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POTENTIAL BENEFITS OF A CERAMIC THERMAL BARRIER COATING ON LARGE POWER GENERATION GAS TURBINES

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16. Abstract

The purpose of this study was to determine which thermal barrier coating design option offers the greatest benefit in terms of reduced electricity costs when used in utility gas turbines. Options considered include: increased firing temperature, increased component life, reduced cooling air requirements, and increased corrosion resistance (resulting in increased tolerance for dirty fuels). Performance and cost data were obtained via contracts with Westinghouse and United Technologies Corporation. Simple, recuperated and combined cycle applications were considered, and distillate and residual fuels were assumed. The results indicate that thermal barrier coatings could produce large electricity cost savings if these coatings permit turbine operation with residual fuels at distillate-rated firing temperatures. The results also show that increased turbine inlet temperature can result in substantial savings in fuel and capital costs.

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SUMMARY

The purpose of this study was to determine which thermal barrier coating (TBC) design option offers the greatest benefit to the nation when used on the hot section components of utility gas turbine engines. Benefits were measured by cost-of-electricity savings. Some of the design options include: increased turbine firing temperature, reduced cooling air requirements, increased component life, and, possibly, increased corrosion protection - resulting in a tolerance for dirtier fuels.

Performance and cost data were obtained via contracts with Westinghouse and United Technologies Corporation. Simple-cycle, recuperated-cycle and combined-cycle cases were studied. Distillate and residual fuels were assumed. Westinghouse studied the uprating potential of their current production W-501 - a large (~95 MW) single shaft machine. UTC studied the effect of thermal barrier coatings on their FT-50 engine - a multi-shaft, large (~105 MW), high-temperature machine.

Cost-of-electricity comparisons indicate that the largest savings occur if thermal barrier coatings permit operation of utility turbines on residual fuels at distillate-rated firing temperatures. This result is strongly dependent upon the price of the different fuels. In this study, distillate fuel was assumed to cost $2.60 per million Btu, and residual fuel $2.15 per million Btu - a seventeen percent reduction.

Increased turbine firing temperature will also result in substantial cost savings, and thermal barrier coatings may permit this increased temperature. Capital costs are reduced significantly as firing temperatures increase. This benefit is expected to be particularly attractive to the electric power generation industry.

Several other design options were considered and resulted in small benefits. Design improvements made possible by thermal barrier coatings should supplement design improvements made in other technologies, however, such as improved materials or improved cooling techniques.

INTRODUCTION

A study has been made of the potential benefits of ceramic thermal barrier coatings on large, high temperature, power generating gas turbines. The study included an analytical investigation of thermal barrier coatings (TBC) on a large, current-production, single-shaft machine (W-501) by Westinghouse Electric Corporation, Generation Systems Division, and a study of thermal barrier coatings on a large, high-temperature three-shaft engine (FT-50) by United Technologies Corporation (UTC). NASA managed both contract activities and performed an independent assessment of TBC benefits making use of the performance and cost data developed by the two contractors. The UTC contract (NAS3-20067) was funded by the U.S. Energy Research and Development Administration (ERDA), Division of Conservation Research and Technology, and managed by NASA via Interagency Agreement. The Westinghouse contract (NAS3-19407) was funded by the NASA Office of Energy Programs.

The addition of a thermal barrier coating (TBC) to cooled hot section components of industrial gas turbine engines offers several potential benefits. Since the TBC provides an insulating protective layer between the hot gas and the metallic substrate, several turbine design tradeoffs exist. Turbine inlet temperature may be increased to improve thermodynamic cycle efficiency while maintaining the same coolant flow schedules and metal temperatures (and hence component life). Or, the coolant flow schedules may be reduced to increase efficiency while maintaining current turbine inlet temperatures and metal temperatures (T_m). Similarly, component life may be extended by maintaining current turbine inlet temperatures and coolant flow schedules and reducing metal temperatures. The presence of the TBC could also extend cyclic life of components by reducing the temperature gradients within the metal during transient operations. A potential major benefit of thermal barrier coatings could result from the potential corrosion, erosion, and oxidation resistance of the TBC. Thus, a successful TBC could be a key to using heavy residual fuel oils in power generation gas turbines at clean-fuel ratings. Although the TBC is only one approach to achieving higher firing temperature and/or heavy fuel tolerance, it has a unique feature; its effect may be added to the effects of other approaches. It should be cautioned that thermal barrier coatings are currently at an early development stage; it is expected that a concentrated development effort will be required to make thermal barrier coatings a viable near-term option for industrial gas turbine engines.

The purpose of this study was to quantify these potential design tradeoffs, where possible, and thereby guide the ongoing thermal barrier coating development programs into the areas of highest payoff. The two contractors were responsible for evaluating the performance and cost of coated components and engine systems; a summary of the Westinghouse study results (ref. 1) is presented in appendix A of this report, and a summary of the UTC results (ref. 2) is presented in appendix B.

The study approach used by each of the contractors was similar; significant differences exist in the basic engines used, however. Westinghouse used their current-production W-501 single-shaft engine as the basic configuration and examined the uprating potential of the machine using thermal barrier coatings. Westinghouse examined simple-cycle and recuperated-cycle systems, for utility peaking applications, and combined cycle systems for utility baseload operations. Westinghouse also studied TBC on an advanced-design engine configuration to determine whether or not TBC with convection cooling could replace transpiration cooling in a high-temperature, high-pressure environment, in a system integrated with a low-Btu coal gasifier. Table I outlines the scope of the Westinghouse study, and illustrates the parameters that were varied in that study. The "ECAS II" frame refers to the advanced-design system studied initially in the Energy Conversion Alternatives Study - ECAS (ref. 3). Table II presents the important characteristics of the Westinghouse base gas turbine engines; tables I and II are discussed in more detail in appendix A.

UTC used their FT-50 engine configuration which is a relatively high-temperature, high pressure machine. Two FT-50 engines have been built, and one has been performance-tested. UTC examined the uprating potential of this machine with thermal barrier coatings in both a simple cycle configuration and a combined cycle configuration. Table III outlines the scope of the UTC study, and table IV presents the important characteristics of the FT-50 engine; these tables are discussed in more detail in appendix B.

The approach used by NASA to calculate potential benefits attributable to thermal barrier coatings consisted of (1) calculating potential savings on a per machine basis and (2) estimating total accumulated savings to the nation for the years 1980 to 2000, assuming all new machines after 1980 used thermal barrier coatings. This second estimate was accomplished by selecting a scenario for gas turbine growth in these applications to the year 2000, and calculating the difference in costs between machines with TBC's and machines without TBC's.

Fuel costs, capital costs and total cost-of-electricity (COE) were calculated and compared. While it is believed that the scenario selected for the total electrical energy growth for this study is reasonable, it is recognized that many other scenarios exist, and conditions that are used to project various scenarios are continually changing. The purpose of the study, however, was to quantify, and hence, rank various tradeoffs. By doing this, the conclusions reached should be relatively insensitive to the scenario chosen. Certain other assumptions used in the study are critical, however, and the sensitivity of the results to these assumptions will be discussed (fuel prices, for example, are extremely critical, and the assumed growth rate of combined cycle systems is also critical for the combined cycle results).

The main body of this report describes the current state of the art for thermal barrier coatings, the state of the art of heavy fuel firing, the comparison of potential TBC benefits, and a comparison of contractor development programs for thermal barrier coatings for near-term application in industrial gas turbine engines. The contract results are summarized in the appendices. It should be noted that both contractors considered major component costs, balance of plant costs, site labor and indirect cost. Westinghouse estimated costs in mid-1975 dollars and UTC estimated costs in mid-1976 dollars. Westinghouse included escalation and interest during construction, while UTC did not. NASA included escalation and interest during construction for the comparisons made in this report.

STATE OF THE ART OF THERMAL BARRIER COATINGS

The NASA Lewis Research Center has been actively involved in turbine blade protective coating research since the early 1950's (ref. 4). More recently, a ceramic thermal barrier coating was tested on the highly cooled surface of a nuclear rocket nozzle chamber (ref. 5). Considerable improvement in coating integrity was noted in furnace tests and in rotating turbine blade tests of calcia-stabilized zirconia using various surface preparation techniques and several bond coatings (ref. 6). These tests helped establish substrate preparation techniques and indicated a critical upper temperature limit of about 1367 K (2000° F) for the ceramic-bond coat interface. The bond coat and ceramic overcoat were applied manually with a plasma spray gun. Figure 1 shows a photograph of a sprayed rotor blade and a schematic of the NASA-developed duplex coating concept - a thin metallic bond coat layer and a ceramic outer insulating layer. Figure 2 is a photograph of the manual plasma-spray application. Other investigators have also tested various thermal barrier coating concepts (refs. 7, 8 and 9).

A further refinement in the NASA duplex coating concept is described in reference 10. A NiCrAlY bond coat, with both yttria-(Y_2O_3) and magnesia-(MgO) stabilized zirconia (ZrO_2) overcoats, were tested in engine and furnace tests. The NiCrAlY bond coat substantially improved coating adherence. Cyclic furnace screening tests of various oxide ceramic outer-layers were then performed and are described in reference 11. These tests indicated the apparent superiority of the yttria-stabilized zirconia to the other specimens tested, on the basis of adherence, thermal shock resistance, and resistance to cracking.

The improved NiCrAlY bond coat was next tested with calcia-, magnesia- and yttria-stabilized zirconia TBC's on J-75 turbine blades in a research engine (ref. 12). After 500 two-minute cycles from full-power to flame-out, all coated blades were in good condition (see fig. 3). Aerodynamic tests of thermal barrier coated vanes were also performed (ref. 13), and it was shown that a simple polishing process should be used to minimize the aerodynamic penalty associated with the rough, as-sprayed TBC.

Tests were recently run at NASA on a JT8D combustor liner (fig. 4), with and without the TBC (ref. 14). In the tests with the thermal barrier coating, the maximum metal temperatures were reduced by 210 K (380° F), with a 0.025 cm (0.010 in) yttria-stabilized zirconia outer layer used with a 0.010 cm (0.004 in) NiCrAlY bond coat, for a high aromatic fuel and a combustor exit temperature of 1325 K (1925° F). For certain operating conditions, smoke and flame radiation were decreased slightly, probably a result of the higher surface temperature of the coated liner, compared to the uncoated liner. There was no measurable reduction in HC, CO or NO_x for the conditions tested, however. United Technologies Corporation has used thermal barrier coating for some time on the inner surfaces of combustor liners, transition ducts, and afterburner duct liners (see fig. 5-2, ref. 2).

Preliminary hot corrosion test results are presented in references 7 and 15. In reference 7 minimal sulfidation attack of either the metal or the ceramic coating was observed. In reference 15, adherence problems were encountered for gas temperatures of 900° C, (1650° F) with sea salt injected into the flame, after only 300 hours of operation. Although these results are conflicting, and certainly not conclusive, it is believed that thermal barrier coatings can be developed to provide corrosion protection in dirty fuel and/or air environments.

As turbine inlet temperatures of industrial gas turbines increase, improved materials or more advanced turbine cooling techniques will be required. One of the concepts currently used to extend turbine inlet temperatures to very high levels is film-cooling, in which a layer of cool air is injected through small holes in the surface of the components to insulate the surface from the hot gas. In turbines fired with heavy fuels, deposits are often formed on the surface of the component. These heavy-fuel deposits might cause plugging of these film-cooling holes, particularly near the leading edge stagnation regions of the blades and vanes, with catastrophic results. Therefore, cooling concepts with little or no film-cooling probably will have a better likelihood of success in a heavy-fuel-fired turbine.

An analytical investigation was made in reference 16 to compare internal convection cooling, convection cooling with a thermal barrier coating, and full-coverage film-cooling, for a range of present and future gas turbine engine conditions. These results are shown in figure 5. Coolant flow per vane or blade row is shown as a function of increasing temperature and pressure. Indicated on the abcissa of the figure are several classes of gas turbine engines from present utility turbine engines to very advanced, future aircraft gas turbine engines. The figure indicates that simple convection cooling has reached its limit at about the level of present utility turbines. Both film-cooling and convection cooling with TBC appear to be viable options for advanced engines, however. Thus, a successful thermal barrier coating can effectively extend the temperature range of convection cooling schemes to levels previously believed to be attainable only with film - or transpiration cooling - without their potential hole-plugging problems.

STATE OF THE ART OF HEAVY FUEL FIRING

Most of the early utility gas turbines in this country were fired with relatively clean fuels - natural gas or No. 2 diesel fuel oil. Relatively low levels of certain contaminants in these fuels, however, caused hot section sulfidation problems, resulting in excessive refurbishment and replacement part costs. Engine manufacturers have worked hard to provide corrosion resistant materials, and all manufacturers recommend firing with the cleanest possible fuel. Similarly, fuel specifications for gas turbine fuels have been tightened recently with regard to fuel contaminants (see, for example, GT No. 2 - ASTM 2880-76: vanadium, sodium plus potassium, and lead, maximum levels went from 2.0, 5.0, 5.0 ppm to 0.5, 0.5, and 0.5, respectively).

As the demand for the clean fuels increases, however, costs also increase. Also, as national energy priorities are established and implemented, these clean fuels will be more difficult to obtain for electric power generation. A recent Senate bill, S273, has been proposed that would prohibit the use of natural gas and oil for electric power generation, except for peaking. Although this bill has not passed to date, dwindling fuel supplies will inevitably lead to the use of less-costly fuels in the generation of electric power. Utilities in this country and abroad have recognized this potential problem and have begun to require fuel-flexibility in their specifications for new systems. This added fuel-flexibility requires additional, substantial capital investment and this probably explains, in part, why more utilities are not currently burning the heavy, less costly fuels in gas turbines.

Hot corrosion of gas turbine components can be controlled by removing contaminants from the fuel and air. Water soluble salts can be effectively removed by water-washing the fuel and separating the fuel from the water electrostatically or centrifugally. Two or more stages of separation may be required to control sodium, potassium and calcium. The effect of vanadium, which is not water soluble, may be controlled by injecting magnesium into the fuel; the magnesium prevents the formation of highly corrosive vanadium compounds. Filtering of the air entering the turbine helps by preventing ingestion of air-borne contaminants. Frequent washing of the turbine components has also been found to be effective in removing deposits which, if not removed, lead to corrosion of the metal parts.

Another, less desirable, means of controlling hot corrosion has been to "derate" the engines (that is, maintain a lower power output, lower firing temperature and lower metal temperatures). There is not a large base of data that would indicate the effect of derating on electricity costs. Therefore, NASA studied this effect parametrically, using some of the results of the Westinghouse study; the results are shown in figures 6 and 7. In these calculations both simple cycle and combined cycle systems were studied. The base cases, shown by the open circles in figure 6, represents a current technology machine, firing a clean, light distillate fuel, at a firing temperature of about 1422 K (2100° F). Figure 6 shows powerplant net efficiency as a function of gas turbine specific power. In figure 7, total cost of electricity (COE), and its components, capital cost, fuel cost and operating and maintenance cost (O&M), are shown for the reference case on the left bar.

The distillate-fired machine is compared in these figures to the same machine burning a heavy residual fuel: at the same firing temperature, derated by 38 K (100° F), and derated by 76 K (200° F). At the same firing temperature as the reference case, net efficiency and specific power decrease slightly because of power losses for the fuel treatment system required with the heavy fuel. The effect of lowering firing temperature on performance is shown clearly in figure 6.

The cost of electricity for burning the heavy residual fuels is a trade-off between reduced fuel costs (fuel prices assumed were $2.60 per million Btu's for distillate fuel and $2.15 per million Btu's for residual fuels) and increased capital cost (fuel treatment system and additional fuel storage requirements), and increased operating and maintenance costs. The O&M costs were assumed to be 0.5 mills/kW-hr higher for the residual fired cases. Fuel costs are a function of fuel prices and net efficiency and are seen to increase as the firing temperature decreases. The biggest change in COE for the derated residual fired cases is seen to be capital cost, however, reflecting the change in specific power output of the turbine as firing temperature decreases.

Thus, if thermal barrier coatings could be developed that would also provide hot corrosion protection, (and thus eliminate the need for derating), the COE difference between the left two bars of figure 7 could be realized. This saving (1.9 mills/kW-hr) is seen to be about 3 percent for the simple cycle cases and 7 percent (2.4 mills/kW-hr) for the combined cycle cases. The COE penalty for derating is also shown on figure 7. The penalty for derating 38 K (100° F) is the difference between the middle two bars on figure 7. This penalty is seen to be 3.4% (2.0 mills/kW-hr) for the simple cycle case, and 5.0% (1.5 mills/kW-hr) for the combined cycle case. Similarly, for derating 76 K (200° F) the corresponding penalties are: 8.9% (5.2 mills/kW-hr) - simple cycle, and 9.9% (3.0 mills/kW-hr) - combined cycle. If residual oil is burned in a 200° F derated engine the corresponding TBC savings would be 8% and 9%, respectively.

COMPARISON OF POTENTIAL TBC BENEFITS

As discussed in the Introduction, there are several potential benefits of thermal barrier coatings in utility gas turbine engines that may be pursued; these benefits may be to the utility company or to the nation in general. In this section, the contractor performance and cost data will be summarized and the various benefits will be quantified and compared. All of the potential benefits will be measured in terms of dollar savings only. Also, some of the potential benefits could not be quantified, but will be discussed qualitatively.

Methodology

Savings per machine. - Using the performance and cost estimates made by Westinghouse and UTC (summarized and discussed in appendix A and appendix B, respectively), an annual cost savings was calculated per unit based on the following assumptions. Simple cycle peakers were taken to be nominally 100 MWe and were assumed to operate 1050 hours per year at rated power. Combined cycle systems were assumed to be nominally 300 MW_e (two gas turbine units) and operated 5700 hours per year at rated power.

Accumulated National Savings. - The approach used to calculate accumulated national savings made possible by thermal barrier coatings was to: (1) assume a reasonable projection of total electrical power generation for the U.S. as a function of time, through the year 2000, (2) estimate the portion of the total annual new capacity required that would be met with peaking gas turbine units and the portion that would be met by combined cycle systems, (3) use heat rate, capital cost and COE estimates made by the contractors (refs. 1 and 2) to calculate incremental benefits attributable to TBC, and (4) integrate the incremental savings to find total accumulated savings through the year 2000 for the various trade-off options.

Electrical Power Generation Growth: In 1975 the electrical power generation in the U.S. approached two trillion (2×10^{12}) kilowatt hours. In the 1940's and 1950's the growth rate was about 8 percent/year - a doubling every nine years. By the 1960's, this rate had diminished slightly to about 7.5 percent/year. In the 1970's the growth rate has been even lower. At present many scenarios on energy are projecting electrical energy to continue growth but at a decreasing growth rate. One such electrical growth projection that is fairly representative of post-energy-crisis projections was presented by Hudson and Jorgenson (H&J) in reference 17. The H&J forecasting model was based on integration of econometric modeling and input-output analysis, with a focus on energy production and utilization, and included a forecast from 1975 to 2000. The H&J electrical power generation growth rate was used in this study and was about 5 percent per year through the year 2000 (see fig. 8(a)). An industry forecast (ref. 18) projected growth to be around 6 percent in the early 1980's, decreasing to 5 percent in the later 1980's and to the upper 4 percent level through the 1990's. ERDA planning projections presented in reference 19 were both above and below the H&J forecast, depending on the scenario; ERDA Scenario II (Synthetics Developed) is very close to the H&J forecast.

Power Generated by Gas Turbines: The cyclic nature of the electric power demand - daily, weekly and seasonally - generally results in three power generation equipment classes. Base load equipment essentially runs continuously, while intermediate load equipment is used to follow daily and weekly load variations above the base. Peaking equipment is used to supply summer and winter peak demands (ref. 20). Gas turbine units have been widely used as peaking units because of low capital cost and rapid start-up characteristics. The growth of gas turbine used as peaking units is shown in figure 9. This growth appears to follow a typical S-shaped introduction curve (logistic curve). In this study, it is assumed that gas turbines level off at eight percent of the total generation capacity. This results in the total gas turbine installed capacity curve for simple cycle gas turbines shown in figure 8(b). Also, to calculate benefits it is assumed that only the new capacity additions would make use of thermal barrier coatings.

In a similar manner, combined cycle equipment (fig. 10) is projected to grow from current levels of approximately six percent of the total installed capacity by the year 2000. Total assumed combined cycle capacity is also shown in figure 8(b). This projection of combined cycle introduction rate was made based on a typical S-shaped curve, projected from the few data points that exist. Obviously, there is much uncertainty in this projection, and the sensitivity of the conclusions of this study to this projection will be discussed in a later section of this report.

Finally, it was assumed that <u>all</u> new additions, both simple cycle and combined cycle, would take advantage of thermal barrier coatings beginning in 1980. Thus, these benefits must be considered an upper bound. If TBC introduction is delayed until 1985, the calculated benefits would be less than ten percent smaller.

In summary, it is assumed that all new utility power generation gas turbines, starting in 1980, have thermal barrier coatings. For simple cycle systems (as peaking units), the new capacity in 1980 is 1500 MW (or, 15 100 MW units). This amount grows to 5800 MW (58 100 MW units) new additions in 2000 for a total installed capacity with TBC of 80,000 MW by 2000. For combined cycle systems, the new capacity installed in 1980 with TBC is 1000 MW (3-1/3 nominal 300 MW units). This grows to 10,000 MW (33-1/3 nominal 300 MW units) by the year 2000 for a cumulative total of 90,000 MW with TBC's by 2000. For this analysis it was further assumed that the combined cycle systems would operate as base load systems or 5,700 hours a year at full power. The peakers were assumed to operate at 1,050 hours per year at full power.

The following sections discuss the many trade-offs involved with thermal barrier coatings, and present estimated fuel, capital and COE cost savings.

Benefits of Improved Efficiency

<u>Increased turbine inlet temperature</u>. - Thermodynamic cycle efficiency generally increases as turbine gas temperature increases. This effect was studied by the contractors and their results are summarized in the appendices. For a simple cycle gas turbine at a given pressure ratio, it was shown that cycle efficiency increased very little (and even decreased for very high temperatures because of the added cooling air

required) with increasing temperature. Gas turbine specific power (power output/engine inlet airflow rate) increased significantly, however, resulting in increased power output for a given hardware size. Capital cost, expressed in $\$/kW_e$, varies inversely with specific power as can be seen in figure 11. In this figure simple cycle advanced configurations are compared with the Westinghouse W-501 current production turbine (CPT). The CPT and NTA (near-term-advanced) designations refer to the cooling techniques used; the NTA scheme employs a more advanced impingement convection scheme than does the CPT. The height of the open bars indicates the corresponding increase in specific power and the height of the shaded bar indicates the resulting decrease in specific capital cost. A correlation between the specific power and the capital cost is apparent, but more important. the benefit of increased firing temperature in reduced capital costs is shown clearly.

This benefit is quantified in table V; cost of electricity (COE) and its components are shown for both simple and combined cycle systems, again using Westinghouse results. For the simple cycle case, the major effect is seen to be the decrease in capital cost caused by the increased specific power, as noted above. Capital costs were estimated in mid-1975 dollars by Westinghouse. Fuel cost remains approximately constant since very small changes in efficiency were calculated and the same fuel cost was assumed for each case. The operating and maintenance (O&M) costs increased for the systems with thermal barrier coatings to account for the refurbishment of the TBC. These results (and all results shown) are for a 0.038 cm (0.015 in) TBC, unless otherwise noted. The percent reduction in COE is shown to be 3 percent for the 1478 K (2200° F) case and 4.9 percent for the 1589 K (2400° F) case. These reductions in COE result in an annual savings for a nominal 100 MW machine operating as a peaker (1050 hr/yr) of $200 K and $310 K, respectively. Total accumulated savings between 1980 and 2000 for all new additions totals $1.5 billion and $2.4 billion, respectively.

For the combined cycle system, capital cost again decreases but the improved efficiency at the higher temperatures also results in reduced fuel costs. The percent reduction in COE was found to be 3 percent and 6.1 percent for the 1478 K (2200° F) and 1589 K (2400° F) cases, respectively. Annual savings for a 300 MW system operating in base load service (5700 hr/yr) total $1.7 million and $3.3 million. Total accumulated savings between 1980 and 2000 amount to $3.5 billion for the 1478 K (2200° F) system and $6.8 billion for the 1589 K (2400° F) system. Because of the uncertainty in the scenario for the combined cycle systems, these potential savings should be considered "possible", not probable, particularly for the distillate-fuel-fired cases. This fuel may not be available for other than peaking operation. Also, there are certainly other means of attaining higher firing temperatures besides TBC, but thermal barriers offer potential and may, in fact, supplement other methods.

Reduced cooling air flow rate. - Application of the thermal barrier coating to all of the cooled hot section components, maintaining constant firing temperature and reducing cooling flow rates should improve efficiency and maintain current component life, provided the metal temperatures remain about the same. Westinghouse made a two-dimensional heat transfer calculation and showed that under such conditions metal temperatures, with or without TBC, would be nearly the same. For the current turbine inlet temperature 1366-1422 K (2000°-2100° F), cooling air was reduced by 13.3 percent, resulting in less than one percent improvement in heat rate and 1.8 percent increase in specific power for a simple cycle. Performance improvements in the combined cycle system were similarly very small.

Table VI shows this effect on cost of electricity and savings. Very small improvements in capital cost due to the increased specific power, and fuel cost, due to the small improvement in efficiency, are nearly balanced by the added O&M cost for the TBC. These benefits are small compared to the benefits of higher gas temperature.

Westinghouse also estimated the effect of increasing the thickness of the TBC from 0.038 cm (0.015 in) to 0.076 cm (0.030 in). Figure 12 shows the effect of increasing TBC thickness and reducing coolant flow rate for a given turbine inlet temperature. Very small improvements in heat rate are indicated.

It can also be shown from the Westinghouse results that increasing the TBC thickness to 0.076 cm (0.030 in) with the current cooling air flow rate schedules would permit increasing turbine inlet temperature to over 1589 K (2400° F). As shown in figure 11, increasing turbine inlet temperature has a pronounced effect on gas turbine specific power and, hence, would substantially reduce capital cost. The optimum coating thickness must be determined for each application but will probably be a function of blade or vane geometry, leading edge radius, and so forth. It is anticipated that the optimum thickness for a utility turbine application will be thicker than an aircraft application because of the relative hardware sizes.

UTC combined the effects of increasing firing temperature and decreasing cooling air requirements. The "optimum" FT-50 configuration with a TBC had a 24 K (44° F) increase in turbine rotor inlet temperature, while reducing cooling air flow rate requirements by 41 percent. This resulted in a 3.8 percent reduction in COE for the simple cycle system and an annual savings of about $200 K per machine, compared to the FT-50 without the TBC. This benefit is seen to be about the same as calculated by Westinghouse for uprating their W-501 CPT to 1478 K (2200° F). The UTC capital costs were estimated in mid-1976 dollars.

Benefits of Increased Component Life

Reduced component metal temperatures. - Both Westinghouse and UTC considerd component life in their calculations. Westinghouse calculated creep rupture life for the air-cooled rotating blades to increase from 30,000-50,000 hours to over 100,000 hours for continuous duty service and clean fuels, as a result of application of 0.038 cm (0.015 in) TBC, assuming no change in firing temperature or cooling air flow rate. Therefore, it was assumed that all air-cooled components with the TBC would have double the life as a result of the reduced metal temperatures. For the cyclic duty application (peaking), it was assumed that the coated parts would have a life 1.5 times that of the uncoated components. Based on these life calculations and assumptions, a differential O&M cost was calculated: -1.137 mills/kW-hr for peaking and -01.72 mills/kW-hr for base load. Table VII summarizes the effect of reduced metal temperature; for simple cycle machines a small benefit results (about $46 K per year per machine). In the combined cycle case, the decreased O&M cost resulting from longer component life is almost exactly balanced by the cost of the TBC and the added fuel cost resulting from the decrease in efficiency with the TBC (due to reduced turbine flow area and subsequent higher, less optimum compressor pressure ratio).

UTC also investigated the effect of reduced metal temperature and subsequent component life increase without a TBC. The UTC reference case was 1144 K (1600° F) metal temperature without a TBC, firing a residual fuel. The reference case was compared to the same system, also without the TBC and firing residual fuel, but with cooling flow rate increased to lower the metal temperature to 1088 K (1500° F). The results are shown in table VIII. Capital costs in table VIII include escalation and interest during construction (added by NASA). The increased cost of extending component life from 10,000 hours to over 30,000 hours without the TBC is substantial. (The capital cost estimates made by UTC are in mid-1976 dollars.)

These estimates and calculations show that although the TBC benefit is small for the lower metal temperature trade-off (table VII), it does represent a means of obtaining increased component durability without an additional cost (table VIII). Thermal barrier coatings must also be shown to have acceptable durability, of course, before this trade-off option can be exercised. There may also be other means of attaining improved durability such as improved superalloys or advanced cooling schemes. An important advantage of the TBC should be clear, however, Whatever design improvements that can be made by other means (such as improved superalloys or advanced cooling) should be further enhanced by the use of thermal barrier coating!

Reduced metal temperature transients. - Although this effect was not calculated or estimated by either contractor, the presence of the TBC on highly cooled vanes, blades and combustors should result in less severe metal temperature gradients during startup and shutdown and should therefore improve the cyclic life of these components, provided the coating can itself withstand these temperature transients.

Effect of Use of Lower Priced Fuels

Both Westinghouse and UTC investigated the effect of using a heavy, lower-price fuel on electricity cost for the systems studied. The fuel prices assumed were supplied by NASA. Distillate fuel was assumed to cost \$2.60 per million Btu and is the same as the distillate fuel price used in the ECAS study (ref. 3). The price assumed for residual fuel was \$2.15 per million Btu (17 percent lower than the distillate fuel price) and this percent reduction in price was typical of the national average differential at the start of the study. It should be noted that these prices vary regionally and with time. Differences have been noted to range from no difference in price to as much as 33 percent lower price for residual fuel.

Fuel price effect is summarized in table IX, using the Westinghouse results and assuming the TBC permits combustion of residual fuels with acceptable life. For both simple and combined cycle systems, a current production turbine (CPT) without thermal barrier coatings and burning a distillate fuel is compared to the same machine with a TBC and an appropriate fuel treatment system burning a residual fuel. The capital cost increase for the residual fuel case is a result of the added cost of the TBC (about \$100,000 per gas turbine) and the added cost of the fuel treatment and storage system (about \$800,000 per gas turbine). The reduced fuel cost in mills/kW-hr results from the lower fuel price even though these cases have slightly lower efficiency (because of additional auxiliary power requirements for the fuel treatment system). The O&M cost increased to account for the refurbishment of the TBC. Westinghouse and UTC studied the refurbishment interval and found it to have a very small effect on COE (See appendices).

A three percent reduction in COE was calculated for the simple cycle system, resulting in an annual savings per 100 ME_e machine of \$200 K and an accumulated savings of \$1.5 billion from 1980 to 2000. The combined cycle benefit is even larger: 7.7 percent decrease in COE, \$4.5 million annual savings per 300 MW_e system and a total accumulated savings of \$8.5 billion. For the simple cycle the benefit of burning residual fuel in a current machine is seen to have the same savings as increasing firing temperature from 1366-1422 K (2000°-2100° F) to 1478 K (2200° F) and burning distillate fuel (see table V). This benefit is much larger for the combined cycle system since the yearly fuel cost is much larger for base load than for peaking. The combined effect of higher firing temperature - 1478 K (2200° F) - and burning residual fuel is also shown in table IX.

Since the fuel cost benefit results from a trade-off between reduced fuel price assumed and estimated capital cost increase due to the fuel treatment system, there exists a fuel price differential (between distillate and residual) for which the COE with distillate fuel and residual fuel would be exactly equal. A residual fuel price 11 percent lower than distillate fuel results in equal COE's. The fuel cost benefit (which is potentially very large) is very sensitive to the fuel price; the price of residual must be more than 11 percent lower than distillate fuel or there will be no cost benefit at all.

Extension of Cooling Schemes to Higher Temperatures

Westinghouse calculated that the TBC could increase the turbine inlet temperature of their current production W-501 to 1478 K (2200° F) with no cooling configuration change. Their calculations also indicated that a more advanced impingement-convection scheme could allow uprating of the W-501 to 1589 K (2400° F). Further, Westinghouse calculated that the TBC with the advanced impingement-convection cooling scheme could be used in a more advanced machine with higher pressure ratio in place of transpiration cooling at a turbine inlet temperature of 1644 K (2500° F). The UTC calculations indicate that impingement cooling with a TBC could replace showerhead film-cooling on their FT-50 engine with an increase in firing temperature and a substantial reduction on cooling air requirements.

The benefit in terms of lower component cost is obvious for the simpler cooling configurations. The viability of film-cooling and transpiration cooling in a heavy fuel environment has not been experimentally vertified. Similarly, thermal barrier coatings have not been shown to be tolerant of the heavy fuel combustion environment. The incentive to develop such a coating appears clear, however. UTC also studied the effect of applying the thermal barrier coating to the combustor liner and transition duct of the FT-50. It was found that a simple reverse flow convection cooling method could be used on the transition duct instead of film-cooling. This change permitted use of the air required for cooling of the transition duct to be used for dilution of the hot combustion gases, permitting better mixing and possibly improving pattern factors. Although potential pattern factor reduction was not estimated, it was noted by UTC that a reduction from 0.4 to 0.3 could permit an increase in turbine rotor inlet temperature of 67 K (120° F) - a substantial benefit in terms of improved performance.

COMPARISON OF TBC DEVELOPMENT PLANS

As discussed earlier, thermal barrier coatings are currently at an early development stage for gas turbine airfoils. Each contractor (refs. 1 and 2) discussed TBC development requirements; from these discussions and in conjunction with the ongoing NASA TBC development activities, a preliminary TBC development plan for utility gas turbine engines has been proposed (ref. 15). The proposed development plan logic is shown in figure 13. The goals of the plan are to achieve and demonstrate production readiness of the thermal barrier coating in a utility gas turbine test, with a distillate fuel by 1981, and with a heavy fuel by 1983. Benefit studies, such as this one, have been made to indicate direction and scope. A major coating development effort is planned to determine the tolerance of thermal barriers to heavy fuel combustion environments and to improve the durability of the coatings. As coating chemistries evolve, automated application techniques will be required and must be developed. Simiarly, physical and mechanical properties of the coatings must be determined. Promising coatings will be included in component designs for existing utility turbines, hardware will be sprayed, and the coating integrity verified in a manufacturer's test bed engine. Finally, endurance tests are planned in utility turbines.

TBC development plans were requested from each of the contractors and are included in their reports. Significant corporate differences exist regarding their approach to TBC development. Because of these differences, NASA desired an independent evaluation of TBC development requirements from each contractor. For example, UTC has a strong in-house technical background in TBC and thermal barrier coatings are currently bill-of-material on Pratt & Whitney F-100, J-58, TB-30, JT8D-17, and JT9D combustors and afterburners. A graded CoCrAlY-ZrO_2-M_gO is currently the most advanced of the UTC coatings. UTC has in-place plasma-spraying capability for applying the coatings to combustors and afterburners. The drive to higher and higher firing temperatures for military and commercial engines at P&W has undoubtedly contributed to the development of these protective coatings at UTC. On the other hand, Westinghouse currently has no thermal barrier coatings on any components. Also, Westinghouse selects qualified vendors to supply components; the TBC technology must, therefore, reside with a coating vendor or a component supplier. Westinghouse has been involved in EPRI-funded corrosion tests of thermal barrier coatings and has performed some mechanical property testing.

The UTC development plan emphasized technology development in the following critical areas: application process, durability, and erosion-corrosion resistance. Substrate application temperatures and resulting residual stress control was cited as an example of an important technology area that must be investigated. No heavy fuels activities were identified in the UTC plan. Coating verification tests were shown but not detailed, for subsequent testing in a utility FT-4 engine. The test program was independent of the FT-50 engine.

Westinghouse also presented detailed technology development plans followed by phased engine tests. Engine tests are proposed in two steps from 1478 K (2200° F) to 1589 K (2400° F), including performance testing in their in-house W-251 test bed engine on Concordville, Pa., to W-501 utility endurance test. Fuels considered range from No. 2 distillate to heavy oils.

SUMMARY OF RESULTS

The significant results of this benefit study are summarized below and in table X:

(1) One of the largest benefits occurs when a distillate fired turbine is converted to residual fuel and fired at current distillate rated firing temperatures. These savings were calculated for a current production engine at current temperatures to be \$200 K per machine per year (up to \$1.5 billion accumulated between 1980 and 2000) in peaking cost-of-electricity, and \$4500 K per 300 MW system per year (up to \$8.5 billion accumulated from 1980 to 2000). Uprating these same machines to 1478 K (2200° F) would result in even larger benefits; these benefits are extremely sensitive to the fuel prices assumed. These benefits could be realized with or without TBC; the TBC is believed to be a near-term means of improving gas turbine tolerance to heavy fuels.

(2) For distillate-fired turbines, turbine inlet temperature has the largest effect on costs. Uprating a current peaking turbine from 1366-1422 K (2000°-2100° F) to 1478 K (2200° F) firing temperature could result in savings of \$200 K per machine per year (accumulated savings up to \$1.5 billion). Uprating to 1589 K (2400° F) increased the benefit to \$310 K per machine per year (accumulated savings of up to \$2.4 billion). For combined cycle systems the uprated 1478 K (2200° F) system could save \$1700 K per 300 MW system per year (\$3.5 billion from 1980 to 2000) and the 1589 K (2400° F) system could save \$3300 per 300 MW system per year (\$6.8 billion from 1980 to 2000). Again, thermal barrier coating represents only one attractive near-term means of attaining these higher temperatures.

(3) Increasing the thermal barrier coating thickness should permit further increasing of firing temperature and lower costs. Doubling of the TBC thickness may permit increasing the firing temperature by about 110 K (200° F).

(4) Use of the thermal barrier coating in the combustor and transition duct should reduce cooling air requirements and should allow better mixing for improved pattern factor. Reduced pattern factor permits operation at higher turbine inlet temperatures without locally exceeding maximum temperature limits. Improved life and/or better cycle efficiency should result.

(5) The thermal barrier coating could also be used to reduce cooling air flow rate or to reduce metal temperature to improve component durability. These cost benefits were shown to be small.

(6) The TBC is currently at an early development stage and a substantial development effort will be required before thermal barrier coatings will be accepted in utility gas turbines. Each contractor submitted a TBC development plan; both contractors stressed TBC technology development and Westinghouse outlined a detailed performance and endurance test program.

(7) Design improvements made possible by thermal barrier coatings should supplement design improvements made in other technologies (superalloys, combustion or improved cooling techniques).

APPENDIX A - WESTINGHOUSE STUDY RESULTS

Description of Systems Studied

A summary of the parametric variations investigated by Westinghouse is shown in table I. Simple, recuperated and combined cycle powerplant configurations have been studied. The Westinghouse W-501 gas turbine engine was used for most of the parametric variations. In addition, a simple and combined cycle case was investigated using the Westinghouse ECAS (Energy Conversion Alternatives Study), Phase II gas turbine engine concept. In ECAS, this gas turbine operated at a turbine stator inlet temperature, T_{SIT}, of 1644 K (2500° F), and used transpiration cooling in the first stage. In this thermal barrier study this engine was modified by replacing the transpiration cooling with thermal barrier coated parts using advanced convection/impingement cooling methods. A performance comparison is made between the Westinghouse ECAS II combined cycle with integrated, low-Btu gasifier using transpiration cooling, and the thermal barrier coated case, investigated in this study.

For each cycle configuration, the performance and cost of a reference case using distillate fuel without the thermal barrier was calculated. The effect of adding the thermal barrier was investigated in a number of ways. The turbine inlet temperature was increased while keeping the same metal surface temperatures, thereby increasing performance and specific power. Performance and specific power was also increased by maintaining the same turbine inlet temperatures and metal surface temperatures, and reducing the coolant flow rates. Hot section component lives were increased by keeping the turbine inlet temperature and coolant flow rates constant, and reducing the metal surface temperatures. Also, the effect of using a relatively dirty residual fuel with the thermal barrier was investigated.

The turbine inlet temperatures were varied parametrically over the ranges shown, with a simple convection/impingement cooling method being used at the lower temperatures (below 1478 K (2200° F)), and advanced convection-impingement cooling above that temperature. The re-coating and refurbishment intervals for thermal barrier coated parts were parametrically varied for the simple and combined cycles, and two thermal barrier thicknesses, 0.038 cm (0.015 in) and 0.076 cm (0.030 in) were studied for the simple and combined cycles.

Simple Cycle. - The operating characteristics of the uncoated, Westinghouse base case gas turbine engines are presented in table II. The W-501 is a single shaft, axial flow gas turbine consisting of a four-stage turbine, at a turbine inlet temperature of 1366-1422 K (2000°-2100° F); two stages are air cooled.

Part of the compressor air used for turbine cooling is precooled to 478 K (400° F). The net electrical power output of one unit is approximately 95 MW_e at the turbine inlet temperature and pressure ratio shown.

The gas turbine used in a combined cycle application in ECAS Phase II was also analyzed as a simple cycle in this study. The characteristics of this engine as shown in table II are the operating points used for that configuration. At this turbine inlet temperature - 1644 K (2500° F), Westinghouse used highly advanced transpiration cooling methods in the first stage. The first three turbine stages were cooled; the last rotating blade stage is uncooled. As with the W-501 engine, part of the cooling air is precooled to 478 K (400° F). (In the Phase II design, this was accomplished by evaporating gasifier feedwater). Due to the higher turbine inlet temperature and compressor pressure ratio the ECAS Phase II design has a higher efficiency and specific power than the state-of-the-art gas turbine.

Recuperated Cycle. - For this configuration, the W-501 gas turbine was used with a 0.827 effectiveness recuperator. This effectiveness was chosen by Westinghouse after examination of the ECAS Phase I parametric data. The compressor pressure ratio of 12-13 is somewhat high for optimum performance in a recuperated cycle, especially at turbine inlet temperatures below 1589 K (2400° F). Therefore, the results for the recuperated gas turbines are not indicative of the best performance or cost possible for a recuperated cycle. The W-501 gas turbine operates at these pressure ratios for simple and combined cycle applications.

Combined Cycle. - The W-501 gas turbine was used for the combined cycle systems with a 8.62 Mpag/783 K (1250 psig/950° F) steam bottom cycle. The waste heat from the gas turbine exhaust was used to raise steam for the steam bottoming plant in the heat recovery steam generator (HRSG).

Supplementary fuel firing was utilized in the HRSG to maintain a constant gas temperature into the superheater sections. The amount of firing varied as the topping cycle parameters were varied and the gas turbine exhaust temperature changed. The use of supplementary firing in the HRSG allowed the use of a fixed HRSG and steam cycle design while uprating the turbine inlet temperature. The elimination of supplementary firing would be possible and desirable at turbine inlet temperatures higher than about 1366-1422 K (2000°-2100° F) by redesigning the HRSG, adjusting the steam flow rates of the combined cycle, or choosing a steam cycle with different throttle conditions. However, the scope of the study did not include any major design changes of the W-501 gas turbine or its steam bottom cycle.

The ECAS, Phase II combined cycle with integrated, low Btu gasifier modified by the use of TBC was also investigated. The gas turbine used for this application was discussed in the simple cycle description. This gas turbine was bottomed by a 16.5 MPag/811 K/811 K (2400 psig/1000° F/ 1000° F) reheat steam cycle, which used a single steam induction. This power system is highly integrated with an advanced fluidized bed gasifier. Air for the gasifier was supplied at pressure from the gas turbine compressor and gasifier process steam was supplied by the steam bottoming plant. The gasifier utilized in-bed desulfurization with dolomite and the hot, low-Btu gas was cleaned by cyclones, multiclones, and granular bed filters before injection into the gas turbine combustors. The fuel used in ECAS Phase II was Illinois No. 6 coal. Due it the high degree of integration of the power system, the high efficiency of the gasifier subsystem, and also due to the advanced gas turbine design, this system had a high, overall efficiency (coal pile to bus bar) of 46.8%.

Approach and Assumptions

Performance. - Each of the configurations investigated by Westinghouse included total powerplant equipment and siting considerations. The simple and recuperated cycle gas turbine powerplants consisted of four gas turbine units, with the power output calculated at the specified flow rates, turbine inlet temperatures and compressor pressure ratios. The combined cycle systems using the W-501 frame gas turbine consisted of two gas turbine units bottomed by a single steam plant. The ECAS II design consisted of four gas turbine units with a single steam bottomer. Each gas turbine unit exhausted to its individual HRSG.

The efficiencies calculated by Westinghouse are powerplant efficiencies; they include all auxiliary powerplant requirements and losses including losses due to pumps, generators, and fuel treatment and heating. A generator efficiency of 0.987 was assumed for all cases. For the distillate fueled simple and recuperated cycles, a powerplant auxiliary requirement of 940 kW_e per gas turbine unit was assumed. For the combined cycles, an additional 3100 kW_e of auxiliary load requirement was estimated. For all residual fired cases, an additional 20 kW_e/MW_e of gas turbine power was assumed to be required for fuel heating and 800 kW_e for electrostatic precipitators for fuel cleanup. All powerplant efficiencies are calculated based on the higher heating value (HHV) of the fuel being used.

One and two dimensional heat transfer effects of the thermal barrier were analyzed by Westinghouse for the blade profiles and cooling methods used. From this, correlations of heat flux, temperature and cooling requirements were calculated and employed in the systems' performance when thermal barriers were added. Also, the additional thickness of the thermal barrier coating was found to have a nonnegligible effect on the combustion gas flow area through the turbine. To accomodate this, Westinghouse chose to increase the compressor pressure ratio slightly while keeping the compressor inlet air flow rate constant. It is stated by Westinghouse that such an increase in pressure ratio could be done within the surge margins of the compressor designs incorporated in these engines. Also, Westinghouse did not incorporate aerodynamic losses due to the coating roughness of the thermal barrier in their engine performance calculations.

Capital Cost. - For each of the cases considered by Westinghouse, costs were estimated for major components and balance-of-plant material, and for site labor in plant construction.

For costing purposes, the simple and recuperated cycle gas turbine systems were assumed to be located on the outskirts of a large city near a commercial or industrial area. The combined cycle plants were assumed to be located at the Middletown, USA industrial site (ref. 21). All costs for powerplant equipment are expressed in terms of mid-1975 dollars.

Major component costs, which include gas turbines, heat recovery steam generators, steam turbines, recuperators, and residual fuel treatment equipment, were estimated by Westinghouse. Balance of plant costs, including structural steel for construction, site development, buildings and structures, and direct and indirect labor costs, were estimated using a computer data base that contained information provided to Westinghouse in the ECAS Phase I study by the architectural and engineering firm, Chas. T. Main, Inc. Powerplant construction times of 2.5 years for the simple and recuperated cycles, and 3.0 years for combined cycle plants were estimated by Westinghouse. Additional capital costs for escalation and interest during construction were included in the cost estimates. An annual escalation and interest rate of 6.5% and 10% respectively, were chosen by Westinghouse based on the ECAS ground rules, and these were applied using a cash flow curve during construction which was also used in ECAS Phase II.

The residual fuel treatment cost was estimated by Westinghouse to be $787,500 per gas turbine unit. This includes fuel treatment equipment, fuel heating equipment, and storage tanks for treated and untreated fuel. For the simple and recuperated powerplants with four gas turbine units, this cost comes to $3.15 million and for the combined cycle powerplants, consisting of two gas turbine units, the cost is $1.575 million.

The thermal barrier stripping and coating costs were:

$100/individual combustor
$200/individual combustor-turbine transition piece
$150/vane or blade airfoil

and were supplied to Westinghouse by NASA. NASA is investigating the feasibility of automated plasma spraying of turbine components under Contract NAS3-20112, "Automated Plasma Spray Process Feasibility Study", with TRW, Inc. The cost estimates used were a "best estimate" possible at the time, of stripping and coating costs, assuming a successful automated process. When these costs were used for the W-501 gas turbine, the total cost per gas turbine engine of applying the thermal barrier coating was $71,000 for stages 1 and 2 airfoils, and $116,000 for stages 1, 2 and 3 airfoils and combustor and transition pieces. At a turbine inlet temperature of 1366-1422 K (2000°-2100° F) the combustor and transition piece and third stage airfoils were assumed to not need a coating.

Operation and Maintenance Costs. - Westinghouse relied upon a report on operation and maintenance cost models for power systems which reflect the viewpoint of a user of such equipment (ref. 22). The base values used for O&M costs estimated for the simple and combined cycles are shown in figure 14. Here the O&M costs as a function of capacity factor are shown for a simple cycle system burning distillate fuel and combined cycle systems burning both residual and distillate fuel. The values used in this study were 3.8 mills/kW-hr for the simple cycles and 1.75 mills/kW-hr for the combined cycles, both when using distillate fuel. Using the combined cycle curves as a guide, an additional 0.5 mills/kW-hr was estimated when using residual fuel for both the simple and combined cycles. Also, the O&M costs for the recuperated cycle were assumed to be the same as for the simple cycle.

Three situations were considered for which the effect of thermal barrier coatings on O&M costs were estimated. The first consists of applying the thermal barrier while keeping the turbine inlet temperature and metal temperature constant, and reducing the cooling flow and thus increasing performance. The O&M cost difference between the coated and uncoated cases was calculated based on an assumption that both the uncoated and coated turbines would have a biennial service inspection in which the casing would be removed. At this inspection, the coated parts would be stripped and recoated, and the extra costs to do this would increase the O&M cost for the coated cases. Based on the costs for stripping and coating which were supplied by NASA and mentioned previously, the extra O&M charge for gas turbines with thermal barrier coatings, while keeping the metal temperatures constant, were 0.391 mills/kW-hr for the simple and recuperated cases and 0.048 mills/kW-hr for the combined cycles.

The second situation considered the application of thermal barriers while keeping the same turbine inlet temperatures and cooling flow rates, thereby reducing metal temperatures and increasing the life of the components. It was estimated by Westinghouse that the blade life would be increased by a factor of 2 for continous duty (base load) and 1.5 for cyclic duty (peak load), if the thermal barrier were applied and the metal temperatures were lowered by keeping the cooling flow rates the same. A calculation was not done of this effect on combustor, transition piece and vane lifetimes, and it was assumed that their lifetimes would also be increased as mentioned above. The differential O&M cost between this case and the one previously discussed is -1.137 mills/kW-hr for simple cycles and -0.172 mills/kW-hr for combined cycles; that is, the O&M is lower for a coated case when the coolant flow is kept constant and the metal temperature is lowered than if the thermal barrier is applied and the coolant flow is reduced and the metal temperature is kept constant.

For the two situations just discussed, it was assumed that the thermal barrier was replaced every two calendar years. The final situation considers the variation of the replacement interval for thermal barriers. Thus the differential O&M for one and five year replacement intervals was also calculated. A one year replacement time resulted in an increase in O&M cost over the two year assumption by 0.985 mills/kW-hr for simple cycles and 0.121 mills/kW-hr for the combined cycle.

When a five-year replacement time was assumed, the O&M was estimated to decrease by 0.657 mills/kW-hr for simple cycles and 0.081 mills/kW-hr for combined cycles. All of the incremental O&M costs quoted in this section were calculated from the stripping and coating costs supplied to Westinghouse by NASA.

Cost of Electricity. - The capital cost portion of COE was calculated assuming an 18% fixed charge rate, a capacity factor of 0.12 for the simple and recuperated cycles, and 0.65 for the combined cycle power plants. The fuel portion of COE was calculated assuming fuel prices of $2.60/MBtu for distillate and $2.15/MBtu for residual fuel. These fuel prices were specified for this study by NASA. Also, for all of the COE results shown in this appendix, the 2 calendar year refurbishment time assumption was used for the O&M portion of COE for the coated cases.

Discussion of Results

In this section, the performance, capital cost and COE data for the cases investigated by Westinghouse are discussed. These results are summarized in figures 15 through 18. The results for the various tradeoff analyses performed by Westinghouse are discussed in the following order: (1) turbine inlet temperature effects, (2) keeping the turbine inlet temperature constant and reducing the coolant flow rate, (3) coating thickness effect, (4) residual fuel effect, and (5) the ECAS Phase II combined cycle. Unless otherwise noted, the coating thickness for the TBC cases shown in the figures is 0.038 cm (0.015 in).

Turbine Inlet Temperature Effects. - For the three configurations studied, the turbine inlet temperature was varied from the base value of 1366-1422 K (2000°-2100° F) to a maximum value of 1589 K (2400° F) for the simple and combined cycle, and 1561 K (2350° F) for the recuperated cycle. This maximum value was determined to be the highest turbine inlet temperature possible without cooling the last stage rotor blades of the 4-stage turbine. Due to its large size and high twist, it was not considered attractive by Westinghouse to cool these blades. So that an uncooled last row blade design life of 100,000 hours could be achieved, an advanced version of the cast nickel base alloy, IN 792, was chosen for the blade stress analysis.

The effect of turbine inlet temperature on the simple cycle performance of the W-501 is shown in figure 15(a). The current production type (CPT) cases shown used state-of-the-art convection/impingement cooling, while the near-term advanced (NTA) cases used an advanced convection/impingement method.

Generally, after the thermal barrier is applied and the turbine inlet temperature is increased, the powerplant efficiency increases up to 1478 K (2200° F) (compare bars 1, 3, 4 and 6). The efficiency drops when the temperature is increased to 1589 K (2400° F), due to the large increase in cooling air required. The compressor pressure ratio is held approximately constant, with slight increases in pressure ratio for the coated cases as previously mentioned. Even though the efficiency decreases slightly for the 1589 K (2400° F) case, it should be noted that the specific power increases continuously from 1366-1422 K (2000°-2100° F) to 1589 K (2400° F).

The addition of the thermal barrier permitted the use of impingement/convection cooling at 1589 K (2400° F), and resulted in an 8% increase in specific power over the 1478 K (2200° F), uncoated NTA case (a 19% increase over the base case), with only a slight decrease in efficiency. This is important for peaking units where maximum power output is an important consideration. Also, the changes in efficiency as the turbine inlet temperature is increased are noted to be quite small, due primarily to the nearly constant pressure ratio of these cases.

The recuperated cases have higher efficiency than the simple cycle cases, but the changes in efficiency when adding the thermal barrier coating and increasing the turbine inlet temperature, produced essentially the same effects as noted for the simple cycle cases. The recuperated cases had slightly lower compressor pressure ratios (11.9 for reference case) compared to the simple and combined cycles (12.4 for reference case). This slight decrease was accomplished by changing the turbine geometry of the W-501 slightly in an attempt to operate this gas turbine at a more optimum pressure ratio in a recuperated cycle configuration. Due to this lower pressure ratio, the last turbine stage encounters higher gas temperatures for the same turbine inlet temperatures used for the simple and combined cycles, and as a result, the maximum turbine inlet temperature for the recuperated cases is slightly lower at 1561 K (2350° F), than for the simple and combined cycle (see table I).

In figure 15(b) the effects of turbine inlet temperature on the W-501 combined cycle efficiency is displayed. In comparison with the simple cycle cases (fig. 15(a)), the increases in efficiency with the addition of the thermal barrier coating and increasing temperature is much larger (compare bars, 1, 3, 4 and 6). For combined cycle systems, increasing the turbine inlet temperature, or decreasing the turbine cooling requirement by adding the thermal barrier, increases the turbine exhaust temperature. Since more waste heat is available for recovery in the HRSG's, less supplementary firing is necessary, thus resulting in further fuel savings and larger changes in efficiency. All of the cases shown in figure 15(b) utilize supplementary firing, but the amount of supplementary firing decreases at higher turbine inlet temperatures. It is noted that at 1589 K (2400° F), the combined cycle efficiency continues to increase; the efficiency of the simple cycle case decreased at the same temperature (see fig. 15(a)). Even though the cooling flow requirements are high for this case (the same as in fig. 15(a)), supplementary firing is reduced by 70% compared to the uncoated, NTA case at a turbine inlet temperature of 1478 K (2200° F), due to the higher gas turbine exhaust temperature. The powerplant efficiency thus increases.

The effect of turbine inlet temperature on the Westinghouse simple cycle gas turbine cost estimates is shown in figure 16(a). The capital cost, in $\$/kW_e$, decreases with increasing turbine inlet temperature due to the higher specific power of the engine (compare bars 1, 3, 4 and 6); the effect of turbine inlet temperature on capital cost for the recuperated cycle plants is similar to the results for the simple cycle cases. Also, similar results are shown in figure 16(b) for the combined cycle cases, again due to the higher specific power.

The cost of electricity for the simple cycle cases using distillate fuel is seen in figure 17(a). The numbers corresponding to the letters C, F, and OM for each bar represent the capital, fuel and O&M portion of COE, respectively, which make up the total COE. The 2-calendar year coating refurbishment interval was assumed for the O&M portion of COE for the coated cases. The largest single decrease in COE is obtained when turbine inlet temperature is increased for the CPT from 1366-1422 K (2000°-2100° F) to 1478 K (2200° F) (bars 1 to 3). The capital portion of COE decreases since the electrical power output increases. Also, the fuel portion of COE decreases since the efficiency increases, so the total COE decreases. For the NTA cases, in going from 1478 K (2200° F) to 1589 K (2400° F), the same effect is seen, although the decrease is not as prominent (compare bars 4 and 6). The reason for this is that the gas turbine efficiency actually decreases when going to 1589 K (2400° F) because of the increase in cooling air as mentioned previously (fig. 15(a)). The capital portion of COE continues to decrease, and the overall effect is a decrease in COE.

The results for the recuperated cases are similar to the simple cycle results. The COE for the combined cycle cases is shown in figure 17(b). The results are similar to the simple cycle cases discussed above.

<u>Constant Turbine Inlet Temp. - Reduced Coolant Flow Rate</u>. - In figure 15, the effect of the thermal barrier, while keeping the turbine inlet temperature constant, on simple and combined cycle powerplant performance is shown. In both (a) and (b), the effects on efficiency of the barrier for the CPT at 1366-1422 K (2000°-2100° F) and for the NTA engine at 1478 K (2200° F) are shown to be very small (compare bars 1 and 2, or 4 and 5). The increases in efficiency are due to decreased cooling flow requirements in the turbine and slight increases in the compressor pressure ratio due to the coating thickness on the blades. At 1478 K (2200° F), the same performance can be achieved with the CPT gas turbine using the coating with simple convection/impingement, as can be achieved by an uncoated NTA engine using the advanced convection/impingement cooling method. Greater increases in efficiency are possible by increasing the turbine inlet temperature. In this respect, the thermal barrier allows the use of convection/impingement cooling at 1589 K (2400° F). To achieve that temperature without the coating, more advanced transpiration, film or other similar method would be required. Therefore, the thermal barrier appears

to be a factor in increasing the upper limit of maximum turbine inlet temperature for convection/impingement cooling methods, and does not affect efficiency appreciably at a constant turbine inlet temperature and pressure ratio for a thickness of 0.038 cm (0.015 in).

As shown in figure 16, the capital cost per kW_e decreases slightly for the CPT and NTA engines when the thermal barrier is added and the turbine inlet temperature remains constant (bars 1 and 2, or 4 and 5). The capital cost, in dollars, increases for the thermal barriers as mentioned previously. However, the power output of the coated cases is larger than the uncoated cases, due to the reduction in cooling flow requirements. The net result is a slight decrease in capital cost in $\$kW_e$. As with the performance results shown in figure 15, the effect of adding the thermal barrier at a given turbine inlet temperature for CPT or NTA engines is small.

The COE results are displayed in figure 17. In comparing bars 1 and 2 for the CPT and 4 and 5 for the NTA, it is seen that the application of the thermal barrier when keeping the turbine inlet temperature constant offers only a slight benefit in the COE. The increases in performance are relatively small and the capital portion of COE does decrease due to the increased power output, but the O&M portion of COE increases due to the biennial stripping and coating costs, so the total COE benefit is quite small.

Coating Thickness Effect. - A simple and combined cycle case were investigated at a turbine inlet temperature of 1366-1422 K (2000°-2100° F) with a 0.076 cm (0.030 in) coating thickness. For both cases this resulted in an 18.6% decrease in cooling air usage compared to the reference case. The efficiency of the uncoated, simple cycle base case was 29.4%, and this was increased to 29.6% with the application of a 0.038 cm (0.015 in) coating (constant turbine inlet temperature - reduced coolant) and further increased to 30.0% with a coating thickness of 0.076 cm (0.030 in). The corresponding efficiency values for the combined cycles are 41.5%, 41.7% and 42.0% respectively. The thicker coating reduces the heat flux, and thus reduces the cooling air requirements and results in increased efficiency.

The additional coating thickness at a turbine inlet temperature of 1366-1422 K (2000°-2100° F) results in about the same performance increase as increasing the turbine inlet temperature to 1478 K (2200° F) with a 0.038 cm (0.015 in) TBC, shown in figure 15. Therefore, larger performance improvements than seen in figure 15 can be achieved with thicker coatings. However, other factors such as thermal gradients on startup, might have an effect in determining the optimum coating thickness.

Also, the capital cost, in dollars per kW_e, decreases due to the increased specific power with the thicker coating. The capital costs for the uncoated base case and two coated cases with the 0.038 cm (0.015 in) and 0.076 cm (0.030 in) thickness are 166.2, 164.8 and 163.0 dollars per

kW_e for the simple cycles and 330.5, 327.9 and 321.9 dollars per kW_e for the combined cycle cases, respectively. Again, these decreases in capital costs in dollars per kW_e are due to the increased specific power as a result of decreased coolant flow while keeping the turbine inlet temperature constant. In comparison with the results shown in figure 16, the decrease in capital cost with the thicker coating is not as large as that shown when the turbine inlet temperature is increased from 1366-1422 K (2000°-2100° F) to 1478 K (2200° F).

The effect of increasing the coating thickness from 0.038 cm (0.015 in) to 0.076 cm (0.030 in) at 1366-1422 K (2000°-2100° F) results in a 1.1% decrease in COE for the simple cycle and 2.0% for the combined cycles, compared to their respective uncoated reference cases. The COE is expected to decrease with increasing coating thickness since the efficiency and specific power increases (a result of reduced cooling air requirements) and the added cost for the heavier application of the barrier was assumed to be negligible. The optimum coating thickness will probably be determined by other factors such as stress considerations at the leading edge radius, thermal cycling, and the ability of the thermal barrier to withstand harsh environments at different thicknesses.

Residual Fuel Effects. - The Westinghouse results indicate that a residual fuel fired gas turbine plant has a lower efficiency and power output than an identical plant firing distillate oil. This is a result of the extra auxiliary electrical requirements for fuel heating, and treatment with electrostatic precipitators which are needed when using residual fuel with gas turbine engines. The estimated values for the auxiliary power losses were discussed in the approach and assumptions section. For the simple cycle base case, the gross power output (including generator efficiency but not auxiliary electrical requirements) is 383.6 MW_e for a system including four gas turbine units. The auxiliary powerplant electrical requirements are 3.8 MW_e when firing distillate fuel and 12.2 MW_e when burning resdiual fuel. Likewise, for the combined cycle base case with two gas turbine units (gross power output = 303.9 MW_e), the auxiliary requirements are 5.0 MW_e when fired with distillate fuel and 9.5 MW_e when using residual fuel.

The effect of the use of residual fuel on capital cost of the systems studied is to increase capital cost, on a $\$/kW_e$ basis. This is due to a combination of performance and cost effects. When residual fuel is used, additional auxiliary power requirements are needed for fuel heating and treatment. Likewise, the additional capital cost for fuel treatment, heating and extra storage tanks for treated and untreated fuel increases the total plant capital cost relative to a plant using distillate. These additional costs were also previously discussed in the approach and assumptions section. These two effects result in an increase in capital cost on a $\$kW_e$ basis. For the coated simple cycle case at a turbine inlet temperature of 1366-1422 K (2000°-2100° F), the capital cost increases from $\$164.8/kW_e$ when burning distillate to $\$179.5/kW_e$ when using residual fuel. For the combined cycle at the same turbine inlet temperature, the capital cost increases from \$327.9/kW$_e$ for the distillate fueled case to \$344.8/kW$_e$ for the case using residual fuel.

The effect of using residual oil on COE is shown in figure 18 for the simple and combined cycle systems. Results are shown for both the CPT and NTA engines. The use of residual fuel offers a substantially greater decrease in COE than just the application of the thermal barrier at a constant turbine inlet temperature. This is due to the lower price of residual fuel at \$2.15/MBtu compared to distillate at \$2.60/MBtu (17% lower price for residual, compared to distillate). This result, of course, depends upon the relative fuel prices of these two fuels, which were assumed for this study. As the relative residual fuel price is raised the COE advantage of residual fuel decreases. Using the Westinghouse capital costs and O&M costs for the coated, CPT engine at a turbine inlet temperature of 1366-1422 K (2000°-2100° F), the breakeven residual fuel price is 11% lower than the distillate fuel price. At this time, residual fuel is not widely used for gas turbines due to problems of hot corrosion and cooling-air hole plugging caused by fuel impurities. The thermal barrier might offer a solution to this problem. The use of the thermal barrier coating is seen as a protection of the metal blading surfaces from erosion and corrosion caused by the dirty fuel, as well as a thermal insulation of these surfaces. If fuel pretreatment and the use of thermal barriers allows the use of residual fuel, the lower COE that results could be significant, as shown in figure 18.

ECAS Phase II Design. - The ECAS II gas turbine engine used transpiration cooling and a pressure ratio of 16. When the TBC was applied, the transpiration cooling was replaced by advanced convection/impingement cooling and the compressor pressure ratio increased to 16.6. The resulting efficiency was 32.9%, which is 3.5 points higher than the simple cycle base case, and 2.8 points higher than the highest efficiency case shown in figure 15(a). This higher efficiency is due primarily to the higher compressor pressure ratio (16.6 compared to 12). The cooling flow requirement for this case was 21.9% higher relative to the reference case cooling flow requirement. But the cooling flow was slightly lower for this case than the W-501, NTA engine at a turbine inlet temperature of 1589 K (2400° F), since at higher pressures, the coolant exhibited higher heat transfer coefficients within the blade passages.

The performance of the ECAS II combined cycle system with integrated gasifier using the thermal barrier coating was essentially the same as the transpiration cooled system studied in Phase II of ECAS (approximately 47%). With the exception of the cooling method, both systems were identical.

For the ECAS II combined cycle case using the thermal barrier, a COE of 29.8 mills/kW-hr was estimated by Westinghouse. A comparison of this estimate with the ECAS Phase II results is not strictly valid, however, since the capital cost-estimating procedures for this study were based on a computer program used in the ECAS Phase I parametric evaluation, whereas the ECAS Phase II costs were estimated using a more detailed, powerplant conceptual design. Therefore, using the Phase II cost results, NASA estimated the COE for the coated ECAS II combined cycle with integrated gasifier as 29.2 mills/kW-hr, compared to 29.1 mills/kW-hr for the uncoated design using transpiration cooling. The COE, as well as performance of these two cases are approximately the same.

APPENDIX B - UTC STUDY RESULTS

Description of Systems Studied

A summary of the cases investigated by United Technologies Corporation (UTC) is presented in table III. Both simple and combined cycle configurations were considered. The UTC FT-50 developmental gas turbine engine was used for all of the cases considered. The operating characteristics of the base case FT-50 gas turbine are shown in table IV. The FT-50 is a three shaft gas turbine consisting of a high and low pressure turbo-compressor gas generator with a power turbine. The high and low pressure turbine are each one stage and are air-cooled. The two-stage power turbine is not cooled and is connected to a generator to produce electric power. This gas turbine engine utilizes showerhead film cooling in the leading edge of the first-stage blade and vane and required a considerable amount of coolant at the specified rotor inlet temperature. The coolant air is used at the compressor discharge temperature. This turbine is still in development and has not been sold for commercial utility use at this time. The electrical power output for this gas turbine is 106 MW_e when the turbine parts are cooled to 1088 K (1500° F) and 110 MW_e when cooled to 1144 K (1600° F).

As shown in table III for both simple and combined cycle configurations, two uncoated base cases were considered in which the metal temperature was cooled to 1144 K (1600° F) and 1088 K (1500° F). The base engine at the 1144 K (1600° F) metal temperature had an airfoil creep life of 10,000 hours while the cases cooled to 1088 K (1500° F) had lifetimes of greater than 30,000 hours. These base cases operated at a rotor inlet temperature of 1454 K (2160° F). No attempt was made to estimate the corrosion lifetimes of these base case engines.

For the TBC cases, a 30,000-hour structural life to 1% creep was chosen as a design criteria and it was assumed that the coated parts had greater than 30,000-hour corrosion lives. With these critieria, UTC increased the rotor inlet temperature and adjusted the cooling flow to maintain the 30,000-hour life criterion. A limiting factor on the rotor inlet temperature, T_{RIT}, of the high pressure turbine was the stress life of the "free" or power turbine, which was uncooled. The maximum possible inlet temperature to the power turbine was limited to 1088 K (1500° F), while still maintaining the 30,000-hour life criterion. The maximum rotor inlet temperature of the high pressure turbine corresponding to this limit was found to be 1480 K (2204° F), and this was the temperature chosen for the thermal barrier coated cases.

The gas turbine engine used for the combined cycle system is the same as described above. The FT-50 gas turbine is bottomed by a non-reheat steam cycle with throttle conditions of 4.14-5.03 Mpag/744-772 K (600-730 psig/880°-930° F). These throttle conditions vary in this range for the different cases so that a 422 K (300° F) stack temperature could be maintained for all cases. This steam cycle raised steam at two pressure levels, with the low pressure steam being inducted at the inlet to the low pressure turbine. The steam throttle conditions and flow rates were adjusted for different gas turbine conditions so that supplementary firing in the heat recovery steam generator (HRSG) was not required.

Approach and Assumptions

Performance. - The simple cycle power plants considered by UTC consisted of single gas turbine units. The combined cycle systems had two gas turbine units bottomed by a single steam plant. The exhaust from both gas turbines enters a single HRSG unit, where the waste heat is recovered by raising steam for the bottom cycle.

Although powerplant siting and other necessary equipment were considered for costing purposes, powerplant electrical auxiliary requirements were not considered in the calculation of efficiencies and determining the net electrical output of each case. Therefore, the UTC performance results are slightly optimistic in that for an actual powerplant the efficiency and power output of these cases would be slightly lower. The efficiencies quoted are based on the HHV of the fuel being used.

A one-dimensional heat transfer analysis of the thermal barrier effects on coolant flow was done for the 30,000-hour blade life criterion. It was assumed that the showerhead film cooling of the uncoated cases was replaced by impingement/convection cooling when the coating was applied; film cooling was used on the suction surface near the leading edge, and on the pressure surface near the trailing edge of the first stage vanes. Showerhead film-cooling was also eliminated on the first stage blade. In addition to the heat transfer effects, the aerodynamic losses due to the rough surface of the thermal barrier were included in the performance analysis. In addition to coating the blades, the combustor and transition pieces were also coated. For the uncoated engine cases, the transition piece is film cooled and requires a large amount of cooling air. This contributes to the combustor pattern factor of 0.4. With the TBC, the film cooling is replaced by simple convection cooling and the amount of cooling is reduced, which would allow better gas mixing to reduce the pattern factor. It was noted by UTC that a pattern factor improvement to 0.3 would permit an increase in turbine rotor inlet temperature of 67 K (120° F). This potential benefit, clearly a result of using a thermal barrier coating, was not analytically quantified, and was not incorporated into the performance calculations.

Capital Cost. - The capital cost of the powerplants considered were estimated by UTC using a proprietary computer cost program. Balance of plant equipment and site labor costs were estimated by UTC and included in the capital cost estimate. For costing purposes the simple cycle gas turbine systems have been assumed to be located on the outskirts of a large city near a commercial or industrial area. Also, the combined cycle system costs were estimated using the same assumption, and then the total cost was modified to reflect the Middletown, U.S.A. site. All costs were estimated in mid-1976 dollars. Escalation and interest during construction were not included by UTC, but were included by NASA using a 6.5% annual escalation rate, 10% annual interest rate, and a cash flow curve as used in the ECAS Phase II study. The construction times, estimated by UTC, were two years for simple cycle and four years for combined cycle systems.

The residual fuel treatment cost was estimated by UTC to cost an additional $\$1.96/\text{kW}_e$ of gas turbine power over the distillate fueled cases. These costs are primarily due to the fuel treatment system and other capital expenses associated with it. For the simple cycle systems, the costs for the residual fuel treatment range from $204,500 to $230,700. A similar cost range for the combined cycle systems is $403,000 to $456,900.

The costs of applying the thermal barrier were estimated by UTC, based on their experience with thermal barrier coatings. The net increase in capital cost for applying the thermal barrier on an FT-50 engine was estimated to by $50,000. This net cost not only includes the cost of coating the various hot section components but also includes cost savings associated with replacing the rather complicated film cooling arrangement with a simpler impingement/convection cooling method.

All of the capital costs were estimated by UTC, with the exception of the distillate fired combined cycle case with thermal barrier. The performance of this case was calculated by UTC, but the cost was not, so NASA estimated this cost based on the residual fueled case by subtracting the extra costs associated with residual fuel treatment.

O&M Costs. - A summary of the O&M costs estimated by UTC is shown in figure 19. The basic O&M cost, except for the hot section of the turbines, was assumed to be 2.0 mills/kW-hr for both simple and combined cycle systems. As shown in appendix A, the O&M is actually a function of capacity factor and would be different for simple and combined cycles. However, UTC stated that their base cost estimates were arbitrary, and the changes in O&M costs shown in figure 19 were calculated using UTC and utility cost data.

The changes in O&M costs are shown for the uncoated cases with metal temperatures at 1088 K (1500° F) and 1144 K (1600° F) and the O&M costs for the thermal barrier coating are also parametrically varied for different replacement intervals. It is noted that cases where the metal temperature was cooled to 1144 K (1600° F), the combustor was coated with a magnesium zirconate coating whereas the case in which the metal temperature is cooled to 1088 K (1500° F), it was assumed not to be necessary to coat the combustor. The increased lifetime of this case over the higher metal temperature case is reflected in lower delta O&M costs (darkened areas), where the delta O&M cost is 9 to 10 times larger for the case with higher metal temperature. However, since this portion of O&M is so small compared to the total cost of electricity, the overall effect on the electric production costs is small. Likewise, the parametric variation of the replacement intervals shown in the last bar indicate that this interval will have a very small effect on the total cost of electricity.

Cost of Electricity. - As was done in the Westinghouse study, the cost of electricity was calculated by UTC assuming an 18% fixed charge rate and fuel costs of \$2.60/MBtu for distillate and \$2.15/MBtu for residual. UTC calculated COE's at capacity factors of 0.12 (peaking) and 0.45 (intermediate) for the simple cycle systems and at 0.45 and 0.65 (base) for the combined cycle systems. Only the results at 0.12 capacity factor for simple cycles and 0.65 for the combined cycles are reviewed in this report. Also, the COE's presented in this report have been recalculated by NASA to include the escalation and interest charges during construction. The COE's for the coated systems shown on the following figures assume the 5,000-hour interval for thermal barrier replacement costs.

Discussion of Results

In the following discussion of the UTC results, the performance, capital cost and cost of electricity are reviewed for the trade-off analyses in the following order: (1) metal temperature effects, (2) residual fuel effects, and (3) thermal barrier effects. The performance, capital cost and COE data for the cases investigated by UTC are shown in figures 20, 21 and 22 respectively.

Metal Temperature Effect. - A performance comparison for the simple and combined cycle systems investigated by UTC is shown in figure 20. The effect of cooling the metal temperature to different levels on performance can be seen by comparing the uncoated cases burning residual fuel. The difference in efficiency between the 1088 K (1500° F) case and the 1144 K (1600° F) case is due to the increased coolant required to cool the metal temperatures down to 1088 K (1500° F). The difference in efficiency amounts to 0.8 percentage points for the simple cycle systems and 0.9 percentage points for the combined systems, while the hot section life was increased by over a factor of three from the 1144 K (1600° F) case. The increased lifetime would have an effect on the operation and maintenance costs (O&M), as was discussed previously.

The capital costs for the systems studied by UTC are displayed in figure 21. It is seen that the uncoated case in which the metal temperature is cooled to 1144 K (1600° F) has a lower capital cost compared to the uncoated case cooled to 1088 K (1500° F). The case cooled to 1144 K (1600° F) has a lower cooling air flow rate, and thus the electrical power output is higher resulting in a lower cost in $\$/kW_e$.

The cost of electricity estimates for the cases investigated by UTC are shown in figure 22. The letters C, F, OM and the values associated with the letters indicate the capital, fuel and operation and maintenance portions of the total COE. A comparison of the uncoated-residual fuel fired cases indicates that the case with a metal temperature of 1144 K (1600° F), has a lower COE than the case in which the metal temperature is cooled to 1088 K (1500° F). As mentioned previously the higher metal temperature case has a slightly better performance, and this is reflected in the capital and fuel portion of the COE. Also, the lower life of the blade components is also reflected in the higher O&M cost due to more frequent replacing of the blades. However, it is seen that the decreases in the capital and fuel portions of COE are greater than the increase in the O&M costs relative to the lower metal temperature case which has increased life, and the total effect is a lower COE for the case where the metal temperature is kept at 1144 K (1600° F).

Residual Fuel Effects. - From figure 20, the cases fired by residual fuel are shown having a slightly higher efficiency than the distillate fueled cases, but this is not a real difference. Since auxiliary electrical requirements were not considered by UTC for their performance calculations, the additional electrical loads for the fuel heating and treatment of the residual fuel have not been included. If the efficiencies were expressed in terms of the lower heating value, the efficiencies would be very nearly the same, as would be expected when not including auxiliary power losses. Since the ratio of the higher heating value to lower heating value of the residual fuel is less than the same ratio for distillate fuel, the efficiency is higher for the residual fueled case if expressed in terms of the higher heating value.

From figure 21, the capital costs of the cases using residual fuel are only slightly higher than a comparable case using distillate fuel (compare bars 1 and 3, 4 and 5). The only increase in $\$/kW_e$ resulted from the slight increase in the capital cost due to the residual fuel treatment, as mentioned previously. If the auxiliary load requirements of the powerplants were included in the performance calculations, the residual fueled cases would have slightly lower net power output than the distillate fueled cases. This would increase the capital cost in $\$/kW_e$ of the residual fueled cases in comparison with the distillate fueled cases.

As shown in figure 22, the residual fueled cases have lower COE's than a comparable case fueled with distillate (again compare bars 1 and 3, 4 and 5). This is due to the assumed relative fuel costs of distillate and residual fuel. The capital portions of COE are slightly higher for the residual fueled cases due to the cost of fuel treatment and heating as mentioned earlier. The O&M portion of COE is identical to the distillate fueled cases, since UTC did not consider additional O&M charges when using residual fuel. The fuel portion of COE is considerably lower for the residual fueled case, solely due to the lower price of residual fuel assumed for this study.

Thermal Barrier Effects. - The effect of the thermal barrier on the efficiency is shown in the last two bars in figures 20(a) and (b). For these two simple and combined cycle system cases, the showerhead film cooling was replaced with impingement/convection cooling and the turbine rotor inlet temperature was increased to 1480 K (2204° F). These cases represent the maximum efficiency achievable with the thermal barrier coating using the FT-50 gas turbine model, within the constraints mentioned previously. The best direct comparison of the performance of a coated and uncoated turbine is between the coated case using residual fuel and the uncoated case using residual fuel with metal temperatures of 1088 K (1500° F). Both cases have hot section component lifetimes of at least 30,000 hours. The difference in efficiency for the simple cycle cases (fig. 20(a)) is 1.3 points. This gain in efficiency for the coated case is due to the increased rotor inlet temperature and a 42.6% decrease in cooling flow requirements. The power output also increases by 12.8%. For the same comparison in the combined cycles (fig. 20(b)), the increase in efficiency and power output is 1.9 points and 13.4%, respectively, for the same increase in turbine inlet temperature and decrease in coolant flow requirements.

As shown in figure 21, the use of the thermal barrier at the higher rotor inlet temperature 1480 K (2204° F) resulted in lower capital costs than the uncoated cases. Although the capital cost in absolute dollars is greater due to the application cost of the thermal barrier, the increased power output due to the elevated rotor inlet temperature and decreased cooling flow requirements more than compensates for the increased cost, and the capital cost, in $\$/kW_e$, actually decreases. In comparing the coated and uncoated cases with 30,000-hour component lifetimes using the residual fuel, the capital cost decreases by 10% for the simple cycle systems and 8% for the combined cycle systems.

The effect of thermal barriers on the COE can be seen in figure 22 by comparing the coated and uncoated cases burning the residual fuel and having 30,000-hour component lives (bars 2 and 5). This data indicates a decrease in COE of 7% for the simple cycles and 5% for the combined cycles when the thermal barrier is applied and the turbine rotor inlet temperature is increased. The capital portion of COE is lower due to the increased power output and the fuel portion is lower due to the increased efficiency. The O&M costs are slightly higher for the coated cases, but this has little effect on the total COE.

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TABLE I. - WESTINGHOUSE STUDY SCOPE (PARAMETRIC VARIATIONS)

SIMPLE CYCLE:

FRAME	TBC	CAPACITY FACTOR	FUEL*	T_{SIT}, K (°F)		TYPE COOLING**	REFURBISHING INTERVAL, calender yr	TBC THICKNESS, cm (in.)
W-501	WITHOUT WITH - REDUCED COOLANT WITH - SAME COOLANT	0.12	D, R	1366-1422 1478 1589	(2000-2100) (2200) (2400)	a, b	1, 2, 5	0.038 (0.015) .076 (0.030)
ECAS II	WITH	.12	D, R	1644	(2500)	b	2	.038 (0.015)

RECUPERATED CYCLE:

FRAME	TBC	CAPACITY FACTOR	FUEL*	T_{SIT}, K (°F)		TYPE COOLING**	REFURBISHING INTERVAL, calender yr	TBC THICKNESS, cm (in.)
W-501	WITHOUT WITH - REDUCED COOLANT	.12	D, R	1366-1422 1478 1561	(2000-2100) (2200) (2350)	a, b	2	.038 (0.015)

COMBINED CYCLE:

FRAME	TBC	CAPACITY FACTOR	FUEL*	T_{SIT}, K (°F)		TYPE COOLING**	REFURBISHING INTERVAL, calender yr	TBC THICKNESS, cm (in.)
W-501	WITHOUT WITH - REDUCED COOLANT WITH - SAME COOLANT	.65	D, R	1366-1422 1478 1589	(2000-2100) (2200) (2400)	a, b	1, 2, 5	.038 (0.015) .076 (0.030)
ECAS II	WITH	.65	ILL #6 COAL -LBTU	1644	(2500)	b	2	.038 (0.015)

*D - DISTILLATE
R - RESIDUAL
**a - CONVECTION/IMPINGEMENT
b - "ADVANCED" CONVECTION/IMPINGEMENT

TABLE II. - WESTINGHOUSE BASE (NO TBC) GAS TURBINE ENGINES

	W-501	ECAS II
COMPRESSOR AIRFLOW, kg/sec (lb/sec)	356 (785)	340 (750)
TURBINE INLET TEMP, K (°F)	1366-1422 (2000-2100)	1644 (2500)
COMPRESSOR PRESSURE RATIO	12.4	16
COOLING METHOD	CONVECTION/ IMPINGEMENT	TRANSPIRATION
COOLING AIR TEMP, K (°F)	478 (400) - PRECOOLED	478 (400) - PRECOOLED

TABLE III. - UTC STUDY SCOPE

SIMPLE CYCLE:

FRAME	TBC	T_m, K (°F)	CAPACITY FACTOR	FUEL*	T_{RIT}, K (°F)	TYPE COOLING**	REFURBISHMENT INTERVAL, operating hr	TBC THICK, cm (in.)
FT-50	NO	1144 (1600)	0.12, 0.45	D, R	1454 (2160)	S	-----	------
	NO	1088 (1500)	.12, 0.45	D, R	1454 (2160)	S	-----	------
	YES	1088-1144 (1500-1600)	.12, 0.45	D, R	1480 (2204)	T	5 000	0.0381
							10 000	(0.015)
							15 000	
							30 000	

COMBINED CYCLE:

FRAME	TBC	T_m, K (°F)	CAPACITY FACTOR	FUEL*	T_{RIT}, K (°F)	TYPE COOLING**	REFURBISHMENT INTERVAL, operating hr	TBC THICK, cm (in.)
FT-50	NO	1144 (1600)	0.45, 0.65	R	1454 (2160)	S	-----	-----
	NO	1088 (1500)	.45, 0.65	R	1454 (2160)	S	-----	-----
	YES	1088-1144 (1500-1600)	.45, 0.65	R	1480 (2204)	T	5 000	0.0381
							10 000	(0.015)
							15 000	
							30 000	

*D - DISTILLATE
R - RESIDUAL
**S - "SHOWERHEAD" FILM-COOLING
T - TBC/IMPINGEMENT/CONVECTION/LOCAL FILM-COOLING

TABLE IV. - UTC FT-50 BASE CASE

COMPRESSOR AIRFLOW, kg/sec (lb/sec)	368.5 (81[illegible])
TURBINE ROTOR INLET TEMP, K (°F)	1454 (2160)
COMPRESSOR PRESSURE RATIO	18:1
COOLING METHOD	"SHOWERHEAD" LEADING EDGE CONVECTION/IMPINGEMENT LOCAL FILM COOLING PEDESTAL TRAILING EDGE

TABLE V. - EFFECT OF HIGHER FIRING TEMPERATURE ON COST OF ELECTRICITY (MILLS/kW-HR) PER MACHINE

	1366-1422K 2000-2100° F CPT NO TBC	1478K 2200° F CPT TBC	1589K 2400° F NTA TBC
SIMPLE CYCLE:			
CAPITAL	28.45	26.68	25.31
FUEL	30.16	29.70	29.97
O&M	3.80	4.19	4.19
TOTAL	62.41	60.57	59.47
Δ		-3.0%	-4.9%
ANNUAL SAVINGS PER 100 MW MACHINE:		$200K	$310K
TOTAL ACCUMULATED SAVINGS (1980-2000):		$1.5B	$2.4B
COMBINED CYCLE:			
CAPITAL	10.50	10.06	9.65
FUEL	21.49	20.89	20.34
O&M	1.75	1.80	1.80
TOTAL	33.74	32.75	31.79
Δ		-3.0%	-6.1%
ANNUAL SAVINGS PER 300 MW SYSTEM:		$1700K	$3300K
TOTAL ACCUMULATED SAVINGS (1980-2000):		$3.5B	$6.8B

TABLE VI. - EFFECT OF REDUCED COOLING AIR FLOWRATE ON COE AND SAVINGS FOR CURRENT W-501 TURBINE

	NO TBC	TBC
SIMPLE CYCLE:		
COE (mills/kW-hr)		
CAPITAL	28.45	28.22
FUEL	30.16	29.93
O&M	3.80	4.19
TOTAL	62.41	62.34
Δ		-0.1%
ANNUAL SAVINGS PER 100 MW MACHINE:		$ 7K
TOTAL ACCUMULATED SAVINGS (1980-2000):		$61M
COMBINED CYCLE:		
CAPITAL	10.50	10.42
FUEL	21.49	21.37
O&M	1.75	1.80
TOTAL	33.74	33.59
Δ		-0.4%
ANNUAL SAVINGS PER 300 MW SYSTEM:		$250K
TOTAL ACCUMULATED SAVINGS (1980-2000):		$540M

TABLE VII. - EFFECT OF REDUCED METAL TEMPERATURE ON COE AND SAVINGS FOR CURRENT W-501 TURBINE

SIMPLE CYCLE:			
COE (mills/kW-hr)		NO TBC	TBC
CAPITAL		28.45	28.74
FUEL		30.16	30.18
O&M		3.80	3.05
	TOTAL	62.41	61.97
	Δ		-0.7%
ANNUAL SAVINGS PER 100 MW MACHINE:			$46K
COMBINED CYCLE:			
CAPITAL		10.50	10.55
FUEL		21.49	21.55
O&M		1.75	1.63
	TOTAL	33.74	33.73
	Δ		--
ANNUAL SAVINGS PER 300 MW:			-

TABLE VIII. - EFFECT OF REDUCED METAL TEMPERATURE WITHOUT TBC ON COE AND SAVINGS FOR FT-50 GAS TURBINE

SIMPLE CYCLE:			
COE (mills/kW-hr)	Tm	1144K (1600°F)	1088K (1500°F)
CAPITAL		29.55	31.06
FUEL		21.59	22.12
O&M		2.54	2.06
	TOTAL	53.68	55.24
	Δ		+2.9%
ANNUAL SAVINGS PER 100 MW:			-$151K
COMBINED CYCLE:			
CAPITAL		10.03	10.45
FUEL		15.70	16.00
O&M		2.41	2.04
	TOTAL	28.14	28.49
	Δ		+1.2%
ANNUAL SAVINGS PER 300 MW			-$547K

TABLE IX. - EFFECT OF HEAVY FUEL FIRING ON COST OF ELECTRICITY (MILLS/kW-HR) PER MACHINE

	DIST. 1366-1422K 2000-2100^{0}F CPT NO TBC	RESID. 1366-1422K 2000-2100^{0}F CPT TBC	RESID. 1478K 2200^{0}F NTA TBC
SIMPLE CYCLE:			
CAPITAL	28.45	30.74	28.75
FUEL	30.16	25.09	24.68
O&M	3.80	4.69	4.69
TOTAL	62.41	60.52	58.12
△		-3.0%	-6.9%
ANNUAL SAVINGS PER 100 MW MACHINE:		$200K	$450K
TOTAL ACCUMULATED SAVINGS (1980-2000):		$1.5B	$3.4B
COMBINED CYCLE:			
CAPITAL	10.50	10.95	10.72
FUEL	21.49	17.87	17.30
O&M	1.75	2.30	2.30
TOTAL	33.74	31.13	30.32
△		-7.7%	-10.1%
ANNUAL SAVINGS PER 300 MW SYSTEM:		$4.5M	$ 5.8M
TOTAL ACCUMULATED SAVINGS (1980-2000)		$8.5B	$11.3B

TABLE X. - SUMMARY OF COST SAVINGS COMPARED TO DISTILLATE-FIRED CURRENT TURBINE - 1366 - 1422 K (2000^0 - 2100^0 F)

	SIMPLE CYCLE		COMBINED CYCLE	
	ANNUAL SAVINGS $K/MACHINE/YR	ACCUMULATED SAVINGS (1980-2000)	ANNUAL SAVINGS $K/MACHINE/YR	ACCUMULATED SAVINGS (1980-2000)
RESIDUAL FUEL FIRING				
1366-1422K (2000-2100^{0}F)	200	1.5B	4500	8.5B
1478K (2200^{0}F)	450	3.4B	5800	11.3B
HIGHER FIRING TEMPERATURE WITH DISTILLATE FUEL				
1478K (2200^{0}F)	200	1.5B	1700	3.5B
1589K (2400^{0}F)	310	2.4B	3300	6.8B
REDUCED COOLING AIR FLOWRATE	7	61M	250	540
REDUCED METAL TEMPERATURE	46	345M	-	--

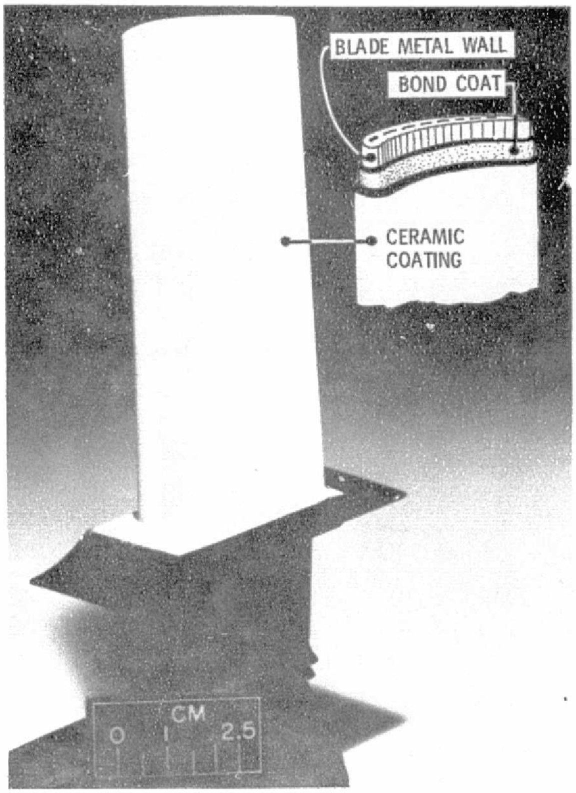

Figure 1. - Ceramic coated turbine blade.

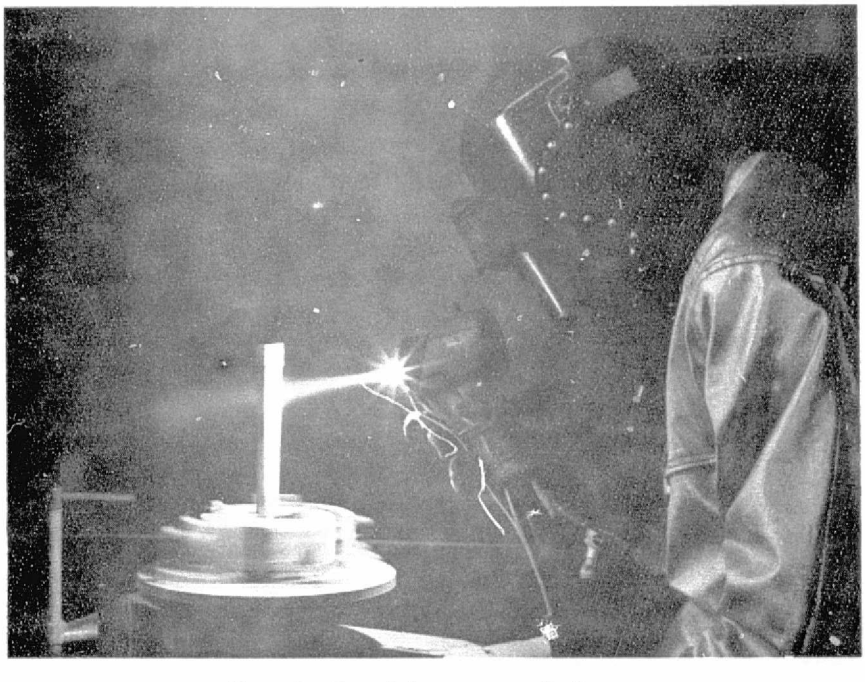

Figure 2. - Manual plasma spray application.

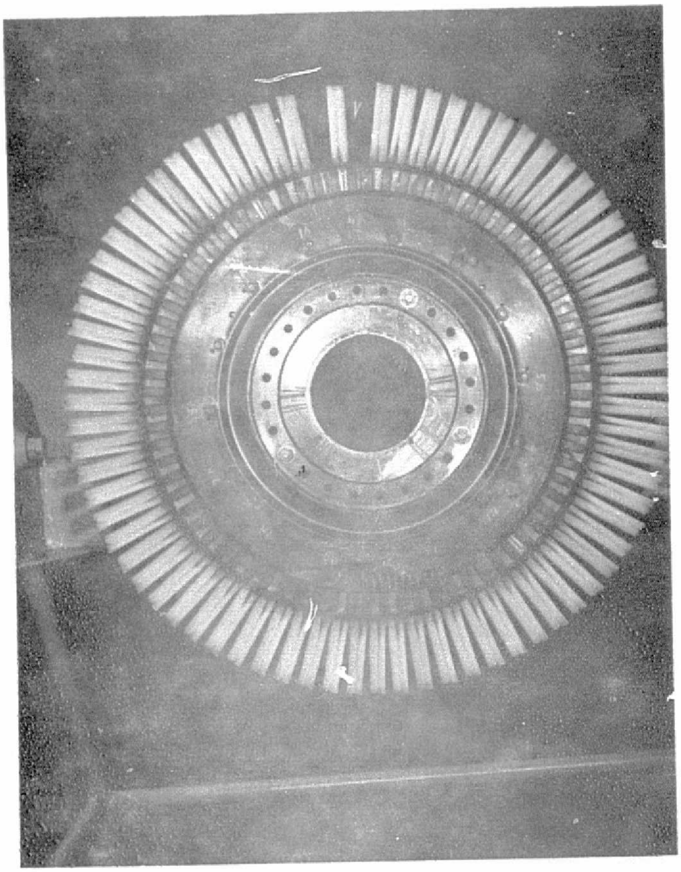

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Figure 3. - Ceramic TBC J-75 turbine wheel after 500 hours of testing.

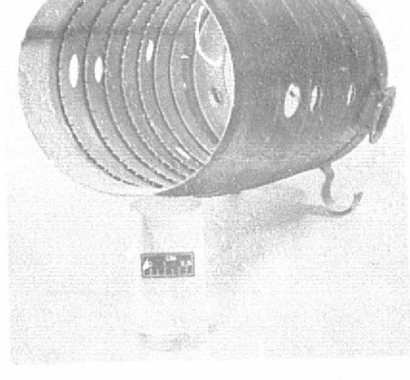


Figure 4. - Ceramic TBC JT8D combustor liner.

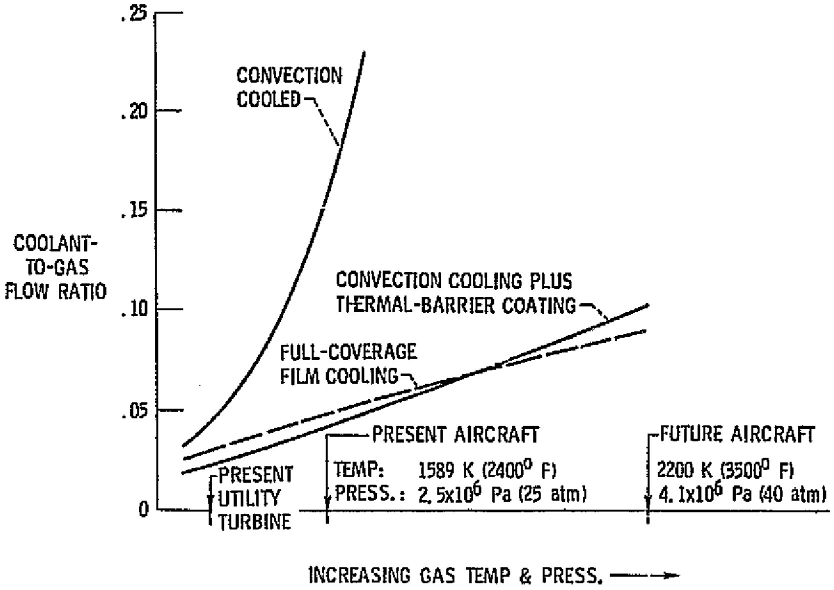


Figure 5. - Comparison of full-coverage film-cooling, convection-cooling, and convection-cooling with 0.038 cm (0.015 in.) TBC.

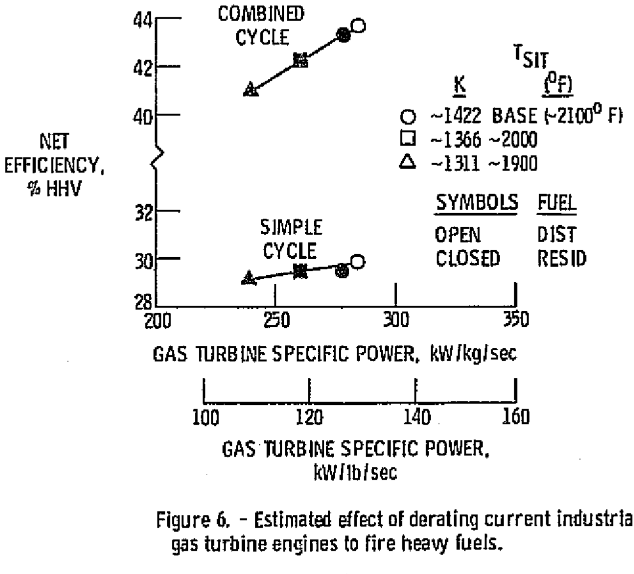
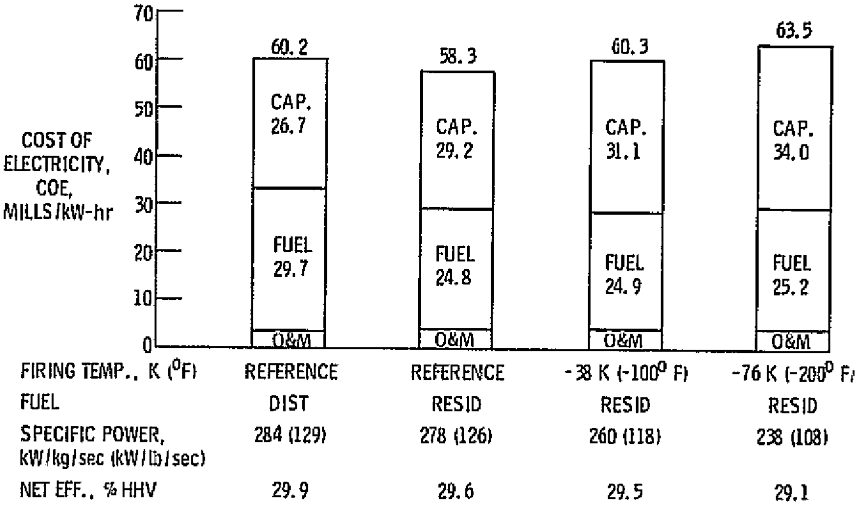
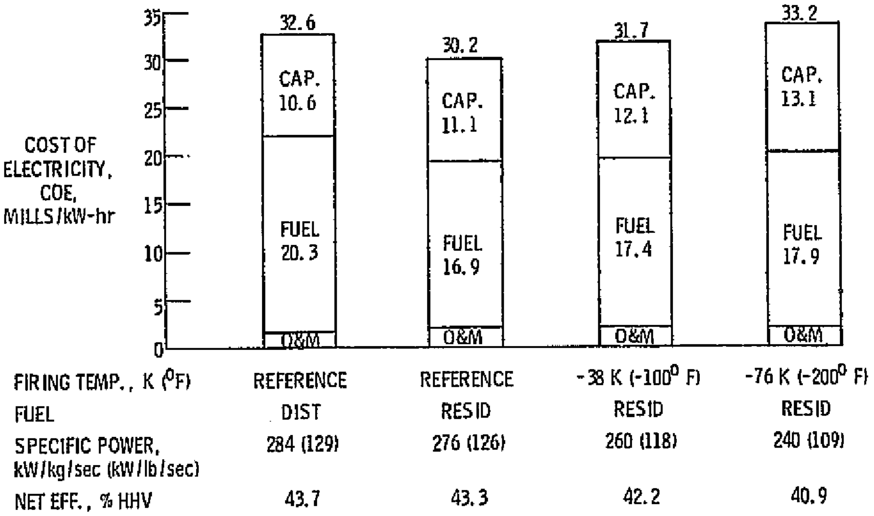


Figure 6. - Estimated effect of derating current industrial gas turbine engines to fire heavy fuels.



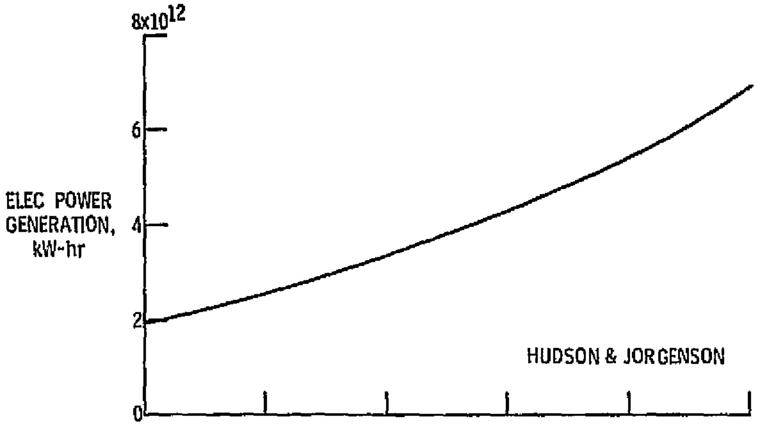
(a) SIMPLE CYCLE

Figure 7. - Estimated effect of derating firing temperature on cost of electricity.

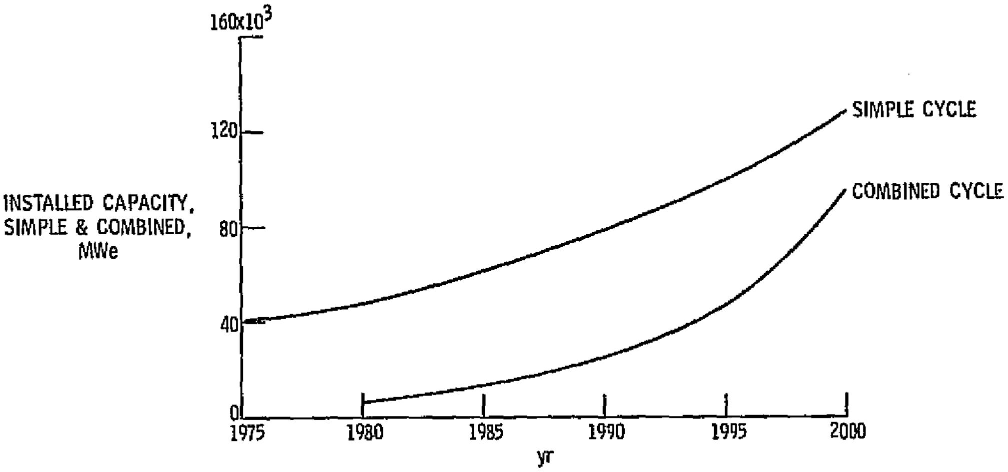


(b) COMBINED CYCLE.

Figure 7. - Concluded.



(a) Electric power generation.



(b) Installed gas turbine capacity.

Figure 8. - Electrical energy and gas turbine capacity projection.

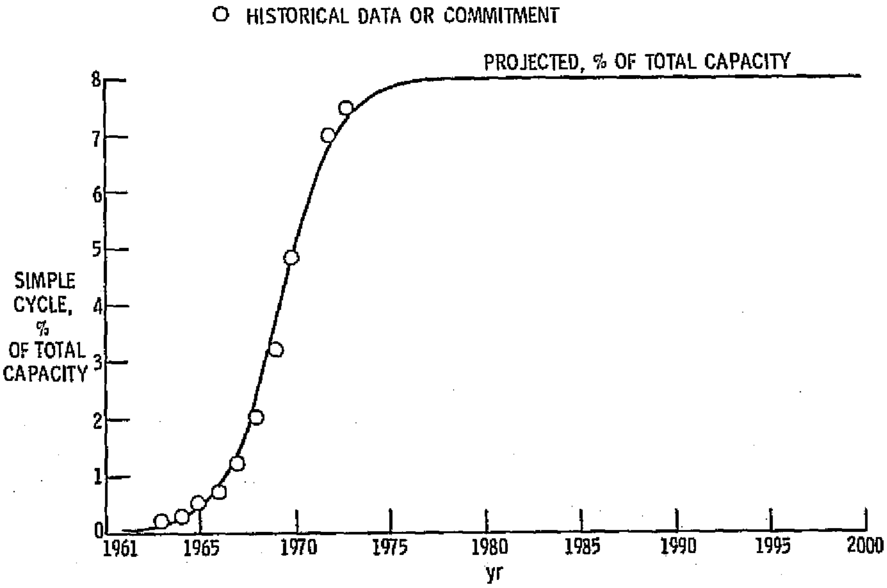


Figure 9. - Growth of gas turbines used in peaking duty.

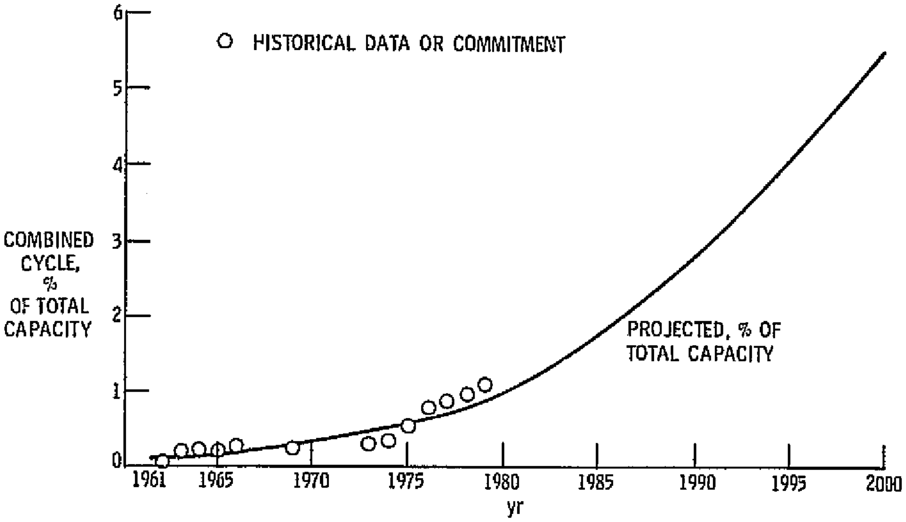


Figure 10. - Growth of combined cycle plants.

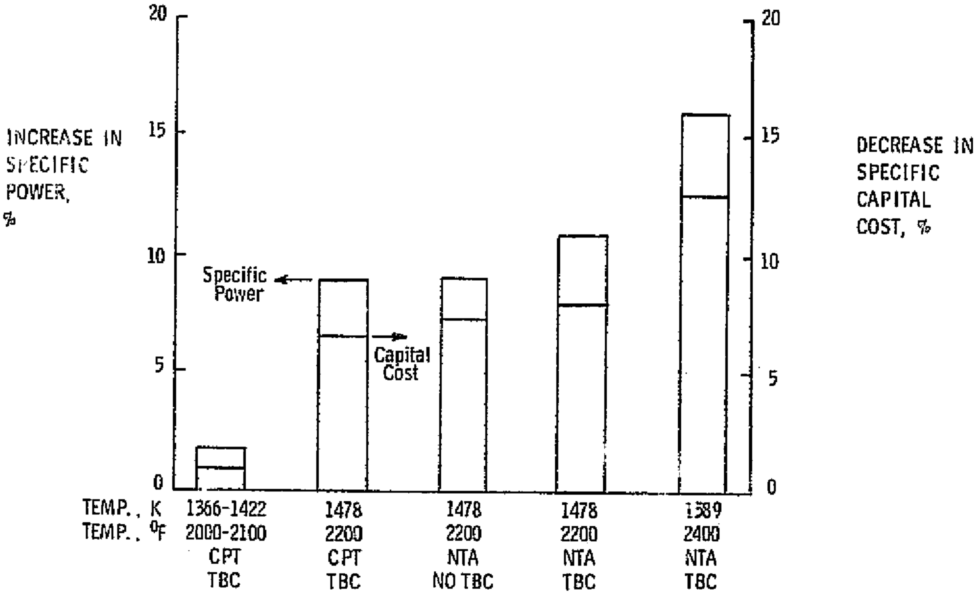


Figure 11. - Effect of turbine inlet temperature on specific power and capital cost - simple cycle systems, Westinghouse results.

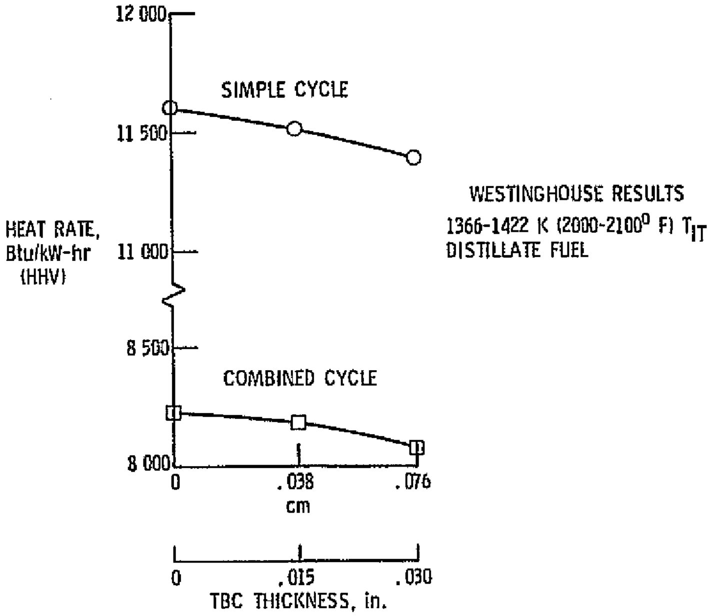


Figure 12. - Effect of coolant flow rate reduction on heat rate.

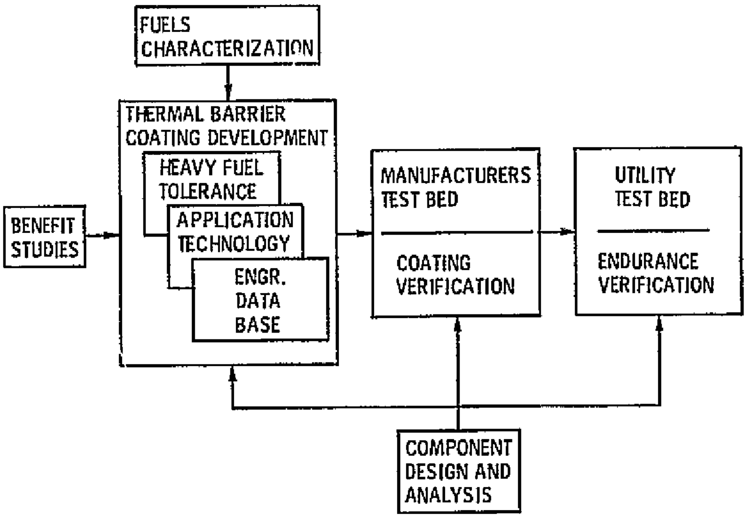


Figure 13. - Utility thermal barrier coating development logic.

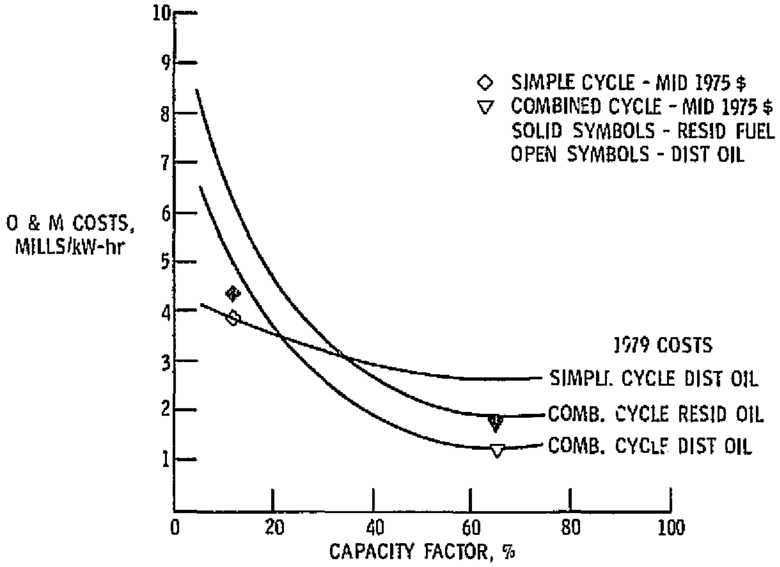
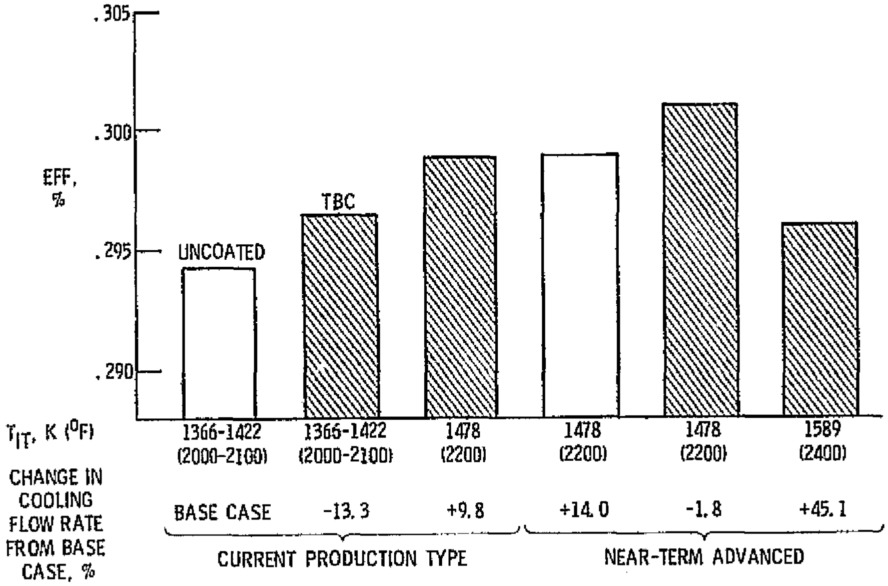
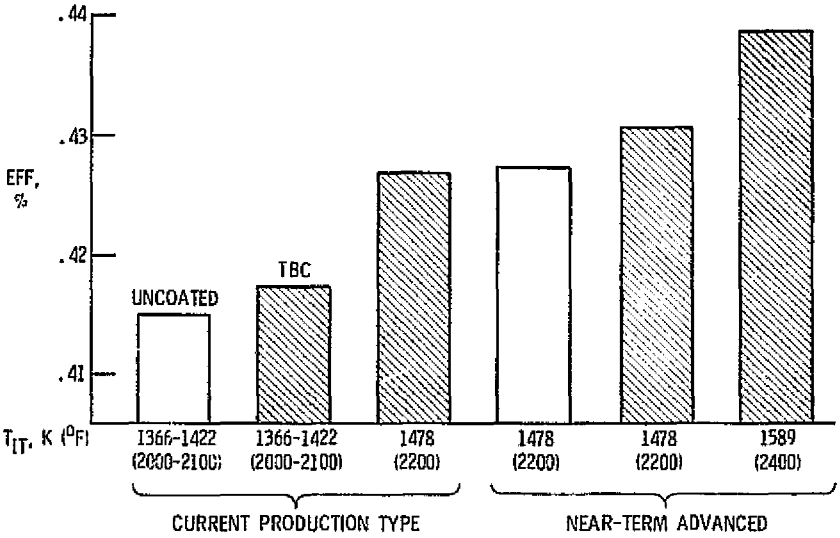


Figure 14. - Simple and combined cycle operating and maintenance cost as function of capacity factor.



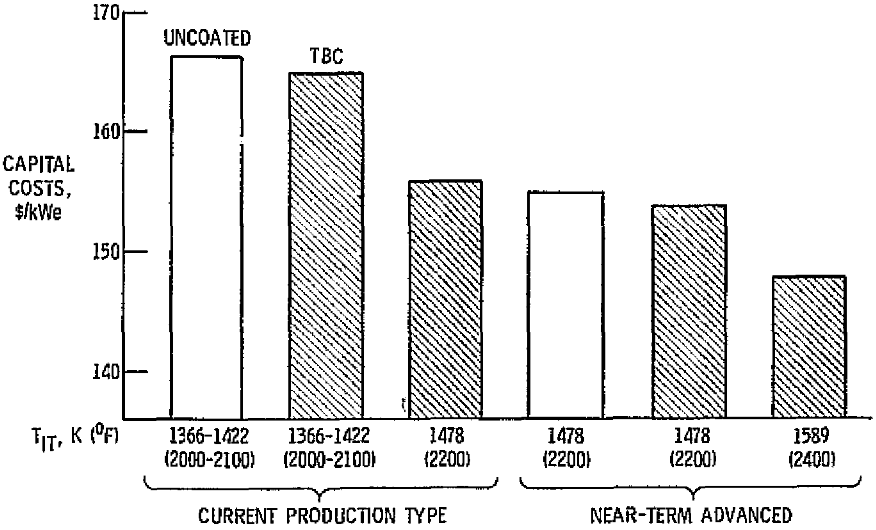
(a) SIMPLE CYCLE GAS TURBINES.

Figure 15. - Westinghouse performance comparison - distillate fuel.



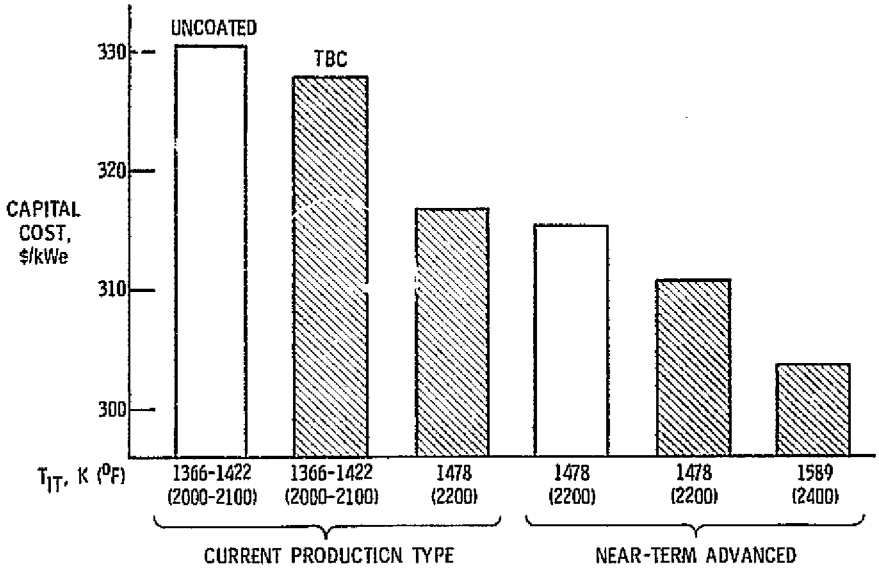
(b) COMBINED CYCLE SYSTEMS.

Figure 15. - Concluded.



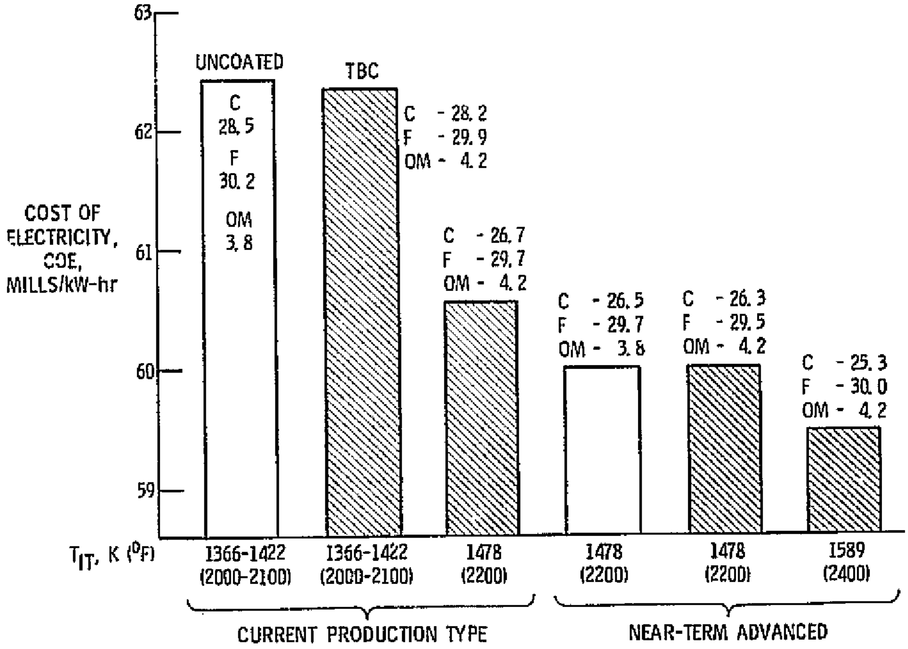
(a) SIMPLE CYCLE GAS TURBINES (DISTILLATE FUEL).

Figure 16. - Westinghouse capital cost estimates - MID 1975 DOLLARS.



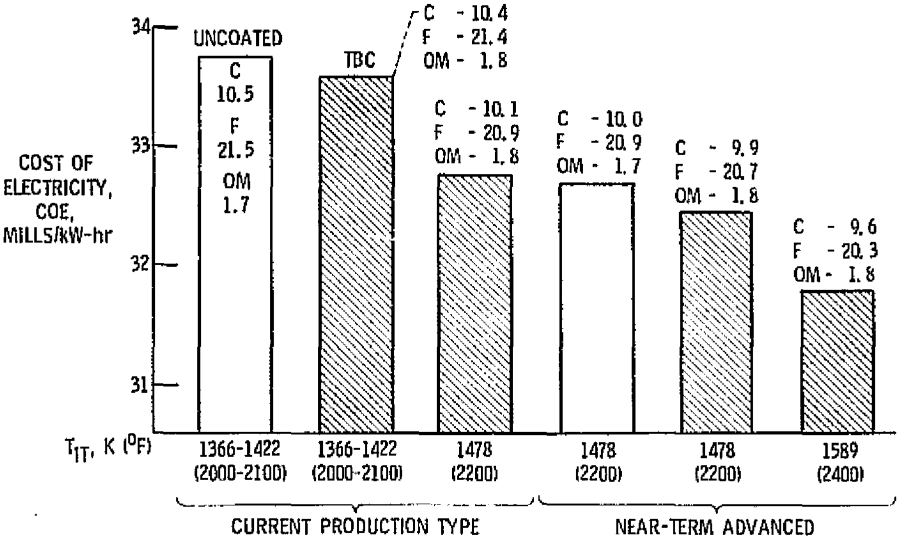
(b) COMBINED CYCLE SYSTEMS (DISTILLATE FUEL).

Figure 16. - Concluded.



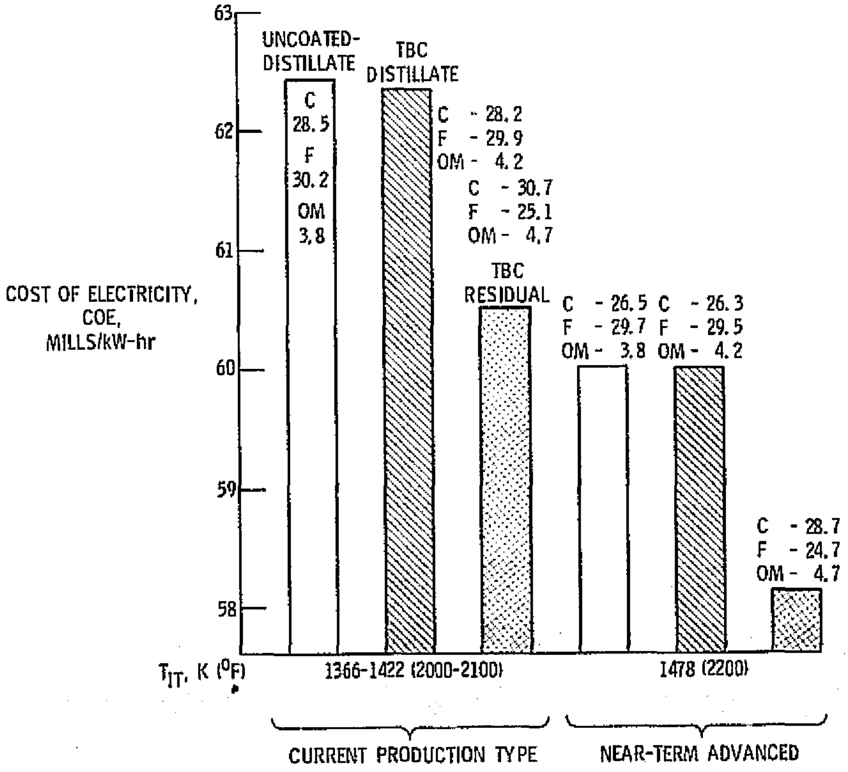
(a) SIMPLE CYCLE GAS TURBINES.

Figure 17. - Westinghouse COE estimates - distillate fuel.



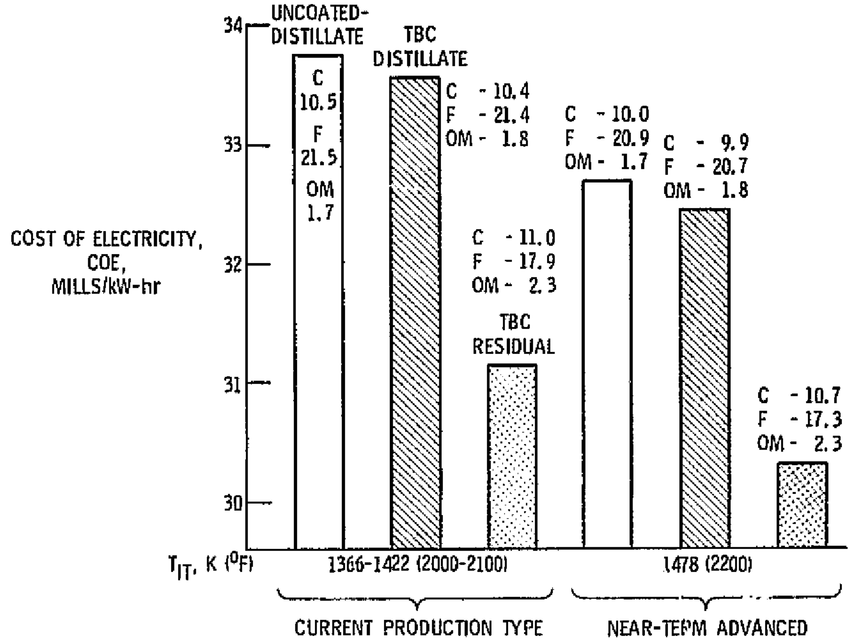
(b) COMBINED CYCLE.

Figure 17. - Concluded.



(a) WESTINGHOUSE SIMPLE CYCLE GAS TURBINES.

Figure 18. - Effect of residual oil firing and thermal barrier on COE.



(b) WESTINGHOUSE COMBINED CYCLE SYSTEMS.

Figure 18. - Concluded.

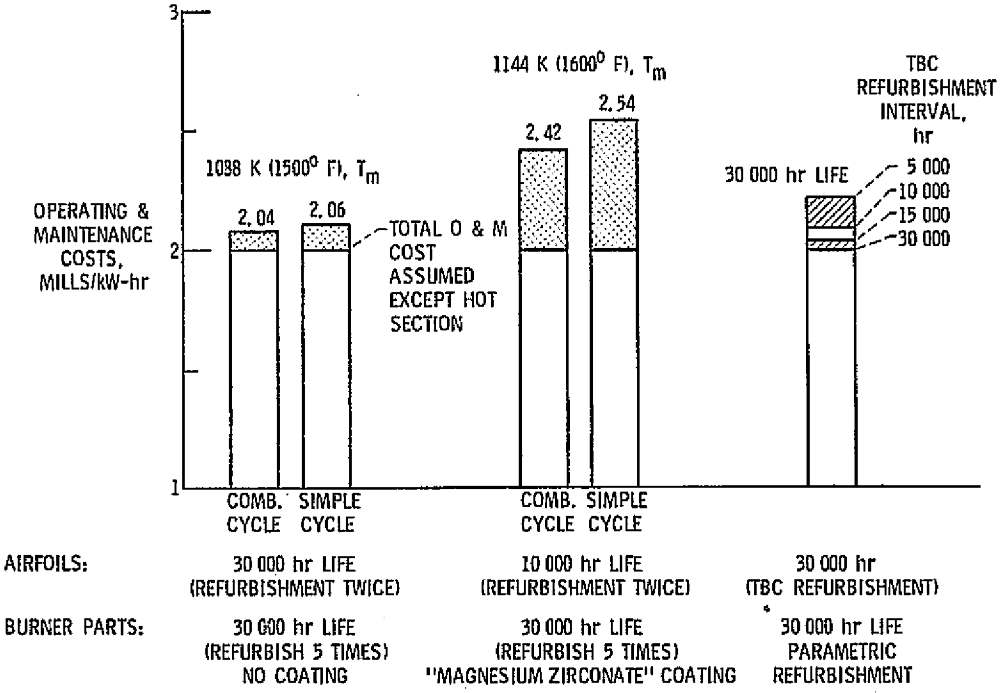
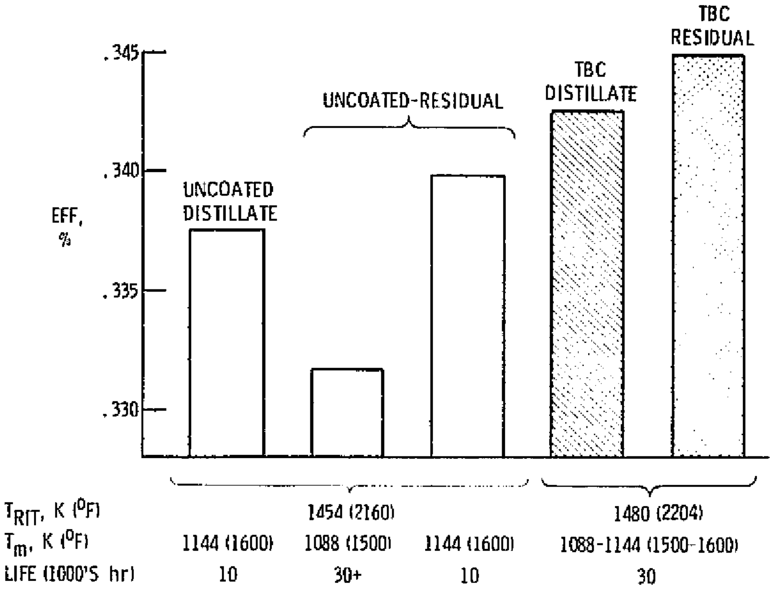
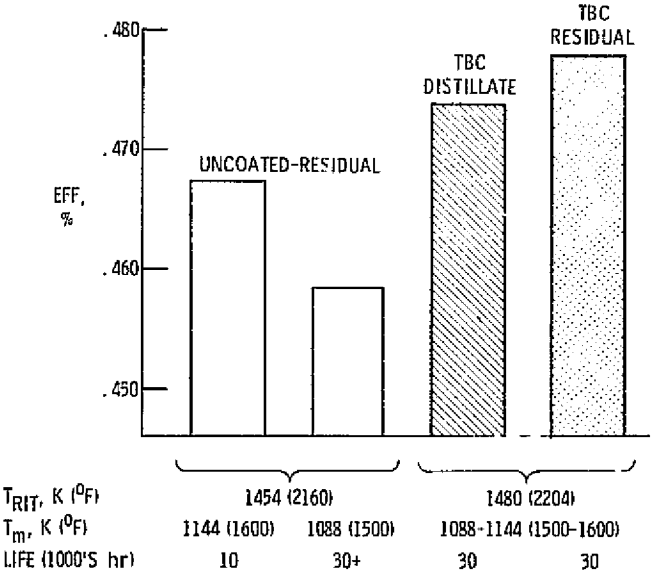


Figure 19. - UTC operation and maintenance costs.



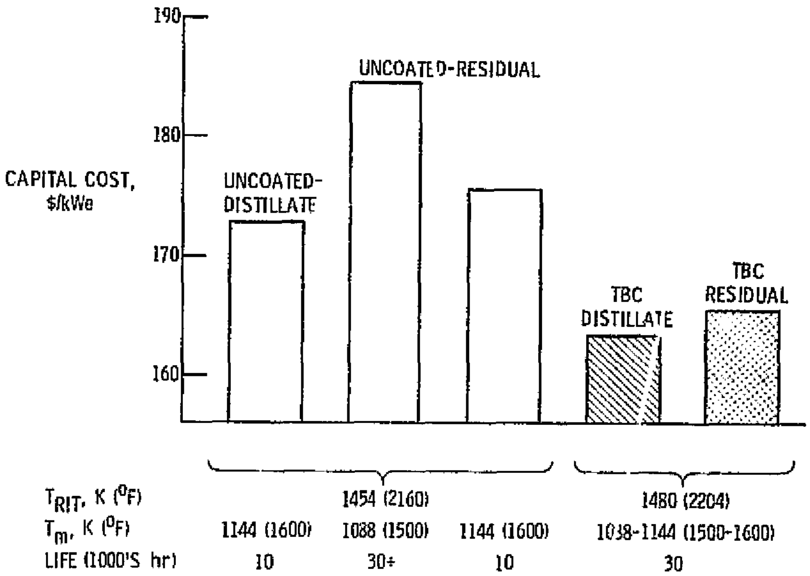
(a) SIMPLE CYCLE GAS TURBINES.

Figure 20. - UTC performance comparison.



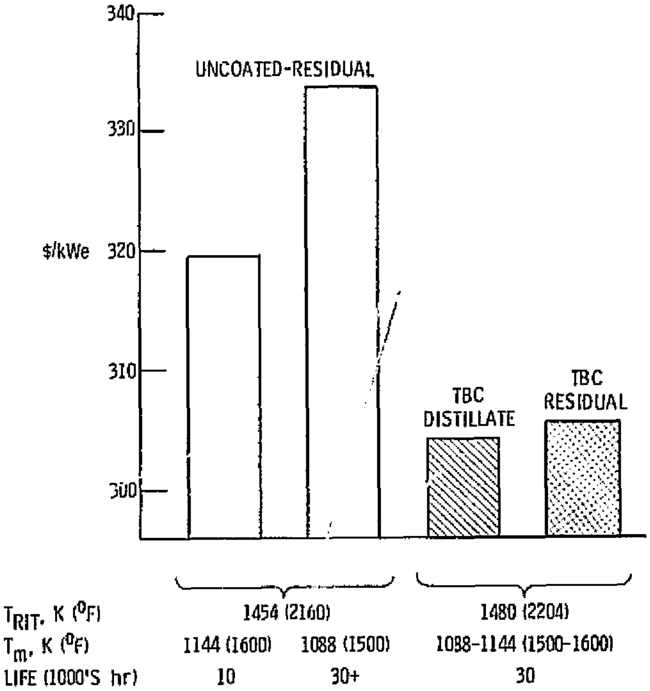
(b) COMBINED CYCLE SYSTEMS.

Figure 20. - Concluded.



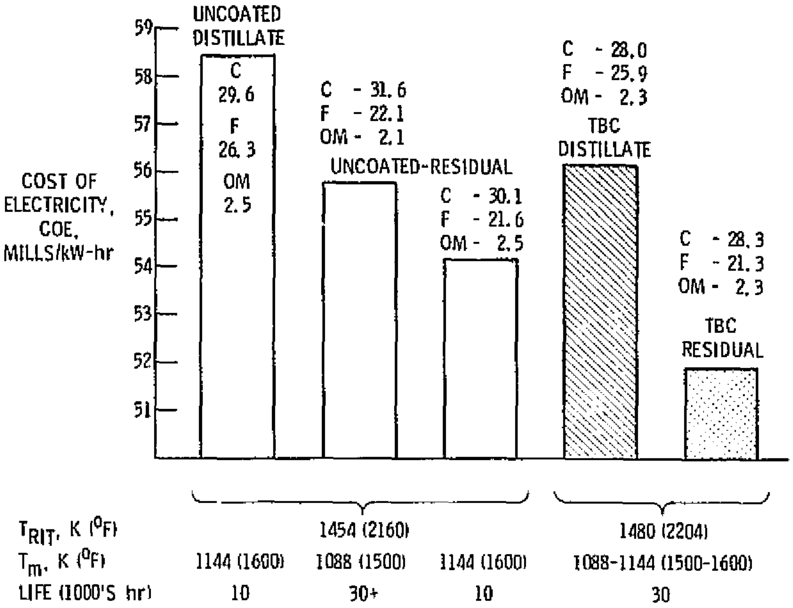
(a) SIMPLE CYCLE GAS TURBINES

Figure 21. - UTC capital cost estimates - mid-1976 dollars.



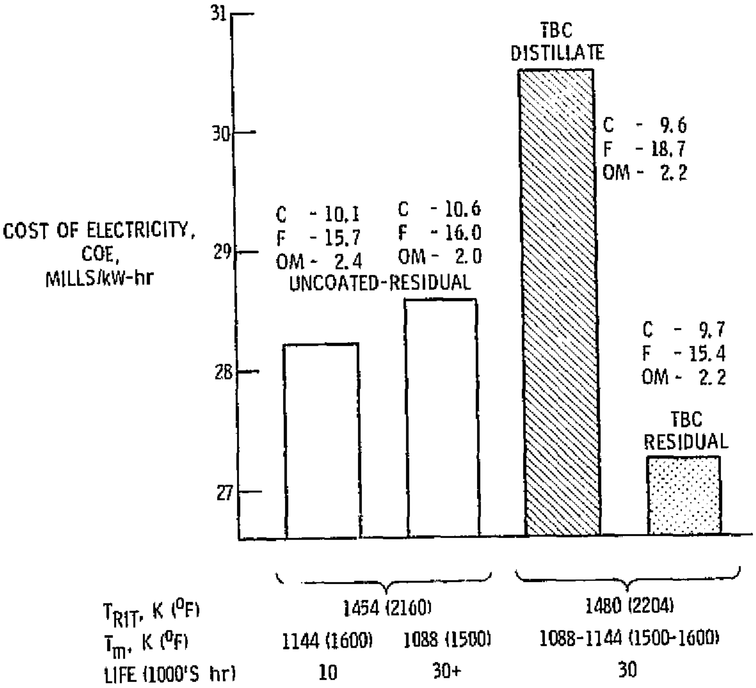
(b) COMBINED CYCLE SYSTEMS.

Figure 21. - Concluded.



(a) SIMPLE GAS TURBINES.

Figure 22. - UTC COE estimates.



(b) COMBINED CYCLE SYSTEMS.

Figure 22. - Concluded.