NASA CR-134941
VOLUME IV

ENERGY CONVERSION ALTERNATIVES STUDY
-ECAS-
WESTINGHOUSE PHASE I FINAL REPORT

Volume IV — OPEN RECUPERATED AND BOTTOMED GAS TURBINE CYCLES

by
D.J. Amos and J.E. Grube

WESTINGHOUSE ELECTRIC CORPORATION RESEARCH LABORATORIES

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
NATIONAL SCIENCE FOUNDATION

NASA Lewis Research Center
Contract NAS 3-19407

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-134941 Volume IV		

4. Title and Subtitle
ENERGY CONVERSION ALTERNATIVES STUDY (ECAS),
WESTINGHOUSE PHASE I FINAL REPORT
VOLUME IV - OPEN RECUPERATED AND BOTTOMED GAS TURBINE CYCLES

5. Report Date
February 12, 1976

6. Performing Organization Code

7. Author(s)
D. J. Amos and J. E. Grube

8. Performing Organization Report No.
Westinghouse Report No.
76-9E9-ECAS-R1v.4

10. Work Unit No.

9. Performing Organization Name and Address
Westinghouse Electric Corporation
Research Laboratories
Pittsburgh, PA 15235

11. Contract or Grant No.
NAS 3-19407

13. Type of Report and Period Covered
Contractor Report

12. Sponsoring Agency Name and Address
Energy Research and Development Administration
National Aeronautics and Space Administration
National Science Foundation
Washington, D.C.

14. Sponsoring Agency Code

15. Supplementary Notes
Project Managers:
W. J. Brown, NASA Lewis Research Center, Cleveland, OH 44135
D. T. Beecher, Westinghouse Research Laboratories, Pittsburgh, PA 15235

16. Abstract

Open-cycle recuperated gas turbine plant with turbine inlet temperatures of 1255 to 1644°K (1800 to 2500°F) and recuperators with effectiveness values of 0, 70, 80 and 90% are considered. A 1644°K (2500°F) gas turbine would have a 33.5% plant efficiency in a simple cycle, 37.6% in a recuperated cycle and 47.6% when combined with a sulfur dioxide bottomer. The distillate burning recuperated plant was calculated to produce electricity at a cost of 8.19 mills/MJ (29.5 mills/kWh). Due to their low capital cost $170 to 200 $/kW, the open cycle gas turbine plant should see duty for peaking and intermediate load duty.

17. Key Words (Suggested by Author(s))

gas turbine	R-12	cost
recuperator	methyl amine	
temperature,	bottoming	
sulfur dioxide	efficiency	

18. Distribution Statement
Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	110	

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev. 10-75)

ACKNOWLEDGMENTS

Section 5 entitled "Open Recuperated and Bottomed Gas Turbine Cycles" was centered in the Westinghouse Gas Turbine Engine Division and was coordinated by D. J. Amos.

Others contributing to the concept study were:

- R. G. Glenn, who prepared the turbine island arrangement drawings and turbine engine cross sectional drawings.
- J. E. Grube, who was responsible for the majority of the recuperated open cycle thermodynamic efficiency calculations and prepared the correlations for gas turbine pricing including the price variations for the several parametric points.
- R. M. Lee, who assisted in the open-recuperated cycle efficiency calculations.
- C. T. McCreedy and S. M. Scherer of Chas. T. Main, Inc. of Boston, who prepared the balance of plant description and costing, site drawings, and provided consultation on plant island arrangements and plant constructability.

TABLE OF CONTENTS

EXPANDED TABLE OF CONTENTS

Volume IV

EXPANDED TABLE OF CONTENTS (Continued)

SUMMARY

The open recuperated and bottomed gas turbine cycles includes both simple and recuperated gas turbine systems with and without inter-cooling and gas turbine topping-organic vapor Rankine bottoming cycles. The parametric investigation covers gas turbine inlet temperatures of 1255 to 1644°K (1800 to 2500°F) with a base case value of 1478°K (2200°F), a modest extension of present day state of the art. Pressure ratios ranging from 6 to 24 to 1 are investigated. These gas turbines have air cooled vanes and blades, burn clean fuels from coal and are fully assembled-rail shippable modules having power outputs of approximately 100 MW.

The generator is driven from the cold end, thereby allowing a minimum pressure loss axial arrangement of an exhaust duct, recuperator or waste heat boilers.

Tension braze recuperators with effectiveness values of 0, the unrecuperated case, 70, 80 and 90% are considered. A total pressure drop ratio of 3% is used. The cycle efficiency increases with turbine inlet temperature in all cases. An optimum pressure ratio of about 10 to 1 is found for recuperated cycles with higher pressure ratios resulting in improved efficiency for the simple cycles. Efficiencies of 33.5 and 37.6% are found for the simple and recuperated systems with a 1644°K (2500°F) turbine inlet temperature. The use of ceramic blades and vanes would reduce the needed cooling air and improve the cycle efficiency 3.5 to 5 points.

The sulfur dioxide bottoming cycle with a 1644°K (2500°F) air cooled gas turbine would have an efficiency of 47.6%. The highly super-critical sulfur dioxide fluid with turbine inlet conditions of 17.236 MPa (2500 psi)/811°K (1000°F) has a nearly straight heating line which

results in an excellent fit with the gas turbine exhaust gas cooling curve giving a cycle with relatively high availability. The sulfur dioxide superheats on expansion so no turbine moisture problems occur and a desuperheating feed heater is required.

The resultant sulfur dioxide turbine is much smaller than the equivalent steam turbine for the same duty.

The cost of electricity (COE) for the recuperated cycles is 8.19 mills/MJ (29.5 mills/kWh) and 8.75 mills/MJ (31.5 mills/kWh) for the simple cycle at a 65% capacity factor. The more capital intensive SO_2 bottoming cycle has a COE of 9.14 mills/MJ (32.9 mills/kWh). The simple and recuperated cycles have the lowest COE of any plants at capacity factors less than 40% due to their lower capital cost of 170 to 200 $/kW, respectively, and are, therefore, recommended for peaking and intermediate load duty.

5. OPEN RECUPERATED AND BOTTOMED GAS TURBINE CYCLES

5.1 State of the Art

5.1.1 Open-Cycle Gas Turbine Engines

The last two decades have seen a remarkable growth in the application of the industrial gas turbine. During that period, the specific output of the engines has doubled from about 150 to 300 kW/(kg/s airflow) [70 to 140 kW/(lb/s airflow)], and the thermal efficiency has increased from about 20 to 33%. Today, combined gas turbine and steam turbine power plants are commercially available with thermal efficiencies of about 43%. Current gas turbine engine unit sizes of up to approximately 100 MW are available as prepackaged, fully assembled, and rail-shippable power plants. The relatively low investment cost connected with installation of these units has made the open-cycle gas turbine the economic choice of the electric utilities for meeting their peak-load requirements.

The evolution of the industrial gas turbine to the current state of the art has resulted from combining the well-established long-life design features of steam turbines with the advanced technology of aircraft jet engines. The latter has contributed advances in such areas as the axial flow compressor, combustion system, and high-temperature metallurgy. Over the years, the use of gas turbines has covered a diversity of industrial applications including: electric power generation, natural gas transmission, compressor drives, oil-field repressurization, marine propulsion, petrochemical auxiliary power generation, steel mill blast furnace blowing, mobile power generation, mobile process air plant drives, and locomotive power plants. These applications have involved the use of a wide variety of fuels, environments, control systems, and installation arrangements and system configurations. This variation of

Curve 682083-A

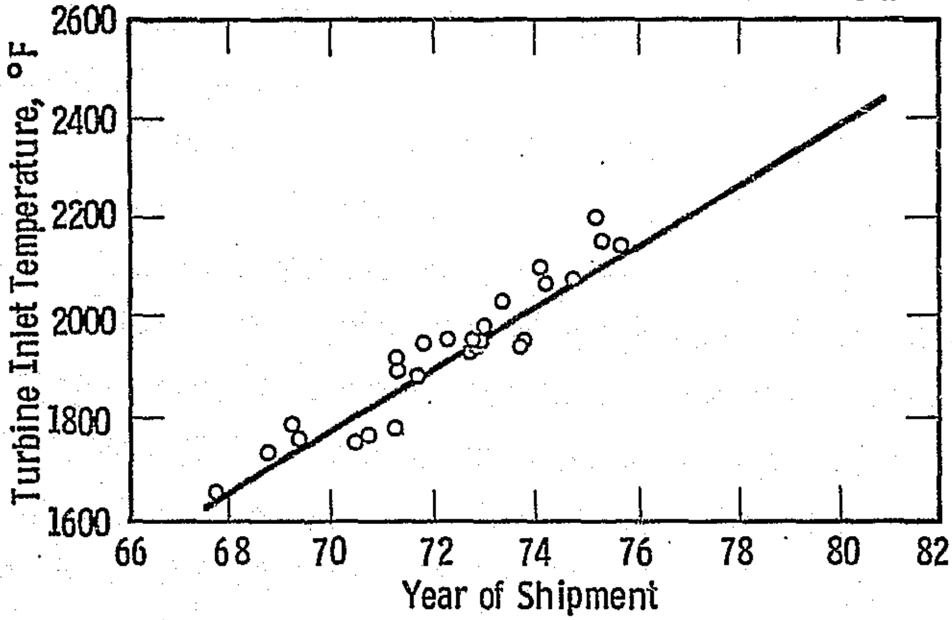


Fig. 5.1 --Industrial gas turbine inlet temperature forecast

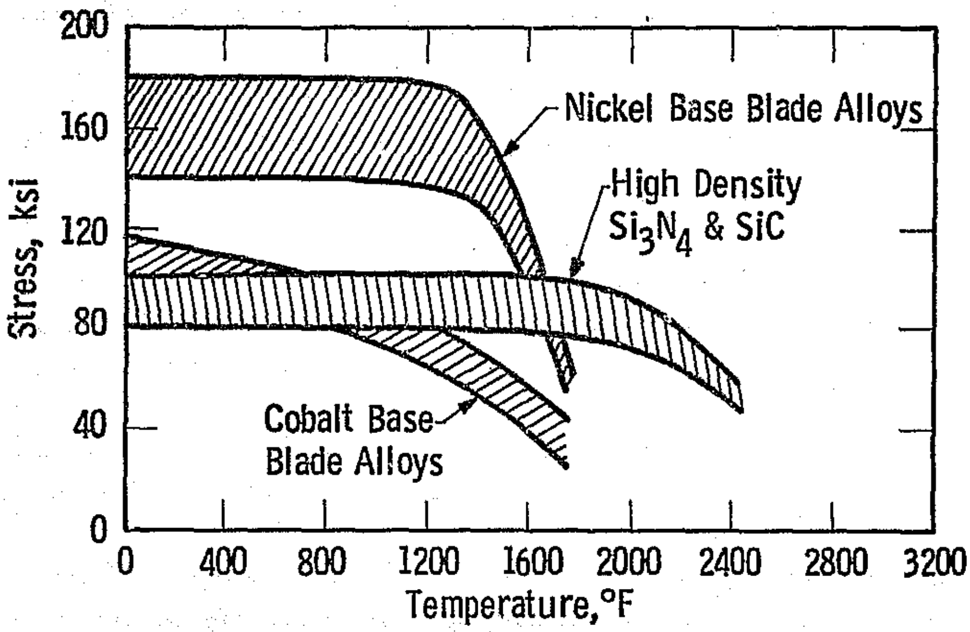


Fig. 5.3 —4 Pt. flexural strength of high density Si_3N_4 & SiC vs ultimate tensile strength of metals

possible configurations has been attained through units installed with either one or two shafts, recuperators, evaporative coolers, superchargers, steam helpers, or as part of a combined cycle or waste heat recovery arrangement.

5.1.1.1 Turbine Inlet Temperature Considerations

The advancement and growth of the industrial gas turbine is primarily the direct result of increased turbine inlet temperature capability. Figure 5.1 illustrates the temperature growth history for industrial gas turbines over the past ten years. The model W-501 engine pictured in Figure 5.2 generally follows this trend. This advance in the state of the art has been made possible by two major technical efforts which resulted in materials with improved temperature capability and the cooling of hot parts with air.

For long-life duty, uncooled turbines using state-of-the-art superalloy blade and vane materials are limited by oxidation and corrosion to a turbine inlet temperature of about 1172°K (1650°F). Internal cooling of turbine vanes and blades with air has allowed inlet temperatures to advance while maximum metal temperatures are maintained within allowable limits. Current industrial designs, employing combined impingement/convection/film-cooling techniques, are capable of operation at about 1478°K (2200°F) in peaking service.

Although performance continues to improve with increased turbine inlet temperatures in the convection/impingement/film air-cooled simple cycle arrangement, studies have indicated that the major benefits from higher inlet temperature air-cooled gas turbines accrue to the combined-cycle systems. Potential improvements for all types of cycle arrangements would be greatly enhanced if more efficient cooling concepts could be developed.

There are several approaches to gas turbine design using improved cooling systems. Five such approaches are: high-temperature materials, transpiration cooling, advanced convection/impingement/film

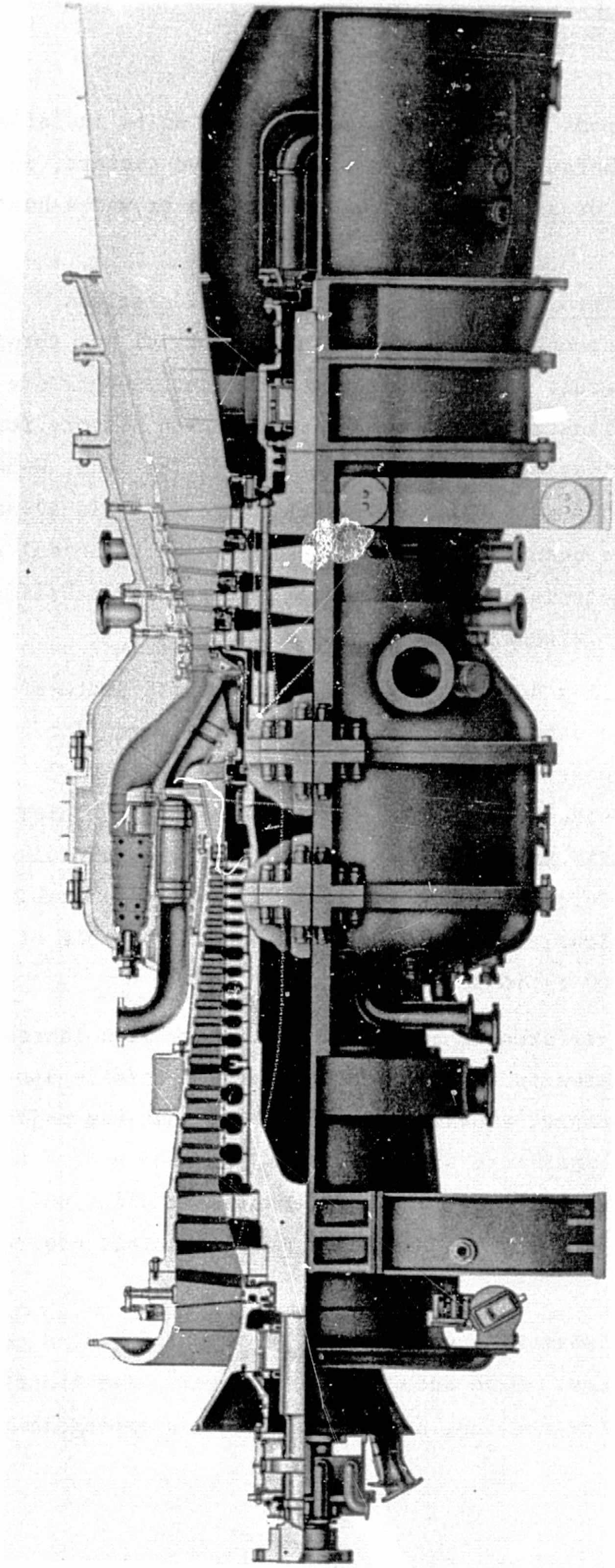


Fig. 5.2—Westinghouse Gas Turbine Engine Model W-501

air-cooling, steam cooling, and water cooling. These are discussed briefly below.

Uncooled Turbine Components - High Temperature Materials. Any reduction in the cooling air required would improve the cycle efficiency. Thus, if everything else remains the same, an uncooled turbine has the highest potential cycle efficiency. However, the oxidizing and sometimes highly corrosive atmospheres seen by the turbine element, as well as creep consideration, limits the temperatures of the uncooled turbine to about 1170°K (1650°F) using current materials. To advance this limit, development programs are under way for ceramic and composite blade and vane materials aimed at significant improvements in uncooled turbine temperature capability. A significant cycle efficiency improvement over the present state of the art would result as uncooled ceramics elements replace air-cooled metal blades and vanes. Two candidate materials, high-density silicon nitride and silicon carbide ceramics, have superior strength at high temperatures, as shown by Figure 5.3. Laboratory stationary rig tests have been successfully run on full-size vanes at gas temperatures in excess of 1500°K (2250°F), and design and test work is continuing on designs suitable for temperatures of approximately 1644°K (2500°F). Composite materials also have great potential for extending the limitation of turbine temperatures. Their superior strength will be useful for last-stage turbine blade applications where extremely high stresses occur, and the required airfoil shape make this blade difficult to cool. The added strength of composite materials permit higher last-row blade temperatures and enable the designer to maintain an efficient blade design.

Transpiration Cooling. The heat transfer coefficients on the flow surfaces of transpiration cooled turbine blades and vanes are very high. Ideal transpiration cooling is characterized by the coolant transpiring through the blade surfaces, issuing from that surface at close to the blade surface temperature, and thus requiring the minimum amount of coolant flow. Transpiration cooling, therefore, has the minimum cooling loss penalty on cycle efficiency. (These losses are due to the mixing of

Curve 682539-A

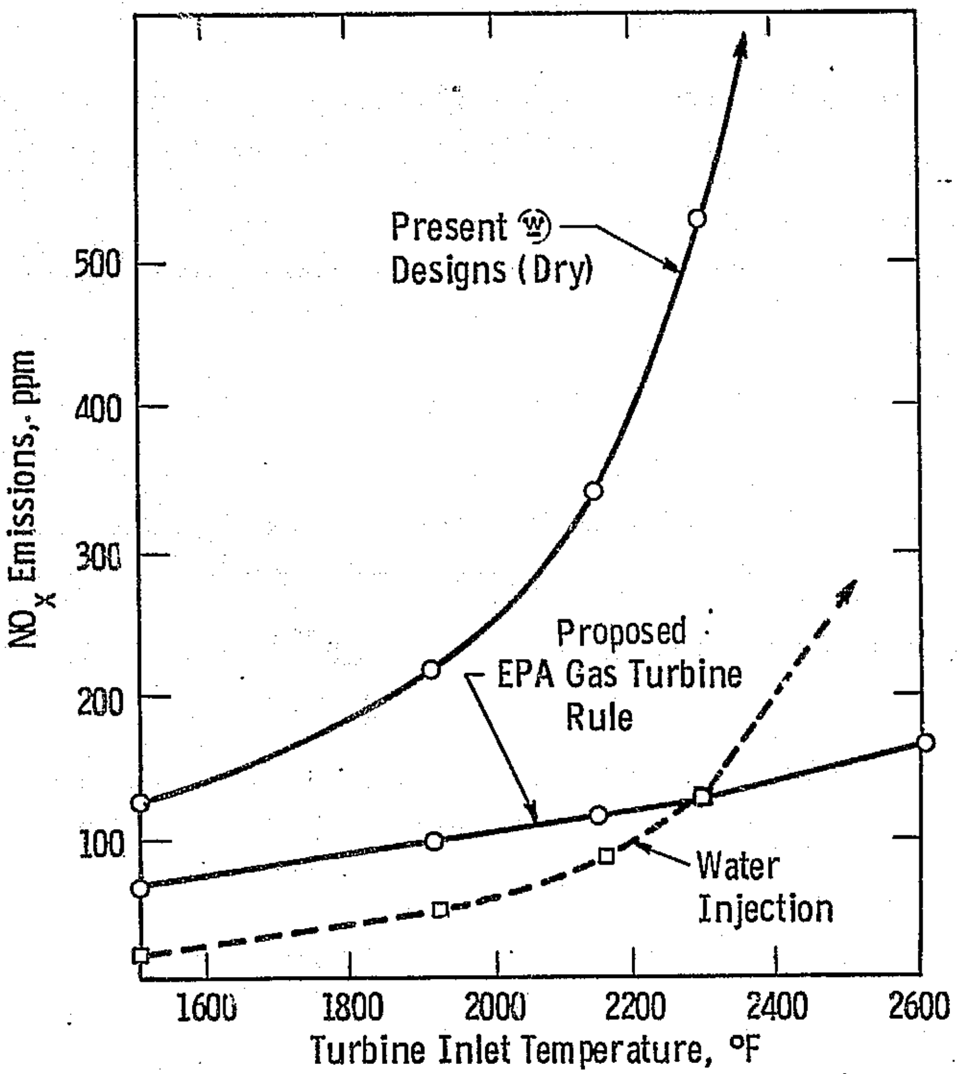


Fig. 5.4 — NO_x emissions state of-the-art and proposed EPA regulation for gas turbines

the coolant with the main flow path fluid which results in a mixing pressure loss and a decrease in mixed-out main path fluid temperature.)

Advanced Convection/Impingement/Film Cooling. Advances in turbine inlet temperature to as high as 1589 to 1644°K (2400 to 2500°F) for industrial engines is considered possible by means of utilizing advanced cooling system designs based on combined convection/impingement/film techniques. Although this approach does not have the same growth potential as transpiration cooling, it is considered to be an important step in the progression of the state of the art.

Steam Cooling. Steam cooling offers advantages over air cooling because of the possibility of elevated coolant pressure, a clean inert coolant, superior heat transfer characteristics, and reduced pressure mixing losses since less fluid is required. The superior heat transfer characteristics provide means of absorbing more heat and permit high gas temperatures with fixed outside metal surface temperatures. Thus, steam cooling may increase permissible gas temperatures by as much as 222°K (400°F) above those arising from air cooling without changing coolant channel geometry.

Water Cooling. The use of water as a gas turbine blade and vane coolant has been and is currently the subject of considerable technology development. Water has excellent cooling characteristics, and as such it has cooling potential with gas-path temperatures well into the 1644 to 1922°K (2500 to 3000°F) range.

5.1.1.2 Combustion Considerations

In contrast to the advances in gas turbine engine size and performance, the state of the art of gas turbine combustion systems has not experienced a significant comparable change. The basic design technology employed today is not very different than that used 20 years ago. With the environmental difficulties already seen with increasing turbine firing temperature, however, a fundamental change in the way fuels are burned in gas turbines will be required. This is illustrated in Figure 5.4, which shows the effect of turbine inlet temperature on NO_x

Dwg. 6250A64

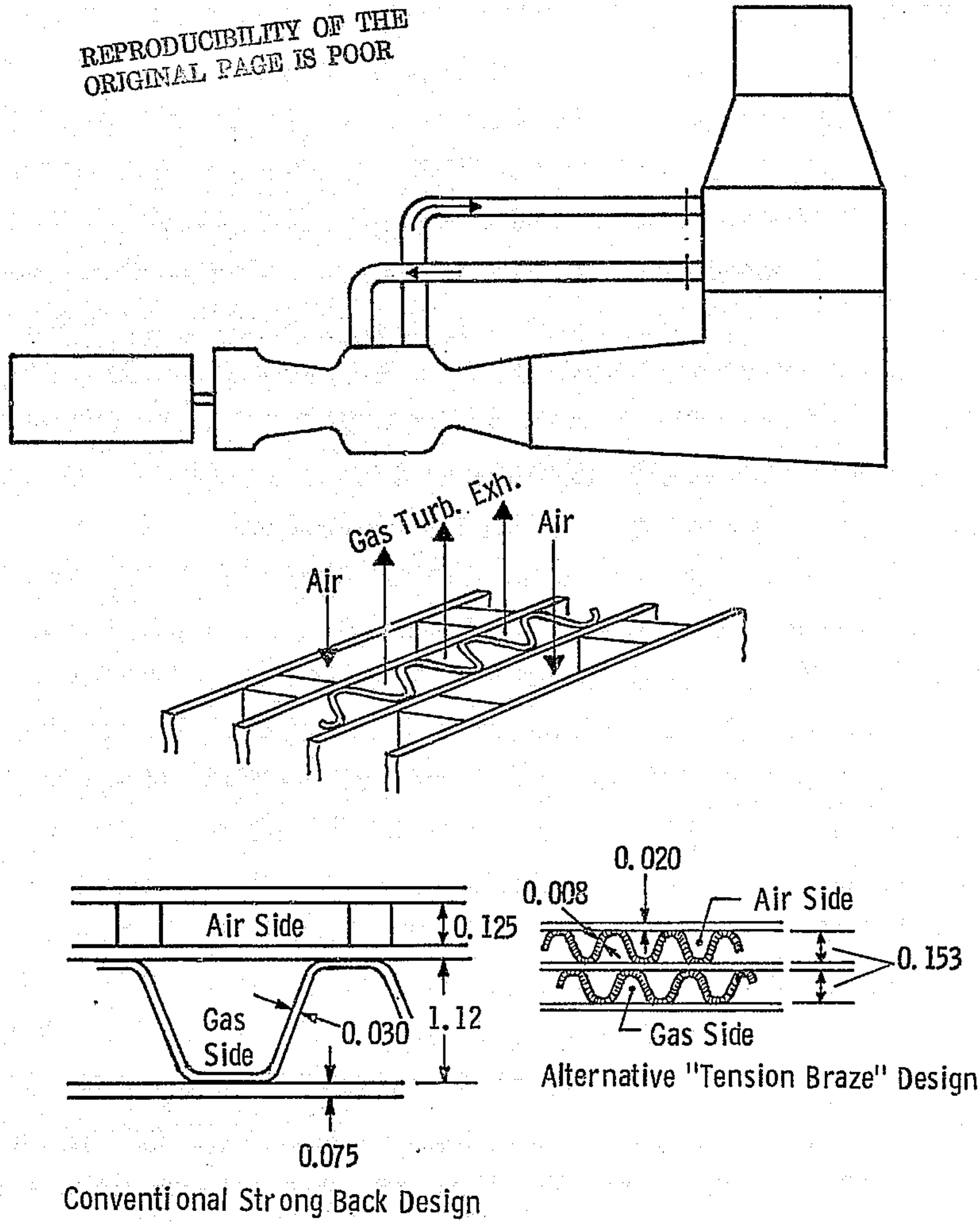


Fig. 5.5—Plate-fin recuperator

emission levels with current dry combustion systems and with water injection. Superposed on this is the proposed EPA NO_x rule for utility gas turbines burning liquid fuels. Clearly, present dry combustors will not be satisfactory—and the NO_x problem grows rapidly worse as higher temperatures are achieved. Water injection is expedient to meet the current situation but has its own environmental drawbacks and is of limited effectiveness in controlling NO_x when the fuel has a relatively high nitrogen content, as do liquid fuels derived from coal, and with coal gases containing ammonia. For the long range, several advanced combustor design approaches will have to be developed to suit the turbine temperatures and fuels of the future. Concepts considered to hold the greatest promise include:

- Staged combustion
- Fuel/air premixing
- Catalytic combustion.

The advanced state-of-the-art gas turbines will include an advanced combustor concept in order to achieve high performance goals in an environmentally acceptable manner.*

5.1.2 Gas Turbine Recuperators

There are several approaches to gas turbine recuperator design, ranging from automotive moving-surface rotating regenerators to land-based gas turbine fixed-surface recuperators. Consideration here is limited to the latter. Two types of fixed-surface recuperator have found application in power generation gas turbine systems: plate-fin recuperators and shell-and-tube recuperators.

As shown in Figure 5.5, the plate-fin recuperator utilizes a basic counterflow arrangement to transfer heat from exhaust gases to compressor discharge air. The sectional view at the bottom left side of the figure shows the conventional design approach commonly referred to as the strong-back design. Extended surface is utilized on the gas side only,

* Conventional combustor costing has been used for this study.

Dwg.6250A65

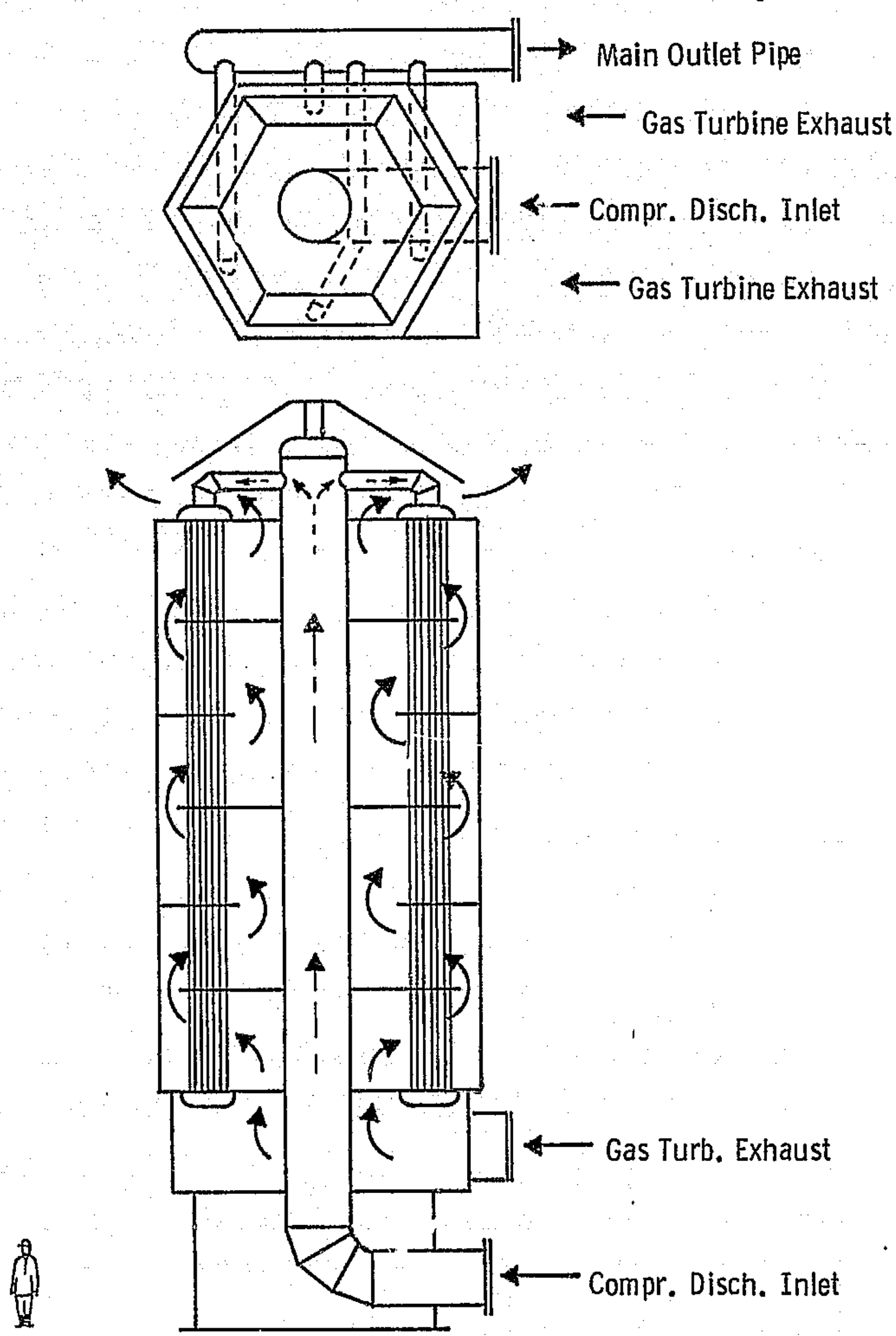


Fig. 5.6 — Shell tube recuperator

and multiple layers of the air- and gas-side combinations are sandwiched together in compression by rigid strong-back end pieces.

The section at the bottom right of the figure illustrates an alternative plate-fin design approach known as the tension-braze recuperator. The principal difference between this and the strong-back approach is that extended surface is utilized on both air and gas sides. This has resulted in a lighter and more compact design. The distinguishing characteristic leading to the name tension braze is that instead of resisting the pressure loading between air and gas sides by massive strong-back end pieces, individual air-side channels are held together by high-temperature nickel alloy braze, loaded in tension between air-side extended surface and the adjacent channel walls.

Figure 5.6 illustrates the alternative shell-and-tube recuperator design approach. This design is characterized by relatively massive size and weight and higher cost. As shown in the figure, compressor discharge air is heated as it passes downward through vertical tubes while combustion gases sweep the exterior tube surfaces. The multiple tubes are supported at their relatively cool top ends and because of thermal growth are left to expand freely downward. The entire structure is supported by the central vertical pipe which directs the cooler compressor discharge air to the top of the unit.

Current design plate-fin and shell-and-tube recuperators are commonly constructed of relatively low-cost carbon steels. These designs are generally limited to turbine exhaust temperatures of about 811°K (1000°F). Advanced designs assumed herein utilize higher alloy materials (400 series SS).

5.1.3 Organic Bottoming Cycles

The electric power industry has utilized the exhaust heat of a gas turbine cycle to generate vapor and to heat the feed liquid of a Rankine bottoming cycle in the form of the combined gas and steam cycle. This is covered separately in detail in Section 6. The use of working fluids other than steam for the bottoming cycle has been studied extensively but has never been implemented in a commercial power plant application. In general, these studies have shown that the advantages associated with even the most promising and best suited fluids are not great enough to warrant developing the organic fluid power plant.

The requirements of fluids that should be considered for power cycle application have long been recognized because of the suitability of their chemical and physical properties. They are the types of fluid generally utilized in the refrigeration industry where water is usually an inappropriate working fluid. The rather mature state of the art of that industry suggests that the risk of developing an organic fluid cycle for power production may not be as great as generally considered in the past. The payoff will depend on achieving improvements in cycle performance that would result from overcoming some of the disadvantages of using steam.

The relatively large specific volume of steam at the heat rejection temperature makes it uneconomical to fully utilize lower sink temperatures even when available.

At the high-temperature end of the gas turbine bottoming cycle, the boiling characteristic of the most commonly used subcritical water cycles requires a relatively large heat input at constant temperature. This represents a relatively poor thermodynamic fit for effective utilization of heat from the falling temperature heat input line of the gas turbine exhaust.

Although the state of the art of the organic fluid bottoming cycle is not well developed, a firm analytical data base does exist. Information is available related to the fluid properties, stability, corrosiveness, toxicity, and general thermodynamic suitability of many candidate working fluids. Investigation continues into the results of implementing a better thermodynamic fit for a gas turbine bottoming cycle than is currently available with water. [This subject is discussed further in Section 7.2 where the criteria for selecting a bottoming cycle working fluid are covered in some detail (References 5.7 through 5.8).]

5.2 Description of Parametric Points to Be Investigated

The recuperated open-cycle gas turbine cycles studied were classified into two general categories: recuperated open cycles and combined recuperated open cycles with an organic fluid Rankine bottoming cycle.

The parametric points covered by the study are summarized on Table 5.1, which shows the range of parameters studied and the general grouping of parametric variation investigated. Of the 97 cases included, 94 are simple or recuperated gas turbine cycles. The remaining three cases examine combined cycles using three different working fluids: refrigerant R-12; methylamine, and sulfur dioxide (SO_2). All the cases investigated are enumerated in Section 5.4 (Table 5.2), where the study results are presented.

The recuperated cycle, typical of state-of-the-art air-cooled gas turbine systems, was chosen as the base case for this study. The performance parameters assumed for this case are: (See Section 5.3 for an explanation of terms and further assumptions.)

- Turbine inlet temperature = 1478°K (2200°F)
- Compressor pressure ratio = 10 to 1
- Recuperator effectiveness = 0.80
- Recuperator pressure drop $(\frac{\Delta P}{P})$ = 0.030.

The fuel for this case is assumed to be a distillate oil derived from coal. The general cycle configuration represented by the base case and the bulk of the points calculated are shown on Figure 5.7. The major components contained in the system are the gas turbine engine and recuperator. As shown in Table 5.1, the parametric variation around the base case involved two major groupings: recuperator parameter variation and gas turbine engine parameter variation. First, the effect of varying the recuperator effectiveness was investigated. Values of 0, 0.7, 0.8, and 0.9 were selected, and the cycle performance was calculated at a fixed turbine inlet temperature of 1478°K (2200°F) and with compressor pressure ratios

TABLE 5.1– RECUPERATED OPEN CYCLE PARAMETRIC POINTS

	Turb. Inlet Temp, °F	Comp. Press. Ratio	Gas Turbine Cooling See Note B	Recuperator Effectiveness	Recuperator Pressure Loss, ΔP/P	Inter-cooling	Reheat See Note D	Fuel	Bottoming Cycle Organic Fluid	Organic Fluid Turbine Inlet Temp. °F	Organic Boiler Pinch Point Temp. Diff. ΔT, °F	Organic Boiler Exit Temp. Diff. ΔT, °F	Boiler Gas Side Press. Drop, ΔP/P
Base Case	2200	10	1	0.80	0.030	No	No	Dist. from Coal	None	–	–	–	–
Recuperator Parameter Variations		8, 10, 12 16, 20		0.70, 0.80, 0.90									
					0.020, 0.030 0.040								
Gas Turbine Parameter Variations	1800, 2000 2200, 2500	8, 10, 12 16, 20, 24											
	1800, 2000 2200, 2500	8, 10, 12 16, 20, 24		0	0								
	2200	8, 10, 12	2										
	2500	16, 20, 24	3										
See Note C		12, 16, 20				Yes							
							Yes						
Fuel Variation								Hi-Btu Gas					
Bottoming Cycle Parameter Variations	2000	8							R12	400	Super-Critical	100	0.05
	2000	8							Methyl-amine	600	Super-Critical	100	0.05
	2500	16		0	0				SO_2	1000	Super-Critical	100	0.05

Notes:
A. All blank spaces have same value as base case unless otherwise noted
B. Gas turbine blade cooling configurations
1. Turbine vanes and blades air cooled
2. Turbine vanes ceramic, blades air cooled
3. Turbine vanes ceramic, blades ceramic
C. For 1800°F turbine inlet temperature compressor pressure ratio will be varied as follows 6, 8, 10, 12, 16 instead of the values shown in the table
D. The reheat case was omitted from the study in agreement with NASA

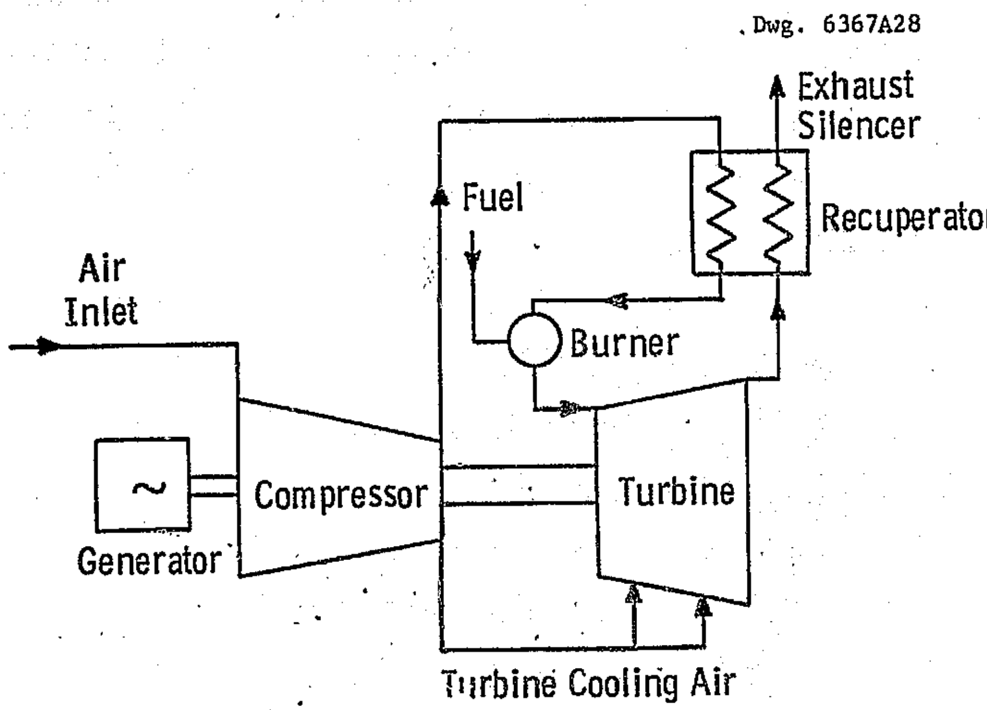


Fig. 5.7—Schematic diagram of recuperated open-cycle gas turbine system

Dwg. 6367A31

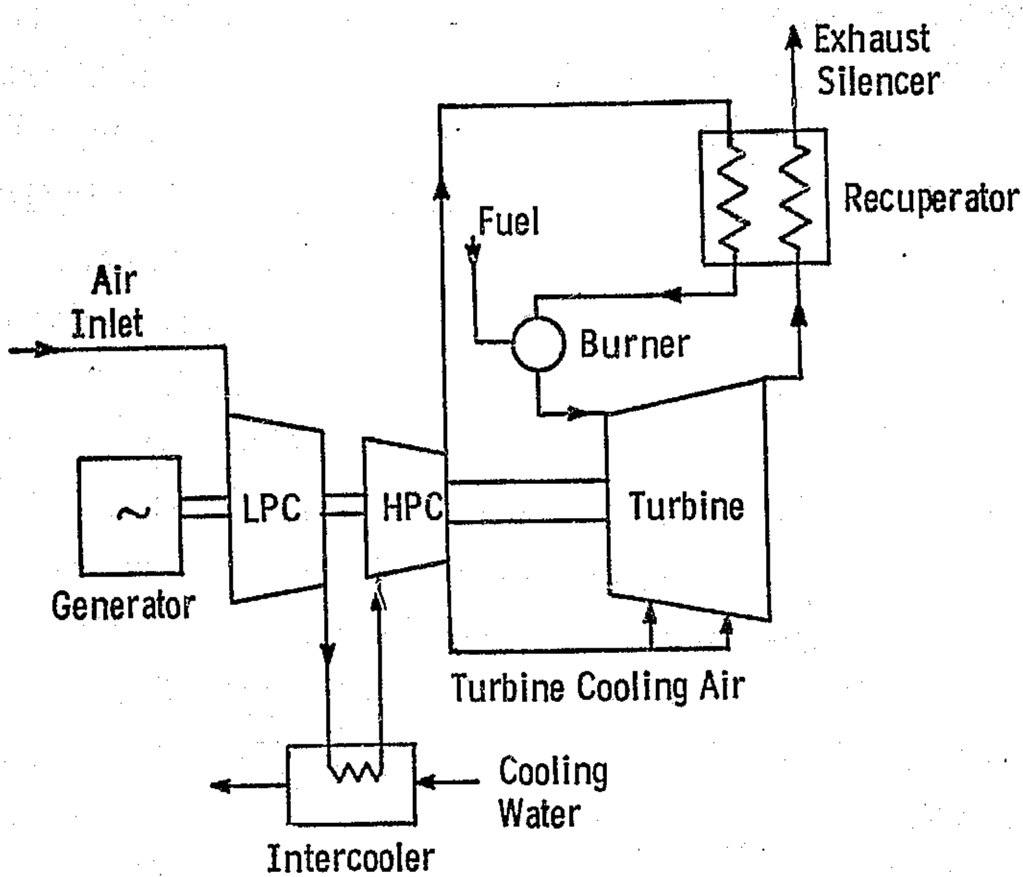


Fig. 5.8—Schematic diagram of intercooled recuperated open-cycle gas turbine system

8, 10, 12, 16, and 20. Effectiveness values of 0.80 to 0.82 are common in current commercial practice. Variation of recuperator pressure drop was also examined. With effectiveness set at 0.8 and at 1477°K (2200°F) turbine inlet temperature, the recuperator pressure drop ratio, $\Delta P/P$, was assigned values of 0.02, 0.03, and 0.04. The compressor pressure ratio was varied from 8 to 20 for this group of parametric points in the same step as during the effectiveness investigation.

The gas turbine engine parametric study involved investigation of system performance and cost over a range of turbine inlet temperatures from 1255 to 1644°K (1800 to 2500°F) and compressor pressure ratios from 6 to 24. For the air-cooled cases, both recuperated and nonrecuperated cycles were included. The latter is the so-called simple cycle and parametrically represents the case of recuperator effectiveness and pressure drop set to zero. Also, included in the higher temperature recuperated cases are two variations in gas turbine cooling schemes. In one case a design is assumed that combines ceramic (uncooled) stator vanes and air-cooled rotor blades; the second case assumes uncooled ceramic vanes and blades. The use of ceramics is accomplished parametrically by a programmed reduction in compressor bleed air used for cooling the turbine section (see Section 5.3).

A set of points was included to investigate gas turbine engine compressor intercooling. Figure 5.8 is a schematic illustrating the general cycle arrangement for this case. It assumes a single stage of intercooling and a similar pressure ratio for both the high- and low-pressure compressor sections. The intercooler was assumed to be fed with water from a cooling tower. The intercooler parameters selected for the study were an intercooler approach ($T_{Air, Out} - T_{Water, In}$) of 16.7°K (30°F) and a water range ($T_{Water, Out} - T_{Water, In}$) of 12.8°K (23°F).

The intercooled cases covered a pressure ratio range of 8 to 24, with all other system parameters set at the base case values.

One fuel variation was considered. In this case a high-Btu gas derived from coal was selected to replace the coal-derived liquid fuel.

Dwg. 6367A29

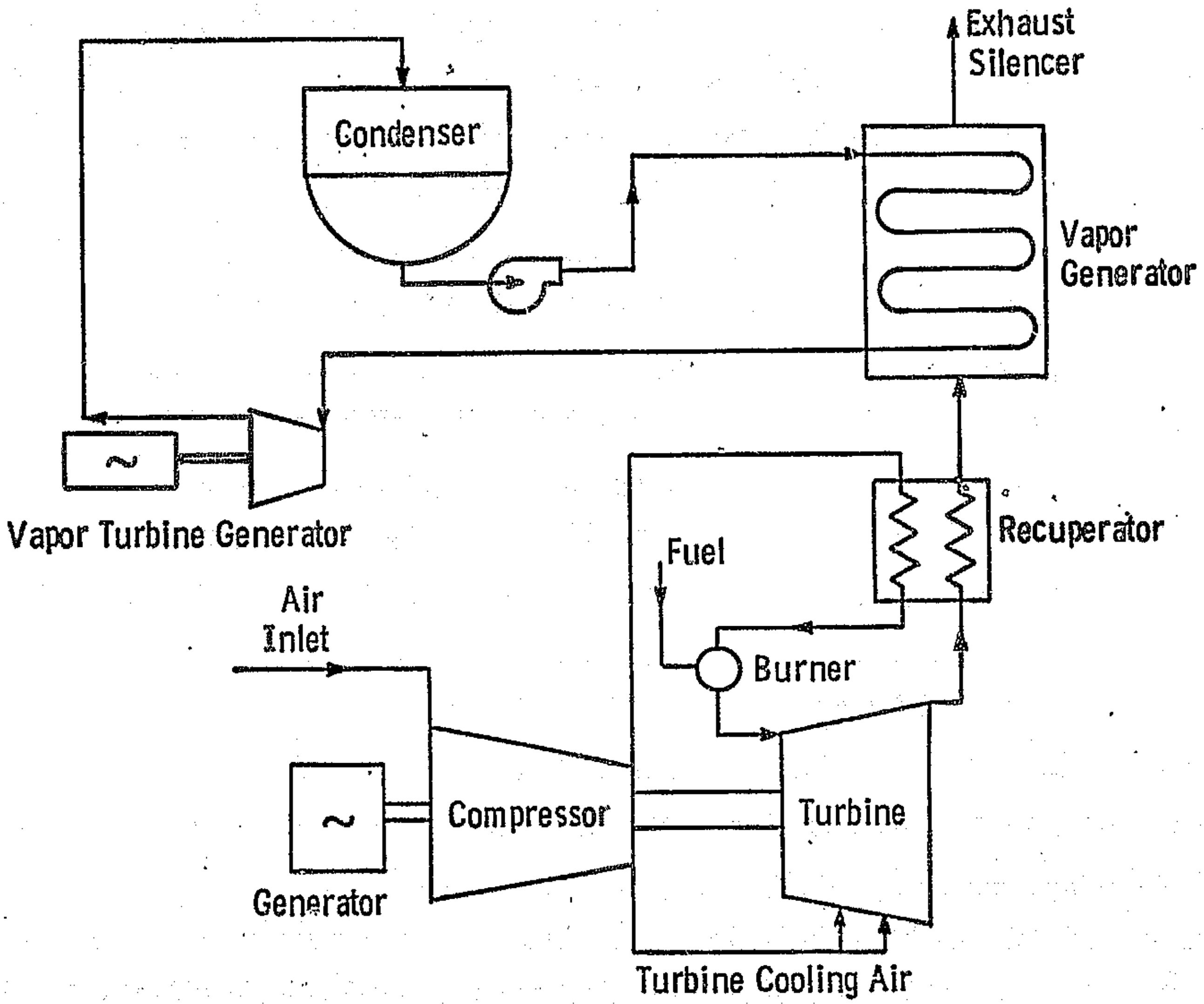


Fig. 5.9—Schematic diagram of recuperated open-cycle gas turbine system combined with organic fluid bottoming cycle

Since the attraction of simple and recuperated open-cycle systems has historically been their relatively low investment cost (and, therefore, their economy in peaking and intermediate duty application), a capital-intensive integrated coal gasification low-Btu gas fuel system was not selected for inclusion in this portion of the study.

The three working fluids chosen for the bottoming cycles were selected primarily on the basis of their stability at the relatively high temperature associated with the gas turbine exhaust and their relatively high density at low temperature and pressure as would be reflected in the size of the bottom-cycle turbine exhaust area requirement. These selection criteria are discussed in more detail in Section 7.2. The cycle arrangement used for both the R-12 and methylamine bottoming cycles is shown schematically in Figure 5.9. The topping cycle (recuperated gas turbine cycle) parameters used for these cases were selected from among the values used in the overall parametric study to provide the best fit between the heat source (turbine exhaust) temperature and the bottom-cycle fluid heat absorption characteristic. This resulted in the selection of a turbine inlet temperature of 1366°K (2000°F) and pressure ratio of 8 to 1. The bottoming cycles were designed for supercritical operation; that is, above the constant temperature boiling regime to fit better the gas turbine exhaust gas cooling line.

The cycle arrangement for the sulfur dioxide bottomed system is shown schematically in Figure 5.10. In this case the bottoming cycle is fitted beneath a simple gas turbine cycle and incorporates some added complexity as additional measures to optimize the match between the heat source and absorption temperature lines. The gas turbine parameters selected for this case [1644°K (2500°F) and 16 to 1] also reflect the attempt to optimize the fit with the sulfur dioxide bottoming cycle. (The importance of matching the topping and bottoming cycles is fully discussed for the closed-cycle systems in Sections 7.2 and 7.4.)

Dwg. 6367A30

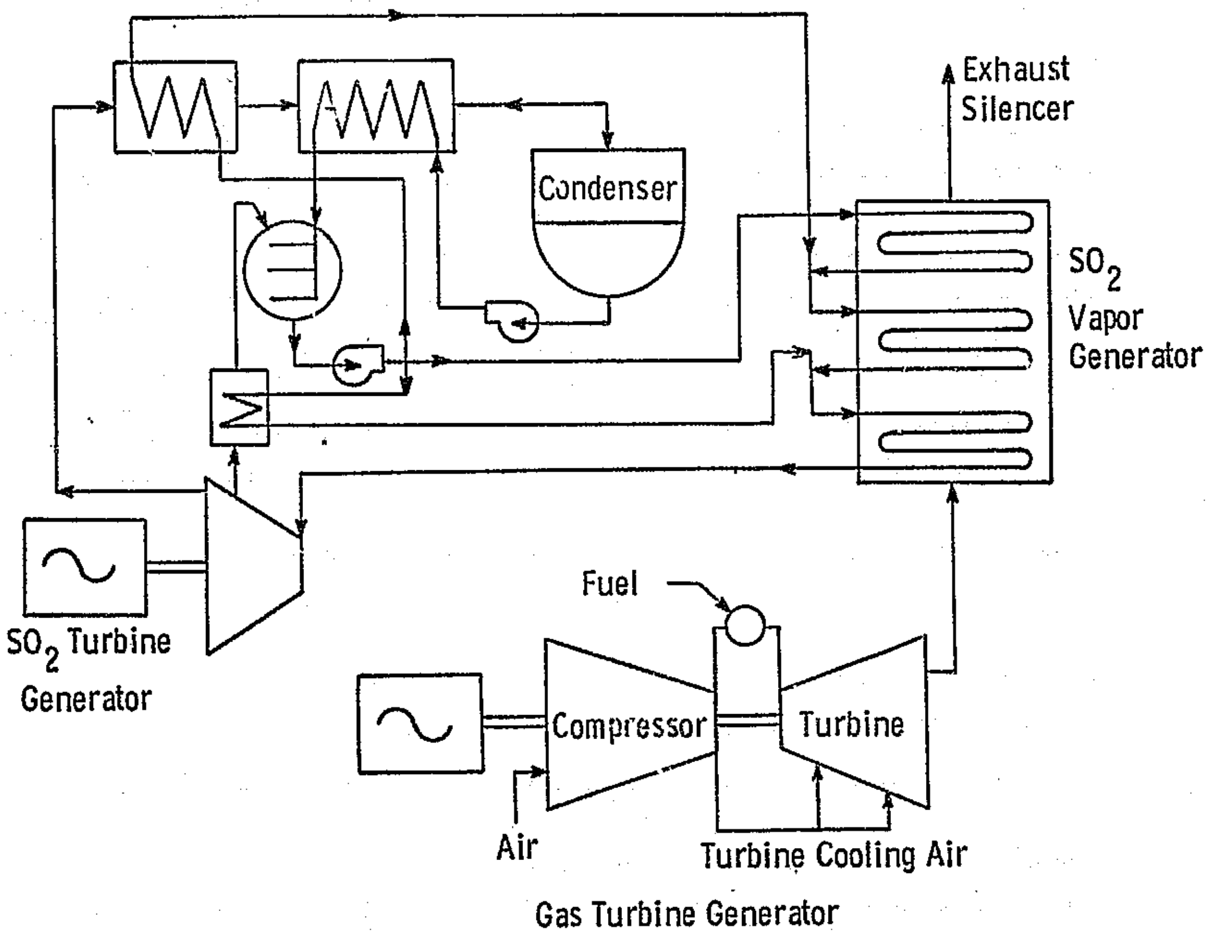


Fig. 5.10—Schematic diagram of open-cycle gas turbine system combined with SO_2 bottoming cycle

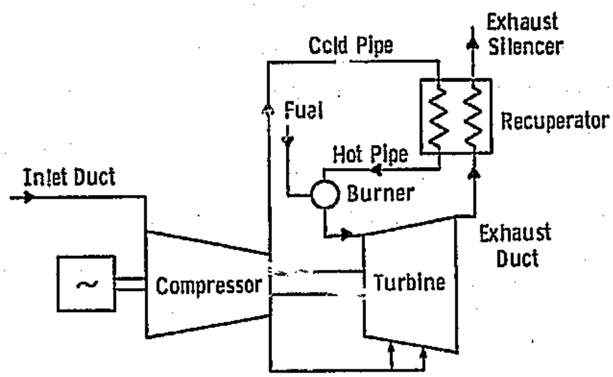
5.3 Approach

With the exception of the organic fluid portions of the bottomed cycles, all performance evaluations for the gas turbine cycle parametric studies were made using the Westinghouse proprietary computer program OPTCYC. This program is a performance optimization tool for preliminary design. It is capable of handling simple or combined (gas and steam), and recuperated and intercooled cycles with a nonreheat or reheat steam cycle burning various types of fuels. It uses gas and steam properties based on U. S. National Bureau of Standards, Series III, data and the Keenan and Keyes steam tables. It also accounts for all losses encountered in power plants, such as cooling, pumping, and pressure drop, etc. No allowance has been made for the station-building power requirements.

The base case cycle calculation model and assumed specifications are shown in Figure 5.11. For a given airflow, ambient condition, component efficiencies, effectiveness, and losses; together with fuel properties, gas turbine inlet temperature, and compressor pressure ratio; and the steam cycle condition (in the combined plant case), the OPTCYC program computes the thermodynamic conditions (temperature, pressure, enthalpy, and flows) at each state point across the components. Compressor performance is determined by using an efficiency calculation as a function of pressure ratio based on a proprietary, empirical formula derived from various compressors built and tested. When an intercooler is present, the given pressure ratio is reached by assuming equal compression ratios for the high- and low-pressure compressors. The quantity of fuel required to attain a specified gas turbine inlet temperature is computed iteratively. A double iteration is performed for a recuperated cycle.

Requirements for gas turbine cooling were deduced from heat transfer and flow network analyses of various high-temperature machines designed to date. These analyses were based on the use of state-of-the-art gas turbine materials, as described in Section 3. The cooling air

Dwg. 1675857



Component or Location	Specification	
Ambient Air	Temperature Pressure Relative Humidity	59°F 14.7 psia 60%
Inlet Duct Pressure Drop	ΔP/P	0.0075
Compressor Adiabatic Efficiency	Function of Pressure Ratio	
Cold Pipe, Hot Pipe, and Burner Pressure Drop	ΣΔP/P	0.055
Recuperator Pressure Drop	ΔP/P Air Side ΔP/P Gas Side	0.012 0.018
Fuel Dist From Coal	HHV LHV	18,700 Btu/lb 17,700 Btu/lb

Fig. 5.11—Calculation model and specifications for Base Case recuperated open-cycle gas turbine

usage curves used in the calculations are shown in Figure 5.12 where, for simplicity, the cooling flow is assumed to be a function of turbine inlet temperature only. For a given inlet temperature, coolant is extracted from the compressor discharge according to the cooling scheme considered. It is returned to the turbine as required for each stage. In the turbine, expansion takes place with mixed gas properties at a given efficiency. Using the thermodynamic data acquired, the program then calculates the gas turbine and compressor power. Total net output of the plant is obtained after the mechanical and generator losses, as well as auxiliary power required, are deducted from the gross power. The auxiliary power, as applicable to the cycle analyzed, includes such items as boiler feed pump, circulating pump, cooling tower fan power, lubrication oil, and fuel pump, etc. Finally, combined plant efficiency is calculated on the basis of the high heating value of the fuel. Net plant specific power is computed per pound of airflow at compressor inlet.

In the cycle computations made with the OPTCYC program, system components are defined by performance parameters that are defined in conformance with accepted convention. For clarity, these definitions and, where applicable, assumed values, are presented below:

- Turbine inlet temperature is the gas temperature immediately upstream of the first-row stationary vane.
- Turbine efficiency is calculated on the basis of polytropic stage efficiency = 0.90.
- Compressor pressure ratio is the ratio of total pressures at the compressor outlet flange to those at the compressor inlet flange.
- Compressor efficiency is an empirical function of pressure ratio derived from tests.

$$\eta_C = \frac{\text{isentropic enthalpy rise for given pressure ratio}}{\text{actual enthalpy rise}}$$

Curve 680348-B

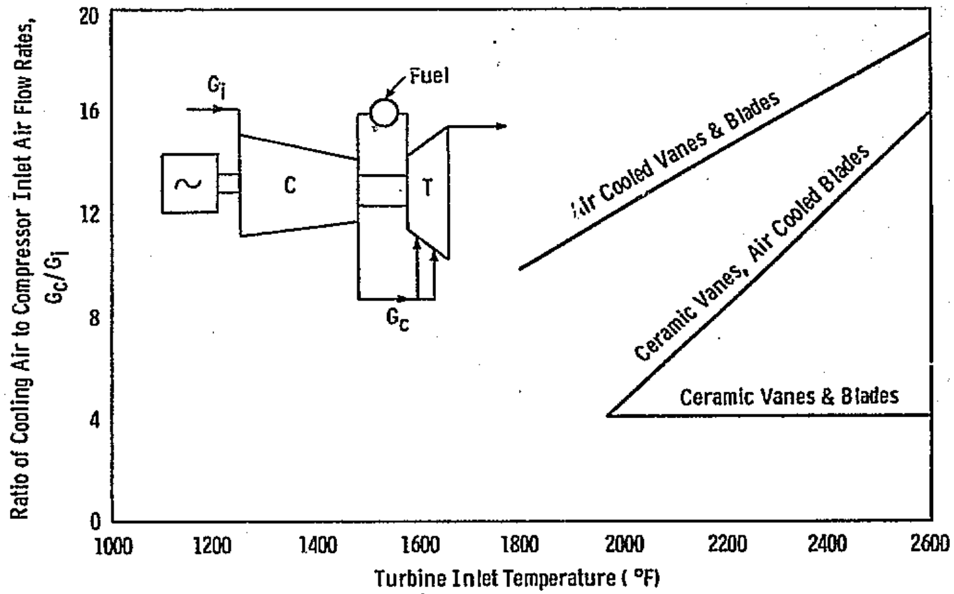


Fig. 5.12—Gas turbine blade cooling flow usage

- Recuperator effectiveness:

$$\varepsilon_R = \frac{T_{Combustor\ Inlet} - T_{Compressor\ Discharge}}{T_{Turbine\ Outlet} - T_{Compressor\ Discharge}}$$

- Recuperator pressure drop ratio:

$$\frac{\Delta P}{P} = \frac{\Delta P_{T\ Cold\ Side}}{P_{T\ Cold\ Side,\ In}} + \frac{\Delta P_{T\ Hot\ Side}}{P_{T\ Hot\ Side,\ In}}$$

where, typically, for $\frac{\Delta P}{P} = 0.030$.

$$\frac{\Delta P_{T\ Cold\ Side}}{P_{T\ Cold\ Side,\ In}} = 0.012$$

$$\frac{\Delta P_{T\ Hot\ Side}}{P_{T\ Hot\ Side,\ In}} = 0.018$$

That is,

$$\left(\frac{\Delta P_T}{P_T}\right)_{Hot} = 1.5 \left(\frac{P_T}{P_T}\right)_{Cold}$$

- Intercooler approach ($T_{Air,\ Out} - T_{Water,\ In}$) is assumed to be 16.7°K (30°F).

- Intercooler range ($T_{Water,\ Out} - T_{Water,\ In}$) is assumed to be 12.8°K (23°F).

5.4 Results of Parametric Study

This section presents the results of the parametric analysis of power system performance. For convenience in referring to the calculation

Dwg. 256C487

TABLE 5.2 — RECUPERATED OPEN CYCLE GAS TURBINE INVESTIGATION

Sheet 1 of 6

Parametric Point	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Power Output, MWe																	
Fuel																	
Distillate	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
High-Btu Gas																	
Gas Turbine																	
Inlet Temp., °F	2200	1800	1800	1800	1800	1800	1800	1800	2000	2000	2000	2000	2000	2000	2200	2200	2200
Pressure Ratio	10	6	8	10	12	16	20	24	8	10	12	16	20	24	8	10	12
Cooling ①	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ
Recuperator																	
Effectiveness	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ΔP/P	0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Intercooler Effectiveness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reheat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bottoming System																	
Fluid																	
R-12																	
Methylamine																	
SO_2																	
Turbine Inlet Temp., °F																	
Bottoming Vapor Generator																	
Pinch Point ΔT, °F																	
Exit ΔT, °F																	
Gas Side, ΔP/P																	
Specific Power, kW/lb/s	131.6	95.8	100.5	101.4	100.0	93.7	85.0	75.2	116.8	119.3	119.1	114.5	107.2	98.3	132.4	136.4	137.3

Note:

① Gas Turbine Blade Cooling Configurations
- ⓐ Turbine Vanes & Blades Air Cooled
- ⓑ Vanes Ceramic, Blades Air Cooled
- ⓒ Vanes Ceramic, Blades Ceramic
- ⓓ Vanes Ceramic, Blades Watercooled

results, the parametric variations investigated and summarized earlier in Table 5.1 have been numbered and presented in an expanded form in Table 5.2. Point 1 represents the base case, an air-cooled gas turbine with an inlet temperature of 1478°K (2200°F), a pressure ratio of 10 to 1, a recuperator effectiveness, ϵ_R, of 0.8, and a recuperator pressure drop, ΔP/P, of 0.03, which burned distillate fuel. Points 2 through 26 have been assigned to the simple-cycle gas turbine parametric evaluations, covering turbine inlet temperatures of 1255 to 1644°K (1800 to 2500°F) and pressure ratios of from 6 to 1 to 24 to 1. Points 27 through 44 cover the same range of gas turbine engine parameters for recuperated cycles with a recuperator effectiveness, ϵ_R, of 0.80 and a pressure drop ratio, ΔP/P, of 0.03. Points 45 through 64 provide for recuperator parametric variation covering ϵ_R of 0.7, 0.8, and 0.9 and ΔP/P of 0.02, 0.03, and 0.04. Points 65 through 70 examine the intercooled recuperated cycle, using the base cycle, with pressure ratio variation from 8 to 1 to 24 to 1. Points 71 through 92 repeat a portion of the high-temperature recuperated cases, except that turbine cooling air requirements are varied by assuming a substitution of ceramics for air-cooled components. Point 93 was assigned to a turbine reheat case. (This point was later omitted and was not calculated.) Point 94 is the base case variation burning high-Btu gas. Points 95, 96, and 97 cover the R-12, methylamine, and sulfur dioxide bottoming cycle cases, respectively.

In addition to the parametric description of each case point, Table 5.2 lists the corresponding results of specific power calculations. Selected case results and the results of the parametric investigation are discussed below.

5.4.1 Selected Case Results

Figure 5.13 presents a summary of calculated performance data for the base case recuperated open-cycle case. The calculation procedure and assumptions related to operating conditions and component parameters are discussed in Section 5.3. With the exception of long-time commercial demonstration of this turbine inlet temperature, this base case performance

Dwg. 256C4B8

TABLE 5.2– RECUPERATED OPEN CYCLE GAS TURBINE INVESTIGATION (CONT'D.)

Parametric Point	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Power Output, MWe																	
Fuel																	
Distillate	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
High-Btu Gas																	
Gas Turbine																	
Inlet Temp., °F	2200	2200	2200	2500	2500	2500	2500	2500	2500	1800	1800	1800	1800	2000	2000	2000	2000
Pressure Ratio	16	20	24	8	10	12	16	20	24	6	8	10	12	8	10	12	16
Cooling ①	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ
Recuperator																	
Effectiveness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
ΔP/P	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Intercooler Effectiveness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reheat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bottoming System																	
Fluid																	
R-12																	
Methylamine																	
SO_2																	
Turbine Inlet Temp., °F																	
Bottoming Vapor Generator																	
Pinch Point ΔT, °F																	
Exit ΔT, °F																	
Gas Side, ΔP/P																	
Specific Power, kW/lb/s	13.46	128.3	120.6	154.4	160.6	163.2	162.9	158.4	151.9	91.6	96.8	98.1	97.1	112.4	115.2	115.5	111.8

Note:

① Gas Turbine Blade Cooling Configurations
- ⓐ Turbine Vanes & Blades Air Cooled
- ⓑ Vanes Ceramic, Blades Air Cooled
- ⓒ Vanes Ceramic, Blades Ceramic
- ⓓ Vanes Ceramic, Blades Watercooled

Dwg. 2560489

TABLE 5.2—RECUPERATED OPEN CYCLE GAS TURBINE INVESTIGATION (CONT'D.)

Sheet 3 of 6

Parametric Point	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
Power Output, MWe																	
Fuel																	
Distillate	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
High-Btu Gas																	
Gas Turbine																	
Inlet Temp., °F	2200	2200	2200	2200	2500	2500	2500	2500	2500	2500	2200	2200	2200	2200	2200	2200	2200
Pressure Ratio	8	12	16	20	8	10	12	16	20	24	8	10	12	16	20	8	10
Cooling ①	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ
Recuperator																	
Effectiveness	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.9	0.9
$\Delta P/P$	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Intercooler Effectiveness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9
Reheat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bottoming System																	
Fluid																	
R-12																	
Methylamine																	
SO_2																	
Turbine Inlet Temp., °F																	
Bottoming Vapor Generator																	
Pinch Point ΔT, °F																	
Exit ΔT, °F																	
Gas Side, $\Delta P/P$																	
Specific Power, kW/lb/s	127.2	133.0	131.2	125.8	148.1	154.7	157.9	158.5	155.0	149.3	127.5	131.9	133.2	131.3	125.8	126.9	131.4

Note:

① Gas Turbine Blade Cooling Configurations
- ⓐ Turbine Vanes & Blades Air Cooled
- ⓑ Vanes Ceramic, Blades Air Cooled
- ⓒ Vanes Ceramic, Blades Ceramic
- ⓓ Vanes Ceramic, Blades Watercooled

Dwg. 256C490

TABLE 5.2 – RECUPERATED OPEN CYCLE GAS TURBINE INVESTIGATION (CONT'D.)

Parametric Point	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68
Power Output, MWe																	
Fuel																	
Distillate	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
High-Btu Gas																	
Gas Turbine																	
Inlet Temp., °F	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200
Pressure Ratio	12	16	20	8	10	12	16	20	8	10	12	16	20	8	10	12	16
Cooling ①	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ
Recuperator																	
Effectiveness	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
ΔP/P	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03
Intercooler Effectiveness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.844	0.862	0.875	0.891
Reheat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bottoming System																	
Fluid																	
R-12																	
Methylamine																	
SO_2																	
Turbine Inlet Temp., °F																	
Bottoming Vapor Generator																	
Pinch Point ΔT, °F																	
Exit ΔT, °F																	
Gas Side, ΔP/P																	
Specific Power, kW/lb/s	132.9	131.1	125.8	128.2	132.6	134.0	132.1	126.6	126.2	130.7	132.1	130.4	125.0	139.4	148.2	154.2	161.8

Note:

① Gas Turbine Blade Cooling Configurations
- ⓐ Turbine Vanes & Blades Air Cooled
- ⓑ Vanes Ceramic, Blades Air Cooled
- ⓒ Vanes Ceramic, Blades Ceramic
- ⓓ Vanes Ceramic, Blades Watercooled

TABLE 5.2 – RECUPERATED OPEN CYCLE GAS TURBINE INVESTIGATION (CONT'D.)

Parametric Point	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
Power Output, MWe																	
Fuel																	
Distillate	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
High-Btu Gas																	
Gas Turbine																	
Inlet Temp., °F	2200	2200	2200	2200	2200	2200	2200	2500	2500	2500	2500	2500	2500	2200	2200	2200	2200
Pressure Ratio	20	24	8	10	12	16	20	8	10	12	16	20	24	8	10	12	16
Cooling ①	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ	ⓐ
Recuperator																	
Effectiveness	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
ΔP/P	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Intercooler Effectiveness	0.901	0.908	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reheat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bottoming System																	
Fluid																	
R-12																	
Methylamine																	
SO_2																	
Turbine Inlet Temp., °F																	
Bottoming Vapor Generator																	
Pinch Point ΔT, °F																	
Exit ΔT, °F																	
Gas Side, ΔP/P																	
Specific Power, kW/lb/s	165.7	167.9	138.9	144.1	146.2	145.6	141.1	156.4	163.6	167.2	168.8	165.9	160.8	147.3	153.1	155.7	156.0

Note:

① Gas Turbine Blade Cooling Configurations
ⓐ Turbine Vanes & Blades Air Cooled
ⓑ Vanes Ceramic, Blades Air Cooled
ⓒ Vanes Ceramic, Blades Ceramic
ⓓ Vanes Ceramic, Blades Watercooled

TABLE 5.2 – RECUPERATED OPEN CYCLE GAS TURBINE INVESTIGATION

Sheet 6 of 6

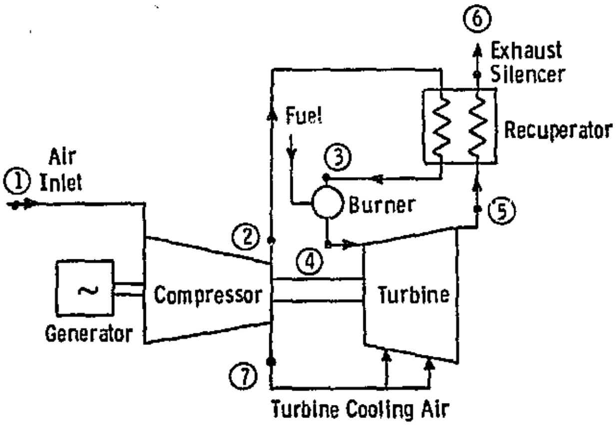
Parametric Point	86	87	88	89	90	91	92	93	94	95	96	97					
Power Output, MWe																	
Fuel																	
Distillate	X	X	X	X	X	X	X	X		X	X	X					
High-Btu Gas									X								
Gas Turbine																	
Inlet Temp., °F	2200	2500	2500	2500	2500	2500	2500	2200	2200	2000	2000	2500					
Pressure Ratio	20	8	10	12	16	20	24	10	10	8	8	16					
Cooling ①																	
Recuperator																	
Effectiveness	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.0					
ΔP/P	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.0					
Intercooler Effectiveness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
Reheat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2200	0.0	0.0	0.0	0.0					
Bottoming System																	
Fluid																	
R-12										X							
Methylamine											X						
SO_2												X					
Turbine Inlet Temp., °F										400	600	1000					
Bottoming Vapor Generator																	
Pinch Point ΔT, °F										•							
Exit ΔT, °F										100							
Gas Side, ΔP/P										0.05							
Specific Power, kW/lb/s	152.1	178.8	187.6	192.6	196.6	195.5	191.7		135.7								

• Supercritical

Note:

① Gas Turbine Blade Cooling Configurations
- ⓐ Turbine Vanes & Blades Air Cooled
- ⓑ Vanes Ceramic, Blades Air Cooled
- ⓒ Vanes Ceramic, Blades Ceramic
- ⓓ Vanes Ceramic, Blades Watercooled

Dwg. 1679348



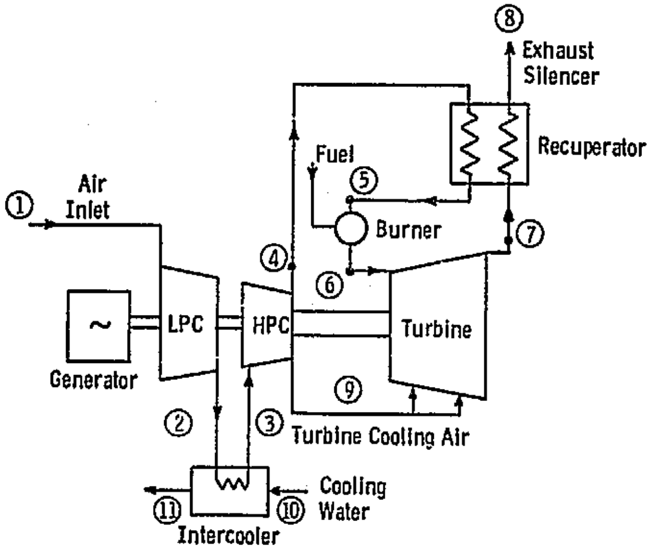
BASELINE CASE CYCLE DATA SUMMARY (Point 1)

Station	Pressure, psia	Temperature, °F	Flow, lb/s
1	14.7	59	750
2	147.0	600	642
3		991	642
4	144.0	2200	654
5	15.0	1102	763
6	14.7	773	763
7		600	108

Fuel: distillate from coal (18,700 Btu/lb HHV) ; Flow = 13 25 lb/s
Cycle Efficiency: 37.8%
Specific Power: 131.6 kW/(lb/s)

Fig. 5.13—Base Case recuperated open-cycle results

Dwg. 1679B51



CYCLE DATA SUMMARY (Point 69)

Station	Pressure, psia	Temperature, °F	Flow, lb/s
1	14.7	59	750
2	147.0	367	750
3		96	750
4	294.0	425	642
5		777	642
6	283.0	2200	657
7	15.0	865	765
8	14.7	581	765
9		425	108
10		66	
11		89	

Fuel: distillate from coal (18,700 Btu/lb HHV); Flow = 15.4 lb/s
Cycle Efficiency = 41.0%
Specific Power = 165.7 kW/(lb/s)

Fig. 5.14--Sample recuperated intercooled open-cycle results

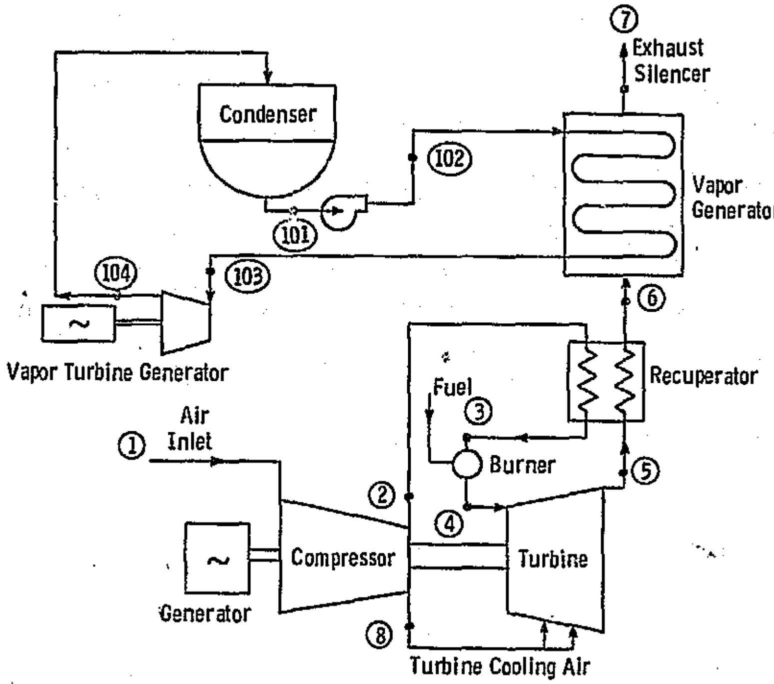
is typical of state-of-the-art systems currently available on the commercial market.

Figure 5.14 provides sample results of the recuperated/intercooled open-cycle cases. The results are shown for Point 69 with a turbine inlet temperature of 1478°K (2200°F) and a combined LP and HP compressor pressure ratio of 20 to 1, which, as shown later, represents the most economical case of this type investigated. It should be noted that the same amount of turbine cooling airflow was used for this case as for the base case. This is because of the simplifying assumption that the cooling air requirement is a function of turbine inlet temperature only. In reality, however, the lower temperature cooling air available in an intercooled system (at a given pressure ratio) would result in a lower cooling flow requirement. This would be reflected in even greater cycle performance improvements with intercooling than those shown here.

Figure 5.15 shows the cycle data for the bottoming cycles cases with the R-12 and methylamine working fluids (Points 95 and 96, respectively). The gas turbine topping cycle parameters selected for these cases were those of Point 31, that is, 1366°K (2000°F) and 8 to 1. The cycle efficiency for that case was 36.7%, so that the effect of adding the bottoming cycles is a 16.6 and 20.7% improvement in efficiency with the R-12 and methylamine cycles, respectively. The bottoming cycle turbine inlet parameters used for both cases were set at 589°K (600°F) and 17.23 MPa (2500 psi) abs.

The results for the sulfur dioxide bottoming cycle, Point 97, are summarized on Figure 5.16. For this case the gas turbine cycle parameters selected are 1644°K (2500°F) and 16 to 1. Note that the results for this case are for compressor airflow rates of 442 kg/s (975 lb/s) compared to 340 kg/s (750 lb/s) for all other cases. Also, the sulfur dioxide bottoming cycle was fitted beneath a simple gas turbine topping cycle, rather than a recuperated cycle as in the cases of R-12 and methylamine. Point 24 represents the corresponding simple-cycle case for which a cycle efficiency of 33.5% was calculated. This indicates that the

Dwg. 1679B49



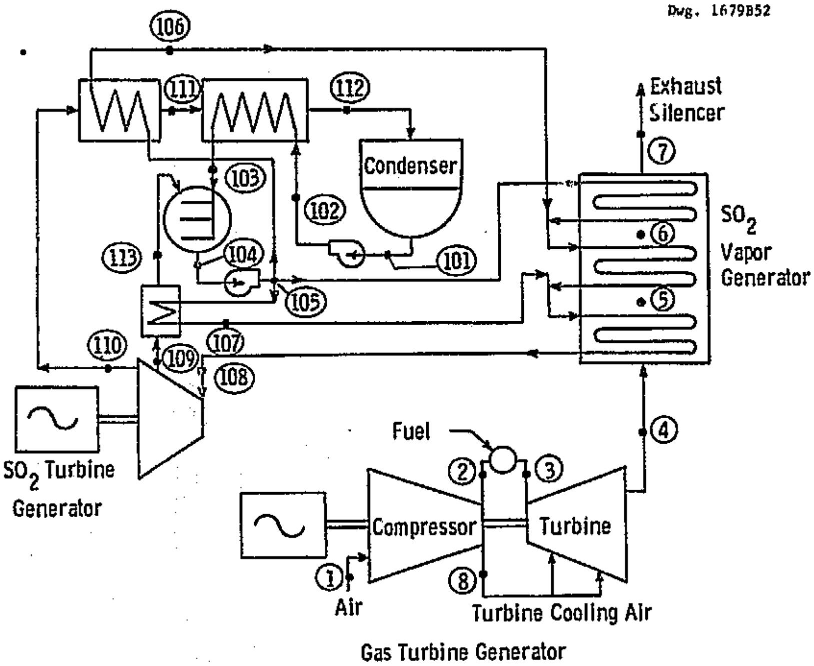
CYCLE DATA SUMMARY (Point 95 and 96)

Station	P, psia	T, °F	h, Btu/lb	G, lb/s
Gas Turbine				
1	14.7	59		750.0
2	117.0	529		659.0
3		959		659.0
4	109.0	2000		670.5
5	15.8	1067		761.5
6	15.5	708	191.3	761.5
7	14.7	290	85.4	761.5
8		529		91.0
R-12				
101	135.0	102	31.5	695.2
102	2941.0	111	40.3	
103	2500.0	600	156.3	
104	135.0	312	124.1	
Methylamine				
101	83.4	104	109.3	163.4
102	2694.0	111	125.5	
103	2500.0	600	619.1	
104	83.4	227	484.0	

Fuel: distillate from coal (18,700 Btu/lb); Flow = 11.5 lb/s
Cycle Efficiency = 42.8% (R-12); 44.3% (Methylamine)
Specific Power = 129.5 kW/(lb/s) (R-12);
= 134.0 kW/(lb/s) (Methylamine)

Fig. 5.15—Organic fluid bottoming cycle results

Dwg. 1679B52



CYCLE DATA SUMMARY (Point 97)

Station	P, psia	T, °F	h, Btu/lb	G, lb/s
1	14.7	59.0		975.0
2	233.0	769.0		801.4
3	220.0	2500.0		825.8
4	15.0	1090.0	295.3	999.4
5		693.0	188.7	999.4
6		408.0	115.4	999.4
7		306.0	89.8	999.4
8	14.7	769.0		173.6
101	86.0	101.3	65.7	824.0
102	449.0	110.0	66.8	824.0
103	436.0	158.0	91.7	824.0
104	436.0	220.0	110.8	950.5
105	2768.0	250.0	119.1	950.5
106	2713.0	368.0	167.5	349.7
107	2632.0	550.0	250.6	70.4
108	2500.0	1000.0	362.8	950.5
109	450.0	662.0	308.3	126.5
110	89.5	408.0	266.7	824.0
111	87.8	290.0	246.2	824.0
112	86.0	145.0	221.3	824.0
113	436.0	290.0	235.2	126.5

Fuel: distillate from coal (18,700 Btu/lb); Flow = 24.4 lb/s
Cycle Efficiency = 48.2%
Specific Power = 238.7 kW/(lb/s)

Fig. 5.16—SO_2 bottoming cycle results

Curve 679873-B

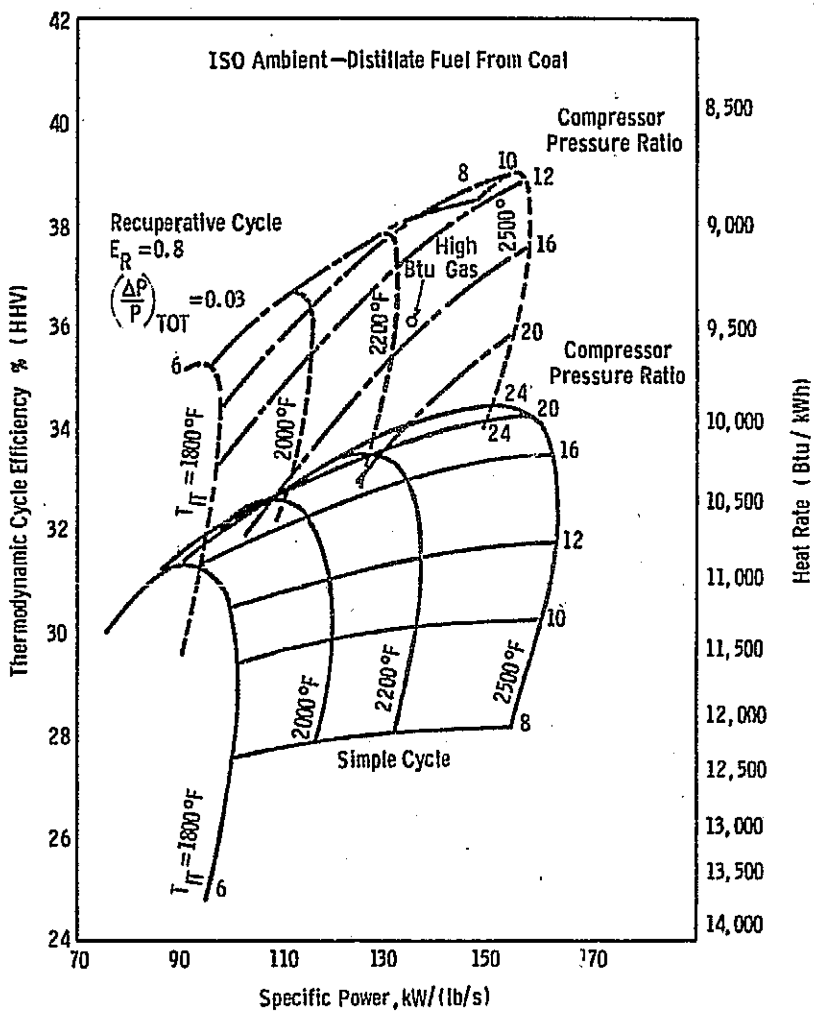


Fig. 5.17—Gas turbine cycle efficiency vs specific power

effect of the sulfur dioxide bottoming cycle was to increase efficiency by 43.9% over the simple-cycle case. Compared to the corresponding recuperated cycle (Point 42), the sulfur dioxide bottoming cycle represents an efficiency improvement of 28.1%.

5.4.2 Results of Parametric Variation

The results of the basic gas turbine cycle parametric investigation are presented on Figure 5.17. Curves of cycle efficiency and/or heat rate as functions of specific power (gas turbine generator net output divided by compressor inlet airflow) are drawn at constant turbine inlet temperature and constant compressor pressure ratio for both recuperated (at ε_R = 0.8 and $\Delta P/P$ = 0.03) and simple (ε_R = 0.0 and $\Delta P/P$ = 0) cases. These show the general trends of improved cycle efficiency with increased turbine inlet temperature.

At constant temperature, the nature of the pressure ratio effect upon efficiency is seen to be reversed for the two cases. For the recuperated cycle, efficiency peaks at a relatively low pressure ratio and falls off steeply as the pressure ratio is increased. This is actually the result of decreasing gains through recuperation as the compressor discharge temperature increases, with increased pressure ratio, to approach the turbine exhaust temperature. At higher pressure ratios, the turbine exhaust would actually be colder than the compressor discharge and negative recuperation would occur, resulting in an efficiency loss. This can be seen where the efficiency curves for the recuperative cycles fall below those for the corresponding simple-cycle cases.

In general, Figure 5.17 shows that a substantial gain in efficiency can be realized by recuperation. For example, the base case at 1478°K (2200°F) and 10 to 1 has a cycle efficiency of 37.8% which represents a 25.2% improvement over the corresponding simple-cycle efficiency of 30.2%. Comparing the peak efficiencies shown for a 1644°K (2500°F) turbine inlet temperature, a recuperative cycle with a 10 to 1 pressure ratio would have an efficiency 13.3% greater than a simple cycle with a 24 to 1 compressor.

Curve 679871-B

ISO Ambient—Distillate Fuel From Coal

$T_{IT} = 2200°F$

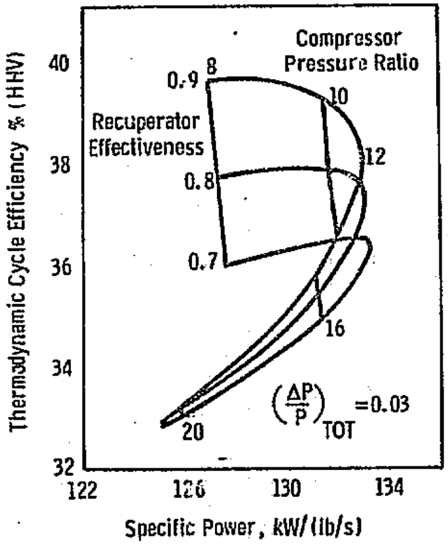


Fig. 5.18

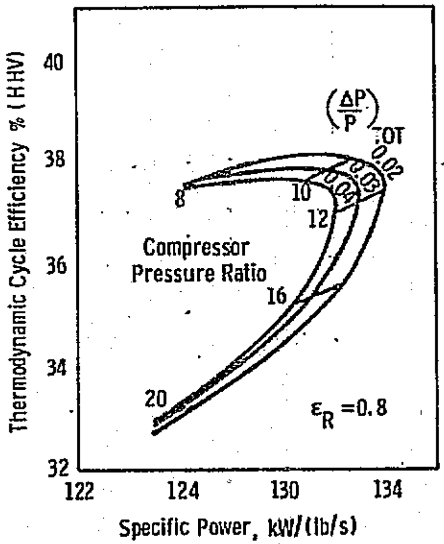


Fig. 5.19

Gas turbine recuperator performance variations

Also of significance is the observation that efficiency gains through turbine inlet temperature increases at a given pressure ratio are greater for the recuperated cycles. For example, at a pressure ratio of 12 to 1, an increase in turbine inlet temperature from 1366 to 1644°K (2000 to 2500°F) results in a 9.4% gain in efficiency with recuperation, but the corresponding simple-cycle parametric variation results in only a 2.2% gain.

The results of varying recuperator design parameters are shown on Figures 5.18 and 5.19. The former shows the recuperator effectiveness on cycle efficiency, and the latter shows the effect of recuperator pressure drop (gas side + air side) at constant effectiveness. The significant impact of effectiveness at a lower cycle pressure ratio is evident. This is expected since, as discussed earlier, the benefit of recuperation is greatest with large temperature differences between turbine exhaust and compressor discharge. At 20 to 1, there is essentially no improvement in performance with an increase in recuperator effectiveness from 0.70 to 0.90.

Only a negligible effect on performance was observed over the whole range of pressure drop variation investigated.

The results of investigating the effect of substituting uncooled ceramics for air-cooled components in a recuperative cycle are presented on Figure 5.20. Efficiency as a function of specific power curves is shown for the air-cooled ceramic vanes and ceramic vanes/blades cases evaluated at 1478 and 1644°K (2200 and 2500°F) with parametric variation of compressor pressure ratio. The cooling air usage variation assumed for this investigation was discussed earlier and was shown in Figure 5.12. The results show that a gain of about five points in efficiency (or a 12.7% improvement) and an increase of nearly 21.3% in power output can be realized with the indicated reduction in the required amount of cooling air at the 1644°K (2500°F) turbine inlet temperature. Further, it is shown that a ceramic turbine at 1478°K (2200°F) inlet temperature provides a significant performance advantage over an air-cooled system operating

Curve 679872-B

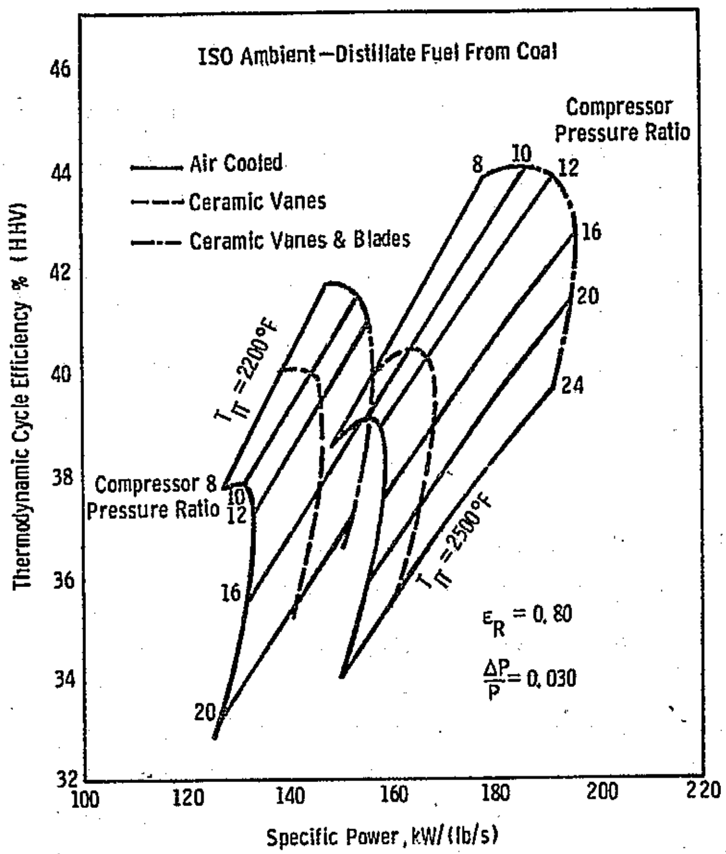


Fig. 5.20—Cycle efficiency vs specific power for gas turbine recuperative cycle blading variations

at 1644°K (2500°F). Although this turbine cooling variation was examined for only the recuperative-cycle, similar results would be expected for the simple-cycle case.

Figure 5.21 displays the results of the investigation of the effect of intercooling upon recuperative cycle performance. The curves show efficiency versus specific power for the 1478°K (2200°F) turbine inlet temperature selected for the study. Significant effects were observed. The optimum cycle pressure ratio shifts upward from about 10 to 1 to 16 to 1. This results from the lowering of the compressor discharge temperature and the effect that this has upon the benefits of recuperation. Also, a gain of about 3.6 points (or nearly a 9.6% improvement) in peak efficiency and of 23.9% in power output (at peak efficiency) were calculated.

Figure 5.22 displays the results of the computations of the bottomed cycles in relation to other selected open-cycle parametric points. It can be seen that the bottomed cycles resulted in the highest efficiencies, even though the R-12 and methylamine cases utilized a relatively low-temperature [1366°K (2000°F)] gas turbine. (The unbottomed cycle point is also shown for comparison.) The sulfur dioxide bottoming cycle represented the highest efficiency (48.2%) and specific power [nearly 529.1 kW/(kg/s) (240 kW/(lb/s)] of all cases studied in this category. The various other cycle points with the same gas turbine parameters are plotted for comparison, as is the base case point and an intercooled recuperated-cycle point. The result of the case calculated with high-Btu gas fuel is also shown.

5.5 Capital and Installation Costs of Plant Components

The approach for developing plant capital costs has been first to develop, as completely as possible in the available time, a description of the base case plant. Pricing data are developed for this plant and subsequently expanded for the remaining parametric points.

Curve 679874-B

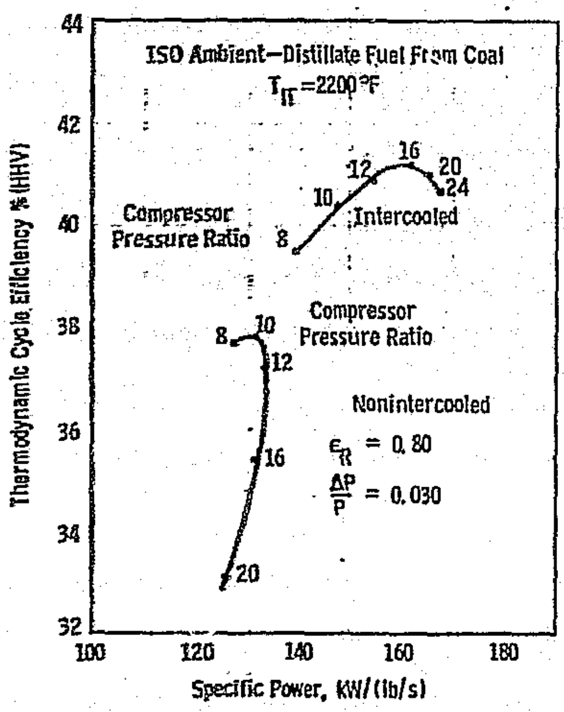


Fig.5.21—Recuperative gas turbine cycle efficiency vs specific power for cycle with and without intercooling

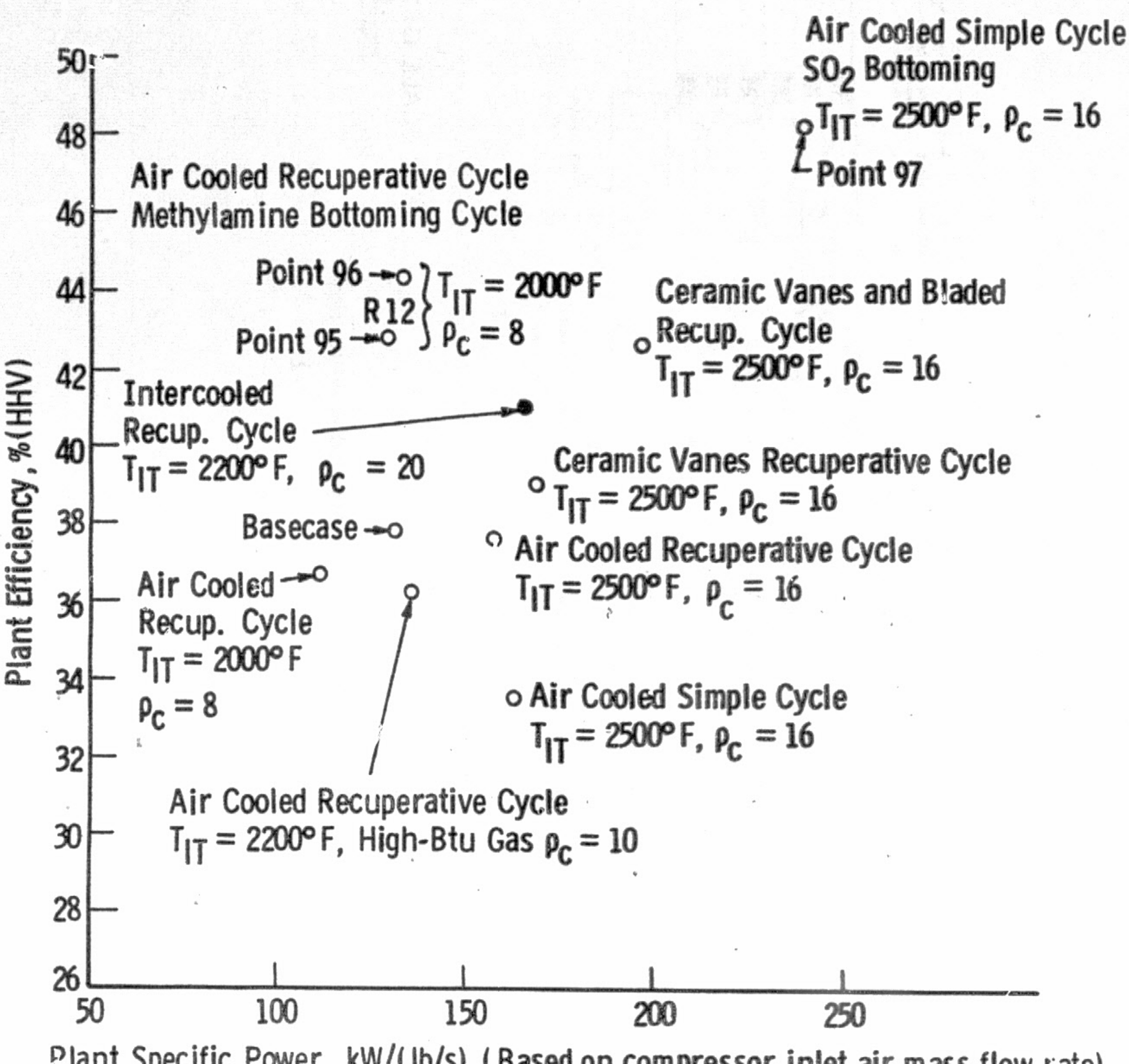


Fig.5.22 —Organic bottomed cycles cycle efficiency versus specific power (Iso Ambient Distillate Fuel from Coal Unless Noted)

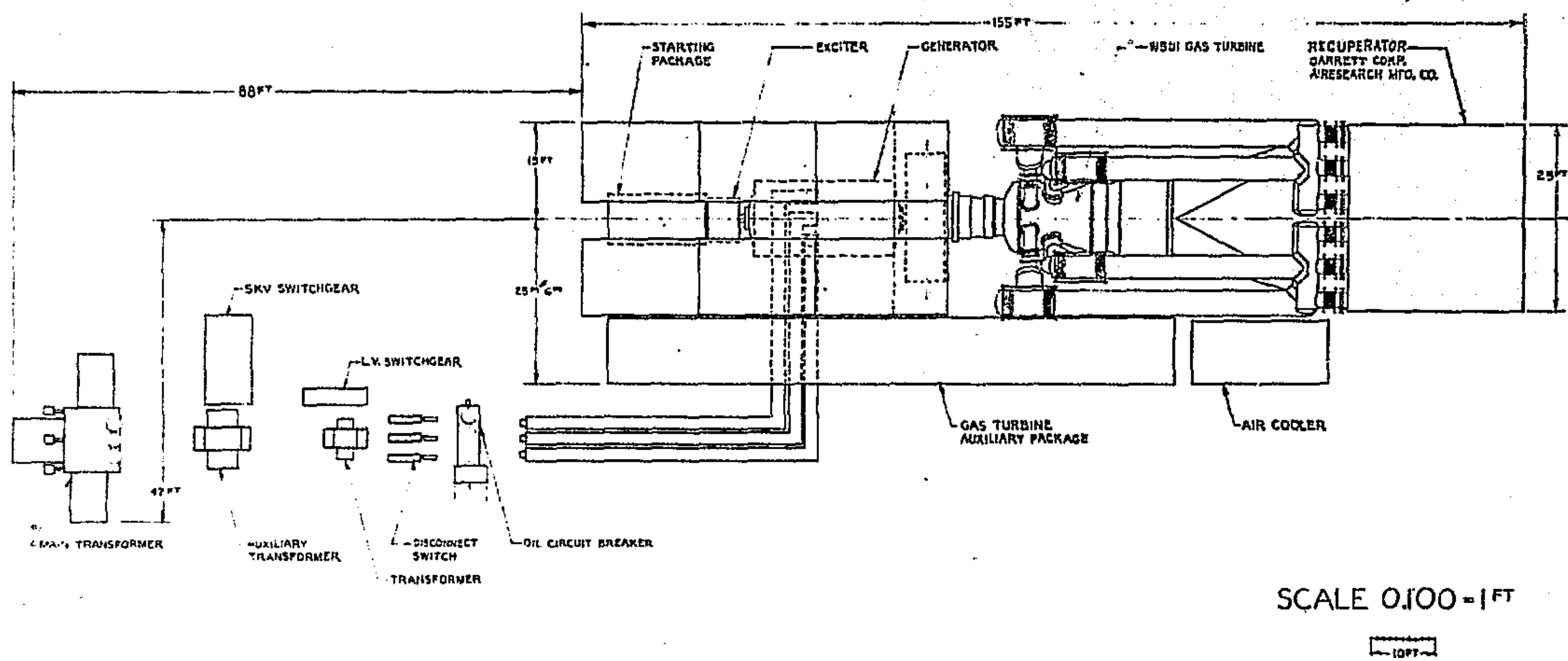


Fig. 5.23—Plant arrangement study W501 gas turbine with recuperator

5.5.1 Description of the Base Case Power Plant

The power plant arrangement for the base case is shown in Figure 5.23, and the overall ECAS study plot plan arrangement is illustrated by Figure 5.24. The power plant consists of four nominal 100 MW recuperated gas turbines for an overall plant rating of approximately 400 MW. The fuel selected for use is a distillate derived from coal. No major heat rejection equipment, such as cooling towers, is required.

5.5.1.1 Starting Package

The starting package is a self-contained module which provides break-away torque for initial rotation and acceleration to self-sustaining speed. This electrically operated device also contains provision for slow roll of the combined turbine and generator shafting during cool-down periods.

5.5.1.2 Generator and Exciter

The generator and exciter are directly coupled to the gas turbine shaft at the compressor end. The generator is hydrogen-cooled and uses shaft-mounted axial blowers for hydrogen circulation within the generator.

5.5.1.3 Gas Turbine

The conceptual design selected for the base case gas turbine is shown in Figure 5.25. The 60 rps (3600 rpm), single-shaft design incorporates an axial-flow compressor passing 340 kg/s (750 lb/s) at a pressure ratio of 10 to 1. The multiple-can burner system raises the products of combustion temperature to 1478°K (2200°F) at the turbine inlet. The three-stage turbine utilizes air cooling of vanes and blades, incorporating impingement/convection/film-cooling techniques. The unit utilizes two fluid film journal bearings, horizontal joint construction, and compressor end drive; and features fully assembled rail shipment capability.

5.5.1.4 Recuperator System

The heart of the recuperator system is an advanced type tension-braze plate-fin heat exchanger. A conceptual picture of one module of

Dwg.1674848

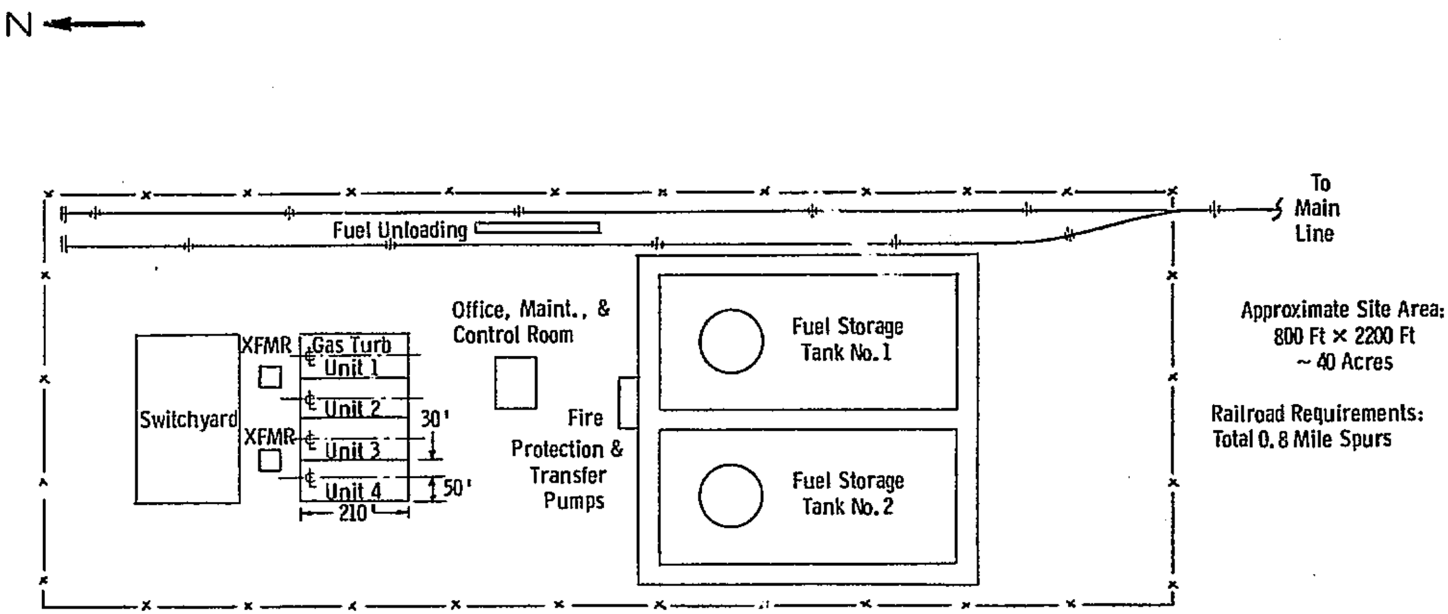


Fig. 5.24—Recuperated open-cycle gas turbine plant base case

Scale:

0 50 100 200

Dwg. 1679873

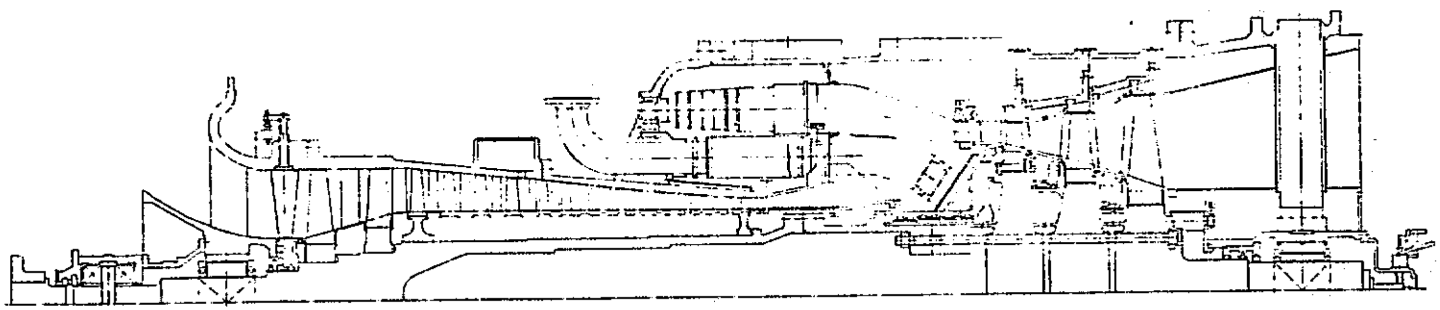


Fig. 5.25—Base Case gas turbine engine

Dwg. 6352A12

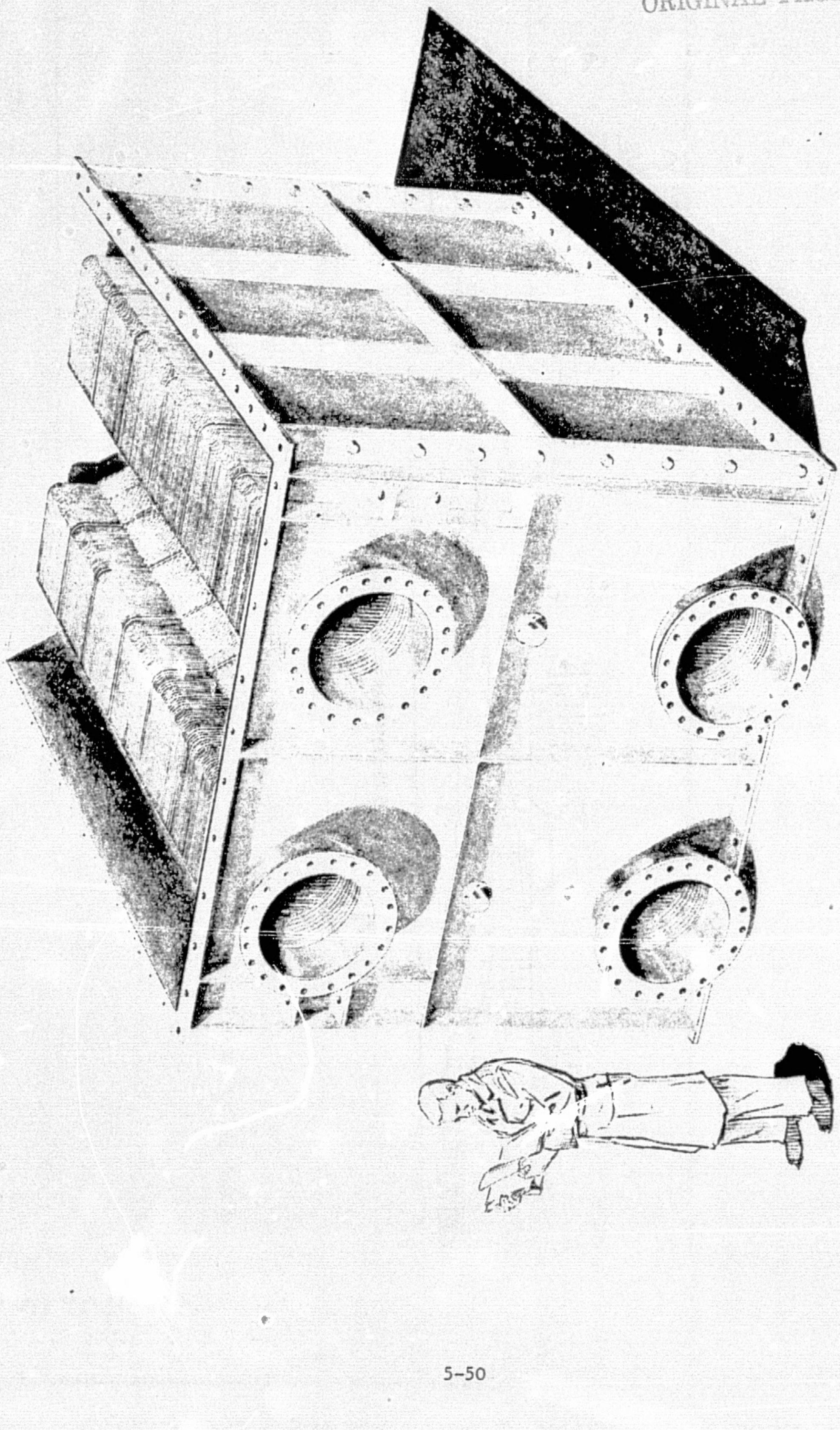


Fig. 5.26—Basic recuperator module

such a heat exchanger is shown in Figure 5.26. The unit uses thin gauge, 400 series SS, in a lightweight design optimized for cyclic duty operation at turbine exhaust temperatures of about 866°K (1100°F). The cold-air piping is constructed of carbon steel, and the hot-air return piping is 1-1/4 Cr alloy steel. Series 300 SS bellows-type expansion joints are used for this design.

5.5.1.5 Gas Turbine Auxiliary Skids

The self-contained mechanical skid assembly includes lubricating oil pumps, filters and reservoir, air-system pressure switch and gauge cabinet, and seal oil system. Included in the electrical and control skid are the battery equipment, motor control center, voltage regulator, generator relay panel, and certain control equipment. The fuel skid includes fuel pumps, filters, and related equipment.

5.5.1.6 Switchgear

The switchgear equipment includes the isolated phase bus, oil-circuit breakers, the disconnect switch, and the main and auxiliary transformers.

5.5.1.7 Balance of Plant

Due to the compact nature of the power plant, a site located outside of a city near an industrial area—not the Middletown site—has been selected. Railroad service consisting of two parallel spurs, each with a 20 tank-car capacity, has been provided for fuel delivery. Two oil-storage tanks of API standard construction are sized for 2.592 Ms (30 day) operation at a capacity factor of 45%. The tanks are positioned on a compacted sand foundation and are surrounded by a retaining dike system.

Foundations for the power plant are reinforced concrete not requiring pile supports.

The station building—557 m^2 (6000 ft^2) floor area—includes all necessary offices, plant maintenance, control room, and toilet and locker facitilies. It is designed for steel frame and concrete block or

Table 5.3 - Approximate Size and Mass of Base Case Recuperated-Cycle Major Components

Component	Basic Dimensions, m (ft)			Mass (Weight), kg (lb)
Gas Turbine	Length	Diameter		
Turbine section	3.0	4.0		75,300*
	(10.0)	(13.3)		(166,000)*
Compressor section	7.1	3.2		88,000*
	(23.3)	(10.4)		(194,000)*
Recuperator, Module	Length	Width	Height	
(Three required)	8.3	3.0	3.6	34,000
	(27.0)	(9.8)	(11.8)	(75,000)

*Includes recuperator piping mass (weight).

insulated metal siding. Steel frame metal siding enclosures are provided for fuel oil tank farm fire protection equipment.

The fuel unloading station is designed for rail or truck delivery and includes three 94.63 l/s (1500 gpm) pumps. Three 50% capacity fuel transfer pumps supply the gas turbine units through a common header. Complete fire protection is provided, including a liquid foam system for the fuel oil tank farm and unloading station and a deluge system at the main transformers.

The control room, located in the station building, includes the computer control package for the gas turbine units.

One three-phase, 500 kV transformer is supplied for each gas turbine unit.

5.5.2 Approximate Sizes and Weights of Major Components

Major components of the recuperated open-cycle gas turbine system, simplest of the ECAS energy conversion concepts, include the gas turbine engine and the recuperator. The relative sizes of these components are illustrated by the power plant arrangement plan view of Figure 5.23. A more detailed listing of the size and mass of these major components of the base case is given in Table 5.3.

It is important to note the arbitrary nature of the classification of the sections of the gas turbine unit. The compressor, turbine, and combustion sections (for most open-cycle turbines) are integral parts of each turbomachine unit, and, therefore, the combustion section has been grouped arbitrarily with the compressor section. The gas turbine would be rail shippable as a single unit, as would the individual recuperator modules.

5.5.3 Gas Turbine and Auxiliaries Price Determination Procedure

For the determination of parametric variations in gas turbine price a macro (as opposed to a micro) viewpoint has been selected. That is, gas turbine components have been segregated into groups of major

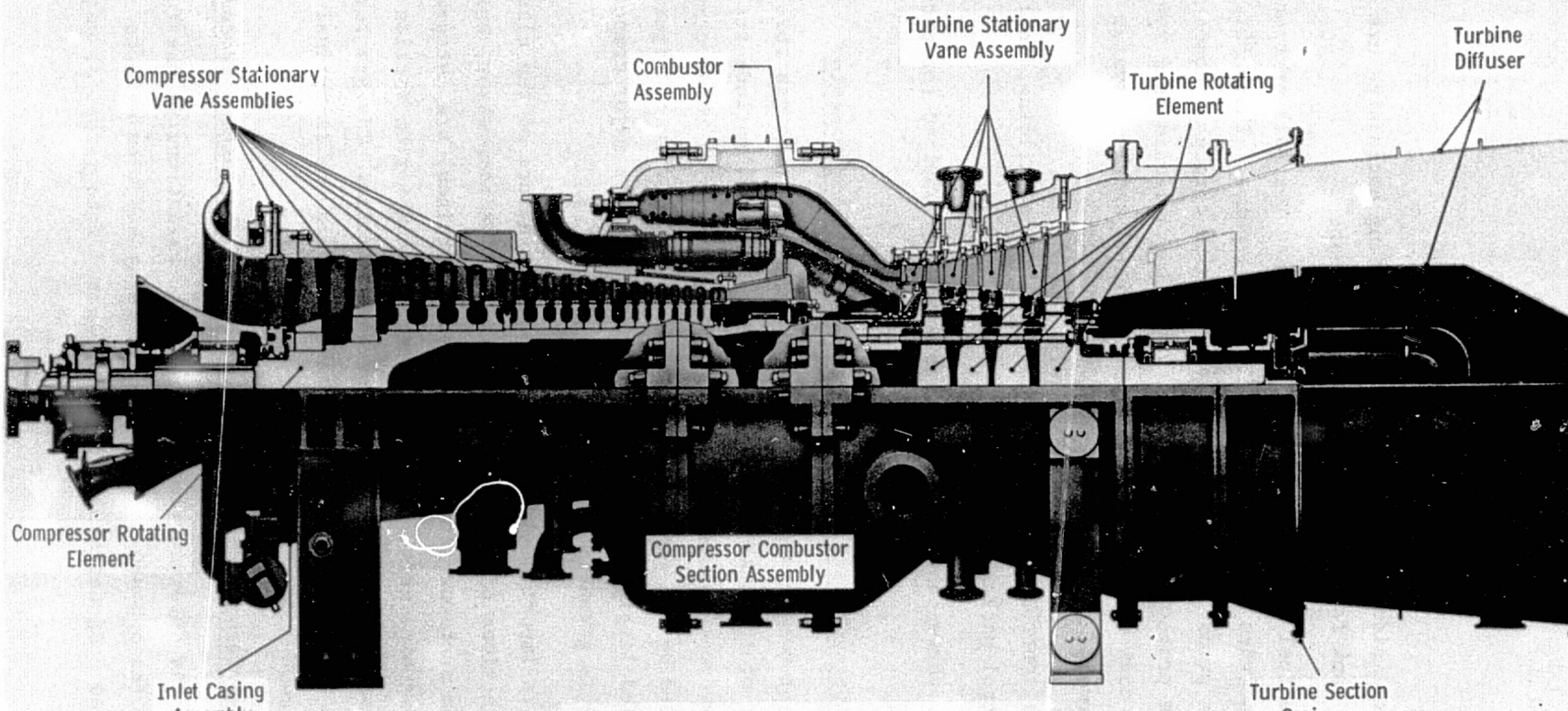


Fig. 5.27—Gas turbine major functional pricing groups

functional areas for examination with respect to price analysis. For example, compressor section stationary vane blading, combustion system, and turbine section rotating elements have been classified as wholes for representation by a single price as opposed to identifying single items such as individual turbine disk forgings or individual turbine or compressor section blades.

The model for partitioning of the whole gas turbine into the major functional groups is illustrated by Figure 5.27. A group of production and conceptual design engines were analyzed with respect to selling price and with prices segregated according to the functional group breakdown of the model. These engines all reflect current heavy-duty design practice and span a range in power output from approximately 25 to 130 MW. The segregated data were correlated with respect to selected independent parametric variables and were found to be representative over a wide range of parametric values. Additional price correlations were developed for the gas turbine auxiliaries and ancillary equipment necessary for a complete gas turbine plant. The data in normalized form are displayed by Figures 5.28 through 5.43, and incorporate the nomenclature given in Table 5.4.

Table 5.4 - Nomenclature

G_{1C}	= Compressor inlet airflow
ρ_c	= Compressor pressure ratio
N	= Shaft rotational speed
ΔH Combustor	= Enthalpy rise from compressor discharge to turbine inlet
ΔH Turbine	= Enthalpy drop from turbine inlet to turbine exit
T_{1T}	= Turbine inlet temperature (temperature at inlet to first stationary vane row)
T_{2c}	= Compressor discharge temperature.

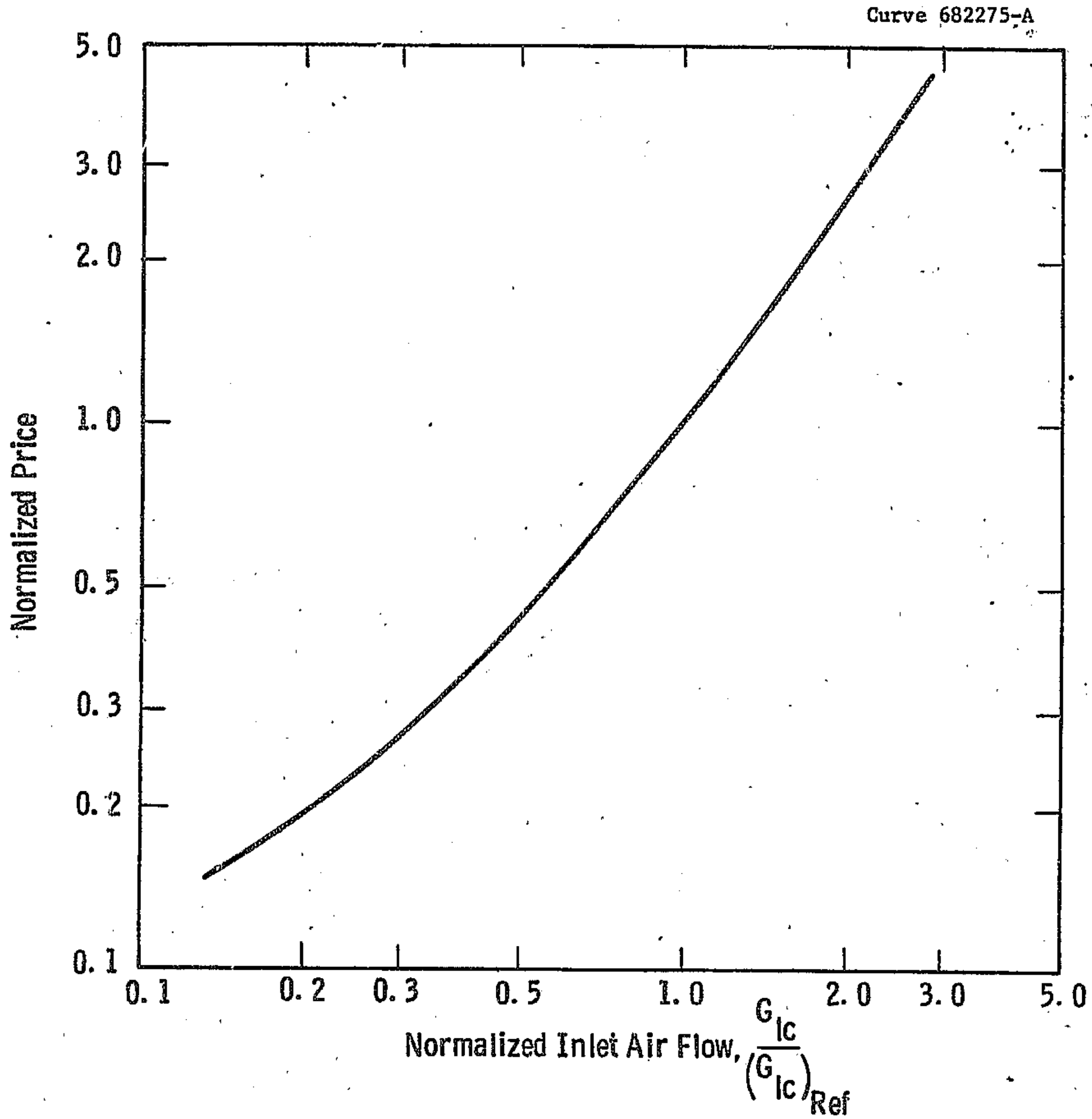


Fig. 5.28—Inlet manifold price

Curve 682278-A

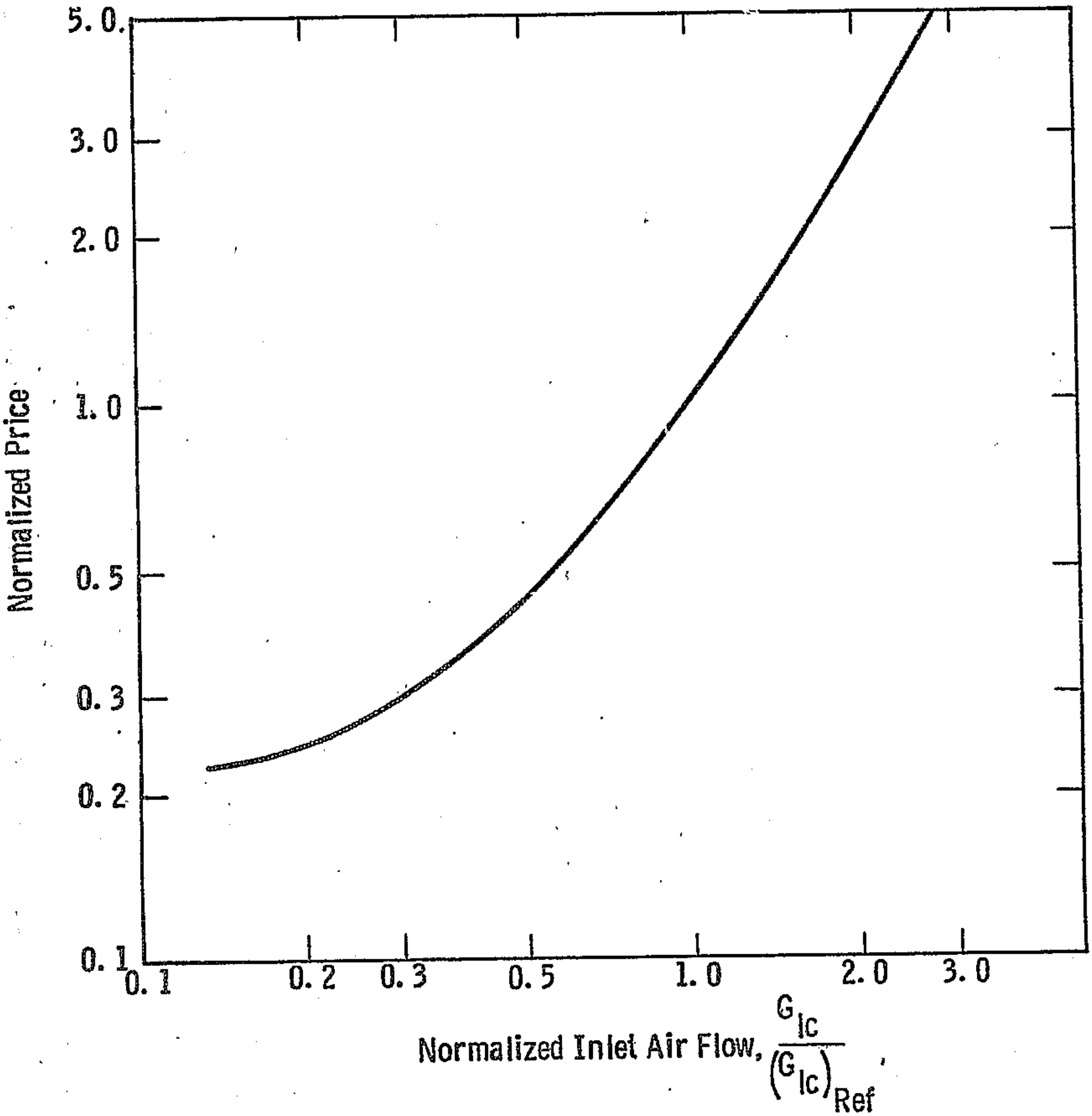


Fig.5.29— Inlet casing assembly price

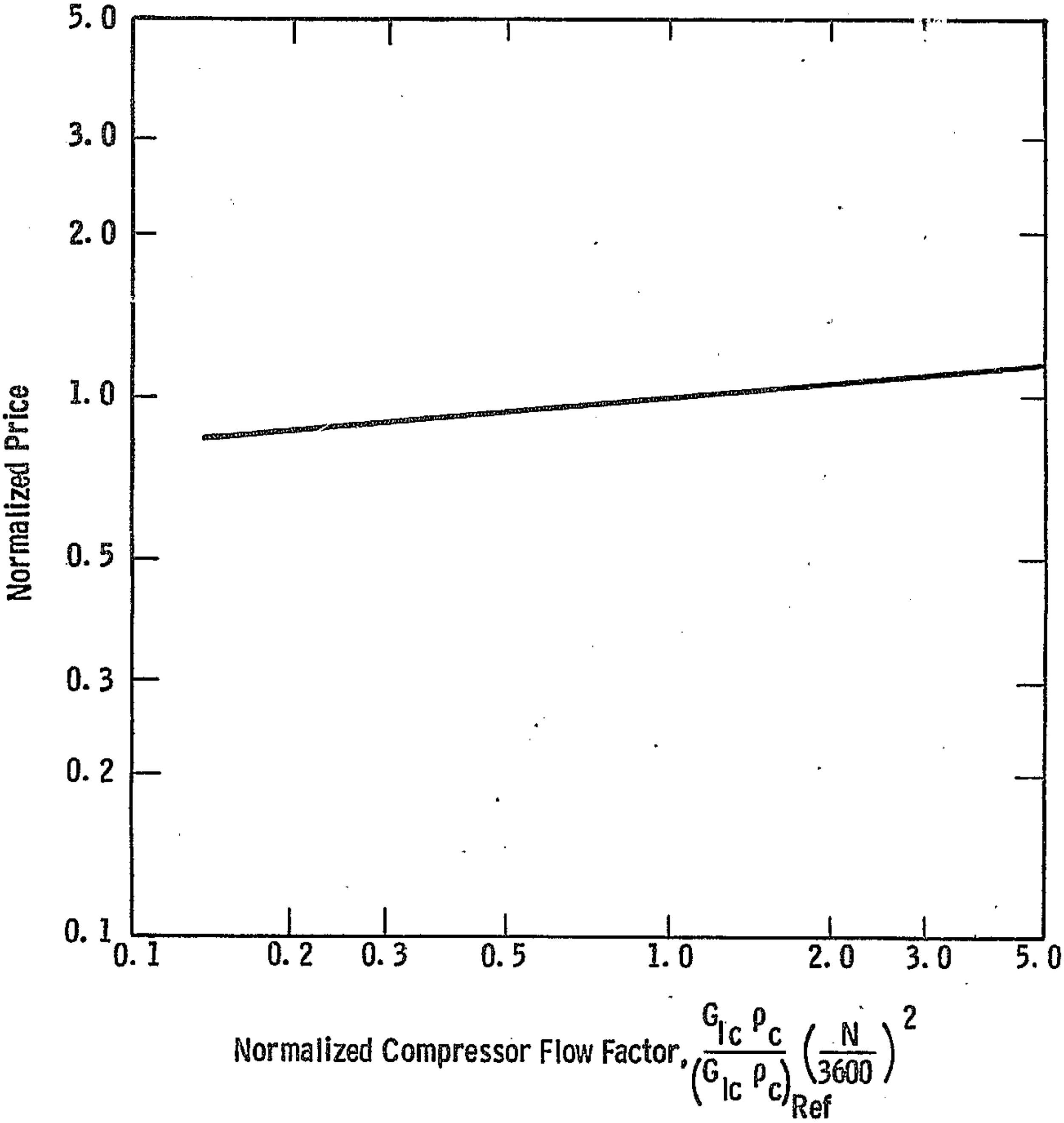


Fig.5. 30– Compressor-combustor section casing price

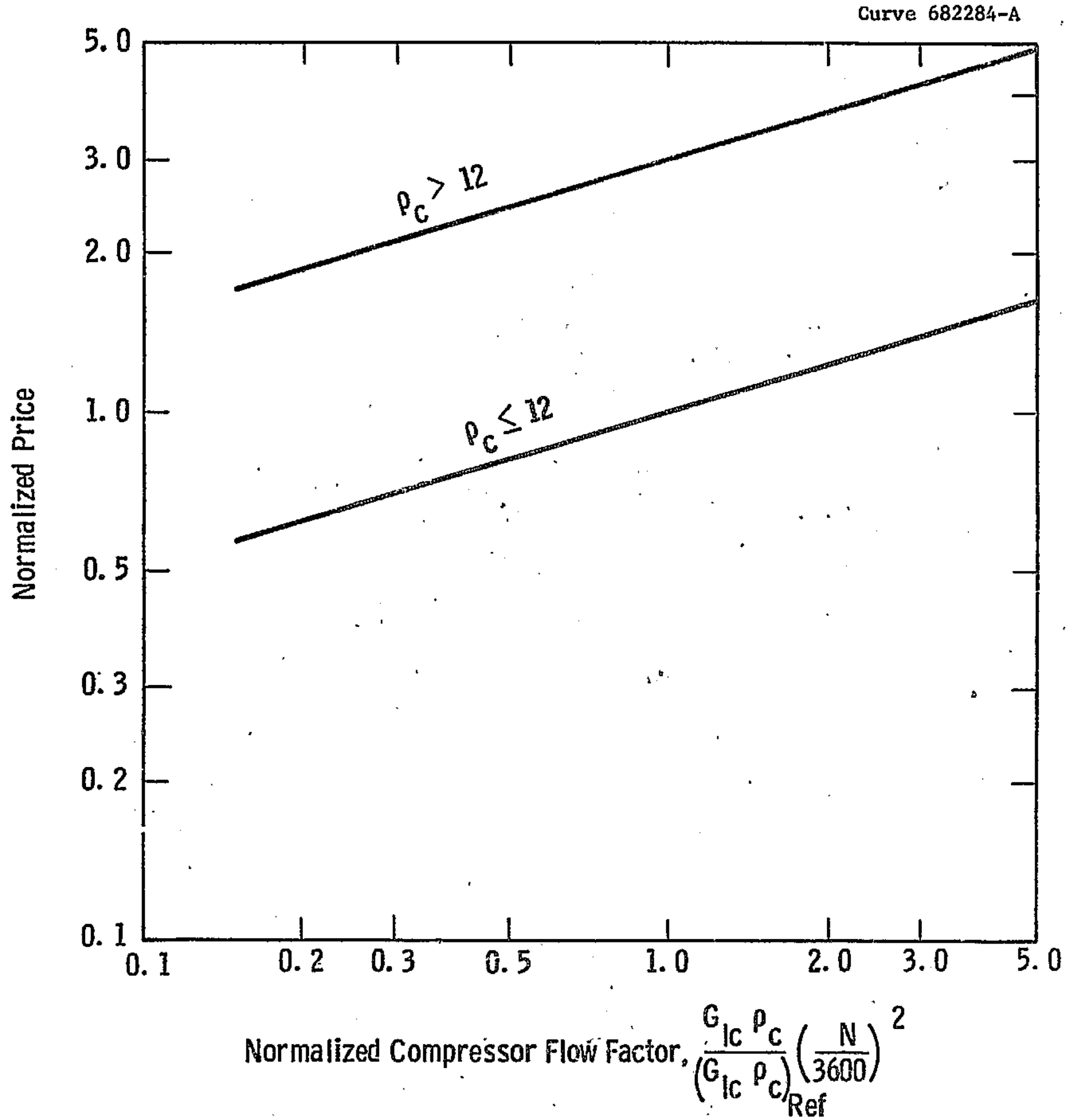


Fig. 5.31– Compressor stationary vane assemblies price

Curve 682279-A

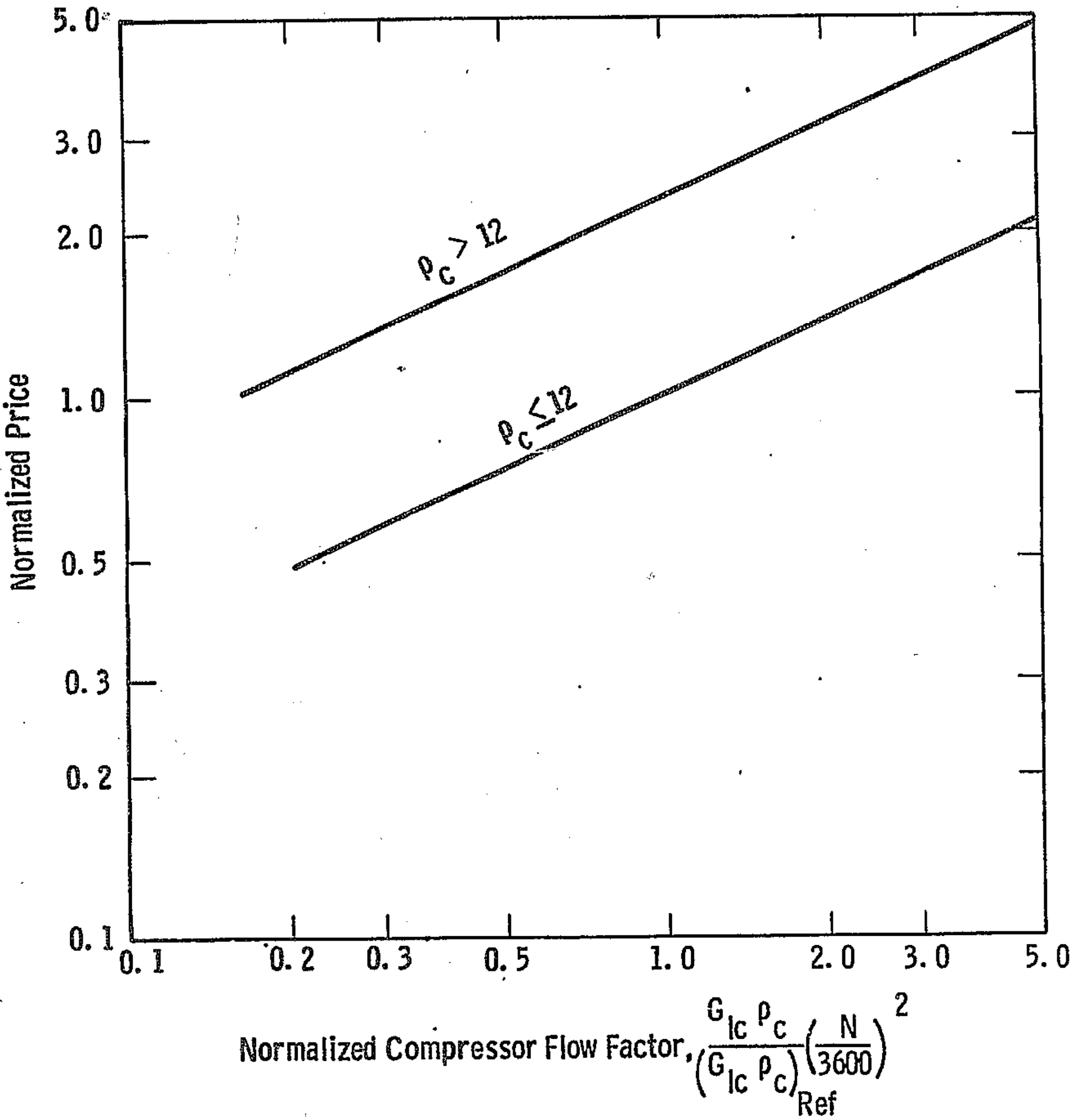


Fig. 5.32— Compressor rotating element price

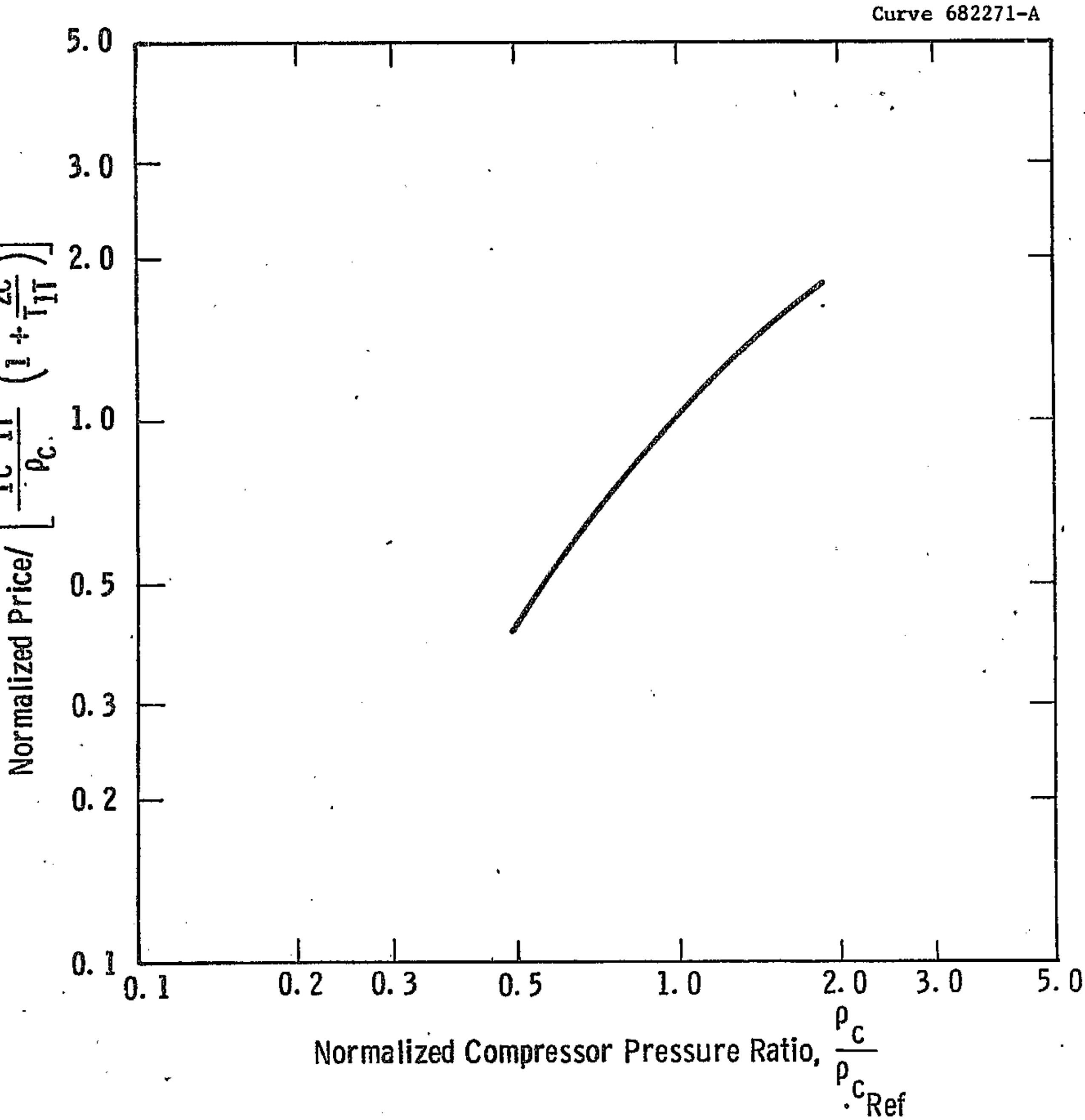


Fig. 5.33—Combustor assembly price

Curve 682281-A

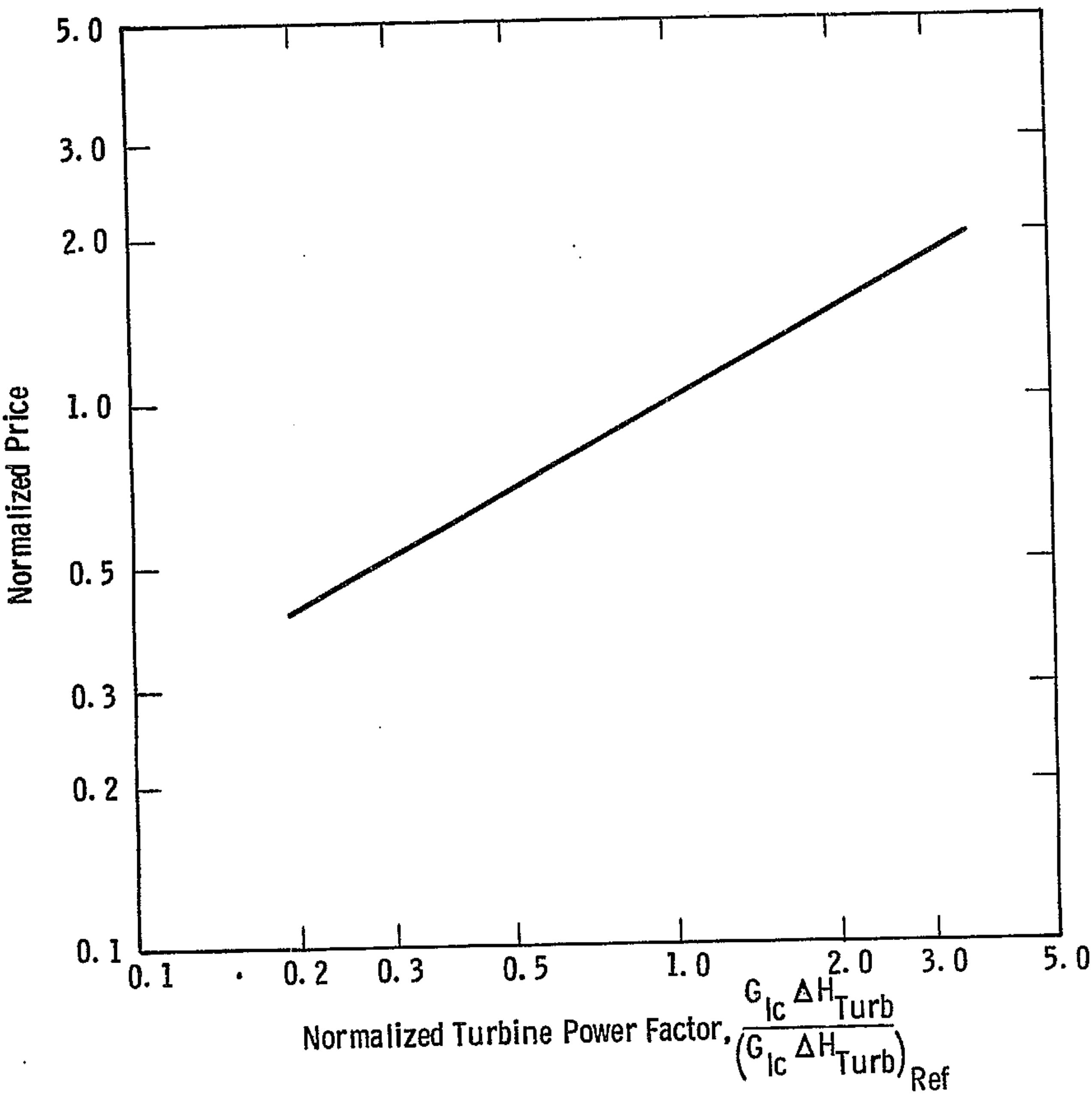


Fig. 5.34 – Turbine section casing price

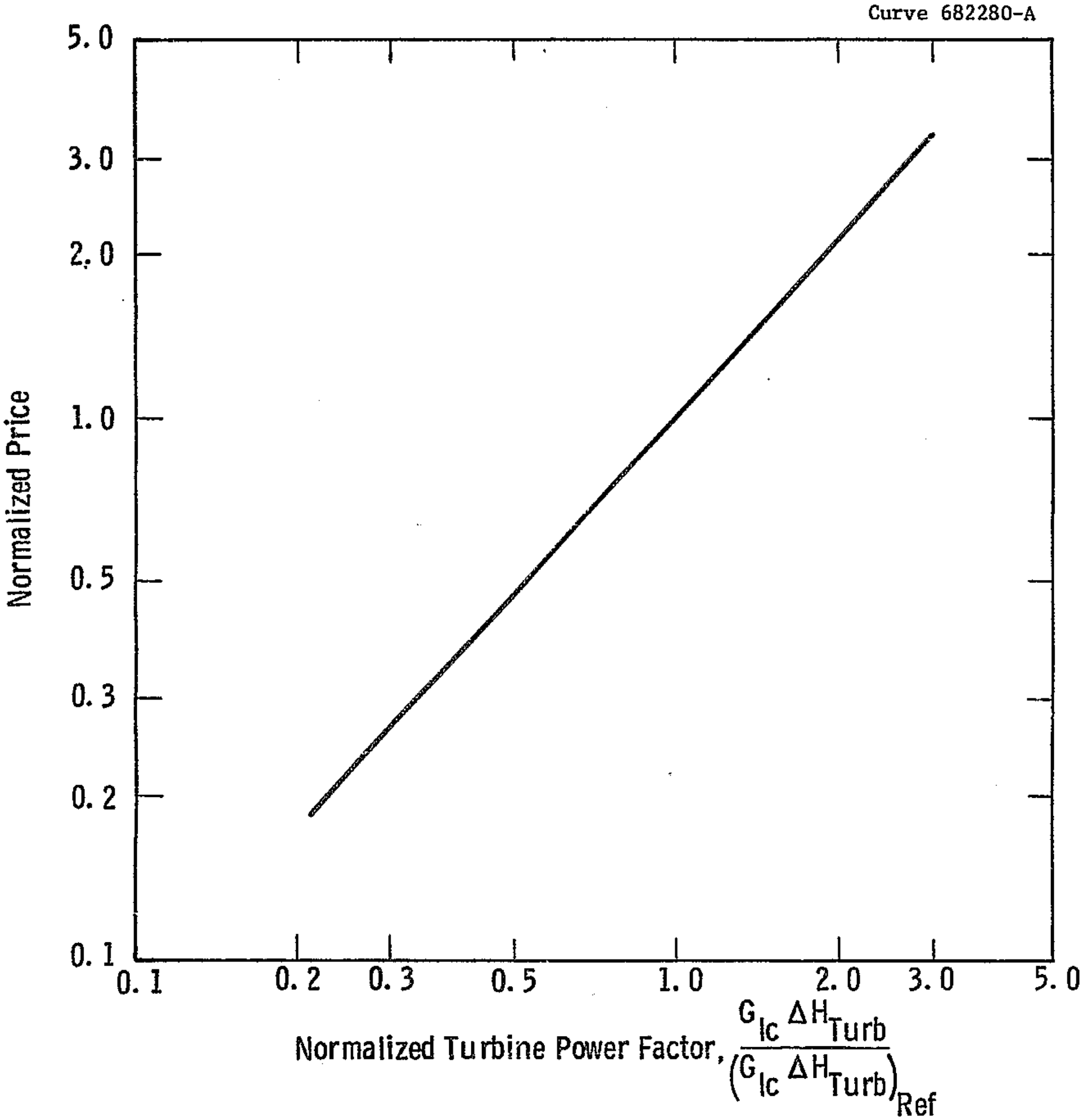


Fig.5.35—Turbine stationary vane assemblies price

Curve 682282-A

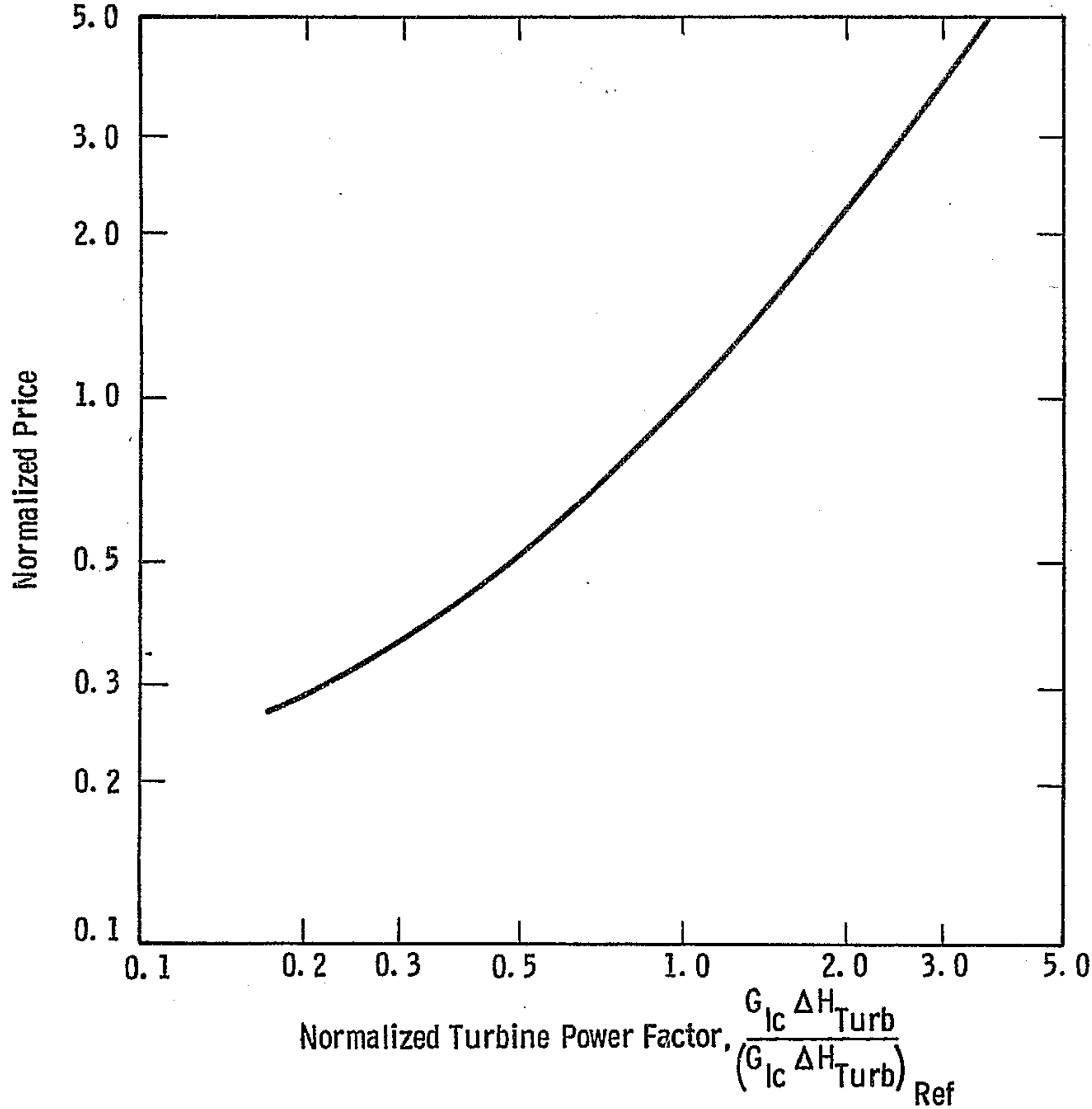


Fig.5.36 - Turbine rotating element price

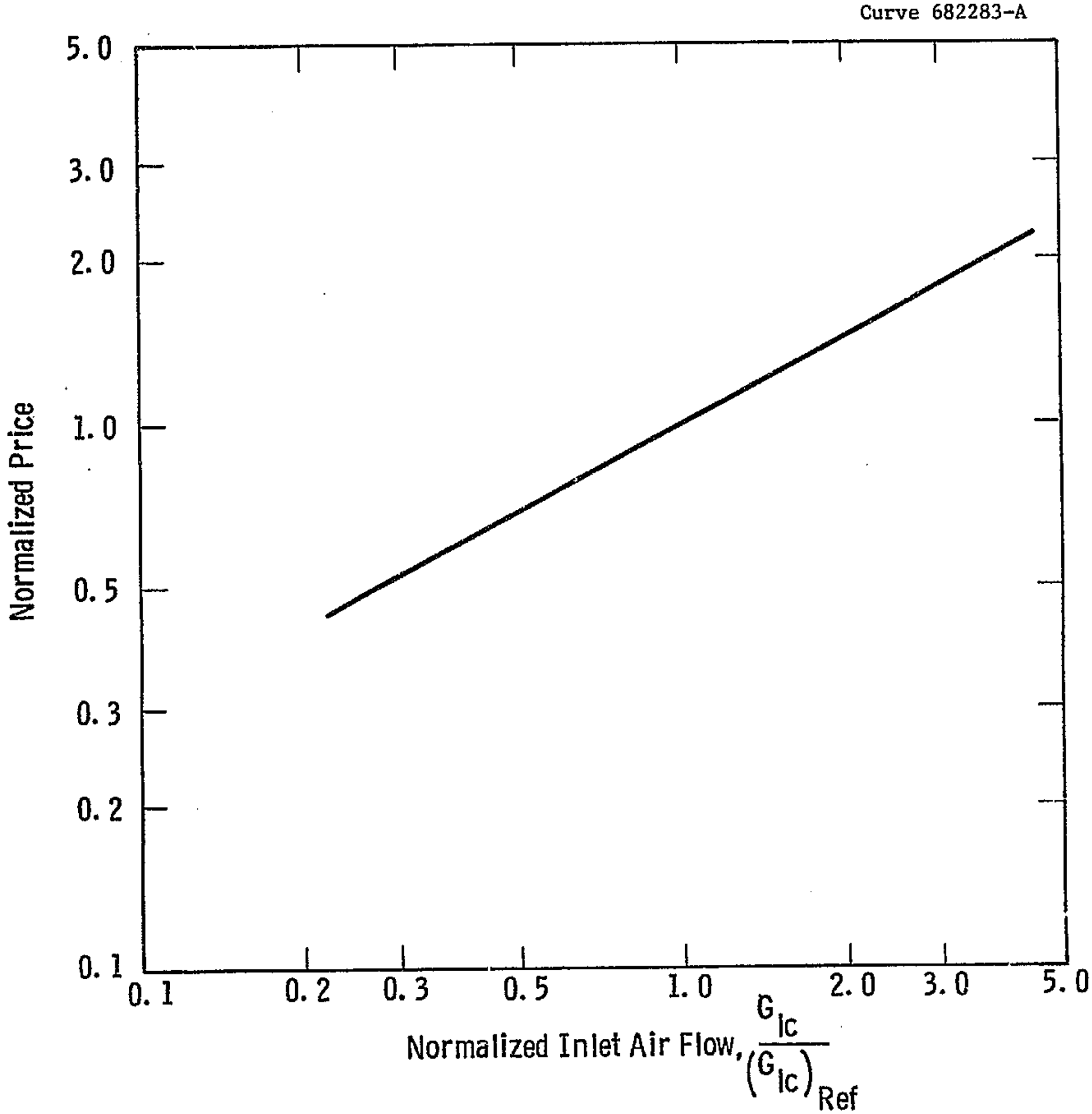


Fig.5.37—Turbine diffuser price

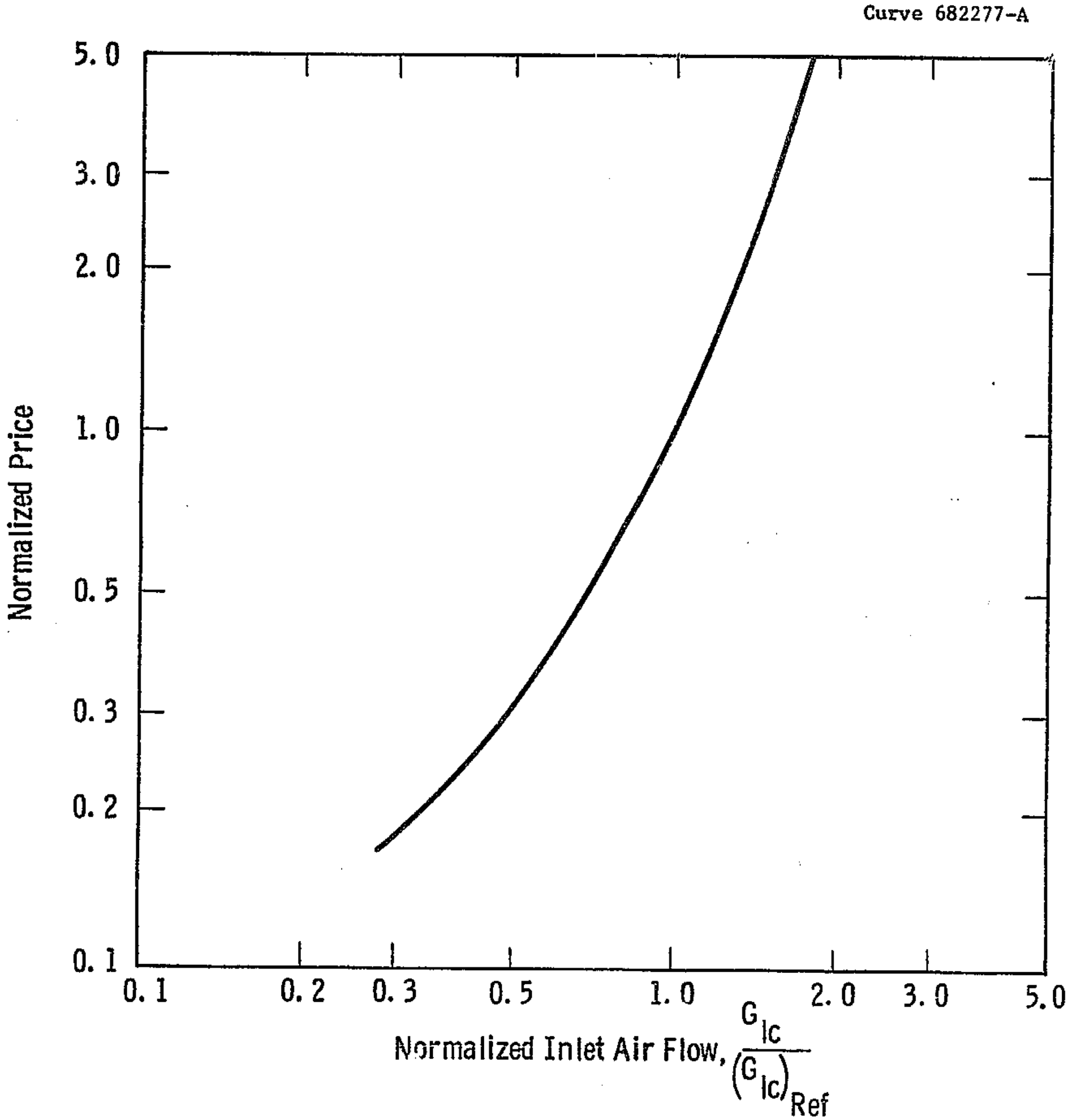


Fig. 5.38– Turbine exhaust manifold price

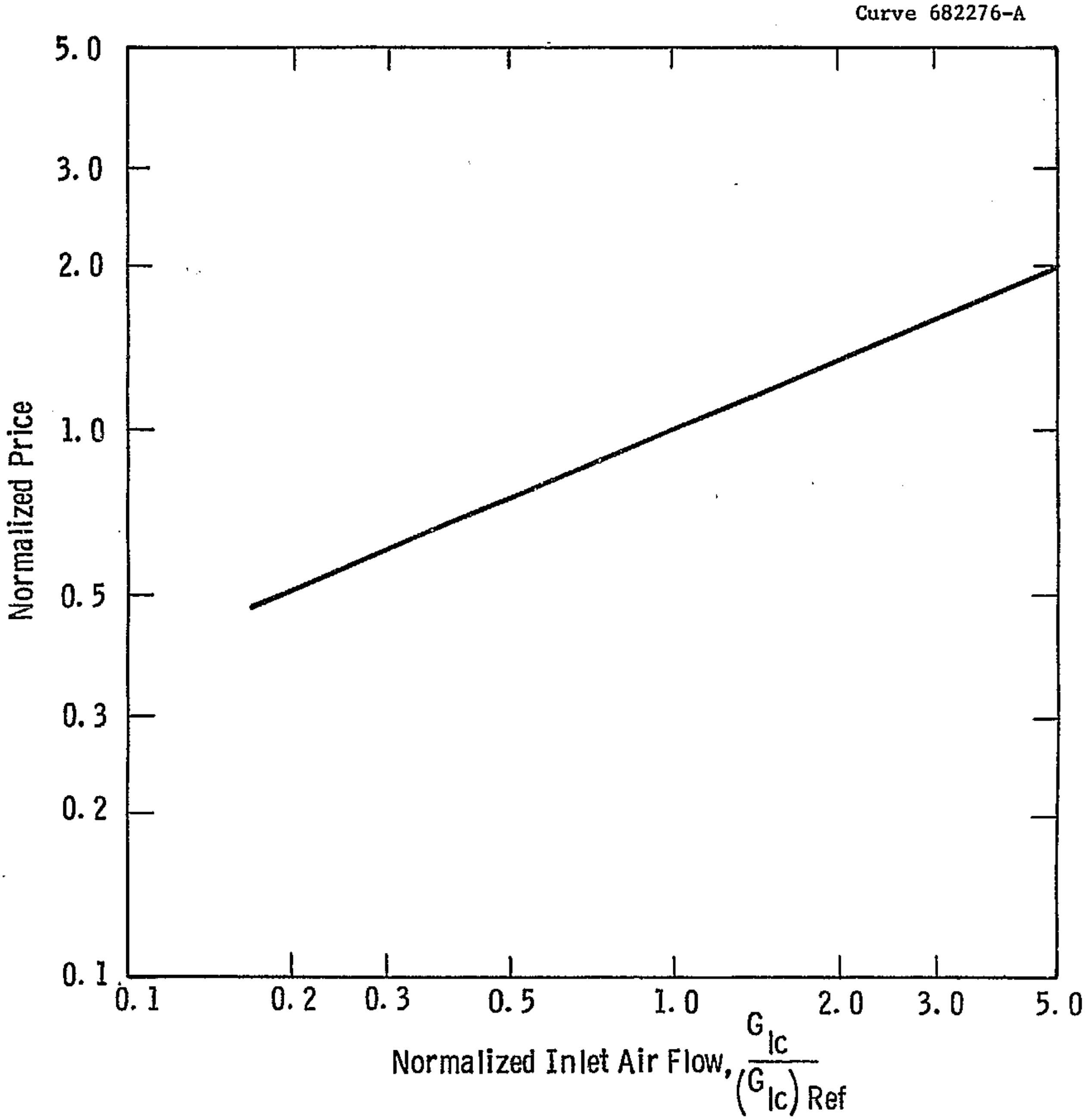


Fig. 5.39 - Turbine support system price

Curve 682272-A

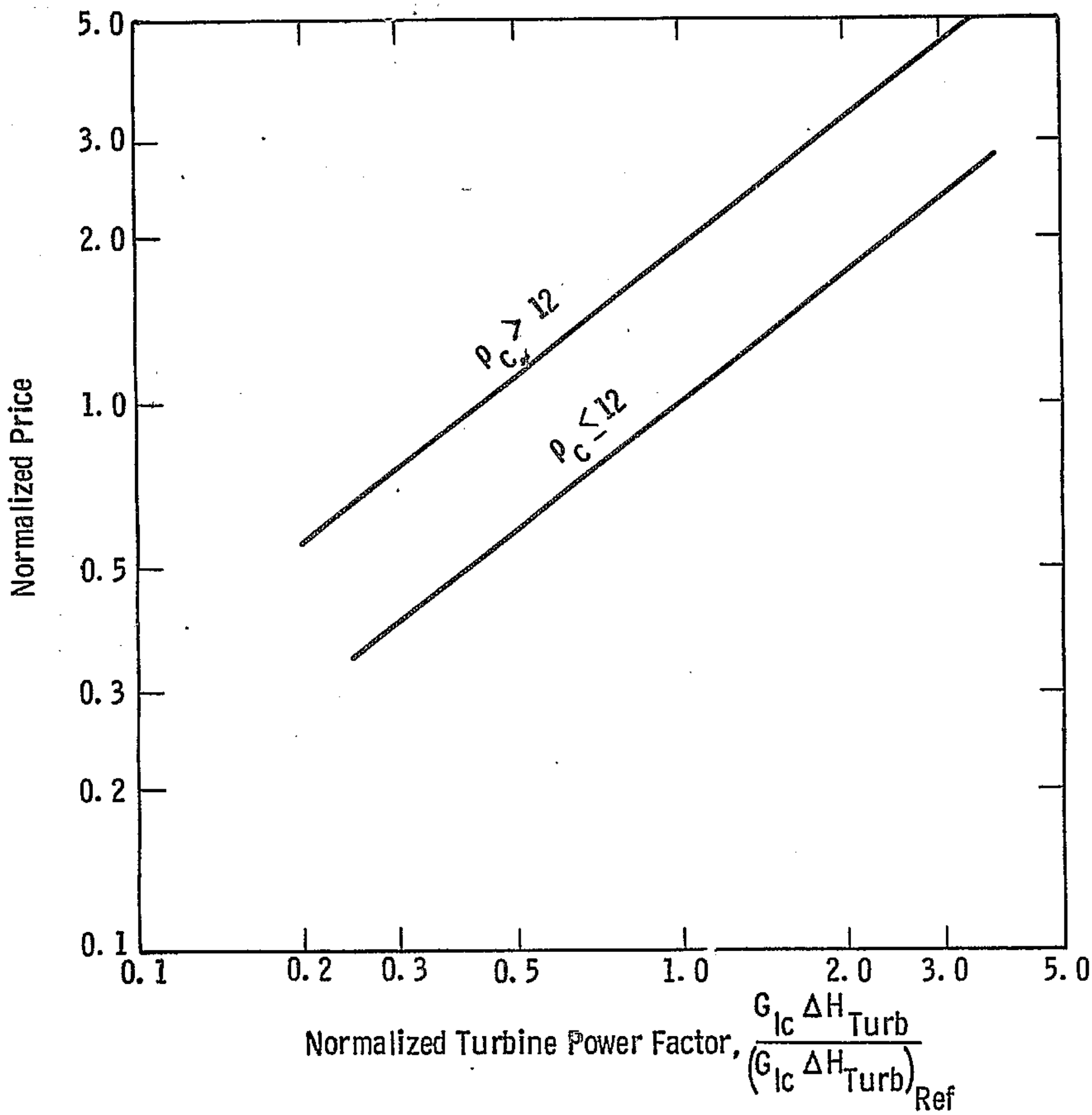


Fig.5.40— Price for assembly of complete rotating element

Curve 682285-A

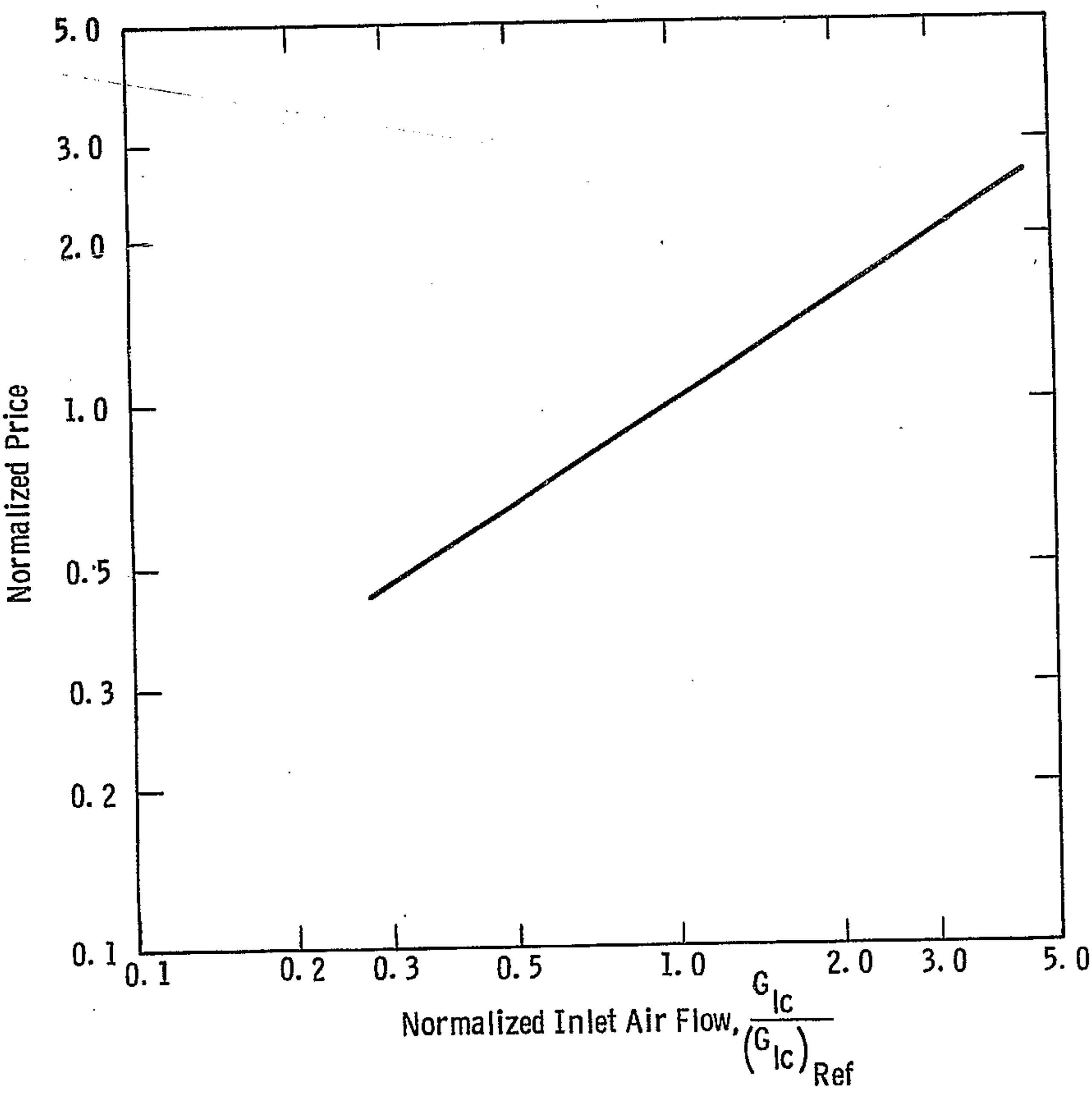


Fig. 5.41- Price for assembly of complete gas turbine

Curve 682274-A

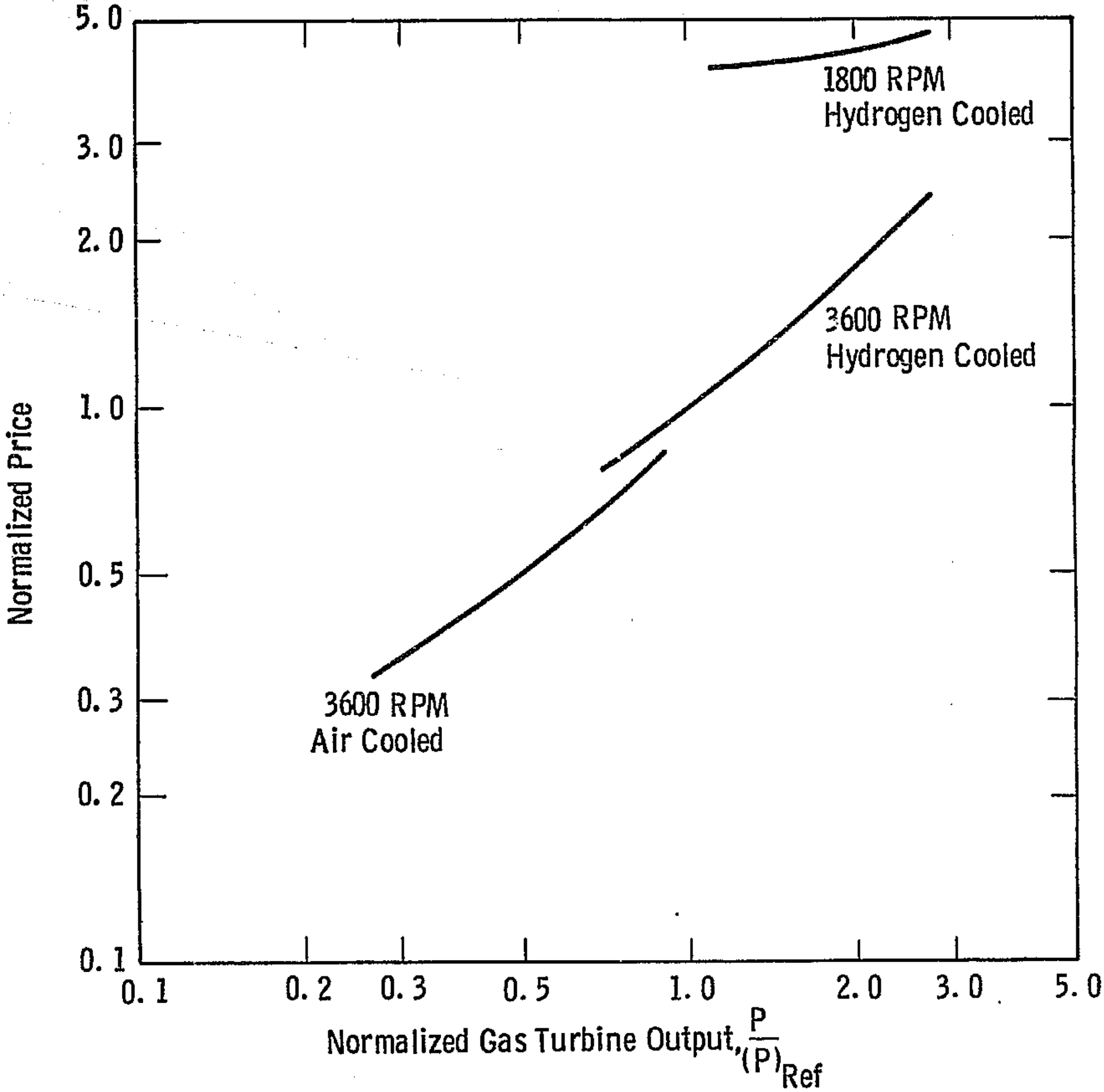


Fig. 5.42— Generator/ Exciter prices

Certain aspects of the price correlation curves are worthy of further description.

Dual curves, for different compressor pressure ratio ranges, are shown for pricing certain gas turbine elements. This representation was arbitrarily selected as an optimum means of reporting prices determined from manufacturing experience and conceptual design studies of these selected components. The price variations reflect fundamental changes in the design philosophy incorporated as pressure ratio is increased.

At higher pressure ratios, greater sensitivity to compressor surge or stall during start-up and higher operating temperatures at compressor discharge are encountered. Typical design approaches involve the use of higher-temperature alloys in the final compressor sections. In certain cases the use of variable stationary vanes or the use of a series compressor section arrangement is incorporated for higher pressure ratios. Such design changes can be identified as occurring in the range of pressure ratios 12 and 16 to 1; arbitrarily, the cutoff point for price representation was assumed to occur at a compressor pressure ratio of 12 to 1.

For the case of the compressor stationary vane assembly price, Figure 5.31, the higher price curve reflects changes in materials for high-temperature sections such as higher alloy vanes, shroud material, and changes in design such as the use of variable stationary vanes.

In the case of the compressor rotating elements price, as reported in Figure 5.32, the increased price reflects the higher-temperature alloys materials price and the generally increased complexity in design and manufacturing processes. Similar price effects are shown on the assembly cost of the rotating element, Figure 5.40, reflecting the increased complexity of assembling higher-pressure design rotating elements.

Figure 5.42 shows the form of price correlation used for gas turbine generators. The majority of parametric point calculations were

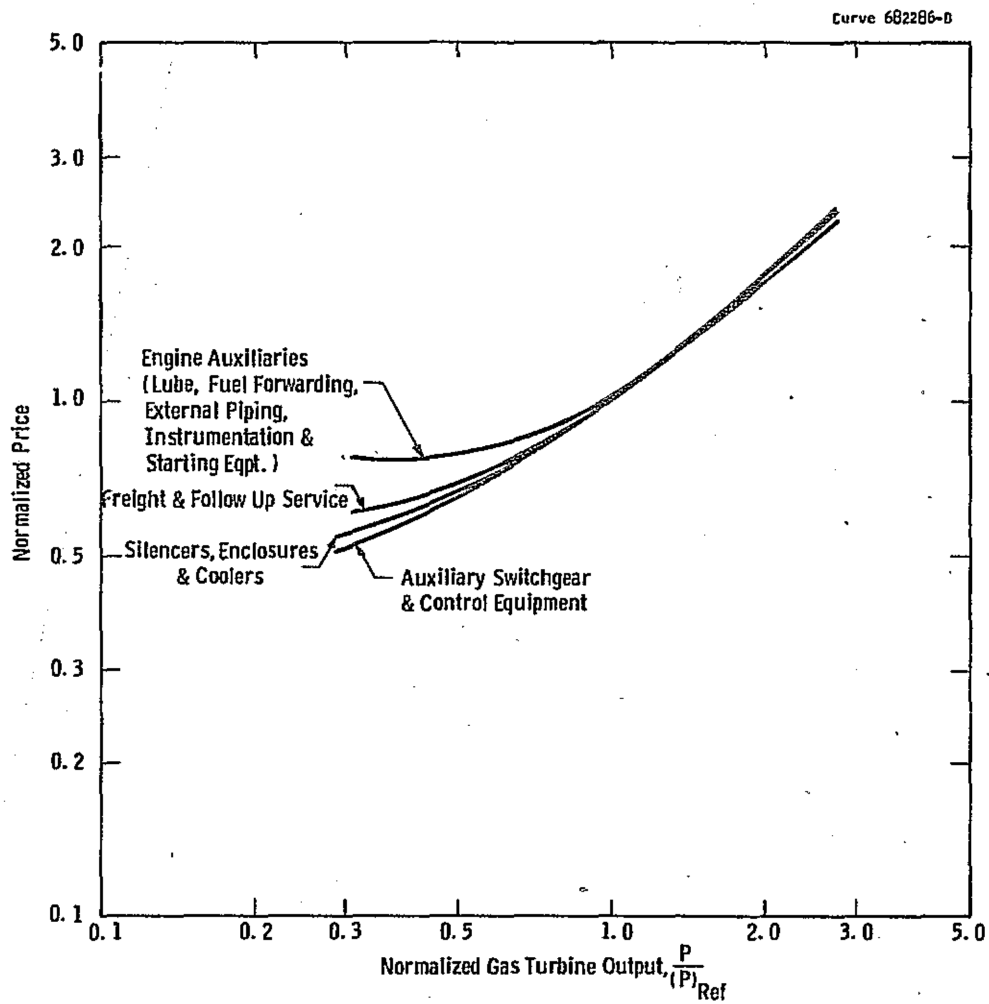


Fig. 5.43 – Plant accessories

made using the hydrogen-cooled 60 rps (3600 rpm) correlation. For certain calculations regarding the effect of gas turbine unit output on overall plant cost, the air-cooled 60 rps (3600 rpm) generator price relation was used. This type of unit is most often available commercially in the 25-to-75 MW size. Although shown at a slightly lower price, the units have a somewhat lower efficiency relative to hydrogen-cooled generators as a result of higher windage losses and other effects. A price correlation for 30 rps (1800 rpm) generator is also shown in Figure 5.42.

Figure 5.43 shows the pricing correlations used for the associated gas turbine plant auxiliaries.

Two investigations regarding the accuracy of the gas turbine price correlations were made. First, the degree of accuracy with which the price relations reproduced the original gas turbine price data was determined. The relations were found to be accurate to within 5% over the whole range of variables.

A second check was made to assess the validity of using the price relations for extrapolation beyond the range of data used in their generation. The relations were used to estimate the price of the conceptual design engine shown in Figure 5.44. This design, consisting of multiple compressor sections and separate power turbine, and projected to operate at a firing temperature of 1644°K (2500°F) and a compressor pressure ratio of 25 to 1, was independently priced by value engineering personnel. The price values from the correlations and independent estimation agreed to within approximately 10%.

Parametric price variation determination was implemented by curve fitting and computer calculation of the many individual parametric point values.

5.5.4 Gas Turbine Recuperator System Pricing

The recuperator system used in this study is based on an advanced plate-fin tension-braze design of the Airesearch Manufacturing Division of the Garrett Corporation (Reference 5.9). The approach used

Dwg. 6366A97

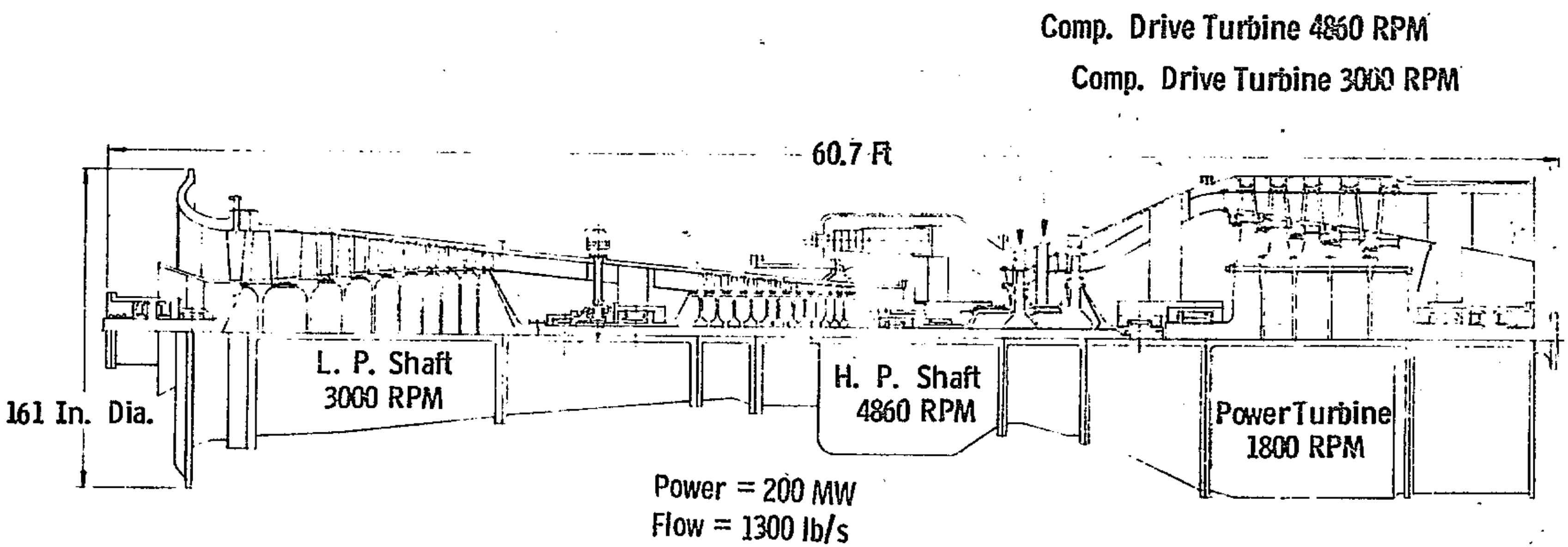


Fig. 5.44—Large Multiple Shaft Gas Turbine Engine

in expressing parametric price variation is summarized in Figure 5.45. This plot expresses the variation of weight and price as a function of pressure drop and effectiveness relative to the base recuperator for which an accurate price estimate has been made. For parametric point variations where turbine exhaust temperature is different from the base case value, the recuperator price is further modified relative to this value according to the relationship of Figure 5.46.

The recuperator piping system consists of carbon steel piping for the cold lines, 1-1/4 Cr alloy steel piping for the hot return lines, and an extensive system of bellows-type expansion joints.

5.5.5 Tabulation of Overall Plant Material and Installation Costs

The prices of major components were determined by the procedures previously described. Additional price estimates for balance of plant equipment was provided by Chas. T. Main, Inc. of Boston. The pricing of heat rejection equipment, including steam turbine condensers and cooling towers, was handled by means of parametric relations incorporated in the actual cost of the electricity calculation computer program (Section 2). The input used for these and other aspects of the calculation is summarized for the base case (Point 1) in Table 5.5. (Inclusion of this table is made for the sake of completeness only, as none of the recuperated open-cycle parametric points utilized steam bottoming cycles. Note also that the auxiliary power requirements of the recuperated-cycle tabulation have been set to zero, as the originally calculated plant powers and efficiencies had been calculated with auxiliary power allowances.)

The direct costs for materials (equipment) as well as estimates for installation costs were then tabulated according to account code listing (itemized by categories, e.g., 1.0 Site Development through 21.0 Stack-Gas Cleaning) for each parametric point.

Table 5.6 illustrates the detailed account listing for Point 1, the recuperated-cycle base case. The account listing gives first the

Curve 680316-B

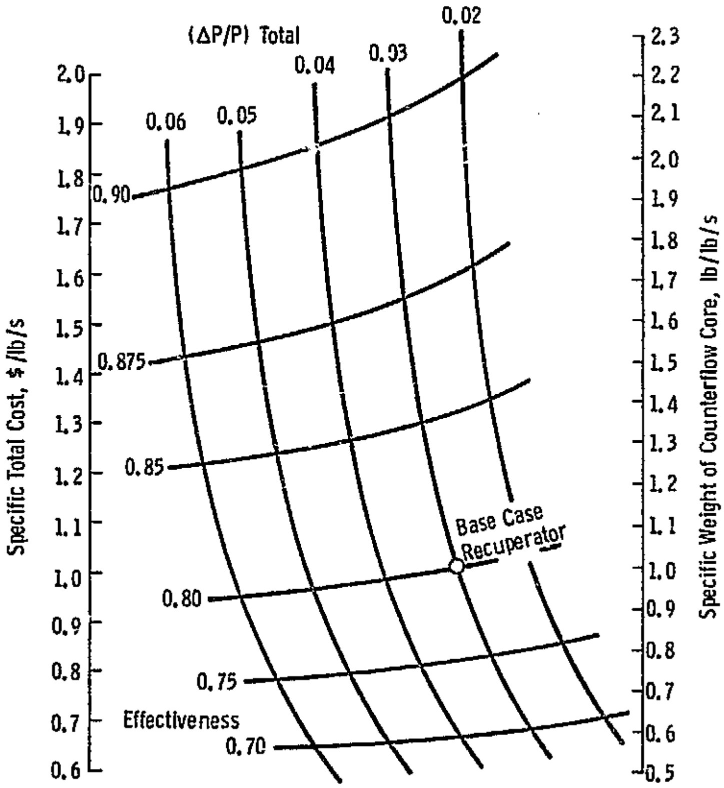


Fig. 5.45 — Parametric variation of plate-fin tension brazed recuperator sizes and weights relative to Base Case recuperator:
Effectiveness = 0.80
(ΔP/P) Total = 0.30

Curve 680266-A

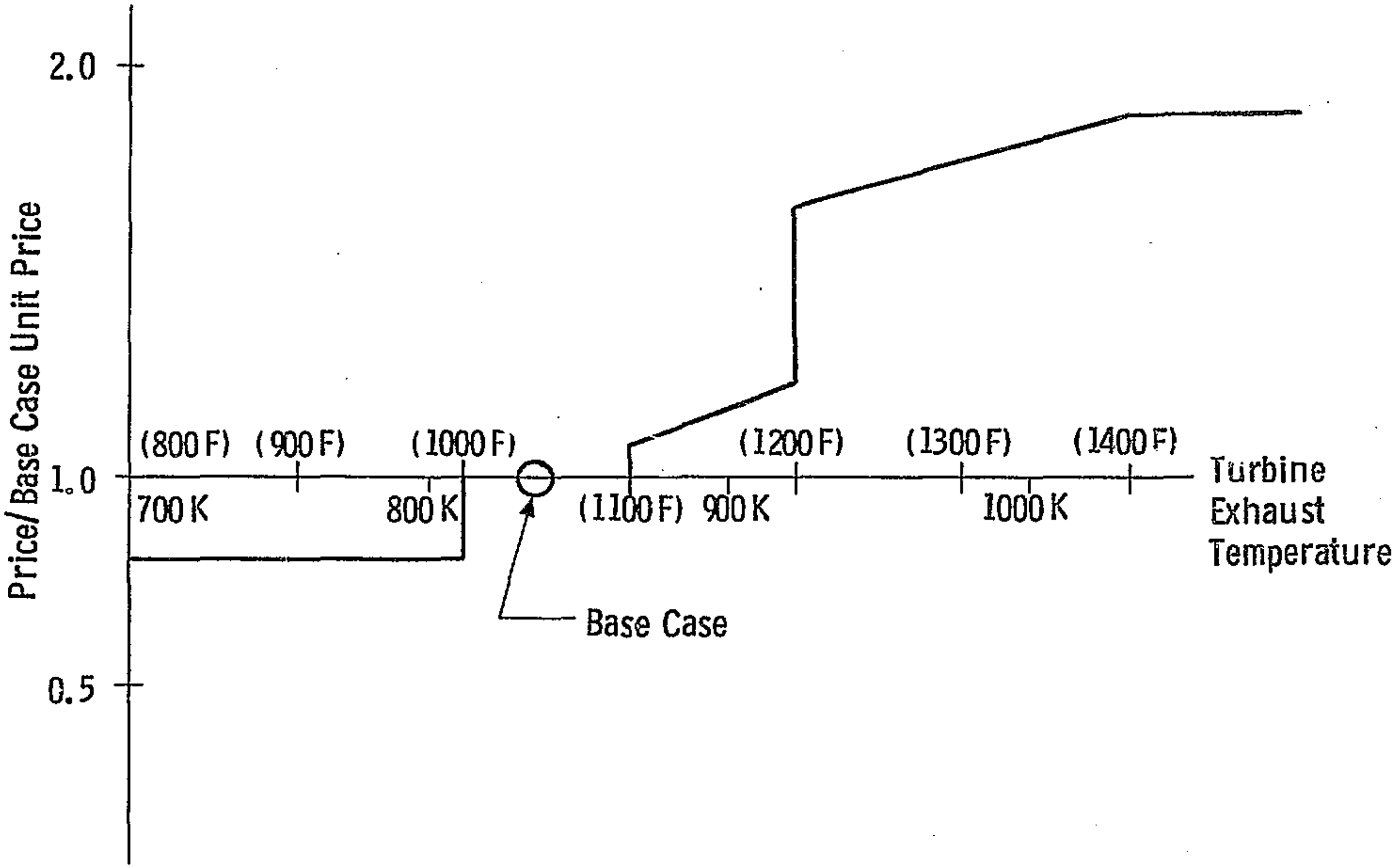


Fig. 5.46 —Recuperator price variation with turbine exhaust temperature

Table 5.5

OPEN CYCLE GAS TURBINE

ACCOUNT NO	AUX POWER, MWE	PERC PLANT POW	OPERATION COST	MAINTENANCE COST
TOTALS	.00000	.00000	.00000	.00000

OPEN CYCLE GAS TURBINE BASE CASE INPUT

NOMINAL POWER, MWE	394.8800	NET POWER, MWE	394.8800
NOM HEAT RATE, BTU/KW-HR	9033.2186	NET HEAT RATE, BTU/KW-HR	9033.2185
OFF DESIGN HEAT RATE	.0000		
CONDENSER			
DESIGN PRESSURE, IN HG A	.0000	NUMBER OF SHELLS	.0000
NUMBER OF TUBES/SHELL	.0000	TUBE LENGTH, FT	.0000
U, BTU/HR-FT2-F	.0000	TERMINAL TEMP DIFF, F	.0000
HEAT REJECTION			
DESIGN TEMP, F	.0000	APPROACH, F	.0000
RANGE, F	.0000	OFF DESIGN TEMP, F	.0000
OFF DESIGN PRES, IN HG A	.0000	LP TURBINE BLADE LEN, IN	.0000

1	98.720	2	.378	3	.000	4	.000	5	2.500
6	.000	7	.000	8	.000	9	.000	10	.000
11	.000	12	.000	13	1.000	14	1.000	15	.000
16	.000	17	40.000	18	4.000	19	.000	20	.000
21	1.000	22	4950.000	23	.000	24	600.000	25	.000
26	.000	27	6000.000	28	.000	29	8950000.000	30	.000
31	.300	32	60.000	33	.000	34	.200	35	.200
36	200000.000	37	.000	38	1.000	39	1.000	40	.000
41	.000	42	.000	43	.000	44	60000.000	45	36000.000
46	.000	47	.000	48	3.000	49	1.000	50	.000
51	.000	52	.000						

1	4.000	2	4.000	3	4.000	4	4.000	5	4.000
6	4.000	7	4.000	8	1026700.000	9	.050	10	307300.000
11	.050	12	2166900.000	13	.050	14	1168100.000	15	.140
16	2061200.000	17	.090	18	940700.000	19	.100	20	274700.000
21	.350	22	385000.000	23	231600.000	24	.000	25	4.000
26	1881100.000	27	.150	28	.000	29	4.000	30	.000

Table 5.6

OPEN CYCLE GAS TURBINE ACCOUNT LISTING
PARAMETRIC POINT NO. 1

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
SITE DEVELOPMENT						
1. 1 LAND COST	ACRE	40.0	10000.00	.00	400000.00	.00
1. 2 CLEARING LAND	ACRE	13.3	.00	600.00	.00	7999.20
1. 3 GRADING LAND	ACRE	40.0	.00	3000.00	.00	120000.00
1. 4 ACCESS RAILROAD	MILE	.0	115000.00	110000.00	.00	.00
1. 5 LOOP RAILROAD TRACK	MILE	.0	120000.00	70000.00	.00	.00
1. 6 SIDING R R TRACK	MILE	1.0	125000.00	80000.00	125000.00	80000.00
1. 7 OTHER SITE COSTS	ACRE	.0	.00	.00	95557.31	95557.31
PERCENT TOTAL DIRECT COST IN ACCOUNT 1 = 1.675 ACCOUNT TOTAL,$					620557.30	303556.51
EXCAVATION & PILING						
2. 1 COMMON EXCAVATION	YD3	14850.0	.00	3.00	.00	44550.00
2. 2 PILING	FT	33600.0	6.50	8.50	257400.00	336600.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 2 = 1.158 ACCOUNT TOTAL,$					257400.00	381150.00
PLANT ISLAND CONCRETE						
3. 1 PLANT IS. CONCRETE	YD3	4950.0	70.00	80.00	346500.00	396000.00
3. 2 SPECIAL STRUCTURES	YD3	.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 3 = 1.346 ACCOUNT TOTAL,$					346500.00	396000.00
HEAT REJECTION SYSTEM						
4. 1 COOLING TOWERS	EACH	.0	.00	.00	.00	.00
4. 2 CIRCULATING H2O SYS	EACH	.0	.00	.00	.00	.00
4. 3 SURFACE CONDENSER	FT2	.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 4 = .000 ACCOUNT TOTAL,$					.00	.00
STRUCTURAL FEATURES						
5. 1 STAT. STRUCTURAL ST.	TON	600.0	650.00	175.00	390000.00	105000.00
5. 2 SILOS & BUNKERS	TPH	.0	1800.00	750.00	.00	.00
5. 3 CHIMNEY	FT	.0	.00	.00	.00	.00
5. 4 STRUCTURAL FEATURES	EACH	1.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 5 = .897 ACCOUNT TOTAL,$					390000.00	105000.00
BUILDINGS						
6. 1 STATION BUILDINGS	FT3	.0	.16	.16	.00	.00
6. 2 ADMINSTRATION	FT2	6000.0	16.00	14.00	96000.00	84000.00
6. 3 WAREHOUSE & SHOP	FT2	.0	12.00	8.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 6 = .326 ACCOUNT TOTAL,$					96000.00	84000.00
FUEL HANDLING & STORAGE						
7. 1 COAL HANDLING SYS	TPH	.0	.00	.00	.00	.00
7. 2 DOLOMITE HAND. SYS	TPH	.0	.00	.00	.00	.00
7. 3 FUEL OIL HAND. SYS	GAL	8950000.0	.00	.00	809080.00	613051.83
PERCENT TOTAL DIRECT COST IN ACCOUNT 7 = 2.578 ACCOUNT TOTAL,$					809080.00	613051.87
FUEL PROCESSING						
8. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 8 = .000 ACCOUNT TOTAL,$					.00	.00

Table 5.6
Continued

OPEN CYCLE GAS TURBINE ACCOUNT LISTING
PARAMETRIC POINT NO. 1

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
FIRING SYSTEM						
9. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 9 = .000 ACCOUNT TOTAL,$					.00	.00
VAPOR GENERATOR (FIRED)						
10. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 10 = .000 ACCOUNT TOTAL,$					.00	.00
ENERGY CONVERTER						
11. 1 GAS TURB COMP SECT	EA	4.0	1026700.00	51335.00	4106800.00	205340.00
11. 2 GAS TURB COMB SECT	EA	4.0	307300.00	15365.00	1229200.00	61460.00
11. 3 GAS TURB TURB SECT	EA	4.0	2166900.00	108345.00	8667600.00	433380.00
11. 4 GAS TURB ENG AUX	EA	4.0	1168100.00	163534.00	4672400.00	654136.00
11. 5 GAS TURB GENERATOR	EA	4.0	2061200.00	185500.00	8244800.00	742031.99
11. 6 G T MUFFLER & COOLERS	EA	4.0	940700.00	94070.00	3762800.00	376280.00
11. 7 GAS TURB ENG MISC	EA	4.0	274700.00	96145.00	1098800.00	384580.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 11 =62.802 ACCOUNT TOTAL,$					31782400.00	2857207.94
COUPLING HEAT EXCHANGER						
12. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 12 = .000 ACCOUNT TOTAL,$					.00	.00
HEAT RECOVERY HEAT EXCH.						
13. 1 RECUPERATOR & PIPING	EA	4.0	1381100.00	282165.00	7524400.00	1128660.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 13 =15.688 ACCOUNT TOTAL,$					7524400.00	1128660.00
WATER TREATMENT						
14. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 14 = .000 ACCOUNT TOTAL,$					.00	.00
POWER CONDITIONING						
15. 1 STD TRANSFORMER	KVA	482631.1	.00	.00	2698623.56	53972.47
PERCENT TOTAL DIRECT COST IN ACCOUNT 15 = 4.991 ACCOUNT TOTAL,$					2698623.56	53972.47
AUXILIARY MECH EQUIPMENT						
16. 1 BOILER FEED PUMP &DR.	KWE	.0	.00	.00	.00	.00
16. 2 OTHER PUMPS	KWE	.0	.88	.12	.00	.07
16. 3 MISC SERVICE SYS	KWE	136740.2	1.17	.73	159986.07	99820.37
16. 4 AUXILIARY BOILER	PPH	.0	4.00	.80	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 16 = .471 ACCOUNT TOTAL,$					159986.07	99820.37
PIPE & FITTINGS						
17. 1 CONVENTIONAL PIPING	TON	60.0	3000.00	1800.00	180000.00	108000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 17 = .522 ACCOUNT TOTAL,$					180000.00	108000.00

Table 5.6
Continued

OPEN CYCLE GAS TURBINE ACCOUNT LISTING
PARAMETRIC POINT NO. 1

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
AUXILIARY ELEC EQUIPMENT						
18. 1 MISC MOTERS,ETC		91160.2	1.40	.17	127624.22	15497.23
18. 2 SWITCHGEAR & MCC PAN	KWE	91160.2	1.95	.45	1717762.30	256622.07
18. 3 CONDUIT,CABLES,TRAYS	FT	200000.0	1.32	1.36	254000.00	272000.00
18. 4 ISOLATED PHASE BUS	FT	.0	510.00	450.00	.00	.00
18. 5 LIGHTING & COMMUN	KWE	455900.8	.35	.43	159530.27	195994.33
PERCENT TOTAL DIRECT COST IN ACCOUNT 18 = 5.455 ACCOUNT TOTAL,$					2268916.72	740113.62
CONTROL, INSTRUMENTATION						
19. 1 COMPUTER	EACH	1.0	.00	.00	926400.00	129696.00
19. 2 OTHER CONTROLS	EACH	1.0	60000.00	36000.00	60000.00	36000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 19 = 2.039 ACCOUNT TOTAL,$					986400.00	165696.00
PROCESS WASTE SYSTEMS						
20. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 20 = .000 ACCOUNT TOTAL,$					.00	.00
STACK GAS CLEANING						
21. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 21 = .000 ACCOUNT TOTAL,$					.00	.00
TOTAL DIRECT COSTS,$					43120263.00	7036228.56

Table 5.7 OPEN CYCLE GAS TURBINE SUMMARY PLANT RESULTS

	PARAMETRIC POINT		1	2	3	4	5	6	7	8
	TOTAL CAPITAL COST	,M$	79.44	51.88	54.15	55.23	55.59	59.43	58.55	57.26
P	GAS TURBINE COMPRESSOR SECT	,M$	4.107	3.721	3.929	4.107	4.264	7.430	7.943	8.398
L	GAS TURBINE COMB BASKETS	,M$	1.229	.734	.841	.908	.951	.996	1.002	.980
A	GAS TURBINE TURBINE SECTION	,M$	8.669	6.096	6.576	6.935	7.213	7.681	7.978	8.212
N	MISC GAS TURBINE AUXILIARY	,M$	9.534	7.906	8.112	8.151	8.089	7.818	7.450	7.061
T	GAS TURBINE GENERATOR	,M$	8.245	6.589	6.804	6.944	6.780	6.494	6.101	5.674
	RECUPERATOR & PIPING SYSTEM	,M$	7.524	.000	.000	.000	.000	.000	.000	.000
R	TOT MAJOR COMPONENT COST	,M$	39.307	25.036	25.262	26.945	27.297	30.419	30.474	30.325
E	TOT MAJOR COMPONENT COST	,$/KWE	99.541	87.123	87.076	88.566	90.989	108.190	119.564	134.371
S	BALANCE OF PLANT COST	,$/KWE	22.319	24.225	23.629	23.524	23.694	24.500	25.826	27.686
U	SITE LABOR	,$/KWE	17.819	15.630	15.421	15.459	15.639	16.779	17.802	19.163
L	TOTAL DIRECT COST	,$/KWE	139.679	126.977	125.125	127.549	130.323	149.470	163.192	181.220
T	INDIRECT COSTS	,$/KWE	9.088	7.971	7.804	7.884	7.976	8.557	9.079	9.773
	PROF & OWNER COSTS	,$/KWE	11.174	10.158	10.090	10.204	10.426	11.358	13.055	14.498
B	CONTINGENCY COST	,$/KWE	7.682	6.812	6.792	6.873	7.015	8.005	8.675	9.545
R	ESCALATION COST	,$/KWE	16.295	13.930	13.957	14.131	14.393	16.255	17.401	18.862
E	INT DURING CONSTRUCTION	,$/KWE	17.255	14.684	14.722	14.908	15.181	17.129	18.312	19.817
A	TOTAL CAPITALIZATION	,$/KWE	201.173	180.532	179.551	181.549	195.314	211.374	229.719	253.715
K	COST OF ELEC-CAPITAL	,MILLS/KWE	6.360	5.707	5.676	5.739	5.858	6.682	7.262	8.020
D	COST OF ELEC-FUEL	,MILLS/KWE	23.486	35.779	32.137	30.131	29.121	28.317	28.586	29.597
O	COST OF ELEC-OP&MAIN	,MILLS/KWE	.715	.715	.715	.715	.715	.715	.715	.715
W	TOTAL COST OF ELEC	,MILLS/KWE	30.561	42.201	38.529	36.646	35.694	35.710	36.563	38.333
N	COE 0.5 CAP. FACTOR	,MILLS/KWE	32.594	44.038	40.356	38.492	37.577	37.839	38.866	40.869
	COE 0.9 CAP. FACTOR	,MILLS/KWE	29.283	41.046	37.379	35.484	34.511	34.372	35.116	35.794
	COE 1.2XCAP. COST	,MILLS/KWE	31.833	43.347	39.664	37.793	36.866	37.046	38.010	39.937
	COE 1.2XFUEL COST	,MILLS/KWE	35.259	49.357	44.956	42.684	41.519	41.372	42.281	44.252
	COE (CONTINGENCY=0)	,MILLS/KWE	30.270	41.945	38.273	36.387	35.421	35.409	36.239	37.977
	COE (ESCALATION=0)	,MILLS/KWE	30.005	41.728	39.054	36.165	35.205	35.157	35.973	37.693

	PARAMETRIC POINT		9	10	11	12	13	14	15	16
	TOTAL CAPITAL COST	,M$	58.53	60.05	60.73	65.05	64.55	63.38	64.39	66.63
P	GAS TURBINE COMPRESSOR SECT	,M$	3.929	4.107	4.264	7.430	7.943	8.398	3.929	4.107
L	GAS TURBINE COMB BASKETS	,M$	.893	.962	1.007	1.052	1.057	1.032	.945	1.017
A	GAS TURBINE TURBINE SECTION	,M$	6.983	7.274	7.575	8.092	8.409	8.660	8.286	8.771
N	MISC GAS TURBINE AUXILIARY	,M$	8.842	8.956	8.947	8.738	8.407	8.015	9.569	9.760
T	GAS TURBINE GENERATOR	,M$	7.553	7.668	7.658	7.447	7.109	6.702	8.279	8.466
	RECUPERATOR & PIPING SYSTEM	,M$	.000	.000	.000	.000	.000	.000	.000	.000
R	TOT MAJOR COMPONENT COST	,M$	28.100	28.968	29.451	32.750	32.924	32.809	31.007	32.122
E	TOT MAJOR COMPONENT COST	,$/KWE	80.194	80.952	82.450	95.325	102.390	111.246	78.096	78.499
S	BALANCE OF PLANT COST	,$/KWE	21.947	21.731	21.750	22.156	22.882	23.902	20.719	20.491
U	SITE LABOR	,$/KWE	14.487	14.448	14.530	15.317	15.925	16.724	13.945	13.865
L	TOTAL DIRECT COST	,$/KWE	116.628	117.131	118.730	132.799	141.197	151.872	112.759	112.809
T	INDIRECT COSTS	,$/KWE	7.388	7.369	7.410	7.812	8.122	8.529	7.112	7.071
	PROF & OWNER COSTS	,$/KWE	9.330	9.370	9.498	10.624	11.296	12.150	9.021	9.024
B	CONTINGENCY COST	,$/KWE	6.354	6.392	6.478	7.224	7.641	8.164	6.204	6.222
R	ESCALATION COST	,$/KWE	13.285	13.390	13.553	15.019	15.750	16.649	13.146	13.222
E	INT DURING CONSTRUCTION	,$/KWE	14.043	14.159	14.341	15.867	16.628	17.557	13.922	14.008
A	TOTAL CAPITALIZATION	,$/KWE	167.030	167.811	170.020	189.339	200.634	214.921	162.153	162.351
K	COST OF ELEC-CAPITAL	,MILLS/KWE	5.280	5.305	5.375	5.985	6.242	6.794	5.126	5.172
D	COST OF ELEC-FUEL	,MILLS/KWE	31.758	29.706	28.531	27.946	27.268	27.695	31.555	29.930
O	COST OF ELEC-OP&MAIN	,MILLS/KWE	.715	.715	.715	.715	.715	.715	.715	.715
W	TOTAL COST OF ELEC	,MILLS/KWE	37.753	35.726	34.621	34.196	34.326	35.195	37.396	35.278
N	COE 0.5 CAP. FACTOR	,MILLS/KWE	39.462	37.442	36.358	36.067	36.354	37.358	39.059	36.942
	COE 0.9 CAP. FACTOR	,MILLS/KWE	36.673	34.646	33.529	32.939	33.052	33.836	36.350	34.230
	COE 1.2XCAP. COST	,MILLS/KWE	38.809	36.787	35.696	35.343	35.595	36.554	38.422	36.309
	COE 1.2XFUEL COST	,MILLS/KWE	44.105	41.667	40.327	39.635	39.780	40.732	43.707	41.164
	COE (CONTINGENCY=0)	,MILLS/KWE	37.513	35.484	34.376	33.874	34.038	34.888	37.161	35.091
	COE (ESCALATION=0)	,MILLS/KWE	37.301	35.270	34.159	33.635	33.790	34.629	36.947	34.826

unit measure and quantity for each item, followed by the unit cost and unit installation cost, and finally the total equipment and installation cost. At the end of each account section is listed the percent of the total equipment and installation cost contained within that account.

Similar cost tabulations were provided to NASA Lewis Research for the remaining parametric points. Only the summary sheets are included here as Table 5.7. In this tabulation, major component (e.g., gas turbine compressor, combustor, turbine section, etc.) total direct material costs are itemized for each parametric point. Additional information tabulated includes those remaining costs going to make up the total plant cost.

These are each expressed on a dollar per kilowatt basis. Note that line 1, "Total Capital Cost," for each point expresses the total cost on a straight dollar basis for the categories making up the total plant cost, namely the costs of:

- Total direct major component material
- Balance of plant direct material
- Site labor
- Indirect expenses
- Professional services and ownership costs
- Contingency
- Escalation
- Interest during construction.

Cost of electricity data for each parametric point are given in this tabulation and list the breakdown with respect to capital, fuel, and operating and maintenance costs; as well as the effect of selected parameters on the cost of electricity.

Table 5.7
Continued

OPEN CYCLE GAS TURBINE SUMMARY, PLANT RESULTS

	PARAMETRIC POINT	17	18	19	20	21	22	23	24
	TOTAL CAPITAL COST ,M$	65.73	70.55	70.29	69.44	70.59	73.28	74.85	80.52
P	GAS TURBINE COMPRESSOR SECT,M$	4.254	7.430	7.943	8.398	3.929	4.107	4.264	7.430
L	GAS TURBINE COMB BASKETS ,M$	1.063	1.109	1.113	1.085	1.022	1.099	1.147	1.194
A	GAS TURBINE TURBINE SECTION,M$	7.924	8.471	8.820	9.096	9.769	9.307	9.724	10.412
N	MISC GAS TURBINE AUXILIARY ,M$	9.807	9.674	9.378	9.015	10.640	10.949	11.083	11.067
T	GAS TURBINE GENERATOR ,M$	3.513	8.383	8.089	7.728	3.326	9.614	9.741	9.726
	RECUPERATOR & PIPING SYSTEM,M$	.000	.000	.000	.000	.000	.000	.000	.000
R	TOT MAJOR COMPONENT COST ,M$	31.571	35.068	35.342	35.322	33.680	35.076	35.959	39.830
E	TOT MAJOR COMPONENT COST,$/KWE	76.628	86.887	91.818	97.661	72.712	72.808	73.422	81.485
S	BALANCE OF PLANT COST ,$/KWE	20.391	20.560	21.009	21.621	19.391	19.083	18.958	18.973
U	SITE LABOR ,$/KWE	13.750	14.331	14.725	15.245	13.195	13.088	13.073	13.481
L	TOTAL DIRECT COST ,$/KWE	110.760	121.785	127.562	134.527	105.297	104.979	105.452	113.939
T	INDIRECT COSTS ,$/KWE	7.013	7.309	7.515	7.775	6.730	6.675	6.667	6.875
	PROF & OWNER COSTS ,$/KWE	8.961	9.743	10.205	10.762	9.424	8.398	9.430	9.115
B	CONTINGENCY COST ,$/KWE	6.112	6.710	7.002	7.348	5.866	5.867	5.901	6.375
R	ESCALATION COST ,$/KWE	13.006	14.206	14.734	15.344	12.646	12.698	12.791	13.782
E	INT DURING CONSTRUCTION ,$/KWE	13.781	15.048	15.597	16.227	13.423	13.486	13.588	14.641
A	TOTAL CAPITALIZATION ,$/KWE	159.532	174.801	182.614	191.982	152.386	152.103	152.836	164.728
K	COST OF ELEC-CAPITAL ,MILLS/KWE	5.043	5.526	5.773	6.069	4.817	4.808	4.831	5.207
D	COST OF ELEC-FUEL ,MILLS/KWE	28.179	26.888	26.511	26.590	31.454	29.255	27.912	26.471
O	COST OF ELEC-OP&MAIN,MILLS/KWE	.715	.715	.715	.715	.715	.715	.715	.715
W	TOTAL COST OF ELEC ,MILLS/KWE	33.930	33.130	32.999	33.375	36.987	34.779	33.459	32.394
N	COE 0.5 CAP. FACTOR ,MILLS/KWE	35.574	34.912	34.055	35.320	38.556	36.346	35.033	34.081
	COE 0.8 CAP. FACTOR ,MILLS/KWE	32.905	32.008	31.831	32.151	35.998	33.792	32.467	31.332
	COE 1.2XCAP. COST ,MILLS/KWE	34.945	34.235	34.154	34.588	37.950	35.741	34.425	33.435
	COE 1.2XFUEL COST ,MILLS/KWE	39.572	38.507	39.301	38.693	43.277	40.630	39.041	37.688
	COE (CONTINGENCY=0) ,MILLS/KWE	33.704	32.875	32.734	33.097	36.763	34.555	33.233	32.150
	COE (ESCALATION=0) ,MILLS/KWE	33.492	32.644	32.496	32.851	36.554	34.344	33.021	31.922

	PARAMETRIC POINT	25	26	27	28	29	30	31	32
	TOTAL CAPITAL COST ,M$	78.69	78.14	64.27	67.19	66.03	66.47	71.62	72.99
P	GAS TURBINE COMPRESSOR SECT,M$	7.943	8.398	3.721	3.929	4.107	4.264	3.929	4.107
L	GAS TURBINE COMB BASKETS ,M$	1.196	1.165	.938	1.050	1.120	1.167	1.102	1.175
A	GAS TURBINE TURBINE SECTION,M$	9.413	9.716	6.008	6.509	6.872	7.157	6.799	7.197
N	MISC GAS TURBINE AUXILIARY ,M$	10.842	10.517	7.728	7.948	8.005	7.961	8.640	8.771
T	GAS TURBINE GENERATOR ,M$	9.512	9.202	6.399	6.632	6.691	6.646	7.348	7.481
	RECUPERATOR & PIPING SYSTEM,M$	.000	.000	7.335	7.400	6.179	6.166	7.439	7.475
R	TOT MAJOR COMPONENT COST ,M$	38.906	39.998	32.129	33.464	32.974	33.362	35.257	36.206
E	TOT MAJOR COMPONENT COST,$/KWE	91.874	85.597	116.900	111.145	112.082	114.566	104.584	104.726
S	BALANCE OF PLANT COST ,$/KWE	19.191	19.526	26.589	25.217	25.666	25.802	24.625	23.697
U	SITE LABOR ,$/KWE	13.581	13.889	20.941	19.931	19.816	20.009	19.058	18.831
L	TOTAL DIRECT COST ,$/KWE	114.646	119.012	164.429	156.292	157.564	160.371	148.267	147.254
T	INDIRECT COSTS ,$/KWE	6.926	7.084	10.680	10.165	10.106	10.202	9.719	9.604
	PROF & OWNER COSTS ,$/KWE	9.172	9.521	13.154	12.503	12.605	12.830	11.861	11.780
B	CONTINGENCY COST ,$/KWE	6.400	6.621	8.791	8.415	8.468	8.612	8.054	8.014
R	ESCALATION COST ,$/KWE	13.795	14.197	17.921	17.329	17.381	17.649	16.798	16.757
E	INT DURING CONSTRUCTION ,$/KWE	14.648	15.065	19.879	18.278	18.328	18.608	17.747	17.711
A	TOTAL CAPITALIZATION ,$/KWE	165.587	171.499	233.854	222.992	224.452	228.272	212.446	211.120
K	COST OF ELEC-CAPITAL ,MILLS/KWE	5.235	5.421	7.393	7.049	7.095	7.216	6.716	6.674
D	COST OF ELEC-FUEL ,MILLS/KWE	25.884	25.742	25.208	25.179	25.757	26.742	24.151	24.357
O	COST OF ELEC-OP&MAIN,MILLS/KWE	.715	.715	.715	.715	.715	.715	.715	.715
W	TOTAL COST OF ELEC ,MILLS/KWE	31.834	31.379	33.316	32.944	33.567	34.674	31.582	31.746
N	COE 0.5 CAP. FACTOR ,MILLS/KWE	33.529	33.670	35.658	35.183	35.821	36.964	33.722	33.873
	COE 0.8 CAP. FACTOR ,MILLS/KWE	30.767	30.777	31.844	31.536	32.152	33.236	30.238	30.409
	COE 1.2XCAP. COST ,MILLS/KWE	32.891	32.963	34.794	34.353	34.986	36.117	32.926	33.081
	COE 1.2XFUEL COST ,MILLS/KWE	37.011	37.027	38.357	37.979	38.719	40.023	36.413	36.617
	COE (CONTINGENCY=0) ,MILLS/KWE	31.590	31.626	32.986	32.627	33.249	34.350	31.278	31.493
	COE (ESCALATION=0) ,MILLS/KWE	31.362	31.393	32.707	32.354	32.976	34.074	31.010	31.175

Table 5.7
Continued

OPEN CYCLE GAS TURBINE SUMMARY PLANT RESULTS

	PARAMETRIC POINT		33	34	35	36	37	38	39	40
	TOTAL CAPITAL COST	,M$	73.80	76.25	78.66	78.93	83.95	81.80	90.56	92.74
P	GAS TURBINE COMPRESSOR SECT	,M$	4.264	7.430	3.929	4.264	7.430	7.943	3.929	4.107
L	GAS TURBINE COMB BASKETS	,M$	1.223	1.273	1.153	1.279	1.330	1.338	1.231	1.311
A	GAS TURBINE TURBINE SECTION	,M$	7.307	8.030	9.174	7.842	8.405	8.772	8.631	9.177
N	MISC GAS TURBINE AUXILIARY	,M$	8.782	8.615	9.326	9.602	9.515	9.260	10.332	10.657
T	GAS TURBINE GENERATOR	,M$	7.492	7.322	8.038	8.312	3.226	7.373	9.023	9.336
	RECUPERATOR & PIPING SYSTEM	,M$	7.478	6.226	8.391	7.542	7.519	6.277	11.851	11.426
R	TOT MAJOR COMPONENT COST	,M$	36.746	38.896	39.010	38.842	42.425	41.552	44.997	46.014
E	TOT MAJOR COMPONENT COST	,$/KWE	106.066	115.956	102.229	97.309	107.777	110.116	101.245	99.125
S	BALANCE OF PLANT COST	,$/KWE	23.674	24.044	22.658	22.216	22.350	22.758	21.233	20.863
U	SITE LABOR	,$/KWE	18.886	19.207	18.369	17.654	18.247	18.268	18.268	17.820
L	TOTAL DIRECT COST	,$/KWE	148.625	159.207	143.256	137.179	148.373	151.151	140.745	137.809
T	INDIRECT COSTS	,$/KWE	9.632	9.795	9.368	9.003	9.306	9.316	9.317	9.088
	PROF & OWNER COSTS	,$/KWE	11.990	12.737	11.460	10.974	11.870	12.092	11.260	11.025
B	CONTINGENCY COST	,$/KWE	8.090	8.644	7.858	7.551	8.158	8.284	7.815	7.678
R	ESCALATION COST	,$/KWE	16.914	17.960	16.610	16.043	17.265	17.434	16.804	16.585
E	INT DURING CONSTRUCTION	,$/KWE	17.877	18.973	17.580	16.991	18.282	18.450	17.826	17.605
A	TOTAL CAPITALIZATION	,$/KWE	213.030	227.316	206.132	197.743	213.255	216.728	203.766	199.790
K	COST OF ELEC-CAPITAL	,MILLS/KWE	6.734	7.186	6.516	6.251	6.741	6.851	6.441	6.316
D	COST OF ELEC-FUEL	,MILLS/KWE	24.960	26.799	23.524	23.840	25.094	26.823	23.035	22.728
O	COST OF ELEC-OP&MAIN	,MILLS/KWE	.715	.715	.715	.715	.715	.715	.715	.715
W	TOTAL COST OF ELEC	,MILLS/KWE	32.409	34.700	30.755	30.806	32.551	34.330	30.192	29.760
N	COE 0.5 CAP. FACTOR	,MILLS/KWE	34.554	36.981	32.835	32.806	34.698	36.570	32.249	31.779
	COE 0.8 CAP. FACTOR	,MILLS/KWE	31.061	33.268	29.448	29.549	31.201	33.020	28.899	28.490
	COE 1.2XCAP. COST	,MILLS/KWE	33.756	36.138	32.059	32.056	33.899	35.760	31.480	31.023
	COE 1.2XFUEL COST	,MILLS/KWE	37.401	40.060	35.960	35.574	37.569	39.755	34.799	34.305
	COE (CONTINGENCY=0)	,MILLS/KWE	32.109	34.374	30.458	30.520	32.241	34.070	29.894	29.467
	COE (ESCALATION=0)	,MILLS/KWE	31.933	34.088	30.199	30.258	31.951	33.795	29.617	29.192

	PARAMETRIC POINT		41	42	43	44	45	46	47	48
	TOTAL CAPITAL COST	,M$	89.88	94.09	92.43	91.95	75.16	76.42	75.89	80.88
P	GAS TURBINE COMPRESSOR SECT	,M$	4.264	7.430	7.943	8.398	3.929	4.107	4.264	7.430
L	GAS TURBINE COMB BASKETS	,M$	1.363	1.415	1.421	1.393	1.153	1.230	1.279	1.330
A	GAS TURBINE TURBINE SECTION	,M$	9.603	10.312	9.344	9.664	8.179	8.673	7.846	8.407
N	MISC GAS TURBINE AUXILIARY	,M$	10.813	10.844	10.668	10.390	9.339	9.546	9.611	9.520
T	GAS TURBINE GENERATOR	,M$	9.484	9.515	9.346	9.079	8.051	8.256	8.321	8.230
	RECUPERATOR & PIPING SYSTEM	,M$	8.663	7.627	7.583	7.512	6.232	5.658	5.676	5.652
R	TOT MAJOR COMPONENT COST	,M$	44.190	47.144	46.305	46.435	36.884	37.470	36.996	40.570
E	TOT MAJOR COMPONENT COST	,$/KWE	93.307	99.141	99.606	103.659	96.443	94.717	92.556	102.975
S	BALANCE OF PLANT COST	,$/KWE	20.698	20.665	20.843	21.165	22.635	22.302	22.202	22.343
U	SITE LABOR	,$/KWE	16.836	16.890	17.008	17.374	17.502	17.090	16.941	17.528
L	TOTAL DIRECT COST	,$/KWE	130.841	136.696	137.457	142.199	136.581	134.115	131.699	142.850
T	INDIRECT COSTS	,$/KWE	8.586	8.614	8.674	9.861	8.926	8.719	8.640	8.939
	PROF & OWNER COSTS	,$/KWE	10.407	10.936	10.997	11.376	10.926	10.729	10.536	11.428
B	CONTINGENCY COST	,$/KWE	7.302	7.631	7.660	7.900	7.493	7.377	7.250	7.855
R	ESCALATION COST	,$/KWE	15.802	16.486	16.508	16.948	15.842	15.651	15.406	16.623
E	INT DURING CONSTRUCTION	,$/KWE	16.779	17.506	17.524	17.980	16.768	16.573	16.317	17.602
A	TOTAL CAPITALIZATION	,$/KWE	189.778	197.869	198.820	205.293	196.535	193.164	189.848	205.298
K	COST OF ELEC-CAPITAL	,MILLS/KWE	5.999	6.255	6.285	6.489	6.213	6.106	6.002	6.490
D	COST OF ELEC-FUEL	,MILLS/KWE	22.822	23.586	24.696	26.074	24.648	24.323	24.457	25.381
O	COST OF ELEC-OP&MAIN	,MILLS/KWE	.715	.715	.715	.715	.715	.715	.715	.715
W	TOTAL COST OF ELEC.	,MILLS/KWE	29.537	30.557	31.696	33.279	31.576	31.145	31.174	32.586
N	COE 0.5 CAP. FACTOR	,MILLS/KWE	31.461	32.558	33.706	35.350	33.564	33.102	33.099	34.658
	COE 0.8 CAP. FACTOR	,MILLS/KWE	28.326	29.298	30.432	31.977	30.326	29.915	29.964	31.284
	COE 1.2XCAP. COST	,MILLS/KWE	30.736	31.808	32.903	34.576	32.819	32.366	32.375	33.884
	COE 1.2XFUEL COST	,MILLS/KWE	34.101	35.274	36.635	38.494	36.505	36.010	36.066	37.662
	COE (CONTINGENCY=0)	,MILLS/KWE	29.258	30.205	31.404	32.978	31.292	30.865	30.899	32.288
	COE (ESCALATION=0)	,MILLS/KWE	28.995	29.992	31.131	32.693	31.035	30.611	30.648	32.019

Table 5.7
Continued

OPEN CYCLE GAS TURBINE SUMMARY PLANT RESULTS

PARAMETRIC POINT		49	50	51	52	53	54	55	56
PLANT	TOTAL CAPITAL COST ,M$	79.33	88.69	88.12	87.63	92.66	88.79	79.30	80.02
	GAS TURBINE COMPRESSOR SECT,M$	7.943	3.929	4.107	4.264	7.430	7.943	3.929	4.107
	GAS TURBINE COMB BASKETS ,M$	1.339	1.153	1.230	1.279	1.330	1.338	1.153	1.230
	GAS TURBINE TURBINE SECTION,M$	8.772	8.168	8.662	7.838	8.403	8.771	8.195	8.689
	MISC GAS TURBINE AUXILIARY ,M$	9.261	9.313	9.524	9.594	9.510	9.260	9.373	9.580
	GAS TURBINE GENERATOR ,M$	7.974	8.025	8.234	8.303	8.220	7.972	8.085	8.290
	RECUPERATOR & PIPING SYSTEM,M$	4.782	14.492	12.798	12.816	12.794	10.498	8.600	7.705
RESULT BREAKDOWN	TOT MAJOR COMPONENT COST ,M$	40.068	45.081	44.555	44.094	47.688	45.781	39.336	39.601
	TOT MAJOR COMPONENT COST,$/KWE	106.147	118.384	113.026	110.623	123.245	121.307	102.267	99.560
	BALANCE OF PLANT COST ,$/KWE	22.767	22.679	22.336	22.229	22.359	22.770	22.579	22.249
	SITE LABOR ,$/KWE	17.672	20.792	19.840	19.650	20.265	19.946	18.380	17.826
	TOTAL DIRECT COST ,$/KWE	146.586	161.855	155.202	152.502	163.869	164.023	143.225	139.634
	INDIRECT COSTS ,$/KWE	9.013	10.604	10.118	10.021	10.335	10.173	9.374	9.091
	PROF & OWNER COSTS ,$/KWE	11.727	12.948	12.416	12.200	13.110	13.122	11.458	11.171
	CONTINGENCY COST ,$/KWE	8.033	8.876	8.535	8.399	9.010	8.989	7.861	7.684
	ESCALATION COST ,$/KWE	16.906	18.761	18.102	17.832	19.071	18.925	16.632	16.313
	INT DURING CONSTRUCTION ,$/KWE	17.891	19.856	19.168	18.885	20.194	20.027	17.605	17.276
	TOTAL CAPITALIZATION ,$/KWE	210.156	232.900	223.542	219.834	235.588	235.258	206.154	201.169
	COST OF ELEC-CAPITAL,MILLS/KWE	6.644	7.362	7.067	6.949	7.447	7.437	6.517	6.359
	COST OF ELEC-FUEL ,MILLS/KWE	26.848	22.390	22.641	23.215	24.799	26.799	23.387	23.375
	COST OF ELEC-OP&MAIN,MILLS/KWE	.715	.715	.715	.715	.715	.715	.715	.715
	TOTAL COST OF ELEC ,MILLS/KWE	34.207	30.468	30.423	30.931	32.962	34.951	30.620	30.450
	COE 0.5 CAP. FACTOR ,MILLS/KWE	36.324	32.801	32.668	33.090	35.321	37.307	32.699	32.482
	COE 0.8 CAP. FACTOR ,MILLS/KWE	32.976	29.002	29.013	29.492	31.480	33.472	29.312	29.172
	COE 1.2XCAP. COST ,MILLS/KWE	35.535	31.940	31.837	32.271	34.452	30.439	31.923	31.722
	COE 1.2XFUEL COST ,MILLS/KWE	39.576	34.946	34.952	35.529	37.922	40.311	35.297	35.125
	COE (CONTINGENCY=0) ,MILLS/KWE	33.902	30.131	30.100	30.562	32.620	34.611	30.322	30.158
	COE (ESCALATION=0) ,MILLS/KWE	33.630	29.823	29.805	30.272	32.311	34.306	30.052	29.893

PARAMETRIC POINT		57	58	59	60	61	62	63	64
PLANT	TOTAL CAPITAL COST ,M$	79.49	84.49	82.28	78.11	78.94	78.44	83.47	81.38
	GAS TURBINE COMPRESSOR SECT,M$	4.264	7.430	7.943	3.929	4.107	4.264	7.430	7.943
	GAS TURBINE COMB BASKETS ,M$	1.279	1.330	1.338	1.153	1.230	1.279	1.330	1.338
	GAS TURBINE TURBINE SECTION,M$	7.960	8.422	8.788	8.152	8.646	7.824	8.388	8.755
	MISC GAS TURBINE AUXILIARY ,M$	9.647	9.556	9.299	9.278	9.489	9.558	9.474	9.222
	GAS TURBINE GENERATOR ,M$	8.355	8.266	8.012	7.991	8.200	8.269	8.185	7.934
	RECUPERATOR & PIPING SYSTEM,M$	7.722	7.698	6.422	8.231	7.385	7.403	7.381	6.164
RESULT BREAKDOWN	TOT MAJOR COMPONENT COST ,M$	39.128	42.703	41.801	38.734	39.057	38.598	42.188	41.356
	TOT MAJOR COMPONENT COST,$/KWE	97.353	107.771	110.025	102.309	99.635	97.371	107.888	110.295
	BALANCE OF PLANT COST ,$/KWE	22.149	22.286	22.702	22.737	22.392	22.283	22.416	22.836
	SITE LABOR ,$/KWE	17.664	18.256	18.267	18.377	1[illegible].820	17.659	18.2[illegible]3	18.282
	TOTAL DIRECT COST ,$/KWE	137.166	148.313	150.934	143.422	13[illegible].854	137.313	14[illegible].357	151.413
	INDIRECT COSTS ,$/KWE	9.008	9.310	9.316	9.372	9.092	9.006	9.309	9.324
	PROF & OWNER COSTS ,$/KWE	10.973	11.865	12.079	11.474	11.188	10.985	11.905	12.113
	CONTINGENCY COST ,$/KWE	7.555	8.159	8.279	7.862	7.688	7.555	8.169	8.294
	ESCALATION COST ,$/KWE	16.063	17.280	17.439	16.604	16.292	16.038	17.264	17.942
	INT DURING CONSTRUCTION ,$/KWE	17.019	18.300	18.456	17.571	17.251	16.984	18.279	18.456
	TOTAL CAPITALIZATION ,$/KWE	197.780	213.228	216.567	206.305	201.365	197.890	21[illegible].458	217.042
	COST OF ELEC-CAPITAL,MILLS/KWE	6.252	6.741	6.846	6.522	6.366	6.255	6.748	6.861
	COST OF ELEC-FUEL ,MILLS/KWE	23.719	24.974	26.694	23.655	23.605	23.956	25.215	26.954
	COST OF ELEC-OP&MAIN,MILLS/KWE	.715	.715	.715	.715	.715	.715	.715	.715
	TOTAL COST OF ELEC ,MILLS/KWE	30.686	32.430	34.256	30.893	30.686	30.926	32.678	34.530
	COE 0.5 CAP. FACTOR ,MILLS/KWE	32.687	34.576	36.474	32.974	32.720	32.928	34.827	36.713
	COE 0.8 CAP. FACTOR ,MILLS/KWE	29.429	31.080	32.887	29.584	29.407	29.668	31.328	33.158
	COE 1.2XCAP. COST ,MILLS/KWE	31.937	33.778	35.625	32.197	31.959	32.177	34.028	35.902
	COE 1.2XFUEL COST ,MILLS/KWE	35.430	37.424	39.594	35.624	35.407	35.718	37.721	39.921
	COE (CONTINGENCY=0) ,MILLS/KWE	30.400	32.120	33.942	30.595	30.394	30.640	32.369	34.216
	COE (ESCALATION=0) ,MILLS/KWE	30.138	31.840	33.661	30.326	30.130	30.379	32.089	33.935

Table 5.7
Continued

OPEN CYCLE GAS TURBINE SUMMARY PLANT RESULTS

PARAMETRIC POINT	65	66	67	68	69	70	71	72
TOTAL CAPITAL COST ,M$	86.87	91.90	94.56	98.15	99.55	101.09	94.64	92.63
PLANT								
GAS TURBINE COMPRESSOR SECT,M$	6.315	6.416	6.496	6.637	6.740	6.832	3.929	4.107
GAS TURBINE COMB BASKETS ,M$	1.148	1.224	1.272	1.314	1.332	1.304	1.153	1.230
GAS TURBINE TURBINE SECTION,M$	8.092	7.928	7.760	8.326	8.704	9.000	12.925	13.772
MISC GAS TURBINE AUXILIARY ,M$	11.764	12.292	12.648	13.196	13.516	13.708	9.881	10.133
GAS TURBINE GENERATOR ,M$	8.598	9.024	9.332	9.372	9.960	10.100	8.585	8.831
RECUPERATOR & PIPING SYSTEM,M$	6.448	7.732	7.812	7.920	6.804	6.840	12.199	9.122
RESULT BREAKDOWN								
TOT MAJOR COMPONENT COST ,M$	44.356	44.116	45.320	46.772	47.056	47.734	48.572	47.196
TOT MAJOR COMPONENT COST,$/KWE	100.420	99.627	98.042	96.736	93.888	93.719	110.592	109.188
BALANCE OF PLANT COST ,$/KWE	19.961	23.133	22.728	22.713	22.637	22.550	21.698	21.354
SITE LABOR ,$/KWE	18.163	19.986	19.684	19.676	19.288	19.246	19.439	18.125
TOTAL DIRECT COST ,$/KWE	144.544	142.756	140.453	139.095	135.863	135.525	157.715	148.667
INDIRECT COSTS ,$/KWE	9.263	10.193	10.039	10.014	9.837	9.815	9.911	9.244
PROF & OWNER COSTS ,$/KWE	11.564	11.420	11.236	11.127	10.363	10.392	12.617	11.893
CONTINGENCY COST ,$/KWE	7.984	7.926	7.825	7.778	7.620	7.612	8.711	8.236
ESCALATION COST ,$/KWE	17.021	17.118	16.930	16.967	16.693	16.706	18.551	17.598
INT DURING CONSTRUCTION ,$/KWE	18.039	18.158	18.024	18.022	17.742	17.760	19.659	18.660
TOTAL CAPITALIZATION ,$/KWE	209.414	207.571	204.558	202.992	198.624	198.291	227.165	214.298
COST OF ELEC-CAPITAL ,MILLS/KWE	6.588	6.562	6.407	6.417	6.279	6.267	7.191	6.774
COST OF ELEC-FUEL ,MILLS/KWE	22.464	22.044	21.777	21.630	21.746	21.910	22.183	22.205
COST OF ELEC-OP&MAIN,MILLS/KWE	.715	.741	.742	.746	.749	.750	.715	.715
TOTAL COST OF ELEC ,MILLS/KWE	29.767	29.347	28.936	28.793	28.773	28.927	30.079	29.695
COE 0.5 CAP. FACTOR ,MILLS/KWE	31.869	31.443	31.052	30.845	30.785	30.935	32.258	31.852
COE 0.9 CAP. FACTOR ,MILLS/KWE	28.447	28.030	27.696	27.503	27.509	27.665	28.649	28.339
COE 1.2XCAP. COST ,MILLS/KWE	31.085	30.660	30.279	30.076	30.029	30.181	31.516	31.050
COE 1.2XFUEL COST ,MILLS/KWE	34.260	33.756	33.341	33.119	33.123	33.309	34.516	34.135
COE (CONTINGENCY=0) ,MILLS/KWE	29.464	29.095	28.687	28.496	28.482	28.630	29.748	29.382
COE (ESCALATION=0) ,MILLS/KWE	29.186	28.762	28.405	28.212	28.202	28.355	29.446	29.093

PARAMETRIC POINT	73	74	75	76	77	78	79	80
TOTAL CAPITAL COST ,M$	92.90	97.22	97.84	100.40	103.55	105.06	106.62	104.65
PLANT								
GAS TURBINE COMPRESSOR SECT,M$	4.264	7.430	7.943	3.929	4.107	4.269	7.430	7.943
GAS TURBINE COMB BASKETS ,M$	1.279	1.330	1.338	1.231	1.311	1.363	1.415	1.421
GAS TURBINE TURBINE SECTION,M$	14.514	14.366	15.128	13.011	13.994	14.761	15.986	15.361
MISC GAS TURBINE AUXILIARY ,M$	10.237	10.207	9.988	10.742	11.101	11.284	11.262	11.216
GAS TURBINE GENERATOR ,M$	8.932	8.902	8.690	9.915	9.758	9.930	10.009	9.867
RECUPERATOR & PIPING SYSTEM,M$	8.113	8.110	8.054	12.608	12.354	11.833	8.605	7.974
RESULT BREAKDOWN								
TOT MAJOR COMPONENT COST ,M$	47.345	50.346	51.140	51.015	52.624	53.435	54.904	53.781
TOT MAJOR COMPONENT COST,$/KWE	107.935	115.272	120.829	108.729	107.221	106.521	108.248	100.072
BALANCE OF PLANT COST ,$/KWE	21.225	21.262	21.543	20.653	20.291	20.122	20.051	20.183
SITE LABOR ,$/KWE	17.755	19.142	18.568	18.439	18.042	17.786	17.187	17.130
TOTAL DIRECT COST ,$/KWE	146.915	154.676	160.940	147.821	145.554	144.429	145.486	145.385
INDIRECT COSTS ,$/KWE	9.055	9.252	9.470	9.404	9.201	9.071	8.765	8.736
PROF & OWNER COSTS ,$/KWE	11.733	12.379	12.875	11.926	11.649	11.554	11.639	11.631
CONTINGENCY COST ,$/KWE	8.148	8.576	8.901	8.243	8.147	8.098	8.163	8.146
ESCALATION COST ,$/KWE	17.431	19.309	18.923	17.792	17.662	17.592	17.713	17.691
INT DURING CONSTRUCTION ,$/KWE	18.497	19.417	20.059	18.889	18.764	18.695	18.827	18.746
TOTAL CAPITALIZATION ,$/KWE	211.790	222.605	231.167	213.974	210.972	209.479	210.594	210.285
COST OF ELEC-CAPITAL ,MILLS/KWE	6.695	7.037	7.308	6.764	6.669	6.621	6.657	6.648
COST OF ELEC-FUEL ,MILLS/KWE	22.521	23.561	24.981	22.250	21.985	22.089	22.740	23.731
COST OF ELEC-OP&MAIN,MILLS/KWE	.715	.715	.715	.715	.715	.715	.715	.715
TOTAL COST OF ELEC ,MILLS/KWE	29.931	31.314	33.004	29.729	29.370	29.425	30.113	31.094
COE 0.5 CAP. FACTOR ,MILLS/KWE	32.064	33.549	35.321	31.893	31.495	31.536	32.235	33.213
COE 0.9 CAP. FACTOR ,MILLS/KWE	28.590	29.909	31.548	28.376	29.034	28.098	28.779	29.763
COE 1.2XCAP. COST ,MILLS/KWE	31.270	32.721	34.465	31.082	30.704	30.749	31.444	32.424
COE 1.2XFUEL COST ,MILLS/KWE	34.435	36.026	38.000	34.179	33.767	33.843	34.661	35.841
COE (CONTINGENCY=0) ,MILLS/KWE	29.621	30.987	32.665	29.415	29.058	29.110	29.800	30.783
COE (ESCALATION=0) ,MILLS/KWE	29.335	30.689	32.357	29.120	28.765	28.823	29.506	30.490

Table 5.7
Continued

OPEN CYCLE GAS TURBINE SUMMARY PLANT RESULTS

PARAMETRIC POINT	81	82	83	84	85	86	87	88
PLANT								
TOTAL CAPITAL COST ,M$	104.73	107.73	101.91	103.44	108.95	110.27	113.68	118.37
GAS TURBINE COMPRESSOR SECT,M$	8.398	3.929	4.107	4.264	7.430	7.943	3.929	4.107
GAS TURBINE COMB BASKETS ,M$	1.393	1.153	1.230	1.279	1.370	1.338	1.231	1.311
GAS TURBINE TURBINE SECTION,M$	15.976	16.538	17.817	18.825	20.060	21.186	15.838	17.075
MISC GAS TURBINE AUXILIARY ,M$	10.958	10.288	10.574	10.705	10.718	10.526	11.876	12.336
GAS TURBINE GENERATOR ,M$	9.622	9.992	9.256	9.392	9.394	9.211	10.484	10.909
RECUPERATOR & PIPING SYSTEM,M$	7.910	13.123	9.771	9.204	8.542	8.494	14.660	14.735
RESULT BREAKDOWN								
TOT MAJOR COMPONENT COST ,M$	54.257	54.013	52.755	53.660	57.475	58.698	58.017	60.474
TOT MAJOR COMPONENT COST,$/KWE	112.501	122.257	114.884	114.873	122.831	128.633	108.185	107.467
BALANCE OF PLANT COST ,$/KWE	20.430	21.106	20.776	20.634	20.620	20.829	19.572	19.235
SITE LABOR ,$/KWE	17.480	19.534	18.202	17.992	18.240	18.642	18.027	17.750
TOTAL DIRECT COST ,$/KWE	150.412	162.897	153.862	153.499	161.691	168.104	145.783	144.452
INDIRECT COSTS ,$/KWE	8.915	9.962	9.283	9.176	9.302	9.507	9.194	9.053
PROF & OWNER COSTS ,$/KWE	12.033	13.032	12.309	12.280	12.935	13.448	11.663	11.556
CONTINGENCY COST ,$/KWE	8.407	9.040	8.565	8.557	9.015	9.353	8.219	8.176
ESCALATION COST ,$/KWE	19.132	19.346	18.393	18.401	19.352	20.009	17.985	17.978
INT DURING CONSTRUCTION ,$/KWE	19.258	20.520	19.521	19.534	20.545	21.239	19.134	19.190
TOTAL CAPITALIZATION ,$/KWE	217.155	234.797	221.933	221.446	232.940	241.656	211.977	210.355
COST OF ELEC-CAPITAL ,MILLS/KWE	6.865	7.422	7.016	7.000	7.361	7.639	6.701	6.650
COST OF ELEC-FUEL ,MILLS/KWE	24.925	21.289	21.360	21.663	22.601	23.833	20.281	20.171
COST OF ELEC-OP&MAIN,MILLS/KWE	.715	.715	.715	.715	.715	.715	.715	.715
TOTAL COST OF ELEC ,MILLS/KWE	32.505	29.427	29.032	29.379	30.677	32.189	27.698	27.536
COE 0.5 CAP. FACTOR ,MILLS/KWE	34.689	31.778	31.321	31.603	33.010	34.604	29.833	29.656
COE 0.8 CAP. FACTOR ,MILLS/KWE	31.132	27.949	27.691	27.991	29.211	30.670	26.356	25.204
COE 1.2XCAP. COST ,MILLS/KWE	33.878	30.911	30.495	30.779	32.149	33.710	29.038	28.866
COE 1.2XFUEL COST ,MILLS/KWE	37.490	33.684	33.364	33.711	35.197	36.955	31.754	31.570
COE (CONTINGENCY=0) ,MILLS/KWE	32.184	29.082	28.765	29.052	30.337	31.831	27.383	27.222
COE (ESCALATION=0) ,MILLS/KWE	31.984	28.765	28.462	28.749	30.015	31.503	27.081	26.919

PARAMETRIC POINT	89	90	91	92	93	94	95	96	97
PLANT									
TOTAL CAPITAL COST ,M$	120.46	127.23	123.52	122.45	79.44	77.79	43.50	44.03	99.13
GAS TURBINE COMPRESSOR SECT,M$	4.264	7.430	7.943	8.398	4.107	4.107	.982	.982	2.097
GAS TURBINE COMB BASKETS ,M$	1.363	1.415	1.421	1.393	1.229	1.230	.275	.275	.388
GAS TURBINE TURBINE SECTION,M$	18.053	19.617	20.720	21.272	8.663	8.758	1.700	1.700	3.368
MISC GAS TURBINE AUXILIARY ,M$	12.602	12.811	12.756	12.556	9.534	9.730	2.160	2.160	3.409
GAS TURBINE GENERATOR ,M$	11.193	11.394	11.292	11.110	8.245	8.438	1.837	1.837	3.022
RECUPERATOR & PIPING SYSTEM,M$	14.126	13.306	9.842	8.991	7.529	7.576	1.537	1.417	4.763
							2.400	2.400	10.750
RESULT BREAKDOWN									
TOT MAJOR COMPONENT COST ,M$	61.562	65.923	63.974	63.670	33.307	39.838	10.892	10.772	27.797
TOT MAJOR COMPONENT COST,$/KWE	100.537	111.802	109.081	110.691	99.541	97.835	113.670	108.688	121.077
BALANCE OF PLANT COST ,$/KWE	19.057	18.924	18.959	19.087	22.319	19.373	96.523	95.736	71.097
SITE LABOR ,$/KWE	17.463	17.488	16.797	16.901	17.919	15.786	67.026	66.101	53.809
TOTAL DIRECT COST ,$/KWE	143.059	148.215	144.826	146.579	139.679	132.994	277.219	270.525	252.022
INDIRECT COSTS ,$/KWE	6.906	8.919	8.561	8.508	9.088	8.051	34.183	33.711	30.523
PROF & OWNER COSTS ,$/KWE	11.445	11.857	11.596	11.726	11.174	10.640	22.178	21.692	20.162
CONTINGENCY COST ,$/KWE	8.115	8.421	8.225	8.311	7.682	7.333	16.019	17.640	17.038
ESCALATION COST ,$/KWE	17.887	18.571	18.112	18.254	15.295	15.546	48.872	48.049	52.554
INT DURING CONSTRUCTION ,$/KWE	19.052	19.786	19.295	19.440	17.255	16.470	53.522	52.658	58.606
TOTAL CAPITALIZATION ,$/KWE	208.462	215.769	210.605	212.879	201.173	191.033	453.993	444.225	431.785
COST OF ELEC-CAPITAL ,MILLS/KWE	6.590	6.821	6.658	6.730	6.300	6.039	14.352	14.043	13.650
COST OF ELEC-FUEL ,MILLS/KWE	20.263	20.761	21.495	22.384	23.486	24.559	21.015	20.306	18.659
COST OF ELEC-OP&MAIN,MILLS/KWE	.715	.715	.715	.715	.715	.715	.599	.587	.585
TOTAL COST OF ELEC ,MILLS/KWE	27.568	29.297	28.868	29.829	30.561	31.313	35.957	34.936	32.894
COE 0.5 CAP. FACTOR ,MILLS/KWE	29.670	30.468	30.990	31.973	32.594	33.250	40.373	39.260	37.100
COE 0.8 CAP. FACTOR ,MILLS/KWE	26.247	26.933	27.534	28.482	29.283	30.096	33.191	32.228	30.260
COE 1.2XCAP. COST ,MILLS/KWE	28.886	29.661	30.200	31.175	31.833	32.521	38.827	37.745	35.624
COE 1.2XFUEL COST ,MILLS/KWE	31.621	32.449	33.167	34.306	35.299	36.225	40.160	38.997	36.626
COE (CONTINGENCY=0) ,MILLS/KWE	27.207	27.973	28.552	29.510	30.270	31.035	35.221	34.215	32.134
COE (ESCALATION=0) ,MILLS/KWE	25.354	27.659	28.246	29.203	30.005	30.782	34.236	33.243	31.010

5.6 Analysis of Overall Cost of Electricity

Using the tabulated capital costs for the recuperated open-cycle gas turbine systems in conjunction with calculated power plant efficiencies, and designated values of fuel price, capacity factor, time of construction, fixed charge rates, contingency provisions, and escalation rates, the cost of electricity was computed for each parametric point variation. The results of these calculations, summarized for each parametric point, are given in Table 5.8.

In addition, a more detailed examination of the effects of selected parameters included:

- Labor rate
- Contingency
- Escalation rate
- Interest during construction
- Fixed charge rate
- Fuel cost
- Capacity factor.

Table 5.9 gives the results of the variation of these parameters on the overall cost of electricity for the base case.

The effect of the basic gas turbine parameters of compressor pressure ratio and turbine inlet temperature on the cost of electricity was investigated for both simple and recuperated gas turbine plant arrangements. By comparison with other ECAS energy conversion systems, these recuperated gas turbine plants are generally well suited for low-capacity factor operation. It is important, therefore, to consider in addition to compressor pressure ratio and turbine inlet temperature the effects of capacity factor on the overall cost of electricity.

In Figure 5.47 the simple cycle cost of electricity variations are plotted against compressor pressure ratio and turbine inlet temperature

C-2

Table 5.8 OPEN CYCLE GAS TURBINE SUMMARY PLANT RESULTS

PARAMETRIC POINT	1	2	3	4	5	6	7	8
THERMODYNAMIC EFF	.378	.248	.276	.294	.305	.313	.310	.300
POWER PLANT EFF	.378	.248	.276	.294	.305	.313	.310	.300
OVERALL ENERGY EFF	.191	.125	.139	.148	.154	.158	.157	.151
CAP COST MILLION $	79.439	51.878	54.153	55.234	55.594	59.430	58.549	57.258
CAPITAL COST,$/KWE	201.173	180.532	179.551	181.549	185.314	211.374	229.714	253.715
COE CAPITAL	6.360	5.707	5.676	5.739	5.858	6.682	7.262	8.020
COE FUEL	23.486	35.779	32.137	30.191	29.121	28.313	28.586	29.597
COE OP & MAIN	.715	.715	.715	.715	.715	.715	.715	.715
COST OF ELECTRIC	30.561	42.201	38.529	36.646	35.694	35.710	36.563	38.333
EST TIME OF CONST	2.500	2.365	2.385	2.388	2.383	2.356	2.316	2.267

PARAMETRIC POINT	9	10	11	12	13	14	15	16
THERMODYNAMIC EFF	.279	.299	.311	.323	.325	.321	.281	.302
POWER PLANT EFF	.279	.299	.311	.323	.325	.321	.291	.302
OVERALL ENERGY EFF	.141	.151	.157	.163	.164	.162	.142	.152
CAP COST MILLION $	58.527	60.050	60.731	65.099	64.516	53.384	64.385	66.434
CAPITAL COST,$/KWE	167.030	167.811	170.020	189.339	200.634	214.921	162.163	162.351
COE CAPITAL	5.280	5.305	5.375	5.985	6.342	6.794	5.126	5.132
COE FUEL	31.758	29.706	28.531	27.446	27.268	27.685	31.555	29.430
COE OP & MAIN	.715	.715	.715	.715	.715	.715	.715	.715
COST OF ELECTRIC	37.753	35.726	34.621	34.146	34.326	35.195	37.396	35.278
EST TIME OF CONST	2.448	2.457	2.457	2.440	2.412	2.376	2.502	2.516

PARAMETRIC POINT	17	18	19	20	21	22	23	24
THERMODYNAMIC EFF	.315	.330	.335	.334	.282	.303	.318	.335
POWER PLANT EFF	.315	.330	.335	.334	.282	.303	.318	.335
OVERALL ENERGY EFF	.159	.166	.169	.168	.142	.153	.160	.169
CAP COST MILLION $	65.727	70.550	70.292	59.436	70.585	73.277	74.853	80.519
CAPITAL COST,$/KWE	159.532	174.801	182.614	191.982	152.386	152.103	152.836	164.728
COE CAPITAL	5.043	5.526	5.773	6.069	4.817	4.808	4.831	5.207
COE FUEL	28.178	26.888	26.511	26.590	31.454	29.255	27.912	26.471
COE OP & MAIN	.715	.715	.715	.715	.715	.715	.715	.715
COST OF ELECTRIC	33.936	33.130	32.999	33.375	36.987	34.779	33.459	32.399
EST TIME OF CONST	2.519	2.510	2.489	2.462	2.571	2.589	2.596	2.595

PARAMETRIC POINT	25	26	27	28	29	30	31	32
THERMODYNAMIC EFF	.343	.345	.352	.352	.345	.332	.367	.364
POWER PLANT EFF	.343	.345	.352	.352	.345	.332	.367	.364
OVERALL ENERGY EFF	.173	.174	.178	.178	.174	.167	.185	.184
CAP COST MILLION $	78.697	78.135	64.273	67.135	66.034	66.473	71.620	72.998
CAPITAL COST,$/KWE	165.587	171.499	233.854	222.982	224.452	228.272	212.446	211.120
COE CAPITAL	5.235	5.421	7.393	7.049	7.095	7.216	6.716	6.674
COE FUEL	25.884	25.742	25.208	25.179	25.757	26.742	24.351	24.357
COE OP & MAIN	.715	.715	.715	.715	.715	.715	.715	.715
COST OF ELECTRIC	31.834	31.879	33.316	32.944	33.567	34.674	31.582	31.746
EST TIME OF CONST	2.582	2.563	2.346	2.384	2.374	2.370	2.432	2.443

PARAMETRIC POINT	33	34	35	36	37	38	39	40
THERMODYNAMIC EFF	.356	.331	.377	.372	.354	.331	.385	.390
POWER PLANT EFF	.356	.331	.377	.372	.354	.331	.385	.390
OVERALL ENERGY EFF	.179	.167	.190	.188	.178	.167	.194	.197
CAP COST MILLION $	73.802	76.251	78.660	78.931	83.946	81.802	90.562	92.743
CAPITAL COST,$/KWE	213.030	227.316	206.132	197.743	213.255	216.728	203.766	193.790
COE CAPITAL	6.734	7.186	6.516	6.251	6.741	6.851	6.441	6.316
COE FUEL	24.960	26.799	23.524	23.840	25.094	26.823	23.035	22.728
COE OP & MAIN	.715	.715	.715	.715	.715	.715	.715	.715
COST OF ELECTRIC	32.409	34.700	30.755	30.806	32.551	34.390	30.192	29.760
EST TIME OF CONST	2.443	2.430	2.485	2.505	2.499	2.480	2.552	2.572

Table 5.8
Continued

OPEN CYCLE GAS TURBINE SUMMARY PLANT RESULTS

PARAMETRIC POINT	41	42	43	44	45	46	47	48
THERMODYNAMIC EFF	.389	.376	.359	.340	.360	.365	.363	.350
POWER PLANT EFF	.389	.376	.359	.340	.360	.365	.363	.350
OVERALL ENERGY EFF	.190	.190	.181	.172	.182	.184	.183	.176
CAP COST MILLION $	89.879	94.090	92.427	91.950	75.163	76.416	75.886	80.879
CAPITAL COST,$/KWE	189.778	197.869	198.820	205.263	196.536	193.164	189.848	205.298
COE CAPITAL	5.999	6.255	6.285	6.489	6.213	6.106	6.002	6.490
COE FUEL	22.822	23.585	24.696	26.074	24.648	24.323	24.457	25.381
COE OP & MAIN	.715	.715	.715	.715	.715	.715	.715	.715
COST OF ELECTRIC	29.537	30.557	31.696	33.279	31.576	31.145	31.174	32.586
EST TIME OF CONST	2.581	2.533	2.572	2.556	2.436	2.501	2.505	2.499

PARAMETRIC POINT	49	50	51	52	53	54	55	56
THERMODYNAMIC EFF	.330	.396	.392	.382	.358	.331	.379	.380
POWER PLANT EFF	.331	.396	.392	.382	.358	.331	.379	.380
OVERALL ENERGY EFF	.167	.200	.198	.193	.180	.167	.191	.191
CAP COST MILLION $	79.330	88.698	88.120	87.626	92.662	88.796	79.295	80.017
CAPITAL COST,$/KWE	210.156	232.900	223.542	219.834	235.588	235.258	206.154	201.169
COE CAPITAL	5.644	7.362	7.067	6.949	7.447	7.437	6.517	6.359
COE FUEL	26.848	22.390	22.641	23.216	24.799	26.799	23.387	23.375
COE OP & MAIN	.715	.715	.715	.715	.715	.715	.715	.715
COST OF ELECTRIC	34.207	30.468	30.423	30.881	32.962	34.951	30.620	30.450
EST TIME OF CONST	2.480	2.484	2.499	2.504	2.498	2.480	2.489	2.503

PARAMETRIC POINT	57	58	59	60	61	62	63	64
THERMODYNAMIC EFF	.374	.355	.332	.375	.376	.370	.352	.329
POWER PLANT EFF	.374	.355	.332	.375	.376	.370	.352	.329
OVERALL ENERGY EFF	.189	.179	.168	.189	.190	.187	.178	.166
CAP COST MILLION $	79.492	84.490	82.276	78.107	78.935	78.440	83.471	81.382
CAPITAL COST,$/KWE	197.780	213.228	216.562	206.305	201.365	197.980	213.458	217.042
COE CAPITAL	6.252	6.741	6.846	6.522	6.366	6.255	6.748	6.861
COE FUEL	23.719	24.974	26.694	23.655	23.605	23.956	25.215	26.954
COE OP & MAIN	.715	.715	.715	.715	.715	.715	.715	.715
COST OF ELECTRIC	30.686	32.430	34.256	30.893	30.686	30.926	32.678	34.530
EST TIME OF CONST	2.508	2.502	2.483	2.482	2.497	2.502	2.496	2.477

PARAMETRIC POINT	65	66	67	68	69	70	71	72
THERMODYNAMIC EFF	.395	.404	.409	.412	.410	.407	.400	.400
POWER PLANT EFF	.395	.403	.407	.410	.408	.405	.400	.400
OVERALL ENERGY EFF	.199	.203	.206	.207	.206	.204	.202	.202
CAP COST MILLION $	85.867	91.905	94.557	98.147	99.548	101.096	94.637	92.628
CAPITAL COST,$/KWE	208.414	207.571	204.558	202.992	198.624	198.261	227.165	214.298
COE CAPITAL	6.598	6.562	6.457	6.417	6.279	6.267	7.181	6.774
COE FUEL	22.464	22.044	21.777	21.630	21.746	21.910	22.183	22.205
COE OP & MAIN	.715	.741	.742	.746	.749	.750	.715	.715
COST OF ELECTRIC	29.767	29.347	28.986	28.793	28.773	28.927	30.079	29.695
EST TIME OF CONST	2.524	2.552	2.572	2.592	2.609	2.617	2.524	2.540

PARAMETRIC POINT	73	74	75	76	77	78	79	80
THERMODYNAMIC EFF	.394	.377	.355	.399	.404	.402	.390	.374
POWER PLANT EFF	.394	.377	.355	.399	.404	.402	.390	.374
OVERALL ENERGY EFF	.199	.190	.179	.201	.204	.203	.197	.189
CAP COST MILLION $	92.899	97.225	97.839	100.397	103.545	105.063	106.620	104.646
CAPITAL COST,$/KWE	211.790	222.605	231.167	213.974	210.972	209.439	210.594	210.285
COE CAPITAL	6.695	7.037	7.308	6.764	6.669	6.621	6.657	6.648
COE FUEL	22.521	23.561	24.981	22.250	21.985	22.089	22.740	23.731
COE OP & MAIN	.715	.715	.715	.715	.715	.715	.715	.715
COST OF ELECTRIC	29.931	31.314	33.004	29.729	29.370	29.425	30.113	31.094
EST TIME OF CONST	2.546	2.544	2.531	2.577	2.597	2.607	2.611	2.603

Table 5.8
Continued

OPEN CYCLE GAS TURBINE SUMMARY PLANT RESULTS

PARAMETRIC POINT	81	92	83	84	95	86	37	88
THERMODYNAMIC EFF	.356	.417	.415	.410	.393	.372	.438	.440
POWER PLANT EFF	.356	.417	.415	.410	.393	.372	.438	.440
OVERALL ENERGY EFF	.180	.210	.210	.207	.198	.188	.221	.222
CAP COST MILLION $	104.730	103.733	101.912	103.442	108.950	110.272	113.679	118.371
CAPITAL COST,$/KWE	217.155	234.797	221.933	221.446	232.840	241.656	211.977	210.355
COE CAPITAL	6.865	7.422	7.016	7.000	7.361	7.639	6.701	6.650
COE FUEL	24.925	21.289	21.360	21.663	22.603	23.833	20.281	20.171
COE OP & MAIN	.715	.715	.715	.715	.715	.715	.715	.715
COST OF ELECTRIC	32.505	29.427	29.092	29.379	30.677	32.188	27.698	27.536
EST TIME OF CONST	2.589	2.550	2.567	2.575	2.575	2.554	2.638	2.660

PARAMETRIC POINT	89	90	91	92	93	94	95	96	97
THERMODYNAMIC EFF	.438	.427	.413	.396	.378	.361	.000	.000	.000
POWER PLANT EFF	.438	.427	.413	.396	.378	.361	.422	.437	.476
OVERALL ENERGY EFF	.221	.216	.208	.200	.191	.243	.213	.220	.240
CAP COST MILLION $	120.458	127.226	123.516	122.448	79.439	77.789	43.502	44.026	99.129
CAPITAL COST,$/KWE	208.462	215.769	210.605	222.879	201.173	191.033	453.993	444.225	431.785
COE CAPITAL	6.590	6.821	6.658	6.730	6.360	6.039	14.352	14.043	13.650
COE FUEL	20.263	20.761	21.495	22.384	23.486	24.559	21.015	20.306	18.659
COE OP & MAIN	.715	.715	.715	.715	.715	.715	.589	.587	.585
COST OF ELECTRIC	27.568	28.297	28.868	29.829	30.561	31.313	35.957	34.936	32.894
EST TIME OF CONST	2.672	2.682	2.679	2.670	2.500	2.513	3.500	3.521	4.078

Table 5.9 OPEN CYCLE GAS TURBINE COST OF ELECTRICITY,MILLS/KW.HR
PARAMETRIC POINT NO. 1

ACCOUNT	RATE, PERCENT	LABOR RATE, $/HR 6.00	8.50	10.60	15.00	21.50
TOTAL DIRECT COSTS,$	.0	52103033.	53762521.	55156491.	58077190.	62391858.
INDIRECT COST,$	51.0	2031213.	2877552.	3598476.	5078033.	7278514.
PROF & OWNER COSTS,$	8.0	4168243.	4301002.	4412519.	4646175.	4991349.
CONTINGENCY COST,$	5.5	2865667.	2956939.	3033607.	3194245.	3431352.
SUB TOTAL,$	.0	61168155.	63898013.	66191092.	70995642.	78093272.
ESCALATION COST,$	6.5	5946253.	6211626.	6434540.	6901598.	7591570.
INTREST DURING CONST,$	10.0	6296651.	6577663.	6813713.	7308293.	8038923.
TOTAL CAPITALIZATION,$	.0	73411059.	76687302.	79439344.	35205533.	93723764.
COST OF ELEC-CAPITAL	18.0	5.87694	6.13922	6.35954	6.82115	7.50308
COST OF ELEC-FUEL	.0	23.48637	23.48637	23.48637	23.48637	23.48637
COST OF ELEC-OP & MAIN	.0	.71538	.71538	.71538	.71538	.71538
TOTAL COST OF ELEC	.0	30.07869	30.34097	30.56129	31.02290	31.70483

ACCOUNT	RATE, PERCENT	CONTINGENCY, PERCENT -5.00	.00	5.50	5.00	20.00
TOTAL DIRECT COSTS,$	.0	55156491.	55156491.	55156491.	55156491.	55156491.
INDIRECT COST,$	51.0	3588476.	3588476.	3588476.	3588476.	3588476.
PROF & OWNER COSTS,$	8.0	4412519.	4412519.	4412519.	4412519.	4412519.
CONTINGENCY COST,$	70.0	-2757825.	0.	3033607.	2757825.	11031298.
SUB TOTAL,$	.0	60399661.	63157486.	66191092.	65915310.	74188784.
ESCALATION COST,$	6.5	5871546.	6139635.	6434540.	6407731.	7212008.
INTREST DURING CONST,$	10.0	6217543.	6501433.	6813713.	6785324.	7636995.
TOTAL CAPITALIZATION,$	.0	72488750.	75798557.	79439344.	79108364.	89037787.
COST OF ELEC-CAPITAL	18.0	5.80311	6.06807	6.35954	6.33304	7.12794
COST OF ELEC-FUEL	.0	23.48637	23.48637	23.48637	23.48637	23.48637
COST OF ELEC-OP & MAIN	.0	.71538	.71538	.71538	.71538	.71538
TOTAL COST OF ELEC	.0	30.00485	30.26982	30.56129	30.53479	31.32969

ACCOUNT	RATE, PERCENT	ESCALATION RATE, PERCENT 5.00	6.50	8.00	10.00	.00
TOTAL DIRECT COSTS,$	.0	55156491.	55156491.	55156491.	55156491.	55156491.
INDIRECT COST,$	51.0	3588476.	3588476.	3588476.	3588476.	3588476.
PROF & OWNER COSTS,$	8.0	4412519.	4412519.	4412519.	4412519.	4412519.
CONTINGENCY COST,$	5.5	3033607.	3033607.	3033607.	3033607.	3033607.
SUB TOTAL,$	.0	66191092.	66191092.	66191092.	66191092.	66191092.
ESCALATION COST,$	.0	4926716.	6434540.	7956070.	10006104.	0.
INTREST DURING CONST,$	10.0	6693681.	6813713.	6934457.	7096558.	6298765.
TOTAL CAPITALIZATION,$	.0	77811489.	79439344.	81081619.	83293754.	72489857.
COST OF ELEC-CAPITAL	18.0	6.22922	6.35954	6.49101	6.66810	5.80319
COST OF ELEC-FUEL	.0	23.48637	23.48637	23.48637	23.48637	23.48637
COST OF ELEC-OP & MAIN	.0	.71538	.71538	.71538	.71538	.71538
TOTAL COST OF ELEC	.0	30.43097	30.56129	30.69276	30.86985	30.00494

ACCOUNT	RATE, PERCENT	INT DURING CONST,PERCENT 6.00	8.00	10.00	12.50	15.00
TOTAL DIRECT COSTS,$	.0	55156491.	55156491.	55156491.	55156491.	55156491.
INDIRECT COST,$	51.0	3588476.	3588476.	3588476.	3588476.	3588476.
PROF & OWNER COSTS,$	8.0	4412519.	4412519.	4412519.	4412519.	4412519.
CONTINGENCY COST,$	5.5	3033607.	3033607.	3033607.	3033607.	3033607.
SUB TOTAL,$	.0	66191092.	66191092.	66191092.	66191092.	66191092.
ESCALATION COST,$	6.5	6434540.	6434540.	6434540.	6434540.	6434540.
INTREST DURING CONST,$	15.0	4073958.	5441439.	6813713.	8535839.	10265537.
TOTAL CAPITALIZATION,$	.0	76693590.	79067071.	79439344.	81161471.	82891169.
COST OF ELEC-CAPITAL	18.0	6.14021	6.24968	6.35954	6.49740	6.63587
COST OF ELEC-FUEL	.0	23.48637	23.48637	23.48637	23.48637	23.48637
COST OF ELEC-OP & MAIN	.0	.71538	.71538	.71538	.71538	.71538
TOTAL COST OF ELEC	.0	30.34195	30.45143	30.56129	30.69915	30.83762

Table 5.9
Continued

OPEN CYCLE GAS TURBINE COST OF ELECTRICITY,MILLS/KW.HR
PARAMETRIC POINT NO. 1

ACCOUNT	RATE, PERCENT	FIXED CHARGE RATE, PCT 10.00	14.40	18.00	21.60	25.00
TOTAL DIRECT COSTS,$	.0	55156491.	55156491.	55156491.	55156491.	55156491.
INDIRECT COST,$	51.0	3588476.	3588476.	3588476.	3588476.	3588476.
PROF & OWNER COSTS,$	8.0	4412519.	4412519.	4412519.	4412519.	4412519.
CONTINGENCY COST,$	5.5	3033607.	3033607.	3033607.	3033607.	3033607.
SUB TOTAL,$	.0	66191092.	66191092.	66191092.	66191092.	66191092.
ESCALATION COST,$	6.5	6434540.	6434540.	6434540.	6434540.	6434540.
INTREST DURING CONST,$	10.0	6813713.	6813713.	6813713.	6813713.	6813713.
TOTAL CAPITALIZATION,$	.0	79439344.	79439344.	79439344.	79439344.	79439344.
COST OF ELEC-CAPITAL	25.0	3.53308	5.08763	6.35954	7.63145	8.83269
COST OF ELEC-FUEL	.0	23.48637	23.48637	23.48637	23.48637	23.48637
COST OF ELEC-OP & MAIN	.0	.71538	.71538	.71538	.71538	.71538
TOTAL COST OF ELEC	.0	27.73482	29.28938	30.56129	31.83319	33.03444

ACCOUNT	RATE, PERCENT	FUEL COST, $/10**6 BTU 1.50	2.60	4.00	2.08	3.12
TOTAL DIRECT COSTS,$	.0	55156491.	55156491.	55156491.	55156491.	55156491.
INDIRECT COST,$	51.0	3588476.	3588476.	3588476.	3588476.	3588476.
PROF & OWNER COSTS,$	8.0	4412519.	4412519.	4412519.	4412519.	4412519.
CONTINGENCY COST,$	5.5	3033607.	3033607.	3033607.	3033607.	3033607.
SUB TOTAL,$	.0	66191092.	66191092.	66191092.	66191092.	66191092.
ESCALATION COST,$	6.5	6434540.	6434540.	6434540.	6434540.	6434540.
INTREST DURING CONST,$	10.0	6813713.	6813713.	6813713.	6813713.	6813713.
TOTAL CAPITALIZATION,$	.0	79439344.	79439344.	79439344.	79439344.	79439344.
COST OF ELEC-CAPITAL	18.0	6.35954	6.35954	6.35954	6.35954	6.35954
COST OF ELEC-FUEL	.0	13.54983	23.48637	36.13287	18.78909	28.18364
COST OF ELEC-OP & MAIN	.0	.71538	.71538	.71538	.71538	.71538
TOTAL COST OF ELEC	.0	20.62475	30.56129	43.20779	25.86401	35.25856

ACCOUNT	RATE, PERCENT	CAPACITY FACTOR, PERCENT 12.00	45.00	50.00	65.00	80.00
TOTAL DIRECT COSTS,$	.0	55156491.	55156491.	55156491.	55156491.	55156491.
INDIRECT COST,$	51.0	3588476.	3588476.	3588476.	3588476.	3588476.
PROF & OWNER COSTS,$	8.0	4412519.	4412519.	4412519.	4412519.	4412519.
CONTINGENCY COST,$	5.5	3033607.	3033607.	3033607.	3033607.	3033607.
SUB TOTAL,$	.0	66191092.	66191092.	66191092.	66191092.	66191092.
ESCALATION COST,$	6.5	6434540.	6434540.	6434540.	6434540.	6434540.
INTREST DURING CONST,$	10.0	6813713.	6813713.	6813713.	6813713.	6813713.
TOTAL CAPITALIZATION,$	.0	79439344.	79439344.	79439344.	79439344.	79439344.
COST OF ELEC-CAPITAL	18.0	34.44750	9.18600	8.26740	6.35954	5.16712
COST OF ELEC-FUEL	.0	23.48637	23.48637	23.48637	23.48637	23.48637
COST OF ELEC-OP & MAIN	.0	3.60000	1.69872	.84000	.71538	.63000
TOTAL COST OF ELEC	.0	61.53386	34.37108	32.59377	30.56129	29.29349

Curve 680367-A

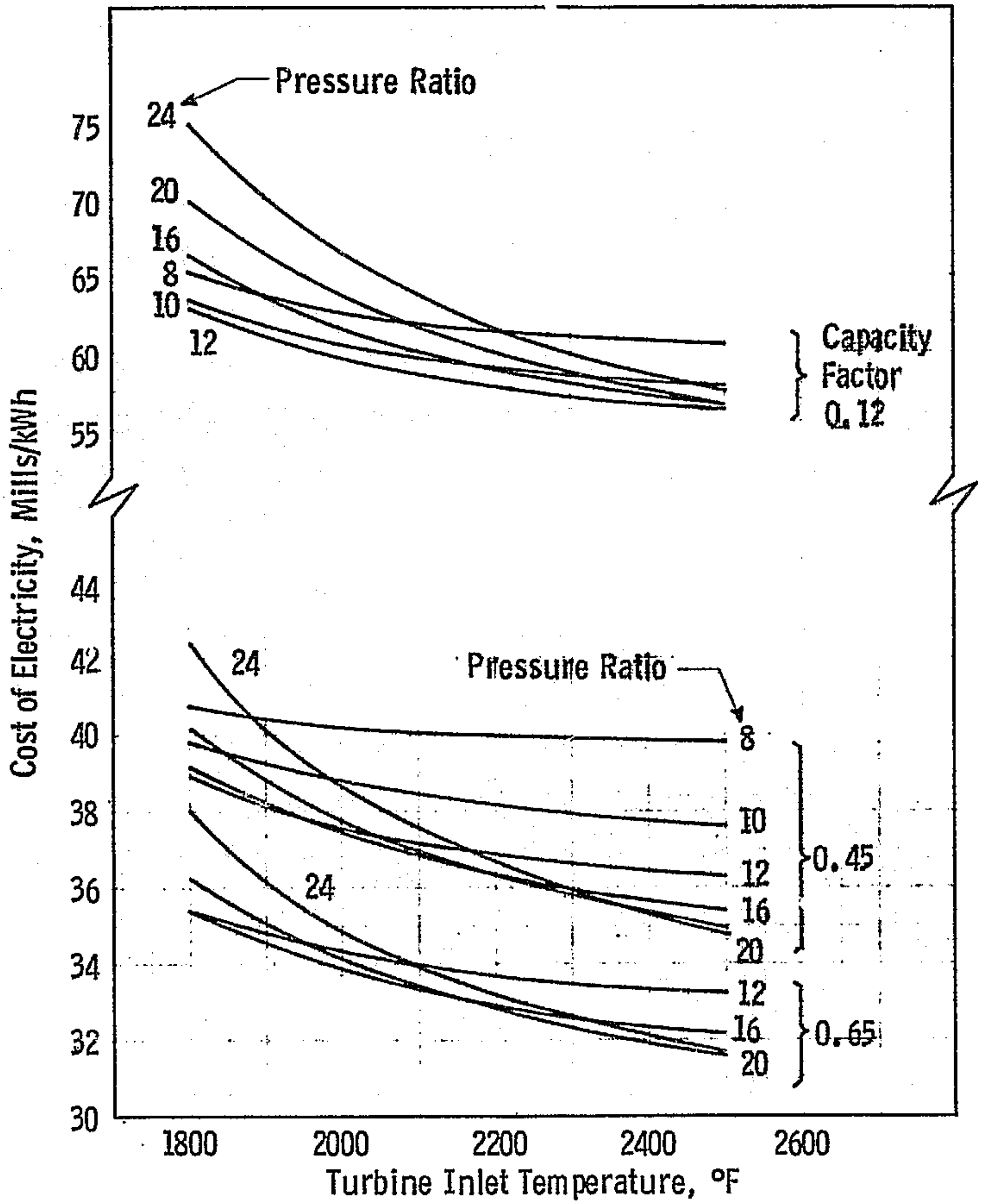


Fig. 5.47 —Effect of turbine inlet temperature and compressor pressure ratio on cost of electricity for a simple gas turbine cycle

Curve 680369-A

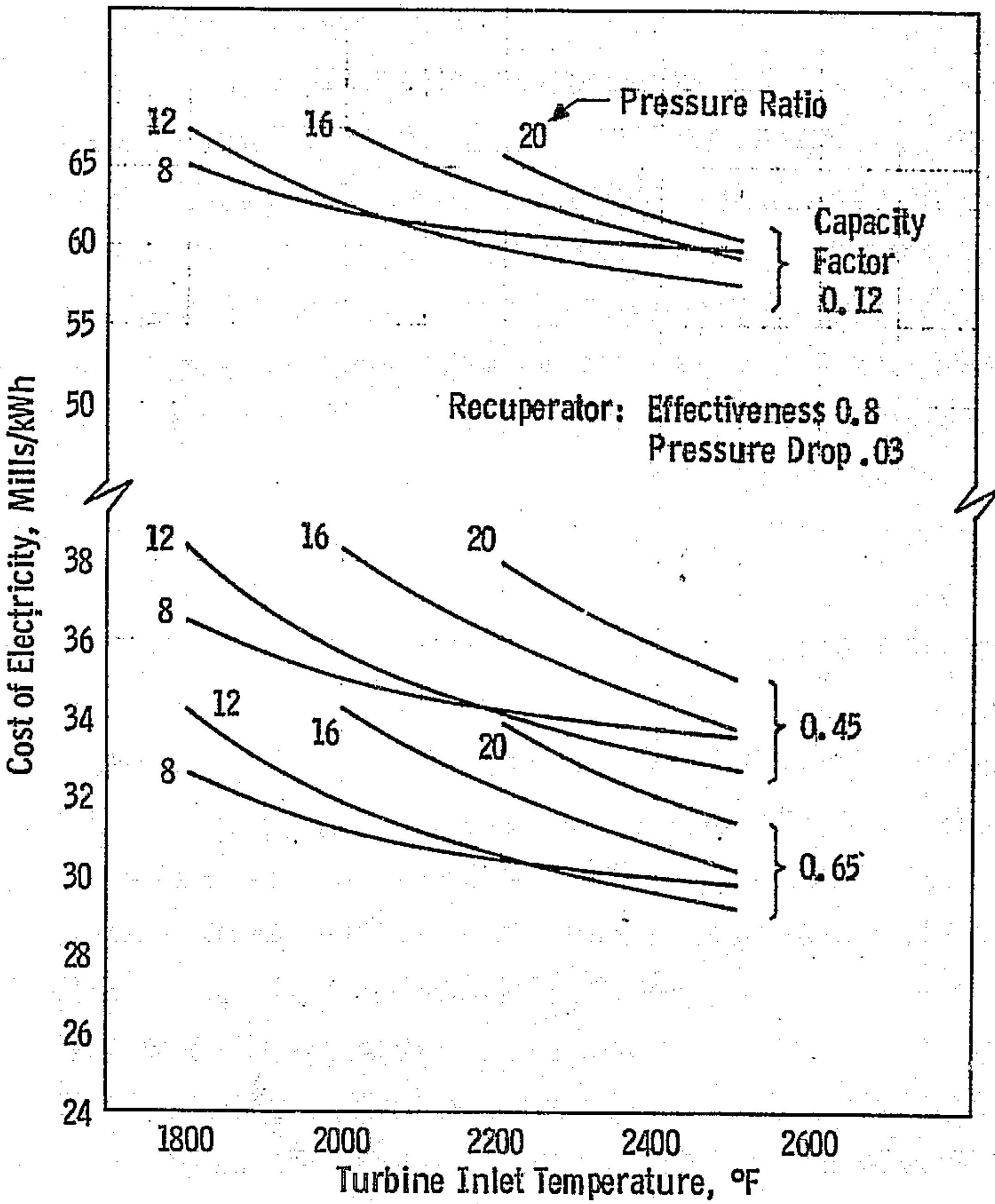


Fig. 5.48 — Effect of turbine inlet temperature and compressor pressure ratio on cost of electricity for a recuperated gas turbine cycle

for capacity factors of 12, 45, and 65%. The results show that for all capacity factors, the cost of electricity steadily decreases as turbine inlet temperature increases. Further, it indicates that higher compressor pressure ratios (above 16) generally give the lowest cost of electricity only at the highest turbine inlet temperatures investigated.

Results for similar calculations using the recuperated gas turbine cycles are shown in Figure 5.48. These results, all calculated for recuperator effectiveness of 0.8 and recuperator pressure drop of 0.03, similarly show that the cost of electricity steadily decreases as turbine inlet temperature is increased. It should be noted that the optimum pressure ratios for this recuperated cycle are generally lower than those for the simple cycle.

Figure 5.49 compares representative results of both the simple and recuperated cycle at the various capacity factor levels. At each capacity factor identical values of O&M expense were used; and for each system, compressor pressure ratios near the optimum for each system were selected. The results indicate that for these conditions the simple cycle enjoys a cost of electricity advantage at the 12% capacity factor, and the recuperated cycle enjoys the advantage at both 45 and 65% capacity factor.

All of the above studies were performed in conjunction with the use of conventionally air-cooled turbine blading. Additional attention was focused on the application of ceramic turbine blading. The results of this work are shown in Figure 5.50. Two levels of ceramic blading implementation have been introduced. First, ceramic stationary vanes in conjunction with air-cooled rotating blading have been considered; and second, both ceramic stationary vanes and rotating blading have been utilized. Each case has been considered at turbine inlet temperatures of 1478 and 1644°K (2200 and 2500°F). Cost of electricity results plotted against compressor pressure ratio indicate an optimum value of pressure ratio at 1478°K (2200°F) turbine inlet temperature of near 10 to 1. At 1644°K (2500°F) turbine inlet temperature, the optimum value is 12 to 1.

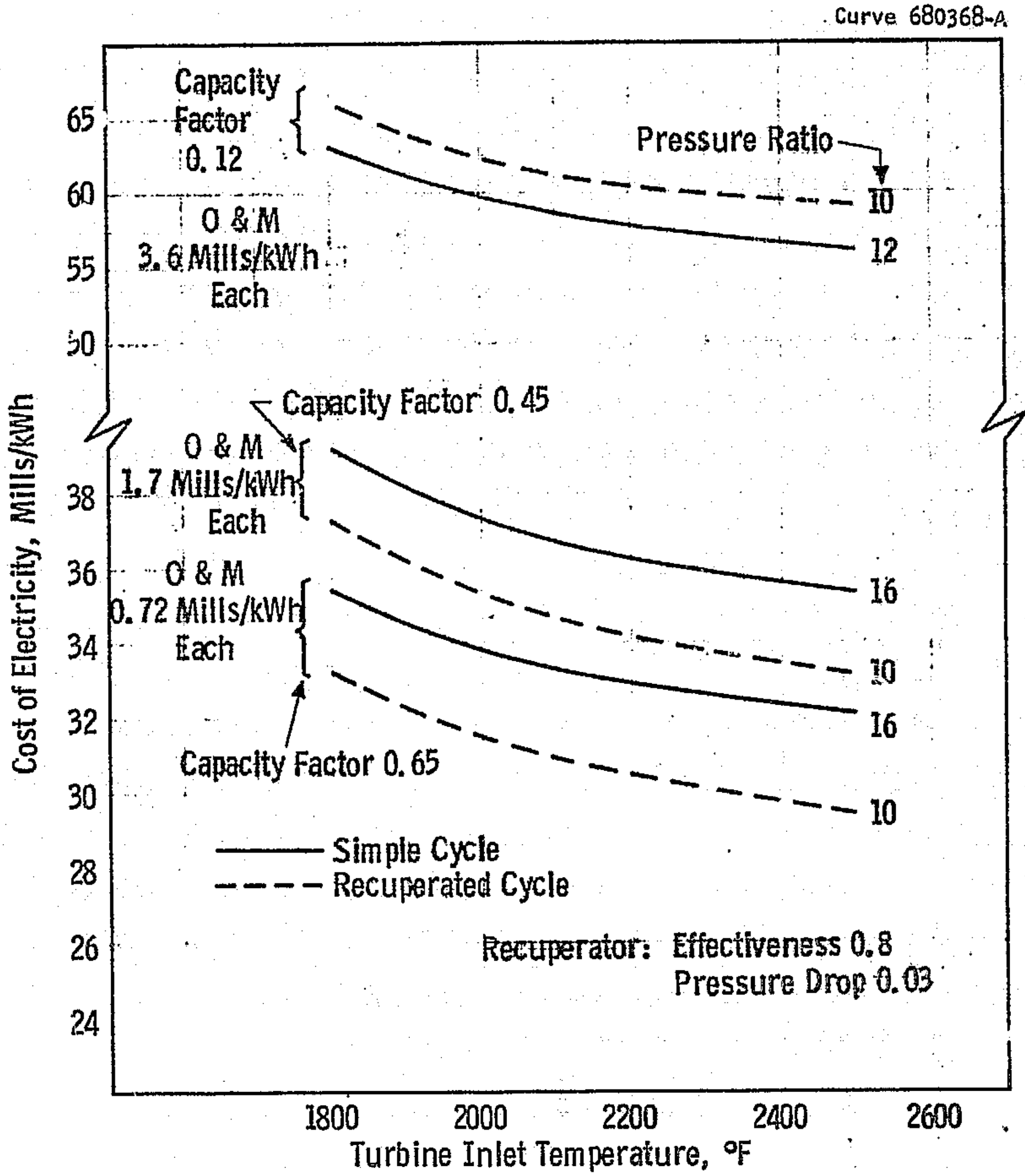


Fig. 5.49 —Effect of turbine inlet temperature on the cost of electricity for simple and recuperated gas turbine cycles using equal operating and maintenance costs

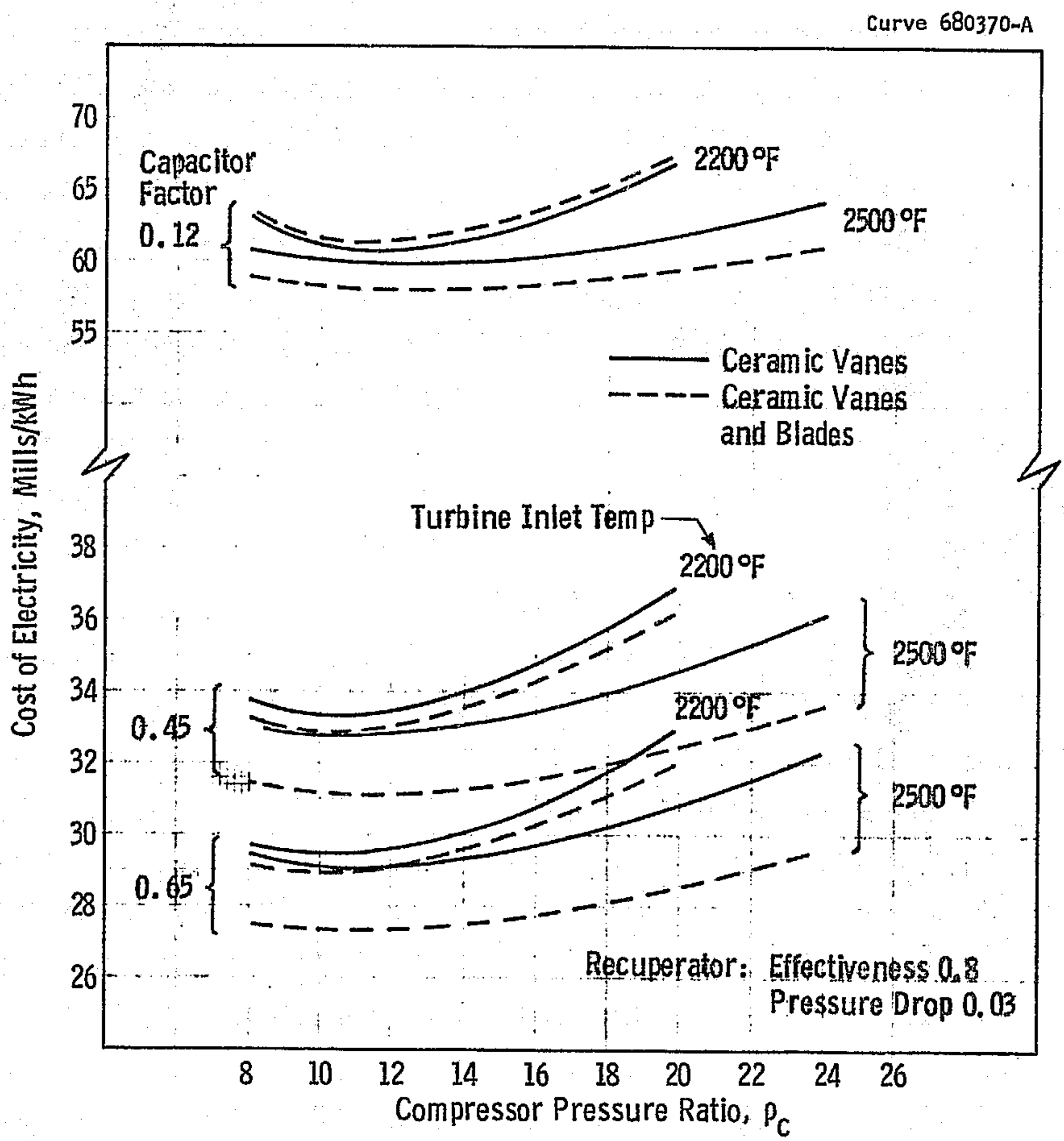


Fig. 5.50 —Effect of ceramic blading turbine inlet temperature and compressor pressure ratio on cost of electricity for a recuperated gas turbine cycle

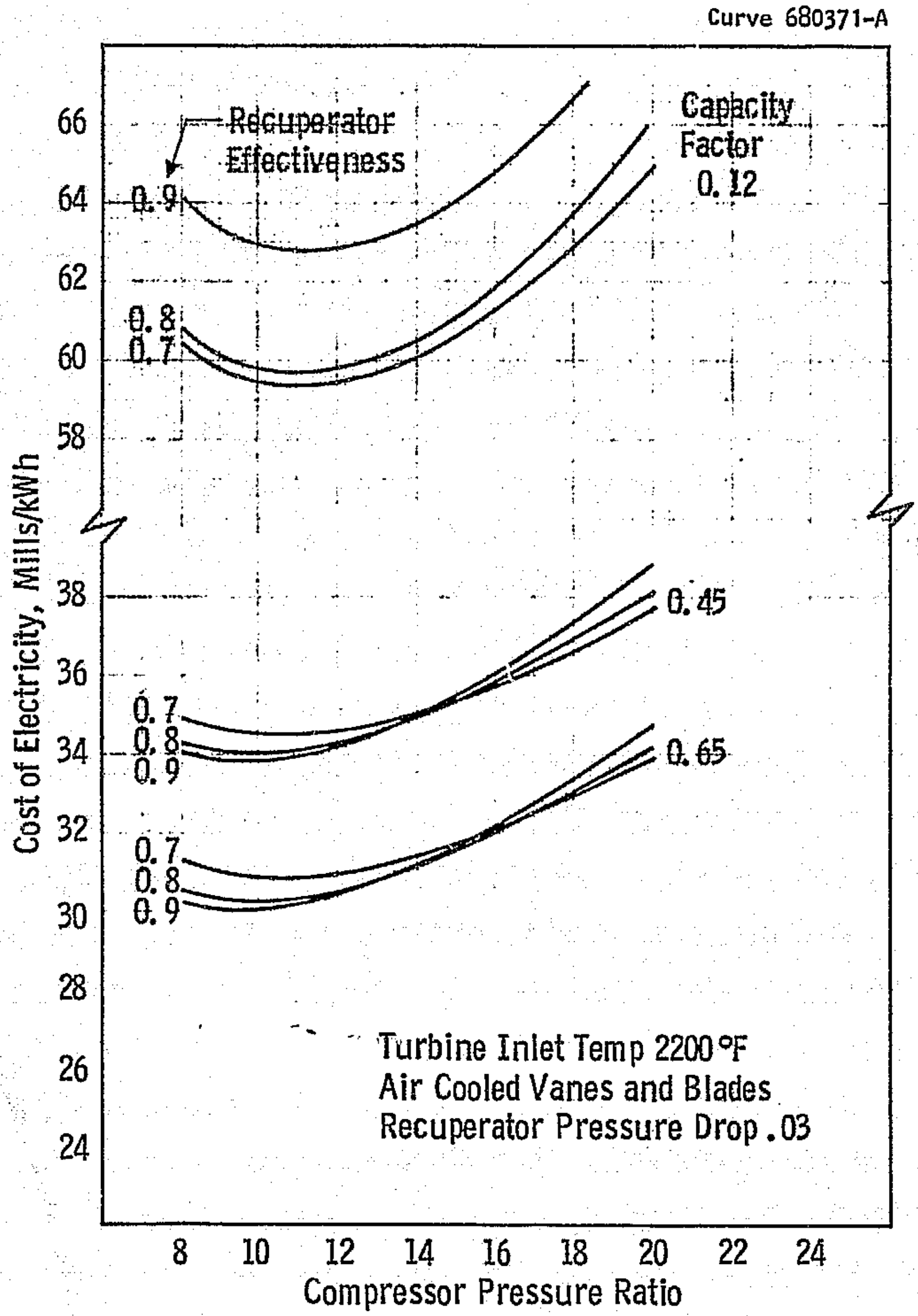


Fig. 5.51—Influence of recuperator effectiveness and compressor pressure ratio on cost of electricity for a recuperated gas turbine cycle

In nearly all cases the use of both ceramic vanes and blades yields a lower calculated cost of electricity than does the use of ceramic vanes alone.

The influence of recuperator effectiveness on the cost of electricity has been investigated for a turbine inlet temperature of 1478°K (2200°F) used in conjunction with air-cooled vanes and blades. The results plotted in Figure 5.51 show the cost of electricity versus compressor pressure ratio for three values of capacity factor. It is evident that capacity factor plays a significant role in determining optimum recuperator effectiveness. A closer look at the influence of recuperator effectiveness is shown in Figure 5.52. This curve for 1478°K (2200°F) turbine inlet temperature and 10 to 1 compressor pressure ratio shows that for a 45% capacity factor operation, the optimum recuperator effectiveness is 0.83; and for a 12% capacity factor, the optimum value is 0.73.

The use of compressor intercooling in conjunction with recuperation has been studied at a turbine inlet temperature of 1478°K (2200°F). In this analysis, compressor pressure ratio was varied, and recuperator effectiveness was held constant at 0.8. The results of this calculation, as compared with the corresponding nonintercooled cycle variation, are shown on Figure 5.53. The first significant result of this comparison is that compressor pressure ratio optimizes at much higher values for the intercooled cycle, the optimum being 20 to 1 as compared with 10 to 1 for the nonintercooled case. The second important result is that optimum cost of electricity is generally lower for the intercooled case than for the nonintercooled variation.

Natural resource requirements consisting of coal requirements and land usage have been calculated for each parametric point. These results are given in Table 5.10. The coal usage rates for this tabulation are based on initial amounts required prior to coal processing.

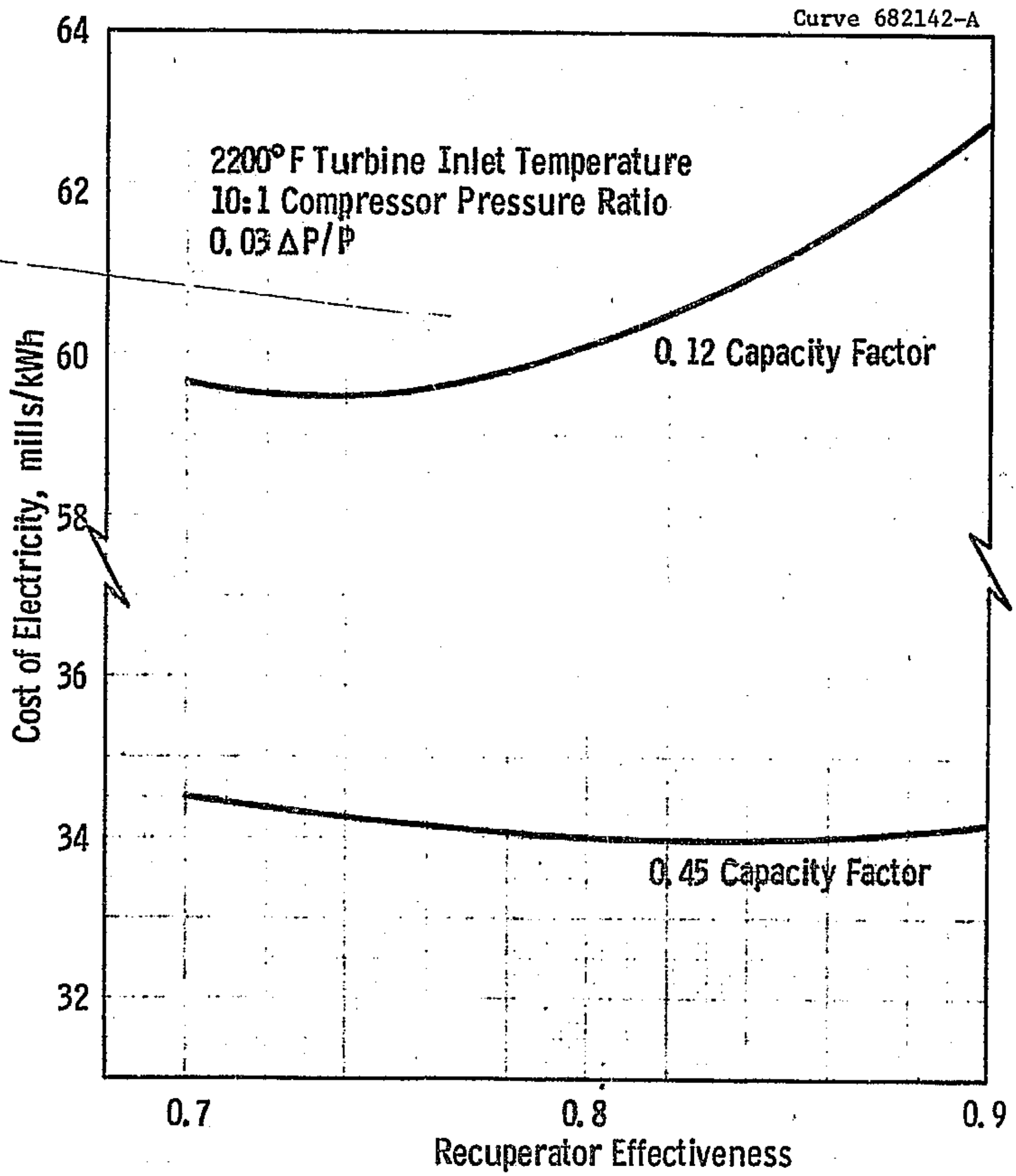


Fig. 5.52 —Influence of recuperator effectiveness on cost of electricity

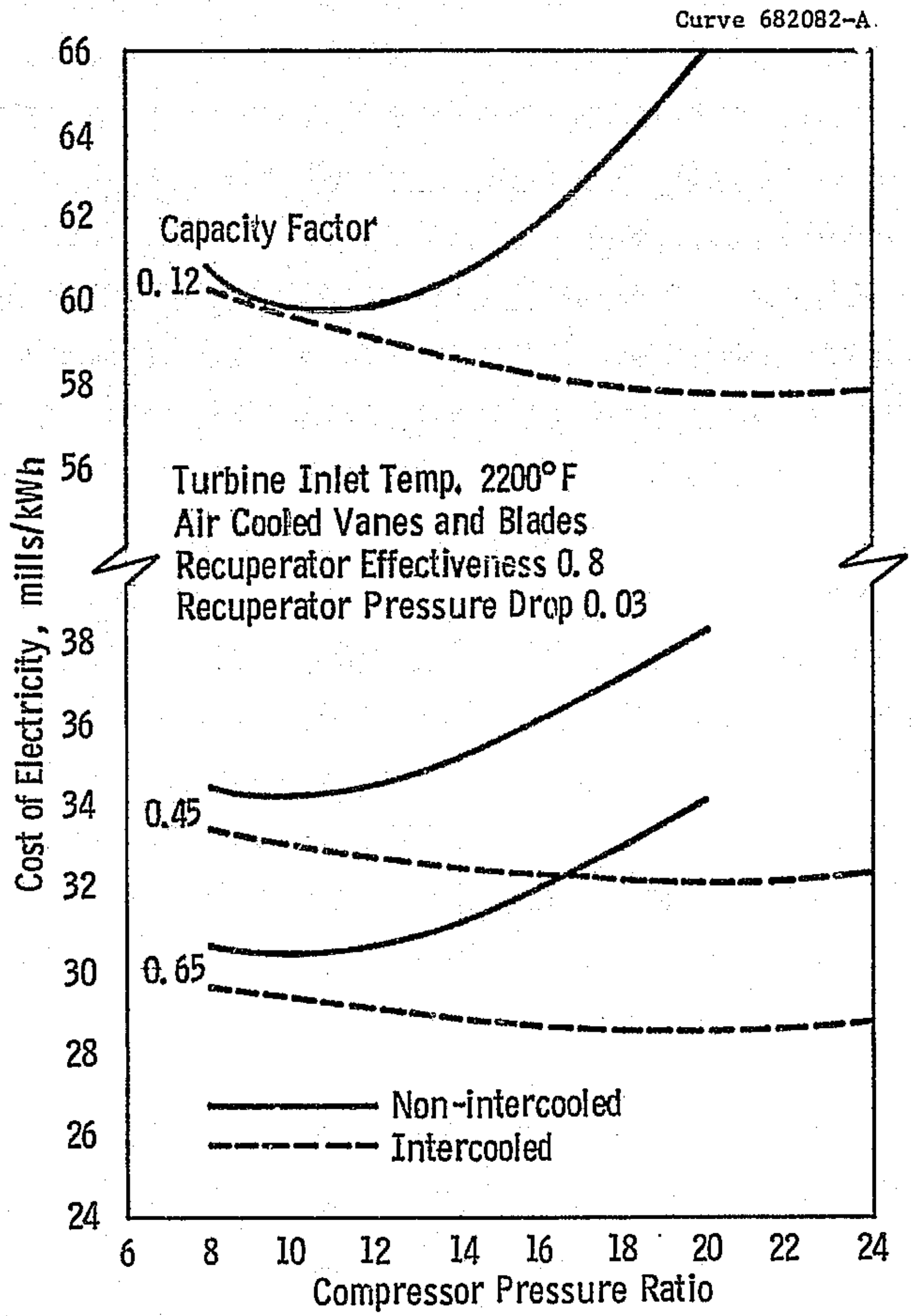


Fig. 5.53 —Recuperated cycle cost of electricity comparison intercooled and non-intercooled cycles

Table 5.10 OPEN CYCLE GAS TURBINE NATURAL RESOURCE REQUIREMENTS

PARAMETRIC POINT	1	2	3	4	5	6	7	8
COAL, LB/KW-HR	1.66000	2.52682	2.27195	2.13388	2.05825	2.00111	2.02045	2.09189
SORBANT OR SEED,LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.000	.000	.000	.000	.000
COOLING WATER	.000	.000	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP ,	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/100MWE	10.13	12.26	11.91	11.85	11.95	12.42	13.17	14.17
MAIN PLANT	10.13	12.26	11.91	11.85	11.95	12.42	13.17	14.17
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	.00	.00	.00	.00	.00	.00	.00

PARAMETRIC POINT	9	10	11	12	13	14	15	16
COAL, LB/KW-HR	2.24462	2.09959	2.01655	1.97983	1.92731	1.95678	2.23026	2.08009
SORBANT OR SEED,LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.000	.000	.000	.000	.000
COOLING WATER	.000	.000	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP ,	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/100MWE	10.88	10.75	10.76	11.01	11.46	12.07	10.10	9.92
MAIN PLANT	10.88	10.75	10.76	11.01	11.46	12.07	10.10	9.92
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	.00	.00	.00	.00	.00	.00	.00

PARAMETRIC POINT	17	18	19	20	21	22	23	24
COAL, LB/KW-HR	1.99158	1.90045	1.87376	1.87938	2.22314	2.06775	1.97278	1.87097
SORBANT OR SEED,LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.000	.000	.000	.000	.000
COOLING WATER	.000	.000	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP ,	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/100MWE	9.87	10.00	10.29	10.68	9.20	8.99	8.90	8.91
MAIN PLANT	9.87	10.00	10.29	10.68	9.20	8.99	8.90	8.91
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	.00	.00	.00	.00	.00	.00	.00

PARAMETRIC POINT	25	26	27	28	29	30	31	32
COAL, LB/KW-HR	1.82949	1.91940	1.78157	1.77955	1.82046	1.89014	1.70699	1.72151
SORBANT OR SEED,LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.000	.000	.000	.000	.000
COOLING WATER	.000	.000	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP ,	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/100MWE	9.06	9.30	12.59	11.92	12.09	12.16	11.14	10.97
MAIN PLANT	9.06	9.30	12.59	11.92	12.09	12.16	11.14	10.97
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	.00	.00	.00	.00	.00	.00	.00

Table 5.10
Continued

OPEN CYCLE GAS TURBINE NATURAL RESOURCE REQUIREMENTS

PARAMETRIC POINT	33	34	35	36	37	38	39	40
COAL, LB/KW-HR	1.76413	1.89413	1.66264	1.68498	1.77361	1.89585	1.62811	1.60642
SORBANT OR SEED, LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.000	.000	.000	.000	.000
COOLING WATER	.000	.000	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/100MWE	10.96	11.17	10.34	10.06	10.15	10.41	9.44	9.19
MAIN PLANT	10.96	11.17	10.34	10.06	10.15	10.41	9.44	9.19
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	.00	.00	.00	.00	.00	.00	.00

PARAMETRIC POINT	41	42	43	44	45	46	47	48
COAL, LB/KW-HR	1.61303	1.66706	1.74547	1.84293	1.74208	1.71916	1.72863	1.79390
SORBANT OR SEED, LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.000	.000	.000	.000	.000
COOLING WATER	.000	.000	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/100MWE	9.08	9.06	9.18	9.39	10.33	10.12	10.06	10.14
MAIN PLANT	9.08	9.06	9.18	9.39	10.33	10.12	10.06	10.14
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	.00	.00	.00	.00	.00	.00	.00

PARAMETRIC POINT	49	50	51	52	53	54	55	56
COAL, LB/KW-HR	1.89757	1.58251	1.60027	1.64089	1.75279	1.89413	1.65300	1.65213
SORBANT OR SEED, LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.000	.000	.000	.000	.000
COOLING WATER	.000	.000	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/100MWE	10.41	10.35	10.14	10.07	10.15	10.41	10.29	10.09
MAIN PLANT	10.41	10.35	10.14	10.07	10.15	10.41	10.29	10.09
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	.00	.00	.00	.00	.00	.00	.00

PARAMETRIC POINT	57	58	59	60	61	62	63	64
COAL, LB/KW-HR	1.67542	1.76512	1.89673	1.67195	1.66839	1.69316	1.78218	1.90507
SORBANT OR SEED, LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.000	.000	.000	.000	.000
COOLING WATER	.000	.000	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/100MWE	10.02	10.11	10.37	10.39	10.17	10.11	10.19	10.45
MAIN PLANT	10.02	10.11	10.37	10.39	10.17	10.11	10.19	10.45
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	.00	.00	.00	.00	.00	.00	.00

Table 5.10 OPEN CYCLE GAS TURBINE NATURAL RESOURCE REQUIREMENTS

Continued

PARAMETRIC POINT	65	66	67	68	69	70	71	72
COAL, LB/KW-HR	1.58772	1.55808	1.53917	1.52880	1.53698	1.54857	1.56787	1.56944
SORBANT OR SEED,LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	13.462	14.368	16.046	17.287	18.492	.000	.000
COOLING WATER	.000	.000	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP ,	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	13.46231	14.36756	16.04561	17.28722	18.49169	.00000	.00000
TOTAL LAND ACRES/100MWE	9.81	25.90	24.96	27.79	30.56	30.10	9.81	9.59
MAIN PLANT	9.81	9.47	9.23	8.99	8.80	8.71	9.81	9.59
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	16.43	15.73	18.80	21.77	21.40	.00	.00

PARAMETRIC POINT	73	74	75	76	77	78	79	80
COAL, LB/KW-HR	1.59175	1.66529	1.76562	1.57259	1.55388	1.56123	1.60725	1.67731
SORBANT OR SEED,LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.000	.000	.000	.000	.000
COOLING WATER	.000	.000	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP ,	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/100MWE	9.51	9.54	9.72	9.13	8.89	8.77	8.73	8.82
MAIN PLANT	9.51	9.54	9.72	9.13	8.89	8.77	8.73	8.82
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	.00	.00	.00	.00	.00	.00	.00

PARAMETRIC POINT	81	82	83	84	85	86	87	88
COAL, LB/KW-HR	1.76165	1.50467	1.50974	1.53112	1.59742	1.68952	1.43348	1.42566
SORBANT OR SEED,LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.000	.000	.000	.000	.000
COOLING WATER	.000	.000	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP ,	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/100MWE	8.98	9.47	9.25	9.16	9.15	9.29	8.43	8.19
MAIN PLANT	8.98	9.47	9.25	9.16	9.15	9.29	8.43	8.19
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	.00	.00	.00	.00	.00	.00	.00

PARAMETRIC POINT	89	90	91	92	93	94	95	96	97
COAL, LB/KW-HR	1.43217	1.45736	1.51325	1.58211	1.66000	1.30089	1.48535	1.43524	1.31884
SORBANT OR SEED,LB/KW-HR	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.000	.000	.000	.496	.456	.414
COOLING WATER	.000	.000	.000	.000	.000	.000	.494	.454	.410
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP ,	.00000	.00000	.00000	.00000	.00000	.00000	.00164	.00191	.00328
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/100MWE	8.06	7.96	7.99	8.08	10.13	3.73	90.13	87.82	62.56
MAIN PLANT	8.06	7.96	7.99	8.08	10.13	3.73	52.18	51.13	30.89
DISPOSAL LAND	.00	.00	.00	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	.00	.00	.00	.00	.00	37.95	36.69	31.[illegible]

@BRKPT PRINT$

5.7 Conclusions and Recommendations

5.7.1 Conclusions

An analysis of the recuperated open-cycle gas turbine system in comparison with the other ECAS Task I power generation concepts indicates that the simple cycle, recuperated cycle, and recuperated cycle with intercooling are lowest in cost of electricity over a wide range of intermediate- and low-capacity factors.

Conclusions regarding identification of optimum configurations within the scope of the recuperated gas turbine cycle can be drawn with respect to several criteria.

It was determined that cost of electricity is a steadily decreasing function with progressively higher turbine inlet temperatures. This result was found to apply to both simple and recuperated cycles (turbine inlet temperature variations were not studied with the intercooled recuperated cycle). Further, up to the maximum turbine inlet temperatures studied, 1644°K (2500°F), no minima in the cost of electricity versus turbine inlet temperature curves were found.

Selection of compressor pressure ratio for a minimum cost of electricity is a function of several variables, the principal ones of which are turbine inlet temperature, cycle configuration and capacity factor. For the simple cycle at 12% capacity factor, optimum pressure ratios for turbine inlet temperatures 1478 to 1644°K (2200 to 2500°F) lie in the range of 12 to 16 to 1. For the nonintercooled recuperated-cycle configuration at a 1478°K (2200°F) turbine inlet temperature and 45% capacity factor the optimum compressor pressure ratio is approximately 10 to 1, while at 1644°K (2500°F) and the same capacity factor the optimum is 12 to 1. The recuperated cycle with compressor intercooling has markedly higher optimum compressor pressure ratios. At a turbine inlet temperature of 1478°K (2200°F), it was determined that the optimum compressor pressure ratio is 20 to 1.

Of the recuperator parameters studied, recuperator effectiveness has the most significant impact on the cost of electricity. In turn, selection of recuperator effectiveness for minimum cost of electricity is strongly influenced by power generation capacity factor, as discussed in Section 5.6. It is concluded that since the recuperated cycle is ideally suited for intermediate duty, the optimum recuperator effectiveness identified for 45% capacity factor (recuperator effectiveness 0.83) should be used for further conceptual design and development assessment work.

Related studies have shown the last-row turbine blade to be a key limiting item in higher-temperature design considerations. Due to the relatively low optimum compressor pressure ratio of the nonintercooled recuperated cycle and the corresponding higher exhaust temperatures, the potential problem is especially important. Although not explicitly determined in this study, it has been tentatively concluded that uncooled last-row turbine blades of conventional materials would not have sufficient strength and life for operation at higher temperature conditions than 1478°K (2200°F) at a 10-to-1 compressor pressure ratio. Higher temperature recuperated-cycle operation with the size of units under consideration will in all likelihood require a breakthrough in materials development, such as fiber-reinforced composite blading materials.

The performance and cost results for the intercooled option are most encouraging. Relatively little optimization of parameters was performed, however (turbine inlet temperature variations were not considered; the effect of water condensation in the compressor was not considered; and a complete turbomachine cross-sectional arrangement drawing was not prepared). Further work in defining more completely the conceptual plant layout would be most useful.

5.7.2 Recommendations

In order to realize the potential benefits of the recuperated open gas turbine cycle and its associated variations, development work must proceed in the following areas:

- A tension-braze plate-fin recuperator capable of low-capacity factor cyclic operation with low maintenance requirements at turbine exhaust temperatures to 922°K (1200°F) is not currently commercially available. Development of such a unit will be required.

- Turbine blade air-cooling techniques, capable of continuous operation to at least 1644°K (2500°F) or higher must be developed to achieve maximum benefit with the recuperated cycle.
- Material developments in the areas of turbine blading and combustion section components will be required to realize the benefits that accrue from minimizing the expenditure of cooling air. Recommended areas for development include the application of ceramics to turbine blading and combustion section components.
- It is recommended that composite fiber reinforced turbine blade development be initiated for eventual application in last-row turbine blade designs.
- Preparation of a more complete conceptual design study of a recuperated, intercooled gas turbine power plant is recommended. To be included in such a study would be a detailed engine cross-sectional design, selected thermodynamic parameter variation, and consideration of specific operational details such as compressor condensation.

5.8 References

5.1 B. F. Dodge. Chemical Engineering Thermodynamics. New York: McGraw-Hill Book Company, 1944.

5.2 T. L. Kang, L. J. Hirth, K. A. Kobe, and J. J. McKelta. "Pressure-Volume-Temperature Properties of Sulfur Dioxide," Journal of Chemical and Engineering Data, Vol. 6: 2 (April 1961), pp. 220-226.

5.3 E. I. DuPont de Nemours and Company. "Thermodynamic Properties of FREON[R] 12 Refrigerant (Dichlorodifluoromethane)," Pamphlet T-12, 1956.

5.4 B. J. McBride, S. Heimal, J. G. Ehlers, and S. Gordon, "Thermodynamic Properties of 6000°F for 210 Substances Involving the First Eighteen Elements," NASA Report SP-3001, 1963.

5.5 J. R. West and G. P. Giusti, "The Thermodynamic Properties of SO_2," Journal of Physical Chemistry, Vol. 54, (1950), pp. 601-605. (without tables); Document 2708, American Documentation Institute (with tables).

5.6 T. L. Kang and J. J. McKetta, "Application of Benedict-Webb-Rubin Equation of State to SO_2," Journal of Chemistry and Engineering Data Vol. 6, 2 (April, 1961), pp. 227-228.

5.7 T. L. Kang and J. J. McKetta, "Thermodynamic Properties of SO_2," Journal A.I.Ch.E., Vol. 7:3 (1961), pp. 418-422. Reprint No. 59, University of Texas, Bureau of Engrg. Research (has more complete tables).

5.8 O. A. Hougen and K. M. Watson, Chemical Process Principles, New York, John Wiley and Sons, Inc., 1947.

5.9 Private Communication, Airesearch Manufacturing Company Division of the Garrett Corporation, Recuperator Pricing Variation.

☆USGPO: 1976 — 660-301