Advanced Microturbine Systems

Program Plan for Fiscal Years 2000 through 2006

March 2000

U.S. Department Of Energy
Office of Energy Efficiency and Renewable Energy
Office of Power Technologies

Table of Contents

Executive Summary

This multi-year program plan outlines proposed activities of the Department of Energy, Office of Energy Efficiency and Renewable Energy to develop advanced microturbine systems for distributed energy resource applications. These systems range in size from 25 kilowatts to 1,000 kilowatts.

Since 1994 hundreds of industry executives from various industries have met in dozens of vision and roadmap workshops to discuss the elements critical to success in the global marketplace over the next twenty years. Cleaner and more efficient, affordable, and reliable heat and power systems is one of the most prominent re-occurring needs raised during these sessions.

The rapidly changing marketplace for utility energy services is opening new opportunities for the nation's heat and power users to reduce energy costs, increase power quality and reliability, and reduce environmental emissions. In addition, over the next twenty years, a significant portion of the nation's aging stock of boiler and power generation equipment will reach its useful life and need to be replaced.

One opportunity is investment in smaller-scale distributed energy resources that can be integrated into overall manufacturing plant or building operations. These technologies can be controlled locally to optimize performance and satisfy needs for both electricity and thermal energy. Energy managers and building operators want to have heat and power services for less cost, less emissions, better reliability, and greater control than what they can get from the utility grid. Because of their compact size, modularity, and potential for relatively low cost, efficient, and clean operations, microturbines are emerging as a leading candidate for meeting these needs for electricity and thermal energy.

The mission of this program is to lead a national effort to design, develop, test, and demonstrate a new generation of microturbine systems that will be cleaner, more fuel efficient, more fuel-flexible, more reliable and durable, and lower cost than the first generation products that are just entering the market today. This mission is consistent with the goals set forth in the Department's Comprehensive National Energy Strategy to improve the efficiency of the energy system, ensure against energy supply disruptions, expand future energy choices, and promote energy production and use in ways that respect health and environmental values.

This plan covers fiscal years 2000 through 2006. The projected funding requirement for the program is $63 million in appropriations from the U.S. Congress and at least $63 million of additional funding is expected in cost sharing.

The program's planned activities are aimed at achieving the following performance targets for the next generation of advanced microturbine systems:

- **High Efficiency -** Fuel-to-electricity conversion efficiency of at least 40 percent.
- **Environmental Superiority -** NOx emissions lower than 7 parts per million for natural gas machines in practical operating ranges.
- **Durable -** Designed for 11,000 hours of operation between major overhauls and a service life of at least 45,000 hours.

- **Economical -** System costs lower than $500 per kilowatt, costs of electricity that are competitive with alternatives (including grid-connected power) for market applications, and the option of using multiple fuels including natural gas, diesel, ethanol, landfill gas, and other biomass-derived liquids and gases.

There is a tremendous amount of uncertainty about the market potential of microturbines. Markets could evolve in ways to make the impact significant. Microturbines could be the kind of "disruptive" technology that causes users to abandon business-as-usual practice.

There is considerable interest in using microturbines for stationary power applications in the industrial, commercial, institutional, and residential sectors of the economy. Based on current practices, the most attractive industrial opportunities lie in the chemicals, wood and agricultural products, petroleum extraction and production, mining, and textiles industries. Potential commercial sector markets for microturbines include office buildings, restaurants and food services, and retail services. Institutional markets include hospital complexes, schools and university campuses, government buildings and facilities, and office/industrial power parks. Residential markets include multi-family dwellings and community-based systems.

The majority of the potential market involves applications that have needs for thermal and mechanical energy as well as electricity. This means that the largest opportunity for microturbines could be as the "prime mover" in cooling, heating, and power (CHP) systems and as a clean power source for distributed generation applications.

Realizing the full market potential for microturbines will help keep U.S. manufacturers on the "cutting edge" of turbine technology for power generation and enhance the industrial competitiveness of the U.S. manufacturing base in international markets. This could be lead to the creation of high-paying jobs for American workers. Realizing this potential could also produce substantial public benefits in terms of lower energy consumption, lower industrial energy costs, and lower emissions.

The program's RD&D activities have been organized in four main program areas: 1) Concept development, 2) Components, subsystems, and integration, 3) Demonstrations and 4) Technology base (which includes materials development, combustions systems, and sensors and controls). This program's activities in these areas will be implemented over a seven year period. The primary implementation mechanism will be competitive solicitations.

Figure 1 depicts the expected portfolio mix and shows how the emphasis could change during the implementation of the program. Potential RD&D performers will be able to participate at any point in the program. Concept development will be emphasized during the first several years of the program. The development and testing of components, subsystems and integrated systems will be a major emphasis during the middle years of the program, but efforts will be supported in this area from the outset, depending on proposals received from potential bidders. Pre-commercial demonstration(s) of advanced systems will be emphasized during the last several years of the program but support will be provided for demonstrations of existing microturbine systems and subsystems from the outset. Potential RD&D

performers will be able to opt in and out of these various activities during the course of the program depending on their capabilities, corporate interests, and the progress of the RD&D.

This program will be managed by the Office of Power Technologies with assistance from the Department's Chicago Operations Office. Implementation will be accomplished by a competitive solicitation process that will result in projects by equipment manufacturers, universities, and national laboratories. Coordination will involve the Offices of Industrial Technologies; Buildings Technologies, State and Community Programs; and Fossil Energy; and equipment manufacturers, electric and gas utilities, energy services providers, project developers, and other federal and state agencies. Joint planning activities are currently underway with the California Energy Commission, the New York State Energy Research and Development Administration, and the Association of State Energy Research and Technology Transfer Institutions in accordance with *memoranda of understanding* that the Department has signed with these organizations.

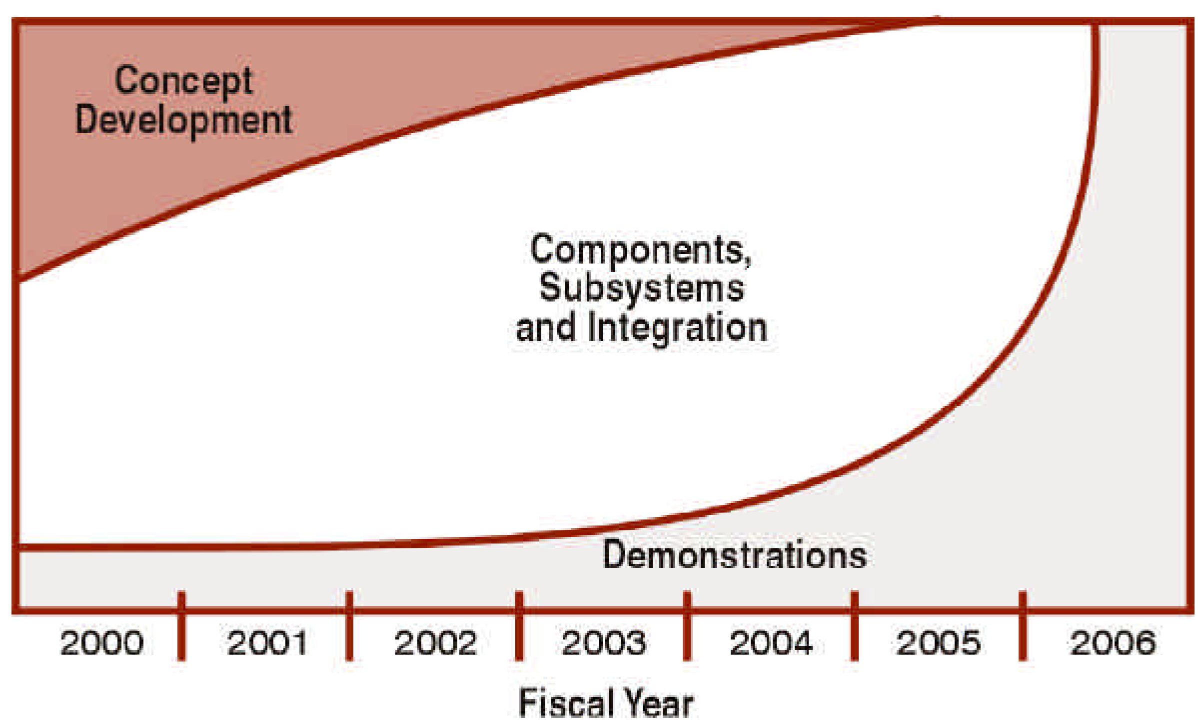

Figure 1. Program diagram

1. Introduction

This document presents the multi-year plan of the Department of Energy's *Advanced Microturbine Systems Program*. The plan outlines the mission, goals, performance targets, and proposed research, development, and demonstration (RD&D) activities of the program over the next seven fiscal years (2000 through 2006).

This program will be managed by the Office of Power Technologies in the Office of Energy Efficiency and Renewable Energy. The program's strategy is to conduct research, development, and demonstration (RD&D) projects in collaboration with industry, universities, and the national laboratories to accomplish a discrete mission in a fixed period of time.

This program will culminate in an 8,000 hour field test demonstration of the next generation of microturbine system(s). It is expected that this design will be ready for commercialization by manufacturers and installation by industrial power users early in the next century. Reliability, availability, maintainability, durability (RAMD) testing will probably involve field demonstrations exceeding 8,000 hours of operation. Government involvement in such efforts will be considered at that point in the program. This program strategy is similar to the one used successfully by the Advanced Turbine Systems Program in developing a new generation of industrial turbines. However, as shown in Figure 1, this plan calls for the mix of activities to evolve over the course of the program.

U.S. industries such as petroleum refining, chemicals, pulp and paper, steel, aluminum, and light manufacturing are among the biggest electricity users in the economy and currently rely heavily on utility generation, self generation, and combined heat and power systems to meet their electric power needs. With the restructuring of electric power markets, these industries are finding a wide array of new electric power opportunities including distributed generation, innovative pricing and risk management strategies, and energy management services. Industrial interest in distributed generation technologies such as microturbines and reciprocating engines is rising because these systems can cut power costs and boost reliability while lowering overall emissions.

Microturbines can also be used in commercial, institutional, and residential buildings. Promising commercial building markets include offices, restaurants and food services, and retail services. Institutional markets include hospital complexes, schools and university campuses, industrial/office power parks, and government buildings and facilities. Residential markets include multi-family dwelling and community energy projects. It will take some time for customers, manufacturers, and energy services providers to identify and exploit all of the promising applications markets for microturbines.

As defined for this program, the microturbine system comprises the flange-to-flange microturbine core, rated at up to 1000 kW at ISO conditions. The system definition includes all secondary components such as the fuel compressor, recuperator/regenerator, generator or alternator, CHP equipment, sound attenuation, and power conditioning equipment. Although further development of power conditioning equipment could result in easier interconnection by microturbine systems with the grid, the system definition of secondary components does not include equipment solely for that purpose.

Microturbines offer a number of potential advantages compared to other technologies for small-scale power generation; for example, a small number of moving parts, compact size and light weight, multi-fuel capabilities, and opportunities for greater energy efficiency, lower emissions, and lower electricity costs. Realizing these advantages would mean substantial public benefits in terms of cleaner, more affordable, and more reliable power options for the nation's electricity users.

The size range of commercial microturbines varies and depends primarily on economics and customer power needs; but technical constraints and permitting/policy considerations are also factors. In recognition of the diversity of potential applications, and the need for flexibility in designing the next generation of microturbine systems, this plan does not contain an exact specification for the size of the next generation of microturbine systems. That decision will be made by the system designers and manufacturers based on market needs and opportunities. Existing microturbine systems range in size from 25 to 75 kW; future products up to 1000 kW are planned. It is expected that the advanced microturbine prototype developed under this program will be in the 25 to 1000 kW range. Support for larger advanced microturbine systems could be provided if those designs represent evolutionary changes in microturbine development.

The specifics outlined in this plan are the result of numerous consultations with industry experts and market studies that have explored the future of distributed energy resource technologies and the potential role of microturbines in industrial, commercial, institutional, and residential power applications.

For example, the *Microturbine Technology Summit* was held in December 1998 as part of the consultation process to discuss the future outlook for microturbines including public policies, market barriers and opportunities, and technology challenges.[1] More than 60 stakeholders with expertise in microturbines, utility systems, industrial power and markets, and government regulations attended the Summit.

Among the issues raised at the Summit was the need for the Department of Energy to establish RD&D partnerships with industry to develop the next generation of microturbine systems. The stimulus created by government involvement was deemed a necessary ingredient for overcoming the engineering, technical, and institutional barriers facing the development and deployment of the next generation of microturbine systems.

In the absence of a focused and appropriate government role, the Summit participants generally agreed that industry would not be able to develop the next generation system on their own and a substantial opportunity for cleaner, more reliable, and more affordable power options for the industrial, commercial, institutional, and residential sectors might be lost.

Market studies have been conducted by Arthur D. Little, Incorporated[2] and Resource Dynamics Corporation[3] to estimate the potential for microturbines and other small-scale power systems such as fuel cells and reciprocating engines to meet power needs in the future industrial market. Based on current industry practice, both of these studies identified potential markets for microturbines in the manufacturing sector serving needs for continuous power generation, peak shaving, back-up generation, remote power, premium power, and combined heat and power. The studies found that certain scientific, engineering, and institutional barriers would need to be addressed and cost, efficiency, and emissions performance targets achieved for the market potential of microturbine systems to be fully realized. Many of the same applications and barriers that the studies found for the manufacturing sector also apply to the commercial, institutional, and residential sectors.

[1] Summary of the Microturbine Technology Summit *prepared by Energetics, Incorporated for Oak Ridge National Laboratory, March 1999 DOE/ORO 2081.*

[2] Opportunities for Micro power and Fuel Cell/Gas Turbine Hybrid Systems in Industrial Applications *prepared by Arthur D. Little for Oak Ridge National Laboratory, April 1999.*

[3] Industrial Applications for Micropower: A Market Assessment *prepared by Resource Dynamics Corporation for Oak Ridge National Laboratory, April 1999.*

2. Situation Analysis and Market Assessment

U.S. consumers used approximately 3,240 billion kWh of electricity in 1998 at a cost of $218 billion. Industrial electricity consumers used 32 percent of the total, commercial consumers used 30 percent, and residential consumers used 35 percent.[4] Electricity sales are expected to grow by 1.4 percent annually over the next twenty years. To meet this growing demand, electric generating capability in the U.S. is expected to grow from approximately 740 gigawatts in 1998 to approximately 957 gigawatts in 2020[5], representing an annual increase of 1.2 percent.

Growth in the use of electricity outside of the U.S. is expected to be even greater. Annual electricity use is expected to grow 2.5 percent worldwide by 2020, including both industrialized and developing countries. For developing countries only, electricity use is expected to grow 4.4 percent annually by 2020.[6]

The role of non-utility generation in U.S. markets is changing. In 1998, over 23 gigawatts of electric capacity were sold by utility companies to non-utility buyers. As a result, the number of states that have a non-utility share of electric generation greater than 25 percent doubled from two in 1998 to four in 1999.[7]

Distributed Energy Resources

The concept of distributed energy resources refers to local energy systems that generate electric, thermal, or mechanical energy on sites near the customer's premise. Also included are energy efficiency measures that can be installed on customer buildings and equipment that affect the need for electricity and thermal energy. Many distributed energy resource systems are located on-site, others are connected to customers through the utility's transmission and distribution grid. Various technologies are used in distributed energy resource applications including combustion turbines, reciprocating engines, solar power systems, wind turbines, energy storage systems, and fuel cells.

One of the factors in the growing interest to use distributed energy resources is concern about the reliability of the existing electric power system, the need to minimize production losses from power outages, the importance of protecting sensitive electronic equipment from power quality disruptions. Industrial processes, manufacturing production systems, and commercial business operations rely on computers, information systems, and telecommunications equipment to a greater extent than ever before. Power interruptions and spikes or sags in voltage or frequency can cost companies millions in lost production and damaged equipment. Many of the companies that have concerns about the reliability of the electric grid under competitive market conditions or who cannot withstand the costs of weather-related disturbances view distributed energy resources as an important supplement or alternative to grid-connected power.

Private investment in the development and deployment of the various distributed energy resource technologies is increasing. This includes investment in advanced technologies for combustion turbines, reciprocating engines, fuel cells, energy storage devices, and solar and renewable power. If these

[4] Electric Power Annual 1998 Volume II *U.S Department of Energy, Energy Information Admninistration December 1999 DOE/EIA-0348(98)/2*

[5] Annual Energy Outlook 2000 With Projections to 2020 *U.S. Department of Energy, Energy Information Administration December 1999 DOE/EIA-0383(2000)*

[6] International Energy Outlook 1999 With Projections to 2020 *U.S. Department of Energy, Energy Information Administration March 1999 DOE/EIA-0484(99)*

[7] Electric Power Annual 1998 Volume I *U.S. Department of Energy, Energy Information Administration April 1999 DOE/EIA-0348(98)/1*

systems are adopted in large numbers, the resulting "distributed energy system," could stimulate new interconnection requirements for the electric power grid and natural gas pipelines. Utilities have been voicing concerns about the safe and effective interconnection of distributed energy technologies and the possibility of negative impacts on electric grid operations. There is a great deal of interest in developing standardized interconnection protocols that balance utility concerns for safe grid operations with the concerns of distributed energy resource developers for quick and low cost interconnection procedures.

For microturbines and other distributed energy resources to be competitive in power markets, electricity costs from these systems will have to be more attractive than they are today. Without cost reductions, most electricity users will prefer grid-connected power and energy-efficient distributed energy resources will be confined to a relatively small market niche.

To achieve these cost reductions, the installed costs of distributed energy resources will have to be lower to reduce the up-front investment for electricity users. In addition, operation and maintenance requirements will have to be lower and service lives longer to reduce the "hassle factor" associated with on-site power systems, the costs of service contracts, the need for major equipment overhauls, and the costs of other day-to-day expenses. Finally, the efficiency and environmental performance of the systems will have to be better to reduce the costs of fuel and compliance with environmental regulations.

Utility Restructuring

The continued restructuring of the electric and natural gas utility industries in the U.S. is expected to increase the role of non-utility generation in the nation's power mix even more. Since 1996, 22 states have enacted major electricity restructuring legislation, while two others have issued comprehensive regulatory orders. These actions have also led to growth in the competitive energy services industry. There is now a greater array of choices for electricity consumers than ever before.

Electricity and natural gas users in the states that are active in the restructuring process are frequently able to get electricity providers to tailor service offerings to suit their individual needs. In particular, the larger industrial and commercial users, including municipalities, school, and irrigation districts, are increasingly being offered flexible contractual terms and conditions, innovative pricing options, financial risk management strategies, energy efficiency audits and services, and distributed energy resource options.

Environmental Policies

Implementation and enforcement of existing environmental laws and regulations affect today's technology choices for power generation. As existing power plants get replaced, the new ones will necessarily incorporate new designs and advanced systems to achieve greater efficiency and lower emissions. Power plant emissions are currently subject to regulatory controls for sulfur dioxide, oxides of nitrogen, particulates, volatile organic compounds, carbon monoxide, and air toxics. In addition, global concerns about climate change have led to interest in tracking carbon emissions from power production. In the future, carbon dioxide and other "greenhouse" gases could be added to the list of power plant emissions subject to regulatory controls.

The designs for advanced microturbines and other distributed energy resource options must include features to ensure that they comply with all foreseeable environmental siting and permitting regulations. The trend is clearly toward increasingly stringent environmental requirements. If the next generation of microturbine systems have lower emissions and higher efficiencies compared to today's models, then commercialization of these advanced products could yield substantial public benefits. Use of clean and renewable fuels, highly efficient combustion equipment and turbines, advanced materials, and advanced recuperators are among the options that can be used to control environmental emissions from microturbine systems. Use of microturbines in combined heat and power systems can double or triple overall thermal efficiency compared to electricity-only units, thus providing even greater opportunities for emissions reductions.

One of the promising applications for microturbines involve their use in buildings for cooling, heating, electricity, humidity control, and indoor air quality. In these cases, building codes and fire and safety codes will need to be considered along with environmental siting and permitting requirements.

Market Applications

Microturbines can be used in a variety of electricity and thermal energy applications due to their small size, low unit costs, and useful thermal output. The market assessments recently completed by Arthur D. Little, Inc. and Resource Dynamics Corporation identified eight potential types of applications for microturbines: 1) continuous generation, 2) peak shaving, 3) back-up power, 4) premium power, 5) remote power, 6) cooling, heating and power, 7) mechanical drive and 8) wastes and biofuels.

The use of microturbines for ***continuous generation*** will typically involve applications requiring over 6,000 hours of operation per year. To succeed in this market application, microturbines will have to be able to generate electricity at costs competitive with grid-connected power. In certain circumstances, users that have deep concerns about the reliability of the grid or about power quality may be willing to pay more for on-site power generation than for grid-connected electricity.

Peak shaving[8] applications for microturbines would typically require much less than 1,000 hours of operation per year. For peak shaving, users would run on-site generation to avoid paying high on-peak prices or utility demand charges. In some areas, avoidance of these costs can justify investment in on-site power facilities that operate only several hundred hours per year. The shift toward competitive electricity markets has also meant a shift toward real-time pricing of electricity. During peak periods, it is not unusual for the cost of power to be 3-5 times higher than it is during off-peak periods. During system emergencies, on-peak power costs can be 10 times greater or more than off-peak power costs. Short term price spikes 20-100 times higher occurred in wholesale spot markets in the Midwest during the summer of 1998.

Back-up power users require 100% reliable electricity. Some users, like hospitals and airports, are required by regulations to install and maintain back-up power units. Back-up power systems may run less than 100 hours per year but they must be ready to come on line at a moments' notice in the event of a power outage. Diesel generators currently have a large fraction of the back-up power market. The use of microturbines in this market will be driven by a variety of factors, particularly their costs relative to diesel generator sets, but also their ability to start-up rapidly and reliably. Relatively low expected O&M costs could be an advantage for microturbines in back-up power applications.

Markets for ***premium power*** exist where the industrial process requires power with a higher quality than provided from the grid. This could include AC power with a well-defined wave form, frequency, and/or power factor. Power quality concerns are found in industries that use sensitive electronic equipment that requires tightly controlled, sinusoidal AC wave forms, or machinery that operates on well-defined DC power. The use of microturbines for premium power could defray power conditioning costs to the user, allow for more precise and flexible manufacturing processes,

[8] Although efficient, clean, durable gas turbines are not necessarily required for intermittent modes such as peak shaving and backup, the incremental cost of installing advanced microturbines for these purposes would extend the parameters for economical operation, thus improving the benefits.

and reduce losses in production from outages and other types of power quality disruptions.

Remote power applications are for off-grid locations such as oil and gas production and certain mining operations. Locations that lack grid access often lack access to natural gas distribution systems as well. The ability to use portable fuels such as diesel or propane is a distinct advantage for remote power equipment. System reliability is a top priority.

Markets for ***cooling, heating, and power*** systems include those manufacturing processes and building applications that have needs for thermal energy as well as electric power. There is potential for expanded use of industrial combined heat and power systems. The possibilities expand when economical off-site uses for the thermal energy are identified, as in district energy systems. The use of microturbines in cooling, heating, and power applications could open up new opportunities for smaller scale systems in manufacturing plants to meet specific needs for thermal or mechanical energy as well as electric power. Buildings cooling, heating, and power systems can provide electricity and thermal energy for cooling and humidity control.

Mechanical drive applications would use microturbines to run shaft-driven equipment such as gas and air compressors, refrigeration units, chillers, desiccant humidity control systems, and pumps. Operation and maintenance costs are a critical driver along with the cost of electricity and the ease of access to fuels.

The market for ***wastes and biofuels*** burning microturbines are found in those industries that produce solid, liquid, or gaseous fuels as a waste or by-product such as pulp and paper, food processing, and steel making. The amount of power produced from these applications is a function of the amount of waste material produced and the technologies available to convert the waste into usable fuel.

Market Potential

The U.S. Department of Energy's Energy Information Administration[9] reports that approximately 380 gigawatts of new electric capacity will be added to the nation's power fleet by 2020, including retirements of existing facilities. The market share for distributed energy resources has been estimated to range from 10 to 20 percent of these capacity additions, or 38 to 76 gigawatts.[10] Because of their compact size, relatively low capital costs, and expected low operations and maintenance costs, microturbines are expected to capture a significant share of the potential distributed generation market.

While substantial, these estimates are based on the assumption that in the future power users will face largely similar power choices under generally similar market conditions. However, there is a widely held alternative view that holds distributed generation as a potentially revolutionary technology with "disruptive" impacts that "...reshape the fundamental value network of an industry."[11] Examples given of other revolutionary technologies that have had disruptive impacts include personal computers, the internet, cellular telephones, and mini-mills. Such possibilities for distributed generation make it difficult to assess the market potential for microturbines.

The technical potential for microturbines in the manufacturing industries has been estimated recently by Onsite Sycom Energy.[12] There are approximately 100,000 industrial sites in the U.S.

[9] Annual Energy Outlook 1999 *Energy Information Administration, December 1998, DOE/EIA-0383(99).*

[10] *"Small Generators Fuel Big Expectations" by John C. Zinc,* Power Engineering*, February 1999.*

[11] Distributed Generation Primer: Building the Factual Foundation *— An Arthur D. Little Multi-Client Study Draft October 1, 1999*

[12] *Onsite Sycom Energy Inc* Estimates of Technical Potential for Micropower in Manufacturing Industies *Technical Memorandum November, 1999*

with average electrical demand between 100 kW and 3,000 kW. This represents about 70 GW of electrical demand today and 91 GW in 2010 that could be supplied by microturbines or other power technologies. For example, electrical demand in the forest products industries at facilities between 100 kW and 3,000 kW is estimated to be about 9 GW in 2010. For chemicals the 2010 estimate is 6.3 GW.

Several recent studies have attempted to estimate the potential industrial power market for microturbines. However, these studies do not take the potential for disruptive impacts into account. They also do not address the full market potential because of the difficulty of capturing the industrial market for mechanical drives or the extent to which grid reliability and power quality will be a factor. The studies also do not account for the market for microturbines in buildings for power, heat, hot water, cooling, and humidity control. Even so, the studies by Arthur D. Little, Incorporated and Resource Dynamics Corporation (see footnotes 2 and 3 on page 2 in the Introduction) conclude that the market potential for existing microturbine products is significant and that the potential market could increase substantially if the cost, efficiency, durability, reliability, and environmental emissions of the existing designs are improved.

3. Overview of Microturbine Systems

Microturbines have primarily evolved from automotive and aerospace applications. Figure 2 is a schematic of a microturbine in a generic stationary commercial or industrial application.[13] For the urposes of stationary energy generation combustion turbines such as microturbines have advantages over other kinds of heat engines in terms of atmospheric emissions, fuel flexibility, noise, size, and vibration levels. Combustion turbines have limitations which include relative efficiency, costs, and rotational speeds. All of these relate directly to the size of the machine. While this relationship between size and performance level generally holds for other types of heat engines, the scaling laws tend to be more restrictive for combustion turbines than for the other types of heat engines, such as piston-driven reciprocating engines, for example.

Within the class of heat engines known as combustion turbines, certain design features as well as size distinguish the various types. Figure 3 illustrates how specific design features relate to the size and performance of turbines. This figure provides a basis for discussing the differences between microturbines and other types of combustion turbines.

Large Combustion Turbines

For electricity generation, large combustion turbines are generally characterized by the following major design features:

- Axial flow multi-stage compressors and turbines
- Internally cooled turbine vanes and blades
- Cooled disks and vane support structures

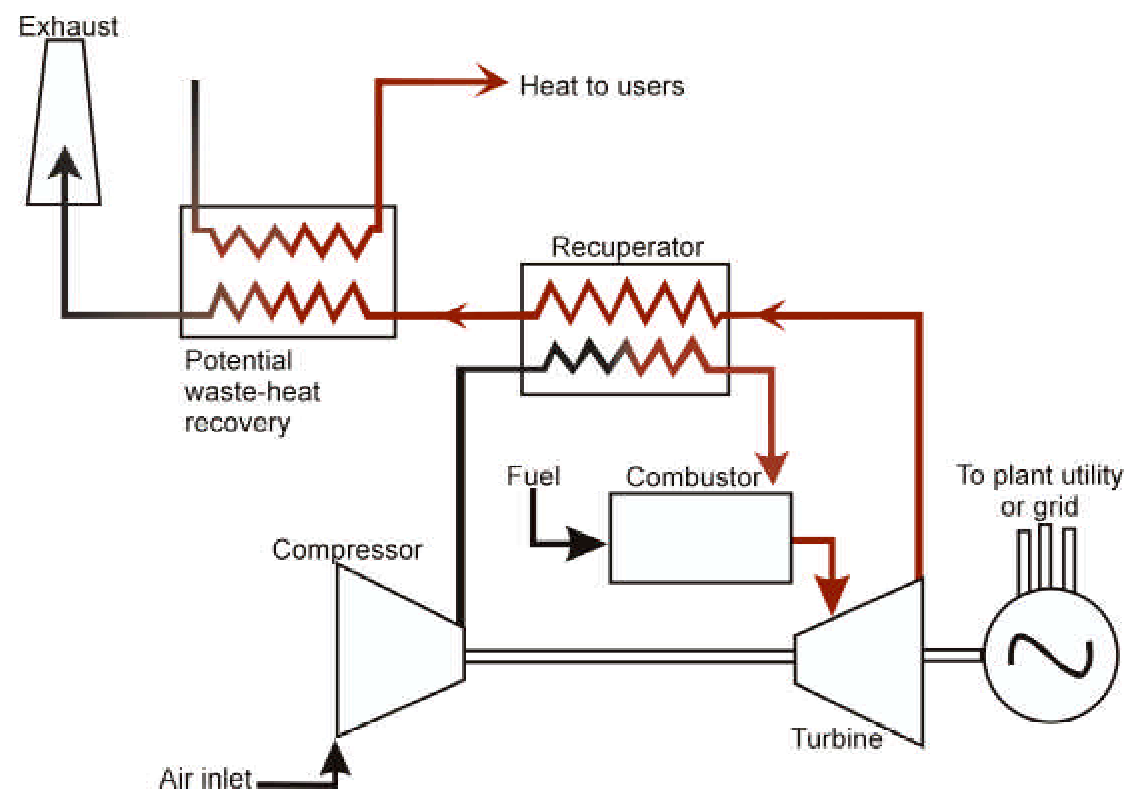

Figure 2. A schematic of a generic microturbine system.

[13] The figure is presented for illustrative purposes and is intended to describe common or possible gas turbine systems. It is not intended to constrain conceptual designs or configurations for advanced microturbine systems.

- Low NO_x combustion systems based on lean premix for natural gas or water/steam injection for fuels other than natural gas
- Multiple burner combustion systems
- Single shaft layouts

The larger size systems (150-400 megawatts) frequently are designed for use with steam bottoming cycles, and newer advanced turbine system designs are adopting closed-loop, steam cooling. With this in mind, pressure ratios are typically 16:1. Design features such as intercooling, staged combustion, and methods to reduce parasitic heat losses may also be incorporated.

Aeroderivative Industrial Combustion Turbines

Aeroderivative combustion turbines are generally characterized by the following design features:

- Axial flow multi-stage compressors and turbines
- Higher pressure ratios (over 25:1)
- Higher temperatures (2400º F)
- Internal cooling (as in the large gas turbines)
- Multi shaft arrangements
- Multiple burner combustion systems
- Greater use of advanced alloys, especially single crystal alloys for blade castings

There generally is less use of refinements to reduce heat losses, but more use of variable compressor geometry to improve part load performance. Compressor intercooling may be used, depending on the design of the core aircraft engine and the way in which it is adapted for stationary use.

Heavy Frame Industrial Combustion Turbines

Industrial combustion turbines are generally characterized by the following design features:

- Usually axial flow multi stage compressors, but sometimes radial flow compressors are used in smaller models
- Axial flow turbines
- Single or split shaft arrangements, depending on the application
- Internal cooling in early stage vane rows, but less use of blade cooling and advanced alloys than in other types of turbines
- Cooled disks and vane support structures
- Geared output shafts for electric power

In the industrial turbine size range of 2-20 MW there is a pronounced gradation in the design characteristics. In the larger size ranges, industrial turbine designs tend to be similar to those of the large combustion turbines, although geared output shafts are still usual where electric power is produced. Direct mechanical drive, with a separate power turbine shaft are also used. Gas compression is one example. In the smaller size ranges, radial flow compressors are sometimes used, pressure ratios tend to decrease as size decreases, blade cooling is seldom used, and single side-mounted combustors are often used (rather than the in-line arrangements used in larger turbines).

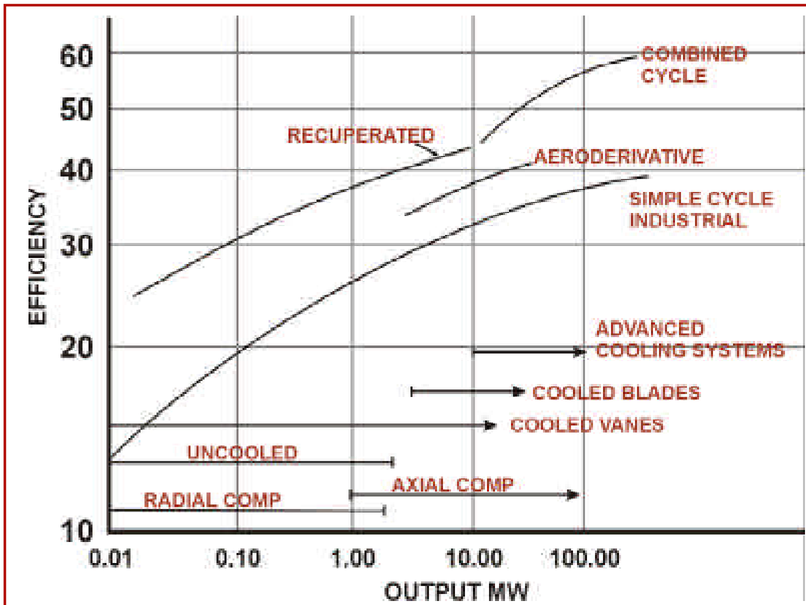

Figure 3. Gas Turbine Design Features Related to Output Capacity

Since economies-of-scale do not apply in the smaller size ranges, design simplification and production economics assume greater importance. The materials and mechanical design issues, and the increased aerodynamic penalties associated with smaller size systems, tend to reduce thermodynamic efficiency.

Microturbines

Microturbines are the newest type of combustion turbine that are being used for stationary energy generation applications. There are certain design features that distinguish microturbines from the other types of combustion turbines discussed above. However, there is not a distinct size limit that distinguishes microturbines from smaller sized industrial turbines. In fact, small industrial turbine designs inevitably share some of the microturbine features.As a result, small industrial turbines will benefit from advances made in the design features used in microturbines.

Microturbines are generally characterized by the following design features:

- Radial flow compressors
- Low pressure ratios defined by single-or possibly two-stage compression
- Minimal use of vane or rotor cooling
- Recuperation of exhaust heat for air preheating
- Use of materials that are amenable to low cost production
- Very high rotational speeds on the primary output shaft (25,000 RPM, or more)

With these design elements the simple cycle efficiency (without the use of a recuperator) would be substantially lower than the efficiency of competing systems such as reciprocating engines, particularly in high load factor applications with base-load or intermediate-load requirements. However, for applications such as emergency power, where the duration of operations is relatively low and fuel costs are of secondary concern, where other factors such as ease of installation and maintenance are considered, unrecuperated microturbines may be used.

In many applications the very high rotational speeds require gear reduction equipment. In the case of electricity generation a commonly used alternative is a direct drive high frequency alternator coupled with a stationary rectifier and mains frequency alternator.

Microturbines have been produced in very small sizes (e.g., a few kilowatts), but commercially viable products are in the range of tens to hundreds of kilowatts. This range spans two to three orders of magnitude, and the efficiencies that can be achieved in practice will vary significantly.

Existing Microturbine Systems

Microturbine systems are just entering the market and the manufacturers are targeting both traditional and non-traditional applications in the industrial and buildings sectors including combined heat and power, backup power, continuous power generation, and peak shaving to reduce costs during peak demand periods. So far, four U.S. manufacturers have made commitments to enter the microturbine market. Honeywell (AlliedSignal) is offering a 75 kW product, Capstone has a 30 kW product, Elliott has 45 and 80 kW products, and Northern Research and Engineering Company will have several products in the 30 to 250 kW size range. These manufacturers are entering into marketing and distribution alliances with other firms. Other companies such as Allison Engine Company, Williams International, and Teledyne Continental Motors have expressed interest in developing microturbine products. European (Volvo and ABB) and Japanese (Toyota) companies are also developing microturbine products and are expected to enter the U.S. market within the next several years.

4. Program Mission, Goals, and Strategy

Through partnerships with industry, government, and non-government organizations, the Office of Power Technologies develops and delivers advanced technologies and practices to assist in meeting challenging goals in the areas of renewable resource development, environmental protection, and global competitiveness. The mission of the Office is to lead the national effort to support and develop clean, competitive, reliable power technologies for the 21st century. This mission is accomplished by:

- Encouraging electricity suppliers to choose and deploy renewable energy and energy efficiency technologies on an equitable basis with other supply technologies.
- Addressing the technological and institutional constraints that impede the adoption of renewable energy and energy efficiency technologies worldwide.
- Working with utility, industry, and other stakeholders to realize the full market potential for renewable energy and energy efficiency technologies, both in the United States and in other countries.

The mission, goals, and strategies of the Advanced Microturbine Systems Program support these aims.

The **mission** of the Advanced Microturbine Systems Program is to lead a national effort to design, develop, test, and demonstrate a new generation of microturbine systems that will be cleaner, more fuel efficient, more fuel-flexible, more reliable and durable, and lower cost than the existing fleet of first generation products that are just entering the market today.

The overall ***goals*** of the program are to improve energy efficiency, reduce environmental emissions, and increase the competitiveness of U.S. businesses through the development and deployment of advanced microturbine systems. The program's mission and goals are consistent with the Department's overall goals as set forth in the Comprehensive National Energy Strategy to improve the efficiency of the energy system, ensure against energy disruptions, promote energy production and use in ways that respect health and environmental values, and expand future energy choices.[14]

The program's mission and goals are consistent with the goals of several recent initiatives of the Department of Energy in the areas of energy grid reliability and distributed energy resources. The program can also contribute to the President's Executive Orders on increasing the use of energy efficiency and renewable systems in federal facilities and on increasing the use of bioenergy and biobased products throughout the economy.

The ultimate aim of the program is to produce "ultra-clean, highly efficient" microturbine product design(s) by fiscal year 2006 that are ready for commercialization and achieve the following performance targets:

- **High Efficiency** — Fuel-to-electricity conversion efficiency of at least 40 percent.
- **Environmental Superiority** — NO_x emissions lower than 7 parts per million for natural gas machines in practical operating ranges.
- **Durable** — Designed for 11,000 hours of operation between major overhauls and a service life of at least 45,000 hours.
- **Economical** — 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/optional fuels includ-

[14] Comprehensive National Energy Strategy, *U.S. Department of Energy, DOE/S-0124, April 1998.*

ing natural gas, diesel, ethanol, landfill gas, and other biomass-derived liquids and gases.

There are a number of scientific, engineering, and institutional barriers that need to be addressed for these mission goals and performance targets to be achieved. The ***strategy*** is to implement a multi-year RD&D program that is tightly integrated with research programs on microturbine systems in industry, universities, national laboratories, and other federal programs and agencies. The program will build on recent and existing RD&D efforts sponsored by the Office of Energy Efficiency and Renewable Energy and Fossil Energy and others in advanced materials, combustion systems, turbines and engine components, power electronics, and sensors and controls.

An important aspect of the proposed RD&D activities will be complementary efforts in technology transfer, technical analysis and coordination, and communications. In part, these efforts will help to ensure that the RD&D projects stay well-aligned with market needs. Efforts will be undertaken to monitor and analyze industrial, commercial, institutional, and residential needs for all types of renewable and fossil-fueled distributed energy resources, particularly microturbine systems. Projects to develop information clearinghouses, workshops, program review meetings, and conferences will be undertaken to foster better communications among the many stakeholder groups with interests in distributed generation and microturbines, including federal and state government officials, equipment manufacturers, electric and gas utilities, energy services providers, independent power producers, and potential users from the industrial and buildings sectors.

5. RD&D Needs

For microturbines to reach their full market potential and compete successfully with grid-connected power and other distributed energy resource options such as reciprocating engines, fuel cells, wind, and solar power systems improvements must be made in the technology. While there is a significant market for the existing technology microturbines, improvements in the efficiency, cost, durability, and environmental performance can expand the potential market two-to-three fold.[15]

For example, new system designs are needed as well as improved performance of subsystems and components to increase the efficiency and reliability of microturbines, and to lower system costs. Significant progress can be made through development and use of advanced materials to improve the reliability, durability, and useful life of various subsystems and component parts, and to enable operations at higher temperatures. Long term improvements can come from materials research and development in ceramics and metal alloys to improve recuperators and other system parts including hot section components such as rotors and combustor liners.

In addition, promising designs need to be field tested for users to gain confidence in their performance. Certain problems can only be detected and resolved though monitoring of field installations to determine microturbine failure and maintenance requirements and in answering questions about the service life of the equipment.

Microturbine Systems, Subsystems, and Components

In order to meet the program mission and goals, research must be conducted on the performance of the entire microturbine system, including their integration into market applications and the utility grid. The total system must be designed properly to work together efficiently and reliably. Component integration will be an important task especially as individually improved components are integrated into existing and new product designs. System modeling and simulation will be an important part of this task. System-level RD&D will be important in determining the research priorities for specific components through better understanding of trade-offs in cost, efficiency, and environmental performance.

Modeling and Simulation

To conduct systems studies and develop promising designs for advanced microturbines, it will be necessary to model and simulate the performance of various subsystems and components. A particularly important challenge is combustion modeling to develop more detailed understanding of the emissions characteristics and controls. Work is needed to identify innovative cycles, to optimize cycles, and to optimize heat recovery. Simulation modeling of aerodynamics and heat transfer in turbine blades in small machines will aid in the development of advanced microturbine designs.

Improved models that can simulate operations of complete microturbine systems under a variety of environmental and operating conditions need to be developed to analyze trade-offs in the integration of individual subsystems and components. Also needed are simulation models that can analyze the potential impacts of microturbine systems on the stability and operations of the utility's power grid. These simulations should cover the full range of potential applications for microturbines, including continuous generation, peak shaving, back-up power, combined heat and power, and remote operating modes.

[15] Opportunities for Micropower and Fuel Cell/gas Turbine Hybrid Systems in Industrial Applications *prepared by Arthur D. Little for Oak Ridge National Laboratory, April 1999, and* Industrial Applications for Micropower: A Market Assessment *prepared by Resource Dynamics Corporation for Oak Ridge National Laboratory, April 1999.*

Manufacturing Costs

In commercializing advanced microturbine designs, manufacturing scale-up techniques will be significant in lowering system costs. In fact, existing microturbine systems have yet to be mass produced. Studies are needed to identify scale-up issues for the next generation of systems since these could include greater use of advanced alloys, coatings, ceramic components and other electronic parts. As ceramic subsystems and components are developed and tested, the RD&D effort should include more detailed research and analysis on manufacturing scale-up issues and techniques. Concurrent engineering techniques should be used in the design of ceramic components. The ceramic components design team should consist of both engine and component designers. The concurrent engineering design team should aim for components that can be fabricated at high yields to reduce costs and waste of materials.

Recuperators/Regenerators

Conventional recuperators are sheet-metal heat exchangers that recover some of the heat from an exhaust stream and transfer it to the incoming air stream. The preheated incoming air is then used in the combustion process. If the air is preheated, less fuel is required to raise its temperature to the required level at the turbine inlet. The most effective conventional metal recuperators can produce 30-40 percent fuel savings from preheating.

However, conventional stainless steel recuperators can be used only with exhaust-gas inlet temperatures below 1200° F. At higher temperatures, the metal is susceptible to creep and oxidation, which causes fouling and structural deterioration and leaks, rapidly reducing the effectiveness and life. Advanced metal or ceramic recuperators will be necessary as engine operating gas temperatures increase to increase efficiency. Further recuperator development is needed to reduce costs, extend service life, and enable reliable operation at higher temperatures. Work needs to continue in the development of advanced metal materials and designs that have the capability of operating at higher temperatures and that have improved corrosion resistance. Many of the advanced metal and ceramic materials remain largely untested. Cost effective manufacturing with these materials will play a crucial role in decreasing the cost of advanced recuperators. Manufacturing research is needed to identify cost reduction techniques such as near net-shape fabrication of ceramic recuperator elements that require minimal machining and assembly.

Combustion

To meet market and regulatory requirements and achieve the performance targets set forth by this plan, research on combustion characteristics and emissions is needed. Techniques for pollution prevention and control of the criteria pollutants and carbon dioxide should be researched. Trade-offs among pollution control, energy efficiency, and cost must be understood and optimized. Technologies such as catalytic combustion, hot wall liners, dry controls, lean premix, selective catalytic reduction, and others need to be investigated to determine how they can be applied to reduce NO_x emissions in microturbines.

Other Fuels

Fuel options other than natural gas include diesel, landfill gas, industrial off-gases, ethanol, and other biobased liquids and gases. The development of biomass-derived fuels is a top priority of the Department's *Biobased Products and Bioenergy Initiative* and opportunities to use these fuels for distributed generation need to be explored.

Natural Gas Compression

Natural gas is currently the preferred fuel for microturbines due to favorable costs and combustion and emissions characteristics. Fuel gas compression equipment will be needed in locations where the gas pressure is too low for direct firing in microturbines. Needed are lower cost, more reliable, and more durable gas compression equipment in size and pressure ranges suitable for microturbines. Gas compression equipment have been used in larger power plants, but are not readily available for smaller, low-cost microturbines where capital and O&M costs are critical. A concern to be addressed is that when used in industrial power applications other than continuous power or combined heat and power operations, the starting and stopping of multiple, gas-powered microturbines could place strain on the natural gas supply system, potentially leading to local gas main pressure fluctuations.

Fuel flexibility is a desirable product attribute for industrial power users and is one of the performance targets of this program for microturbine systems. Many potential users of microturbines value the ability to switch fuels to control costs. The capability of a combustor to handle multiple fuels without increasing emissions would greatly increase the number of opportunities for microturbines. For example, the ability to utilize waste fuels could give microturbines an important advantage in expanding its share of the distributed generation market.

Power Electronics

Because most microturbines typically generate high frequency AC that must be converted to DC and then back to grid compatible AC, the systems require reliable and efficient electronic power conditioning devices. Improved power conditioning equipment such as thyristors and inverters would greatly benefit the performance and packaging of microturbines. Other distributed generation technologies as well as conventional power plants would benefit from improvements in these power electronic devices. While power electronic equipment is commercially available, the costs are high due to small production volumes.

Sensors and Controls

Advances in sensing and controls technology enable the optimization of the system in ways not previously imagined. These advances include the development of sensors permitting in-situ combustion and power quality measurement. Advanced controls technologies permit rate optimization, economic load allocation, and predictive and data-centric control. Integrated into advanced distributed sensing and control architectures, these technologies allow new trade-offs to be made in the design that achieve the system requirements called for in this plan.

Advanced Materials

New materials will be a key enabling technology for advanced microturbine systems, subsystems, and components. Advanced materials will have to be designed and tested to endure and perform properly in microturbine-specific environments. These environments will reflect the operating conditions in terms of pressure and temperature.

In fact, a big jump in microturbine efficiency can be achieved with significant increases in engine operating temperatures, and the most likely materials to accomplish this are ceramics. Current microturbine designs utilize metallic components without air-cooling, and the resulting high metal temperatures result in shortened lifetimes. There is a lack of proven low-cost ceramic components for turbines and recuperators for achieving such high temperature operation. In general, research is needed on cost effective, high temperature materials and manufacturing processes for use in microturbine systems as well as design and life prediction tools for subsystems and components.

Structural ceramics such as silicon carbide or silicon nitride have long been considered primary candidates for hot section components in advanced gas turbines. Initial property limitations such as low strength, low Weibull modulus, and poor creep resistance were successfully addressed in a number of materials development programs. In spite of these advancements, recent engine tests have shown that the long-term performance of ceramic components may still be limited by environmental degradation and foreign object damage. In addition to these technology barriers, several manufacturing challenges including high component costs and unacceptable product yields remain to be solved. These challenges can be addressed by the concurrent design of the components.

The materials requirement for recuperators used in near-term microturbines may be categorized by recuperator maximum operating temperatures: 1200°F (type 347 stainless steel), 1500°F (Inconel) or >1600°F (ceramics). These limits are imposed by existing materials properties such as strength and corrosion, oxidation, and creep resistance that affect recuperator failure. Metallic alloys are now usable within the two, lower temperature ranges, while ceramics would be needed for the higher temperature environments if required.

Development of advanced materials for energy technologies is a top priority RD&D area for the Department of Energy and other federal agencies including the Department of Defense, the National Aeronautics and Space Administration, and the National Institute of Standards and Technologies. As a result, there are opportunities to leverage existing RD&D investments in advanced materials and apply them to microturbines through enhancement of existing or creation of new industry-government RD&D partnerships.

Technology Evaluations and Demonstrations

Microturbines are relatively new and untested in commercial applications. Users have no independent, statistically significant data on performance, reliability, and life of microturbines for comparison with reciprocating engine characteristics and grid supplied electricity. In fact, much of the existing field test information on microturbines is considered proprietary and is not widely shared.

Durability, reliability, and useful service life remain significant unknowns for potential users who are trying to decide among alternatives. Both technical performance and O&M costs over the life of the machines must be proven through reliable data collected from demonstrations and field tests.

Computer simulations, calibrated with field data, can be a valuable tool for supporting field testing and demonstration projects.

Achieving fuel flexible systems will be a major technical challenge. Testing will be needed to determine the optimal combustion conditions for different types of fuels.

The market entry phase for the existing generation of microturbines provides an opportunity to gather data and answer a variety of questions about operating performance, cost, and life expectancies. Also, there are concerns to address related to interconnection with the grid.

In general, demonstrations are an area for extensive joint industry-government collaborations, with industry providing the majority of the resources needed. Government involvement can include financial assistance as well as technical assistance in disseminating results to a wide audience of potential users.

Reliability and Durability

Although some testing has been done by the manufacturers, from the customer's standpoint the reliability and durability of microturbines remains unproven. There is a great need to gather data on microturbine systems running in a variety of environments, operating modes, and utility interconnections. Extensive RAMD (reliability, availability, maintainability, durability) testing should be conducted. Government support for RAMD testing beyond the 8,000 hour field test will be considered at that point in the program. Demonstration of the reliability of the hot gas path parts will be especially important. A database of microturbine operating experience is needed and to be made available to potential users of systems. The data could also be used to guide RD&D.

Grid Interconnection

Interconnection with the electric grid has posed a significant barrier to microturbines and other small distributed energy resources. There are disagreements between utilities and developers of distributed energy equipment about how to address this problem. One issue is that interconnection standards vary from utility to utility. Many project developers say they face interconnection standards that require them to use outdated equipment, undertake costly engineering studies, and go through lengthy approval procedures. On the other hand many utilities worry about maintaining reliable grid operations for customers located on feeders where distributed power systems have been installed. The utilities also worry about worker safety issues. The efforts of the Institute of Electrical and Electronic Engineers (IEEE) to develop standard interconnection protocols for distributed generation systems are being supported by the Department. The IEEE activities should be extremely helpful in specifying equipment needs for safe grid interconnection.

With more units placed in the field, a better understanding of the safety and reliability requirements of grid interconnection can be determined. For example, modification of protective relaying schemes may be needed at both ends of the circuit to insure proper coordination between upstream and downstream protective devices and to fully protect line repairmen and equipment.

Application Issues

Packaging of microturbine systems for the full range of potential applications remains an important, market-driven need. For example, microturbines can be used in cooling, heating, and power applications and in this mode they offer large possibilities for public benefits in terms of higher energy efficiency and reduced emissions. Simple water heating and other forms of thermal energy connections are needed so the unit becomes a "plug and play" type of installation.

For cooling, heating, and power and other applications the potential customer base for microturbine systems is still not well understood. At the same time, potential customers are not aware of the product and its capabilities. While this is largely a marketing issue for the manufacturers, demonstrations and reliable data available to the public can play a useful role in serving customer needs. This can be accomplished through field tests that are conducted over a range of applications, geographic locations, and operating conditions.

Table 1 summarizes the research, development, technology evaluation, and and demonstration needs of microturbine systems.

AREA	RD&D NEEDS
Modeling and Simulation	◆ Cost, efficiency, emissions trade-offs. ◆ Impacts on utility system operations.
Manufacturing Costs	◆ Scale-up issues for systems and ceramic parts. ◆ Education of designers on uses of advanced materials.
Recuperator/regenerator	◆ Cost, efficiency, and durability. ◆ Advanced ceramics and metal alloys.
Turbine	◆ High temperature capabilities.
Combustor	◆ Fuel switching capabilities. ◆ High temperature capabilities. ◆ Ultra-low emissions of NOx and other pollutants.
Natural Gas Compressor	◆ Cost, efficiency, and smaller size. ◆ Durability and reliability.
Advanced Fuels	◆ Waste fuels. ◆ Biobased liquids and gases.
Power Electronics	◆ Cost and durability. ◆ Parasitic losses and grid interconnections.
Sensors and Controls	◆ Prognostic health monitoring. ◆ System monitoring.
Materials (Metals Alloys and Ceramics)	◆ High temperature capabilities ◆ Corrosion Resistance ◆ Manufacturing large number of units. ◆ cost, durability, and life.
Reliability and Durability	◆ RAMD testing. ◆ Database on operating experience.
Grid Interconnection	◆ Analysis on grid impacts. ◆ IEEE interconnection standards.
Application Issues	◆ "Plug and play" options.

Table 1. Summary of RD&D Needs for Microturbines

6. RD&D PLAN — FISCAL YEARS 2000 THROUGH 2006

This RD&D plan calls for activities in three main areas toward the development of advanced microturbine systems over the next seven fiscal years. The four areas are:

1. concept development,
2. components, subsystems, and integration,
3. demonstrations, and
4. technology base development.

The Department is planning to co-fund activities with industry in these three areas to produce new technologies that can be developed into commercial products or designs that satisfy the efficiency, economics, durability, and emissions goals of this program. Table 2 summarizes the estimated annual government funding requirements to implement this program. The total government funding requirement over the next seven fiscal years is $63 million. It is expected that the total industry cost share will be fifty percent over the life of the program. Applicants will have the flexibility to allocate the cost sharing requirements among the members of the bidding team.

Industrial plants and commercial, institutional, and residential buildings are important targets for commercial application of the advanced technologies developed under this program. As a result, each funded activity must be able to demonstrate that its products address the needs of one or more of these potential market applications for clean, affordable, and reliable electric power, steam, hot water, process heat, refrigeration, air compression, space heating and cooling, humidity control, and/or mechanical drive.

The Department plans to implement the program by allowing all program areas to be developed simultaneously as depicted in Figure 1 on page iii in the Executive Summary. Potential RD&D performers will be able to participate at any point in the program. The first several years of the program will emphasize concept development. However, projects that design and conduct initial tests of advanced components, subsystems and integrated microturbine systems could also be undertaken. A small effort to demonstrate existing microturbine systems, subsystems, and/or components could also be initiated from the outset of the program, depending on the applications that are received.

The advanced testing, fabrication and prototyping of new components, subsystems and integrated microturbine systems will be emphasized during the middle years of the program. It is expected that the concept development area of the program will be completed by fiscal year 2005.

The last two fiscal years will focus on the completion of an 8,000-hour field test demonstration of one or more advanced microturbine systems that meet the goals of the program.

	REQUESTED		PROJECTED					
	FY 2000	FY 2001	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006	Total
Concept Development	1.5	1.5	1.0	0.5	0.5	--	--	5.0
Components, subsystems, and integration	1.0	5.5	10.0	9.0	9.0	8.0	2.0	44.5
Demonstrations	0.5	1.0	1.0	2.5	2.5	3.0	3.0	13.5
Total[16]	3.0	8.0	12.0	12.0	12.0	11.0	5.0	63.0
Technology Base Development[17]	3.0	5.5	12.0	12.0	12.0	12.0	12.0	68.5

Table 2. Requested and Projected Government Funding Requirements of the Advanced Microturbine Systems Program ($ M)

[16] FY 2000 and 2001 includes funding from the Industrial Distributed Generation Program
[17] The technology base development efforts focus on enabling technologies that support several programs in distributed energy resources including the Advanced Microturbine Systems program.

Concept Development

This area consists of new and novel concepts and conceptual designs that can be developed into commercial products that satisfy the goals of the program. The starting point for activities in this area will be, at minimum, technological concept(s) that have prior experimental evidence that indicate potential for contributing to the development of more efficient and cleaner advanced microturbine systems.

New and novel concepts and conceptual designs will be supported for components, subsystems, and integrated microturbine systems. Successful concept development projects will include preliminary designs for advanced components, subsystems, and integrated systems. Preliminary design studies should include sufficient testing, empirical evidence, and/or computer analysis to prove the robustness of the concept in meeting the goals of the program.

Potential applicants who have an innovative concept but lack the development experience to prepare a detailed design and fabricate and test prototypes can choose to team with firms who have that kind of experience or they can end their involvement in the program after submitting their concept.

Concept development will continue through fiscal year 2004 to leave the door open for new and innovative concepts to have an impact on the design, fabrication, and testing of advanced microturbine components, subsystems, and integrated systems. It will also be possible for applicants to propose new concepts and preliminary designs based on lessons learned from on-going RD&D.

It is conceivable that concept development activities could be supported through fiscal year 2005 as it would be ill advised to rule out the potential for support for truly merit worthy ideas. However, support for concept development beyond fiscal year 2004 is not planned at this time and would ultimately depend on the quality of the concept and the amount of funding available at that point in the program.

Components, Subsystems, and Integrated Systems

This area is expected to cover the majority of research and development activities of this program. The area consists of a wide variety of potential activities that can be aimed at single components, multiple components and subsystems, and/or integrated microturbine systems. Activities in this area will be supported up to the last year of this program. During the program's final year emphasis will be on the 8,000 field test demonstration project(s) of the advanced microturbine system(s).

Activities in this area will begin with the development of detailed designs of the selected components, subsystems, and integrated systems. The detailed designs will include investigations of all process and economic parameters. The analysis will include all facets of operations under a variety of environmental conditions. Detailed designs for the development of components and subsystems will include plans for the subsequent integration into a microturbine system that meets the goals of the program.

The detailed designs will be manufactured and assembled into components, subsystems, and integrated systems suitable for bench-scale testing. Further development studies and testing will be done to verify the design, provide operating and control parameters, and full-scale definition such as allowable operating ranges, sensitivity to fuel variability, and other factors that could affect the cost and performance of the advanced microturbine components and subsystems. This area will include fully verified and tested designs and/or bench-scale prototypes of components, subsystems, and integrated systems.

Design and testing of advanced microturbines will include development of control systems. Such systems will include sensors, controllers, and logic that direct the operation of the advanced microturbine components and subsystems and the integration of the entire microturbine system into the operations of users and the electric power and natural gas distribution system. Control system activities could include hardware and software development for the implementation of operating procedures for start-up, steady operations over usual power ranges, maintenance schedules, and unplanned outages.

Depending on the relative maturation of the technology, detailed design and testing activities of components and subsystems could begin during fiscal year 2000 and will continue through fiscal year 2005.

The design and testing of the advanced microturbine itself will be developed in parallel to the development of components and subsystems to assure compatibility, optimum fit, and functionality. It is possible, but not expected, for work to begin immediately in fiscal year 2000 on a complete microturbine system that meets all of the goals of the program. This activity will be a major aim from fiscal year 2005 through the completion of the project in fiscal year 2006. Such activities include fabrication of a complete microturbine system that incorporates the scientific and engineering principles, components, and subsystems (including controls). The entire microturbine system could be the result of concept development funded under this program, or not. Through testing, computational analysis, and other means, the performance of the advanced microturbine system will be verified and validated to achieve the design parameters. Prior to proceeding to field test demonstrations, the design(s) for the advanced microturbine system(s) must be shown to achieve the goals of the program and account for potential trade-offs in the targets for efficiency, economics, durability, and emissions. Proof testing will be based on natural gas fuels but it should be acknowledged that multi-fuel capability is an important marketing issue that advanced microturbines may address under this program.

Demonstrations

One of the first activities in this area will be the development of a plan for conducting field test demonstration projects over the course of the program. Because of the small size and modularity of microturbine units, it is critical to obtain operating data across a wide range of sites, sizes, environmental conditions, and applications. Because of funding constraints, it will be necessary to limit demonstration projects to those that offer the greatest information and value.

As mentioned, the focus of the demonstration activities in the last two years of the program will be on an 8,000 hour field test of the advanced microturbine system(s). Reliability, availability, maintainability, durability (RAMD) testing will probably involve field demonstrations exceeding 8,000 hours of operation. Government involvement in such efforts will be considered at that point in the program. Throughout the program, demonstration projects will be supported to obtain information on components and subsystems (including controls), as long as those activities can be shown to contribute to achieving the goals of the program.

At minimum, all demonstration projects will be designed for 4,000 hours of operation. Host sites will be sought from industrial, commercial, institutional, and residential buildings and will cover a range of geographical and weather conditions and include buildings cooling, heating, and power applications, if possible. Each demonstration project will include a coordinated plan for the demonstration that incorporates the perspectives of all parties and explains how the results will be disseminated to interested users. The plan will include a discussion of assignment for responsibility of various tasks including business arrangements, balance of plant equipment, site construction, licenses and permits, site integration, periodic inspections, third party visits, data acquisition, and reporting.

Demonstration projects must be representative of significant market segments or applications of the distributed power generation industry. Successful demonstrations will be expected to exemplify resolution of critical engineering and/or institutional barriers such as interconnection with the local electric power and/or natural gas distribution system.

Because of the widespread perception of utility interconnection as a barrier to the use of microturbines and other distributed power systems, it is expected that most of the demonstration projects will address this issue. In this regard, it is expected that all hours of operation accumulated under the demonstrations shall be gained while the microturbine is generating electric power. Additionally, all such hours of operation may be accumulated while the host site is interconnected with the existing electric power and natural gas distribution grid. However, information from demonstrations of mechanical drive and combined heat and power applications are also encouraged. Accelerating the use of cooling, heating, and power systems is one of the top priorities of the Department.

Technology Base Development

The technology base development effort is a crosscutting activity that contributes to several programs in distributed energy resources, including the Advanced Microturbine Systems program. This area consists of work in advanced combustion systems, materials, and sensors and controls that could be used in the development of advanced microturbine concepts, subsystems, components, and integrated systems. The most critical issue facing users of advanced combustion equipment are increasingly stringent environmental standards for air emissions. One of the major targets will be continued development of low NO_x burner technologies. Also needed are combustion processes for using biobased, wastes and off-gases, and low Btu fuels cleanly and efficiently. One of the more promising areas of advanced materials development is in engineered ceramics such as continuous fiber ceramic composites and advanced metal alloys for high temperature operations of turbine systems. Efforts are underway for demonstrating advanced materials such as engineered ceramics and alloys in advanced turbines. These efforts need to be continued for microturbine applications. Advanced sensors and control systems are needed to support microturbine development and application in buildings and manufacturing process environments. Data acquisition systems for gathering and processing measurements on performance parameters could lead to expanded use of adavnced microturbine systems in distributed energy resource applications.

7. Program Management Plan

This program will be managed by the Office of Power Technologies in the Office of Energy Efficiency and Renewable Energy. A number of other organizations will be involved in the implementation and coordination of the planned RD&D activities. Figure 5 outlines the program structure and lists some of the major organizations that will be involved in the implementation and coordination of the program.

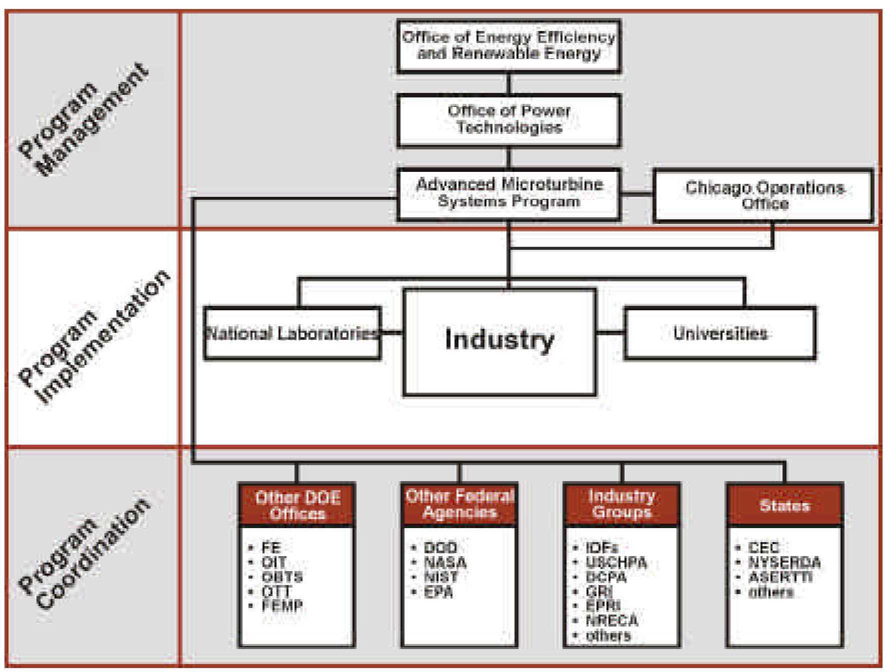

Figure 4. Program Structure

Program management responsibilities include development and defense of the program's annual funding request to Congress, development and dissemination of programmatic guidance and technical directions, coordination with related programs, priority setting, procurements, monitoring and tracking of projects, and achievement of the program's mission, goals, and milestones. To assist in carrying-out these functions, the Chicago Operations Office will be assigned responsibility for conducting major procurements and for managing the execution of work by the industrial teams.

Program implementation will be handled primarily by a variety of private industry contractors; the national laboratories and universities will also be involved. Selection of specific performers will be determined by a series of competitive solicitations and direct contracting under existing competitively awarded contract mechanisms. Periodic program review meetings will be held to track progress toward completion of program milestones.

Coordination with other offices in the Department, other federal agencies, industry groups, and state agencies is an important program management responsibility. Within the Department, the Office of Industrial Technologies (OIT) is working on the *Industries of the Future* process, including manufacturing needs for industrial power and cooling, heating, and power technologies. The Office of Buildings Technologies and State and Community Programs (OBTS) is developing advanced energy systems for buildings. The Office of Transportation Technologies (OTT) conducts research and technology transfer activities in advanced combustion technologies and high temperature ceramics for vehicle engines. The Federal Energy Management Program is promoting the use of renewable energy, energy efficiency, and distributed energy resource technologies in federla buildings and facilities. The Office of Fossil Energy (FE) conducts research for large-scale gas turbines for central station utility applications. Coordination with these offices will include identification of opportunities for cost sharing of joint activities.

There are other federal agencies that have RD&D programs related to the development of advanced microturbine systems. These agencies include the Department of Defense (DOD), National Aeronautics and Space Administration (NASA), Environmental Protection Agency (EPA), and the National Institutes of Standards and Technologies (NIST). Opportunities for joint sponsorship and other forms of collaboration will be explored with these agencies.

There are a number industry groups that have interest in or conduct RD&D activities related to microturbines. The end user industries that have the greatest estimated market potential for microturbines include food processing, large and small chemicals, mining, oil and gas production and exploration, pulp and paper, wood product, and textiles. This group includes several of the Industries of the Future (IOF). The utility industry (electricity and natural gas) have significant interest in microturbine development including a number of individual utility companies, energy services companies, and independent power producers. Several industry groups have formed that have specific interest in distributed power technologies including microturbines. These groups include the U.S. Combined Heat and Power Association (U.S.CHPA), the Distributed Power Coalition of America (DPCA), and the California Alliance for Distributed Energy Resources (CADER). Research organizations such as the Electric Power Research Institute (EPRI), the National Rural Electric Cooperative Association (NRECA), and the Gas Research Institute (GRI) have identified distributed generation in general and microturbines specifically as strategic technology opportunities for their members.

Several states have energy research offices that have interest in microturbine development. For example, the California Energy Commission (CEC) and the New York State Energy Research and Development Administration (NYSERDA) have programs underway, funding available for demonstration projects of microturbine systems, and interest in working with the U.S. Department of Energy. The Association of State Energy Research and Technology Transfer Institutes (ASERTTI), an organization representing agencies in over a dozen states (including the CEC and NYSERDA) also has interest in working with the Department on microturbines. The CEC, NYSERDA, and ASERTTI have already signed memoranda of understanding with the Department of Energy to conduct collaborative activities in a number of areas, including microturbines.