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GASEOUS FUELED VEHICLES: A ROLE FOR NATURAL GAS AND HYDROGEN

by

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Abstract

The commercialization of gaseous hydrogen fueled vehicles requires both the development of hydrogen fueled vehicles and the establishment of a hydrogen fueling infrastructure. These requirements create a classic chicken and egg scenario in that manufacturers will not build and consumers will not buy vehicles without an adequate refueling infrastructure and potential refueling station operators will not invest the needed capital without an adequate market to serve. One solution to this dilemma is to create a bridging strategy whereby hydrogen is introduced gradually via another carrier. The only contending alternative fuel that can act as a bridge to hydrogen fueled vehicles is natural gas.

To explore this possibility, IGT is conducting emission tests on its dedicated natural gas vehicle (NGV) test platform to determine what, if any, effects small quantities of hydrogen have on emissions and performance. Furthermore, IGT is actively developing an adsorbent based low-pressure natural gas storage system for NGV applications. This system has also shown promise as a storage media for hydrogen. A discussion of our research results in this area will be presented. Finally, a review of IGT's testing facility will be presented to indicate our capabilities in conducted natural gas/hydrogen vehicle (NGHV) research.

Introduction

IGT's involvement in natural gas vehicle (NGV) research spans more than twenty five years, including the development and operation of

compressed natural gas, liquified natural gas (LNG) and adsorbed natural gas (ANG) vehicles. Coincidentally, IGT's involvement in promoting the hydrogen economy and conducting hydrogen related research spans nearly the same time frame. Recent events in the Middle East and the growing concern for reduced vehicle emissions have encouraged the growth of alternative fueled vehicles. The fuel that has benefited the most from this concern is natural gas. Currently, over 50,000 natural gas vehicles are operating in North America. This number is projected to grow dramatically over the next few years; encouraged by the clean burning characteristics of natural gas and its low price (\$0.70 per gallon equivalent). As Figure 1 indicates, the Natural Gas Vehicle Coalition and the American Gas Association have projected that as many as 7 million NGVs may be on the road in the U.S. by the year 2005. Commercialization efforts for natural gas vehicles are being further enhanced by the production announcement by General Motors of a dedicated natural gas fueled pickup truck and the installation of compressed natural gas refueling dispensers by AMOCO and Shell Oil at select service stations.

At first glance this growth in natural gas vehicles may appear to be at the expense of hydrogen. In reality, the development of a gaseous fuel vehicle and infrastructure, as opposed to alternative liquid fuels such as methanol, may pave the way for the use of hydrogen in the transportation fuels market. Although hydrogen does not yet compete in terms of economics with natural gas, niches for hydrogen may exist. One such niche is

the use of hydrogen as a fuel enhancer. Combustion research at IGT on chemically recuperated reheat gas turbines (IR-CRGT) indicates that the presence of hydrogen in the fuel may decrease nitrous oxide (NO_x) to below 5 ppm. This represents an order of magnitude reduction of NO_x over the current state-of-the-art. For internal combustion engines, the presence of hydrogen in the natural gas fuel will lower the amount of carbon monoxide and carbon dioxide emissions. Additional research is required to determine the impact of hydrogen on NO_x and unburned hydrocarbon emission both in lean burn and stoichiometric operation for optimized and dual fueled vehicles. Should this research indicate a reduction in emission of internal combustion engines, supplementing natural gas with hydrogen for vehicular applications would be desirable from an environmental if not an economic standpoint.

The intent of this paper is to briefly highlight other alternative fueled vehicle concepts as they relate to hydrogen fueled vehicles and to discuss more fully IGT's research in internal combustion (I.C.) engine dedicated natural gas/hydrogen fueled vehicles (IGT is also involved in fuel cell research). This includes emission tests on natural gas and hydrogen blends, and our research on carbon based adsorbent for on-board vehicle fuel storage. Additional information will be presented on IGT's other NGV/hydrogen related efforts including on-board fuel management system evaluations, and refueling station research.

Background - State-of-the-Art

A great deal of research and development is currently underway to support the commercialization of natural gas vehicles. Some of this research, development, and commercialization effort also has a direct bearing on the future commercialization of hydrogen fueled vehicles using conventional vehicles platforms. To a large extent, these future dedicated NGV may be "hydrogen friendly." However, as emission requirements become more stringent, small segments of the vehicle market will be required to produce ultra-low emissions and even no emissions. These segments of the market will in most likelihood be serviced by a new class of vehicle. These vehicles will be hybrid electric or totally electric vehicles. In the hybrid vehicle either a small gas fueled I.C. engine or fuel cell will be used to generate electricity to charge the battery system. The advantage of a hybrid vehicle includes increased driving range and reduced weight due to a

reduction in the on-board battery storage requirements.

A number of hybrid and electric vehicle efforts are currently underway. These include the announced commercialization by General Motors of an all electric vehicle as well as fuel cell related research at GM's Allison Division using the Ballard PEM fuel cell system. Other hybrid research efforts are being conducted by San Diego Gas & Electric (SDG&E) and Unique Mobility as well as the American Academy of Science. The SDG&E/Unique Mobility project is based on a clean burning natural gas engine driving a continuously variable electronic transmission that recovers both regenerative braking energy and available idling energy. This electric flywheel integrates a brushless DC motor/alternator into a composite flywheel rotor where kinetic energy is accumulated in a hermetically sealed vacuum container operating at a rotational speed of up to 30,000 rpm. Mechanical speed reduction is not required since this is performed electrically. The system has a power handling capability of up to 40 kW and an energy storage capability of 500 watt hours. In this system the engine operation (speed) is decoupled from the vehicle wheel speed. The batteries act as a flywheel to remove the engine load transients. This allows for optimized engine operation since the engine speed and torque can be controlled independently.¹

The current development efforts are being conducted on a Chrysler minivan platform. A Ford industrial 1.3 liter, 4 cylinder engine operating on natural gas provides the on-board power. Other components include a UNIQ motor and controller operating in a starter/alternator configuration, two UNIQ drive motors and controllers and planetary gear reduction sets for independent front wheel drive, an engine management system, a vehicle control module, and a battery pack. The system operates at a nominal voltage of around 180 volts DC. The Unique Mobility alternator has a rated power of 25 kW @ 3750 rpm and a peak current of 260 A. The high power density (3 kW/kg) brushless DC motors (50 kW) employ high energy rare-earth permanent magnets. Heat and air conditioning are supplied from the engine while power steering and brakes are provided by independent electrical systems. The total weight of the vehicle has been estimated to be 4,530 pounds which includes 440 pounds for the engine/alternator, 640 pounds for the battery pack, 405 pounds for the

electric drive, and 250 pounds for the compressed natural gas fuel system.

Another hybrid vehicle project which is being conducted by the American Academy of Science involves the use of a fuel cell. This project employs the LaserCeltm, developed by the American Academy of Science, which is a Nafion-type PEM fuel cell. The LaserCELtm has a peak current density of 1000 amps per square foot and a power output of 17.5 kW. This cell is fabricated using a new laser and robot assisted production technique. This enables the fuel cell design to be extremely light weight and compact, weighing only about 1.8 lbs/kW. The current program involves a Ford Fiesta platform, and is being sponsored by the Commonwealth of Pennsylvania. Hydrogen is stored on board using a metal hybrid system developed at the American Academy of Science. Projected range of the vehicle is 300 miles, more than four times the range of current electric vehicles. Projected cost of the fuel cell in mass production is \$3,500.²

Gaseous Fueled Vehicle Research at IGT

IGT's gaseous fueled vehicle research efforts include:

- Development and testing of NGVs and refueling station components
- Advanced research in on-board gas storage including adsorbent based storage
- NGV related equipment testing and evaluation
- System studies, economic analysis and fleet surveys
- Design of advanced NGV refueling stations and intelligent real-time control systems
- NGV catalysis (emissions) research
- Development of computer aided support tools for refueling station design and NGV fleet marketing evaluations
- Development of on-board data acquisition systems to support NGV studies
- Provide alternative fuels related consulting and support services

Vehicle and Emissions Research

IGT's dedicated natural gas vehicle testing platform is a 1990 GMC Safari XT SLE minivan equipped with a 4.3 liter Vortec V-6 H.O. EFI

engine. This vehicle acts as a rolling test bed for purposes such as fuel management system evaluations, component research, storage system development, and exhaust treatment system testing. The vehicle is currently fitted with a Garretson advanced closed loop fuel management system and is configured with three Pressed Steel Tank CNG and four aluminum ANG storage containers. Total on-board natural gas storage capacity is 2532 scf, 1,660 scf at 3000 psig and 872 scf of adsorbed storage at 900 psig, for a projected driving range of over 400 miles. The vehicle is also outfitted with a comprehensive portable on-board data acquisition system which interfaces with the vehicle's computer and adsorbent system sensors to log over 50 operational and performance parameters in real-time.

The vehicle is also equipped with a Sherex quick connect coupling located behind the gas fill door on the side of the vehicle. In order to fill the lower pressure ANG tanks, an on-board manually adjustable regulator reduces the 3000 psi fill pressure to 500-900 psi for ANG operation. Filling of the ANG tanks can be performed directly from the high pressure refueling system or on-the-fly from the on-board CNG tanks. Furthermore, an electrically operated gas shut-off valve with a switch located on the dashboard allows for operation on either CNG or ANG during the driving cycle. The van has two natural gas fuel lines: a 1/2 -inch line to accommodate reduced pressure operations on ANG, and a 1/4 -inch line for the high pressure operation (both lines rated for 4000 psig).

This vehicle is currently slated for a full Federal Test Procedure (FTP-81) battery of emission tests in early April, 1991. Three gas compositions will be evaluated; natural gas, a 5% blend of hydrogen with methane, and a 10% blend of hydrogen with methane. Briefly, the FTP consists of vehicle preconditioning, heat buildup or diurnal breathing loss test, dynamometer procedure, and hot soak test. Vehicle preconditioning involves placing the vehicle on an emission chassis dynamometer (which reproduces vehicle inertia and road horsepower loads) and driving the vehicle through a prescribed urban driving schedule (LA-4 Prep). For a sealed gaseous fueled vehicle the diurnal breathing loss test is omitted since this procedure tests for evaporative emissions. After a prescribed time the vehicle is once again placed on the chassis dynamometer to conduct an exhaust

emissions test. This test consists of three steps; cold start, steady state, and soak and hot start. During the test the chassis dynamometer reproduces vehicle inertia which takes into account rolling resistance and aerodynamic drag. The emission test produces data on hydrocarbon speciation (to C10), NO_x, CO, and CO₂. The driving schedule also produces the city fuel economy data. For gaseous fueled vehicles the hot soak test which records volatile hydrocarbon emissions is eliminated.

Figure 2 presents some preliminary test results on NGV emissions from the FTP cycle. These tests were performed using a range of natural gas compositions on two different bi-fueled vehicles. The 1987 vehicle was a full sized passenger car equipped with an open loop fuel management system. The 1989 vehicle was a full size van equipped with a state-of-the-art closed loop fuel management system. The closed loop system operates in conjunction with the on-board computer and oxygen sensor whereas the open loop system operates as an independent system. As can be seen, natural gas vehicle emissions easily meet both the stringent 1998 non-methane hydrocarbon and CO California LEV (low emission vehicle) emission standard. Ongoing research on optimized engines indicates that NGV's will be able to meet the future NO_x emissions as well.

To understand emissions more fully, one must understand the trade-offs which occur in engine operation and design. Figure 3 presents the engine power output versus equivalence ratio for a range of natural gas compositions. The equivalence ratio is defined as the inverse of the air-to-fuel ratio. At an equivalence ratio of 1 the engine is operating on a stoichiometric ratio (an air to fuel ratio that reacts completely). At values less than 1 an excess amount of air is present ("lean burn"), and at a ratio greater than 1 the engine is "rich" (more fuel than required air for complete combustion). Although this figure indicates that power increases with the equivalence ratio, higher theoretical engine efficiency occurs during lean burn operation at compression ratios in the 12 to 15:1 area.

Emissions are also affected by the equivalence ratio. As presented in the experimental results in Figure 4, hydrocarbon emissions tend to be lower at lower equivalence ratios. At very low equivalence ratios methane is more difficult to ignite and the flame speed may be too low for complete combustion to occur during the power stroke. At

higher equivalence ratios incomplete combustion may be occurring in crevice volumes near the top of the piston and near the quench boundary near the combustion chamber walls. Carbon monoxide emissions are affected by combustion temperatures. CO exists in chemical equilibrium with CO₂ and as temperatures decrease the equilibrium shifts to CO₂ if sufficient oxygen is present. However, reaction rates decrease at lower temperatures and CO emissions can remain higher than equilibrium concentrations. The rate of NO_x formation is a function of oxygen availability and is exponentially dependant on temperature. Figure 5 presents the experimental relationship of NO_x to the equivalence ratio. Peak NO_x concentrations occur at an equivalence ratio of 0.9.³

The addition of hydrogen to natural gas can have a number of effects on vehicle emissions. Hydrogen's higher flame speed may promote a more complete combustion even at very lean conditions. This may decrease both hydrocarbon and CO emissions if sufficient oxygen is present. On the other hand, hydrogen's higher flame temperature (4010 °F for hydrogen versus 3484 °F for methane - theoretical) may promote the formation of NO_x unless sufficient quenching occurs to a high air to fuel ratio (lower equivalence ratio). Upcoming emission tests on IGT's NGV using 2 methane/hydrogen blends will contribute to the understanding of hydrogen's effect on NGV emissions.

Compressor/Cascade Refueling Station

This experimental refueling station was designed for operation at a variety of service pressures; both high- and low-pressure natural gas vehicles can be refueled. The refueling station is being used as a test bed for new compressor technology development/demonstration as well as for quick fill cascade controls and configuration optimization experiments. The experimental refueling station utilizes a cascade-type ground storage system based upon a rack of 24 DOT pressure vessels with a natural gas capacity of 525 scf each, rated for 3600 psig operation. These storage cylinders can be configured into as many as 6 separate storage cascades. The compressor currently being evaluated at this facility is an oil cooled and lubricated wobble plate compressor rated at 3600 psig, with a capacity of 12.5 scfm at a 10 psig inlet pressure. The unit is manufactured by

RIX Compressors and sold as their COM-GAS model and is intended for small fleet service.

The station itself has been specially designed to accommodate high delivery flow rates (>2000 scfm). The 1 inch O.D. piping is rated for 6000 psi with all fittings back welded except for unions and gasketed joints. The facility is extensively instrumented and all electrically operated control valves are controlled using a real-time PC-based process control system. The facility has been constructed in compliance with all natural gas related standards and is rated Class I, Division I, Group C. Consideration is being given to upgrading this facility to a Group B rating for hydrogen service. The 4 hose refueling dispenser, with shut-off valves, is equipped with a Hanson, Sherex and probe type quick connect couplings for universal CNG vehicle refueling.

Adsorbent Research

During the last eight (8) years IGT has been actively involved in adsorbent storage research. After extensive experimental investigations on a number of low-pressure storage methods, IGT determined that carbon based adsorbents offer the best potential for low pressure natural gas storage. In this system the gas is adsorbed onto the high surface area of microporous structures within the activated carbon particle. Macroporous spaces and void volumes between particles store primarily in the compressed state.

Figure 6 presents the experimental adsorption isotherm data for methane at 25 °C using AX-21 activated carbon (AMOCO) at a packing density of 0.4 g/cc. As can be seen total storage is nearly 3.34 grams at 500 psig. Approximately 2.34 grams of this storage capacity is adsorbed methane. Similarly, Figure 7 presents adsorption isotherm data for a 5% hydrogen and 95% methane by volume gas blend. In this experiment the weight of gas stored decreased to 3.11 grams of which 2.13 grams represents the adsorbed gas weight. As might be expected this trend continues as more hydrogen is added to the blend (Figure 8). For a 10% hydrogen and 90% methane blend the adsorption isotherm data produced a total gas storage capacity of 2.97 grams with nearly 2.09 grams being adsorbed gas.

One way to increase the storage capacity of the adsorbent system is to lower the storage temperature. As can be seen in Figure 9, the

storage capacity of the 10% hydrogen and 90% methane gas blend increases dramatically to nearly 6 grams at 500 psig. However, the percentage of adsorbed gas in the system begins to decrease beyond 100 psig.

Another aspect of adsorbent research that IGT is actively involved is the issue of heat management. As an adsorbent system is quickly charged, the heat of adsorption dramatically increases the bed temperature as shown in Figure 10. Conversely, the bed cools down when gas is rapidly desorbed from the system. Both phenomena have a deleterious effect to bed performance. To manage this problem IGT has developed a patented heat management approach based on encapsulated phase change materials. By placing these passive phase change encapsulants within the bed, the effects of temperature change are mitigated.

To understand more fully the storage capacity of different activated carbons and the effect that pressure, temperature and gas composition have on storage capacity, IGT has developed a number of unique experimental units. These bench scale studies focus on operating and design conditions which affect the storage/delivery of gas mixtures from frequently cycled adsorbent beds. Among the unique pieces of equipment is an adsorption isotherm rig which can determine the storage capacity of adsorbents from vacuum to 3600 psi at temperatures from -100°F to +200°F. A second unit can determine the charge/discharge characteristics of high capacity adsorbent systems measuring temperature, pressure, and mass flow as a function of time. Another unique apparatus is a heat-cycling test rig which was developed to determine the congruent behavior of phase change materials (PCMs). This test stand is capable of automatically cycling as many as seven PCMs in parallel over a temperature range of -100 °F to +200 °F. The laboratory also contains encapsulant production equipment for the TES system.

Fuel Storage Laboratory

The fuel storage laboratory at IGT is a multi-purpose testing facility and has been constructed in accordance with NFPA Class I, Division II, Group C requirements. The facility is capable of performing full-scale adsorbed natural gas (ANG) and/or high pressure gas container testing as well as testing new refueling station metering technologies

and compression equipment. High pressure gas for this facility is supplied directly from the adjacent compressor/cascade refueling station or from a bank of bottled storage. Discharge of gas from the container test stand is controlled by back pressure regulators and control valves simulating engine demands.

The cornerstone of this facility is our precision floor scale. The system weighting range is 0-3000 pounds with a readability of 0.0022 pounds (1 gram). In practice, our tests show that with a 1526 pound tarred load and a differential load of 9.5 pounds, the scale produced a measurement repeatability within +/- 4 grams. This level of precision allows IGT to offer testing and verification services for devices such as high pressure and high flow rate flow meters as well as highly accurate ANG cycling tests.

During the ANG charge or discharge cycling, the mass of the gas stored/delivered, the pressure and delta pressure, temperature within the adsorbent bed/container, around the thermal energy storage (TES) system, inlet/outlet and the skin of the container are measured against time using a PC-based computer control and data acquisition system. An on-line gas chromatograph monitors changes in gas composition. All gas discharged from the facility is routed back to the compressor/cascade refueling station for repressurization.

Conclusions

With the recent passage of more stringent emission standards for transportation vehicles the 1990's represent a decade of change for all transportation fuels. These changes represent an unprecedented opportunity for alternative fuels to enter the market place. Unlike past efforts to introduce hydrogen, the economics of hydrogen fueled vehicles may play a secondary role to their market acceptance. However, economics will play a role in hydrogen's ability to compete with other clean fuels in the market place. Even in the zero emissions vehicle market, pure electric vehicles represent strong competition. In this market features such as reduced weight, increased driving range and better performance must be stressed if hydrogen vehicles are to enter this niche market.

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FIGURE 1.

**NGVs ON THE ROAD ATTRIBUTABLE TO CLEAN AIR ACT
1995-2005**

Millions of Vehicles

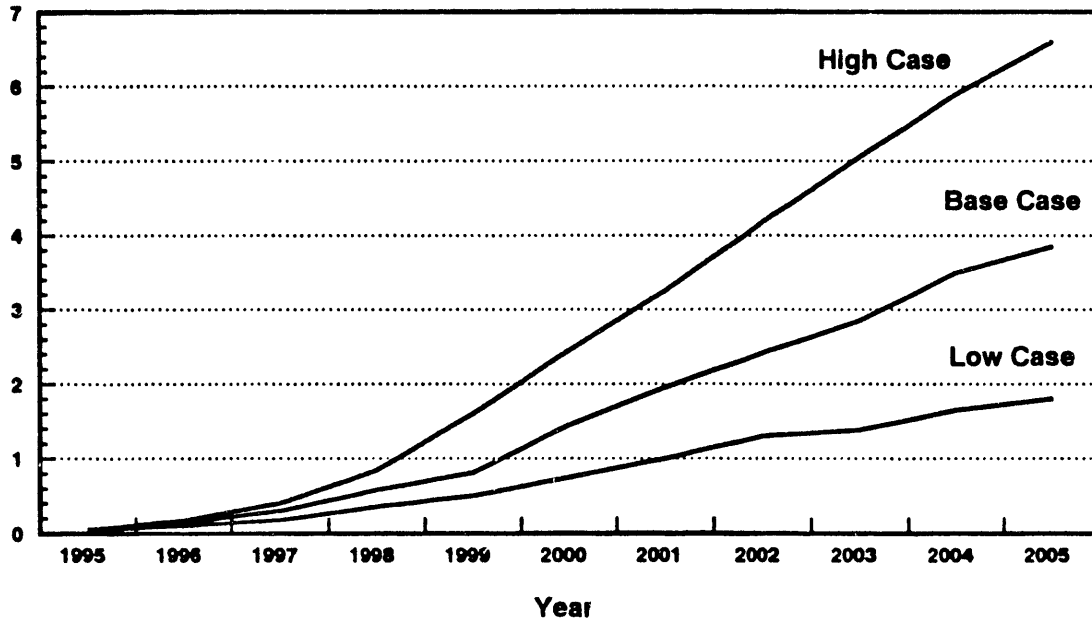


FIGURE 2.

Example FTP Emission Test Data

Pollutant	Vehicle Type	Natural Gas	California 1998 LEV Emission Standards
NMHC	'89 Closed Loop	0.05 to 0.16	0.125 (NMOG)
	'87 Open Loop	0.05 to 0.11	
NOx	'89 Closed Loop	0.75 to 0.80	0.4
	'87 Open Loop	0.92 to 1.16	
CO	'89 Closed Loop	0.65 to 0.71	3.4
	'87 Open Loop	0.21 to 0.27	

* Units are grams/mile

FIGURE 3.

Engine Power Output vs. Equivalence Ratio

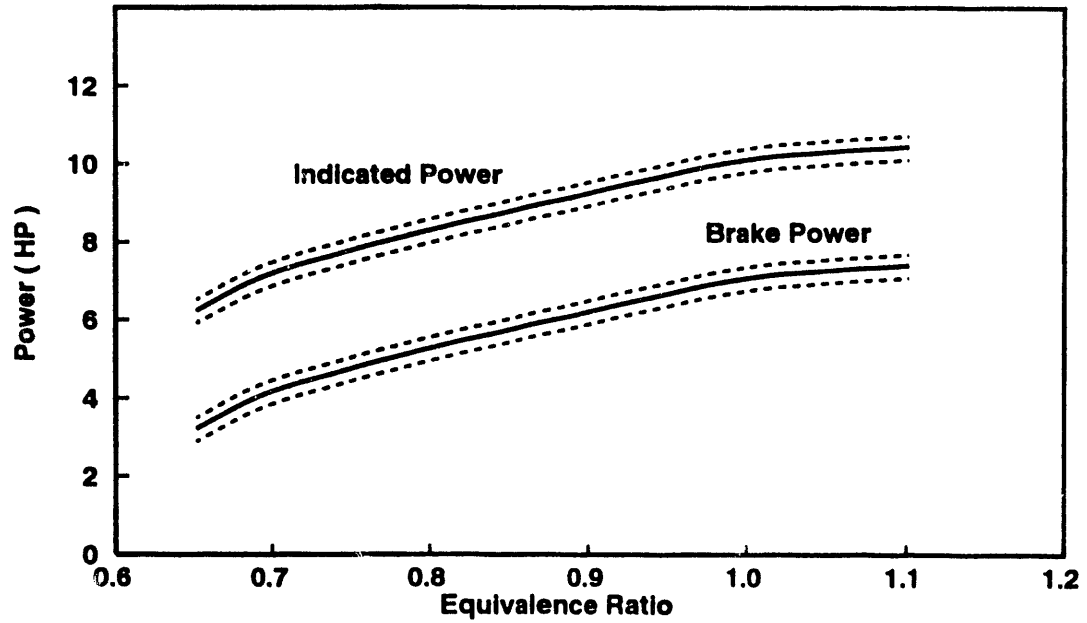


FIGURE 4.

Hydrocarbon Concentration vs. Equivalence Ratio

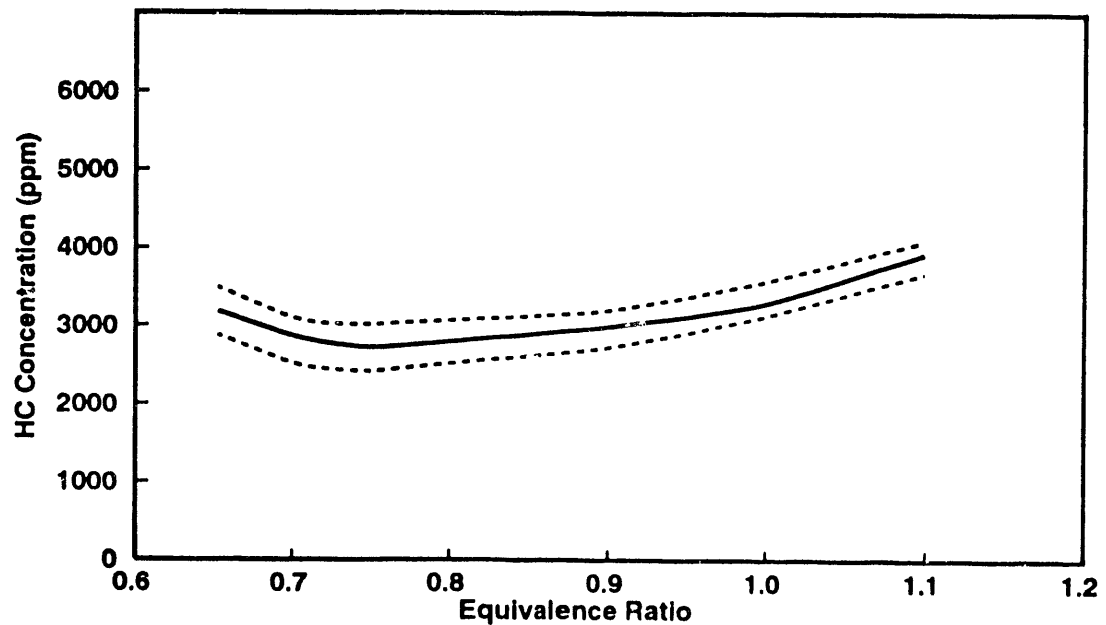


FIGURE 5.

NOx Concentration vs. Equivalence Ratio

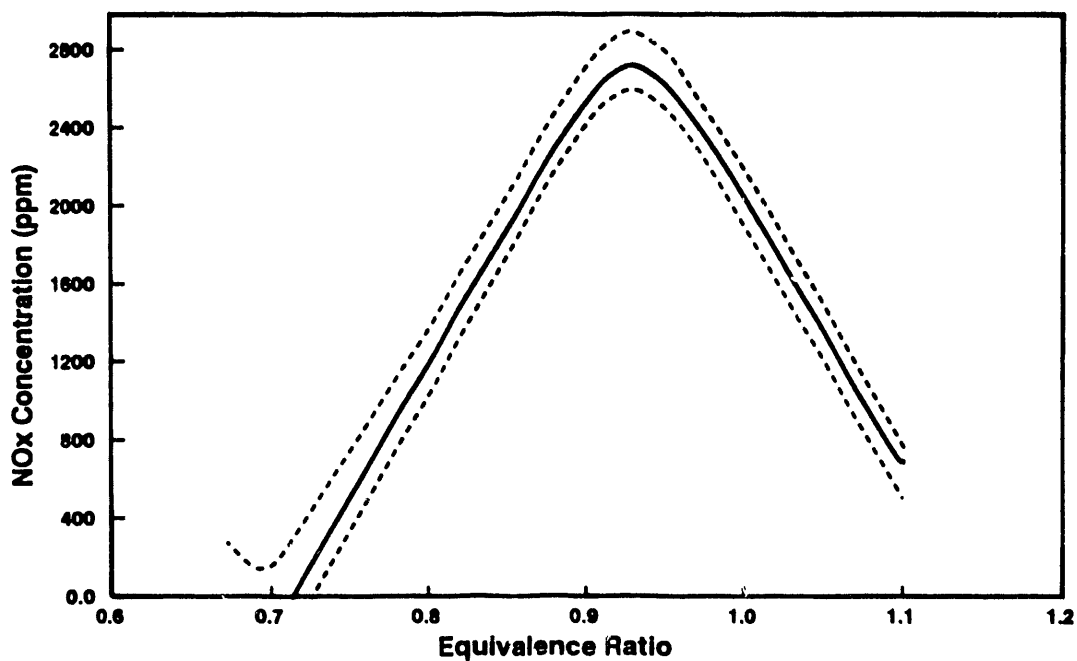
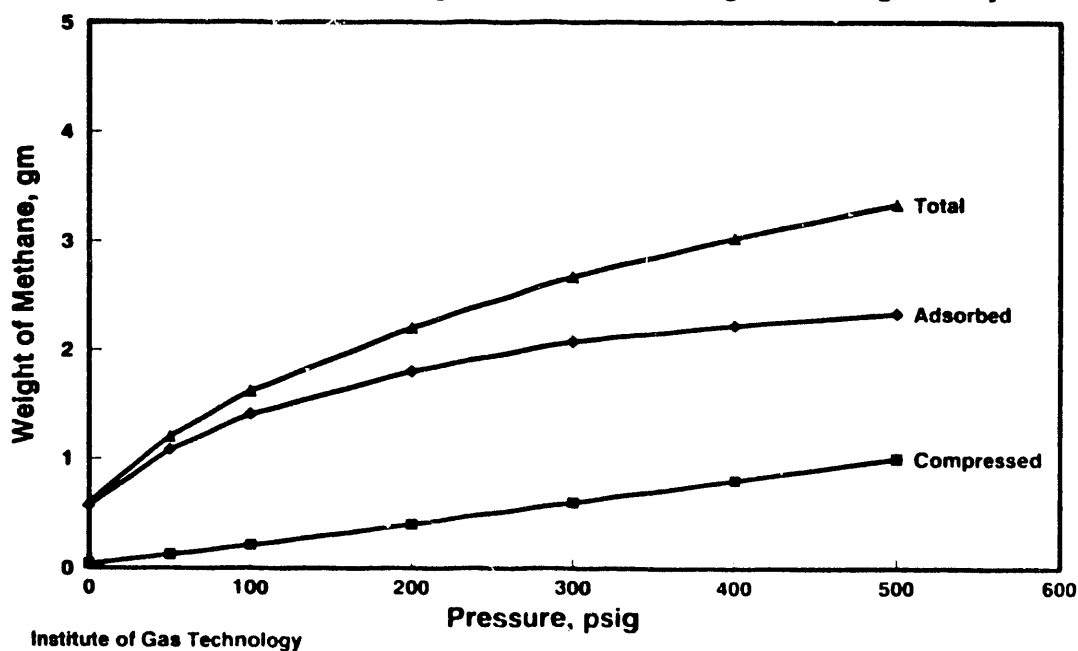


FIGURE 6.

Adsorption Isotherm Data for Methane

40 cc. Cylinder, 25 deg. Celsius, AX-21, 0.4 g/cc Packing Density

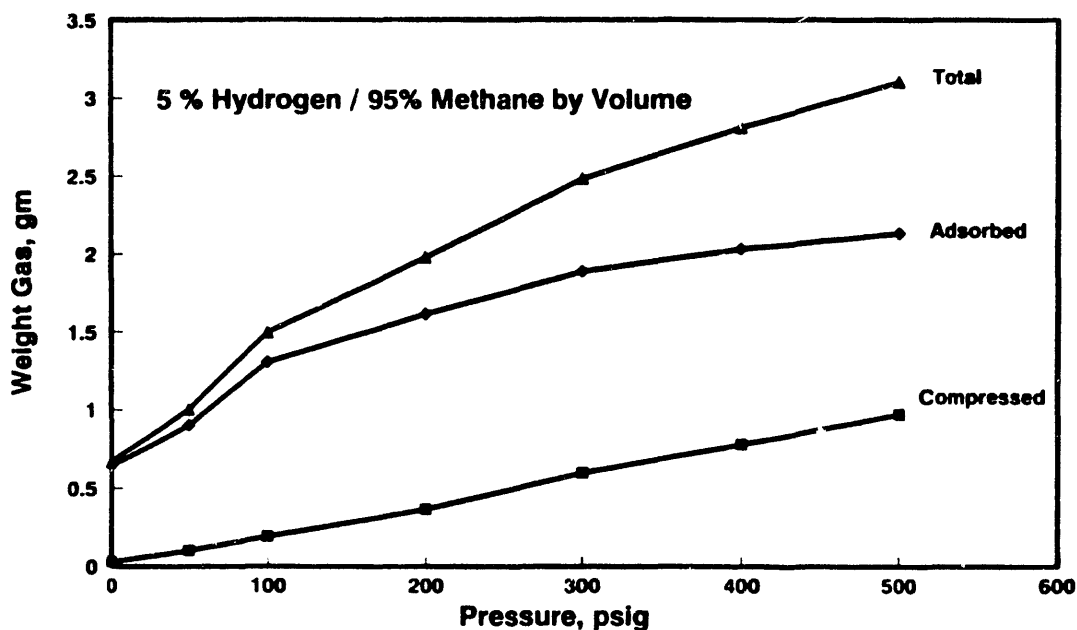


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FIGURE 7.

Adsorption Isotherm Data for Hydrogen/Methane Blend

40 cc. Cylinder, 25 deg. Celsius, AX-21, 0.4 g/cc Packing Density

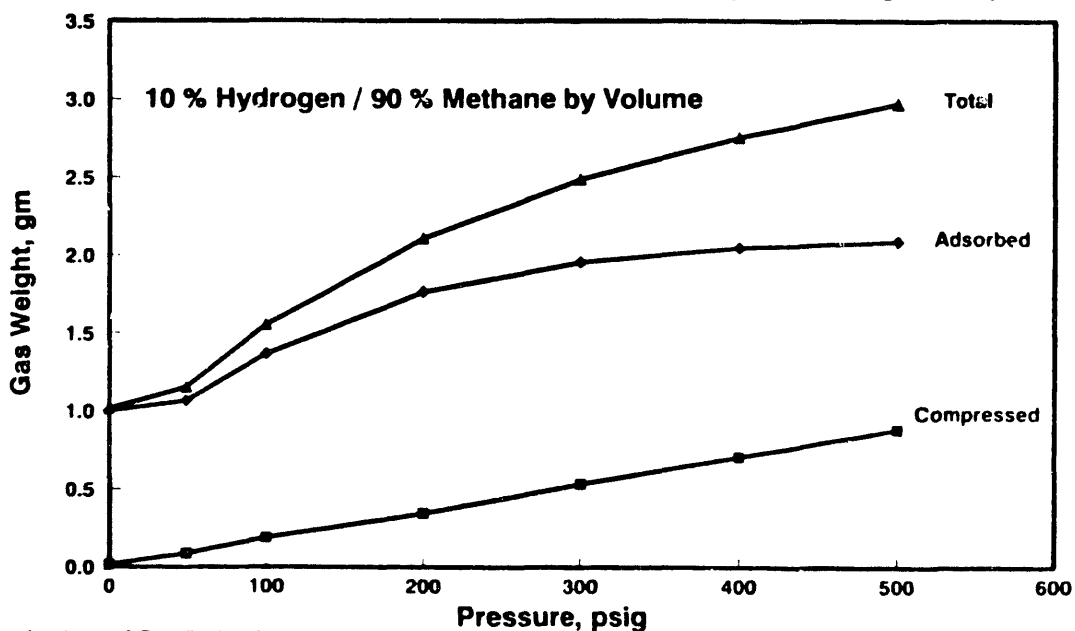


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FIGURE 8.

Adsorption Isotherm Data for Hydrogen/Methane Blend

40 cc. Cylinder, 25 deg. Celsius, AX-21, 0.4 g/cc Packing Density



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FIGURE 9.

Adsorption Isotherm Data for Hydrogen/Methane Blend

40 cc. Cylinder, - 80 deg. Celsius, AX-21, 0.4 g/cc Packing Density

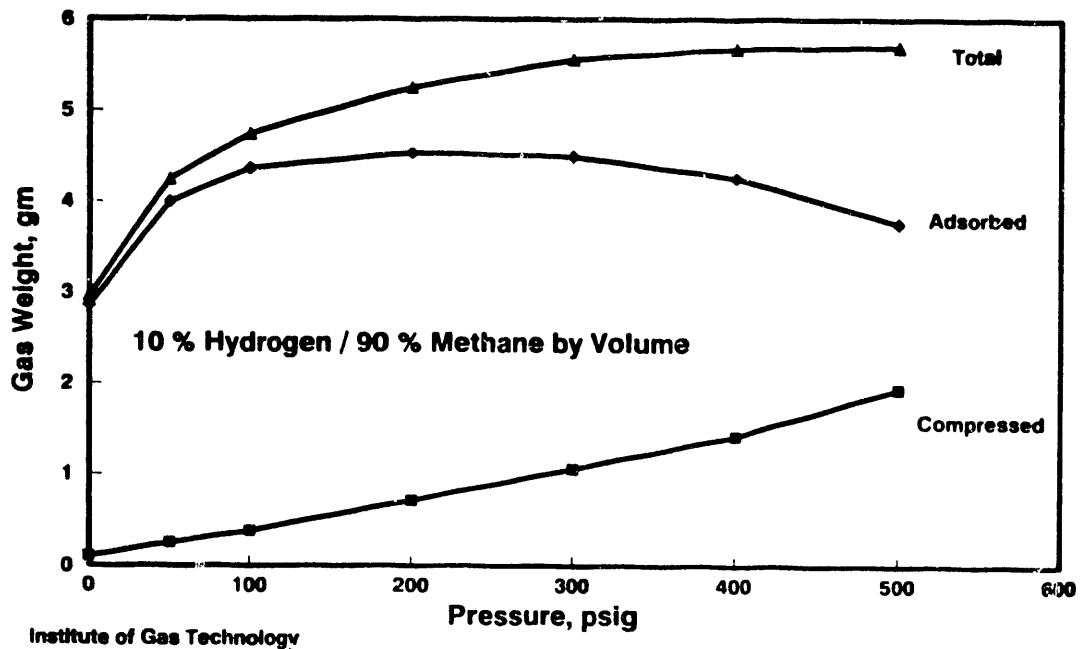
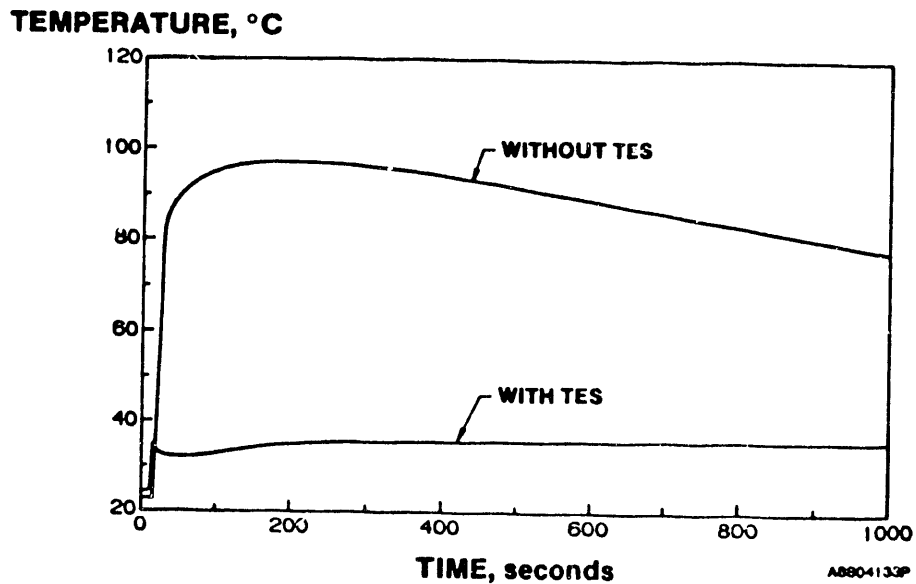


FIGURE 10.

COMPARISON OF FAST-FILL BED TEMPERATURE PROFILES (1-35 atm)

Methane Quick-Charge; AX-21 Adsorption Bed, Density = 0.4 g/cc



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