DOE/CE/90049--T1

FINAL TECHNICAL REPORT

November 18, 1994

Investigation
of a
Rotary Valving System
with
Variable Valve Timing
for
Internal Combustion Engines

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Sponsored by:

United States Department of Energy
Office of Energy Research
Contract #DE-FG01-89CE90049

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ABSTRACT

The objective of the program was to provide a functional demonstration of the Hansen Rotary Valving System with Variable Valve Timing (HRVS/VVT), capable of throttleless inlet charge control, as an alternative to conventional poppet-valves for use in spark ignited internal combustion engines. The goal of this new technology is to secure benefits in fuel economy, broadened torque band, vibration reduction, and overhaul accessibility. Additionally, use of the variable valve timing capability to vary the "effective" compression ratio is expected to improve "multi-fuel" tolerance and efficiency.

Efforts directed at the design of HRVS components proved to be far more extensive than had been anticipated, ultimately requiring that proof-trial design/development work be performed. Although both time and funds were exhausted before optical or ion-probe types of in-cylinder investigation could be undertaken, a great deal of laboratory data was acquired during the course of the design/development work. This laboratory data is the basis for the information presented in this Final Report.

The laboratory data and test experience obtained in the course of this demonstration program provide the following general characterizations of the HRVS/VVT technology:

1. The variable valve timing capability of the rotary valving system is able to achieve throttleless inlet charge control by using "early intake valve closing." In the case of homogenous charge spark ignition types of combustion, this eliminates the customary "throttling-loss" portion of the pumping-work during part-load operation of the engine.
2. The volumetric efficiency of the HRVS/VVT engine surpassed that of the stock poppet valved engine as well as the HRVS "non-VVT" engine throughout the speed range tested, and was dramatically improved at low speeds where optimized valve-timing aided the trapping efficiency. Further gains can be expected in future designs which can be air-flow optimized with flow-bench development efforts.
3. This rotary valving system has demonstrated effective containment of substantial chamber pressures, with naturally-aspirated operations up to 937 kPa (136 psi) Indicated Mean Effective Pressure and peak pressures to 7 Mpa (1000psi).

Areas of further research opportunity include exploration of a "multi-fuel" HRVS/VVT adaptation. The ability to provide variable valve timing control enables the engine to adjust its cylinder peak-pressures to the highest knock-free level for a given fuel-octane characteristic. This control may now be accomplished without a significant "throttling-loss," even when utilizing fuels combusted as a homogenous mixture. Part-load operation with such fuels may also be obtained without the customary throttling-loss.

1.0 INTRODUCTION

1.1 Background

The Hansen Rotary Valving System (HRVS/VVT) offers potential gains in the areas of: (1) valve control features, (2) ceramic materials compatibility, (3) combustion control features, and (4) maintenance features. These new features have been precluded in rotary-valved engines of the past, primarily because of excessive frictional losses required to rotate the valve and/or excessive leakage of the high pressure working gases from the combustion chamber. The configuration of the HRVS/VVT seeks to overcome these historic disqualifications through the unique design of the valve, the valve-seal geometry, and the combustion chamber shape. Having achieved friction and leakage levels similar to poppet-valved engines, the inherent positive features of this rotary valving system may now be utilized.

While the scope of this research contract did not provide for exploration and utilization of all the potential features, a brief review of the implications offered by this new technology follows:

With respect to (1) valve control features, variable valve-timing has been difficult to achieve with poppet-valves because of their reciprocating masses and the associated limitations on acceleration and valve-seat impact. The HRVS/VVT components are not limited by these inertial effects; valve opening and closure timing may be variably controlled over a broad crankangle range. As a result:

- * The ability to control and vary valve-timing as engine speeds and loads change provides for optimal timing under all conditions. The gas-dynamic characteristics at each condition may be optimized for a broadened torque band.
- * The capability to control air intake for part-load operation of homogenous charge spark ignition engines by varying the intake dwell of the rotary-valve allows for the elimination of the throttle-plate. The intake manifold then operates at atmospheric pressure, thus eliminating the throttling-loss portion of part-load pumping work. The resulting gain in efficiency has previously been unique to Diesel engines. (Diesel engines do not throttle their intake-air since fuel metering controls their power output level while allowing the bulk air/fuel ratio to vary accordingly). So-called "multi-fuel" engines would also benefit from elimination of their part-load throttling-loss when utilizing a homogenous charge combustion system.
- * In "multi-fuel" engines, the ability to control air-intake without the customary throttling-loss provides the opportunity to limit the cylinder peak-pressure to that level tolerated by the octane nature of a given fuel.

With regard to the (2) ceramic materials compatibility of the HRVS/VVT, it should be noted that the design accommodates the relatively lower tensile strength and emphasizes the high compressive strength of ceramic materials. Thus, efforts by those seeking to develop an "all-ceramic" combustion chamber will be enhanced by the low tensile loadings and vibration-free nature of the HRVS/VVT technology. (Also note that the use of conventional

metal alloys with customary heat-treatments is suitable for conventional engine applications.)

- * Unlike poppet-valves, the Hansen Rotary Valve experiences little or no vibratory shock, thus avoiding ceramic brittle fracture tendencies.
- * The Hansen Rotary Valve experiences less tensile stresses than poppet valves, thereby taking advantage of the excellent compressive strength and wear resistance presented by ceramic materials.

With regard to (3) combustion control features, the HRVS/VVT design alters turbulence and other combustion parameters:

- * All Hansen Rotary Valve components are exposed to both cool intake gases and hot exhaust gases, while a conventional exhaust poppet-valve only releases hot exhaust gases. Thus, the Hansen Rotary Valve functions at a lower average operating temperature. This reduces the sources of "hot-spot" pre-ignition and/or detonation in conventional spark ignition engines.
- * Turbulence imparted to the mixture by so-called "squish" characteristics tends to decrease the potential for detonation in spark ignition engines, and reduce the timing losses of burn delay in Diesel engines. The turbulence is not acquired at the expense of volumetric efficiency, as would be expected in the case of a shrouded intake poppet-valve.

With regard to (4) the maintenance features of the HRVS/VVT, the design offers the following advantages:

- * Rapid and relatively easy access is achieved by the Hansen Rotary Valving System. Replacement of valve modules does not require the removal of the engine's cylinder head nor its attendant intake/exhaust manifolds and water-cooling system.
- * Frequency of maintenance may be comparable to poppet-valve systems. This will vary with the materials employed, their temperature limitations and lubrication requirements, and the rate of "fouling" contamination in the combustion chamber.
- * No periodic valve adjustments are required: the valve-drive is permanently synchronized at assembly and requires no subsequent adjustments. The valve's seal configuration is not dependent upon close running fits which would be vulnerable to thermal growth or incremental wear changes.

1.2 Design Objectives

1.2.1 Participation in the combustion process

While other rotary valve designs have influenced only the intake and exhaust functions of the engine, the HRVS/VVT influences such combustion parameters as turbulence, stratification, squish, and "hot-spot" shielding. This is because the combustion chamber is predominantly the gas passageway between the radial and axial ports of the rotor, comprising more than 90 percent of the clearance volume at piston TDC.

1.2.2 Friction reduction; pressure load reaction

While other rotary valve designs have required the pressure loading of the valve-rotor to be reacted out as increased sliding unit-loads on the opposite side of the valve rotor, the HRVS/VVT rotor carries all axial and lateral pressure loads on low-friction rolling contact bearings. This provides for friction reductions of 1-2 orders of magnitude from most prior rotary valve configurations.

1.2.3 Friction reduction; pressure active seals

Some rotary valve designs have relied solely upon spring-loaded seals to obtain those contact unit-loads necessary for effective gas sealing during the high pressure phases of compression and expansion; unnecessary frictional penalties during the low-pressure intake and exhaust phases have been the result.

The HRVS/VVT design uses combustion chamber pressure to actuate pressure active seal elements which generate only the necessary contact unit-loads required to seal that instantaneous chamber pressure. Therefore, the frictional losses due to these sealing unit-loads are minimized.

1.2.4 Friction reduction; reduced normal forces

The historical paradox of the rotary valve involved a trade-off between sliding-seal friction and gas-leakage. Attempts to reduce frictional losses through various techniques which reduce normal forces resulted in corresponding increases in gas-leakage.

The HRVS/VVT design has resolved this seeming paradox through the simultaneous reduction of both the pressure-active area and the contact unit-load area, thereby reducing undesirable normal forces while maintaining or improving the contact unit-loads necessary for sealing.

1.2.5 Thermal growth and rotor "run-out" accommodation

Some rotary valve designs have relied upon close running fits to restrict the leakage of high pressure combustion gases. However, the clearances required to accommodate such

variables as thermal expansion and rotor "run-out" allow prohibitive gas leakage. The HRVS/VVT design utilizes a pressure-active seal element which is allowed to "float" with respect to both the rotor and the ported-sleeve which contains it. This provides the economy of relaxed fabrication tolerances while accommodating both thermal growth and rotor "run-out."

1.2.6 Quenched clearance volumes

The annular running clearances between the rotor and the ported-sleeve of prior rotary valve designs provided undesirable clearance volumes which filled with dense fuel/air mixtures. These gases could not participate in combustion as the flame-front was quenched in the close clearance spaces. The effect of such quenched volumes was to increase timing losses, increase HC emissions, and decrease fuel economy.

The HRVS/VVT design locates the seal elements such that the annular clearance around the rotor does not contain any fuel/air mixture. This clearance volume is an inert chamber, sealed from the combustion chamber, and thus precludes the adverse consequences of some prior rotary valve designs discussed in the preceding paragraph.

1.2.7 Port flow-area vs. clearance volume

The geometry of the rotary valve should allow the gases to flow freely to and from the working chamber, thereby producing maximum power for a given cylinder size. On the other hand, increased port flow-area through the rotor increases the clearance volume which the valve contributes to the combustion chamber. This clearance volume must be controlled by design to be appropriate for the desired compression ratio of the engine.

The HRVS/VVT design provides reasonable port flow-areas at moderate compression ratios and the potential for elevated compression ratios when used in conjunction with minimum-clearance type piston-crown projections. This may add improved "squish" characteristics as well.

1.2.8 Accessibility

The HRVS/VVT design provides for direct valve removal. The cylinder head with its attendant intake/exhaust manifolds and cooling system need not be removed from an HRVS/VVT engine in order to access the rotary valve. Poppet-valves cannot be as readily accessed in conventional engines.

1.2.9 No adjustment requirement

Neither initial installation nor accumulated wear effects require adjustment of HRVS/VVT valve components. All fits and clearances are established by manufactured dimensions such that initial assembly consists of simple synchronous indexing of the valve drive-shaft.

1.2.10 Valve train timing

Conventional poppet valve-trains exhibit reciprocating mass dynamics which vary with engine speed. Thus, the valve timing is properly synchronized with piston position at only one engine speed. Spring float and system elasticity are responsible for the varying mass dynamics of the lifters/poppets (and the resultant deformation and timing changes). The HRVS/VVT system is a non-reciprocating design which will maintain valve timing over the engine's entire speed range and beyond.

1.3 **Program Objective and Program Approach**

Program Objective:

To investigate the Hansen Rotary Valving System with Variable Valve Timing (HRVS/VVT) as an alternative to conventional poppet-valves for use in both homogenous charge and spark-assisted Diesel engines, including laboratory evaluation of such potential benefits as fuel economy, volumetric efficiency, vibration reduction, overhaul accessibility, and variable valve timing characteristics.

Program Approach:

For the purposes of the design / development proof-trials required prior to commencing in-cylinder investigations, a fully instrumented single-cylinder spark ignition gasoline engine on-hand from a previous Army contract was selected because it presented the most streamlined and cost-effective avenue to gaining experience with certain HRVS/VVT seals and variable valve timing hardware. Crucial areas of study included materials, fits, bearings and lubrication, basic port geometry, and seal-element integrity.

1.4 Configuration and Operation

1.4.1 Components

Figure 1-4a illustrates in simplified fashion an HRVS/VVT in juxtaposition to the piston/cylinder for which it handles gas exchange and for which it in part controls the combustion process. A general description of the configuration follows:

A gas flow passageway connects a port on the rotor's cylindrical (radial) surface to a port on the rotor's flat (axial) face. This passage comprises the majority of the combustion chamber when the cylindrical port is sealed-off. A shaft-protrusion of the rotor serves to bearing-mount and

Figure 1-4a: Cross-sectional view of HRVS modified engine.

drive the rotor. A sparkplug is centrally located in the rotor, with electrodes positioned to initiate the flame-front at a position nearly central to the combustion chamber.

A cylindrical sleeve provides an intake-port and an exhaust-port. The inside diameter of the cylindrical sleeve serves as the running-surface for a pressure-activated sliding circumferential seal. The circumferential seal of the current design has a uniform and relatively small radial wall thickness, and is called an "arcuate-seal." (It is a derivative of the more distortion-prone "segment-seal" which was first referenced in the "Proposal.") A rectangular passage through the seal serves as a port for gas-flow. The cylindrical inner surface of the arcuate-seal interfaces with a pack of pressure active seal elements, while its cylindrical outer surface slides and seals against the inside diameter of the cylindrical sleeve. No relative sliding occurs between the arcuate-seal and the pack of seal elements. Drive-pins in the rotor engage the arcuate-seal to position and drive it.

The firedeck is a ported plate which separates the cylinder head from the block of the engine. It serves to mount the face-seal and keeps the annular clearance volumes surrounding the rotor sealed against combustion gases. It also reduces the pressure-active area of the rotor, thereby reducing the rotor bearing loads.

The face-seal is a continuous-ring type of seal which is loaded by a pressure-active seal pack in order to seal between the axial face of the rotor and the firedeck. It is located concentric to the rotor's axial port.

The pressure-active seal packs are high-temperature alloy materials which are located at both the rotor arcuate-seal interface and the rotor face-seal/firedeck interface. They provide seal unit-loads which are proportional to the pressure acting within the seal. As the gas pressures increase, the contact unit-loads increase correspondingly at all seal interfaces, thus minimizing the leakage of the pressurized combustion gases from the chamber.

The pressure-active seal-elements are free to translate in order to accommodate relative "run-out" movement of the rotor such that the seals maintain constant surface-contact.

1.4.2 Sequence of Operation

Figure 1-4b illustrates the 4-stroke sequence of operation for the HRVS/VVT, described as follows:

Induction: As the piston approaches top-dead-center ("TDC") at the completion of the exhaust stroke, the radial rotor-port begins to overlap the leading edge of the intake-port of the ported-sleeve. Continued travel of the piston corresponds to continued opening of the rotor-port to the intake-port until, at about mid-stroke of the piston, the intake port is fully-open. This coincides maximum port-area with maximum piston speed. As the piston passes through bottom-dead-center ("BDC"), the rotor-port is sliding past the trailing edge of the intake-port, providing a sealed working chamber. The dynamics of gas flow will define the lead-angle before TDC for intake-port opening, and the lag-angle after BDC for intake-port closure.

Figure 1-4b: Sequence of Operation - - The rotor port position is shown at the mid-point of each stroke, as seen along View A-A of Figure 1-4a.

Compression: As the piston compresses the gases in the working chamber, the radial rotor-port is sealed against the inner diameter of the ported-sleeve. A sparkplug is mounted inside the rotor, with its electrodes located in a centralized position for optimum flame front propagation. As is customary, the ignition occurs prior to the piston having reached TDC, such that peak-pressure of the ignited mixture occurs 10 to 20 degrees after TDC.

Expansion: As the combusting high-pressure mixture drives the piston through its expansion stroke, the radial rotor-port is again sealed against the inner diameter of the ported-sleeve. Prior to the piston reaching BDC, the rotor-port slides past the leading edge of the exhaust-port of the fixed ported-sleeve. As is customary, the "blow-down" of exhaust gases from the working chamber to the exhaust-manifold is timed such that approximately one-half of the blow-down pressure drop has occurred by the time the piston reaches BDC.

Exhaust: As the piston begins its exhaust stroke, the radial rotor-port increasingly overlaps the exhaust-port of the ported-sleeve. When the piston reaches approximately mid-stroke position, the exhaust port is fully-open. This coincides maximum port-area with maximum piston speed. As the piston passes TDC, the rotor-port passes the trailing edge of the exhaust-port, leaving the rotor-port exposed only to the leading edge of the intake-port for subsequent induction. As with the intake-port edges, the exhaust-port edges are defined in their lead-lag angles for opening/closing by the dynamics of gas flow.

2.0 TEST CONDITIONS AND PROCEDURES

2.1 Test Conditions

Laboratory testing requires the creation of test conditions which will produce consistent data from which valid comparisons may be made. Although such test conditions as the weather do not lend themselves to control, careful measurement of their variation does allow for some degree of data "correction" to account for these effects. Conditions which were considered to be controllable for data consistency included the following:

- 2.1.1 Engine compression ratio was fixed at 9.2 : 1 in the stock and HRVS/VVT engine tests.
- 2.1.2 Engine crankcase oil was re-circulated and cooled to maintain 175 to 190 degrees Fahrenheit. Synthetic oil (Mobil One) was used.
- 2.1.3 Engine cylinder-walls were air-cooled with a thermostatically-controlled external blower to maintain the root of the cooling fins at 200 to 220 degrees Fahrenheit.
- 2.1.4 Fuel characteristic variations were avoided by performing all tests with the same fuel (Unleaded gasoline with RON = 91, MON = 83, $((R+M)/2) = 87$)).
- 2.1.5 Ignition timing was set to 30 degrees BTC for the majority of the tests, having found this to be a representative setting for "Minimum Best Torque" timing (MBT). Data taken at other timings are indicated as such, and were generally set to place peak-pressure near 15 degrees after TDC for that engine operating condition.
- 2.1.6 Fuel/Air ratio was generally adjusted for best power, although exhaust CO level was found to be the most convenient method of monitoring this variable and re-setting the fuel injection system (or carburetor, in the case of "stock" engine tests).
- 2.1.7 Intake manifold "tuning" was made similar by using similar manifold diameter, length, and up-stream restrictions on all engines. Some degree of confirmation of this similitude is provided by the matched engine speed-points of volumetric efficiency minima and maxima.
- 2.1.8 Instrument calibration was confirmed repeatedly and with the same procedure for all engines. Also, the same data reduction algorithms and software were used consistently for all engine testing.

Figure 2-2: Schematic of engine test equipment

2.2 Procedures

- 2.2.1. Valve train torque is measured at the driven-pulley of the belt system
- 2.2.2. Volumetric Efficiency is based upon Cubic Feet per Minute (CFM) of air at the existing ambient conditions. Note that the anemometer is calibrated for standardized volumetric measurement at 70 degrees F. and 14.7 psia, and must therefore be converted to actual CFM for the volumetric efficiency calculation.
- 2.2.3. Crank-angles corresponding to valve-timing events for the Intake Opening, Intake Closing, Exhaust Opening, and Exhaust Closing of the poppet valves or HRVS/VVT ports are noted and recorded for each data set. In the case of the HRVS/VVT engine, the Intake Closing event is varied as required for a desired load condition, and then a mechanical pointer on the control slide is observed for the corresponding timing.
- 2.2.4. Cylinder-Wall temperature is measured at a location in the root of the air-cooling fins adjoining the outer cylinder wall near mid-stroke position.
- 2.2.5. Coolant return is the temperature of the coolant returning from the cylinder head.
- 2.2.6. Lube return/supply temperatures are for oil circulated through the bearings and gear chamber of the cylinder head.
- 2.2.7. Intake air temperature is measured downstream of all air-flow measurement equipment.
- 2.2.8. Crankcase temperature is measured by a probe located in the crankcase oil.

- 2.2.9 As noted in "Section 3.0 Instrumentation / Data Acquisition System," Item 3.23, we have defined "BHPcorr" = $BHP \times K$, where K is an environmental correction factor shown in Item 3.22. Both items have been consistently applied as defined by the SAE J607a "Small Engine Test Code."

It is interesting to note that an alternative definition for "BHPcorr" is given in SAE J1349 "Engine Power Test Code - Spark Ignition and Diesel," where: $BHP_{corr} = ((IHP_{observed} \times K) - FHP_{observed})$. Solving for the magnitude of the discrepancy between these two definitions, we find the difference in "BHPcorr" values to be $((K-1) \times FHP_{observed})$. Thus, for $K = 1.1$ and $FHP_{observed}$ ranging from 1 to 3 HP, the difference in "BHPcorr" definitions is between 0.1 and 0.3 HP. This discrepancy is of the same magnitude as the resolution/accuracy of the "BHP" transducer/dynamometer system.

3.0 INSTRUMENTATION / DATA ACQUISITION SYSTEM

The instrumentation and Data Acquisition System (DAS) components were selected and procured in order to measure specific performance characteristics of the engine. Figures 3-1 through 3-15 present each respective component manufacturer's specification data sheet. A listing of each measured characteristic and its associated transducer(s) follow:

- 3.1 Brake torque (Tb)
 - 3.1.1 Strain-gage load-beam
 - Hottinger - Baldwin Measurements, Inc. Model BBS-100
 - 3.1.2 Daytronics 10A70 Strain-gage Conditioner
 - 3.1.3 Calibration method: Dead weight loading on the dynamometer
- 3.2 Engine Speed (RPM)
 - 3.2.1 Magnetic Pickup / 60 tooth gear
 - Daytronics MP-1 (TTL output) transducer
 - 3.2.2 Daytronics 10A40 Frequency Input Conditioner
- 3.3 Brake Horsepower (BHP) (Computation)
 - 3.3.1 $BHP = ((RPM \times Tb) / \text{constant})$
- 3.4 Valve-drive Torque (Tv) (HRVS/VVT engines only)
 - 3.4.1 Strain-gage rotary torque transducer
 - Lebow Model 1388-102
 - 3.4.2 Daytronics 10A78 AC Strain-gage Conditioner
- 3.5 Valve Speed (RPMv) (Computation)
 - 3.5.1 1/2 of Engine Speed (RPM)

3.6 Valve-Drive Horsepower (HP_v) (Computation)

3.6.1 $HP_v = ((RPM_v \times T_v) / \text{constant})$

3.7 Instantaneous Cylinder Pressure (P)

3.7.1 Kistler # 6121A2 Piezoelectric quartz transducer

3.7.2 Kistler # 5004 charge amplifier

3.7.3 PEI, Inc. 12 bit #504 amplifier/signal digitizer waveform recorder
and engine cycle analyzer.

3.7.4 Calibration: Chandler #61-001R-B-T Dead-weight Pressure Calibrator

3.8 Instantaneous Crankshaft Position (CP)

3.8.1 Heidenhain ROD 426A (1800 pulse) shaft angle encoder

3.9 Instantaneous Cylinder Volume (V) (Computation)

3.9.1 Cylinder bore (B)

3.9.2 Connecting rod length (L)

3.9.3 Piston Stroke (S)

3.9.4 $V = S \times (B \exp 2) \times \text{constant} \times ((1 - \cos(cp)) + ((S/(4 \times L)) \times ((\sin (CP)) \exp 2))$

3.10 Indicated Mean Effective Pressure (Computation)

3.10.1 Summation through one full cycle (four strokes) of each incremental change in instantaneous pressure multiplied by its corresponding change in instantaneous volume. PEI's software performs this summation for "Net-IMEP" which implicitly subtracts both pumping work and compression work from the expansion work. Because only the Net-IMEP is identified by the PEI software, post-processing by Hansen Engine Corporation's software inspects for the exact pumping-loop portion ("PMEP") in order to determine exact changes in the "IMEP" ("positive" or compression / expansion loop) portion..

$$\text{Net-IMEP} = \text{IMEP} - \text{PMEP}$$

3.11 Indicated Horsepower (IHP) (Computation)

3.11.1 $IHP = ((IMEP \times RPM) / \text{constant})$

3.12 Frictional Horsepower (FHP) (Computation)

3.12.1 $FHP = IHP - BHP$

3.13 Standard Cubic Feet per Minute air-flow (SCFM)

3.13.1 Datametrics #810L mass flow meter

3.13.2 Daytronics 10A63 voltage conditioner.

3.14 Ambient Pressure (Pa)

3.14.1 strain-gage absolute pressure transducer Viatran # 118, 0-20 psia

3.14.2 Daytronics 10A70 strain-gage conditioner

3.15 Ambient Temperature (Ta)

3.15.1 YSI thermistor #705

3.15.2 Daytronics 10A15 Thermistor conditioner

3.16 Actual Cubic Feet per Minute (CFM)

3.16.1 $CFM = (T_a/530) \times (14.7/P_a) \times (SCFM)$

3.17 Volumetric Efficiency (V_e)

3.17.1 $V_e = CFM / ((RPM/2) \times 27.66 / 1728))$

3.18 Inlet Temperature (T_i)

3.18.1 YSI #703 Thermistor

3.18.2 Daytronics 10A15 thermistor conditioner

3.19 Inlet pressure (P_i)

3.19.1 strain-gage absolute pressure transducer Viatran #118, 0-20 PSIA

3.19.2 Daytronics 10A70 strain-gage conditioner

3.20 Wet-bulb Temperature (T_{wb})

3.20.1 sling psychrometer

3.21 Water Vapor Pressure (P_v)

3.21.1 chart lookup and interpolation

3.22 Horsepower correction factor (K)

3.22.1 SAE "Small Spark Ignition Engine Test Code" SAE J607a

3.22.2 $K = (29.92 / (P_b - P_v)) \times (SQRT((460 + T_i)/520))$

3.23 Corrected Brake Horsepower (BHP_{corr})

3.23.1 $BHP_{corr} = BHP \times K$

3.24 Indicated Horsepower, Motoring (IHP_m)

3.24.1 same transducers and calculation as "IHP"

3.24.2 negative value represents pumping work plus compression/expansion work loss due to leakage

3.25 Brake Horsepower, Motoring (BHP_m)

3.25.1 same transducers as "BHP"

3.25.2 negative value represents total work required to rotate crankshaft

3.26 Frictional Horsepower, Motoring (FHP_m)

3.26.1 $FHP_m = IHP_m - BHP_m$

QUARZKRISTALL DRUCKAUFNEHMER, MINIATURSONDE
QUARTZ PRESSURE TRANSDUCER, MINIATURE PROBE

Miniatur Druckaufnehmer für universellen Einsatz in Brennkraftmaschinen, Raketen, Explosionskammern usw. Arbeitet zuverlässig bei Umgebungstemperaturen bis 350°C und erträgt intermittierende Flammtemperaturen bis 2500°C.

Miniature pressure transducer for universal application on internal combustion engines, rockets, explosionchambers etc. Works reliably in ambient temperatures of up to 350°C and withstands intermittent flash temperatures of up to 2500°C.

- Neues Polystable® Quarzkristallelement
New Polystable® quartz element
- Betriebstemperatur bis 350°C. Normalerweise keine Wasserkühlung nötig.
Operating temperature up to 350°C. Normally no watercooling required.
- Empfindlichkeit ändert sich weniger als ±0,5 % im Bereich 100...300°C.
Sensitivity varies less than ±0,5 % in the range 100...300°C.
- Unempfindlichkeit auf hohe Flammtemperaturen.
Insensitive to high flash temperatures
- Masseisolierte Ausführung
Groundinsulated design

Type 6121

Technische Daten

Technical data

Messbereich	measuring range	bar	0...250
kalibrierte Teilbereiche	calibrated partial ranges	bar	0...25
		bar	0...2,5
max. Druck	max. pressure	bar	350
Empfindlichkeit	sensitivity	pC/bar	14
Eigenfrequenz	resonant frequency	kHz	60
Frequenzgang ±1 %	frequency response ±1 %	kHz	6
Linearität	linearity	% FSO	< ±1,0
Hysteresis	hysteresis	% FSO	< 0,5
Beschleunigungsempfindlichkeit	acceleration sensitivity		
axial	axial	bar/g	0,003
normal zur Achse	transverse	bar/g	0,0005
Schock und Vibration	shock and vibration	g	< 2000
Temperaturkoeffizient der Empfindlichkeit	temperature coefficient of the sensitivity	°C ⁻¹	< ±10 ⁻⁴
kalibriert im Bereich	calibrated in range	°C	20...350
Betriebstemperaturbereich	operating temperature range	°C	-80...350
Transient Temperaturfehler (Propanflamme intermittierend auf Front, 10 Hz)	transient temperature error (propane flame intermittent on front, 10 Hz)	bar	< 0,005
Isolation: bei 20°C	insulation: at 20°C	Ω	> 10 ¹³
bei 350°C	at 350°C	Ω	> 10 ¹⁰
Masseisolation	groundinsulation	Ω	> 10 ⁸
Gewicht	weight	g	9,5

1 bar = 10⁵ N·m⁻² = 1,019...at = 14,50...psi; 1 at = 1 kp·cm⁻² = 1 kgf·cm⁻² = 0,080665 bar; 1 psi = 0,06894...bar; 1 in = 25,4 mm

Polystable® Quarzkristallelemente sind international durch Patente geschützt
Polystable® quartz elements are internationally patented

Pressure Transducer Specification

Figure 3-1

Engine Cycle Analyzer Installation & Setup

PEI/EngineTech Series

1.2 DAB-500/504 Specification

Throughput:	500 K samples per second (sps)
Noise Discrimination:	70 dB
Input Channel:	(4) analog channels +/- 5 V, through multiplexer (1) Syn input (external trigger) (1) Timing marks CA, CB, TDC (external trigger)
Sample Rate:	125 K pps for (4) channels 250 K pps for (2) channels 500 K pps for (1) channel
Analog Output Channels:	(2) 12 bits D/A
Sample Capacity:	Continuous data acquisition up to 512 K points at one shot for 1024 kB expansion memory. For 8 MB RAM version 4 M points are possible
Resolution:	12 bits (0.025% of full range)
Frequency Response:	DC to 100 kHz (-3 dB)
FIFO Buffer Memory:	1 K 16-bit FIFO through data bus to access computer RAM by DMA
Internal Trigger:	1 Hz - 500 kHz produced by internal hardware timer (AM9513)
Input Impedance:	1 M Ohm
Test Voltage:	+/- 12 V
Zero Drift:	10 mV
Accuracy:	< 0.5% full scale
Sample & Hold:	504 System only
Individual Gain Control:	504 System only, gains of 1, 10, 100 and 500.
Multi-Station Syn:	504 System only

PEI Inc. Analog to Digital Converter

Figure 3-3

1 INTRODUCTION

1.1 General Description

Engine Analyzer - PEI's Engine Analyzer hardware is PC-based with MS DOS operating system plus Data Acquisition Board (DAB) system.

DAB-500 System - DAB-500 system is basically a 4-channel, 12-bit A/D data digitizer with fixed gain. The maximum sample rate is 500,000 samples per second (when only one channel is used). A full-size expansion board, DAB-500, is used in this system.

DAB-504 System - DAB-504 System is composed of the basic DAB-500 plus 4-channel individual gain control and sample and hold (S & H) features. These added features allow 4-channel data processing, taking data simultaneously and continuously and multi-analyzer synchronization for additional high sample rate data taking and storing. DAB-504 board includes the full-size DAB-500 mother board and a half-size daughter board.

PEI's DAB 500 or 504 and ECA software are matched with IBM-AT compatible. For computer, PEI recommends ACER 1100/25 for its competitive pricing, advanced features, on-site warranty S/H availability. The 512 K byte memory is needed for software and graphics. Additional RAM expansion (up to 16 MB) is required for data storage.

Fig 1.1 Engine Analyzer System

DAB-504 System

PEI Inc. Engine Cycle Analyzer Setup

Figure 3-4

ENGINE CYCLE ANALYSIS - VERSION 911

PEI/ENGINE TECH SERIES

1. General

1.1 Introduction

The ECA version 911 has a four (4) channel capability and can be used in conjunction with either the DAB 500 or DAB 504 systems. In the DAB 500 system, the data is taken by consecutive pulse sampling. In the DAB 504 system, however, the sample and hold feature allows data from all four (4) channels to be taken simultaneously and consecutively at every pulse.

Instead of rewriting the entire ECA manual, we have provided a simple step-by-step "road map" for the user. The software will be delivered with this version 911 manual. The ECA 892 manual is also enclosed as a reference.

The ECA 911 program is composed of five (5) sections:

- o system set-up and input
- o on-line data taking and statistics
- o engine cycle analysis, on-line and off-line
- o hot motoring analysis, on-line and off-line
- o additional off-line features including off-line statistics, input parameter modification, etc...

A. System Set-Up and Input

A set-up file is required before performing any of the data acquisition tasks. The set-up file contains the necessary input on engine design data, data acquisition configurations, and operating conditions. This is information required to process the signals and compute the analytical results. In this section, the user has the freedom to create a new set-up file or modify an existing one. The procedure is menu driven.

B. Data Taking and Statistics

A friendly step-by-step user operation procedure is provided in this section. The user can monitor and take up to four (4) dynamic signals simultaneously. These signals can be things like the cylinder pressure in different cylinders of an engine or a set of cylinder pressures, injection pressure and needle lift of a single power cylinder, etc... The maximum cycle number of total sample points that can be taken at one time is dependent on the size of the RAM in the computer being used.

After data acquisition, all this data is stored in the computer's RAM through Direct Memory Access (DMA). The user has the following options:

- a. displaying a 3-D diagram (waterfall) for each channel - consecutive, single cycle test results are presented on a real-time basis on-line;
- b. viewing on-line statistics and graphics' results;
- c. storing averaged cycle data on disk for off-line engine cycle or hot motoring analysis;
- d. storing individual cycle data on disks for off-line statistics or transient data study.

PEI Inc. Engine Cycle Analyzer Version 911 Capability

Figure 3-5

NOTES:

- 1. Resolutions above 2540 are only available in 5 volt TTL single ended output configuration, with or without marker; or 5 volt line driver without marker.
- 2. Resolutions above 2540 have $\pm 45^\circ$ quadrature tolerance.
- 3. Sine-wave units with marker pulse have square wave marker output from a TTL compatible device.

	TTL	HTL and CMOS	LINE DRIVERS	SINE WAVE
Supply Voltage, V_s	5V DC $\pm 5\%$	12-15 VDC $\pm 5\%$ (Specify)	5V DC $\pm 5\%$ or 12V DC $\pm 5\%$	5V DC $\pm 5\%$
Supply Current, I_s	150 ma	140 ma	175 ma	150 ma
V _{OH} (logic "1")	2.4V min.	V_s thru 3.5 K Ω pull up	These characteristics vary with cable length and receiver circuitry	1.5 volts p-p signal on ± 2.4 volt DC offset
V _{OL} (logic "0")	0.4V max.	1.0V max.		NA
Signal Rise/Time (10%-90%)	0.2 μ s	Varies with load		
Signal Fall/Time (90%-10%)	0.1 μ s	Varies with load		
Useful Frequency Range	0 to 100 KHz			Flat 0 to 25 KHz 6 db/octave roll off above
Max. Sink Current	16 ma	20 ma	5V 40 ma 12V 33 ma	Min. load resistance 200 Ω
Max. Source Current	400 μ s	4 ma	40 ma 60 ma	To common
Output Device	7404 or 7486	MC 689 with internal 3.5 K Ω passive pullup	DM8830 is 5V line driver. MM88C30 is 12V line driver.	RC3403 TM
Symmetry	180 $^\circ$ $\pm 10^\circ$ (electrical) at data rates below 50 KHz 180 $^\circ$ $\pm 15^\circ$ (electrical) at data rates above 50 KHz			
Interchannel Phase Angle (Quadrature)	90 $^\circ$ $\pm 30^\circ$ electrical TM			
Pulse-to-any-other-pulse accuracy	± 2 minutes of arc			
Pulse-to-adjacent-pulse accuracy	± 0.5 minutes of arc			

Physical Specifications

Shaft Loading	
Radial	35 lbs. max. at end of shaft
Axial	40 lbs. max.
Rated Speed	3000 RPM at max. shaft loading - Up to 5000 RPM at lower loads
NOTE: The use of flexible couplings is strongly recommended to minimize shaft loads due to misalignment.	
Starting Torque	1.5 oz. - in. max. (5 oz. - in. with shaft seal)
Rotating Inertia	2.8×10^{-4} oz. - in. - sec ²
Maximum Acceleration	50,000 radians/sec ²
Bearings	Shielded and sealed stainless steel ball bearings, ABEC-7
Materials	
Shaft	Type 303 stainless steel
Housing	Die-cast aluminum
Weight	12 oz.
Operating Temperature	32 $^\circ$ to 150 $^\circ$ F (0 $^\circ$ to 65 $^\circ$ C)

Outline Dimensions

Shaft Angle Encoder Specification

Figure 3-6

Model 10A10-4 Quad Isolated Thermocouple Conditioner Card

This input conditioner is identical to the Model 10A9-8, described on p. 4, *except that*

- a. it accepts *four* independent TC signals (rather than eight); and
- b. its inputs are *transformer-isolated*, so that sensor-to-chassis and/or sensor-to-sensor common-mode voltages as high as 500 V can be accommodated without damaging the instrument or perceptibly affecting measurement accuracy.

Like the Model 10A9-8, the Model 10A10-4 includes a rear-panel connector block with *screw-type* terminals for attachment of TC leads (which cannot be soldered), and operates in conjunction with the Model 10A11 Thermocouple Output Processor Card. One Model 10A11 must be installed in every A-Card "deck" containing one or more Model 10A10-4's.

Additional 10A10-4 Specifications:

Identical to the Model 10A9-8, page 4, *except for*

Common-Mode Isolation: 350 V at 60 Hz, 500 V-DC.

Common-Mode Rejection: Down 120 dB at 50-60 Hz.

Accuracy: $\pm 0.02\%$ of full scale, $\pm$ one least significant digit. Least significant digit can be 1.0 or 0.1 degree, depending on range and TC type selected. This accuracy is predicated on TC input voltages conforming to NBS Circular, No. 561. The user is cautioned that actual thermocouples may vary from table values.

Model 10A15-8 Eight-Channel Thermistor Card

Within designated ranges, Thermistor Probes offer higher accuracy and greater long-term dependability than thermocouples. Providing regulated excitation current, the Model 10A15-8 can condition up to *eight* independent temperature signals from many 3-wire,

dual-thermistor, bead-type probes. A variety of suitable fast-response sensors is available in the Daytronic Series 700 Thermistor Temperature Probes (see the latest Daytronic Transducers Catalog).

Additional 10A15-8 Specifications:

Range and Resolution: See table, below. Automatically selected by CENTRAL PROCESSOR—on an individual channel basis—when setup values are entered.

Range	Resolution
0 to +100 degrees C	0.1 degree C
+32 to +212 degrees F	0.1 degree F
0 to +100 degrees C	0.01 degree C
+32 to +212 degrees F	0.02 degree F

Normal-Mode Filtering: DC to 4 Hz, 3-pole low-pass active filter per channel.

Absolute Accuracy: ± 0.3 degree F (± 0.5 degree C), including probe interchangeability errors.

Repeatability: ± 0.1 degree F (± 0.2 degree C).

Model 10A40 Frequency Input Conditioner Card

This *single-channel* conditioner is for measurement of flow, rpm, and other phenomena that can be sensed by turbine flowmeters, tachometer pickups, and similar frequency-generating transducers. Accepting a wide range of wave shapes and voltage levels, it can accommodate virtually all mechanical measurement

requirements. The CENTRAL PROCESSOR controls frequency-range selection and applies an appropriately calculated scaling factor to each measurement, if desired. A precise *crystal frequency reference* ensures accuracy of all calibrations.

Additional 10A40 Specifications:

Input:

Type: Any AC or unipolar pulse signal, grounded or floating, *irrespective of waveform*.

Threshold Level: "Smart Schmitt" input automatically adjusts to accommodate signals from 100 mV to 200 V.

Common-Mode Rejection: Greater than 60 dB to 2 kHz and greater than 30 dB to 32 kHz.

Frequency Ranges: 250, 500, 1000, 2000, 4000, 8000, 16000, and 32000 Hz. Operating frequency range is automatically selected by the CENTRAL PROCESSOR when setup values are entered.

Excitation Supply (for "Zero-Velocity" sensors): 10 V-DC, split (i.e., +5 V and -5 V), 50 mA (max).

Ripple and Noise: Readings are stable to $\pm$ one least significant digit from 10% to 100% of frequency range in use.

Thermocouple, Thermistor, and Frequency Conditioner Specifications

Figure 3-7

Model 10A63-2 Dual Voltage Conditioner Card

This is a premium two-channel voltage input conditioner. It is similar to the Model 10A60-4, p. 7, but offers a wider range of input voltages, greater

allowable common-mode range, and substantially higher accuracy.

Additional 10A63-2 Specifications:

Input Voltage Ranges: ± 0.05 , ± 0.1 , ± 0.2 , ± 0.5 , ± 1 , ± 2 , ± 5 , ± 10 , ± 20 , ± 100 , or ± 200 VDC. Operating input ranges automatically selected by the CENTRAL PROCESSOR—on an individual channel basis—when setup values are entered.

Input Impedance: 1 megohm, all ranges.

Common-Mode Range: 500 V, operating; 700 V without damage.

Common-Mode Rejection: -60 to 120 dB, depending on range selected.

Common-Mode Input Impedance: 0.5 megohm.

Normal-Mode Filtering: DC to 4 Hz, 3-pole low-pass active filter per channel.

Accuracy: $\pm 0.1\%$ of full scale, ± 1 least significant digit.

Repeatability: $\pm 0.02\%$ of full scale.

Model 10A70-2 Dual Strain Gage Conditioner Card

This is a two-channel signal conditioner for input of pressure, force, torque, weight, and other variables that may be measured by conventional strain gage transducers. Its advanced design techniques overcome errors that traditionally plague the strain-gage conditioning process. Separate excitation for each channel uses remote sensing of bridge voltage and is slaved to a common System Reference Voltage. The result is stable ratio-metric measurement, unaffected by possible drift in any power supply. Input impedances in excess of 100 megohms are presented to both sensing and signal leads to eliminate cable resistance as a

source of error. Allowable cable length has virtually no practical limits.

An amplifier-per-channel design with solid-state chopper stabilization and low-pass active filtering yields noise-free output of known and stable gain factor. Additional digital filtering is applied by the CENTRAL PROCESSOR. For steady indication and smooth, dependable control action, the Model 10A70-2 provides a true average value of the measured variable, even in the face of substantial dynamic content.

Additional 10A70-2 Specifications:

Transducer Types: Conventional 4-arm strain gage, nominal 350 ohms (or higher); 0.75, 1.50, or 3.00 mV/V, full scale (automatically selected by CENTRAL PROCESSOR—on an individual channel basis—when setup values are entered). Since channel zeroing is by digital techniques, no input balance control is provided. The allowable input range, therefore, must include any initial unbalance—which, in commercially produced strain gage transducers, is usually negligible. Other transducers may have to be externally trimmed to be used with the Model 10A70-2.

Transducer Excitation: Individual-channel regulated supplies, 10 VDC nominal, remotely sensed.

Common-Mode Rejection Ratio: -120 dB.

Normal-Mode Filtering: DC to 4 Hz, 3-pole low-pass active filter per channel.

Accuracy: $\pm 0.02\%$ of full scale, $\pm$ one least significant digit.

Model 10A78 AC Strain Gage Conditioner Card

This card is similar to the 10A70-2, described above, but is a single-channel conditioner of phase-sensitive carrier-amplifier design (rather than a two-channel, fully DC instrument). Intended for applications involving transformer-coupling to the transducer bridge (as with rotary-transformer torque sensors), it can also be used when high sensitivity is required or where the electrical environment is especially noisy. Responding only to the modulated carrier frequency, the 10A78 rejects extraneous voltages that can cause errors in DC systems, particularly when there is a need to "blow up" a portion of the transducer range.

Additional 10A78 Specifications:

Identical to the Model 10A70-2, except for

Transducer Types: Conventional 4-arm strain gage, nominal 350 ohms (or higher); 1, 2, or 4 mV/V full scale (automatically selected by CENTRAL PROCESSOR when setup values are entered).

Transducer Excitation: Regulated 3 VAC at 3280 Hz.

Strain-gage and Voltage Conditioner Specifications

Figure 3-8

BBS

BENDING BEAM LOAD CELL
0-50 to 0-7500 lbs

- EXCELLENT LINEARITY, HYSTERESIS, CREEP
- WATERTIGHT CONSTRUCTION
- LOW PROFILE
- ALLOY STEEL SENSING ELEMENT
- NICKEL PLATED SURFACES
- FLEXIBILITY OF APPLICATION
- mV/V/ohm CALIBRATION AVAILABLE
- LOW COST

The BBS bending beam load cell is designed for precision weight and force measurements where excellent performance under adverse environments is required. The proven bending beam construction combined with low cost make the BBS an excellent choice for use by scale manufacturers.

TECHNICAL DATA

	50	100	200	250	500	1K	2.5K	5K	7.5K
Rated Capacity (lbs.)				250	500	1K	2.5K	5K	7.5K
Rated Output (mV/V)				2.0 ± 0.3/-0			2.05 ± 0.03		
Nonlinearity (%)				0.03					
Hysteresis (%)				0.02					
Nonrepeatability (%)				0.01					
Creep in 20 min. (%)				0.03					
Zero Balance (%)				1.0			± 2.0/-0		
Compensated Temp. Range (°F/°C)				+15 to +115/-10 to +45					
Temp. Effect:				Output (% of load/100F)					
				0.08					
				Zero Balance (%/100F)					
				0.15					
Terminal Resistance:				810			375 ± 10		
Input (ohms min.)									
Output (ohms)				750 ± 10			347 ± 3		
Excitation Voltage:				18					
Maximum VDC or VAC rms				5000 at 50 VDC					
Insulation Resistance (megohms min.)				150					
Max. Load, Safe (%)				300					
Max. Load, Ultimate (%)									
Deflection at Rated Load (inches)	.015	.025	.030	.030	.020	.040	.120	.090	.120
Weight (lbs.)				2.2			8.4		24.7

Percentages relative to rated output, except as noted.

REQUEST CERTIFIED DRAWINGS BEFORE DESIGNING MOUNTINGS OR FIXTURES—DIMENSIONS AND SPECIFICATIONS ARE SUBJECT TO CHANGE WITHOUT NOTICE.

Dynamometer Strain-gage Load-beam Specification

Figure 3-9

Model MP2

ZERO-VELOCITY PICKUP

*for accurate speed sensing
down to "zero speed"*

The Model MP2 Zero-Velocity Pickup is an "active" sensor, containing its own signal-conditioning circuitry to generate a clean square-wave output pulse (+5V) for each ferrous discontinuity passing the head of the pickup.* This is a true *digital* output, being either ON or OFF, depending on the presence or absence of ferrous material. The MP2 will sense motion down to "zero velocity," since, unlike a *magnetic* pickup, it always produces a pulse train of *constant* amplitude—irrespective of the rotational speed of the gear.

Another advantage of the Model MP2 over standard magnetic pickups is its ability to operate with gear-tooth gaps of up to 0.050 inch. 20-pitch (or coarser) gears are recommended. The gearface width should be at least $\frac{1}{4}$ ", so as to completely cover the sensing element in the head of the pickup, and thus to make mounting less critical.

The Model MP2's #303 Stainless-Steel "blind-end" housing must be mounted such that the "orientation flats" on the hex housing are aligned parallel to the gear teeth ($\pm 15^\circ$ allowable).

* The user may furnish his own external power from a well-regulated supply, or may obtain a standard 12 V-DC power supply from *Airpex Electronics, Controls Division*, 6801 W. Sunrise Blvd., Ft. Lauderdale, FL 33313, Phone: (305) 587-1100. Daytronic Models 9140, 9141, 3140, 3240, and 3340 provide suitable excitation for the Model MP2.

Specifications, Model MP2

Excitation	7-14 V-DC; 50 mA max.
Sensed Frequency	DC to 10,000 Hz.
Output Voltage	Essentially square-wave, fanout to 10 standard TTL loads, 50 $\pm$ 10% duty cycle. Logic 0: $\pm$ 0.6 V-DC peak (max); Logic 1: 4.5 $\pm$ 0.5 V-DC peak with load resistance greater than 2k ohms.
Short-Circuit Output Current	6 mA peak (max), with 12 V-DC power supply.
Source Impedance	Less than 50 ohms for load resistance greater than 2k ohms; less than 2k ohms for load resistance below 2k ohms.
Air Gap (recommended)	Up to 0.025" (with 20-pitch gear); up to 0.050" (with 8-pitch gear).
Operating Temperature	-25°C to +70°C (-13°F to +158°F).

22

Magnetic Speed Pickup Specification

Figure 3-10

CALIBRATION CERTIFICATE

ACCELEROMETER

Model Number 8044 Serial Number C12684

Range +30,000 g, -20,000 g

Resonant Frequency, mounted 56.6 kHz

Transverse Sensitivity 4.7 %

Capacitance 621 pF

Range	Charge Sensitivity*
10 g	<u>0.272</u> pCb/g
100	<u>0.273</u>
1000	<u>0.274</u>
10,000	<u>0.278</u>
30,000	<u>0.283</u>

* at 24°C, mounting torque 2.5 ± 0.2 Nm

The calibrations of all basic standards used in these tests are directly traceable to the National Bureau of Standards.

By P. B. [Signature] Date 8/24/84
Customer _____ AUG 30 1984
Sales Order Number _____

KISTLER INSTRUMENT CORPORATION
Amherst, New York, 14120

Accelerometer Specification

Figure 3-11

DATAMETRICS - DRESSER INDUSTRIES, INC.
340 FORDHAM ROAD • WILMINGTON, MASS. 01887 • (617) 658-6410

CERTIFICATE OF CALIBRATION

CUSTOMER HANSEN ENGINE
P.O. _____
READOUT MODEL 810L - DAX
SENSOR MODEL 1202
READOUT SERIAL # 1144
SENSOR SERIAL # 3632 'ADX'
FILAMENT CODE "ADX"
E1 1.000 V_{DC}
E1G 2.321 V_{DC}

This is to certify that the above items were calibrated using a Brooks Vol-U-Meter serial # 369/239, American Meter Co., Prover #4048, Datametrics - Dresser Industries HX-85 Test Stand (DWG. 1414), whose Calibration is traceable to the U.S. National Bureau of Standards. (Ref. N.B.S. Publication 250, calibration and test services, Art. 205.301)
These items meet the following Specifications published by Datametrics - Dresser Industries:

ACCURACY: + 2% of reading or .5% of full scale, whichever is larger.

REPEATABILITY: + 1% of reading or .25% of full scale, whichever is larger.

Flow Temp. Range: -60°F to 300°F (-50° to 150°C)

Flow Temp. Coeff.: + 0.2% of reading or 0.05% f.s., whichever is larger, per °F change.

Circuit Temp.: 40°F to 122°F (5° to 50°C)

REFERENCE CONDITIONS: All calibrations are referenced to 70°F temp. and 14.7 PSIA line pressure.

Calibrated By: Michael J. Amint

Date 9/4/81

Remarks : FULL SCALE (10.00v at OUTPUT) = 50.0 SCFM

Mass Air-flow Transducer Specification

Figure 3-12

Model 118 Range 0-20 PSIA

Serial Number 06241715

Pressure % Full Scale	Output Millivolts	Calibration Input Voltage 10V DC All Calibrations performed at 70°F	Output Millivolts	Bidirectional Differential Units Only
0	0.37			
20	6.13			
40	12.68			
60	19.22			
80	25.74			
100	32.24			

REPAIR

This Viatran Transducer has been designed to be easily repaired and recalibrated if necessary. If a failure occurs, the transducer should be returned to the factory for inspection and testing. If the transducer failure is covered by our one year warranty policy, the unit will be repaired as necessary and reshipped without delay. Usually, transducers not covered by warranty can be repaired within two weeks for approximately thirty to sixty per cent of the purchase price. Simple repairs can often be made for the \$75.00 minimum charge. Units should be returned to the attention of the Repair Department.

CALIBRATION CIRCUIT

An advantage of Viatran strain gage pressure transducers is that the gain or span of the readout system can be set without applying a known pressure input. The system setup can be accomplished by using a calibrate circuit as explained below.

INTERNAL CIRCUIT - Some transducer models are supplied with an internal shunt calibrate circuit either as a standard or by special order. If this transducer has the circuit included, it will be noted below. Simply shorting the proper pins will produce the calibration output signal listed.

EXTERNAL CIRCUIT - If the transducer does not include the calibration circuit, the same type calibration can be accomplished by connecting a resistor of the value indicated across the proper pins. This technique is accurate for cable lengths of up to 200 ft.

Calibration Circuit Is:

☐ Internal - Shorting pins & will produce a calibration output signal

☒ External - Connecting 32.87 K ohms across pins 2 & 4 will produce a 16.0 PSIA calibration output signal

NOTE: All calibrations should be performed only after the transducer has been adjusted for zero.

Absolute Pressure Transducer Specification

Figure 3-14

TABLE 1

TESTER SPECIFICATIONS

Maximum Pressure:	Up to 20,000 psi (or 101100 kPa)
Minimum Pressure:	3 to 50 psi depending on range (see Figure 1)
Accuracy:	0.1% of indicated pressure
Certificate of Calibration:	Available upon request. Accuracy 0.05% Special 0.02% Certificate available upon request.
Calibration Temperature:	77 F (25°C) Calibration based on standard gravity of 980.665.
Calibration Meets:	MIL-C-45662A
Temperature Limit:	40 to 120 F (4° to 50°C)
Humidity:	0 to 95% RH
Vibration:	Small amplitude, high frequency only.
Environment:	Minimize dust and corrosive atmosphere
Physical Size:	Series 23: 19 x 6 x 13 inches (47.5 x 15 x 32.5 cm) Series 2: 22 x 8 x 14 inches (55 x 20 x 35 cm) Series 55: 22 x 14 x 18 inches (55 x 35 x 45 cm)

Dead-weight Pressure Calibrator Specification

Figure 3-15

4.0 ENGINE SPECIFICATION

The engine chosen for the prior Army contract was a Tecumseh Products Company Model # OH-160, Industrial XL (Extra-Life) Series 916211 CB (with Counter-balancing).

Compression ratio	9.16 to 1
Bore	3.500 inches
Stroke	2.874 inches
Displacement	27.66 cubic inches
Rated Power	16 horsepower
Rated Speed	3600 rpm
Valving	Overhead poppet-valves
Crankshaft Bearings	Tapered roller bearings
Rod Bearings	Plain journal bearings
Lubrication System	Splash oil lubrication
Flywheel Proof "Spin-Test"	9000 rpm
Fuel System	Float-type carburetor

The stock engine was evaluated in its stock production configuration with the exception of its valve-springs. The contractual requirement of 5000 RPM test speeds mandated their replacement with springs which would not "float" at this elevated speed. (Stock springs began to "float" at 4200 RPM). Perfect Circle brand valve-springs #212-1172 were substituted for the stock springs. The spring-force at installed height was raised from 30 lbs to 66 lbs, and at compressed height from 60 lbs to 123 lbs. Guidance for this spring selection was taken from the square of the maximum speeds ratio. (ie. $((5000/3600) \exp 2) = 1.93$). Thus, springs of approximately twice the force were identified for this substitution.

The accompanying Figures 4-1, 4-2 and 4-3 provide further specifications and dimensional information.

Figure 4-3

5.0 VALVE DESIGN

The general configuration of the HRVS/VVT and its assembly onto an engine were described in Section 1.4 and shown in Figures 1-4a and 1-4b. The following discussions pertain to the design and fabrication considerations of certain specific components.

5.1 Seal-Element Alternatives

Maintaining a gas-tight seal between the combustion chamber within the rotor and its surrounding components is an essential function; one which plays a major role in resolving the historic trade-off between the friction and leakage penalties experienced by prior rotary-valving technology. Discussion of the two types of seal-elements which were designed and fabricated for use as alternative seals follow:

5.1.1 Face-Seal / Gapped-Ring:

A gapped-ring, similar to a conventional piston-ring, fits tightly into a counterbore while one of its axial faces lies against a flat continuous ring (commonly called a "face-seal"). This face-seal, in-turn, lies against the flat axial surface of the rotor. The aspect ratio of the gapped-ring's wall section is somewhat different from a conventional piston ring in that it is thin axially and wide radially. This characteristic provides for positive axial positioning loads with minimal radial loads which would resist axial travel. The assembly procedure does not require the "stretching" of the gapped-ring, as it is not contained in a gland (piston ring-groove). Thus, its radial wall thickness is not limited by such a "stretch" requirement.

Although this seal is free to travel axially in the counterbore, it actually travels only very short distances; the accommodation of bearing runout and thermal growth differentials is less than .010 inch. As such, mild concern was felt over the potential for a type of surface finish degradation called "fretting corrosion." This type of corrosion, while somewhat unpredictable by nature, is generally associated with sliding components which have only slight relative motion, thus allowing abraded asperities to accumulate in the interface. These residual particles then serve to further abrade the remaining surface in a progressive manner. To-date, only minimal traces of this phenomenon have been evidenced by slight changes in the surface finish of the counterbore. No apparent gas-leakage resulted. Certain coating materials are expected to alleviate this potential concern in future programs.

5.1.2 Arcuate-seal / Flex-box Seal-pack:

The "free-body" forces acting upon the arcuate-seal result from two pressure gradients acting on two respective areas; chamber pressure distributed uniformly over the seal-pack area of the rotor acts radially outward, while a diminishing pressure gradient on the arcuate face of the arcuate-seal acts radially inward. The net difference between these pressure induced forces is carried as a sliding reaction force at the sleeve's inside surface. This sliding reaction force must be sufficient to maintain the arcuate-seal in its correct sealing position against the sleeve surface. On the other hand, a sliding reaction force which is greater than necessary for correct positioning will cause unnecessary friction and wear.

The method for varying the intended reaction force (called "pressure-bias") involves increasing or decreasing the pressure-active area on the arcuate face of the arcuate-seal. This area consists primarily of a "contact-band" of material surrounding the port which is intended to maintain sealing contact with the sleeve's inside surface. All other areas of the arcuate-seal's arcuate face are "vented" areas; areas which are relieved back from contact with the sleeve surface or otherwise vented so that no pressure can be sustained in areas outside the intended "contact-band." For example, doubling the width of the contact band then doubles the area over which the pressure gradient acts. This would double the radial inward force, reducing the net outward reaction carried against the sleeve surface. These contact / vented regions, called "relief patterns," are varied to suit particular port shapes, and to alter the sliding lubrication characteristics of the arcuate-seal.

The "seal-pack" referenced above must fit into a cavity in the circumferential side surface of the rotor, and maintain a gas-tight seal under changing and relatively high temperatures. During the course of this program, a seal-pack referred to as the "flex-box" seal was developed by Hansen Engine Corporation for this application. This technology was then reduced to practice in a shared fashion between this contract and US Army TACOM contract # DAAE-07-88-C-R137. Therefore, the requisite "US Government Rights" legend has been applied to the resulting patent application, with notice to the US Government on DD Form 882.

5.2 Variable Valve Timing Mechanism.

A sliding variable valve timing mechanism was designed and developed to serve as a moveable "closing-edge" for the intake port of the ported sleeve (Reference Figure 1-4b for "Moveable port edge B"). This technology was also reduced to practice in a shared fashion between this contract and US Army TACOM contract # DAAE-07-88-C-R137. Therefore, the requisite "US Government Rights" legend has been applied to the resulting patent application, with notice to the US Government on DD Form 882.

The position of this sliding "shutter" is determined by a push / pull rod which is controlled by the operator. In this approach to achieving variable valve timing, the motion and mass-dynamics of the rotor are not altered and the moveable shutter is not required to move once positioned for a desired load-setting. Therefore, this means of achieving variable valve timing does not limit the allowable peak engine speed, the allowable valve timing range, or the peak flow capacity of the valving system. Furthermore, there is no significant mass air-flow occurring during the "closed" portion of an unthrottled part-load intake stroke. Therefore, the parasitic loss conventionally caused by the throttle during the pumping loop is virtually eliminated with a corresponding improvement in part-load fuel economy.

5.3 Lubrication Scheme

A previous oil lubrication system served well in its intended reductions of both friction and wear. Indications were, however, that deposits in the combustion chamber were increased by the presence of oil along with some effects on the emission characteristics. Therefore, efforts were undertaken to confirm the feasibility of using dry-lubricant techniques to eliminate oil lubrication from the combustion chamber.

Potential tribological material "couples" were identified and tested. Pure Carbon Corporation's #P3310 graphite running against a chromium-carbide surface performed the best, but was rather cumbersome to fabricate. The same graphite running against electro-plated chrome held up well enough for the laboratory data-acquisition activities, did not impose as much distorting compressive stress on the surface of the components, and did not require expensive diamond grinding / lapping operations.

6.0 HRVS/VVT FABRICATION

Fabrication of the metal HRVS/VVT was accomplished with conventional milling machines, lathes, and grinders. "Numerical Control" (NC) machining was utilized only in the fabrication of a 3:1 scale-up pattern of the combustion chamber. This pattern was then traced by a 3-axis pantographing mill in the creation of the actual rotors. Except for the Inconel X-750 seal-elements, the materials were also conventional; #4140 alloy steel was utilized for combustion chamber components including the rotor, sleeve, arcuate-seal, and firedeck. Aluminum alloy 6061-T6 was utilized for the cylinder head.

In order to achieve the "dry-lubricant" materials couple discussed in Section 5.3 above, a graphite liner was thermally shrink-fitted into the steel ported-sleeve, and the steel arcuate-seal was electro-plated with chrome and ground to dimension. The face-seal was also fabricated of graphite, and ran against a chromium-carbide coating which was "D-gun" sprayed by Union Carbide Corporation onto the axial face of the rotor.

It is noteworthy that the feasibility design used for this demonstration program was tailored, in fact constrained, to designs which suit fabrication processes which are practical in proto-type work. For instance, passageways for air-flow can be cast with rather complex shapes in production designs, where proto-types are restricted to the somewhat more elementary shapes which may be obtained using conventional milling machine operations.

7.0 LABORATORY DATA; single-cylinder engine

This section presents data acquired from an HRVS/VVT engine during the proof-trial and development stage of this program. When available, comparative "baseline" data is presented which was acquired from the same single-cylinder short-block operating in the same test cell, but with overhead poppet-valves. This data had been acquired under a previous contract (reference contract #DAAE07-84-C-R089) in order to establish baseline performance for subsequent comparisons with HRVS configurations.

Performance characteristics and comparisons shown in Figures 7-1 through Figure 7-7 provide the basis for this section's discussions regarding each of these respective performance characteristics:

<u>Figure</u>	<u>Parameter</u>
7-1a	Volumetric Efficiency
7-1b	Valve Flow Area
7-2	Indicated Mean Effective Pressures
7-3	Indicated Specific Fuel Consumption
7-4	Valve-drive Power
7-5	Burn-rate Measurements
7-6	Throttleless Control Benefits
7-7	Idle Stability Measurements

Figure 7-1a: Volumetric Efficiency Comparison

7.1 Volumetric Efficiency

As shown in Figure 7-1a, the HRVS/VVT engine exhibited volumetric efficiency superior to that of the stock poppet-valved engine throughout the speed spectrum in comparative testing.

The area for air flow is shown as a function of crankangle in Figure 7-1b. Air-flow bench testing with steady-state flow conditions of 28 inches of water pressure drop have confirmed capacity on the order of "4-valve" poppet systems.

Figure 7-1b: Area vs. crankangle for the intake and exhaust ports of the HRVS / VVT system.

7.2 Indicated Mean Effective Pressures

Figure 7-2: Indicated Mean Effective Pressures for the HRVS / VVT at full-load conditions.

7.3 Indicated Specific Fuel Consumption

Figure 7-3: Indicated Specific Fuel Consumption for the HRVS / VVT at full-load conditions.

Figure 7-4a: Valve train MEP as a percentage of IMEP at four engine speeds.

Figure 7-4b: Valve train MEP vs. IMEP at four engine speeds.

7.4 Valve-Drive Power

7.4.1 Valve-drive Power - - Percentage of Indicated Power

Data presented in Figure 7-4a illustrates the percentage of Indicated Power which is consumed in driving the valve-train of the HRVS/VVT engine. Corresponding "stock" valve-train data was not provided within the scope of the prior program. The HRVS/VVT valvetrain MEP values shown indicate full-load values of 7 to 8% of IMEP.

7.4.2 Valve-drive Power - - Speed and Pressure Effects

Effects of both "Indicated Mean Effective Pressure" (IMEP) and engine speed are shown in Figure 7-4b. It is noteworthy that the HRVS/VVT design's drive-power requirement is relatively unaffected by increases in the average chamber pressure. At 5000 RPM, for example, increasing average chamber pressure 300% above its initial value only raised the valvetrain drive-power requirement 28% above its initial value; a ratio greater than 10 : 1.

7.4.3 Valve-drive Horsepower - - Poppet-valve Systems

An understanding of the spring-related losses in a cam-shaft/poppet-valve system helps to clarify the HRVS/VVT benefit. The mass dynamics of reciprocating poppet-valves require that valve-springs be sufficiently forceful to provide cam following accelerations when the system is operated at the maximum design speed for a given engine. The crucial consequence of this spring force determination is that this same spring force will then be ever-present, even at slower engine speeds which would not have required such high, friction-inducing forces. Contrast this characteristic of poppet-valve systems with the HRVS/VVT system; the HRVS/VVT has no mass-dynamic reciprocating motions, and requires only light biasing springs for component position retention.

7.5 Combustion Performance and Burn-rate Measurements

As a means of characterizing the nature of the combustion process in the HRVS system, two extremely divergent conditions are shown. It is noteworthy that while the piston speeds differed by a factor of two in the test cases of Table 7-5, their burn initiation periods were virtually identical, as were their burn duration periods.

TABLE 7-5	CASE #1	CASE #2
RPM	2210	4540
IGNITION TIMING	23	23
IVC (ATC)	195	240
IVO (BTC)	5	5
EVC (ATC)	5	5
EVO (BBC)	55	55
NET-IMEP (kPa)	839	937
IMEP (kPa)	844	974
PMEP (kPa)	5	37
THROTTLE POSITION	WOT	WOT

Figure 7-5a: Comparison of $\log(p)$ vs. $\log(V)$ results at maximum IMEP for two engine speeds.

Figure 7-5b: Comparison of mass burn rate calculations for the two conditions shown in Figure 7-7a.

7.6 Throttleless Control Benefits

The HRVS/VVT system allows for throttleless control of the inlet charge. Various benefits and implications of this ability were discussed in the Introduction (Section 1.1). Data acquired over a range of part-load conditions is presented in Figure 7-6a to present the efficiency gained from throttling-loss elimination. The specific condition noted in Table 7-6 is further explained by the pressure and burn-rate data presented in Figures 7-6b and 7-6c. While producing the same "Net-IMEP," the throttleless engine needed 12% less IMEP. (Definitions in Section 3.10) Assuming similar mechanical power requirements for their respective valve trains, this would be expected to translate into a corresponding 12% reduction in fuel consumption.

TABLE 7-6	CASE #1	CASE #2
RPM	2519	2502
IGNITION (BTC)	40	30
IVC (ATC)	65	240
IVO (BTC)	5	5
EVC (ATC)	5	5
EVO (BBC)	55	55
NET-IMEP (kPa)	213.6	212
IMEP (kPa)	261.1	230
PMEP (kPa)	47.5	18
CONTROL TYPE	VVT	Throttled

Figure 7-6a: Percent IMEP savings vs. Net-IMEP using VVT over conventionally throttled HRVS.

Figure 7-6b: Comparison of the $\log(p)$ vs. $\log(V)$ results for HRVS operation under part-load conditions with:
i) EIVC using HRVS/VVT
ii) HRVS with a conventional throttle

Figure 7-6c: Comparison of burn rate calculations for the two conditions shown in Figure 7-6a.

7.7 Idle Stability Measurements

For the case of throttleless inlet charge control, the idle stability was studied in order to gain insights into the nature of in-cylinder fluid motion, timing and magnitude of inlet charge inertia, and so on. The standard of deviation was calculated for IMEP for a sequential series of combustion cycles, along with the mean value for these cycles. Figure 7-7a shows the Coefficient of Variation Percentage (COV%) plotted against IMEP for three engine speeds at light loads, where COV% is defined as the standard deviation divided by the mean value taken as a percentage.

Another visual representation of idle stability can be obtained from cycle-to-cycle scatter-plots of IMEP. A tight grouping of data points along the unit slope line for $IMEP(n)$ vs. $IMEP(n-1)$ would indicate stochastic processes occurring within a given cycle, while prior cycle effects would tend to show cycles grouping on horizontal or vertical lines. Often prior cycle effects would exhibit gaps in the groupings of cycle points. Figures 7-7b and 7-7c present two typical scatter-plots.

Figure 7-7a: COV% vs. IMEP, light load combustion stability measurements at three engine speeds.

Figure 7-7b: Scatter-plot of IMEP(n) vs. IMEP(n-1) for an engine speed of 546 rpm, mean IMEP of 222 kPa, and COV(IMEP) of 1.8%.

Figure 7-7c: Scatter-plot of IMEP(n) vs. IMEP(n-1) for an engine speed of 994 rpm, mean IMEP of 206 kPa, and COV(IMEP) of 6.9%.

8.0 LABORATORY DATA; 4-cylinder engine

This section presents data acquired from a 4-cylinder HRVS/VVT engine during the performance of a company-funded program. This data is included here to contrast multi-cylinder conditions with those of a single-cylinder engine. Because the engines were geometrically similar, their characteristics were generally comparable. Certain distinctions were apparent, however, and have been shown in Figures 8-1 through Figure 8-6 to provide the basis for this comparison:

<u>Figure</u>	<u>Parameter</u>
8-1	Valve Flow Area
8-2	Valve Flow Capacity
8-3	Valve Flow Pseudo-Velocity
8-4	Valve-drive Power
8-5	Pumping Work under Throttleless Control
8-6	Idle Stability Measurements

8.1 Valve Flow Area

The flow areas shown below are for a valve which has been scaled to service a cylinder which has a swept displacement of approximately 550 cc.

Figure 8-1: Flow area vs. crankangle for the intake and exhaust ports of the HRVS / VVT system.

8.2 Valve Flow Pseudo-Velocity

The ability of the valve to provide instantaneous air flow to match the change of volume in the cylinder is indicated by the "pseudo-velocity" plot.

Figure 8-2: Pseudo-velocity vs. crankangle for the intake and exhaust ports of the HRVS / VVT system.

8.3 Valve Flow Capacity

As a means of determining the flow capacity of the valve, flow-bench data was acquired with a pressure differential across the valve of 6.89 kPa (28 inches of H₂O).

Figure 8-3: Air-flow capacity of the HRVS / VVT system at each crankangle position.

8.4 Valve-drive Power

The levels of valve-drive power shown below for the multi-cylinder engine are less than the single-cylinder engine because certain "fixed overhead" losses of the valve-drive are distributed over multiple cylinders.

Figure 8-4: Valvetrain MEP vs. Net-IMEP for the HRVS / VVT system applied to a 4-cylinder engine.

8.5 Throttleless Pumping Work

The Pumping Mean Effective Pressure ("PMEP") loss plotted below has been determined by numerically integrating the "net-negative" area of the Pressure vs. Volume diagram. The "neutral" area which overlaps both positive and negative areas is not included.

Figure 8-5: PMEP-% vs. Net-IMEP with throttleless inlet charge control.

8.6 Idle Stability Measurements

The cycle-to-cycle variations are reduced in the multi-cylinder engine, presumably because the intake air flow pulsations are reduced and the fuel metering system maintains a more consistent air/fuel ratio.

Figure 8-6: COV% vs. Net-IMEP

9.0 RECOMMENDED AREAS FOR FURTHER RESEARCH

The following section discusses potential areas for future research efforts which can further establish the relative benefits offered by the HRVS/VVT technology in its various configurations. Having established some of the basic materials, geometry, and clearance requirements through the execution of this spark ignition gasoline engine program, subsequent research efforts can explore such technical aspects as "Spark-Assisted Diesel" adaptation, the benefits of variable valve-timing control, and "Multi-fuel" capability. These efforts would benefit greatly from application of the "in-cylinder studies" which had been contemplated for this program, had time and funding allowed.

The researchers anticipate the opportunity to further explore and refine this technology, subject to receipt of appropriate funding. An SAE Technical Paper (#940813) titled "A Rotary Valve Combustion System with Throttleless Inlet Charge Control," prepared by Paul Cross, Craig Hansen, and Dr. Jay K. Martin, was based in-part on the research described herein. This paper was presented at the SAE International Congress and Exhibition in March, 1994, acknowledging the contribution of DOE sponsorship to this new technology.

9.1 Spark-Assisted Diesel Adaptation

Exploration of the potential of an "HRVS/VVT" adaptation for "Spark-Assisted- Diesel" (SAD) operation can be expected to determine the benefits available from: (1) enhanced volumetric efficiency; (2) "Squish" induced turbulence for reduced burn-delay; (4) the cold start benefits achieved by utilizing a homogenous charge fuel and spark ignition combustion system during the start phase, followed by normalized "hot" operation in a SAD mode, (5) the cold start benefits achieved by tailoring the intake valve closure to that which is optimum for cold cranking speeds, thereby improving the effective compression ratio for easier starting, and (6) alternatively, the "hot, dynamic" compression ratio can intentionally be lowered to the extent that variable valve timing is able to increase the cold-cranking effective compression ratio. This would benefit the fuel economy because, as research by others has shown, the peak trade-off point for mechanical / thermodynamic efficiency is achieved in the range of 12:1 to 14:1.

In the course of such efforts, air-flow development and bench-testing would play an important role in optimizing volumetric efficiency while minimizing the clearance volume associated with the air-flow passageway. Tribology efforts would seek to establish oil-free lubrication and compatible materials for the valving components. Fuel-injection alternatives would be explored in terms of injector type, location, spray pattern, and timing considerations.

9.2 Materials - - Metals and Ceramics

Experience gained in the course of this research program has shown that both the metal and ceramic materials are compatible with the temperatures and mechanical loading characteristics of the HRVS/VVT technology. In "Ceramic HRVS/VVT" components, the relative freedom from vibratory shock and tensile loading provides a good environment. Thus, "Low Heat Rejection" engine designs requiring ceramic valving and combustion chamber materials are presented with a favorable ceramic design alternative. In the "Metal HRVS/VVT" components, the temperatures developed were found to be easily accommodated by current metallurgical techniques. Thus, conventional metal engine designs can obtain the performance features offered by rotary valving while retaining the ease of fabrication offered by metal components.

9.3 Variable Valve-Timing

9.3.1 Variable Valve-Timing Benefits in Diesel Cycle Operations

The ability to control valve-timing to obtain peak volumetric efficiency at any desired operating speed alleviates the necessity to manufacture engines which are tailored to operate at specific design speeds, and suffer in their specific power output and efficiency when operated off the specified design speed.

9.3.2 Variable Valve-Timing Load-Control vs. Density-Throttled Engines

Engines burning fuels which customarily require control of the fuel/air ratio for proper combustion while operating at part-load have normally needed to utilize density-throttling in the intake manifold. A resulting indicated throttling-loss during part-load operation is caused by the manifold vacuum acting on the piston during the intake stroke. Elimination of this throttling-loss can be achieved in engines with variable valve timing through a technique known as "early intake closure." The intake manifold is unthrottled so that when intake flow is occurring, the piston is drawing from an intake manifold which is essentially at atmospheric pressure. This creates no significant pressure differential for throttling loss. Control of air mass for part-load mixture requirements is obtained by closing the intake valve early. Subsequent piston motion pulls a vacuum which does not involve any net expansion or compression work until the piston passes the position in which the cylinder gases are again at atmospheric pressure. The compression stroke progresses from this point exactly as it would have in a density-throttled engine at the same part-load condition. This timing variability is not easily achieved in poppet-valved systems where reciprocating mass dynamics limit their high speed operation. The HRVS/VVT System can achieve the required timing variation without mass dynamic constraints.

9.4 "Multi-fuel" Capability

The "HRVS/VVT" technology presents an opportunity which had not been practical with poppet-valved engines or with previous rotary valving designs. Benefits inherent to rotary valving had been precluded by disqualifying leakage and/or friction. Overcoming these historic constraints creates the potential to develop a truly "Multi-fuel" engine which can utilize the full spectrum of fuels, from Cetane rated Diesel fuel through Octane rated gasoline. Simple re-phasing of injector and ignitor timing can immediately accommodate a new fuel characteristic, while variable control of intake valve-timing controls the air mass for those fuels which require mixture control, as described in the preceding Section 9.3.2. Note that this means of air mass control incurs none of the customary throttling loss. Additionally, the same means of air mass control can be used to limit peak pressures to acceptable levels when burning fuels which would otherwise be prone to detonation. This technique is only practical where the customary throttling-loss has been eliminated. Since the mass dynamics of reciprocating poppet-valves have presented inherent barriers to their use in variable valve-timing systems, the "HRVS/VVT" technology does create a new and practical opportunity.

10.0 APPENDIX OF INDIVIDUAL DATA SETS

The following are representative individual data sets taken over a range of speeds and loads. In each case, a printout of the measured conditions is presented, followed by graphic plots of the pressure vs. volume data. The printout also identifies each data set as having been obtained from the single cylinder engine ("ENGINE: Tecumseh OH160") or the four cylinder engine ("ENGINE: Chev 2.2 l in-line 4-cyl").

Hansen Engine Corporation Engine Test Data

Date: 9/ 2/1993 Time: 6:56:38.1 PM
File: 18560700

ENGINE SPEED	746 rpm
BRAKE TORQUE	0.4 ft-lbs
BRAKE HORSEPOWER	0.1 bhp
VALVE-TRAIN TORQUE	10.0 in-lbs
VALVE-TRAIN FHP	0.12 fhp
AIR INTAKE @ STP	1.1 scfm
VOL. EFF.	20 %
current 'CF'	1.063
BMEP	2.3 psi
IMEP	16.3 psi
PMEP	2.6 psi
NMEP	13.7 psi
Pmax	61.8 psi
Location Pmax	34.4 deg ATC
CORR.HORSEPOWER	0.1 bhp corr
AIR FUEL RATIO	not measured
BSFC	not measured
FUEL FLOW	not measured
AMBIENT PRESSURE	28.80 in-Hg
INJECTION START	110 deg BTC
INJECTION END	89 deg BTC
IGNITION TIMING	18 deg BTC
CYLINDER WALL	231 deg F
EXHAUST GAS	856 deg F
AMBIENT AIR	84.1 deg F
HEAD COOLANT	179.4 deg F
GEAR LUBE	171.0 deg F
CRANKCASE OIL	178.4 deg F
HYDROCARBONS	not measured
CARBON MONOXIDE	not measured

Annotation File: TEC.ANO

ENGINE: Tecumseh OH160 #2 Set-up File: T-VV-02 ANNO REV: 93-08-28

Bore: 3.5 Stroke: 2.875 Displacement: 27.66 Comp-Ratio: 8.33

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal not radiused
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 93-08-28
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injector replaced 93-08-28

Exhaust Open: 50 Degrees BBC

Exhaust Close: 12 Degrees ATC

Intake Open: 17 Degrees BTC

Intake Close: Density-Throttled Mode: Fixed at 235 Deg ATC

VVT Mode: Varies with load (range 60 to 245 Deg ATC, idle @ 65)

PSIA

Hansen Engine IMEP Post Processor
File: c:\edata\930902\18560700.DAT
IMEP = 16.27 PSI
PMEP = 2.60 PSI
NIMEP = 13.67 PSI
Pmax = 62 PSIA @ 34.4 Deg ATC

Hansen Engine IMEP Post Processor
File: c:\nedata\930902\18560700.DAT

Hansen Engine Corporation Engine Test Data

Date: 9/ 2/1993 Time: 6:47:58.0 PM
File: 18472203

ENGINE SPEED	2221 rpm
BRAKE TORQUE	3.1 ft-lbs
BRAKE HORSEPOWER	1.3 bhp
VALVE-TRAIN TORQUE	13.6 in-lbs
VALVE-TRAIN FHP	0.48 fhp
AIR INTAKE @ STP	4.5 scfm
VOL. EFF.	27 %
current 'CF'	1.063
BMEP	16.7 psi
IMEP	35.9 psi
PMEP	2.4 psi
NMEP	33.5 psi
Pmax	139.0 psi
Location Pmax	24.6 deg ATC
CORR.HORSEPOWER	1.4 bhp corr
AIR FUEL RATIO	not measured
BSFC	not measured
FUEL FLOW	not measured
AMBIENT PRESSURE	28.79 in-Hg
INJECTION START	162 deg BTC
INJECTION END	83 deg BTC
IGNITION TIMING	34 deg BTC
CYLINDER WALL	224 deg F
EXHAUST GAS	1244 deg F
AMBIENT AIR	84.0 deg F
HEAD COOLANT	163.8 deg F
GEAR LUBE	159.8 deg F
CRANKCASE OIL	183.9 deg F
HYDROCARBONS	not measured
CARBON MONOXIDE	not measured

Annotation File: TEC.ANO

ENGINE: Tecumseh OH160 #2 Set-up File: T-VV-02 ANNO REV: 93-08-28

Bore: 3.5 Stroke: 2.875 Displacement: 27.66 Comp-Ratio: 8.33

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal not radiused
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 93-08-28
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injector replaced 93-08-28

Exhaust Open: 50 Degrees BBC

Exhaust Close: 12 Degrees ATC

Intake Open: 17 Degrees BTC

Intake Close: Density-Throttled Mode: Fixed at 235 Deg ATC

VVT Mode: Varies with load (range 60 to 245 Deg ATC, idle @ 65)

Hansen Engine IMEP Post Processor
File: c:\edata\930902\18472203.DAT
IMEP = 35.87 PSI
PMEP = 2.42 PSI
NIMEP = 33.45 PSI
Pmax = 139 PSIA @ 24.6 Deg ATC

Hansen Engine IMEP Post Processor
File: c:\edata\930902\18472203.DAT

Hansen Engine Corporation Engine Test Data

Date: 9/ 2/1993 Time: 7:31:07.1 PM
File: 19312206

ENGINE SPEED	2209 rpm
BRAKE TORQUE	5.7 ft-lbs
BRAKE HORSEPOWER	2.4 bhp
VALVE-TRAIN TORQUE	14.1 in-lbs
VALVE-TRAIN FHP	0.49 fhp
AIR INTAKE @ STP	6.0 scfm
VOL. EFF.	36 %
current 'CF'	1.064
BMEP	30.9 psi
IMEP	52.6 psi
PMEP	2.8 psi
NMEP	49.8 psi
Pmax	240.6 psi
Location Pmax	17.2 deg ATC
CORR.HORSEPOWER	2.5 bhp corr
AIR FUEL RATIO	13.6
BSFC	0.83 lbs/hp-h
FUEL FLOW	2.0 lbs/h
AMBIENT PRESSURE	28.79 in-Hg
INJECTION START	180 deg BTC
INJECTION END	81 deg BTC
IGNITION TIMING	28 deg BTC
CYLINDER WALL	239 deg F
EXHAUST GAS	1241 deg F
AMBIENT AIR	84.6 deg F
HEAD COOLANT	182.3 deg F
GEAR LUBE	178.0 deg F
CRANKCASE OIL	178.0 deg F
HYDROCARBONS	150 ppm
CARBON MONOXIDE	2 %

Annotation File: TEC.ANO

ENGINE: Tecumseh OH160 #2 Set-up File: T-VV-02 ANNO REV: 93-08-28

Bore: 3.5 Stroke: 2.875 Displacement: 27.66 Comp-Ratio: 8.33

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal not radiused
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 93-08-28
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injector replaced 93-08-28

Exhaust Open: 50 Degrees BBC

Exhaust Close: 12 Degrees ATC

Intake Open: 17 Degrees BTC

Intake Close: Density-Throttled Mode: Fixed at 235 Deg ATC

VVT Mode: Varies with load (range 60 to 245 Deg ATC, idle @ 65)

Hansen Engine IMEP Post Processor
File: c:\edata\930902\19312206.DAT
IMEP = 52.61 PSI
PMEP = 2.77 PSI
NIMEP = 49.84 PSI
Pmax = 241 PSIA @ 17.2 Deg ATC

Hansen Engine IMEP Post Processor
File: c:\edata\930902\19312206.DAT

Hansen Engine Corporation Engine Test Data

Date: 9/ 2/1993 Time: 7:42:55.3 PM
File: 19422214

ENGINE SPEED	2210 rpm
BRAKE TORQUE	14.3 ft-lbs
BRAKE HORSEPOWER	6.0 bhp
VALVE-TRAIN TORQUE	12.0 in-lbs
VALVE-TRAIN FHP	0.42 fhp
AIR INTAKE @ STP	10.8 scfm
VOL. EFF.	65 %
current 'CF'	1.064
BMEP	77.8 psi
IMEP	100.7 psi
PMEP	2.3 psi
NMEP	98.4 psi
Pmax	442.8 psi
Location Pmax	15.6 deg ATC
CORR.HORSEPOWER	6.4 bhp corr
AIR FUEL RATIO	13.6
BSFC	0.59 lbs/hp-h
FUEL FLOW	3.5 lbs/h
AMBIENT PRESSURE	28.79 in-Hg
INJECTION START	238 deg BTC
INJECTION END	69 deg BTC
IGNITION TIMING	24 deg BTC
CYLINDER WALL	235 deg F
EXHAUST GAS	1348 deg F
AMBIENT AIR	84.7 deg F
HEAD COOLANT	184.2 deg F
GEAR LUBE	180.5 deg F
CRANKCASE OIL	186.0 deg F
HYDROCARBONS	100 ppm
CARBON MONOXIDE	2 %

Annotation File: TEC.ANO

ENGINE: Tecumseh OH160 #2 Set-up File: T-VV-02 ANNO REV: 93-08-28

Bore: 3.5 Stroke: 2.875 Displacement: 27.66 Comp-Ratio: 8.33

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal not radiused
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 93-08-28
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injector replaced 93-08-28

Exhaust Open: 50 Degrees BBC

Exhaust Close: 12 Degrees ATC

Intake Open: 17 Degrees BTC

Intake Close: Density-Throttled Mode: Fixed at 235 Deg ATC

VVT Mode: Varies with load (range 60 to 245 Deg ATC, idle @ 65)

Hansen Engine IMEP Post Processor
File: c:\edata\930902\19422214.DAT
IMEP = 100.72 PSI
PMEP = 2.34 PSI
NIMEP = 98.38 PSI
Pmax = 443 PSIA @ 15.6 Deg ATC

Hansen Engine IMEP Post Processor
File: c:\edata\930902\19422214.DAT

Hansen Engine Corporation Engine Test Data

Date: 9/ 2/1993 Time: 8:30:04.1 PM
File: 20302218

ENGINE SPEED	2195 rpm
BRAKE TORQUE	17.7 ft-lbs
BRAKE HORSEPOWER	7.4 bhp
VALVE-TRAIN TORQUE	13.5 in-lbs
VALVE-TRAIN FHP	0.47 fhp
AIR INTAKE @ STP	13.2 scfm
VOL. EFF.	80 %
current 'CF'	1.064
BMEP	96.5 psi
IMEP	122.5 psi
PMEP	1.4 psi
NMEP	121.1 psi
Pmax	512.5 psi
Location Pmax	13.2 deg ATC
CORR.HORSEPOWER	7.9 bhp corr
AIR FUEL RATIO	13.8
BSFC	0.58 lbs/hp-h
FUEL FLOW	4.3 lbs/h
AMBIENT PRESSURE	28.81 in-Hg
INJECTION START	267 deg BTC
INJECTION END	62 deg BTC
IGNITION TIMING	24 deg BTC
CYLINDER WALL	238 deg F
EXHAUST GAS	1329 deg F
AMBIENT AIR	85.5 deg F
HEAD COOLANT	183.8 deg F
GEAR LUBE	176.1 deg F
CRANKCASE OIL	188.7 deg F
HYDROCARBONS	120 ppm
CARBON MONOXIDE	2 %

Annotation File: TEC.ANO

ENGINE: Tecumseh OH160 #2 Set-up File: T-VV-02 ANNO REV: 93-08-28

Bore: 3.5 Stroke: 2.875 Displacement: 27.66 Comp-Ratio: 8.33

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal not radiused
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 93-08-28
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injector replaced 93-08-28

Exhaust Open: 50 Degrees BBC

Exhaust Close: 12 Degrees ATC

Intake Open: 17 Degrees BTC

Intake Close: Density-Throttled Mode: Fixed at 235 Deg ATC

VVT Mode: Varies with load (range 60 to 245 Deg ATC, idle @ 65)

Hansen Engine IMEP Post Processor
File: c:\edata\930902\20302218.DAT
IMEP = 122.50 PSI
PMEP = 1.35 PSI
NIMEP = 121.14 PSI
Pmax = 512 PSIA @ 13.2 Deg ATC

Hansen Engine IMEP Post Processor
File: c:\edata\930902\20302218.DAT

Hansen Engine Corporation Engine Test Data

Date: 9/ 2/1993 Time: 7:50:37.8 PM
File: 19503606

ENGINE SPEED	3625 rpm
BRAKE TORQUE	5.6 ft-lbs
BRAKE HORSEPOWER	3.8 bhp
VALVE-TRAIN TORQUE	17.2 in-lbs
VALVE-TRAIN FHP	0.99 fhp
AIR INTAKE @ STP	10.1 scfm
VOL. EFF.	37 %
current 'CF'	1.063
BMEP	30.4 psi
IMEP	57.5 psi
PMEP	3.6 psi
NMEP	53.9 psi
Pmax	233.0 psi
Location Pmax	16.8 deg ATC
CORR.HORSEPOWER	4.1 bhp corr
AIR FUEL RATIO	12.6
BSFC	0.94 lbs/hp-h
FUEL FLOW	3.6 lbs/h
AMBIENT PRESSURE	28.80 in-Hg
INJECTION START	213 deg BTC
INJECTION END	66 deg BTC
IGNITION TIMING	34 deg BTC
CYLINDER WALL	235 deg F
EXHAUST GAS	1462 deg F
AMBIENT AIR	84.7 deg F
HEAD COOLANT	182.2 deg F
GEAR LUBE	180.8 deg F
CRANKCASE OIL	183.5 deg F
HYDROCARBONS	50 ppm
CARBON MONOXIDE	1 %

Annotation File: TEC.ANO

ENGINE: Tecumseh OH160 #2 Set-up File: T-VV-02 ANNO REV: 93-08-28

Bore: 3.5 Stroke: 2.875 Displacement: 27.66 Comp-Ratio: 8.33

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal not radiused
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 93-08-28
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injector replaced 93-08-28

Exhaust Open: 50 Degrees BBC

Exhaust Close: 12 Degrees ATC

Intake Open: 17 Degrees BTC

Intake Close: Density-Throttled Mode: Fixed at 235 Deg ATC

VVT Mode: Varies with load (range 60 to 245 Deg ATC, idle @ 65)

PSIA

Hansen Engine IMEP Post Processor
File: c:\edata\930902\19503606.DAT
IMEP = 57.48 PSI
PMEP = 3.58 PSI
NIMEP = 53.90 PSI
Pmax = 233 PSIA @ 16.8 Deg ATC

Hansen Engine IMEP Post Processor
File: c:\edata\930902\19503606.DAT

Hansen Engine Corporation Engine Test Data

Date: 9/ 2/1993 Time: 7:58:45.8 PM
File: 19583613

ENGINE SPEED	3617 rpm
BRAKE TORQUE	13.5 ft-lbs
BRAKE HORSEPOWER	9.3 bhp
VALVE-TRAIN TORQUE	18.4 in-lbs
VALVE-TRAIN FHP	1.06 fhp
AIR INTAKE @ STP	17.9 scfm
VOL. EFF.	66 %
current 'CF'	1.065
BMEP	73.5 psi
IMEP	105.1 psi
PMEP	3.3 psi
NMEP	101.9 psi
Pmax	401.6 psi
Location Pmax	17.2 deg ATC
CORR.HORSEPOWER	9.9 bhp corr
AIR FUEL RATIO	13.2
BSFC	0.66 lbs/hp-h
FUEL FLOW	6.1 lbs/h
AMBIENT PRESSURE	28.76 in-Hg
INJECTION START	313 deg BTC
INJECTION END	48 deg BTC
IGNITION TIMING	24 deg BTC
CYLINDER WALL	230 deg F
EXHAUST GAS	1508 deg F
AMBIENT AIR	84.9 deg F
HEAD COOLANT	183.0 deg F
GEAR LUBE	180.4 deg F
CRANKCASE OIL	174.1 deg F
HYDROCARBONS	75 ppm
CARBON MONOXIDE	1 %

Annotation File: TEC.ANO

ENGINE: Tecumseh OH160 #2 Set-up File: T-VV-02 ANNO REV: 93-08-28

Bore: 3.5 Stroke: 2.875 Displacement: 27.66 Comp-Ratio: 8.33

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal not radiused
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 93-08-28
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injector replaced 93-08-28

Exhaust Open: 50 Degrees BBC
Exhaust Close: 12 Degrees ATC
Intake Open: 17 Degrees BTC
Intake Close: Density-Throttled Mode: Fixed at 235 Deg ATC
VVT Mode: Varies with load (range 60 to 245 Deg ATC, idle @ 65)

Hansen Engine IMEP Post Processor
File: c:\edata\930902\19583613.DAT
IMEP = 105.12 PSI
PMEP = 3.27 PSI
NIMEP = 101.85 PSI
Pmax = 402 PSIA @ 17.2 Deg ATC

Hansen Engine IMEP Post Processor
File: c:\edata\930902\19583613.DAT

Hansen Engine Corporation Engine Test Data

Date: 9/ 2/1993 Time: 8:04:42.1 PM
File: 20043619

ENGINE SPEED	3622 rpm
BRAKE TORQUE	19.4 ft-lbs
BRAKE HORSEPOWER	13.4 bhp
VALVE-TRAIN TORQUE	24.5 in-lbs
VALVE-TRAIN FHP	1.41 fhp
AIR INTAKE @ STP	24.4 scfm
VOL. EFF.	90 %
current 'CF'	1.066
BMEP	105.9 psi
IMEP	145.4 psi
PMEP	3.2 psi
NMEP	142.2 psi
Pmax	587.9 psi
Location Pmax	13.6 deg ATC
CORR.HORSEPOWER	14.3 bhp corr
AIR FUEL RATIO	13.2
BSFC	0.62 lbs/hp-h
FUEL FLOW	8.2 lbs/h
AMBIENT PRESSURE	28.73 in-Hg
INJECTION START	65 deg BTC
INJECTION END	39 deg BTC
IGNITION TIMING	22 deg BTC
CYLINDER WALL	229 deg F
EXHAUST GAS	1461 deg F
AMBIENT AIR	85.1 deg F
HEAD COOLANT	186.5 deg F
GEAR LUBE	178.3 deg F
CRANKCASE OIL	180.6 deg F
HYDROCARBONS	25 ppm
CARBON MONOXIDE	2 %

Annotation File: TEC.ANO

ENGINE: Tecumseh OH160 #2 Set-up File: T-VV-02 ANNO REV: 93-08-28

Bore: 3.5 Stroke: 2.875 Displacement: 27.66 Comp-Ratio: 8.33

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal not radiused
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 93-08-28
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injector replaced 93-08-28

Exhaust Open: 50 Degrees BBC

Exhaust Close: 12 Degrees ATC

Intake Open: 17 Degrees BTC

Intake Close: Density-Throttled Mode: Fixed at 235 Deg ATC

VVT Mode: Varies with load (range 60 to 245 Deg ATC, idle @ 65)

Hansen Engine IMEP Post Processor
File: c:\edata\930902\20043619.DAT
IMEP = 145.38 PSI
PMEP = 3.18 PSI
NIMEP = 142.20 PSI
Pmax = 588 PSIA @ 13.6 Deg ATC

Hansen Engine IMEP Post Processor
File: c:\edata\930902\20043619.DAT

Hansen Engine Corporation Engine Test Data

Date: 9/ 2/1993 Time: 8:23:19.4 PM
File: 20234517

ENGINE SPEED	4525 rpm
BRAKE TORQUE	17.1 ft-lbs
BRAKE HORSEPOWER	14.7 bhp
VALVE-TRAIN TORQUE	29.2 in-lbs
VALVE-TRAIN FHP	2.10 fhp
AIR INTAKE @ STP	30.8 scfm
VOL. EFF.	91 %
current 'CF'	1.068
BMEP	93.1 psi
IMEP	141.4 psi
PMEP	5.4 psi
NMEP	136.0 psi
Pmax	564.8 psi
Location Pmax	15.4 deg ATC
CORR.HORSEPOWER	15.7 bhp corr
AIR FUEL RATIO	13.0
BSFC	0.72 lbs/hp-h
FUEL FLOW	10.5 lbs/h
AMBIENT PRESSURE	28.69 in-Hg
INJECTION START	146 deg BTC
INJECTION END	34 deg BTC
IGNITION TIMING	22 deg BTC
CYLINDER WALL	238 deg F
EXHAUST GAS	1528 deg F
AMBIENT AIR	85.5 deg F
HEAD COOLANT	185.4 deg F
GEAR LUBE	178.8 deg F
CRANKCASE OIL	193.1 deg F
HYDROCARBONS	25 ppm
CARBON MONOXIDE	2 %

Annotation File: TEC.ANO

ENGINE: Tecumseh OH160 #2 Set-up File: T-VV-02 ANNO REV: 93-08-28

Bore: 3.5 Stroke: 2.875 Displacement: 27.66 Comp-Ratio: 8.33

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal not radiused
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 93-08-28
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injector replaced 93-08-28

Exhaust Open: 50 Degrees BBC

Exhaust Close: 12 Degrees ATC

Intake Open: 17 Degrees BTC

Intake Close: Density-Throttled Mode: Fixed at 235 Deg ATC

VVT Mode: Varies with load (range 60 to 245 Deg ATC, idle @ 65)

PSIA

Hansen Engine IMEP Post Processor
File: c:\edata\930902\20234517.DAT
IMEP = 141.43 PSI
PMEP = 5.43 PSI
NIMEP = 136.00 PSI
Pmax = 565 PSIA @ 15.4 Deg ATC

Hansen Engine IMEP Post Processor
File: c:\edata\930902\20234517.DAT

Hansen Engine Corporation Engine Test Data

Date: 9/ 2/1993 Time: 8:12:05.8 PM
File: 20125011

ENGINE SPEED	5002 rpm
BRAKE TORQUE	11.5 ft-lbs
BRAKE HORSEPOWER	10.9 bhp
VALVE-TRAIN TORQUE	26.0 in-lbs
VALVE-TRAIN FHP	2.07 fhp
AIR INTAKE @ STP	25.3 scfm
VOL. EFF.	68 %
current 'CF'	1.067
BMEP	62.5 psi
IMEP	107.4 psi
PMEP	6.4 psi
NMEP	101.1 psi
Pmax	416.5 psi
Location Pmax	15.6 deg ATC
CORR.HORSEPOWER	11.6 bhp corr
AIR FUEL RATIO	13.4
BSFC	0.78 lbs/hp-h
FUEL FLOW	8.8 lbs/h
AMBIENT PRESSURE	28.72 in-Hg
INJECTION START	179 deg BTC
INJECTION END	35 deg BTC
IGNITION TIMING	25 deg BTC
CYLINDER WALL	230 deg F
EXHAUST GAS	1599 deg F
AMBIENT AIR	85.1 deg F
HEAD COOLANT	186.5 deg F
GEAR LUBE	180.2 deg F
CRANKCASE OIL	186.4 deg F
HYDROCARBONS	25 ppm
CARBON MONOXIDE	2 %

Annotation File: TEC.ANO

ENGINE: Tecumseh OH160 #2 Set-up File: T-VV-02 ANNO REV: 93-08-28

Bore: 3.5 Stroke: 2.875 Displacement: 27.66 Comp-Ratio: 8.33

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal not radiused
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 93-08-28
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injector replaced 93-08-28

Exhaust Open: 50 Degrees BBC

Exhaust Close: 12 Degrees ATC

Intake Open: 17 Degrees BTC

Intake Close: Density-Throttled Mode: Fixed at 235 Deg ATC

VVT Mode: Varies with load (range 60 to 245 Deg ATC, idle @ 65)

PSIA

Hansen Engine IMEP Post Processor
File: c:\edata\930902\20125011.DAT
IMEP = 107.42 PSI
PMEP = 6.36 PSI
NIMEP = 101.05 PSI
Pmax = 417 PSIA @ 15.6 Deg ATC

Hansen Engine IMEP Post Processor
File: c:\edata\930902\20125011.DAT

Hansen Engine Corporation Engine Test Data

Date: 9/ 2/1993 Time: 8:17:27.0 PM
File: 20175016

ENGINE SPEED	4984 rpm
BRAKE TORQUE	16.0 ft-lbs
BRAKE HORSEPOWER	15.2 bhp
VALVE-TRAIN TORQUE	27.6 in-lbs
VALVE-TRAIN FHP	2.18 fhp
AIR INTAKE @ STP	32.2 scfm
VOL. EFF.	87 %
current 'CF'	1.069
BMEP	87.5 psi
IMEP	136.8 psi
PMEP	6.1 psi
NMEP	130.7 psi
Pmax	530.0 psi
Location Pmax	17.0 deg ATC
CORR.HORSEPOWER	16.3 bhp corr
AIR FUEL RATIO	13.5
BSFC	0.71 lbs/hp-h
FUEL FLOW	10.8 lbs/h
AMBIENT PRESSURE	28.67 in-Hg
INJECTION START	170 deg BTC
INJECTION END	19 deg BTC
IGNITION TIMING	22 deg BTC
CYLINDER WALL	229 deg F
EXHAUST GAS	1572 deg F
AMBIENT AIR	85.3 deg F
HEAD COOLANT	181.7 deg F
GEAR LUBE	176.3 deg F
CRANKCASE OIL	187.4 deg F
HYDROCARBONS	25 ppm
CARBON MONOXIDE	2 %

Annotation File: TEC.ANO

ENGINE: Tecumseh OH160 #2 Set-up File: T-VV-02 ANNO REV: 93-08-28

Bore: 3.5 Stroke: 2.875 Displacement: 27.66 Comp-Ratio: 8.33

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal not radiused
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 93-08-28
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injector replaced 93-08-28

Exhaust Open: 50 Degrees BBC

Exhaust Close: 12 Degrees ATC

Intake Open: 17 Degrees BTC

Intake Close: Density-Throttled Mode: Fixed at 235 Deg ATC

VVT Mode: Varies with load (range 60 to 245 Deg ATC, idle @ 65)

Hansen Engine IMEP Post Processor
File: c:\edata\930902\20175016.DAT
IMEP = 136.82 PSI
PMEP = 6.08 PSI
NIMEP = 130.74 PSI
Pmax = 530 PSIA @ 17.0 Deg ATC

Hansen Engine IMEP Post Processor
File: c:\edata\930902\20175016.DAT

Date:, 9/12/1994 ,
Time:,10:42:39.0 AM ,
File:,10420706,
ENGINE SPEED,720,rpm,
BRAKE TORQUE,5.6,ft-lbs,
BRAKE HORSEPOWER,0.8,bhp,
VALVE-TRAIN TORQUE,37.4,in-lbs,
VALVE-TRAIN FHP,0.43,fhp,
AIR INTAKE @ STP,6.8,scfm,
VOL. EFF.,22,%,
current 'CF',1.048, ,
BMEP,6.4,psi,
CORR.HORSEPOWER,0.8,bhp corr,
AIR FUEL RATIO,-9999.0, ,
BSFC,-9999.00,lbs/hp-h,
FUEL FLOW,-9999.0,lbs/h,
AMBIENT PRESSURE,29.02,in-Hg,
INJECTION START,185,deg BTC,
INJECTION END,154,deg BTC,
IGNITION TIMING,29,deg BTC,
AMBIENT TEMP,76.9,deg F,
HYDROCARBONS,-9999,ppm,
CARBON MONOXIDE,-9999.0,%,
IMEP,26.7,psi,
PMEP,2.4,psi,
NMEP,24.3,psi,
Pmax,179.3,psi,
Location Pmax,11.0,deg ATC,

Annotation File: 4CYL.ANO

ENGINE: Chev 2.2 L4 Set-up File: 4cyl1 ANNO REV: 94-5-11

Bore: 3.504 in Stroke: 3.465 in Displacement: 133.6 in³ Comp-Ratio: 9.2
(3.465 in x 4 cyl, 33.4 in³ x 4 cyl)

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal radiused one
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 94-04-27
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injectors replaced 94-04-27

Exhaust Open: 50 Degrees BBC

Exhaust Close: 10 Degrees ATC

Intake Open (mini-rotor): 10 Degrees BTC (main rotor): 9 Degrees ATC

Intake Close: Density-Throttled Mode: Fixed at 250 Deg ATC

VVT Mode: Varies with load (range 70 to 250 Deg ATC, idle > 75)

Mini-sleeve: closed 60 deg / open 120 degrees

Piston crown: nominal 0.125 clearance to fire-deck

Sleeve liner: P3310 graphite, interference fit to anchor in place
last replacement: 4\27\94

Arcuate seal: elctroplated chrome on 4140; last replaced 94-04-27

sides @ 1.0:1 ratio, venting at top and bottom

top @ 1.0:1 ratio, venting thru side grooves

bottom @ 1.0:1 ratio, venting thru side grooves

driven on center line, above & below port

Band Seal: chrome plated 4140; continuous type
driven on leading edge

Hansen Engine IMEP Post Processor
File: c:\E400T\940912ID\10420706.DAT

Hansen Engine IMEP Post Processor
File: c:\E4VUT\940912ID\10420706.DAT
IMEP = 26.69 PSI
PMEP = 2.36 PSI
NIMEP = 24.33 PSI
Pmax = 179 PSIA @ 11.0 Deg ATC

Date:, 9/14/1994 ,
Time:, 2:48:13.2 PM ,
File:, 14482613,
ENGINE SPEED, 2560, rpm,
BRAKE TORQUE, 13.4, ft-lbs,
BRAKE HORSEPOWER, 6.5, bhp,
VALVE-TRAIN TORQUE, 47.2, in-lbs,
VALVE-TRAIN FHP, 1.92, fhp,
AIR INTAKE @ STP, 28.4, scfm,
VOL. EFF., 26, %,
current 'CF', 1.064, ,
BMEP, 15.2, psi,
CORR. HORSEPOWER, 7.0, bhp corr,
AIR FUEL RATIO, -9999.0, ,
BSFC, -9999.00, lbs/hp-h,
FUEL FLOW, -9999.0, lbs/h,
AMBIENT PRESSURE, 28.73, in-Hg,
INJECTION START, 347, deg BTC,
INJECTION END, 243, deg BTC,
IGNITION TIMING, 29, deg BTC,
AMBIENT TEMP, 82.9, deg F,
HYDROCARBONS, -9999, ppm,
CARBON MONOXIDE, -9999.0, %,
IMEP, 35.3, psi,
PMEP, 2.5, psi,
NMEP, 32.8, psi,
Pmax, 137.1, psi,
Location Pmax, 27.5, deg ATC,

Annotation File: 4CYL.ANO

ENGINE: Chev 2.2 L4 Set-up File: 4cyl1 ANNO REV: 94-9-14

Bore: 3.504 in Stroke: 3.465 in Displacement: 133.6 in³ Comp-Ratio: 9.2
(3.465 in x 4 cyl, 33.4 in³ x 4 cyl)

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal radiused one
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 94-04-27
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injectors replaced 94-04-27

Exhaust Open: 50 Degrees BBC

Exhaust Close: 10 Degrees ATC

Intake Open (mini-rotor): 10 Degrees BTC (main rotor): 9 Degrees ATC

Intake Close: Density-Throttled Mode: Fixed at 250 Deg ATC

VVT Mode: Varies with load (range 50 to 250 Deg ATC, idle > 75)

Mini-sleeve: closed 60 deg / open 120 degrees

Piston crown: nominal 0.125 clearance to fire-deck

Sleeve liner: P3310 graphite, interference fit to anchor in place
last replacement: 4/27/94

Arcuate seal: electroplated chrome on 4140; last replaced 94-07
sides @ 1.0:1 ratio, venting at (top/bottom) + 2 slits each side
top .125" land, venting thru side grooves + (4) .028" holes
bottom @ 1.0:1 ratio, venting thru side grooves
driven on center line, above & below port

Band Seal: chrome plated 4140; continuous type
driven on leading edge

Hansen Engine IMEP Post Processor
File: c:\E4UUT\940914U\14482613.DAT

Hansen Engine IMEP Post Processor
File: c:\E4UUT\940914U\14482613.DAT
IMEP = 35.30 PSI
PMEP = 2.52 PSI
NIMEP = 32.78 PSI
Pmax = 137 PSIA @ 27.5 Deg ATC

Date:, 9/15/1994 ,
Time:, 5:39:25.1 PM ,
File:, 17394062,
ENGINE SPEED, 3979, rpm,
BRAKE TORQUE, 62.4, ft-lbs,
BRAKE HORSEPOWER, 47.3, bhp,
VALVE-TRAIN TORQUE, 84.2, in-lbs,
VALVE-TRAIN FHP, 5.32, fhp,
AIR INTAKE @ STP, 85.4, scfm,
VOL. EFF., 52, %,
current 'CF', 1.099, ,
BMEP, 70.4, psi,
CORR. HORSEPOWER, 52.0, bhp corr,
AIR FUEL RATIO, 13.6, ,
BSFC, 0.61, lbs/hp-h,
FUEL FLOW, 28.3, lbs/h,
AMBIENT PRESSURE, 27.82, in-Hg,
INJECTION START, 110, deg BTC,
INJECTION END, 191, deg BTC,
IGNITION TIMING, 25, deg BTC,
AMBIENT TEMP, 82.8, deg F,
HYDROCARBONS, -9999, ppm,
CARBON MONOXIDE, -9999.0, %,
IMEP, 101.7, psi,
PMEP, 1.8, psi,
NMEP, 100.0, psi,
Pmax, 488.3, psi,
Location Pmax, 12.8, deg ATC,

Annotation File: 4CYL.ANO

ENGINE: Chev 2.2 L4 Set-up File: 4cyl1 ANNO REV: 94-9-14

Bore: 3.504 in Stroke: 3.465 in Displacement: 133.6 in³ Comp-Ratio: 9.2
(3.465 in x 4 cyl, 33.4 in³ x 4 cyl)

ROTARY VALVE CONFIGURATION

Dual Nested Shutters; primary bridge-seal radiused one
; secondary bridge-seal radiused

Ignition System: Intelligent Controls "IDI" System with "IC 5460" controller
Spark-plug located on rotor centerline; Champion RFN14LY replaced 94-04-27
Injection system: Multi-port sequential type with IC 5460 controller; MAF mode
Bosch injectors replaced 94-04-27

Exhaust Open: 50 Degrees BBC

Exhaust Close: 10 Degrees ATC

Intake Open (mini-rotor): 10 Degrees BTC (main rotor): 9 Degrees ATC

Intake Close: Density-Throttled Mode: Fixed at 250 Deg ATC

VVT Mode: Varies with load (range 50 to 250 Deg ATC, idle > 75)

Mini-sleeve: closed 60 deg / open 120 degrees

Piston crown: nominal 0.125 clearance to fire-deck

Sleeve liner: P3310 graphite, interference fit to anchor in place
last replacement: 4\27\94

Arcuate seal: elctroplated chrome on 4140; last replaced 94-07
sides @ 1.0:1 ratio, venting at (top/bottom) + 2 slits each side
top .125" land, venting thru side grooves + (4) .028" holes
bottom @ 1.0:1 ratio, venting thru side grooves
driven on center line, above & below port

Band Seal: chrome plated 4140; continuous type
driven on leading edge

Hansen Engine IMEP Post Processor
File: c:\E40UT\940915U\17394062.DAT

Hansen Engine IMEP Post Processor
File: c:\NE4UUT\940915U\17394062.DAT
IMEP = 101.73 PSI
PMEP = 1.77 PSI
NIMEP = 99.96 PSI
Pmax = 488 PSIA @ 12.8 Deg ATC