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Collaborative Advanced Gas Turbine Program Phase I

Final Report

Ralph Hollenbacher
Keith Kesser
Dan Beishon

December 1994

Work Performed Under Contract No.: DE-FG21-93MC30180

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Pacific Gas & Electric
San Ramon, California

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Dedication

This report is dedicated to Mr. Holmes "Sandy" Webb of the Department of Energy's Morgantown Energy Technology Center. Until his untimely death in a recent airplane crash, he had been the DOE observer and liaison with the CAGT project. His objective style of conducting research projects and his wealth of experience greatly benefited the CAGT project as it evolved from an analytical study into a desire to develop actual hardware. Sandy's wry sense of humor also made several project meetings seem a lot shorter than they really were. He is deeply missed by all CAGT participants.

Description and Purpose

The Collaborative Advanced Gas Turbine (CAGT) Program is an advanced gas turbine research and development program whose goal is to accelerate the commercial availability, to within the turn of the century, of high efficiency aeroderivative gas turbines for electric power generating applications. In this, the first of three planned project phases, research was conducted to prove or disprove the research hypothesis that advanced aeroderivative gas turbine systems can provide a promising technology alternative, offering high efficiency and good environmental performance characteristics in modular sizes, for utility applications in the next decade.

This $5 million, Phase I research effort reflects the collaborative efforts of a broad and, significantly, international coalition of industries and organizations, both public and private, that have pooled their resources to assist in this research. Included in this coalition are: electric and gas utilities, the Electric Power Research Institute, the Gas Research Institute and the principal aircraft engine manufacturers. Additionally, the US Department of Energy (DOE) and the California Energy Commission have interacted with the CAGT on both technical and executive levels as observers and sources of funding. The three aircraft engine manufacturer-led research teams participating in this research include: Rolls-Royce, Inc., and Bechtel; the Turbo Power and Marine Division of United Technologies and Fluor Daniel; and General Electric Power Generation, Stewart and Stevenson, and Bechtel. Each team has investigated advanced electric power generating systems based on their high-thrust (60,000 to 100,000 pounds) aircraft engines. These aircraft engines power current and planned wide body aircraft. Industrial versions of these engines currently in the electric power generation market include: the 40 MW, General Electric LM6000, based on GE's 60,000 pounds of thrust CF6-80C2 aircraft engine, and the recently introduced 50 MW, Rolls-Royce Trent, based on the Trent 800 aircraft engine. The Trent 800 is scheduled for flight certification at 90,000 pounds of thrust in January, 1995. Turbo Power and Marine is planning to introduce an aeroderivative version of the Pratt & Whitney PW4000, currently rated at 84,000 pounds-of-thrust, but has made no official product announcement to date.

The ultimate goal of the CAGT program is that, by close and cooperative collaboration, the community of stakeholders in the growing market for natural-gas-fueled, electric power generation can collectively provide the right combination of market-pull and technology-push to substantially accelerate the commercialization of advanced, high efficiency aeroderivative technologies.

Research Approach

The manufacturer-led research teams contracted to complete three primary research tasks in Phase I: an advanced cycle screening study, a site specific design study and a commercialization plan. These activities were designed to determine: (1) what performance levels can be achieved with aeroderivative engines and advanced cycles, (2) whether the cost and performance goals established for these advanced engine and cycle concepts are attractive in comparison to competing industrial gas turbine systems, and (3) how to encourage and/or accelerate the development process.

The Technology Base

The most significant factor in defining the potential performance of advanced aeroderivative cycles that could be developed over the next 10 years was each aircraft engine manufacturer's technology base. These technology bases, which defined the limits of what could be achieved in advanced cycles, include: 1) the existing turbomachinery and technologies incorporated into current high-thrust aircraft engines, 2) ongoing gas turbine technology development programs, and 3) the capability to quickly design and develop new components from existing technologies.

Aircraft engine manufacturers were chosen for this research effort because they are the world leaders in state-of-the-art high temperature gas turbine materials and cooling technologies, technologies that are critical for improving gas turbine performance. Traditionally, due to the high cost, the development of advanced gas turbine technologies has been financed primarily by government research grants for military and space applications. Subsequently, these advanced technologies are transferred first to high volume commercial aircraft engine applications, which can justify the additional development costs, and eventually to the smaller volume industrial gas turbine markets. Gas turbine technology transfer from aircraft engine to industrial applications has typically occurred by either developing aeroderivative versions of aircraft engines or through technology transfer agreements with industrial gas turbine manufacturers. Due to problems with the significantly larger scale-up required and the significantly smaller and changing market volume, this latter approach has resulted in a significant lag between the time advanced technologies begin service in commercial aircraft engines and when they are used in industrial applications.

The new high-thrust aircraft engines, developed at costs in excess of $1 billion each to compete in an aircraft engine market valued at more than $60 billion over the next 20 years, were selected because they incorporate some of the world's most efficient high pressure compressor and turbine components and advanced cooling technologies and materials. The larger size of the high-thrust engines also makes them more promising candidates for utility generation than previous aircraft engines.

In ongoing aircraft engine technology development programs, manufacturers have even more advanced materials, air foil cooling and component technologies either operating on advanced military engines or on test stands. These technologies will significantly improve gas turbine performance in the next 10 years beyond that incorporated into current high-thrust engines. Working with aircraft engine manufacturers offers the possibility of accelerating the transfer of these advanced technologies directly to gas turbine systems developed for power generation. A component design and development capability also allows aircraft engine manufacturers to develop advanced aeroderivative components like dry low NO_x combustors that are not common with the parent aircraft engine through technology exchange agreements with industrial partners and current aeroderivative engine component development programs.

Advanced Cycle Screening Studies

A fundamental assumption of all manufacturer-led research teams was that a reasonably priced aeroderivative gas turbine system must use the aircraft engine's high pressure compressor with no modifications other than possibly removing one or two high pressure stages. The reason for this assumption, which established the capacity for all advanced cycles, was that the high pressure compressors are the most expensive aircraft engine components to develop and, correspondingly, are also very costly to modify. In contrast, high pressure turbines, while also expensive to develop are significantly less costly to modify and therefore represent less of a design constraint.

With the size and operating characteristics of the high pressure compressor established, the key elements to obtaining high efficiency aeroderivative gas turbine cycles are:

- compressor intercooling,
- higher turbine rotor inlet temperatures,
- reheat combustor and turbine systems, and
- high efficiency bottoming cycles.

Compressor intercooling improves gas turbine cycle performance by reducing compressor work, increasing mass flow and reducing the high pressure compressor exit temperature which, correspondingly, reduces the cooling air temperature for the high pressure turbine blades and vanes and the combustor. Colder turbine blade and vane cooling air, in turn, increases cooling capabilities allowing the gas turbine to reach higher firing temperatures without raising bulk metal temperatures. In addition, colder combustor cooling air allows the combustor to be cooled with less air, leaving more air for leaning out the combustion process.

Raising the high pressure turbine rotor inlet temperature (TRIT) is the most effective means for improving cycle efficiency. In the past, the ability to raise TRITs was limited primarily by the design limits set by high temperature materials and cooling technologies. Phase I research indicates that with the continuing improvements projected for these technologies, future limiting gas turbine design constraints will be attributable to NO_x formation. For intercooled cycles, TRITs in the range of 2700-2750° F can be achieved with acceptable NO_x emissions. Because NO_x formation increases with increasing combustion pressure as well as temperature, acceptable NO_x levels are defined as levels from which the CAGT program goal of 6 ppm can be achieved by incorporating a selective catalytic reduction unit combined with a dry low NO_x combustion system. Obtaining even higher cycle efficiencies and still maintaining NO_x emissions will require either a gas turbine reheat system or modifications to the combustion process, e.g., using a catalytic (flameless) combustion or moisture injection to lower flame temperature thereby reducing NO_x formation. Gas turbine reheat systems, because they add energy at an intermediate point in the cycle, significantly increase capacity but offer only modest cycle efficiency gains.

The final key element, improving heat recovery performance, is required to take advantage of the heat rejected from the intercooler as well as the lower temperature exhaust heat available from several intercooled cycles. Four high efficiency heat recovered cycles: the chemically recuperated, the humid air turbine, the intercooled steam injected cycles and the Kalina combined cycle were investigated in Phase I. When used in combination with advanced technologies and components, each of these bottoming cycles could theoretically create advanced aeroderivative cycles with net cycle efficiencies of approximately 60%+ (LHV).

Based on the advanced cycle screening study performance results and the estimated development costs, it became apparent that the intercooled aeroderivative (ICAD) simple cycle was an attractive product. This cycle therefore became the focus of all three manufacturer-led research teams' site specific design studies

Site Specific Design Studies

Selecting preferred engine and cycle concepts for detailed evaluation in the site specific design studies proved to be the most difficult task. Phase I differed from more traditional utility research projects in the sense that the research goals were established collaboratively by all of the stakeholders—including the aircraft engine manufacturers. If an aircraft engine manufacturer was going to fund a significant part of the development of these advanced engines and cycles, their commercial venture analysis requirements, i.e., development costs, estimated market, and return on invested capital, must be satisfied. Conversely, to be sold in sufficient quantities to satisfy the venture analysis, they must also satisfy the needs of utility customers more than competing gas turbine systems.

As a precursor to the manufacturer's venture analysis, the advanced screening study cycles were evaluated in three areas: estimated development costs, product development pathways and market potential.

For the cycles studied, estimated product development costs ranged from approximately $75 million to $200 million dollars, depending on cycle complexity. With the simple and combined ICAD cycles representing the lower end of the range and the high efficiency heat recovered cycles like the chemically recuperated intercooled steam injected (CRISTIG) cycle and humid air turbine (HAT) cycle (due to their increased complexity) representing the higher end of the range. For comparison, recent development program costs for industrial gas turbines like the Frame "F"s and aeroderivatives like the Trent have been estimated in the range of $100 million. In general, significant departures from the core engine design and the development of totally new components, like a reheat combustor and turbine system or a totally new power turbine, significantly increased development costs.

Product development pathways were considered as a way of reducing the estimated development costs and technology risks of the more advanced heat recovered cycles. For example, if the intercooled gas turbine was in its own right a successful product that recouped its development costs, then the intercooled gas turbine would provide an expanded technology base for building more advanced cycles. Components and technologies used in the intercooled cycle could also be used in a more complex cycle like a CRISTIG or a HAT, thereby lessening their development costs.

In assessing market potential, all screening study cycles were evaluated in terms of: 1) product positioning, i.e., evaluating aeroderivative cycles against existing and planned gas turbine product offerings, 2) product differentiation, i.e., evaluating the differences between aeroderivative and competing gas turbine cycles and 3) market targeting, i.e., targeting potential markets for these aeroderivative cycles. This methodology was used in lieu of the more common cost of electricity (COE) analysis to compensate for three apparent weaknesses in the COE methodology: 1) the COE methodology tends to favor higher capacity cycles over high efficiency cycles under current natural gas pricing assumptions; 2) it does not consider how gas turbines are actually used, i.e., with varying capacity factors to meet a range of needs from peak to base load; and 3) it is difficult to evaluate niche markets for aeroderivative cycles relative to competing products, e.g., the current and future versions of industrial gas turbines and industrial gas turbine combined cycle power plants. Using the product positioning methodology makes it easier to identify potential niche market opportunities such as the recent successful introduction of the General Electric LM6000.

Product positioning diagrams for simple and recuperated ICAD cycles and high efficiency, heat recovered aeroderivative cycles, e.g., the Rankine combined, Kalina combined, HAT and CRISTIG, are shown in Figures 1 and 2. From the simple cycle diagram (Figure 1), the simple cycle and recuperated ICAD cycles offer a 25% efficiency improvement (approximately 9% LHV) over current Frame "F" industrial gas turbine technology. Assuming that industrial gas turbines retain their high exhaust temperatures, this performance advantage is likely to be maintained even considering the improved performance of the next generation of industrial gas turbines.

Of the high efficiency, heat recovered cycles, the ICAD combined cycles will offer similar efficiencies to current Frame "F" technology (2350° F TRIT) and the next generation of geared, industrial gas turbines (2600° F TRIT) in combined cycle plants. The combined Kalina cycle offers approximately a 2 1/2 point efficiency and a 10% capacity increase over the conventional steam bottoming cycle. The estimated CRISTIG and the HAT cycle performances shown in the shaded bubbles (Figure 2) illustrate a range of advanced technology levels. Because both of these cycles operate at very high water to fuel ratios, NO_x formation is inherently low. This allows these cycles to operate with higher flame and, correspondingly, higher TRITs and still achieve low NO_x emissions.

At the low end of the shaded areas (Figure 2), these cycles assume the same technology level that was used for the upper end of the simple ICAD cycle. This corresponds to technology currently flying in military engines that, given proper R&D support, could be commercialized in aeroderivative engines before the year 2000. The technology level assumed for the upper range corresponds with technology that is currently in use on development engines and could be in use on aeroderivative engines on or before 2003. It should be noted that upper end of the HAT cycle range reflects an optimized HAT cycle that, in addition to the higher technology level, assumes an optimized compressor split which requires a significantly larger low pressure compressor and turbine than are used in the ICAD cycle.

In contrast, the estimated performance for the industrial gas turbine combined cycles assumes that this technology will continue to follow the current trend of increasing firing temperature and adjusting compression ratios to maintain exhaust temperatures in the 1100-1150° F range. Current indications are that industrial gas turbines will achieve 2600° F rotor inlet temperatures by the late 1990s or early next decade. To the extent that industrial gas turbine manufacturers are able to deviate from this trend by adding advanced cycle features like gas turbine reheat and external blade and vane cooling systems, advanced industrial gas turbine performance could potentially be better than indicated (Figure 2). However, CRISTIG and HAT cycle performance are expected to be at least competitive with advanced industrial gas turbine technology available within the same time frame.

Market potential was also assessed in terms of product differentiation or how aeroderivative cycles differ from competing industrial gas turbines that will be commercially available at the same time.

The most striking difference is in the simple ICAD cycle, where the gas turbine topping cycle produces 82% of the available combined cycle power. In comparison, an industrial gas turbine topping cycle produces only 68% of the combined cycle power. Assuming that ICAD can be competitively priced, it would be targeted initially at an intermediate duty rather than a peaking market. Although higher simple cycle efficiency clearly offers utilities greater operating flexibility, this constitutes a new market class for gas turbines that requires buyer education to properly evaluate. In combined cycle, the intercooled gas turbine's smaller bottoming cycle and rapid start-up time offers greater siting and operating flexibility but no significant economic advantages.

The CRISTIG and the HAT cycle, due to their size and lack of cogeneration potential must compete in the bulk, i.e., base load, power market against advanced industrial gas turbine combined cycle plants. To be differentiated from industrial gas turbine cycles, they must offer a lower cost of electricity. It is therefore critical that these cycles offer either higher efficiency and/or lower plant capital costs. The current low cost of natural gas in conjunction with the estimated high development cost of the CRISTIG and HAT cycles relative to historical industrial gas turbine development costs make it unlikely that either cycle could be developed without an intermediate development step, i.e., the ICAD cycle.

Based on this analysis, the manufacturer-led research teams all selected ICAD cycles for more detailed analysis. Additional cycles selected by some of the research teams for more detailed evaluation included: the intercooled recuperated, ICAD combined, ICAD combined Kalina and the HAT cycle. The site specific design studies used site specific design criteria for an inland and a coastal site to develop more detailed evaluation of power plant cost and performance. The most restrictive of the design criteria were the lack of fresh water for both sites and the high ambient peak temperatures at the inland site. Cost and performance goals developed for ICAD cycles in the site specific design studies are shown in Table 1. Study results indicate that ICADs can offer the same advantages of their smaller aeroderivative counterparts in terms of prepackaged, baseplate mounted units that offer easy field installation and quick maintenance turnarounds.

Commercialization Plans

The projected world market for gas turbines, sizes 20 MW and larger, will grow from the current 40% share to approximately 63% of all new generating capacity by year 2015. Of this, gas turbines in the 76-140 MW category, which includes the ICAD, are expected to retain a 24% share of the world market. The larger 140 MW+ sized, large gas turbines will capture the remainder of the market. The ICAD would therefore compete for a significant share of the world gas turbine market. Because this market forecast did not consider the ICAD as a product and the potential of product switching from other turbine sizes, the market potential for the ICAD could be larger than stated.

Product development pathways, Figure 3, to all high efficiency, heat recovered, aeroderivative cycles incorporate intercooling. Although not all cycles can directly use the ICAD's low pressure (LP) compressor, the experience gained in intercooling and operation at high TRITs will significantly benefit more complex cycles. Development costs for ICADs are estimated in the range of $75 to $120 million, depending upon the manufacturer's required component and technology development. These costs compare favorable with the estimated costs of recent aeroderivative and industrial gas turbine development programs. Although total development costs are not as well defined for more complex cycles like the CRISTIG and HAT, successful development of an ICAD will reduce these development costs significantly.

Development plans submitted by each manufacturer indicate that the time required to develop an ICAD will be approximately 4-5 years assuming that adequate development funding is available. For more complex cycles like the CRISTIG and the HAT, the estimated development schedule is 6-9 years. The Kalina bottoming cycle, which is currently under development, could be available within 1-2 years if market economics justify its market entry. All manufacturers stressed the need to adequately define the product and evaluate how the evolving design satisfies the product definition as the development proceeds.

Product pricing is difficult to assess in the context that gas turbine prices are constantly changing due to the normal competitive forces within the industry. Historically, three pricing methods have been used for gas turbines: cost, market and value based pricing. Clearly, no manufacturer would undertake the risk of developing a new product on cost based pricing, i.e., a price based primarily on the manufacturing costs. Aeroderivative cycles must therefore be priced on either market based pricing, i.e., priced competitively with existing products or value based pricing, i.e., priced based on the perceived additional value gained over competing equipment. For all aeroderivative cycles, value based pricing appears to be more likely. For the ICAD simple cycle, the higher efficiency should warrant a premium price. Although difficult to determine, a premium of up to 10% above the equipment price of comparably sized industrial gas turbines appears reasonable. Using current equipment prices of comparably sized industrial gas turbines, GE 7FA ($213/kW) and lower TRIT gas industrial gas turbines like the Asea Brown-Boveri 11N2 and the Westinghouse W501D which range in price from $180 to 215/kW, depending on order size, the ICAD cost should be in the price range of $200 to $240/kW. The upper end of this range is in good agreement with the goal price of $240/kW listed in Table 1. The applications studies indicate that heat recovered aeroderivative cycles like the CRISTIG and the HAT cycle have similar efficiencies to advanced industrial gas turbine combined cycles (~2600° F TRITs). Therefore, any premium price must be based on lower installed plant costs or greater operating flexibility.

Significant barriers exist to market entry of any new product. The gas turbine market, in particular, is known for buyer conservatism. It is very common for gas turbine buyers to buy older technology, even when more efficient and cheaper alternatives exist. To overcome this barrier, manufacturers' must "buy" their way into the market and wait several years to prove the reliability of new gas turbines. Buyer reluctance to own the first-of-a-kind unit increases manufacturer's development costs and risk.

Applications Studies

Applications studies were conducted to determine how aeroderivative cycles would compare with industrial gas turbine simple and combined cycles. These studies confirm that the ICAD has a lower COE compared to simple and combined cycle industrial gas turbines in intermediate duty cycle applications (10 to 60% capacity factor), Figure 4. Due to its aircraft engine parentage, the ICAD also offers lower variable O&M costs than either the industrial simple or combined cycle plants in cycling operation. In base load applications, larger industrial gas turbine combined cycle plants will continue to offer a lower cost of electricity than ICAD combined cycle plants. However, where opportunities to install the larger plant do not exist, the ICAD combined cycle offers a competitive alternative in approximately half the plant size of state-of-the art industrial gas turbine technology.

The performance characteristics of the ICAD offer intriguing possibilities for phased construction, distributed generation, and repowering applications. For risk averse utilities with uncertain load growth, the ICAD provides greater planning flexibility by insuring that regardless of whether an energy or capacity is forecast future requirements can be met with minimal risk. Distributed generation applications are also promising due to the ICAD's greater siting flexibility. Although repowering applications vary considerably depending upon existing power plant equipment, the ICAD's lower exhaust temperature offers opportunities to consider applications like generator repowering, feedwater heating and hot windbox repowering.

NO_x Control Technologies

For ICAD engines, all manufacturers' led research teams proposed the use of dry low NO_x combustion systems based on lean premixed combustion systems. Based on current research, NO_x formation in extremely well premixed flames operating at less than 2960° F: 1) does not vary with gas turbine combustor pressure, 2) is not a function of combustor inlet temperature and 3) does not increase with increased residence time. This indicates that for the same flame temperature high compression ratio gas turbines can achieve NO_x levels similar to lower compression ratio gas turbines.

Research on selective catalytic reduction units was conducted to determine how their performance was expected to improve over the next 5 years and if these catalysts would be able to withstand the approximately 850-875° F exhaust temperatures of ICADs as well as the 1100° F temperatures of industrial gas turbines. Major NO_x catalyst manufacturers indicate that zeolite catalysts capable of performing at the above stated temperatures are currently undergoing field demonstration and are commercially available. These catalysts are capable of achieving up to 95% reduction in NO_x emissions regardless of catalyst inlet concentration.

Conclusions And Recommendations For Further Research

Gas turbine technology is expected to improve dramatically over the next 10 years as a result of government funded defense and space related research programs. This advanced technology promises to benefit both aircraft engines and industrial gas turbines at a time when the electric utility industry is planning a dramatic shift to gas turbine technology for future power generation.

Aircraft engines, due to the emphasis placed on high performance and their large market size, are the commercial market technology leaders. Advanced gas turbine technology has typically been transferred from aircraft engine to industrial gas turbines in two ways: 1) technology transfer agreements between aircraft engine and industrial gas turbine manufacturers, and (2) development of aeroderivative gas turbines. Of the two, aeroderivative engines provide a faster technology transfer mechanism due to the strong economic incentives to develop technology for the parent aircraft engine and the small scale-up issues involved in designing aeroderivative gas turbines.

ICADs are the most clearly differentiated of all aeroderivative cycles (Figure 1). For their size range, ICADs offer high efficiency in both simple and combined cycle and improved siting flexibility. In simple cycle, their biggest target market, ICADs have a sustainable competitive advantage over advanced industrial gas turbines. In addition, estimated development costs, in the range of $80 to 120 million, are similar to the estimated development costs for recently built aeroderivative and industrial gas turbines. The 75-140 MW size range, in which ICADs are positioned, is conservatively estimated to capture a 25% share of the post year 2000 world gas turbine market, indicating that there is sufficient market interest in the ICADs size range.

ICADs provide an excellent vehicle for adapting this advanced technology and proceeding to more complex aeroderivative cycles. The colder cooling air provided by the intercooler enables ICADs to operate at significantly higher TRITs, with higher TRITs being the key element to higher efficiency in all aeroderivative and industrial gas turbine cycles. In addition, rapid technology transfer from the parent aircraft engine will allow ICADs to consistently lead industrial gas turbines in advanced technology and TRITs. Two direct benefits to the electric utility industry of encouraging the development of ICAD engines are providing: 1) an inexpensive test vehicle for demonstrating operation at high TRITs, and 2) a vehicle that makes development of high efficiency heat recovery aeroderivative cycles more affordable.

Based upon applications studies, ICADs offer utility operators significant operating and planning flexibility. For base load applications, the weak economy of scale between the 125-150 MW ICAD combined cycle and the much larger industrial gas turbine combined cycle plants provides the opportunity for small plant owners to compete with the large central station plants in what promises to become an increasingly competitive electric generating market. In distributed generation applications the ICAD's modular size, high efficiency and low water use offers greater siting flexibility allowing them to be sited more easily near major load centers.

The most significant barriers to the development of the ICAD are the reluctance of historically conservative gas turbine buyers to adopt new technologies and the manufacturer's difficulty in determining if there is a significant market interest in a new intermediate duty cycle gas turbine to justify its development costs. Clearly, market interest will help manufacturers develop confidence in offering the product in the same manner that demonstrated operation inspires buyer confidence. If the new intermediate duty cycle class of gas turbines represented by the ICAD is important to utility customers as the data in this report suggests, then it is important for utility gas turbine buyers to take steps to remove these barriers and thereby insure the ICADs development. Suggested ways of reducing these barriers include:

- market verification, i.e., expressing interest in buying the product,
- product definition, i.e., defining product features desired by potential buyers,
- supporting research by both assisting in obtaining DOE ATS Phase III/IV funding and providing research funding targeted at accelerating technology transfer, and
- supporting ICAD demonstration programs.

Each of these methods will be used in Phase II of the CAGT program to assist manufacturers in developing the ICAD.

High efficiency heat recovery aeroderivative cycles also provide promising opportunities to improve upon future industrial combined cycle power plant performance and to reduce plant capital costs. The decision to actually develop either an aeroderivative CRISTIG or HAT cycle will be based on technical and economic considerations that are well beyond the scope of this research effort. However, as a starting point to the development of high efficiency heat recovery aeroderivative cycles, we recommend that additional screening level research is conducted in: 1) high temperature and pressure combustion in high moisture and low oxygen content environments, 2) development and testing of advanced cooling technologies for high TRIT operation, and 3) development and testing of reheat combustion systems. Pursuing this research will help clarify major areas of technical uncertainty involving these cycles and will form a basis for broader technical support in the future.

Each manufacturer has its own technology base and existing product line. They will only develop a product that builds upon the their core technology base and complements or strengthens their existing product line. Given that only limited development support will be available from utility R&D budgets and government funded programs in the foreseeable future, manufacturers are expected to fund most of the development costs for advanced gas turbines. In this environment, the electric power industry is best served by research and development programs like the CAGT program that take a proactive role in helping manufacturers define and build the generating equipment of tomorrow.

Table 1
Cost and Performance Goals For ICAD Simple Cycle Gas Turbines

	Introductory	Advanced
Simple Cycle Capacity (MWe net)	100	125
Net Simple Cycle Efficiency (% LHV)	45%	46%
Turbine Generator Cost ($/kW, Gas Turbine World Basis)	$250	$240
Exhaust Temperature ($^{\circ}$F)	850	875
Combined Cycle Capacity (MWe net)	120	150
Net Combined Cycle efficiency (% LHV)	55%	56%
Minor/Major overhaul intervals (000's of hours)	25/50	25/50
NO_x Emissions with SCR	6 ppm	6 ppm

Figure 1
Simple Cycle Product Positioning Diagram

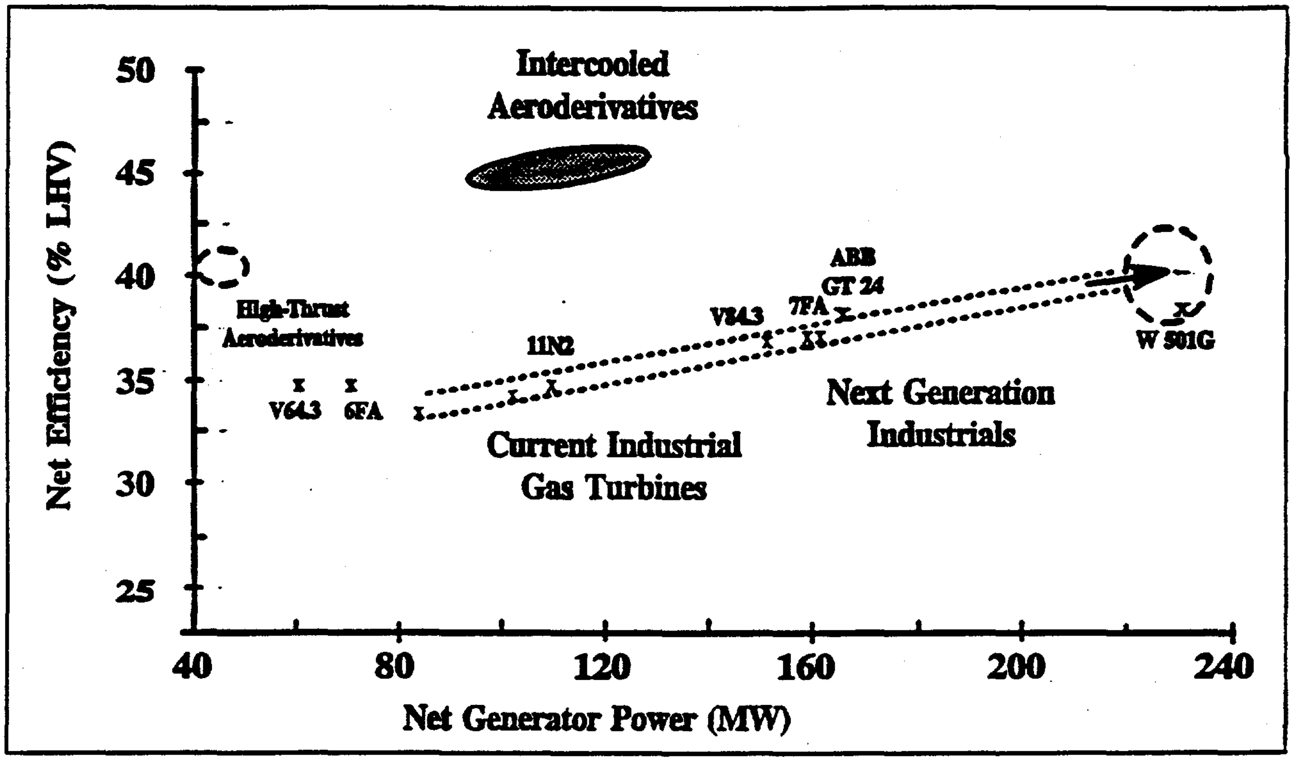

Figure 2
Heat Recovered Cycle Product Positioning Diagram

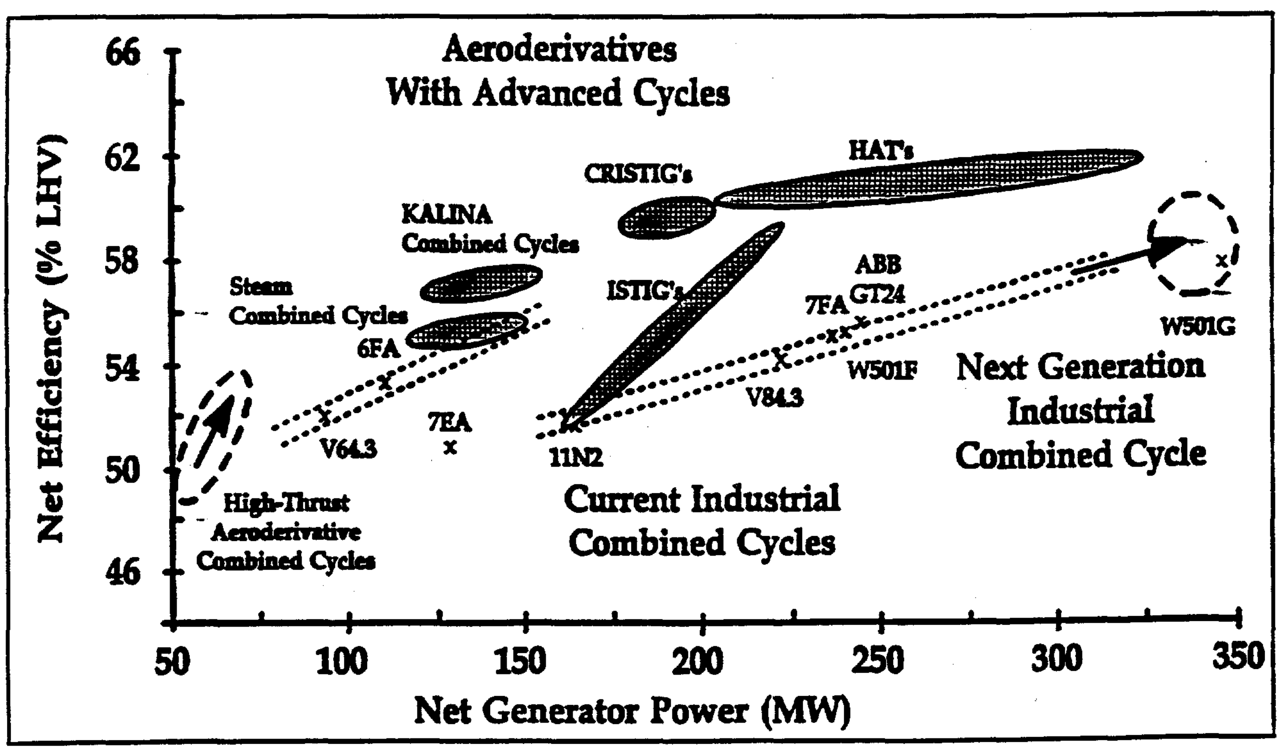

Figure 3
Technology Development Pathway To High Efficiency Gas Turbine Cycles

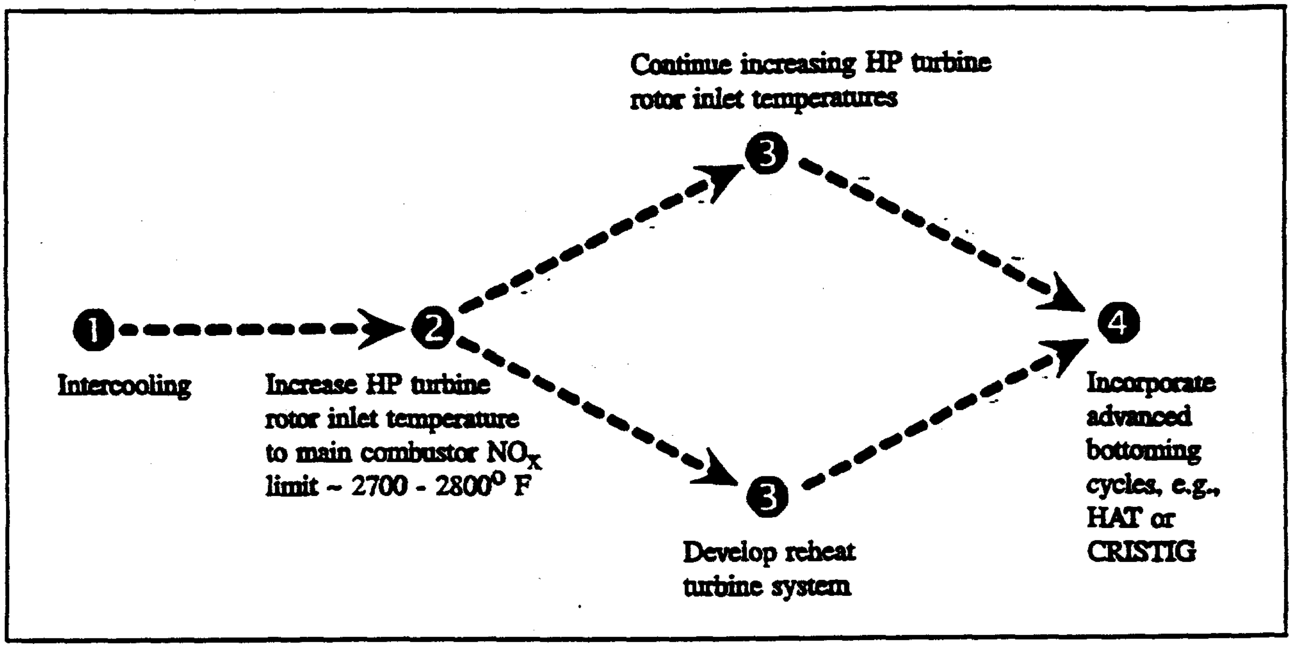

Figure 4
Distributed Generation Energy Cost Comparison