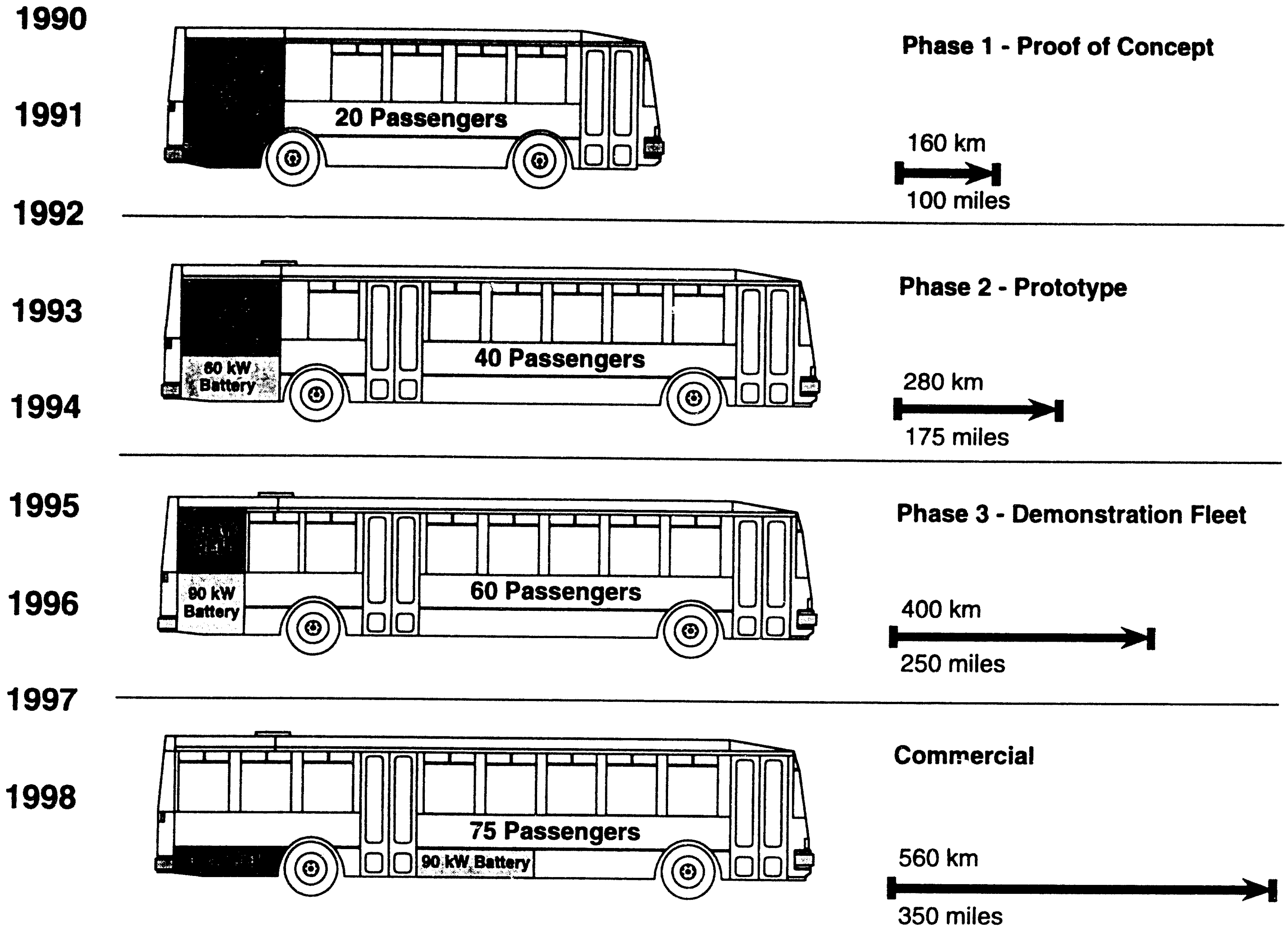
Driver Controls

Complete Bus/Wheelchair Lift

Ballard

Demonstration Program - Achievements

• Startup	Instantaneous - 4 seconds
• Dynamic Response	Accelerator Command Rapid Response < 0.1 second Simulated Routes
• Full Power (Air)	Highest Power - 120 kW Highest Voltage - 280 Vdc Largest System - 24 stacks
• Efficiency	47%
• Bus Works	



Commercialization Plan

Ballard

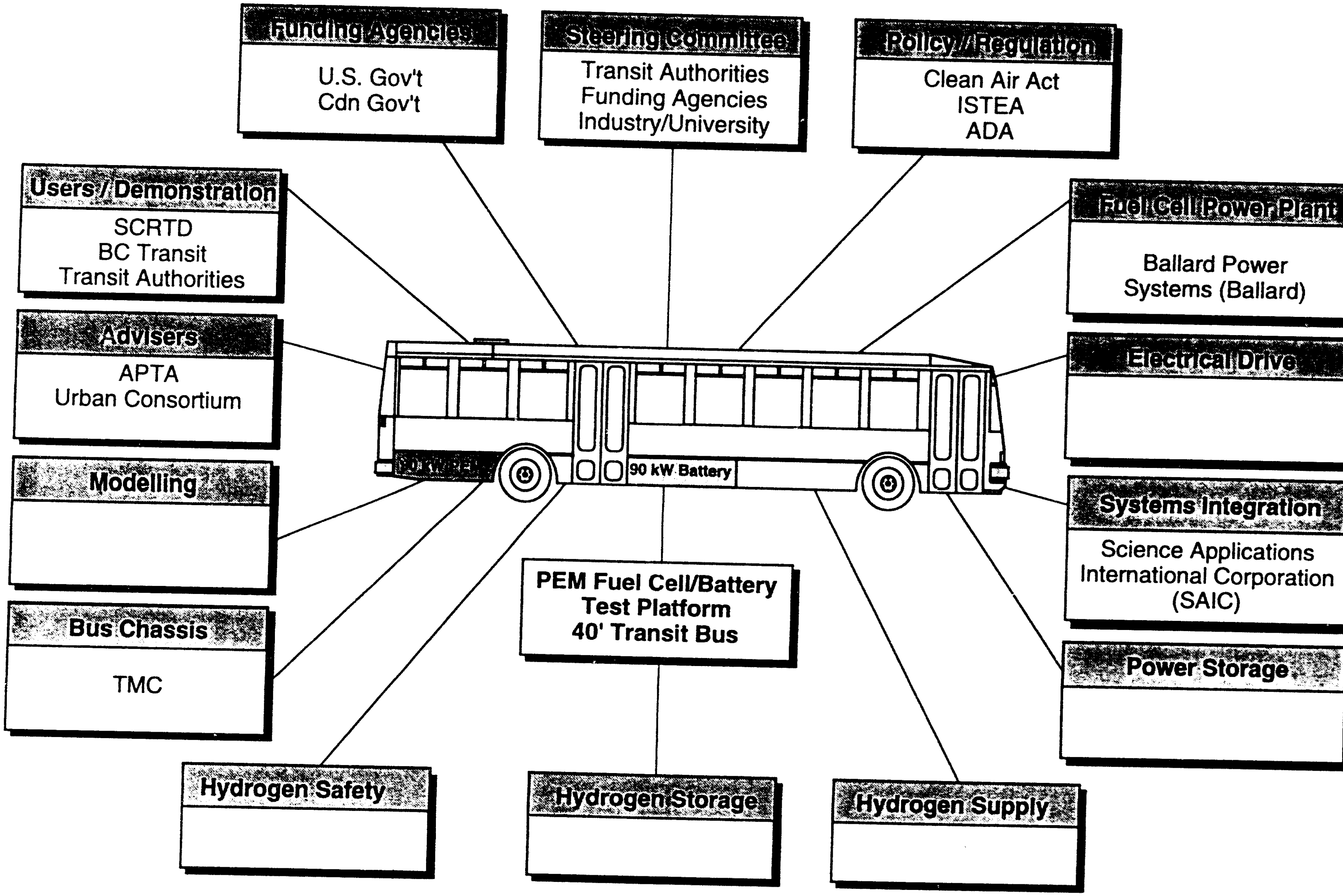
Phase 2 - Commercial Prototype - Scope

- 40′ ZEV PEM Fuel Cell / Electric Transit Bus — Design/Fabricate/Test; Demonstrate
- 32′ ZEV PEM Fuel Cell / Electric Bus — Evaluation/Reliability Testing; Showcase in Various Cities
- April 1993 to September 1995 - 30 Months
- $6 Million Funding Assistance

Ballard

Phase 2 - Commercial Prototype - Technical Approach

- Ruggedize / Repackage PEM Fuel Cell Power Plant
  - Air Compression
  - Cooling System
  - Control System
- Add Battery Hybrid / Regeneration - 240 HP (180 kW)
- 40′ Transit Duty Bus
  - Improved Electric Propulsion
  - Fuel Storage Integration
  - Air Conditioning



Alliance Structure

Ballard

Benefits

- Economically Efficient
- Environmentally Sound
- Competes in Global Economy
- Air Quality Goals - No Pollutants
- Energy Security Goals
- Economic Growth - Emerging $1 billion Market

Acknowledgements

- Energy, Mines and Resources Canada / CANMET
- British Columbia Ministry of Energy
- British Columbia Ministry of Advanced Education
- BC Transit

SUMMARY OF VERBAL COMMENTS OR QUESTIONS AND SPEAKER RESPONSES

BALLARD FUEL CELL POWERED ZERO EMISSION BUS
Paul Howard, Ballard Power Systems, Inc.

Q. Rodica Baranescu, Navistar International: Is there a concern abut hydrogen diffusion and embrittlement?

A. Yes, we are aware of the hydrogen purge and are working with others on the problem.

Q. Anthony Bobelis, Brooklyn Union Gas Co.: I understand that fuel cells are sensitive to CO in the air. How do you purify the air?

A. That is one of our concerns. We plan to convert the carbon monoxide to carbon dioxide, and we have technology to remove the carbon dioxide. There is a lot to learn about the effect of contaminants.

Q. Mostafa Kamel, Cummins Engine Co.: What other fuels could be used in the fuel cell?

A. We have considered methanol and natural gas which are being used in two other programs being developed.

Q. What is the top gas temperature?

A. The fuel cell operates on 160 to 180° F.