CALIFORNIA
ENERGY
COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Environmentally-Preferred Advanced Generation

IMPROVED OPERATIONAL TURNDOWN OF AN ULTRA-LOW EMISSION GAS TURBINE COMBUSTOR

FEASIBILITY ANALYSIS

December 2001
P500-01-026F

Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

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Environmentally-Preferred Advanced Generation

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LEGAL NOTICE

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 of which $2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

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

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
    - o Appendix A: Final Report (under separate cover)
    - o Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049 or email
eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at
http://www.energy.ca.gov/research/index.html.

Executive Summary

Introduction

Alzeta Corporation is a manufacturer of industrial burners and combustion systems. Alzeta is developing an advanced low-emissions combustor for use in industrial gas turbines and micro-turbines. Alzeta's goal is to develop a low emissions combustor that is effective, relatively low cost and can be designed to fit into most existing gas turbine engines. The final report (see Appendix A) details design and testing of Alzeta's Gas Turbine Surface Burner (GTSB). Testing was accomplished at atmospheric conditions and in Honeywell's 75 kilowatt combustor test rig.

In California's changing electricity market, small gas turbine generators may be playing an increasingly important role. These units hold the promise of bringing cheaper, more reliable electricity to California's ratepayers. To reduce harmful air emissions, these units must be equipped with combustors that reduce the oxides of nitrogen to less than 5 ppm. Alzeta's GTSB is being developed to address emissions reduction to these levels without significantly increasing capital equipment costs.

The low-emissions performance of the GTSB derives from its ability to stabilize combustion at low adiabatic flame temperatures where side reactions responsible for NO_X formation are thermodynamically less favorable than complete combustion of hydrocarbon fuel. To reduce the adiabatic flame temperature, more air than necessary for complete combustion is premixed with gaseous fuel and directed through the combustor. In the gas turbine industry, this approach is called lean-premixed, dry low-NO_X (DLN) combustion. The GTSB differs from existing DLN systems. Its stabilization mechanism removes heat from the combustion reactions by radiant heat transfer resulting in lower NO_X formation than attainable by well-stirred premixed combustion with the same amount of excess air.

A potential barrier to commercialization of the GTSB, as with other DLN systems, is the problem of operational turndown. It is difficult for DLN systems to sustain combustion when the power level is reduced from full power to levels as low as 50% power. Increasing the operational turndown of the GTSB requires precise local control of the air-fuel ratio over selected regions of the burner surface. This level of control can be accomplished by partitioning the GTSB into independent segments. Under low fuel-flow conditions, the air-fuel ratio can be maintained in an individual segment while fuel-free air passes through adjoining ones. The number and size of the segments can be adjusted to provide stable combustion over the load range. At full load, the entire GTSB is fired with fuel divided among its segments such that each is operated at the same air-fuel ratio.

Goal and Objectives

The goal of this project was to determine the feasibility of a segmented GTSB. Alzeta's strategy is to develop a low emissions gas turbine combustor that is effective, relatively low cost, adaptable to existing engines, and has the flexibility to operate over a broad engine turndown ratio. This project's focus is on increasing the operational turndown ratio of the GTSB while maintaining low emissions over the load range. Alzeta partitioned the burner into segments to achieve this result. They planned to add a fuel-air mixture to the segments in a sequential manner as engine load increased. To be successful, the segmented GTSB had to meet emissions targets of sub-5 ppm NO_X (referenced to 15% O_2), sub-10 ppm CO and sub-10 ppm unburned hydrocarbons over the operating range of a micro-turbine engine. The following project objectives were established:

1. Provide three conceptual designs of segmented GTSB. The designs should be differentiated by geometry and number of segments. Create criteria to identify and select the most promising design. Produce design drawings for a GTSB that will fit into the Honeywell 75 kWe combustor test rig.

2. Build and instrument the test combustor. This design objective is important because a segmented GTSB is a new concept and has not been previously designed for testing at gas turbine conditions.

3. Test the segmented GTSB at atmospheric conditions. Measure combustor emissions at six engine-operating conditions from idle to full power. Vary the fuel flow split to the segments at each operating condition to optimize emissions. Measure and record NO_X and CO emissions at each operating condition and each segmented fuel flow condition. The objective is to prove the capability of the segmented GTSB to achieve NO_X emissions less than 5 ppm at atmospheric pressure over simulated engine operating conditions. This atmospheric pressure test, while less rigorous than Objective 4, provides relatively low cost data to the designers early in the development cycle so that adjustments can be quickly and easily made.

4. Test the segmented GTSB at pressures typical of the Honeywell 75 kilowatt Parallon engine. Measure combustor emissions at six engine-operating conditions from idle to full power. Vary the fuel flow split to the segments at each operating condition to optimize emissions. Measure and record NO_X and CO emissions at each engine condition and each segmented fuel flow condition. The Honeywell engine operates at conditions typical of most micro-turbines. Gas turbine emissions often increase with increasing engine pressures. Testing at simulated engine pressures provides information about the pressure sensitivity of the emissions from a combustor without developing a full engine test.

Outcomes

1. Three GTSB concepts were evaluated. A two-segment GTSB was selected based on ease of fabrication, control system integration and the effect of internal baffles on air-fuel mixing. Alzeta engineers designed the selected GTSB concept to mate with both the Alzeta test facility and Honeywell's test facility for the Parallon 75 micro-turbine.

2. The GTSB was fabricated. The test GTSB was instrumented with thermocouples and gas-sample lines. No unusual problems were encountered.

3. The segmented GTSB was tested at atmospheric conditions at the Alzeta test facility. It was operated stably at six conditions that simulated engine power conditions from idle to full power. The NO_X emissions were less than 5 ppm (adjusted to 15% oxygen) and CO emissions were less than 10 ppm. The fuel flow split between the two segments was adjusted at each operating condition to optimize the emissions.

4. The segmented GTSB for the Parallon 75 was fabricated and installed in the pressurized test facility at Honeywell. Testing of the segmented GTSB was accomplished at five of the six planned engines conditions. The selected set points were established in terms of air flow through the GTSB. These points were: 13.6 pounds per hour (pph), 18.5 pph, 24.7 pph, 30.8 pph, 37 pph, and 41.6 pph (full power). The test was halted during the transition to full power test conditions due to a mechanical failure of the GTSB. Alzeta engineers believed that the failure was caused by flashback (the flame-front moved backwards toward the GTSB surface and rapidly burned the air-fuel mixture inside of the fuel injector). All tests performed up to the full engine operating condition demonstrated NO_X below 5 ppm (adjusted to 15% oxygen) and CO less than 10 ppm. Unburned hydrocarbon emissions were undetectable under most conditions. All tests were accomplished using only one segment of the two-segment GTSB. The tests using various fuel splits between segments could not be accomplished after the failure of the test GTSB. Since only one day of testing was available at the Honeywell test facility, retesting could not be accomplished.

Conclusions

Alzeta's segmented GTSB operated as planned at atmospheric pressure conditions. Alzeta's GTSB is capable of producing sub-5 ppm NO_X , sub-10 ppm CO, and near zero unburned hydrocarbons at partial load operating conditions of the Honeywell Parallon 75 micro-turbine. Collected temperature data demonstrate that GTSB combustion performance is consistent with Honeywell's combustor design and can be adapted without changing the materials of construction. Demonstration of the segmented GTSB at full engine load conditions was not accomplished due to component failure.

Subsequent to the completion of this project, Honeywell decided to exit the micro-turbine business. This does not diminish the value of the research conducted during this project. Even though the important technical objective of testing a segmented GTSB at engine pressures is yet to be achieved, this EISG funded project has advanced segmented GTSB technology.

Recommendations

Successful demonstration of the segmented GTSB at points traversing the startup fuel schedule and over the entire load range at atmospheric conditions could lead to an engine ready design and testing in a micro-turbine or full size turbine. Once the GTSB is installed in an engine, the engine start schedule and control logic will have to be developed to provide low emissions over the load range. Extended demonstration in a test or field engine will provide critical operating data for the commercial GTSB micro-turbine product. Finally, GTSB durability and flashback prevention should be objectives of subsequent research and development. The California Energy Commission awarded Alzeta another development program for this burner concept in March of 2001 and has recently announced its intention to expand this line of research under the Environmentally Preferred Advanced Generation subject area of the PIER program. The Program Administration endorses these actions.

Benefits to California

Once commercialized, the GTSB may allow low emissions turbine generators to be sited in California at a reasonable cost. Actual engine emissions with the GTSB must meet emission control standards in effect at the time of commercialization. The segmented GTSB appears to provide low emissions over a broader load range than currently available technology. This increases design and operational flexibility for turbine engine manufacturers. Distributed power generation has the potential to reduce peak demand on California's power grid and provide reliable backup power in the face of potential power shortages.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: http://www.energy.ca.gov/research/innovations and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market. Demonstration of the GTSB at Honeywell's test facility helped to define the GTSB's role in the micro-turbine market. The capability of the GTSB to provide low emissions under partial load operation distinguishes it from existing technologies that rely on a diffusion pilot for stability during partial load. While Honeywell has exited the micro-turbine business, Alzeta has been building relationships with other potential users of this technology such as Solar Turbines, Inc.

Testing also reinforced the importance of a segmented burner design. A properly designed segmented burner may be less likely to fail during load transients and more able to follow the startup fuel schedule. Future research and demonstration of the segmented burner will resolve these issues that are important to market acceptance.

Engineering/Technical. Two of three technical goals were realized during the project: the GTSB was successfully demonstrated in Honeywell's test facility in micro-turbine hardware and a segmented GTSB was designed and fabricated.

Results from this project were sufficiently encouraging that Alzeta intends to continue developing the GTSB. Demonstration of the segmented GTSB in an operating engine is the next logical step in proving technical feasibility.

Legal/Contractual. No new patent issues arose during this project.

Environmental, Safety, Risk Assessments/ Quality Plans. No work related to this activity was performed.

Strategic. Development of the GTSB continues to be supported by funding agencies. The U.S. DOE awarded a contract for the GTSB in September 2000, shortly after Alzeta completed its Small Grant project. The PIER Environmentally Preferred Advanced Generation (EPAG) subject area awarded Alzeta Contract number 500-00-004 on February 14, 2001 to continue GTSB development for both industrial and micro-turbines. In September of 2001 the CEC released a Notice of Proposed Awards for the EPAG subject area. The Commission approved that award on October 31, 2001.

Production Readiness/Commercialization. Alzeta has developed a production readiness plan.

Public Benefits. PIER research public benefits are defined as follows:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary public benefit offered by the proposed technology is to make electrical energy more affordable in California by reducing the cost of emission reduction systems and extending the operational range of low emission gas turbine engines used in power generation and combined heat and power applications.

Program Administrator Assessment:
After taking into consideration: (a) research findings in the grant project, (b) overall development status as determined by stages and gates and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow-on funding within the PIER program. The CEC has taken action to provide funding for the next development steps.

Receiving follow-on funding ultimately depends upon: (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation and (c) successful evaluation of the proposal.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

Appendix A to FAR 99-13

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

IMPROVED OPERATIONAL TURNDOWN OF AN ULTRA-LOW EMISSION GAS TURBINE COMBUSTOR

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Grant #: 99-13
Grant Funding: $74,103
Term: Sep. 1999 – Jun. 2001
PIER Subject Area: Environmentally-Preferred Advanced Generation

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For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at: Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

Acknowledgement Page

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, Bill Fruchterman
- California Energy Commission, especially David Hatfield
- Energy Innovations Small Grant Project Manager, Hal Clark
- Honeywell

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Abstract

Alzeta Corporation is a product-oriented manufacturer of industrial burners and combustion systems. A leader in low-NO_X surface-stabilized burner technology, Alzeta has over 18 years of experience with cutting-edge contract research and development. Alzeta is currently developing the Gas Turbine Surface Burner (GTSB) to address emissions reduction without significantly increasing capital equipment costs. The low-emissions performance of the GTSB derives from its ability to stabilize combustion at low adiabatic flame temperatures where side reactions responsible for NO_X formation are thermodynamically less favorable than complete combustion of hydrocarbon fuel. The project objective is evaluation of the innovative concept of segmenting the GTSB's to increase operational turndown. Emissions targets for the segmented GTSB are sub-5 ppm NO_X (referenced to 15% O_2), sub-10 ppm CO and sub-10 ppm unburned hydrocarbons under partial load operating conditions.

The Alzeta GTSB was successfully demonstrated over a broad range of microturbine operating conditions in a modified Honeywell Parallon 75 combustor using Honeywell test facilities. NO_X emissions below 5 ppm were achieved for partial load operating conditions. CO emissions below 10 ppm were also achieved at each partial load operating pressure and unburned hydrocarbon emissions were undetectable under most conditions. A segmented GTSB was designed and fabricated for future testing at Honeywell.

Alzeta's GTSB is capable of producing sub-5 ppm NO_X , sub-10 ppm CO, and near zero unburned hydrocarbons under partial load operating conditions of Honeywell's Parallon 75 microturbine. Temperature data collected demonstrate that GTSB combustion performance is consistent with Honeywell's current combustor design and can be adopted without changing the materials of construction. Demonstration of the GTSB at Honeywell's test facility established a working relationship between the companies that will speed development the GTSB and accelerate its acceptance as an alternative low emissions combustion technology for microturbines.

Keywords

Lean premix combustion, surface stabilization, low emissions, natural gas, turbine

Executive Summary

Introduction

Alzeta Corporation is a product-oriented manufacturer of industrial burners and combustion systems. A leader in low-NO_X surface-stabilized burner technology, Alzeta has over 18 years of experience with cutting-edge contract research and development. Alzeta is in the process of developing an advanced low-emissions combustor for use in industrial gas turbines and microturbines. This report details design and testing of Alzeta's Gas Turbine Surface Burner (GTSB) in Honeywell's 75 kilowatt combustor test rig—a significant step in bringing the GTSB to market.

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 air pollutant emissions harmful to the global environment. Alzeta's GTSB is being developed to address emissions reduction without significantly increasing capital equipment costs.

The low-emissions performance of the GTSB derives from its ability to stabilize combustion at low adiabatic flame temperatures where side reactions responsible for NO_X formation are thermodynamically less favorable than complete combustion of hydrocarbon fuel. To reduce the adiabatic flame temperature, more air than necessary for complete combustion is premixed with gaseous fuel and directed through the combustor. In the gas turbine industry, this approach is known as dry low-NO_X (DLN) combustion. The GTSB, however, is not just another DLN system. Its unique stabilization mechanism also removes heat from the combustion reactions by radiant heat transfer resulting in lower NO_X formation than attainable by well-stirred premix combustion with the same amount of excess air.

A potential barrier to commercialization of the GTSB, as with other DLN systems, is the problem of operational turndown. Increasing the operational turndown of the GTSB requires precise local control of the air-fuel ratio over regions of the burner surface. This can be accomplished by partitioning the GTSB's into independent segments. Under low fuel flow conditions, the air-fuel ratio can be maintained in an individual segment while fuel free air passes through adjoining ones. Number and size of the segments can be adjusted to provide stable combustion over the load range. At full load, the entire GTSB is fired with fuel divided among its segments such that each is operated at the same, global air-fuel ratio.

Project Objectives

The overall project objective was evaluation of the innovative concept of segmented GTSB's to increase operational turndown. Emissions targets for the segmented GTSB are sub-5 ppm NO_X (referenced to 15% O_2), sub-10 ppm CO and sub-10 ppm unburned hydrocarbons under partial load operating conditions.

In the course of Alzeta's GTSB development program, talks with Honeywell resulted in an opportunity to evaluate the GTSB for application to their 75 kilowatt Parallon 75 microturbine. The project plan was changed to take advantage of this opportunity and the following objective was added:

- demonstrate low emission performance of GTSB in Honeywell's 75 kilowatt rig.

The original project objectives set out in the proposal were:

- design several segmented GTSB's of various geometry and segment configurations
- identify most promising fabricated GTSB's via atmospheric pressure testing
- demonstrate low emissions performance over gas turbine operating range (to be done in Honeywell's 75 kilowatt rig under the revised project plan).

Project Outcomes

The Alzeta GTSB was successfully demonstrated over a broad range of microturbine operating conditions in a modified Honeywell Parallon 75 combustor. Emissions performance was excellent with sub 5 ppm NO_X recorded for each partial load operating point. Full load operation was not realized as the GTSB experienced a failure during transition to the full load condition. However, the GTSB's advantage over Honeywell's existing technology is low emissions under turndown operation which was successfully demonstrated.

Project results include:

- A GTSB combustor was engineered and designed to mate with both Honeywell's test facility and the Parallon 75 microturbine. The GTSB combustor was fabricated; instrumented with thermocouples and gas sample lines; and operated under gas turbine operating conditions.
- NO_X emissions below 5 ppm were achieved for every partial load operating pressure along the load ramp defined in Table 1. CO emissions below 10 ppm were also achieved at each operating pressure and unburned hydrocarbon emissions were undetectable under most conditions.
- The segmented GTSB was fabricated and installed in the GTSB combustor previously used in testing at Honeywell.
- As only one test of the segmented GTSB was to be performed in Honeywell's facility, screening tests under atmospheric pressure were not conducted.
- Testing of the segmented GTSB at Honeywell encountered several delays and was eventually postponed beyond the term of this project.

Conclusions

Alzeta's GTSB is capable of producing sub-5 ppm NO_X , sub-10 ppm CO, and near zero unburned hydrocarbons under partial load operating conditions of Honeywell's Parallon 75 microturbine. Temperature data collected demonstrate that GTSB combustion performance is consistent with Honeywell's current combustor design and can be adopted without changing the materials of construction. Demonstration of the GTSB at Honeywell's test facility established a working relationship between the companies that will speed development of the GTSB and accelerate its acceptance as an alternative low emissions combustion technology for microturbines.

A segmented GTSB is required to start Honeywell's Parallon 75 and provide low emissions while load following in the 50 to 100% load range. A two segment design with axial division of the burner surface is the preferred configuration. Two segments can be accommodated by modification of the existing fuel circuits and control system on the Parallon 75. Axial division of the burner surface is compatible with the swirl based mixing design of existing combustor elements.

Experimental testing of the designed and fabricated segmented GTSB was not completed during this project due to repeated delays in scheduling time in Honeywell's facility. Alzeta is continuing to work towards completing this next step in development of the GTSB with plans to test a segmented burner in the summer of 2001. Even though this important technical goal is yet to be achieved, this Commission funded project has advanced segmented GTSB technology to the point of experimental proving.

Recommendations

Successful demonstration of the segmented GTSB at points traversing the startup fuel schedule and over the entire load range on Honeywell's test rig should lead to an engine ready design and testing in a microturbine. Once the GTSB is installed in an engine, a start schedule and control logic will have to be developed to provide low emissions over the load range. Finally, extended demonstration in a test or field engine will provide critical operating data for the commercial GTSB microturbine product.

Benefits to California

Once commercialized, the GTSB will allow low emissions microturbines to be sited throughout California providing reliable, local power generation with minimal environmental impact. The segmented GTSB will provide low emissions over a broader load range than currently possible increasing flexibility and market appeal for microturbines. Distributed power generation has the potential to reduce peak demand on California's distressed power system and provide reliable backup power in the face of potential power shortages.

Introduction

Alzeta Corporation is a product-oriented manufacturer of industrial burners and combustion systems. A leader in low-NO_X surface-stabilized burner technology, Alzeta has over 18 years of experience with cutting-edge contract research and development. Alzeta is in the process of developing an advanced low-emissions combustor for use in industrial gas turbines and microturbines. This report details design and testing of Alzeta's Gas Turbine Surface Burner (GTSB) in Honeywell's 75 kilowatt combustor test rig—a significant step in bringing the GTSB to market. This work addresses the California Energy Commission's (Commission's) Environmentally Preferred Advanced Generation subject area within the Public Interest Energy Research (PIER) program.

Background and Overview

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 air pollutant emissions harmful to the global environment. However, as distributed power gas turbine generators are an emerging technology, a number of advances must be made before their full potential is realized. Emissions of harmful pollutants such as NO_X, CO and hydrocarbons must be further reduced. The engine efficiency must be increased to minimize the use of environmental and financial resources. Finally, capital and operating costs of the engines need to be reduced for them to gain complete market acceptance. Alzeta's GTSB is being developed to address emissions reduction without significantly increasing capital equipment costs.

The low-emissions performance of the GTSB derives from its ability to stabilize combustion at low adiabatic flame temperatures where side reactions responsible for NO_X formation are thermodynamically less favorable than complete combustion of hydrocarbon fuel. To reduce the adiabatic flame temperature, more air than necessary for complete combustion is premixed with gaseous fuel and directed through the combustor. This so called "excess air" absorbs heat from the combustion reactions maintaining a low flame temperature and reducing the activity of NO_X forming reactions. In the gas turbine industry, this approach is known as dry low-NO_X (DLN) combustion in contrast to steam injection in which water vapor is used to absorb some of the combustion heat. The GTSB, however, is not just another DLN system. Its unique stabilization mechanism also removes heat from the combustion reactions by radiant heat transfer resulting in lower NO_X formation than attainable by well-stirred premix combustion with the same amount of excess air.

Laboratory tests of the GTSB have demonstrated its ability to achieve sub-2 ppm (referenced to 15% O_2) NO_X, sub-10 ppm CO and nearly zero ppm unburned hydrocarbon emissions at elevated operating pressures and combustion air preheat. While this may serve as proof of concept, the feasibility of GTSB application in industrial turbines and microturbines has not been firmly established.

A potential barrier to commercialization of the GTSB, as with other DLN systems, is the problem of operational turndown. Distributed power gas turbine engines must operate under a variety of load conditions, each with a different air-fuel ratio. Air-fuel ratio is a commonly used variable with one-to-one correspondence to excess air. The performance of the GTSB is sensitive to air-fuel ratio and to achieve the full benefits described above, steps must be taken to minimize variation of this parameter. The goal of this project is to explore the operating range of the GTSB and identify methods for increasing its operational turndown.

Increasing the operational turndown of the GTSB requires precise local control of the air-fuel ratio over regions of the burner surface. This can be accomplished by partitioning the GTSB's internal volume and dividing incoming air streams among the separate plenums. Fuel flow to each segment can then be varied by independent fuel circuits while air flow to each segment is fixed by geometry of the segmented GTSB. Under low fuel flow conditions, the air-fuel ratio can be maintained in an individual segment while fuel free air passes through adjoining ones. Number and size of the segments can be adjusted to provide stable combustion over the load range. At full load, the entire GTSB is fired with fuel divided among its segments such that each is operated at the same, global air-fuel ratio.

Project Objectives

The overall project objective was evaluation of the innovative concept of segmented GTSB's to increase operational turndown. Dividing a single burner into multiple segments allows for tighter local control of the air-fuel ratio. This, in turn, extends the operating range of the combustor and improves emissions performance without requiring complex control schemes or costly exhaust gas treatment. Emissions targets for the segmented GTSB are sub-5 ppm NO_X, sub-10 ppm CO and sub-10 ppm unburned hydrocarbons under partial load operating conditions.

In the course of Alzeta's GTSB development program, talks with Honeywell resulted in an opportunity to evaluate the GTSB for application to their 75 kilowatt Parallon 75 microturbine. The project plan was changed to take advantage of this opportunity and the following objective was added:

- demonstrate low emission performance of GTSB in Honeywell's 75 kilowatt rig.

The original project objectives set out in the proposal were:

- design several segmented GTSB's of various geometry and segment configurations
- identify most promising fabricated GTSB's via atmospheric pressure testing
- demonstrate low emissions performance over gas turbine operating range (to be done in Honeywell's 75 kilowatt rig under the revised project plan).

Report Organization

The remaining three sections of this report detail the tasks undertaken, present project results and discuss how the project has contributed to development of Alzeta's GTSB. Each section is arranged according to the above list of objectives.

Project Approach

Alzeta's gas turbine development program targets both industrial gas turbine and microturbine applications. Significant synergies exist between these efforts due in large part to the multiple injector arrangement found in industrial turbines with annular combustors—each injector being similar in kilowatt rating to a microturbine injector. To reduce time to commercialization, Alzeta has actively pursued partnerships with turbine manufacturers in developing the GTSB. It is believed that successful demonstration of GTSB technology in a manufacturer's own facilities will raise awareness of Alzeta's alternative low emissions technology and build relationships to ease integration of the GTSB into their product lines. The possibility of moving our experiments into Honeywell's test facility was seen as a great opportunity to increase the GTSB's visibility in the microturbine community. To increase the likelihood of a positive outcome, it was decided that demonstration of GTSB without staged fuel segments should precede experiments with the untested segmented injector.

GTSB Demonstration

Alzeta had already designed and tested a GTSB in the 75 kilowatt range using in-house pressurized test facilities. However, moving to Honeywell required engineering a combustor to mate Alzeta's GTSB with Parallon 75 engine hardware. Honeywell's test facility utilizes Parallon 75 hardware interfaces to exactly duplicate the engine environment while being able to independently vary total air flow, fuel flow, preheat and pressure.

Honeywell provided one of their combustors to be modified for use with the GTSB. The combustor housing was modified to accept Alzeta's louvered liner and GTSB. The louvered liner transitioned to the Parallon 75 combustor liner to mate with the combustion zone outlet. A precision milled flange mated the modified housing to the test rig and established proper insertion length for the combustion liner. Honeywell's air swirl and gas injection components were used to supply premixed fuel and air to the GTSB. The central pilot used by Honeywell was capped and not used during this test sequence. Ignition was provided by passing a spark ignitor through the housing and louvered liner. A viewing port and sight glass were provided to allow observation of the GTSB during testing. A cut-away view of the modified combustor is shown in Figure 1 and a photograph of the assembled combustor with spare burner is shown in Figure 2. The assembled combustor installed in Honeywell's test rig could also have been installed on a Parallon 75 engine.

The combustor was instrumented with 20 type-K thermocouples to record temperatures throughout the test sequence. Thermocouple locations and numbering are shown in Appendix I. A gas sampling line was inserted into the GTSB's interior volume to measure premix air-fuel ratio. The final assembly was shipped to Honeywell and installed in the 75 kilowatt test rig.

One day of testing was conducted with assistance from Honeywell engineers and technicians. The test plan attempted to simulate an increasing ramp in engine load. As increasing fuel was supplied to the combustor, air flow, preheat and pressure were simultaneously increased

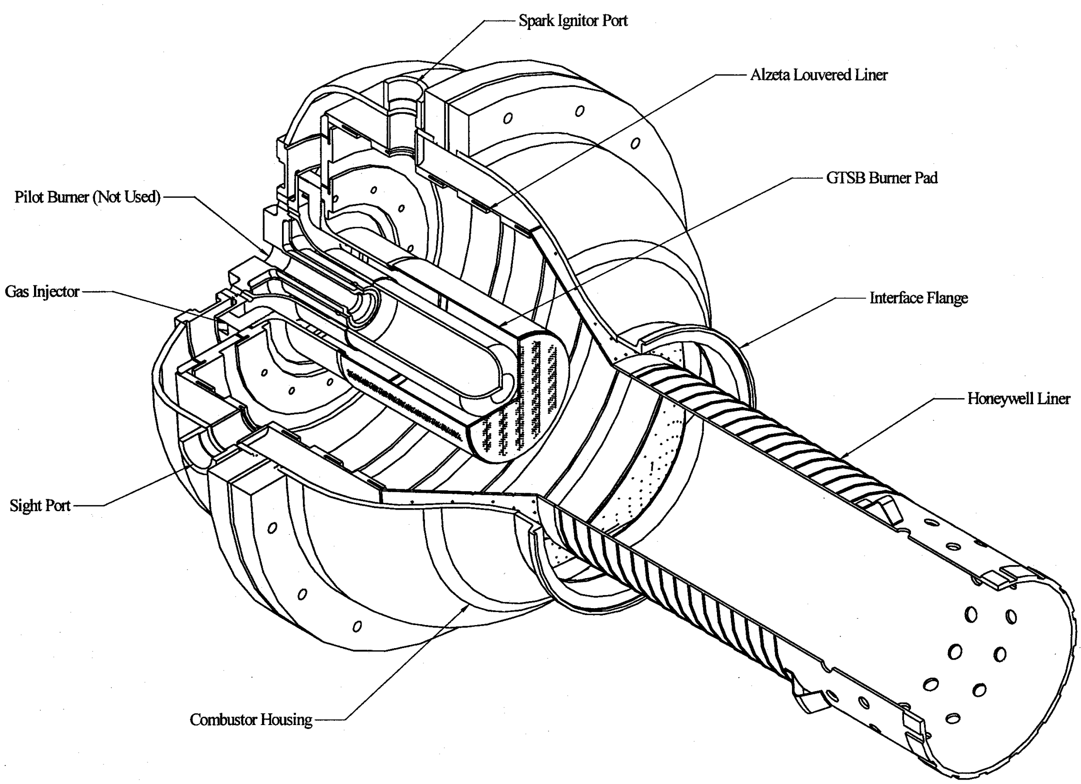


Figure 1: GTSB Combustor for Honeywell 75 kilowatt test rig, cut-away view.

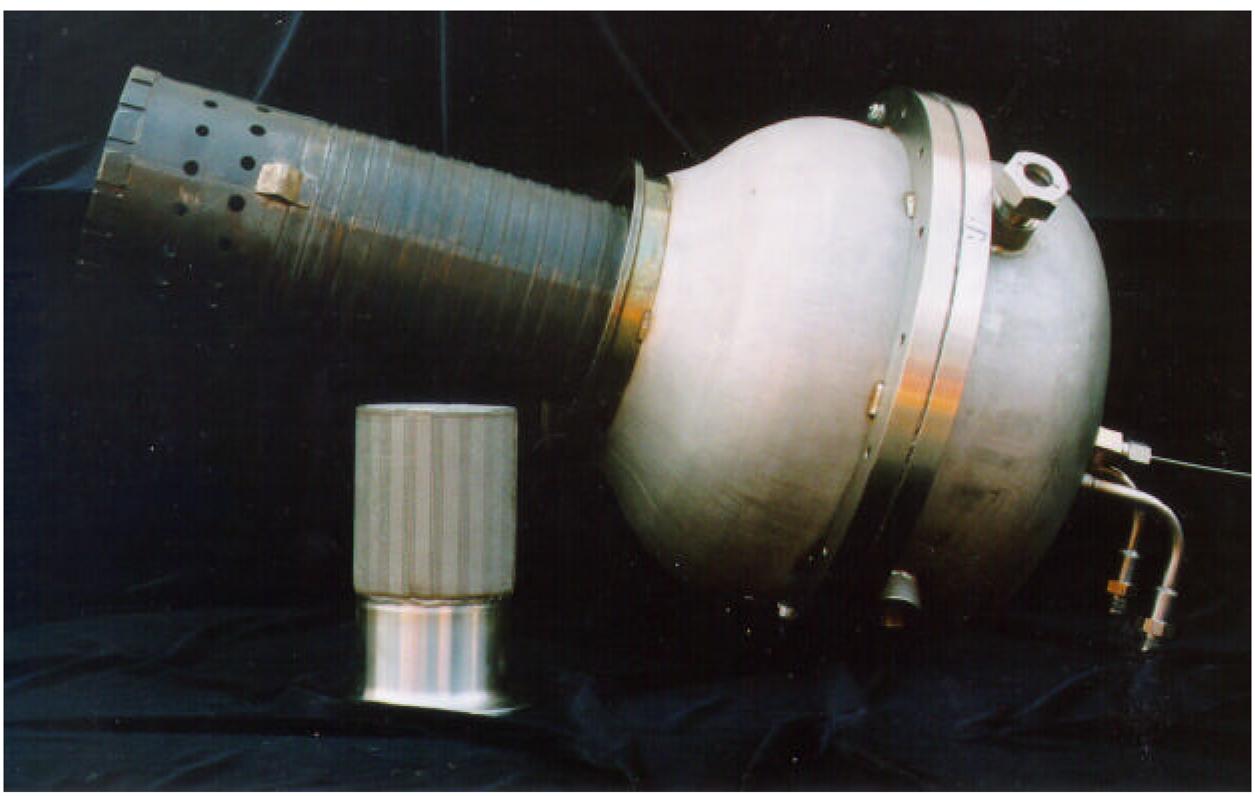


Figure 2: Assembled GTSB Combustor and Spare GTSB.

approximating the response of a recuperated single shaft turbine. Table 1 lists target values for these parameters that define a ramp from light-off to full load operation. While no effort was made to match engine operation at the intermediate points, part load performance in the engine should yield similar results.

Table 1: Test Plan for GTSB Combustor in Honeywell's Facility

	Fuel Flow	Air Flow	Pressure	Inlet Temp
		TurboGenerator	(Inlet)	(Preheat)
	pph	pps	psia	^oF
light-off	13.6	0.289	17.0	80
	18.5	0.507	22.1	700
	24.7	0.710	29.4	800
	30.8	0.935	36.8	900
	37.0	1.189	44.1	1000
full load	41.6	1.418	49.6	1110

At each operating pressure after light-off, data were collected at several points differentiated by combustor air-fuel ratio as measured online with a Thermox combustible mixture analyzer. Air-fuel ratio was adjusted by varying fuel flow to reduce adiabatic flame temperature and thereby reduce NO_X emissions. Experimental data included fuel flow, air flow, inlet pressure, exit pressure, inlet (preheat) temperature, exit temperature, multiple internal temperatures, exhaust O_2 concentration, exhaust CO_2 concentration, exhaust NO_X concentration, and exhaust CO concentration. The combustor was coated with thermal paint to assess temperature uniformity during testing.

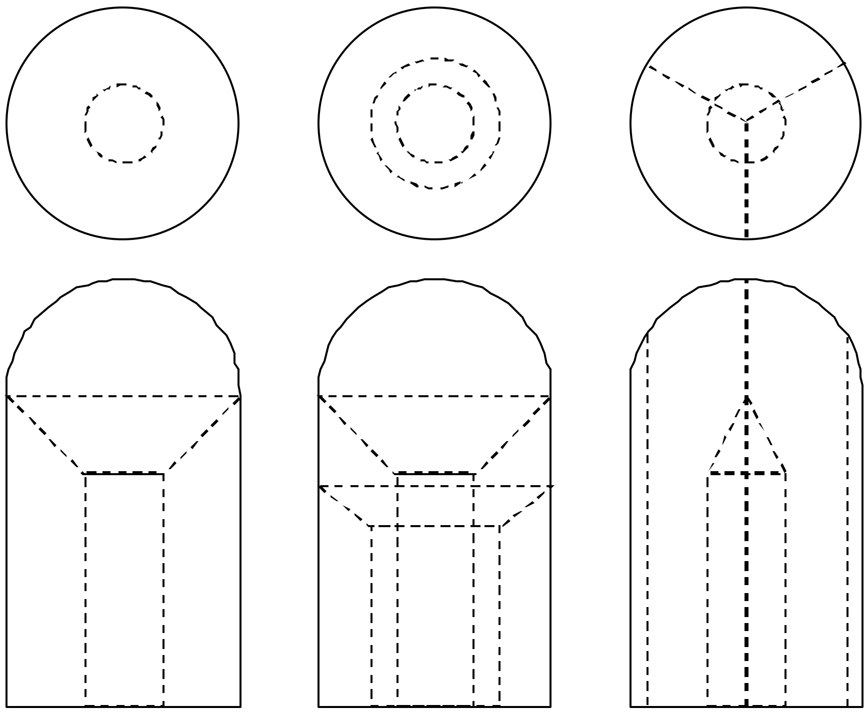
Segmented GTSB Development

The concept behind segmenting the burner surface was to give local control of the air-fuel ratio over regions of the burner surface. This was accomplished by partitioning the GTSB's internal volume and dividing incoming air streams among the separate plenums. Fuel flow to each segment could be varied by independent fuel circuits while air flow to each segment was fixed by geometry of the segmented GTSB. Under low fuel flow conditions, the air-fuel ratio could be maintained in an individual segment while fuel free air passed through adjoining ones. Number and size of the segments could be adjusted to provide stable combustion over the load range. At full load, the entire GTSB would be fired with fuel divided among segments such that each operated at the same, global air-fuel ratio.

Building upon results from testing at Honeywell as well as thermodynamic analysis of the Parallon 75 cycle, several segmented GTSB designs were conceived to provide low emissions over the load range. Examples of segmented designs are shown in Figure 3. Combinations with either two or three segments and varied proportional areas were evaluated by thermodynamic modeling to determine if stable combustion would be supported over the entire load range. The criterion used was maintaining an adiabatic flame temperature between 2550 and 3200 ^oF at each point along the ramp to full load. Secondary considerations were ease of fabrication, control system integration, fuel system integration and internal baffle impact on fuel-air mixing.

The two segment design depicted in Figure 3A was chosen for testing at Honeywell even though thermodynamic analysis predicted high flame temperatures near the 20% load condition.

A two segment design was preferred as the Parallon 75 is designed with two fuel circuits—pilot and main fuel. Axial division of the GTSB volume allowed use of Honeywell's current swirl mixers. These practical limitations eliminated competing segmented GTSB designs so the planned screening under atmospheric conditions was not performed.



A B C

Figure 3: Conceptual Segmented GTSB Designs

Segmented GTSB Demonstration

The preferred segmented GTSB design was fabricated and installed into the GTSB combustor from the first test series at Honeywell. The previously capped pilot was re-commissioned as the premix source for a secondary segment of the burner surface. The air stream was divided between the segments according to the relative flow resistance of the air passages to each segment. The combustor was again instrumented as detailed in Appendix I with 20 type-K thermocouples.

A single day of testing at Honeywell was planned, but not completed. The plan was to follow the ramp defined in Table 1 up to the point with 900 ^{o}F preheat fueling the entire burner surface. Once stable operation was confirmed, a series of tests in which fuel to the GTSB segments would be alternatively cycled on and off was planned. Crossfire ignition of inactive segments and the effect of unfired segments on emissions performance of fired segments was to be evaluated.

Project Outcomes

The Alzeta GTSB was successfully demonstrated over a broad range of microturbine operating conditions in a modified Honeywell Parallon 75 combustor. Emissions performance was excellent with sub 5 ppm NO_X recorded for each partial load operating point. Full load operation was not realized as the GTSB experienced a failure during transition to the full load condition. However, the GTSB's advantage over Honeywell's existing technology is low emissions under turndown operation which was successfully demonstrated.

Project results include:

- A GTSB combustor was engineered and designed to mate with both Honeywell's test facility and the Parallon 75 microturbine. The GTSB combustor was fabricated; instrumented with thermocouples and gas sample lines; and operated under gas turbine operating conditions.
- NO_X emissions below 5 ppm were achieved for every partial load operating pressure along the load ramp defined in Table 1. CO emissions below 10 ppm were also achieved at each operating pressure and unburned hydrocarbon emissions were undetectable under most conditions.

  In tests conducted at Honeywell's test facility, the GTSB was ignited at nearly atmospheric pressure and operated at successively higher pressure, preheat temperature and fuel flow according to Table 1. A flashback failure occurred during transition to the full load operating condition destroying the GTSB, but without damaging the combustor assembly or test stand.

  NO_X, CO and unburned hydrocarbon emissions were measured during the tests. NO_X and CO values are reported in Figure 4. At each operating pressure, three excess air levels were tested. NO_X emissions decreased with increasing excess air as expected and lower than 5 ppm NO_X results were obtained at each operating pressure. These data will feedback into design of the GTSB combustor to assure low emissions performance over the load range.

  CO emissions are also reported in Figure 4. Unexpected high CO and unburned hydrocarbon readings were recorded at the first two operating points. These data suggest incomplete combustion of the fuel. At the third operating point, CO emissions were below 10 ppm and unburned hydrocarbon emissions were nearly undetectable. CO emissions of less than 10 ppm were achieved at each subsequent operating pressure and unburned hydrocarbon emissions were nearly undetectable.

  Temperature rise through the combustor was also monitored during the tests by comparing exit and preheat temperatures as shown in Figure 5. Preheat temperature increased with increasing pressure as would occur in a recuperated engine. Exit temperature was maintained below 1600 ^oF to prevent turbine damage. Combustor temperature was consistent with Honeywell's combustor design and no extreme hot spots were revealed by thermocouples or thermal paint.

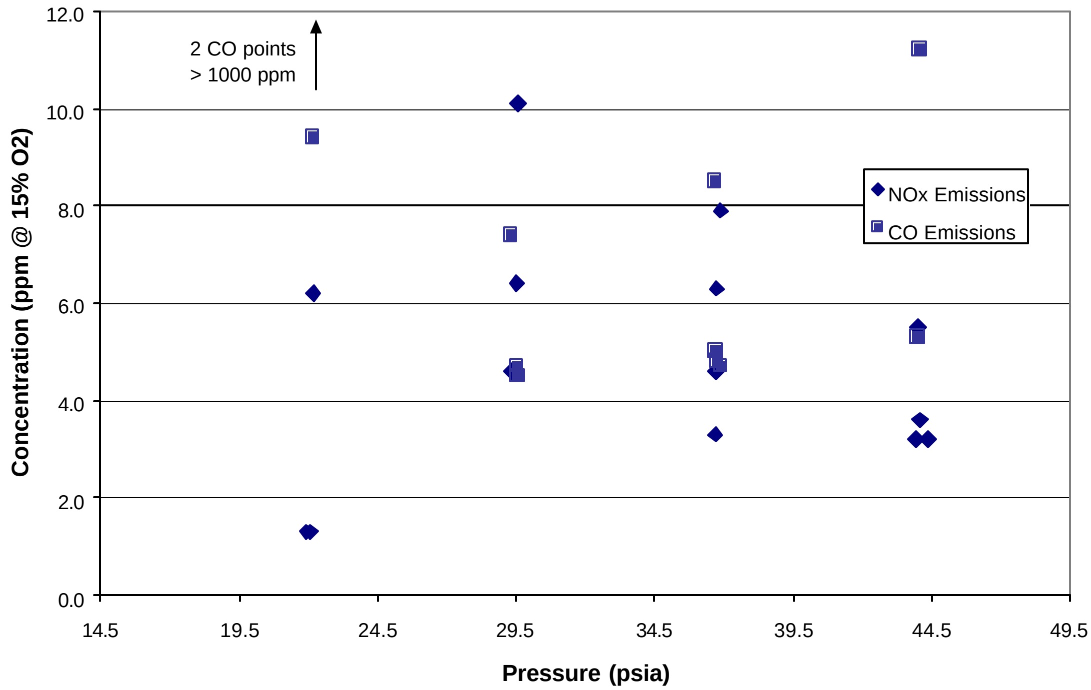


Figure 4: NO_X and CO emissions versus combustor pressure.

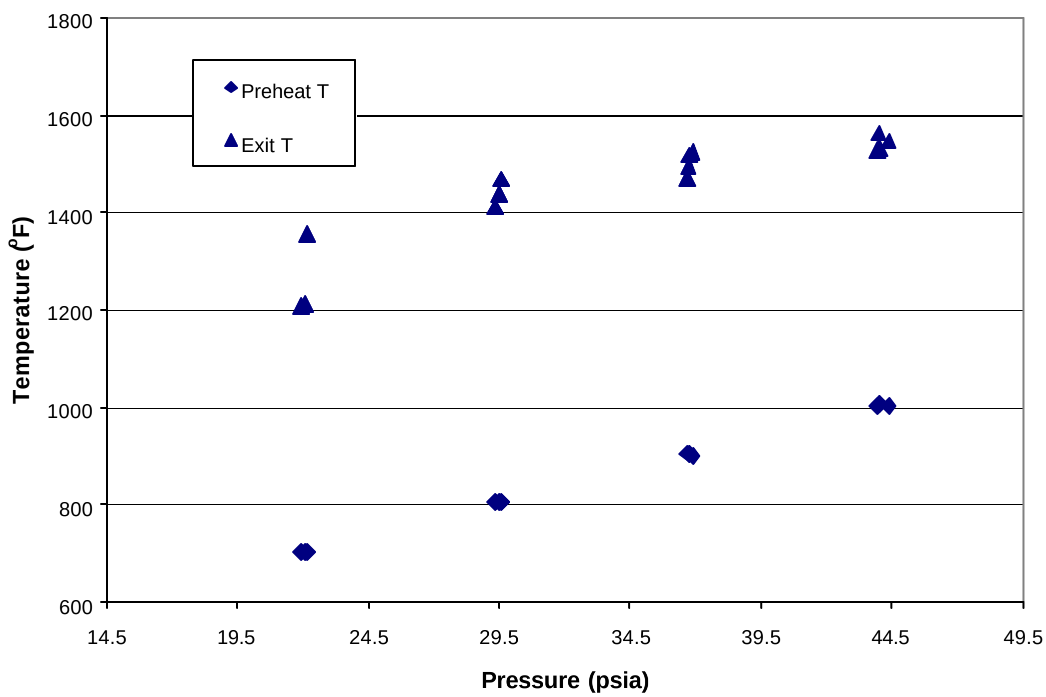


Figure 5: Preheat and Exit Temperature versus combustor pressure.

Complete test data are recorded in Appendices II and III. Test results were very encouraging to both Alzeta and Honeywell as low emissions performance was successfully demonstrated under partial load operation. A segmented GTSB would allow a lower surface firing rate under full load to reduce the risk of failure under the associated high pressure and preheat temperature conditions.

- Segmented GTSB designs with either two or three segments were designed and analyzed using thermodynamic models. While not fully optimized, a two segment GTSB with axial division was identified as most suitable for the Honeywell Parallon 75.

  Thermodynamic analysis using Alzeta's proprietary code was used to evaluate two and three segment designs shown in Figure 3 over the Parallon 75 operating range. Figure 6 shows a sample spreadsheet used to evaluate split burner designs. The sample is for a two segment burner with axial division and was the basis for the final segmented burner design. Limits on the adiabatic flame temperature, as predicted by Alzeta's code, were met except for three points near 20% load. Testing will determine if the combustion could be sustained during startup through the questionable region at 20% load. Normally the engine would not be operated below 50% load. A brief period of over-fire might be acceptable during start transients. If not, an alternative design or fuel strategy must be devised.

	SPLIT BURNER		BURNER CONDITIONS								
	Back Half ft²	Front Half ft²	Burner Split %	Air Back scfm	Air Front scfm	Firing Rate MM/hr	Surface FR MM/hr/ft²	Normalized FR MM/hr/ft²/atm	Excess Air %	AFT F	Burn? 2550 3200
Light	0.00	0.18	27%	0	15	0.078	0.4	0.44	15%	3331	
0%	0.00	0.18	27%	0	81	0.26	1.5	0.65	87%	2651	YES
5%	0.00	0.18	27%	0	82	0.29	1.6	0.71	70%	2849	YES
10%	0.00	0.18	27%	0	82	0.32	1.8	0.76	56%	3038	YES
15%	0.00	0.18	27%	0	83	0.34	2.0	0.82	45%	3214	NO
20%	0.00	0.18	27%	0	83	0.37	2.1	0.88	35%	3380	NO
25%	0.00	0.18	27%	0	84	0.40	2.3	0.92	26%	3531	NO
30%	0.33	0.00	27%	157	0	0.43	1.3	0.53	121%	2588	YES
35%	0.33	0.00	27%	159	0	0.46	1.4	0.56	108%	2698	YES
40%	0.33	0.00	27%	162	0	0.49	1.5	0.58	97%	2803	YES
45%	0.33	0.00	27%	164	0	0.53	1.6	0.61	88%	2906	YES
50%	0.33	0.00	27%	166	0	0.56	1.7	0.63	79%	3006	YES
55%	0.33	0.00	27%	169	0	0.59	1.8	0.65	72%	3101	YES
60%	0.33	0.00	27%	171	0	0.62	1.9	0.67	65%	3192	YES
65%	0.33	0.18	27%	174	94	0.66	1.3	0.46	144%	2598	YES
70%	0.33	0.18	27%	177	95	0.70	1.4	0.47	134%	2661	YES
75%	0.33	0.18	27%	180	97	0.73	1.5	0.48	126%	2727	YES
80%	0.33	0.18	27%	182	98	0.77	1.5	0.50	119%	2790	YES
85%	0.33	0.18	27%	186	100	0.81	1.6	0.51	112%	2847	YES
90%	0.33	0.18	27%	189	102	0.85	1.7	0.52	106%	2900	YES
95%	0.33	0.18	27%	193	104	0.89	1.8	0.54	100%	2954	YES
100%	0.33	0.18	27%	196	106	0.93	1.9	0.55	95%	3005	YES

Figure 6: Sample thermodynamic analysis spreadsheet for split burner.

The two-segment design with axial division was also preferred due to secondary considerations such as ease of fabrication and adaptation of existing hardware elements of the Parallon 75. Three segments would have required an additional fuel circuit and attendant controls compared to the existing pilot-main fuel configuration of the Parallon 75. The swirl mixing elements of the existing design were more amenable to axial division of the GTSB than azimuthally segmenting the burner surface.

- The segmented GTSB was fabricated and installed in the GTSB combustor previously used in testing at Honeywell.
- As only one test of the segmented GTSB was to be performed in Honeywell's facility, screening tests under atmospheric pressure were not conducted.
- Testing of the segmented GTSB at Honeywell encountered several delays and was eventually postponed beyond the term of this project.

Conclusions and Recommendations

Alzeta's GTSB is capable of producing sub-5 ppm NO_X , sub-10 ppm CO, and near zero unburned hydrocarbons under partial load operating conditions of Honeywell's Parallon 75 microturbine. Temperature data collected demonstrate that GTSB combustion performance is consistent with Honeywell's current combustor design and can be adopted without changing the materials of construction. Demonstration of the GTSB at Honeywell's test facility established a working relationship between the companies that will speed development of the GTSB and accelerate its acceptance as an alternative low emissions combustion technology for microturbines.

A segmented GTSB is required to start Honeywell's Parallon 75 and provide low emissions while load following in the 50 to 100% load range. A two segment design with axial division of the burner surface is the preferred configuration. Two segments can be accommodated by modification of the existing fuel circuits and control system on the Parallon 75. Axial division of the burner surface is compatible with the swirl based mixing design of existing combustor elements.

Experimental testing of the designed and fabricated segmented GTSB was not completed during this project due to repeated delays in scheduling time in Honeywell's facility. Alzeta is continuing to work towards completing this next step in development of the GTSB with plans to test a segmented burner in the summer of 2001. Even though this important technical goal is yet to be achieved, this Commission funded project has advanced segmented GTSB technology to the point of experimental proving.

Successful demonstration of the segmented GTSB at points traversing the startup fuel schedule and over the entire load range on Honeywell's test rig should lead to an engine ready design and testing in a microturbine. Once the GTSB is installed in an engine, a start schedule and control logic will have to be developed to provide low emissions over the load range. Finally, extended demonstration in a test or field engine will provide critical operating data for the commercial GTSB microturbine product.

Once commercialized, the GTSB will allow low emissions microturbines to be sited throughout California providing reliable, local power generation with minimal environmental impact. The segmented GTSB will provide low emissions over a broader load range than currently possible increasing flexibility and market appeal for microturbines. Distributed power generation has the potential to reduce peak demand on California's distressed power system and provide reliable backup power in the face of potential power shortages.

Development Stage Assessment

All activities had progressed through stage 2 before work on the project began as supported by the main text of Alzeta's proposal presented in Appendix IV.

During the project term, activities consistent with stage 3 were performed. Table 2 indicates the progress in terms of stages for the seven activity areas.

Table 2: Stages and Gates Activity Matrix.

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

Marketing

Demonstration of the GTSB at Honeywell's test facility helped to define the GTSB's niche in the microturbine market. The ability of the GTSB to provide low emissions under partial load operation distinguishes it from existing technologies that rely on a diffusion pilot for stability during partial load. Testing at Honeywell established a relationship between Alzeta and a potential customer or commercialization partner for the GTSB.

Testing also reinforced the importance of a segmented burner design. A properly designed segmented burner will be less likely to fail during load transients and able to follow the startup fuel schedule. Future demonstration of the segmented burner will resolve these barriers to market acceptance.

Engineering/Technical

Two of three technical goals were realized during the project: the GTSB was successfully demonstrated in Honeywell's test facility in microturbine hardware and a segmented GTSB was designed and fabricated.

Results from this project were sufficiently encouraging that Alzeta intends to continue developing the GTSB and Honeywell is willing to support that effort. Demonstration of the segmented GTSB is the next logical step in proving technical feasibility.

Legal/Contractual

No new patent issues arose during this project.

Risk Assess/Quality Plans

No work related to this activity was performed.

Strategic

Development of the GTSB continues to be supported by the commission under PIER's environmentally preferred advanced generation subject area. Contract number 500-00-004 was executed in March 2001 to continue GTSB development for both industrial and micro-turbines.

Production Readiness/Commercialization

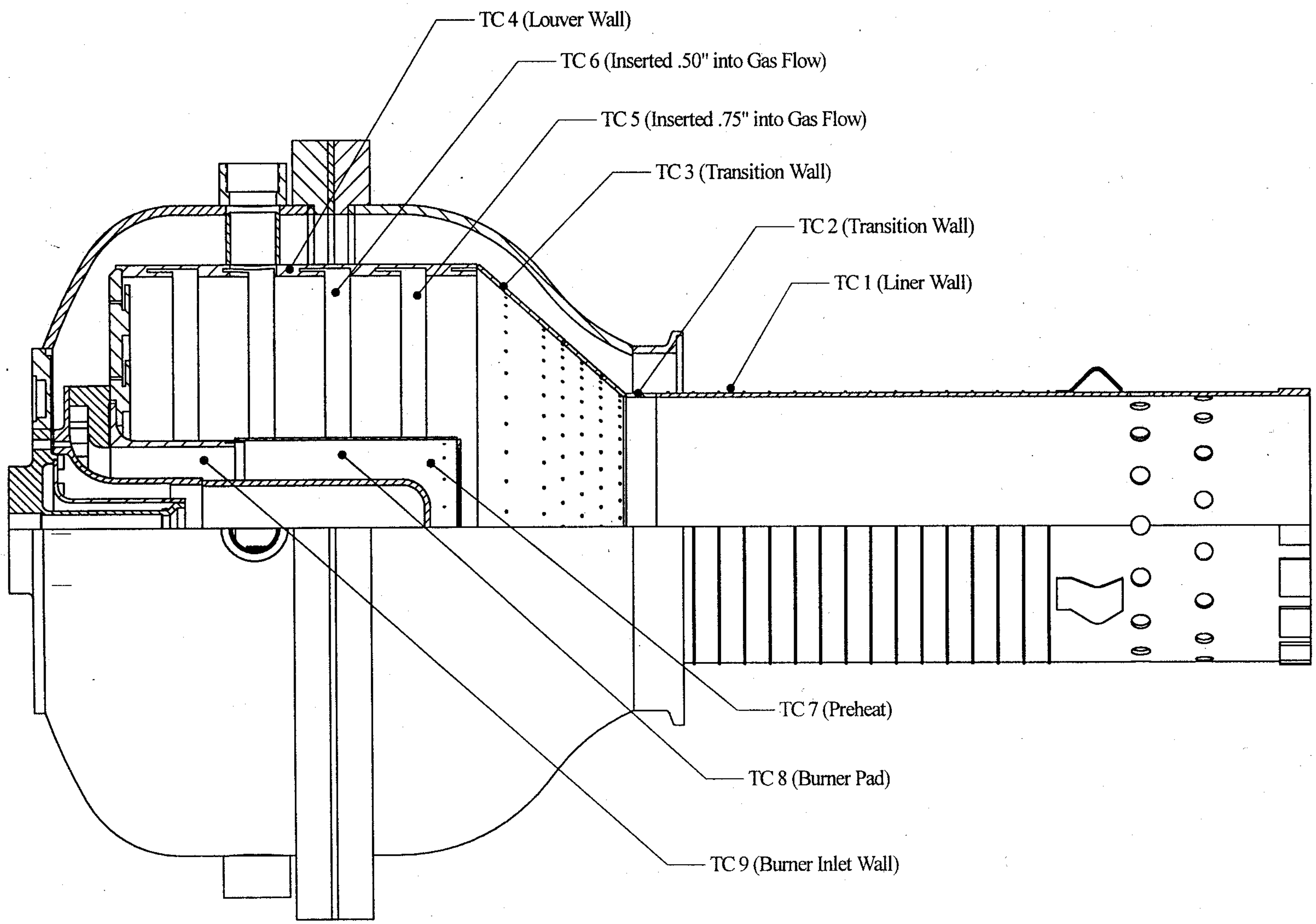
Alzeta has developed the production readiness plan presented in Appendix V.

Public Benefit/Cost

Once commercialized, the GTSB will allow low emissions microturbines to be sited throughout California providing reliable, local power generation with minimal environmental impact. The segmented GTSB will provide low emissions over a broader load range than currently possible increasing flexibility and market appeal for microturbines. Distributed power generation has the potential to reduce peak demand on California distressed power system and provide reliable backup power in the face of potential power shortages.

Appendix I

Thermocouple Locations for GTSB combustor.



Appendix II

Flow and Emissions Data

TurboGenerator Parameters					GTSB Combustor Parameters													Emission and DP				
Condition Number	Fuel Flow	Air Flow TurboGen	Pressure (inlet)	Inlet Temp (preheat)	Fuel Flow FR	SFR	NFR	Air Flow TurboGenerator	Pressure	Preheat	Burner Air Airflow	% to burner	AFT	EA	Thermox	EA Tot	Exit T	HC PPM	CO PPM	NOX PPM	O2	DP/P
	pph	pps	psia	F	MMBtu/hr	MM/hr/ft²	MM/hr/ft²/atm	scfm	atm	F	scfm	%	F	%	% O2	%	F	15% O2	15% O2	15% O2	%	%
5006	12.0	0.510	22.1	702	0.27	0.7	0.5	402	1.5	702.3	85	21%	2713	94%	9.7%	820%	1199	1142.1	1370.9	1.3	19	7.1%
5007	11.8	0.510	22.0	703	0.26	0.7	0.5	402	1.5	703	88	22%	2621	105%	10.3%	836%	1191	9007.4	1977.0	1.3	19.3	6.9%
5010	15.6	0.510	22.2	703	0.35	0.9	0.6	402	1.5	703	NA	NA	NA	NA	NA	NA	NA	7.2	9.4	6.2	18.36	6.8%
6000	21.4	0.720	29.5	805	0.48	1.3	0.6	567	2.0	805.3	136	24%	2960	75%	8.5%	628%	1414	0.0	4.7	6.4	18.4	7.6%
6010	22.5	0.710	29.6	805	0.50	1.3	0.7	559	2.0	805.3	NA	NA	NA	NA	NA	NA	NA	0.0	4.5	10.1	18.26	7.6%
6020	20.4	0.710	29.3	805	0.45	1.2	0.6	559	2.0	804.9	135	24%	2893	82%	9.0%	653%	1394	0.0	7.4	4.6	18.5	7.4%
7000	28.0	0.930	36.9	900	0.62	1.7	0.7	732	2.5	900.2	184	25%	2971	81%	8.9%	619%	1507	0.0	4.7	7.9	18.36	8.3%
7010	27.5	0.930	36.7	903	0.61	1.6	0.7	732	2.5	903.3	184	25%	2949	84%	9.1%	632%	1500	0.0	4.8	6.3	18.41	8.1%
7020	26.5	0.940	36.7	904	0.59	1.6	0.6	740	2.5	904	184	25%	2883	91%	9.5%	668%	1474	0.0	5.0	4.6	18.52	8.1%
7030	25.2	0.930	36.7	906	0.56	1.5	0.6	732	2.5	905.5	183	25%	2813	100%	10.0%	698%	1455	0.0	8.5	3.3	18.63	8.1%
8000	31.5	1.190	44.4	1002	0.70	1.9	0.6	937	3.0	1002	229	24%	2886	100%	10.0%	718%	1531	8.2	14.1	3.2	18.68	7.3%
8010	30.1	1.190	43.9	1003	0.67	1.8	0.6	937	3.0	1003	235	25%	2779	115%	10.7%	756%	1510	8.6	14.1	3.2	18.8	7.3%
8020	30.2	1.190	44.1	1006	0.67	1.8	0.6	937	3.0	1006	350	37%	2269	219%	14.0%	753%	1514	8.6	11.2	3.6	18.78	7.0%
8030	31.9	1.190	44.0	1007	0.71	1.9	0.6	937	3.0	1007	257	27%	2738	121%	11.0%	707%	1542	4.1	5.3	5.5	18.66	7.0%

Appendix III

Thermocouple Data

Alzeta Combustor Test in Honeywell Parallon 75 Combustor Test Rig

	COMBUSTION TESTS												
CONDITION LABEL	5006	5007	5010	6000	6010	6020	7000	7010	7020	7030	8000	8010	8020
Liner													
TK1.1 ....(F)	964	939	1053	1131	1151	1123	1203	1202	1192	1180	1252	1244	1250
TK1.2 ....(F)	1082	1055	1169	1235	1253	1230	1281	1277	1265	1254	1281	1269	1265
TC 1 Average	1023	997	1111	1183	1202	1177	1242	1240	1229	1217	1267	1257	1258
Transition Small													
TK2.1 ....(F)	1054	1026	1158	1239	1264	1229	1311	1311	1296	1281	1348	1336	1343
TK2.2 ....(F)	1072	1035	1170	1245	1268	1236	1313	1310	1297	1281	1347	1332	1337
TK2.3 ....(F)	1123	901	1272	1329	1362	1317	1405	1401	1384	1361	1440	1425	1429
TC 2 Average	1083	987	1200	1271	1298	1261	1343	1341	1326	1308	1378	1364	1370
Transition Large													
TK3.1 ....(F)	903	898	1002	1078	1098	1075	1148	1148	1137	1127	1203	1193	1201
TK3.2 ....(F)	936	883	1048	1111	1131	1109	1168	1167	1159	1148	1215	1204	1211
TK3.3 ....(F)	1030	881	1296	1330	1377	1320	1375	1375	1352	1317	1362	1337	1346
TC 3 Average	956	887	1115	1173	1202	1168	1230	1230	1216	1197	1260	1245	1253
Louver													
TK4.1 ....(F)	887	867	1023	1112	1143	1108	1177	1174	1159	1131	1183	1164	1177
TK4.2 ....(F)	908	839	1016	1094	1114	1096	1148	1147	1136	1123	1174	1166	1172
TK4.3 ....(F)	830	794	949	1060	1127	1063	1144	1130	1105	1079	1130	1116	1126
TC 4 Average	875	833	996	1089	1128	1089	1156	1150	1133	1111	1162	1149	1158
Gas													
TG5 ....(F)	1645	1542	1947	1995	2030	1971	2047	2028	2010	1975	2024	1982	1994
TG6 ....(F)	1057	934	1813	1910	1962	1880	1983	1964	1929	1883	1930	1892	1910
Preheat													
TK7.1 ....(F)	777	757	800	889	898	895	954	957	956	953	1017	1019	1023
TK7.2 ....(F)	777	758	801	890	899	896	954	958	957	954	1018	1019	1024
TC 7 Average	777	758	801	890	899	896	954	958	957	954	1018	1019	1024
Burner Pad													
TK8.1 ....(F)	777	760	803	895	903	900	965	968	967	965	1040	1041	1046
TK8.2 ....(F)	770	753	785	874	881	879	940	943	943	941	1008	1009	1013
TC 8 Average	774	757	794	885	892	890	953	956	955	953	1024	1025	1030
Burner Inlet													
TK9.1 ....(F)	796	765	819	905	913	911	969	971	970	968	1031	1031	1035
TK9.2 ....(F)	828	788	853	942	951	947	1003	1005	1002	999	1061	1060	1064
TC 9 Average	812	777	836	924	932	929	986	988	986	984	1046	1046	1050
Station 2.9													
TT2.9A ....(F)	703	704	704	806	806	806	902	904	906	907	1002	1003	1007
TT2.9B ....(F)	701	702	702	804	804	804	899	902	903	905	1002	1002	1005
TC 2.9 Average	702	703	703	805	805	805	901	903	905	906	1002	1003	1006
Station 4.0													
TT4.0A ....(F)	1161	1085	1279	1368	1396	1356	1448	1444	1426	1408	1479	1463	1468
TT4.0B ....(F)	1145	1067	1264	1351	1377	1337	1427	1422	1405	1387	1453	1436	1442
TT4.0C ....(F)	1185	1104	1310	1396	1425	1382	1475	1470	1452	1432	1503	1486	1490
TT4.0D ....(F)	1040	976	1133	1221	1242	1211	1290	1287	1274	1257	1320	1306	1309
TC 4.0 Average	1133	1058	1247	1334	1360	1322	1410	1406	1389	1371	1439	1423	1427
Thermal Avg. Exit Temp..(F)	1213	1208	1356	1439	1469	1412	1525	1518	1496	1471	1547	1528	1532
Alzeta Exit AFT (F)	1199	1191	NA	1414	NA	1394	1507	1500	1474	1455	1531	1510	1514
Alzeta Flame Temp (F)	2713	2621	NA	2960	NA	2893	2971	2949	2883	2813	2886	2779	2269

Appendix IV

Excerpt from Alzeta's original proposal to the Commission.

Executive Summary

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. However, as distributed power gas turbine generators are an emerging technology, a number of advances must be made before their full potential is realized. Emissions of harmful pollutants such as NO_x, CO and hydrocarbons must be further reduced. The efficiency of the engines must be increased to minimize the use of environmental and financial resources. Finally, the operating costs of the engines need to be reduced in order for them to gain complete market acceptance. With this EISG, Alzeta plans to address some of these important problems.

Alzeta Corporation is a product-oriented manufacturer of industrial burners and combustion systems. A leader in low-NO_x surface-stabilized burner technology, Alzeta has over 16 years of experience with cutting-edge contract research and development. Alzeta is in the process of developing an advanced combustor for use in industrial gas turbines. With the support of the CEC and several industrial partners, including Solar Turbines, Alzeta 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% O_2) emissions of NO_x, 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's SoLoNOx injector, which can meet regulations of 25 ppm or more.
- Efficiency – DOE's Advanced Turbine System (ATS) program has pushed turbine efficiencies near the 40% 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% 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.

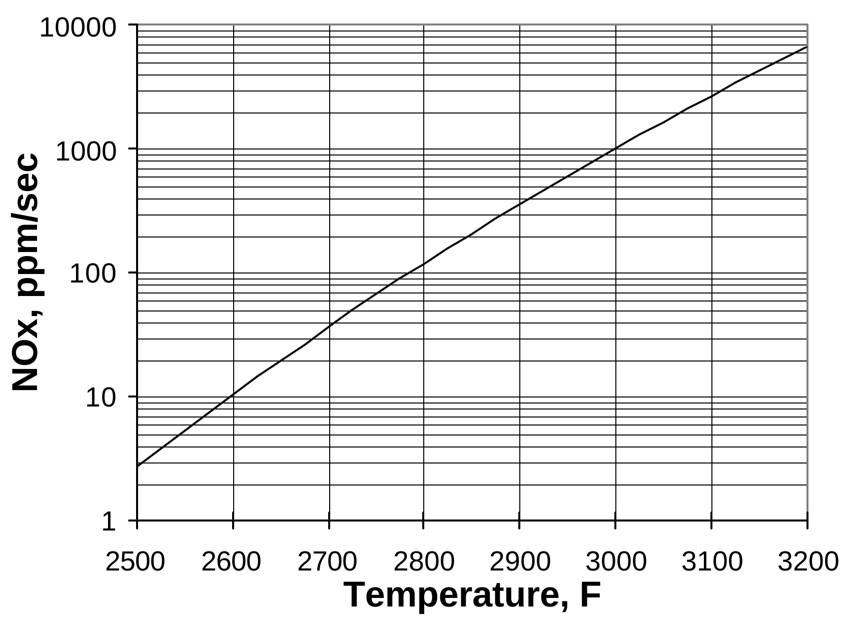
One of the barriers to complete commercialization of the GTSB is the problem of operational turndown. Distributed power gas turbine engines must operate under a variety of load conditions, each with a different air-to-fuel ratio. The performance of the GTSB is fairly sensitive to the air-to-fuel ratio, and therefore in order to achieve the full benefits described above, steps must be taken to minimize the variation in this parameter that the burner experiences. The purpose of this EISG will be to explore and test methods for increasing the operational turndown of the GTSB with an eye toward ultimately increasing the competitive advantages and market acceptance of this developing product.

Work on this project will focus on evaluating the innovative concept of segmented GTSB's, specifically for eventual use in Solar Turbines engines. Dividing a single burner into multiple segments will allow for tighter local control of the air-to-fuel ratio. This will, in turn, extend the operating range of the combustor and improve emissions without requiring complex control schemes or costly exhaust gas treatment. The scientific approach to the problem will involve the design of several different segmented GTSB's. The most promising designs will be fabricated and subjected to rigorous testing in Alzeta's combustion laboratory. A final evaluation of the designs and recommendations for follow-on work will be included in the project's final report.

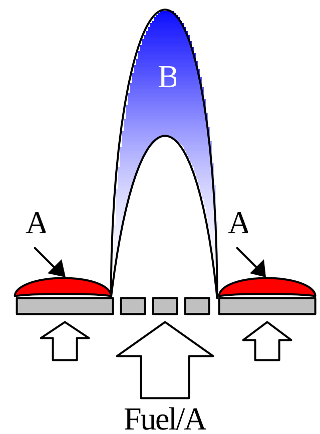
The GTSB Technology

The basis of the GTSB combustion system began with the same technology used 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. However, basic scientific questions remain before the burner can be fully engineered to gas turbine specifications.

The key to the technology is stable operation at low adiabatic flame temperature. As shown in the figure below, the key to low emissions is low temperature and short residence time. This curve is obtained from thermal NO_x production calculations from Alzeta's Chem code, an equilibrium chemistry solver. The figure indicates, for example, that emissions of about 1-ppm would be realized at a flame temperature of 2800^{o}F and a residence time of 0.01 seconds. A reduction of temperature to 2700^{o}F further reduces the NO_x production rate by a factor of 3. A key 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

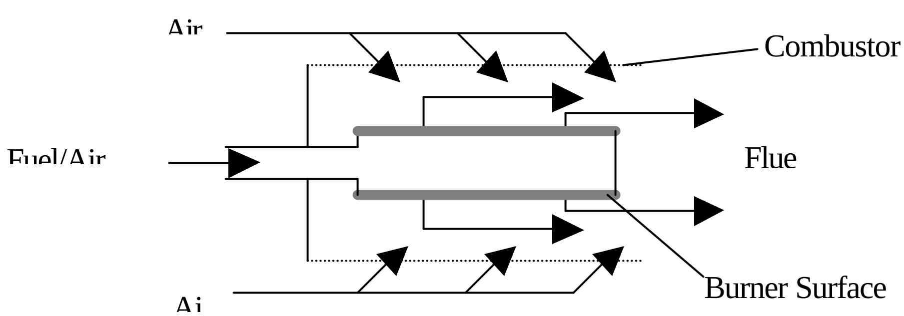


done by first establishing a radiant flame zone over a porous metal surface. Premixed fuel comes



through this low conductivity surface and burns in narrow zones, A, as it leaves the surface. Secondly, adjacent to these radiant zones, the porous plate 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. A picture of an atmospheric burner in operation clearly shows the technology in action.

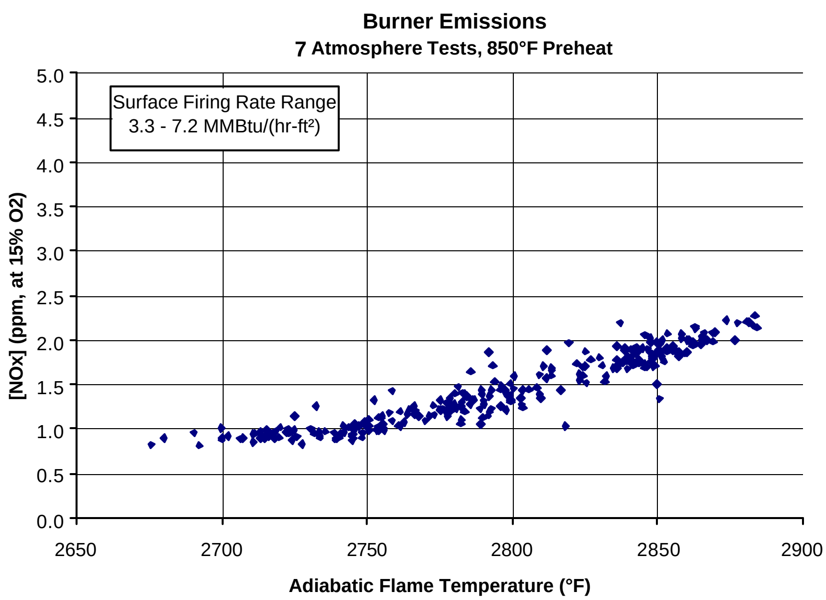
The application of this technology to the high pressure, high preheat, and compact environment of gas turbine combustors has been established in tests performed over the last year. These tests focused on the determination of the optimal configuration for gas turbine combustion. Typical combustors require volumetric firing rates greater than 2 MMBtu/hr/ft^3. Various folded geometries were investigated in order 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 shown below. 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-5ppm respectively.



Successful Outward-Fired Configuration

Low Emissions Results

Alzeta immediately recognized the importance of these low emissions results to the gas turbine community because NO_x levels below 2.5ppm over a 200°F range of excess air (see below) 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 5MW industrial turbine with a baseline cost of only $2,000,000. 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.



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 2-4% of the system pressure.
- Operation at combustion air preheat temperatures up to 1150°F.

- Volumetric firing rates approaching 2 MMBtu/hr/atm/ft³.
- Turbine Rotor Inlet Temperatures (TRIT) over 2200°F (valid for the Mercury 50, 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 AlliedSignal 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 temperatures below 1500°F will be a key measure of success.

Anticipated Benefits of the GTSB

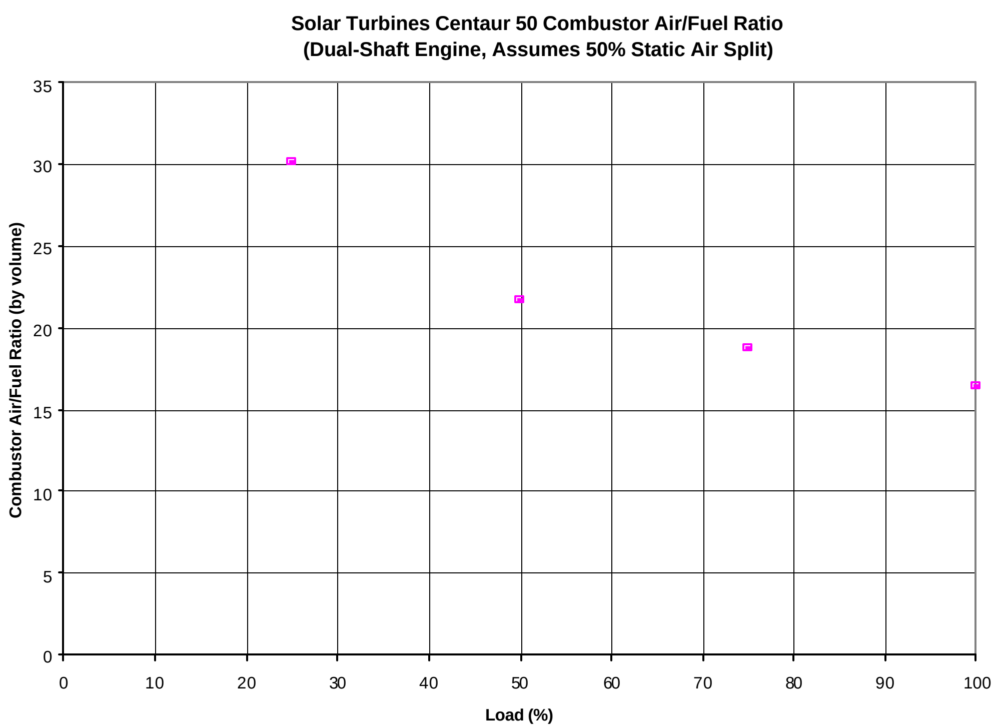
The benefits stemming from the successful implementation of the GTSB will be available to all California ratepayers in the form of cheaper electricity, a more efficient power supply, and a cleaner environment in which to live. These significant benefits are a direct result of the magnitude of the power generation/gas turbine market. DOE estimates show up to 2000 gigawatts of power plant additions from gas turbines in the next twenty years, resulting in a domestic market as large as $5 billion per year after 2000. In addition, U.S. manufacturers of gas turbines export up to $3 billion per year, which the Department of Commerce equates to the creation of 60,000 jobs. The 15% efficiency improvement from the ATS turbines will account for annual savings of 1 trillion cubic feet of natural gas by 2020, resulting in the same 1 trillion cubic feet decrease in CO_2 production. The additional 15% improvement in efficiency allowed by the GTSB combustor would nearly double the decrease in fuel use and CO_2 production to almost 2 trillion cubic feet each. While these statistics are based on nationwide estimates, it is fair to say that California, as an industrial leader, will receive a significant portion of these benefits.

The benefits from this project will not be limited to a specific market segment. The technical advances of the GTSB combustor will be licensed to all interested gas turbine manufacturers. Initially, the development will be engineered with Solar Turbines and the Mercury 50 will be the targeted engine. The advantage of funding Alzeta (a company that does not manufacture the gas turbine) is that we have an *incentive* to give our technology to as many gas turbine manufacturers as possible. This will serve to extend the use of the GTSB injector to products supplied by Allison, GE, Westinghouse, and AlliedSignal.

The Challenge of Operational Turndown

The GTSB has shown great promise throughout the initial qualification process. However, several challenges must be met before the GTSB can be commercialized in a variety of turbines. One of these challenges, the focus of this proposal, is operational turndown. The GTSB is a fully premixed burner. This is the key to many of the benefits outlined above. However, this also restricts the range of air-to-fuel ratios within which the burner can successfully operate. Typically, the GTSB will operate best at burner volumetric air-to-fuel ratios between 15 and 25. Preheat temperature will effect these values, but the size of the available window remains essentially the same. If the air-to-fuel ratio becomes too great, a lean flameout will result. If the air-to-fuel ratio is too low, high emissions of NO_x and/or burner failure may occur.

Gas turbines require combustors that operate throughout a broad range of air-to-fuel ratios. This is because of operational turndown. As the demand for electricity decreases from a full-load operating condition, fuel consumption decreases proportionately. The amount of air passing through the turbine also decreases, but much less quickly than the fuel. The resulting effect is that as the load on the engine decreases, the air-to-fuel ratio increases, often by a factor of 2 or more. The figure below shows air-to-fuel ratios found under different load conditions in a Solar Turbines Centaur 50 combustor, assuming a 50% static air flow split (no variable geometry) in a dual-shaft engine. In order for a single combustor to power the turbine throughout all load conditions, it must be able to handle the entire range of air-to-fuel ratios.



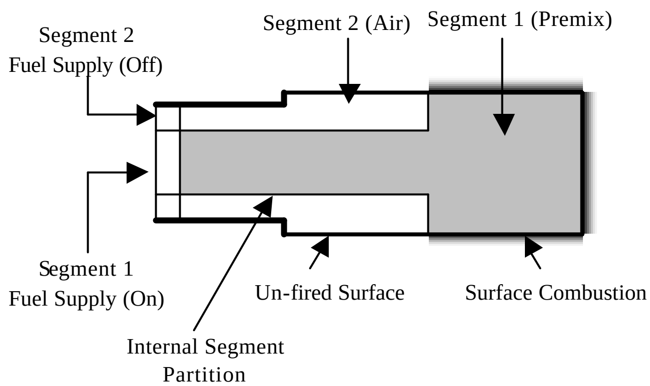
Several solutions to this problem have been proposed or implemented with existing combustors. The most common solution is to employ variable geometry. Variable geometry is a method by which the physical configuration of the combustor hardware is changed in response to changing load conditions. This, in turn, effects a change in the proportion of air that reaches the burner (primary or combustion air) to air that is diverted around the burner (secondary or dilution air). Careful manipulation of this air split can ensure that the air-to-fuel ratio of the burner remains essentially the same under all load conditions. The drawback to variable geometry is that it is an expensive and complex option to implement. The nature of the solution requires that moving parts be placed inside the combustor itself, where temperatures can often exceed 1000°F. This can create maintenance and lifetime issues. Furthermore, the controls that actuate the variable geometry mechanism must be fairly precise in order to realize the full benefits of the variable geometry. Such controls are costly to implement and program. Thus, variable geometry has come to carry negative connotations in the gas turbine R&D community. Alzeta's industrial partners have made it clear that the GTSB will gain much more acceptance if it does not require the use of variable geometry.

A second solution is to use a secondary "pilot burner" to handle some of the lower load conditions, and switch over operation to the primary burner only at or near full load where the air-to-fuel ratios become favorable. This is generally a more simple solution than true variable geometry. The required controls are less complex and the fuel valves required to actuate the change are less specialized. Moving parts can be located away from the most hostile environments. However, the pilot burners employed with this scheme are generally not premixed. In fact they resemble some of the more primitive gas turbine combustors from decades past, and possess many of the same drawbacks. Emissions will be exceedingly high and efficiency will suffer whenever the engine operates in off-load pilot mode. In many applications, this is a large portion of time and represents a significant amount of the overall fuel used by the engine. If a pilot-hybrid strategy were employed with the GTSB, many of the benefits of the GTSB would be diminished and the incentive for commercializing the technology might be lost.

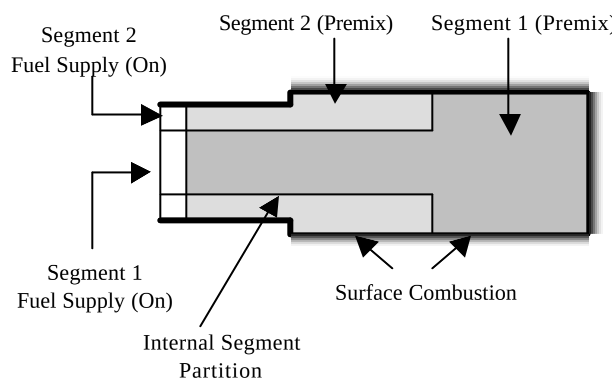
Alzeta's proposed solution to the turndown problem involves the implementation of a segmented GTSB. This scheme will be described in detail in the following section. The segmented GTSB concept holds the promise of eliminating many of the drawbacks that plague the above-mentioned systems. Moving parts will be minimized, and located in easily accessible areas. Control schemes will be relatively simple. The GTSB will operate throughout the entire required turndown without need for a pilot burner, allowing its benefits to be fully realized. These incremental advantages over competing combustors will allow the GTSB to achieve increased performance, gain increased market penetration, and offer increased benefits to California's ratepayers.

Technical Approach

The concept of the segmented GTSB holds the promise of eventually providing a superior solution to the problem of premixed combustion throughout the operational turndown required in a gas turbine engine. Without using moving parts, it is possible to divide the interior of a GTSB burner into several discrete segments. The advantage of this scheme is that fuel can be delivered to any or all of the individual segments, as required. When the engine is operating at full load, all of the segments would be utilized. As demand decreases, air would continue to be delivered to all segments according to the fixed geometry of the combustor. However, in the face of rapidly decreasing fuel requirements, the fuel supply to certain segments would be shut off. The remaining segments would continue to operate with essentially the same air-to-fuel ratio, virtually unaffected by the change. A conceptual sketch of a GTSB operating under two different modes is included below.



One-Segment



Two-Segment Operation

A single GTSB burner could conceivably contain an unlimited number of segments. The more segments the burner contains, the more smoothly the air-to-fuel ratio in each segment can be controlled. However, an unnecessarily large number of segments will carry with it high fabrication and controls costs. Ultimate commercial burners may require 3-4 segments for optimal operation. Nevertheless, the design and engineering principles required to divide a burner into segments are the same regardless of the number of desired segments. Therefore, for simplicity, this initial research effort will focus only on two-segment burners.

Project Plan

The work on this project will be divided into three distinct tasks (two technical and one reporting), each with its own objectives. The milestones and completion dates of these tasks are described in the table on page 9. The first task will involve initial design of the segmented GTSB. There are many possible methods for dividing the burner into distinct segments. Several alternatives will be considered and evaluated with regard to ease of fabrication, ease of implementation, quality and completeness of segmentation, and failure risk analysis. These segmentation options combined with the existing variety of GTSB geometries and pad configurations will generate an array of possible burners to be fabricated. A small number of these candidates (approximately 4) will be chosen and fabricated. While the prototypes are being fabricated, Alzeta engineers will evaluate different control strategies that might ultimately be implemented with a commercial segmented GTSB. This will complete the work for Task 1.

The second task of the project will involve qualification testing of the prototypes fabricated in Task 1. All of the burners will first be tested at atmospheric conditions in Alzeta's burner screening bay. This facility allows excellent visual access to operating burners. The prototypes will be evaluated for combustion stability, hardware integrity, flashback potential, and initial emissions. The burners displaying the best operating characteristics will be chosen and will undergo more complete testing in Alzeta's 75 kW gas turbine combustor test rig. The burners will be tested at a variety of conditions designed to simulate critical parameters of a distributed power generation gas turbine engine. These parameters include air flow, fuel flow, system pressure, and preheat. The data collected during these tests will be critical in the future development of the segmented GTSB technology.

The final task of the project will be project reporting. Monthly progress reports will be furnished throughout the duration of the project. At the end of the project, a final report will be provided, including specifications of the most successful designs, test results, and a discussion of future work to be performed in the development cycle.

Performance Schedule

Task	Milestones	Completion
1. Initial Design	a. Design several segmented GTSB's. Different methods of segmenting will be considered, as well as multiple geometries and pad configurations.	Month 1
	b. Fabricate selected designs. While hardware is being fabricated, test plans will be developed and potential control schemes will be considered.	Month 2
2. Prototype Testing	a. Test all fabricated burners at 1 atm. Tests to include flashback potential, stability range, and emissions as well as qualitative analysis of impact of segmenting.	Month 3
	b. Test selected burners at pressure under specific gas turbine operating conditions. These tests will illustrate the potential benefits of segmenting in terms of emissions and stability.	Month 4
3. Project Reporting	a. Monthly reports	Each Month
	b. Final report	Month 6

Qualifications

Key Personnel

There are three key Alzeta personnel that will contribute to the success of this project. Dr. Scott Smith will serve as the Principal Investigator. He is the Project Manager at Alzeta Corporation for all R&D efforts. Dr. Robert Kendall, Chairman at Alzeta, will serve as Technical Reviewer to ensure the success of the project. Steve Greenberg is the lead Project engineer, and has worked actively with Alzeta's gas turbine combustor development for over three years. The resumes of all three are included as attachments with this proposal.

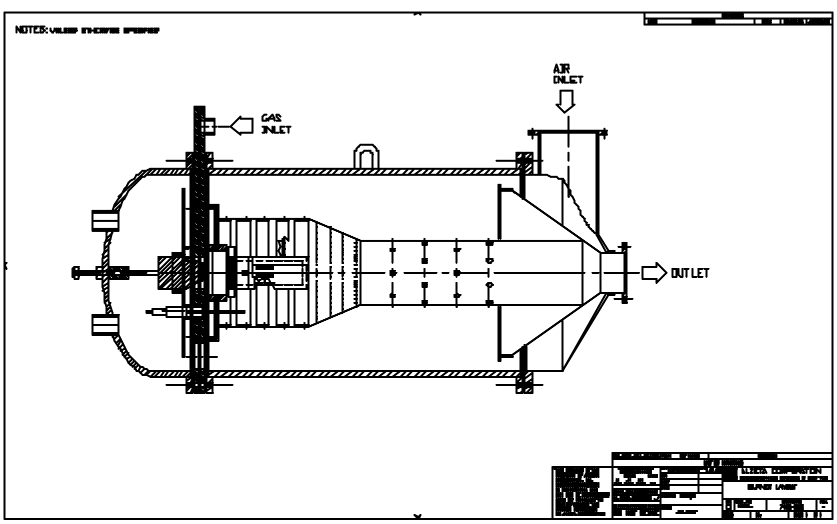
R&D Experience

Alzeta project teams have a strong history of commercializing products stemming from R&D projects. A list of recent successes is included below:

Customer/Agency	Contract Number	Project Title	Product Commercialized?
U.S. DOE	DE-AC04-89CE40918	Advanced Radiant Combustion System	Yes
Gas Research Institute	5090-253-1929	Packaged Thermal Destruction System for VOC Emissions	Yes
Sematech	Award from RFP119	Point of Use Volatile Organic Management System	Yes
California Energy Commission	500-91-026	Ultra-Low Emissions TEOR Steam Generator	Yes
California Energy Commission	500-95-021	High Efficiency Low Emissions Boiler Demonstration	Yes

Facilities and Equipment

Pressurized burner testing will be performed at Alzeta using the 75kW combustion facility. A sketch of this facility is included below. Additional support tests will be performed using the ambient-pressure burner screening bay. The 75kW test facility is a fully-operational pressurized combustor with the following characteristics: (1) gas flow delivery to fire burners up to 1MMBtu/hr, equivalent to a single Mercury 50 injector scaled to pressure; (2) pressures of up to 4 atm; (3) combustion air preheat up to 1150°F; (4) Air flow rate up to 1 lb/s when operated with a diesel air compressor; (5) continuous emissions monitoring of NO_x, NO, NO_2, CO, CO_2, O_2 and unburned hydrocarbons; and (6) high speed digital data recording of pressure, temperature and emissions data.



Appendix V

Production Readiness Plan

1 Introduction and Product Description

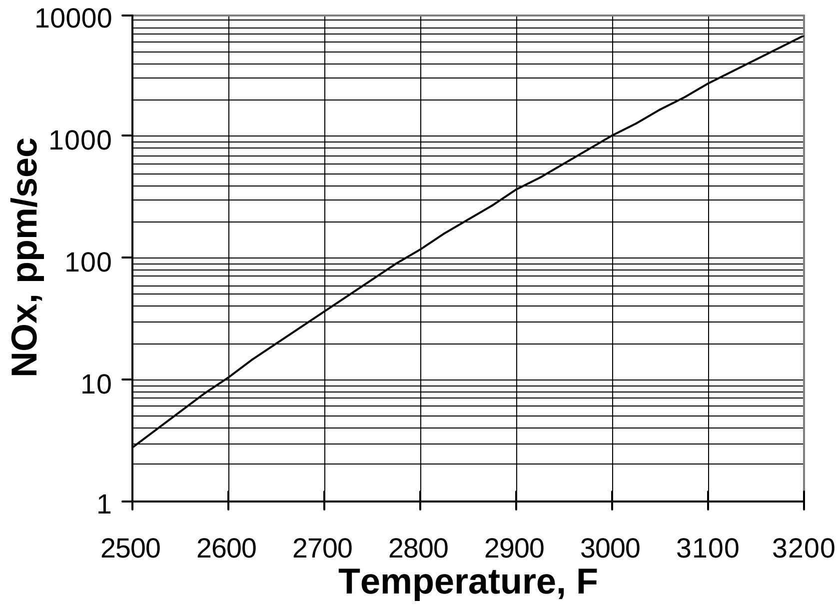
In California's deregulated electricity market, distributed power gas turbine generators are playing an increasingly important role. This technology holds the promise of bringing cheaper, more reliable electricity to California's ratepayers while reducing the use of natural resources and the impact on 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% O_2) emissions of NO_x, 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% 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% 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.

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 shown in the figure below, 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. 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 (see **Figure 4-1**). 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/ft² at atmospheric pressure. A picture of an atmospheric burner in operation (**Figure 4-2**) clearly shows the technology in action.

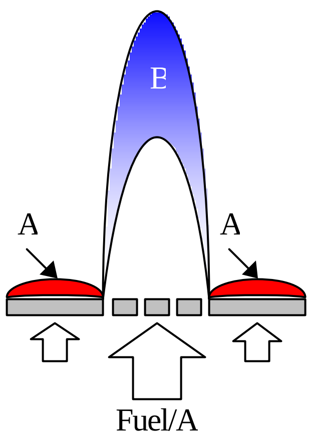
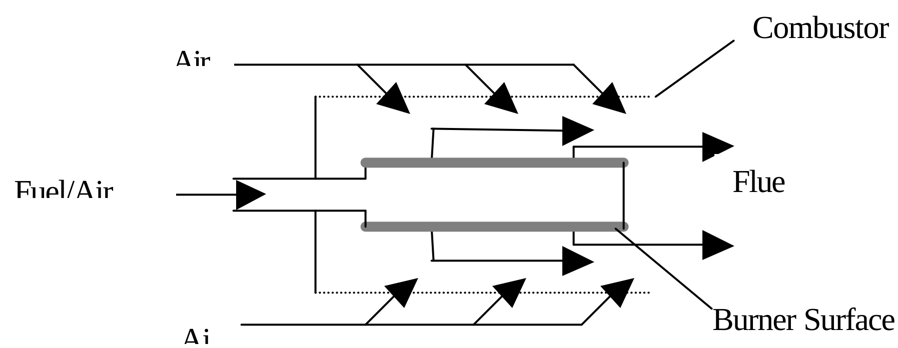


Figure 4-1: Schematic of GTSB Burner Pad And Dual Flow Zones

Figure 4-2: 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/ft³. Various folded geometries were investigated in order to apply surface combustion (where the firing rate scales per ft²) 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 shown below. 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.



Successful Outward-Fired Configuration

Low Emissions Results

Alzeta immediately recognized the importance of these low emissions results because NO_x levels below 2.5ppm 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 5MW industrial turbine with a baseline cost of only $2,000,000. 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.

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 2-4% 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.

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 and the Honeywell Parallon 75. 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.

2 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% 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 following estimates of GTSB 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 these estimates of GTSB 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

According to these estimates, the combined sales of GTSB combustors to Solar Turbines and Honeywell over the next decade will be:

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.

3 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.

4 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 2 vendors to produce burner pads and 3 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.

5 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 4 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. The current costs are summed below to derive the cost of the first production unit:

Item	Qty.	Unit	Unit Cost	Ext. Cost
Hastelloy Pad Material	0.4	ft^2	$80.00	$32.00
Laser Drill Holes	6382	holes	$0.07	$446.74
Backing Plate	0.35	ft^2	$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% within a few years. This discount and the two strategies discussed above will have the following impact on production cost:

Item	Qty.	Unit	Unit Cost	Ext. Cost
Hastelloy Pad Material	0.4	ft^2	$80.00	$32.00
Punch Holes	6382	holes	$0.001	$6.38
Backing Plate	0.35	ft^2	$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% or more, assembly cost can be reduced by 50%, 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. Implementation of these advanced techniques will have the following impact on the cost:

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.

6 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% 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.

The following table summarizes the steps required to ramp up to full production and details an approximate timeline for the completion of these tasks:

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