A NEW GAS TURBINE ENGINE CONCEPT FOR ELECTRICITY GENERATION WITH INCREASED EFFICIENCY AND POWER

FEASIBILITY ANALYSIS AND FINAL EISG REPORT

Prepared For:
California Energy Commission
Energy Innovations Small Grant Program

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ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

FEASIBILITY ANALYSIS REPORT (FAR)

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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 $3 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
- Energy Systems Integration

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
    - Appendix A: Final Report (under separate cover)
    - 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.

A New Gas Turbine Engine Concept For Electricity Generation With Increased Efficiency And Power

EISG Grant #: 99-09

Awardee: University of California, Irvine
Principal Investigator: William A. Sirignano
PI Contact Info: Phone: (949) 824-3700; Email: sirignano@uci.edu

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Introduction

Most of the new electrical generators installed in California are large (>50MW), gas-fueled combustion turbines. A small increase in the efficiency beyond that of those turbines would have a major, positive impact on the price and availability of electricity on the California market.

This project investigated the potential of a new gas turbine cycle that the researcher named the "turbine-burner". In this cycle heat is added to the turbine gas flow using a conventional combustion system, and additional heat is added to the turbine gas flow by combustion inside the turbine itself. The researcher investigated both continuous stage-to-stage combustion (CTB) and discrete inter-stage burners (ITB). The ITB concept is similar to the inter-stage combustor found in the commercial Alstrom GT 24 gas turbine engine. There are two major benefits to sequential addition of fuel to a combustion turbine. First, the temperature of the gasses entering the next turbine stage is at the highest safe level, protecting the turbine while offering the greatest energy transfer to the turbine. Second, the energy in the compressed gasses is almost fully exploited by burning out nearly all of the oxygen in the air.

Further, this project investigated the effects of combining heat regeneration with continuous and discrete inter-stage combustion, and this was the principle focus of the analysis. Regeneration is the process of recovering heat from the exhaust gasses and transferring that heat to the high-pressure air exiting the turbine compressor. Solar Turbines Inc. has recently developed a 4.5 MW gas turbine with a regenerator. Micro-turbine manufacturers also offer regenerated engines. None has combined the regenerator and inter-stage combustor features into one engine model.

The researcher claims that the proposed cycle offers the potential to increase gas turbine thermal efficiency to a theoretical 65%, and to double the power density of the existing engines. Heat regeneration has a significant effect on the cycle efficiency, while inter-stage combustion increases the power density. The proposed engine is a recuperated engine with inter-stage burners. It is not a combined cycle gas turbine. Today's best combined-cycle gas turbines are approximately 60% efficient.

Objectives

The goal of this project was to determine the feasibility of implementing continuous combustion in the turbine section of a gas turbine combined with heat regeneration to increase thermal efficiency to the 65% level. The researcher established the following project objectives:

1. Determine the optimum design configuration for a gas turbine with continuous combustion and a regenerator. Perform detailed cycle analysis of several design concepts. Optimize the

design by varying engine parameters such as turbine inlet temperature, pressure ratio and power distribution in the turbine stages.

2. Develop engine design tools using aero-thermodynamic and combustion analysis to evaluate the effects of continuous, in-stage combustion flow in the turbine section.
3. Calculate theoretical efficiency and power density for an engine with continuous combustion.

Outcomes

1. The project developed a computer code for the analysis of turbine cycles with inter-stage and continuous (in-stage) combustion. The researcher identified preferred design configurations.
2. The researcher developed a computational method and code for the compressible Navier-Stokes equations with multiple species and chemical reactions. Using this code the researcher studied a two-dimensional diffusion flame in a transonic flow with large stream-wise and transverse pressure gradients typical of conditions in a turbine passage.
3. The researcher calculated theoretical efficiencies and power densities.

Conclusions

1. The project found that the discrete inter-stage burner (ITB) cycle is a good intermediate solution before the technological challenges of the continuous turbine-burner cycle can be resolved. Direct combustion in the turbine section can lead to material failures if the ignition, flame-holding and control techniques are not properly developed.
2. The researcher determined that ignition and flame-holding in the turbine passage under conditions of high acceleration of the flow is possible for methane/air mixtures when the incoming air is sufficiently heated.
3. The theoretical maximum efficiency is 65%. The best power density is approximately 2.5 times that of an engine with a single traditional combustor. These numbers represent best theoretical values and may not be achievable in practice.

The researcher has established the theoretical feasibility of the ITB and CTB concepts using analytic modeling as originally proposed. In addition the researcher has identified several issues for further research. These include studies of combustion in a turbine passage, ignition and flame holding methods, and the development of a large eddy simulation code. The PA identified several practical obstacles that could impede the progress toward a physical realization of the CTB concept. These include materials challenges in the turbine section, durable high-temperature regenerators, high-effectiveness regenerators, sensors and controls for the continuous burning section, controls for load following, and manufacturing problems associated with a rather complex system. These many issues remain to be addressed through follow-on RD&D.

The major contributions of this research are the analytical tools and models developed to study combustion within the turbine section of the engine. In addition, the concepts developed in this project are better suited to combustion turbines less than 50 MW. The size and cost of regenerators will limit the size of regenerated, combustion turbines. If the proposed concepts can be commercialized, the resulting combustion turbines will be highly efficient offerings in the distributed generation market.

Turbine design engineers are very conservative because their customers demand very high reliability. The gas turbine industry may adopt the concepts developed in this project, but at a very measured pace. The Alstrom GT24 already employs one inter-stage combustion chamber that approximates the ITB concept described by the researcher. Other manufacturers have offered regenerated engines.

Benefits to California

This project provides the theoretical background for a combustion turbine system with increased efficiency and power density. Many technical hurdles stand between the concept and a practical turbine engine. For this reason California will only realize benefits after a significant amount of applied research and development. The PA estimates that this line of research might provide ratepayer benefits in the 2017 to 2022 timeframe. The project concept, if successful, will reduce fuel consumed to produce electricity and could significantly lower the initial capital cost of a turbine generator.

Recommendations

The PA recommends that the researcher engage a gas turbine manufacturing company in the evaluation and development of the CTB concept. The manufacturer must develop an engineering development plan utilizing the researcher's concepts before further study should begin. Significant additional research is required before commercial application of these concepts can occur. Thus, the researcher should seek follow-on funds from institutions that focus on basic research to reduce the perceived level of risk. The addition of a gas turbine manufacturer to the research team could significantly reduce the time required to bring this technology to the market.

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

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

The researcher published four technical papers, reporting on aspects of this research. Initial publications stimulated interest by aircraft engine researchers. It is appropriate to recognize that so- called "aero-derivative" gas turbines are commonly used to power electric generators.

Engineering/Technical

This project further investigated the turbine-burner cycle. The cycle described is a high risk, high reward research area. The knowledge and understanding of this new cycle is far too preliminary to claim that feasibility was proven. The project developed significant tools and knowledge, illuminating areas of prior technological unknowns. However, additional testing is needed to understand and optimize the operating parameters for the cycle.

Legal/Contractual

The researcher did not address patent issues in this project.

Environmental, Safety, Risk Assessments/ Quality Plans

This research is not sufficiently advanced to warrant these detailed plans. Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere

Production Readiness/Commercialization

This research is not sufficiently advanced to warrant analysis in this subject area.

Public Benefits

Public benefits derived from PIER research and development are assessed within the following context:

- 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 benefit to the ratepayer from this research will be in the area of increased affordability of electricity to the California ratepayer. It is too early to estimate potential cost saving from the concepts developed in this project. While theoretical efficiencies appear to be high, it is not clear at this time what will be achieved in practice.

Appendix A: Final Report (under separate cover)

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

EISG FINAL REPORT

PIER
Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

A New Gas Turbine Engine Concept for Electricity Generation with Increased Efficiency and Power

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Legal Notice

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Table of Contents

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.

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

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.

Executive Summary

While California has taken concrete steps in constructing windmill and solar power plants to supplement its total production of electricity, by far the most electricity is still generated by thermal power plants using gas. The efficiency of the gas turbines used in power generation is of major importance to the competitiveness of businesses and the conservation of energy for the state of California. A small percentage increase in the efficiency of such turbomachines would have significant economic implications for the energy use of the state. This project investigates the potential of an innovative gas turbine cycle using augmented combustion inside the turbine (turbine-burner) and heat regeneration for electricity generation. The project seeks to

(1) Perform detailed cycle analysis of such advanced concepts, and optimization on design configurations and parameters such as turbine inlet temperature, pressure ratio, and power distribution in the turbine stages,

(2) Perform aerothermodynamic and combustion analysis on the flow through the turbine blade rows with the aim of deriving new design principles which must be drastically modified over the conventional turbine design in order to enable the ``turbine-burner'' technology.

(3) Identify potential issues for further research and development concerning this technology.

The following tasks have been accomplished.

(1) A computer code for cycle analysis of turbine-burner engines has been developed. Both concepts of continuous turbine-burners (CTB) and discrete inter-stage turbine-burners (ITB) have been investigated. It is found that the ITB design is a good intermediate solution before the technological challenges of the CTB concept can be resolved.
(2) A computational method is developed for the compressible Navier-Stokes equations with multiple species and chemical reactions. The code is used to study a two-dimensional diffusion flame in a transonic flow with large streamwise and transverse pressure gradients typical of conditions in a turbine passage. Ignition and flame-holding in these high acceleration channels is shown to be possible for methane/air mixtures when the incoming air is sufficiently heated.
(3) Several issues for further research and development are identified; these include: further studies of combustion in a turbine passage, ignition and flame holding methods, need for large eddy simulation, and the potential of using a condenser in combination with a turbine-burner.

Based on the findings of this project, it is recommended that further theoretical, computational, and experimental research be conducted in the technological development of the turbine-burner concept for power generation. The proposed concept is of "high risk". However, the potential technological advancement and commercial gain in the power and utility industry is tremendous.

Abstract

This project investigates the potential of an innovative gas turbine cycle using augmented combustion inside the turbine (turbine-burner) and heat regeneration for electricity generation. A computer code for cycle analysis of turbine-burner engines has been developed. Both concepts of continuous turbine-burners (CTB) and discrete inter-stage turbine-burners (ITB) have been investigated. It is found that the ITB design is a good intermediate solution before the technological challenges of the CTB concept can be resolved. A computational method is developed for the compressible Navier-Stokes equations with multiple species and chemical reactions. The code is used to study a two-dimensional diffusion flame in a transonic flow with large streamwise and transverse pressure gradients typical of conditions in a turbine passage. Ignition and flame-holding in these high acceleration channels is shown to be possible for methane/air mixtures when the incoming air is sufficiently heated. Several issues for further research and development are identified, these include: further studies of combustion in a turbine passage, ignition and flame holding under realistic conditions, and the need for large-eddy simulation.

MAIN REPORT

Introduction

According to Reference [1], electricity generation and transportation accounts for more than half of California's total energy consumption. Nationwide, 36% of the total energy consumption is for electric generation and 27% for transportation [2]. While California has taken concrete steps in constructing windmill and solar power plants to supplement its total production of electricity, by far the most electricity is still generated by thermal power plants using gas [1]. The efficiency of the gas turbines used in power generation is of major importance to the competitiveness of businesses and the conservation of energy for the state of California. A small percentage increase in the efficiency of such turbomachines would have significant economic implications for the energy use of the state.

An innovative gas turbine cycle using augmented combustion inside the turbine (turbine-burner) and heat regeneration is investigated. Preliminary calculations show that gas turbine engines using this cycle maintain the same compactness of the conventional gas turbine engine and thus the same level of capital investment and flexibility in installment while greatly increasing the thermal efficiency and power output with potential decreased environmental impact (less NOx emission). The potential thermal efficiency of the proposed turbine-burner engine can be as high as 65%, a 15 to 20% increase over conventional engines. The specific power of such an engine, however, is doubled over its conventional counterpart. The goals of this work are:

(1) Perform detailed cycle analysis of such advanced concepts, and optimization on design configurations and parameters such as turbine inlet temperature, pressure ratio, and power distribution in the turbine stages;

(2) Perform aerothermodynamic and combustion analysis on the flow through the turbine blade rows with the aim of deriving new design principles which must be drastically modified over the conventional turbine design in order to enable the "turbine-burner" technology; and

(3) Identify potential issues for further research and development concerning this technology.

Project Approach and Outcome

(1) **The Turbine-burner Cycle Analysis**

Gas turbine engine designers are attempting to increase power and efficiency without increasing pollutant formation. In a conventional gas turbine engine as schematically shown in Figure 1, fuel is burned in a separate combustion chamber before the high temperature and high-pressure gas expands through the turbine that drives the compressor and produces the needed shaft power. The conventional thinking has been to prevent any residual burning in the turbine after the flow has exited the combustor. In a study concerning mostly aircraft engines (Sirignano and Liu, 1999), the PIs have shown, however, that significant benefit can result from augmented burning in the turbine. It is well known that the overall thermal efficiency of such an engine is a function of only the compressor pressure ratio in the ideal case. A higher pressure ratio gives higher thermal efficiency, but it also reduces the total power output of the engine because the gas temperature at the exit of the compressor becomes higher so that fuel addition to the main combustor has to be reduced in order to maintain the same maximum temperature at the turbine inlet. The turbine inlet temperature is limited by the material of the turbine blades. Consequently, it is clear that there is a contention between efficiency and power output. The power output directly influences the size and weight of the engine, which are critical for aircraft engines. Although not as critical as for aircraft engines, size and weight are also important for ground-based engines because they affect the initial capital investment, operational cost, and flexibility and versatility in installment. In order to increase the power output, one solution is to add an inter-turbine reheater between the HP (higher pressure) turbine and the LP (low pressure) turbine as shown in Figure 2. This proposal, however, is a ``half way'' solution for two reasons. First, the heat added in the reheat chamber is still of limited amount. Second, the extra heat is added at low pressures (after the HP turbine), and therefore, the resulting cycle efficiency is low.

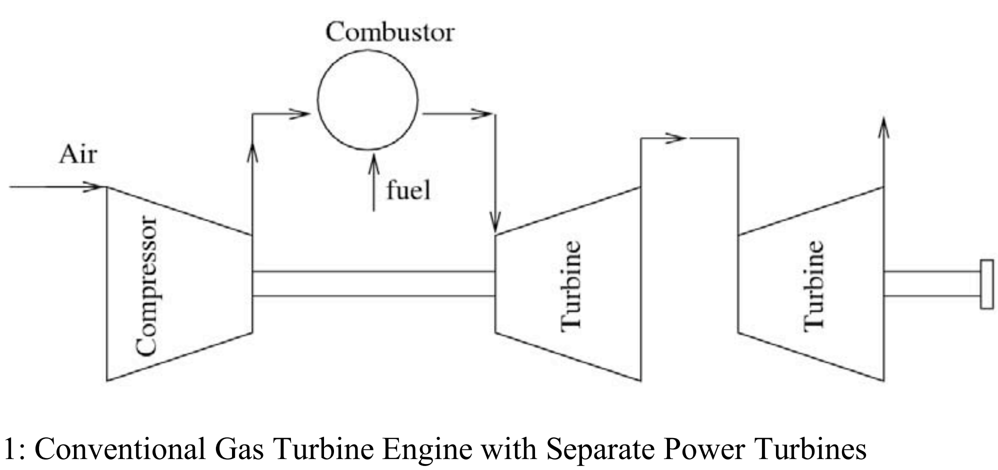

Figure 1: Conventional Gas Turbine Engine with Separate Power Turbines

We propose to perform continuous burning inside the turbine as shown in Figure 3. We call such a turbine a turbine-burner. In the turbine-burner, fuel is burned, heating the flow while doing work on the rotor at the same time. Depending on the relative magnitude of the two processes, the stagnation temperature of the flow may increase or decrease. The former is not desirable since it will cause the total temperature to exceed the material limit. For a given temperature range, we know that the most efficient cycle is the Carnot cycle, in which heating occurs at a constant temperature. It appears then that the ideal option is to organize the heating so that the stagnation temperature in the turbine stays constant. In this way, the amount of heat that can be added can be significantly increased and a large portion of it is added in the high-pressure turbine, giving a higher cycle efficiency contribution. Now that the power output is increased due to the additional heating in the turbine, we may increase the compressor pressure ratio to further increase efficiency. For ground-based gas turbine engine, another means for increasing efficiency is available, that is, to use heat regeneration, in which the high temperature gas from the turbine-burner can be used to preheat the flow before going into the main combustor. The thermodynamic cycle for such a regenerative turbine-burner engine is show in Figure 4(a).

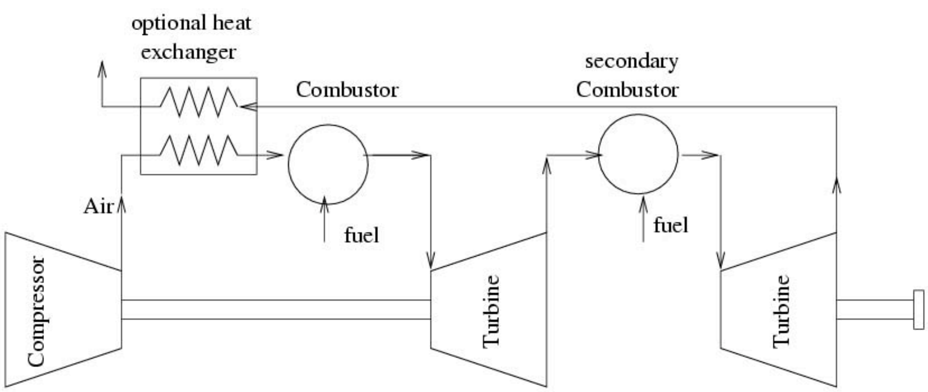

Figure 2: Conventional Gas Turbine Engine with Inter-Turbine Burner and Optional Heat Regeneration (ITB Configuration)

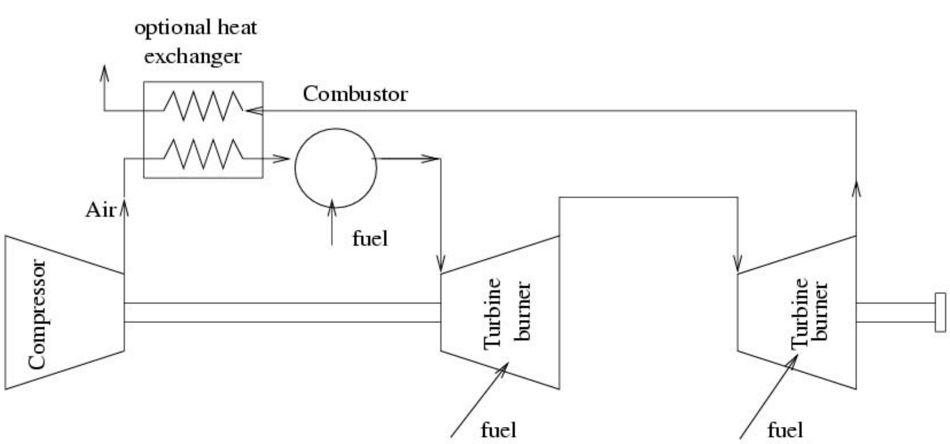

Figure 3: Turbine-burner Engine with Optional Heat Regeneration (CBT Configuration)

A cycle analysis computer code that calculates the specific power and overall thermal efficiency of both conventional engines and the new turbine-burner engines has been developed.
Figure 4(b) shows the comparison of the thermal efficiency and specific power for a conventional gas turbine and one with a turbine-burner with and without heat regeneration.
Performances are calculated for a given turbine temperature of 1500K and compressor pressure ratios ranging from 6 to 28, which are marked in the figure. A 95% heat regeneration effectiveness is assumed. Polytropic efficiencies of 0.92 and 0.95 for the compressor and turbine, respectively, are used in the calculations.

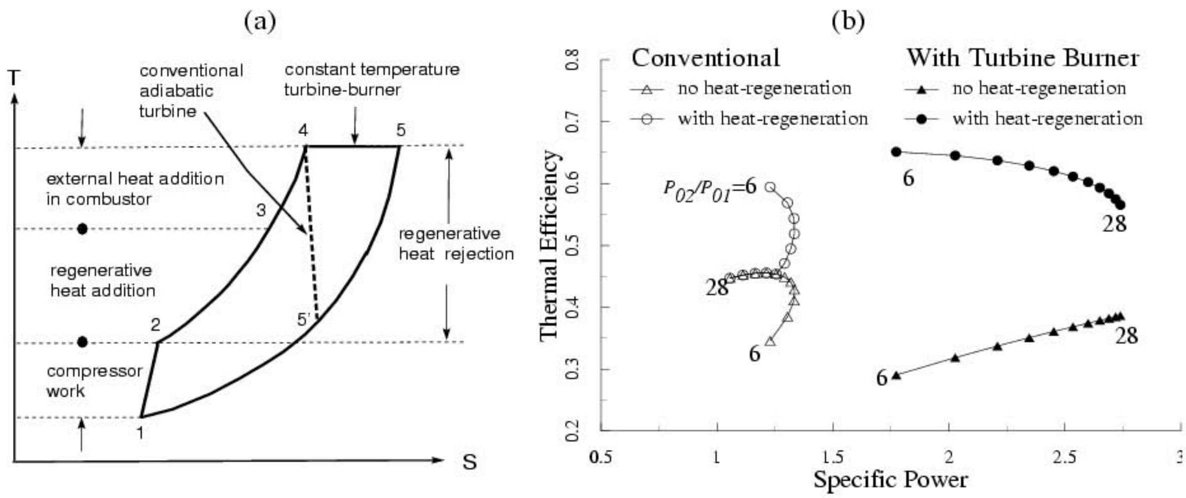

Figure 4: Thermodynamic Cycle and Performance Comparisons of the Turbine-burner Engine with Optional Heat Regeneration

Consider first the case without heat regeneration. As pressure increases from 6, both the specific power and the thermal efficiency increase until the pressure ratio reaches 11. At that point the temperature at the entrance of the combustor becomes high enough so that heat addition in the main combustor is limited. At this time, the specific power starts to decrease while the thermal efficiency continues to increase and reaches almost a plateau. Figure 4(b) shows that the turbine-burner configuration gives a dramatically larger specific power although the thermal efficiency is slightly lower than that of the conventional engine. In addition, both the specific power and the thermal efficiency show a continuous increase as the compressor pressure ratio increases from 6 to 28. The lower thermal efficiency of the turbine-burner option compared to the conventional configuration is due to the lower pressure levels in the turbine-burner than in the main combustor as we noted before. However, this situation can be easily corrected by using heat regeneration to utilize the high heat content of the exhaust gas. As shown by Figure 4(b), both specific power and thermal efficiencies are higher than the conventional configuration with heat regeneration.
A 10%-20% increase in efficiency can be achieved. The increase in specific power is, in particular, dramatic. A more than two-fold increase in specific power can be achieved at the higher compressor pressure ratio end. Higher specific power means a smaller engine, and thus a lesser capital investment, for the same power level.

The above analysis clearly demonstrates the substantial performance gain by the use of a turbine-burner for ground-based gas turbine-engines, a major mover for electric generation and industrial utility use. Mixing and exothermic chemical reaction in the turbine passages offers, therefore, an opportunity for a major technological improvement. Many research problems, however, must be solved in order to advance the technology of the turbine-burner. A new computer code that takes into account of variable thermal properties of the working fluid has been developed in this project. This computer code can be used to perform optimization studies given any design mission. However, at this early phase of developing the turbine-burner technology and also due to lack of actual design mission, any detailed and design and optimization of the cycles are not performed.

(2) **Aerothermodynamic and Combustion Analysis**
Combustion in the turbine passages presents a new challenge to both combustion engineers and turbomachinery engineers. High-speed combustion is itself a field in its infancy. Mixing and reaction in the turbine passages involves certain specific new challenges: (a) transonic speeds with the inherent complications of mixed subsonic and supersonic flows; (b) unsteady flow due to the intermittency of the rotating blades; and (c) the very large three-dimensional acceleration that can combine with the stratified mixture flowing through the turbine to produce potential hydrodynamic instability and large straining of the flow. There is a lack of fundamental treatment in the literature of multi-dimensional flows with mixing and chemical reaction in the presence of strong pressure gradients that support a transonic flow. It was proposed to perform analytical and computational studies on combustion in the turbine in three stages. In the first stage, a reacting, transonic turbulent mixing layer under the influence of a streamwise pressure gradient was to be considered. In the second stage, the same mixing layer with the added effect of a transverse pressure gradient (and associated curvature) was to be examined. In the third stage, a computational fluid dynamics code for solving turbulent reacting flow in channels with curvature and streamwise acceleration was to be developed and used to analyze the multi-dimensional reactive flow field in the turbine passages.

All goals in the three stages have been achieved. A boundary layer code with reactive flows was developed to study mixing and combustion in a transonic flow with large transverse pressure gradients. Results are published in Fang, Liu, and Sirignano (2001) and Mehring, Liu, and Sirignano (2001). A Reynolds averaged Navier-Stokes code with a k-w two-equation turbulence model and reactive flow was developed to study ignition and flame structure in a mixing layer with both strong streamwise and transverse pressure gradients. Computations were also done for flows in a typical turbine passage. Results are published in Cai, Icoz, Liu, and Sirignano (2001a,b). Figure 5, 6, 7, and 8 show the velocity, temperature, density, and species mass fraction profiles at x=5.0 cm and x=7.5 cm downstream of the trailing edge of a splitter plate the separates a fuel and a air stream. The flow accelerates as it moves downstream. The velocity profiles show constant velocity distributions in the freestream on both the fuel and air sides away from the mixing layer region.
Within the mixing layer, however, the flow accelerates more than in the freestream region. This is due to the high temperature of the flame as shown in Figure 6 that causes a lower density distribution in the mixing layer shown in Figure 7. Since the flow is subject to the same pressure gradient in and outside of the mixing layer, the low density mixture of gas in the mixing layer is accelerated more than that in the freestream, resulting in the velocity peak within the mixing

layer. Such studies are performed in both straight and curved channels simulating the condition in a turbine passage in Cai, Icoz, Liu, and Sirignano (2001a,b). Figure 9 shows the geometric configuration and the computed Mach number distribution in a curved channel typical of a turbine blade passage. The Mach number at the inlet of the duct is close to 0.1. The flow accelerates inside the duct from subsonic to supersonic. The Mach number at the exit of the duct is 1.4. There are large pressure gradients along the flow direction and also normal to the flow direction. Fuel is injected in the middle of this channel at the inlet. Figure 10 plots the temperature contours in the channel. The two flames at the interfaces between fuel and air are clearly seen. The higher temperatures result in the lower Mach numbers in the flame regions shown in Figure 9. It is also seen from Figure 10 that the peak temperature in both flames decreases as one moves downstream due to flow acceleration. This indicates that there may be a potential of reduced NOx production for such combustion configurations.

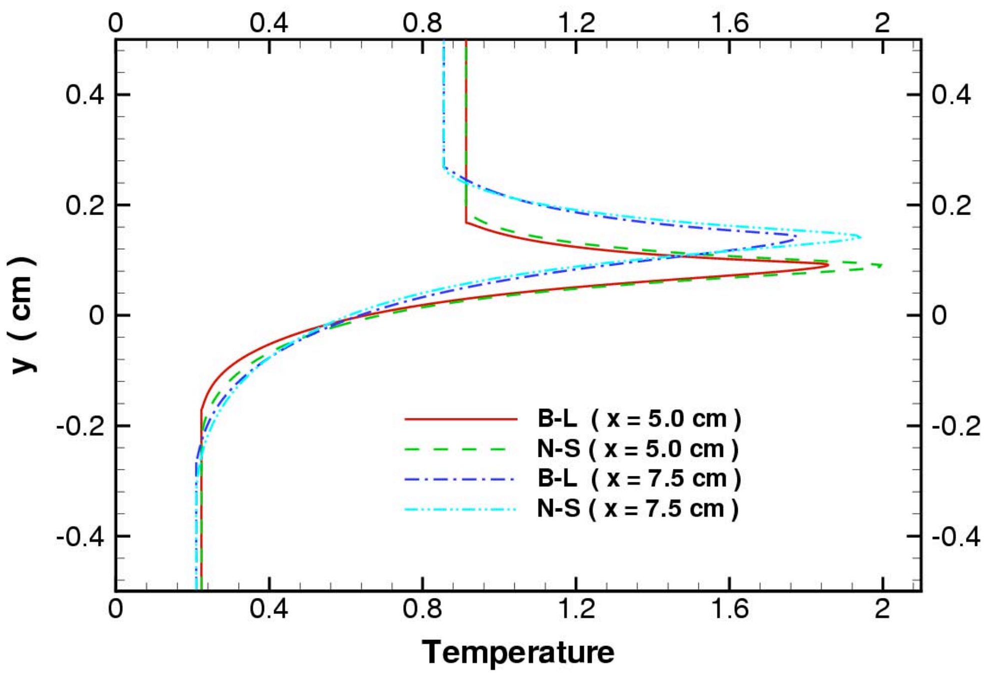

Figure 5: Velocity profiles at x=5 cm and 7.5 cm, turbulent flow. Comparison of Boundary-Layer (B-L) and Navier-Stokes (N-S) solutions.

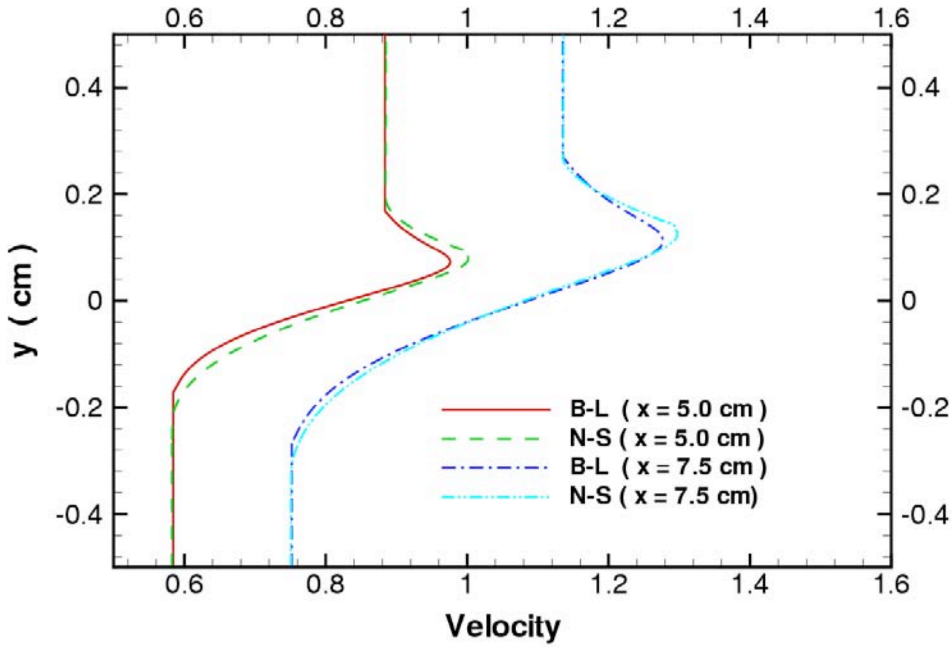

Figure 6: Velocity profiles at x=5 cm and 7.5 cm, turbulent flow. Comparison of Boundary-Layer (B-L) and Navier-Stokes (N-S) solutions.

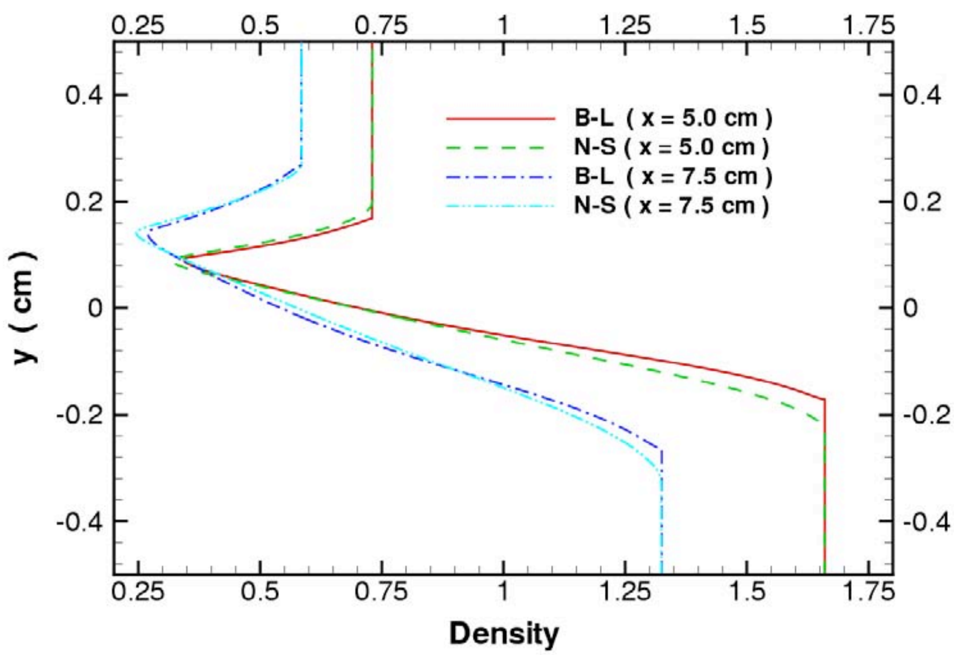

Figure 7: Density profiles at x=5 cm and 7.5 cm, turbulent flow. Comparison of Boundary-Layer (B-L) and Navier-Stokes (N-S) solutions.

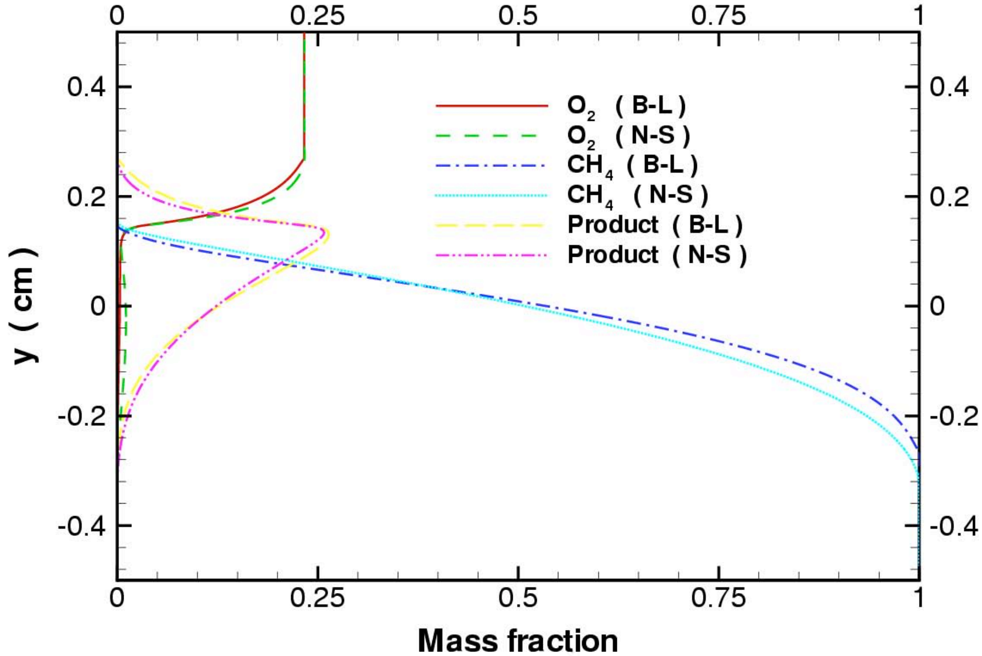

Figure 8: Mass fraction profiles at x=5 cm and 7.5 cm, turbulent flow. Comparison of Boundary-Layer (B-L) and Navier-Stokes (N-S) solutions.

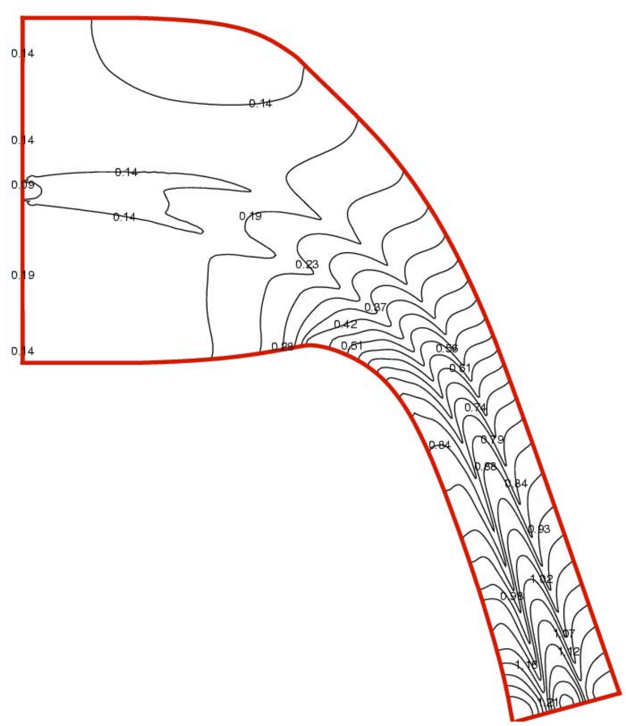

Figure 9: Mach number contours in a channel typical of a turbine passage.

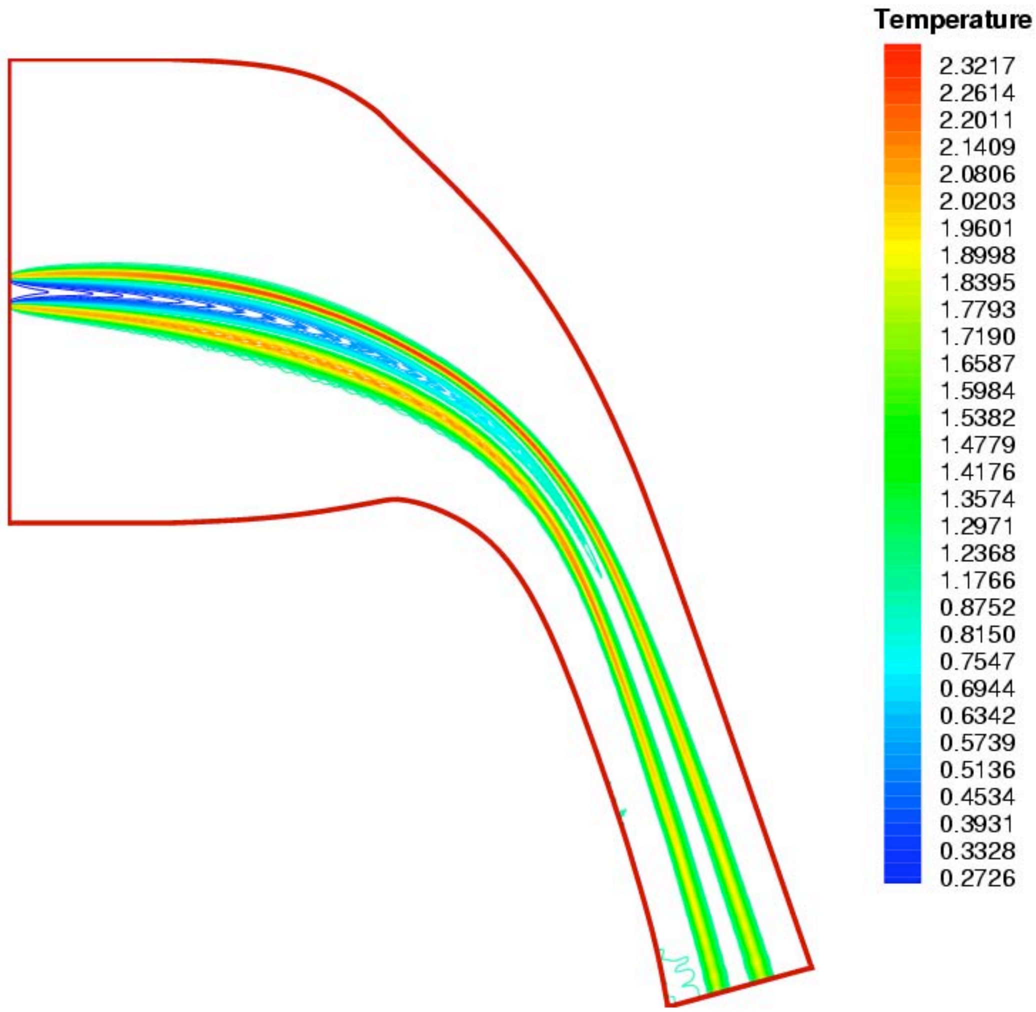

Figure 10: Temperature contours in a channel typical of a turbine passage.

(3) Further Research Issues

The turbine-burner concept is a "high risk" project with potential of high yield. Many research problems, however, must be solved in order to advance the technology of the turbine-burner. One of the goals of this project is to identify important future research issues. Several research topics have been identified. (a) In the area of cycle design and optimization, it has been identified that the use of a condenser combined with the turbine-burner concept can further increase the efficiency of the engine. (b) Our combustion studies were limited to the use of single-step chemistry. A multi-step reaction must be pursued for more accurate prediction on ignition and flame structures in an accelerating flow. (c) Our computations did not reveal significant differences in combustion in the presence of large transverse pressure gradients. This was because the Reynolds-averaged Navier-Stokes equations are not adequate of predicting hydrodynamic stability effects. A large-eddy simulation method must be pursued.

Conclusions and Recommendations

- A turbine-burner gas-turbine engine has been proposed and studied for high-efficiency power generation. A cycle analysis code has been developed and used to analyze the turbine-burner engine with heat-regeneration. It was found that an increase of 10-20% in efficiency can be achieved by using the turbine-burner engine concept. The efficiency of the turbine-burner engine may be further increased if combined with a condenser. Detailed engine cycle design and optimization remain to be performed when specific missions are provided. California will directly benefit from the success of this technology in conserving its energy consumption because of the large increase of efficiency in power generation.
- A computer code for the Navier-Stokies equations with a two-equation turbulence model and reactive flow has been developed. This computer code has been used to study ignition and flame structures in a transonic mixing layer with large streamwise and transverse pressure gradients typical of those in a turbine passage. Results show that methane/air ignition and flame-holding is feasible in spite of streamwise and transverse accelerations that are of the order of 100,000 meters per square second. Diffusion flames are established in the accelerating flow with a decrease in peak temperature as expansion occurs in the downstream direction, which may have the added benefit of less production of NOx.
- In order to account for hydrodynamic stability of the mixing layer due to density stratification under large transverse pressure gradients, a large-eddy simulation is desirable. Further detailed computation and analysis are needed to investigate the dependence of ignition and flame structures on the flow conditions and chemical kinetics of the fuel in order to explore the feasibility and technological advantages of the turbine-burner concept in the application of jet propulsion and ground power generation.

References

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Appendices

Four papers have been published or presented at conferences that have been sponsored by this project. They are listed in the References as [4], [5], [6], and [7]. These are attached here as appendices.