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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 NOx 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 has not been demonstrated.

Our approach to overcoming these problems will be 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.

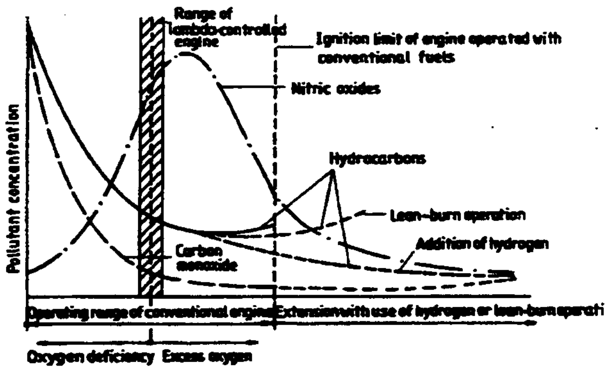
A three year test plan has been developed to perform the investigations into the issues described above. During this initial year of funding research has progressed in the following areas: a) a cost effective single-cylinder research platform was constructed; b) exhaust gas speciation was performed to characterize the nature of hydrocarbon emissions from hydrogen-enriched natural gas fuels; c) three H_2/CH_4 fuel compositions were analyzed using spark timing and equivalence ratio sweeping procedures and finally;

d) a full size pick-up truck platform was converted to run on HCNG fuels. The testing performed in year one of the three year plan represents a baseline from which to assess options for overcoming the stated barriers to success.

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.

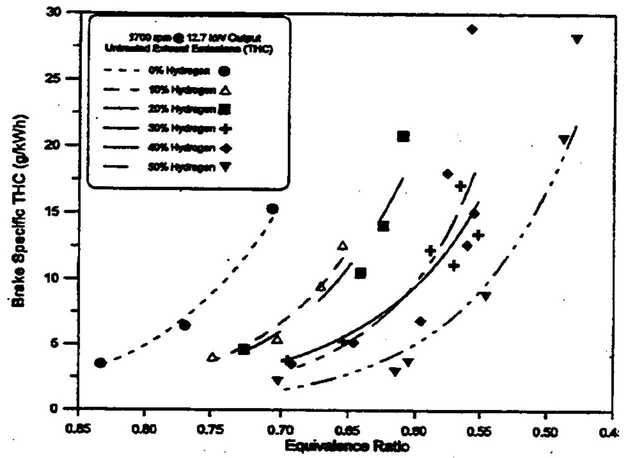
Figure 1. Lean Burn Emissions Trends



For conventional fuels operating in conventional engines, the emissions of 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 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.)

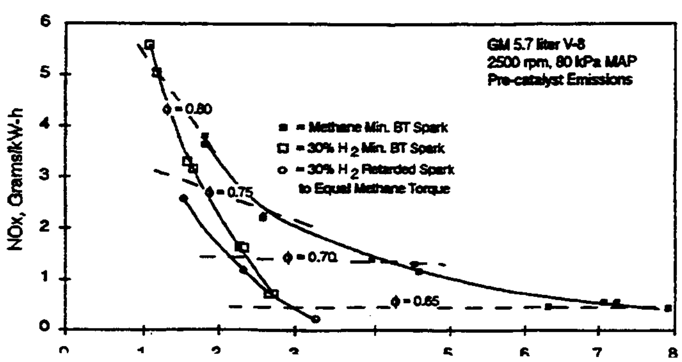


Other research dealing with hydrogen-natural gas mixtures and lean burn has been conducted. The Bartlesville Energy Research Center (Eccleston 1972) and a joint project between Hydrogen Consultants, Inc. and Colorado State University (Fulton 1993) have published results. The BERC project investigated 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.

The HCI/CSU work looked at 15 to 30% hydrogen addition. Although that work looked at many other aspects to hydrogen-natural gas mixtures, one lean-burn result is shown in Figure 3. With retarded spark timing, they were able to produce extremely low NOx emissions with 30% hydrogen mixtures and equivalence ratios below 0.65. These data essentially verify the Florida Solar Energy Center work.

Figure 3. Emissions of HCNG, CNG Fuels and Spark Timings (From Fulton et. al.)



Critical Areas of Interest To Be Investigated During Three Year Project

Relationship Between Hydrogen Content, Spark Timing and Emissions

To be a commercial success, the cost of the fuel must be kept to a minimum. This means that the hydrogen content of the fuel should be minimized. Although the work at FSEC was an important first step, the same degree of thoroughness must be applied to percentages of hydrogen other than 30%.

Photoreactive Hydrocarbon Emissions

Total hydrocarbon emissions are not sufficient to judge the efficacy of the concept. The portion of those emissions that are photoreactive in the atmosphere is the determining factor. At this time, that data is not available, but is critical to the technology.

Recuperating Power Loss

A critical component of any automobile application is driveability. Generally speaking, the amount of power output will be proportional to the amount of fuel burned. Since the air fuel ratio is predetermined to achieve low emissions, the critical factor in determining power output will be the amount of air that can be passed through the engine. For the same amount of air, lean burn engines, will produce less power. To maintain driveability and consumer acceptance, this power loss must be compensated for.

Emissions Verification Under Transient Conditions

Here-to-fore all of the emissions data available for lean bum mixtures of hydrogen and natural gas have been steady state data. Real world driving conditions as well as vehicle certification emissions testing involve transient driving conditions. It is mandatory that low exhaust emissions under transient conditions be demonstrated for the technology.

Engine Design Parameters

Compression ratio, valve timing, piston and cylinder head design, bore-to-stroke ratio, exhaust gas recirculation, and intake air charging strategies are all engine design features that have important effects on engine performance, efficiency, and emissions. The long term potential of any new fuel and emissions control concept cannot be fully assessed until an optimized system is developed. NRG's three year test plan incorporates testing in all of the areas stated above in order to make a fair evaluation of the technology and to use the optimization of these engine design parameters to overcome the barriers to success of lean burn technologies utilizing HCNG fuels.

Summary of Year-One Engine Testing Activities

Test Platform and Instrumentation

This paper reports on the year-one work completion for what is targeted to be a three year program. An initial phase of this work involved the preparation of a cost-effective platform for conducting internal combustion engine research using H_2/CH_4 fuel blends. The platform chosen is a Ford 2.3L engine mounted to a 50 hp eddy-current dynamometer. The 2.3L Ford was chosen because there are a substantial number of aftermarket racing components available for this system. Race components for engines typically involve apparatus for increasing air flow to the engine for the purpose of increasing power. Therefore, NRG will attempt to use these systems to facilitate lean burn operation while maintaining equivalent power to passenger car systems.

Three of the engine's pistons and rocker arm groups were removed to create a "single-cylinder" arrangement. Intake and exhaust passages were blocked on the three disabled cylinders. Single-cylinder operation was chosen because it is more cost effective in terms of fuel, componentry, and engine modification expenses. It also results in more reliable control of air/fuel ratio parameters which would otherwise be affected by cylinder-to-cylinder distribution inconsistencies common to multi-cylinder engines.

NRG's research revolves around the quantification of an engine's characteristics during varying degrees of lean burn operation. Therefore, much focus was placed on using hardware that would accurately measure air and fuel flow. Air flow is measured by using a laminar flow element system while fuel flow is measured with a Coriolis effect device. The Coriolis device measures gas mass flow directly with no dependency on fuel type, pressure, temperature, or viscosity. Emissions data is taken with nondispersive infrared, chemiluminescent, and flame ionization detectors for CO, NO_x, and THC emissions, respectively.

There are multiple ways of defining the lean limit. While some researches use hydrocarbon emissions as an indication of the lean limit, NRG Technologies uses combustion stability as the determining factor. Therefore, a pressure transducer was mounted in the spark plug and its output was directed into a combustion analysis program. This program calculates the indicated work of individual combustion cycles from PV data and then calculates the average and standard deviation of indicated work for a given series of cycles. The standard deviation in indicated work divided by the average indicated work for a series of cycles calculates the "coefficient of variation" or COV. A COV of 10% is an accepted limit of combustion stability (Heywood year) and has been adopted by NRG as the definition of the lean limit. A COV greater than 10% implies that the engine is running beyond the lean limit and, in an automotive application, that the driver would actually feel the instability.

Engine Testing Methodology

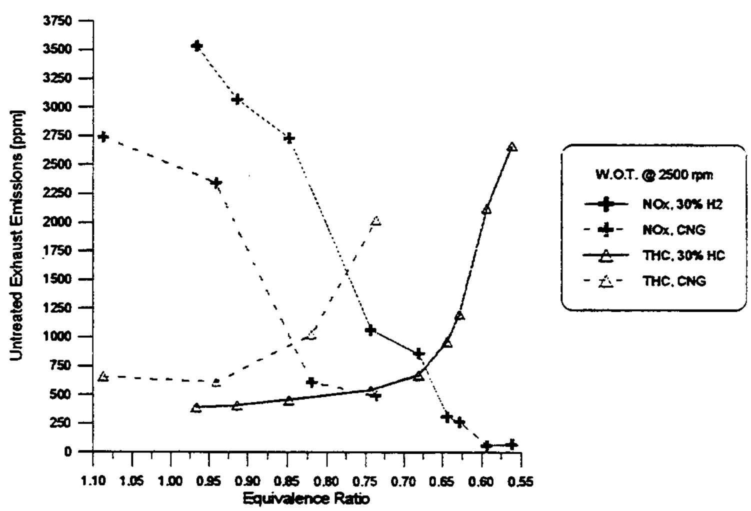
Single-cylinder engine emissions data was taken on 25/75, 30/70, and 35/65 blend ratios of hydrogen and methane, respectively. The testing includes "equivalence sweeps" and "spark maps." Equivalence sweeps were performed by keeping engine load constant and timing at MBT for all points while using air flow as the changing parameter to make sweeps across a range of equivalence ratios. The term MBT is defined as the minimum ignition advance for best brake torque. It essentially represents the ignition timing for optimum thermal efficiency without regards to exhaust emissions. Equivalence sweeps at MBT are useful in that they represent a common baseline by which researches can compare subsequent data. However, commercial automotive engines do not typically have the luxury of operating at MBT because of emissions trade-offs. Therefore, data that illustrates the effects of excess air only is supplemented with ignition mapping data also.

Spark maps were performed by running at designated equivalence ratios using ignition timing as the variable between engine operating points. Adjustments in timing affect emissions, efficiency, and combustion stability. Therefore, the trade-offs among all of these parameters must be assessed before the final "optimal" timing can be determined for any given engine configuration.

Challenge – Hydrogen Not Inherently a Low-NOx Fuel

Hydrogen is often said to be an inherently clean fuel in internal combustion engines because its use eliminates carbon emissions. However, hydrogen burns hotter and faster than conventional fuels which results in higher NO_x emissions when compared at the same equivalence ratios and power output. Figure 4 shows this complication. The two fuels compared are CNG and a 30% hydrogen blend with methane. Both fuels were tested in the single-cylinder research engine at equivalent loads. It can be seen from this case that the HCNG blend can produce more than double the NO_x of CNG at a specific equivalence ratio. Hydrogen's redeeming value, however, is that it allows the HCNG blend to operate far leaner than CNG alone which results in an extension of lean burn's NO_x reducing mechanisms and ultimately a significant reduction in NO_x over CNG.

FIGURE 4. Unoptimized HCNG NO_x Emissions as a Function of Equivalence



Equivalence (Φ) Sweeps

Equivalence sweeps were performed at 2500 rpm on the single-cylinder engine with 25%, 30%, and 35% H_2 blends. Figures 5 and 6 from these tests show that even the modest H_2 content variations between the three blends tested have quantifiable effects on the lean limit of combustion. Figure 5 indicates that the rapid rise in hydrocarbons associated with the lean limit occur at less excess air when there is less hydrogen in the fuel. Similarly, Figure 6 shows the coefficient of variation plotted against equivalence ratio. At an equivalence = 0.57, the 25% H_2 blend reaches COV = 10% (defined lean limit) whereas the 30% and 35% H_2 fuels are only at COV = 4%. The conclusion that incremental amounts of hydrogen addition have incremental effects on combustion is important. Previous work at FSEC on a Ford 4.6L V8 suggested that a range of H_2 compositions would produce similar results until a H_2 concentration threshold was broken that would produce and observable shift in combustion characteristics.

Figure 5. THC Vs. Equivalence

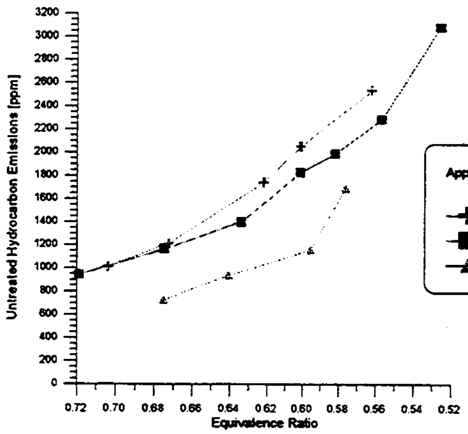
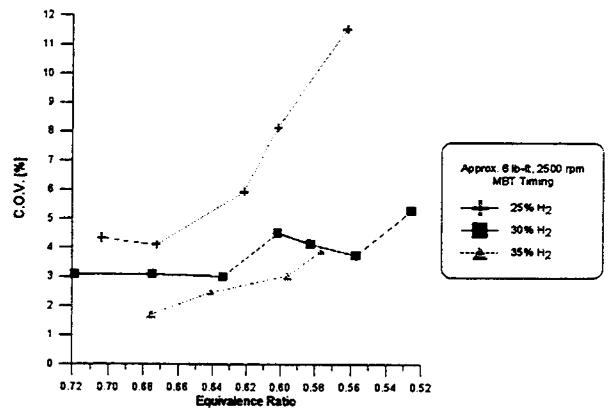


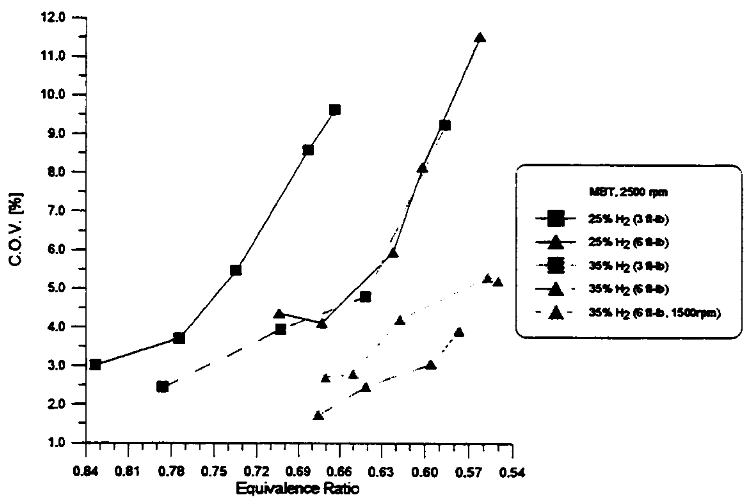
Figure 6. COV Vs. Equivalence



Speed and Load Effects on Combustion

Figure 7 shows the effects of speed and load on combustion stability for 25% and 35% hydrogen blends. Note when comparing equivalent loads that there is always an extension of the lean limit with more hydrogen. Also, increasing the load increases the engine's ability to operate at leaner conditions. This suggests that lean burn power recuperation techniques will aid in the goal of extending lean burn combustion stability. Figure 7 suggests increased engine speed will also be a mechanism to achieve leaner operating points also.

Figure 7. H_2 Content, Speed, and Load Relationships



Spark Map Testing

Figure 8 shows the affects of ignition timing on NOx emissions for 25%, 30%, and 35% H_2 fuel blends each run at different equivalence ratios. A very important principle becomes apparent. The tendency for NOx to be reduced by an engine operating at leaner conditions with the aid of increased hydrogen can overcome hydrogen's propensity to increase NOx emissions. For instance, 35% H_2 at $\Phi = 0.61$ produces less NOx than 30%

H_2 at $\Phi = 0.65$ which subsequently produces less NOx than 25% H_2 at $\Phi = 0.70$ over the entire timing sweep range. If equivalence and timing were equal for the three fuels, then more H_2 would equate to more NOx.

Figure 8. NO_x as a Function of H_2, Timing, and Equivalence at 2500 rpm

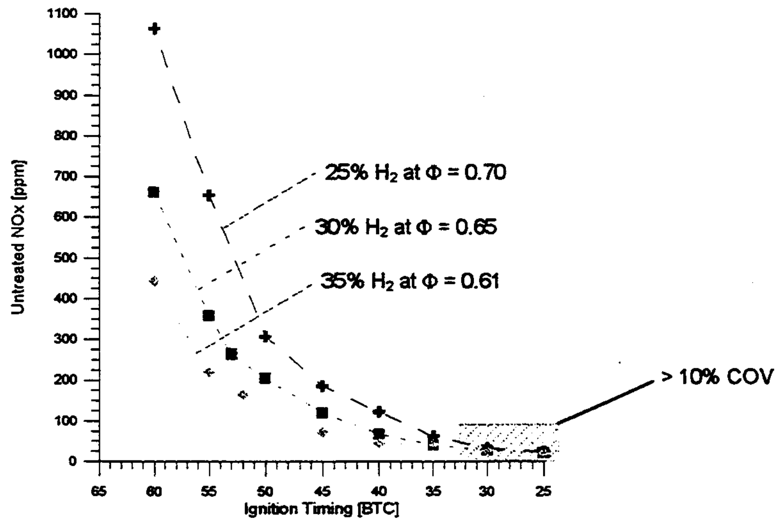
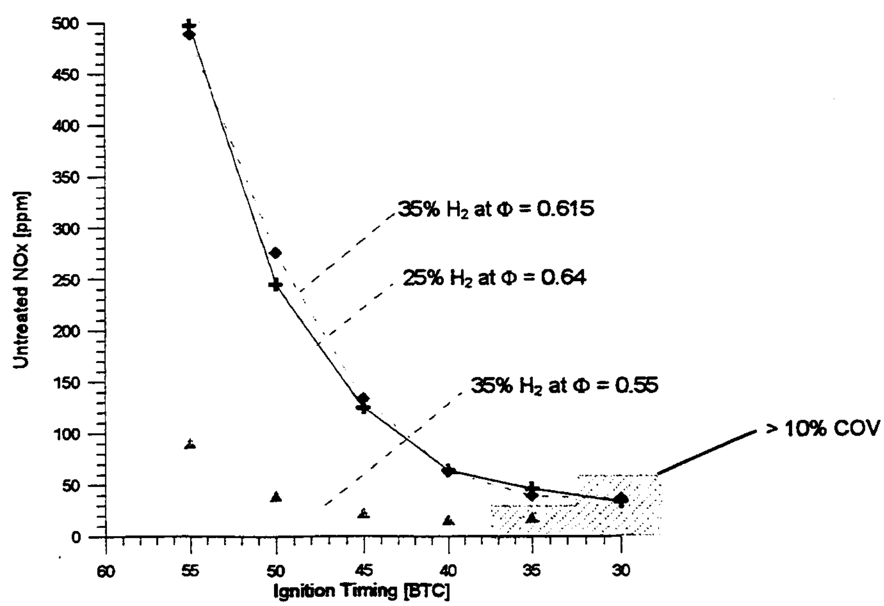


Figure 9 is another spark map set taken at 1500 rpm between 25% and 35% H_2. This data shows another important feature of hydrogen-enriched fuels. If NO_x reductions from hydrogen enrichment are the goal, then the engine must capitalize on incremental lean limit extensions with hydrogen addition in order to make the goal be successful. Even though the 35% H_2 blend was run leaner at $\Phi = 0.615$ than 25% H_2 at $\Phi = 0.64$, it produced no NO_x benefits over the ignition timing range. Note, however, that when 35% H_2 was run at $\Phi = 0.55$ that the NO_x benefits are substantial, especially at the more advanced timing points. This is important because retarding timing to reduce NOx has limitations as efficiency trade-offs are encountered.

Figure 9. NO_x as a Function of H_2, Timing, and Equivalence at 1500 rpm



Initial Intake Boost Test

Although testing under intake air boost conditions is not scheduled to be a "year one" task, NRG constructed an external supercharging system shown in Figures 10 and 11. An Eaton supercharger was mounted and powered independent of the engine because of the overwhelming parasitic losses that would occur if a supercharger designed for a multi-cylinder engine were placed on a four cylinder assembly that is actually running only one piston. The supercharger is powered by a 5 hp electric motor. An inverter controls motor speed and hence boost out of the supercharger.

Figure 10. Motor Driven Supercharger

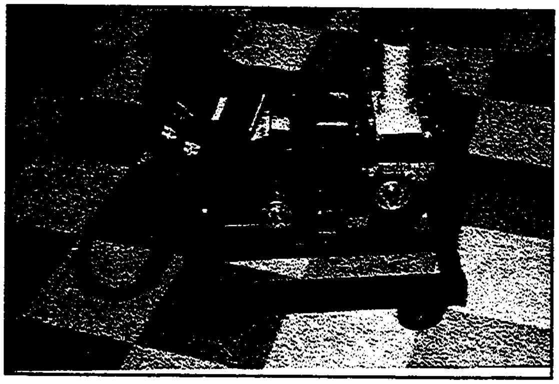
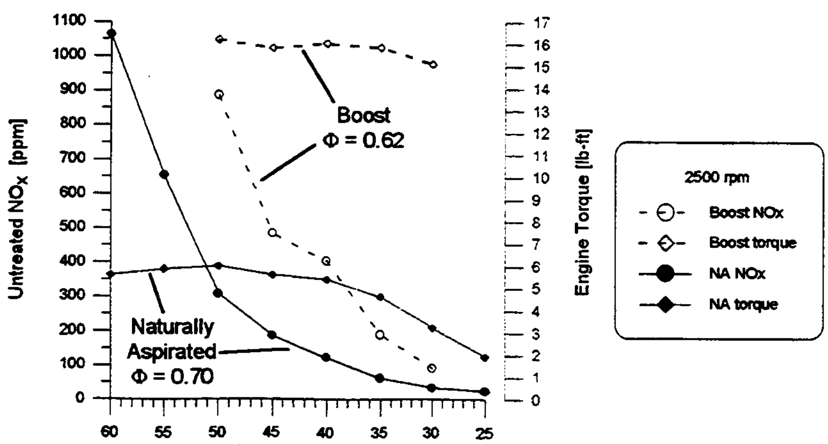


Figure 11. External Supercharger Setup

Only one 25% H_2 emissions test was performed by the time of this report but the initial results shown in Figure 12 demonstrate an important issue to be scrutinized in future power recuperation investigations. The supercharged run with about three times the load produced more NO_x than the naturally aspirated run over the entire spark map even though it was run at a much leaner condition. The higher NO_x emissions at the much leaner condition are believed to be attributable to the fact that an intercooler was not incorporated into the original supercharger setup. Running at steady-state for long periods to stabilize emissions allowed the supercharger to create "runaway" intake air temperature rise conditions because the air was the only heat sink to cool the supercharger's rotors. Higher intake air temperatures before combustion lead to higher NO_x emissions in the exhaust. Therefore, this initial exercise illustrated that laboratory supercharging tests in the future would require intercooling in order to properly assess the impacts of superchargers as power recuperation techniques on NO_x emissions.

Figure 12. Early Intake Boost Test Results



Exhaust Gas Speciation

Natural gas does not consist solely of methane. The other significant hydrocarbon constituents of natural gas are ethane and propane. Because the amounts of these other constituents in natural gas can vary significantly with location and time of year, a series of tests were conducted to speciate hydrocarbon emissions. The purpose of the tests was to determine the relationship between exhaust gas and natural gas hydrocarbon composition and to identify the existence of any new, photoreactive compounds created during the combustion process.

Six gas mixtures, all containing 30% hydrogen, were prepared with varying combinations of propane, ethane, and methane. Each test was conducted with an equivalence ratio such that the total hydrocarbon emissions measured were about 1800 ppm. Gas speciations were performed by Desert Research Institute (DRI) in Stead Nevada using gas chromatograph with FID technology. The fuel gas compositions and a complete tabulation of speciation results are shown in Table 1. The major finding from these data is that ethene emissions are produced without the presence of either ethane or propane and they are increased by the presence of both ethane and propane. Significant propene emissions only occur if propane exists in the fuel. It also appears that ethane emissions are created simply from the combustion of methane. For all tests without ethane in the fuel, ethane exhaust emissions of about 10 ppm were observed.

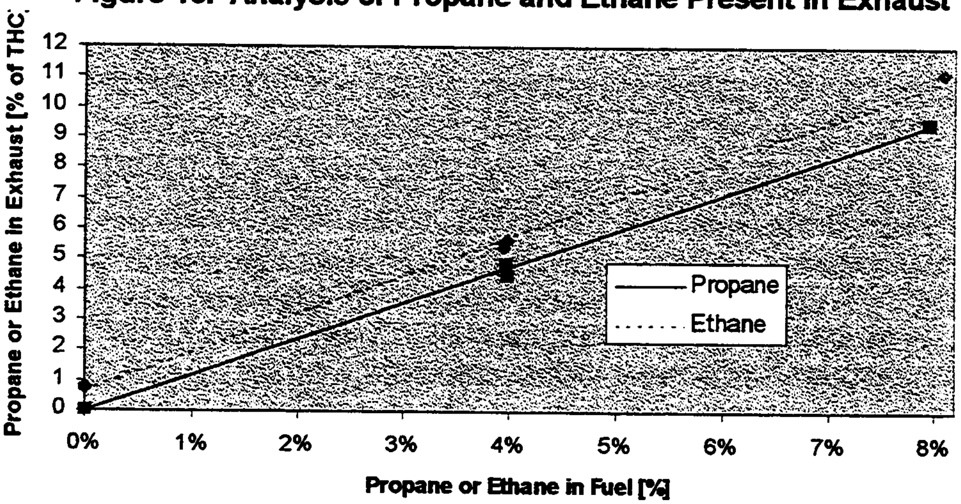
Table 1. Hydrocarbon Speciation of Six Fuel Compositions

Fuel*	0% propane 0% ethane	8% propane 0% ethane	4% propane 0% ethane	0% propane 8% ethane	0% propane 4% ethane	4% propane 4% ethane
Methane (ppm)	1,226.0	1,264.2	1,238.5	1,612.1	1,459.0	1,821.6
Ethane (ppm)	10.3	11.3	10.2	210.3	89.1	113.6
Ethene (ppm)	13.8	38.1	24.2	51.3	28.9	47.4
Propane (ppm)	0.3	140.6	60.7	0.5	0.3	102.1
Propene (ppm)	1.7	17.2	8.6	1.8	1.5	10.9
Acetylene (ppm)	1.6	3.9	3.0	3.2	2.2	3.7
Isobutane (ppm)	0.0	0.2	0.1	0.0	0.0	0.1
Butane (ppm)	0.0	0.0	0.0	0.0	0.0	0.0
Trans-2-Butene (ppm)	0.1	0.1	0.1	0.1	0.1	0.1
1-Butene (ppm)	0.4	0.8	0.6	0.4	0.4	0.6
Isobutene (ppm)	0.3	0.3	0.3	0.3	0.3	0.3
Cis-2-Butene (ppm)	0.1	0.0	0.0	0.1	0.1	0.0
Isopentane (ppm)	0.0	0.0	0.0	0.0	0.0	0.0
Pentane (ppm)	0.0	0.0	0.0	0.0	0.0	0.0
1,3-Butadiene (ppm)	0.3	0.4	0.2	0.3	0.2	0.3
Hexane (ppm)	0.0	0.0	0.0	0.0	0.0	0.0
* All fuel mixes contained approximately 30% hydrogen and the balance methane.						

Figure 13 shows the relationship between ethane and propane composition of the fuel and their composition in the exhaust gas hydrocarbon emissions. The propane fraction of total hydrocarbon exhaust emissions is very nearly equal to that contained in the fuel.

Ethane emissions are slightly higher. If the ethane emissions due to methane combustion are subtracted from the total, the ethane fractions are also are nearly equal. In either case, the fractional compositions of both ethane and propane, between exhaust and fuel are linear.

Figure 13. Analysis of Propane and Ethane Present In Exhaust

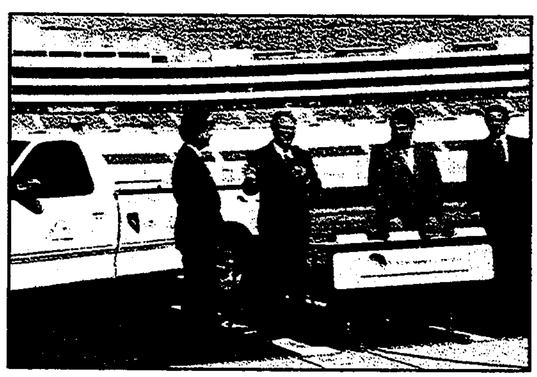


Truck Conversion

NRG was tasked to convert a full-size pickup truck to operate on HCNG fuels for use as a real-world platform to test the HCNG technology advancements expected to be made in the laboratory. NRG has converted a gasoline 1997 Ford F-150 pickup truck to run on gaseous fuels. This truck is currently controlled with an aftermarket engine computer. In October 1997 it was demonstrated at a ride-and-drive event at the Las Vegas Motor Speedway during a Memorandum of Understanding signing between the U.S. Department of Energy and LVMS (Figures 14, 15). Good reviews were received from the participants that drove the truck around the track on 30% hydrogen. As power recuperation techniques are developed on the single-cylinder laboratory engine, they will be incorporated into this platform.

Figure 14. LVMS Ride-&-Drive

Figure 15. MOU Signing With NRG Truck



Summary

This report summaries the first year of research activities by NRG Technologies, Inc. in what is outlined to be a three year program developing engine technology for hydrogen-enriched fuels. A single-cylinder engine was created out of a Ford 2.3L four-cylinder platform and mounted to a 50 hp eddy current electric dynamometer. The engine is instrumented to make very accurate air and fuel measurements for quantification of equivalence ratio at all operating points. In-cylinder combustion data is used to quantify combustion stability for determination of the lean limit.

Engine emissions testing was performed at 2500 and 1500 rpm with data representing over 100 individual operating conditions. The effects of varying excess air at constant load and MBT timing with 25%, 30%, and 35% hydrogen supplementation to methane showed that even these 5% variations in hydrogen had observable impacts on combustion stability in lean regimes. Ignition mapping data demonstrates very clearly that adding hydrogen to extend lean burn capabilities reduces NO_x emissions at a greater rate than the tendency of NOx emissions to rise with increases in hydrogen at equivalent excess air ratios. Furthermore, the ignition mapping data suggests that maximum emissions reductions can be gained if engines fully capitalize on the extensions in the lean limit that the added hydrogen can provide.

Exhaust speciation of hydrocarbon emissions from a 30% hydrogen fuel blend was performed by Desert Research Institute in Stead, Nevada. The results showed a linear relationship between both the propane and ethane content in the fuel and the content of these gases in the exhaust hydrocarbons. In addition, the relative methane, ethane, and propane composition in the exhaust gas were almost equal to that of the fuel.

A 1997 Ford F-150 pick-up with a 4.6L V8 was converted by NRG Technologies, Inc. to operate on hydrogen-enriched natural gas mixtures. The truck represents an applications platform for engine development concepts that will be learned from the single-cylinder engine testing during the three year project.

Future Work

NRG's statement of work for year two and three includes continuation of ignition mapping data with multiple fuel compositions. Assessment of alternative engine design work will begin with combustion chamber design, compression ratio, and EGR strategies in year two and will move on to intake air charging and special coatings in year three. Advancements discovered in the single-cylinder development process will be applied to the Ford F-150 throughout the program for real world evaluation.

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Eccleston, D.B., and R.D. Fleming, "Engine Emissions Using Natural Gas, Hydrogen-Enriched Natural Gas, and Gas Manufactured from Coal (Synthane)," Bureau of Mines Automotive Exhaust Emissions Program, U.S. Department of Interior, Technical Progress Report-48, 1972.

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