CONSULTANT REPORT

PIER
Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Environmentally-Preferred
Advanced Generation

LOW NOx GAS TURBINE COMBUSTORS FOR DISTRIBUTED POWER GENERATION

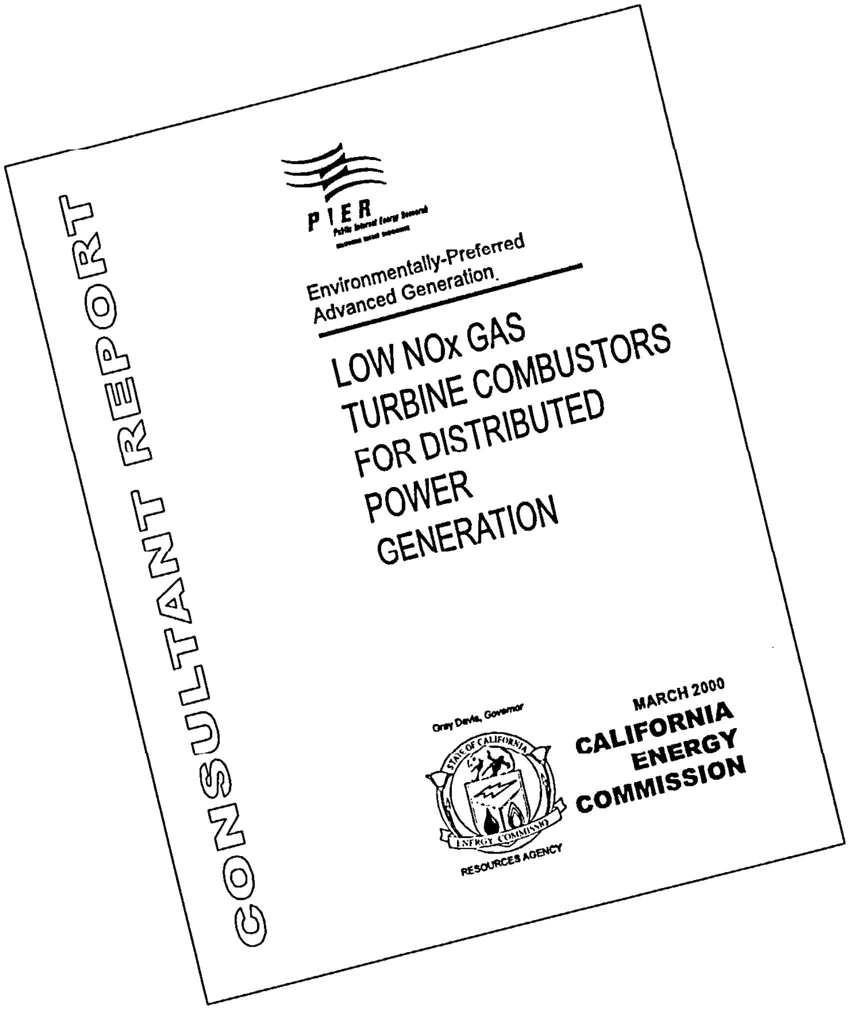
Gray Davis, *Governor*

MARCH 2000

CALIFORNIA ENERGY COMMISSION

RESOURCES AGENCY

P600-01-002



CALIFORNIA ENERGY COMMISSION

Prepared for:
CALIFORNIA ENERGY COMMISSION

Prepared by:
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Contract No. 500-97-031
Contract Amount: $878,788

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ENVIRONMENTALLY-PREFERRED ADVANCED GENERATION

LEGAL NOTICE

Acknowledgements

Alzeta would like to recognize the following individuals and organizations for their contributions to the success of this project:

- Our staff, especially Scott Smith, Steve Greenberg, and Bill Fruchterman
- Federal Energy Technology Center, especially Kent Castleton and Dan Malone
- California Energy Commission, especially David Hatfield
- Solar Turbines
- Honeywell Engine Systems

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Environmentally-Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Strategic Energy Research.

What follows is the final report for the Low NOx Gas Turbine Combustors for Distributed Power Generation, Contract #500-97-031, conducted by the Alzeta Corporation. The report is entitled Low NOx Gas Turbine Combustors for Distributed Power Generation. This project contributes to the Environmentally-Preferred Advanced Generation PIER program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Gas turbine engines play an important role in the generation of efficient, low cost electric power and process heat for applications ranging from small 75-kilowatt (kW) distributed power systems up to 200 megawatt (mw) utility combined cycle power plants. Currently, market acceptance of gas-turbine-based distributed power systems and co-generation systems is hampered by their inherently high nitrogen oxide (NOx) emissions that necessitate the use of expensive, temperamental, and maintenance-intensive NOx control strategies such as steam injection and selective catalytic reduction (SCR). Efforts have been made to reduce gas turbine emissions at lower cost by using lean premixed combustion or Dry Low NOx (DLN) techniques. DLN combustors are designed to reduce thermal NOx emissions by burning with large amounts of excess air. So far, however, successful commercialization of DLN combustors has been limited by issues of noise, large size, durability, and cost as well as by the difficulties in maintaining consistent low emissions performance.

During work on prior contracts, the concept of the Surface Stabilized Combustor (SSC) was developed, and a new product, the Gas Turbine Semi-radiant Burner (GTSB) emerged. A number of combustor prototypes were manufactured and tested under simulated gas turbine conditions. Testing of the GTSB occurred at the Federal Energy Technology Center (FETC), Honeywell Engine Systems (Honeywell), and Solar Turbines. While flame stability was sometimes difficult to achieve, we obtained a wealth of positive emissions data. Simultaneous low NOx and carbon monoxide (CO) (sub nine parts per million (ppm)) were reached at every pressure from 1 to 12 atmospheres (atm). Both NOx and CO were measured under one ppm at various times throughout the testing.

Objectives

This project continued to develop, test, and demonstrate SSC that is reliable, quiet, compact, and operates with low NO_x, CO, and unburned hydrocarbon emissions. Our research focused on the development of the GTSB into a commercial product.

The technical and economic objectives of the project were to develop a SSC with the following characteristics:

- Operation with preheat temperatures up to 1000°F and excess air levels exceeding 100 percent without bypassing.
- Reliable ignition, off-speed stability, and turndown over a suitable range of operating pressures, including an operational turndown ratio of 4:1

- NO_x emissions from the burner of less than 9 ppm corrected to 15 percent oxygen, meeting or exceeding the best available control technology (BACT).
- Combustor pressure losses no greater than currently acceptable levels (three percent to six percent of operating pressure).
- Life cycle cost that yields a NO_x reduction cost factor of less than $1,000 per ton of controlled NO_x.
- Extremely low levels of CO and unburned hydrocarbons.
- Extreme thermal shock resistance to tolerate instantaneous fuel cut off at full load.
- Ease of inspection and field maintenance

Outcomes

Several new combustors were designed, each representing a significant improvement in manufacturing techniques and engineering features. Initial testing of combustors was performed in Alzeta's 50 kW pressurized test facility. Successful results featuring superior emissions led to a demonstration of the technology at Honeywell (formerly AlliedSignal). The combustor was tested in a rig that qualifies combustors for use in the Parallon 75 engine (formerly the TurboGenerator engine). Preliminary results encouraged continued interest from Honeywell and combustor development is continuing toward full commercialization.

Successful operation was displayed off-site during four separate rigorous test sessions, one at FETC in July 1998, two at Solar Turbines in October and December 1998, and one at Honeywell in February 2000. Although the combustor has yet to be tested in an actual engine, the project technical goals were achieved.

The most interesting results of this project included:

- Preheat in excess of 1000°F was applied during the tests. The combustors survived these elevated preheat temperatures and were actually able to operate at lower flame temperatures, resulting in lower NO_x emissions. Increased preheat resulted in greater flame stability which ultimately reduced NO_x emissions.
- Project goals regarding ignition and turndown were consistently met and demonstrated over a suitable range of operating pressures. Off speed stability was not addressed because the combustor was never run in an engine.
- NO_x emissions of less than 2 ppm, comparable to or lower than existing steam injection and SCR control systems, were displayed in tests at Alzeta and Honeywell.
- Combustor pressure losses were consistently less than five percent of operating pressure

- Lower life cycle costs resulted from a number of improvements made in manufacturing techniques.
- In the majority of the tests, CO and hydrocarbon emissions were extremely low (less than 9 ppm).
- The combustors displayed good thermal shock resistance to tolerate instantaneous fuel cut off at full load.
- All of the designs were modular, and thus easily maintained both in Alzeta's manufacturing facility and in the field.

After carefully considering patent claims, Alzeta filed a U.S. patent application for the GTSB combustor on January 22, 1999.

Conclusions

The GTSB has now been tested at the facilities of two major gas turbine manufacturers and full commercialization is imminent. Several facts became clear as a result of this project:

- Excellent emissions are attainable at reproducible operating conditions corresponding to actual turbine operating conditions.
- Outward-fired burners are the preferred configuration for the targeted engines.
- It is possible to successfully package an entire mixer/burner assembly within the space available in commercial gas turbine engines.
- The flow rate of premix through the burner surface (or firing rate) needs to be increased linearly as pressure is increased to maintain a nearly constant velocity through the burner surface.
- Increased levels of preheat typical of recuperated gas turbines, such as the Parallon 75, lead to increased flame stability at lower flame temperatures and thus result in lower NO_x emissions.
- Any injection of cooling air into the primary combustion zone needs to be carefully controlled to minimize interaction with the burner surface. Such interaction can result in high emissions of CO and hydrocarbons.

Benefits to California

When the GTSB is commercialized in gas turbine engines, it will provide the State of California with:

- Improved fuel efficiency through enabling clean, cost effective, high efficiency co-generation to remain competitive in the face of increasing NO_x controls

- Lower fuel usage due to potential elimination of SCR that requires ammonia derived from natural gas.
- Reduced cost of power due to reduced capital and operating costs associated with production of peak power.
- Reduced environmental pollutant emissions from industrial and power generation facilities.
- Improved capital utilization that reduces power costs and improves industrial competitiveness.
- Products manufactured in California creating jobs and economic activity.

Recommendations

Future research should attempt to accomplish the following:

- Ensure stable, low-emission combustion throughout the entire operational turndown required by the targeted engines.
- Reduce combustor pressure drop while maintaining adequate mixing and flow uniformity through computational and experimental analysis of several components.
- Further refine capital equipment, operation, and maintenance cost estimates through extended cycle analysis and lifetime testing.
- Improve manufacturing techniques to reduce costs and increase combustor life without sacrificing performance.
- Adapt the burner for use in additional engines, potentially including dual-fuel operation or highly recuperated engines.
- Develop simple, reliable control systems to operate the burner in industrial turbines.
- Demonstrate field operation of the combustor installed in an operational gas turbine engine.

Abstract

Gas turbine engines play an important role in the generation of efficient, low cost electric power and process heat. But market acceptance of gas-turbine-based distributed power systems and co-generation systems is hampered by their inherently high nitrogen oxide (NO_x) emissions. Efforts have been made to reduce gas turbine emissions at lower cost by using lean premixed combustion or Dry Low NO_x (DLN) techniques that burn with large amounts of excess air. The term Dry Low NO_x relates to the fact that NO_x control is provided by controlled combustor stoichiometry, eliminating the need for steam / water injection.

This project continued Alzeta's efforts to commercialize the GTSB combustor into gas turbine engines for distributed power generation. The current program optimized and demonstrated Alzeta's DLN gas turbine combustor technology in conjunction with several industrial turbine manufacturers. The demonstrated technology is derived from an adiabatic Surface Stabilized Combustor (SSC) that operates with NO_x, carbon monoxide (CO), and unburned hydrocarbons (UHC) at or below the current state of the art (<9 parts per million (ppm) NO_x @15 percent oxygen (O_2)).

The Alzeta Pyromat super burner (SB) metal fiber burners are the basis for the new radiant burners, firing up to 1 MMBTU / hr / ft^2 while maintaining low NO_x and CO levels. The technology employs a folded geometry, which increases the firing rate for any given frontal area. GTSB combustors were demonstrated at elevated pressures (>10 atm) and maintained broad operating conditions and low emissions (<5 ppm NO_x and <10 ppm CO @15 percent O_2) at all operating pressures.

The program consisted of several technical tasks: (1) thermodynamic cycle analysis of the target gas turbine engines, (2) optimization of the combustor design for use in these engines, (3) testing of the new combustor in Alzeta's combustion laboratory, and (4) testing of the combustor in a gas turbine test rig at Honeywell's test facility in Phoenix, Arizona. Close cooperation between Alzeta engineers and engineers from Honeywell and Solar Turbines occurred throughout all the technical tasks.

The research and development program accelerated the time to market for GTSB. GTSB technology, applicable to natural gas-fired turbine distributed generation systems in California, will enable efficient, flexible, and cost effective means of low emissions power generation to remain competitive in the face of increasingly stringent NO_x regulations.

Key Words: gas turbine, microturbine, combustion, surface combustion, power generation, distributed generation, lean premix, low NO_x, low emissions, pressure, preheat

1.0 Introduction and Summary

1.1 Project Background and Product Description

Gas turbine engines play an important role in the generation of efficient, low cost electric power and process heat for applications ranging from small, 75 kW distributed power systems up to 200 mw utility combined cycle power plants. Currently, market acceptance of gas-turbine-based distributed power systems and co-generation systems is hampered by their inherently high NO_x emissions, which necessitate use of expensive, temperamental, and maintenance-intensive NO_x control strategies such as steam injection and selective catalytic reduction (SCR).

The most straightforward manner of reducing gas turbine NO_x production without using exhaust treatment is to reduce flame temperature by operating the combustor at higher excess air levels. This is done by using lean premixed combustion or Dry Low NO_x (DLN) techniques and reducing the amount of dilution air introduced downstream of the primary combustion zone. The term DLN relates to the fact that NO_x control is provided by controlled combustor stoichiometry, eliminating the need for steam / water injection. DLN combustors are designed to reduce thermal NO_x emissions by burning with large amounts of excess air. Excess air dilution produces lower flame temperatures and hence less thermal NO_x. DLN combustors try to achieve flame stability with high excess air by using sophisticated flow configurations which create recirculation zones where stable lean combustion is maintained, or alternatively, by using catalytic combustion.

Successful commercialization of DLN combustors has been limited by problems with noise, large size, durability, cost, and by difficulties in maintaining consistent low emissions performance. Catalytic combustors have yet to demonstrate sustained combustion efficiency and low NO_x performance over life spans considered adequate for industrial equipment. Expensive and primitive lean premix combustors have been marketed for large utility turbine applications, but lean premix has not been adapted for use in small and medium size co-generation applications. Flow-stabilized lean premix combustors suffer from a myriad of problems, including high CO emissions and flame instabilities at low NO_x operating conditions, large size compared to conventional combustors, poor turndown capability, poor downstream temperature uniformity, and high frequency combustion noise or screech.

The purpose of this project was to continue to develop, test, and demonstrate a new lean premix DLN gas turbine combustor technology called an adiabatic Surface Stabilized Combustor (SSC) that is reliable, quiet, compact, and operates with low NO_x, CO, and unburned hydrocarbon emissions. This technology will be applicable to gas turbine co-generation systems, enabling an efficient, flexible, and cost-effective means of low emissions power generation. Thus, gas-turbine-based co-generation systems will remain competitive in the face of increasingly stringent NO_x regulations within California.

Rather than employing catalysts or flow-induced recirculation, the SSC combustor, marketed under the product name Gas Turbine Semi-radiant Burner (GTSB), uses radiant surface combustion and adiabatic operation to maintain stable operation at high excess air levels and low flame temperatures. As with all radiant burners, the conditions that produce low NO_x are the same conditions that produce stable combustion and low CO. This is not the case with steam injection or lean premix combustors. The GTSB enables low NO_x emissions with simultaneously low CO levels without durability and operational life problems associated with catalytic combustors.

The GTSB technology is an extension of Alzeta's proven Pyromat SB metal fiber burner technology. The Pyromat SB burner was originally developed for use in small commercial atmospheric boilers and has already been successfully commercialized. Further development has extended the capabilities of the SB product to include industrial process heating and VOC incineration applications. The core technology behind the Pyromat SB product is extremely flexible and provides the basis for a family of very low emissions burners designed for applications with capacities ranging from 30,000 Btu/hr to 62,500,000 Btu/hr (9 kW to 18 MW).

The primary technical challenge of this program was to extend the performance of the Pyromat SB to applications operating at pressures of 2 to 30 atmospheres (atm). This was accomplished by operating the Pyromat SB in a patented adiabatic radiant configuration. This concept, although unique, did not require any fundamental breakthroughs, new technologies, or new materials in order to achieve technical success.

Reducing the cost of NO_x control will enhance the viability of distributed power and industrial co-generation systems in California's emissions-impacted areas. With adiabatic SSC technology, a gas turbine could efficiently produce power without relying on costly steam injection or SCR NO_x control strategies to meet sub-9 ppm BACT requirements. In the future, the same technology could be applied to larger gas turbines intended for large co-generation and advanced power plant applications.

While the Pyromat SB technology has been successfully commercialized for industrial boiler and process heater applications, a number of engineering challenges needed to be addressed in order to adapt this technology to pressurized gas turbine combustor applications. The most significant technical issues are summarized below:

- Operation with high inlet temperatures and operating pressures.
- Maintenance of flame stability and low NO_x operating characteristics over transient heat input rates and operating pressures during startup.
- Development of reliable combustor ignition systems.
- Development of a rugged mechanical design tolerant of rapidly changing pressures, temperatures, and loads.
- Minimization of combustor physical size in order to facilitate adaptation to a variety of gas turbine platforms.
- Development of fuel-air mixing systems that achieves the necessary degree of mixing in a limited space with minimal pressure drop.

1.2 Expenditures

Project expenditures met the expectations of the California Energy Commission (Commission). Figure 1 gives the task budget detail of the reimbursable expenditures, broken into project work tasks and billing categories. The Commission expenditures for this contract are complete and the final total is $878,788.

The task budget breakdown gives the six primary technical tasks as well as the associated kickoff and reporting tasks. Tasks were spent to within 10 percent of their original budget, due in part to the Commission’s monitoring of the contract. The figure lists current invoice spending, total for the prior invoice, total for all prior invoices, original budget, and remaining balance for each category. This combination of five line items gives a clear picture of spending during the invoice period, the rate at which task spending occurred, and the manner in which the value figures into the entire project.

CONTRACTOR:	ALZETA CORPORATION	PREPARED BY:	M. Papasin
CONTRACT #:	500-97-031	DATE:	02/07/00
CONT INVOICE #:	7109-12	CEC INVOICE #:	12
INV. PERIOD:	01-Nov-99 Thru 31-Jan-00	INVOICE DATE:	01/31/00

Task	Fully Loaded Labor	Sub Contrct Services	Equip	Materials	Travel	Misc.	Non-Labor Subtotal	G & A Overhead	Task Total	Cumulative Fraction Expended %
X.XX GRAND TOTAL										
(A) Current Invoice	$11,659	$144	$0	$718	$699	$461	$2,022	$667	$14,349	*1.63%*
(B) Tot. Prior Inv.	$639,247	$92,242	$0	$68,435	$4,859	$5,409	$170,945	$56,412	$866,604	
(C) Tot. All Inv. (=A+B)	$650,906	$92,386	$0	$69,153	$5,558	$5,870	$172,967	$57,079	**$880,953**	*100.25%*
(D) Budget	$659,114	$27,228	$0	$47,440	$8,200	$82,300	$165,168	$54,506	$878,788	
(E) Bal Remain (=D-C)	$8,208	($65,158)	$0	($21,713)	$2,642	$76,430	($7,799)	($2,573)	**($2,165)**	
2.1 TASK 2.1 (PHASE 7109.21) COMBUSTOR DEFINITION										
(A) Current Invoice	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	*0.00%*
(B) Tot. Prior Inv.	$77,251	$0	$0	$372	$1,205	$91	$1,668	$550	**$79,468**	
(C) Tot. All Inv. (=A+B)	$77,251	$0	$0	$372	$1,205	$91	$1,668	$550	**$79,468**	*100.27%*
(D) Budget	$59,492	$1,200	$0	$3,000	$3,060	$7,600	$14,860	$4,904	**$79,256**	
(E) Bal Remain (=D-C)	($17,759)	$1,200	$0	$2,628	$1,855	$7,509	$13,192	$4,354	**($212)**	
2.2 TASK 2.2 (PHASE 7109.22) COMBUSTOR DEVELOPMENT TESTS										
(A) Current Invoice	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	*0.00%*
(B) Tot. Prior Inv.	$130,870	$12,906	$0	$23,543	$1,727	$449	$38,625	$12,746	**$182,241**	
(C) Tot. All Inv. (=A+B)	$130,870	$12,906	$0	$23,543	$1,727	$449	$38,625	$12,746	**$182,241**	*109.19%*
(D) Budget	$114,717	$9,050	$0	$11,390	$0	$18,800	$39,240	$12,949	**$166,906**	
(E) Bal Remain (=D-C)	($16,153)	($3,856)	$0	($12,153)	($1,727)	$18,351	$615	$203	**($15,335)**	
2.3 TASK 2.3 (PHASE 7109.23) DESIGN FOR MANUFACTURABILITY										
(A) Current Invoice	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	*0.00%*
(B) Tot. Prior Inv.	$114,683	$22,308	$0	$5,904	$330	$172	$28,714	$9,475	**$152,872**	
(C) Tot. All Inv. (=A+B)	$114,683	$22,308	$0	$5,904	$330	$172	$28,714	$9,475	**$152,872**	*106.91%*
(D) Budget	$102,244	$7,988	$0	$9,450	$0	$13,200	$30,638	$10,111	**$142,993**	
(E) Bal Remain (=D-C)	($12,439)	($14,320)	$0	$3,546	($330)	$13,028	$1,924	$636	**($9,879)**	
2.4 TASK 2.4 (PHASE 7109.24) PRODUCTION COMBUSTOR TESTING										
(A) Current Invoice	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	*0.00%*
(B) Tot. Prior Inv.	$119,837	$32,088	$0	$16,950	$349	$1,326	$50,712	$16,735	**$187,284**	
(C) Tot. All Inv. (=A+B)	$119,837	$32,088	$0	$16,950	$349	$1,326	$50,712	$16,735	**$187,284**	*108.41%*
(D) Budget	$118,507	$8,990	$0	$9,300	$2,600	$19,900	$40,790	$13,461	**$172,758**	
(E) Bal Remain (=D-C)	($1,330)	($23,098)	$0	($7,650)	$2,251	$18,574	($9,922)	($3,274)	**($14,526)**	
2.5 TASK 2.5 (PHASE 7109.25) FIELD DEMONSTRATION										
(A) Current Invoice	$5,405	$144	$0	$718	$699	$461	$2,022	$667	**$8,094**	*4.72%*
(B) Tot. Prior Inv.	$117,239	$24,939	$0	$21,668	$1,249	$3,347	$51,203	$16,897	**$185,338**	
(C) Tot. All Inv. (=A+B)	$122,644	$25,083	$0	$22,385	$1,948	$3,808	$53,225	$17,564	**$193,432**	*112.69%*
(D) Budget	$126,037	$0	$0	$14,300	$2,200	$17,800	$34,300	$11,319	**$171,656**	
(E) Bal Remain (=D-C)	$3,393	($25,083)	$0	($8,085)	$252	$13,992	($18,925)	($6,245)	**($21,776)**	

Figure 1. Task Budget Detail of Reimbursable Expenditures

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CONTRACT #:	500-97-031	DATE:	02/07/00
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INV. PERIOD:	01-Nov-99 Thru 31-Jan-00	INVOICE DATE:	01/31/00

Task	Fully Loaded Labor	Sub Contrct Services	Equip	Materials	Travel	Misc.	Non-Labor Subtotal	G & A Overhead	**Task Total**	***Cumulative Fraction Expended %***
2.6 TASK 2.6 (PHASE 7109.26) PRODUCTION READINESS PLAN										
(A) Current Invoice	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	***0.00%***
(B) Tot. Prior Inv.	$29,125	$0	$0	$0	$0	$0	$0	$0	**$29,125**	
(C) Tot. All Inv. (=A+B)	$29,125	$0	$0	$0	$0	$0	$0	$0	**$29,125**	***50.93%***
(D) Budget	$50,540	$0	$0	$0	$0	$5,000	$5,000	$1,650	**$57,190**	
(E) Bal Remain (=D-C)	$21,415	$0	$0	$0	$0	$5,000	$5,000	$1,650	**$28,065**	
3.1 TASK 3.1 (PHASE 7109.31) MONTHLY PROGRESS REPORTS										
(A) Current Invoice	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	***0.00%***
(B) Tot. Prior Inv.	$28,778	$0	$0	$0	$0	$24	$24	$8	**$28,810**	
(C) Tot. All Inv. (=A+B)	$28,778	$0	$0	$0	$0	$24	$24	$8	**$28,810**	***81.82%***
(D) Budget	$35,031	$0	$0	$0	$136	$0	$136	$45	**$35,212**	
(E) Bal Remain (=D-C)	$6,253	$0	$0	$0	$136	($24)	$112	$37	**$6,402**	
3.2 TASK 3.2 (PHASE 7109.32) FINAL REPORT										
(A) Current Invoice	$6,254	$0	$0	$0	$0	$0	$0	$0	**$6,254**	***17.76%***
(B) Tot. Prior Inv.	$21,465	$0	$0	$0	$0	$0	$0	$0	**$21,465**	
(C) Tot. All Inv. (=A+B)	$27,720	$0	$0	$0	$0	$0	$0	$0	**$27,720**	***78.72%***
(D) Budget	$35,031	$0	$0	$0	$136	$0	$136	$45	**$35,212**	
(E) Bal Remain (=D-C)	$7,311	$0	$0	$0	$136	$0	$136	$45	**$7,492**	
3.3 TASK 3.3 (PHASE 7109.33) FINAL MEETING										
(A) Current Invoice	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	***0.00%***
(B) Tot. Prior Inv.	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	
(C) Tot. All Inv. (=A+B)	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	***0.00%***
(D) Budget	$17,515	$0	$0	$0	$68	$0	$68	$22	**$17,605**	
(E) Bal Remain (=D-C)	$17,515	$0	$0	$0	$68	$0	$68	$22	**$17,605**	
Budget--All Tasks	$ 659,114	27,228	-	47,440	8,200	82,300	165,168	54,506	$ 878,788	
Current Invoice Total --All Tasks	$11,659	$144	$0	$718	$699	$461	$2,022	$667	$14,349	1.63%
Retention	$1,166	$14	$0	$72	$70	$46	$202	$67	$1,435	
							NET INVOICE		$12,914	

Figure 2 and Figure 3 include matching funds expenditures. Alzeta partnered with the Federal Energy Technology Center (FETC) and a wide variety of gas turbine manufacturers during this project. Total matching funds were $569,592. Disabled Veteran Business Enterprise (DVBE) participation is also found in Figure 2. With DVBE spending of $34,007.62, Alzeta exceeded its three percent responsibility based on total Commission expenditures.

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2.6 TASK 2.6 (PHASE 7109.26) PRODUCTION READINESS PLAN										
(A) Current Invoice	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	*0.00%*
(B) Tot. Prior Inv.	$29,125	$0	$0	$0	$0	$0	$0	$0	**$29,125**	
(C) Tot. All Inv. (=A+B)	$29,125	$0	$0	$0	$0	$0	$0	$0	**$29,125**	*50.93%*
(D) Budget	$50,540	$0	$0	$0	$0	$5,000	$5,000	$1,650	**$57,190**	
(E) Bal Remain (=D-C)	$21,415	$0	$0	$0	$0	$5,000	$5,000	$1,650	**$28,065**	
3.1 TASK 3.1 (PHASE 7109.31) MONTHLY PROGRESS REPORTS										
(A) Current Invoice	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	*0.00%*
(B) Tot. Prior Inv.	$28,778	$0	$0	$0	$0	$24	$24	$8	**$28,810**	
(C) Tot. All Inv. (=A+B)	$28,778	$0	$0	$0	$0	$24	$24	$8	**$28,810**	*81.82%*
(D) Budget	$35,031	$0	$0	$0	$136	$0	$136	$45	**$35,212**	
(E) Bal Remain (=D-C)	$6,253	$0	$0	$0	$136	($24)	$112	$37	**$6,402**	
3.2 TASK 3.2 (PHASE 7109.32) FINAL REPORT										
(A) Current Invoice	$6,254	$0	$0	$0	$0	$0	$0	$0	**$6,254**	*17.76%*
(B) Tot. Prior Inv.	$21,465	$0	$0	$0	$0	$0	$0	$0	**$21,465**	
(C) Tot. All Inv. (=A+B)	$27,720	$0	$0	$0	$0	$0	$0	$0	**$27,720**	*78.72%*
(D) Budget	$35,031	$0	$0	$0	$136	$0	$136	$45	**$35,212**	
(E) Bal Remain (=D-C)	$7,311	$0	$0	$0	$136	$0	$136	$45	**$7,492**	
3.3 TASK 3.3 (PHASE 7109.33) FINAL MEETING										
(A) Current Invoice	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	*0.00%*
(B) Tot. Prior Inv.	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	
(C) Tot. All Inv. (=A+B)	$0	$0	$0	$0	$0	$0	$0	$0	**$0**	*0.00%*
(D) Budget	$17,515	$0	$0	$0	$68	$0	$68	$22	**$17,605**	
(E) Bal Remain (=D-C)	$17,515	$0	$0	$0	$68	$0	$68	$22	**$17,605**	
Budget--All Tasks	$ 659,114	27,228	-	47,440	8,200	82,300	165,168	54,506	$ 878,788	
Current Invoice Total --All Tasks	$11,659	$144	$0	$718	$699	$461	$2,022	$667	$14,349	1.63%
Retention	$1,166	$14	$0	$72	$70	$46	$202	$67	$1,435	
							NET INVOICE		$12,914	

Figure 2. Task Budget Details, Matching Funds

PARTNER MATCH FUNDS UPDATE 01/31/00
CEC CONTRACT NO. 500-97-031

PARTNER	REQUIRED MATCH	CURRENT LABOR THRU 01/31/00	CURRENT ODC THRU 01/31/00	CUMULATIVE MATCH THRU 01/31/00	REMAINING
Alzeta Corporation	175,000	30,894	2,165	411,867	(236,867)
Solar Turbines	37,500	-	-	43,450	(5,950)
Allied Signal	37,500	-	-	11,350	26,150
General Electric	15,000	-	-	3,300	11,700
Global Concepts	5,000	-	-	1,175	3,825
FETC	195,000	-	-	10,650	184,350
AeroVironment	7,500	-	-	900	6,600
Capstone	2,500	-	-	1,200	1,300
Arcadis/ Geraghty & Miller	-	-	-	70,000	(70,000)
Demonstration Sites	200,000	-	-	15,700	184,300
TOTAL NON-CEC MATCH	675,000	30,894	2,165	569,592	105,408
California Energy Commission	878,788	11,659	525	878,788	(0)
TOTAL FUNDING	1,553,788	42,553	2,689	1,448,381	105,408

Disabled Vetran Business Enterprise PARTICIPATION FUNDS UPDATE 11/30/99

Company Name	Type / Task	Planned Match	Period Total	To Date Total	Required Remaining
Communication & Real Time	DVBE	667.00	-	-	
Caton Moving & Stoirage	DVBE	667.00	-	-	
SDV_SCC	DVBE	25,030.00	-	34,007.62	
DVBE SUBTOTAL		26,364.00	-	34,007.62	(7,643.62)

Figure 3. Alzeta's Matching Funds

1.3 Project Objectives

The key technical and economic objectives of the project remained the same from the previous contracts. The primary goal was to demonstrate a reliable, compact, economical, high performance, dry low NO_x gas turbine combustor in a gas turbine engine. The technical and economic objectives of the project are quantified and summarized below:

- Operation with preheat temperatures up to 1000°F and excess air levels exceeding 100 percent without bypassing.
- Reliable ignition, off-speed stability, and turndown over a suitable range of operating pressures, including an operational turndown ratio of 4:1
- NO_x emissions from the burner of less than 9 ppm corrected to 15 percent oxygen, meeting or exceeding the best available control technology (BACT).
- Combustor pressure losses no greater than currently acceptable levels (three percent to six percent of operating pressure).
- Life cycle cost that yields a NO_x reduction cost factor of less than $1,000 per ton of controlled NO_x.
- Extremely low levels of CO and unburned hydrocarbons.
- Extreme thermal shock resistance to tolerate instantaneous fuel cut off at full load.
- Ease of inspection and field maintenance

To achieve these objectives, we divided work on the contract into the following tasks:

Definition of burner and cycle performance. This task included obtaining hardware specs from turbine manufacturers and modeling the thermodynamic cycles of the combustion systems.

In-house combustor development tests. We conducted testing in Alzeta's 50 kW pressurized test facility to determine the ideal burner configuration and to optimize the burner pad of the GTSB.

Combustor testing at turbine manufacturer's facilities. Tests were performed in the same facilities that Honeywell uses to test combustors confirmed the benefits and feasibility of the GTSB.

Production readiness plan. This document identifies the market, costs, and manufacturing requirements for the commercial GTSB. It serves as the plan for reaching full production. Appendix I contains the Production Readiness Plan.

1.4 Report Organization

Section 2.0 provides our approach to this project while Section 3.0 provides a discussion of initial and final combustor design and testing. Section 4.0 presents project outcomes and Section 5.0, our conclusions and recommendations.

2.0 Project Approach

2.1 Gas Turbine Combustors

In the 1 MW to 25 MW capacity range, gas turbines offer the possibility of highly economical distributed co-generation of electricity and heat for commercial and industrial user. Co-generation plants frequently combine gas turbine electric generators with waste heat recovery boilers that convert a major portion of the turbine exhaust to steam. This steam is used for process heat applications or is fed to steam turbines to create highly efficient combined cycle power plants. Current combined cycle power plants operate at capacities of 25 mw to 200 mw and with cycle efficiencies that exceed 50 percent. Consequently, gas turbine powered combined cycle installations have evolved as a preferred means of generating base and intermediate load electricity from gaseous and liquid fossil fuels.

The functionality, efficiency, and cost effectiveness of gas turbine co-generation plants are hampered by the inherently high NO_x emissions of the gas turbine engines. Because combustion stability considerations for most gas turbines require low excess air levels that produce flame temperatures significantly higher than the maximum allowable power turbine temperature. Typical industrial turbine combustion chamber temperatures can exceed 3500°F. Combustion chamber temperatures above 2500°F inevitably produce extremely high levels of thermal NO_x.

The South Coast Air Quality Management District (SCAQMD) defines best available current technology (BACT) for NO_x emissions as 2.5 ppm NO_x corrected to 15 percent O_2. Currently these levels are obtainable only through the application of a $SCONO_x$ treatment system, which uses a catalyst and NO_x absorption/regeneration post-process to convert CO and NO_x to carbon dioxide (CO_2), water (H_2O), and nitrogen (N_2). Like steam injection, $SCONO_x$ control technology is a large support sub-system with distinct disadvantages in terms of reliability, combustion stability, life cycle and operating cost, high maintenance requirements, and reduced plant efficiency.

DLN combustors can achieve low NO_x operation without water or steam injection, but are plagued by problems with flame stability, inconsistent low NO_x performance, elevated CO emissions, complexity, large size, and lack of reliability.

2.2 Adiabatic Surface Stabilized Combustor

Compared to lean premix strategies, radiant adiabatic surface stabilized combustor (SSC) burner technology offers the possibility of more compact combustors of simpler configuration, metal or ceramic composite construction, and low pressure drop to improve engine efficiency and reduce operating costs. The apparent flexibility of the SSC configuration also means that the technology may be suitable for retrofits than other lean premix combustors. Figure 4 summarizes radiant burner operation.

In the Pyromat burner premixed vaporized fuel and air and flows through a porous fiber mat comprised of small metal fibers compressed and sintered together to make a layer one to four mm thick with 80 to 90 percent porosity. The mixture heats as it passes through the mat; combustion takes place on the outer surface at 1500 to 2000°F. The combustion process continues in the gas phase as the flow leaves the hot face of the mat so that peak gas temperatures occur slightly beyond the hot face. Heat transfer and diffusion of combustion products from the gas phase region back to the burner provide the feedback necessary to sustain stable combustion. The flow of the fuel-air mixture through the fiber mat provides cooling as the cold face of the mat is very near the incoming gas mixture temperature. Combustion occurs without any visible flame, and occurs without noise or pressure fluctuations. (See references 3, 4, 5, and 6.)

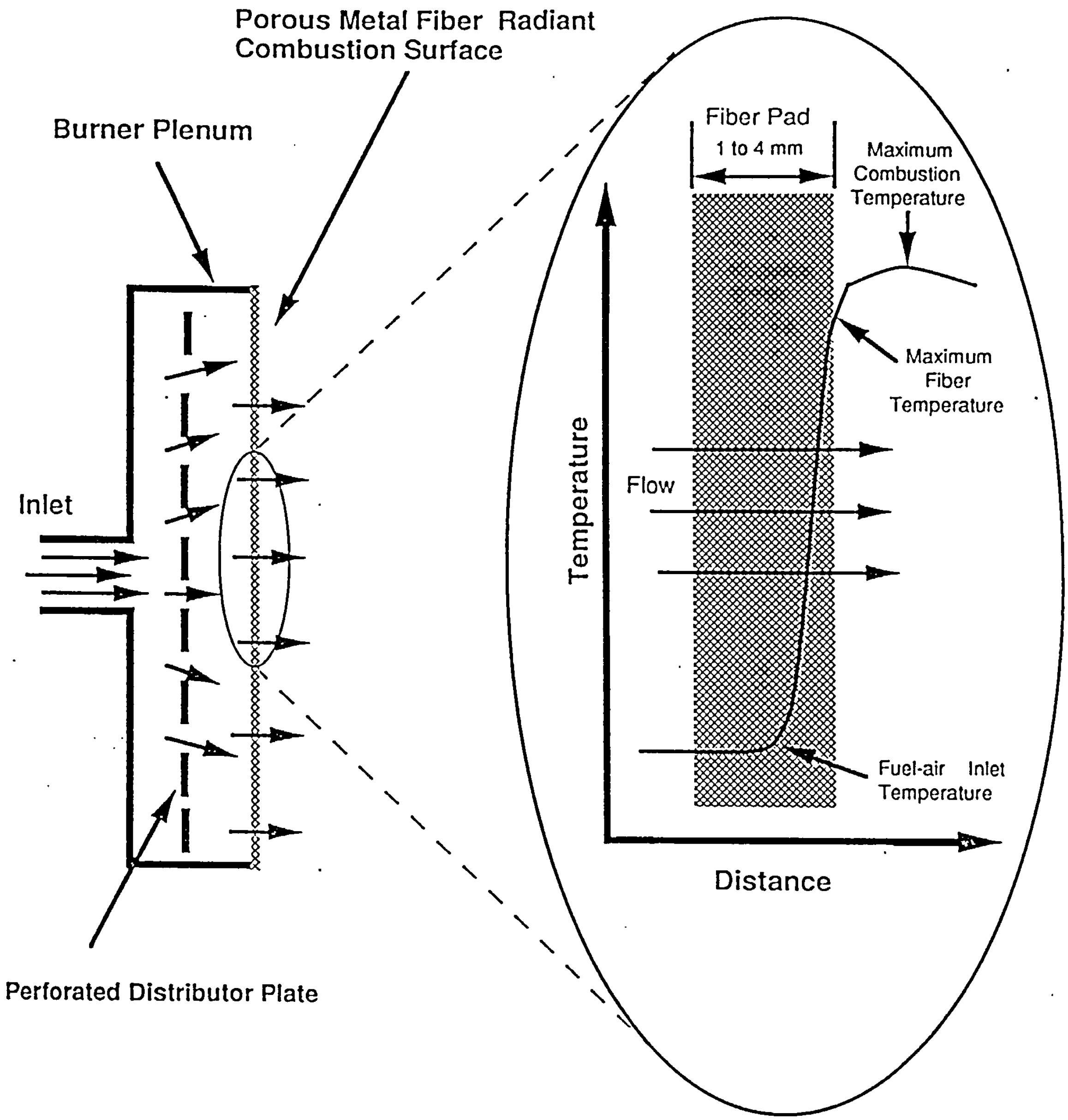


Figure 4. Radiant Surface Combustor Principles of Operation

The Pyromat super burner (SB) employs a selectively perforated variation of the Pyromat metal fiber material. The perforated regions of the SB product produce significant gradients in local mass flux through the metal fiber mat, allowing substantially higher firing rates to be achieved before flame liftoff occurs. These local mass flux gradients result in differences in flame length over the burner's surface, creating integral flue gas recirculation (FGR) effects. As a result, the Pyromat SB product is capable of stable, low NO_x operation at surface firing rates in excess of one MMBtu/hr/ft^2 (at atmospheric pressure).

The GTSB uses the Pyromat SB metal fiber burner surface in an adiabatic radiant mode. Pressure and temperature conditions within a gas turbine combustor are a function of design pressure ratio and the level of recuperation or heat recovery used. Table 1 summarizes combustor inlet and outlet temperatures and operating pressures associated with a variety of industrial gas turbines.

Table 1. Typical Industrial Gas Turbine Specifications

Engine Type	Pressure Ratio	Combustor Inlet Temperature	Turbine Inlet Temperature	Combustor Temperature Rise at Full Power
Recuperated Small Co-gen	4	1150°F	1800°F	650°F
Industrial	8	550°F	1700°F	1150°F
Large Utility	14	750°F	2300°F	1550°F
Aircraft Derivative	20	850°F	2300°F	1450°F
New Aircraft Derivative	30	1050°F	2450°F	1500°F

Combustion air temperature increases when recuperators and high-pressure ratios are used to increase efficiency. The effect of combustion air preheat on adiabatic radiant combustors is relatively benign, provided that the auto-ignition temperature of the fuel is not exceeded. The Pyromat material has demonstrated extraordinary capabilities as a flame holder/arrestor, minimizing the likelihood of burner flashback. As long as the turbine inlet temperature does not exceed 2500°F, the effect of increased combustion air preheat is simply to reduce the amount of fuel required to maintain the desired turbine inlet temperature.

Ultimately GTSB may have a pressure loss equivalent to or less than that of conventional gas turbine combustors. At atmospheric conditions, pressure drop through a Pyromat SB burner is approximately three inches water column at a nominal one MMBtu/hr/ft^2 and 15 percent excess air. A distribution screen used to achieve uniform firing produces the majority of the pressure drop. A low-pressure drop GTSB combustor can be expected to provide improvements in terms of efficiency and reduced fuel consumption.

For industrial gas turbine applications where reference velocities of 50 feet per second and combustion pressures of 10 atm are nominal, volumetric firing intensities of 10 MMBtu/hr/ft^3 are required. To achieve this space heat release with a GTSB combustor, flame speed predictions indicate the need for porous surface areas of perhaps one to two square feet per cubic foot. Designing a functional combustor geometry with an adequate surface area to volume ratio was one of the most significant technical challenges of this project.

2.3 Project History

In early 1995, Alzeta embarked on a Cooperative Research and Development Agreement (CRADA) with the Federal Energy Technology Center (FETC) in Morgantown, West Virginia to test Alzeta's radiant porous ceramic burner, the Pyrocore, in a pressurized environment. FETC's newly constructed Low Emissions Combustor Test and Research (LECTR) facility provided us the opportunity to explore the operating characteristics of the Pyrocore under system pressures up to 30 atm.

Pressurized testing of the Pyrocore burners confirmed that lean premix surface combustion was achievable at pressure. However, it also became apparent that the Pyrocore burners would not provide sufficient surface firing rates to deliver the required heat input to industrial sized gas turbines in a reasonably sized package. Focus shifted to the use of Alzeta's perforated metal fiber burner, the Pyromat SB. In general, at atmospheric conditions, the Pyromat SB is capable of approximately ten times the surface-firing rate of the Pyrocore.

Initial consideration of the gas turbine application led to the concept of firing two Pyromat SB burners in an opposed-face, surface-stabilized configuration. This arrangement allows the burner surfaces to radiate to each other allowing flame to be sustained at elevated levels of excess air. Additionally, the inward-fired configuration would make the best use of the combustor space available and would easily adapt to a Solar Turbines gas turbine.

Following the successful atmospheric testing of the parallel-burner SSC at Alzeta, we began the design of a combustor for pressurized testing at FETC. Discussions with Solar Turbines indicated that the preferred ultimate product would most likely be a relatively large annulus of opposing faced burner surfaces.

To simulate this configuration, two facing burners were again used. However, to ensure a more uniform velocity profile and make the most efficient use of available space, the burners were arranged so that their faces sloped away from each other as the flow moved toward the combustor exit. This concept entailed the design and fabrication of unique wedge-shaped burners.

Figure 5 illustrates two such burners assembled in an inward-fired configuration to form the SSC. The combustor was designed to handle a heat input of 1 MMBtu/hr at atmospheric conditions, which would scale to approximately 5-7 MMBtu/hr at elevated pressures.

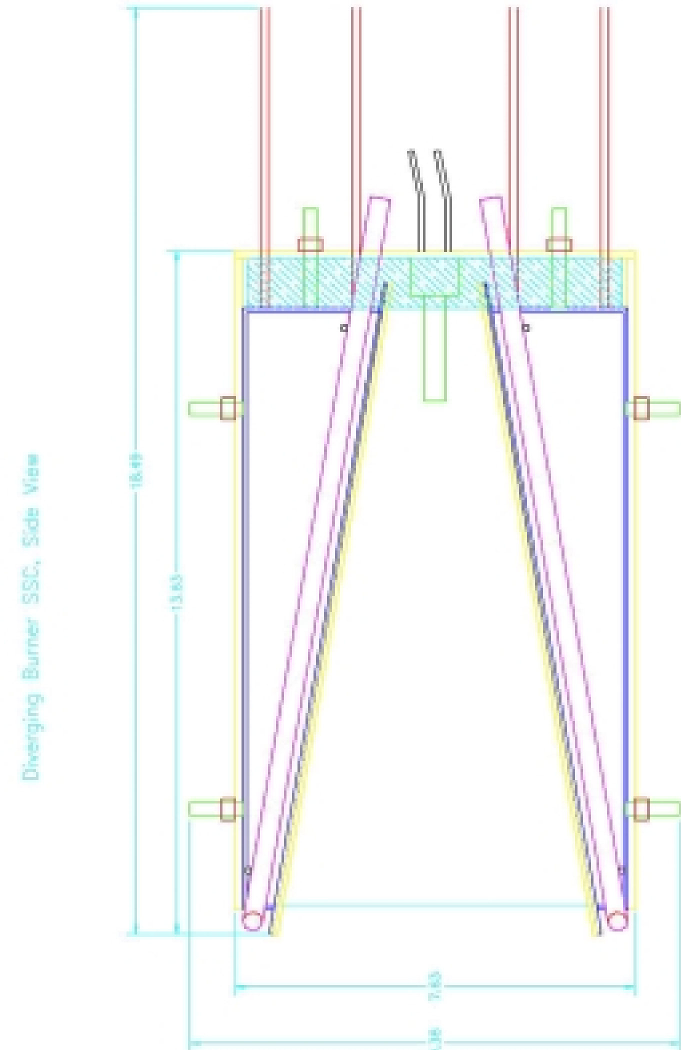


Figure 5. Diverging Burner SSC, Side View

Despite excellent performance at atmospheric conditions, the diverging-burner SSC experienced difficulties operating at elevated pressures. During the first three days of a scheduled ten day run at FETC, both the original combustor and the fully functional spare sustained damage. However, several encouraging facts came to light and much was learned about operating the SSC in a pressurized environment and running a test in the LECTR facility. Merely sustaining a flame under pressure was a significant accomplishment since it had never before been attempted with an Alzeta SSC combustor. Under most operating conditions, excellent emissions were observed. Concentrations of CO were virtually negligible and NO_x could easily be held below 9 parts per million, corrected to 15 percent O_2.

The first SSC test at FETC illustrated that while positive results at elevated pressures could be achieved, there remained much to be learned about the operating envelope and hardware requirements for these extreme conditions. For this reason, two additional test runs were scheduled with FETC. The first of these runs would take a step back and attempt to characterize pressurized combustion with a single, open-faced Pyromat SB burner. The information gained during this characterization would justify further testing and aid in the design of hardware and test plans for a final pressurized test several months later.

The design of the single burner was reasonably simple. The hardware ultimately featured a 6.25” square of active burner surface and a tube manifold for impingement of cool air on the backside of the fastening flange. The week of testing at FETC began with successful duplication of known atmospheric Pyromat SB operating points. It was decided that before executing a central composite test plan, several elevated pressure operating limits would be explored. This would allow a more focused and executable test plan to be created.

Two complete central composite test plans were run. The first one employed ambient-temperature premix while the second incorporated pre-heat as a function of pressure in order to simulate the compressor in an actual gas turbine. Both test plans featured operation between 1.8 and 12.2 atmospheres. Excess air and surface firing rate were also varied in an effort to characterize the combustor under a variety of different conditions that might be encountered in a gas turbine. No burner failures were encountered while running these test plans, and emissions were excellent. Figure 6 shows the range of operating conditions that was demonstrated during the preheated test plan. It is important to note that the limits of operation were not fully explored, so it is likely that the combustor could perform well outside of the illustrated envelope. Figure 7 presents the emissions data for the same preheated test plan. Levels of carbon monoxide were again negligible. NO_x production of less than 9 ppm (corrected to 15 percent O_2) was attainable at every pressure.

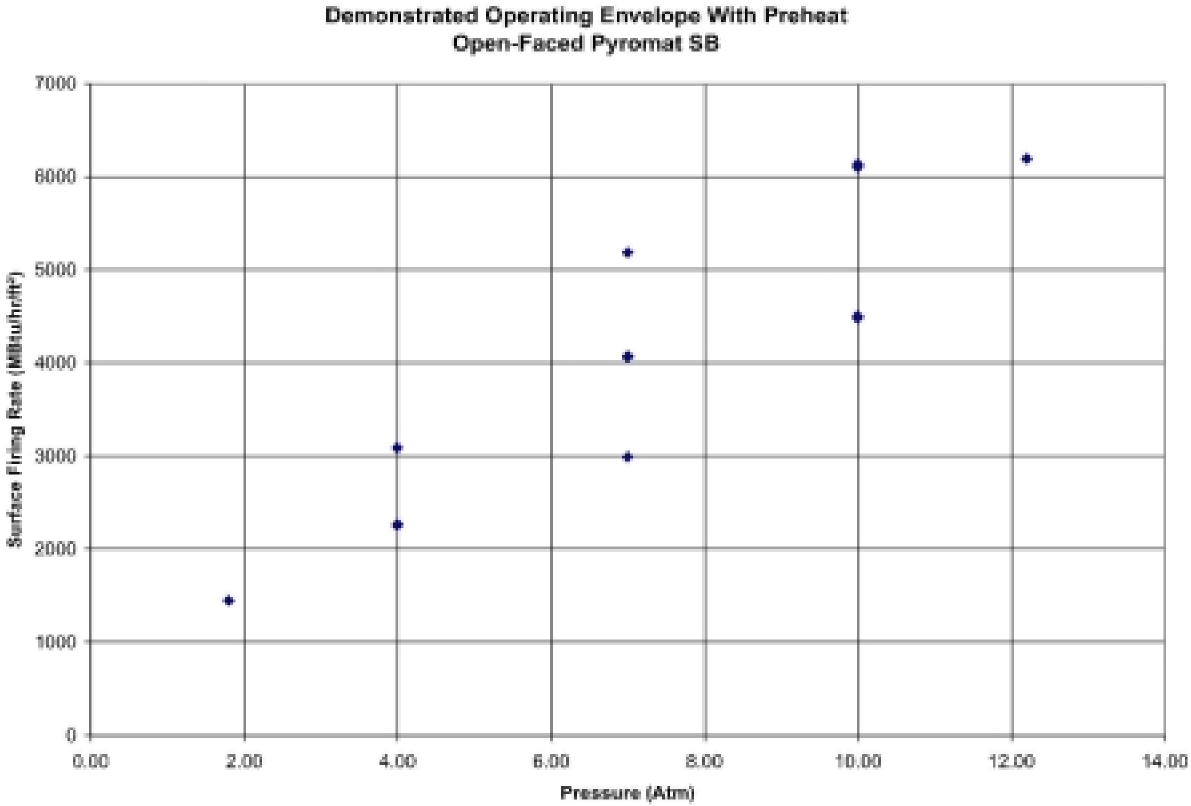


Figure 6. Demonstrated Operating Envelope, Preheat, Open-Faced Pyromat SB

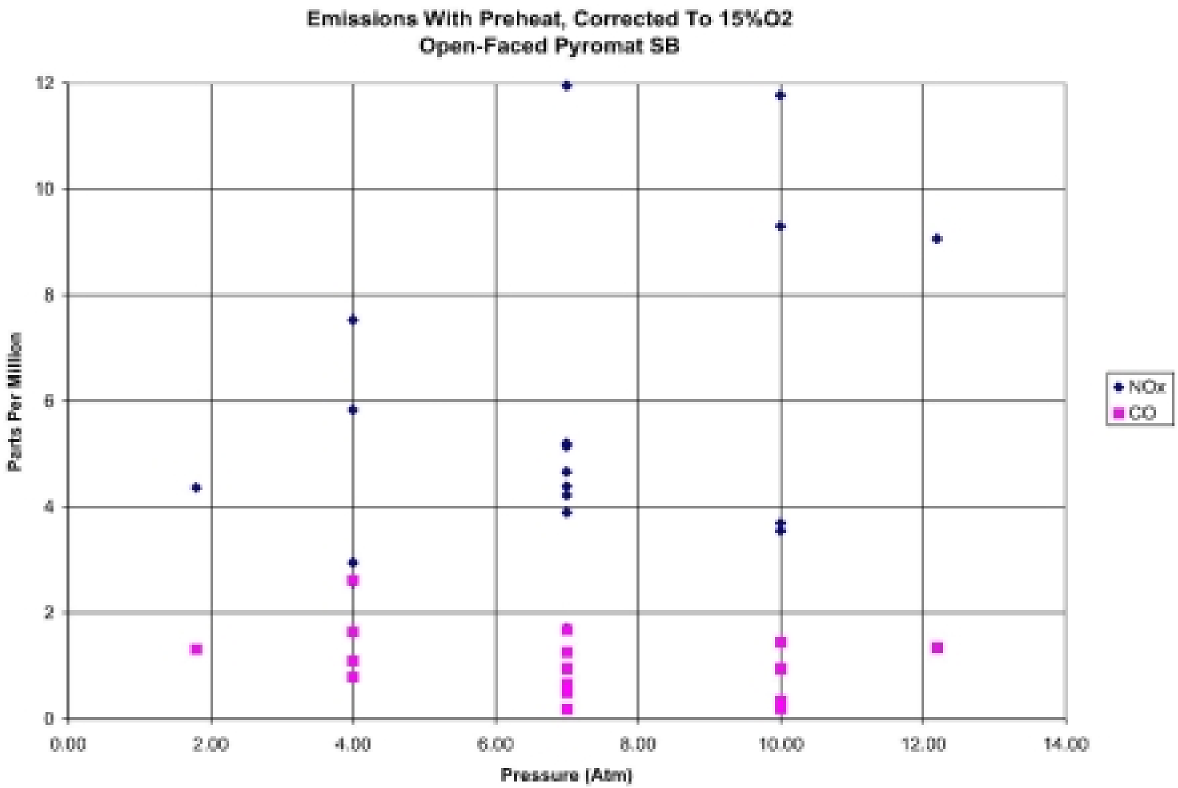


Figure 7. Emissions with Preheat, Open-Faced Pyromat SB

The single, open-faced burner test at FETC was a success in every way. It confirmed that operation of the Pyromat SB burner in a gas turbine environment was possible, and proved that emissions targets were relatively easy to achieve. It restored confidence in the concept, the hardware, and the LECTR facility. This paved the way for continued research of the pressurized SSC concept.

All of the information gathered in the early phases of the project was incorporated into a revised hardware and test design. Further discussions with Solar Turbines indicated the possibility of using an array of small can combustors in the ultimate application. They expressed interest in testing one such can at FETC. This input shifted the final design from the dual-burner box used in the first FETC test to an inward-fired cylinder combustor. This would allow for a greater volumetric heat release, more uniform radiation and flows, and fewer cooling problems.

Another week of testing at FETC was scheduled in early February 1997, and a simplified test was designed. The surface firing rate at any given pressure was fixed (following the 0.75 exponential rule discovered in the flat-plate test) and the excess air levels were varied in an effort to define limits of operation and observe direct effects on emissions. The test plan included points at 4, 6, 8, 10, and 12 atmospheres and scaled surface firing rates based on 900 Mbtu/hr/ft^2 at one atm.

Again, operating the inward fired SSC proved to be a success. Quality data points were taken in the range of one to six atmospheres (higher pressures were unattainable). Figure 8 shows the stable operating points that were achieved. A number of flameouts occurred for what appeared to be several different reasons. Fortunately, the interlock system on the LECTR facility performed well, and most of these events did not damage the combustor at all. The combustor exhibited stable operation at four atm.

Figure 9 presents the emissions data for the inward fired cylinder SSC. Carbon monoxide readings were generally higher than in previous tests due to an adjustment in the positioning of the LECTR emissions probe. Although the combustor produced large amounts of CO under certain operating conditions, concentrations under 30 ppm (corrected to 15 percent O2) were available at all operating pressures. The new sampling method increased confidence in these positive results. NO_x emissions were excellent, often below three ppm and in some instances below one ppm.

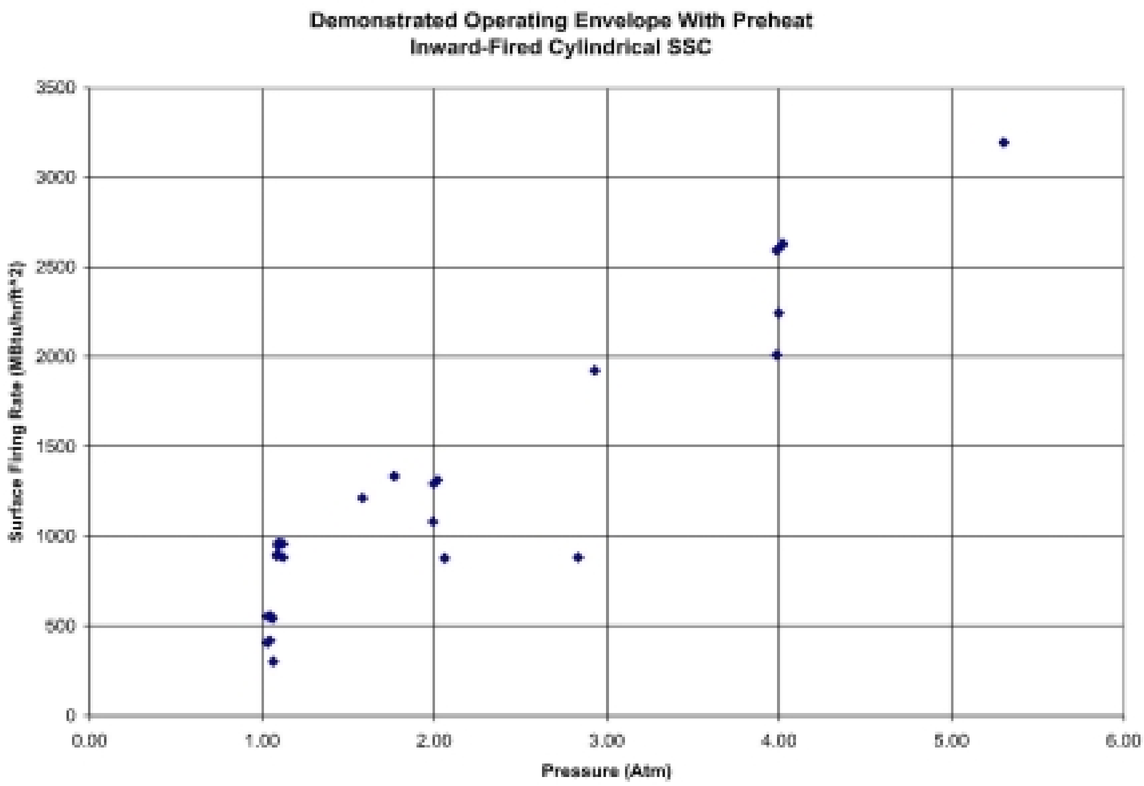


Figure 8. Demonstrated Operating Envelope with Preheat, Inward Fired Cylinder

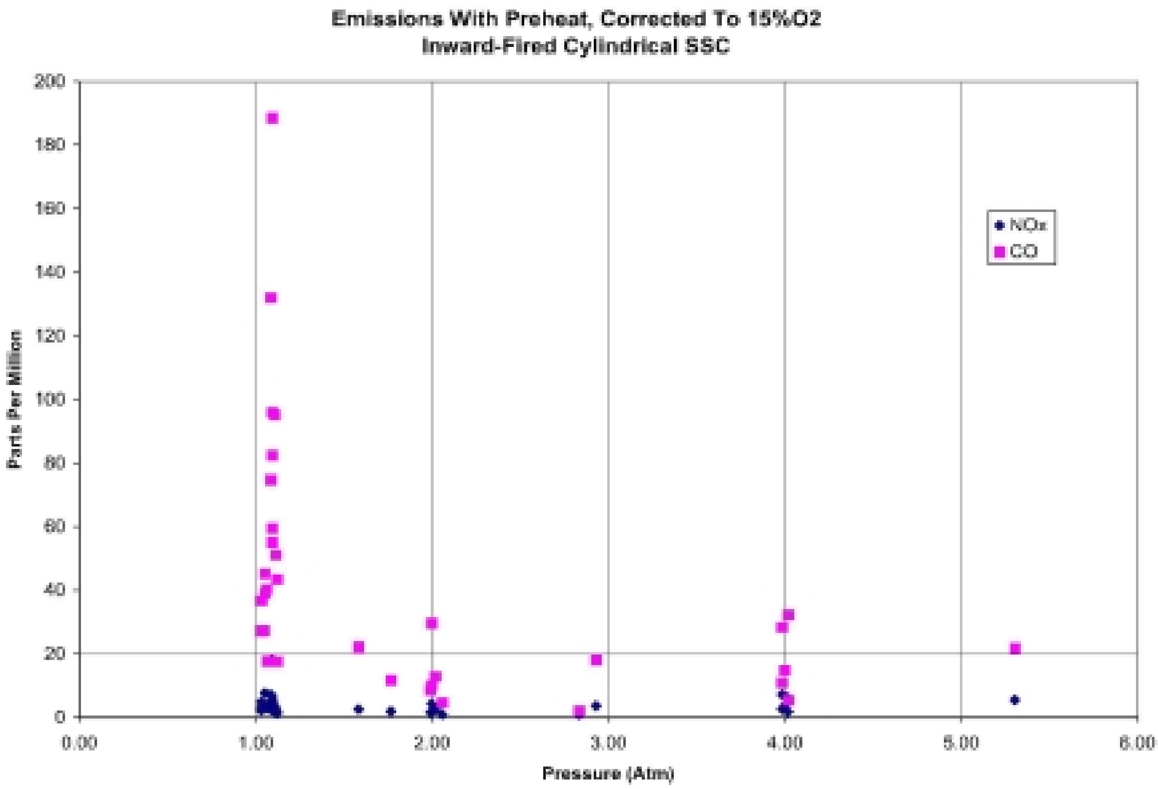


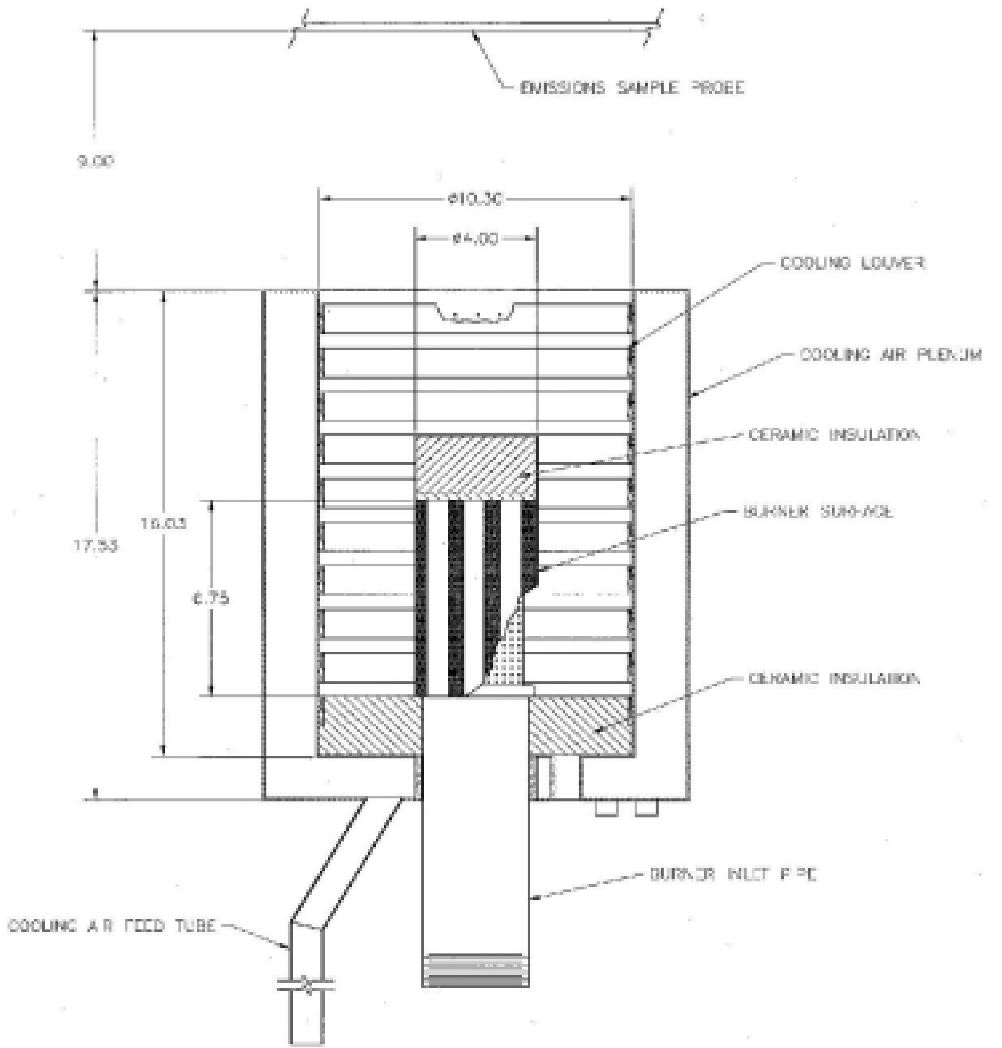
Figure 9. Emissions with Preheat, Inward Fired Cylinder

On the heels of the successful test sequence described above, Alzeta embarked on another Commission contract to optimize the combustor for use in a gas turbine. The most significant issue to be addressed was selecting an appropriate combustor geometry. While the flat plate burner performed the best at elevated pressures, this geometry simply could not offer a high enough volumetric heat release rate. Other inward-fired geometries displayed flame stability and overheat problems when tested under gas turbine conditions. The natural choice for a new geometry seemed to be an outward-fired combustor. Such a combustor would take full advantage of the space available and would eliminate durability problems caused by firing multiple burner surfaces at each other.

A detailed analysis of the Solar Centaur 50 Gas Turbine Engine and the data collected to date indicated that the required heat release rate could be achieved by an array of 6 to 12 small, cylindrical burners. These burners could be easily substituted for the current SoloNox injectors currently used by Solar. They would also be similar in proportion to Cylindrical SB's (CSBs) that Alzeta has successfully developed and marketed for installation in fire tube and water tube boilers.

Another critical factor in the combustor optimization was the cooling system selection. Many of the inward-fired burners did not require a primary cooling system because the hot combustion products were surrounded by the relatively cool premix plenum. These burners did however require complicated and often troublesome secondary cooling systems to protect un-fired edges from the intensely concentrated heat. The outward fired burner did not require such secondary cooling, but cooling of the combustion chamber walls was now necessary. Solar Turbines typically uses a louvered combustor liner that injects a portion of the turbine dilution air into the primary combustion zone in order to achieve film cooling of the liner. Initial laboratory tests at Alzeta confirmed that the Pyromat SB burner could maintain flame stability in close proximity with a wall cooled in such a manner. Thus, the Solar Turbines cooling design was adapted and incorporated into the test combustor design.

The scale of the new gas turbine burner would be significantly smaller than existing Alzeta CSBs, so several design improvements were required. The fastening clips featured on most Pyromat SB's were clearly too large and cumbersome for this application. After several alternative methods of fastening the burner pad were considered, welding emerged as the most promising option. Due to its high porosity and high temperature alloy composition, the burner pad proved difficult to weld. However, careful application of resistance spot welding created acceptable seams for both pad-to-pad and pad-to-substructure joints. These welding techniques allowed for re-design of the inlet and end-cap of the CSB to minimize exposed un-fired surfaces. Cooling fins and insulation were added to the end cap and the burner design was finalized. Figure 10 shows the burner and liner test assembly as installed in the LECTR facility.



Combustor Assembly, FETC Test

Figure 10. FETC Test Combustor Assembly

Testing at FETC was conducting over the course of two weeks in July 1998. In keeping with the theme of prior tests at FETC, a central composite test matrix was designed. The adiabatic flame temperature is the key factor in determining NO_x production and was varied from 2650°F to 2900°F. Firing rates ranged from 0.5 MMBtu/hr to 5 MMBtu/hr and were scaled to maintain a normalized surface firing rate of approximately one MMBtu/hr/ft^2/atm. Pressures ranged from atmospheric light off to 12.2 atm, with the majority of the test points lying between 4 and 10 atm (typical operating pressures for the Centaur 50 at various load conditions). The Central Composite test matrix features 15 distinct operating conditions, and several repetitions of a baseline center point in order to ensure the statistical significance of the results. Appendix II provides the data collected from these test points.

Figure 11 shows the NO_x emissions recorded for these test points. Figure 12 shows CO emissions along with several data points from a later test.

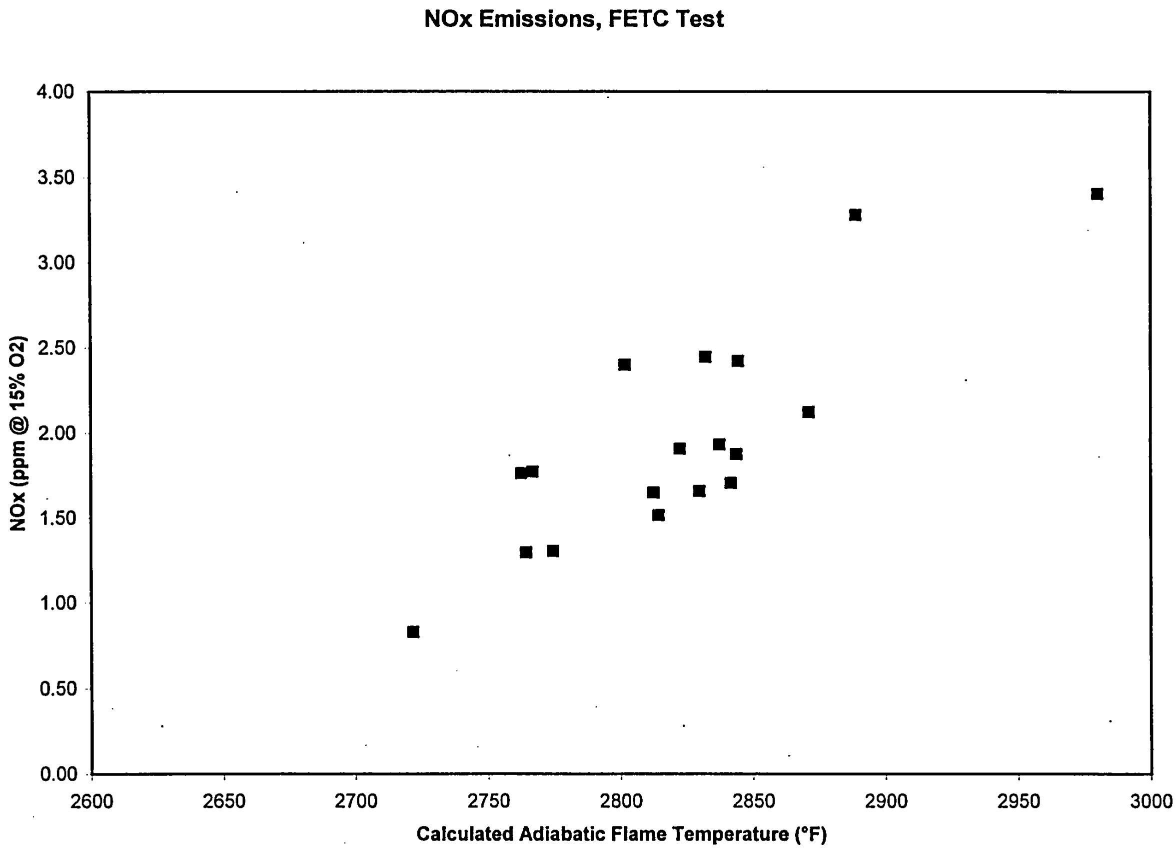


Figure 11. NO_x Emissions, FETC Test

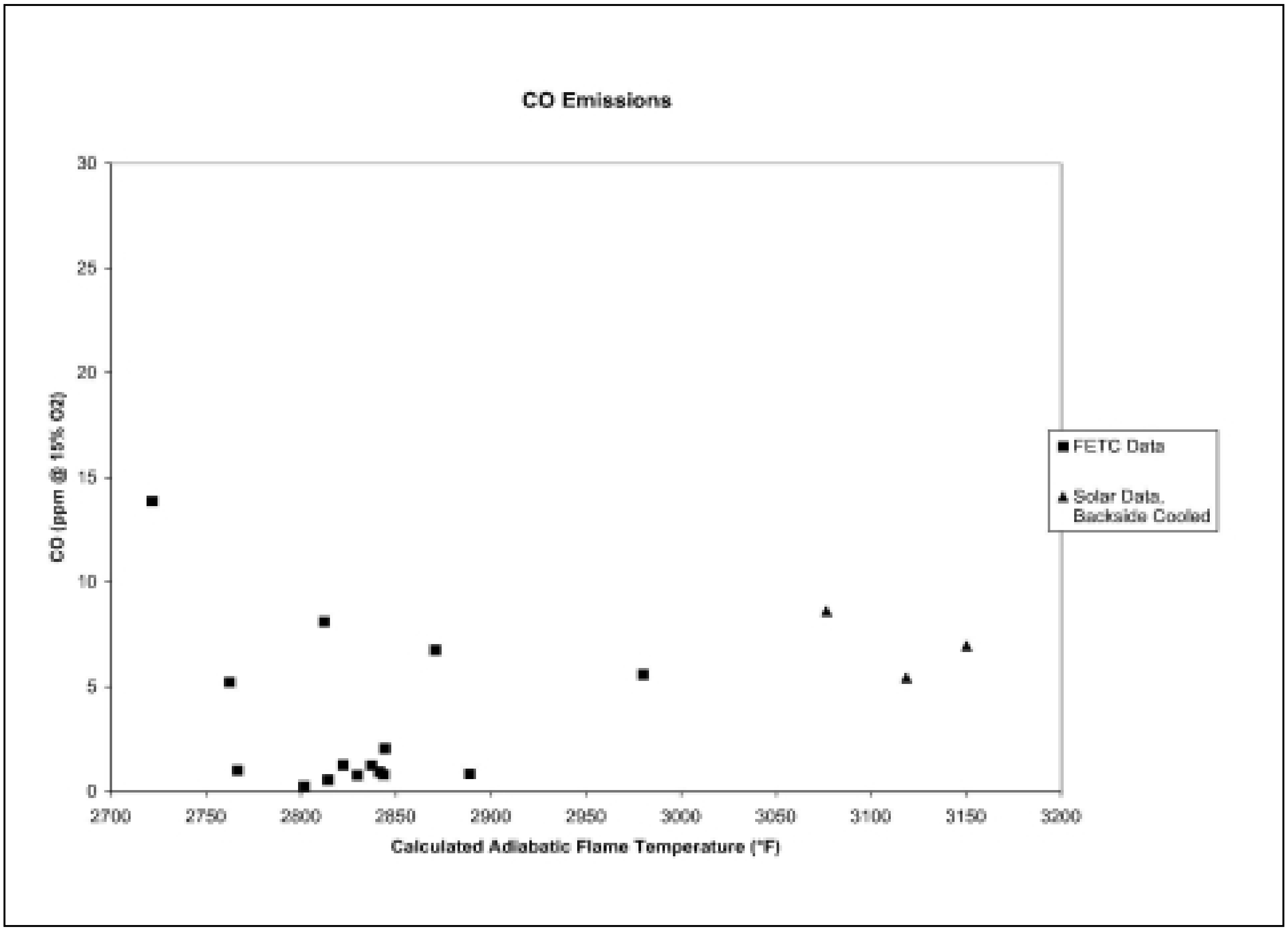


Figure 12. CO Emissions

Further tests were conducted beyond the central composite test matrix in order to define the lean operating limit of the combustor at various conditions. With airflow, combustor pressure, and preheat held constant, the fuel flow was reduced until the flame stability limit was reached. This resulted in extremely low flame temperatures and thus extremely low No_x emissions. These tests were conducted at four, seven, and ten atm at preheat levels consistent with both polytropic compression and recuperated gas turbine cycles. For these tests, data points were collected every 15 seconds by an automated data acquisition system. Figure 13 and Figure 14 show typical emissions plots from these tests.

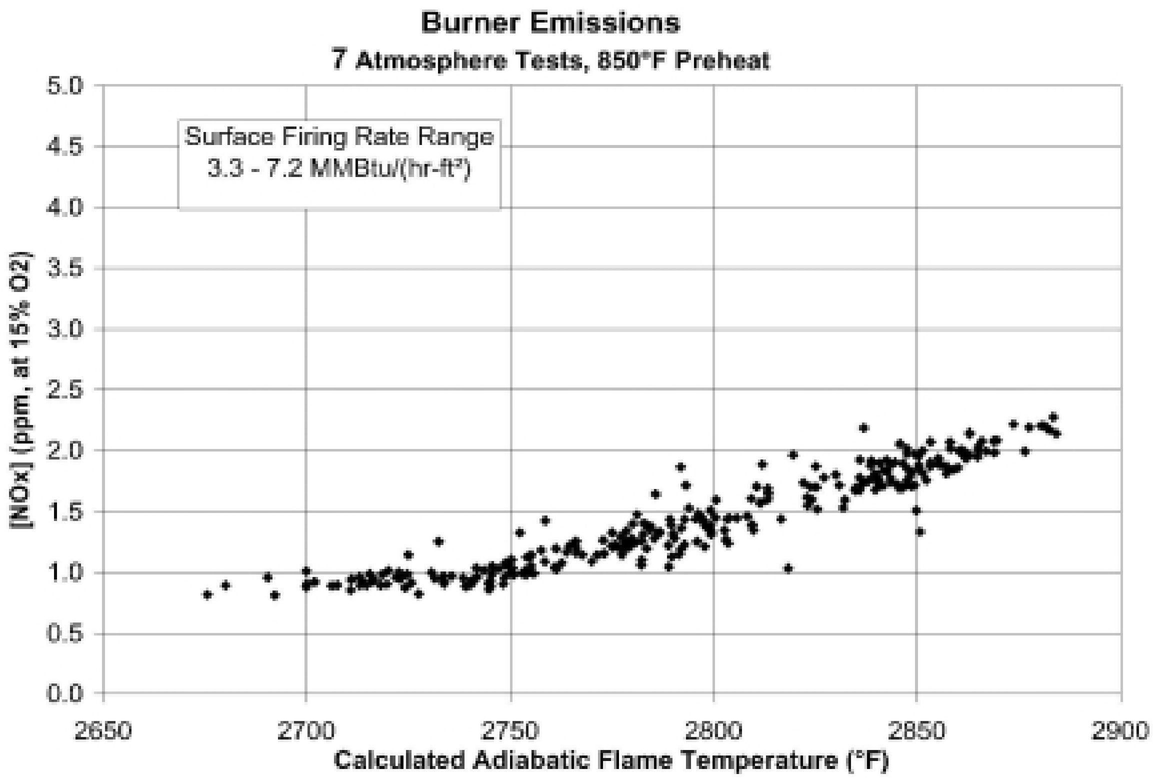


Figure 13. FETC Emissions Data: NO_x at Seven atm, 850°F Preheat

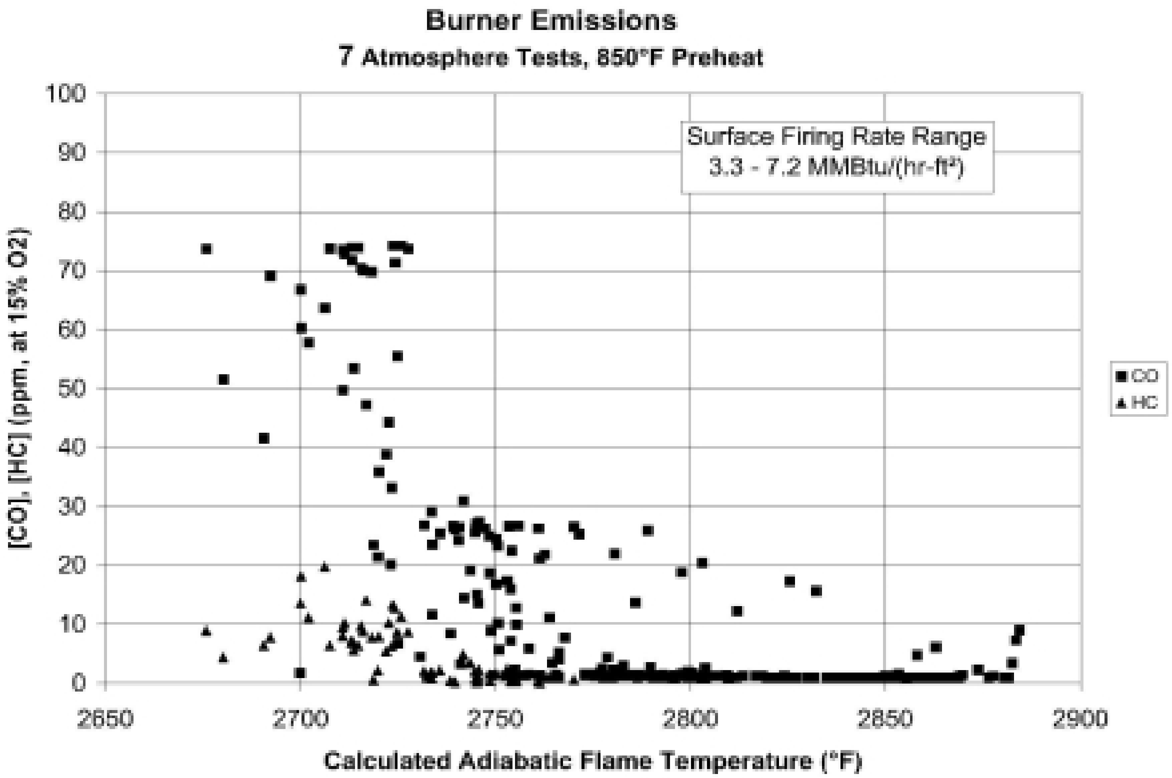


Figure 14. FETC Emissions Data: CO and HC at Seven atm, 850°F Preheat

The burner displayed consistent, stable operation at all pressures and over a range of adiabatic flame temperatures of approximately 250°F. NO_x emissions followed well-behaved trends, decreasing with reductions in flame temperature. At the lower flame temperatures, NO_x emissions were generally below 2 parts per million (corrected to 15 percent O_2) and were sometimes below one ppm. CO production was also low, with sub-10 ppm data points recorded at every pressure tested. Pressure loss through the burner (excluding losses from the mixing of the fuel and air) was approximately two percent of the system pressure.

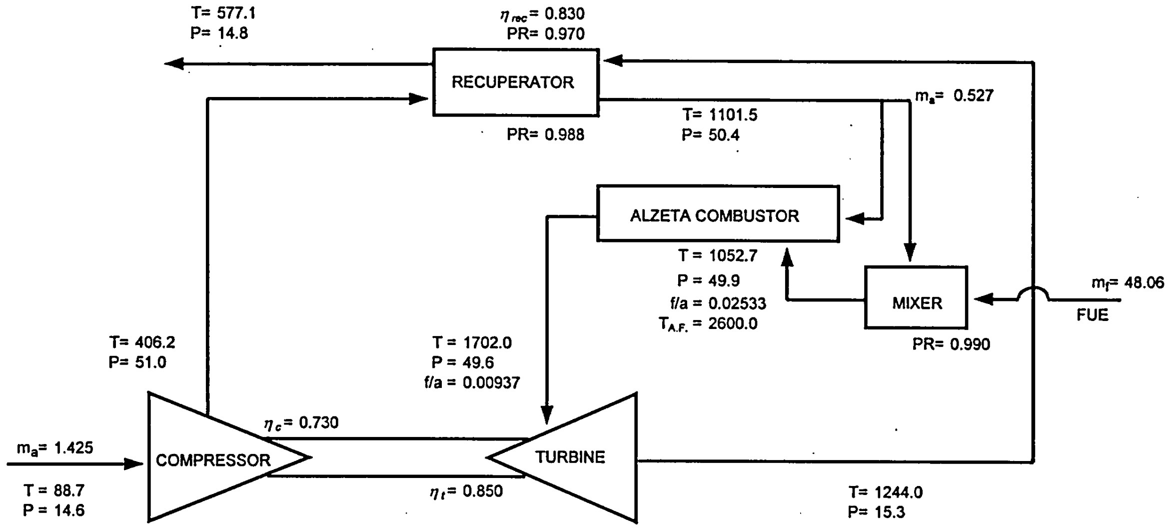
The tests of the optimized combustor at FETC were a success. The burner displayed excellent operating capabilities throughout the range of Centaur 50 operating pressures. NO_x and CO emissions were well within project targets and were far superior to currently available dry low NO_x technology. The flame was reliably sustained throughout and beyond the Central Composite test matrix. The burner again displayed minimal pressure loss.

3.0 Discussion

3.1 Turbine Thermodynamic Cycle Data

To gain a deeper understanding of the engineering requirements of our turbine manufacturing partners, Alzeta conducted a detailed analysis of the thermodynamic cycles of Solar's Centaur 50 turbine and Honeywell's Parallon 75 engine (formerly AlliedSignal's TurboGenerator). This analysis was then used to estimate GTSB performance at various load conditions and with various static airflow splits in each turbine. The most significant fact highlighted by this analysis is the fact that in all of the turbine cycles, the air-to-fuel ratio of the turbine changes dramatically throughout the range of operational turndown. Typically, the air-to- fuel ratio is three times higher at a no load condition than at a full load condition. With a static airflow split between the burner and the bypass, this would imply a factor of three change in the GTSB air-to-fuel ratio, making it impossible to sustain stable combustion. Ideally, the GTSB would use about 33 percent of the total airflow at full load, but only about 15 percent of the total airflow at a no load condition. This problem is common to both of the targeted engines, but can be addressed by employing a variable geometry or multiple burner configurations.

Cycle efficiencies were also investigated using a unique computer code developed by Alzeta for this purpose. The code is capable of analyzing both recuperated and non-recuperated gas turbine cycles. It requires input such as air pressures and temperatures at various locations throughout the engine, and thermodynamic efficiencies of several key components. The resulting output is an overall cycle efficiency, combined with an easy-to-follow graphic representation of the turbine cycle. Input parameters can be easily modified in order to quickly assess the impact of engineering changes on the efficiency of the engine. An entire series of plots were generated for both engines at a variety of operating conditions. Full load plots are included for the AlliedSignal TurboGenerator (Figure 15) and the Solar Centaur 50 (Figure 16). This detailed analysis of the targeted engines enabled the specialized design and testing of GTSBs engineered to customer specifications.



CYCLE EFFICIENCY = 28.2%

Standard Conditions for the AS75 TurboGenerator @ 0%

Figure 15. Typical Cycle Analysis for Allied Signal Turbo Generator

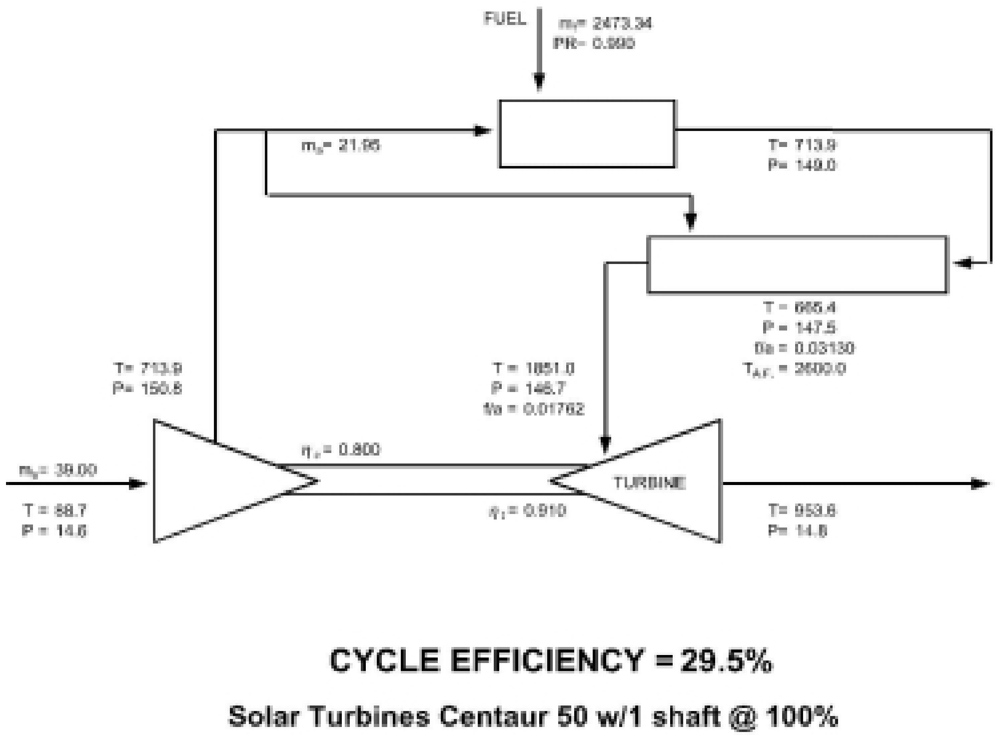


Figure 16. Typical Cycle Analysis for Solar Turbines Centaur 50

3.2 Test Summary

The results of the combustor tests in Alzeta's lab were once again very encouraging. The GTSB continued to display its characteristic excellent emissions and flame stability. The hardware used in these tests was, for the first time, sized and configured almost exactly as it would be in an actual turbine. The operating conditions were also very similar to real turbine conditions, allowing a high degree of confidence that similar results could be achieved when the combustor is tested in a turbine.

illustrates an important result of this round of tests. A classic problem in gas turbine combustion is the tradeoff between static airflow splits and variable geometry. While employing a static airflow split is far simpler and more robust, emissions and flame stability concerns often make it less attractive. The GTSB features a similar tradeoff. When configured for a 25 percent static airflow split to the burner, the GTSB can achieve stable turndown only to about a 50 percent Parallon load condition. This configuration also yields unnecessarily high emissions at full load conditions. While variable geometry would solve this problem from a combustion standpoint, simpler acceptable solutions are available. These solutions include using a pilot burner at lower load conditions or employing a segmented burner design. These options will be discussed in detail in the following section.

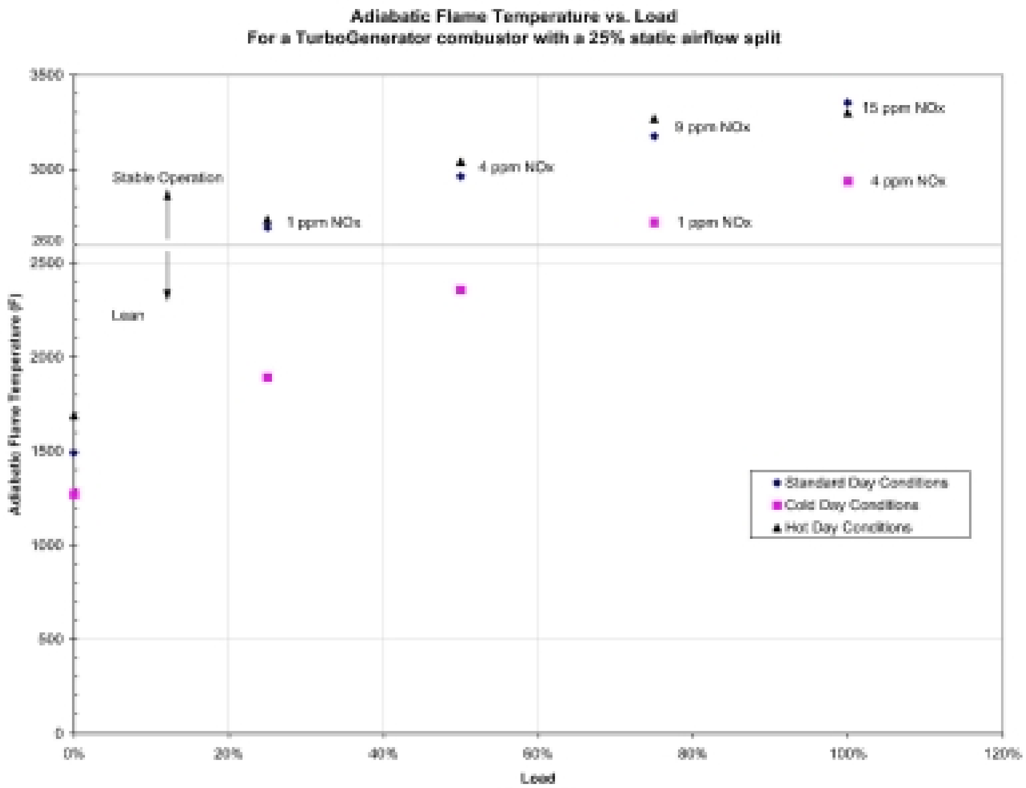


Figure 17. Adiabatic Flame Temperature versus Load

Alzeta Test Rig Modifications

Before testing could begin in Alzeta’s 50 kW test facility, some modifications and upgrades to the facility needed to be performed. The test facility was originally constructed and used for a different series of pressurized combustor tests a number of years ago. The GTSB combustor tests required a different, unique test configuration, and several parts of the facility needed repairs.

is a process and instrumentation diagram of the 50 kW test facility. The combustor air is preheated through a combination of a regenerative heat exchanger (HX-1) and a process air heater (R-2 with transfer accomplished via HX-2). Natural gas is fed to a compressor (B-3), and is pressurized for use in the combustor. Mass flow control valves control fuel and airflows. The fuel and air mix inside the pressure vessel and are burned by the GTSB. The combustor exhaust is cooled, and then passes through a backpressure valve which controls the combustor pressure.

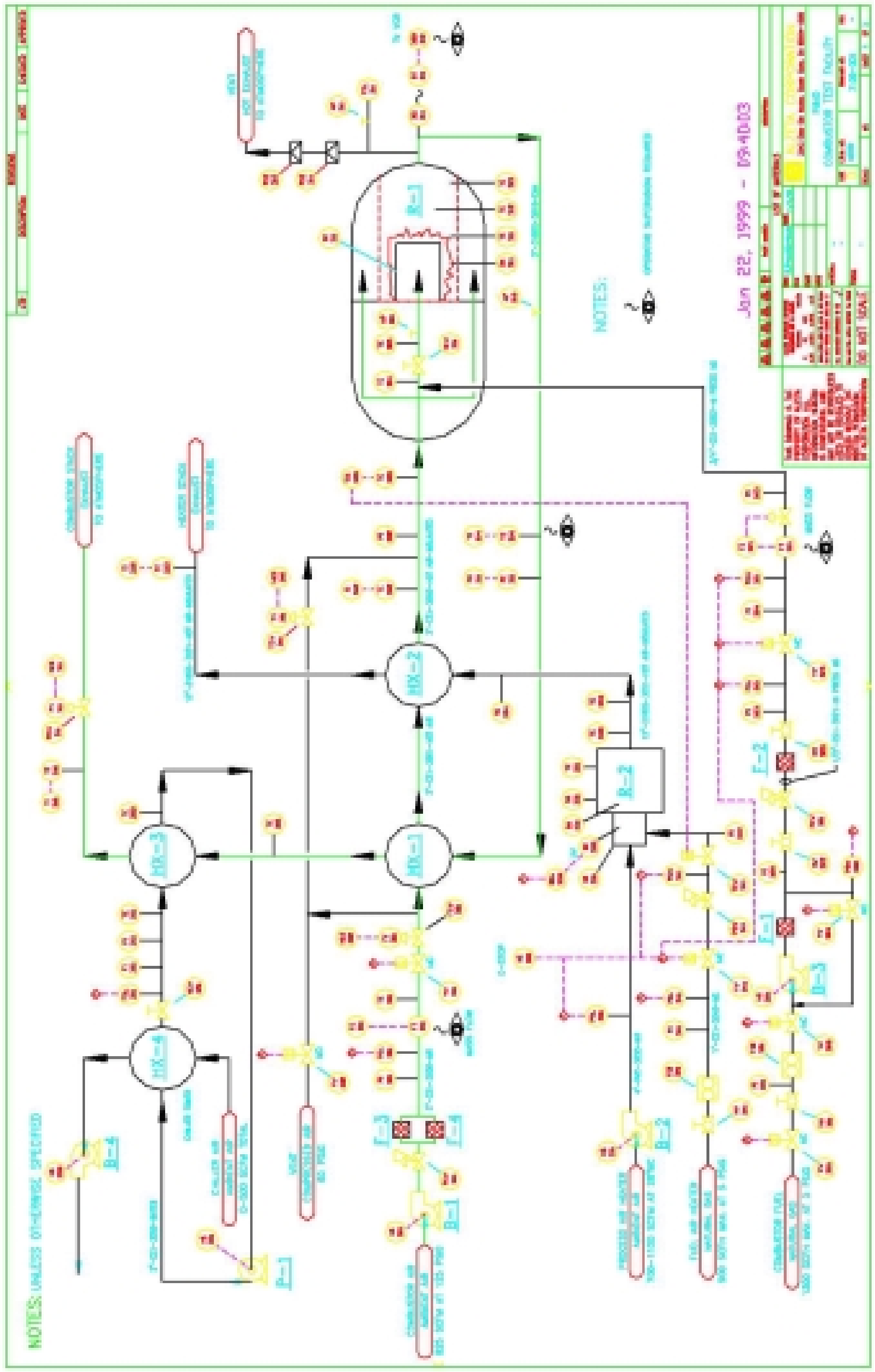


Figure 18. Piping & Instrumentation Diagram, Alzeta's In-House 50 kW Test Rig

The gas compressor required a thorough overhaul before being able to consistently deliver the required flow rates. Filters on both the gas and air lines were replaced. The process air heater was outfitted with a new set of thermocouples. Both the gas and air flow meters were calibrated, and new display modules were required for each. The backpressure valve also required repairs.

The interfaces between the test rig and the combustor itself required some re-design and repairs as well. New gaskets were installed. A threaded rod assembly was devised to allow adjustment of airflow splits. Pass throughs for thermocouples and premix sample lines were implemented. The sight glass was replaced and adjustments were made to the ignition spark rod. Figure 19 shows the test rig assembly.

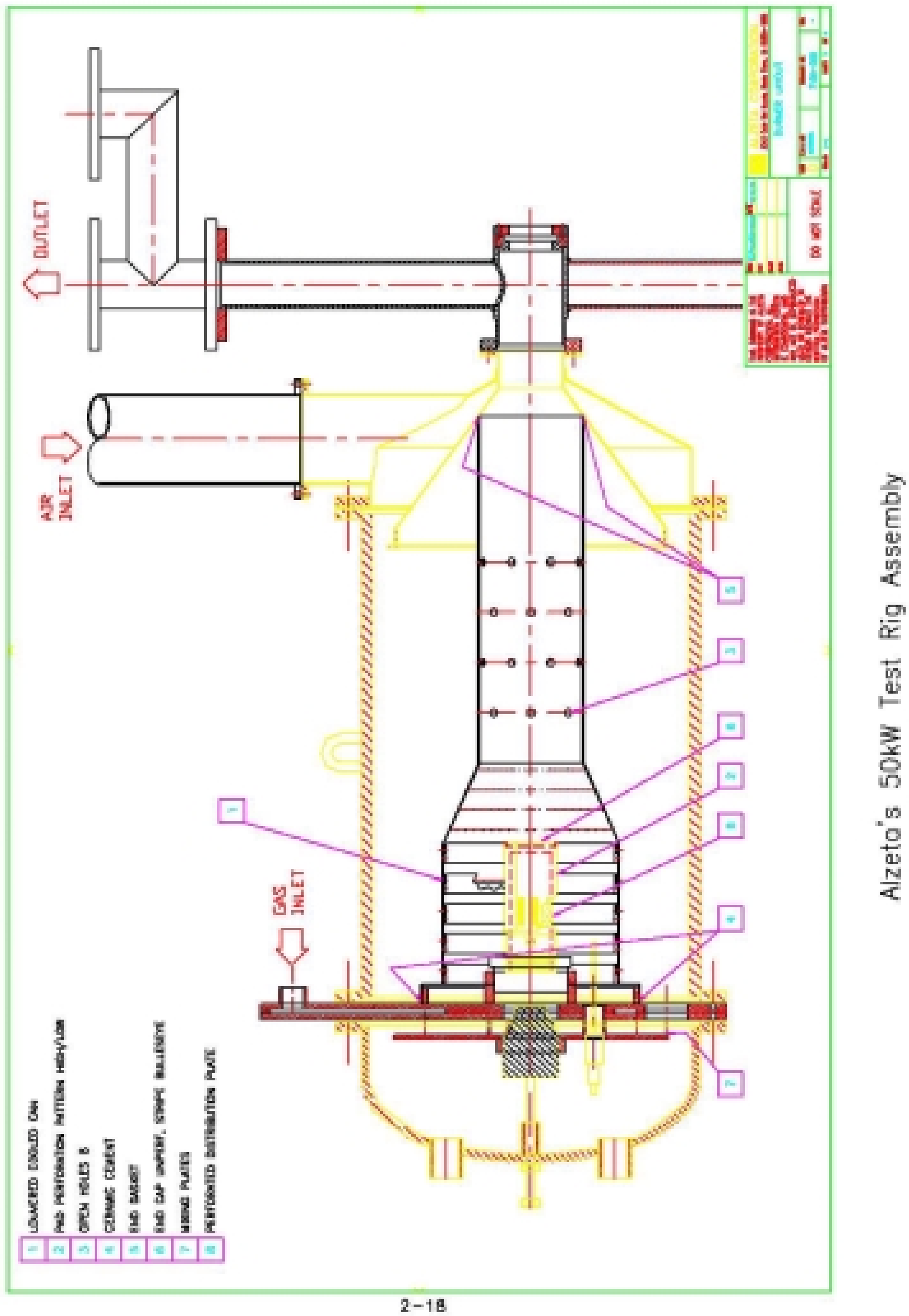


Figure 19. Alzeta's 50 kW Test Rig Assembly

Shakedown tests of the test rig itself were required before actual combustor testing could begin. First, air was preheated to over 800°F and run through the rig. Leak checks were performed and safety interlocks were tested. It was determined that Alzeta's in-house air compressor was unable to deliver adequate flow for the planned series of combustor tests. Therefore, an 850 cubic feet per minute (cfm) diesel air compressor was rented to bring the facility up to full capacity.

3.2.1 Initial Characterization Tests

The first set of tests, conducted at Alzeta early in 1999, was designed to explore the operating characteristics of the GTSB. While test plans were devised and data was analyzed within the context of the Parallon 75, no attempt was yet made to match the specific operating conditions supplied by Honeywell.

Figure 20 formed the basis of an initial, exploratory test plan. This figure shows expected performance for a burner with 0.4 ft^2 of surface area in the Alzeta test rig. Pressure drop limitations of the test rig dictate maximum firing rates that can be achieved at each pressure for a given air split to the burner. The Parallon 75 run conditions are plotted in this context, and it is immediately apparent that in order to exactly reach all of those run conditions in the Alzeta test rig, the GTSB must operate with an air split that sends more than 25 percent of the total air to the burner.

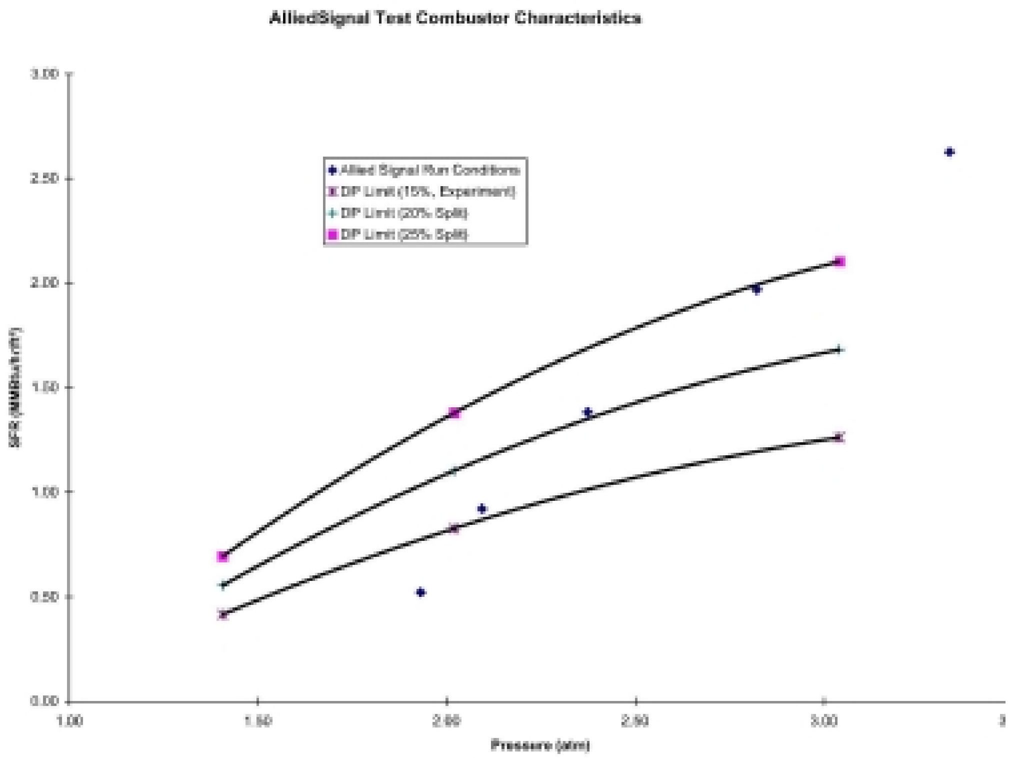


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Figure 20. Initial Characterization Test Plan Basis

Initial testing was conducted with a variety of air splits.

Figure 21 provides the complete data set, sorted by the percentage of the total air split to the burner, acquired during these tests. This shows a broad operating range with surface firing rates ranging from 0.5 to just over 2.25 MMBtu/hr/ft^2. These data were acquired with the intent of passing air splits to the burner that will be typical of the Parallon 75.

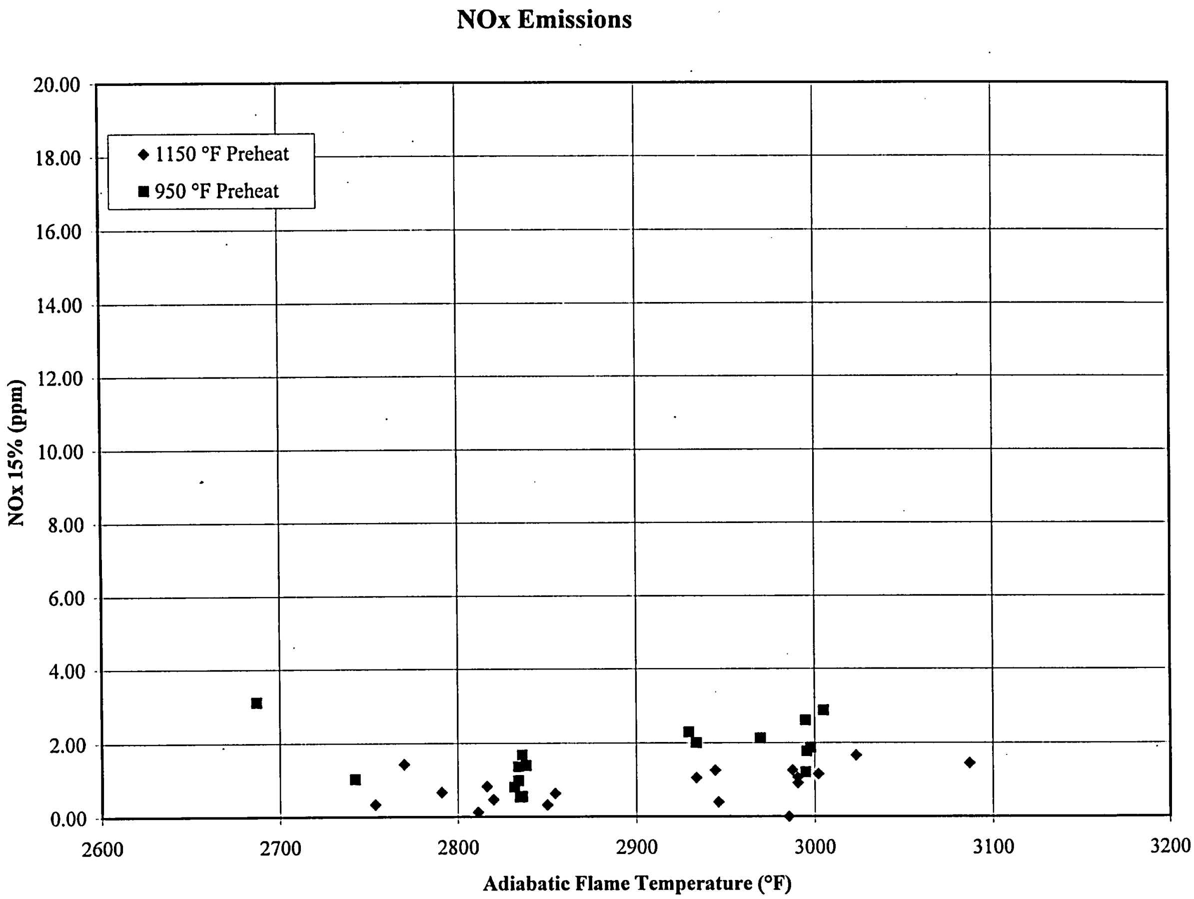

Figure 22 provides the NO_x emissions results for the 1150°F and 950°F data. This plot shows NO_x emissions under three ppm, corrected to 15 percent O_2, through a range of adiabatic flame temperatures from 2700°F to 3100°F. Figure 23 shows the CO emissions data, corresponding to the same test conditions shown in

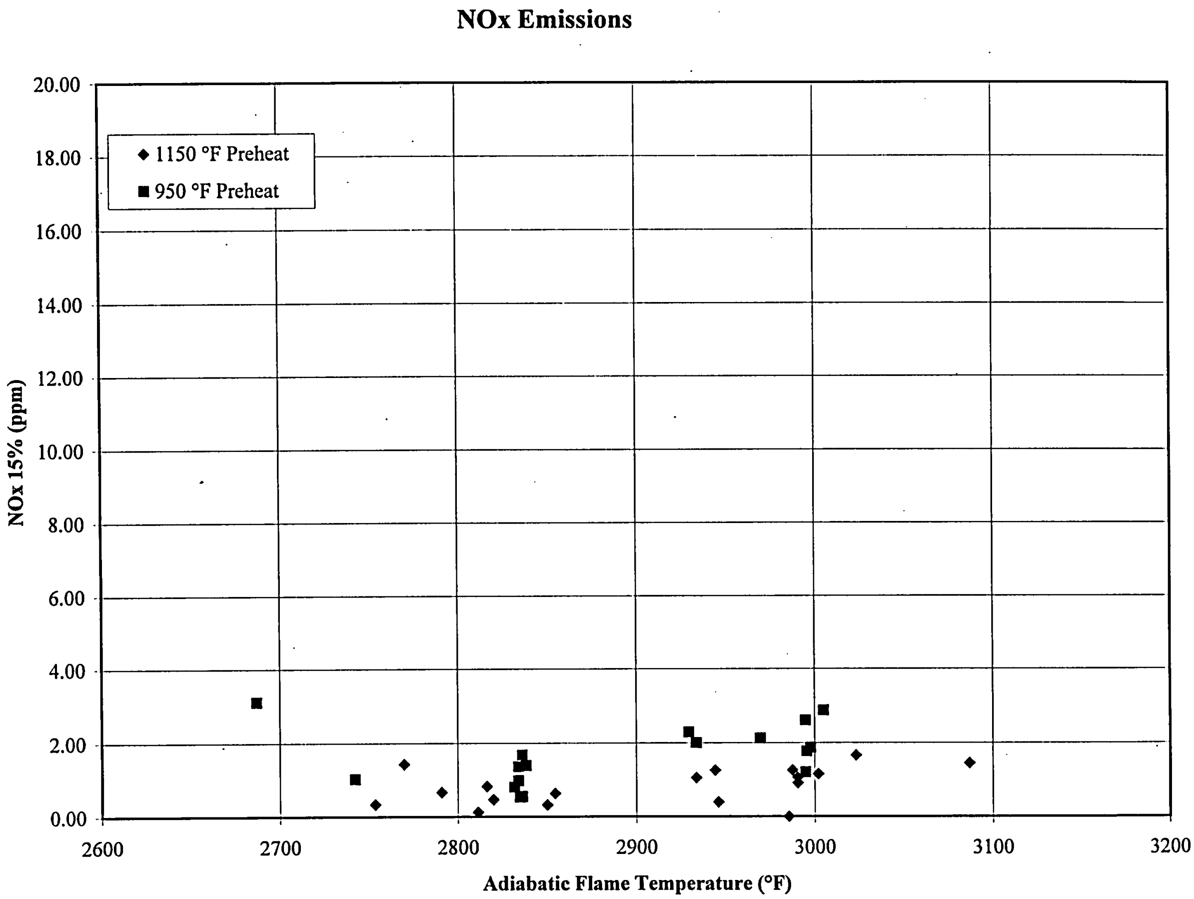

Figure 22, are all below 20 ppm. The majority of the data are below 10 ppm.

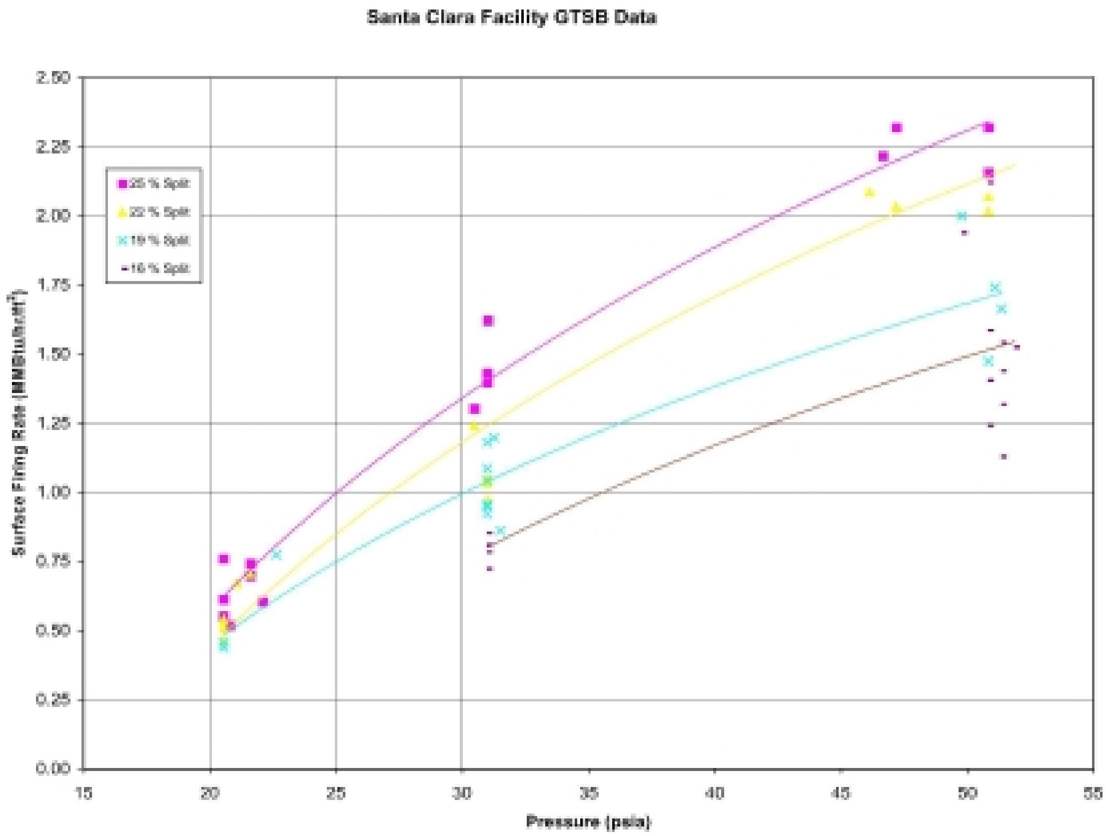

Figure 21. Initial Characterization Test Results

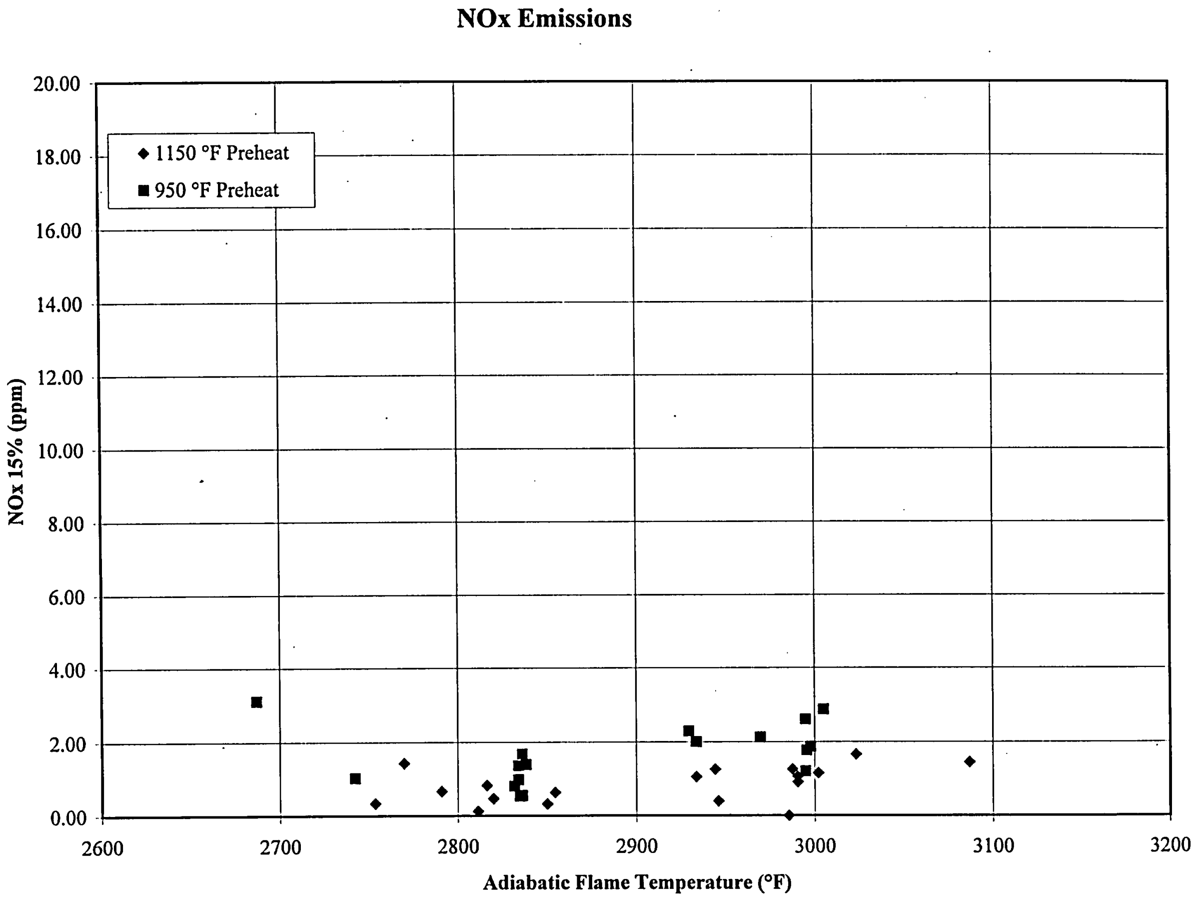

Figure 22. NO_x Emissions Data From Initial Characterization Tests

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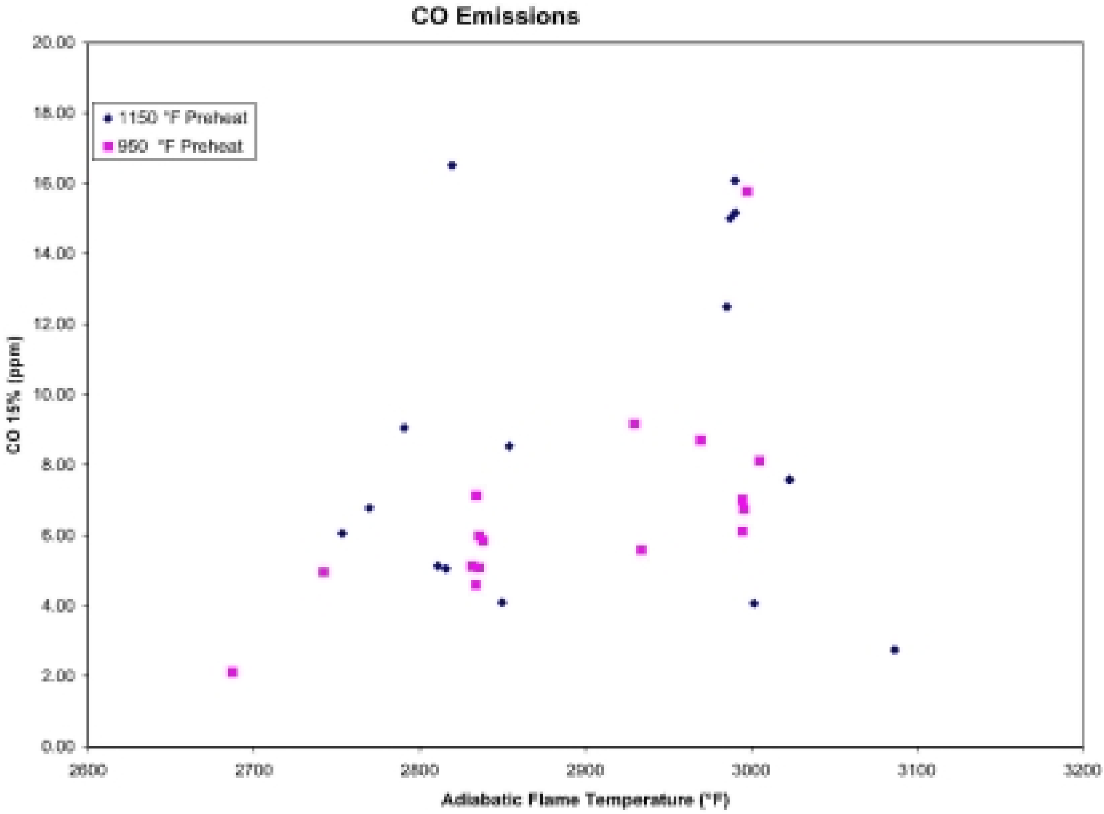

Figure 23, CO Emissions Data From Initial Characterization Tests

3.2.2 Load Matching Tests

After the initial characterization tests of the GTSB were completed, a series of tests were devised to investigate GTSB performance at specific Parallon 75 engine operating conditions. Appendix III contained the compiled raw data collected during these so-called load-matching tests. The most significant results are summarized in the following three figures. Figure 24 illustrates that turbine conditions ranging from zero load to 100 percent load were indeed fired successfully.

Figure 25 shows typical emissions data collected at various load conditions. The levels of NO_x and CO encountered here are similar to those found in previous testing at FETC and Solar Turbines, and are low enough to meet project objectives. The final plot,

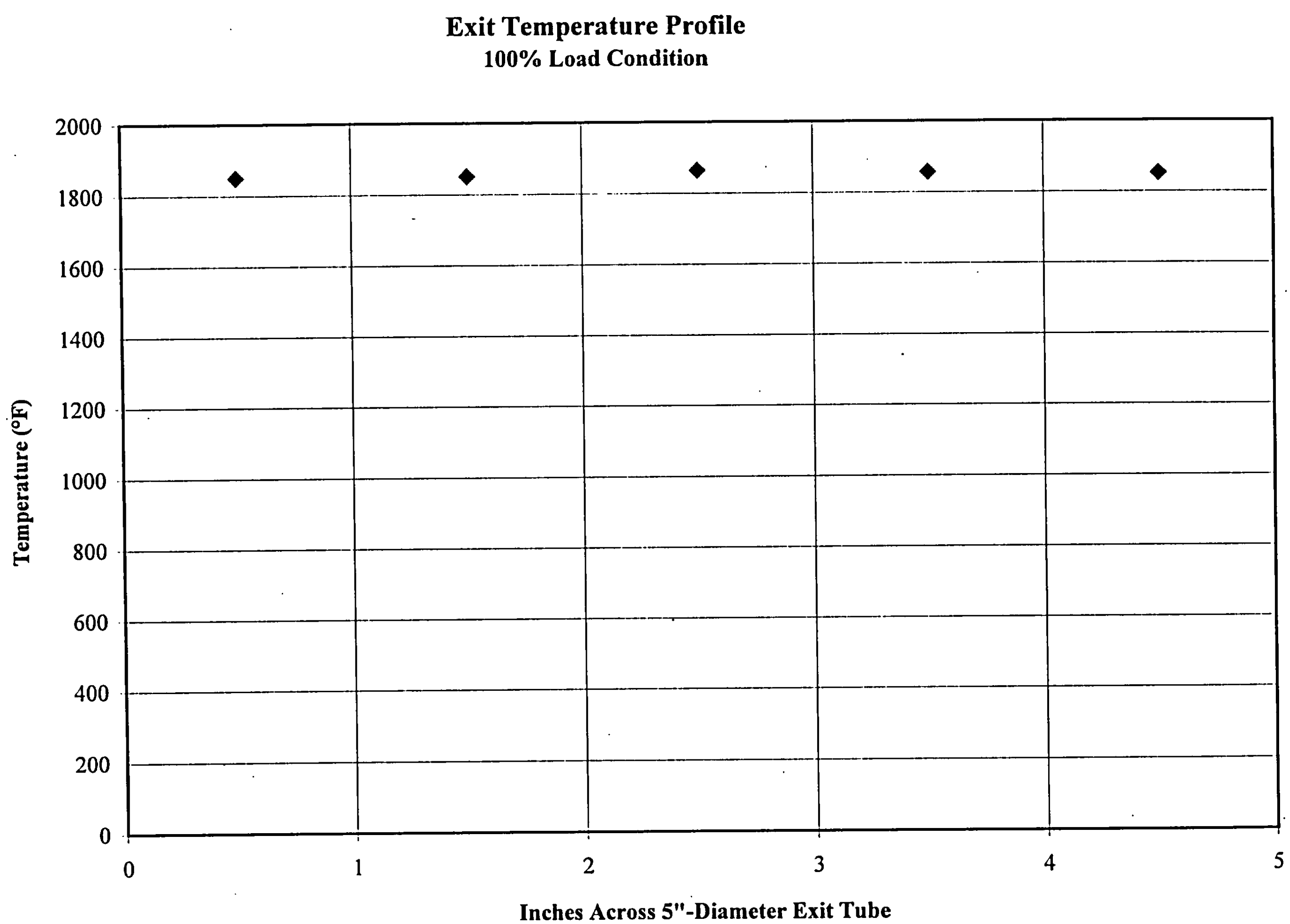

Figure 26, shows a typical temperature profile across the combustor exit. In order to minimize thermal stresses on turbine blades, turbine manufacturers prefer this profile to be as flat as possible. The profiles observed during tests at Alzeta were all nearly uniform.

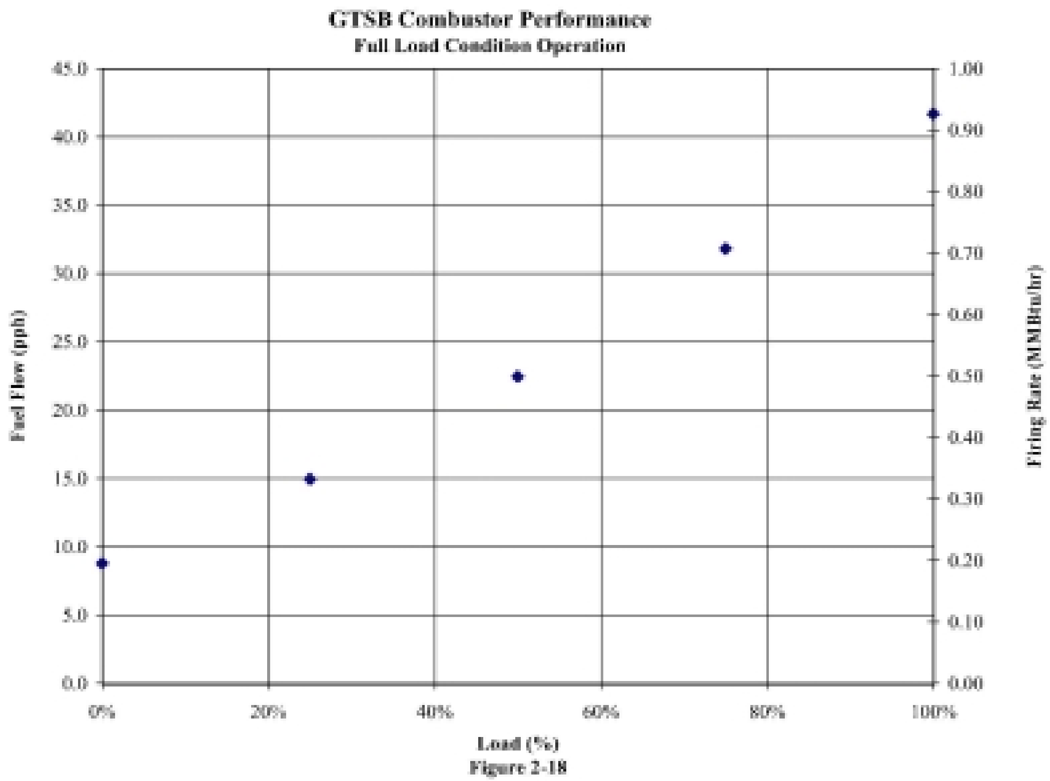

Figure 24. GTSB Combustor Performance, Full Load Condition Operation

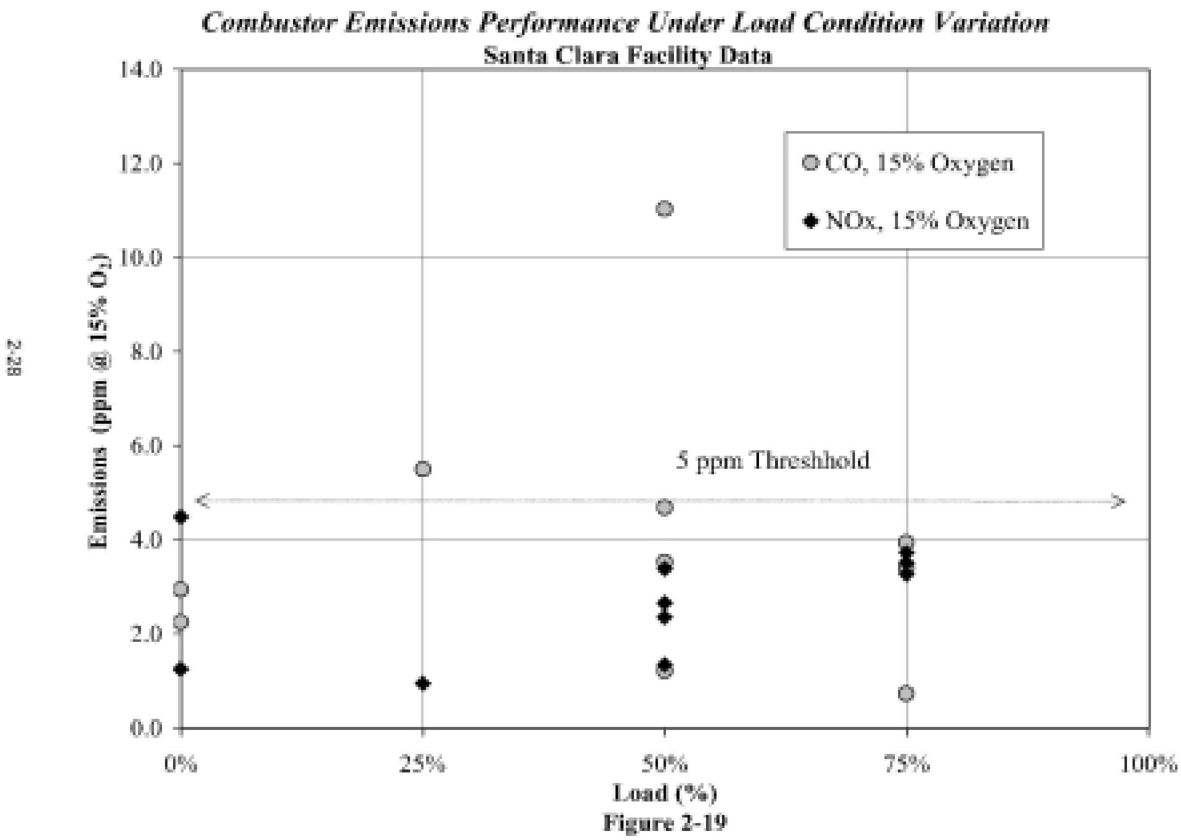

Figure 25. Combustor Emissions Performance Under Load Condition Variation

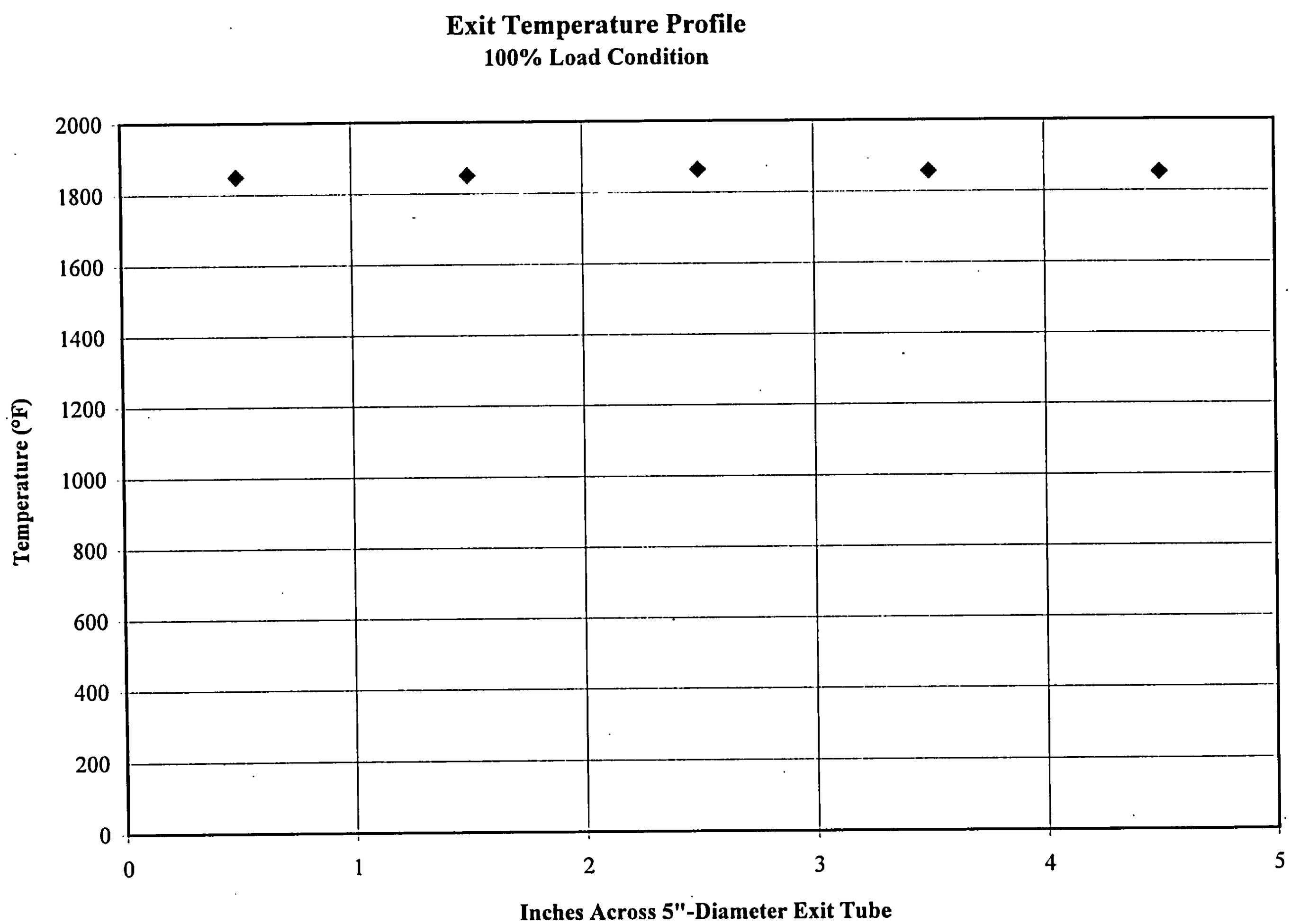

Figure 26. Exit Temperature Profile, 100% Load Condition

3.3 Combustor Testing at Turbine Manufacturers' Facilities

3.3.1 Preliminary Tests at Solar Turbines

Following the successful testing of the optimized burner at FETC, all parties were ready to proceed with a demonstration of the technology at Solar Turbines. Solar conducts initial qualification tests of new combustors in a small “single can” test rig. Successful combustors then proceed to a partial annulus test rig, a full annulus test rig, and ultimately to an actual engine test. The available single can test rig featured a louver-cooled combustion can just under 8” in diameter. This is a more constricting environment than the actual Centaur 50 combustion chamber, and thus would provide a challenging test for the Alzeta combustor. The 4” diameter burner was too large for this test fixture. There would likely be a strong interaction between the flame cones extending from the burner and the film cooling air of the combustor liner, possibly resulting in high CO emissions. Further improvements were also necessary in welding techniques and end cap design. However, Alzeta decided to take advantage of the first available test window, in mid-October, to conduct preliminary testing at Solar Turbines using the same burner design that had been tested at FETC. It was believed that these tests would maintain interest in the project while offering vital information that would be used to re-design the combustor for a more comprehensive test at Solar a couple of months later.

To ensure optimum mixing of the fuel and air within the tight space constraints of the Solar test rig, a SoloNox fuel injector was employed. The SoloNox injector is Solar's current low NO_x technology. It achieves thorough mixing in a very short distance. Normally, that mixture would then be combusted in volumetric burning within the combustion chamber. However, for the purposes of this test, the injector was mounted on the upstream end of the Alzeta burner and used simply as a mixer. This was believed to be a logical mating of the two technologies. Ultimately, a new mixer based on the SoloNox injector could be designed through collaboration between Alzeta and Solar.

Another difference in the Solar test rig was that, for the first time, Alzeta would not be able to independently vary the combustion and dilution air flow rates. The relative effective areas of the burner/injector assembly and the louver-cooled liner solely determined this split. No variable geometry was employed for these tests. An Alzeta premix analyzer was used to determine the composition of the mix actually reaching the burner. This information was used to calculate the approximate split of air between the burner and the liner. Limitations of the test facility and the desire to more closely simulate actual turbine conditions led to cooling air flow rates well beyond those which were employed at FETC. Typically, the amount of air flowing through the liner at Solar was approximately equal to that flowing through the burner. This too would contribute to the strong interaction between the flame and the cooling air and would create a challenging test. Figure 27 shows the Alzeta burner mounted inside the Solar combustor liner as installed in the Solar test rig.

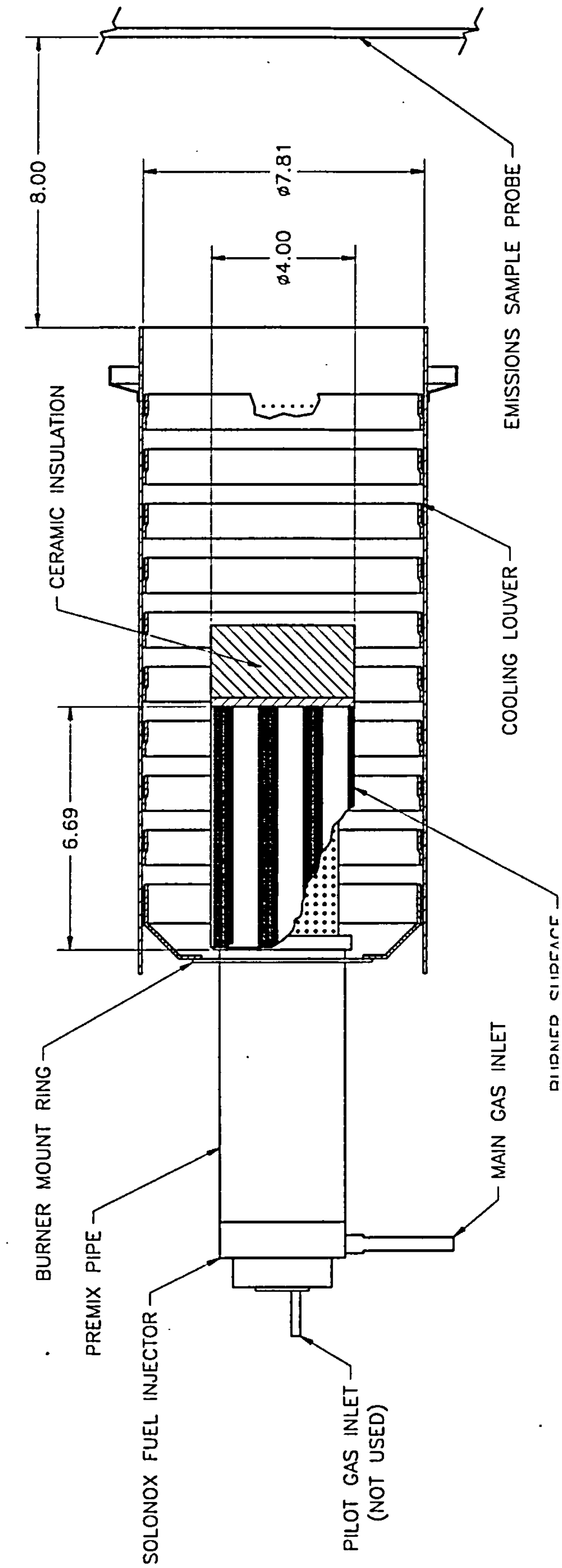

Figure 27. Preliminary Solar Test Combustor Assembly

The results of this first test at Solar Turbines were mixed (Appendix IV). The data collected from these tests are included in. Each data point represents time-averaged data from 24 data points collected by computer over the course of approximately 15 seconds. Test points were chosen to mimic those used at FETC. The combustor did display stable operation at pressures up to and including full-load conditions (10 atm). NO_x emissions followed the usual trends, but were slightly higher than those recorded at FETC. Figure 28 shows these emissions data. Emissions of CO and hydrocarbons were unfortunately very high. This was due to significant intrusion of the cooling air into the combustion zone just above the surface of the burner, resulting in incomplete combustion over portions of the burner. This intrusion was greater than at FETC for three reasons:

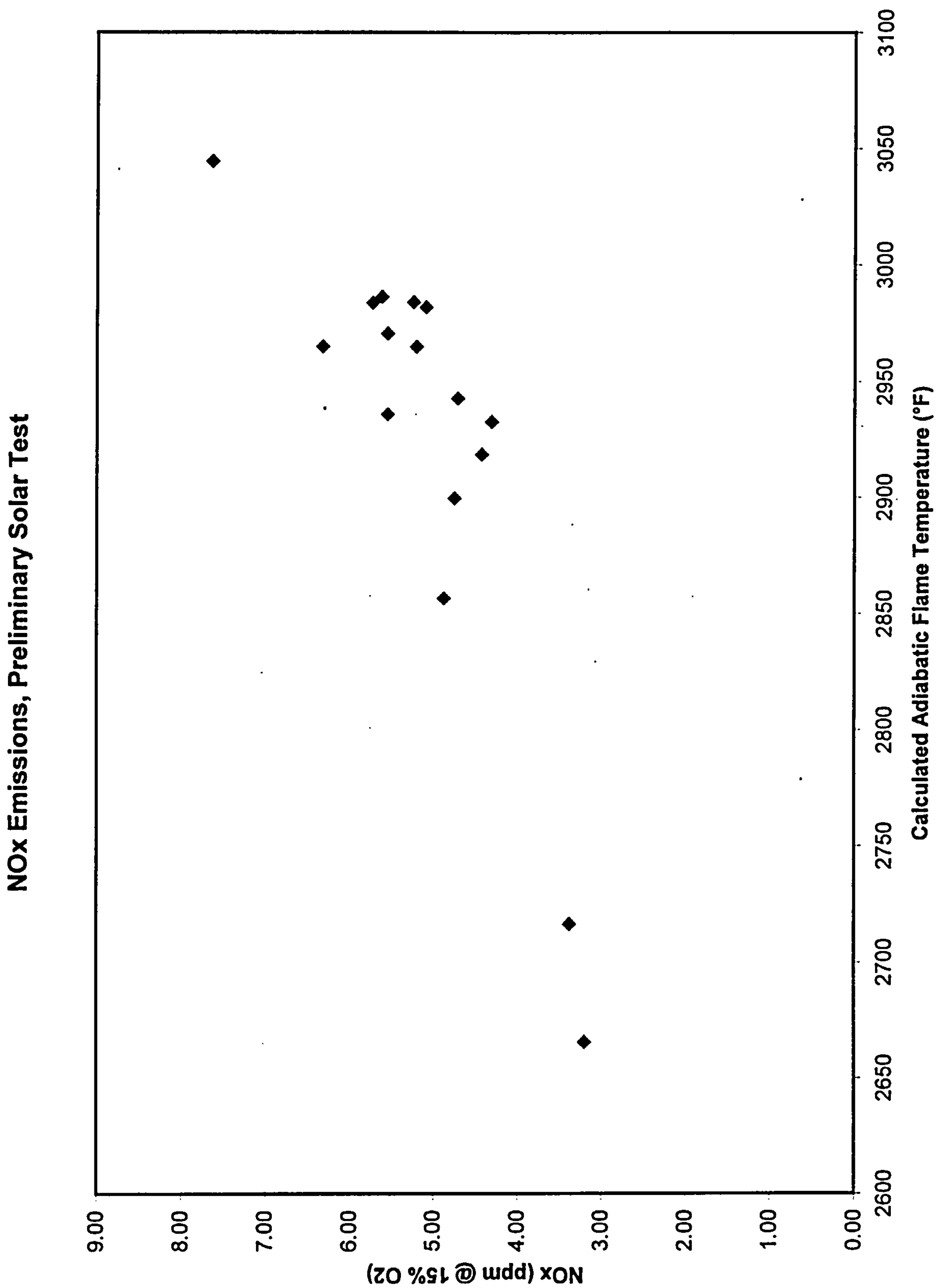

Figure 28. NO_x Emissions, Preliminary Solar Test

The total cooling air flow rate, relative to the combustion air flow rate, was approximately 3 times larger in the Solar tests than in the FETC tests.

The distance between the burner surface and the liner surface was about half what it was at FETC, causing the burner's flame cones to impinge upon the liner.

There was a small leak of cooling air through the burner/liner interface that resulted in a flow of air directly across the burner surface.

Nevertheless, these initial tests at Solar Turbines were deemed a success. Collaboration between Solar and Alzeta occurred smoothly. The combustor displayed NO_x emissions low enough to maintain interest in the project and prompt further testing. The difficulties with CO were easy to explain and could be addressed in a straightforward manner. Alzeta was in an excellent position to adjust the burner design and return for another single-can test at Solar.

The primary goal in the re-design of the burner was the reduction of the CO emissions displayed in the initial Solar tests. Since the size of the Solar combustor liner was essentially fixed, the burner diameter needed to be reduced in order to increase the separation distance between the two surfaces. A 2.5" diameter was chosen as being the smallest diameter possible using current fabrication techniques. Further benefit could be realized by reducing the height of the flame cones that extend from the perforated portions of the burner surface. The height of these cones is proportional to the width of the perforated zone, and therefore a new burner pad design featuring narrower stripes was created. These special burner pads were fabricated using laser cutting rather than traditional punching techniques in order to allow quick turnaround and flexibility of design.

The other end of the CO problem was the combustor liner itself. Alzeta collaborated with Solar to devise a solution and two viable options emerged. The first involved switching to a different liner that did not require injection of cooling air into the primary combustion zone. This so-called backside cooled liner is being developed with good success by Solar in conjunction with the DOE ATS program, but is not currently used in any production engine. Nonetheless, this liner presents an ideal solution for the Alzeta combustor. Although the total amount of dilution air used with this liner is somewhat greater than that used with the louvered liner, the air passes through a narrow annulus on the outside of the combustion zone, thus achieving convective cooling. The cooling air then joins the main flow through a series of holes placed far enough downstream that they do not interfere with the combustion.

The second solution to the liner problem was to modify the existing louvered liner. Although no modification to this concept could completely remove the cooling air from the primary combustion zone, the air could be re-distributed so that more of it would be diverted downstream. In order to accomplish this goal, 2/3 of the primary zone cooling holes were plugged. The effective area lost to this plugging (approximately one square inch) was made up by the addition of several large holes downstream of the combustion zone. The net result was a great reduction in the primary zone cooling air without compromising the cooling of the liner or the combustor outlet temperature. Alzeta and Solar agreed to test both the backside-cooled liner and the modified louvered liner during the December 1998 test session.

Further improvements made to the burner included the addition of an active-fired endcap. This self-cooling component eliminated the need for cumbersome ceramic insulation on the end of the burner. It also marginally increased the volumetric heat release capabilities of the burner. The quality of the welded seams increased significantly when Alzeta identified a welding subcontractor who could weld the pad material cleanly using specialized TIG welding. The interface between the burner and the liner was altered to allow easy switching between the two liners. Finally, the burner materials, component sizes and fabrication techniques were adjusted with ultimate cost reduction in mind. Figure 29 is a photograph of the new burner with the SoloNox injector attached. Figure 30shows the re-designed burner installed in the backside-cooled liner and Figure 31 shows it in the modified louver liner.

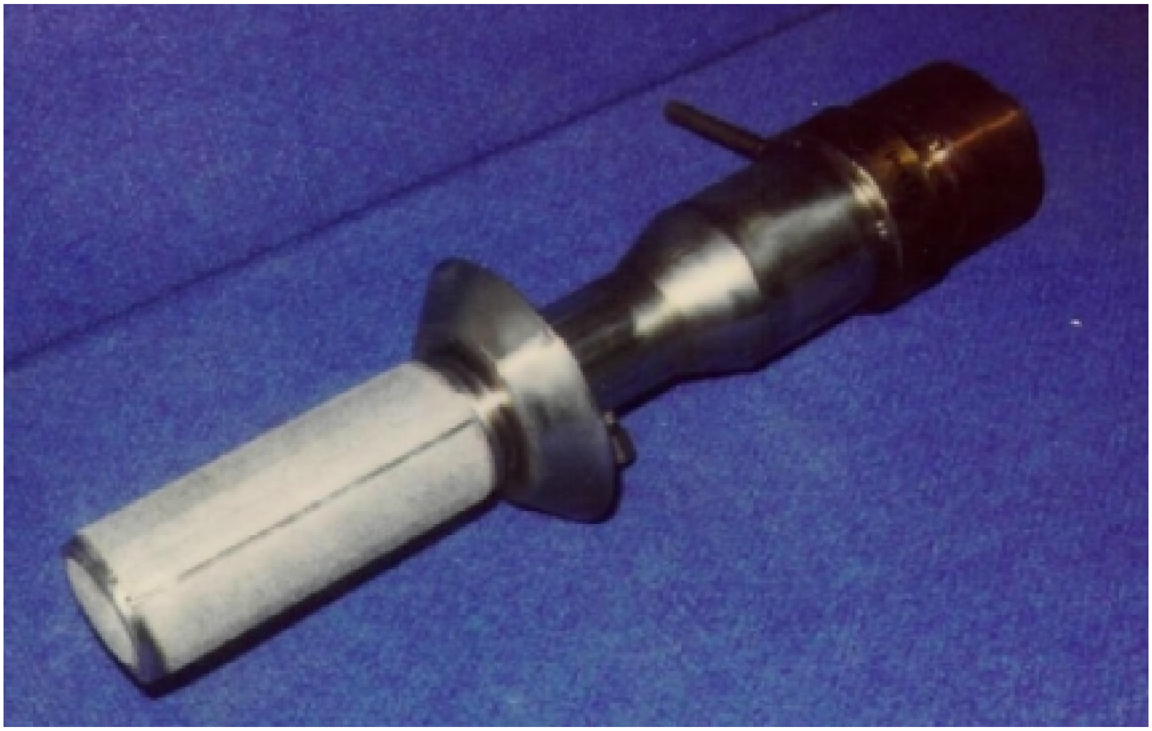

Figure 29. Photograph of Re-Designed Burner

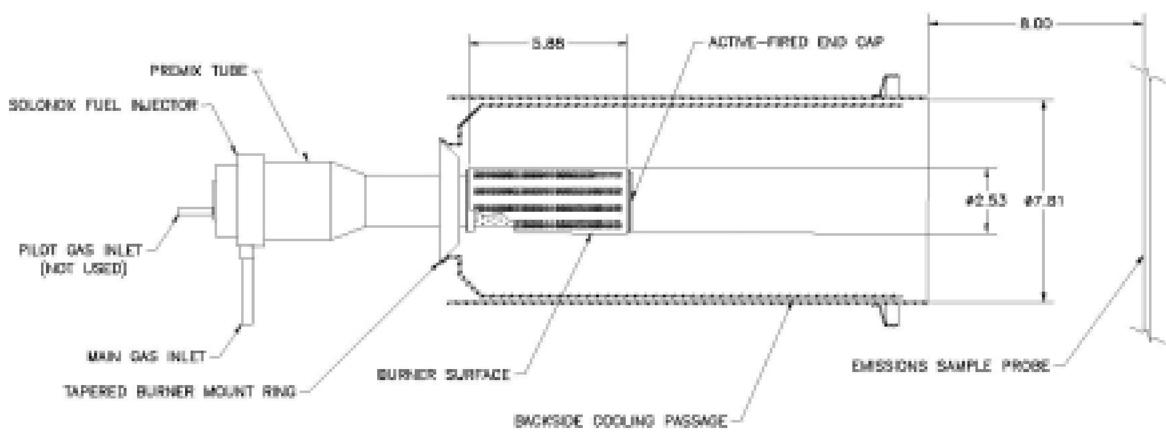

Figure 30. Backside-Cooled Liner Test Assembly

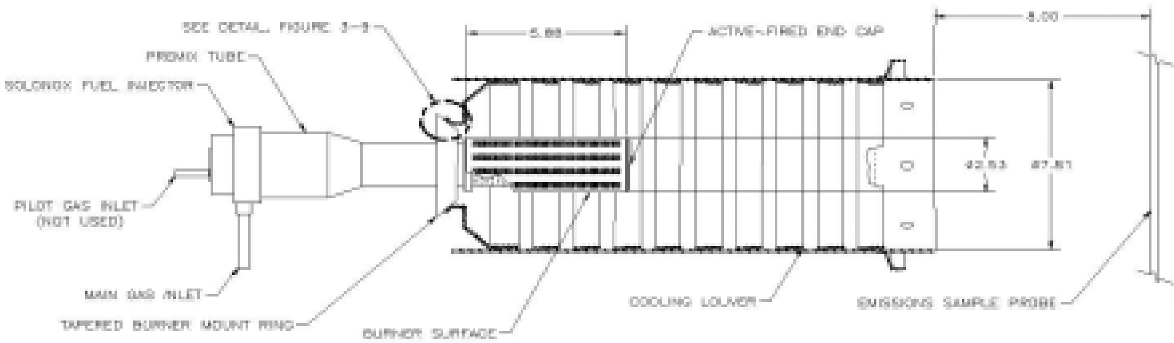

Figure 31. Modified Louvered Liner Test Assembly

The second set of tests at Solar occurred over the course of several days in December 1998. A test plan was devised using the same three critical process variables: adiabatic flame temperature, firing rate, and pressure. Pressures were carefully chosen to correspond to various load conditions of the Centaur 50 engine (25 percent, 50 percent, 75 percent, and 100 percent load). Firing rates were constrained by the size of the test rig and the burner, and were again scaled to maintain normalized surface firing rates around 1 MMBtu/hr/ft^2/atm. Adiabatic flame temperatures were varied from 3250°F at the high-temperature limit to low limits near lean flameout.

The burner was first tested in the backside-cooled liner (Appendix V). NO_x emissions for this test were very similar to the previous test at Solar. Figure 32 shows the NO_x emissions for both liner tests using the re-designed burner. CO and hydrocarbon emissions were at first surprisingly high, not significantly reduced by the change in liner. Ultimately, the CO was controllable in this liner by operating at high adiabatic flame temperature. Several test points were recorded with CO emissions below 10 ppm (Figure 12). However, the NO_x production at these conditions was relatively high, nearing and occasionally exceeding 10 ppm. Excellent flame stability was displayed at all test pressures and no overheat problems were encountered.

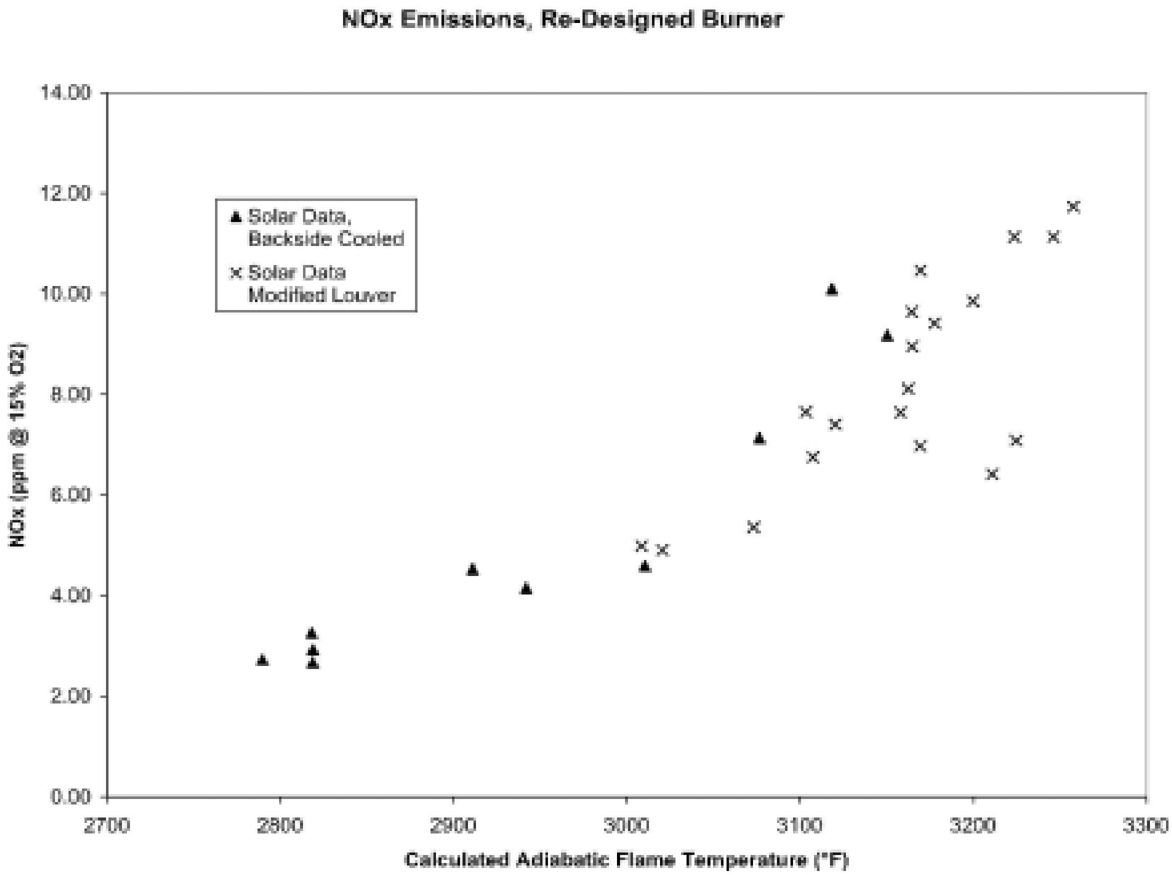

Figure 32. NO_x Emissions, Re-Designed Burner

The modified louvered liner was then installed and another set of tests was executed (Appendix VI). Again, the NO_x emissions essentially duplicated the earlier data when plotted against adiabatic flame temperature (Figure 32 and Figure 33). However, flame stability was difficult to achieve at the customary adiabatic flame temperatures. Thus the burner was generally operated at elevated flame temperatures, and NO_x emissions were correspondingly higher. The CO levels produced in this liner were as high as those in the original louvered liner and could not be brought down without risking a burner overheat. The test matrix was adjusted to account for the flame stability problems and the revised matrix was successfully completed without incident.

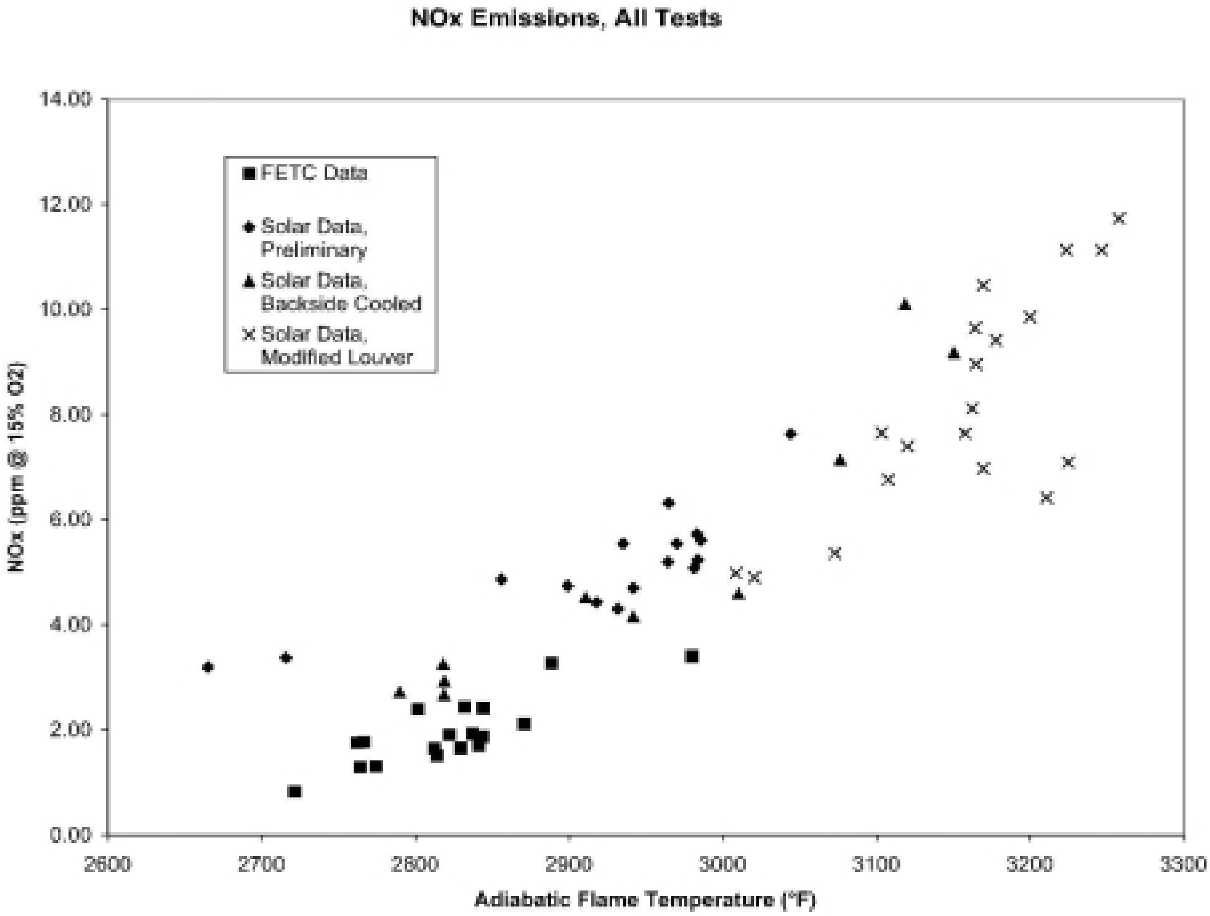

Figure 33. NO_x Emissions, All Tests

The testing of the re-designed burner in two different liners at Solar Turbines was largely a success. NO_x emissions continued to be low enough to offer a significant advantage over currently available technology. With increased experience, burner operation and testing continued to grow easier. A comfortable operating envelope for the burner was well defined. It centers on a normalized surface firing rate of 1 MMBtu/hr/ft²/atm where stable operation was demonstrated in all testing (Figure 34).

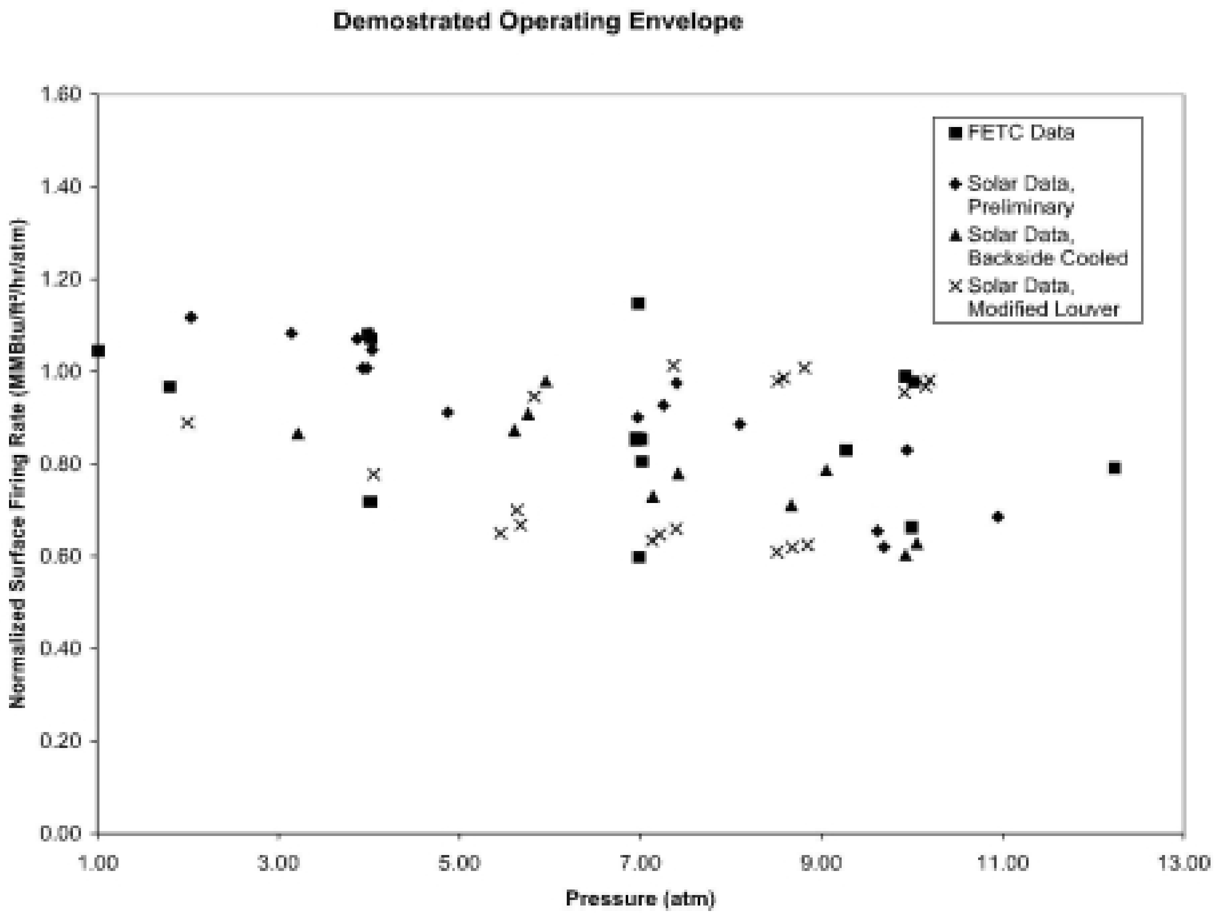

Figure 34. Demonstrated Operating Envelope

The continued high emissions of CO and hydrocarbons were again due to the intrusion of cooling air. The improvements made in the burner and liner designs were counteracted by a more substantial leak at the burner/liner interface. Only at the hottest of operating conditions was the combustor hot enough to effect a downstream burnout of the CO and hydrocarbons produced at the inlet due to this leak. At all other operating conditions, the ultimate emissions that were recorded were adversely affected.

3.3.2 Honeywell Combustor Design

Successful results in previous testing showed that the Alzeta GTSB combustor was capable of achieving extremely low emissions when fired under simulated gas turbine operating conditions. However, the combustor had not yet been engineered and designed for any one specific gas turbine application. Furthermore, several improvements in the design and manufacturing process were required in order to bring the combustor into an actual turbine. Honeywell's Parallon 75 was chosen as the target engine, and the effort to mate the two technologies was begun.

There are five independent variables that control combustion in the GTSB. These are:

- System pressure
- Preheat
- Fuel flow (or firing rate)
- Total system air flow
- Air flow to the burner (or percent air split)

The operating characteristics of the Parallon 75 dictate specific values for the first four parameters in the above list. These values vary depending on ambient temperatures and load conditions, but are intrinsic to the turbine and must be adhered to by any viable combustor. The only parameter that Alzeta could manipulate in the design was the airflow to the burner. Adjusting the effective area of the combustor liner relative to the burner, thus diverting either more or less air around the burner could control this flow rate. All test plans for Alzeta lab testing were constructed to simulate the Parallon 75 operating conditions and adjust the air split to achieve optimal emissions and flame stability.

The burner hardware itself required a number of changes from the design tested at FETC in July 1998. Most significantly, the FETC burner was oversized for use in the Parallon 75 application. Extensive testing has determined that the optimal Normalized Surface Firing Rate for the GTSB is approximately one MMBtu/hr/ft^2/atm. Thus, at a full-load four atm, one MMBtu/hr operating condition, the Parallon 75 would only require about .25 ft^2 of burner surface compared to the .50 ft^2 FETC burner. Furthermore, the FETC burner had a four-inch outer diameter and was designed to fire in an 11-inch diameter combustor liner. The Parallon 75 liner is only about 7 inches in diameter. Thus a reduction in burner diameter was necessary in order to avoid flame impingement and quenching of combustion by the liner. The revised burner design, also shown in Figure 19, featured an outer diameter of 2.5 inches and a length of 4 inches in order to yield the proper firing rate.

The shift to a smaller burner precipitated the need for advances in perforation and welding techniques. The tight space constraints of the Parallon 75 liner and the decrease in burner diameter demanded that both the perforated stripes and the unperforated regions between stripes be narrower. This meant a departure from Alzeta’s standard SB perforation pattern. In order to achieve rapid prototyping of a variety of patterns, automated laser punching of individual holes was employed. While prohibitively expensive for production volumes, this technique offered excellent versatility and quality control for test units. The pattern that was utilized featured stripes of about half the former width, resulting in flame cones of about half the height. The custom perforating also allowed for the placement of an un-perforated margin of material along all required seams. This resulted in cleaner welds and less potential for leaking. Furthermore, the welding technique was revised from an intermittent resistance spot weld to a continuous butt weld. Not only did this increase weld integrity, but it also made the welded seams narrower, thus reducing the potential for overheating in these low-flow zones.

Another required advance was the introduction of an active-fired end cap. The FETC burner, being an early prototype, featured a solid steel end cap externally insulated with ceramic blanket and board. While this design was adequate for initial tests, it carried the risk of overheating, increased the potential for debris reaching the turbine blades, and failed to take full advantage of the available space for burner surface. An active-fired end cap clearly was a superior design and its implementation was a high priority. Several end cap styles were considered and a handful were fabricated and tested. These included an un-perforated disc, a standard linear perforation pattern, and a concentric “bulls-eye” perforation pattern. The bulls-eye pattern displayed the greatest flame stability and best emissions characteristics and is currently the preferred design. Figure 35 shows an end-on view of a burner with this end cap being test fired in the Alzeta 75 kW facility.

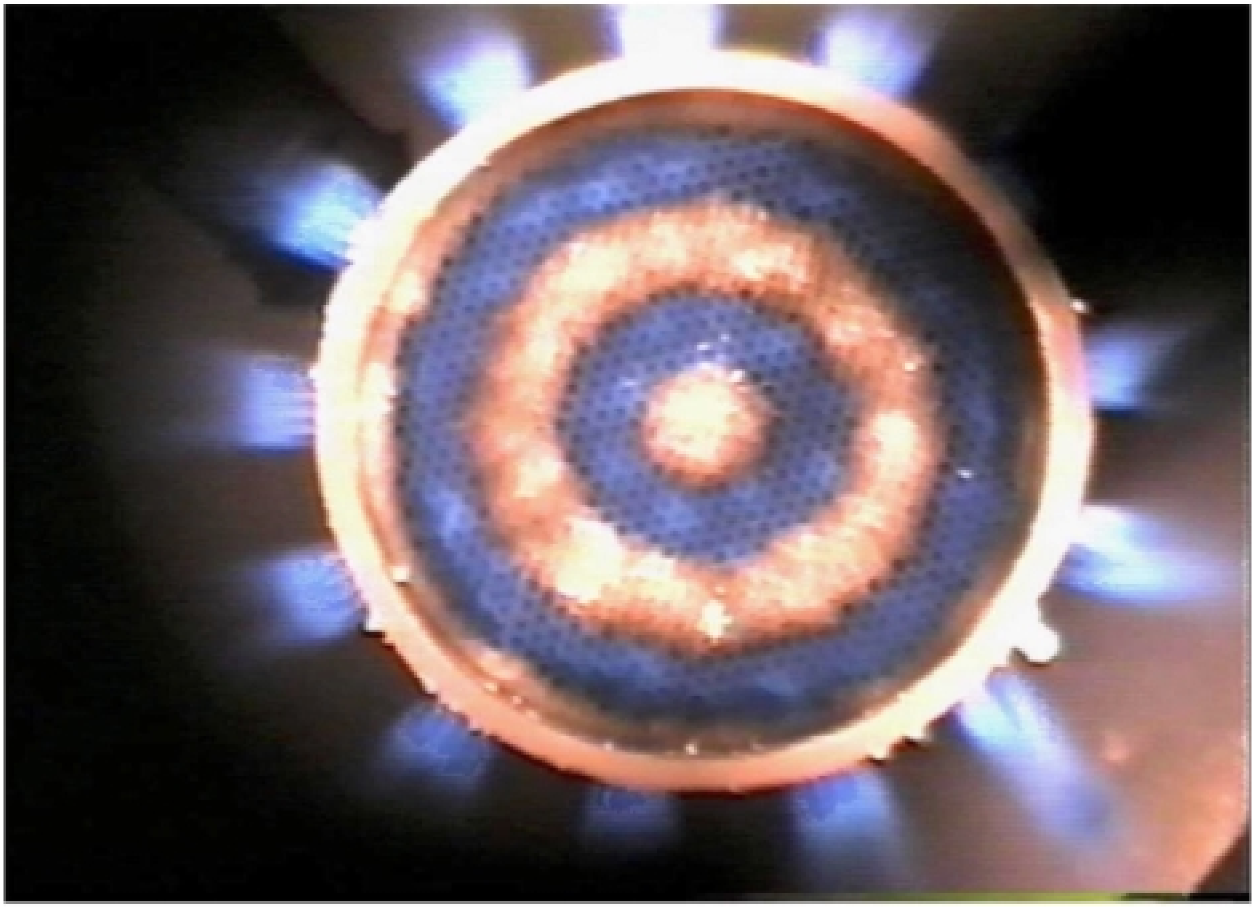

Figure 35. GTSB Combustor With an Active-Fired End Cap

A final improvement was made in the method of mixing the fuel with the combustion air. At FETC, an oversized mixing tube was used for simplicity and in order to ensure a successful test. However, space is at a premium in the Parallon 75 and the air delivery comes from the downstream portion of the combustor and is redirected at the burner entrance. In order to properly mix under these constraints, a new mixing plate was designed. This system injected fuel through a ring of equally spaced jets. These jets were positioned at the point where the airflow turns around and begins to enter the burner itself. This method proved adequate and was used in all of the testing at Alzeta.

3.3.3 Combustor Testing at Other Places

3.3.3.1 Motivation and Design

With successful laboratory tests at Alzeta complete, the GTSB combustor was now ready to undergo preliminary qualification testing at Honeywell's test site. This test marked the first side-by-side cooperative effort between Alzeta engineers and Honeywell engineers, making Honeywell the second major industrial partner to host GTSB testing. Also, for the first time, the GTSB was tested in actual turbine hardware. The Honeywell Engines test rig features the same air inlet, combustor housing, and interfaces as the actual Parallon 75 gas turbine engine. Thus, this test was a major step forward in the development of the GTSB.

As mentioned earlier thermodynamic analysis of the turbine and the combustor indicated that a simple static air split between the burner and the liner would not provide low emissions and flame stability at every Parallon load condition. Possible solutions to this dilemma include variable air geometry, multiple or pilot burners, or a segmented burner design. However, since each of these solutions represented a significant advance in the current design, Alzeta opted to first perform a simpler test at Honeywell. This first test would demonstrate the GTSB operating with low NO_x at the full-load Parallon operating condition. Several other intermediate points would be visited on the way to full-load, but these would not necessarily correspond to the air-to-fuel ratios required by Parallon partial load conditions. This test, though not comprehensive, would provide an important stepping stone in the process of qualifying the GTSB for use in the Parallon 75. Alzeta and Honeywell would gain experience working together and with each other's hardware. Any basic hardware problems could be identified and troubleshot. This test would also allow quantification of the basic air split between the GTSB burner and the combustor liner. This information will be critical in future advanced designs. Finally, an uncomplicated test increased the chances that excellent results would be achieved on the first attempt.

The design of the combustor for this test presented several novel challenges. The burner itself and the louvered liner would be essentially the same as the ones used in the most recent round of Alzeta tests. However, the new combustor design would implement Honeywell's air swirler and gas injector. These components are integral parts of Honeywell's existing combustor technology. Much like the SoloNox injector used in GTSB testing at Solar, the Honeywell injector achieves a uniform mixture of gas and air in a short distance. This mixture is then fed to the GTSB burner rather than immediately combusted as it would be in the current Honeywell configuration. Honeywell's pilot burner, which is located in the center of the main burner and used for ignition and partial-load conditions, was capped off and not utilized in this test.

For testing purposes, several features were added to the combustor design that would not be present in an actual production model. First, a viewing port and sight glass were added to the side of the combustor to allow visual access to the burner. By utilizing a video camera and TV monitor, Alzeta engineers would be able to view the burner surface while the test was in progress and make adjustments to the operating conditions based on burner appearance. In previous testing, this visual access had been a valuable tool, so this was considered an important design feature.

To calculate the air split mentioned above, it is necessary to know the amount of excess air in the premix reaching the burner itself. For this reason, a sample tube was inserted on the inside of the burner and run through a pressure-tight penetration in the combustor shell. This sample line was then run to Alzeta's Thermox premix analyzer for real-time measurement of the oxygen content of the premix. In addition to aiding data reduction calculations, this information would also help the test operators to make adjustments in air-to-fuel ratio while the test was being run. Furthermore, this same sample line allowed for a pressure measurement inside the burner itself, providing information on the pressure losses encountered through the burner surface. A high voltage spark rod entering the combustor from the side and grounding directly to the burner surface provided ignition for this test.

To successfully mate with the test rig, the combustor design needed to maintain several strict tolerances. This first combustor shell was designed to utilize standard pipe parts and package the combustor in a compact and durable housing. Precision-milled flanges provided the exterior interface to the test rig and established a specific insertion depth of the hardware. Within the shell, the exit end of the GTSB liner had to insert into the test rig exhaust inlet. To ensure a smooth and leak-free fit, it was essential that concentricity be maintained between the liner and the external flange. This was accomplished through alignment rods and careful fabrication techniques. Figure 36 is a drawing of the combustor and Figure 37 is a photograph of the assembled combustor, including a spare burner element.

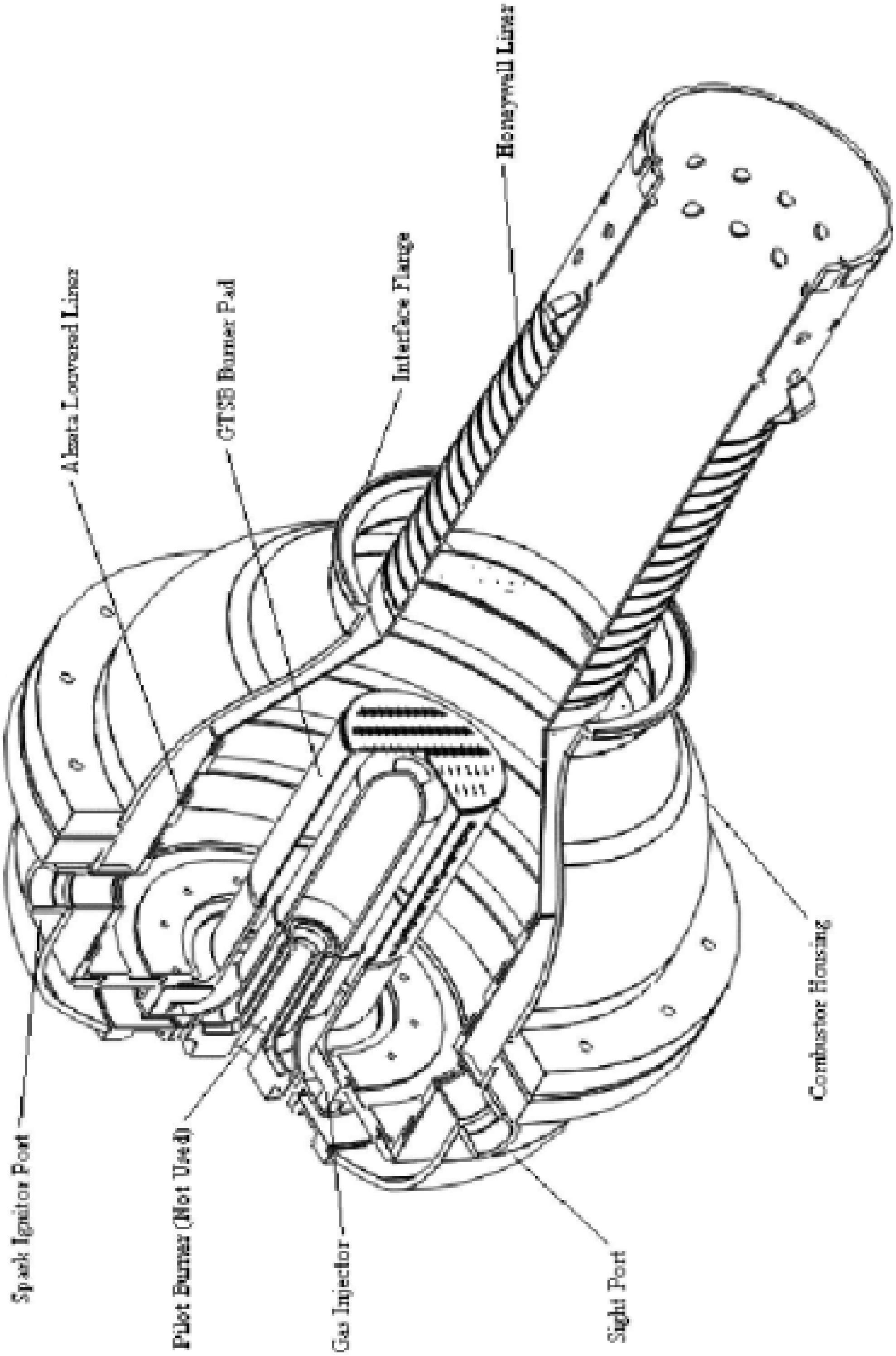

Figure 36. GTSB Combustor For Honeywell Test, Cut-Away View

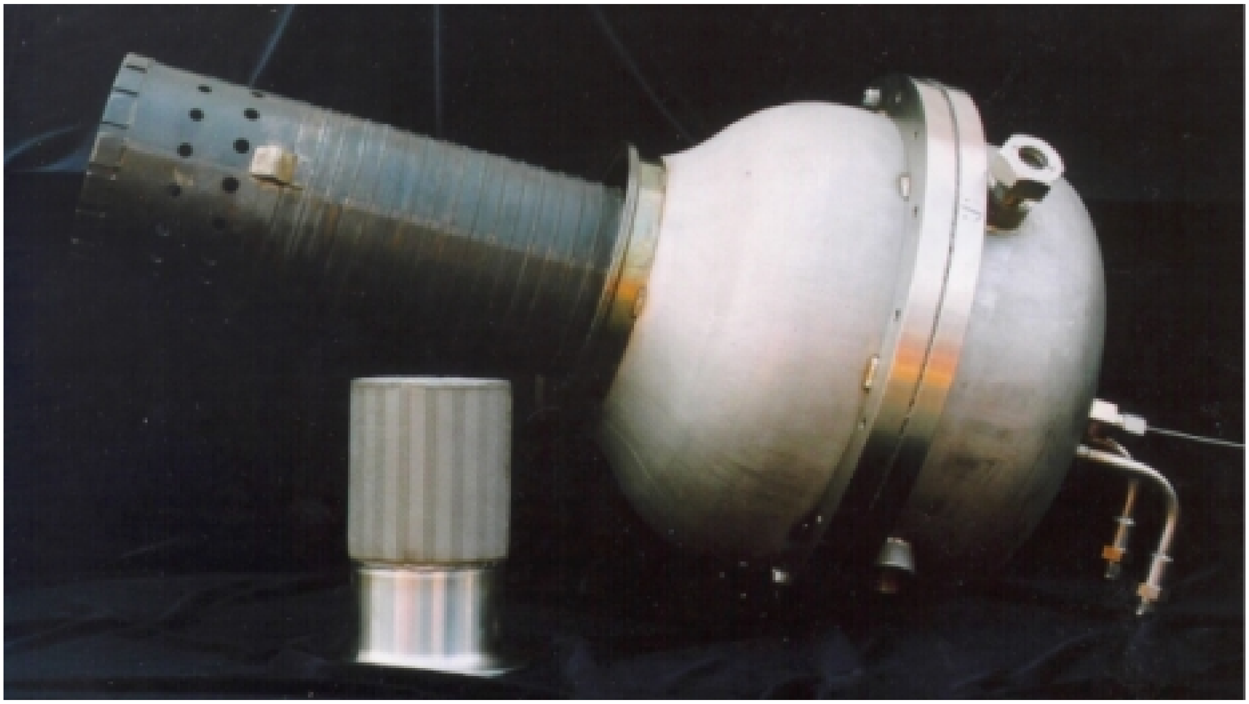

Figure 37. Photograph of GTSB Combustor For Honeywell Test

A final challenge in the design and assembly of the new combustor was the placement of an array of thermocouples inside the combustor. Honeywell requested temperature data a lot more thorough than Alzeta had been able to provide in previous tests. Consequently, 20 type-K thermocouples were attached to the inside of the combustor. Figure 38 shows the locations of these thermocouples. Most of these were welded in place, though a couple inside the burner was freestanding. The thermocouples were then routed through the combustor and out through pressure-tight penetrations in the combustor shell. The leads were connected to Honeywell's digital data acquisition system, allowing both real-time temperature monitoring and permanent recording of the data.

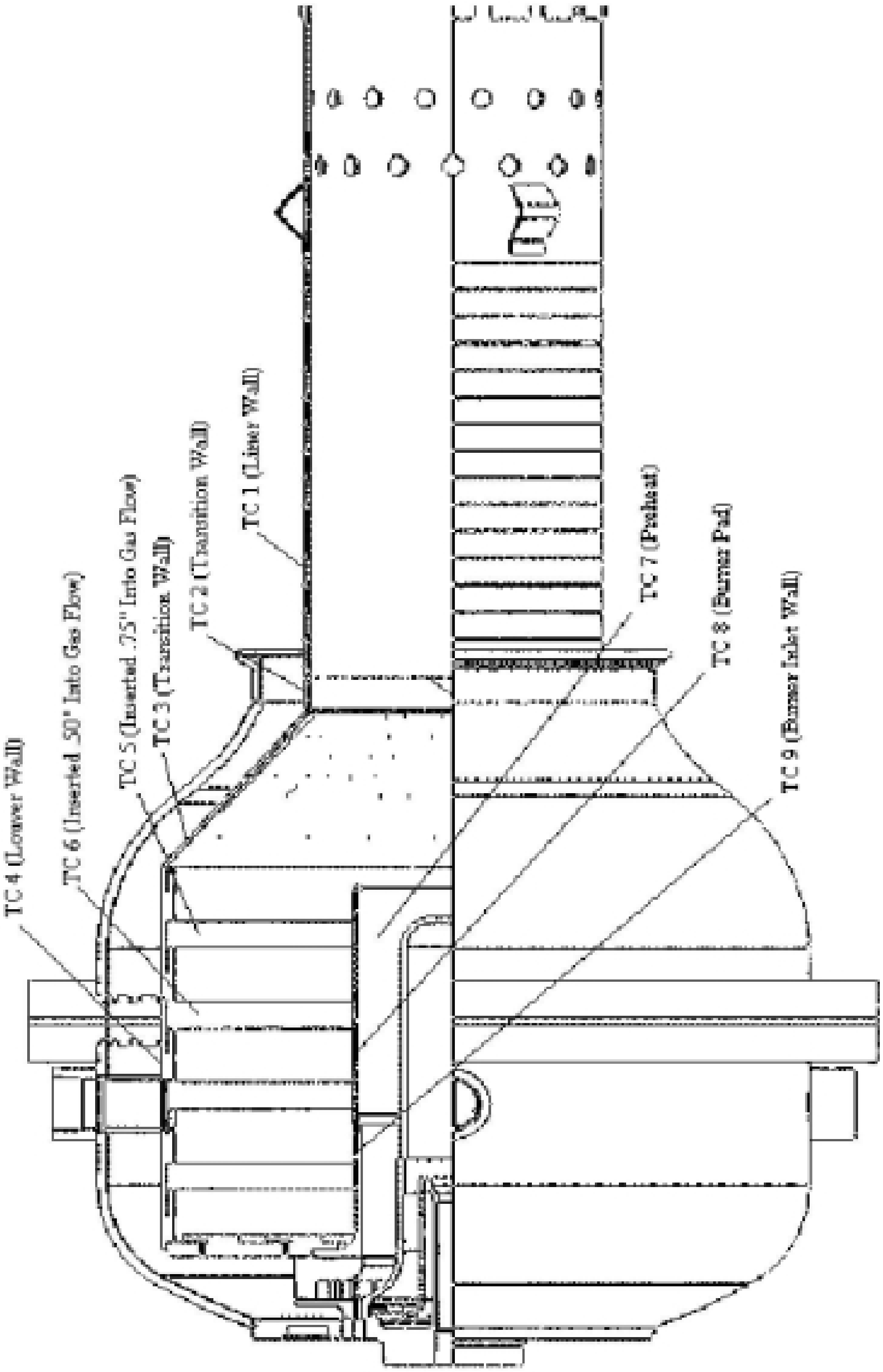

Figure 38. Thermocouple Locations for Honeywell Test

3.3.3.2 Test Results

Testing of the new combustor was conducted on February 1, 2000 at Honeywell Engines' Phoenix test facility. The rig used for this test was the same one that Honeywell uses to qualify their own Parallon 75 combustors. The facility is capable of supplying air flow rates, fuel flow rates, preheat temperatures, and combustor pressures in excess of those found in the Parallon 75 gas turbine engine. The rig itself features actual parts from the Parallon turbine design. It is fully equipped with thermocouples, pressure transducers, and flow meters. All of the instrumentation and controls wiring runs from the test rig to the operator controls and data acquisition system located in an adjacent control room. Data from these instruments were displayed during the test and time-averaged samples were digitally recorded at various points.

This control room is isolated from the test for safety reasons by a thick concrete wall. A pair of small windows provides visual access to the test bay in case of emergency. For the purposes of this test, a Thermox premix analyzer was placed inside the test bay so that it would be visible through one of these windows. The Thermox was connected to the combustor and provided real-time information about the air split between the burner and the combustor liner.

A video camera was placed inside the test cell in order to allow visual access to the burner. The video feed from the camera was run to the control room and connected to a 27" television monitor and VCR. Images from the camera were recorded throughout testing. Emissions samples were taken continuously by Honeywell's portable emissions truck, located just outside the building. Emissions data from the truck were available inside the control room for real-time analysis of combustor performance. At discrete conditions specified by the test plan, these data were also recorded for future reduction.

Honeywell provided a test technician to actuate the valves that control airflow, fuel flow and pressure. Alzeta engineers guided the technician based on the pre-determined test plan and observations of combustor performance. A Honeywell engineer was also present at all times to oversee the test and perform data collection. This team of three to four personnel successfully guided the combustor through this complicated test sequence.

The physical hookup of the combustor hardware and instrumentation occurred smoothly. Ignition at near atmospheric pressure was reliable and repeatable. The combustor displayed stable operation up to three atmospheres pressure and with fuel flows ranging from 12 lb/hr to 32 lb/hr. No combustion noise or pressure oscillations were observed during testing.

Appendix VII provides the raw data collected during this test. Each data point represents time-averaged data captured over the course of two seconds. The emissions data were excellent, confirming data collected during previous tests. Figure 39 provides a plot of NO_x vs. Flame Temperature. This plot shows the expected trend of NO_x production increasing with flame temperature. Minimal NO_x production occurred at a flame temperature just over 2600°F, the lowest flame temperature successfully stabilized. NO_x production was frequently below five ppm (corrected to 15 percent O_2), and a handful of points were recorded near 1 ppm. NO_x and CO were simultaneously below nine ppm at many of the test conditions. Unburned hydrocarbons were virtually non-existent except at the leanest of conditions.

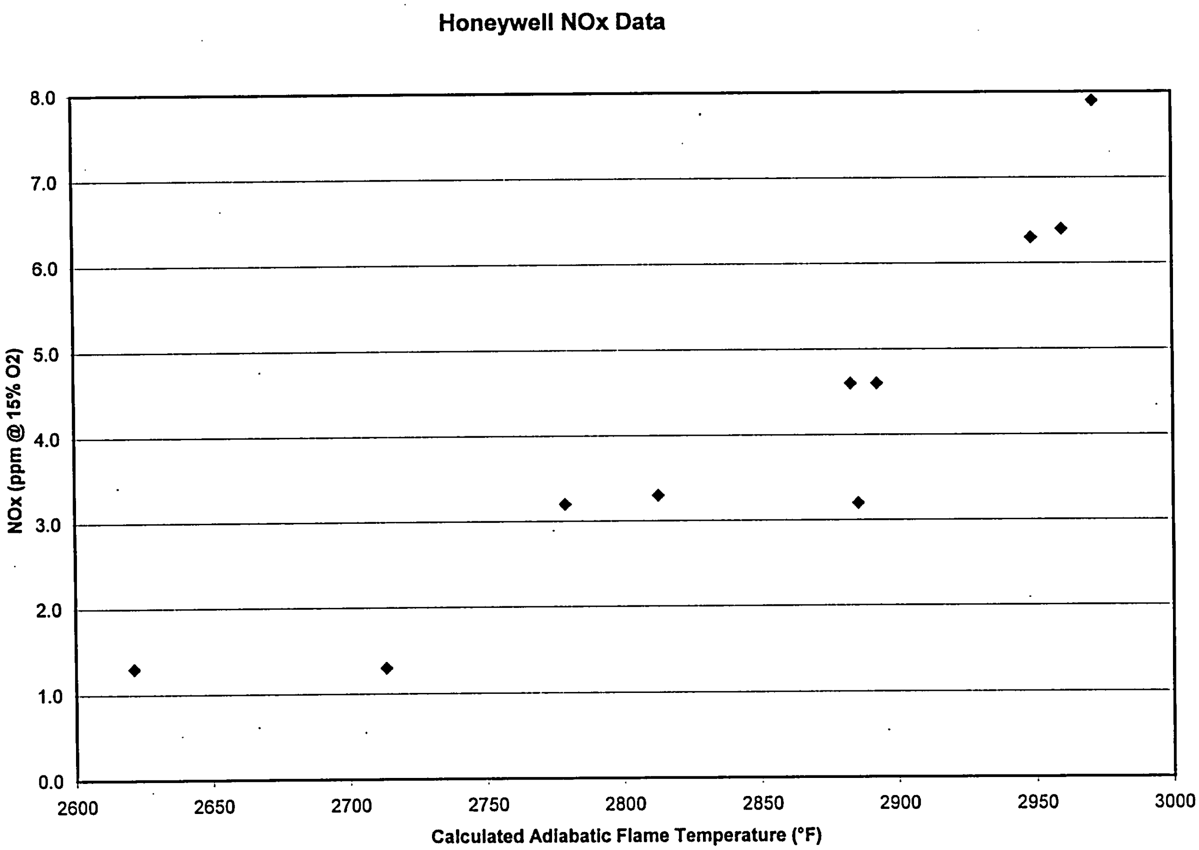

Figure 39. NO_x Emissions from Honeywell Test

The thermocouple data provided a good deal of insight into the thermal environment inside the combustor. Figure 40 is a plot of temperatures collected from thermocouples at various points on the combustor liner. The observed temperatures were quite uniform around the circumference of the combustor, so each point on this plot represents the average of the three thermocouples at the indicated station. The temperatures are plotted against the condition numbers, which are arranged chronologically and thus give a reasonable picture of the progression of the tests. Figure 41 displays temperatures collected from on or inside the burner itself. Finally, Figure 42 shows relevant gas temperatures such as the preheat and cooling air temperatures. All of these temperatures are adequately low to not present a detriment to the lifetime of the combustor.

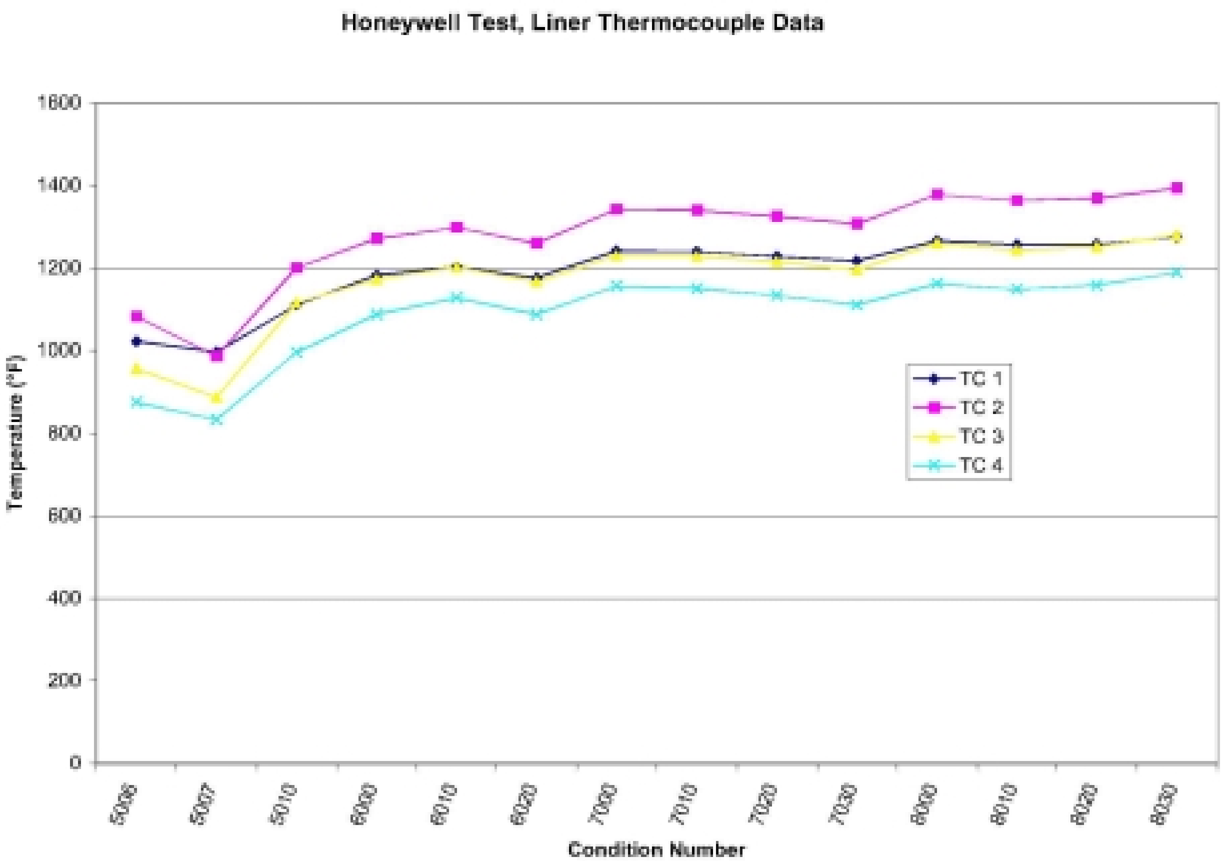

Figure 40. Honeywell Test, Liner Thermocouple Data

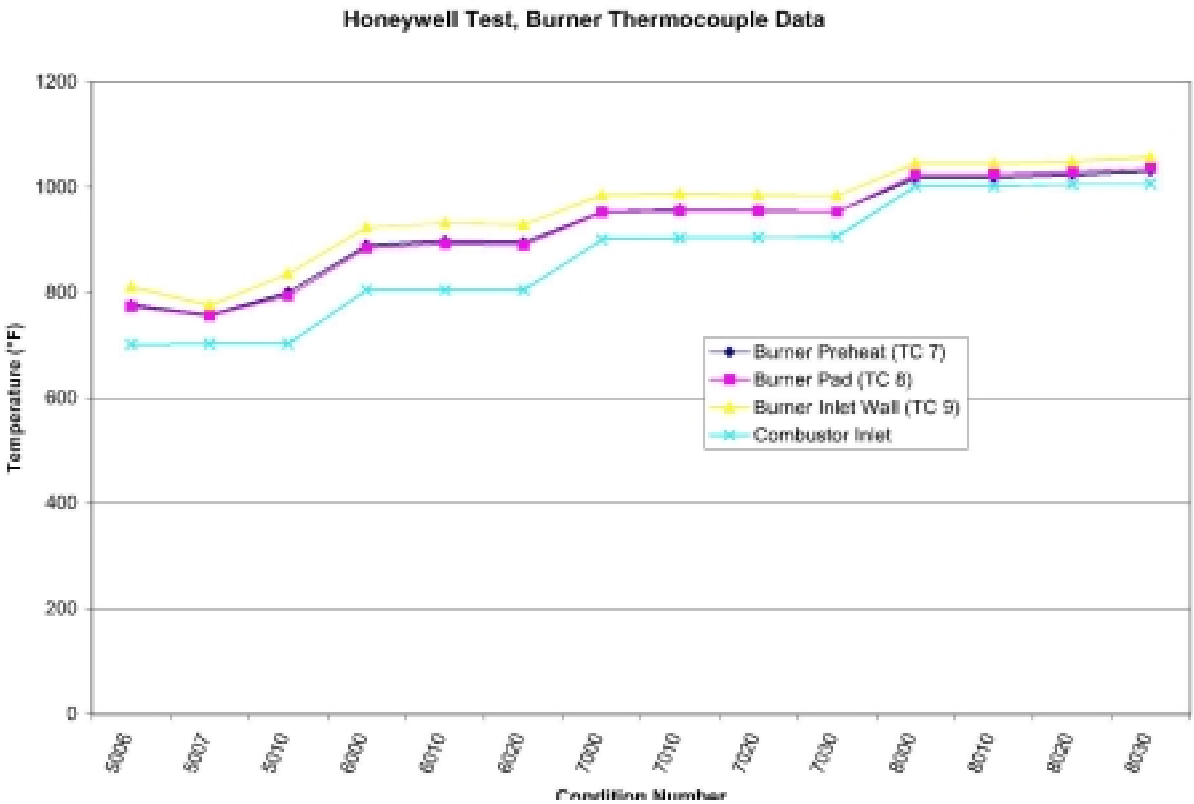

Figure 41. Honeywell Test, Burner Thermocouple Data

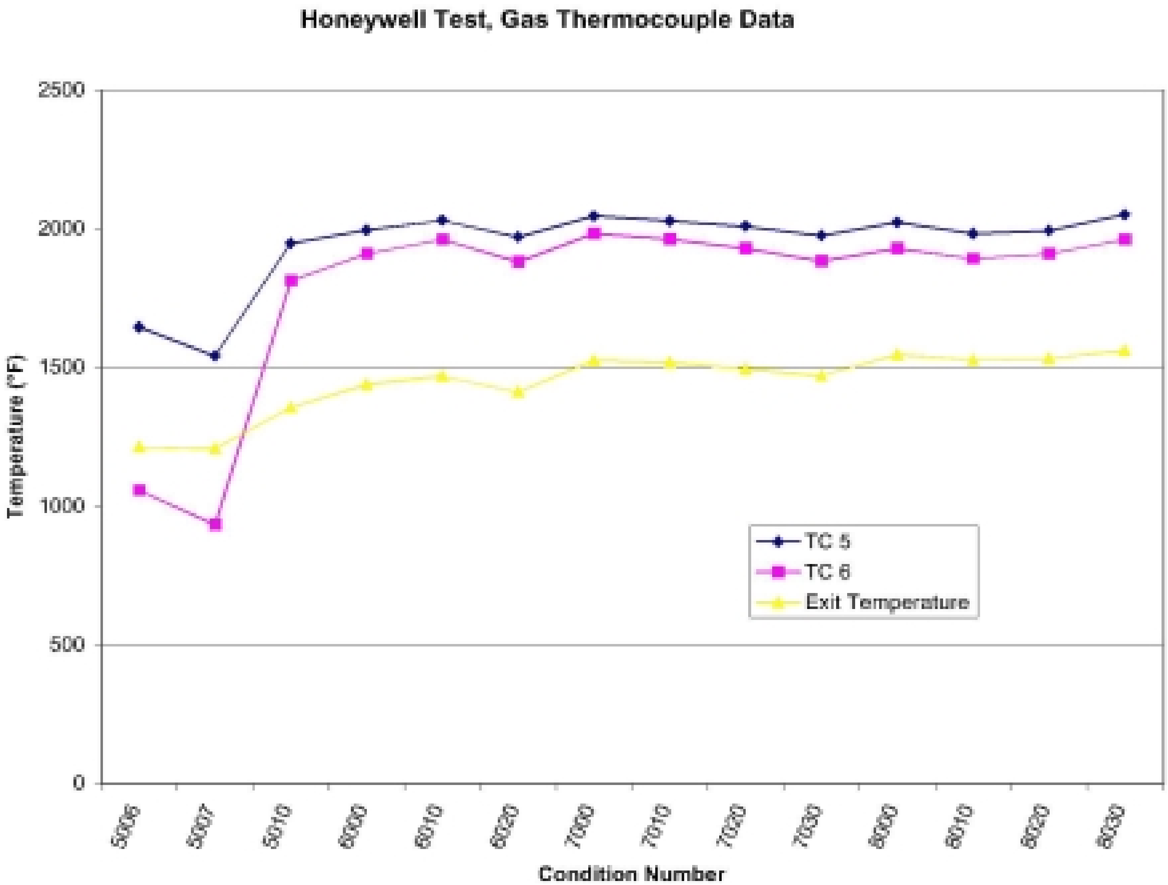

Figure 42. Honeywell Test, Gas Thermocouple Data

The temperature data for all of the thermocouples increase nearly monotonically throughout the test. This is because the test plan called for a continually increasing preheat temperature, and the effects of this preheat are seen throughout the combustor. However, the liner and burner temperatures do seem to increase less dramatically as the tests progress. For instance, Condition 5010 features a combustor inlet temperature of 700°F, a burner inlet wall temperature of 840°F and a liner (TC1) temperature of 1110°F. At the end of the data, Condition 8030, the inlet temperature has increased 300°F to 1000°F. However the inlet wall temperature is 1060°F (an increase of 220°F) and the liner temperature is only 1275°F (an increase of 165°F).

Pressure loss data were also collected throughout the test. Since the design essentially added additional hardware downstream of Honeywell's existing hardware, the pressure drops observed were expectedly higher than Honeywell's standard combustor. Pressure losses averaged between seven percent and eight percent of the combustor inlet pressure, as opposed to the three percent or four percent normally seen in turbines. This pressure loss increased as preheat and total airflow increased. However, there was a slight dip in the pressure loss at one point, most likely due to the development of a small air leak somewhere on the combustor or test rig.

Near the completion of the intended test cycle, the burner did experience a failure. Fuel flow and pressure had reached a level about 80 percent of the way to the full-load condition. At this highly recuperated hot operating condition, ignition occurred inside the burner behind the pad surface. Unfortunately, the burner itself was destroyed before fuel flow could be shut down, but no damage to the liner or test rig was evident.

3.3.3.3 Summary

Although the full-load operating condition was not achieved, the initial tests at Honeywell were considered a success. The emissions were consistently below project goals, and far below Honeywell's existing combustor technology. Ultra-low NO_x numbers below 2 ppm were demonstrated, and Honeywell engineers were quite impressed. The temperature data collected were also impressive to Honeywell. Prior to testing, concerns had been raised about the temperature of the combustor liner and the impact it might have on material selection and component lifetime. However, even at the hottest operating conditions, the liner temperatures never exceeded 1400°F. This is well within the realm where standard turbine materials are appropriate, so no thermal barrier coatings appear to be required. Furthermore, the temperatures collected at various locations around the circumference of the combustor were reasonably uniform. This is important in order to minimize thermal stresses on the rotor and stator blades downstream.

The combustor pressure losses experienced in this test were unacceptably high for a commercial product. However, there are several things that can be done in future designs to significantly reduce these losses. The most important change involves opening up larger passages for air to reach the burner itself. The existing Honeywell air swirler could be modified to include larger passages, or the entire component could be re-designed. Since the GTSB features inherent flame stability and an extended mixing length, these changes should not negatively impact combustor performance. Once the air passages to the burner are opened up, dilution holes downstream can be added to further reduce pressure loses while maintaining acceptable air splits. Furthermore, Honeywell’s pilot burner, capped off for this test, provides additional airflow passages. Future GTSB designs will take advantage of these passages in one form or another. All of these changes, when incorporated into future designs, will reduce the combustor pressure loss and should bring it within commercially acceptable ranges.

An important result of this preliminary test was the determination of the static airflow split between the burner and the liner in this version of the GTSB combustor. Prior to testing, it was estimated that approximately 35 percent of the air entering the engine would reach the burner. Test results indicate that the appropriate number is more like 25 percent. Adjustments were made to the test conditions while the test was being conducted in order to compensate for this discrepancy. The quantification of this split will allow a more precise design for the next combustor, which will be configured to provide low emissions at both full and partial load conditions. This will be accomplished through the implementation of a segmented burner design. The segmented design will allow for fuel flow to specific parts of the burner to be turned on or off as load conditions dictate. This scheme allows for simple gas controls, outside of the harsh environment combustor itself, to provide the actuation required for load tracking, thus avoiding one of the major drawbacks of traditional variable geometry.

The path for continued development of the GTSB combustor for use in the Honeywell Parallon 75 turbine has been fairly well defined. The first cooperative step between Alzeta and Honeywell was the initial test described in this section. This test established the functionality of the GTSB in the Parallon 75 environment. The next step in the development involves the design and testing of a preliminary segmented burner of the type mentioned above. Although analysis seems to indicate that a production-model combustor would need to include 3 or more segments, the first segmented burner will employ only two segments. This scheme will be easily adaptable to the current Honeywell controls configuration, and will provide a simple proof-of-concept test for the segmented burner design. The burner for this test is currently being designed, and will hopefully be demonstrated in Honeywell's test facility within the next few months.

The next step in the development would involve the design and demonstration of a 3-segment burner. This burner would use the same segmentation concepts as its predecessor, but the addition of a third segment would allow it to display stable, low-emissions operation from full load down to 50 percent load and possibly beyond. Although changes would be required to Honeywell's controls and upstream hardware in order to implement such a combustor, the scheme would still be preferable to traditional variable geometry. Following the successful completion of the 3-segment burner test, proof-of-concept testing would be complete. The GTSB design would be refined to meet production standards, and final qualification testing could begin.

Parallel to this test sequence would be a research and development effort to improve the materials of the GTSB burner. Welding of the burner pad at various seams along the surface removes the porosity of the pad and reduces the inherent cooling provided by the premix flow. This reduction of cooling generates hot spots that are likely the cause of burner failures such as the one experienced in this test sequence. Ultimately, Alzeta hopes to remove the need for welds altogether by manufacturing a "monolithic" burner pad. Such a pad would be cast directly into the required cylindrical or conical shape, thus removing several manufacturing steps and the hot spots created by seems. This monolithic burner pad development is a large undertaking, however, and successful results may not be available immediately. Another more readily available method of cooling the seems involves a post-assembly process. After the burner pad has been welded together, additional holes could be punched or laser drilled in the low-porosity region of the weld. These holes would increase the convective cooling in this area to levels close to those experienced in the fully porous areas. The additional cooling may be enough to significantly reduce hot spots and the potential for burner failure. Further details on the future of the GTSB combustor development can be found in Section 4 and Section 6 of this report.

4.0 Outcomes

Great strides were made toward ultimate commercialization of the combustor, and the GTSB is approaching production readiness. Further development work on the GTSB is being planned. The main results of this project are summarized below:

- The combustor design went through several more iterations, each bringing it closer to full commercialization. A final combustor design incorporated all necessary hardware and interfaces to be mated to a Honeywell Parallon 75 gas turbine engine.
- Multiple on-site tests were performed in Alzeta's 50 kW gas turbine combustor test facility. These tests provided valuable information that enabled the GTSB to be designed directly to customer specifications.
- Successful operation was displayed off-site during four separate rigorous test sessions, one at FETC in July 1998, two at Solar Turbines in October and December 1998 and one at Honeywell in February 2000.
- A wide variety of data were collected by systematic variation of combustor pressure (up to 12 atm), preheat temperature (up to 1100°F), heat release rate (up to five MMBtu/hr) and flame temperature (as low as 2650°F and spanning several hundred degrees).
- NO_x emissions consistently met project goals of under 9 ppm (corrected to 15 percent O2) and often were less than two ppm.
- CO and hydrocarbon emissions were extremely low in the majority of the tests (under nine ppm).
- Project goals regarding pressure loss, turndown, and ignition were consistently met.
- Volumetric heat release rates were increased by employing an outward-fired folded geometry, reducing the size of peripheral components, and experimentally defining burner mass flow as a function of operating pressure.
- A number of improvements were made in manufacturing techniques that will lead to improved performance and reduced costs in production units.

5.0 Conclusions And Recommendations

5.1 Conclusions

The GTSB has now been tested at the facilities of two major gas turbine manufacturers and full commercialization is imminent. Several facts became clear as a result of this project:

- Excellent emissions are attainable at reproducible operating conditions corresponding to actual turbine operating conditions.
- Outward-fired burners are the preferred configuration for the targeted engines.
- It is possible to successfully package an entire mixer/burner assembly within the space available in commercial gas turbine engines.
- The flow rate of premix through the burner surface (or firing rate) needs to be increased linearly as pressure is increased to maintain a nearly constant velocity through the burner surface.
- Increased levels of preheat typical of recuperated gas turbines, such as the Parallon 75, lead to increased flame stability at lower flame temperatures and thus result in lower NO_x emissions.
- Any injection of cooling air into the primary combustion zone needs to be carefully controlled to minimize interaction with the burner surface. Such interaction can result in high emissions of CO and hydrocarbons.

Although the combustor has yet to be tested in an actual engine, the project technical goals were achieved. NO_x emissions comparable to or lower than existing steam injection and selective catalytic reduction (SCR) control systems were consistently exhibited. The potential for ultra-low NO_x emissions (under 2 ppm) was demonstrated at a number of specific operating conditions. Low levels of CO and unburned hydrocarbons could be achieved throughout many operating conditions. The GTSB has now been tested at the facilities of two major gas turbine manufacturers, and full commercialization is imminent.

The combustors displayed good thermal shock resistance to tolerate instantaneous fuel cut off at full load**.** Increased cooperation with Solar Turbines and Honeywell has steered the GTSB design closer and closer to one that can be easily retrofitted into existing engines. The optimized burner became even more compact due to the restrictive nature of the test facilities and the intended engines. The burner demonstrated turndown over the full range of operating pressures that would be encountered in the Honeywell Parallon 75 engine. Preheat in excess of 1000°F was applied during the tests. The combustors survived these elevated preheat temperatures and were actually able to operate at lower flame temperatures, resulting in lower NO_x emissions.

Manufacturing improvements resulted in a more reliable combustor with an increased expected lifetime. All of the designs were modular, and thus easily maintained both in Alzeta's manufacturing facility and in the field. Combustor pressure losses were consistently less than five percent of operating pressure and can easily be reduced further with simple design modifications. Estimates of combustor lifetime and cost were refined and remain encouraging.

5.2 Benefits to California

When the GTSB is commercialized in gas turbine engines, it will provide the State of California with:

- **Improved fuel efficiency** through enabling clean, cost effective, high efficiency co-generation to remain competitive in the face of increasing NO_x controls
- **Lower fuel usage** due to potential elimination of SCR, which requires ammonia, derived from natural gas.
- **Reduced cost of power** due to reduced capital and operating costs associated with production of peak power.
- **Reduced environmental pollutant emissions** from industrial and power generation facilities.
- **Improved capital utilization** that reduces power costs and improves industrial competitiveness.
- **Products manufactured in California** creating jobs and economic activity.

5.3 Recommendations

Many interesting phenomena have been discovered during the course of work on this contract. An exhaustive exploration of pressurized combustion using a GTSB combustor would now be possible and would certainly be interesting. However, this process is not a necessary precursor to commercialization of the GTSB in a gas turbine environment. Several facts have become clear as a result of this study:

- Excellent emissions are attainable at reproducible operating conditions corresponding to actual turbine operating conditions.
- Outward-fired burners are the preferred configuration for the targeted engines.

- It is possible to successfully package an entire mixer/burner assembly within the space available in commercial gas turbine engines.
- The flow rate of premix through the burner surface (or firing rate) needs to be increased linearly as pressure is increased to maintain a nearly constant velocity through the burner surface.
- Increased levels of preheat typical of recuperated gas turbines, such as the Parallon 75, lead to increased flame stability at lower flame temperatures and thus result in lower NO_x emissions.
- Any injection of cooling air into the primary combustion zone needs to be carefully controlled to minimize interaction with the burner surface. Such interaction can result in high emissions of CO and HC.

Future research should attempt to accomplish the following:

- Ensure stable, low-emission combustion throughout the entire operational turndown required by the targeted engines.
- Reduce combustor pressure drop while maintaining adequate mixing and flow uniformity through computational and experimental analysis of several components.
- Further refine capital equipment, operation, and maintenance cost estimates through extended cycle analysis and lifetime testing.
- Improve manufacturing techniques in order to reduce costs and increase combustor life without sacrificing performance.
- Adapt the burner for use in additional engines, potentially including dual-fuel operation or highly recuperated engines.
- Develop simple, reliable control systems to operate the burner in industrial turbines.
- Demonstrate field operation of the combustor installed in an operational gas turbine engine.

5.3.1 Design Modifications

There are several design and manufacturing improvements that, when implemented, will increase the attractiveness of the GTSB product. One of the most important advances will be an increase in the operational turndown of the GTSB. Currently, when operating with fixed geometry, the GTSB has difficulty maintaining low-emission operation throughout the full range of air-to-fuel ratios experienced as an engine varies from 0 to 100 percent load. If configured for low NO_x at full load, the GTSB will flameout somewhere around 50 percent load.

In order to maintain a flame at all conditions, the GTSB must be tuned fairly hot at full load, thus producing an unacceptable amount of NO_x. Alzeta is researching several solutions to this problem that do not require traditional variable geometry. One promising solution involves segmenting the GTSB burners such that portions can be turned on and off independently of each other. This would allow low-emission operation at every possible load condition, decreasing the total emissions of the GTSB combustor in the field.

The manufacturing techniques used to assemble the burner must further refined. Many of the potential improvements are outlined in the Production Readiness Plan (see Section 4). These improvements are largely driven by cost reduction efforts, but also offer engineering advantages. Any non-uniformity or asymmetry in the burner surface (such as a seam) can be a potential cause of problems. Unfired regions can overheat when operated under certain conditions. Other areas near the edges of the burner could be subject to incomplete combustion, which contributes to high emissions of CO and HC. Every effort must be made to manufacture the burner in a way that minimizes the number and size of these trouble spots without compromising the overall durability of the product.

The pressure loss associated with the GTSB combustor can be reduced in a number of ways. The SoloNox injector used in tests at Solar Turbines included a swirler and a pilot, both of which contributed to the total pressure loss but may be unnecessary in the final design. Tests at Honeywell used similar pre-existing mixing devices that were not optimized for the GTSB. Alzeta will ultimately cooperate with the turbine manufacturers to design an improved, efficient fuel mixer for use with the GTSB burners. The perforated plate located behind the burner surface, which is used for flow distribution, may also be made obsolete by careful design of the burner geometry. At the very least, the open area of this plate should be able to be increased without adverse effects. The burner surface itself has yet to undergo final optimization with respect to the pattern of perforation. The liner designs also need to undergo further development with respect to the distribution of the cooling air. Any or all of these changes could reduce the pressure loss in the combustor and increase the overall efficiency of the engine.

6.0 Glossary

atm	Atmospheres
BACT	Best Available Control Technology
cfm	Cubic feet per minute
CO	Carbon monoxide
CO_2	Carbon dioxide
Commission	California Energy Commission
CRADA	Cooperative Research and Development Agreement
CSB	Cylindrical super burner
DLN	Dry Low Nox
DVBE	Disabled Veteran Business Enterprise
FETC	Federal Energy Technology Center
FGR	Flue gas recirculation
GTSB	Gas Turbine Semi-radiant Burner
H_2O	Water
Honeywell	Honeywell Engine Systems
KW	Kilowatt

LECTR	Low Emissions Combustor Test and Research
Mbtu	Thousand BTU (British Thermal Unit)
mm	Millimeter
MMBtu	Million BTU
MW	Megawatt
N_2	Nitrogen
Nox	Nitrogen oxide
O_2	Oxygen
PIER	Public Interest Energy Research
ppm	Parts per million
SB	Super burner
SCAQMD	South Coast Air Quality Management District
$SCONO_x$	Trade name for alternative Nox control technology
SCR	Selective catalytic reduction
SSC	Surface Stabilized Combustor
UHC	Unburned hydrocarbons

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Appendix I

Production Readiness Plan

Appendix II

FETC Test Data

Appendix III

Honeywell Load Matching Data

Appendix IV

Preliminary Solar Test Data

Appendix V

Solar Test Data: Backside-Cooled Liner

Appendix VI

Solar Test Data: Louvered Liner

Appendix VII

Honeywell Test Data

Appendix I

Production Readiness Plan

1.0 Introduction and Product Description

In California's deregulated electricity market, distributed power gas turbine generators are playing an increasingly important role. This technology holds the promise of bringing cheaper, more reliable electricity to California's ratepayers while reducing the use of natural resources and the impact on the global environment. With the support of the CEC and several industrial partners, Alzeta Corporation has demonstrated the promise of the Gas Turbine Surface Burner (GTSB). This lean-premix combustor will ultimately offer the following significant advantages over current gas turbine combustors:

- Emissions – Simultaneous sub-2-ppm (corrected to 15 percent O2) emissions of NOx, CO, and hydrocarbons have been repeatedly demonstrated under certain operating conditions in lab tests of the GTSB. A commercial goal of 5 ppm seems viable and would represent a major advance over current lean-premix technology such as Solar Turbines' SoLoNOx injector, which can meet regulations down to 25 ppm.
- Efficiency – DOE's Advanced Turbine System (ATS) program has pushed turbine efficiencies near the 40 percent target for industrial turbines. This efficiency is ultimately limited by the turbine rotor inlet temperature, which cannot exceed maximums set by material concerns. However, the GTSB features a uniform-temperature, controlled flame front, which will enable an increase in operating temperature and a 15 percent increase in turbine efficiency.
- Cost – The increase in efficiency without a corresponding increase in capital equipment cost will result in cheaper electricity generation than current gas turbines can offer. Ultimately, these savings will be passed directly to the California ratepayers.

1.1 The GTSB Technology

The basis of the GTSB combustion system began with the same technology used by Alzeta in many boiler applications. Cost competitiveness in this mature market is at a premium, so the technology has survived in a lean environment. For boilers, the burner surface pad is fixed to an inexpensive carbon steel weldment for placement into a firebox, and premixed gases are pushed through the pad, combusting 1-2 mm above the outer surface. Boilers ranging in size from 3 MMBtu / hr to 180 MMBtu / hr are currently in operation. Proof-of-concept testing of the burner in high-pressure operation is complete and simultaneous emissions of NO_x, CO and unburned hydrocarbons below 2 ppm have been measured. Turbine-compatible designs have been successfully demonstrated in test rigs at both Solar Turbines and Honeywell. The GTSB is nearly ready for commercial production.

The key to the GTSB technology is stable operation at low adiabatic flame temperature. As **Figure I-1** shows, low temperature and short residence time combine to produce low emissions. This curve is obtained from thermal NO_x production calculations from Alzeta's proprietary equilibrium chemistry solver. The figure indicates, for example, that emissions of about 1-ppm would be realized at a flame temperature of 2800°F and a residence time of 0.01 seconds. A reduction of temperature to 2700°F further reduces the NO_x production rate by a factor of 3.

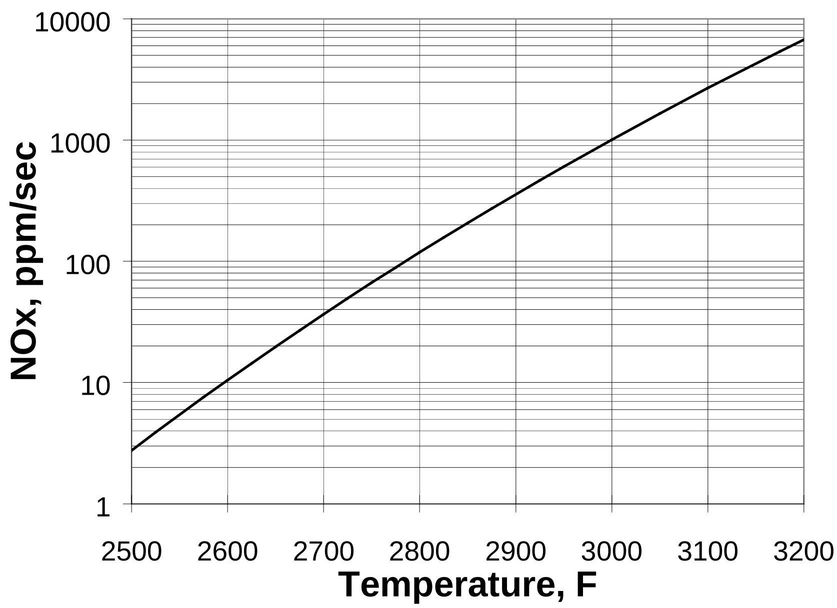

Figure I-1. Typical GTSB NO_x Emissions

An important factor is the uniformity of this temperature, which is only possible with a fully premixed combustion system. Since flame speed also is reduced rapidly with decreasing temperature, it is critical to develop methods to stabilize the flame front.

In the semi-radiant GTSB burner this is done by first establishing a radiant flame zone over a porous metal surface (**Figure I-2**). Premixed fuel comes through this low conductivity surface and burns in narrow zones, A, as it leaves the surface. Secondly, adjacent to these radiant zones, the porous surface is perforated to allow a high flow of the premixed fuel and air. This flow forms a high intensity flame, B, stabilized by the radiant zones. It is possible to achieve very high fluxes of energy, up to 2MMBtu / hr / ft^2 at atmospheric pressure. A picture of an atmospheric burner in operation (**Figure I-3**) clearly shows the technology in action.

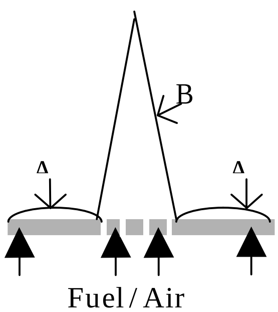

Figure I-2. Schematic of GTSB Burner Pad And Dual Flow Zones

Figure I-3. Photograph of GTSB Burner Pad Firing at Atmospheric Conditions

The application of this technology to the high pressure, high preheat, and compact environment of gas turbine combustors has been established in tests performed over the last year. These tests focused on the determination of the optimal configuration for gas turbine combustion. Typical combustors require volumetric firing rates greater than 2 MMBtu / hr / ft^3. Various folded geometries were investigated to apply surface combustion (where the firing rate scales per ft^2) to the firing rates necessary for gas turbine use.

Tests performed during the summer of 1998 at FETC were configured with the successful outward-fired configuration (**Figure I-4**). These tests demonstrated successful operation to 12 atm, where testing was stopped, and no upper limit has been established. Emissions levels for NO_x and CO during these tests are consistently sub-2 ppm and sub-5 ppm respectively.

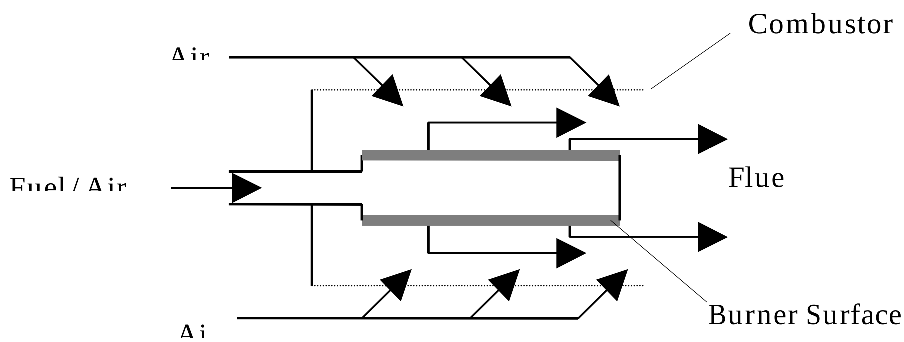

Figure I-4. Successful Outward-Fired Configuration

1.1.1 Low Emissions Results

Alzeta immediately recognized the importance of these low emissions results because NO_x levels below 2.5 ppm over a 200°F range of excess air are unprecedented in the gas turbine community. Current NO_x reduction techniques include steam and water injection, Selective Catalytic Reduction, SCONOX, catalytic combustion and lean premixed combustion. Not coincidentally, the techniques that provide the lowest emissions are also the least cost effective. SCONOX, for example, can achieve NO_x emissions levels below 2.5 ppm if used in conjunction with steam injection. The installed cost for this system is nearly $700,000 for a 5 MW industrial turbine with a baseline cost of only $2 million. The champion of catalytic combustion, Catalytica, has an impressive list of industrial partners including Allison and General Electric. After more than a decade of development, Catalytica has a single demonstration site operating for an electric customer (a 1.5 MW Kawasaki engine at the Gianera Generating Station of Silicon Valley Power). No other low emissions solution for gas turbine combustion offers the promise of ultra-low emissions and cost effectiveness, as the Alzeta GTSB does.

1.2 Application to Gas Turbines

Compared to other low emissions strategies, the GTSB technology offers the possibility of a compact combustor of simple configuration, metal or ceramic composite construction, and low pressure drop. The flexibility of the cylindrical configuration also means that the technology is more likely to be suitable for retrofits than other lean premix combustors, and thus potentially applicable to many more engines. In particular, the following characteristics form the key specifications for distributed power generation gas turbine combustors:

- Total combustor pressure drop limited to two to four percent of the system pressure.
- Operation at combustion air preheat temperatures up to 1150°F.
- Volumetric firing rates approaching 2 MMBtu / hr / atm / ft^3.
- Turbine Rotor Inlet Temperatures (TRIT) over 2200°F (valid for the Solar Turbines Mercury 50 engine, although Allison has operated combustors at 2600°F).
- Operation with axial combustors or external can combustors.
- Expected component lifetimes of 30,000 hours for industrial turbines.

This list of characteristics results from a combination of contact with Solar Turbines and Honeywell systems engineers, and the use of Alzeta's proprietary gas turbine thermodynamics code.

The Alzeta GTSB combustor is capable of meeting and surpassing each of the six bulleted items above. The system pressure drop is low, and can be adjusted by varying the percent open area of the burner perforations. High preheat temperatures have been found to increase the burner stability, allowing for greater excess air and lower NO_x results. This is due in part to the greater turbulent flame speed found as a result of increased preheat. Volumetric firing rate considerations are met by placing the pad in the cylindrical configuration previously discussed. Turbine Rotor Inlet Temperatures up to 2600°F are possible due to the uniform flame temperature, producing NO_x emissions under 2 ppm at 2600°F. Also, the use of expensive thermal barrier coatings will be minimized by the same uniform thermal properties. Testing with uncoated stainless steel has resulted in no obvious thermal defects. The cylindrical geometry can also be varied to fit many different physical configurations. In particular, single-can injection (the only possible configuration for a catalytic system) is possible, as well as the 8-12 injectors found in axial combustors. Component lifetimes of 30,000 hours will depend primarily upon surface temperatures. Maintaining peak surface temperatures below 1500°F will be a key measure of success.

1.2 Production Readiness

All laboratory testing up until now has indicated that the GTSB holds the promise of becoming the leading low emissions combustion system in industrial gas turbines. The technology is on the verge of being commercialized. Alzeta is currently partnered with two leaders in the gas turbine community, Solar Turbines and Honeywell. Currently, the targeted engines are the Solar Turbines Mercury 50 and Taurus 60, pictured in **Figure I-5** and **Figure I-6**, and the Honeywell Parallon 75, pictured in **Figure I-7**. Together with these partners, and potentially others, Alzeta will execute the necessary steps to begin offering the GTSB as a commercial product. This report will serve as the guideline for these efforts. The following chapters will describe the GTSB market potential, the process by which it is manufactured, the manufacturing facilities required to meet demand, estimates of the ultimate production costs, and a plan to ramp up to full production.

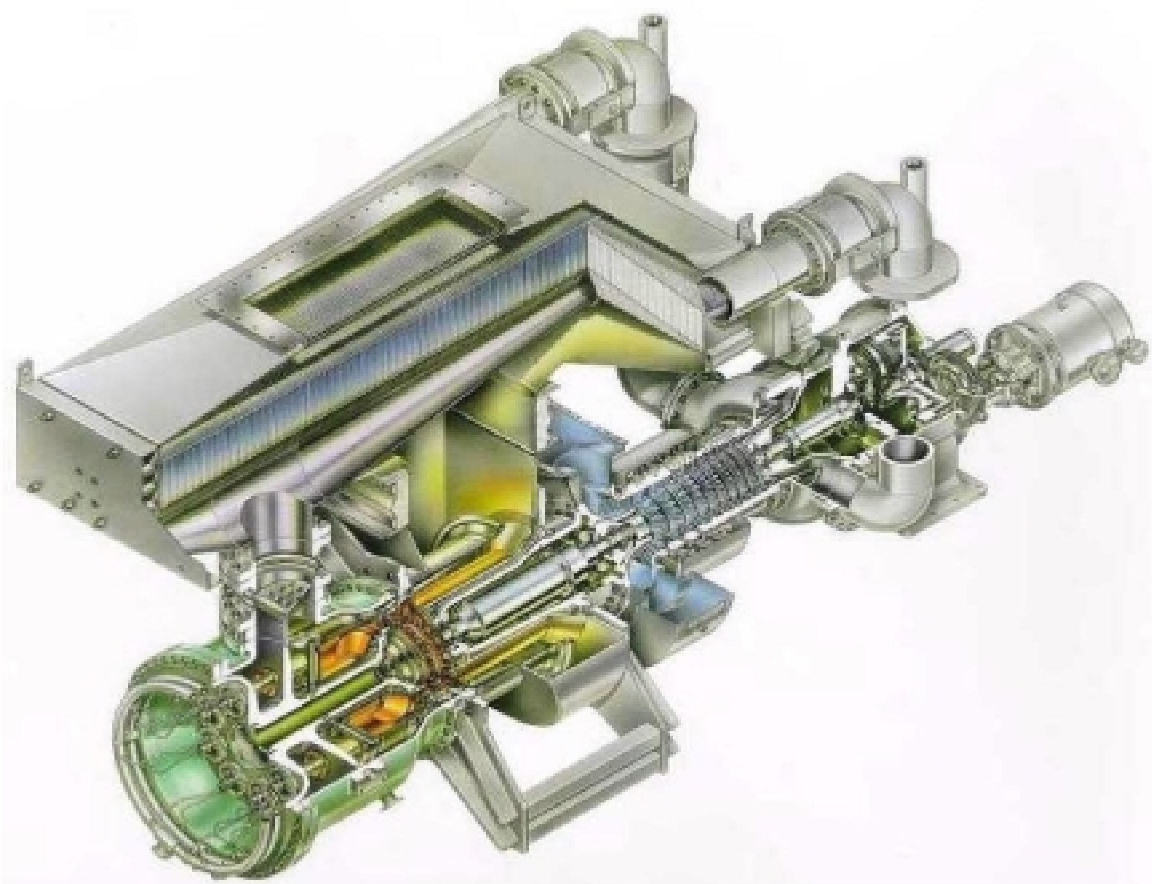

Figure I-5. Solar Turbines Mercury 50 Gas Turbine

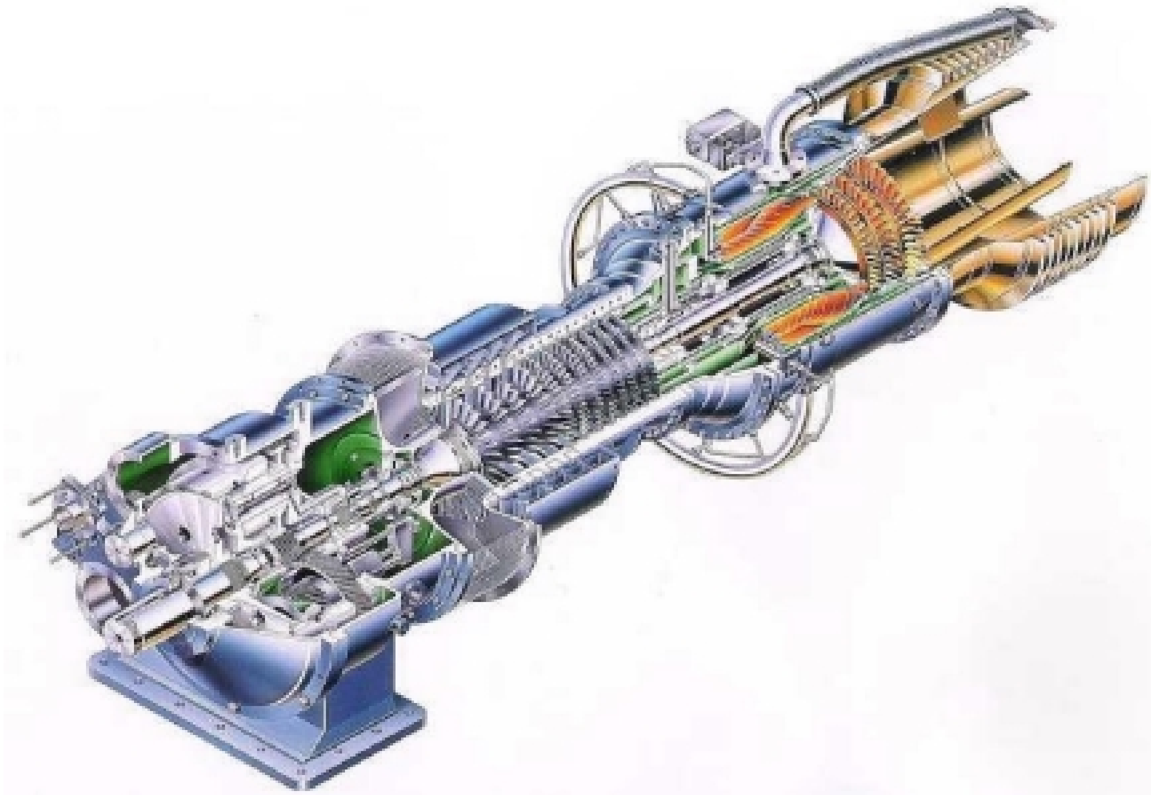

Figure I-6. Solar Turbines Taurus 60 Gas Turbine

Figure I-7. Honeywell's Parallon 75 Gas Turbine

1.3 Market Estimates

With the successful commercialization of the GTSB combustor, Alzeta intends to become the exclusive supplier of low emissions combustion technology to both Solar Turbines and Honeywell. Solar Turbines' sales now exceed $1 billion per year, and low emissions turbines account for an increasing portion of these sales each year. Approximately 50 low emissions units will be sold in the year 2001. Additional non-attainment zones and the growing popularity of gas turbines as viable alternative power sources justify assuming a 10 percent annual increase in low emissions sales over the next decade. Turbines sold in the 4MW-6MW range will require an average of 10 GTSB burners each, and Alzeta has targeted an initial sale price of $1000 per burner. These assumptions result in the estimates of GTSB sales to Solar Turbines shown in **Table I-1**.

Table I-1. Estimates of Sales to Solar Turbines

Solar Turbines			
Year	Units	Burners	Sales
2001	50	500	$500,000
2002	55	550	$550,000
2003	61	610	$610,000
2004	67	670	$670,000
2005	74	740	$740,000
2006	81	810	$810,000
2007	89	890	$890,000
2008	98	980	$980,000
2009	108	1080	$1,080,000
2010	119	1190	$1,190,000

Honeywell's Parallon 75 is a much smaller turbine than those offered by Solar, and will only require one burner per unit. The Parallon 75 is still being beta tested, but Honeywell has orders in house for over 3000 units. Once the product is established, it is reasonable to expect sales of about 1,000 low emissions units in the year 2001. The same growth and price assumptions outlined above result in the estimates of GTSB sales to Honeywell shown in **Table I-2**.

Table I-2. Estimates of Sales to Honeywell

Honeywell			
Year	**Units**	**Burners**	**Sales**
2001	1000	1000	$1,000,000
2002	1100	1100	$1,100,000
2003	1210	1210	$1,210,000
2004	1331	1331	$1,331,000
2005	1464	1464	$1,464,000
2006	1610	1610	$1,610,000
2007	1771	1771	$1,771,000
2008	1948	1948	$1,948,000
2009	2143	2143	$2,143,000
2010	2357	2357	$2,357,000

Table I-3 show the combined sales of GTSB combustors to Solar Turbines and Honeywell over the next decade.

Table I-3. Combined Sales to Solar Turbines and Honeywell

Combined			
Year	**Units**	**Burners**	**Sales**
2001	1050	1500	$1,500,000
2002	1155	1650	$1,650,000
2003	1271	1820	$1,820,000
2004	1398	2001	$2,001,000
2005	1538	2204	$2,204,000
2006	1691	2420	$2,420,000
2007	1860	2661	$2,661,000
2008	2046	2928	$2,928,000
2009	2251	3223	$3,223,000
2010	2476	3547	$3,547,000

Alzeta intends to aggressively pursue partnerships with additional manufacturers of industrial gas turbine generators. However, sales levels for these potential partners are impossible to estimate at this time. For the purpose of planning, Alzeta will target manufacturing capability for 1500 burners 1 year from now, 2250 burners 5 years from now, and 3500 burners 10 years from now.

1.4 Manufacturing Process

In its simplest form, the GTSB burner consists of only 3 components: an inlet support pipe, the burner surface itself, and an optional perforated distributor plate behind the burner surface. Depending on the specific burner geometry, the burner surface (or burner pad) and the distributor plate may actually be manufactured from multiple pieces. The ultimate goal for low-cost, high volume production, of course, would be to minimize the number of pieces by eliminating the distributor plate and always manufacturing the burner pad as a single piece. However, Alzeta's current manufacturing methods involve multiple pieces, and those methods will be described in this section.

The GTSB burner pad is a highly specialized material and is the key to the excellent combustion features displayed by the GTSB. Alzeta purchases sheets of unperforated material, then uses a subcontractor to cut and selectively perforate the burner pad to the individual GTSB specification. The unperforated material is a porous mat approximately 2 mm thick. The mat is constructed from small fibers of high-temperature stainless steel alloys, often Hastelloy. These fibers are 10 microns in diameter and vary in length. The fibers are water or air laid onto a surface, then pressed to a desired density. Finally, the mat is sintered in a reducing environment. The result is a low-porosity sheet with the flexibility of a piece of cardboard.

The burner pad material can be cut, perforated and welded much like an ordinary piece of sheet metal. Alzeta's subcontractors individually cut tiny holes to form the selective perforation pattern using a standard automated sheet metal laser cutter. While time-consuming, this process offers a precision and design-flexibility that cannot be matched. The same machine is used to cut the burner pad to size, leaving an unperforated border on all sides. The burner pad is now ready for final assembly.

The distributor plate or backing plate is not exposed to extreme temperatures and therefore is generally constructed from 304 or 316 stainless steel. This thin-gauge sheet metal is uniformly perforated by an industrial punching process. Alzeta generally purchases the perforated metal in large sheets. It is then either sheared or laser cut to the size required for the GTSB burner. Engineering concerns sometimes require different perforation patterns for different GTSB burners. Most of these perforation patterns are available as standard, in-stock products from the perforated metal suppliers. However, a custom pattern will occasionally be required, and can be laser-cut to exact specifications by the same subcontractors that cut the burner pad. Further research is being conducted to quantify the benefits of the distributor plate. Ultimately it may be deemed unnecessary, which would significantly reduce the labor and materials required to construct a GTSB burner.

The final part required to build the GTSB burner is the inlet/support pipe. This ordinary length of pipe serves as the interface to the fuel/air mixer and provides a structure on which to mount the burner pad and the distributor plate. Again, 304 or 316 stainless steel is generally adequate for this part. Schedule 40 pipe in the appropriate diameter is used, and is readily available from a large number of suppliers. The pipe may be purchased in large lengths. The subcontractor, using a lathe, then parts it to the required length.

Assembling these parts into a GTSB burner has proven to be a challenge. Alzeta's larger CSB burners, used in industrial boiler applications, are assembled using a complex system of rivets, washers, and custom stainless steel clips. This scheme has proven adequate in those applications, but the small size of the GTSB burner and the desire to minimize the number of individual pieces meant new methods needed to be developed. These new methods centered around welding of the burner pad, both to itself, and to the support pipe. Due to its porosity, thin fibers, and exotic alloys, the burner pad is somewhat difficult to effectively weld using traditional techniques. Welding was first attempted using a series of resistance spot welds. This method proved to be time-consuming and sloppy, often leaving significant leak paths in between welds. The weld zone was also too wide, creating a high potential for overheat of the burner during operation. A different welding subcontractor was able to TIG weld the material to itself by first crushing the edges. These edges were then bent 90 degrees to the surface, creating a lip about 1/8" in length. The two edges were mated to each other and the TIG weld was run down the length of the seam. Some of the 1/8" lip burned away, forming the material for the weld bead, but the seam still protruded some distance into the flame zone. While this method resulted in an improved seal, the protrusion of the seam also carried risk of overheat. Furthermore, the bending of the edges created an imprecision in the sizing of the burner pad. This method was ultimately rejected in favor of a true butt weld. A third subcontractor was able to TIG weld the material to itself and to ordinary stainless steel in a consistent manner. This weld has proven to be higher quality, quicker and narrower than the other two welds, and it is currently the preferred method of assembling the burners.

Before the burner pad is assembled, the distributor plate is put in place. First it is rolled into a cylinder with an outer diameter matching the inner diameter of the inlet pipe. A circular end cap for the cylinder is also cut from the perforated sheet metal, and the cylinder and cap are tack welded together. The cylinder is then tack welded such that it protrudes out one end of the pipe. The burner pad is assembled into a cylinder as well. It is rolled to have an inner diameter matching the outer diameter of the pipe. The axial seam is sealed and the circular end cap is attached using the butt weld process described above. The burner pad cylinder is then slipped over the distributor plate and welded to the inlet pipe. The thickness of the pipe serves as a standoff, maintaining a set distance between the burner pad and the distributor plate.

1.5 Current Facilities and Required Improvements

Currently, Alzeta uses subcontractors to perform most of the steps required to manufacture the GTSB. Alzeta maintains only a small manufacturing staff of approximately 4-5 people and devotes most of these resources to assembling large air purification systems and manufacturing the Pyrocore burner product line. Specialty fabrication equipment, such as laser cutters and lathes, are not available on the premises. For these reasons, contracting metal fabrication shops to manufacture the GTSB has been the most cost-effective route in the early, low-volume stages of development. However, in order to meet the market demand projected in Section 2, Alzeta will need to carry an increasing portion of the workload and / or explore larger, alternate subcontractors. This section will describe the present facilities available, both internal and external, and the upgrades that will be required to reach full production.

There are several metal fabrication shops that have been qualified to manufacture parts of the GTSB. One fabricator has perfected the butt welding technique described in Section 3. They have built a number of fixtures to aid in the welding process, and they are the primary shop currently used for assembly. They can perform a wide variety of welds, and also have a fully equipped machine shop and excellent quality control measures. However, this particular fabricator does not have a laser cutter in house. A second fabricator has a laser cutter that is capable of cutting the burner pad to specifications provided via CAD files. This is the shop that pioneered the bent-edge method of welding the pad, but their shop capacity generally prevents them from being able to perform this welding work. A third fabricator is a long-time subcontractor of Alzeta for sheet metal work. They too have a CAD-enabled laser cutter to automatically produce burner pads. They have also demonstrated welding capability using both the bent-edge and the butt weld techniques. Thus, Alzeta has qualified two vendors to produce burner pads and three vendors to perform acceptable pad welds.

In addition to maintaining and expanding a qualified vendor base, Alzeta is beginning to internalize portions of the manufacturing process. Though no in-house pad welding has yet been completed, all of the required equipment has been purchased, and several Alzeta personnel have been trained. The two major pieces of equipment acquired by Alzeta were a 90 Amp TIG welder with torch, and a 40” wide 3-in-1 shear, break, and roller. This equipment is an excellent addition to Alzeta’s considerable manufacturing facilities and will allow GTSB assembly to be done in-house in the near future.

Despite the excellent quality provided by Alzeta’s team of subcontractors, when production grows to 1500 burners in the year 2001 (approximately 6 per day), alternate subcontractors and in-house upgrades will be required. The maximum production level that could be reached with the current subcontractors and facilities available would be approximately 200 burners per year. The primary change that will increase production efficiency will be switching from laser cutting to a punching operation for producing the burner pads. Alzeta has already qualified several vendors for punching holes in the burner pad material. This process is used on all of the burners in Alzeta’s SB and CSB product lines. Once a standard hole pattern has been defined for a GTSB intended for a particular turbine, it becomes worthwhile to pay the tooling cost required to set up the punch. Then high-speed, low cost production of the burner pads is possible. Production levels of several thousand per year could easily be handled through subcontractors, though in several years the purchase of an industrial punch may become cost-justifiable.

The welding process is already fairly well refined and does not seem to be a good candidate for automation. Each burner welded will always require one TIG welder and one person doing the welding. With proper fixturing, a burner could be welded in about an hour, allowing the 2001 production level to be reached with one man and one machine working full-time. Any further increase in production would almost certainly require the purchase of another welder and the addition of more personnel.

Another major advance in the manufacturing technique is now being researched, and is worth mentioning here. It may be possible for Alzeta to form single-piece burner pads in-house by water-laying metal fibers directly into the required shape, then pressing and sintering the burner as is currently done. The perforation pattern could be built into this process, or could be added afterwards by laser. This one-piece burner has several engineering advantages, including an increased resistance to overheating. It also has several manufacturing advantages. The only weld that would be necessary would be that of the burner pad to the support pipe. Another step of the process would be brought under Alzeta's direct control, allowing for more efficient and cost-effective manufacturing of the burners. This operation is just beginning to be considered, so it is impossible to estimate what equipment would be required to perform it at full production levels, or if it will even be at all viable. However, it presents the possibility of an exciting advance that would ultimately lower the cost and improve the quality of the GTSB product.

1.6 Cost Estimates and Required Investment

When manufactured in low volumes, the GTSB is fairly expensive. However, as process improvements are made and production levels increase, manufacturing costs can be significantly reduced. This section will outline the costs for a typical GTSB burner, and detail how these costs will be reduced in the coming years.

There are four items that significantly contribute to the GTSB cost: the unperforated burner pad, the cost of perforating the pad, the backing plate, and the cost of assembly (welding). The cost of the burner pad itself is fairly well established. Alzeta already purchases this material in large quantities for use in other products. This same material will continue to be used, and must be purchased until if and when Alzeta becomes capable of manufacturing single-piece burner pads in-house (see Section 4).

The perforation of the burner pad is the most critical item that needs to be addressed in order to reduce the cost of manufacturing the GTSB. The current method used for perforating burner pads is a CAD-enabled laser cutter. While this method is extremely precise and flexible, and requires little labor once programming is complete, it is also slow and therefore expensive. Laser cutting by subcontractors currently costs Alzeta approximately 8 cents per hole. With typical burners requiring thousands of holes, the cost of laser cutting can quickly become prohibitive for commercial production.

The cost of the backing plate is also quite well established. Though volume discounts have not been fully explored, Alzeta currently pays $11 per square foot of this perforated sheet metal. This price is for 304 stainless steel, and will change slightly if a different alloy is required. However, Alzeta's research has shown that this material is adequate for the intended applications. Since less than half a square foot is required to build a burner, changes in material will not impact burner cost very much. It is also possible that the backing plate will be eliminated altogether in the future.

The final cost to be considered is the cost of welding the assembly together. The current preferred vendor charges $150 per assembly. This price might decrease slightly as order volumes increase and the vendor gains further experience with the material and the design. **Table I-4** shows the current costs summed to derive the cost of the first production unit.

Table I-4. Cost of the First Production Unit

Item	Qty.	Unit	Unit Cost	Ext. Cost
Hastelloy Pad Material	0.4	ft²	$80.00	$32.00
Laser Drill Holes	6382	holes	$0.07	$446.74
Backing Plate	0.35	ft²	$10.00	$3.50
Welding	1	assembly	$150.00	$150.00
Total				$632.24

The total cost of $632 is slightly lower than typical prototype costs and the $1000 sales price target. Several changes can be implemented in the near future in order to significantly reduce this cost. As mentioned above, laser-drilling holes in the burner pad is not a very cost-effective approach. Once a standard hole pattern has been established for a particular GTSB model, the holes can be punched by a subcontractor rather than individually cut. Alzeta uses this method on many commercial products, and high-volume costs are as low as a tenth of a cent per hole. Special tooling charges may be required by the subcontractor to set up the required pattern, but this investment will be recovered quickly by the savings realized.

Another short-term strategy to reduce the production cost is to weld the assembly at Alzeta, rather than relying on a subcontractor and paying the associated premium. Most of the required equipment is already in place in Alzeta's shop. All that is required is additional training and practice for Alzeta's manufacturing staff. It is reasonable to expect that within a couple of years the GTSB burners could be assembled at Alzeta for less than 2/3 of what the subcontractor is currently charging.

Volume discounts on the backing plate material should reduce the cost of that item by 25 percent within a few years. **Table I-5** shows the impact this discount and the two strategies discussed above will have on production cost.

Table I-5. Impact on Production Costs

Item	Qty.	Unit	Unit Cost	Ext. Cost
Hastelloy Pad Material	0.4	ft²	$80.00	$32.00
Punch Holes	6382	holes	$0.001	$6.38
Backing Plate	0.35	ft²	$7.50	$2.63
Welding	1	assembly	$100.00	$100.00
Total				$141.01

Thus, there is a well-defined plan in place to bring the unit cost below $150 within the first few years of production. The sales price target of $1000 is more than reasonable. Further cost reductions *may* be realized if research into advanced manufacturing techniques is successful. Alzeta is beginning to consider methods of forming metal fibers directly into a burner-shaped surface. Such a technique would reduce assembly time considerably, eliminating all but one pad weld from the process. Conceivably the burner hole pattern could also be directly created during the casting process. This manufacturing process is still hypothetical, and a significant investment would be required both in research and in capital equipment. However, if the process is implemented, a more robust and less expensive product will result. Pad cost can be reduced by 25 percent or more, assembly cost can be reduced by 50 percent, and the cost of creating holes will effectively be eliminated.

Another possible way to reduce costs after further research would be the elimination of the backing plate. The backing plate is used to evenly distribute the premix flow across the burner surface. However, this introduces undesirable pressure losses into the turbine, which consequently reduces the system efficiency. For this reason, Alzeta is conducting research that may eventually lead to the elimination of the backing plate from the GTSB product. **Table I-6** shows what impact the implementation of these advanced techniques will have on the cost.

Table I-6. Impact of Implementation

Item	Qty.	Unit	Unit Cost	Ext. Cost
Hastelloy Pad Casting	0.4	ft^2	$60.00	$24.00
Holes (Formed In Casting)	6382	holes	$0.00	$0.00
Backing Plate (N/R)	0	ft^2	$7.50	$0.00
Welding	1	assembly	$50.00	$50.00
Total				$74.00

Thus, the burner cost may be reduced to $74. This cost should be viewed as a lower bound on the production cost for the next decade, as it relies on several significant advances. The $141 cost derived above is more realistic, and costs should approach that number within the first few years of production.

1.7 Full Production Ramp-Up Plan

While the merits of the GTSB product have been repeatedly proven in lab tests, a number of steps must be taken before full production levels can be reached. In the year 2001, Alzeta intends to sell over 1000 GTSB burners into commercial applications. This section will tie together the strategies mentioned in the previous sections and provide a step-by-step outline for increasing production over the coming years.

Initial production units will continue to rely heavily on subcontractor labor. For this reason, it is essential that Alzeta maintains a large base of qualified subcontractors, both for laser cutting burner pads and for welding the burner assemblies. A large base of vendors helps guarantee the best possible price and delivery for the required work. It also ensures that Alzeta will be ready and able to meet any surge in demand that might be experienced. By the middle of next year, Alzeta will qualify 2-3 additional vendors to laser cut the burner pads. This should not be a difficult task since many sheet metal shops possess appropriate CAD-enabled laser cutters. A more difficult task is locating shops willing and able to perform the specialty welding necessary to assemble the burners. However, Alzeta personnel are well informed of the welding process used by the current subcontractors and should be able to teach new vendors the techniques involved. By October of next year, 2-3 additional vendors will be qualified to perform GTSB assembly.

Shortly after production begins, Alzeta would like to begin assembling production burners in-house. The equipment and personnel required to do this in low volumes are already in place. In the early stages of production, burner assembly will still be performed mainly by subcontractors, but Alzeta will slowly ramp up in-house welding with the goal of ultimately assembling all burners internally. By the beginning of 2002, additional manufacturing staff will be required to meet the demand for burners. One welder could be employed full-time welding the more than 1500 burners estimated to be sold in that year. As sales continue to increase and Alzeta relies less and less on subcontractors, additional welding equipment will need to be purchased to that more than one burner can be processed at a time. Finally, by the beginning of 2003, Alzeta should be prepared to assemble 100 percent of the burners expected to be sold.

Laser cutting will continue to be the method of perforating the burner pad at the beginning of production. However, shortly thereafter, Alzeta will require a cheaper, faster method. By the middle of 2001, standard hole patterns will be defined for all production burners. Metal-perforating subcontractors can then use these patterns to set up dies on industrial punches. A few months later, Alzeta should be ready to make the switch from laser cutting to punching. This transition should be fairly sharp, eliminating laser cutting as a production method by the end of 2001.

The remaining production advances have to do with research and development. With information gathered over the next year and a half, Alzeta should be in position to quantify the merits and drawbacks of the backing plate in April 2001. At this point a decision will be made regarding whether or not to include the backing plate in production burners. From a production standpoint, it is obviously desirable to remove the backing plate. However, engineering concerns may not allow this. The last possible step in the production ramp-up is the implementation of the direct casting method of producing burner pads. Significant research and development needs to be done before a decision can be made on the feasibility of this technique. About 2 years from now, Alzeta should be in a position to decide if this will be an effective manner in which to produce GTSB burners. If so, the necessary equipment will be purchased, and early in 2003 Alzeta will be producing burner pads in-house.

Table I-7 summarizes the steps required to ramp up to full production and details an approximate timeline for the completion of these tasks.

Table I-7. Steps and Timelines to Full Production

Approximate Date	Action
7/3/00	Qualify additional laser cutting subcontractors
10/2/00	Qualify additional welding subcontractors
1/1/01	Begin in-house production welding
4/2/01	Decide on necessity of backing plate
7/2/01	Standardize burner hole patterns
10/1/01	Switch to punching holes
1/7/02	Increase manufacturing staff
4/1/02	Determine feasibility of direct pad casting
7/1/02	Purchase additional welding equipment
1/6/03	Perform all welding in-house
4/7/03	*Implement direct pad casting for production

Appendix II

FETC Test Data

FETC TEST DATA

DATE	TIME	Pressure	AFT	Firing Rate	Norm. SFR	Preheat T	Burner EA	Air Split	NOx (@15%)	CO (@15%)	HC (@15%)	O2	DP/P
		atm.	°F	MMBtu/hr	FR/atm/ft²	°F	%	% to burner	ppm	ppm	ppm	%	%
21-Jul-98	14:34:00	9.93	2889	4.91	0.99	604	0.69	0.762	3.28	1	0	12.5	2.61
21-Jul-98	15:08:00	12.24	2802	4.84	0.79	674	0.82	0.720	2.40	0	0	13.4	2.05
21-Jul-98	15:31:00	9.27	2812	3.85	0.83	555	0.73	0.734	1.65	8	0	13.0	1.86
21-Jul-98	15:53:00	7.01	2837	2.99	0.85	505	0.67	0.761	1.93	1	0	12.5	1.79
20-Jul-98	16:48:00	10.02	2767	4.90	0.98	600	0.80	0.774	1.77	1	0	12.2	2.84
20-Jul-98	17:20:00	10.00	2762	3.31	0.66	599	0.81	0.738	1.76	5	0	12.9	1.38
21-Jul-98	11:16:00	3.99	2775	2.15	1.08	360	0.63	0.761	1.30	80	27	12.2	2.41
21-Jul-98	11:30:00	4.02	2871	2.15	1.07	357	0.55	0.746	2.12	7	0	11.9	2.16
21-Jul-98	9:58:00	1.80	2832	0.87	0.97	186	0.48	0.659	2.44	57	18	11.8	1.38
21-Jul-98	11:54:00	4.00	2764	1.44	0.72	356	0.64	0.722	1.29	88	22	12.8	1.11
21-Jul-98	12:05:00	4.02	2844	1.44	0.72	356	0.57	0.715	2.42	2	0	12.4	1.02
21-Jul-98	12:50:00	6.95	2844	2.98	0.86	499	0.66	0.761	1.87	1	0	12.3	1.81
21-Jul-98	13:06:00	6.99	2822	2.09	0.60	496	0.68	0.727	1.91	1	0	12.6	0.91
21-Jul-98	13:22:00	6.95	2830	2.97	0.85	503	0.68	0.761	1.66	1	0	12.2	1.83
16-Jul-98	9:31:00	1.01	2980	0.53	1.04	78	0.32	0.674	3.40	6	0	10.9	1.19
20-Jul-98	13:22:00	7.00	2814	2.99	0.85	499	0.69	0.792	1.51	1	0	11.6	1.85
20-Jul-98	15:33:00	6.98	2842	4.00	1.15	504	0.67	0.788	1.70	1	0	11.6	3.15
20-Jul-98	14:18:00	7.01	2722	2.83	0.81	507	0.78	0.791	0.83	14	0	12.4	1.83

Appendix III

Honeywell Load Matching Data

HONEYWELL TEST DATA

DATE	COND. #	Pressure	AFT	Firing Rate	Norm. SFR	Preheat T	Burner EA	Air Split	NOx (@15%)	CO (@15%)	HC (@15%)	02	DP/P
		atm.	°F	MMBtu/hr	FR/atm/ft²	°F	%	% to burner	ppm	ppm	ppm	%	%
1-Feb-00	5006	1.50	2713	0.00	0.48	702	0.94	0.211	1.3	1371	1142	19.0	7.1%
1-Feb-00	5007	1.49	2621	0.00	0.47	703	1.05	0.219	1.3	1977	9007	19.3	6.9%
1-Feb-00	5010	1.51	N/A	0.00	0.62	703	N/A	N/A	6.2	9	7	18.4	6.8%
1-Feb-00	6000	2.01	2960	0.00	0.63	805	0.75	0.240	6.4	5	0	18.4	7.6%
1-Feb-00	6010	2.01	N/A	0.00	0.67	805	N/A	N/A	10.1	5	0	18.3	7.6%
1-Feb-00	6020	2.00	2893	0.00	0.61	805	0.82	0.242	4.6	7	0	18.5	7.4%
1-Feb-00	7000	2.51	2971	0.00	0.66	900	0.81	0.252	7.9	5	0	18.4	8.3%
1-Feb-00	7010	2.50	2949	0.00	0.66	903	0.84	0.251	6.3	5	0	18.4	8.1%
1-Feb-00	7020	2.50	2883	0.00	0.63	904	0.91	0.249	4.6	5	0	18.5	8.1%
1-Feb-00	7030	2.50	2813	0.00	0.60	906	1.00	0.251	3.3	9	0	18.6	8.1%
1-Feb-00	8000	3.02	2886	0.00	0.62	1002	1.00	0.245	3.2	14	8	18.7	7.3%
1-Feb-00	8010	2.99	2779	0.00	0.60	1003	1.15	0.251	3.2	14	9	18.8	7.3%
1-Feb-00	8020	3.00	2269	0.00	0.60	1006	2.19	0.374	3.6	11	9	18.8	7.0%
1-Feb-00	8030	2.99	2738	0.00	0.63	1007	1.21	0.274	5.5	5	4	18.7	7.0%

Appendix IV

Preliminary Solar Test Data

PRELIMINARY SOLAR TEST DATA

DATE	TIME	Pressure	AFT	Firing Rate	Norm. SFR	Preheat T	Burner EA	Air Split	NOx (@15%)	CO (@15%)	HC (@15%)	O2	DP/P
		atm.	°F	MMBtu/hr	FR/atm/ft²	°F	%	% to burner	ppm	ppm	ppm	%	%
15-Oct-98	14:17:24	2.04	2965	1.14	1.12	292	0.44	0.415	5.20	1893	394	16.5	4.94
15-Oct-98	14:37:34	3.15	2982	1.71	1.08	315	0.44	0.376	5.09	1817	444	17.0	4.83
15-Oct-98	14:45:49	3.87	2984	2.07	1.07	318	0.44	0.373	5.24	1782	462	17.2	4.69
15-Oct-98	14:53:30	4.87	2986	2.22	0.91	322	0.44	0.369	5.62	1641	428	16.9	3.42
15-Oct-98	15:20:39	3.98	2936	2.01	1.01	348	0.49	0.385	5.55	1739	471	17.3	4.36
15-Oct-98	15:27:09	3.93	2932	1.98	1.01	344	0.49	0.380	4.31	1684	548	17.8	4.45
15-Oct-98	15:33:01	7.40	3045	3.61	0.98	345	0.41	0.372	7.64	1475	388	16.5	3.65
15-Oct-98	15:41:13	6.97	2918	3.14	0.90	483	0.59	0.381	4.43	1866	526	17.6	4.32
15-Oct-98	15:51:05	8.10	2970	3.59	0.89	495	0.55	0.379	5.55	1932	470	17.2	4.07
15-Oct-98	16:16:55	9.95	2965	4.13	0.83	588	0.61	0.385	6.32	1720	431	16.9	4.02
15-Oct-98	16:33:21	10.95	2899	3.76	0.69	855	0.86	0.386	4.75	1865	500	17.5	4.45
15-Oct-98	16:39:04	9.62	2665	3.16	0.66	933	1.21	0.398	3.20	3013	910	19.0	5.80
15-Oct-98	16:48:15	9.69	2716	3.01	0.62	1003	1.21	0.387	3.38	3389	887	19.0	5.78
16-Oct-98	10:37:39	4.01	2984	2.17	1.08	318	0.44	0.576	5.73	1759	411	16.7	4.55
16-Oct-98	10:59:45	4.04	2856	2.12	1.05	317	0.54	0.576	4.88	1599	464	17.2	4.50
16-Oct-98	11:30:59	7.26	2942	3.37	0.93	496	0.57	0.480	4.71	2079	421	16 8	4.42

Appendix V

Solar Test Data: Backside-Cooled Liner

SOLAR TEST DATA: BACKSIDE-COOLED LINER

DATE	TIME	Pressure	AFT	Firing Rate	Norm. SFR	Preheat T	Burner EA	Air Split	NOx (@15%)	CO (@15%)	HC (@15%)	O2	DP/P
		atm.	°F	MMBtu/hr	FR/atm/ft²	°F	%	% to burner	ppm	ppm	ppm	%	%
7-Dec-98	18:38:19	3.22	3011	0.86	0.87	356	0.44	0.298	4.60	593	1031	19.5	2.62
7-Dec-98	20:32:44	5.76	2942	1.62	0.91	701	0.70	0.300	4.16	213	65	18.2	5.04
7-Dec-98	20:41:08	5.61	2790	1.52	0.87	703	0.86	0.303	2.73	1608	778	18.8	5.43
7-Dec-98	20:47:43	5.96	3151	1.81	0.98	705	0.53	0.296	9.18	7	1	17.9	4.80
7-Dec-98	21:22:06	7.14	2819	1.62	0.73	701	0.83	0.303	2.93	1062	689	18.5	3.55
7-Dec-98	21:27:20	7.42	3077	1.79	0.78	703	0.59	0.293	7.14	9	1	18.0	3.33
7-Dec-98	21:40:58	8.67	2818	1.91	0.71	700	0.83	0.322	3.26	1741	795	18.8	3.45
7-Dec-98	21:45:47	9.06	3119	2.21	0.79	701	0.55	0.316	10.10	5	1	18.0	3.18
7-Dec-98	21:52:10	10.06	2911	1.96	0.63	701	0.73	0.313	4.53	330	96	18.3	2.46
7-Dec-98	21:55:27	9.93	2819	1.86	0.60	701	0.83	0.313	2.68	1255	708	18.5	2.51

Appendix VI

Solar Test Data: Louvered Liner

SOLAR TEST DATA: LOUVERED LINER

DATE	TIME	Pressure	AFT	Firing Rate	Norm. SFR	Preheat T	Burner EA	Air Split	NOx (@15%)	CO (@15%)	HC (@15%)	02	DP/P
		atm.	°F	MMBtu/hr	FR/atm/ft²	°F	%	% to burner	ppm	ppm	ppm	%	%
9-Dec-98	16:02:21	2.00	3225	0.55	0.89	558	0.39	0.284	7.09	1479	1888	20.0	3.26
9-Dec-98	16:11:14	4.06	3211	0.98	0.78	595	0.42	0.255	6.42	1559	847	18.9	2.67
9-Dec-98	16:24:44	5.68	3165	1.18	0.67	589	0.45	0.255	8.96	1386	619	18.1	1.87
9-Dec-98	16:28:34	5.46	3009	1.10	0.65	588	0.57	0.257	4.99	2138	753	18.6	1.98
9-Dec-98	16:35:41	5.64	3224	1.23	0.70	594	0.41	0.252	11.14	1162	586	17.9	1.94
9-Dec-98	16:49:34	7.21	3170	1.45	0.65	595	0.45	0.250	6.98	1613	546	17.7	1.84
9-Dec-98	16:53:11	7.13	3073	1.40	0.63	598	0.53	0.253	5.37	2108	618	18.1	1.91
9-Dec-98	17:04:03	7.40	3170	1.51	0.66	595	0.45	0.260	10.47	1283	510	17.5	1.76
9-Dec-98	17:18:44	8.68	3104	1.67	0.62	601	0.50	0.261	7.66	1561	545	17.7	1.68
9-Dec-98	17:25:39	8.51	3021	1.61	0.61	605	0.57	0.264	4.91	1896	586	17.9	1.77
9-Dec-98	17:29:41	8.85	3165	1.71	0.63	607	0.46	0.261	9.65	1344	523	17.6	1.66
9-Dec-98	19:43:27	5.83	3158	1.71	0.95	598	0.46	0.272	7.65	1740	786	18.7	3.76
9-Dec-98	19:56:28	7.37	3200	2.32	1.01	599	0.43	0.269	9.86	1485	597	18.0	4.22
9-Dec-98	20:01:18	8.82	3258	2.76	1.01	604	0.39	0.272	11.74	1336	505	17.4	3.87
9-Dec-98	20:04:58	8.59	3163	2.63	0.99	604	0.46	0.272	8.12	1664	534	17.6	4.08
9-Dec-98	20:09:21	8.52	3121	2.59	0.98	605	0.49	0.272	7.41	1960	576	17.9	4.18
9-Dec-98	20:15:05	10.20	3247	3.10	0.98	607	0.40	0.268	11.14	1503	519	17.5	3.79
9-Dec-98	20:17:39	10.15	3178	3.05	0.97	607	0.45	0.273	9.42	1642	537	17.6	3.83
9-Dec-98	20:20:50	9.92	3108	2.94	0.96	606	0.50	0.271	6.76	2070	593	18.0	4.07

Appendix VII

Honeywell Test Data

DATE	COND. #	Pressure	AFT	Firing Rate	Norm. SFR	Preheat T	Burner EA	Air Split	NOx (@15%)	CO (@15%)	HC (@15%)	O2	DP/P
		atm.	°F	MMBtu/hr	FR/atm/ft²	°F	%	% to burner	ppm	ppm	ppm	%	%
1-Feb-00	5006	1.50	2713	0.00	0.48	702	0.94	0.211	1.3	1371	1142	19.0	7.1%
1-Feb-00	5007	1.49	2621	0.00	0.47	703	1.05	0.219	1.3	1977	9007	19.3	6.9%
1-Feb-00	5010	1.51	N/A	0.00	0.62	703	N/A	N/A	6.2	9	7	18.4	6.8%
1-Feb-00	6000	2.01	2960	0.00	0.63	805	0.75	0.240	6.4	5	0	18.4	7.6%
1-Feb-00	6010	2.01	N/A	0.00	0.67	805	N/A	N/A	10.1	5	0	18.3	7.6%
1-Feb-00	6020	2.00	2893	0.00	0.61	805	0.82	0.242	4.6	7	0	18.5	7.4%
1-Feb-00	7000	2.51	2971	0.00	0.66	900	0.81	0.252	7.9	5	0	18.4	8.3%
1-Feb-00	7010	2.50	2949	0.00	0.66	903	0.84	0.251	6.3	5	0	18.4	8.1%
1-Feb-00	7020	2.50	2883	0.00	0.63	904	0.91	0.249	4.6	5	0	18.5	8.1%
1-Feb-00	7030	2.50	2813	0.00	0.60	906	1.00	0.251	3.3	9	0	18.6	8.1%
1-Feb-00	8000	3.02	2886	0.00	0.62	1002	1.00	0.245	3.2	14	8	18.7	7.3%
1-Feb-00	8010	2.99	2779	0.00	0.60	1003	1.15	0.251	3.2	14	9	18.8	7.3%
1-Feb-00	8020	3.00	2269	0.00	0.60	1006	2.19	0.374	3.6	11	9	18.8	7.0%
1-Feb-00	8030	2.99	2738	0.00	0.63	1007	1.21	0.274	5.5	5	4	18.7	7.0%