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HYDROGEN-ENRICHED FUELS

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Abstract

NRG Technologies, Inc. is attempting to develop hardware and infrastructure that will allow mixtures of hydrogen and conventional fuels to become viable alternatives to conventional fuels alone. This commercialization can be successful if we are able to achieve exhaust emission levels of less than 0.03 g/kw-hr NO_x and CO; and 0.15 g/kw-hr NMHC at full engine power without the use of exhaust catalysts. The major barriers to achieving these goals are that the lean-burn regimes required to meet exhaust emissions goals reduce engine output substantially and tend to exhibit higher-than-normal total hydrocarbon emissions. Also, hydrogen addition to conventional fuels increases fuel cost, and reduces both vehicle range and engine output power. Maintaining low emissions during transient driving cycles is a difficult challenge that is often overlooked in lean-burn testing.

Our approach to overcoming these problems has been to investigate the applicability of know concepts and technologies that can overcome the barriers to success. To recuperate lost engine power, super/turbocharging, and increasing volumetric efficiency, compression ratio, engine speed and displacement are options. Combustion chamber design, valve timing and the "optimization" of tradeoffs between engine power and efficiency with spark timing are also important parameters.

A three-year test plan has been developed to perform the investigations into the issues described above. This paper outlines the major work performed during "Year 2" of the three year plan. Exhaust gas recirculation investigations were initiated on a single-cylinder engine, but the majority of work was performed on a 4.6L V8 engine. An innovative supercharger system was used for lean-burn power recuperation. Steady-state engine dynamometer testing was performed to document the effects of excess air, speed,

load, ignition timing, and catalyst effects on emissions with 30% H_2 and natural gas mixtures. Two different cylinder head designs were also evaluated on the V8. The engine dynamometer testing progressed into vehicle driveability evaluations and then to transient emissions testing at an independent laboratory. Finally, pre and post-catalyst exhaust gas speciation was performed in order to assess OEM CNG fuel catalyst performance when operated with hydrogen-enriched natural gas.

Background

The purpose of adding hydrogen to conventional fuels is to extend the lean limit of combustion to the point where harmful exhaust emissions are lowered significantly below the level achievable by existing catalyst technology. Figure 1 shows a graphical representation of this principle. Figure 1 shows a region where increases in excess air in a combustible mixture result in a reduction in oxides of nitrogen (NO_x), carbon monoxide (CO), and total hydrocarbons (THC). The reduction in NO_x is a function of a reduction in peak combustion temperature as the excess air increases the specific heat of the combustible mixture. The reduction in CO and THC results from more complete combustion as the fuel easily and more completely reacts with the greater abundance of oxygen. However, a point is reached in which increases in excess air critically weakens the combustible mixture strength. This reduction in mixture strength results in a decline in combustion stability that induces a rapid increase in THC which is known as the lean limit of combustion.

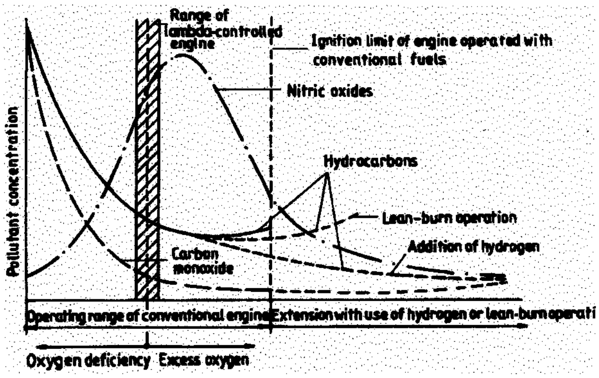


Figure 1. Lean Burn Emissions Trends

For conventional fuels operating in conventional engines, the emissions nitrogen oxides, or NO_x, cannot be reduced sufficiently using lean-burn strategies to out-perform commercial catalyst technology. The addition of hydrogen to conventional fuels increases the volatility of the combustible mixture and allows stable combustion to occur in extended lean regimes that would otherwise not be possible. This extension of the lean limit with hydrogen allows an extension of the NO_x reduction trend with increasing amounts of excess air depicted in Figure 1. The question is, "How much hydrogen must be added to achieve desired exhaust emissions?"

Previous work in this area was performed by the NRG Technologies staff while at the Florida Solar Energy Center (Collier, et al 1996). Figure 2 from this work shows the total hydrocarbon emissions as a function of equivalence ratio and percent of the volume of fuel mixture that is hydrogen. The base fuel is natural gas, consisting of 96% methane, and the engine is a Ford 4.6L V8. Notice that as hydrogen is added to the base fuel, the rapid rise in hydrocarbon emissions occurs at greater amounts of excess air (lower equivalence ratio). An anomaly is apparent in that 10 and 20 percent hydrogen acted similarly, as did 30 and 40 percent. The major extensions of the lean limit occurred between 0 and 10, 20 and 30, and 40 to 50 percent hydrogen. A highlight from that work was the achievement of < 0.05 g/kWh NO_x for bmeps up to 500 kPa and rpms above 1700 due to the extension of the lean burn limit with 30% H_2.

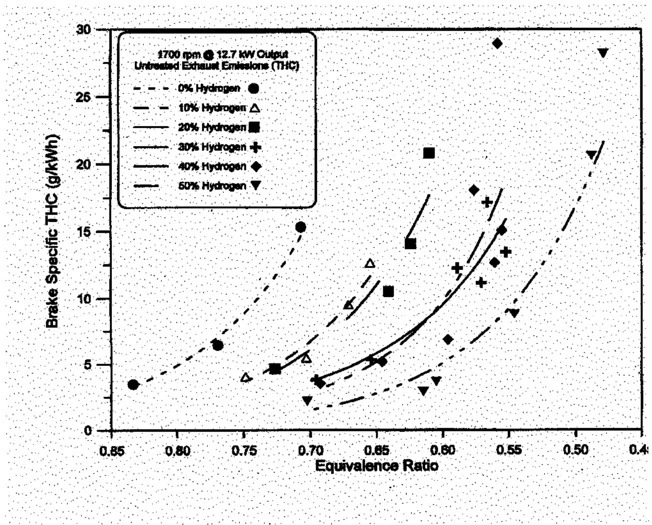


Figure 2. THCs As a Function of H_2 and Equivalence (From Collier et. al.)

Other research dealing with hydrogen-natural gas mixtures and lean burn has been conducted. The Bartlesville Energy Research Center (Eccleston 1972) and a joint project between Hydrogen Consultants, Inc. and Colorado State University (Fulton 1993) have published results. The BERC project investigated up to 20%, by volume, of hydrogen supplementation of natural gas. They concluded that:

1. The lean limit of combustion is extended by the addition of hydrogen.
2. The lean limit is not extended sufficiently to obtain exhaust emissions lower than that achieved by catalyst systems with only 20% hydrogen.
3. Exhaust gases are generally less reactive with hydrogen addition.

Critical Areas of Interest To Be Investigated During Three Year Project

The critical areas of interest for this project are based on the desire to demonstrate and automotive engine platform that produces superior emissions to conventionally fueled technologies (including natural gas) by using hydrogen-enriched natural gas (HCNG) in ultra-lean burn combustion. To achieve this goal NRG Technologies is conducting fundamental fuel and engine research in-order-to address issues that are foreseen as potential barriers to success. The three year project involves work in the areas below.

- Ultra lean-burn power losses must be recuperated with turbocharging or supercharging and all final emissions work must be based on an engine system that can meet customer's performance expectations.
- More thorough investigations of advantages/disadvantages of various hydrogen percentages in the fuel will be conducted. More H_2 can achieve leaner combustion and lower NO, but at the expense of less power output, higher fuel cost, less vehicle range and greater engineering difficulties if too much H_2 is desired.
- Transient emissions testing using established protocol for a more appropriate look at the emissions performance compared to conventional technologies.
- Engine design parameter evaluations with HCNG to appropriately gauge the maximum potential of HCNG as a fuel. Compression ratio, valve timing, piston and cylinder head design, bore-to-stroke ratio, exhaust gas recirculation, intake air charging strategies, and catalysts are all engine design features that have important effects on engine performance, efficiency, and emissions. OEMs tailor these parameters for the fuel being used and the performance/emissions needs of the market.
- Exhaust gas speciation is necessary to assist catalyst optimization investigations and to quantify the concentration of photoreactive hydrocarbons which are the compounds of interest in emissions certification standards.

Summary of Current Year Activities

R&D Methodology

NRG Technologies' basic research approach is to perform initial investigations of engine design and control methodologies on an in-house single-cylinder research engine. This platform is a cost-effective starting point for evaluating engine operating issues such as hydrogen content in the fuel, intake air charging, exhaust gas recirculation, exhaust aftertreatment, cylinder head design, and compression ratio. Successful concepts from the single-cylinder engine are then incorporated into a real-world multi-cylinder engine for further evaluation. The multi-cylinder platform is also tested using a steady-state approach on an engine dynamometer. Once promising component design, equivalence ratio, emissions and other engine management relationships are sufficiently defined, then the evaluation progresses to in-vehicle testing of driveability. The final evaluation phase is transient emissions verification on a chassis dynamometer. Complete vehicle transient emissions testing under a known testing protocol is essential to producing a final quantitative gauge of the technology's benefits compared to conventional fuels.

Single-Cylinder Engine Research

Single-Cylinder Platform Description

NRG Technologies' in-house single-cylinder engine is based on a Ford 2.3L in-line four. Three of the piston and connecting rod pairs were removed to create the "single-cylinder" arrangement. The engine was rebalanced and all applicable intake and exhaust tracks were deactivated with sheet metal gaskets. This platform was selected early on for initial basic strategy evaluations because it consumes far less fuel, assures no air/fuel ratio data variation due to cylinder-to-cylinder distribution, and aftermarket variations in major components, such as pistons and cylinder heads, exist for the base four-cylinder structure.

This makes it a cost-effective arrangement for broad scopes of engine design evaluations. The engine is sufficiently equipped with sensors to monitor all critical pressures, temperatures, air flow, fuel flow, and in-cylinder combustion data.

Previous Single-Cylinder Work

"Year One" work consisted mainly of single-cylinder evaluations under varying speeds and loads for 25, 30, and 35% hydrogen contents in natural gas. This research was based on the stock piston and cylinder head components of the original Ford 2.3L gasoline engine with a 8.7: 1 compression ratio. This early work laid a sound emissions characterization base for subsequent evaluations of alternative engine design variations.

Current Year Single-Cylinder Activities

In the current reporting year (Year Two) the cylinder head was replaced with one that allowed two spark plugs per cylinder. This dual-plug head was chosen because it would allow evaluation of a second spark plug's ability to extend the lean limit by adding extra ignition energy to the initial stage of combustion. Furthermore, the face of this new head was milled to create a 12:1 compression ratio for a major engine parameter change from the relatively low stock 8.7:1 compression. Other than the shaving of the head and the extra port for an additional spark plug, this new cylinder head has the same basic flow geometry of the original. The investigation of the effects of compression ratio on the hydrogen-enriched mixtures is underway at this time and no data is presented here.

Exhaust Gas Recirculation

An investigation of exhaust gas recirculation (EGR) on the single-cylinder platform has also been initiated. EGR is a commonly applied technique to reduce NO_x emissions in conventional automotive engines under part load conditions. The exhaust gas acts as an air/fuel charge dilutant just as excess air does in lean-burn, the major difference being the lack of oxygen in EGR. Each method of charge dilution increases the specific heat of the charge thereby lowering the peak combustion temperature and subsequently NO_x emissions.

A comparison between EGR and lean burn and their relative NO, reducing effectiveness was performed using 28% hydrogen at wide-open-throttle, 1800 rpm, and a constant 6% exhaust oxygen content as measured by a heated NTK wide-range oxygen sensor. Here the term "EGR" will mean a combination of excess air and recirculated exhaust gas and the term "lean-burn" is intended to mean excess air only. An Optrand pressure transducer was mounted in the spare spark plug port to allow acquisition of real-time P-V data for indicated work analysis. A coefficient of variation (COV) for a set of 300 combustion cycles was determined for each stable operating condition measured. COV is an indication of combustion stability or consistency and is calculated by dividing the standard deviation between individual indicated work cycles by the average indicated work for the P-V data set. A COV greater than 10% is generally accepted as an unacceptable condition in which a driver would perceive erratic engine operation.

Figure 3 shows a plot of NO_x emissions against "equivalent lambda," or in other words, the equivalent level of charge dilution based on the quantity of molecules that cannot contribute to oxidation of the fuel. Figure 3 shows that the NO_x reducing tendencies of EGR and lean burn are remarkably similar under the stated conditions. Also shown is the corresponding total hydrocarbon emissions (THCs) and COV, respectively. It appears from the data that lean burn has an advantage in COV over EGR but a disadvantage in THC emissions. Although neither methodology has a clear advantage, the results show that EGR is certainly a viable compliment to lean burn. These results are an important step in understanding the value of EGR for HCNG fuels because it is such a commonly applied NO_x reduction technique in gasoline engines but is rarely studied in combustion regimes as lean as those NRG Technologies is investigating.

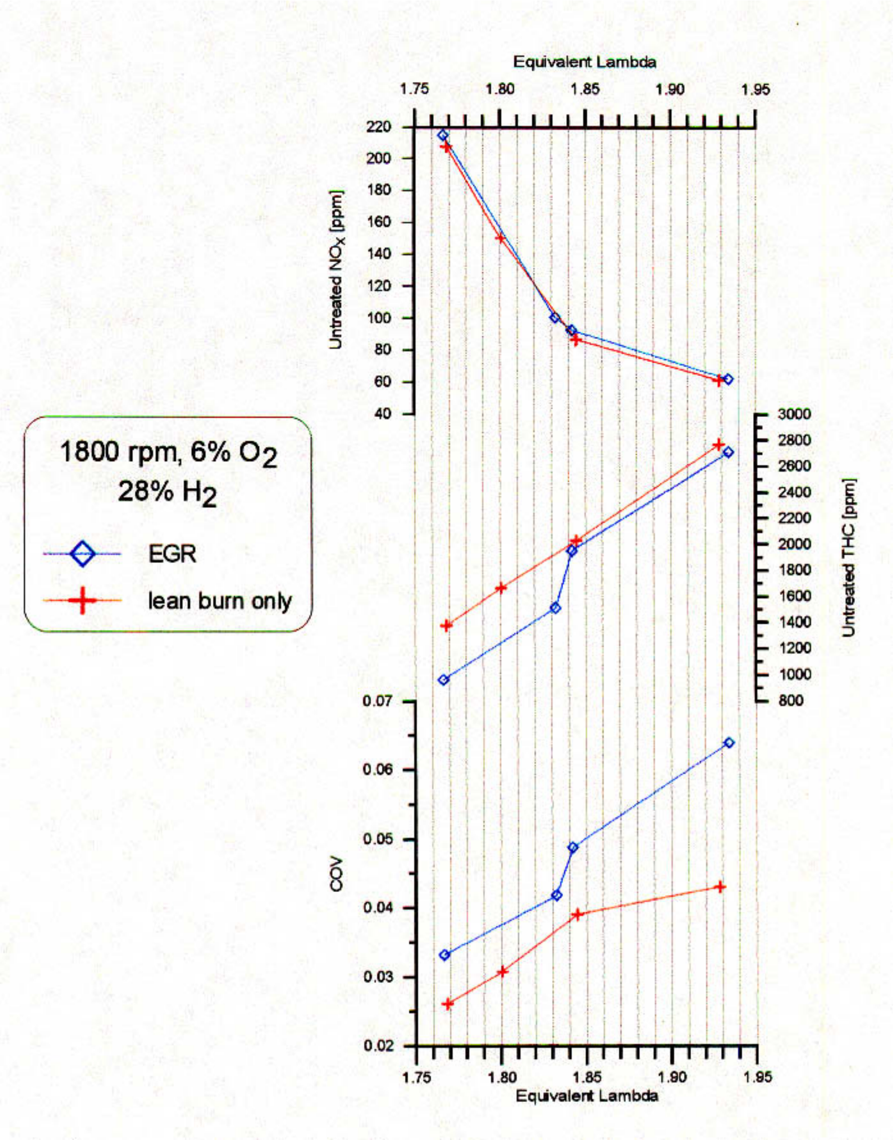


Figure 3 – EGR Vs. Lean Burn

Equipment Failures and Timeline Setbacks

The timetable for testing EGR and increased compression ratios has fallen behind schedule on the single-cylinder engine due to two unexpected circumstances. First, we experienced a series of single-cylinder engine driveshaft wear issues and one catastrophic failure. Eventually, the rigid driveshaft/U-joint arrangement was replaced with a torsionally compliant flexible coupling between the engine and dynamometer. This flexible coupling also failed even with the manufacturer's direct assistance in selecting the appropriate model. The manufacturer has since identified our overall problem as a resonance issue typical of single-cylinder engines and has supplied couplings of alternative natural frequencies that should eliminate the problem. Each failure, though, has taken a toll on the testing timeline because of the time and care taken to ensure the long-term safety of equipment and personnel.

The second delay in the testing timeline was due to a failure in our spark plug mounted in-cylinder pressure transducer. This unit is the basis for all combustion stability quantification and is a critical instrument in the research of lean combustion. Its replacement took over four months to arrive due to manufacturing setbacks with its OEM. The replacement is appropriate for block or head mounting rather that the weaker spark plug mountable unit. This problem happened somewhat in series with the driveshaft issues resulting in a significant setback in single-cylinder testing.

V8 Testing of Hydrogen-Enriched Natural Gas

A significant amount of 30% H_2 testing was performed on a Ford 4.6L V8 engine. The engine started life as the power plant for a dedicated CNG Crown Victoria full size passenger car offered directly from Ford. NRG installed an identical 4.6L mule block on a Midwest eddy current dynamometer for steady state emissions testing. The wiring harness, cylinder heads, and fuel system from the car were transferred to the dyno engine. NRG installed a programmable engine control unit (ECU) and an integrated intake manifold/supercharger assembly. The programmable ECU allows NRG to dictate air/fuel ratio and ignition timing over the entire speed and load range of the engine.

The 4.6L engine development process for operation on 30% H_2 proceeded in the following manner:

- Supercharger assessed and modified for lean-burn power recuperation
- Characterized pre-catalyst emissions over a range of speed and load as a function of excess air (or O_2 content in exhaust)
- Compared the performance of two cylinder head designs
- Tuned ignition timing and air/fuel ratio for best post-catalyst emissions
- Speciated pre and post-catalyst emissions to evaluate stock CNG catalyst performance
- Installed system back into vehicle and tuned ECU further for driveability
- Performed transient emissions test of vehicle system at independent facility
- Submitted vehicle for six month field evaluation in Las Vegas, NV

Supercharger

The stoichiometric air/fuel ratio for a mixture of 30% H_2 and 70% natural gas is approximately 18:1. The lean burn regimes required to maintain superior NO_x emissions with HCNG fuels is approximately 30:1. Most CNG engines are based on gasoline engine structures and gasoline is typically cornbusted at 14.7:1. Therefore, it is appropriate to say that an HCNG engine running at 30:1 will require approximately double the amount of naturally aspirated air flow using conventional fuels under stoichiometric operation in order to make equivalent power. It is this characteristic of extreme lean-burn operation that mandates the use of a supercharger or turbocharger to satisfy vehicle driveability requirements

The supercharger incorporated into the 4.6L HCNG engine by NRG Technologies features a screw compressor integrated into a cast aluminum intake manifold. It is sold by Ford's Specialty Vehicle Operations (SVO) arm for enhancing the performance of Ford Mustangs which also use the Ford 4.6L engine. Figure 4 shows a comparison between the SVO unit (left) and the original intake manifold for naturally aspirated operation. The SVO system makes excellent use of the overhead cam engine's "V" valley and results in an intake system that has the same vertical dimensions as the original. This was essential for this platform because the engine bay is not conducive to larger centrifugal blowers that are mounted like conventional accessories.

Figure 6 shows air flow curves for the SVO supercharger with two supercharger drive pulleys. The 3 inch diameter drive pulley was ultimately selected because it drove the supercharger faster than the original 3.6 inch pulley for any given engine speed. These superchargers are normally installed in competition engines that are expected to perform at 6,000 – 8,000 engine rpm. However, passenger cars like the Crown Victoria normally redline at about 5,000 rpm and downshift between gears at about 2,500 - 3,000 rpm during normal accelerations. An even smaller pulley for higher rpm would probably have been incorporated by NRG if not for belt slippage issues.

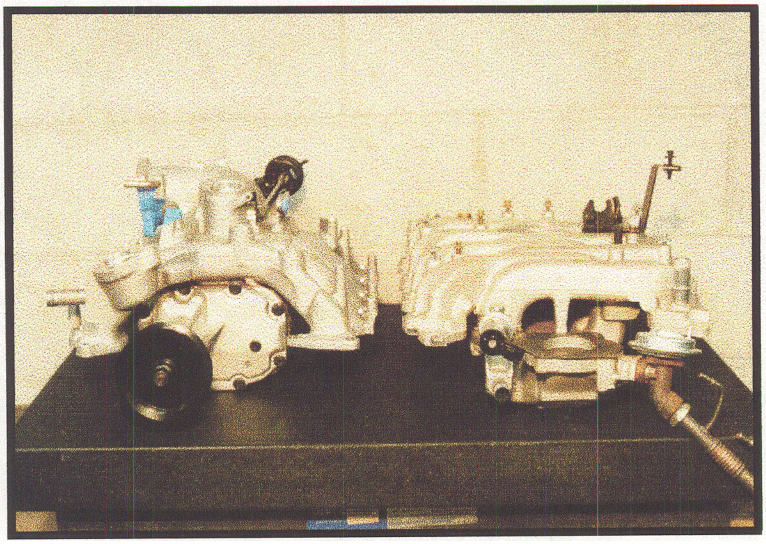


Figure 4 – SVO integrated supercharger/intake manifold (left)

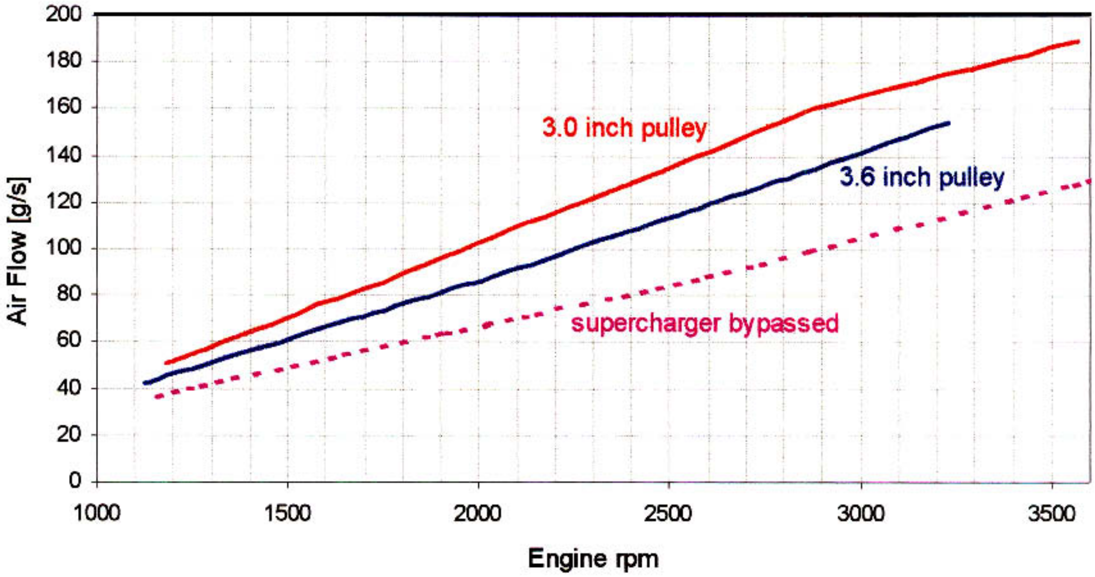


Figure 6 - Supercharger Air Flow Data

Full Load Emissions

Figure 7 shows the emissions characteristics of the 4.6L V8 under wide open throttle (WOT) conditions with a constant 10% excess oxygen in the exhaust. These operating points are rarely expected in normal driving but are a good indication of worse case emissions. It can be seen that a higher supercharger rotor drive speed does increase air flow and power as desired, but at the expense of higher intake air temperatures due to enhanced boost and subsequently higher NO_x emissions. It is NRG's intent to investigate inter-cooler options to address the temperature induced NO_x increases.

NO_x Emissions as a Function of Speed, Load, and 0_2 Content

The WOT supercharger evaluation described above was made to assure vehicle driveability under lean-burn operation before moving forward with efforts to characterize and tune the engine for emissions under more realistic conditions. Engines for passenger cars and pick-up trucks are operated at part throttle conditions for the majority of a normal day's driving cycle so most emissions characterization was performed at part load. Figure 8 shows NO_x emissions as a function of engine speed, load percent and O_2 content at MBT timing. Obviously, NO_x emissions were lowest with 12% excess O_2 in the exhaust, but the THCs for these runs showed that 12% O_2 was too close to the lean limit. This mapping proved to be very useful in determining the safety margin between clean, stable operation and high THC, unstable operation.

Effects of Cylinder Head Design on Emissions

A visual inspection of the stock cylinder heads indicated that they were designed to enhance in-cylinder swirl generation. Swirl is a method of increasing air/fuel charge mixing by inducing large rotational flow movement in the charge stream as it fills the cylinder during the intake stroke. Swirl generally results in lower hydrocarbon emissions as is promotes a more homogeneous air/fuel charge, but at the expense of higher NO_x emissions and lower engine power due to flow losses. An aftermarket high-flow cylinder head for the 4.6L engine was installed. High-flow heads are generally characterized by large intake ports, valves and other refined flow feathers that minimize pressure losses. These heads are generally designed to minimize swirl.

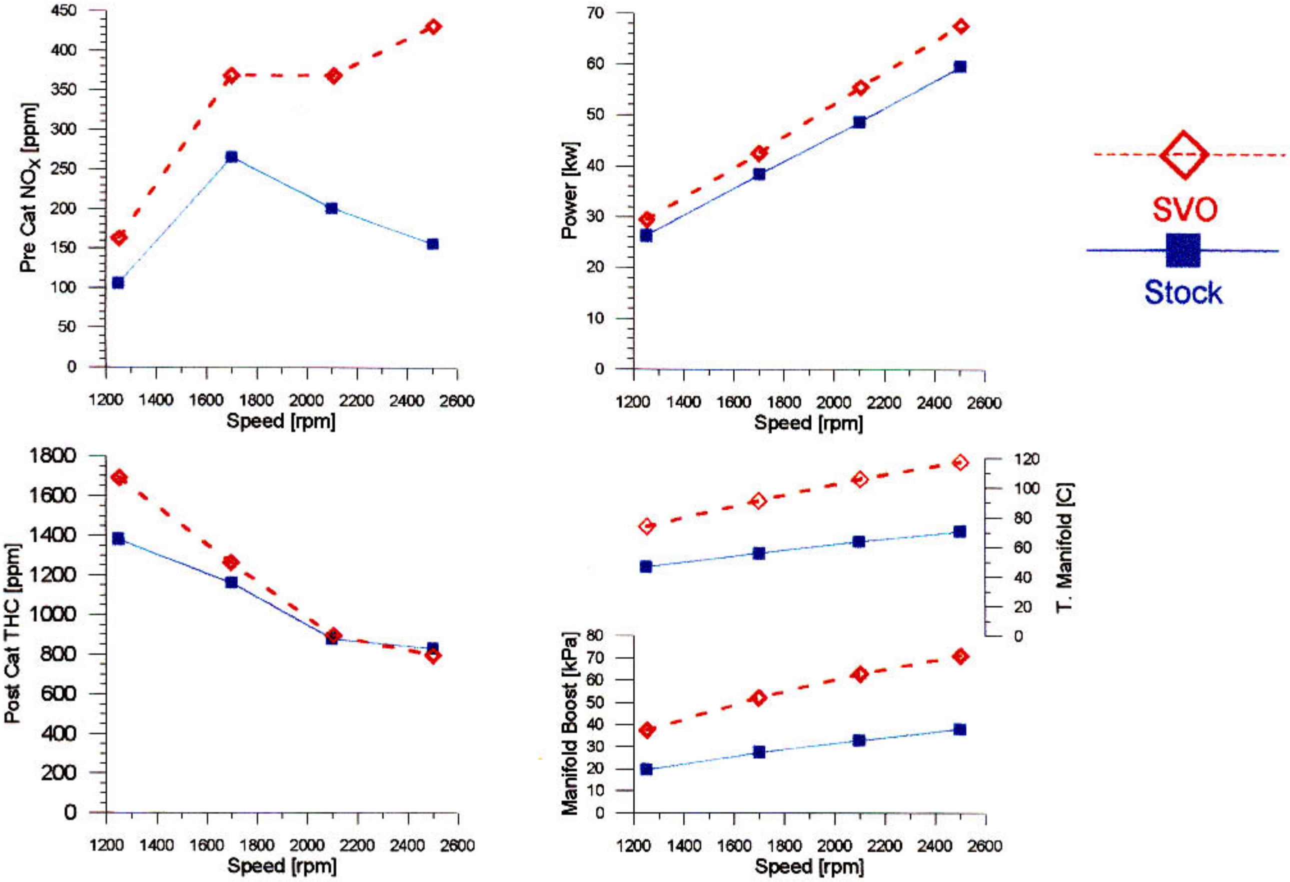


Figure 7 – Full Load Emissions & Performance on 30% H_2

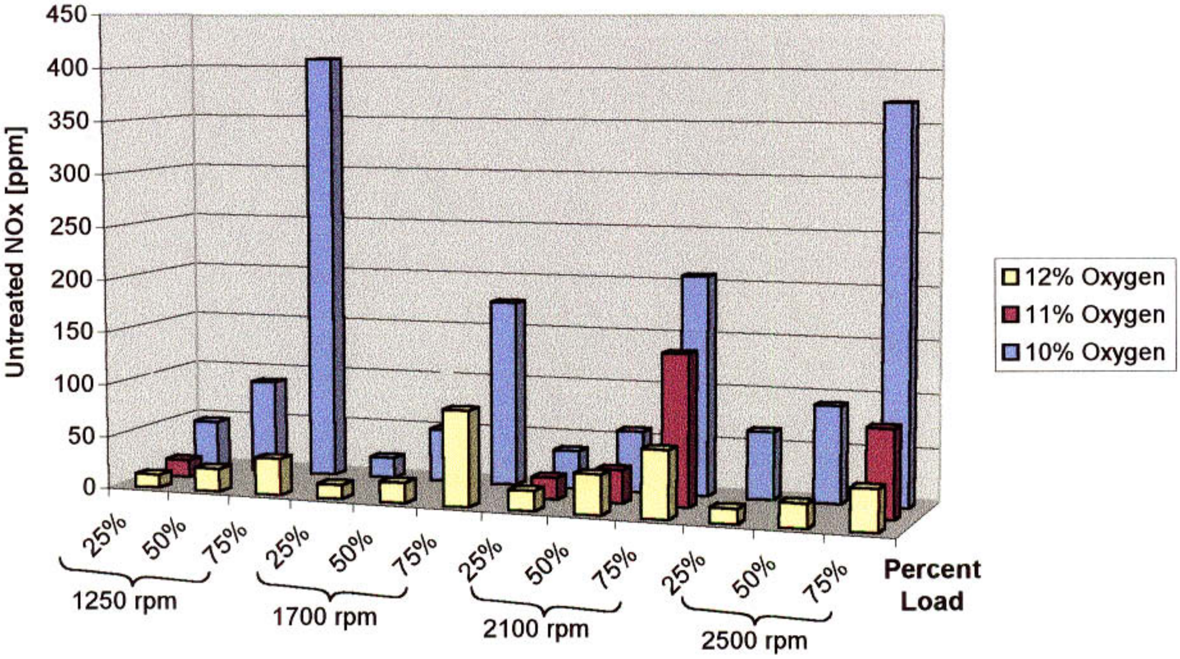


Figure 8 – Part Load NO_x Emissions at MBT Timing

The six graphs in Figure 9 show NO_x and THC performance at various speeds and loads for both the stock and high-flow aftermarket cylinder heads. All data was taken while holding excess exhaust O_2 content to 10% to keep the same lean air/fuel ratio. The high-flow heads show a clear advantage in NO_x emissions. The increase in THCs using the high-flow heads is considered to be an acceptable trade-off. These results agree with other CNG studies that more swirl results in more NO_x at lean air/fuel ratios (Sakurai 1993). Based on these results the aftermarket cylinder heads were permanently selected as the heads of choice.

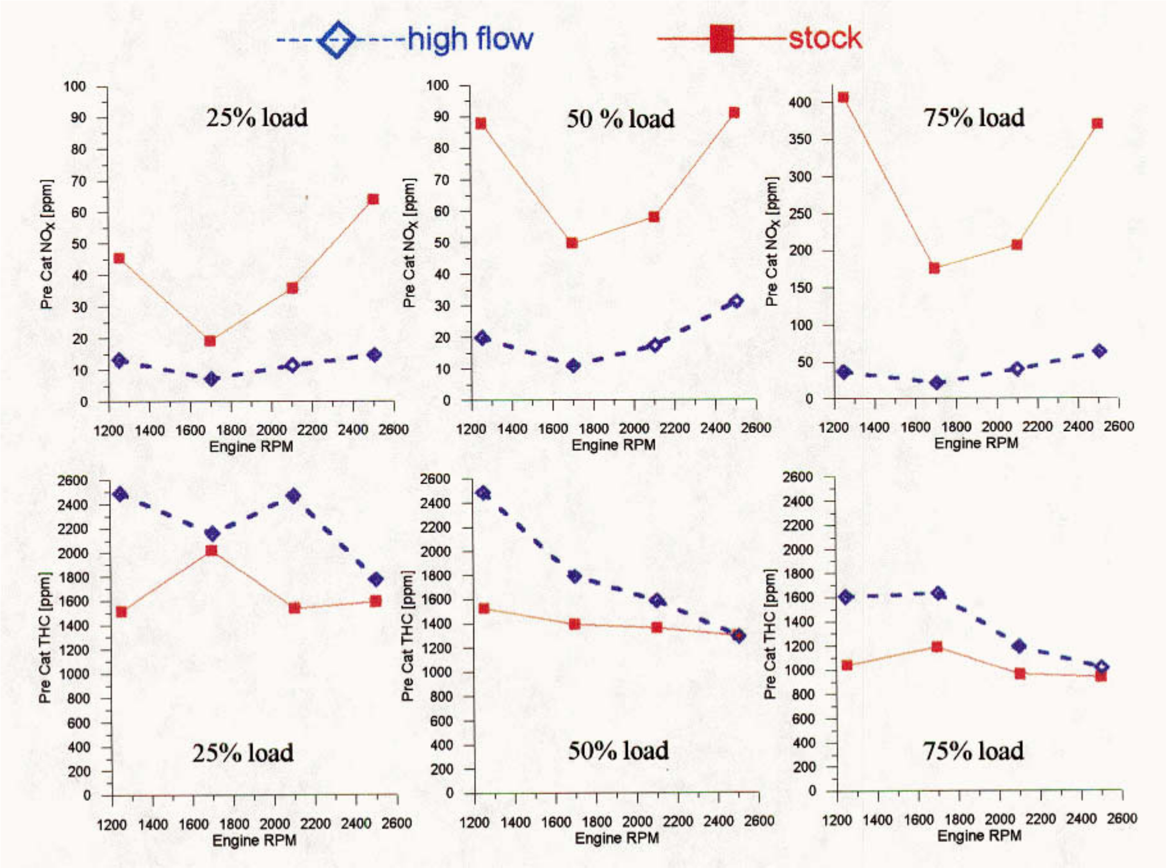


Figure 9 – Comparison of SVO High-flow & Stock Cylinder Heads

Ignition Timing and Exhaust Aftertreatment

After the effects of excess air are were properly assessed, attention moved to tuning ignition timing. Timing, or spark advance, plays an important role in an engine's power, efficiency, and emissions. Figure 10 shows the typical 4.6L pre-catalyst emissions data as ignition timing was retarded at 1700 rpm, 50% load, and 10% excess exhaust O_2. Again the advantages in NO_x emissions are viewed as a worthy trade-off for the increase in THCs. Also shown are the typical effects of running the HCNG exhaust stream through the stock Ford catalyst. Combined NO and NO_2 emissions were not affected by the catalyst in lean burn, but the ratio between the two was altered. Some NO_2 seems to have been converted back to NO through the catalyst. Hydrocarbons are only marginally affected. However, CO is eliminated due to the abundant O_2 concentration that is readily available for oxidation. All lean-bum post catalyst emissions testing showed 0.0 ppm of CO.

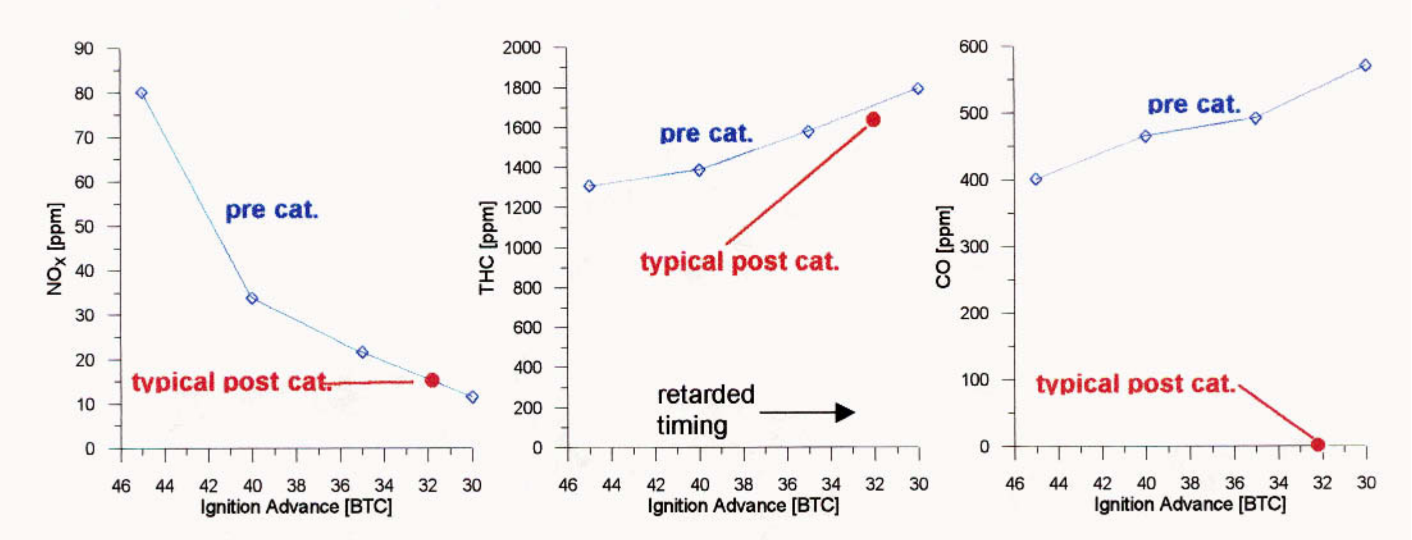


Figure 10 – Effects of Timing and Catalyst

Figure 11 is a broad look at the typical NO_x and THC emissions under a very broad range of tuning conditions. The data represents an equivalence ratio of anywhere from 0.54 to 0.68 and a load range of 2% to 80%. Figure 11 is intended to show that very low NO_x emissions can be obtained over a broad range of conditions.

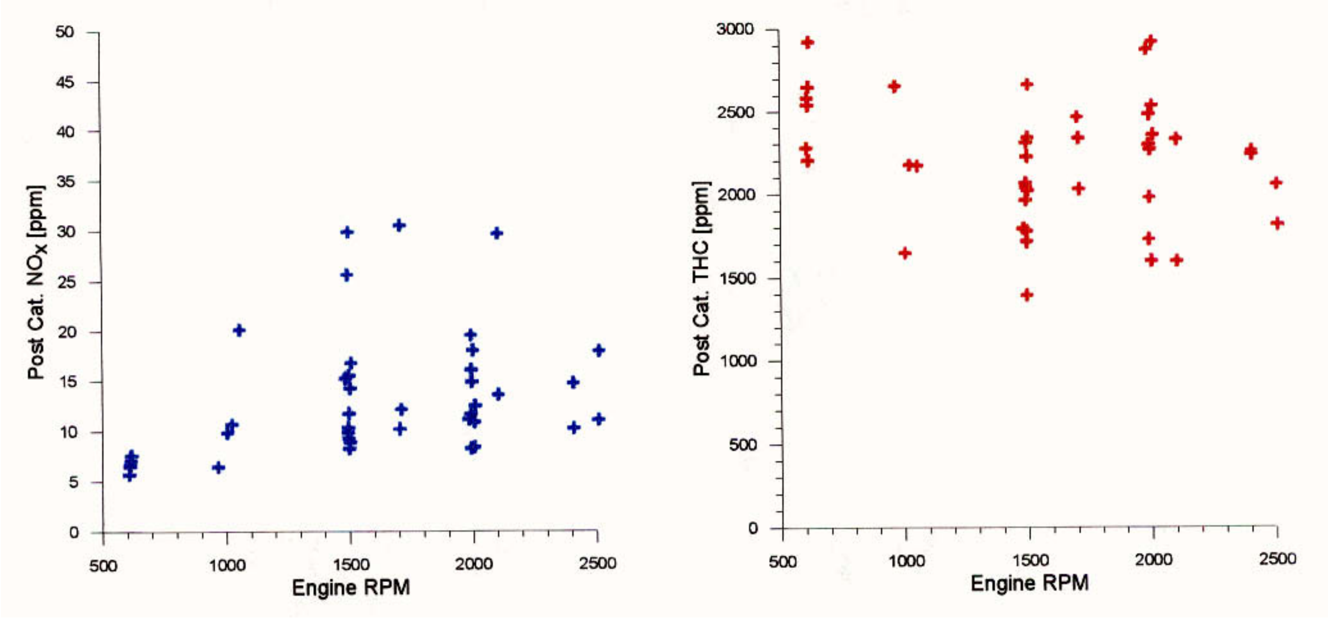


Figure 11 – Typical Scope of NO_x and THC Tuned Emissions

Transient Emissions Testing

The HCNG fuel system was installed back into the Crown Victoria once steady-state engine dynamometer testing was completed. This included the supercharger, the high-flow cylinder heads, the programmable ECU, and the air/fuel ratio and ignition timing parameters determined from engine dynamometer tuning. Initial street driveability evaluations led to a decision to change the rear axle gear ratio from 2.73:1 to 3.08:1. This allowed for better take-off feel from a dead stop. More tuning modifications were made for transient driveability. Once the street tuning was complete, the vehicle was delivered to the Clean Air Vehicle Technology Center (CAVTC) in Hayward, CA for independent evaluation of transient emissions performance.

The Crown Victoria was evaluated using the Hot 505 portion of the Federal Test Procedure (FTP). The light-duty FTP is a transient 2477 second chassis dynamometer test with four phases as shown in Figure 12. The first 505 second phase is performed with the vehicle having first soaked overnight at a regulated temperature to account for the emissions effects of a cold engine that is in the process of warming up. This first section is known as the Cold 505. The 506-1372 second phase is referred to as the stabilized phase and simply represents inner city driving with a warm engine. The vehicle's engine is then turned off for ten minutes for a hot soak before being started again for the last 505 seconds of the test. This last portion is known as the Hot 505 and is identical the first phase of the FTP except for the engine being at normal operating temperature. The Hot 505 is considered a very good gauge of a vehicle's transient emissions, especially with gaseous fuels. The difference in emissions between the Cold 505 and Hot 505 is usually more pronounced in gasoline vehicles. Gasoline vaporization is reduced with cold engine temperatures leading to higher THC emissions. Obviously there will be cold catalyst disadvantages to the Cold 505 with any fuel. The emissions from each phase are bagged and later measured to determine the total mass emissions for CO, THC and NO_x. The total mass of each pollutant is divided by the driving distance of the test procedure to give emissions values in grams per mile.

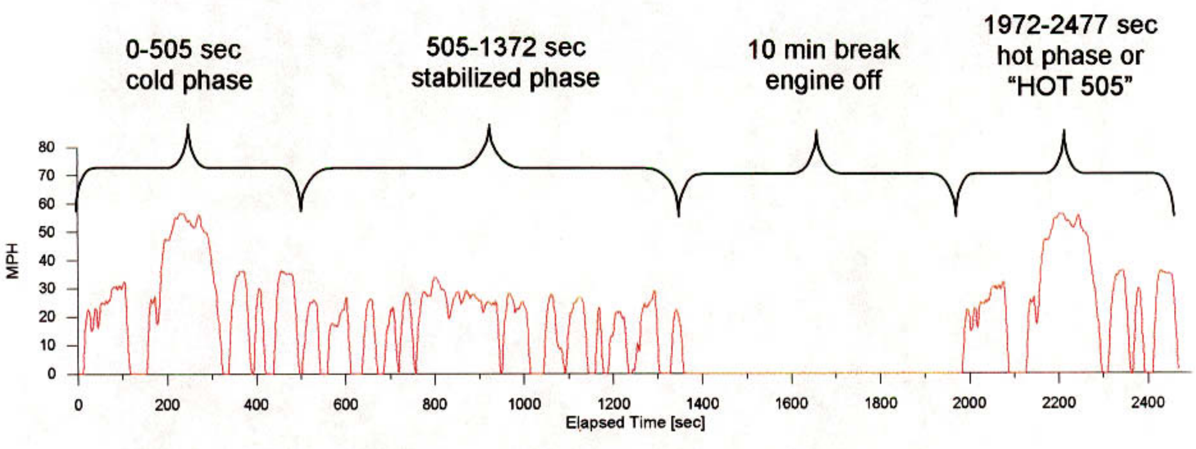
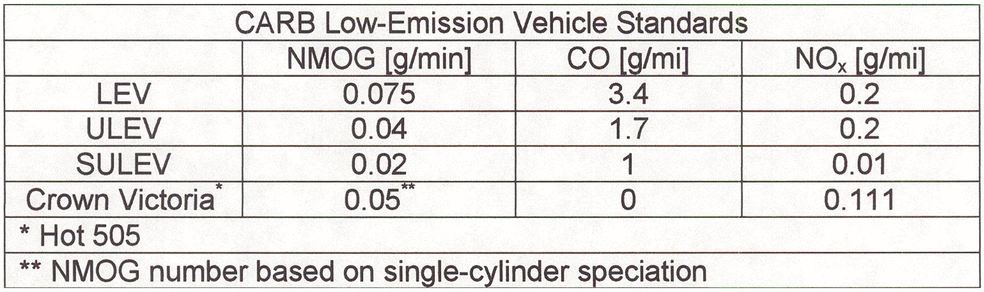


Figure 12 – Light-Duty Federal Test Procedure

Table 1 shows the results of the Crown Victoria's Hot 505 performance in relation to California's LEV, ULEV, and SULEV emissions certification standards. The methane organic gas (NMOG) concentration had to be estimated from the total hydrocarbon data based on previous exhaust gas speciation data. Methane hydrocarbons are non-reactive for photochemical smog generation and as such only the NMOG are regulated. Although the NMOG was in the LEV category, NRG believes that SULEV NMOG emissions can be achieved with closed-loop feedback control and/or better catalyst selection.

The Crown Victoria's NO_x emissions from the Hot 505 are impressive and may also reach the SULEV level with feedback control to prevent deviations from desired air/fuel ratio during transient operation. Carbon monoxide emissions continued to be 0.0 as it always did during steady-state post-catalyst testing on the engine dynamometer.

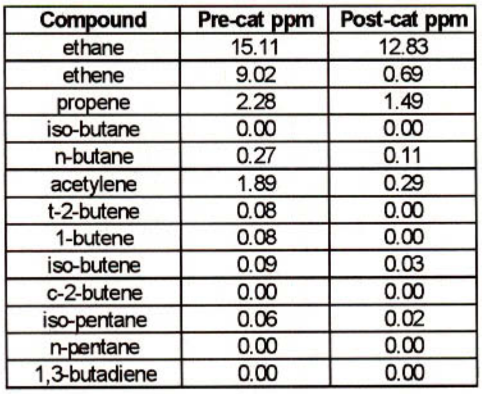
Table 1 – Transient Emissions Performance and Standards



CARB Low-Emission Vehicle Standards			
	NMOG [g/min]	CO [g/mi]	NO$_x$ [g/mi]
LEV	0.075	3.4	0.2
ULEV	0.04	1.7	0.2
SULEV	0.02	1	0.01
Crown Victoria*	0.05**	0	0.111
* Hot 505			
** NMOG number based on single-cylinder speciation			

Pre and Post-Catalyst Exhaust Speciation

Pre and post-catalyst exhaust gas samples were taken from the 4.6L engine in order to understand the effectiveness of Ford's catalyst to reduce HCNG based hydrocarbon emissions and to understand the composition of the HCs for estimation of non-methane organic gas content. Figure 13 shows the results of the speciation tests performed by Desert Research Institute in Stead, Nevada using gas chromatographs. The results suggest that unsaturated hydrocarbons such as ethene, propene, and acetylene are more easily converted to harmless products than the saturated hydrocarbons like ethane. More extensive catalyst work is expected to take place with the single-cylinder engine. The effects of natural gas composition on engine out hydrocarbon characteristics using exhaust speciation was performed in Year 1.



Compound	Pre-cat ppm	Post-cat ppm
ethane	15.11	12.83
ethene	9.02	0.69
propene	2.28	1.49
iso-butane	0.00	0.00
n-butane	0.27	0.11
acetylene	1.89	0.29
t-2-butene	0.08	0.00
1-butene	0.08	0.00
iso-butene	0.09	0.03
c-2-butene	0.00	0.00
iso-pentane	0.06	0.02
n-pentane	0.00	0.00
1,3-butadiene	0.00	0.00

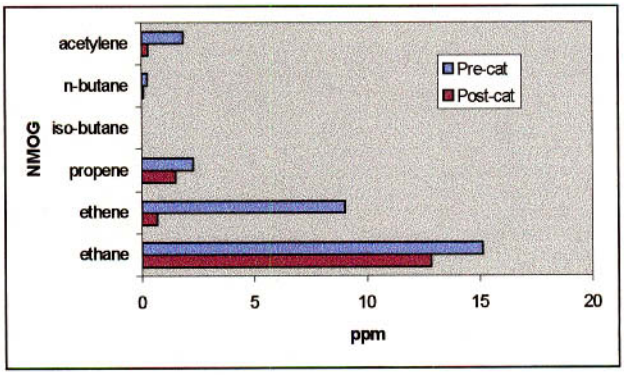


Figure 13 – Effects of Ford Catalyst on HCNG Hydrocarbons

Conclusion

NRG Technologies, Inc. is conducting a three year research program to develop the technical knowledge base for producing HCNG fueled lean-burn engines that are significantly cleaner than conventional technology, yet meet the market's needs for conventional performance. The program is following a cost effective research approach with both single- and multi-cylinder engine testing. Testing to date has addressed H_2 content in the fuel, recuperated power with supercharging, EGR, cylinder head design issues, transient emissions evaluations, and hydrocarbon speciation. More research data will be generated in each of these areas as the project continues through its third year. Investigations into combustion chamber shape, exhaust catalysts, compression ratio, and special coatings are in NRG's Statement of Work (SOW) as well. It is important to note that the 4.6L HCNG powered Crown Victoria served a Las Vegas fleet for six months with no component failures or problems to address which, with the impressive transient emissions data, is a testament to the success of the program to date.

Optimization of the Crown Victoria package has been added to the three year SOW. This type of work was intended for a Ford F150 platform that had been removed from the SOW earlier. The goal for the reinstated vehicle optimization with the Crown Victoria will be to incorporate closed-loop feedback control to the ECU algorithms and investigate catalyst and EGR strategies further to achieve the California Air Resources Board's SULEV emissions classification.

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List of Figures