Final Report for

Cooperative Research and Development for Advanced Microturbines

Program on

Advanced Integrated Microturbine System

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Executive Summary

Project Overview

The Advanced Integrated Microturbine Systems (AIMS) project was kicked off in October of 2000 to develop the next generation microturbine system. The overall objective of the project was to develop a design for a 40% electrical efficiency microturbine system and demonstrate many of the enabling technologies. The project was initiated as a collaborative effort between several units of GE, Elliott Energy Systems, Turbo Genset, Oak Ridge National Lab and Kyocera. Since the inception of the project the partners have changed but the overall direction of the project has stayed consistent.

The project began as a systems study to identify design options to achieve the ultimate goal of 40% electrical efficiency. Once the optimized analytical design was identified for the 40% system, it was determined that a 35% efficient machine would be capable of demonstrating many of the advanced technologies within the given budget and timeframe. The items that would not be experimentally demonstrated were fully produced ceramic parts. However, to understand the requirements of these ceramics, an effort was included in the project to experimentally evaluate candidate materials in representative conditions. The results from this effort would clearly identify the challenges and improvement required of these materials for the full design.

Following the analytical effort, the project was dedicated to component development and testing. Each component and subsystem was designed with the overall system requirements in mind and each tested to the fullest extent possible prior to being integrated together. This method of component development and evaluation helps to minimize the technical risk of the project. Once all of the components were completed, they were assembled into the full system and experimentally evaluated.

Project Successes

Throughout the AIMS project there were many benefits gained from the initiative. While the ultimate goal of a 40% electrical efficient machine was not achieved, several significant advances were made. One great example is the combustion system. The system that was developed to achieve ultra low emissions levels while maintaining good operability and low cost. The design was accomplished by merging two combustion technologies, annular and can, to develop a truly novel system that produced world leading emissions levels. This novel combustion system design is now being considered for other larger gas turbines.

Another significant achievement by the project was a novel casting method. One of the scrolls was a very large and complex design thus requiring considerable thought on how to cast the part. The team worked closely with the vendor and the result was the thinnest casting ever of a GTD-222 part. This is very significant because GTD-222 is used in many other hot gas path applications and by allowing for castings to be thinner results in lighter more cost efficient parts.

Overall Results and Conclusions

The AIMS project was a broad initiative that involved many people form many organizations all with the same goal of developing an advanced microturbine. The team took a novel approach for the new design by looking at the challenge from a systems perspective. By considering all of the components together and how they interact allowed for the identification of improvements beyond the traditional method of higher temperatures and pressures. Items such as system layout, inlet flow designs, exhaust paths, advanced electronics and controls all lead to an overall design that could reach the performance goals within realistic thermal conditions.

The program was not able to demonstrate the performance goals however, as noted above there were several significant achievements of the project. In general the concept of a microturbine is a technically interesting idea that warranted the overall DOE and Industry support to advance the state of the art. The industry continues to struggle to find acceptable market penetration however the support from the DOE over the past 7 years has done a great deal to continue to improve the technology.

Program Tasks:

Subtask A: Market Study

The Market Study for the AIMS project was conducted by Onsite Sycom. In order to ensure a quality effort, GE has been working closely with Onsite to scope out the study and we decided that the effort should provide a quantified estimate of the US technical market potential for the AIMS system. This estimate will be based on heat rate, capital cost, operating costs, emissions and footprint. Also, the study takes into account the following applications/markets: Base load CHP, Base load Electricity Generation, Intermediate Duty, Parallel Power, and Peak Shaving.

The detailed market study report will follow this quarterly report however, some of the key findings are represented in the graphs below. Figure 1 below shows the projection of microturbine units in a base load electricity generation application. The figure shows applications where the microturbine could be implemented into a existing facility and the growth potential. The take away from this figure is that if the product can meet the required specifications there is a sizable market.

Figure 2 is similar to figure 1 except the application presented here are for CHP applications, a subset of the prime power market. The data is represented the same fashion with the existing and new growth potential. The interesting point with this data is that the CHP market is showing a larger growth rate in the future than prime power. This point is significant since microturbines are ideally suited for CHP applications.

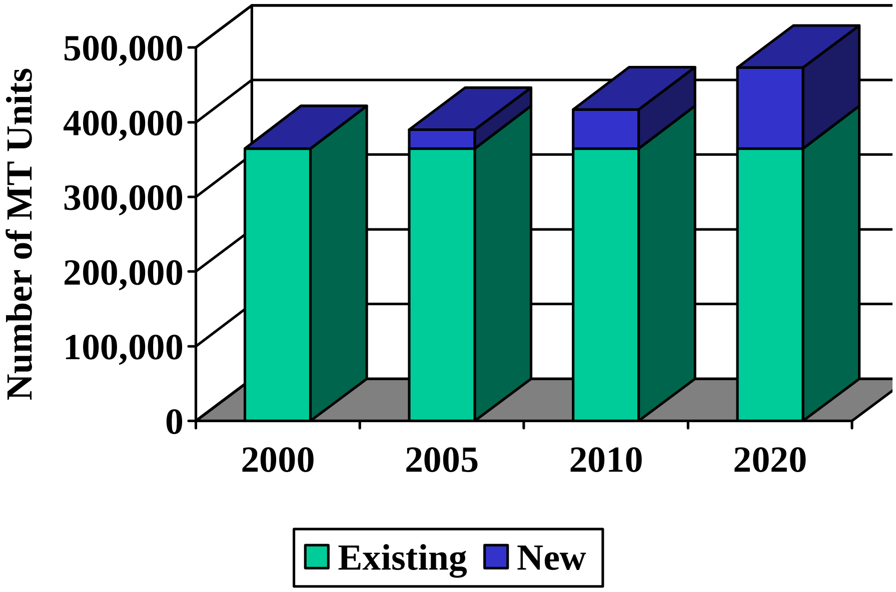

Figure 1: Market projections for distributed prime power applications in the United States.

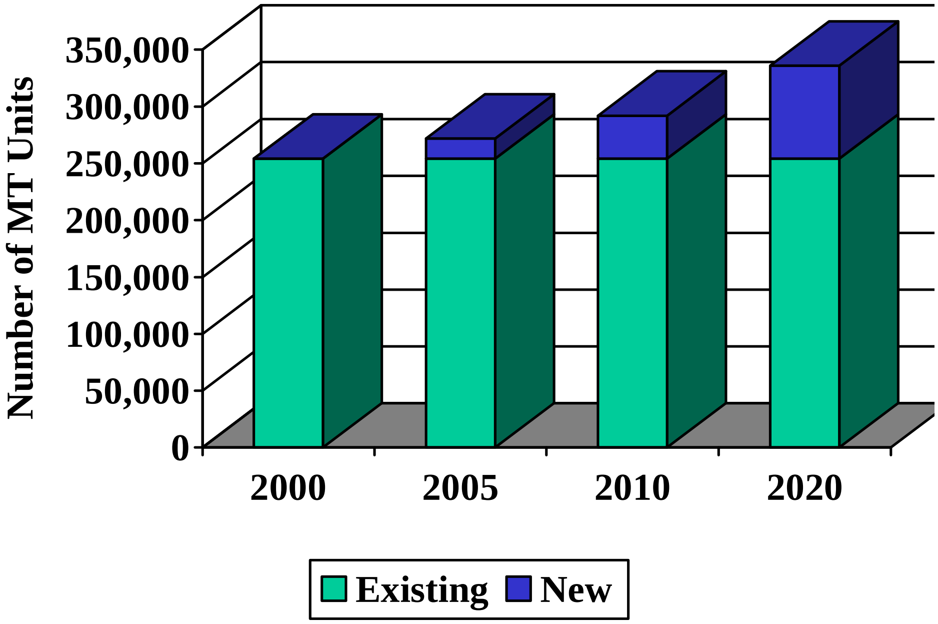

Figure 2: Market projections for distributed prime CHP applications in the United States.

Task 1: Technology Assessment

Under Task 1, the work has been focused on brainstorm sessions to determine the topology of the AIMS system. We have set out to do the detailed modeling utilizing both Gate Cycle™, as well as internal cycle decks to determine the thermal conditions of the system. Included in this activity we have been working with Materials Engineers to create a matrix of materials options for given cycle conditions. The outcome was a short list of potential materials for the different components that was used throughout the initial trade-off analysis.

The other portion of Task 1 activities has been with the power electronics and control. We have been working with GE Power Systems Engineering Consulting (PSEC) on requirements of the power electronics and control system based on market information. The motivation is to make sure the resulting system is in accordance with industry standards as well as the utility's and customer's expectations.

Task 1.1: Cycle Analysis

A cycle deck study was conducted to investigate trade-offs between pressure ratios and firing temperatures to reach the program goals, see figure 3. The effort was directed at determining the optimum condition considering material and component efficiency constraints. The outcome of this effort is suggesting for a 250kW unit, a firing temperature of 1950 F, and a pressure ratio of 3.8. This configuration appears to be achievable given the component efficiency requirements. The study will continue taking into account the materials work with the focus on cost and risk.

To achieve the high efficiencies of the AIMS microturbine, there are two main elements, high efficiency components and high temperature materials. Considering the component efficiencies of the turbine and compressor, the vehicle for increasing these values is clearance control. A literature search was completed with respect to the effect of clearances on turbine and compressor efficiencies. The results suggest that 1% increase in axial clearance can cause a change in efficiency by 0.15% whereas the same increase in radial clearance causes 1.6% change in efficiency. It is therefore, feasible to achieve total efficiency gains of between 3 - 4% from the turbine and the same from the compressor by reducing clearances from 7 to 3% of the passage heights. This level of increase would support the current expectations of the component efficiencies.

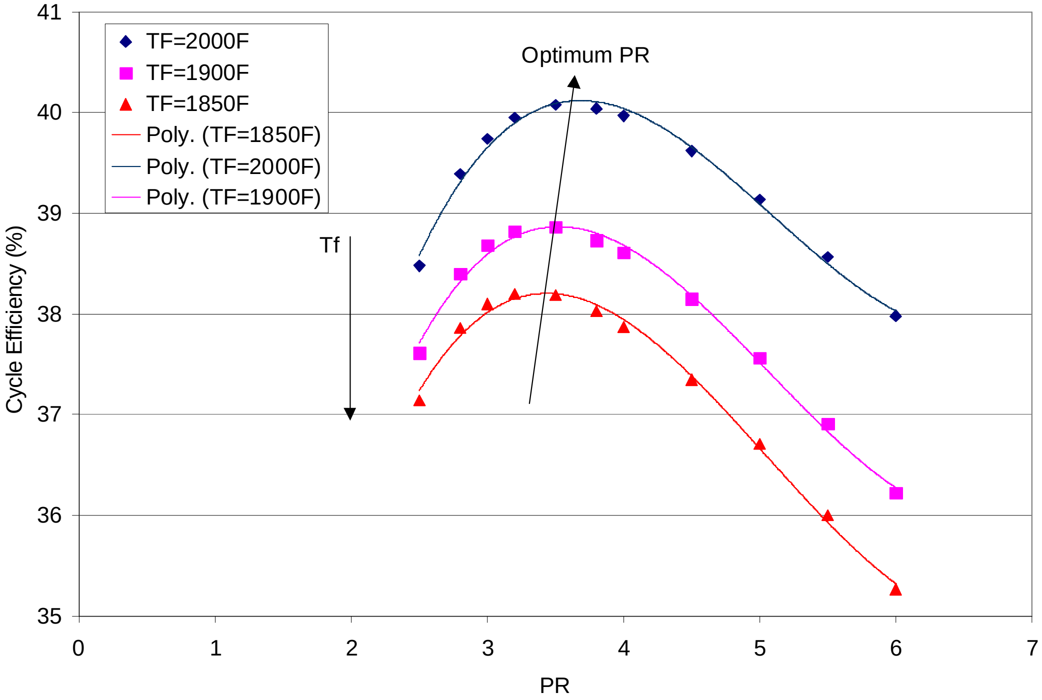

Figure 3: Results of cycle analysis showing the trade-off between pressure ratio and firing temperature and the resulting cycle efficiency.

Nominal radial & axial clearances of 20 & 40 mils were proposed for both the turbine and compressor aiming to minimize performance loss due to leakage. It is proposed that the use of abradable seals help to provide consistent sealing. These values may have to be revised as new design features emerge. Selection of the type of abradable seals for compressor and turbine is strongly dependent on the operating conditions, i.e. temperature, tip speed, axial & radial incursions between the rotor & the casing.

Efforts regarding the micro-turbine mechanical systems have been focused on improving the existing performance models and acquiring further data from products that are commercially available.

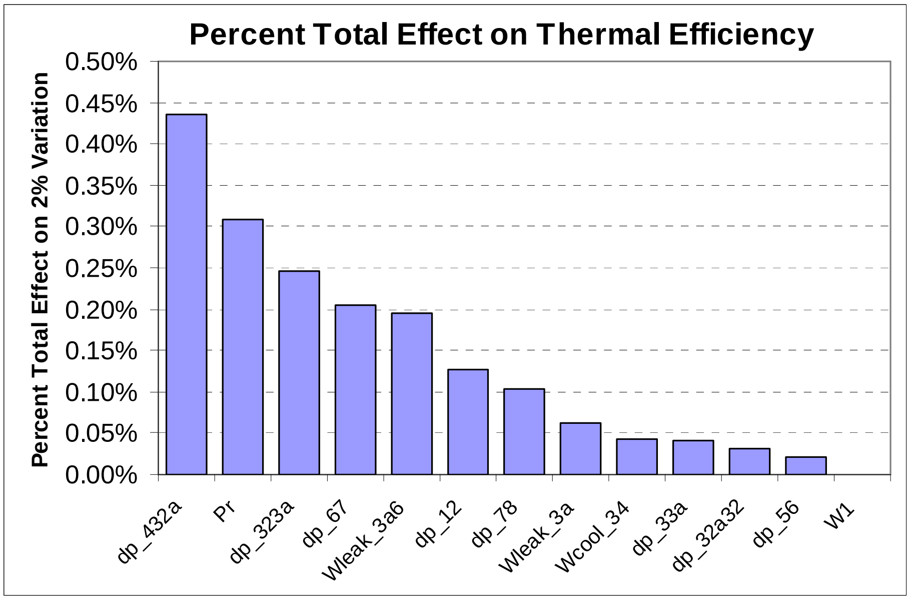

Figure 4: Sensitivity Analysis

To better predict micro-turbine performance, an improved steady state cycle deck has been completed. The new cycle deck accounts for theoretical pressure losses, flow leakages, and contains a more accurate combustion model. The cycle deck has proven useful in predicting the limits of efficiency and power as well as conducting a sensitivity analysis. The sensitivity analysis has revealed the temperature and pressure losses that are most critical to the efficiency and power output of a small scale Brayton Cycle like the one currently under development. The results from the sensitivity analysis shown in Figure 4 have helped to confirm that there may be added benefit to a gas path design that is different than that currently employed on most commercially available micro-turbines.

The limits of efficiency and power have also been modeled and explored in order to determine the growth opportunities available for a micro-turbine of the size being considered. In addition to conventional analysis that uses only the 1st Law of Thermodynamics, Availability (2nd Law of Thermodynamics) has also been determined at each station throughout the cycle. The addition of an Availability analysis has helped to further identify loss mechanism and was used to determine the theoretical maximum of power and efficiency for potential growth opportunities. Figure 5 shows predictions for growth as a function of the adiabatic flame temperature (T4) based on the current model and design configuration.

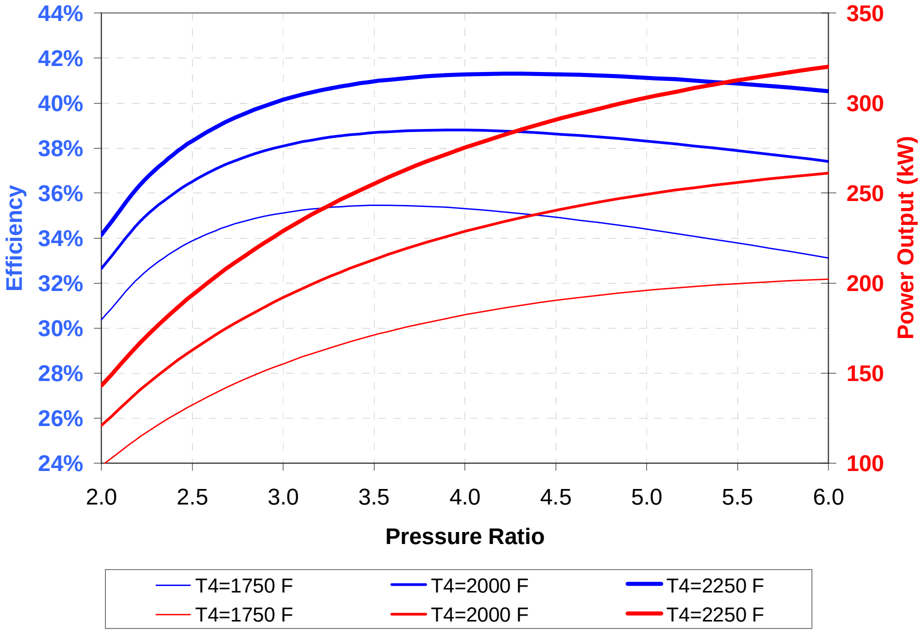

Figure 5: Growth predictions as a function of adiabatic flame temperature

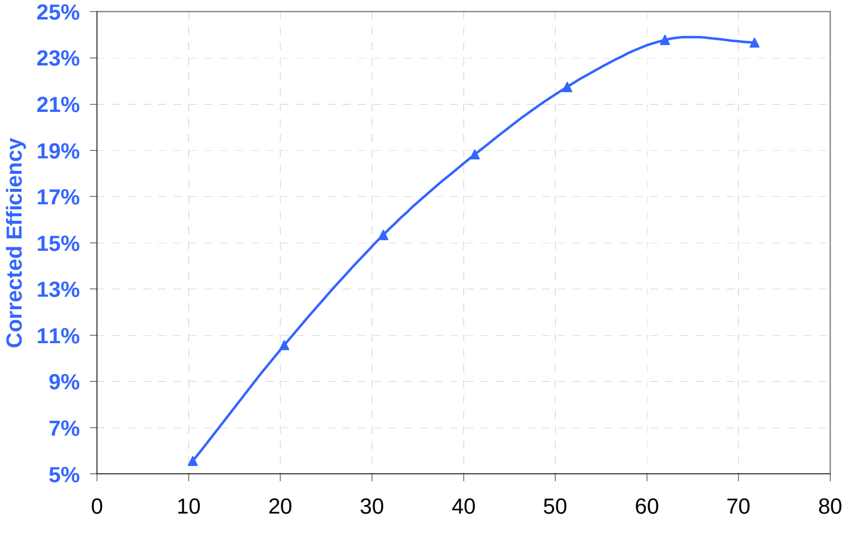

Figure 6: Experimental Data from Existing Products

In order to exceed the performance specifications available in today's commercially available products, a number of baseline experiments have been run on existing micro-turbines. The results of the experiments have revealed a number of areas in which improvements can be made and the overall system efficiency increased. Examples of these improvements include preheating the fuel, a new inlet design, a more efficient gas path, better thermal insulation, and improved heat transfer in the recuperator. Figure 6 shows the constant speed efficiency curve for a 75kW unit that could significantly benefit from the improvements mentioned above.

Task 1.2: Advanced Technologies

Materials Effort:
A list of potential materials choices for critical microturbine components was completed. The list includes six engine components that will require alternative materials to meet AIMS performance goals: combustor can; combustor scroll; nozzle assembly; turbine rotor; recuperator; and compressor rotor. The list includes various metal and ceramic material options for two different potential firing temperatures. As the thermal design becomes final, this matrix will be used to select the optimum material for each specific component.

For design considerations of ceramics, both NASA Glenn and Honeywell were contacted to acquire current versions of their respective probabilistic ceramic design codes. The NASA code is CARES/Life. The Honeywell code is Ceramic/Erica. Related papers and documentation were acquired for both probabilistic design codes. The appropriate code will be utilized given the ceramic material choice.

The materials to be used for components in the hot section of the microturbine include mostly superalloys. However, some design options may require consideration of higher temperature materials including monolithic ceramics such as silicon nitride for selected turbine components. It is widely recognized that a key challenge in the use of ceramics for high temperature structural application is the probabilistic nature of component strength and life. During this reporting period, we have prepared for the probabilistic design and analysis of ceramic components. Various probabilistic design programs for ceramics have been created in the past, including CERAMIC/ERICA, CERITS-L and CARES/LIFE. The CARES/LIFE program was found to have the best combination of desired function and accessibility for our needs. Hence the CARES/LIFE code has been installed and evaluated.

The computer program CARES/LIFE (Ceramics Analysis and Reliability Evaluation of Structures) was developed at the Life Prediction Branch, NASA Glenn Research Center for studying the reliability of monolithic ceramics. The CARES/LIFE program has two basic components: PEST (Parameter ESTimation) and LIFE (LIFE estimation). The PEST program computes the "Weibull" and fatigue parameters, assuming specified flaw types, using experimental fracture data from test specimens. The LIFE program computes the time-dependent reliability of a component subjected to the thermo-mechanical loading. Results from finite element stress analysis are post-processed in CARES/LIFE to obtain the reliability of the component. The CARES/LIFE program interfaces easily with commercially available FEA program such as ANSYS, ABAQUS, and MSC-NASTRAN using the ANSCARES, ABACARES, and NASCARES modules, respectively.

Independent computer programs (in Excel and Matlab) have been developed within the AIMS effort that mimic some of the capabilities of CARES/LIFE and address some of its current limitations. These programs have given us a better understanding of the various parameters used in CARES/LIFE and may allow us to overcome the limitations. For example, two features being incorporated in our computer programs are data pooling (compute "Weibull" parameters using fracture data from different specimen geometries and/or different loading conditions) and confidence bounds on the component probability of failure using Monte Carlo techniques. These features will be very desirable as we analyze fracture data and evaluate component reliability in the future.

A document has been prepared which describes the installation of CARES/LIFE and ANSCARES on a PC. This document also includes a detailed description of the various conventions/nomenclatures associated with the CARES/LIFE program. It also demonstrates the use of the CARES/LIFE and ANSCARES programs on three example problems. Two example problems were obtained from NASA and one example problem was created at GE. This document was originally prepared to help GE users install and execute the CARES/LIFE program and is a useful complement to the user manual provided by NASA.

Upcoming tasks related to the probabilistic analysis capability include further investigation of the statistical and fracture mechanics theories behind the evaluation of reliability of components subjected to static/dynamic/cyclic fatigue. Also, efficient techniques using Fast Probabilistic Integration (FPI) will be utilized to compute confidence bounds on the probability of failure.

The materials to be used for components in the hot section of the microturbine include mostly superalloys. However, some design options may require consideration of higher temperature materials including monolithic ceramics such as silicon nitride for selected turbine components. Accordingly, the materials work during this quarter has focussed on aspects of both superalloys and ceramics.

In support of the metallic components, suitable vendors were identified for supply of hot section components. Preliminary discussions were initiated with Howmet and PCC, and a tentative timeline for prototype parts was obtained. Final discussions on timelines and cost await final part drawings based on the chosen design.

A portion of the recent AIMS microturbine risk assessment was dedicated to analysis of risks associated with materials life and performance. General overall risks were identified, along with risk categories for each major turbine component including the combustor liner, combustor scroll, turbine nozzle, turbine rotor, recuperator, seals and compressor. For each risk item identified, the level of risk and associated plans to mitigate the risk were determined.

In preparation for the possible use of ceramics within the microturbine, several tasks are ongoing. The first is a continuing survey of the literature on monolithic ceramics, in particular silicon nitride. This survey includes literature available in journals as well as reports from organizations such as Oak Ridge National Laboratories and NASA. One of the risks in use of properties from this literature survey is the slow evolution of many ceramic materials over the years. Towards this end, preliminary efforts have begun at Oak Ridge to compile a more current database of silicon nitride properties. GE intends to participate and contribute to this effort. An associated activity that will be carried out soon is to identify gaps in the materials property database as it relates to potential materials for use in the GE microturbine.

It is widely recognized that a key challenge in the use of ceramics for high temperature structural applications is the probabilistic nature of component strength and life. For this reason, GE is performing extensive evaluation and use of the CARES/LIFE (Ceramics Analysis and Reliability Evaluation of Structures) program developed by the Life Prediction Branch at NASA, GRC. In addition, we are developing selected capabilities that extend beyond those of CARES/LIFE to meet our anticipated needs for probabilistic design of ceramic components.

Due to the limited sample size (number of fracture measurements) that is practical to test, there is uncertainty in the estimated “Weibull” scale and shape parameters obtained from fast-fracture tests. Three methods are being developed to quantify that uncertainty: normal approximation method, likelihood ratio technique, and parametric/non-parametric bootstrap methods. For uncensored data, these confidence bound techniques are being compared to results included in the ASTM standard C1239. For fracture data with multiple failure modes (censored data), the confidence bound techniques will be a novel addition to the existing literature. The proposed methods are being evaluated for their statistical characteristics and ease of practical use. The techniques will also be extended to confidence bound estimation using fracture data from various geometries and/or loading conditions. A paper summarizing this work is in preparation.

In order to estimate confidence bounds on the reliability of a monolithic ceramic component under fast-fracture loading, one needs to estimate the effects of uncertainty in the “Weibull” scale and shape parameters from fast-fracture test data. The Fast Probabilistic Integration (FPI) method has been applied to obtain confidence bounds on reliability. However, there are other more convenient and more accurate statistical methods to obtain the scatter in the reliability predictions; namely, normal approximation method, likelihood ratio technique, and parametric/non-parametric bootstrap methods. These methods are being investigated and a document is being prepared summarizing the relevant findings.

A novel technique has been developed as a part of the AIMS effort to incorporate the variability in boundary conditions into the classical Batdorf model of probabilistic failure in multiaxial stress fields. The fracture criterion in the Batdorf’s model is modified to account for the distribution in effective stress (σ_e) generated due to the variation in the boundary conditions. This introduces an integral over the probability density function of the effective stress, which is evaluated numerically after making certain simplifying assumptions. Numerical analysis of two problems are being carried out: spinning annular disk and transversely loaded circular plate. Documentation of this work is under progress.

The effort to develop independent computer programs (in Excel and Matlab) continues replicating the results from CARES/LIFE. These programs have given us a better understanding of the various parameters used in CARES/LIFE. The results from static fatigue have been compared with the results from CARES/LIFE. To get a better qualitative understanding of the various fracture models used in the classical Batdorf's theory, certain "simple" loading cases have been investigated. A GE Global Research Center (GE GRC) report is being prepared which describes this work and verification of numerical results obtained using CARES/LIFE.

Upcoming tasks related to the probabilistic analysis capability include further investigation of the statistical and fracture mechanics theories behind the evaluation of reliability of components subjected to cyclic and transient fatigue. Also, efficient techniques utilizing various statistical methods will be investigated to estimate confidence bounds on parameter estimates and reliability of a component.

Within the reporting period, Drs. C.A. Johnson and M. Manoharan served as reviewers at the Microturbine Materials Merit Review session at Worcester, MA on June 26,27.

The materials for use in the hot section of the microturbine for the first stage of the project are expected to be mostly superalloys. In the second stage, some design options may necessitate the consideration of higher temperature materials such as monolithic ceramics and silicon nitride in particular.

The work during this quarter has therefore been focused on addressing both these issues. In the context of superalloys for the hot sections, Howmet was identified as a suitable vendor for casting parts. A confidentiality agreement is being put in place and once this is complete, they will be supplied with drawings based on the Concepts NREC design and firm estimates on cost and timelines obtained for supply of these parts.

Initial prototypes are expected to be machined and two vendors have been identified. They are Concepts NREC which is designing the compressor and turbine and Turbocam Inc. We are in the process of obtaining cost estimates and timelines for this effort.

We continue to contribute to the design process being carried out at Concepts NREC. 17-4 PH steel was identified as suitable for the compressor. The preliminary design stresses indicate that this choice is viable, though it is possible that the final design may point to the need for a less notch sensitive alloy. For the turbine MarM 247 was chosen as the material. Once again preliminary design calculations indicate the suitability of this alloy. Final design including thermal stresses and possibly low cycle fatigue limited properties is planned.

In the context of ceramics for the microturbine, efforts are ongoing at Oak Ridge to compile a database of properties of silicon nitride. We are participating in this effort. We plan to provide ORNL with test specimens in the near future to test in temperature regimes of interest to us and continue to contribute to the development of the database. Kyocera, which is a supplier for the SN 282 grade of silicon nitride, will provide these specimens.

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In order to estimate confidence bounds on the predicted reliability of a monolithic ceramic component under fast-fracture loading, one needs to estimate the effects of uncertainty in the "Weibull" scale and shape parameters from fast-fracture test data. Instead of applying the conventional Monte Carlo or Fast Probabilistic Integration (FPI) methods, we are investigating three statistical methods that are both more convenient and more accurate. These methods are: normal approximation method, likelihood ratio technique, and parametric/non-parametric bootstrap methods. Computer programs have been developed to compute the confidence bounds on reliability using these methods. A paper summarizing this work is almost complete.

A paper titled – Confidence Intervals on Weibull Fast-Fracture Parameter Estimates – will be presented at the ASME Turbo Expo, June 3-6 2002. The authors of this manuscript are from GE and Honeywell. Four methods have been evaluated for estimating CI's on Weibull parameters from fast-fracture data for monolithic ceramics. The techniques include normal approximation method, likelihood ratio technique, nonparametric and parametric bootstrap methods. The key contribution of the paper was the evaluation of the four CI methods for multiple censored data common in ceramics applications.

A simulation fracture experiment enabled identification of the weaknesses and strengths of the four CI's procedures from a coverage probability point-of-view. The normal approximation method (TNORM) typically works well when the expected number of failures is greater than 50 for the flaw type with less censoring and performs well with even 20 failures due to the flaw type, which is severely censored. The nonparametric bootstrap (NPBS) has very poor coverage for small (<20) expected number of failures. The likelihood ratio (LLR) has excellent coverage even when the expected number of failures is less than 10, especially for the flaw type that is severely censored. The parametric bootstrap (PBS) has very good coverage properties when the expected number of failures is greater than 10. A typical graph depicting the coverage for a 90% nominal CI is shown in Figure 7 for the shape parameter of a volume flaw.

Overall, it was concluded that the likelihood ratio and parametric bootstrap have very similar coverage properties. The likelihood ratio is conceptually more elegant but needs to be programmed carefully to avoid numerical difficulties. On the other hand, parametric bootstrap is conceptually very easy to understand and is also easy to program. However, the computational cost of parametric bootstrap is significantly larger than likelihood ratio technique. Overall, the authors recommend using the likelihood ratio technique, especially for the small expected number of failures.

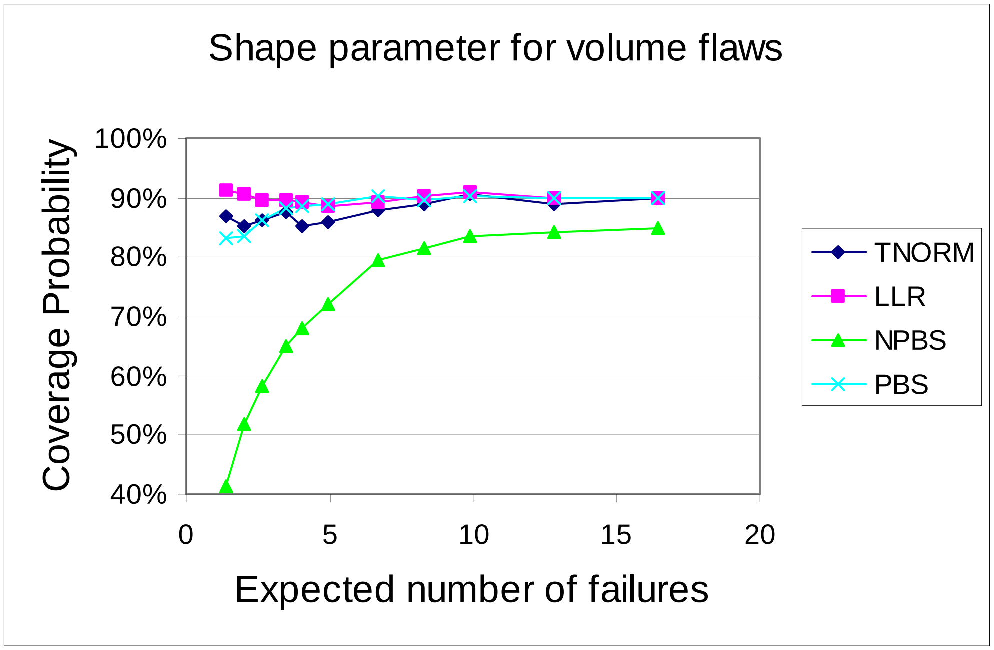

Figure 7: Coverage probability for 90% nominal CI on shape parameter (m) of volume flaws using the four CI procedures

Task 1.3: Control System Definition

The Functional Requirements document is in process using available marketing information. A revision will be due when market data from Onsite becomes available.

Once the market data is integrated, a review of the Functional Requirements document will be scheduled. The report will include following outline.

1 Executive Summary
2 Background and Applications
2.1 Target Markets and CTQ's (based on OnSite and A.D. Little reports)
2.2 Power Quality
2.3 Load Characteristics
2.4 Environmental
2.5 Industry Standards
2.6 Interconnection Issues and Protection
2.7 Recommended Features
3 Functional Requirements
3.1 Specification for Good Quality (equivalent to reciprocation engine generator)
3.1.1 Isolated
3.1.2 Grid parallel
3.2 Specification for Better Quality (equivalent to domestic grid)
3.2.1 Isolated
3.2.2 Grid parallel
3.3 Strategies for Best Quality
4 Unit Design Considerations
4.1 Introduction
4.2 Power Conditioning System
4.3 Energy Storage
4.4 Alternator and DC Link Interface
4.5 System Control
4.6 Protection
4.7 Operator Interface and Communications

Three PQ specifications are included to accommodate a range of applications and cost targets. Lower specification limits (LSL) and upper specification limits (USL) are included where appropriate and supported by available data. For consistency with established practice, three broad levels of quality are defined. These levels roughly correspond to the application classes defined by the Electrical Generating Systems Association (EGSA). Good quality (EGSA class 3 - 4) corresponds to a reciprocation engine generator typically used for standby or backup applications. Better quality (EGSA class 2) is comparable to a typical North American AC power connection. Best quality (EGSA class 1) is intended for premium power applications.

The turbine control system requirements were defined in greater detail. A preliminary turbine control system consisting of a turbine electronic control unit (TECU), sensors, actuators, solenoid valves, and the Power Conditioning System interface was defined. While the architecture for much of the TECU software has been defined, specific requirements for each of the other control system elements will be defined over the next quarter.

Following the turbine control system requirements, a turbine control software architecture has been defined. The turbine control system controls three main outputs consisting of 1.) fuel flow demand, 2.) fuel shutoff demand, 3.) ignition. All other outputs are sent digitally to other parts of the system.

The turbine controls will accept input signals from sensors, feedbacks, and the Power Conditioning System. Using these signals, logic in the engine control will regulate the turbine speed/power through fuel control, coordinate the sequencing of ignition with the fuel shutoff valve and the Power Conditioning System controllers, and provide monitoring, protection and status on the complete micro turbine system. Some of the preliminary architecture for the control laws processing has been defined. A preliminary structure for the control laws is shown in Figure . The structure consists of an inner fuel loop and 4 outer loops that control speed, limit temperature, and limit the minimum and maximum engine acceleration rates. The details of these controllers will be defined after a detailed transient model of the system has been developed.

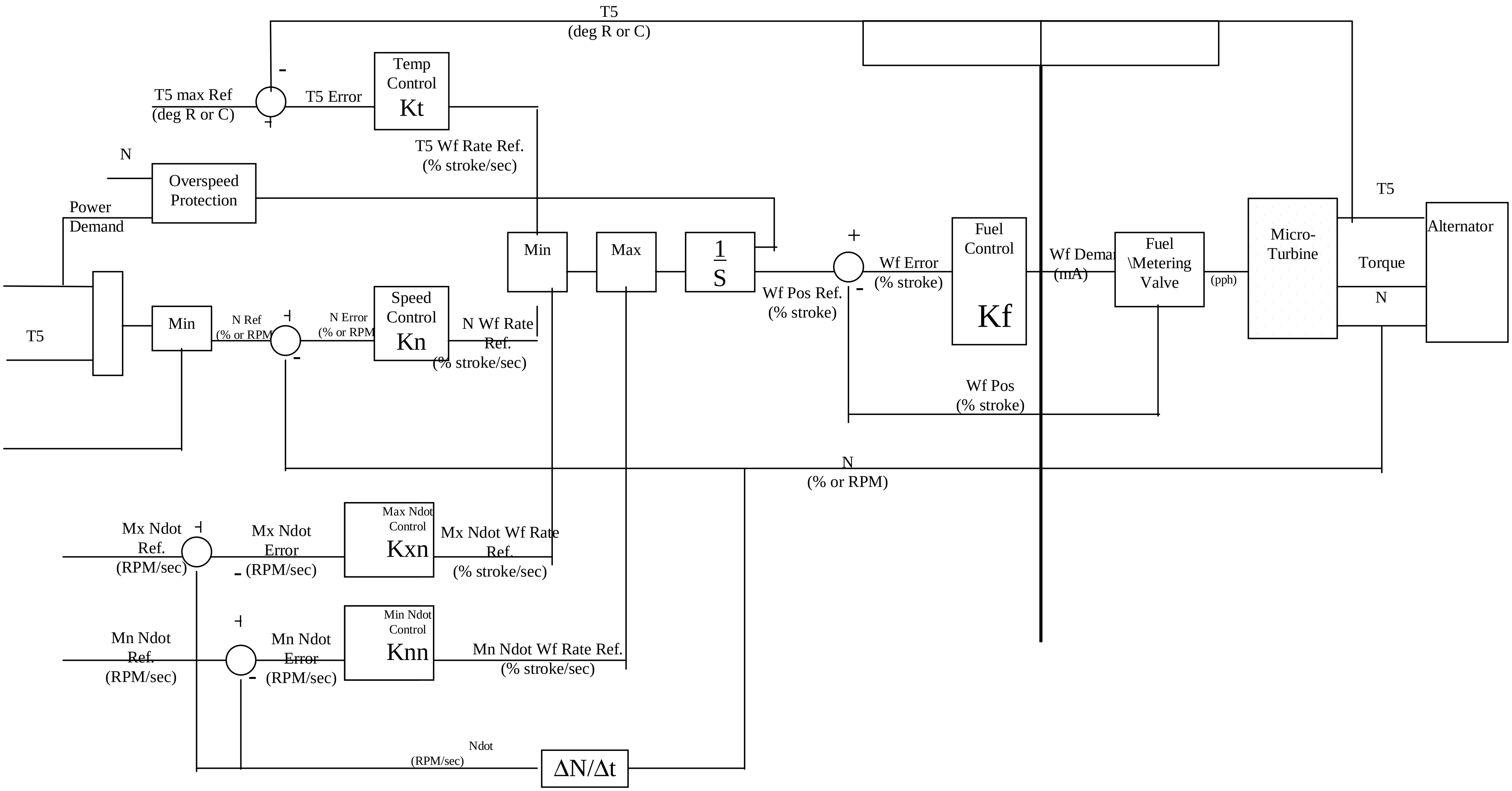

Figure 8: Turbine control laws block diagram

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Figure 9.

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Figure 10

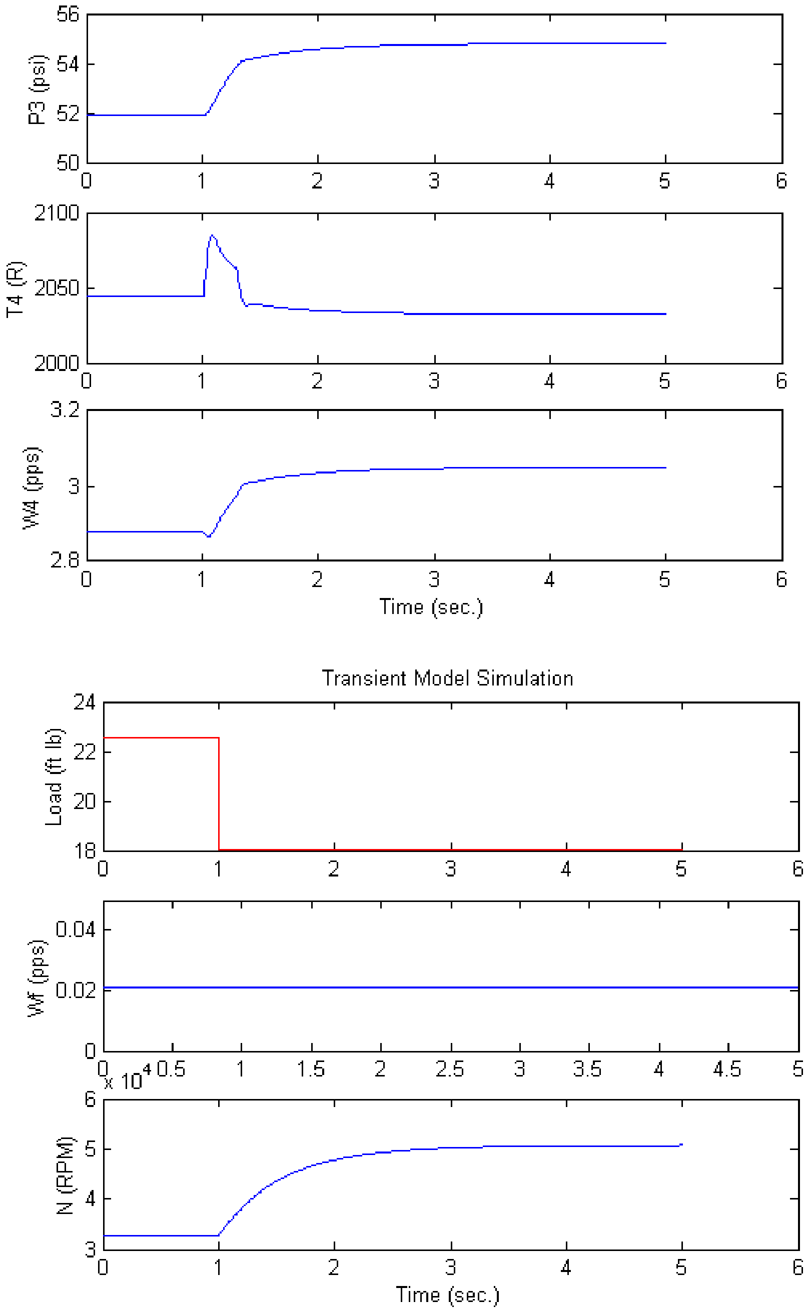

Figure 11.

A transient model has been developed based on the important dynamic elements of the microturbine. Since all of the components of the system have not been selected, guess values of a compressor map, turbine map, and rotor inertia are used to get the modeling running. The transient model will simulate the response of the microturbine to changes in the applied load, fuel flow, ambient conditions, as well as some failure scenarios.
Figure 8. shows the top level system block diagram and the microturbine engine block diagram. The response from the model to a step decrease in the load is given in Figure 11. Such simulations and responses will help guide the control system development. Future

work here will include obtaining actual data to model the compressor, turbine, inertia of the spool, and other elements important to the dynamics in order to obtain an accurate transient response.

Reporting Period July 2 – September 30, 2001

Work is continuing on the transient thermodynamic model of the engine. More data has been received including the compressor map, turbine map, inertias, and initial estimates of the recuperator configuration. A transient model of the recuperator which includes the basic heat transfer equations to obtain both a spatial and temporal variations is complete. This recuperator model, as well as the updated engine maps and inertias, is currently being worked into the complete engine transient model.

The recuperator model is a cross flow type with a wall in between the two fluid flows, see Figure 12 for schematic representation.

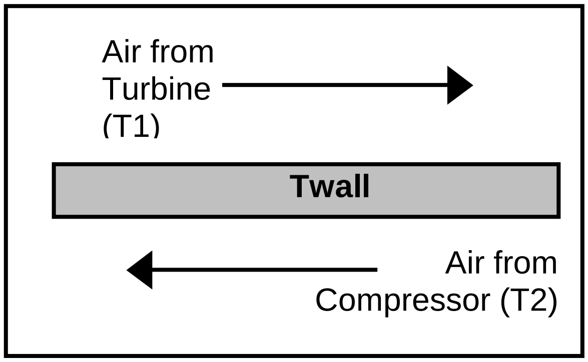

Figure 12: Transient cross flow recuperator model

The physical characteristics of the recuperator including airflow area, heat transfer area, material properties are estimated from knowledge of the Honeywell Parallon 75 recuperator product. Using these values the recuperator model is run through a transient. The following Figure 13 is a time series of plots showing the air from the turbine as T1 flowing from left to right, the temperature of the wall as Tw, and temperature of the air from the compressor as T2 flowing from right to left. The abscissa shows the percentage length along the recuperator and the ordinate shows the temperature in degrees F. There is a step down in the turbine temperature (T1) from 1250 deg F to 850 deg F. The next four frames in the figure show how the air temperatures and wall temperature change over 700 seconds. Figure 14 shows how the transient model compares to the Honeywell Parallon 75 recuperator. In this figure TC5 is the temperature of the air after the turbine, T32A is the air leaving the compressor, and T32A_model is the transient model output using the TC5 temperature profile as the input. This figure shows that for these flow conditions the time constant of the recuperator is between 60 to 80 seconds.

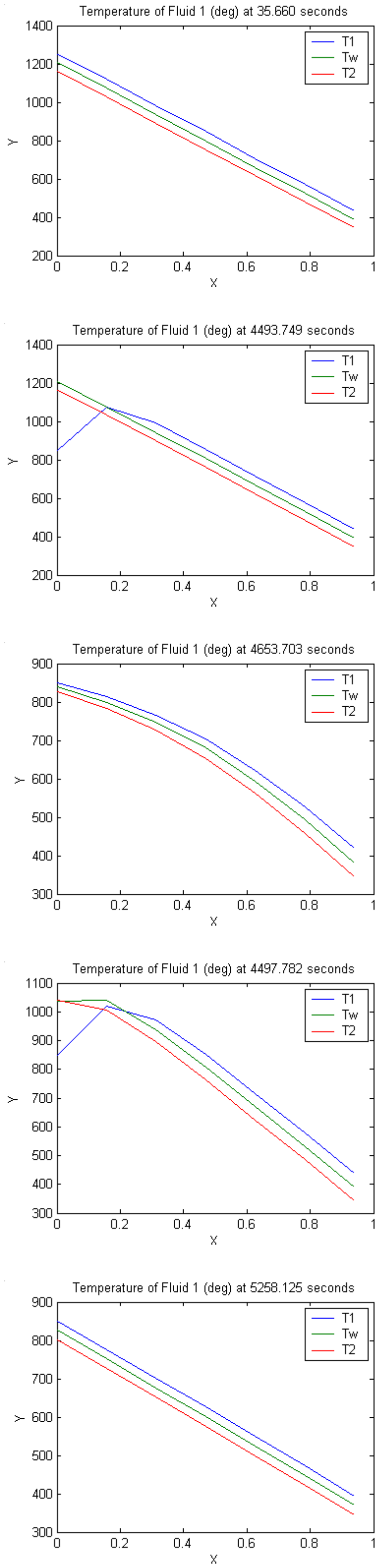

Figure 13: Transient time series of recuperator

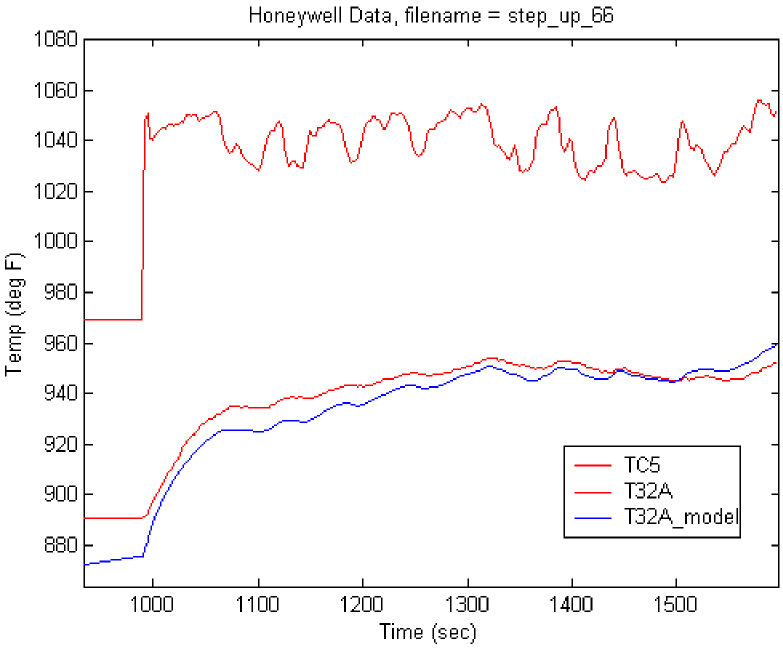

Figure 14: Transient recuperator model versus Honeywell recuperator

Comparison Tests

The Honeywell Parallon 75 constant speed microturbine was tested to understand fuel flow control and monitoring. The fuel metering system consisted of two metering valves for diffusion and premix conditions, as well as two solenoid valves for fuel control. Tests were performed for startup, shutdown, and step change conditions. When reaching full load, the compressor discharge valve opened to dissipate pressure. Results from these tests are shown in Figure 15.

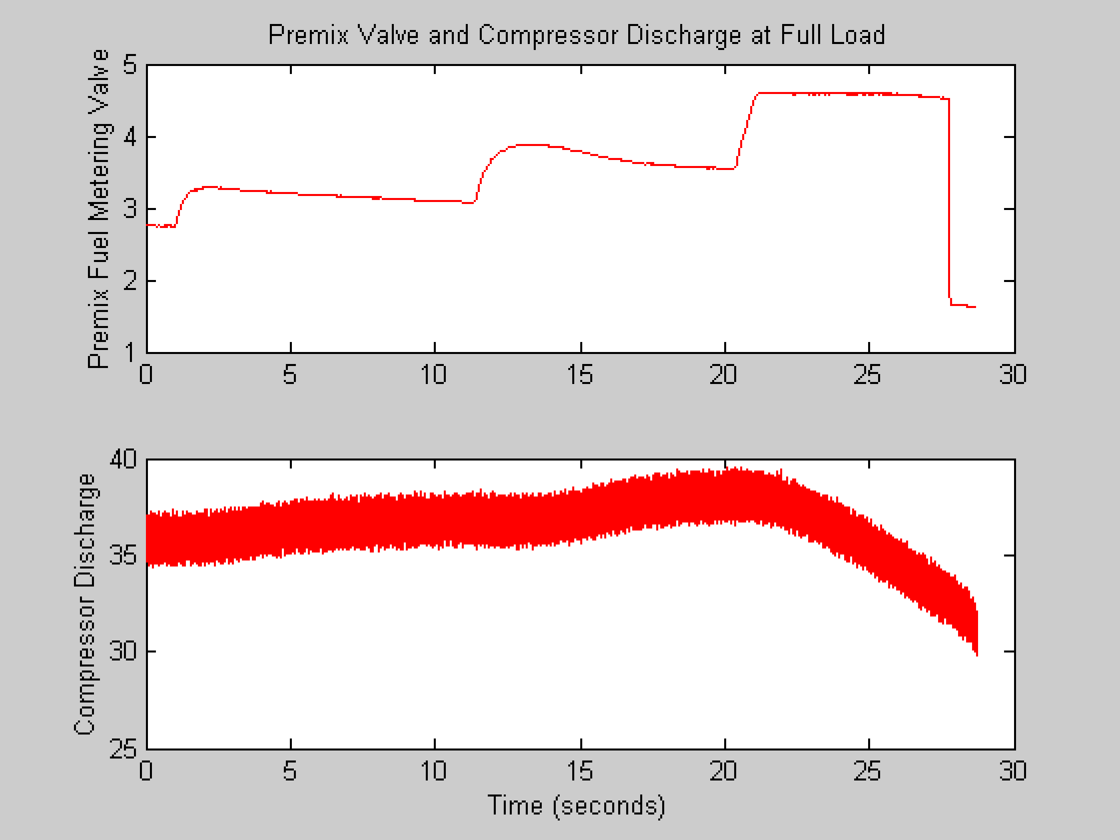

Figure 15: Parallon Step Change to Full Load

The Capstone variable speed microturbine was also tested to determine fuel flow control and monitoring. Capstone used pressure to control fuel flow with four solenoid valves, one of which had the capability of overriding the other three-solenoid valves. Tests were performed during startup, shutdown, and step change conditions. During large increased step changes, the larger solenoid valve, s1, overrode the three smaller valves, s2, s4 and s5. Results from these tests are shown in Figure 16.

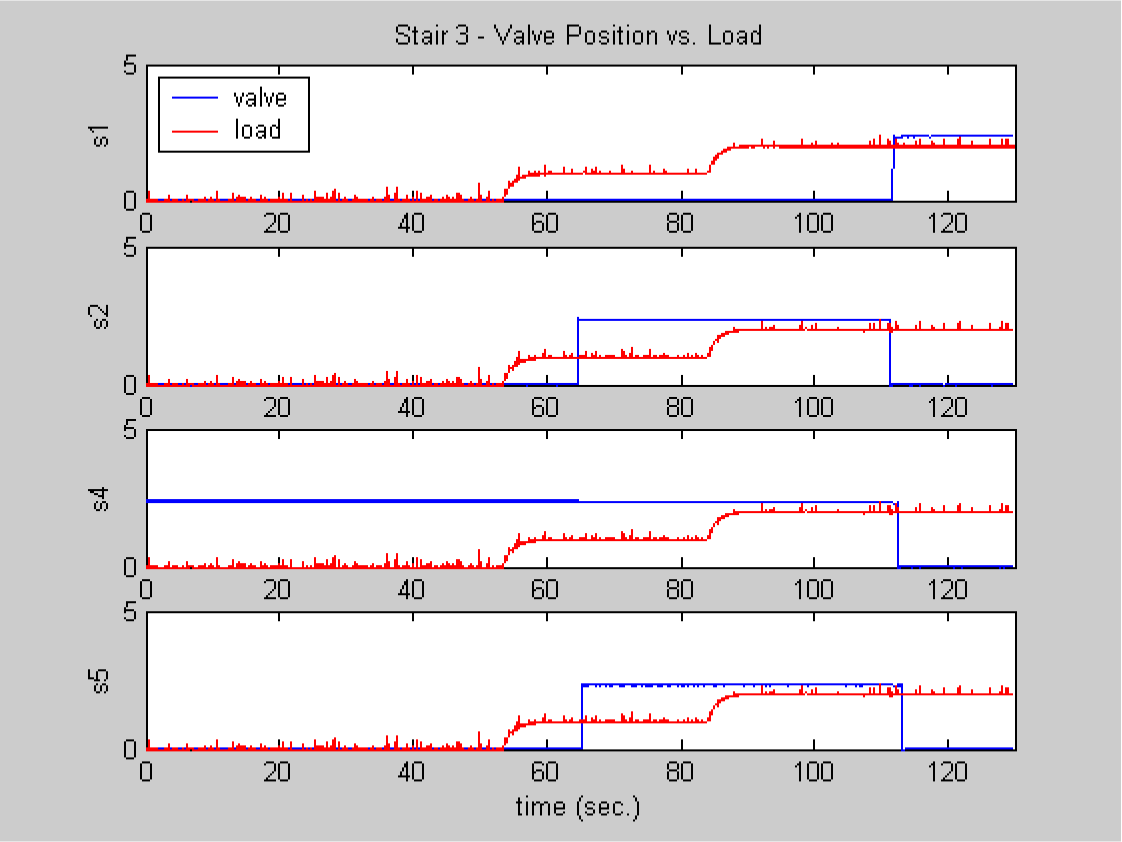

Figure 16: Capstone Step Change to Full Load

Sensor Specification

Sensors have been specified to meet conditions for control accuracy and precision, power consumption requirements, environmental conditions, and lifetime requirements. A final list of sensors for the microturbine is being developed and confirmed. Table 1 shows the current turbine control sensors list. The first 10 items on the list are definite. The final 5 items are TBD because it depends on the final fuel control system as to which sensors we are going to use.

Sensor Name	Description	Units	Min Value	Max Value	Qty	Accuracy
DEFINITE:						
TOIL	Oil Temperature	Deg R	TBD	TBD	1	+/- TBD
T2	Compressor Inlet Air Temperature	Deg R	440	660	1	+/- TBD
TENCL	Enclosure Temperature	Deg R	440	660	1	+/- TBD
T5	Turbine Exit Temperature	Deg R	440	1800	3	+/- TBD
POIL	Oil Pressure	Psia	TBD	TBD	1	+/- TBD
P2	Compressor Inlet Air Pressure	Psia	7.0	16.0	1	+/- TBD
PG	Gas Inlet Pressure	Psia	0	120	1	+/- TBD
N	Turbine Speed	RPM	5000	60000	2	+/- TBD
SV_POS	Shutoff Valve Position	(hi/low)			3	NA
P3_POS	Compressor Discharge Valve Position	(hi/low)			1	NA
TBD:						
TG	Gas Inlet Temperature	TBD		TBD	1	+/- TBD
FCV_POS_PRE	Fuel Control Valve Position premixed	V/V		TBD	1	+/- TBD
FCV_POS_DIFF	Fuel Control Valve Position diffusion	V/V		TBD	1	+/- TBD
FFLOW_PRE	Fuel Flow rate for premixed valve	TBD		TBD	1	+/- 2%
FFLOW_DIFF	Fuel flow rate for diffusion valve	TBD		TBD	1	+/- 2%

Table 1: Turbine Control Sensor List

Input Signal Management

Work has begun on the input signal management for the TECU. All signals that are sent from sensors to the TECU are first converted into engineering units and then are checked to see if there are any anomalies. For signals with redundant sensors there needs to be additional logic to select the optimal value from the sensors. Work has begun on the turbine exit temperature input signal management. The first step is to convert the millivolt output from the sensors to temperature in degrees Rankin. Then it is necessary to detect both hard faults and soft faults for the three redundant temperature measurements. Hard faults are defined as the signal being out side of the acceptable range. Soft faults are defined as a significant difference between two signals that are not hard faulted. Finally, signal selection will determine which measurements to use and will calculate an accurate usable temperature based on the three readings.

Fuel System

The fuel system from the gas compressor to the combustor has been defined. Some of the key items that are being considered for this system are:

- total cost of the subsystem,
- system safety,
- sizing to accommodate full load conditions, as well as rapid transients,
- efficiency impact of the fuel delivery system on overall system.

The current system is being designed as a fuel compressor followed by a shutoff valve and a regulator valve. After this the pipe is split into a premixed flow path and a diffusion flow path. Each of these paths has an instrument to measure flow, and a flow control valve. Figure 17 shows a schematic of the fuel control system.

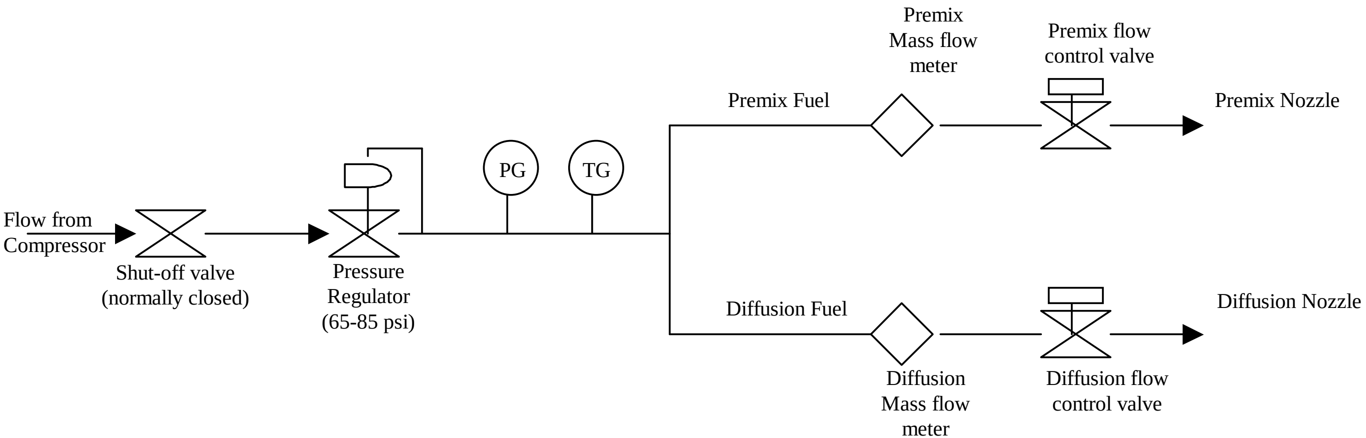

Figure 17: Fuel Control System Schematic

The vendors to make the entire assembly have been down selected to ASCO, South Bend Controls, and WoodWard. Final selection will be made by the end of next quarter.

Task 2. Detailed Design of Subsystem Components

2.2 Recuperator Development

Advanced heat transfer technologies have been examined to determine their applicability to the recuperator design. Two showing significant heat transfer enhancements with acceptable pressure drop increases were chosen for further investigation, including experimental analysis at the relevant Reynolds numbers.

To aid in determining the effect of these technologies as well as the effect of other parameters, an Excel spreadsheet has been developed that uses the effectiveness-NTU heat exchanger analysis method for preliminary design assessment. Correlations for heat transfer and pressure drop effects based on geometry and Reynolds number taken from experimental data for compact heat exchangers have been incorporated into the spreadsheet. In an effort to establish the fidelity of the model, experimentally measured values for the Honeywell Parallon 75 recuperator were compared to those determined by the spreadsheet and there was good agreement between the two. From there, the spreadsheet was adapted for a 175 kW microturbine recuperator, based on the same plate and fin geometry as the Parallon 75, to be used as a baseline for future comparison.

The first quarter of 2002 will include contacting recuperator manufacturers to discuss the feasibility of enhancement techniques. The goal of this is to learn more about the manufacturing process so that we can work with the manufacturers to develop a surface enhancement that will perform well and will be easily manufactured. This will also help to determine which technologies should be pursued with experimental investigation to determine the best configuration for the recuperator and how incorporation into the design can impact the size, weight, and cost of the recuperator.

2.3 Combustion System

A trade-off study between silo and reverse-flow annular microturbine combustors was completed. The study included factors such as NOx/CO/UHC emissions, turn-down ratio, maintainability, overall combustor reliability, material cost, pattern/profile factors, and liner pressure drop. The general consensus extracted from this study was that, for the engine cycle defined in the DOE proposal, the silo combustor is the best geometry to move forward with in designing the microturbine combustor. Nuovo Pignone, a General Electric Power Systems affiliate, has had extensive experience with silo-based combustors (e.g., PGT-2, PGT-5, and PGT-10 gas turbine engines). Moreover, we hope to learn from their best practices in combustor design. Effort was also put forward in specifying the instrumentation (i.e., gage/difference pressure taps, metal temperatures, emissions, exhaust-temperature thermocouple rake) that will be used in benchmarking future combustor liners and casings. By defining the diagnostic instrumentation early in the combustor design process, we will be able to build upon the pool of instrumentation and transducers employed in earlier experiments used for the Elliott TA-45 microturbine combustors.

Following a market analysis and benchmark study of the existing microturbine combustors, the 175 kW machine combustor is a straight flow, can type that uses 4 existing DACRS (Double Annular Counter-Rotating Swirler) premixers currently employed in successful DLE

GE aeroderivatives. The premixers are well understood and were extensively tested at the GE Global Research facilities. Both emissions and flame stability are controlled by splitting the amount of fuel into premix (for operating conditions predicted to be 90%) while the balance is employed in the pilot circuit for flame stability. This arrangement guarantees that the design complies with the emission requirements. The NOx reduction is accomplished by fuel splits (< 10% diffusion flame) and flame temperature whereas the CO reduction is accomplished via geometry of chamber (to increase residence time in the "well stirred reactor" section), flame temperature and fuel split. Acoustics problems are predicted to be minimized due to the increased temperature from the recuperator discharge. The design will be further refined in tests that are planned in the second quarter of 2002.

The conceptual design shown in Figure 18 is a 12" diameter 25" long can combustor that uses 32% of the air flow for highly premixed combustion flame while the balance is employed in cooling of the heatshield, liner and transition piece. Preliminary heat transfer analysis has shown that impingement will be adequate in cooling the heatshield and liner. The system borrows features currently employed in both aeroderivatives and heavy duty gas turbine combustors.

Detailed drawings will be produced by the end of January 2002. Manufacturing will begin mid February and testing of the combustion system will commence in May of 2002. The design will be improved via experiments that will allow fine-tuning the design in order to meet the requirements. DFSS will be employed in the development of the combustor.

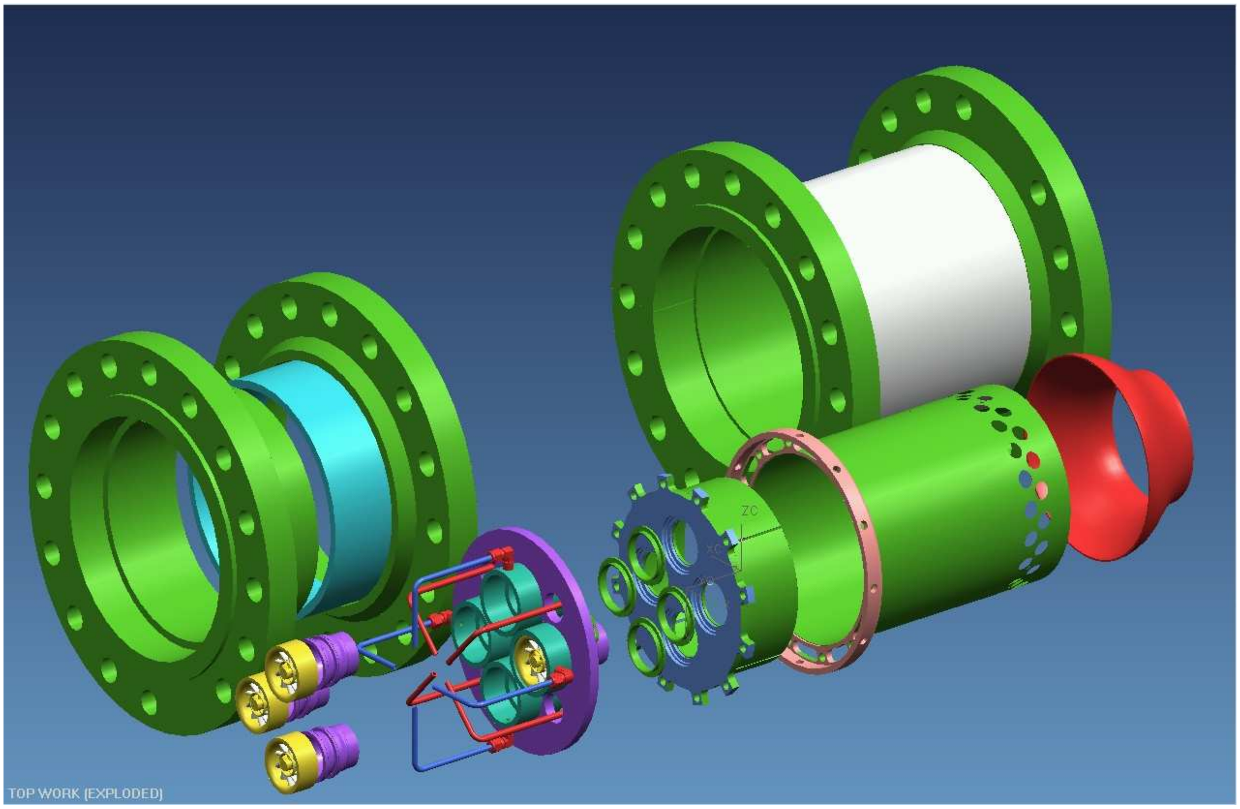

Figure 18: Combustor conceptual design.

2.5 Turbo Machinery

Materials effort continued during this quarter in support of design and fabrication of hot section components for the 35% efficient microturbine design. To evaluate castability of the turbine rotor and the turbine nozzle ring from Rene 108, PCC-Structurals cast one prototype part for each of these components using the investment casting process. The components are shown in Figure 19.

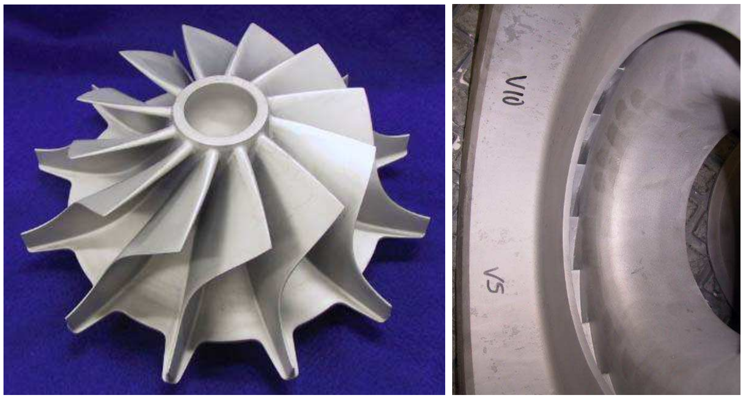

Figure 19: Results of the trial casting of Rene 108 turbine rotor (left) and turbine nozzle vane ring (right)

Both the turbine rotor and the turbine-nozzle vane ring have been successfully cast and have passed non-destructive evaluation (X-ray and FPI), structural, and dimensional evaluations by the PCC Structurals. Metallographic, fatigue, and rupture test specimens are being prepared from the trail components to evaluate the quality and properties of the cast components. Preliminary micro structural examination of the turbine rotor has indicated some unfavorable grain orientations at the perimeter (saddle region) of the rotor disc. Discussions have been held with the process engineers at PCC to modify the parameters of the casting process in order to rectify the grain orientation problem. PCC has now finished casting a second turbine rotor using the modified process conditions and the part is undergoing non-destructive evaluations at the vendor's site. Once received, the new turbine rotor will undergo the same destructive test plan as described above.

2.7 Materials Characterization

Kyocera SN-282 continues to be the leading candidate ceramic material for AIMS hot section components. In preparation for the design and acquisition of prototype silicon nitride ceramic components, GE-GRC is working with ORNL in analysis of the current property database for SN-282 and in extensions of that database for selected critical properties.

A—High Temperature Tensile Testing

Tensile testing of 40 SN-282 specimens (machined and heat-treated) was recently completed in collaboration with Dr. M. Ferber (ORNL) and the University of Dayton Research Institute (UDRI). These 40 specimens consisted of two batches of the material; 25 from a recent procurement by GE-GRC and 15 from a previous procurement by ORNL. Tensile testing was carried out at three temperatures: room temperature, 982 C (1800 F), and 1093 C (2000 F). The testing matrix for the tensile specimens was arranged such that a uniform, randomized mix of the two sets of specimens were tested at each of the selected temperatures. Statistical evaluation of the test results has confirmed that there was no significant difference between the two batches of SN-282 specimens.

In preparation for full analysis of the strength data, preliminary uncensored and censored Weibull analyses were carried out on the tensile strength data. The analyses were conducted based on the fractographic examinations of the fracture surfaces using stereomicroscopic observations at UDRI. These observations suggest that volume flaws dominated the strength of the specimens. A few of the specimens were observed to fail from flaws at or adjacent to the surface. Results of the preliminary Weibull analysis of the tensile strength data are shown in Figure 20. Detailed fractographic examinations of the test specimens using scanning electron microscopy are now in progress at GE-GRC to examine details of the failure-initiating flaws. An example of these fractographic evaluations is shown in Figure 21. Upon completion of SEM examinations, the fractographic information will be catalogued and used in further detailed analysis of the strength data.

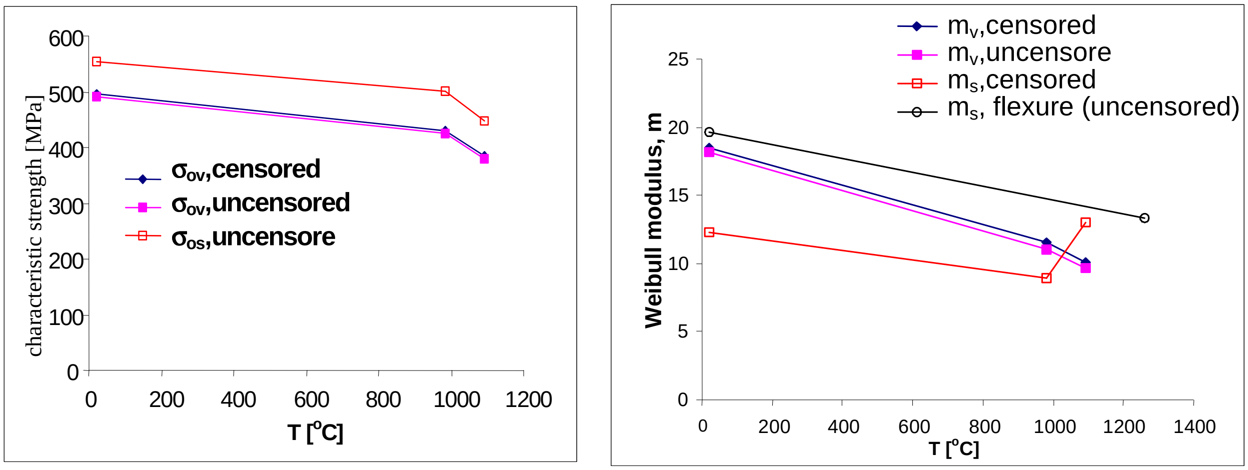

Figure 20: Results of the preliminary censored and uncensored Weibull analysis of the tensile strength data of SN-282 silicon nitride specimens. The subscripts V and S on the graphs refer to failure due to volume and surface flaws, respectively. The flexure data are from the ORNL database.

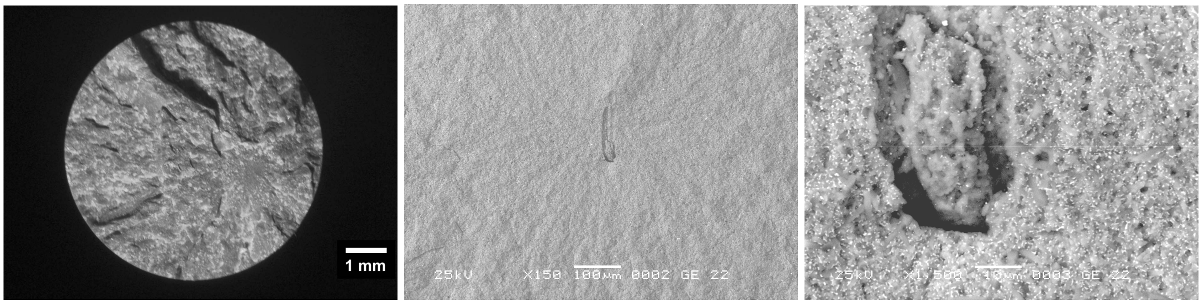

Figure 21: Typical fractographic observations of a failure-initiating volume flaw in SN-282 tensile specimens: left: stereomicroscope observation of the entire fracture surface, middle: electron microscopic observation (backscattered image) of the failure origin and, right: examination of the nature of the flaw at high magnifications. The bright phase in the electron microscopic images corresponds to the lutetium-bearing phase.

B—High Temperature Fracture Toughness Testing

Application of lifing methodologies to ceramics component design requires knowledge of fracture toughness. Due to the absence of such data within the database, we are working with ORNL to plan fracture toughness characterization of the material at elevated temperatures. For this purpose, toughness tests using chevron-notched flexure specimens will be carried out at UDRI under the same temperature conditions as those used in the tensile tests. An SN-282 plate has been submitted to Chand Kare Technical Ceramics for machining of chevron-notched flexure test specimens conforming to ASTM

C1421. It is anticipated that UDRI will complete the toughness tests by early December 2002.

C—High Pressure Combustion Rig (HPCR) Testing

HPCR testing of silicon nitride specimens is now planned for 1000h at temperature and pressure ratio conditions similar to those of the microturbine. The expected start date for the rig test is early November 2002. As mentioned in the previous report, two objectives are being pursued for the HPCR test: 1) to evaluate the recession rate of the SN-282 silicon nitride under the simulated microturbine conditions, and 2) to evaluate the effect of this exposure on the residual strength and Weibull characteristics of the material. The surface recession rate will be monitored after the test by measuring the thickness variation, weight change, and shape/profile change of the specimens. For the strength evaluation, disc specimens, ~12-13 mm diameter and ~0.5 mm thick, will be extracted from the as-received and HPCR-tested specimens. These specimens will be tested in biaxial flexure at room temperature using a ring-on-ring loading geometry conforming to ASTM C1499. Specimen cutup plans include extraction of two thin disc specimens from the same region of HPCR-exposed bars. One specimen will have a surface that had been exposed to the high velocity rig environment. The other will have a surface representing the bulk of the material with no direct exposure to the moisture-bearing environment of the HPCR. The latter will serve to evaluate material that has been exposed to the temperature and time but not to the moisture of the test. A schematic of the test setup showing the arrangement of the specimens and extraction of the post-rig strength specimens is included in Figure 22.

A large SN-282 plate procured in the last quarter has been machined by ORNL into bar-shaped specimens with proper dimensions for installation in the HPCR. Communications have been made with Kyocera to procure and test their proprietary EBC-coated SN-282 material during this HPCR exposure. Kyocera has agreed to provide two plates of their EBC-coated SN-282 material. These would be sufficient to fabricate 6-12 test specimens for exposure in the rig. Discussions related to the HPCR effort were held with ORNL during a recent visit by Dr’s Matt Ferber and H-T. Lin. ORNL will be submitting additional silicon nitride samples for the HPCR test at GE-GRC and will participate in the post-HPCR characterization efforts.

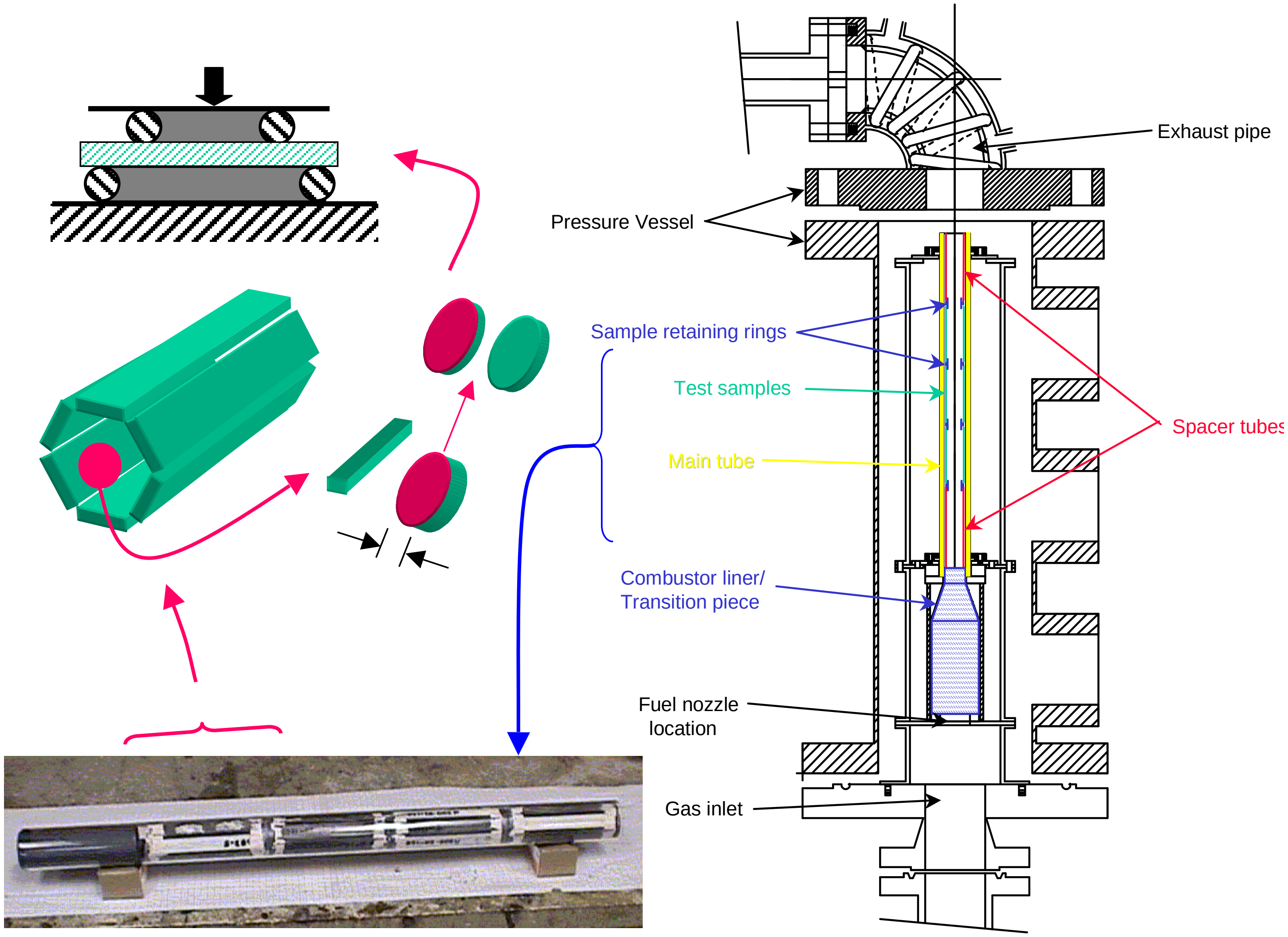

Figure 22: Schematic of the GE-GRC HPCR test setup (right) and the test specimen arrangement in the rig (bottom left). The post-HPCR specimen characterization plan is also schematically shown on left.

D—Probabilistic Design

A working copy of the CERAMIC/ERICA probabilistic design code (only executables, no source code) has been acquired from Honeywell. The CERAMIC/ERICA code has some features essential to design a ceramic component that are currently not present in CARES/LIFE. For example: the ability to "pool" fracture data obtained under various loading conditions and/or geometries; and estimation of confidence intervals for Weibull parameters and reliability. The CERAMIC and ERICA programs have been successfully linked and are now available to be used for ceramic component design. The recently obtained fast-fracture data on silicon nitride will be analyzed using CARES/LIFE and CERAMIC/ERICA to evaluate the strength and weaknesses of these programs.

2.8 Electrical System (Power Electronics and Alternator)

o Fuel System

Current efforts under this subtask have been to begin the design of the fuel delivery system for a natural gas microturbine. The fuel delivery system includes the gas compression, piping, and all valves up to the combustor. Some of the key items that are being considered for this system are:

- Total cost of the subsystem
- System Safety
- Sizing to accommodate full load conditions, as well as rapid transients
- Efficiency impact of the fuel delivery system on overall system

The current system is being designed as a fuel compressor followed by a series of three valves. The three valves are a stop valve, regulator, and a control valve. All of these valves will be electronically controlled via the central control system and will be configured to accommodate all possible operating conditions.

To date a list of vender are being evaluated as suppliers to the above equipment. This effort will continue until a vender is identified at which time hardware will be purchased and the system will be assembled and evaluated.

Functional requirements document

The functional requirements document guides the design development task of the micro-turbine system. It is being led by GE Power Systems Energy Consulting in collaboration with GE-GRC. This document was substantially completed. Feedback from engineers within GE and data gathered from the marketplace lead to a continuous update of the document. See [1] for a draft version.

Alternators

Task 2.802 was initiated with the hiring of an external consultant (US citizen) by GE-GRC to assist the development of the alternator. A preliminary specification document [2] was developed. The alternator is specified to be a 2-pole permanent magnet machine producing 194kWDC. The maximum terminal voltage is less than 637V at 55000 RPM. The high ambient temperatures present a special challenge to the alternator vendors and the design. A 2 oil bearing, integral rotor design is the preferred solution currently.
Six alternator vendors have been contacted with these preliminary specifications and have expressed interest in working with GE. These are Calnetix, Mechatronics LLC, Hamilton-

Sundstrand, Turbo-Genset, Unison and Magmotors. Turbo-Genset has a non-traditional axial air-gap flux design; the others offer a more conventional radial flux design. Currently, GE-GRC is in the process of reviewing the responses and a decision is expected in the next couple of weeks. Alternator fabrication is a long lead (34 weeks, max) task. The responses are summarized in [4].

Control Systems

A preliminary specification document has been drawn up [3]. This document outlines the organization of the micro-turbine controller -the electronic control units, sensors and fuel control systems, ignitor and the power conditioning system. It also describes the sensor requirements, the controller functional requirements, the protectives and the regulatory agency requirements. In addition, the monitoring and diagnostics as well as environmental requirements are described.

Model System development

A Model system (2 GE Innovation Drives 180A frame) was sourced from GE Industrial Systems. This provides GE-GRC with a known platform to exercise the power electronics control algorithms and a limited ability to test possible alternator interactions with the active rectifier.

System design *[1.4010-1.4014]*

Steady state simulations were carried out for 13 power topologies, to identify issues. Operating conditions for the simulations were selected to be representative of the typical load conditions expected to be encountered by the micro-turbine system. Of these, 5 were selected for more detailed study. The main criteria for selecting these five was (a) ability to handle neutral currents and (b) competitive costs.

The five topologies were investigated in greater detail, again using simulations. A very top-level costing exercise was carried out, according to which the estimated costs of the five down-selected topologies were within 10%.

The main features are (a) the transformer-free solution is capable of handling unbalanced loads from the inverter itself. (b) Active rectification directly produces a regulated DC bus required by the inverter and draws unity power factor from the alternator, reducing the thermal load on the alternator (c) The generator can be motored from the rectifier at start.

Preliminary simulation results indicate that Electromagnetic Interference (EMI) will most likely have to be externally mitigated.

Currently detailed simulations are being carried out to assess the transient behavior as well as implementation of the battery based energy management system and possibly a dynamic brake. [2.8000-2.8007]

Thermal design and efficiency studies were initiated with the loss modeling [2.8002] of the inverter, rectifier followed by the passive elements.

Rectifier Control *[1.4016, 2.8005]*

The proposed rectifier is an active 3-phase topology, which can permit bi-directional power flow – enabling the starting of the generator. However due to the high fundamental frequencies (up to 1kHz), special control (synchronous IGBT gating) techniques need to be applied in order to produce a regulated DC bus voltage and draw unity power factor currents from the alternator. There is a need for accurate current and voltage sensing at the rectifier inputs resulting, with a cost and efficiency impact.

Inverter control *[1.4016]*

The four-pole inverter permits independent control of the three phases (line-neutral voltages). Non-linear loads, unbalanced loads as well as unknown grid impedances compound the difficulty in producing low distortion voltage waveforms. An innovative control strategy (the quasi-synchronous reference frame control with active damping of voltage control) is being verified by detailed simulations.

This control strategy is being further investigated and extended for grid parallel mode of operation. The challenges here are that the grid presents a changing and unknown impedance and second, anti-islanding has to be implemented. The control philosophy in the grid parallel mode is that the micro-turbine will behave as a programmable positive sequence only current source. There is a need for an adaptive –active damping loop which could respond to changing grid impedances. Risk assessment and abatement plans. A risk assessment session has also documented the major electrical system concerns – those being cost and efficiency goals. A mitigation plan has been drafted for tracking. References[1] "*Electrical Functional Requirements of the 175kW Micro-turbine*", R. Delmerico et al., GE-CRD, GE-PSEC, June 2001.[2] "*Alternator specifications*", G. Sinha et al., GE-CRD, May 2001[3] "*Controller preliminary specifications*", M. Cardinal et al., GE-CRD, June 2001.[4] "*Vendor comparison matrix*", G. Sinha et al. GE-CRD, June 2001.

Functional requirements

The functional requirements are now complete and peer review is now underway. This document, as well as the market study have identified major design guidelines for the Advanced microturbine. Detailed specifications will depend on the exact application. The proposed system design reflects the following key requirements (features) imposed on the unit.

Grid Parallel Mode

The grid connected mode reflects commercial and light industrial applications where base load or peak shaving is required. Utility "back-feed" protection will be required and some utilities may require an interconnection relay. The unit must be capable of automatically synchronizing with the utility voltages. The PCS should offer functionality that will be required by the emerging IEEE P1547 standard. The PCS will be required to function as a current source. Customer education on breaker clearing capabilities of the PCS will be required.

Voltage-Islanded Mode

The islanded MT will be used in commercial buildings and industrial applications where a part of the load is segregated and isolated from the utility power system. In commercial applications, the load will typically consist of building lighting and electronics (e.g., cash registers, computers). Power quality (i.e. harmonics, regulation, unbalance, transients voltages etc.) will be a key performance metric.

Commercial loads are typically characterized by a substantial level of harmonics - especially the third harmonic (See section 4 on the harmonic current levels to design for) which result in a substantial neutral current which may equal or exceed the phase current. In addition, the electronic loads may be sensitive to high frequency components in the voltage waveform generated by the PCS.

Protection design of the building power system must account for the low fault current capability of the PCS.

Industrial loads will typically consist of lighting, electronics, capacitors and motor loads. The feeder for the isolated load may include a means to transfer to utility power, but the design will prevent the Turbo Alternator from connecting in parallel with the grid. Single or multiple units in parallel will be required. Voltage regulation, unbalance and harmonic voltage generation will be key power quality performance measures.

Other issues which may affect performance and require application guidelines are listed below.

- Overload ratings to handle impact loads and motor starting.
- Power pulsations due to cyclic load changes.
- Induced voltages in the distribution network due to switching of power factor improvement capacitors.
- Undesirable resonance of the PCS output filter with power factor improvement capacitors.
- Protection design of the building power system must account for the low fault current capability of the PCS.

Real-time mode transfer

Real-time transition from one mode to the other will be required of the same PCS unit. Further, mode changes require turbine startups and load power outage. Transition from grid connected to voltage islanded mode of operation requires detection of loss of grid, PCS mode change from current source to a voltage source.

Transition from a voltage-islanded mode to grid-connected mode will be initiated only when the PCS output is synchronized with the incoming grid voltage. At least 2 sets of breakers will be required to effect the transfer from one mode to the other.

Black Start

The PCS shall be required to start the turbine within the prescribed environmental specifications, a minimum of 3 times.

Power Quality

Power quality requirements are summarized as shown in appendix 1.

Multi-unit Capability

The PCS shall be designed to permit multi-unit operation, of upto 10 units other GE MT units, preferably in a ‘wireless’ manner, preferably without using additional matching output impedances.

Paralleling is usually accomplished using paralleling droop impedances (or transformers) in UPS systems and diesel generators.
The PCS controller should have sufficient bandwidth as well as analog and digital i/o points (for example, currents in the droop inductors) to interface with additional hardware that will be required for a multiunit operation.

Load Application & Rejection Capability
Due to the slower response times of the turbine fuel control and the turbine-compressor systems, the generated power lags the demanded power from the PCS. In case of load rejection, the PCS has to be able to dissipate the transient power (upto the rated power of 175kW) to prevent the turbine from tripping. Avoiding a turbine trip is vital to maintaining high availability as the restart time is at least a few minutes. A dynamic brake connected across the PCS DC bus will be the most likely dissipation mechanism.
There is a direct cost impact of the transient load application and rejection ratings. It may be acceptable to specify staged loading of the PCS

Ambient Following
The PCS shall be rated at ISO conditions (STP). *No ambient following characteristic shall be implemented in this generation of PCS.*

Environmental Requirements
Enclosures
The MT system will be pad-mounted in a commercial or a light industrial environment. The MT container will be partitioned to minimize contact of power electronics section from the hot section of the MT. The exact type of NEMA enclosure will depend on the application – for instance NEMA 4.xx waterproofed stainless steel enclosure will suffice for most applications.
Ambient Temperature Operating
-20°F to +120°F ; (above 120°F with derating)
Optional space and oil heaters shall be required for operation below -20°F.
Storage and Shipping Temperature
-20°F to +120°F (for a period not to exceed 14 days – determined by the self- discharge rate of the battery in the black-start option).
Elevation
0 to 1000m with no derating.
Humidity
0% to 100% RH Condensing (rain and snow)
Shock
Up to 3 shocks of 10g maximum with 11 ms ramp on any axis
Vibration
Amplitude 0.075 mm peak (0.15 mm pk - pk), frequency 10-57 Hz
Acceleration 1g, frequency 57-150 Hz
Test per IEC 68.2.6 Test F Sub C
Referenced EN 50178: 1994
Seismic
Uniform Building Code (UBC) seismic zone 2 standard, zone 4 optional.
Siesmic Zone 4 specifications : 2g's at 0.6Hz, 5 g's between 2-5Hz, 1.6g's between 15-50 Hz.
None of the MT vendors specify adherence to any Seismic, shock or vibration standards.

Heat Rejection

A minimum air flow of approx. 600 CFM (at 50° C) is required to dissipated the 23kW of anticipated losses in the PCS.

Safety Compliance

The PCS shall be tested by an external agency to obtain UL certification for the US market (or ETL), the CSA certification for Canada and the CE mark for the European Union.

Alternators

Six alternator vendors (Calnetix, Mechatronics, Hamilton Sundstrand, Unison, Magmotors and Turbo-Genset) had been contacted and provided with the preliminary specifications developed by GE. Based on site visits and a detailed evaluation of the proposals, a vendor evaluation matrix was developed as shown in table 2.

CTQ	Weightage	Calnetix	Magmotors	lechatronic	Sundstrand	urbogense	Unison
Technical capability	10	6.6	1	3.9	10	9.7	7.6
Fabrication	5	1	5.5	1.6	6.1	10	8.7
Cost	6	4.9	1	3.7	1.6	2.5	10
Schedule	8	10	3	10	5	5	10
IP/Contracts issues	10	5	5	8	8	10	5
Overall Score (1-10)		**5**	**1**	**3**	**7**	**9**	**10**

Table 2: Alternator vendor qualification matrix.

There was a 4:1 difference in the quoted rates from Unison and Turbo-Genset, which was ultimately selected. Turbo-Genset has experience in this application space (high power, high speed permanent magnet machines – 400kW, 30krpm), so the AIMS 40krpm, 175kW machine design task would be a very close extrapolation speed wise and an intrapolation power wise for Turbo-Genset.

Subsequently, work has begun at Turbo-Genset on the AIMS machine. The initial design calls for a 8-10 pole axial flux machine – whose characteristics are shown in figure 23. From a power conversion perspective, a low pole count (2) is preferred due to the active rectifier implementation.

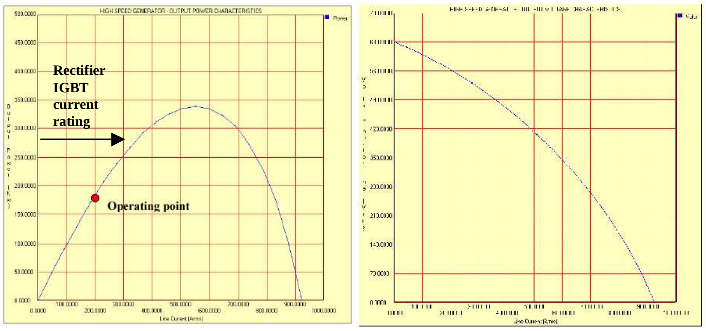

Figure 23: Generator terminal power vs. RMS line current (b) Generator terminal voltage vs. RMS line current.

It is expected that the generator shall be connected to the power conversion system (PCS) using an output filter, which will be discussed in the next section.

Power converstion system (PCS) Design Tasks (1.4, 2.8)

The schematic of the proposed power conversion system is shown in figure 24.

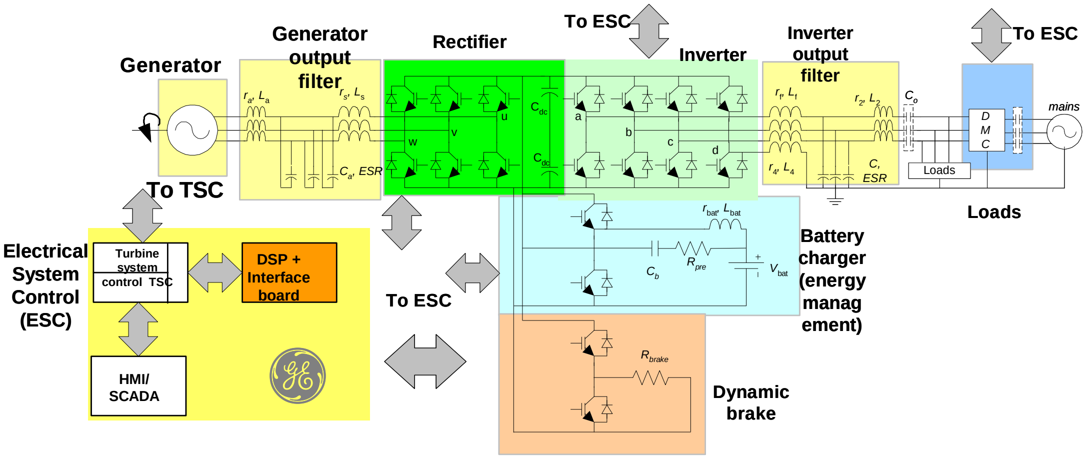

Figure 24: Proposed 175kW MT power conditioning system topology.

Rectifier [1.4016, 2.8005]

The rectifier control has been verified by simulations. The controller block diagram is shown in figure 25.

In figure 26, rectifier operation at challenging operating conditions are shown. For instance, in figure 26.(a), the generator goes from no load to full load, as can be seen from the increased magnitude of the currents. Further the synchnronous ratio (fc/fo) is changed from 7 to 9 and back to 1 – the absence of transients (current spikes) indicates flawless control operation.

For the rectifier to regulate the DC bus voltage and draw unity power factor generator currents, an additional series reactor must be inserted between the generator and the rectifier terminals. Further, an LCL filter structure will be required to eliminate high frequency noise and reduce the current ripple through the generator, thereby improving efficiency.

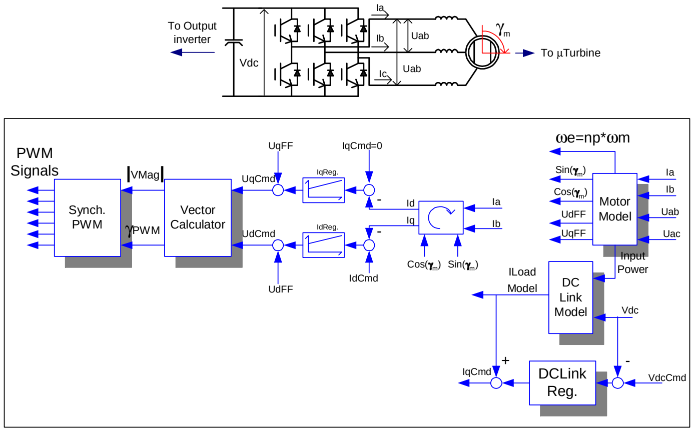

Figure 25: Rectifier control block diagram

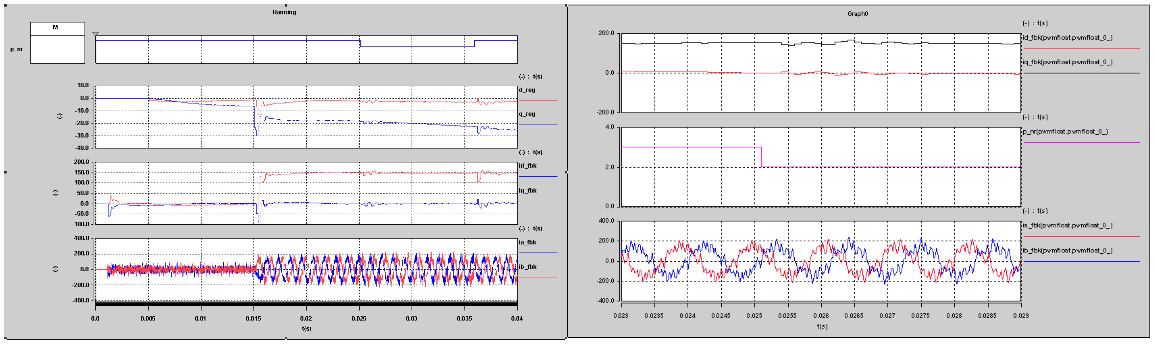

Figure 26: (a) no-load to full load application and 'gear ratio' change; (b) zoomed view of change in gear ratio.

Inverter control *[1.4016]*

The four-pole inverter control has been verified for non-linear, unbalanced as well as DC loads. Currently the focus is on ensuring that the transition from grid-connected to the voltage islanded mode of operation and vice-versa are accomplished in a smooth manner. Figure 27 shows the control structure for the micro-turbine inverter. The key idea is that the distinct voltage mode control and the current mode control are simultaneously run on the processor. If an mode change is commanded or loss of grid (anti-islanding) is detected, the supervisory control selects the appropriate controller output to apply to the inverter modulator.

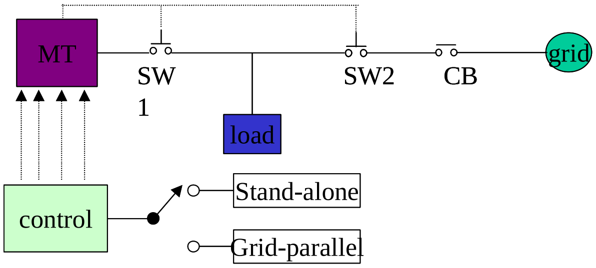

Figure 27: Controller structure for dual mode operation.

Figure 28 shows the waveforms for the case when an islanded mode of operation is detected and the MT was putting out 150kW of power of which 30kW was to the local protected load while the remainder was being exported to the grid. Following the loss of the grid and before the turbine output power falls to 30kW, there is distortion in the load voltage and inverter output current. The load voltage also increases in magnitude, typically triggering opening of SW1 switch (i.e. dropping local protected loads) if the overvoltage protection limits are exceeded.

Figure 29 shows the waveforms for the case when MT transitions from a voltage-islanded mode to grid-parallel mode of operation. In this case, the MT PCS goes form generating the non-linear current demanded by the load to sourcing very small amounts of harmonic currents (the remainder being supplied by the grid).

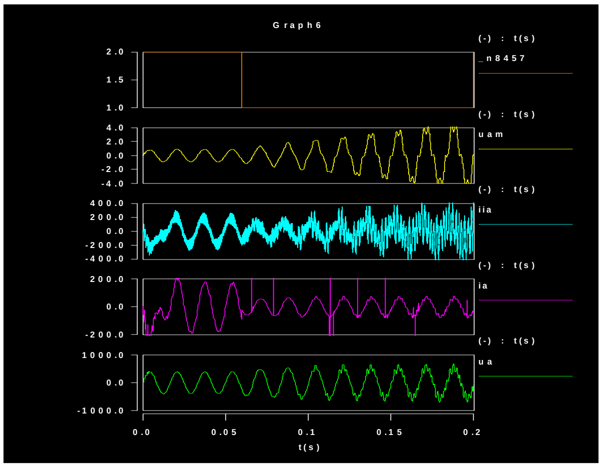

Figure 28: Grid parallel to voltage islanded mode of operation

(a) top: controller mode
(b) Modulator command signal – inverter output voltage is proportional to this waveform.
(c) Inverter output current.
(d) Load current.
(e) Load phase voltage.

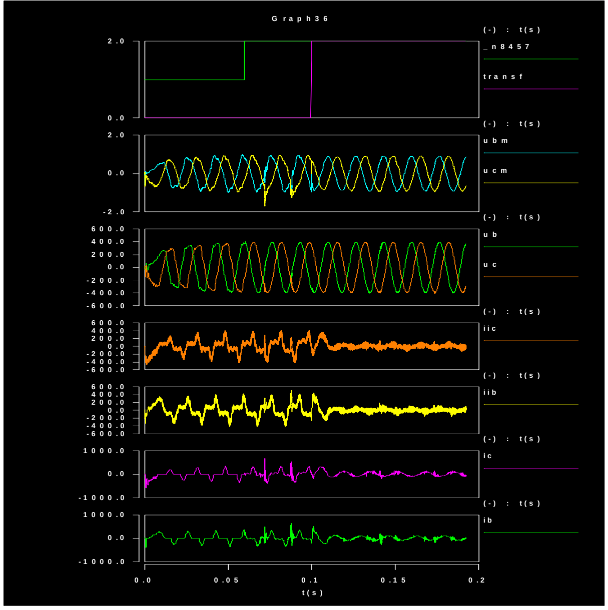

Figure 29: Voltage islanded to grid-parallel mode of operation

(a) top: controller mode
(b) Modulator command signal – inverter output voltage is proportional to this waveform.
(c) Load phase voltages
(d) Inverter output current (phase a)
(e) Inverter output current (phase b)
(f) Load phase c current
(g) Load phase b current.

Energy Management System

Lead acid batteries were selected as the energy storage media, required for black start capability and for supporting load application. Figure 30 shows the power capability of a commercially available VRLA battery. From this curve (which is representative of all batteries) it is evident that capability of the battery to source peak power for a shorter duration is substantially than at its long-term low power rate.

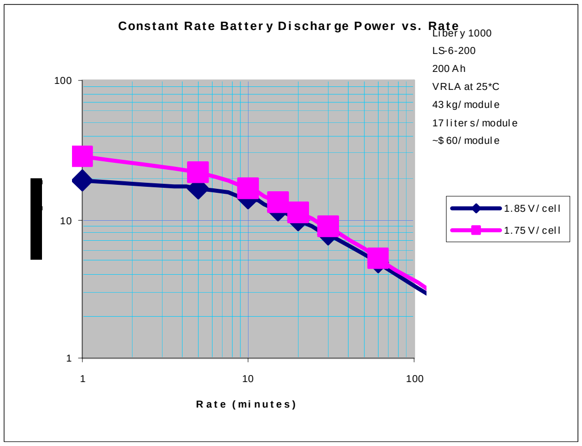

Figure 30: Power capability of a Liberty 1000, 200Ah VRLA

Consequently, by sizing the battery for supporting peak power application, a cost estimate of the VRLA battery required is obtained and shown in figure 31.

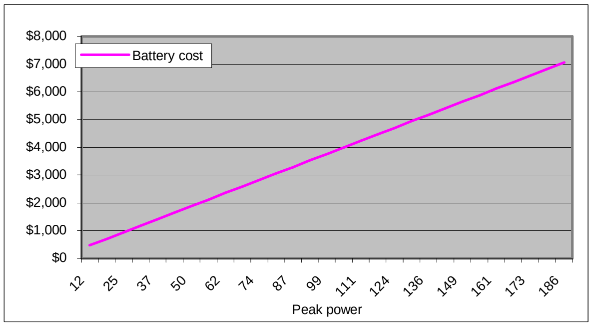

Figure 31: Cost variation of a VRLA battery vs. peak power capability

Implicitly by stacking the modules in series, the DC bus voltage of the battery is increased to increase its peak power rating, figure 32. A higher battery voltage is favored for higher power conversion efficiency, since the DC bus voltage will be 900VDC.

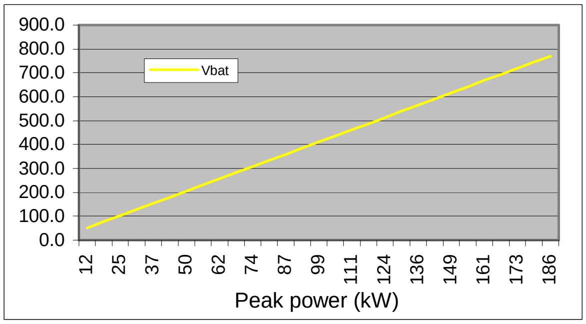

Figure 32: Battery open circuit voltage vs. peak power capability.

The power electronic topology investigations were carried out to determine the component values of the system. It was concluded that there are fundamental building blocks of the MT system are the 'phase legs' – consisting of two IGBT switches in a totem pole structure. With this philosophy, different commercially available products were evaluated for suitability as solutions to the MT requirements. Out of the nine phase legs, four are required by the inverter, three by the rectifier and two for the battery-chopper and the brake resistor.
A feature of this philosophy is that eight of the phase legs are connected on the DC side to the same terminals. The phase legs are rated identically (for the prototype) and are hence interchangeable. The devices are air cooled and make use of an extruded-aluminum heat sink. Some of the salient features of the proposed topology design are discussed next.
According to this schematic of [1], all phase legs are realized using 1200V, 900A Semikron SkiiPacks which are the building blocks of the GE AV300i 3200 Frame Drives. The advantage of using this building block is that the phase legs are pre-packaged with DC link capacitors, have known gate drivers and thus represent a lower technical risk. Further, they permit a DC link voltage of 825V, representing increased dynamic range and bandwidth from the inverter and the rectifier.

The rectifier shall be realized by a conventional three phase DC-AC converter configuration (the standard inverter). At the input side of the rectifier, a contactor is used as a means for disconnecting the power electronics from the alternator and the mechanical prime movers – this is a protective function.

The inverter shall be realized using a four-pole three phase inverter. The filter component values L_1 =225μH, C = 550μF and L_n = 75μH were derived as a result of a design exercise trading of performance specifications (THD) vs. component size vs. current ripple in the inverter currents. Since the switching frequency of the inverter is known (=5kHz), the capacitance required to arrive at a cutoff freq. of 453Hz is determined. The cutoff freq. of the filter is usually selected to be about 1/8th to 1/10th the switching frequency to provide an adequate bandwidth to the inverter control. Further, the resonance point of the filter ($f_o=1/(2\pi\sqrt{LC})$) should not be coincident with any grid harmonics i.e. 60Hz, 120Hz, 180Hz etc.
Two output 'switches' are required. At the load end of the microturbine unit, a circuit breaker will be required since it has fault current interruption capability which will be required for grid parallel mode of operation. The other 'switch' is a contactor, which is simply a means to energize and de-energize local protected loads, and are not required to interrupt fault currents (the inverter output currents are closely monitored).

A 125V, 200A-h VRLA battery bank shall be used as the primary black start energy source. The battery interfaces to the DC link by means of a DC-DC converter that permits bi-directional power flow in both directions in the buck-boost mode. This feature enables the charging of the link capacitor voltage from 0 to 825V using a 125V battery bus. The battery peak power is rated at 30kW to support the transient load application of a 30kW motor (1/6th the rating of the microturbine).

Power for the auxiliaries is derived from a DC-DC converter that is fed directly from the battery. This ensures that there is power available for the control systems during a load outage. Therefore, all auxiliary systems such as fuel pumps, oil pumps, cooling fans and control boards are powered using a 24V DC power supply as the primary source. To prevent excessive drain of the black-start battery, control power will be derived from a 'diode-or' scheme consisting of power input from the main DC-DC inverter, a power input from an auxiliary 480VAC source suitably scaled down using a transformer.

A dynamic brake is connected across the DC link. The function of this brake is to control the link voltage during load rejection, when the generator voltage increases in proportion to the turbine speed. The brake will be realized a 3 ohm disk resistor rated to dissipate 400 kJ of energy. Since the resistor time constant is fairly large (minutes), the microturbine unit shall be disabled for normal operation till the temperature of the brake heat sink falls back to 'safe' limits.

Currently, the design is being refined. A set of possible motor drive based solutions have been identified. These are being differentiated per the following CTQs (Critical to Quality).

1. Performance (match with technical requirements)
2. Cost
3. Footprint
4. Availability

Rectifier control algorithms :

The rectifier control block is summarized in figure 33. This algorithm will be resident on source controller DSPX. The control ensures a four quadrant operation of the synchronous machine. During normal operation, a synchronous PWM scheme is employed per the schedule shown in figure 34. During startup, a pulse-amplitude modulation scheme is used, figure 35. According to this scheme, a fixed pulse pattern is impressed upon the voltage at a gradually increasing frequency; the DC link voltage is gradually increased in proportion to the frequency to prevent overcurrent.

References

[1] "*MT system schematic, v4*", G. Sinha, M.E. Dame, GE-GRC, 12/2001

[2] "BICU PWM Bridge Interface, EPLD FPGA Design Specification, Version 0.1", R. Zhou, GE-GRC 1/2002

System Design Specifications

Rated power	175 kW @ 480VAC, 3 phase, 4 wire, 0.8 power factor, 60Hz at ISO conditions.
Modes :	Stand-alone with support of rated single phase loads, no derating. Grid connected (3 wire) with no derating. Real-time Mode transfer capability.
Start :	Black start. Upto three successive cranks.
Multi-unit :	Upto 10 units in parallel.
Multi-source :	Not required.
Auxiliary source :	Auxiliary 3 phase, 480VAC feed option.
Paralleling :	Upto 10 units.
Transient :	Staged load application (<30kW/event) Trip-free full load rejection.
Safety :	UL/ CE mark certifications required for commercial product
Noise level :	70dBA at 3m (system)
E-Stop :	Required
HMI	Optional for prototype, required for commercial product.
RM&D Capability	Required.
Other technical :	No ambient following characteristic. See Good Quality Tab.
Enclosure :	NEMA 1 (indoor); NEMA 4 for commercial product
Operating Temperature range :	-20 F to +120F with no derating.
Elevation :	0 -1000 m with no derating.
Humidity :	0 - 95% non-condensing.
Seismic :	Uniform Building Code (UBC) seismic zone 2 standard, zone 4 optional. Siesmic Zone 4 specifications : 2g's at 0.6Hz, 5 g's between 2-5Hz, 1.6g's between 15-50 Hz.
Vibration :	Amplitude 0.075 mm peak (0.15 mm pk - pk), frequency 10-57 Hz Acceleration 1g, frequency 57-150 Hz Test per IEC 68.2.6 Test F Sub C Referenced EN 50178: 1994 [Electrical system rubber mounted]
Cooling	Forced air cooling preferred.
Air intake :	900 scfm to handle approximately 23kW power dissipation
Form Factor :	TBD
Weight :	TBD

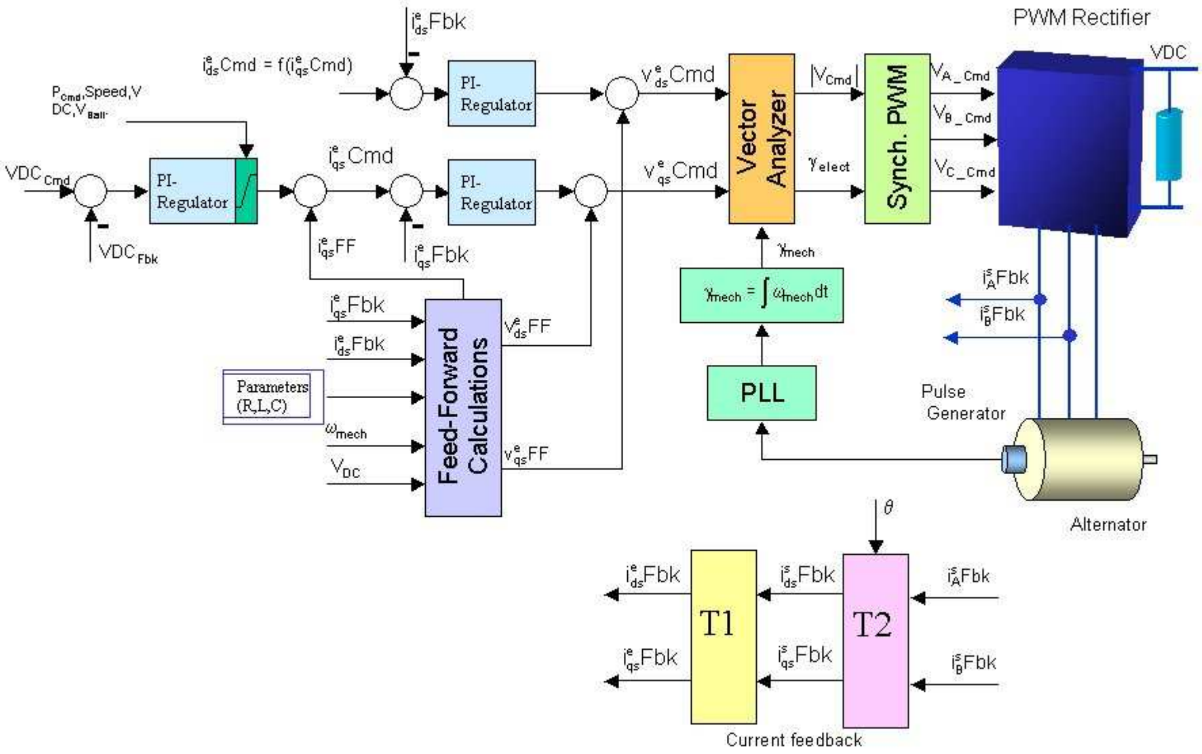

Figure 33: Rectifier control block

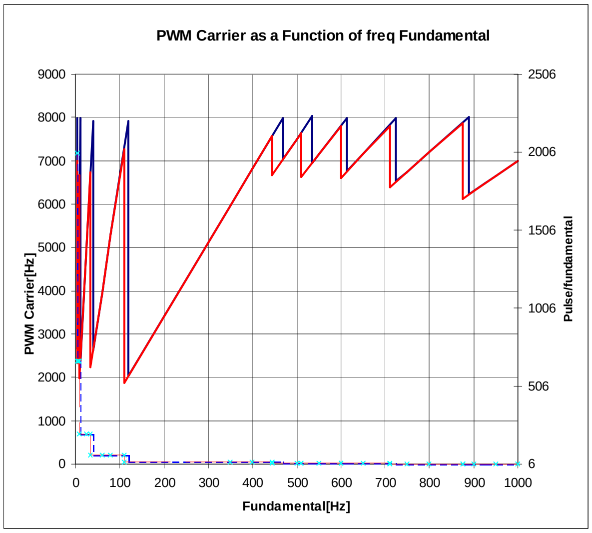

Figure 34: Synchronous PWM frequency schedule

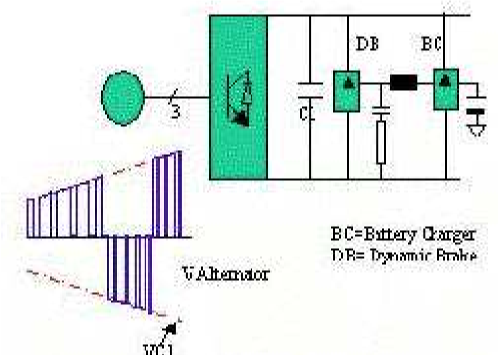

Figure 35: PAM principle.

Control Tasks (Task 3.2)

The MT-PCS control architecture was designed to have the structure shown in figure 36. In this architecture, the Output inverter consisting of the 4 pole inverter and some output contactors will be controlled by an individual DSPX card and bridge interface card (BICU). The BICU card will be designed explicitly to convert high voltage signals to a conditioned form suitable to 5V and 3.3V logic. The DSPX is a Texas Instrument® TMS320Cxx DSP based control engine designed by GE-GRC. Almost all real-time (sub-microsecond) code execution occurs on the DSPX. The control is synchronous (200ms) with tasking rates possible at all integral multiples of the basic 200ms interval.

The active rectifier, dynamic brake and the battery system will be controlled by an identical DSPX and a to-be-designed custom BPIU card. Communication between the two controllers will be via a serial link employing CANBUS[1] or ISbus[2] protocols.

The turbine control platform will be a PLC[3] either OCS250, Versamax or a Series 90, all from GE. The main criteria for selecting a PLC are (a) ability to port code (from matlab to C) (b) cost (c) connectivity.

The PLC will handle all the supervisory level control, turbine control algorithms (milliseconds bandwidth) and HMI, RMD functions. Communication between the PLC and the PCS controllers will be over CANBUS.

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[1] Controller Area Network.

[2] In-Sync

[3] Programmable Logic Controller

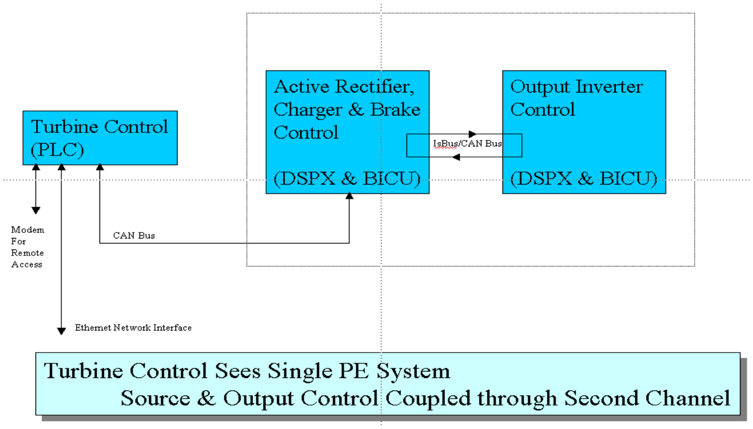

Figure 36: Control architecture of the MT-PCS

Figure 37 shows the detailed proposed layout of the BPIU, DSPX and the power electronics packaging. A list of sensors required was drawn up and characterized. ADCs[4] with programmable interrupts will be used for all voltage measurements while shunts will be used for current measurements. Only state variables will be measured.

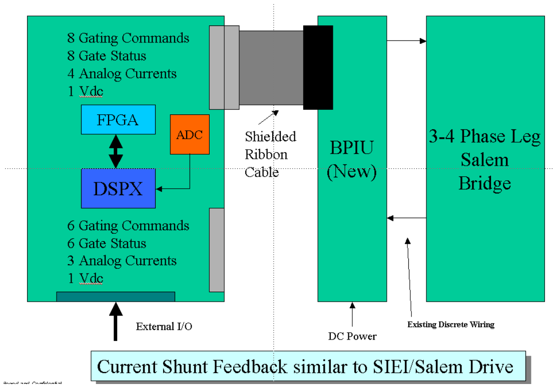

Figure 37: Layout of Bridge interface unit card.

References

[1] "*Electrical Functional Requirements of the 175kW Micro-turbine*", R. Delmerico et al., GE-GRC, GE-PSEC, June 2001.
[2] "*Alternator specifications*", G. Sinha et al., GE-GRC, May 2001
[3] "*Controller preliminary specifications*", M. Cardinal et al., GE-GRC, June 2001.
[4] "*Vendor comparison matrix*", G. Sinha et al. GE-GRC, June 2001.

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[4] Analog to Digital Converters

APPENDIX A

Specification for Good Quality (equivalent to reciprocation engine generator)

Isolated

Good Quality CTQs Isolated	**Lower Spec Limit**	**Target**	**Upper Spec Limit**	Notes
Nominal output phase, voltage and frequency		Discrete		Provide the capability for any of the following[i]: • 3-phase, 4-wire, 208Y/120, 60 Hz • 3-phase, 4-wire, 480Y/277, 60 Hz • 3-phase, 4-wire, 240Δ/120, 60 Hz • 3-phase, 3-wire, 240Δ, 60 Hz • 3-phase, 3-wire, 480Δ, 60 Hz • 3-phase, 4-wire, 415Y/240, 50 Hz • 3-phase, 4-wire, 400Y/230, 50 Hz • 3-phase, 4-wire, 380Y/220, 50 Hz • 3-phase, 4-wire, 220Y/127, 50 Hz
Power Factor Rating		Discrete		0.8 PF continuous rating.[ii] However, the PCS must be capable of supporting a larger transient PF range – consistent with load requirements.
Transient Overload	TBD			See endnote discussion.[iii] Must be coordinated with undervoltage protection[iv].
Neutral		Discrete		Rated to accommodate non-linear loads and unbalance. Generally, equal to the rating of the phase conductor. [v]
Voltage regulation, steady-state			2% +/- 0.25% 1%	No load to full load change[vi]. Voltage band under steady load and temperature For a 25 degC ambient temperature change within the operating range.
Voltage fluctuation from steady-state, repetitive			IEEE std 1250	Borderline of irritation curve, Fig. 6 – Human Response to Flicker Curve. [vii]
Voltage Response – Load Step, infrequent			20%	For an 80% step at 0.8 lagging power factor.[viii]
Voltage fluctuation from nominal, very infrequent			TBD	Valid for transfers between grid and stand-alone.

Voltage Unbalance			5%	With 25% of rated current on one phase and no other load on the MT.[ix]
DC component in AC output voltage			0.1%	Percent of rated for all load conditions[x], or as required based on load testing.
Voltage distortion, full load			5% THD, 3% Single	IEEE 519. Valid for the full KVA rating, including non-linear load.[xi] Consistent with EGSA 101P for class 3 (higher levels allowed for class 4)
Voltage distortion, transient			7.5% THD, 4.5% Single	IEEE 519. For infrequent transient events above the KVA rating.
Telephone Interference Factor			100	Consistent with EGSA 101P for class 3 (higher levels allowed for class 4), per NEMA MG 1-22.43C weighting.
Frequency deviation			5 Hz	For an 80% step at 0.8 lagging power factor.[xii] Recovery to nominal within three (3) seconds.
Electromagnetic Compatibility – conducted		Discrete		Meets xx and FCC class A, or as required for certification.
Electromagnetic Compatibility – radiated		Discrete		Meets xx and FCC class A, or as required for certification.
Electromagnetic Compatibility – immunity		Discrete		Meets xx, or as required for certification.
Surge voltage rating		Discrete		Meets IEEE C62.41. Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits. Also coordinated with switching surges caused by transfer switch operation (if provided).

Grid parallel

Good Quality CTQs Grid Parallel	**Lower Spec Limit**	**Target**	**Upper Spec Limit**	**Notes**
Nominal output phase, voltage and frequency		Discrete		Provide the capability for any of the following[xiii]: • 3-phase, 4-wire, 208Y/120, 60 Hz • 3-phase, 4-wire, 480Y/277, 60 Hz • 3-phase, 4-wire, 240Δ/120, 60 Hz • 3-phase, 3-wire, 240Δ, 60 Hz • 3-phase, 3-wire, 480Δ, 60 Hz

				- 3-phase, 4-wire, 415Y/240, 50 Hz - 3-phase, 4-wire, 400Y/230, 50 Hz - 3-phase, 4-wire, 380Y/220, 50 Hz - 3-phase, 4-wire, 220Y/127, 50 Hz
Power Factor		Discrete		1.0 PF. The ability to supply reactive power may be a useful ancillary feature.
Voltage operating range			-13%/+ 6%	Percent of nominal based on ANSI C84.1, range B.
Power regulation, steady-state		TBD		Fundamental frequency power (real and reactive) - control accuracy as a percent of rated.
Voltage flicker		Discrete		Voltage flicker must not be made worse with MT unit connected.
DC current injection			0.5%	Percent of rated current for all terminal conditions including reasonable terminal voltage distortion and DC voltage offsets[xiv].
Current distortion			IEEE 519	Valid for all terminal conditions including reasonable terminal voltage distortion and DC voltage offsets.
Short circuit contribution			TBD	Reference IEEE std. P1547.
Frequency operating range		+/- 5.0%		Percent of nominal.[xv]
Electromagnetic Compatibility - conducted		Discrete		Meets xx and FCC class A, or as required for certification.
Electromagnetic Compatibility - radiated		Discrete		Meets xx and FCC class A, or as required for certification.
Electromagnetic Compatibility - immunity		Discrete		Meets xx, or as required for certification.
Surge voltage rating		Discrete		Meets IEEE C62.41. Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits.
Turn on transient *		Discrete		Reference IEEE std. P1547 recommendation. - Parallel operation shall be prevented until the service voltage is within specifications (voltage, frequency, and frequency rate-of-change) for 60 seconds. - Connection to the utility should be bumpless (no voltage flicker or power reversal).

* Control and protection settings must be factory adjustable only (i.e., not user adjustable). Requirements and trip times may vary.

Specification for Better Quality (comparable to domestic grid)
Isolated

For comparison, changes beyond the requirements of good quality are highlighted in blue.

Better Quality CTQs Isolated	**Lower Spec Limit**	**Target**	**Upper Spec Limit**	Notes
Nominal output phase, voltage and frequency		Discrete		Provide the capability for any of the following[xvi]: • 3-phase, 4-wire, 208Y/120, 60 Hz • 3-phase, 4-wire, 480Y/277, 60 Hz • 3-phase, 4-wire, 240Δ/120, 60 Hz • 3-phase, 3-wire, 240Δ, 60 Hz • 3-phase, 3-wire, 480Δ, 60 Hz • 3-phase, 4-wire, 415Y/240, 50 Hz • 3-phase, 4-wire, 400Y/230, 50 Hz • 3-phase, 4-wire, 380Y/220, 50 Hz • 3-phase, 4-wire, 220Y/127, 50 Hz
Power Factor Rating		Discrete		0.8 PF continuous rating.[xvii] However, the PCS must be capable of supporting a larger transient PF range – consistent with load requirements.
Transient Overload	TBD			See endnote discussion.[xviii].
Neutral		TBD		Rated to accommodate non-linear loads and unbalance. [xix]
Voltage regulation, steady-state			2% +/- 0.25% 1%	No load to full load change[xx]. Voltage band under steady load and temperature For a 25 degC ambient temperature change within the operating range.
Voltage fluctuation from steady-state, repetitive			IEEE std 1250	Borderline of irritation curve, Fig. 6 – Human Response to Flicker Curve. [xxi]
Voltage fluctuation from steady-state, infrequent	3%	5%	6%	< 1/hour. Valid for infrequent on/off transients including inrush superimposed on the KVA load profile.[xxii]
Voltage fluctuation from nominal, very infrequent			CBEMA curve [xxiii]	Valid for transfers between grid and stand-alone.
Voltage Unbalance			2%	Valid for the full KVA rating. [xxiv]
DC component in AC			0.1%	Percent of rated for all load conditions[xxv], or as required based

output voltage				on load testing.
Voltage distortion, full load			5% THD, 3% Single	IEEE 519. Valid for the full KVA rating, including non-linear load.[xxvi] Consistent with EGSA 101P for class 2.
Voltage distortion, transient			7.5% THD, 4.5% Single	IEEE 519. For infrequent transient events above the KVA rating.
Telephone Interference Factor			75	Consistent with EGSA 101P for class 2, per NEMA MG 1-22.43C weighting.
Frequency deviation			+/- 0.5 Hz	For all load conditions[xxvii].
Time-Frequency			TBD minute per month	Achieved by a crystal clock or by grid following.
Frequency rate-of-change			+/- 1.0 Hz/second	For all load-following conditions [xxviii]
Electromagnetic Compatibility – conducted		Discrete		Meets xx and FCC class A, or as required for certification.
Electromagnetic Compatibility – radiated		Discrete		Meets xx and FCC class A, or as required for certification.
Electromagnetic Compatibility – immunity		Discrete		Meets xx, or as required for certification.
Surge voltage rating		Discrete		Meets IEEE C62.41. Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits. Also coordinated with switching surges caused by transfer switch operation (if provided).

Grid parallel

For comparison, changes beyond the requirements of good quality are highlighted in blue.

Better Quality CTQs Grid Parallel	**Lower Spec Limit**	**Target**	**Upper Spec Limit**	**Notes**
Nominal output		Discrete		Provide the capability for any of the following[xxix]:

phase, voltage and frequency				• 3-phase, 4-wire, 208Y/120, 60 Hz • 3-phase, 4-wire, 480Y/277, 60 Hz • 3-phase, 4-wire, 240Δ/120, 60 Hz • 3-phase, 3-wire, 240Δ, 60 Hz • 3-phase, 3-wire, 480Δ, 60 Hz • 3-phase, 4-wire, 415Y/240, 50 Hz • 3-phase, 4-wire, 400Y/230, 50 Hz • 3-phase, 4-wire, 380Y/220, 50 Hz • 3-phase, 4-wire, 220Y/127, 50 Hz
Power Factor		Discrete		1.0 PF. The ability to supply reactive power may be a useful ancillary feature.
Voltage operating range			-13%/+6 %	Percent of nominal based on ANSI C84.1, range B.
Power regulation, steady-state		TBD		Fundamental frequency power (real and reactive) - control accuracy as a percent of rated.
Voltage flicker		Discrete		Voltage flicker must not be made worse with MT unit connected.
DC current injection			0.5%	Percent of rated current for all terminal conditions including reasonable terminal voltage distortion and DC voltage offsets[xxx].
Current distortion			IEEE 519	Valid for all terminal conditions including reasonable terminal voltage distortion and DC voltage offsets.
Short circuit contribution			TBD	Based on IEEE std. P1547 recommendation.
Frequency operating range		+/- 5.0%		Percent of nominal.[xxxi]
Electromagnetic Compatibility - conducted		Discrete		Meets xx and FCC class A, or as required for certification.
Electromagnetic Compatibility - radiated		Discrete		Meets xx and FCC class A, or as required for certification.
Electromagnetic Compatibility - immunity		Discrete		Meets xx, or as required for certification.
Surge voltage rating		Discrete		Meets IEEE C62.41. Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits.
Turn on transient *		Discrete		Reference IEEE std. P1547 recommendation.

				• Parallel operation shall be prevented until the service voltage is within specifications (voltage, frequency, and frequency rate-of-change) for 60 seconds. • Connection to the utility should be bumpless (no voltage flicker or power reversal).

* Control and protection settings must be factory adjustable only (i.e., not user adjustable). Requirements and trip times may vary.

Strategies for Best Quality (redundancy and DR for high quality and availability, microgrids)

Protection

Circuit Breaker Coordination
Unintended islanding mitigation

Undervoltage Protection		Discrete		UV trip (transfer) at < ??% voltage, > ?? seconds. < ??% voltage, > ?? seconds. Or equivalent on each phase. Continuous between points, or as required based on load testing. Settings to be factory adjustable.
Overvoltage Protection		Discrete		OV trip (transfer) at > ??% voltage, > ?? seconds. > ??% voltage, > ?? second. Or equivalent on each phase. Continuous between points, or as required based on load testing. Settings to be factory adjustable.

* Control and protection settings must be factory adjustable only (i.e., not user adjustable). Requirements and trip times may vary.

Projection of Performance

The GE microturbine was run at no-load to 90% physical speed. During this test, data were taken and used to validate a cycle deck of the system. Shortly after this test, the microturbine experienced a terminal event when the radial turbine back-face rubbed against the back plate making any further testing impossible. Since full-load data was never obtained, an attempt has been made to benchmark the cycle deck with data from the 14SEP05 test and use it to extrapolate the expected full speed, full load performance of the system had the terminal event not occurred.

1. 90% Speed, No Load Performance with 14SEP05 Data

Using temperature and pressure data from the inlet and exhaust of the compressor, turbine, and recuperator as well as an orifice plate to measure the mass flow of air, the performance of the components can be determined at the near-idle state.

Compressor Efficiency	0.66	[-]
Turbine Efficiency	0.81	[-]
Recuperator Efficiency	0.90	[-]
Compressor Pressure Ratio	2.4	[-]
Turbine Expansion Ratio	2.2	[-]
Compressor Corrected Speed	87	%
Turbine Corrected Speed	110	%
Compressor Physical Mass Flow	2.03	[lbm/sec]
Power Output	0	[kW]

Table 3: 90% Speed, No-Load Cycle Deck Performance Using 14SEP05 Benchmark Data

Given the off-design conditions for which the cycle deck is simulating, the component efficiencies that appear in Table 3 are within the design limits. There is however, a discrepancy between the analytical predictions of physical mass flow and the experimental data gathered during the test. Given the compressor pressure ratio and corrected speed noted during the experiment, the compressor map indicates that the mass flow should be approximately 2 lbm/sec. However, the experimental data indicate that the mass flow rate was about 1lbm/sec. This discrepancy can be attributed to a significant leak somewhere downstream of the compressor impeller or experimental error with the orifice plate used to gather the air mass flow data. Given that the fuel flow rate was also measured, it is possible to back-calculate the mass flow rate of the air using the experimentally obtained firing temperature and known fuel flow rate. The fuel flow rate was measured with a calibrated orifice and the firing temperature was directly measured with multiple redundant thermocouples. The result is that the experimental data appears to be consistent indicating that there were some significant leaks throughout the system. It is reasonable to assume that such a large leak would have easily been detectable and corrected had testing been allowed to proceed.

2. Extrapolating Full Speed, Full Load Performance with 14SEP05 Data

By determining some key non-dimensional quantities from the work described in Section 1 above, some predictions of full speed, full load performance have been made. The key non-dimensional quantities used to benchmark the model include head loss coefficients in the piping, exit loss coefficients in the diffusers, and component map scalars that were needed to match on the 14SEP05 data. Table 4 shows the results:

Description	Full Speed, Full Load Performance Extrapolation	Design Value	Units
Compressor Efficiency	0.75	0.83	[-]
Turbine Efficiency	0.86	0.87	[-]
Recuperator Efficiency	0.90	0.90	[-]
Compressor Pressure Ratio	3.5	3.8	[-]
Turbine Expansion Ratio	3.1	3.5	[-]
Compressor Corrected Speed	97	100	[-]
Turbine Corrected Speed	100	100	[-]
Compressor Physical Mass Flow	2.83	3.00	[lbm/sec]
Power Output	146	175	[kW]
System Efficiency	0.28	0.35	[-]

Table 4: Full Speed, Full Load Cycle Deck Extrapolation Using 14SEP05 Benchmark Data

Based on the extrapolation, the compressor performance missed the design efficiency by 8 percentage points and would have a significant effect on the predicted efficiency of the system. Much of the performance discrepancy in the compressor efficiency can be attributed to the intentionally large clearances built into the initial testing. The intent was to run the initial tests with large clearances to prevent any rubs and then disassemble and inspect the machine before a second assembly was conducted with tighter clearances. Furthermore, the leaks noted in Section 1 above have also reduced the predicted power from 175kW to 146 kW.

The recuperator and turbine are performing at or near their design value. Assuming that the compressor clearances were reduced to the 10 mil hot running condition according to the test plan, and the suspected leaks were identified and corrected, the cycle deck predicts a system efficiency of 33%.

Lab Evaluation of Newly Developed Microturbine System

The overall fully assembled and instrumented AMIS unit is shown in figure 38. The objective of this portion of the project was to evaluate the complete system and compare the results with the analytical efforts. Leveraging our operational experience gained while running the first alternator, an improved control scheme was developed which enhanced system operation. Fuel is metered based on certain input criteria such as speed and temperature. The operator, using a lab view based interface (figures 39 & 40) inputs the desired speed and control temperature, the fuel valve is then opened or closed to match the inputs. The control loop has been designed with certain ramp rates (P&ID) that allow a smooth transition from point to point to eliminate/minimize overshoot.

Figure 38: Complete AIMS System.

Standard operation consists of motoring to 9000 rpm and then igniting the combustor. The system would be allowed to thermally soak at 9000 rpm while the recuperator came up to temperature. Once steady state was achieved, the speed would be increased while operating on both the motor and combustion until a stable point was achieved at which time the system was transitioned to 100% combustion. This point was generally around 20K rpm.

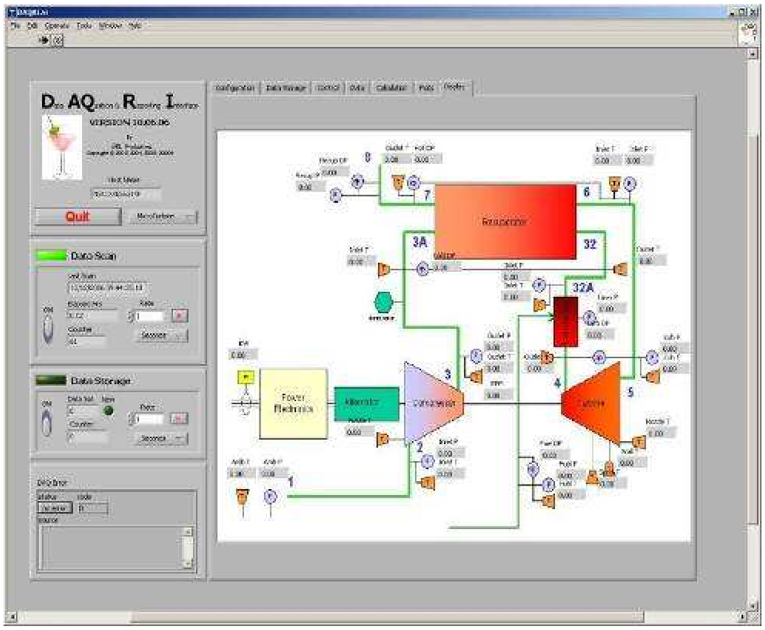

Figure 39: Schematic of the MicroTurbine system. This LabView page allows the operator to clearly see the cycle conditions during the test. This page will also highlight/alarm on values outside of the expected values.

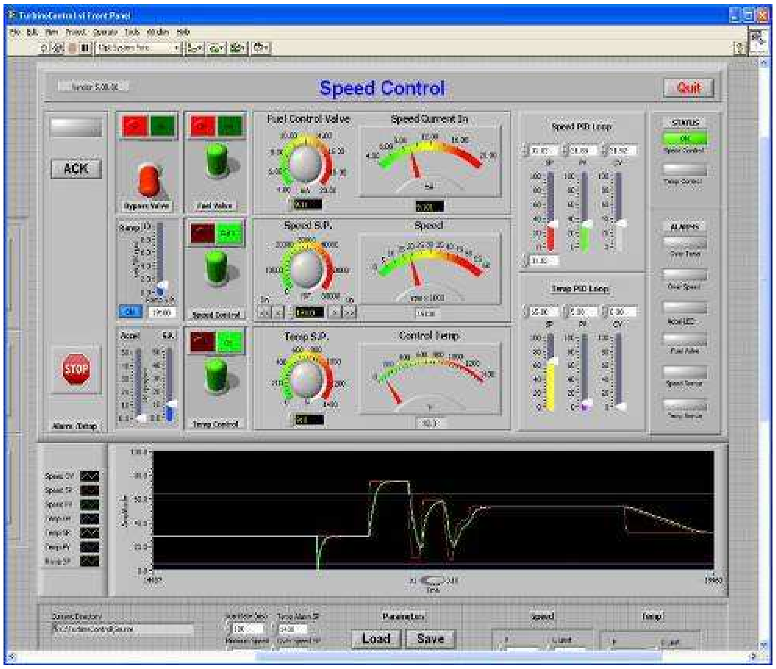

Figure 40: LabView interface page, which allows the operator to input desired temperature and speed.

Initial operation of the system with the new alternator was focused on balancing the rotating equipment and comparing operating information with data fro m the previous testing. During the phase it was difficult to balance the system. Multiple attempts were made but no success and it was eventually determined that there was an issue with one of the bearings. While disassembling the unit it was found that oil passages in the alternator were blocked thereby restricting oil flow to the bearings, figure 41. The appropriate holes were implements and the balancing was reattempted, figure 42 However, again there was an issue that indicated a problem with a bearing. Further disassembly revealed that one of the bearings was broken, figure 43 Conducting detailed investigation of the bearing indicated that the failure was most likely caused by materials flaw and not any operational or assembly problems.

Figure 41: Drive end insulator plate. Oil flow area restricted.

Figure 42: This figure shows the insulator material after being modified to provide the oil passage holes.

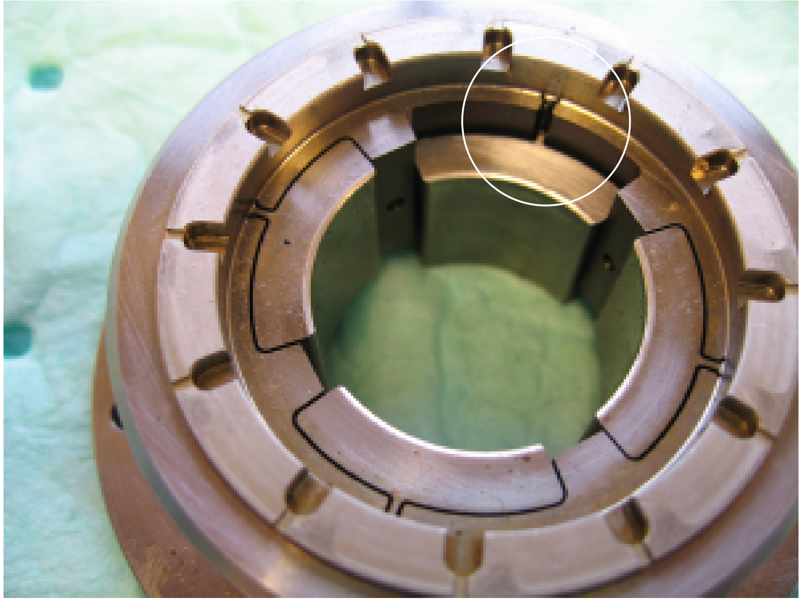

Figure 43: Non-Drive End bearing with broken pad.

Following the balancing of the hardware the overall system was readied for the full peed test point. The objective of this test was to obtain full speed and verify the stability, airflow, pressure and efficiency of the system. This test began and all indicating were that the system was running smoothly. Around a speed of 25k rpm's there was an indication of a rub. This speed was indicated via modeling as a potential second critical so the rub was not of surprise. A lot of time was spent analyzing the system, attempting to high speed balance out this mode and speaking with experts on how to proceed. After careful consideration is was determined to push through the speed range with the expectation of the rotor motion subsiding after the mode was passed. As indicated in figure 44, the rotor movement was took significant to pass through and a significant rub was incurred. This rub was such that the entire system was stopped and damage was incurred.

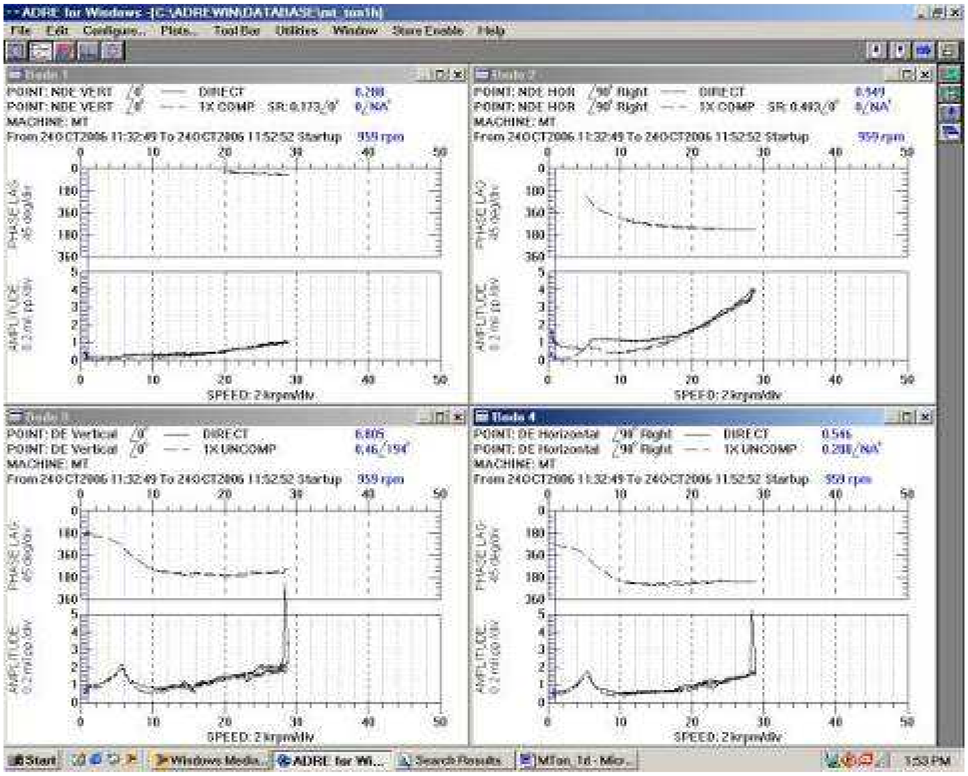

Figure 44: Rotor dynamic data captured during the rub event.

Following the event the system was disassembled to identify the cause of the rub. As the turbine scrolls were removed it became obvious that the rub occurred between the turbine wheel and the turbine backplate plate, figures 45, 46 & 47.

Figure 45: Turbine and Turbine Backplate Damage

Figure 46: Turbine and Turbine Backplate Damage

Figure 47: Close-up of Turbine blade damage

Once the location of the rub was identified an effort took place to identify why this rub occurred. From a design standpoint, the clearance between the turbine and turbine backplate is 100 mils cold and approximately 20 mil hot running. With this know dimension and the modeled turbine movement through the speed range, the objective was to identify a 10 to 15 mil difference in the rotating and/or stationary components. With the exception of the alternator, this build of the microturbine was identical hardware to the original build that achieved 90% full speed and never had any rubs or rotor dynamic issues. Given this fact, the team investigated the difference in the alternators from an overall geometric perspective. Through this analysis there was never a specific difference determined however, it is felt strongly that this was the cause of the rub.

Following this event, the team decided that given the funding remaining on the project as well as the perspective of a market that we would stop any further efforts and finish the project.

Potential Technical Market of an Advanced Microturbine System

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Spring 2001

Table of Contents

Executive Summary

Background

The US Department of Energy (DOE) has initiated a multi-year development program focussing on microturbine systems that will culminate in the demonstration of an advanced system in the year 2006. The mission of the Advanced Microtubrine System (AMTS) Program is to lead a national effort to design, develop, test, and demonstrate a new generation of microturbine systems that will be cleaner, more efficient, fuel-flexible, more reliable, more durable, and more cost-effective than the current commercially available microturbine products.

As stated in the AMTS Program Plan, the ultimate goals of the AMTS Program are to produce "ultra-clean, highly efficient" microturbine systems by fiscal year 2006 the can achieve the following performance targets:

High Efficiency: Fuel to electricity conversion efficiency of at least 40%.

Environmental Superiority: NOx emissions lower than 7 parts per million on natural gas in practical operating ranges.

Durability: Designed for 11,000 hours of operation between major overhauls and a service life of at least 45,000 hours.

Economic Viability: System costs lower than $500 per kilowatt, costs of electricity that are competitive with the alternatives (including grid connected power) for market applications, and capable of using alternative fuels including natural gas, diesel, ethanol, landfill gas, and other bio-mass derived liquids and gases.

Objective

The objectives of the efforts described in this report are the following:

- Define the proposed Advanced Microturbine System (AMT) and its most promising applications
- Quantify potential technical market in those applications
- Identify issues impacting market development

This report addresses the technical potential market in the United States for GE's Advanced Microturbine System (AMT) that will be developed under the AMTS Program. The report covers the primary markets for the AMT, Combined Heat and Power (CHP), Power-Only applications, Commercial Sized Premium Power, and Resource Recovery.

Methodology

The methodology employed to determine the market outlook for the AMT consisted of a literature review of published and proprietary in-house market assessments, surveys, and sales trends and a bottoms-up quantification of technical market potential in likely commercial/institutional, industrial and resource recovery market segments. A review of the current small distributed generation market was conducted, as well as a historical review of past attempts to develop generation products in the same size range as the proposed AMT. Conclusions and recommendations were drawn from the results.

Results

The basic performance characteristics of the AMT are the following:

- Prepackaged, microturbine generator system
- 250 kW net electric output
- 200 kW available thermal output (500 F)
- 9460 HHV net electrical heat rate
- $500/kW base system FOB capital cost
- 0.016 $/kWh O&M costs
- High electrical efficiency (36 % HHV)
- 45,000 hour system life (11,000 hour overhaul included in O&M costs)
- NOx emissions < 7 ppm
- $125,000 FOB price includes turbogenerator, inverter, controls, fuel gas compressor and other auxiliaries
- Package suitable for indoor installation

The total potential technical market is illustrated in Figures 48 through 50. This includes the following applications CHP, Power-only, Premium Power, and Resource Recovery. The LF/CB Recovery category includes Landfill and Coalbed Methane. Market segments are not additive in the commercial and industrial markets, as certain customers are candidates for more than one of the target applications.

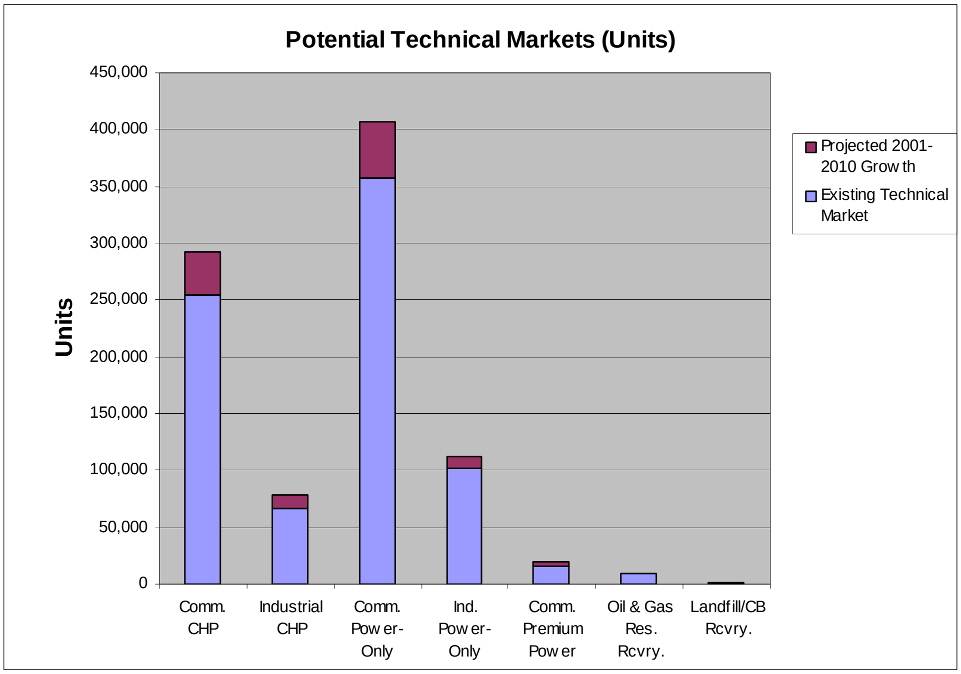

Figure 48: AMT Potential Technical Market by Units

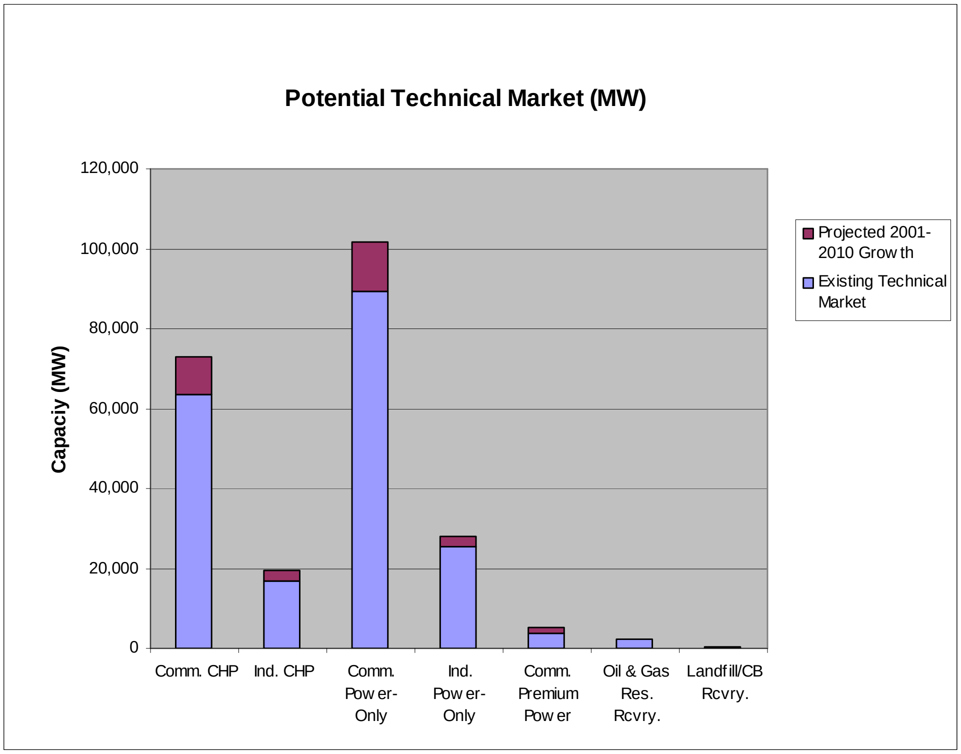

Figure 49: AMT Potential Technical Market by Capacity (MW)

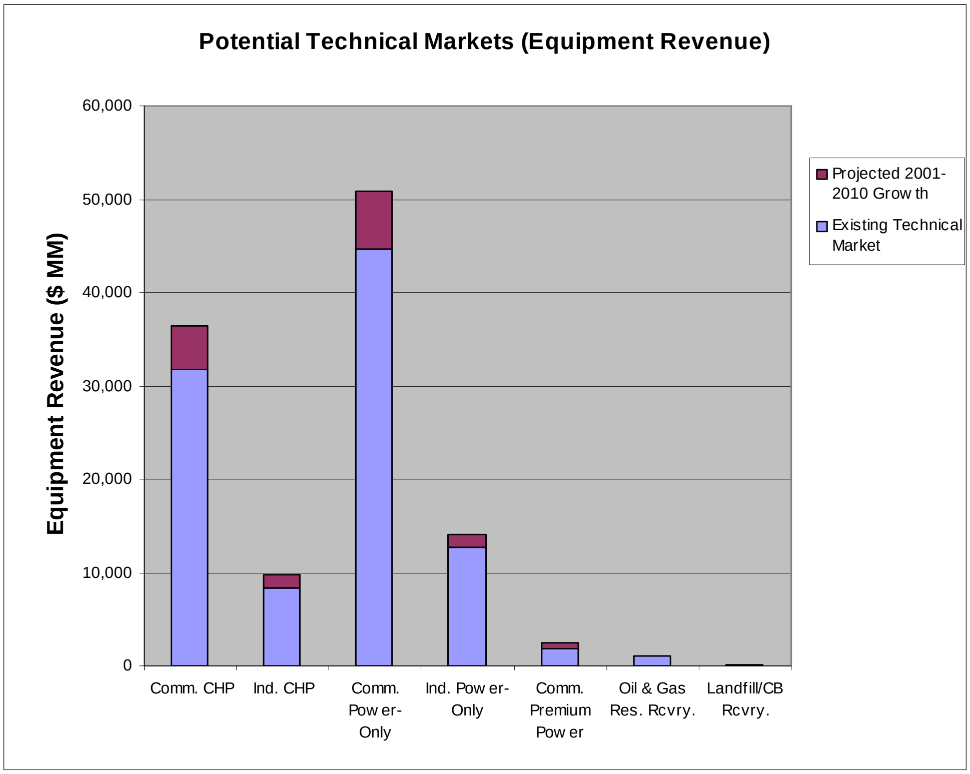

Figure 50: AMT Potential Technical Market by Equipment Sales Revenue ($MM) – revisit O&G

Conclusions and Recommendations

The largest potential technical markets lie in Commercial CHP and Power-Only applications. The most promising regions of the US are the Northeast, California and the Midwest. These regions can be characterized by high electric costs and/or low reliability of electric service. Even though the combination of regulatory trends, advanced technology developments, and customer choice appear to favor these applications, these markets are still not fully developed. Historical market barriers and electric utility resistance to onsite power still exists. The existing incumbent DG options reciprocating engines has a strong position and a well-established sales and service distribution infrastructure. The Resource recovery applications will provide a good initial market for microturbines while the larger onsite power market develops. The positive product attributes of the AMT over retail electricity from the grid (price where it is cheaper, improved reliability, and independence from utilities) and reciprocating engines (physical size, emissions, lower maintenance and ability to run on various fuels with minor modifications) should be aggressively highlighted.

Recommended market development strategies include:

- Define and establish marketing, sales, and service networks
- Differentiate ATM from purchased electricity and other on-site generation options
- Target regions with high retail electric costs and/or low reliability
- Target segments with moderate to high operating hours
- Market CHP initially in active CHP markets
- Exploit near-term niche opportunities
- Monitor indicators of peaking market development

Background

Advanced Microturbine System Program

Changes in the electricity industry coupled with significant technology developments in small power generation options such as microturbines and fuel cells are opening potentially large market opportunities for distributed generation. Increasing competition for energy services at the retail level, continuing electric utility industry restructuring, increasing demand for electricity and concerns about reliability of supply, a recognition of the energy efficiency and reliability benefits of local generation, environmental movement toward pollution prevention and advancements in equipment are all factors which make distributed generation a serious option in the future generation mix of the United States.

As part of a larger Distributed Energy Resource strategy, the US Department of Energy (DOE) has initiated a multi-year development program focussing on microturbine systems that will culminate in the demonstration of an advanced system in the year 2006. The mission of the Advanced Microtubrine System (AMTS) Program is to lead a national effort to design, develop, test, and demonstrate a new generation of fuel-flexible microturbine systems that will be cleaner, more efficient, more reliable, more durable, and more cost-effective than the current commercially available microturbine products.

As stated in the AMTS Program Plan, the ultimate goals of the AMTS Program are to produce "ultra-clean, highly efficient" microturbine systems by fiscal year 2006 that can achieve the following performance targets:

High Efficiency: Fuel to electricity conversion efficiency of at least 40%.

Environmental Superiority: NOx emissions lower than 7 parts per million on natural gas in practical operating ranges.

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Economic Viability: System costs lower than $500 per kilowatt, costs of electricity that are competitive with the alternatives (including grid connected power) for market applications, and capable of using alternative fuels including natural gas, diesel, ethanol, landfill gas, and other bio-mass derived liquids and gases.

The AMTS Program's goals are consistent with overall goals set forth in the Comprehensive National Energy Strategy "to improve the efficiency of the energy system, ensure against disruptions, promote energy production and use in ways the respect health and environmental values and expand energy choices."

Project Objectives

The objectives of the efforts described in this report are the following:

- Define the proposed Advanced Microturbine System (AMT) and most promising applications
- Quantify potential technical market in those applications
- Identify issues impacting market development

This report addresses the technical market potential in the United States for the Advanced Microturbine System (AMT) that will be developed under the AMTS Program. The report covers the two primary markets for the AMT, combined heat and power and intermediate to baseload power-only applications. The technical potential market assessment is derived through a bottoms-up approach taking into consideration commercial and industrial customers' energy utilization and intensities. The commercial sector in particular offers the promise of a large number of potential applications in small size ranges suitable for microturbines.

The report also addresses issues and barriers that will impact the development of the microturbine market. To date, penetration in this market size (<1000 kW) has been extremely limited. A number of small engine CHP packagers have entered and exited the market in the last 15 years, as market conditions have proved too difficult for many. Today, there is a new generation of technologies and developers hoping to reach the large number of customers in this small-end market. These developers envision sales in the tens, even hundreds, of thousands of units.

Microturbine Systems

Current Microturbine State-of-the-Art

Microturbines are very small combustion turbines with outputs of approximately 20 kW to 400 kW. A number of competing systems are under development with commercial production already initiated for several developers. Designed to combine the reliability of auxiliary power systems used on board commercial aircraft with the design and manufacturing economies of turbochargers, the units are targeted at CHP and prime power applications in commercial buildings and light industrial applications.

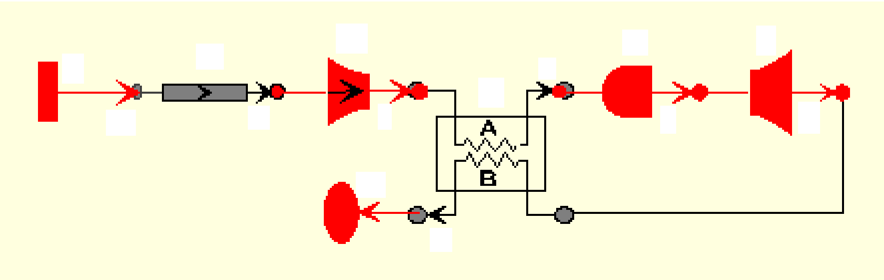
There is not a distinct size limit that distinguishes microturbines from small industrial gas turbines. However, several design features generally characterize microturbines:

- Radial flow compressors
- Low compression ratios (possibly two stage compression)
- No blade cooling
- Recuperation
- Low temperature materials that are amenable to low cost of production

In most configurations, a high speed turbine (100,000 rpm) drives a high speed generator producing direct current (DC) power that is electronically inverted to 60 Hz (or 50 Hz) AC. Current commercial microturbine systems are capable of producing power at around 25-33 percent efficiency by employing a recuperator that transfers exhaust heat back into the incoming air stream. The systems are air cooled and some designs use air bearings, thereby eliminating both water and oil systems used by reciprocating engines. Low emission combustion systems are being demonstrated which provide emissions performance comparable to larger combustion turbines. The potential for reduced maintenance and high reliability and durability remains to be demonstrated in a commercial environment.

Recuperated Cycle

In the recuperated cycle (Figure 51), turbine efficiency is raised by adding a recuperative heat exchanger, which uses the hot exhaust gas of the expansion turbine to preheat the air flowing into the combustor, thereby reducing the fuel required. This cycle is also sometimes referred to as a regenerated cycle. There is no difference between these two designations from a thermodynamic viewpoint. A recuperator is a heat exchanger with passage walls through which heat flows by virtue of the temperature difference between the two fluids on either side of the wall. The fluids in a recuperator do not mix at all. A regenerator is a periodic heat exchanger in which hot and cold gas flow alternately in opposite directions through a matrix of fine passages. In a regenerator, the two fluids mix to a small degree, and leakage can occur from the high-pressure, compressor discharge side to the low-pressure, expansion turbine exhaust side.



Source: S. Freedman

Figure 51: Schematic of Recuperated Cycle

Conventional (solid boundary) recuperative heat exchangers are used most frequently in heating and air-conditioning applications and for industrial heating. Periodic (rotary wheel) regenerative heat exchangers have been tested since the 1950s for use on automotive gas turbines. Regenerators have been researched because they could be compact enough for the gas turbine to fit under the hood of a car. However, the high-pressure seals required in the regenerator have not yet achieved adequate life for this application.

The recuperated turbine cycle produces about 10% less power than a simple cycle of the same compressor pressure ratio and turbine inlet temperature. This is because an inherent pressure drop is associated with the recuperator and with its connections to the engine and gas turbine exhaust. The design of a practical recuperated cycle involves balancing the tradeoffs among the parameters of efficiency, power, and cost. This is accomplished by analyzing various heat exchanger sizes, dimensions, and configurations to obtain a desired level of pressure drop on each side of the recuperator and interconnecting ducting, as well as analyzing recuperator cost. Similar tradeoffs apply to the regenerative cycle.

The exhaust of recuperated turbines gas turbines is lower in temperature due, respectively, to the use of recovered heat for preheating combustion. When generating thermal energy, these lower exhaust temperatures result in a somewhat lower amount of heat recovered and a lower heat recovery efficiency.

Advanced Microturbine System (AMT)

The basic performance characteristics of the Advanced Microturbine System (AMT) are:

- Prepackaged, microturbine generator system

- 250 kW net electric output
- 200 kW available thermal output (500 F)
- 9460 HHV net electrical heat rate
- $500/kW base system FOB capital cost
- 0.016 $/kWh O&M costs
- High electrical efficiency (36 % HHV)
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- NOx emissions < 7 ppm
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- Package suitable for indoor installation

.

Methodology

The methodology employed to determine the market outlook for the AMT consisted of a literature review of published and proprietary in-house market assessments, surveys, and sales trends and a bottoms up quantification of technical market potential in likely commercial and industrial market segments. A review of the current small distributed generation market was conducted, as well as a historical review of past attempts to develop generation products in the same size range as the proposed AMT. Conclusions and recommendations were drawn from the results.

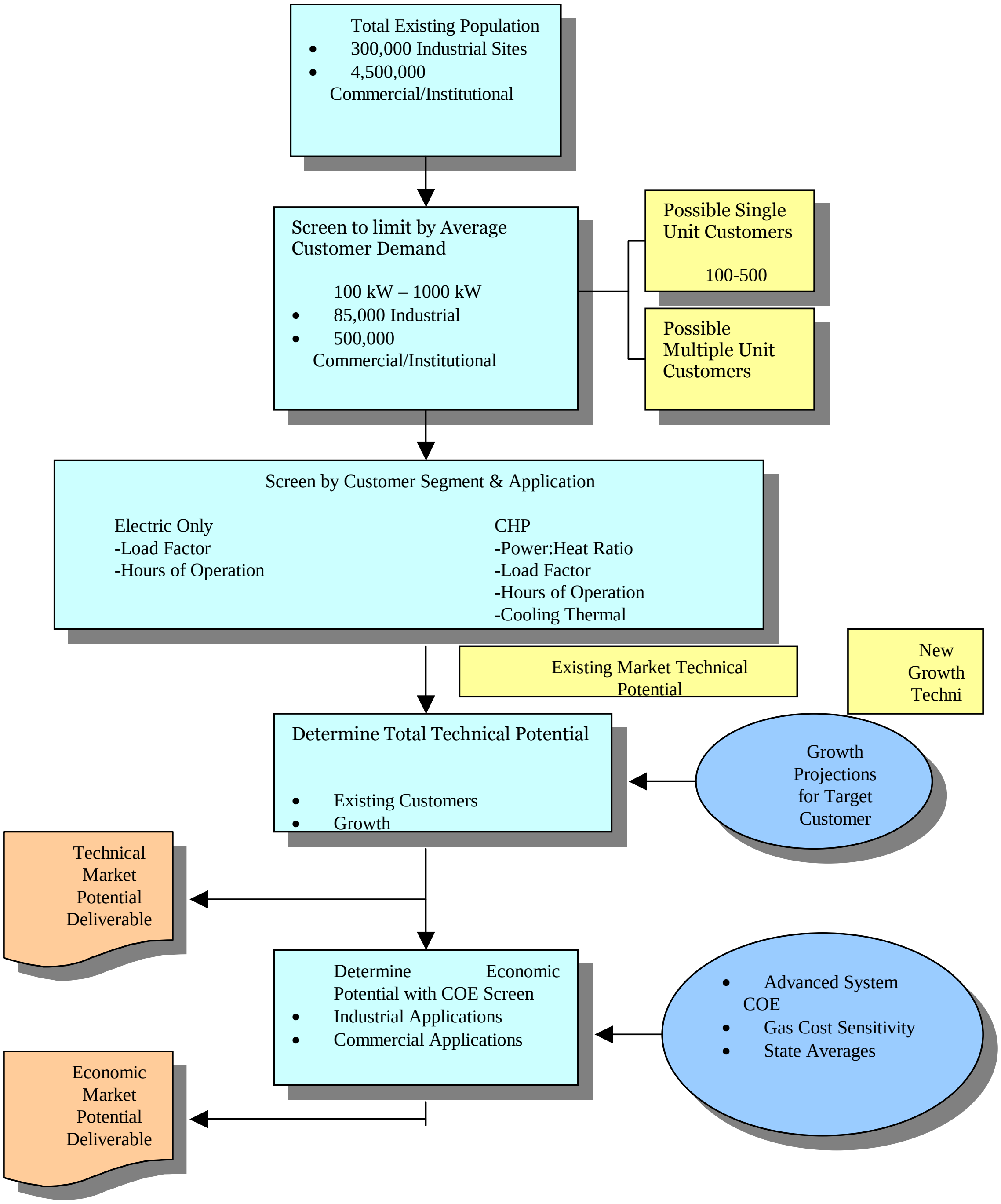
The following approach was used to estimate the technical market potential for the AMT in the commercial/institutional and industrial sectors:

- *Identify applications where the AMT provides a reasonable fit to the electric and thermal needs of the user*. Target applications were identified based on reviewing the electric and thermal energy consumption data for various building types from the DOE EIA *1995 Commercial Buildings Energy Consumption Survey (CBECS)* and various commercial market summaries developed by GRI and the American Gas Association. Similarly, target industrial applications were identified by reviewing electric and thermal energy consumption data for specific industrial applications (by two and four-digit SIC code) from the DOE EIA *1997 Manufacturing Energy Consumption Survey* and industrial market summaries developed by DOE, GRI and the American Gas Association. Existing distributed generation installations in the commercial/institutional and industrial sectors were also reviewed to understand the required profile for CHP applications and to identify target applications.

- *Quantify the number and size distribution of target applications*. Once applications that could technically support the AMT were identified, the iMarket, Inc. *MarketPlace Database* was utilized to identify potential installation sites by SIC code. The *MarketPlace Database* is based on the Dun and Bradstreet financial listings and includes information on economic activity (8 digit SIC), location (metropolitan area, county, electric utility service area, state) and size (employees) for commercial, institutional and industrial facilities. In addition, for select SICs limited energy consumption information (electric and gas consumption, electric and gas expenditures) is provided based on data from Wharton Econometric Forecasting (WEFA). The *MarketPlace Database* was used to identify the number of facilities in target applications and to group them into two size categories based on average electric demand in kW.

- *Estimate technical potential in terms of MW capacity.* Total technical potential was then derived for each target application based on the number of target facilities in each size category. It was assumed that the distributed generation system would be sized based on the average site electric demand for the target applications unless thermal loads limited electric capacity.

The logic and approach for determining the technical market potential are illustrated in Figure 52.



Source: ONSITE Energy

Figure 52: Methodology and Approach

Data Sources

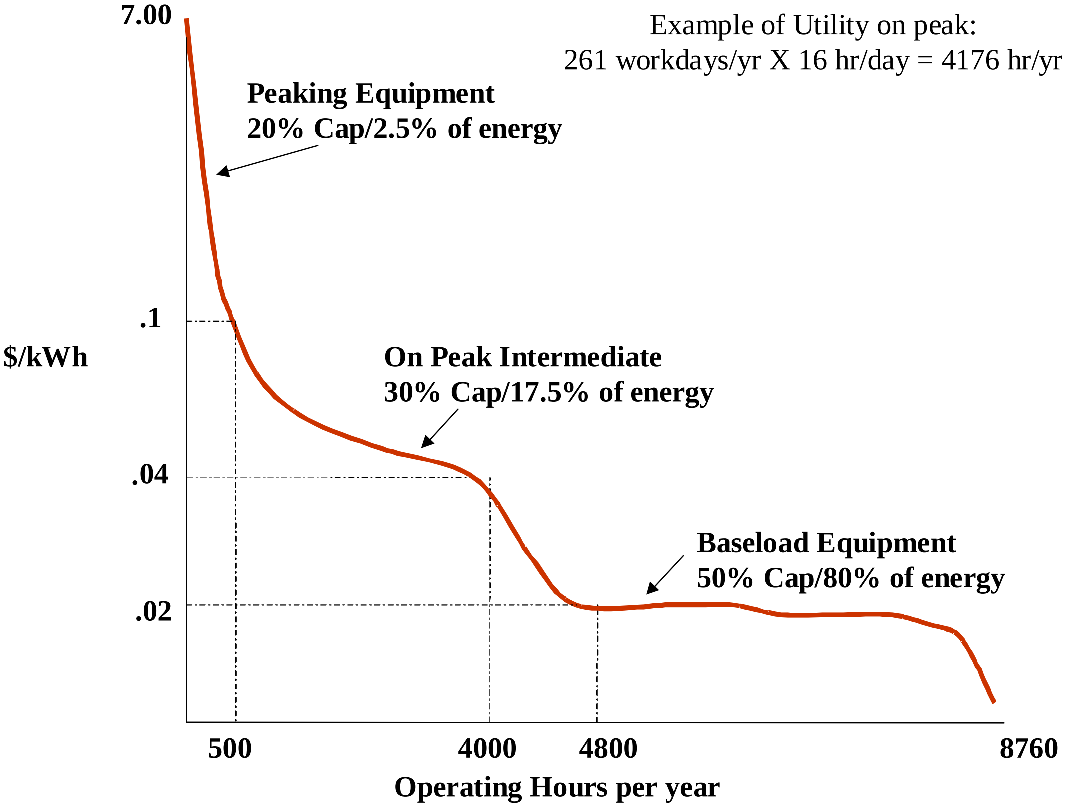
The data sources utilized in the approach described are tabulated below.

Total Population:	iMarket Marketplace database - data on individual facilities, by location, applications (SIC), size ($, employees) Commercial Buildings Energy Consumption Survey (CBECS) - DOE/EIA Manufacturing Energy Consumption Survey (MECS) - DOE/EIA
Screen by Size:	iMarket database CBECS GRI/AGA market analyses
Screen by Application:	CBECS (load factors, P/H ratios, thermal/cooling needs, operating hours, demand metering) MECS (P/H ratios, steam requirements) Primen (load profiles, operating hours, thermal needs) RER (load profiles) Misc market studies - AGA, GRI, ADL, OEC
Sector growth:	DOE/EIA sector economic projections
Gas and electric rates:	DOE/EIA for state and regional averages and projections Individual utility rates for specific peaking structures
Resource Recovery:	DOE/EIA, EPA, AGA, IPAA, State agencies with authority over oil and gas wells, Rig Location & Permit Report Services

Potential Market Applications of the AMT

Potential benefits of distributed generation to energy users include lower energy costs, increased reliability, lower total emissions, improved power quality, enhanced energy management through options such as peak shaving, ability to arbitrage gas and electric costs, and the ability to economically provide both power and heat. Possible applications for AMT include Combined Heat and Power (CHP), Power-Only applications (sometimes referred to as Prime Power), Peak Generation, Premium Power (High Reliability/Power Quality) applications, and Resource Recovery. Results of this analysis indicate the most potential for the AMT are in Combined Heat and Power and Power-Only applications with relatively high hours of annual operation.

Each customer has a unique set of requirements. These requirements must be met either by the utility power grid alone, by on-site power generation alone, or by a combination of on-site power generation and purchased power. Figure 53 shows a hypothetical load duration curve. A customer may have a high peaking demand during a small number of hours per year. Often, the power provider will charge such a high charge for this power that it makes sense for the customer to utilize on-site generation for peaking. In general, peaking equipment needs to inexpensive to install. It is not critical that it is efficient, that it uses a low cost fuel, or that it has a long operating life. In intermediate duty, efficiency and operating costs take on a much greater importance. In addition, the environmental signature of the on-site generation equipment also becomes more important. For equipment that is operating on a continuous basis (baseload), efficiency, operating cost, and environmental residuals become extremely important. For example, capital inexpensive but expensive to operate technologies like diesel engines are ideally suited for peaking and standby duty. High cost, but high efficiency technologies are best suited to baseload applications. The microturbine has flexibility of design so that products can be optimized for diverse individual market segments.



Source: ONSITE Energy, Wartsilla

Figure 53: Customer Load Shape and Its Impact on DG Requirements

Combined Heat and Power

Power generation systems create large amounts of heat in the process of converting fuel into electricity. For the average power plant, over two thirds of the energy content of the input fuel is converted to heat and wasted. As an alternative, an end-user with significant thermal and power needs can generate both its thermal and electrical energy in a single combined heat and power system located at or near its facility. Combined heat and power (CHP), also called cogeneration, can significantly increase the efficiency of energy utilization, reduce emissions of criteria pollutants and CO_2, and lower a user's operating costs.

The outlook for CHP systems in the restructured electric industry is uncertain. Large installations depending on excess power sales that previously dominated the market will have to compete with other wholesale generators that might have advantages in terms of dispatchability or cost. In addition, competition may reduce average retail electricity rates for large industrials, decreasing the value of power generated on-site. At the same time, small to medium sized industrial facilities and commercial/institutional facilities may see their electricity rates increase, as well as a noticeable increase in price volatility, increasing the value of CHP. Coupled with improvements in technologies and pending policy initiatives aimed at encouraging CHP due to its overall efficiency and environmental benefits, the customer base for economic, within-the-fence CHP systems has the potential to expand considerably as an important subset of distributed generation.

Power-Only

Power-Only applications of the AMT include baseload and intermediate duty cycles. Users concerned with the most advantageous generation equipment for their application will need to focus on their particular economics which is a factor of retail electricity prices, fuel costs, equipment prices, and operating hours. Generally, higher efficiency equipment costs more to manufacture and carries a premium for the increased benefits to the user. In selecting a generation option, a very important parameter is the annual full power capacity factor. As the generation equipment gets more use per year, it accumulates more hours over which to spread its fixed carrying charges and is better able to pay a higher price for a higher efficiency. The analysis described in this report indicates that the requirement for cost-effective utilization of the AMT is approximately 3000 hours of utilization. It is at this point which the AMT cost of electricity is comparable with average retail electric rates in some high price states. This includes intermediate to baseload duty cycles. The evolving market and power consumption patterns reveal that in between high usage (CHP) and low usage (standby) extremes may lie a potential market of moderate size and intermediate annual usage (see Peak Generation discussion below). In the historic market, power equipment was purchased mainly for baseload, peaking, and standby applications. Up until recent years there have been insufficient sales to provide major incentive for developing new products for intermediate duty. This has changed due to the ongoing restructuring of the power market. Intermediate duty is defined as approximately 1000-4000 hours of annual operation. Distributed generation resources can compete in the intermediate-duty power market. Likely distributed generation technologies to play in this market include gas reciprocating engines, recuperated small gas turbines, and microturbines. The Solar Turbines Mercury 50 recuperated gas turbine with its high simple-cycle efficiency was developed primarily for this market.

Peak Generation

The costs for power vary by hour depending on demand and the availability of generating assets. Utilities see these variations in costs, but in the regulated market structure customers typically do not. Large customers often pay time-of-use (TOU) rates that convert these hourly variations into seasonal and daily categories such as on-peak, off-peak, or shoulder rates. With the advent of wholesale and retail competition, more of these cost variations are expected to be transmitted directly to the customer as price signals.

In many such cases, it may make sense for a customer to try to “clip” expensive peak load power. Power during peak periods is expensive both on existing rate schedules, but it is also expensive in competitive hourly power markets. This market is also good for customers with poor load factor, high demand charges, and low thermal loads. Typically, peak shaving does not involve heat recovery, but CHP may be warranted where the peak period is more than 2,000 hours/year. Generally, equipment first cost is the primary issue. Where peakshaving can be combined with another value such as standby power, the economics are considerably enhanced. Diesel engines may have emissions limitations if their use is to be expanded from simple stand-by to peakshaving.

There are three possible peakshaving strategies. First, the customer can independently optimize his purchased versus generated power compared to his existing rate structure. Under this strategy the unit would operate during the utility-defined peak periods. This creates an operating strategy that can vary, depending on the tariff, from 900 hours/year to as much as 3500 hours/year. Some utilities offer coordinated peak-shaving programs. The utility offers payments for very limited hours of use. These programs typically require as little as 50 hours/year to as many as 400 hours/year. The optimal technology configuration and the need to integrate with standby value differ markedly between these two operating strategies. For customers that purchase power competitively, there is an opportunity to peak shave from the hourly competitive price or to select competitive power supply contracts from energy service providers that are interruptible. In the competitive market peak shaving, the hours of operation would probably be closer to the coordinated utility model than the independent peak shaving of a published tariff.

Using distributed generation for on-peak periods reduces the customer's overall costs of power as well as reduces the energy service provider's need to generate or purchase very high cost power. The more that the price paid for power is based on actual hourly costs, the greater the economic benefits to both the customer and energy service provider in developing a peak shaving strategy.

Depending on rate schedules and peak power costs, optimal peak shaving strategies could depend on distributed generation resources for 250 to 3000 hours per year. This is the approximate range of peak hours defined in various electric utility tariffs. The results of this analysis indicate the AMT is best suited for peak generation application projects that will allow for more than several thousand hours of annual operation. This is the case in several Midwest states (e.g., northern Illinois and northeast Ohio). Under existing tariffs there is a significant difference between the off-peak and on-peak power, and the tariffs define the on-peak period to be relatively broad.

Premium Power - High Reliability/Power Quality

Premium power is an emerging Power-Only market for systems that either provide quality power to sensitive customers or offer significantly more reliability than the basic utility service. The expanding use of sensitive electronic equipment is making reliability and control of power quality much more important in today's market. Harmonics and transient excursions are potentially harmful to customers such as communications and data centers and to delicate electronic manufacturing processes such as silicon chip manufacturing. Power quality is a multidimensional control issue, including voltage surge/sag, power factor correction, harmonics, transient faults, and more extended faults or outages.

Several developers of distributed generation equipment are packaging their products as components in various systems providing ultra-reliable/ultra-clean power. They are bundled with uninterruptible power systems (UPS), energy storage technologies, power conditioning equipment, and several degrees of redundancy. This is an attempt to capture a small share of the growing power quality segment. The power quality market is being driven by the microprocessor, telecommunications, and data/information businesses that have provided much of the recent growth in our domestic economy. These businesses have a substantially different requirement for power quality than traditional grid power has up until now been able to offer. The need for near perfect power is necessary as these digitally-based businesses are increasingly sensitive to even the most minor of power perturbations. There have been varying estimates of the size of the power quality market; however, most bound the market in the $70-$400 billion range. EPRI estimated the annual cost of poor power to be $400 billion. This estimate factors in idled employee time due to power quality problems. Duke

Power estimated the costs to large industrial customers to be $150 billion annually. Even a small portion of this evolving market is large.

In addition to the need for increased power quality, many electricity customers are beginning to require more reliable service than the grid has traditionally offered. The US has a very reliable electricity infrastructure that is typically 99.9% reliable. The digitally based businesses identified above, and others that depend on electricity 24 hours a day, seven days a week often have the need for even more reliable power. The high reliability market is often referred to as the "High 9's" market in the energy service industry. This alludes to the measure of reliability, i.e., 99.9%, 99.99%, 99.999%, etc. Table 5 illustrates the relation between reliability and downtime per year.

Table 5: Degrees of Reliability

% Reliability	Downtime per Year	Market
99.9	8.8 hours	Residential
99.99	53 minutes	Residential, some commercial and industrial with low tolerance for outages
99.999	5.3 minutes	Commercial and industrial with low outage tolerance
99.9999	32 seconds	High demand commercial and industrial, e.g., internet-based companies, data storage, financial institutions, sensitive manufacturing plants
99.99999	3.2 seconds	High demand commercial and industrial
99.999999	0.32 seconds	High demand commercial and industrial
99.9999999	0.032 seconds	High demand commercial and industrial

Source: Emerson Electric, Bear Stearns

Table 6 shows estimated outage costs for several digitally -based businesses

Table 6: Outage Costs

Application	Outage Costs
Cellular Communications	$41,000 per hour
Telephone Ticket Sales	$72,000 per hour
Airline Reservations	$90,000 per hour
Credit Card Operations	$2,588,000 per hour
Brokerage Operations	$6,480,000 per hour

Source: Teleconnect Magazine, American Gas Cooling Center

There are a variety of measures being marketed today from uninterruptible power systems (UPS) to motor-driven generators that insulate the customer load from power variations. It is also an emerging market for distributed generation. Standby generator systems integrated with power quality control equipment can provide both premium power and outage protection. In certain areas, utilities recruit customers with standby generation for peak load reduction programs, offering payments or rate relief for limited operation during peak periods (typically fewer than 150 hours per year). In other areas, utilities are providing standby generators to customers for a fee, not only to ensure continued electric service during system outages but also to dispatch the generators for system peak needs. Customer choice among competitive power suppliers could stimulate economic preference for standby generators and increase the run-hours for units in the field. Standby generation can be part of an optimal customer strategy that minimizes power costs through combinations of firm and interruptible service and onsite standby capability.

The noteworthy characteristic of the High Reliability/Power Quality market is that the value of the electricity provided is tied to the opportunity cost of being without power rather than traditional power production costs. The cost of poor power quality and interruptions in service to the US economy is very large. The market opportunity for distributed generation is significant even if a small portion of this segment is addressed. This assessment will address commercial sized High Reliability/Power Quality customers that the AMT can technically serve. This includes computer-based companies, data storage centers, telecommunications facilities, and financial institutions.

Resource Recovery

A valuable attribute of microturbines is their ability to be fueled by various fuel sources with minimal modifications to the combustion and control systems. The use of fuels such as waste byproducts in upstream oil and gas markets, waste gases from landfills and coalbed methane, is commonly referred to as the Resource Recovery market. Units installed in these applications capture fuel that would otherwise be flared or directly released into the environment. In most of these applications the fuel is basically free and the projects benefit from the additional economic value streams. For example, most states have attractive mandatory purchase rates for renewable and waste-to-energy plants. Also, in many areas oil and gas wells are assessed fees for the emissions of the waste gases. Finally, some landfill gas to energy projects may qualify under the Energy Policy Act of 1992 for a 1.5 cent per kWh incentive program.

In most installations, output from the units powers equipment used on-site and does not require the costs of connecting to the grid. The Resource Recovery market has been a primary initial entry market for microturbines in the North American market, and the focus of early market providers while the commercial and industrial CHP and Power-Only markets develop. Most microturbine installations in the initial years of commercial introduction have fallen into the category of resource recovery.

Oil and Gas Markets

In the Oil and Gas Market, on-site generation units can be utilized to provide remote power while being fueled with unprocessed gas that would ordinarily be flared or directly released into the atmosphere. The alternative to power these remote sites is costly extension of the electric transmission and distribution system. Onsite power requirements for pumps and other mechanical drive needs range approximately from 60-400 kW per well site. Those sites with sour gases from associated gas and oil are the most promising, as microturbines have an advantage over reciprocating engines in the ability to be fueled by sour gas without operational problems. About 25% of all gas is produced as associated gas. As of January 2001, there were approximately over total 170,000 wells. Several hundred microturbine units were installed in upstream oil and gas markets in 2000.

The key to supplying power to this segment is the ability to operate on low quality fuels such as sour gases that possess high sulfur contents. Sour gases are emitted from underground deposits, deep wells, and flared from oil and gas wellheads. Successful application in this market will be dependent on the demonstrated ability to operate with the varying fuels (low Btu content and high H_2S) and with scheduled maintenance of at least 8000 hours.

Publicly available estimates for this segment indicate why these applications have made up a significant share of current microturbine installations. Cambridge Energy Research Associates (CERA) has estimated the potential market for microturbines in the US oil and gas industry to be in the 30,000-35,000 unit range. Based on the assumption that a single well will have its own generator set, the current generation of microturbine products, all less than 100 kW in output, are better suited for this application than larger products (>200 kW) likely to be developed in the DOE Advanced Microturbine System Program. This is due primarily to the limited amount of fuel energy from the gas flared available at each well. One microturbine distributor has a rental fleet of units that it deploys in upstream oil and gas applications with the narrow geographical focus on the Powder River Basin. According to a recent report by Primen, nearly 100 units were deployed in 2000 by this distributor, and current business plans are based on doubling that in 2001.

Landfill and Coalbed Methane Markets

Other potential segments of the Resource Recovery market are the Landfill and Coalbed Methane recovery. The primary applications of on-site generation in this segment currently are landfill sites and sewage treatment plants. The Coalbed methane recovery application is just emerging with more limited commercial application. In these cases energy production is a secondary objective of customer operations. The use of available combustible gaseous fuels from biomass sources at landfills or at sewage treatment plants has been growing at about 15% per year. In many areas, these DG systems benefit from rules that require utilities to purchase their power output and other incentives to encourage the use of renewable fuels. While growing rapidly now (sales of generation equipment to the landfill market were growing at over a 30% annual rate in the late 1990's), this is ultimately a modest market overall that will likely reach saturation at about the time the AMT is commercially available. As of mid-1999, there were over 270 landfill gas recovery and utilization projects in the US. The US Environmental Protection Agency (EPA) estimates an additional approximately 500 landfill candidate sites for project development, and 79 candidate coal mines. Target sites for the AMT are landfill sites with 200,000 – 1.5 million tons waste in place. Based on the projected efficiency of the AMT, this roughly corresponds to 250 kW to 2.5 MW of electricity generation.

Since the fuel is essentially supplied at no cost, high efficiency is not usually a priority. Fuel quality is an issue as these fuels may have corrosive contaminants, low energy density, and variable characteristics. Management of these fuel characteristics is an important part of a distributed generation system in this application. The fuel flexibility and low maintenance requirements of microturbine systems are an advantage over reciprocating engines in this segment.

Results of Potential Technical Market Assessment

The following section describes the assumptions and results of the assessment of the technical potential for the AMT.

Target CHP Applications

The simplest integration of AMT-based CHP into the commercial, institutional and industrial sectors is in applications that meet the following criteria:

- relatively coincident electric and thermal loads
- thermal energy loads in the form of hot water
- electric demand to thermal demand ratios in the 0.5 to 2.5 range
- moderate to high operating hours (>3000 hours per year)

A review of energy consumption intensity data for commercial/institutional building types as presented in the 1995 CBECS is shown in Table 7. Electric intensities are taken directly from the CBECS data for each building type. Space heating and water heating data in CBECS reflect fuel energy inputs for each category. These fuel inputs were modified to reflect building thermal demands using a conversion efficiency of 85%.

Table 7 Energy Intensities for Commercial/Institutional Buildings

Application	Electricity Use (Tbtu)	Electric Intensity (kWh/sq ft)	Space Heating (1000 Btu/sq ft)	Water Heating (1000 Btu/sq ft)	E/T Ratio (Total)	E/T Ratio (Water Htg)
Education	221	8.4	32.8	17.4	0.67	1.94
Health care	211	26.5	55.2	63	0.90	1.69
Lodging	187	15.2	22.7	51.4	0.82	1.19
Food Service	166	36	30.9	27.5	2.47	5.25
Food Sales	119	54.1	27.5	9.1	5.93	23.86
Office	676	18.9	24.3	8.7	2.30	8.72
Mercantile/Service	508	11.8	30.6	5.1	1.33	9.29
Public Assembly	170	12.7	53.6	17.5	0.72	2.91
Public Order	49	11.3	27.8	23.4	0.89	1.94
Religious Worship	33	3.5	23.7	3.2	0.52	4.35
Warehouse/Storage	176	6.4	15.7	2	1.46	12.92
Other	75	22.0	59.6	15.3	1.18	5.77

Source: ONSITE Energy, EIA CBECS

As described in Technical Specifications Section, the output from available the AMT has an electric to thermal ratio in the range of 0.5 to 2.5. Thermal energy output is typically in the form of hot water.

Thermal loads most amenable to CHP systems in commercial/institutional buildings are space heating and hot water requirements. The simplest thermal load to supply is hot water. Retrofits to the existing hot water supply are relatively straightforward, and the hot water load tends to be less seasonally dependent than space heating, and therefore, more coincident to the electric load in the building. Meeting space heating needs with CHP can be more complicated. Space heating is seasonal by nature, and is supplied by various methods in the commercial/institutional sector, centralized hot water or steam being only one.

For these reasons, primary targets for CHP in the commercial/institutional sectors are those building types with electric to hot water demand ratios consistent with AMT capability: Education, Health Care, Lodging, and certain Public Order and Public Assembly applications. Office Buildings, and certain Warehousing and Mercantile/Service applications can be target applications for CHP if space heating needs can be incorporated.

One difficulty with estimating market potential based on the classifications listed in Table 7 is that the classifications are quite broad in nature. As an example, health care includes not only hospitals that are ideal candidates for CHP because of their extended operating hours and electric and thermal profiles, but also clinics and outpatient services that have limited operating hours and limited thermal needs.

Other categories such as office buildings that in total do not appear to be good candidates have subcategories such as large (>50,000 sq feet), 18 hour a day office buildings where the energy needs and operating characteristics support economic CHP. Table 8 presents the specific building types most amenable to existing the AMT technology based on an analysis of existing CHP in the commercial/institutional sectors and a review of available building energy characteristics.

Table 8: CHP Target Applications

Application	CHP System Size	Thermal Demand
Hotels/Motels	100 kW - 1+ MW	Domestic hot water, space heating, pools
Nursing Homes	100 - 500 kW	Domestic hot water, space heating, laundry
Hospitals	300 kW - 5+ MW	Domestic hot water, space heating, laundry
Schools	50 - 500 kW	Domestic hot water, space heating, pools
Colleges/Universities	300 kW - 30 MW	Centralized space heating, domestic hot water
Commercial Laundries	100 - 800 kW	Hot water
Car Washes	100 - 500 kW	Hot water
Health Clubs/Spas	50 - 500 kW	Domestic hot water, space heating, pools
Country/Golf Clubs	100 kW - 1MW	Domestic hot water, space heating, pools
Museums	100 kW - 1+ MW	Space heating, domestic hot water
Correctional Facilities	300 kW - 5 MW	Domestic hot water, space heating
Water Treatment/Sanitary	100 kW - 1 MW	Process heating
Large Office Buildings*	250 kW - 1+ MW	Domestic hot water, space heating

* (>100,000 sq ft)

Source: ONSITE Energy

Technology development efforts targeted at heat activated cooling/refrigeration and thermally regenerated desiccants could expand the application of AMT-based CHP by increasing the base thermal energy loads in certain building types. Use of CHP thermal output for absorption cooling and/or desiccant dehumidification could increase the size and improve the economics in CHP markets such as restaurants, supermarkets, refrigerated warehouses, and office buildings. Table 9 includes potential CHP target applications that are currently marginal because of inadequate thermal loads but that would be future target applications based on the use of these advanced technologies. These applications are likely to be exclusively applied in new construction applications.

Table 9: CHP Target Commercial Applications - Advanced Technology

Application	CHP System Size	Thermal Demand
Extended Service Restaurants	50 - 300 kW	Domestic hot water, absorption cooling, desiccants
Supermarkets	100 - 500 kW	Desiccants, domestic hot water, space heating
Refrigerated Warehouses	300 kW - 5 MW	Desiccants, domestic hot water
Medium Office Buildings*	100 - 500 kW	Absorption cooling, space heating, desiccants

* (25,000-100,000 sq ft)

Source: ONSITE Energy

Target CHP applications for the AMT in the industrial sector would be those segments with thermal energy needs primarily in the form of hot water, low pressure steam, or low temperature direct heat. Candidate segments are listed in Table 10 based on a review of process energy consumption in the DOE EIA *MECS* and GRI reference sources.

Table 10: Target Industrial CHP Applications

SIC	Application	E/T Ratio	Thermal Demand
20	Food Processing	0.4-1.0	Hot water, low pressure steam
22	Textiles	0.5-1.0	Hot water, low pressure steam
24	Lumber/Wood	2.0-2.5	Low pressure steam, direct heat
25	Furniture	1.5-2.0	Direct heat
26	Paper Products	0.8-2.0	Hot water, low pressure steam
28	Chemicals	0.4-1.0	Hot water, low pressure steam
30	Plastic Products	1.0-2.0	Hot water, direct heat
31	Leather	0.6-1.2	Hot water, direct heat
34	Fabricated Metals	0.75-2.0	Low pressure steam, direct heat
35	Machinery	2.5-3.5	Hot water, low pressure steam
37	Transportation Equipment	1.2-2.2	Hot water, low pressure steam

Source: ONSITE Energy

Power Only Target Market Segments

In determining the potential technical market for the AMT, specific commercial and industrial market segments were targeted. These market sectors were selected based on average electricity demand (100-1000 kW) and expected average hours of operation (>3000 annual hours). Unlike CHP target applications, no screening for thermal energy was needed for Power-Only applications. Table 11 identifies the Power-Only target commercial building types and industrial customers.

Table 11: AMT Target Market Sectors

	Commercial Building Types	Industrial Sectors
Target Market Sectors	Education, Food Sales, Food Service, Healthcare, Lodging, Large Offices, Apartment Buildings, Mercantile & Service, Commercial Laundries, Museums, Refrigerated Warehouses, Health & Sports Clubs, Prisons	Food Processing, Tobacco Products, Textiles, Apparel, Lumber & Wood, Furniture, Paper Products, Printing, Chemicals, Petroleum Products, Rubber & Plastic, Leather,

		Stone/Clay/Glass, Primary Metals, Fabricated Metals, Machinery, Elect. Equipment, Transportation Equipment, Measurement Equipment, Miscellaneous Manufacturing

Source: ONSITE Energy

Assumptions

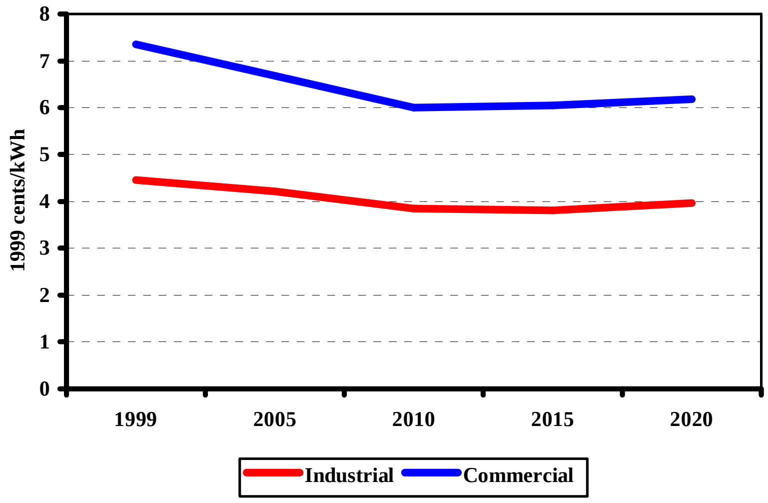
Determination of the technical potential included assessing the applicability of the AMT to both commercial and industrial customers. Energy Information Administration (EIA) data and projections for the electric rates, natural gas rates, and growth in each customer sector was used in the assessment. EIA statistics on state average electric rates for commercial and industrial customers is shown in Table 12.

Table 12: Average Statewide Electric Rates

State	Average Residential Electric Cost (cents/kWh)(1)	Average Commercial Electric Cost (cents/kWh)(1)	Average Industrial Electric Cost (cents/kWh)(1)
Alabama	7.5	7.1	4.4
Alaska	11.6	9.2	7.6
Arizona	8.9	7.6	5.7
Arkansas	7.7	6.1	4.5
California	10.5	9.6	5.4
Colorado	7.3	5.5	4.3
Connecticut	11.1	9.4	7.4
Delaware	9.7	7.2	5.3
Florida	7.8	6.3	5.2
Georgia	8.6	6.7	5.1
Hawaii	16.1	14.6	11.5
Idaho	5.7	4.0	3.5
Illinois	9.5	7.8	4.8
Indiana	6.6	5.7	3.8
Iowa	8.6	7.2	4.6
Kansas	8.1	6.6	4.5
Kentucky	5.5	5.1	3.9
Louisiana	7.7	6.7	4.9
Maine	12.7	10.8	7.4
Maryland	9.5	8.1	5.3
Massachusetts	10.9	10.1	8.7
Michigan	8.5	7.7	5.2
Minnesota	8.0	6.8	5.1
Mississippi	7.0	6.4	4.4
Missouri	8.3	7.0	5.7
Montana	6.3	5.8	3.0
Nebraska	7.6	6.0	4.0
Nevada	6.8	6.6	5.8
New Hampshire	14.2	11.8	9.4
New Jersey	11.8	8.7	7.1
New Mexico	8.4	6.6	4.8
New York	15.7	15.1	5.1
North	8.4	6.6	5.3

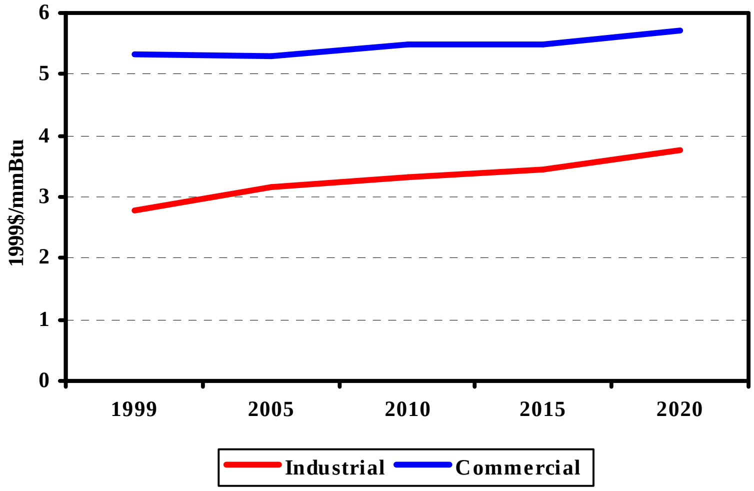
Carolina			
North Dakota	7.2	6.1	4.6
Ohio	9.1	7.5	4.7
Oklahoma	7.5	6.9	4.7
Oregon	6.1	5.1	4.5
Pennsylvania	9.3	6.6	4.5
Rhode Island	11.5	9.9	9.3
South Carolina	7.5	6.2	4.0
South Dakota	7.7	6.7	4.8
Tennessee	6.3	6.2	4.7
Texas	8.3	6.6	4.5
Utah	6.6	5.0	3.6
Vermont	11.3	9.6	6.8
Virginia	8.1	5.7	4.1
Washington	5.2	4.7	3.1
Washington, DC	9.8	9.2	5.6
West Virginia	6.3	5.3	3.8
Wisconsin	7.5	5.9	4.0
Wyoming	7.2	5.4	3.4
Notes:	(1) Electric Rates Obtained from EIA: Electric Utility Average Revenue per Kilowatt-hour to Ultimate Consumers by Sector and State (July) 2000		

Targeted customers for the AMT fall into both commercial and industrial classifications. EIA projects a slight decrease and flattening of electric rates for both industrial and commercial customers. The projections from the 2001 EIA Energy Outlook are shown in Figure 54. In addition to level average electric rates, EIA also projections stable gas prices despite recent price spokes and increased demand. EIA's natural gas price projections are shown in Figure 55.



Source: EIA *Annual Energy Outlook 2001*

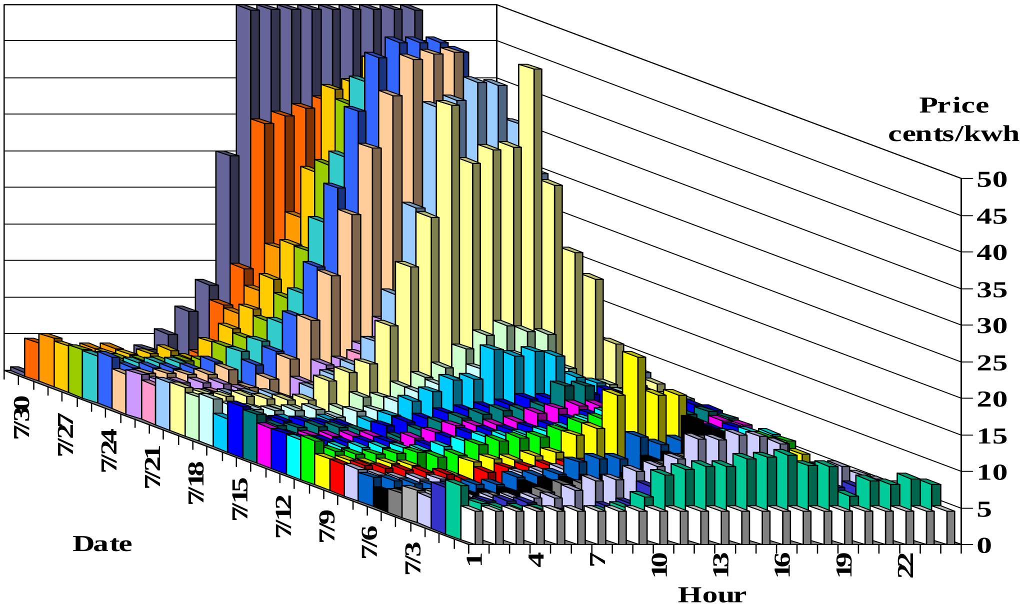
Figure 54: Electric Rate Projections



Source: EIA *Annual Energy Outlook 2001*

Figure 55: Natural Gas Prices

The average energy statistics and projections, although useful, do not provide a clear picture of the price volatility of electricity that is likely to result from deregulation nor the current spikes in natural gas prices. Figure 56 provides an example of the wide swings in electric pricing that could result from restructuring. It illustrates the range of day-ahead hourly wholesale electricity prices in California for the month of July 2000. The figure underscores what was identified early with regard to periods of high price on-peak power costs. Table 13 shows the spot market price for various natural gas trading centers for the week of February 5, 2001. The current prices in Southern California are multiples of the average prices in EIA's projection. After a long period of stability, natural gas prices took a radical excursion upwards toward the end of the year 2000. This increase in price can be seen in the change to the Henry Hub spot market price as it increased considerably above its 2-year running average level of \$2.17/MMBtu shown in Figure 57. High prices and high volatility have persisted through the early part of 2001. This period of high gas prices is expected to end in 12-18 months according to most industry analysts.



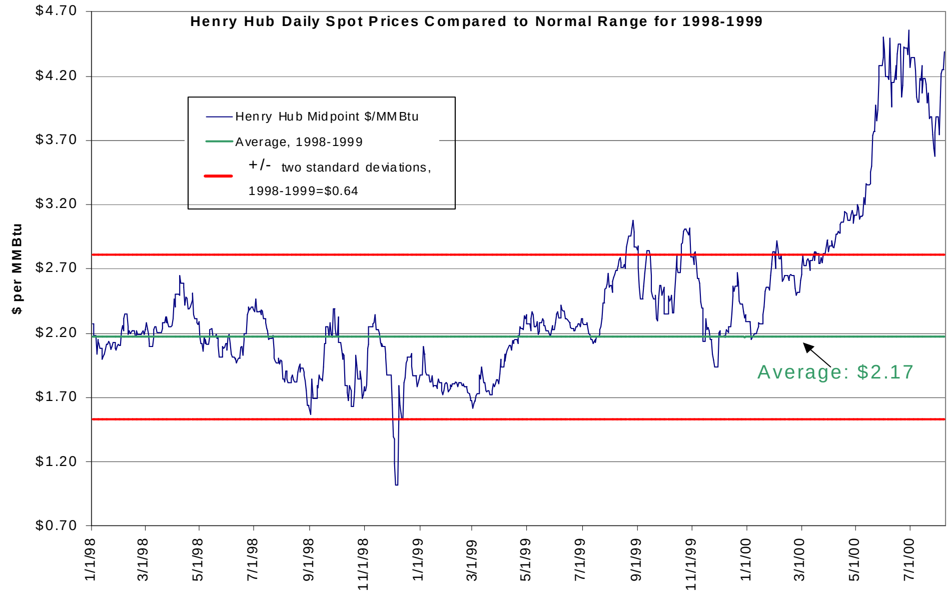
Source: ONSITE Enery

Figure 56: Day-Ahead Wholesale Hourly Electricity Prices for California for July 2000

Table 13: Natural Gas Spot Market Prices at Selected Trading Centers

	2/7/2001	**2/6/2001**	**2/5/2001**	**Prior Week Average (1/27/2001-2/2/2001)**
Henry Hub	$5.67/MMBtu	$5.58/MMBtu	$5.77/MMBtu	$6.50/MMBtu
New York Citygates	$6.10/MMBtu	$5.98/MMBtu	$6.29/MMBtu	$7.03/MMBtu
Chicago Citygates	$5.90/MMBtu	$5.76/MMBtu	$5.96/MMBtu	$6.56/MMBtu
Southern California	$13.33/MMBtu	$12.82/MMBtu	$13.23/MMBtu	$13.54/MMBtu
Near Month Future Settle (March)	$6.235/MMBtu	$5.764/MMBtu	$5.764/MMBtu	$6.213/MMBtu
April Future Settle	$5.957/MMBtu	$5.506/MMBtu	$5.400/MMBtu	$5.620/MMBtu

Source: EIA, Financial Times, *Gas Daily*



Source: ONSITE Energy

Figure 57: Increase in Natural Gas Spot Prices Above the 2-Year Average

AMT Cost and Performance

The AMT system is projected to have the cost and performance profiles in CHP and Power-Only applications presented in Table 14. The table also includes economic assumptions used in the economic screen described in the methodology section.

Table 14: AMT Cost and Performance and Economic Assumptions

	CHP	**Power Only**
Total Installed Costs ($/kW)	900	700
Heat Rate (Btu/kWh)	9,460	9,460
Thermal Energy (Btu/kWh)	2,730	N/A
O&M Costs ($/kWh)	0.016	0.016
Annual Capacity Factor (%)	68	46
Thermal Utilization (%)	80	N/A
Boiler Efficiency (%)	80	N/A
Commercial Natural Gas Price ($/MMBtu)	7.03	7.03
Industrial Natural Gas Price ($/MMBtu)	4.80	4.80
Interest Rate (%)	10	10
Project Life (years)	10	10

Source: GE

Based on these specifications and economic assumptions, the Cost of Electricity (COE) for the AMT is consistent with the top 10% average commercial rates. COE calculations for commercial and industrial applications are shown in Table 15. It is worthwhile noting that the value of the recoverable thermal energy can reduce COE by greater than 15%.

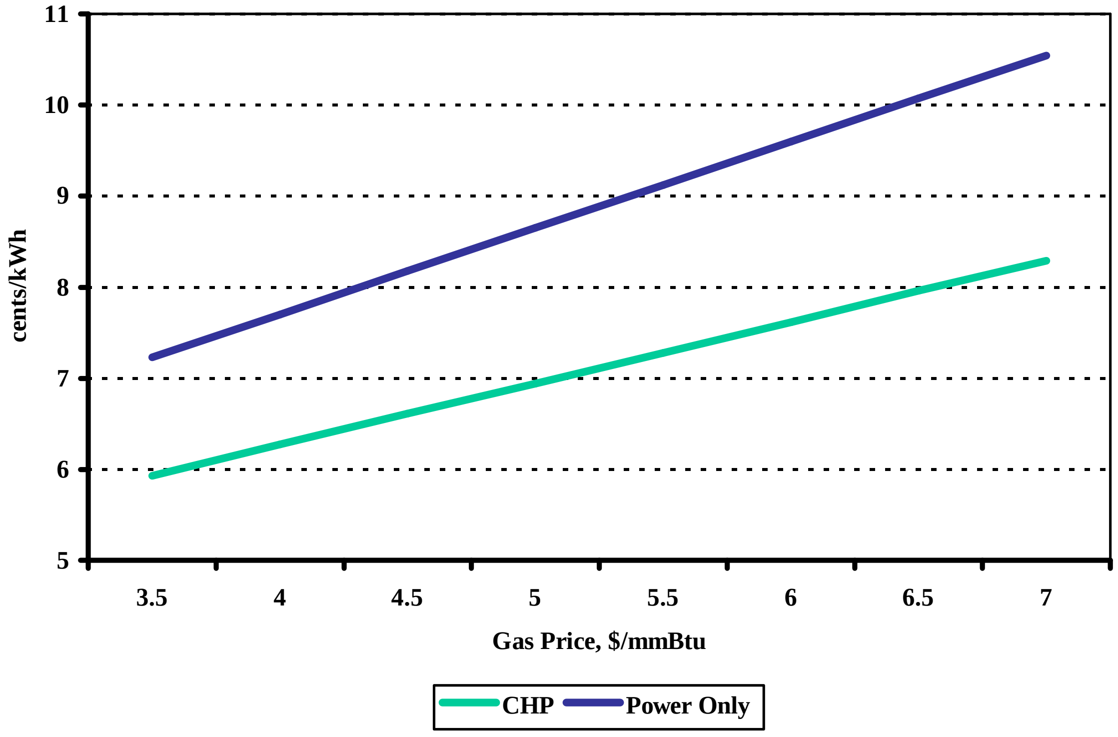
Table 15: AMT Cost of Electricity

	Commercial CHP	**Commercial Power Gen**	**Industrial CHP**	**Industrial Power Gen**
Capital Carrying Charge (cents/kWh)	2.44	2.87	2.44	2.87
O&M Charge (cents/kWh)	1.60	1.60	1.60	1.60
Fuel Charge (cents/kWh)	6.65	6.65	4.54	4.54

Thermal Credit (cents/kWh)	-1.91	0	-1.30	0
NET COE (cents/kWh)	8.78	11.12	7.28	9.01

Source ONSITE Energy

In addition to providing real economic value to customers who can utilized the recoverable thermal energy, it should also be noted that CHP costs are less sensitive to rising gas prices than pure power generation. This is illustrated in Figure 58. This is due primarily to the high total energy efficiency of CHP.



Source: ONSITE Energy

Figure 58: AMT COE Sensitivity to Natural Gas Price

The cost of electricity from the AMT is significantly influenced by annual hours of operation. Given the current competing electric rates, the COE is not competitive unless reasonable hours of operations are achieved. Figure 59 illustrates that approximately 3500 annual hours of operation are required. The recent peak price spikes that have occurred in California indicate that that under a unique set of circumstances, economic operation may occur at lower operating hours.

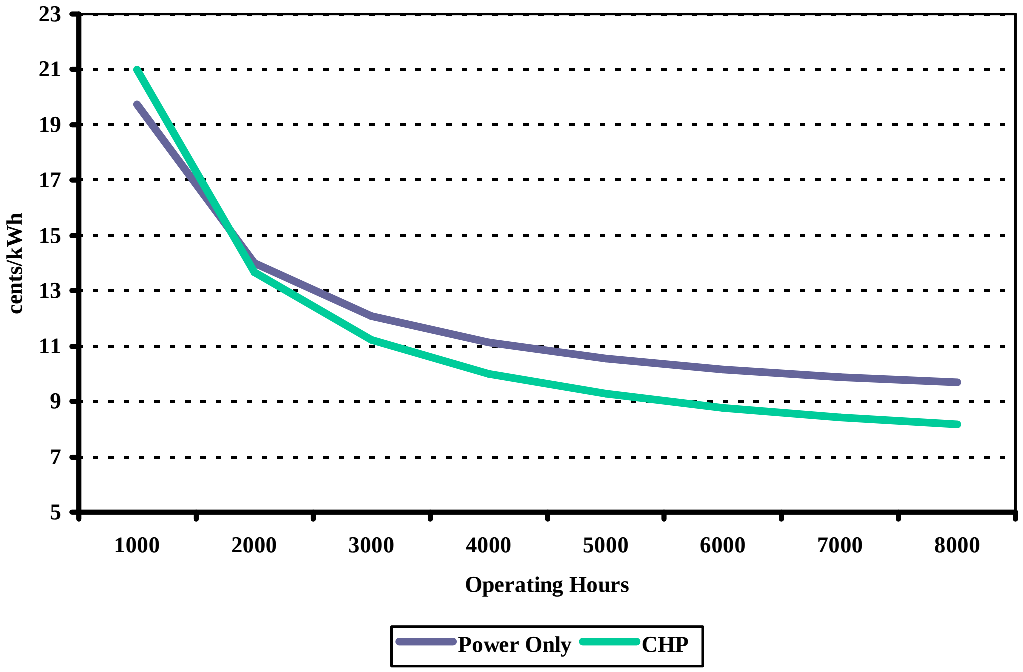


Figure 59: Commercial Customer AMT COE Sensitivity to Annual Operating Hours ($7.03/MMBtu Natural Gas)

Source: ONSITE Energy

Growth rates for these sectors used in the potential technical market assessment were taken from the assumptions in EIA's 2001 Energy Outlook. They are shown in Table 16.

Table 16: Projected Annual Growth Rates

Target Sector	**Projected Annual Growth Rate**
Education	1.6%
Food Sales	1.1%
Food Service	0.9%
Health Care	1.4%
Lodging	1.6%
Mercantile and Service	1.2%
Large Office	0.9%
Small Office	1.0%

Public Assembly	0.9%
Warehouse and Storage	1.3%
Industrial Rate of Replacement	1.5%
Other	1.8%

Source: EIA, ONSITE Energy

Technical Market Potential

The following section describes the technical potential market for the AMT in CHP, Power-Only, Premium Power (High Reliability/Power Quality), and Resource Recovery Markets. *The potential technical market is an estimation of market size constrained only by technological limits—the ability of distributed generation technologies to fit existing customer energy needs. It is not an assessment of likely market penetration nor does it include an economic evaluation.*

The Potential Technical Market for CHP, Power-Only, and Premium Power are broken down into two average demand size categories of potential customers, 100-500 kW and 500-1000 kW.

CHP Potential Technical Market

The potential technical market for CHP applications is shown in Table 17. The potential is broken down into the existing aftermarket potential (existing commercial and industrial facilities) and projected new construction between now and 2010. It was estimated that those facilities in the 100-500 kW range could install a single AMT, while those in the 500-100 kW range could install two units. While significantly smaller than the current aftermarket, the new construction market is likely to have a higher penetration. New construction applications are more likely to more easily justify the capital expenditures associated with new CHP system integration.

Table 17: CHP Potential Technical Market

	Current After Market				**New Construction 2001-2010**		
	Number of Existing Facilitates	Number of Units	Capacity (MW)	Equipment Sales Revenue ($MM)	Number of Units	Capacity (MW)	Equipment Sales Revenue ($MM)
Commercial Sector	206,000	254,000	63,500	31,750	38,000	9,500	4,750
100-500 kW	158,000	158,000	39,500	19,750	29,150	7,287	3,643
500-1000 kW	48,000	96,000	24,000	12,000	8,850	2,213	1,107
Industrial Sector	56,000	67,000	16,750	8,375	11,000	2,750	1,375
100-500 kW	45,000	45,000	11,250	5,625	7,400	1,850	925
500-1000 kW	11,000	22,000	5,500	2,750	3,600	900	450

The top five states in terms of potential sites for commercial and industrial CHP are shown in Table 18. The unit total is the summation of the current after market (existing facilities) plus new construction 2001-2010.

Table 18: Top States for CHP Application

Commercial		Industrial	
State	**Units**	**State**	**Units**
California	29,600	California	8,500
Texas	22,100	Texas	4,600
New York	20,400	Ohio	4,500
Florida	18,200	Michigan	4,100
Pennsylvania	12,500	Illinois	4,000

The top commercial and industrial segments for CHP in terms of numbers of potential units are shown in Table 19. Similar to the identification of top states, the unit total is the summation of the current after market (existing facilities) plus new construction 2001-2010.

Table 19: Top Market Segments for CHP

Commercial		Industrial	
Segment	**Units**	**Segment**	**Units**
Schools	69,200	Machinery	13,900
Office Buildings	44,400	Fabricated Metals	11,900
Food Service	37,600	Plastics	8,900
Apartment Buildings	31,000	Food Processing	8,300
Lodging	21,400	Chemicals	6,000

A first order economic screening of the CHP potential technical market was conducted by identifying those states in which the net CHP cost of electricity from the AMT was lower than the state wide commercial and industrial average retail electricity price. This screen identified when cost savings relative to retail electricity from the grid do occur and provided a quantified Potential Economic Market. While an exhaustive review of appropriate electric tariffs with necessary standby fees, backup charges, and other applicable charges (e.g., competitive transition charges and exit fees) is required to determine true economic viability, this does provide an upper bound and is a step closer toward estimating an actual economic market projection.

Those states in which positive cost savings occur with CHP are predominantly Northeast states and California. The potential economic market screen dramatically reduces the technical potential market. The potential economic market is shown in Table 20 along with those states that indicate positive economic savings relative to their average retail costs of electricity. Similar to the previous tables, the unit total is the summation of the current after market (existing facilities) plus new construction 2001-2010. This screen reflects 27% of the commercial CHP potential technical market and 7% of the industrial potential technical market. The more dramatic reduction in potential for industrial markets is due to the much tighter “spark spreads” in industrial markets. Spark spread is the difference in cost between generating your own power on a fuel (natural gas in this gas) and the retail price of electricity form the grid.

Table 20: Commercial and Industrial CHP Potential Economic Markets

Commercial Potential Economic Market		**Industrial Potential Economic Market**	
States w/ Positive Economics	**Units**	**States w/ Positive Economics**	**Units**
Alaska, California, Connecticut, Hawaii, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont, Washington DC	68,300	Alaska, Connecticut, Hawaii, Maine, Massachusetts, New Hampshire, Rhode Island	4,800

Power-Only Potential Technical Market

The potential technical market for Power-Only applications is shown in Table 21. The Power-Only market includes power generation applications with 3000 or more annual hours of operation, i.e., baseload and intermediate on-peak generation. The potential is broken down into the existing after market potential and new construction between now and 2010.

Table 21: Power-Only Potential Technical Market

	Current After Market				**New Construction 2001-2010**		
	Number of Existing Facilitates	Number of Units	Capacity (MW)	Equipment Sales Revenue ($MM)	Number of Units	Capacity (MW)	Equipment Sales Revenue ($MM)
Commercial Sector	284,000	357,000	89,250	44,625	50,500	12,625	6,313
100-500 kW	211,000	211,000	52,750	26,375	30,000	7,500	3,750
500-1000 kW	73,000	146,000	36,500	18,250	20,500	5,125	2,563
Industrial Sector	85,000	101,500	25,375	12,688	16,000	4,000	2,000
100-500 kW	68,500	68,500	17,125	8,563	10,800	2,700	1,350
500-1000 kW	16,500	33,000	8,250	4,125	5,200	1,300	650

The top five states in terms of number of potential units for commercial and industrial power-only potential technical markets are shown in Table 22. As was the case with previous tables, the unit total is the summation of the current after market (existing facilities) plus new construction 2001-2010.

Table 22: Top States for CHP Application

Commercial		Industrial	
State	**Units**	**State**	**Units**
California	40,700	California	16,300
Texas	31,400	Texas	8,300
Florida	26,800	Ohio	7,500
New York	26,500	Illinois	7,000
Pennsylvania	16,800	Pennsylvania	6,200

The top commercial and industrial segments for CHP in terms of number of units are shown in Table 23. Similar to the identification of top states, the unit total is the summation of the current after market (existing facilities) plus new construction 2001-2010.

Table 23: Top Market Segments for Power-Only

Commercial		Industrial	
Segment	**Units**	**Segment**	**Units**
Retail Services	77,393	Machinery	16,200
Schools	69,200	Fabricated Metals	13,900
Office Buildings	44,400	Plastic and Rubber	10,400
Food Services	37,700	Electric and Electronic Equipment	11,200
Apartment Buildings	31,000	Food Processing	9,600

As was done with the CHP market, a first order economic screening of the Power-Only potential technical market was conducted by identifying those states in which the net cost of electricity from the AMT was lower than the state wide commercial and industrial average retail electricity price. This screen identified when cost savings relative to retail electricity from the grid do occur and provided a quantified Potential Economic Market. While an exhaustive review of appropriate electric tariffs with necessary standby fees, backup charges, and other applicable charges (e.g., competitive transition charges and exit fees) is required to determine true economic viability, this does provide an upper bound and is a step closer toward actual market penetration.

There are a limited number of states in which positive costs savings occur with Power-Only based on average retail electric rates. They are predominantly Northeast states. As discussed in the previous section on on-peak generation, local and regional markets may develop for on-site generation utilized for low annual hours of operation. For example the published tariff in several Midwest areas (e.g., northern Illinois, northeast Ohio, and southeast Michigan) offer the opportunity for a somewhat broad on-peak period of 1500-3200 annual hours of operation. The current power situation in California may offer some very immediate market opportunities for capacity of any kind. It is our assessment that the California power situation will be resolved by the planned date of commercial introduction of the AMT. The potential economic market screen dramatically reduces the technical potential market. The potential economic market is shown in Table 24 along with those states that indicate positive economic savings relative to their average retail costs of electricity. Similar to the previous tables, the unit total is the summation of the current after market (existing facilities) plus new construction 2001-2010. This screen reflects a more than 90% reduction of the commercial power-only potential technical market and a 98% reduction of the industrial potential technical market. The more dramatic reduction in potential for both markets is due to the likely lower annual hours of operation over which to amortize capital costs and not benefiting from the value of thermal energy recovered as was the case with CHP.

Table 24: Commercial and Industrial Power-Only Potential Economic Markets

Commercial Potential Economic Market		**Industrial Potential Economic Market**	
States w/ Positive Economics	**Units**	**States w/ Positive Economics**	**Units**
Hawaii, Maine, New Hampshire, New York,	31,300	Hawaii, New Hampshire, Rhode Island	1,500

It should be noted again that there are local and regional markets where the on-peak periods are broad enough to allow for more than 2000 hours of operation and others where value of peak power is high enough to merit use of the AMT in a peaking mode. The northern Illinois market is an example of the former and capacity-constraint California is an example of the latter.

Premium Power Potential Technical Market

Premium power is an emerging Power-Only market for systems that either provide quality power to sensitive customers or offer significantly more reliability than the basic utility service. This assessment addressed commercial sized High Reliability/Power Quality customers that the AMT can technically serve. This includes computer-based companies, data storage centers, telecommunications facilities, and financial institutions in the commercial size range of 100-1000 kW.

The potential technical market for Premium Power applications is shown in Table 25. The potential is broken down into the existing after market potential and new construction between now and 2010. The microprocessor, telecommunications, and data/information businesses that have provided much of the recent growth in our domestic economy are driving this market. New construction applications for this commercial application are projected to grow at a higher rate than those of the previously examined applications. Most power projects currently being developed to serve the majority of this market are significantly larger than the 100-1000 kW size range examined for this project. For example, projects have been announced dedicated for server farms and high tech office parks in the 10-100 MW size range. The upper end of this range will serve multiple customers in a campus type facility.

Table 25: Commercial Premium Power Potential Technical Market

	Current After Market				New Construction 2000-2010		
	Number of Existing Facilitates	Number of Units	Capacity (MW)	Equipment Sales Revenue ($MM)	Number of Units	Capacity (MW)	Equipment Sales Revenue ($MM)
Commercial Premium Power	13,900	15,100	3,775	1,888	5,100	1,275	638
100-500 kW	12,700	12,700	3,177	1,588	4,300	1,075	538
500-1000 kW	1,200	2,400	600	300	800	200	100

As previously mentioned, this estimate includes only computer-based companies, data storage centers, telecommunications facilities, and financial institutions in the commercial size range of 100-1000 kW.

The top five states for the commercial premium power potential technical market are shown in Table 26. As was the case with previous similar tables, the unit total is the summation of the current after market (existing facilities) plus new construction 2001-2010.

Table 26: Top States for Commercial Premium Power

Commercial Premium Power	
State	**Units**
California	2,275
Texas	1,900
New York	1,200
Florida	1,200
Illinois	1,110

A first order economic screening of the commercial Premium Power potential technical market was conducted. The approach used to determine the first order potential economic market was slightly different than the one used in the two previous applications. As discussed in the previous section on premium power, a noteworthy characteristic of the High Reliability/Power Quality market is that the value of the electricity provided is tied to the opportunity cost of being without power rather than traditional power production costs. In this assessment, the premium power application was given a 25% value premium. We identified those states in which the net cost of electricity from the AMT with the 25% value premium was lower than the state-wide commercial retail electricity price. This screen provided a quantified upper bound of the premium power potential economic market. The potential economic market is shown in Table 27 along with those states that indicate positive economic from premium power.

Table 27: Commercial and Industrial Power-Only Potential Economic Markets

Commercial Premium Power Potential Economic Market	
States w/ Positive Economics	**Units**
Alaska, California, Connecticut, Hawaii, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, Washington DC	5,600

As noted earlier, the premium power market is one expected to grow rapidly; however, it is likely that most power projects developed specifically for this market will be significantly larger in size than the narrow 100-1000 kW segment assessed AMT product.

Resource Recovery Potential Technical Market

Resource recovery is one of the early market niches microturbines have aggressively pursued while the much larger onsite CHP and power-only markets develop. In many cases the gases in these applications would be flared. Environmentally, flaring methane gases is nearly as beneficially as utilizing the methane as fuel, since flaring changes the majority of the methane into carbon dioxide. Emitting carbon dioxide is less harmful in terms of the impact on global warming than is the direct emission of methane. According to EPA, for the purposes of greenhouse gas reductions, the value of recovering one ton of methane and using it to generate energy (in lieu of burning the equivalent amount of natural gas from traditional sources) is equivalent to a twenty-one ton reduction in carbon emissions. Flaring yields greenhouse gas reductions equal to about 87.5% of those through recovery and use. The fuel gas in these applications, which would otherwise be flared, is essentially free and would be used to create electricity, a potential new value stream.

As the fuel is essentially supplied at no cost, high efficiency is not such a priority. Based on the specifications of the AMT and assuming 8000 hours of operation annually, the cost of electricity in resource recovery applications was calculated to be 2.94 cents/kWh. Fuel quality is an issue as these fuels may have corrosive contaminants, low energy density, and variable characteristics. Management of these fuel characteristics is an important part of a DG system in this application. The fuel flexibility and low maintenance requirements of microturbine systems are advantages over reciprocating engines in this segment.

The resource recovery application is presented in two segments, the Upstream Oil and Gas market and Landfill/Coalbed Methane gas markets.

Remote Generation at Oil and Gas Wellheads

In the Oil and Gas Market, on-site generation units are utilized to provide remote power while being fueled with unprocessed gas that would ordinarily be flared or simply emitted pollutants into the atmosphere. The associated gas from oil wells is in many cases uneconomic to produce due to its low production quantity. Consequently it is flared. Utilizing the fuel to provide power at the well site provides several environmental and economic benefits. Principal environmental benefits are listed below:

- *Energy efficiency* is increased by generating electricity from sour natural gas that would otherwise be flared.
- The complete combustion of the methane-based gases greatly *reduces greenhouse gas emissions*
- *Reduced dependency on higher emitting grid power*, which is mostly coal-fueled.

In terms of economic benefits, the generation of power using what is essentially a no cost fuel provides value over other costly alternatives. Onsite power requirements for pumps and other mechanical drive needs range from 60-400 kW per well site. In a baseload application, the AMT generates electricity at less than 3 cents/kWh. Other alternatives for power include extending electric transmission and distribution lines to the remote locations and the utilization of reciprocating engines fueled by diesel fuel that must be transported and stored on site. These sites are typically served by rural electric cooperatives.

The upstream oil and gas market has been an early niche for the current generation of microturbine products. Activity has been high in western Canada with several distribution agreements announced between microturbine manufacturers and retail providers. An assessment of this application, with the assumption that each well will have its own generator set, indicates that those products (all less than 100 kW in output) are better suited for this application than larger products (>200 kW) likely to be developed in the DOE Advanced Microturbine System Program. This is due primarily to the limited amount of fuel energy from the gas flared available at each well. Statewide average generation capability per well in states with a notable amount of vented or flared gas ranges from approximately from 1 to 250 kW per well. Only Wyoming and South Dakota have average generation capability over 100 kW per well. The distribution is highly concentrated at the lower end with the national average of just over 11 kW per well.

The potential technical market for the 250 kW AMT in this application is shown in Table 28. The domestic potential is predominantly concentrated in several western states, with Wyoming being the best suited for the AMT. The potential for the states with an average well generation capability of greater than 40 kW but less than 250 kW (South Dakota, Utah, Alaska, and Mississippi) was estimated by assuming several wells were in close enough proximity to be easily fuel a 250 kW AMT unit. In those cases, a single AMT unit would be fueled by gas from two to six wells. A follow-up assessment of the actual proximity of wells to each other within a field and the economic viability of gathering gas from multiple wells to fuel a unit in these and other states may provide more accuracy in determining the actual penetration of the AMT in the oil and as market.

The projected growth for 2001-2010 was conservatively estimated by assuming that the new well trends of the past four years would continue through 2010. New wells were assumed to have the same state by state distribution as current inventory of wells.

Table 28: Potential Technical Market for Oil and Gas Resource Recovery

Existing US Oil & Gas Resource Recovery						**Projected Growth 2001-2010**		
State	**Vented or Flared Gas (MMcf)**	**Ave. Well Generation Capacity (kW)**	**Potential AMT Units**	**Capacity (MW)**	**Equipment Sales Revenue ($MM)**	**Potential AMT Units**	**Capacity (MW)**	**Equipment Sales Revenue ($MM)**
Wyoming	144566000	253.7	7557	1889.3	944.63	66	16.5	8.25
Utah	13835000	67.5	905	226.3	113.13	29	7.3	3.63
Alaska	7098000	41.5	377	94.3	47.13	19	4.8	2.38
South Dakota	1555000	128.9	160	40.0	20.00	1	0.3	0.13
Mississippi	2745000	47.3	153	38.3	19.13	8	2.0	1.00
Remaining US	180208000	6.0	-	-	-	-	-	-
TOTAL	350007000	11.2	9152	2288.0	1144.0	123	30.8	15.38

Sources: American Gas Association, EIA, Independent Petroleum Association of America, State Oil & Gas Agencies, ONSITE Energy Corp., Rig Location & Permit Report Service

Resource Recovery with Landfill/Coalbed Methane

The primary potential applications of DG in this segment currently are landfill sites, tertiary sewage treatment plants, and coalbed methane. In all of these cases energy production is a secondary objective of customer operations. The use of available combustible gaseous fuels from biomass sources at landfills or at sewage treatment plants has been growing at about 15% per year. Power generation from coalbed methane has been demonstrated, but is not as commercially developed.

Landfill Resource Recovery

In many areas, these DG systems benefit from rules that require utilities to purchase their power output and other incentives to encourage the use of renewable fuels. While growing rapidly now, this is ultimately a small market overall that will likely reach saturation when the AMT is commercially available. As of mid-1999, there were over 270 landfill gas recovery and utilization projects in the US. The US Environmental Protection Agency (EPA) estimates approximately an additional 500 candidate sites for project development. The EPA estimated distribution by top states of existing and candidate waste to energy sites is presented in Table 29. Target sites for the AMT are landfill sites with approximately 200,000 – 1.5 million tons waste in place. Based on the projected efficiency of the AMT, this corresponds to 250 kW to 2.5 MW of electricity generation. This Potential Technical Market is shown in Table 30. The average size plant for this application in the EPA identified candidate sites is in the 2-5 MW range. The average sized AMT power plant identified in this assessment of the market is just under 2 MW.

Table 29: EPA Identified Landfill Waste to Energy Opportunity

State	Existing Waste to Energy Projects	Capacity (MW)	EPA Total Candidate Projects	EPA Estimated Capacity from Total Candidate Projects (MW)
Texas	7	66	57	257
California	56	480	43	235
Illinois	36	209.	38	206
Ohio	6	54	29	145
Indiana	10	74	26	102
North Carolina	10	41	36	95
Florida	9	64	17	77
Alabama	3	18	21	74
Colorado	1	23	9	70
Washington	3	16	11	68
Kentucky	1	31	20	65
Missouri	4	25	15	64
Tennessee	2	10	17	61
Remaining US	85	608	177	532
TOTAL	260	1718	516	2051

Source: EPA Landfill Methane Outreach Program

Table 30: AMT Landfill Waste to Energy Potential Technical Market

State	AMT Candidate Sites	Potential Units	Ave. Plant Size (kW)	Potential Statewide Capacity (MW)	Potential Statewide Equipment Revenue ($MM)
North Carolina	15	129	2150	32.3	16.1
Texas	10	85	2125	21.3	10.6
Alabama	8	67	2094	16.8	8.4
California	13	67	1288	16.8	8.4
Iowa	5	45	2250	11.3	5.6
Kentucky	5	39	1950	9.8	4.9
Tennessee	5	38	1900	9.5	4.8
Florida	4	36	2250	9.0	4.5
Illinois	5	33	1650	8.3	4.1
Wisconsin	5	32	1600	8.0	4.0
Ohio	4	30	1875	7.5	3.8
Louisiana	3	27	2250	6.8	3.4
Maryland	3	27	2250	6.8	3.4
Virginia	3	27	2250	6.8	3.4
Pennsylvania	4	23	1438	5.8	2.9
Georgia	3	20	1667	5.0	2.5
Indiana	3	20	1667	5.0	2.5
New York	2	20	2500	5.0	2.5
Missouri	3	19	1583	4.8	2.4
Nebraska	2	19	2375	4.8	2.4
Oklahoma	2	19	2375	4.8	2.4
Utah	2	19	2375	4.8	2.4
Connecticut	2	18	2250	4.5	2.3
Nevada	2	18	2250	4.5	2.3
Oregon	2	18	2250	4.5	2.3
Kansas	1	9	2250	2.3	1.1
Massachusetts	1	9	2250	2.3	1.1
Minnesota	1	9	2250	2.3	1.1
Washington	1	9	2250	2.3	1.1
New Jersey	1	8	2000	2.0	1.0
Colorado	0	0	0	0.0	0.0
TOTAL/AVE	120	939	1956	234.8	117.4

Landfill methane potential is expected to remain constant between 2001 and 2010. This is due to the implementation of the New Source Performance Standards and Guidelines (referred to as the Landfill Rule) under the Clean Air Act (March 1996). The Landfill rule requires large landfills to collect and combust or use landfill gas emissions.

Coalbed Methane

Coalbed Methane may also be used as a fuel for power generation to either power onsite needs of for export to the grid. Electricity demand at mines comes primarily from ventilation systems that must operate continuously and other mining equipment (e.g., mining machines, conveyor belts, and elevators). Ventilation systems comprise up to 60% of the electricity needs at mines. Onsite demand ranges from approximately 2–50 MW.

With regard to technical feasibility, the heating value is much lower than natural gas. It can range from 300 (gob gas) to 950 (vertical wells) Btu/cf. Table 31 illustrates the wide range of heating value of Coalbed methane utilization options.

Table 31: Heating Values of Coalbed Methane Utilization Options

Recovery Method	Range of Btu Quality (Btu/cf)
Vertical Wells (Pre-mining degasification)	>950
Gob Wells	300-950
In-Mine Bores	Up to 950
Ventilation Air	10-20

Source: EPA

A methane-gas mixture with a heating value of at least 350 Btu/cf is generally suitable for gaseous fuel electricity generation. Vertical wells, gob wells, and in-mine boreholes are acceptable methods of recovering methane for power generation. One potential problem with using gob gas is that production, methane concentration, and rates of flow are generally not predictable. Variations in Btu content of the fuel may cause difficulties. Blending with methane may be needed to ensure variations in the heating value of the fuel remain within an acceptable range.

In its Coalbed Methane Outreach Program, EPA identified 79 potential sites for power generation resource recovery. From that list of candidate mines, those with potential to generate 250-2500 kW were identified as potential sites for the AMT. Table 32 summarizes the AMT potential technical market of those sites. Consistent with the landfill resource technical potential, the energy conversion was based on the efficiency of the AMT.

Table 32: AMT Coalbed Methane Resource Recovery Potential Technical Market

State	AMT Candidate Sites	Potential Units	Ave. Plant Size (kW)	Potential Statewide Capacity (MW)	Potential Statewide Equipment Revenue ($MM)
Kentucky	7	56	2000	14.0	7.0
Illinois	6	34	1417	8.5	4.3
Pennsylvania	3	25	2083	6.3	3.1
Ohio	3	16	1333	4.0	2.0
Colorado	2	11	1375	2.8	1.4
West Virginia	2	9	1125	2.3	1.1
Utah	1	7	1750	1.8	0.9
Virginia	1	5	1250	1.3	0.6
Indiana	1	4	1000	1.0	0.5
New Mexico	1	3	750	0.8	0.4
Alabama	0	0	0	0.0	0.0
TOTAL/AVE	27	170	1574	42.5	21.25

Source: EPA, ONSITE Energy

Since the fuel is essentially available at no cost in resource recovery applications, high efficiency is not critical. Fuel quality is an issue as these fuels may have corrosive contaminants, low energy density, and variable characteristics. Management of these fuel characteristics is an important part of an on-site generation system in this application. The fuel flexibility and low maintenance requirements of microturbine systems are an advantage over reciprocating engines in this segment.

Among the primary factors in determining the economic viability of generating onsite in the applications described include generator costs, total amount and flow of recovered methane, life of the project, and the price of the electricity the site (well-site, waste treatment, or coal mine) pays for the electricity it uses. Based on the specifications of the AMT and assuming 8000 hours of operation annually, the cost of electricity in resource recovery applications was calculated to be 2.94 cents/kWh.

Summary of Total Potential Technical Market

A summary of the total potential technical market is illustrated in Figures 60 through 62. This includes the following applications CHP, Power-only, Premium Power, and Resource Recovery. The LF/Bio/CB Recovery category includes Landfill, Digester Gas and Coalbed Methane. Market segments are not additive in the commercial and industrial markets, as certain customers are candidates for more than one of the target applications.

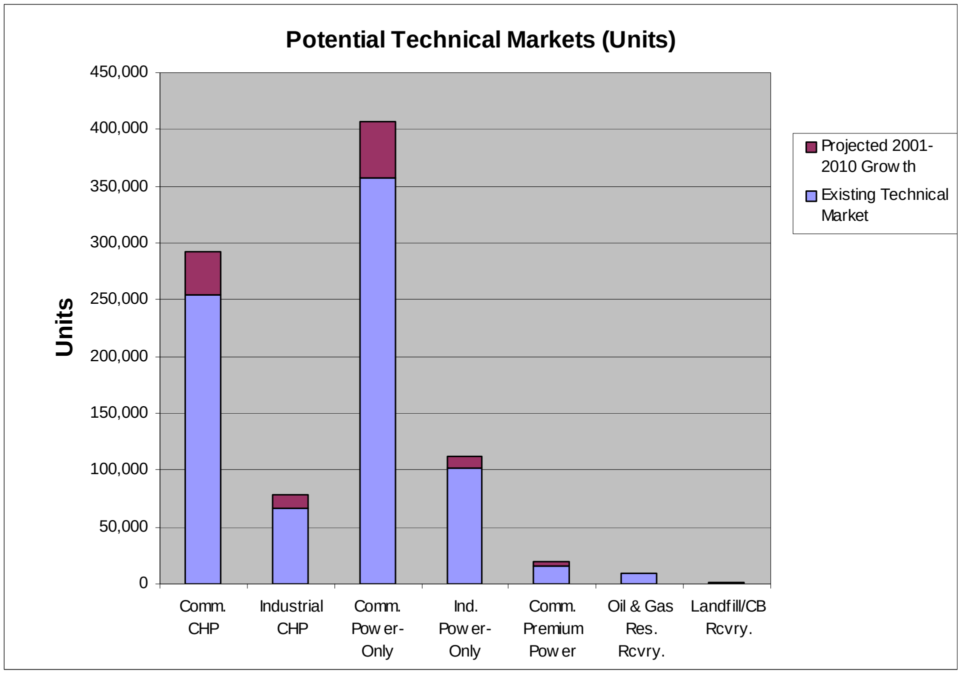


Figure 60: AMT Potential Technical Market by Units

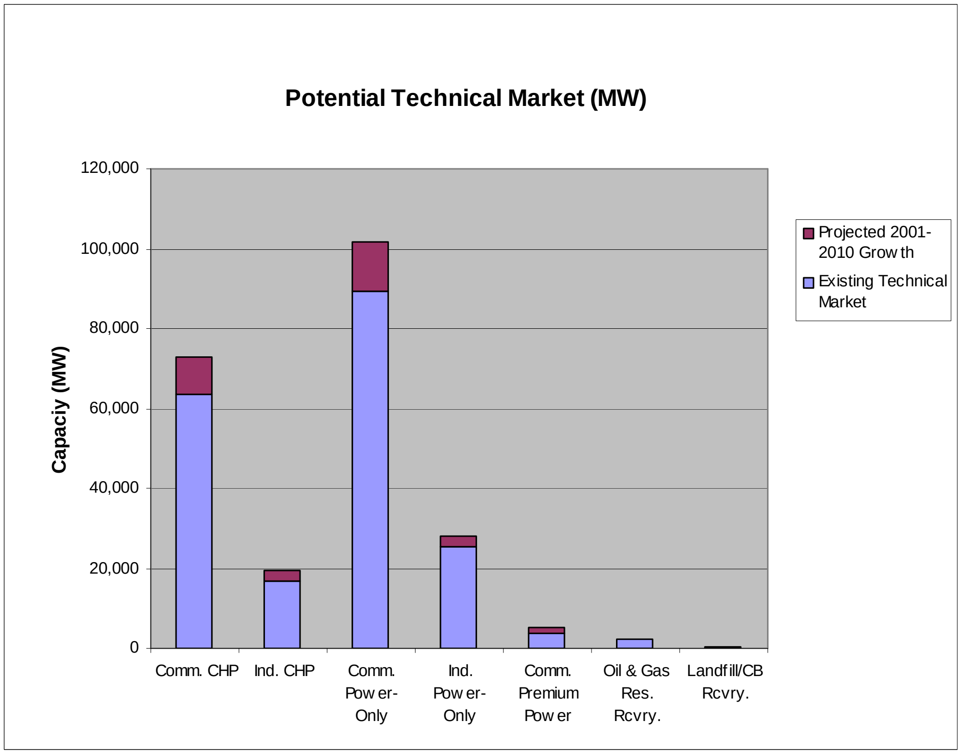


Figure 61: AMT Potential Technical Market by Capacity (MW)

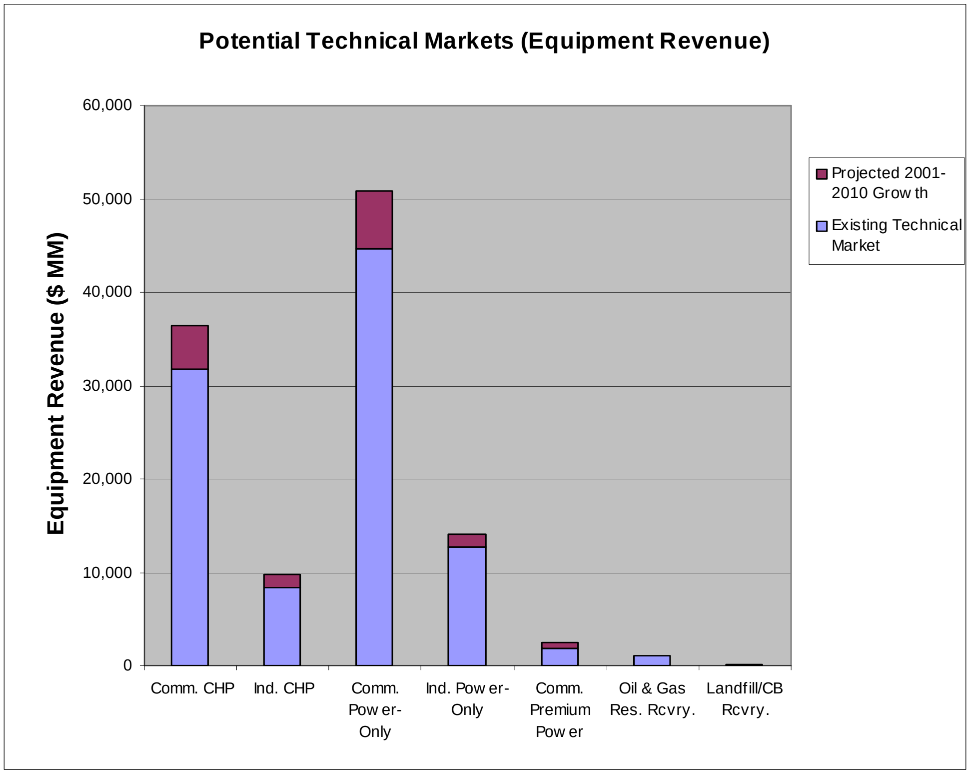


Figure 62: AMT Potential Technical Market by Equipment Sales Revenue ($MM)

The largest potential technical markets lie in Commercial CHP and Power-Only applications. The most promising regions of the US are the Northeast, California and the Midwest. These regions can be characterized by high electric costs and/or low reliability of electric service. Even though the combination of regulatory trends, advanced technology developments, and customer choice appear to favor these applications, these markets are still not fully developed. Historical market barriers and electric utility resistance to onsite power still exists. The existing incumbent on-site generation option, reciprocating engines, has a strong position and a well-established sales and service distribution infrastructure. If reliable operation on low quality fuels can be demonstrated, the resource recovery applications will provide a good initial market for microturbines while the larger onsite power market develops.

Overview of Current Small DG Market

Interest in distributed generation has increased substantially over the last five years because of their potential to provide increased reliability and lower cost of power to the energy end-users. Growing prospects for competition in the electric power industry and customer choice has also contributed to this increased interest. The development of small modular generation technologies, such as micro-turbines and fuel cells have also created optimism for the small end of the distributed generation capacity range, many of which are currently offered at capacities of 300 kW and less. This section provides a brief overview of the history and status of distributed generation market activity. Particular emphasis is placed on small distributed generation equipment in the size range of the AMT. It is organized into the following topics:

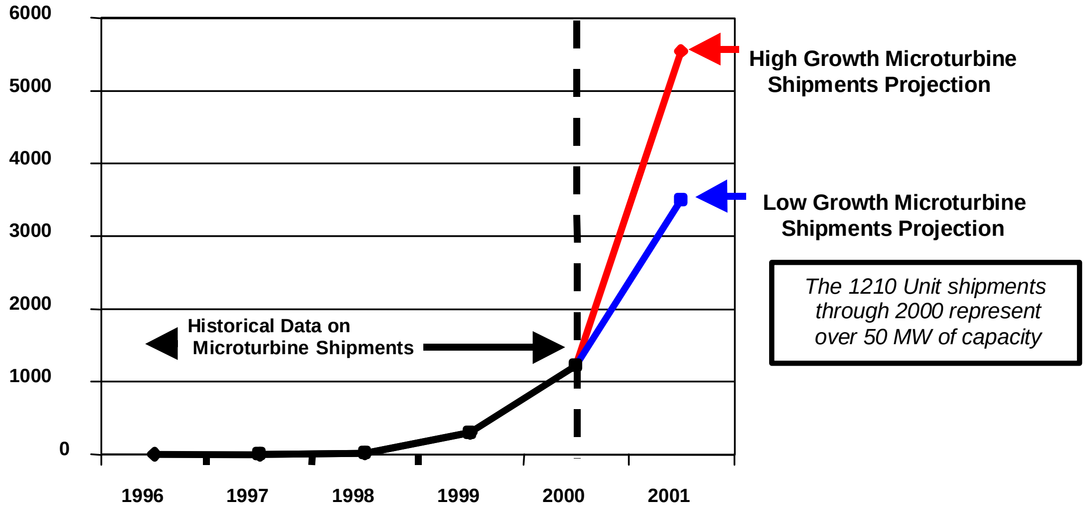
- Current Market Activity
- Historical Market Perspectives
- Market Outlook
- Recommendations for the AMT

Current Market Activity

This section provides a brief summary of the current microturbine market as well as a more detailed description of current market activity in the size range of distributed generation in which the AMT will play. It highlights the incumbent competing distributed generation option, reciprocating engines. Recent sales data form publicly available sources for both microturbines and reciprocating engines is provided..

Current Microturbine Market

The commercial microturbine market is very much in its infancy and dominated by two primary providers Capstone Turbines and Honeywell Power Systems. Figure 63 illustrates that only very recently did microturbine unit sales reach the 1,000 unit level. The number of microturbine units sold in 2000 was approximately 1,200 units, equating to roughly 53 MW. It is expected that 3,500-5,500 units are likely to be shipped in 2001. Current sales are a mix of multiple units in resource recovery applications, multiple units purchased by distributors, and single units purchased by regulated and unregulated energy companies for testing performance, reliability, and durability.



The 1210 Unit shipments through 2000 represent over 50 MW of capacity

Source: Primen

Figure 63: Microturbine Sales

It is fair to say that the bold sales and capital cost projections of just a few years ago have been tempered by the somewhat cold reality of developing a new product in an evolving market. Installed costs for the current generation of product offerings are now publicly stated to be in the more realistic $800-1100/kW rather than the much more optimistic $300-500/kW range that was used in the late 1990's.

Capstone has now delivered more than 1,000 units to the market. Almost all have been on the 28 kW 330 platform. It has announced delivery and field operation of its 60 kW system. A 125 kW system is in development. Units have been deployed in resource recovery, CHP, hybrid vehicle and high power quality/integrity applications.

Honeywell Power systems shipped roughly 300 75 kW Parallon 75 units in 2000. Honeywell Power Systems established an extensive distribution network consisting primarily of unregulated affiliates of electric and gas companies. In the US exclusion regional distribution rights we purchased by the distribution partners. Honeywell in is the process of being acquired by GE.

Competing Technology – Reciprocating Engines

Reciprocating engines are the primary technology competing with microturbines. Microturbines have to compete with both natural gas and diesel oil-fueled reciprocating engines. In sizes below about 300 kW, reciprocating engines have the advantage of being manufactured in large volumes, with corresponding economies of scale. Their production equipment and tooling is amortized over large numbers of engines, and their spare parts are widely available, on a highly competitive basis, from competing aftermarket manufacturers. Reciprocating engines also benefit from a broad technology base resulting from their widespread use over the last 100 years. Reciprocating engine repair and maintenance personnel are more readily available than are gas turbine repair and maintenance personnel. These factors present a competitive environment for microturbines.

Reciprocating Engine Technology

Reciprocating internal combustion engines have a long history of use in power generation. Both natural gas-fueled, spark-ignited and diesel oil-fueled, compression heat-ignited engines are viable options in the distributed generation market. Diesel cycle compression ignition engines are available in a wide range of sizes from several kilowatts to multi-megawatt installations and are used for standby, remote and peaking power applications. Spark ignition natural gas engines are available in sizes ranging from 5 kW to 2 MW and are used for peaking, primary power and CHP applications. Reciprocating engines offer low first cost, easy start-up, proven reliability when properly maintained, and good load-following characteristics.

Reciprocating engine manufacturers typically use the same basic engine block for both fuel types. However, as the natural gas goes into the cylinder as a gas at inlet manifold pressure, it displaces its own volume in air and leaves less air for combustion. Liquid fuel is injected in diesel engines after the inlet valve has closed, so the fuel does not displace combustion air. This reduced air charge per cylinder stroke with gaseous fuel, along with derating due to knock limitations (premature ignition), reduces the power capability of the engine and consequently increases the specific cost ($/kW) of spark-ignited engines over that of diesel engines.

Below about 25 kW, engines are typically used as emergency generators. Intermediate sizes, 25 kW to about 300 kW, are often low-cost, high-volume automobile and truck engines modified for emergency and portable power and for commercial and industrial cogeneration. From about 300 kW to 1 MW, reciprocating engines are typically large versions of truck engines. From 1 to 35 MW, they are uniquely designed stationary engines.

Reciprocating engines operating on the diesel cycle with oil as fuel employ higher compression ratios than can be used in spark-ignited engines, because premature ignition (knock) is not a concern. Diesel cycle engines consequently have somewhat higher efficiencies than spark-ignited engines operated at wide-open throttle condition and built with the same engine block and cylinder size. When operating at part load, most natural gas-fueled and other spark-ignited engines have lower efficiency than diesels of the same size, because output is reduced by throttling the air intake rather than by delivering less fuel. Such throttling creates an irreversible pressure drop in the cycle and dissipates available work, which lowers efficiency. Diesel engines typically have greater emissions of NO_x and particulates than do spark-ignited engines due to several factors, including the higher pressure and temperature of combustion and their need for rapid burning to avoid emission of unburned hydrocarbons. Diesel emissions are being regulated to a greater degree as time progresses, making siting is more difficult than with spark-ignited natural gas engines. Diesel engine manufacturers have been developing staged combustion to reduce NO_x emissions.

In intermediate sizes, up to a few megawatts, the shared technology and production system continues to benefit reciprocating engines through economies of scale, but at sizes of several megawatts, reciprocating engines become purpose designed and manufactured in modest quantities. This results in higher cost per unit of power and more competitive pricing of reciprocating engines and gas turbines in the 3-15 MW size range. Although larger reciprocating engine are being built today, their market niche appears to be based on the use of low-cost fuel, including residual oil, which gas turbines cannot use without compromising reliability or adding cost for fuel cleanup.

Reciprocating engines, particularly stationary diesel engines, have operated with grossly oversize oil sumps and timed additive injection systems so as to permit long service intervals, possibly as infrequently as twice or even once per year. Reciprocating engines are getting to the point where maintenance intervals could become dictated by the need to inspect for degradation of parts due to inherent wear and reliability considerations, rather than due to oil consumption, ignition system tune-up, or surface wear.

The high volume of production and established nature of the technology has evolved an industry capable of applying these products in a wide number of unique uses. Further, the technology is well understood in all areas of the world, permitting a readily established means of servicing these products.

In the under 300 kW range, engines are used in different ways for different purposes:

- Emergency/Standby Service. Gensets are sources of emergency or standby power, as part of a reliability enhancement strategy to complement the primary grid power supply. These applications often use automatic transfer switches to toggle between the primary grid and secondary gen set source. In some instances, gen sets are mandated by safety code requirements, while in other cases they are an economic or security investment by the user.
- Power and Energy Cost Management. Gensets are used simulatenously or independent of a grid source as a means of managing or hedging overall energy costs. Examples include peaksharing, peakshaving, and higher duty cycle applications such as prime power or cogeneration (also referred to as combined heat and power). In some cases, they may also be used to convert opportunity fuels, such as landfill gas, to high-value power.
- Mechanical Drive Service. Engines, as mechanical drives or “shaft power,” are alternatives to electric motors. They may be used due to the unavailability of electricity (e.g., in remote regions or for portable service) or due to high costs for installing or purchasing electrical power (e.g., using engine-driven chillers to trim peak power costs).

As alternatives to electric motors, reciprocating engines are more expensive and normally require higher levels of service. For these reasons, engines are a niche alternative to mainstream electric motors. Situational factors such as lack of electric power or its high cost will drive some users to choose a reciprocating engine product.

As alternatives to electricity, reciprocating engines are normally a meaningful capital investment and will require periodic service. For this reason, engines are a niche alternative to mainstream electricity purchase. Engine users are driven by the high cost of power or need to ensure reliability of electricity for economic, security, or safety reasons.

There are a sizable number of producers of smaller, less than 300 kW, reciprocating engines. Many of these manufacturers make engines in large to very large quantities per year. While often viewed as having a large number of parts, in fact reciprocating engines are produced in such high numbers with an established parts supply infrastructure that the cost per unit of power ($/kW) is relatively low. Higher volume engines can often be purchased at a cost of $50 to$100/kW (even less, depending on the rated power), while lower volume engines are often available at prices of $75 to $300/kW. Addition of generators and other packaged items, along with value-chain mark-up in bringing a product to the market, can result in cost to users of $100 to $500/kW.

Reciprocating Engine Market Channels

Like many industries, the production of reciprocating engines and packaging for stationary markets is comprised of a mix of larger and smaller, more niche players. This is particularly true in the packaging of engines into mechanical drive and genset products. The barriers to entry in designing and assembling a packaged engine generator system are relatively low. The challenges – and market differentiation – more often appear in areas such as marketing, sales, installation, and service of these products on a regional or worldwide basis.

High-volume engine manufacturers – for example, Caterpillar and Cummins – have historically used distributor/dealer networks as primary channels to market. These dealers, usually independent businesses, have a horizontal market strategy based on applying Caterpillar or Cummins engines and products in complementary segments: on-highway trucks, off-highway construction vehicles, mobile and stationary generator sets, mechanical engine drives, etc. These dealers provide marketing, sales, packaging (in some instances), installation, and service – using factory support for areas such as marketing, sales, financing, engineering, and packaging. Some Caterpillar dealers, for example, are substantial business entities with annual revenues in excess of one billion dollars.

Historically, most engine manufacturers were not vertically integrated in generator set segment. Instead, packaging of engines into generator sets has been the domain of independent companies. Engine manufacturers would normally have several OEM customer accounts they supplied with engines. This conventional engine supplier/OEM customer relationship avoided the potential issues that may arise when an engine supplier has a business interest that conflicts with their customer's business line.

While the conventional engine supplier/OEM customer relationship persists today, several engine manufacturers have increasingly made strategic moves to enhance their level of vertical integration (and value chain participation) in the generator set segment. Examples include Caterpillar, who has purchased smaller generator set packaging companies along with building their own internal capability to produce engine generator sets. Cummins also has a significant level of vertical integration in the generator set business through Onan and other enterprises. By contrast, Detroit Diesel (recently acquired by DaimlerChrysler) was more of an engine supplier with established business relationships with generator set packagers such as Kohler (with whom they have a reciprocal marketing arrangement for gensets).

Engine manufacturers and packagers use joint ventures and other collaborative business arrangements. This is particularly true in market segments where an engine manufacturer may not see sufficient volume to justify a large capital investment. Teaming and joint venture design and manufacturing arrangements are more prevalent than ever as a means of spreading capital investment and risk while obtaining desired product and production capabilities.

Smaller or niche engine manufacturers and system packagers often focus a narrow product offering, on limited regional markets, or strive to develop a patchwork market channel strategy to enhance market coverage. The latter may include developing market representatives for sales and a complementary arrangement (e.g., with a regional mechanical contracting firm) for installation and service. In either case, these channels partners often participate in the generator set value chain as a complementary component to other business interests. As an example, several utilities in North America have become dealers for Generac generator sets.

Generator set manufacturers range from producers of standardized products sold in high volume to highly custom engineered products that fit the specific needs of a customer or a narrow market segment.

Reciprocating Engine Sales

Orders for diesel, dual-fuel, and gas engine generators totaled 6,414 units worldwide for the twelve month period ending in May 2000, representing a 23% increase in activity over the previous year. A 22-year history of reciprocating engine electric power generation (EPG) orders is shown in Figure 64. The 1990's have brought on a six-fold increase in equipment sales. Table 33 shows the North American orders for reciprocating engine generators. There have been significant increases in the last three years in the 1.0-3.5 MW size range. There was an increase in orders of these units for standby service reflecting both year 2000 (Y2K) reliability concerns and also reliability in restructured electricity markets.

Source: *Diesel and Gas Turbine Worldwide*

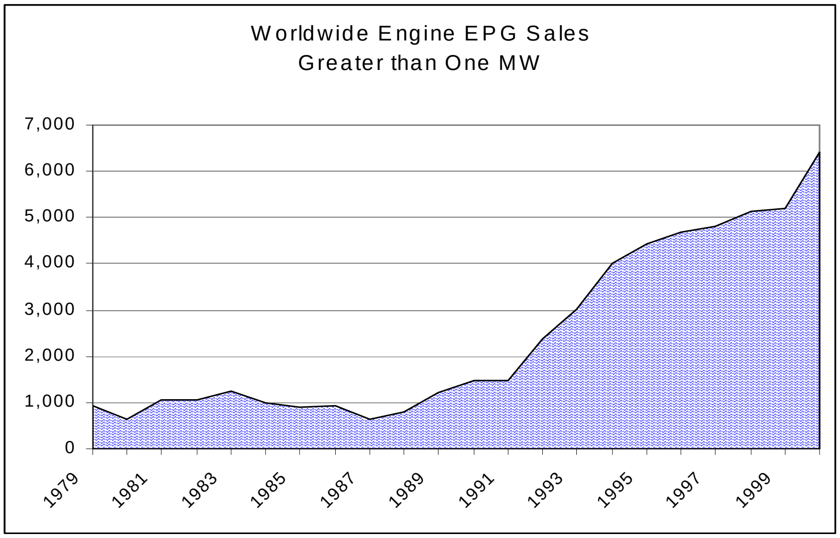


Figure 64: Worldwide Orders for Reciprocating Engine Generators > 1 MW

Table 33: North American Orders for Reciprocating Engine Generators (> 1 MW)

North America						
MW	1995	1996	1997	1998	1999	2000
1.0-2.0	1,377	1,389	1,158	1,641	1,748	2,557
2.0-3.5	11	3	165	177	229	461
3.5-5.0	3	6	11	11	5	2
5.0-7.5			2	21	16	15

7.5-10			0	1		
10-15			1	5		
Totals	1,391	1,398	1,337	1,856	1,998	3,035

Source: *Diesel and Gas Turbine Worldwide*

Table 34 shows the breakdown of engine sales for North America in 1997. These figures include spark-ignited engines (SI) fueled with natural gas and LPG and diesel cycle engines fueled with diesel oil. According to this GRI data set, there were nearly 45,000 engines sold in North America for stationary applications. About 89% of these were diesel engines, most of which went into standby power applications. Natural gas engines make up 11% of the total, and, according to other industry analysts, the this share is continuing to rise. There are 40,000 engines sold each year in North America in the less than 500 kW size range. Looking at the 10% SI share in this size range gives some indication of the market for engines with more attractive operating values than the very inexpensive diesel standby configuration.

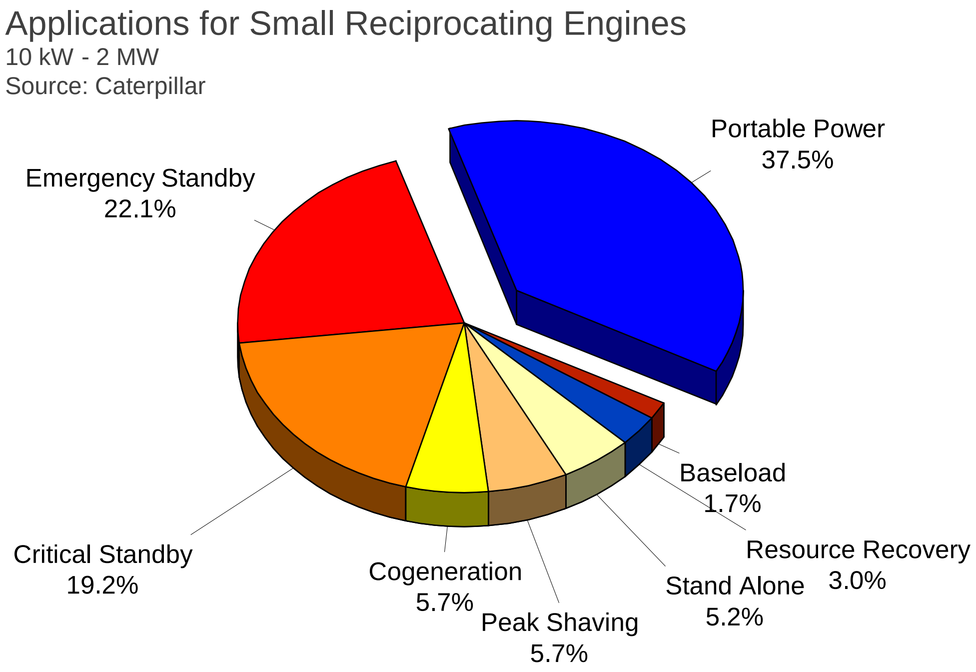
Table 34: North American Sales for Reciprocating Engines (1997)

Output	Total Market*		SI Market**		Diesel Market**		SI Share
kW Range	MW	Units	MW	Units	MW	Units	%
<100	969	25,990	101	1,898	868	24,092	10.4%
101-300	2,080	12,186	234	1,491	1,846	10,695	11.3%
301-500	1,133	2,672	85	229	1,048	2,443	7.5%
501--800	909	1,425	120	198	789	1,227	13.2%
801-1200	1,493	1,478	241	293	1,252	1,185	16.1%
1201-2000	1,517	1,046	82	49	1,435	997	5.4%
2001-5000	322	115	81	31	241	84	25.2%
5001-10000	155	25	12	2	143	23	7.7%
Total	8,578	44,937	956	4,191	7,622	40,746	11.1%

* Dan Kincaid, "Technology Update: Reciprocating Engines," CADER and DPCA Conference, Powering the New Millennium, Sept. 13-14, 1999, San Diego

** Private Communication with Dan Kincaid, SI includes natural gas and LPG but not gasoline. Diesel excludes heavy fuel oil and dual fuel (both small numbers)

Figure 65 shows estimates by Caterpillar on the distribution of the engine generator set applications. Many smaller engines are used in portable power markets. Stationary uses are dominated by low-duty-cycle emergency and standby power service to enhance reliability. These uses are very attractive for engines due to their low capital cost and quick starting capability. The limited duty cycle keeps annual maintenance costs low. As shown in this figure, engines are also used in numerous other higher duty cycle applications such as peakshaving, cogeneration, and prime power.



Source: Caterpillar

Figure 65: Representative Engine Applications

In North America, Caterpillar is the dominant player in terms of production of both diesel and natural gas engines. Table 35 ranks stationary engine manufacturers in North America based on total power made in 1998 (based on data from Power Systems Research).

Table 35: Major Domestic Diesel and Natural Gas Engine

Diesel Engines	**Natural Gas Engines**
Caterpillar	Caterpillar

Cummins	Waukesha
Detroit Diesel	Ford
Deere	Cooper (Superior)
Navistar	Dresser-Rand

Source: Power Systems Research

In Europe, there are significantly more engine manufacturers in the market. Table 36 lists major European engine manufacturers based on their stationary engine production, in total MW, in 1998.

Table 36: Major Diesel and Natural Gas Engine Manufacturers

Diesel Engines	**Natural Gas Engines**
Caterpillar (including Perkins)	Wartsilla
Cummins	Jenbacher
Deutz	Deutz
Daimler Chrysler (including MTU)	Caterpillar (including Perkins)
Volvo	Waukesha

Mergers and acquisitions are widely occurring in the reciprocating engine market, as manufacturers seek to consolidate production capacity and increase market share. Examples include Caterpillar's purchase of Perkins and MaK in recent years. Daimler recently acquired Detroit Diesel to further enhance its position in the diesel engine market. Caterpillar and Daimler recently announced a joint alliance to develop, manufacture, market, and distribute medium duty engines. Cummins, after a joint venture with Wartsilla, is now teaming with CNH Global NV and Iveco in a venture called the European Engine Alliance.

These arrangements are not limited to the reciprocating engine business. For example, Ingersoll-Rand – which recently formed Ingersoll-Rand Energy Systems – has a multi-year exclusive agreement with SDMO Industries of France to market SDMO generator sets. I-R dealers have a history of handling engine-driven air compressor products, leading to mobile and stationary engine generator sets being a reasonable extension of their product offerings. The SDMO/I-R agreement covers 50 Hz products from 15 to 500 kVA. This could be a sign of I-R attempting to make a major move into the power generation business (along with their PowerWorks microturbine product).

The generator set business is a mix of large to small players. Some of the larger companies in the generator set business include:

- Kohler Co.
- Onan (Cummins)

- Generac
- F.W. Wilson (Caterpillar)
- SDMO Industries

Historical Market Perspectives

This section examines the experiences of companies that sell or have sold into the small end of the distributed generation market. The historic small CHP market, which represents the largest potential market for the AMT is examined. This section also presents feedback from a limited number of contacts and their experiences and lessons learned from this market.

CHP Market History

CHP represents a significant distributed generation market segment. There are currently over 50,000 MW of CHP capacity in the US. Figure 66 shows the share by fuel type. Gas-fired CHP is the most common type accounting for nearly two thirds of total capacity. Not all of this CHP capacity, however, can be characterized as distributed generation. Over 88% of total capacity is in large industrial facilities larger than 30 MW as shown in Figure 67. The 30 MW point is typically the upper end of the distributed generation range. Only 6,298 MW are in the size range defined as distributed generation. This capacity does represent 80% of the total number of CHP sites.

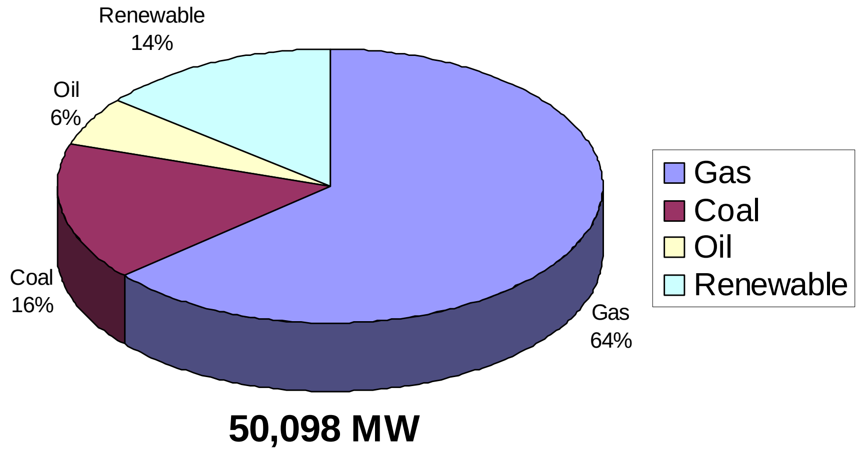


Figure 66: Operating CHP by Fuel Type

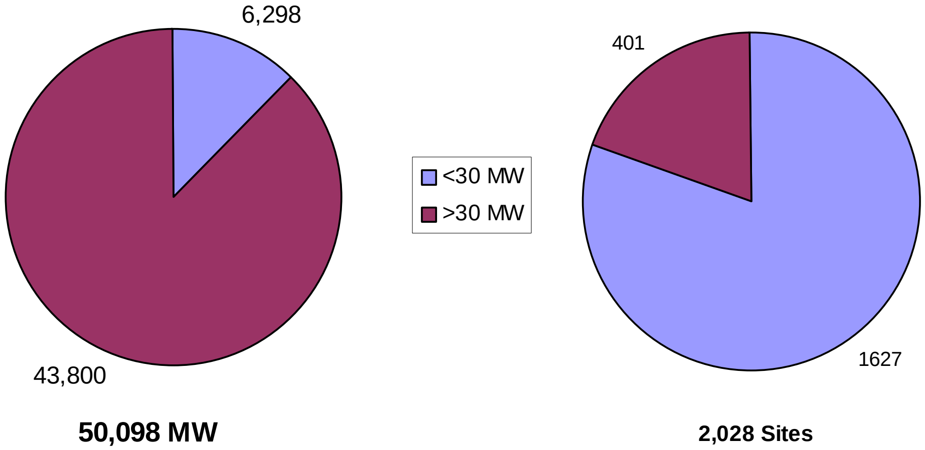
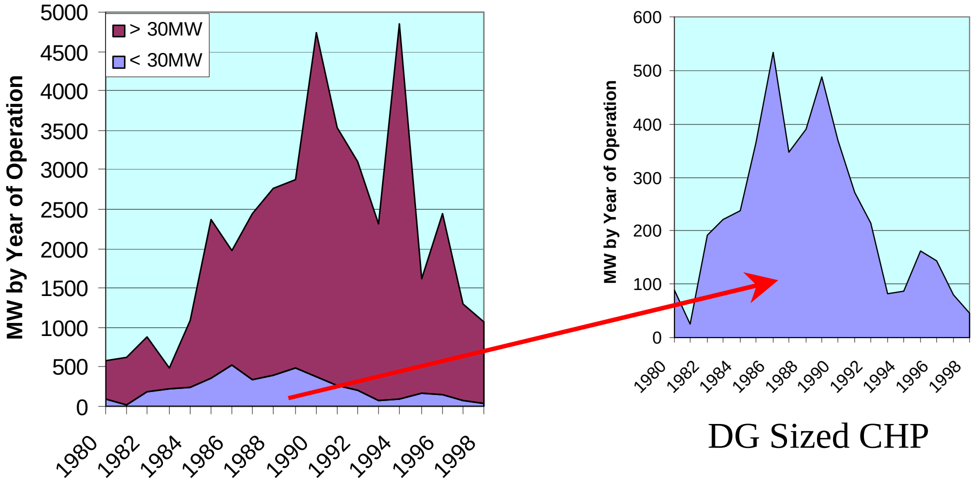


Figure 67: DG Sized Systems Share of Total CHP Units and Capacity

Figure 68 shows the distribution of currently operating sites by year of initial operation. In general and especially for small sized distributed generation systems, there was a "Golden Age of Cogeneration" from the mid-1980s to the very early 1990s. Number of sites added to the operating list each year went from 25-30 per year in the early 1980s to over 200 per year at the peak of the this period. Current levels are averaging 75-100 operating sites added per year. The overall market additions have stabilized, though reciprocating engines are taking an increasing share of total additions.



Total CHP by Year

DG Sized CHP

Figure 68: Total CHP by Year of Installation Compared to DG Sized Systems

A large share of the late 1980s bubble was comprised of small packaged systems with capacities in the 10 to 100 kW size range. Tecogen, ICC, and Goldfire, and North American offered these small packaged systems. Figure 69 shows the breakdown of sales for these units. As can be seen in the figure, sales expanded very rapidly from zero to 60-70 units per year in a few years, and then, just as quickly, sales of these units dropped off to almost nothing again. Many of these small packagers are no longer active in the market. Given the similarity in size and performance of this equipment with early market entry microturbine systems, it is important to evaluate what happened to this market.

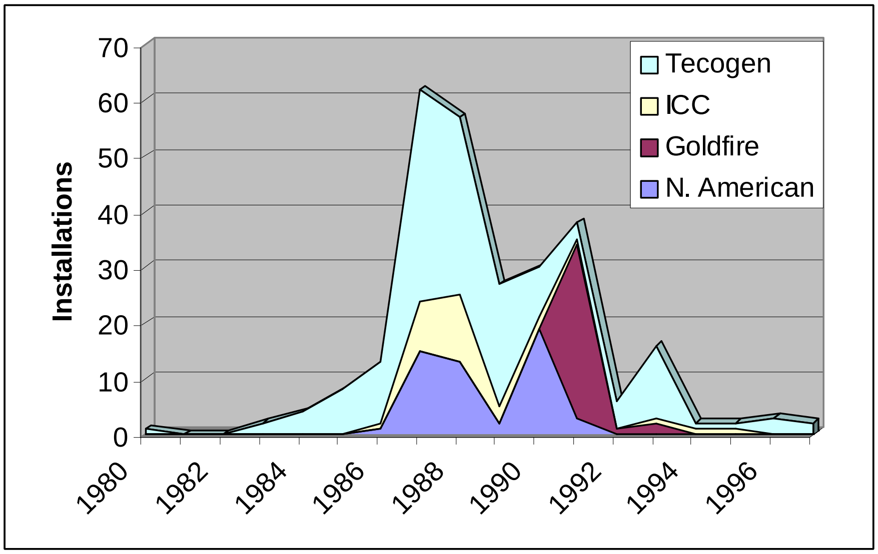


Figure 69: Growth and Decline of 10-100 kW Packaged CHP Systems

The market for these units declined for the following reasons:

- Small production levels kept unit costs high
- Transaction costs (marketing, design, engineering, permitting, etc.) for these small size units pushed installed costs to two or three times the bare equipment costs
- Interconnection costs for small units was very expensive
- Maintenance costs were high and life and reliability issues plagued many units
- Withdrawal of utility standard contract offers reduced the benefits to be derived from the systems.

Microturbines are not expected to be plagued by some of these issues. However, the issue of high transaction costs for small systems is one that needs to be carefully addressed in order to keep installed costs in a competitive range. It is a primary issue identified in the limited interviews and surveys conducted for this effort.

Lessons Learned and Market Perspectives

This section also presents feedback from a limited number of contacts and their experiences and lessons learned from this market. Companies that were contacted include those that *manufacture or package small distributed generation equipment, develop projects and those that supply system components like switchgear and heat recovery equipment*. The companies represented almost all participants in the distributed generation value chain as shown in Figure 70.

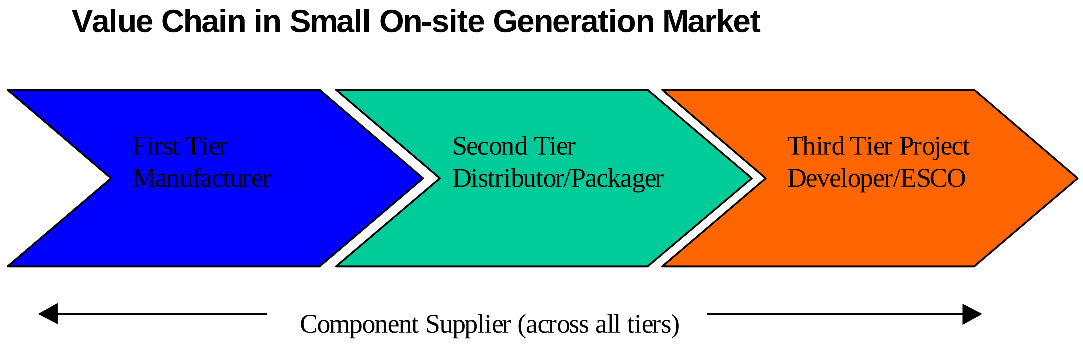


Figure 70: Distributed Generation Value Chain

These results are based on relatively limited industry contacts and should not be construed as a scientific sampling. Topics include:

- **Successful and Unsuccessful Marketing Strategies** – discuss experience with marketing strategies, distribution networks, niche markets, alliances, etc.
- **Technology Issues that Affected Sales** – discuss experience with product technologies and the issues impacting future growth of small DG
- **Barriers that Hindered Sales** – discuss the obstacles of installing small DG including electric utility involvement, air emission permitting, installation costs, financing, etc.
- **Maintenance Issues that Affected Sales** – discuss the impact of maintenance costs on the success of small DG systems
- **Characteristics of a Successful Project** – discuss the criteria necessary to sustain a successful and economically viable small DG system
- **Future Strategies** – discuss how companies are positioned to address the small DG market in light of their past experience and new technologies entering the market

Successful and Unsuccessful Marketing Strategies

Direct factory sales, dealerships, distributors, company representatives and alliances with construction firms and ESCO's have all been successfully employed as effective methods to bring products to market. However, not all these approaches were effective for all companies. The larger engine manufacturers like Caterpillar, Cummins, Waukesha, Kohler, etc., have successfully employed dealership and distributor market channels.

Smaller niche packagers and manufacturers have had less success with distributor networks owing to their limited presence in the market and difficulty identifying distributors that will aggressively market their product. Smaller companies have experimented with company representatives, factory sales forces and simply letting business come to them, all with mixed results. Smaller niche companies appear to thrive on close relationships with customers who have special requirements and who know the product and the capabilities of the company. The customer in this case can include ESCO's who can effectively market it to their commercial and industrial customers.
Sales and marketing approaches differ between distributors and small niche packagers and ESCO's. A distributor's main business typically relies on volume sales of standby generators in a very competitive market with low net margins. Mass marketing techniques and tradeshows to achieve name recognition appear to work successfully. Niche players that include specialty standby generators and small CHP packagers, rely on customer referrals and testimonials as their primary marketing strategy. Net margins are typically higher and volume sales are not as critical. Both distributors and niche companies overwhelming agree that providing good maintenance service following the initial sale is very important for retaining customers and growing business opportunities.

Marketing on-site generation equipment relies on a detailed technical evaluation and good project economics. These systems, however, are negatively impacted by economy-of-scale. The standby market is characterized by high volume sales in a very competitively priced market while small CHP is currently a niche market relying on customer referrals. While customers with good credit are important across all types of projects, they are particularly critical for long-term performance contracts characteristic of systems when offered by ESCO's.

Top marketing issues include:

- **Economics -** Economics and energy savings have driven projects in the past. The standby power market is driven by reliability as an insurance policy against power outages that could disrupt services. Requirements for standby power are considered a necessity dictated by local codes or fears of lost production; the decision process is less subject to changes in future energy prices.
- **Volume Sales -** Distributors are primarily in the engine generator business either for standby or power-only applications and rely on volume sales to stay profitable. Distributors and dealerships seem to have had success with a variety of marketing strategies. Proactively marketing products through mass mailings and telephone campaigns seem to be productive. Other tactics have included conducting seminars and competing in construction bids. Their product lines are more standardized, meeting conventional requirements for commercial and industrial customers. Although not universal, distributors generally lack the engineering capability or incentive to pursue

niche markets like small CHP. Their larger core power-only products have generated the desired net margins and so there has been little reason to enter less profitable segments of the current market; this is especially true for the less than 300 kW market.

- **Economy-of-Scale -** Small on-site generation equipment suffers from "economy-of-scale" issues that equate to much reduced net margins when compare to larger generator products. Increasing the volume of sales was a natural response to this dilemma. However, the sales effort was difficult to maintain for the long term as the best market segments were quickly saturated. An aggressive marketing staff is required to generate new business opportunities and to remain profitable. It has been very difficult to sustain profitability in the less than 300 kW market for smaller products without diversity in other market areas or marketing larger engine products. Other market areas may include standby, other engine driven products (e.g. refrigeration chillers replacing electric motor-driven equipment) or other energy services including energy efficient lighting and motors and direct access planning. In the past "plug and play" concepts for small distributed generation were part of many marketing strategies. For reciprocating engine products, this was seldom the case. Complexities associated with the customer and electric utility grid interface, maintenance and overhauls often overshadowed any net benefits. This significantly hampered the growth of the small on-site generation market. Most contacts felt that the overall CHP market is currently limited and that larger projects are the most attractive projects to actively pursue.
- **Technical Marketing -** Professional technical/engineering evaluation is required for applications. The best marketing strategy is to apply experience from successful applications to other customers in the same sectors such as health care and spas, for example. Mass marketing of such systems has not been successful.

  Large distributors make regular calls on the consulting engineering community, offering technical support and sample specifications to position themselves favorably when the equipment goes to bid.
- **Reputation** - Companies have developed niche markets for their products and services that have sustained their profitability over the years. These companies often capture a piece of the market through good service and a keen awareness of customer requirements. Examples of these markets include the oil and gas industry, and telecommunications. These companies rely on repeat business and referrals. Aggressive marketing to seek new customers is less important. In the 1980s, less scrupulous or "fly-by-night" companies did not properly support their products and gave the small distributed generation market a bad reputation that somewhat persists to this day. Legitimate players recognize this perception and highly value reputation to grow their business.

  Most distributors of the major product lines use their reputation for customer satisfaction as a marketing tool, a concept repeated by many of the respondents. Some of the distributors have been in business in the same place for several decades and their factories demand a high level of support to the end user. This is a very important advantage to these distributors in contrast with the specialized packagers of small equipment. Many end-users have an innate fear of this equipment recognizing their complexity and so a large distributor that can project a strong image of reputation and support is comforting to the end user.

- **Financial Stability of the Customer –** There are sharp contrasts between the less than 300 kW market and larger products, especially for CHP projects. Small equipment is typically installed in smaller facilities that may translate to customers with limited financial capabilities. This has been a serious problem in the past for ESCO's negotiating long-term contracts with customers whose financial condition weakened with the passage of time. These customers often changed ownership or could no longer meet the obligations of the performance contract stranding the ESCO and third party investors.

Technology Issues the Affected Market Development

Most contacts claimed that technology was not a barrier for the small DG market. No significant outstanding technology issues for the standby power market were indicated. For small power-only and CHP, technology deficiencies were discussed primarily in terms of economy-of-scale and the high cost of heat recovery. The following technology issues were identified:

- **Economy-of-Scale** - There was overwhelming agreement that "economy-of-scale" was the most significant issue for small on-site generation equipment, especially when including add-ons like emission controls. The cost to add emission controls on small engines is more expensive on a $/kW basis since the cost of electronic controls and labor do not scale-up with the size of the engine. Emission control has been a requirement for CHP applications for many years. In contrast, engine generators for the standby market have been largely exempt from air quality regulations. Should regulations change, this may be a future issue for the standby market.

  To address "economy-of-scale" in the less than 300 kW market, the product must be mass-produced and fully packaged to minimize engineering time in the factory and in the field. Fixed engineering costs become excessive for small "one-of-a-kind" custom designed systems, eroding company net margins and competitive position. These same products often require additional startup and debugging time in the field that significantly increases the installation cost of small DG on a $/kW basis. Although difficult to attain, "plug and play" is a technology goal that is very important for the small distributed generation market.
- **Reciprocating Engine Technology** - Many contacts did not feel there were significant technology issues between smaller (< 300 kW) and larger reciprocating engines. Small engines are not offered in a lean burn configuration and are penalized slightly on power generation efficiency. Two engine types have been used in the less than 300 kW on-site generation market. Gasoline-fueled automotive engines converted to operate on natural gas and other gaseous fuels like biogas and propane have dominated the low end of the size range, primarily less than 100 kW. The greater than 100 kW size range is mostly diesel-fueled industrial engines configured for spark ignition to allow operation on the same gaseous fuels. There are mixed opinions and compelling arguments that supported both engine types in the small DG market.
- **Engine Selection** - In the 1980s, packagers offered many small packaged systems under 100 kW. The engines used in these packaged systems were not originally designed for

continuous duty. The engines were typically spark-ignited for automotive use, converted from liquid gasoline to natural gas. After logging many hours on these engines, it was discovered that certain materials of construction or component designs were not adequate under continuous operation and had to be modified. Those companies still in the market have likely solved most of these issues. One company continually evaluates engine designs and quality of construction for use in its line of small products.

- **Heat Recovery -** The cost and complexity of the heat recovery system for CHP applications contribute to a high $/kW cost for small systems. Depending on system complexity, the cost to operate and maintain the heat recovery system and its auxiliaries can be a significant cost in addition to the engine generator itself. Simple hot water heating systems are the least expensive to maintain and dominate small CHP under 100 kW. Heat recovery system cost and complexity both increase dramatically for steam generation and absorption cooling that have been installed on systems greater than 100 kW.

Historical Barriers to Market Development

Primary barriers included the electric utility, total installation costs and economic criteria with a clear distinction between standby and CHP systems. No outstanding barriers were cited for standby power except that some manufacturers were offering lower cost (or lower priced) equipment in the less than 300 kW size range to better compete. There was consensus that the most influential impediment to the growth of the small on-site distributed generation market is the electric utility. Other barriers to on-site distributed generation systems include high installed cost and economics. While the electric utility was the primary barrier across all size ranges, installation costs were less of an issue with larger (greater than 300 kW) systems.

Electric Utility

In the standby, emergency and remote power markets, there have been few barriers imposed by the electric utility. However, the electric utility has historically been a barrier to the proliferation of high capacity factor on-site generation such as CHP. Several methods have been successfully implemented to discourage customers from installing equipment in this market.

- **Revising Retail Electric Rates** – By reducing the energy component and increasing the demand component of the retail rate, the overall electric bill for a grid connected customer remains nearly unchanged, however, for a customer with a CHP system, the economics are dramatically altered. Energy savings are achieved by comparing the cost of fuel with the aggregate retail cost of electric energy. A kWh of generated electricity offsets a kWh of purchased electricity. This cost differential (i.e. energy savings) was significantly decreased when electric tariffs were changed. Most small distributed generation systems are installed without redundant capacity such that they rely on the electric utility to furnish backup power when needed. In most cases, these systems experience unplanned outages during the month such that the customer pays the full demand charge in addition to the monthly standby charge. Consequently, a customer's electric bill was not reduced in proportion to the amount of electricity generated. Without adequate energy savings, the project can not continue to operate economically.

- **Lack of Grid Interconnection Standards** – The lack of interconnection standards cause delays and unexpected capital costs according to many respondents. There can be a wide variation in utility response among utilities and within individual utilities. Some utilities may take up to six months to respond, where others will reply in two weeks. The result is uncertainty in the project cost and implementation schedule. One utility requires an on-site demonstration of every small project installed regardless of how many times the same product is placed in the field, a costly and time consuming requirement. And there is no recourse that the customer can pursue if they feel they are being unfairly treated. The Institute of Electrical and Electronic Engineers (IEEE) is sponsoring a working group (P1547) to develop a standard for interconnection of DG to electric power systems. This may help address the lack of uniform treatment by electric utilities for grid interconnection while addressing utility safety and reliability concerns.
- **Costly Grid Interconnection Requirements** – In some cases there is the requirement imposed by some utilities to furnish high cost "utility-grade" switchgear in addition to protective relay functions already furnished with the engine generator. In one example, a 50 kW project was required to absorb the cost of a relay panel costing $15,000 or nearly 30% of the total project cost. Another project experienced a 50% increase in cost for an isolation transformer. These requirements significantly impair the feasibility of small DG systems.
- **Rate Reduction** – Utilities have offered customers discounted retail electric rates in exchange for not implementing an on-site generation system. One example was provided wherein the customer had performed an exhaustive feasibility study and had procured engine generators. Prior to actual installation, the electric utility offered the customer reduced rates for ten years. The engines were returned to the distributor who had to absorb their cost. In another instance, a CHP system, which had been operating successfully for two years, was the motivation for the utility to offer a major ten-year rate reduction with the proviso that the system be physically removed. The owner complied, received the rate concession, and shipped the system to a facility he owned in another state.

Installation Costs

Another major barrier to small distributed generation includes installation costs.

Development and Engineering Costs – Installation and project management costs can reduce net margins of small systems through "economy-of-scale". Many developers do not construct less than 300 kW systems because these projects are not profitable. Many of these costs are fixed and are independent of generator output so that small systems are most affected. They include:

- Numerous meetings with electric utilities to agree to interconnection requirements, protective relay studies and design reviews
- The process and time required to obtain air quality permits
- Additional installation cost due to site specific criteria such as space accommodations for equipment, noise abatement, piping runs, conduit runs, heat recovery system requirements, etc.

- Extended marketing and sales effort to familiarize the customer with the project benefits
- The effort required to execute customer contracts

Complexity of Heat Recovery Systems – The design of a heat recovery system is often site-specific that requires additional engineering. On small systems the cost of heat recovery can be a significant proportion of the project cost. Steam systems and absorption cooling can significantly increase operating complexity and maintenance requirements. Hot water systems are the lowest cost system and are much more widely applied in the small distributed generation market. The market for absorption systems is most competitive for new buildings. In existing applications there are issues of siting the equipment in existing mechanical rooms and also competing with the lower cost of electrically driven equipment. Therefore, the likely target market is in new buildings, not in the existing stock. The variability in daily or seasonal customer demand for heat was also seen as adding to project complexity as well the value of heat recovery to the customer.

Cost of Air Emission Control Technology – Although exhaust emissions are an important public health issue, the cost of installing control equipment on small systems can represent a significant percentage of the project cost.

Sales Approach – The sales approach can be a significant barrier for small on-site generation. Using in-house sales people can be expensive relative to available net margins from the sale of a small system. For these companies, repeat business and referrals have been better marketing techniques.

Economics

Factors in the economic evaluation include:

Differential between Natural Gas and Retail Electric Prices - Electricity prices historically have been relatively low in comparison to the price of natural gas and other variable costs associated with generating electricity on-site. This problem is particularly acute for small systems that generally have lower electrical efficiencies and higher installed costs ($/kW) than larger engines. Without a significant differential, the economics of on-site generation can not justify implementation unless other factors are considered such as the value of onsite power from a reliability perspective or the economic benefits of heat recovery.

Economic Hurdle Rates – Customer imposed hurdle rates have become more stringent. Whereas customers had a five-year return in the past, in some cases, this has been reduced to as low as one year by many end-users before a project moves forward. This is especially true for smaller companies with less than 300 kW demand where future outlooks are measured in months instead of years. Unless the payback is very rapid, most small companies will not entertain a power generation project. This is in contrast to larger companies whose hurdle rates are not as short and consider other factors like reliability and safety.

Financial Stability of the Customer – Small CHP systems were sold to smaller companies and institutions that sometimes lacked financial strength and became a credit risk during the life of the project. Contractual obligations were difficult to enforce, leading many systems to be shutdown. Changes in ownership also contributed to difficulties in enforcing contracts.

Maintenance Issues that Affected Sales

Maintenance is a top priority in customer satisfaction. Excellent maintenance practices are crucial for small continuously operating generator. However, this was not as critical an issue for standby generator sets. Reciprocating engines are maintenance intensive, an issue not always initially recognized by the end-user. The cost of a service call is substantially greater for small systems on a $/kW basis than larger products and that service contracts need to be very well written to protect the service provider, which is especially true for small on-site generation. Cost constraints are stricter for small systems with fewer allowable excursions or lapses in maintenance. The negative impact of unplanned outages was particularly significant for small CHP systems as opposed to larger systems. A large percentage of small systems became victim to changes in utility rate structures during the 1980s that exacerbated the impact of unplanned maintenance outages.

- **Maintenance is a Priority for Reciprocating Engines** – Reciprocating engines require periodic maintenance (oil changes, spark plugs and filters) and overhauls to operate at peak performance and assure long life. Lack of engine maintenance can quickly deteriorate project economics. In the past, some manufacturers did not support their products in the field, forcing customers to seek alternative maintenance providers or attempt service with in-house staff that often led to disastrous results.
- **Unrealistic Expectations** – Many customers assumed that the small packaged CHP systems were “plug and play” requiring little attention. These units were sometimes installed in close-fitting spaces, which stifled necessary cooling air flows. These arrangements were also insufficient during an engine overhaul, complicating and increasing the cost of the service procedure.
- **Economy of Scale –** Maintenance costs for small on-site generation equipment are significantly higher than larger engine generator sets on a $/kW basis. It typically costs the same to perform a service call for a 300 kW system as it does for a 1000 kW system. In contrast, the impact is over three times greater for the smaller system.
- **Engine Type** –The type of engine used for continuous duty impacts maintenance cost. More expensive industrial-type engines designed for continuous operation have their benefits including long life. Others believe that automotive engines could equal industrial engines on a life cycle basis in that they could be replaced instead of rebuilt more cost effectively and with less down-time.
- **Qualified On-Site Staff –** Small customers who are in the market for on-site generation

systems often cannot afford to hire trained operating and maintenance professionals. It is very important for on-site staff to be trained to lessen the risk of catastrophic outages and high repair costs even if others perform maintenance.

- **Qualified Maintenance Service Personnel –** The retention of technicians with solid electrical and mechanical backgrounds is an ongoing issue for maintenance service companies. By having one service technician with a combined background, service companies can reduce the number of service personnel visiting the site and/or the number of site visits for more effective cost control. This is critical for small on-site generation. Maintaining systems of this size is hard and dirty work with long hours. One contact responsible for maintenance feels it will be difficult to find talented people in the future when considering career options in computers and communications where the pay is higher and working conditions easier.
- **Maintenance Service Contracts –** Contracts were often written to favor the customer. When unplanned maintenance issues arose, it was difficult to enforce customer responsibility. Costs of repair parts have escalated faster than that allowed in the contract, forcing the maintenance company to bear the additional cost. Maintenance providers have rectified many of these shortcomings.
- **Funding of Maintenance Accounts** – In many third-party owned and operated systems, a cash account was established from the operating profits as a maintenance reserve. When the system was off-line, revenues ceased which meant that the maintenance account was not being properly funded. This contract structure often led to a spiraling effect where maintenance costs outstripped available funding leading to the ultimate abandonment of the system.
- **Economic Impact of Unplanned Downtime** – Many contacts (primarily developers and ESCO's) agreed that unplanned outages had a serious impact on the economic viability of small on-site generation, especially when utility rate structures had high demand charges. Installing redundant capacity for small commercial systems is usually cost prohibitive, thus requiring standby power from the grid – power that is often too expensive to satisfy the economic model.

  In niche markets like oil and gas exploration, however, customers are willing to pay a premium for equipment and service to achieve minimal outages. In addition to spare engine generators, reliability is enhanced by furnishing redundant control systems and by using mobile units during scheduled maintenance.

Some proactive actions taken by manufacturers to improve maintenance service functions include:

- Carefully written maintenance contracts that balance responsibilities between the customer and the service provider
- Bringing a mobile unit on-site to avoid outages during maintenance
- Offering full service plans backed by a factory trained service department to service equipment
- Providing redundant control systems to lessen the likelihood of a major outage

Characteristics of a Successful Project

For most, this question applies to Power-Only and/or CHP applications. Standby power projects less than 300 kW are fairly routine and are independent of energy savings considerations. For CHP, successful projects have typically been greater than 300 kW. Only a small number of niche companies have had long-term success with less than 300 kW systems. The major issues for a successful small CHP system include a) maintaining a wide price differential between the cost of fuel and the price of retail electricity, b) financial incentives either by an ESCO or a legislative action, c) low installation and transaction costs and d) customers with good financial credentials.

- **Differential between Electric and Natural Gas Price** – The most significant ingredient for an economically feasible system (regardless of size) is to have an adequate differential between the price of fuel to generate electricity and the avoided cost of retail electricity, the "spark spread." If an adequate differential is sustained during the life of the project, it can be profitable. Systems that are dispatched to maximize the economic return (i.e. time-of-use scheduling or peak shaving) can be the most successful. Unfortunately, most do not see an adequate differential between electric and natural gas prices in most parts of the U.S. for significant growth of small on-site generation under current market conditions.
- **Financial Incentives** – For projects less than 300 kW, an important factor is the availability of financial incentives. Two proven concepts include arrangements for low cost financing (often offered by ESCO's) and subsidies from government agencies that promote CHP and energy efficiency.
- **Low Installation Cost** – Lower installed cost is achieved by selecting sites that can easily use the thermal output. Space constraints and expensive retrofits to interface the system with the customer's facilities increase the installed cost thus diminishing the economic feasibility. Lower cost utility interconnection and air emission requirements will also benefit project feasibility. It is very important to minimize engineering and development costs. Mass produced systems have a lower first cost and will have better success in the market, especially for systems less than 300 kW.
- **Incremental Investment Sale** – Customers who already have plans to make an investment in an on-site power system for standby/reliability may be receptive to peak shaving or CHP systems when examined on an incremental investment basis (i.e., looking at the incremental cost above that of a standard diesel generator set).
- **Customer Financial Stability** – For systems that are part of a long-term performance contract, the financial condition of the customer is very important to enforce the customer's contractual obligations. Many projects have failed due to customers that enter bankruptcy or have changed ownership.
- **Good Thermal Credentials** – CHP systems by definition use the recovered heat for a useful purpose. A successful project maximizes the thermal output at the lowest possible investment (engineering and hardware) for the heat recovery system.
- **Good Reputation and Customer Service** – Most respondents acknowledged that customer referrals, good factory and maintenance support, parts availability and remote

monitoring capability were important to sustain a winning relationship with existing customers as well as future sales.

- **Redundancy** – Although this is generally contrary to low installed cost, there are advantages in installing multiple units since redundant capacity increases reliability with fewer total plant outages. In the long term, systems with redundancy offer greater operating flexibility and higher customer satisfaction.

Future Strategies

Except for those companies already engaged in the small on-site generation market, most companies are concentrating on larger products, generally greater than 600 kW. Even those companies that have traditionally marketed small less than 300 kW products are offering higher output products recognizing the improved margins from larger projects. Companies are also carefully watching demonstrations of microturbines and their markets before entering what most consider being a relatively unprofitable market under current market conditions. The standby power market across all size ranges remains strong.

- **Standby Power** – The primary market for distributors is standby generator sets for commercial and industrial markets. In general, they do not envision significant near-term market changes that will shift the emphasis to Power-Only or CHP in the near term; the economics still do not favor these applications. Therefore their near-term strategy is to stay the course and grow the standby market.
- **Deregulation** – Companies are watching developments as deregulation is imposed on a state-by-state basis. Grid reliability and control over energy costs may be key factors in a customer’s decision to install on-site generation equipment in the future deregulated market. This could mean increased sales of standby generators as well as Power-Only applications. Others are disappointed that deregulation has not presented more opportunities for distributed generation and that shifting policy and regulations preclude many commercial customers from making firm commitments in any direction.
- **Alliances with Power Specialists** –Alliances are being formed with ESCO’s and power marketers to promote their products and provide financing to customers.
- **Microturbines** – Some distributors are watching the demonstrations of microturbines with interest as a future product offering. High first cost and low electric generating efficiency are major deficiencies; however, low maintenance requirements are appealing. Manufacturers of heat recovery systems are working with microturbine manufacturers to develop low cost “packaged” systems; this integration may be simpler than recovering engine waste heat from engine radiators and exhaust systems.
- **CHP Market is Constrained** – Some feel that the actual small CHP market is relatively small since there are not enough end-users with a steady thermal demand. This effort and previous ONSITE analyses shows that while actual penetration in this market is low, the potential is quite high. But this is not the perception of current providers. Marketing needs to focus on Power-Only applications to grow the small distributed generation market.
- **Higher Output Products** – Several companies whose main product line is almost exclusively small DG less than 300 kW, are attempting to broaden product offerings to include larger engine generators. The perception is that most of the opportunities and

profitability are in the greater than 300 kW market segments.

- **Examine Alternative Distribution Channels** – Some companies maintain that there is probably a market for power systems less than 300 kW. However, distributors and representatives are not willing to participate recognizing that current demand is strong for higher output products. Alternative business models and means of getting smaller output equipment to market are being evaluated.
- **Maintenance Contracts** – By an evolutionary process, contracts must be written fairly to protect the customer and the service provider, an especially important issue for small on-site generation systems.

Market Outlooks

This section summarizes several market forecasts for distributed generation. They include projections by DOE EIA in the *Energy Outlook 2001*, the GTI Baseline Projection, Frost & Sullivan 1997 Distributed Generation Market Forecast, and Arthur D. Little's *Opportunities for Micropower and Fuel Cell Gas Turbine Hybrid Systems in Industrial Applications* done under sponsorship of DOE.

EIA's Energy Outlook 2001

According to the EIA *Energy Outlook 2001*, growth in electricity demand from 1999 to 2020 is projected to be slower than in the past. However, 393 GW of new generating capacity (excluding cogenerators) is expected to be needed by 2020 to meet growing demand and to replace retiring units. Between 1999 and 2020, 26 GW (27 percent) of current nuclear capacity and 43 GW (8 percent) of current fossil-fueled capacity are expected to be retired.

Of this new capacity, 92% is projected to be fueled by natural gas by combined-cycle or combustion turbine technology and distributed generation capacity. Both large gas turbine based central station capacity and distributed generation technologies are designed primarily to supply peak and intermediate capacity, but combined-cycle technology can also be used to meet baseload requirements.

Approximately 41 GW of distributed generation capacity is projected to be added by 2020 in the EIA base case projection. This distributed generation component is assumed to made up of 13 GW added directly by the electric power industry for grid support, 4 GW of added buildings sector (commercial and institutional) CHP, and 24 GW of added industrial sector CHP. Figure 71 compares the EIA forecast of new central station power plant capacity needed compared with new distributed generation capacity.

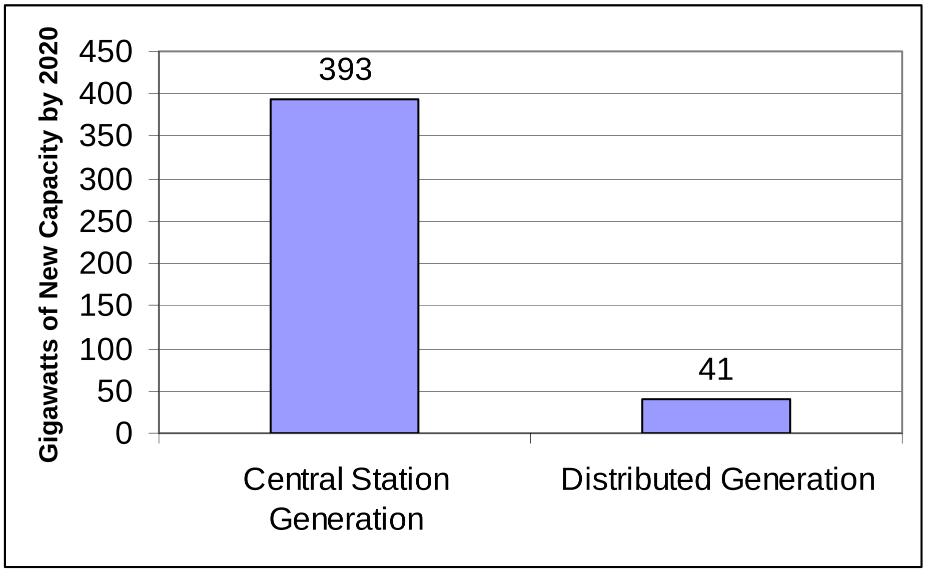
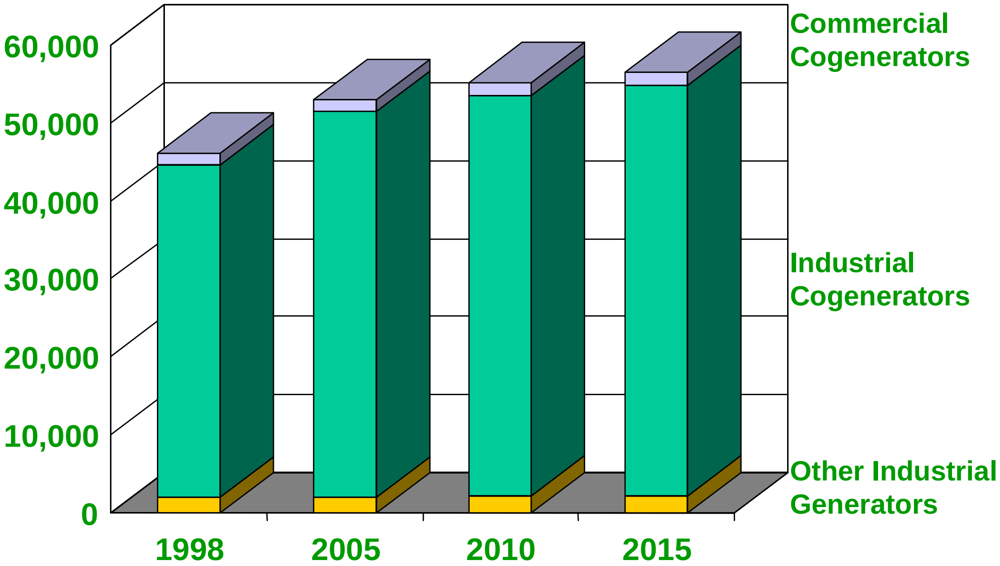


Figure 71: EIA Forecast of Generating Capacity Added between 1999 and 2020

GTI Baseline Projection

The Gas Research Institute (GRI), now GTI, prepares an annual long-range forecast that is used to provide a baseline for evaluating the benefits of ratepayer sponsored R&D. The *baseline* is intended to represent an outlook for the future that contains only evolutionary improvements in technology – it does not include the impact of the GTI research program itself.

The GTI analysis provides an estimate of two types of nontraditional power generation. Large non-central generation capacity is shown in Figure 72. The figure shows a modest growth in large systems to just under 60 GW by 2015.



Source: GRI Baseline Projection

Figure 72: Large Non-Central Generation Capacity (MW)

GTI forecasts a fairly rapid growth in DG sized systems. Figure 73 shows a growth from about 30 GW to nearly 80 GW. This forecast includes back-up power generation, small cogenerators (CHP), and other small generation. Without back-up generation, a category not included in the EIA Annual Outlook, DG is shown to grow from about 10 GW to about 50 GW.

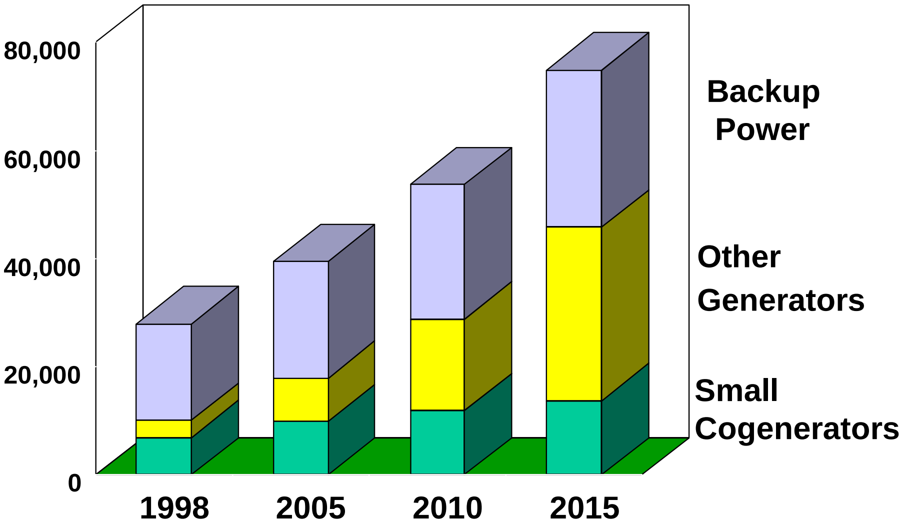


Figure 73: GRI Baseline Forecast of Distributed Generation Capacity (MW)

Frost & Sullivan 1997 Distributed Generation Forecast

Frost & Sullivan is a market research company that prepares market assessments and forecasts of various industrial products for sale to its customers. Frost & Sullivan prepared an assessment of the distributed generation market in 1997. In their analysis, Frost & Sullivan defined DG as generation from 20 kW to 10 MW. They provided detailed discussions of diesel engines, gas engines, combustion turbines, and microturbines.

Frost & Sullivan identifies the following key market drivers:

- Emissions regulations will cause contraction of the stationary diesel market
- Intense competition among equipment suppliers will keep equipment prices down
- Restructuring will encourage utility involvement in DG to better serve customers and to avoid expensive T&D investments

Frost & Sullivan also sees the market being constrained by ongoing uncertainty regarding the scope and timing for electric industry restructuring. Competitive transition charges will delay the market. Figure 74 shows the Frost & Sullivan forecast in projected annual revenue from equipment sales. They see the market growing from a base level of about $1.1 billion per year to $2.1 billion by 2004.

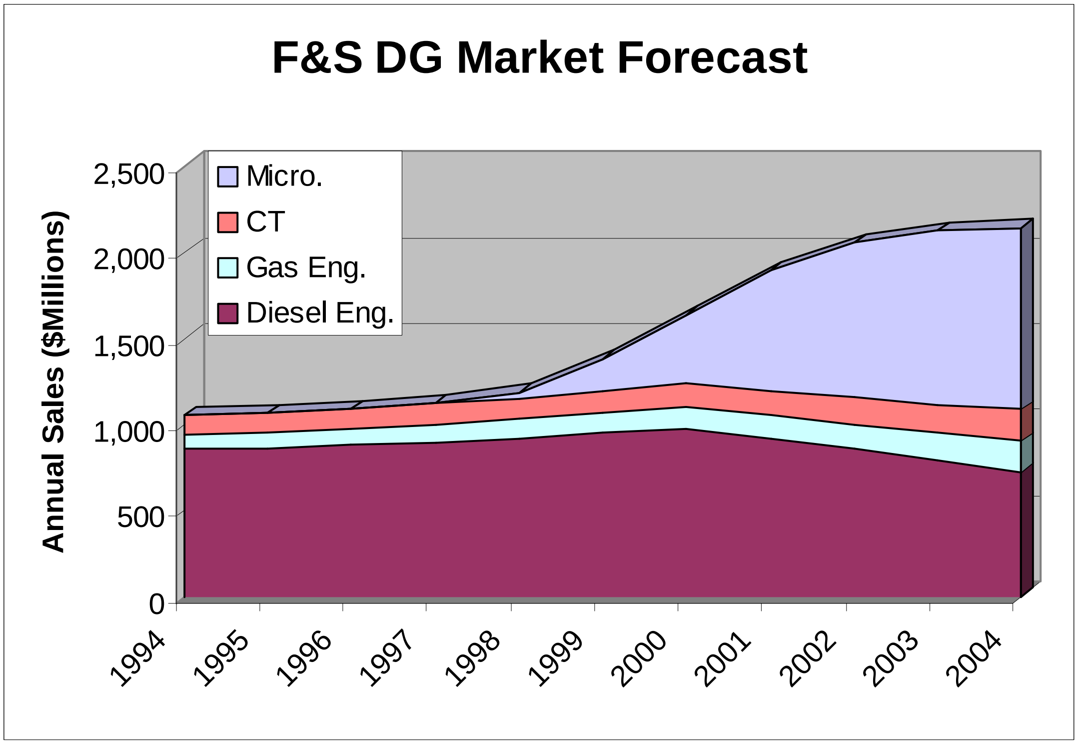


Figure 74: Frost & Sullivan DG Market Forecast

Diesel engine sales were predicted to decline over the forecast period (from $900 to $724 million) due to more stringent environmental regulations. Gas Engines were to grow steadily from 8-10% yearly ($100 million to $182 million). Combustion turbine sales were projected to recover from their existing slump and average 8% yearly growth after 2000 ending up with the same revenue share as gas engines in 2004. Frost & Sullivan projected that microturbine sales would explode from nothing to over a billion dollar market within 10 years -- comprising half the market by 2004.

Overall, the Frost & Sullivan forecast appears to represent a conservative trend analysis for diesel engines, gas engines, and turbines and a very bold market prediction for the explosive growth for microturbines. However, the F&S analysis emphasized the constraining influences that will restrict the microturbine manufacturer's even higher growth estimates rather than considering the implications of the rapid increase that they themselves are projecting.

Arthur D. Little/DOE Assessment for Industrial Micropower

The DOE Office of Industrial Technology commissioned a study of the opportunities for small distributed generation (micropower) in the industrial sector. (*Opportunities for Micropower and Fuel Cell Gas Turbine Hybrid Systems in Industrial Applications*, Arthur D.

Little, Inc., January 2000.) The study evaluated opportunities for microturbines, reciprocating engines, fuel cells, and fuel cell hybrids. Seven categories of use were defined, of which, five were included in the final forecast. These categories consisted of:

- Simple Generation – generation of power only as a substitute for grid power
- Traditional Cogeneration – Simultaneous generation of power and heat as steam or hot water
- Tightly-Coupled Cogeneration – Simultaneous generation of power and heat as direct process heat
- Generation Using Wastes and Biofuels – Generation of power using byproducts of industrial processes that have fuel value.

The study also defined three other uses (remote power, premium power, and backup power) that were not included in the market penetration estimates.

ADL looked at two scenarios. The first, *Modest R&D Success – Deregulated*, showed only modest benefits over time. The second forecast, *Aggressive R&D Success – Deregulated*, is summarized in Table 37. The numbers are additive across technologies within each application category, but not across applications categories as individual sites may have several alternative configurations that could be installed. Ignoring the authors warning about adding across categories, their aggressive market scenario implies a cumulative industrial market for microturbines of about 48 GW over the next twenty years. The largest opportunities are in simple power generation and tightly coupled cogeneration. These two uses account for 68% of the forecast industrial market penetration for microturbines.

Table 37: DOE Office of Industrial Technology Forecast of Market Penetration for Micropower (Aggressive R&D Success Scenario)

	Cumulative MW Installed by 2020				
	Simple Generation	Traditional Cogeneration	Tightly Coupled Cogeneration	Remote Power	Waste & Biomass Generation
Recuperated Microturbines	18,600	2,300	14,500	600	1,200
Unrecuperated Microturbines	<100	9,300	<100	600	1,000
Small Reciprocating Engines	<100	100	<100	<100	200
Large Reciprocating Engines	10,800	9,500	1,900	1,600	1,100
High-Temperature Fuel Cells	<100	100	<100	<100	600
Low-Temperature Fuel Cells	<100	700	<100	<100	1,000
Total Micropower	29,400	22,000	16,400	2,800	5,100
Fuel Cell Hybrids (0.25 to	13,400	1,700	11,300	200	9,100

20 MW)					
Total	42,800	23,700	27,700	3,000	14,200

Comparison of Forecasts

Table 38 provides a summary of the market forecasts presented in this. The GTI and EIA forecasts are based on business-as-usual assumptions in order to provide a background for evaluating opportunities to be derived from aggressive R&D or policy changes. The EIA forecast does not include back-up generators at customer sites whereas the GTI forecast does. Without back-up generation, the GTI forecast is very similar to the EIA Annual Energy Outlook.

Both the Frost & Sullivan and DOE-ADL forecasts are based on fairly aggressive success with technology R&D. The Frost & Sullivan forecast, somewhat dated at this point, shows microturbines equaling all other distributed generation options in terms of value sales in just ten years. Generating capability, derived from their dollar analysis, equals 8 GW for ten years cumulative sales. The cumulative growth of other distributed generation options is 112 GW. These are mostly traditional diesel engine sales for standby applications. Cumulative gas engine and gas turbine capacity additions for the 10-year period equal 14 GW. The DOE-ADL assessment is for the industrial sector only. Their forecast is for 48 GW of microturbine capacity over the next 20 years.

Table 38: Comparison of DG Market Forecasts

Forecast	Period	GW	Comments
EIA Energy Outlook	2000-2020	41	Incremental generation, not defined by size or technology
GTI Baseline	2000-2015	12	Incremental large generation
		50	Incremental DG, not defined by technology (includes standby)
Frost & Sullivan	1996-2004	8	Incremental DG from microturbines (100,000 units sold)
		112	Incremental DG from other technologies mostly diesel engines (14 GW excluding diesels)
DOE-ADL	2000-2020	48	Incremental industrial DG from microturbines
		63	Incremental industrial DG from other technologies

Recommendations for the AMT

The AMT could play a role in providing low-cost total energy in CHP applications, supporting available capacity to meet peak power demands, improving user power quality, and providing remote power in some niche applications. The key success factor for any distributed generation technology in a competitive situation can be best described as "providing the customer with the lowest cost solution to meet his particular needs." In some cases, this may be lowest initial or production cost; in others, it might be the lowest cost after considering site-specific or strategic factors.

The largest potential technical markets lie in CHP and power-only applications. The most promising regions of the US are the Northeast, California and the Midwest. High electric costs and/or low reliability of electric service can characterize these regions. Even though the combination of regulatory trends, advanced technology developments, and customer choice appear to favor these applications, these markets are still not fully developed. Historical market barriers and electric utility resistance to onsite power still exists. The existing incumbent on-site generation option, reciprocating engines, has a strong position and a well-established sales and service distribution infrastructure. If reliable operation on low quality fuels can be demonstrated, the resource recovery applications will provide a good initial market for microturbines while the larger onsite power market develops.

While examining the worldwide market was outside the scope of this effort, it should be noted that there are a number of potential foreign market opportunities. These could well turn out to be as large or larger than the domestic market potential analyzed in this effort. The need for energy (electricity specifically) is great and many growing economies may not possess the energy infrastructure to serve the growth. Distributed generation approaches may be preferable as limited capital is invested in new business opportunities rather than construction of capital intensive electric infrastructure projects.

The AMT faces a challenge due to generally higher specific capital ($/kW) and production costs ($/kWh) than larger generating systems. These challenges must be balanced against positive factors such as the opportunity for waste heat utilization, increased reliability at the site, avoidance of peak load constraints and price spikes, reduction of transmission and some distribution charges, avoidance of energy line losses, improved power quality, and greater flexibility to react to market changes. Providing a specific valuation and a market for these services will allow the AMT to compete effectively where the system needs are greatest.

With regard to product positioning, the AMT has the potential to bring the desired attributes of larger gas turbines into a size range, 200-500 kW, where the range of competing options with similar attributes is limited. Notable attributes include environmental-friendliness, high power density/small footprint, expected low maintenance, and projected high reliability and fuel flexibility. Environmental friendliness refers not only to its emissions profile of criteria pollutants, but also to its suitability to multiple highly fuel efficient CHP applications and the ability to be fueled by methane gases that would otherwise be flared or released into the environment.

The commercial market offers more potential than industrial applications. Historically, however, this market has experienced very low penetration. Perspectives of those who have tried to develop this market are described in previous sections. Reasons for low penetration include electric utility resistance, customer attitudes to non-core investments, reluctance on the part of customers to install equipment until the outcomes of restructuring were better known, and the difficulty of small on-site generation equipment to absorb the costs of marketing, project development and implementation.

A change in market conditions and a new value proposition are needed in order for the AMT to capture a substantial share of this market potential. The results of electric industry restructuring may provide the impetus for that market change. Distributed generation has traditionally faced obstacles from lack of technology maturation, electric utility resistance due to the perceived threat of loss of throughput, a number of regulatory obstacles and traditional barriers to launching a new project. These obstacles will probably slowly be overcome as the industry is restructured and new strategies are adopted. At the dawn of the restructuring movement, it had been projected that average electric rates would decline. Most projections saw the likelihood of more price volatility, but few anticipated the recent California crisis. The California situation has prominently highlighted the issues commercial and small industrial customer will face – increased local and regional power demands, need for improved reliability, significant energy price increases, wide price volatility, and the need to have more control over energy costs. Many more customers are now uncertain on the traditional electricity grid option to reliably provide reasonably and predictably priced power. The concept of owning one's own generation system no longer seems out of the question.

The opportunity is there for products like the AMT. Recommended strategies include:

- ***Define and establish viable marketing, sales, and service networks*** with reputable partners and capitalize on the GE brand name. Many previous attempts to develop the commercial on-site generation market were unable to identify an efficient business model for small systems where costs of marketing, project development transactions, and maintenance could be economically addressed. Ultimately, a model in which the final costs to the actual end-user can be tightly controlled is desired. This may require revisiting the traditional distributor market channel that has been use din this market.
- ***Emphasize product differentiation*** from the grid and other distributed generation options, namely diesel and natural fueled reciprocating engines. In the case of the gird, this means lower electricity costs in regions where it is in deed cheaper, improved service reliability critical to business needs, independence from the utility, and less susceptibility to unintended outcomes of restructuring. In the case of reciprocating engines this means lower environmental impact, better power density/footprint, lower maintenance costs, and the ability to operate on various fuels with minor modifications.
- ***Target geographical markets with high retail electric costs and/or low reliability***. These regions are the Northeast, Midwest, California, and Mid-Atlantic. The California

case is ripe with opportunity for both power-only and CHP applications given the recent power shortages, rolling blackouts and pending rate increases. From an emissions standpoint both diesel and natural gas fueled reciprocating engines face difficulties being sited in California. The Midwest offers an opportunity for customers to optimize purchased versus generated power under his existing bundled rate structure. Under this on-peak generation strategy on-site generation units would be operated between 900 and 3500 hours per year. The AMT can operate cost competitively in power-only applications at the upper end of this range.

- ***Target specific commercial market sectors with moderate to high operating hours*** (>3000 hours per year) and in the case of CHP, coincident electric and thermal loads. Primary targets in the commercial/institutional with AMT capability include Education, Health Care, Lodging, Office Buildings, and Mercantile/Retail Service applications. The analysis quantified the technical potential market in the top five commercial segments of schools, office buildings, food service, apartment buildings and lodging at over 200,000 units.
- ***Market CHP applications in select areas where CHP is selling.*** At the time of product introduction, investigate where small CHP is being installed in specific areas due to very local economics or state and/or local incentive programs (currently New York, Connecticut, Maine). For example, there is currently a school incentive program for CHP in upstate New York. Develop a limited number of successful installations in these markets to demonstrate performance and showcase the AMT product.
- ***Exploit near-term niche opportunities*** while larger markets develop. These niches include the resource recovery market in oil & gas applications, landfill, and potentially coalbed methane. The commercial premium power market is an attractive niche as well. In this segment, traditional power project economics do not completely apply, as high value is placed on reliable and clean power. These customers have evolving power densities (typically much higher than traditional building loads) and load profiles. Diesel generator sets have traditionally dominated redundant standby applications. One possible strategy to compete with diesels is to offer a lower cost AMT package (e.g., non-recuperated or not grid interconnected). Highly publicized premium power projects (e.g., server farms, dedicated data storage facilities) that have been proposed or in development are much larger (10-100 MW) than the AMT addressable size.
- ***Closely monitor telltale signs that indicate market conditions are emerging for the peaking market.*** This market represents the largest but most speculative on-site generation market. Identify those locations that exhibit both capacity and electric transmission and distribution constraints. Identify state and utility-specific regulatory activities that indicate rate making is time-of-day and area dependent. Continue to examine price volatility that will likely occur in certain restructured states and their impact on commercial and light industrial customers identified in this analysis. Demonstrate the reliability and availability of the AMT under operating conditions that reflect frequent cycling.

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[i] Other voltage levels and neutral connections are possible but less common. Isolation transformers may be used to achieve these output voltages from an inverter optimized for maximum rating. Non-standard arrangements may require an interposing transformer.

[ii] Based on the Electrical Generating Systems Association (EGSA) standard 101P. http://www.egsa.org/.

[iii] Standard 101P states "the generator set shall be capable of starting a motor, across the line, having a minimum of 2.7 inrush kVA per the generator set's rated electrical prime power kW." This is equivalent to 216% on the generator's kVA base (assuming 0.8 PF) at rated voltage. This level must be sustained for the duration of the motor start. Perhaps we should limit applications to motors (of this size) that start in within 10 seconds. Provisions for >300% for 6 cycles should be considered to accommodate the magnetizing currents associated with motor starting. These ratings will also improve protection coordination. The overload capability can be automatically adjusted in grid parallel mode for those applications that require limited fault current contribution. In general, we should be able to satisfy the overload with increased reactive current that will not require more turbine/alternator capability. Cost and size tradeoffs with overload rating must be studied.

[iv] For scenarios where the microturbine is unable to operate downstream protective devices, a properly coordinated under voltage protection trip feature is required.

[v] Based on the Electrical Generating Systems Association (EGSA) standard 101P. http://www.egsa.org/. Specifically, "if fluorescent lighting forms a major proportion of the load, the above [neutral] rating should be equal to the line conductor and contactor contact rating."

[vi] Based on the Electrical Generating Systems Association (EGSA) standard 101P. http://www.egsa.org/

[vii] See also the IEEE paper "Flicker Limitations of Electric Utilities", PAS-104, 1985.The flicker curve specifies a maximum voltage magnitude change based on the repetition period of the load. IEC flicker standard 1000-4-15 (formerly IEC 868) may apply. Also reference EN 61000-3-3 and 60555-3.

[viii] Based on the Electrical Generating Systems Association (EGSA) standard 101P. http://www.egsa.org/. Standard 101S states "most industrial applications can tolerate large voltage dips (up to 35% in some cases) as long as they are not so great as to cause motor contactors to drop out or automatic brakes to set. Additional consideration, however, must be given to the effects of voltage transients on computer and/or micro-processor based control equipment which may control the equipment in an industrial application." IEEE Std 1250 states that a 20% dip for 0.5 seconds is acceptable for computer equipment.

[ix] Based on the Electrical Generating Systems Association (EGSA) standard 101P. http://www.egsa.org/. The standard recommends "that efforts are made to balance system loads between phases within approximately 20% in order to eliminate difficulties which could result due to the deterioration in output voltage regulation and its possible effect on other connected loads."

[x] The issue is excessive excitation current and distortion in typical transformers due to magnetic saturation. DC currents must be kept below typical levels of magnetizing current. Other concerns are motor saturation and corrosion of the grounding system caused by dc currents.

[xi] See Appendix 4 for a discussion of load characteristics.

[xii] Based on the Electrical Generating Systems Association (EGSA) standard 101P. http://www.egsa.org/.

[xiii] Other voltage levels and neutral connections are possible but less common. Isolation transformers may be used to achieve these output voltages from an inverter optimized for maximum rating. Non-standard arrangements may require an interposing transformer.

[xiv] "Reasonable" means within IEEE 519 recommendations for voltage at the Point of Common Coupling (PCC). Some DC offset may be caused by commercial/industrial loads (e.g., light dimmers, rectifiers). Load induced DC offset must not interact with the MT control. (Although we might be able to offer the utility a service by actively canceling load induced DC currents). Requirements may also be set by IEEE std. P1547.

[xv] This range is typical of industrial drives.

[xvi] Other voltage levels and neutral connections are possible but less common. Isolation transformers may be used to achieve these output voltages from an inverter optimized for maximum rating. Non-standard arrangements may require an interposing transformer.

[xvii] Based on the Electrical Generating Systems Association (EGSA) standard 101P. http://www.egsa.org/.

[xviii] In general, a microturbine can not match a utility grid connection for stiffness and overload capability. Considerations for defining this requirement are EGSA std. 101P and protection coordination. For scenarios where the microturbine is unable to operate downstream protective devices, a properly coordinated undervoltage protection trip feature is required.

The overload capability can be automatically adjusted in grid parallel mode for those applications that require limited fault current contribution. In general, we should be able to satisfy the overload with increased reactive current that will not require more turbine/alternator capability. Cost and size tradeoffs with overload rating must be studied.

[xix] Single phase non-linear loads draw triplen harmonics that are additive in the neutral. Although the NEC requires full rated neutrals for this type of load, according to [1] the resulting magnitude may reach 173% of the rms phase current. There are no US standards for limiting harmonic currents from single-phase loads and, according to [1], no standards for sizing neutral conductors to accommodate this type of loading. See Appendix 4 for additional discussion.

[xx] Based on the Electrical Generating Systems Association (EGSA) standard 101P. http://www.egsa.org/

[xxi] See also the IEEE paper "Flicker Limitations of Electric Utilities", PAS-104, 1985. The flicker curve specifies a maximum voltage-magnitude change based on the repetition period of the load. IEC flicker standard 1000-4-15 (formerly IEC 868) may apply. Also reference EN 61000-3-3 and 60555-3.

[xxii] By extension of the IEEE paper "Flicker Limitations of Electric Utilities", PAS-104, 1985

[xxiii] Attributed to ITI - Information Technology Industries Council

[xxiv] IEEE 141, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants. EGSA std 101P recommends "that efforts are made to balance system loads between phases within approximately 20%".

[xxv] The issue is excessive excitation current and distortion in typical transformers due to magnetic saturation. DC currents must be kept below typical levels of magnetizing current. Other concerns are motor saturation and corrosion of the grounding system caused by dc currents.

[xxvi] See Appendix 4 for a discussion of load characteristics.

[xxvii] Deviations up to +/- 0.5 Hz generally acceptable for most loads. Reference IEEE Std 446-1995, IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications.

[xxviii] Reference IEEE Std 446-1995, IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications.

[xxix] Other voltage levels and neutral connections are possible but less common. Isolation transformers may be used to achieve these output voltages from an inverter optimized for maximum rating. Non-standard arrangements may require an interposing transformer.

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[xxxi] This range is typical of industrial drives.