ADAPTATION OF A COMMERCIALLY AVAILABLE 200 kW NATURAL GAS FUEL CELL POWER PLANT FOR OPERATION ON A HYDROGEN RICH GAS STREAM

DOE/GO/10135--T1-Vol.1

Technical Report

December, 1997

Valerie A. Maston

FCR 14588A-Vol. 1

Date Published - January, 1998

Prepared for

The United States
Department Of Energy

Under Cooperative Agreement
No. DE-FC36-96GO10135

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

International
Fuel Cells

MASTER

P.O. Box 739
195 Governors Highway
South Windsor, Connecticut 06074

ADAPTATION OF A COMMERCIALLY AVAILABLE 200 KW NATURAL GAS FUEL CELL POWER PLANT FOR OPERATION ON A HYDROGEN RICH GAS STREAM

Draft Final Technical Report
December, 1997

Valerie A. Maston

Prepared By

International Fuel Cells Corporation
195 Governor's Highway
South Windsor, CT 06074

FCR 14588A

Date Published - January, 1998

Prepared For

The United States
Department Of Energy

Under Cooperative Agreement
No. DE-FC36-96GO10135

TABLE OF CONTENTS

SECTION PAGE

see M99000186

Abstract

International Fuel Cells (IFC) has designed a hydrogen fueled fuel cell power plant based on a modification of its standard natural gas fueled PC25™ C fuel cell power plant. The natural gas fueled PC25 C is a 200 kW, fuel cell power plant that is commercially available. The program to accomplish the fuel change involved deleting the natural gas processing elements, designing a new fuel pretreatment subsystem, modifying the water and thermal management subsystem, developing a hydrogen burner to combust unconsumed hydrogen, and modifying the control system. Additionally, the required modifications to the manufacturing and assembly procedures necessary to allow the hydrogen fueled power plant to be manufactured in conjunction with the on-going production of the standard PC25 C power plants were identified. This work was conducted under DOE Cooperative Agreement No. DE-FC36-96GO10135 and establishes the design and manufacturing plan for the 200 kW hydrogen fueled PC25 power plant.

Introduction

This report describes the design of an optimized 200 kW PAFC hydrogen fueled power plant for commercial production. The hydrogen fueled power plant was developed from IFC's commercially available natural gas fueled PC25 C power plant and an existing demonstration hydrogen power plant for a European customer. Figure 1 shows the work breakdown structure for this program.

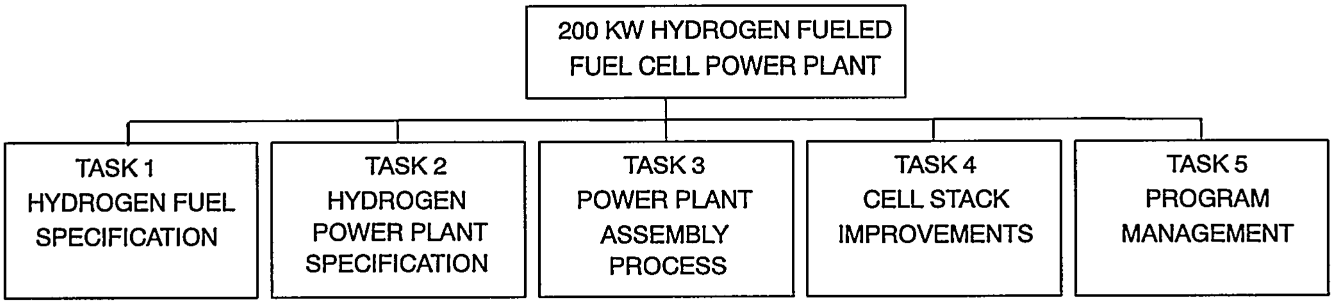


Figure 1. Work Breakdown Structure

Task 1 surveyed currently available hydrogen fuel sources including hydrogen generated by electrolysis powered by wind or solar sources. From this review of potential sources, a hydrogen fuel specification was developed.

In Task 2, IFC conducted cell testing and stack modeling to determine the optimum hydrogen utilization for this new fuel specification. The hydrogen power plant design incorporated the data from the testing and modeling and also examined methods to reduce part count and increase the availability of high grade heat. Task 2 also includes a hydrogen burner development program. The hydrogen burner actively manages the hydrogen not consumed in the stack.

Task 3, the power plant assembly process, was conducted concurrently with power plant design effort. The assembly process for the hydrogen power plant was established and design modifications were made to reduce the power plant assembly time. The specific manufacturing procedures for producing the hydrogen power plant concurrently with standard PC25 C power plant production were established.

Task 4 was IFC's cost share activity. This activity consisted of design and development work on two specific cell stack parts, the separator plates and the coolers. The improved separator plates have been incorporated into the production cell stack bill of material.

SECTION 1

Task 1. Hydrogen Fuel Specification

Objective:

Develop a hydrogen fuel specification based on available hydrogen sources and compatible with renewable hydrogen.

Accomplishments:

Hydrogen Fuel Survey

A survey of available hydrogen fuels was conducted to provide a basis for the fuel specification. The available sources were found to be commercial pressurized hydrogen gas, commercial liquefied hydrogen, hydrogen gas from electrolysis, and hydrogen rich gas by-product from the Chlor-Alkali and Petroleum Industries. Table 1 is the summary of the hydrogen fuel sources and their compositions.

Table 1. Summary of Hydrogen Fuel Sources

	Air Products		Praxair	Renewable Solar/Wind	OxyTech	Oglethorpe Power Customer	Ashland Petroleum
	Std-Purity	Ind-Grade		Electrolysis	Chlor-Alkali (diaph. cell)	Chlorate	Petroleum Process Gas
	Liquid	Gas	Gas	Product	By-Product	By-Product	By-Product
Hydrogen, %	>99.999	>99.95	>99.99	>99.95	99.7-99.8	92.68	86.5
ppm							
Oxygen	<2	<5		<10	1500-2500	18500	
Argon				<10			
Nitrogen	<5	<400	<100	<10	40-200		5000
Methane	<4	<10		<10			39000
Ethane							40000
Propane							28000
Isobutane							8000
n-Butane							6000
Pentanes & heavier							9000
Carbon Dioxide				<10	0-800		
Carbon Monoxide			<3		trace		
CO + CO2	<1	<10					
NaOH					500-700		
NaCl					5-10		
Chlorine						0.3	
Chlorine Dioxide						0.3	
Ammonia						6	

Except for the hydrogen rich gas from the Petroleum Industry, all the other sources of hydrogen fuel were at least 98% hydrogen on a dry basis. The hydrogen rich gas by-product from the Chlor-Alkali Industry, which includes hydrogen from both chlorine and chlorate production, has unacceptably high levels of oxygen and depending on the type of cell used has high levels of chlorine, ammonia, salts, or mercury. The wide range of possible contaminants from the Chlor-Alkali gas made it impossible to establish one gas clean up system for all the Chlor-Alkali off-gases.

Hydrogen Fuel Specification

Table 2 shows the final hydrogen fuel specification for the hydrogen power plant design. The fuel must be greater than 98% hydrogen, on a dry basis, to be used in the power plant. Specific fuel compositions can be evaluated on an individual basis. Fuels not meeting this specification may require clean-up or result in a decrease in the power plants net electrical efficiency.

Table 2. Hydrogen Fuel Specification

HYDROGEN FUEL SPECIFICATION	HYDROGEN	greater than 98%
	CONTAMINANTS*	
	- CARBON MONOXIDE	less than 1%
	- CARBON DIOXIDE	less than 2%
	- AMMONIA	less than 0.2 ppmv
	- CHLORINE	less than 1.0 ppmv
	- SULFUR	less than 1.0 ppmv
	- SALTS	less than 10 ppmv
	- OLEFINS	less than 0.05%
	- METHANOL	less than 500 ppmv
	All measurements are on a dry basis. *Gas compositions from specific sources will be evaluated on an individual basis.	
FUEL INLET PRESSURE	FUEL PRESSURE AT POWER PLANT INTERFACE MUST BE BETWEEN 2 TO 5 PSIG.	

Ashland Petroleum Hydrogen Fuel

The Petroleum Industry hydrogen rich process gas product was addressed separately. This hydrogen rich gas by-product contains substantial amounts of heavy hydrocarbons. These hydrocarbons represent 50% of the heating value of the gas even though they only represent a mole fraction of 15%. Two methods of using such a hydrogen rich gas sources were examined. The first used pressure swing adsorption with activated carbon beds to remove the heavy hydrocarbons prior to the hydrogen power plant. The other method evaluated uses this gas in a natural gas PC25 C with a modified reformer matched to the petroleum by-product gas.

The details of the evaluation of the activated carbon bed method are found in Appendix A. The results indicate that three beds of approximately 25 cubic feet would be required. Two beds would be regenerating while one bed was removing the propane and higher hydrocarbons. The beds would operate at 70° F and 115 psia. The beds would be regenerated at 300° F and ambient pressure. The beds would periodically need to be regenerated at 500° F with the frequency depending on the loading of hydrocarbons heavier than C8. Besides operating at high pressure and being regenerated at high temperatures, there is a concern as to what would be done with off-gas formed during regeneration. IFC does not recommend this solution.

A modified PC25 C natural gas powerplant would make the best use of the Ashland process gas by-product. The high hydrogen content of the gas would require some valve and piping changes to deliver the necessary flow with the proper pressure drops. These changes to the standard power plant would be a much more cost effective approach than to design a new clean-up system. The reformer would provide good protection for the stack by insuring all the heavy hydrocarbons are reduced to methane. A modified natural gas power plant would be a more integrated and efficient solution to accommodate the Ashland process gas by-product.

SECTION 2

Task 2. Hydrogen Power Plant Specification

Objective:

Establish the power plant configuration and develop engineering detail necessary to establish thermal, fluid, and mass balances; component definition and selection; and mechanical design modifications required to define the hydrogen power plant specification.

Accomplishments:

Hydrogen Utilization Study

Cell testing and stack modeling were done to establish flow conditions that would allow for the power plant to be over 44% electrically efficient. The cell tests determined the optimum humidification level for the incoming hydrogen fuel to be at 140° F dew point. The cell test showed a 15 mV increase in performance operating on hydrogen with fuel utilizations up to 95%. Three cell were operated for between 500 to 1000 hours each. These cells performed as expected during their extended runs. The cell testing indicates no issues with operating on humidified hydrogen gas of the conditions selected for the power plant design.

The data gather during the testing was used in IFC's stack modeling program to determine if there were any stack level maldistribution issues. The flow channel on the fuel side were designed to handle reformate gas which has a high percentage of carbon dioxide. This means that a much higher volume of gas flows in the natural gas power plant than that required for the hydrogen power plant. The reduced volumetric flow could lead to fuel distribution issues. The model showed while there was reduced flow there was always a higher partial pressure of hydrogen and therefore no intracellular fuel maldistribution. The recycle flow was selected to provide a higher volumetric flow to the stack and to increase the overall fuel utilization to over 95%, thus increasing the power plant electrical efficiency.

Hydrogen Burner Development

Since the hydrogen delivered to the cell stack is not 100% utilized, an approach must be developed for its disposal. In the European hydrogen power plant, the excess hydrogen was diluted to low levels after phosphoric acid scrubbing by mixing with the condenser exhaust and fuel compartment ventilation exhaust in a cupola on top of the power plant. In the work described here, it was decided to explore the possibility of using a burner instead of an acid scrubber and cupola. Initially, a catalytic burner was proposed. We determined that the phosphoric acid in the hydrogen exhaust stream would be detrimental to the catalyst support. On the other hand, a fired burner readily resolved the phosphoric acid entrainment issue. To maintain power plant reliability a continuous pilot would be required to prevent flame outs on transients. A preliminary burner design was done for a fired burner with a continuous pilot.

A subsection of the burner was built along with a full scale pilot. Laboratory tests were run on the hardware to provide data on the burner element spacing, the optimum distance between the pilot and the elements, the required pilot fuel flow rate, and the proper position of the flame sensor and ignitor. The required pilot fuel flow rate was determined to be 0.07pph. With such a low flow there would be no noticeable impact on the power plant efficiency. With the information gathered during the subscale testing, it was decided to obtain a quote form potential suppliers to build such a burner to see if would be less expensive than the acid scrubber and cupola combination. The burner design was modified to reflect the information gathered during the subscale testing and sent to several vendors for price quotes.

The price for the burner was substantially less than the price for the acid scrubber and cupola. Based on this a test plan for the full scale burner was developed and the burner ordered. Precision Combustion, Inc. (PCI) was selected to do the actual burner testing and Lynn Welding was selected to build the burner. The burner testing successfully confirmed the burner operation over the range of flows and the low emission levels. The testing also provided the information necessary to develop the control logic for the burner. Appendix B contains PCI's burner testing report.

Hydrogen Power Plant Specification

In addition to the design change described previously, other subsystems in the power plant were optimized. The stack cooling flows were changed which optimized steam production and reduced the number of components. The manufacturing procedures were reviewed and modifications were made to the design that would optimize the build sequence and time to produce the power plant. The review of all the power plant subsystems, allowed for hydrogen power plant design that would retain as many features and advantages of the commercial natural gas power plant as possible while taking full advantage of using a simpler fuel. Table 3 compares the natural gas, European demonstrator and the new hydrogen fuel cell power plant design.

Table 3. Power Plant Comparison

Characteristic	Natural Gas PC25 C	European Demonstrator	DOE Hydrogen PC25 C
Stack Hydrogen Utilization	80%	>92%	>95%
Electrical Efficiency	40%	>42%	>44%
Thermal Efficiency		~43%	~45%
High Grade Heat Available	3000,000 BTU/hr	0	400,000 BTU/hr
Low Grade Heat Available	7000,000 BTU/hr	685,000 BTU/hr	700,000 BTU/hr
Voltage/Frequency	400/50 Hz and 480/60 Hz	400/50 Hz	480/60 Hz
Hydrogen in Exhaust	0%	0.3%	0%
Hydrogen Burner	NA	No	Yes
Acid Scrubber	NA	Yes	No
Cupola	NA	Yes	No
Grid Connected	Yes	Yes	Yes
Grid Independent	Yes	No	Yes

The hydrogen power plant designed in this Task includes two possible high grade heat options available for this power plant. The first one, which is the same one for the standard power plant, uses the hot water in the cooling loop to provide the customer with up to 300,000 BTU/hr of 250° F thermal energy. The second option, exclusive to this hydrogen power plant, includes the first option plus takes advantage of excess steam that can be produced by the stack. This second option allows for over 400,000 BTU/hr of high grade heat at 250° F to be removed from the power plant. This power plant is a 60 Hz unit with grid connect and grid independent capabilities.

A description of the power plant operating, installation, and maintenance characteristics is provided in Appendix C. This appendix contains an overview of this new hydrogen power plant design including all the options available.

SECTION 3

Task 3. Power Plant Assembly Process

Objective:

Establish the process necessary to manufacture and assemble the hydrogen fueled version of the PC25 C concurrently with standard PC25 C power plants.

Accomplishments:

The new manufacturing procedures for the hydrogen power plant were imbedded into the natural gas assembly plans and procedures. These new procedures were linked to the hydrogen power plant bill-of-materials through a spreadsheet format. The spread sheet format permits ready access of the procedures and plans to the assembly teams building the power plants.

The other issue that was addressed was the changes required to the power plant controller for operation on hydrogen. There are substantial I/O changes required. Rather than creating a new part for the hydrogen power plant controller, the team established a hydrogen option kit and detailed instructions that would allow for the hydrogen power plant to use the PC25 C power plant controller on the assembly floor. This standardization of the power plant controller prevents installation of the hydrogen power plant controller in a natural gas power plant, eliminates the need for a special inventory of hydrogen controllers and or reduces the possibility of delays in manufacturing due to waiting for special parts.

IFC is available to conduct a proprietary review with DOE on the specifics of the manufacturing process.

SECTION 4

Task 4. IFC's Cost Share Activity: Cell Stack Improvements

Objective:

To define and develop improvements in cell stack components and improvements in the manufacturing and processes for assembling of these components. Two specific cell stack repeat parts, the separator plates and the coolers, were improved in this program.

Separator Plates

IFC focused on improving the separator plate manufacturing process to increase parts yield. A low yield rate had been traced to variability in the thickness and binder content of the non-woven carbon fiber felt. A design of experiment was established for qualifying new separator plates. This design of experiment evaluated ten different combinations of process variables. The process variables that were changed included percent of binder in the felt, the belt speed, add-ons at impregnation, two lamination processes and two lamination pressure levels. Approximately fifty plates were made for each of the ten processes to obtain a statistically valid representation of each process. As a result of this statistical approach to process optimization a new carbon felt for the laminated separator plates was developed which had excellent uniformity, more stability, a higher capacity for impregnation add-ons and a lower gas diffusion. The production lots also had a higher parts yield. These new separator plates have been incorporated into the production power plant bill of material.

Molded Coolers

The development work on the coolers examined going to a molded cooler. IFC used its cell stack model to examine the impact of reducing the cooler thickness. This thinner cooler resulted in increased thermal conductance while reducing material costs. After establishing the final configuration, production trials began. Three new full size coolers were successfully fabricated. All three passed the ASME pressure test requirement of 550 psi. The coolers also passed the electrical resistance and thermal cycling tests. The next steps involve testing in a full size substack and then a full stack. After successful verification testing, the molded coolers are expected to be incorporated into the production bill of material in 1998.

Future Work

The successful completion of this program yielded the design of and manufacturing procedures for the development of a commercial hydrogen power plant. Beyond the scope of this program is demonstration of the power plant.

Acknowledgments

IFC would like to acknowledge the DOE for their funding of this program and the following individuals and companies for their contribution to our program:

T. F. Florkiewicz of OxyTech Systems, Inc.
Tom Halverson of Praxair, Inc.
Jim McElroy of Hamilton Standard
Venki Raman of Air Products and Chemicals, Inc.
Theodore Strickland of Precision Combustion, Inc.
Robert H. Wombles of Ashland Petroleum Company

APPENDIX A

ASHLAND FUEL CLEAN-UP SYSTEM REVIEW

BACKGROUND

A survey was made to determine available hydrogen sources for a hydrogen fueled fuel cell power plants. One of the hydrogen streams that was found was a vacuum gas oil (VGO) hydrotreater make up hydrogen feed stream gas from an Ashland oil company refinery. This hydrogen stream has the following gas composition:

HEATING VALUE OF ASHLAND HYDROGEN GAS to VGO HYDROTREATER

(GAS CONCENTRATIONS FROM LETTER FROM R. WOMBLES TO D. WHEELER)

HEATING VALUE DATA TAKEN FROM "PERRY'S CHEMICAL ENGINEERS HANDBOOK, 4th ed. TABLE 9-16.

COMPOUND	PERCENT	HEATING VALUE (BTU/CU FT)		HEATING VALUE OF ONE CU FT OF GAS (BTU)	
		HIGHER	LOWER	HIGHER	LOWER
HYDROGEN	86.5	325	275	281.1	237.9
METHANE	3.9	1013	913	39.5	35.6
NITROGEN	0.5	0	0	0.0	0.0
ETHANE	4.0	1792	1641	71.7	65.6
PROPANE	2.8	2590	2385	72.5	66.8
ISOBUTANE	0.8	3363	3105	26.9	24.8
n-BUTANE	0.6	3370	3113	20.2	18.7
ISOPENTANE	0.3	4008	3716	12.0	11.1
n-PENTANE	0.1	4016	3709	4.0	3.7
HEAVIER THAN n-PENTANE*	0.5	4762	4412	23.8	22.1
* USED HV OF n-HEXANE					
TOTAL HEATING VALUE (BTU/FT3)				551.8	486.3
FRACTION OF HEATING VALUE THAT IS H2				0.509	0.489
FRACTION OF HEATING VALUE FOR C3 AND HIGHER HYDROCARBONS				0.289	0.303

NOTE: If C3's and above are removed, 30% of the heating value of the gas is lost.

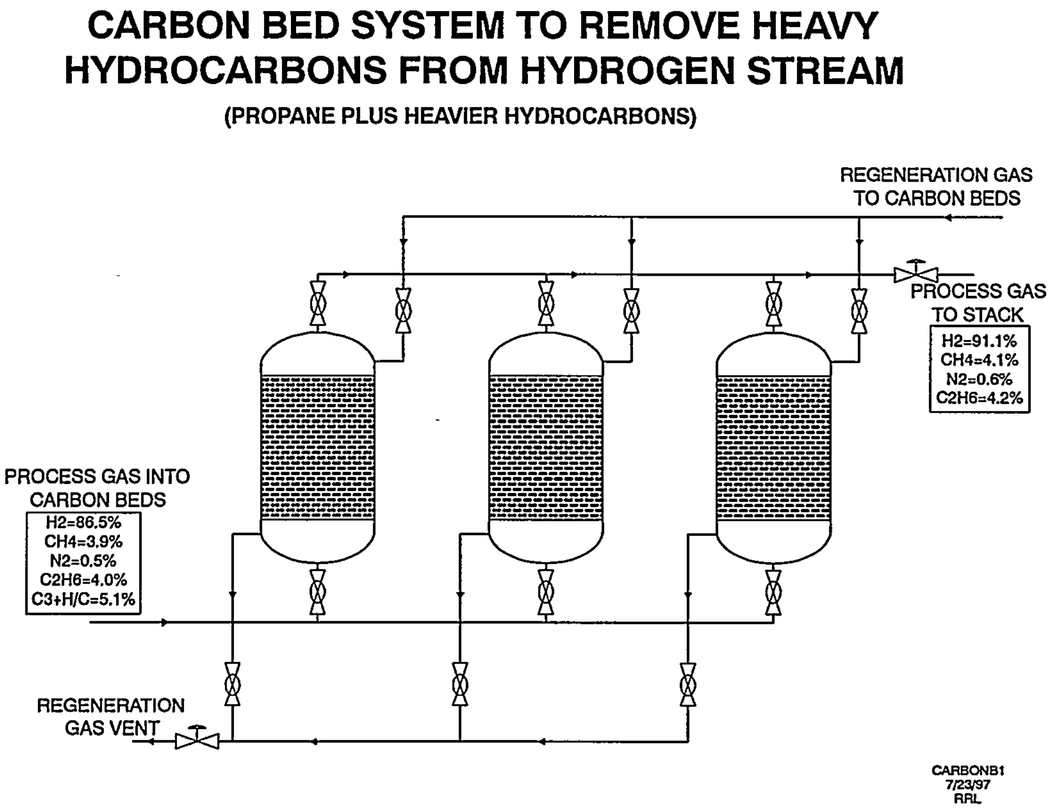
Although the gas is 86.5% hydrogen, only half of the heating value is in the hydrogen, and 30% of the heating value is in propane and heavier hydrocarbons. Heavy hydrocarbons are known to decrease fuel cell performance and so must be removed. Two options are available for using this fuel in a fuel cell. The first is to use a standard reformer to convert the higher hydrocarbons into hydrogen in a standard power plant. This requires high conversion of the fuel and approximately 90% hydrogen utilization in the stack to prevent overheating the reformer when burning the anode exhaust. The second is to eliminate the higher hydrocarbons to avoid poisoning the fuel cell anode. This study evaluated using pressure swing adsorption with activated carbon to adsorb the higher hydrocarbons from the gas stream. Both ethane and methane do not harm the anode, however unsaturates must be absent to avoid poisoning. On the other hand, propane and heavier hydrocarbons will cause problems.

The Bohart-Adams[1] equation was used to define hydrocarbon breakthrough from the carbon bed. A quantitative use of the Bohart-Adams equation to describe effluent vapor profiles exiting charcoal beds was described by Karpowicz, Hearn and Wilkinson[2]. The Bohart-Adams theory is based on the assumption that the rate of reaction, or adsorption, is proportional to the sorbent capacity remaining in the carbon bed and to the concentration of the sorbent in the gas phase. With this equation, all that is needed to define loading and breakthrough curves at any condition is a knowledge of the maximum capacity of the adsorbent and the gas concentration at breakthrough for one test case. Activated carbon capacity for hydrocarbon vapors was calculated based on a study by Wood[3] who provided both correlation coefficients to define the capacity to adsorb hydrocarbon vapors and the property of various commercial carbons. A laboratory breakthrough curve of propane in helium was published by Malek and Farooq[4] and used for the calculated breakthrough curve.

SUMMARY

Breakthrough curves were calculated for the Ashland VGO hydrogen feed based on the calculated capacity of BPL carbon for propane adsorption. For 200 kW flows, assuming 90% hydrogen utilization, there is a total gas flow of 7600 ft^3/hr entering the clean up system, 7200 ft^3/hr coming out and 5900 ft^3/hr of H_2 consumed in the stack. To remove propane and higher hydrocarbons, three 20 to 30 cubic foot beds of charcoal are required. They would operate at 115 psia and ambient temperature, with a regeneration required every 5 to 8 hours at 300°F and ambient pressure. 20 cubic foot beds would have to be regenerated every 5 hours and 30 cubic foot beds would have to be regenerated every 8 hours.

Two beds might be sufficient to do the job; however three beds were included in the design since there is no regeneration data available to define how long it would take to heat, regenerate and then cool each bed. Three beds will insure that each regenerated bed will be fully cooled and ready for use by the time it is needed to come back on stream. It is assumed that the regeneration gas is steam; however some use must be made of the off-gas from the regeneration process, and there is a question of what becomes of the steam condensate which undoubtedly has some hydrocarbons dissolved in it. A diagram of the adsorption system is shown in the Figure 1. Each bed has a ball valve at the inlet and exit to isolate the bed, and a pressure regulator at the end of the train to allow for high pressure adsorption (115 psia) and low pressure venting. While this is an engineering solution, it is not a commercial solution. The costs of equipment, reliability, and operating, while not fully quantified, are likely to be a significant deterrent to this approach.



CARBON BED SYSTEM TO REMOVE HEAVY HYDROCARBONS FROM HYDROGEN STREAM

(PROPANE PLUS HEAVIER HYDROCARBONS)

CARBONB1
7/23/97
RRL

Figure 1. Proposed system for removing hydrocarbons from the hydrogen gas to the fuel cell.

DISCUSSION

Initially it was anticipated that the cycle could be a simple pressure swing without the need for changing temperature; however there is insufficient regeneration when the temperature is maintained at ambient, and breakthrough is very rapid as shown in Figure 2 for carbon beds of from 10 ft^3 to 30 ft^3. It can be seen from Figure 2 that a 30 cubic foot bed would have to be regenerated every 2 hours. This in fact may be more desirable than having to heat the bed if regeneration could be completed in less than four hours. Longer regeneration times would require more adsorption beds. Carbon beds are sometimes used for sulfur removal from natural gas. When used in this service, they are usually regenerated at about 300°F on a regular basis, and then periodically regenerated at 500°F to remove the heavy hydrocarbons >C8 or C10. Depending on the quality of the VGO gas, it may be necessary to frequently regenerate at temperature.

If regeneration is accomplished at 300°F and ambient pressure, a 20 cubic foot bed will last for five hours and a 30 cubic foot bed for eight hours before regeneration is required, as shown in Figure 3. It appears that regeneration at temperature would allow the use of either three 20 cubic foot beds or two 30 cubic foot beds. An analysis would have to be made of the heating and cooling times as well as the regeneration times required to fully define the system. Regeneration data is required for this analysis.

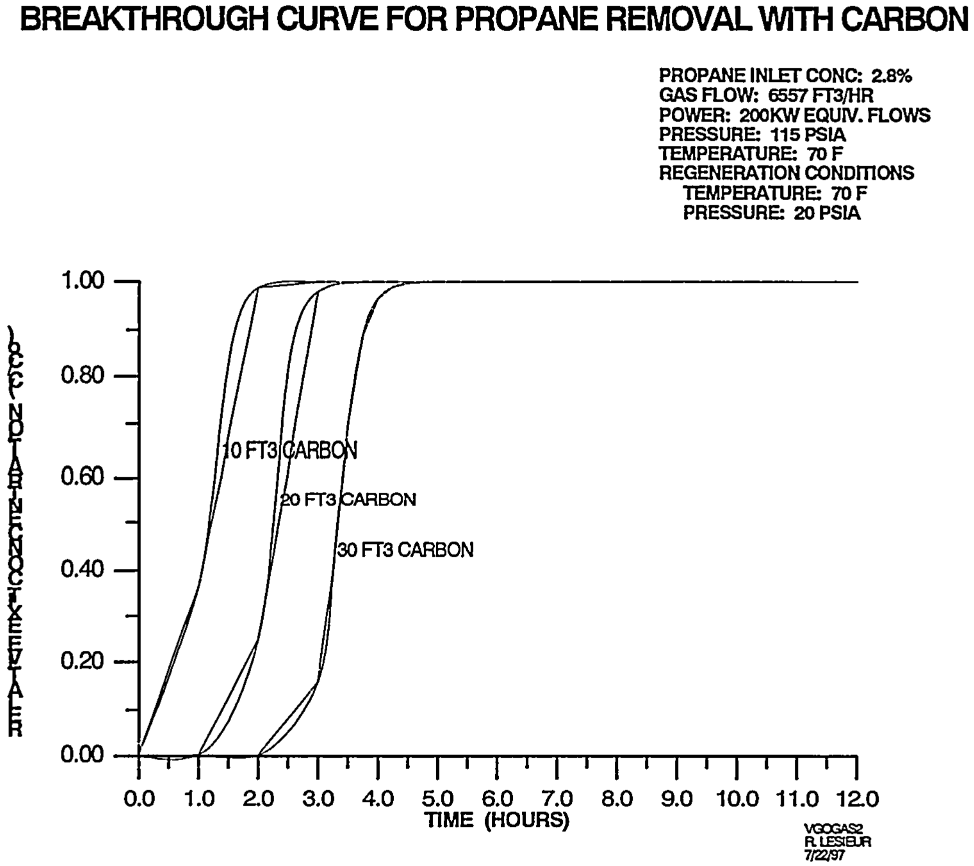


Figure 2. Breakthrough curves for removal of heavy hydrocarbons when regenerating the carbon at room temperature and 20 psia.

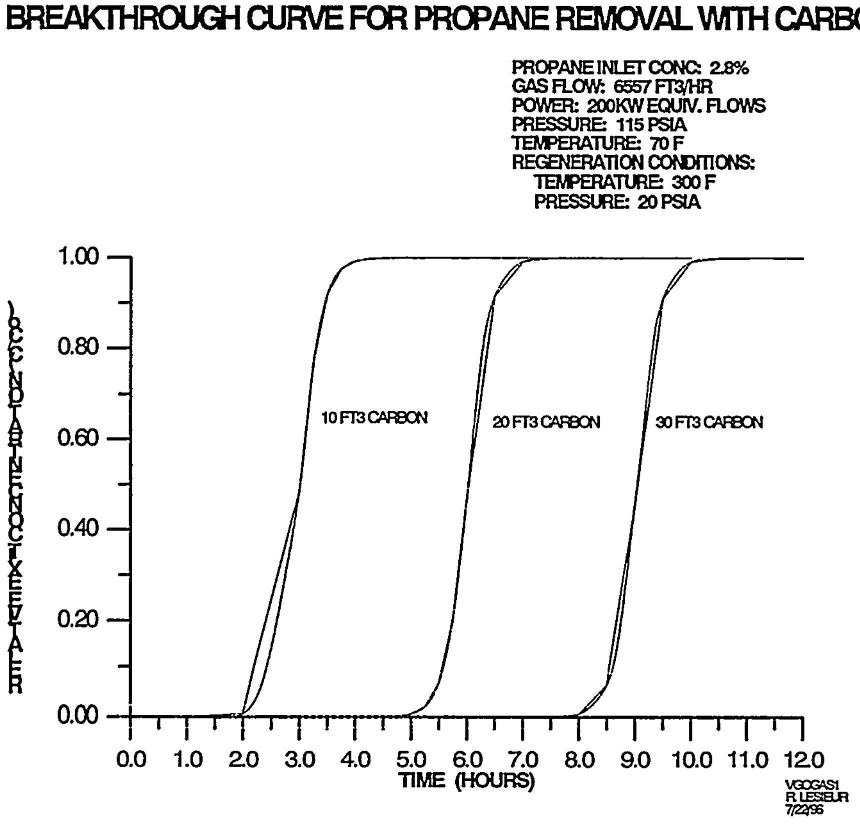


Figure 3. Breakthrough curve for removal of heavy hydrocarbons when regenerating the carbon at 300°F and 20 psia.

The above curves were generated using the Bohart-Adams equations as defined by Karpowwicz, Hearn and Wilkinson. The equation which describes the breakthrough curve is:

$$C/Co = (e^{kCot})/(e^{kCot} + e^{kW/F} - 1)$$

Where:

C = Concentration at time t (lbs/ft^3)

Co = Inlet concentration

k = rate constant (ft^3/hr-lb)

t = time (hours)

W = capacity of charcoal for adsorbent (lbs)

F = Gas flow rate (ft^3/hr)

All that is required to solve this equation is to know the maximum capacity of the adsorbent at the conditions being used, and a concentration at some breakthrough time. The capacity of the charcoal was defined for many hydrocarbons as well as non-hydrocarbons in the paper by Wood. The calculated capacity of BPL carbon for adsorption of propane is shown in Figure 4. It is assumed that if propane is adsorbed, then all of the heavier hydrocarbons will also be removed.

CAPACITY OF ACTIVATED CARBON FOR REMOVAL OF PROPANE AND HIGHER HYDROCARBONS

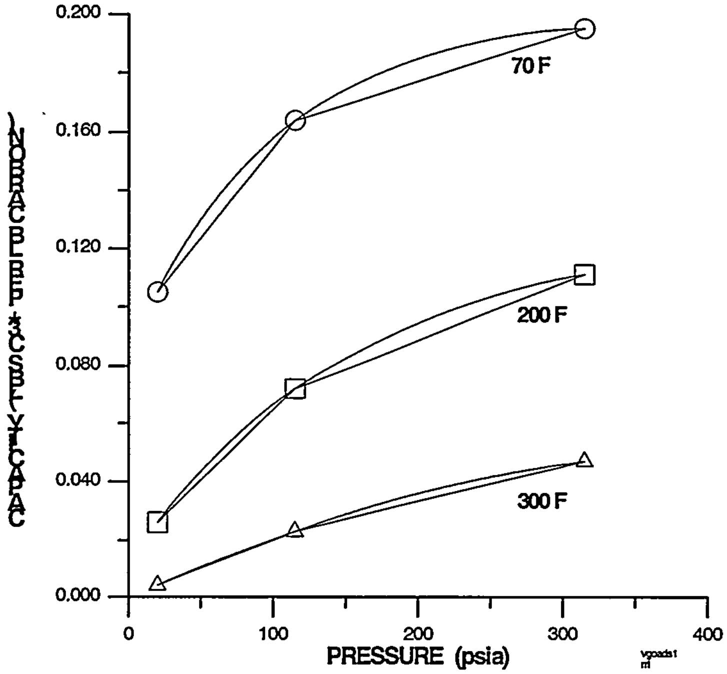


Figure 4. Capacity of activated carbon for the adsorption of propane. Points are calculated.

The above capacity curves were generated from parameters provided in the paper by Wood using the following equations:

$$Wg = Wo*d_L*\exp[-b*Wo*Pe^{-1.8}*R^2*T^2*\{\ln(P/P_{sat})\}^2]$$

and

$$Pe = ((n^2_D - 1)/(n^2_D+2))*(M_w/d_L)$$

where:

Wg = adsorption capacity (g/g)

Wo = micropore volume (cm^3/g)

d_L = density of condensed liquid in the micropores (g/cm^3)

b = "universal" constant $3.56*10^{-5}$ ($mol^2cal^{-2}cm_o^{-3}(cm^3_L/mol)^{1.8}$)

Pe = molar polarization (cm^3/mole)

T = absolute temperature

R = ideal gas constant

P/P_{sat} = partial pressure relative to that at saturation

n_D = refractive index

M_w = molecular weight

Using the above equation, adsorption capacities can be calculated at any temperature and pressure whenever the properties of the carbon and the liquid phase of the sorbent are known.

REFERENCES

1. Bohart, J. S. and E. Q. Adams, "Some Aspects of the Behavior of Charcoal with Respect to Chlorine", *J. Am. Chem. Soc.*, **42**, 523 - 544, (1920).

2. Karpowicz, F., J. Hearn and M. C. Wilkinson, "The Quantitative Use of the Bohart-Adams Equation to Describe Effluent Vapour Profiles from Filter Beds", *CARBON*, **33**, 1573 - 1583, (1995).

3. Wood, G. O., "Activated Carbon Adsorption Capacities for Vapors", *CARBON*, **30**, 593 - 599, (1992).

4. Malek, A. and S. Farook, "Kinetics of Hydrocarbon Adsorption on Activated Carbon and Silica Gel", *AIChE Journal*, **3**, 761 - 776, (1997).

APPENDIX B

PCI BURNER TEST REPORT

Final Report
for the

FC15525 Hydrogen Burner Laboratory Test Program

to

International Fuel Cells Corporation
P.O. Box 739
195 Governors Highway
South Windsor, Connecticut 06074

November, 1997

Work performed by

Theodore Strickland

Precision Combustion, Inc.
25 Science Park
New Haven, CT 06511
(203)-786-5215

Purchase Order: A70412

Summary

This report documents the component test program which was completed in July 1997 on the final prototype FC 15525 Hydrogen burner. The testing was conducted by Precision Combustion, Inc. (PCI) in their test facility which consisted of operational and emissions measurements as outlined in the statement of Work which is included in Figure 1. IFC provided the burner assembly, the UV flame supervision system and the ignition system. PCI provided the balance which included: the fuel gas control system, airflow and control, pressure and temperature measurement system and the emissions system. The vertically positioned diffusion flame burner consists of two concentric annuli and a center core. Air passes through the central core and outer most annulus, while the main fuel and diluent pass through an array of holes and burn in the middle annulus. The burner is housed within a 6 inch diameter tube, the hot exhaust exits through a 4 inch diameter tail pipe which is curved to exit horizontally. A small diffusion flame pilot is located at the burner plane in close proximity to the igniter and main fuel sources. The main fuel consisted of both hydrogen (H_2) and carbon dioxide (CO_2) which is premixed prior to entering the fuel inlet tube. CO_2 was used to simulate the steam diluent which would be added to the H_2 fuel flow in the actual power plant application.

The burner operated flawlessly over the range of conditions tested. Ignition at the idle airflow using only the pilot H_2 gas was instantaneous and was predictable at pilot flows below 0.03 pph. The flame detection system detected the flame within 2 seconds and the UV sensor output voltage was approximately 5 volts as anticipated. The UV sensor output was essentially unchanged at 5 volts over the entire operating range from Idle to ultimate conditions. The burner remained stable at all steady state conditions even with the pilot off. The pilot was on for transients and the burner remained stable with no indication of flame out. At idle, with a pilot flow of 0.04 pph, the burner exit temperature (measured with a half-shielded type K T/C) was approximately 900 F, with corresponding uncorrected NO_x emissions of 17.6 ppmv. The air and fuel pressure drop were below 0.10 inches of water. Increasing the pilot flow to 0.10 pph produced an increase in exit temperature to about 960 F with corresponding increase in NO_x to 23.5 ppmv. Both THC and CO emissions were below detectable limits at all idle conditions. At the rated power condition with a pilot flow of 0.04 pph the burner exit temperature was approximately 1120 F, with NO_x emissions of 11.0 ppmv. The air pressure drop was below 1 inch of water while the fuel pressure drop was 0.20 inches or water. Increasing the pilot flow to 0.10 pph produced an increase in exit temperature to about 1160 F with corresponding increase in NO_x to 13.1 ppmv. THC emissions were below 1 ppmv while CO emissions were 3.5 ppmv. With the pilot flow off, the burner remained stable, the exit temperature and NO_x dropped to 1120 F and 9.8 ppmv respectively. Increasing the fraction of CO_2 dilution by 20% reduced NO_x from 11.0 to 8.5 ppmv with a negligible reduction in exit temperature. Increasing the dilution by 50% reduced the NO_x to a value of 5.6, without any stability or flame detection abnormalities. No flame was visible exiting the burner tailpipe at any test condition in dim light conditions.

International Fuel Cells
Memorandum

FC15525 H_2 Burner Testing Statement of Work

IFC will provide the following items:

1. FC15525 H_2 Burner with pilot ignitor assembly taped in place with metal tape
2. Spark plug and high voltage generator
3. UV sensor and control

The table below defines the flow rates at each operating condition. All gases can be introduced at 70 °F.

Flow rate(pph)	Idle	Rated	Overflow
H_2 fuel	0.29	1.67	2.17
CO_2 fuel diluent	2.78	16.0	20.5
Air	57.3	325	420
H_2 pilot	0.07	0.07	0.07

The vendor shall provide the following services:

1. Verify operation of flame supervision system and measure UV sensor output at each combination of the following conditions (9 total conditions):

Air flow condition	H_2 pilot flow (pph)
idle	0.04, 0.07, 0.10
rated	0.04, 0.07, 0.10
overflow	0.04, 0.07, 0.10

[UV sensor output should be greater than 1.25 V, 5 V max.]

2. Verify burner ignition at idle air flow and 0.07 pph H_2 pilot flow by setting idle fuel flow and checking exhaust temperature rise (T/C in exhaust should be shielded from ambient).
3. Verify that flame length is acceptable at rated condition, and measure the following:
   - steady state exit temperature (1000 °F nominal) and response time
   - fuel and air ΔP to ambient (0.1 - 0.2 iwd nominal)
   - NO_x emissions
4. Verify that flame length is acceptable and burner operation is stable at overflow condition.
5. Conduct post test inspection of fuel ports, pilot, and spark plug.
6. Provide a test report summarizing the results obtained.

Figure 1. Statement of Work

Project Requirements and Objectives

The project test requirements are summarized as follows:

1. Verify burner ignition at the idle airflow and over a range of pilot flows.
2. Verify operation of the flame supervision system and measure UV sensor voltage output at 4 conditions.
3. Measure exit temperature, pressure drop, and emissions at 4 conditions.
4. 4Verify flame retention within the burner.
5. Conduct a post inspection.
6. Provide a test report.

Functions provided by PCI included:

1. Mounting the burner in an appropriate facility to allow safe operation.
2. Designing and assembling a fuel premixer for hydrogen and carbon dioxide gasses.
3. Fabrication of an appropriate averaging emissions probe.
4. Providing accurate mass flow control and measurement for a hydrogen pilot, hydrogen main, carbon dioxide fuel diluent, and atmospheric pressure air.
5. Providing temperature, pressure and voltage instrumentation for monitoring critical burner functions.
6. Accurate measurement of burner exit exhaust gasses, with NO_x being of particular concern.
7. Operating the burner at the described conditions and recording pertinent data.
8. Running special tests with higher CO_2 dilution to show the effect on NO_x.
9. Conducting transient exit temperature measurements at conditions from ignition to idle, and from idle to rated power.
10. Documenting the results in a report.

Test Rig Layout

The fully insulated burner assembly, the ignition system, the flame detection system, and the UV sensor were provided to PCI for performing the required atmospheric pressure performance testing. The rig was mounted vertically to a suitable test stand which provided adequate venting of exhaust gasses as shown in Figure 2. Inlets to the rig included air, an H_2 fuel pilot, and a premix of H_2 fuel and CO_2 dilution for main fuel. The air was provided by a regenerative blower and was measured by a calibrated turbine vane meter. The gasses were independently metered and controlled by Brooks mass flow control valves which were factory calibrated. Instrumentation included type k thermocouples for measuring air and fuel inlet temperatures, a half-shielded exposed junction type K thermocouple for measuring exit temperature, static pressure taps were installed on the air inlet tube and on the fuel premixer manifold. Static pressures were referenced against atmospheric pressure and were measured using a digital differential pressure gauge. The premixer consisted of a stainless steel tee and appropriate 1 diameter pipe fittings. All gas lines were stainless steel or copper. The flame supervision system was coupled to the UV sensor which was positioned in direct line of sight of the burner baseplate. The amplified voltage from the UV sensor was also measured using a digital voltmeter. A stainless steel uncooled emissions averaging probe was inserted across the exit span and was positioned approximately 8 inches from the exhaust pipe exit.

Testing and Instrumentation

The prototype burner was tested per the statement of work and in addition, two transient exit temperature traces were recorded. Transient traces of exit temperature from the ignition condition to idle, and from idle to rated power were taken using a strip chart recorder. was was and modified at PCI to meet the design objectives. Combustion air was supplied by a centrifugal blower and volumetrically measured by a digital rotary vane meter. A bypass valve was used to regulate air flow. The main fuel consisted of both Hydrogen (H_2) and carbon dioxide (CO_2) which is premixed in a stainless steel tee prior to entering the fuel inlet tube. As mentioned above CO_2 was used to simulate the steam diluent which would be present in the H_2 fuel flow in the actual power plant application.

Gas temperatures were measured with type K thermocouples. An unshielded open junction thermocouple measured inlet air temperature and another measured fuel gas temperature in the premixer. A radiation shielded open junction thermocouple measured the exhaust gas temperature at the burner exit.

Air pressure drop and fuel gas pressure drop were measured with a factory calibrated digital manometers (Omega HHP-6150) connected to pressure taps in the air inlet section and in the premixer. The pressure taps consisted of a de-burred 0.020" hole drilled in the side of the inlet pipes, at a location where the flow remained undisturbed by obstructions or flow area changes. The digital manometer accuracy is better than 0.1% of full scale, or within 5% of the pressures measured at the inlet to the combustor.

Exhaust gas emissions were measured with industry and EPA standard equipment. The type of emissions analyzers used for each of the measured species are shown in Table 1, along with instrument accuracy and detectable limits. Exhaust gas was sampled from an 8-hole un-cooled probe, sampling 4 equal annular areas inside the 4 inch tailpipe. The emissions probe was located 6 inches upstream of the tailpipe exit (to prevent sampling of back-flow air due to acoustic pulsations). THC emissions were measured wet while all other emissions are reported on a dry basis.

For each test condition the burner was allowed to reach a steady state operating condition, with stable temperatures and emissions before data was recorded. There are some discrepancies in the temperature data within each power condition since test points were not taken in a particular order. Errors in temperature measurements were expected due to the large thermal inertia and surface area of the burner. Because of the large mass of the burner and large surface areas resulting in radiation losses, extremely long periods of time were required to reach thermal equilibrium. In short, thermal equilibrium was not fully achieved at all of the test conditions within a reasonable time. Testing was conducted from the lower exit temperature idle conditions to the higher exit temperature rated power but pilot flows were varied out of order.

Instrument Calibration

The digital rotary vane meter for air flow measurement was calibrated by running in series with an identical unit calibrated by the Colorado Engineering Experiment Station, a NIST traceable facility. For comparison, the vane meter was also run in series with an ASME standard orifice plate. Meter accuracy was within 2%. Inlet air temperature and pressure were monitored during combustor testing, for calculating SCFM or PPH air flow from the measured ACFM air flow. The Brooks mass flow controllers used for the three independent gas flows were calibrated at the factory and have an accuracy of 1 % of full scale, and are NIST traceable.

The emissions instruments were calibrated with zero and appropriate span gases before and after the test. VOC free nitrogen was used as the zero gas, to verify the zero levels of each emissions analyzer. A mixtures of methane, carbon monoxide, carbon dioxide, and nitrogen were used to calibrate the CO and THC (total hydrocarbon) analyzers. The certified bottled mixture contained 11 ppmv CH_4, 9 ppmv CO, and a balance of N_2. Another mixture containing 1040 ppmv CH_4, 103 ppmv CO, 5.38% CO_2, and a balance of N_2 was used to calibrate the CO_2 analyzer. Room air (20.9% O_2) was used to calibrate the O_2 analyzer. The NO_x analyzer was calibrated with a 10.1 ppmv standard.

Results Summary

Testing began with the ignition tests followed by idle, rated, overflow and finally a special condition called ultimate. Transient tests from the ignition condition to idle was conducted as well as a transient from idle to rated power while monitoring burner exit temperature on a strip chart recorder. The results for all conditions are shown in the following tables as well as the transient temperature plots.

Ignition

Ignition tests were conducted at the idle air flow of 57.3 pph and with only pilot hydrogen fuel. Pilot H_2 flows were varied from 0.04 to 0.10 pph with instantaneous ignition at all conditions. The fuel flow was dropped to 0.03 pph which also produced a successful light. The flame was immediately acknowledged by the flame supervision system which showed a light on the panel. The voltage output from the UV sensor amplifier was independently measured to be approximately 5 volts at all conditions, and was steady. The average exit temperature ranged from 160 to 250 F, depending to pilot flowrate.

Steady state performance

IDLE: After ignition at the 0.04 pph pilot flow the main air flow and fuel mixture were set to the idle conditions which produced an immediate temperature rise. The burner was allowed to stabilize for at least 10 minutes after which all data was recorded. The pilot fuel flow was varied from the 0.04 pph condition to the 0.10 pph and finally was turned off completely. The burner remained lit without the pilot and NO_x emissions dropped to 16.2 ppmv. The NO_x at the high pilot flow was measured to be 23.5 ppmv, while at the 0.04 condition was 17.6. The UV sensor voltage was steady at approximately 5 volts throughout. Off design conditions were then run to determine the effect of increasing the main fuel CO_2 dilution on NO_x production. The pilot flow was maintained at the lowest setting of 0.04 pph for these tests. As anticipated the NO_x dropped significantly with increasing amounts of CO_2. An increase of 73% in CO_2 reduced NO_x by almost 60% to about 11 ppmv. A further increase to 250% of the norm dropped NO_x by a third to around 5 ppmv.

RATED POWER: The rated power conditions were run next using the same procedure as discussed above. Again the pilot flow was varied and lastly was turned off completely and the burner remained stable. NO_x emissions ranged from a low of 9.8 ppmv with no pilot flow to 11.0 ppmv at 0.04 pph and 13.1 ppmv at the 0.10 pph pilot flow. Exit temperatures were approximately 1130 F. Off design conditions were again run to determine the effect of increasing the main fuel CO_2 dilution on NO_x production. The pilot flow was maintained at the lowest setting of 0.04 pph for these tests also. As anticipated the NO_x dropped significantly with increasing amounts of CO_2. An increase of 20% in CO_2 reduced NO_x by almost 23% to about 8.5 ppmv. A further increase to 40% of the norm dropped NO_x in half to 5.6 ppmv. The effect of increasing dilution is plotted in Figure 2. The CO emissions increased from 3.5 ppmv to 11.5 ppmv which is indicative of lowered flame temperatures and an indication of decreased flame stability. CO may not be produced in the actual powerplant which will use steam as the dilution gas. The UV sensor amplified voltage remained steady at 5 volts.

OVERFLOW: Again the same test protocol was followed for the overflow condition. The exit temperatures were measured to be close to 1200 F, while NO_x emissions were slightly lower than those at the rated power condition. These results show the potential benefit from enhanced mixing and reduced reactor residence times due to the increase in airflow. CO emissions were slightly higher that those at the rated power condition which is reasonable. Again the off design conditions showed that increasing CO_2 by 18% reduced NO_x by about 19 % to a value of 7.4 ppmv. The UV sensor voltage was steady at 5 volts.

ULTIMATE: This condition is was not listed on the original statement of work but was requested later in the program. This condition is identical to the overflow condition with the exception of airflow which was increased to 600 pph from 420 pph. Emissions were not taken due to time constraints but based on the trend NOx would be lower and CO higher. The flame temperature was about 1040 F and the UV sensor voltage was steady at 5 volts indicating a stable flame. No flame was detected exiting the tailpipe of the rig at this condition or any other condition.

Transient Results

At the request of IFC engineering, two transient tests were performed while monitoring the burner exit temperature with a strip chart recorder. One transient was completed from ignition to the idle condition, and the other more important one from idle to rated power. Both fuel gas and air were increased at nearly the same time which provided a simulation of expected conditions in the powerplant. For the idle to rated power transient, the exit gas temperature rose at an exponential rate as shown in Figures 4 and 5. The exit gas reached 90% of the expected value within 20 seconds.

Conclusions

The hydrogen burner test was completed without any undesirable events. The burner ignited at the ignition conditions at even lower than anticipated pilot fuel flows. The UV sensor output was steady at all conditions at 5 volts. The burner is stable and quiet at all conditions tested including without any pilot fuel flow. Emissions of THC and CO are generally low and NO_x is not unreasonably high for a diffusion flame burner design. NO_x emissions can be reduced by addition of higher concentrations of dilution gas to the main H_2 flow. A 20% increase in CO_2 reduced NO_x by 23% to an uncorrected value of about 8.5 ppmv with no detrimental effects.

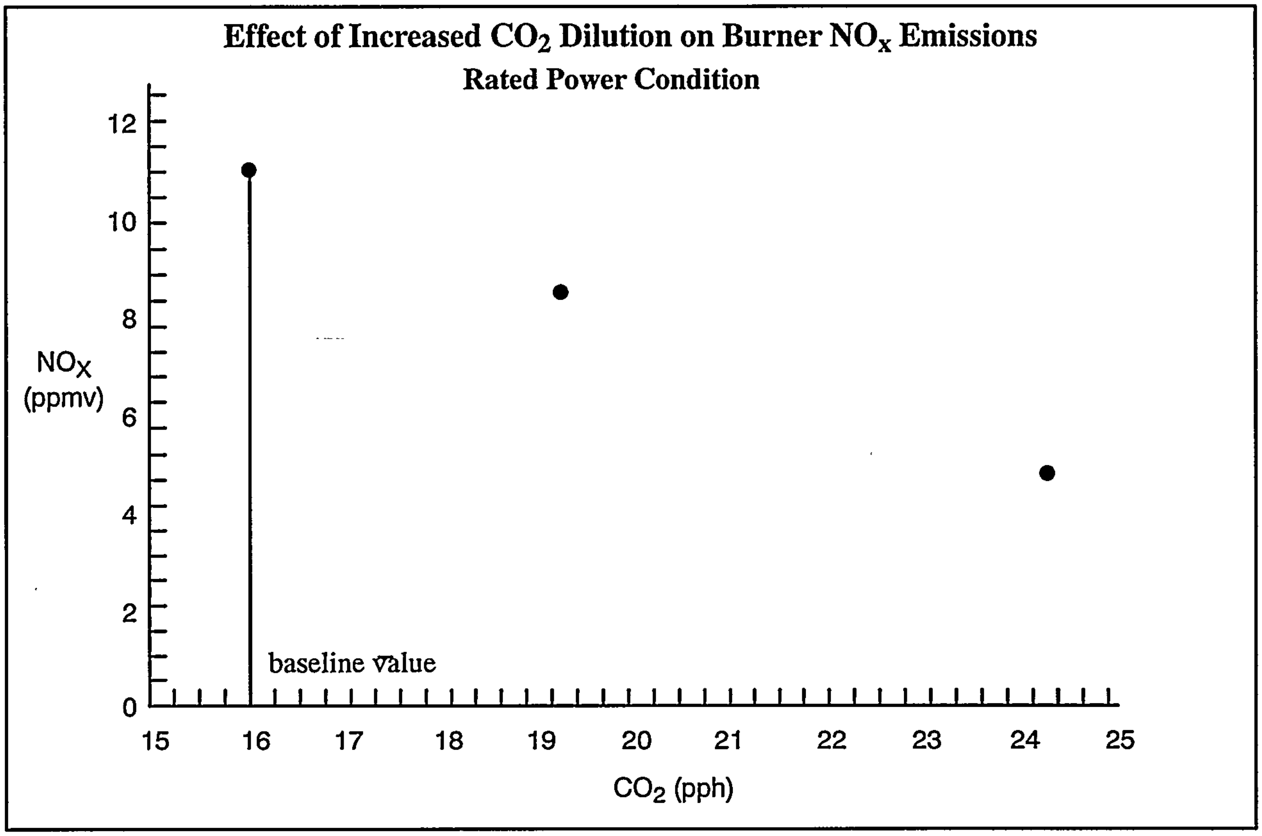


Figure 2. Effect of Increased Dilution to Main Fuel on NO_x Emissions

Table 1. Specification for Exhaust Gas Emissions Instrumentation

Gas Analyzed	*Minimum Detectable Limit*	*Accuracy*	*Ranges*	*Instrument Mfgr. And Model*
O_2	0.002%	± 0.1%	0-5, 10, 25, 50, 100%	Servomex Model 3300 (paramagnetic)
CO	0.1 ppm	± 2% f.s.	0-50, 100, 200, 500, 100, 200, 500, 10000, 20000 ppm	Thermo Environmental Model 48H (NDIR)
CO_2	0.01%	± 1% f.s.	0-5, 20%	Milton Roy Model 3300 (NDIR)
NO_x	0.50 ppb	± 1% f.s.	0-10, 20, 50, 100, 200, 500, 1000, 2000, 5000 ppm	Thermo Environmental Model 42H (chemiluminescent)
Total HC	0.1 ppm as Methane	2% of reading	0-10, 100, 1000, 10000 ppm	Thermo Environmental Model 51 (FID)

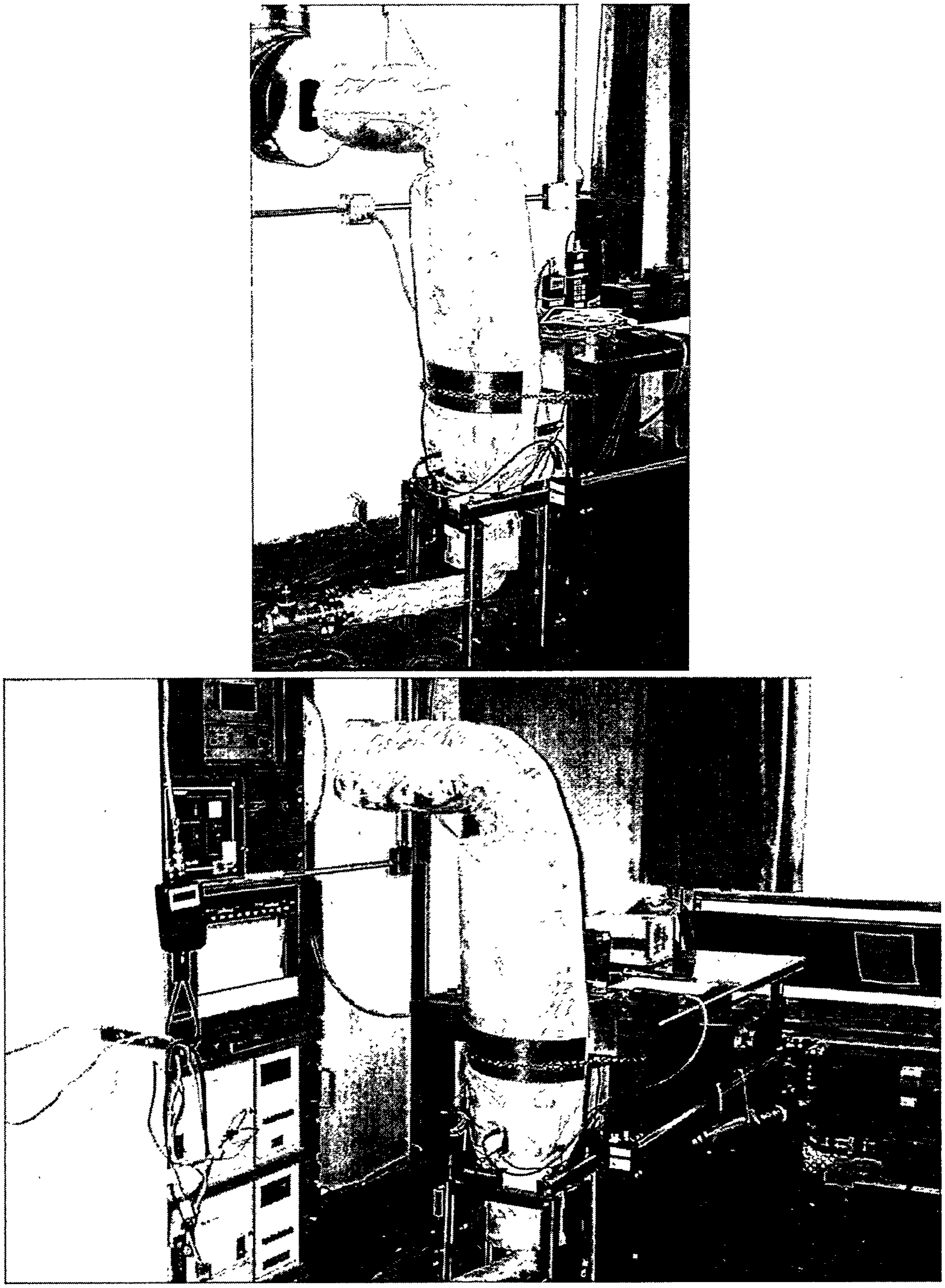


Figure 3. Photographs of the H_2 Burner Rig Test Stand and Set-Up at PCI

Table 2. IFC Diffusion Flame H_2 Burner Test Results at PCI, New Haven, CT 7/21/97

IFC HYDROGEN DIFFUSION FLAME BURNER (FC 15525)					RESULTS SUMMARY									
THC EMISSIONS ON A WET BASIS; ALL OTHERS DRY														
IGNITION			AIR	FUEL	IGNITION					IGNITION				
AIR	MAIN H_2	CO_2	PILOT	INLET T	INLET T	EXIT T	UV SENSOR	AIR DP	FUEL DP	EMIS-SIONS	EMIS-SIONS	EMIS-SIONS	EMIS-SIONS	EMIS-SIONS
PPH	PPH	PPH	PPH	F	F	F	VOLTS	IN H_2O	IN H_2O	NOX PPMV	THC PPMV	CO PPMV	CO2 %	O2 %
57.3	0	0.00	0.04	104	82	162	4.86	0.00	0.00	4.1	4.0	0.0	0.00	20.5
57.3	0	0.00	0.07	99	79	244	4.92	0.00	0.00	8.2	3.0	0.0	0.00	20.2
57.3	0	0.00	0.10	102	81	255	4.95	0.00	0.00	11.4	2.3	0.0	0.00	20.0
IDLE						IDLE				IDLE				
57.3	0.29	2.78	0.04	100	81	725	4.97	0.00	0.00	17.60	0.00	0.00	2.80	17.20
57.3	0.29	2.78	0.07											
57.3	0.29	2.78	0.10	102	82	959	4.97	0.00	0.00	23.50	0.00	0.00	2.80	16.50
57.3	0.29	2.78	0.00	100	82	878	4.97	0.00	0.00	16.20	0.00	0.00	2.80	17.60
57.3	0.29	4.83	0.04	100	82	894	4.80	0.10	0.00	10.89	0.00	1.00	3.62	14.10
57.3	0.29	9.67	0.04	100	82	882	4.80	0.00	0.00	5.22	0.00	16.00	8.90	16.00
	SEE TRANSIENT PLOT OF IGNITION TO IDLE													
RATED POWER						RATED POWER				RATED POWER				
325	1.67	16.00	0.04	104	79	1128	4.97	0.90	0.20	11.0	0.00	3.30	3.07	17.10
325	1.67	16.00	0.07	104	79	1104	4.96	0.90	0.20	11.7	0.60	3.70	3.06	17.10
325	1.67	16.00	0.10	104	79	1166	4.97	0.90	0.20	13.1	0.50	3.40	2.98	17.00
325	1.67	16.00	0.00	104	79	1140	4.97	0.90	0.20	9.8	0.80	4.90	2.97	17.20
325	1.67	19.3	0.04	104	79	1153	4.97	0.90	0.20	8.5	0.60	6.80	3.50	17.00
325	1.67	24.1	0.04	104	79	1106	4.97	0.90	0.20	5.6	0.60	11.50	4.50	16.90
	SEE TRANSIENT PLOT OF IDLE TO RATED POWER													
OVERFLOW						OVERFLOW				OVERFLOW				
420	2.17	20.50	0.04	104	75	1195	4.97	1.40	0.30	9.16	0.50	5.80	3.08	17.00
420	2.17	20.50	0.07	103	75	1216	4.97	1.40	0.30	10.05	0.30	5.70	3.05	16.90
420	2.17	20.50	0.10											
420	2.17	20.50	0.00	104	75	1200	4.97	1.40	0.30	8.43	0.50	6.70	3.07	17.00
420	2.17	24.20	0.04	103	74	1203	4.97	1.40	0.30	7.37	0.40	9.30	3.57	16.80
ULTIMATE						ULTIMATE				ULTIMATE				
600	2.17	20.50	0.07	75	30	1036	4.97	1.760.40						

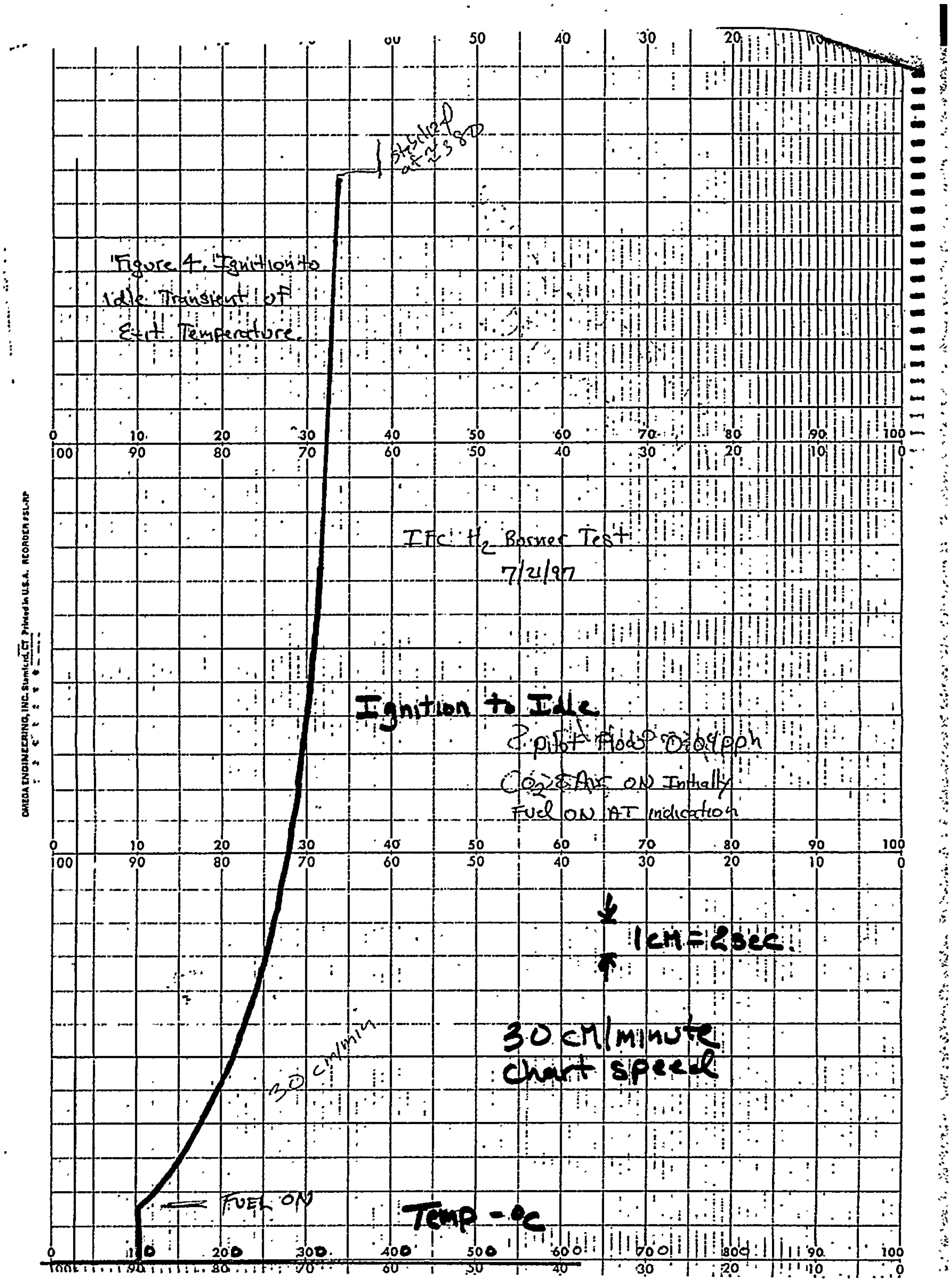


Figure 4. Ignition to Idle Transient of Exit Temperature.

Stabilized at ~380

IFC H_2 Burner Test
7/21/97

Ignition to Idle
2 pilot flow 0.04 pph
CO_2 & Air ON Initially
Fuel ON AT indication

1cm = 2sec.

30 cm/minute Chart speed

30 cm/min

FUEL ON

Figure 4. Ignition to Idle Transient of Exit Temperature

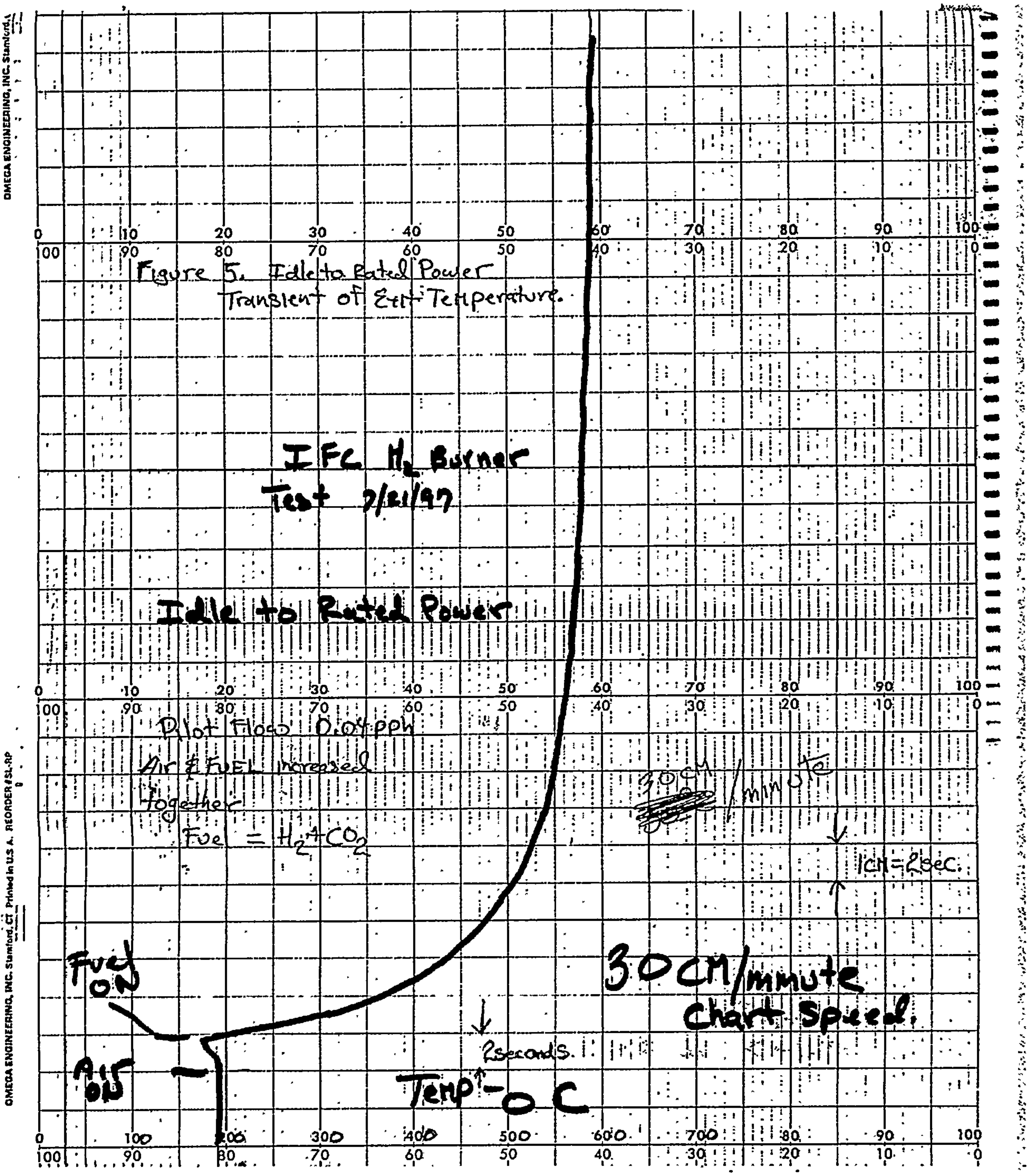


Figure 5. Idle to Rated Power Transient of Exit Temperature