DOE/ET/15020-1634(Exect.Summm.)
(DE85004559)

PHASE II PRIMARY HEATER MODULE

Final Report for the Period February 1980—November 1983

By
John Campbell

December 1983

MASTER

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Morgantown Energy Technology Center
Morgantown, West Virginia
By
Rockwell International, Rocketdyne Division
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EXECUTIVE SUMMARY

JOHN CAMPBELL

DECEMBER 1983

CONTRACT DE-AC21-80-ET15020

ROCKWELL INTERNATIONAL, ROCKETDYNE DIVISION
6633 CANOGA AVENUE
CANOGA PARK, CALIFORNIA 91304

FOREWORD

This program was conducted by the Rocketdyne Division of Rockwell International under Contract DE-AC21-80-ET15020 for the Department of Energy (DOE) during the period February 1980 through November 1983. Major subcontractors were the Battelle Columbus Laboratories and Burns and Roe Pacific, Inc. The DOE manager who initiated the program was Carey A. Kinney, Fossil Energy Division. The program was then transferred to the Morgantown Energy Technology Center in 1982, and the DOE manager was Larry K. Carpenter. Jerry M. Friefeld was the program manager at Rocketdyne. This final report is presented in several volumes:

- RI/RD83-213 Executive Summary

  RI/RD83-213A
  - SECTION 1: Phase II Program
  - SECTION 2: Summary
  - SECTION 3: Program Organization

  RI/RD83-213B
  - SECTION 4: AFB Heat Exchanger Technology

  RI/RD83-213C
  - SECTION 5: PC Heat Exchanger Technology

  RI/RD83-213D
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  - SECTION 7: Working Fluid Corrosion Technology
  - SECTION 8: Planning for Phase III
  - SECTION 9: Interpretation of Program Results, Conclusions, and Recommendations

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  - APPENDIX A: 6' x 6' AFB Combustor/Heater Drawings
  - APPENDIX B: CCGT Cogeneration System Performance

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ABSTRACT

Research was conducted on components and subassemblies of coal-fired heaters suitable to supply the heat input to closed-cycle gas turbine-based cogeneration systems of 25 to 50 MWe electrical output.

Three concepts were researched: (1) a dry bottom, pulverized coal-fired radiant furnace heater for 1450 to 1550 F turbine inlet temperature, (2) an atmospheric pressure fluidized bed fired heater for 1450 to 1550 F, and (3) a heater employing atmospheric pressure fluidized beds in series, for 1750 F turbine inlet temperature. The series beds concept employs ceramic heating surface in its high-temperature bed.

Both laboratory and field testing was conducted on heating surface materials durability in the pulverized coal and fluidized bed environments. Burner and furnace designs were researched for pulverized coal heaters employing large quantities of flue gas recirculation to moderate the furnace heat flux. A 6' by 6' fluidized bed was assembled and tested for materials and operational research on the 1450 to 1550 F heater concept. A ceramic-to-metal joint concept was devised, fabricated and made ready for test. The conceptual commercial heater concepts were refined.

The program results indicate that each of the three heater concepts is technically feasible. The fluidized bed concepts are judged most likely to be both technically and commercially feasible. Their continued development is recommended.

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INTRODUCTION

To encourage the use of coal, instead of the relatively scarce and/or imported oil and gas fuels, the DOE has funded the development of advanced coal-fired cogeneration systems that promise better fuel economy than state-of-the-art coal-fired systems. Indirect-fired gas turbine-based systems have been appropriate candidates for this development activity. Indirect firing separates the products of fuel combustion from the gas turbine working fluid and makes possible the use of coal and other dirty fuels. The gas turbine cycle, when operated under appropriate cycle conditions, provides higher thermal efficiency than current steam turbine-based cogeneration systems. The closed-cycle gas turbine (CCGT), a particular type of indirect fired system, has the additional advantages of smaller equipment size, better part load efficiency, and greater flexibility with respect to accomodating a wide variety of working fluids and fired heater concepts than does its competing system, the indirect-fired open-cycle gas turbine (OCGT).

Prior to the conduct of the program reported herein, the DOE funded the Garrett Company and Rocketdyne to conduct Phase I studies of CCGT power and cogeneration systems and of their coal-fired heaters. These studies are summarized in Ref. 1 through 4. Both contractors found that the inherent thermodynamics of the gas turbine cycle permit significant reductions in fuel consumption as compared to steam turbine-based cogeneration systems generating the same process heat and electrical power. An indication of the range of performance available from cogeneration systems designed for a wide range of operating conditions is presented in Fig. 1. The thermodynamic superiority of the CCGT systems as compared to the 1250 psi 950 F steam turbine-based cogeneration system is demonstrated clearly. The CCGT-based system is able to exploit the existence of a process heat demand to cogenerate a relatively large amount of electrical power at very reduced fuel consumption as compared to the steam turbine-based system producing the same heat and power. The plot also brings out the strong relationship between gas turbine inlet temperature and system efficiency--the higher the temperature, the better the efficiency.

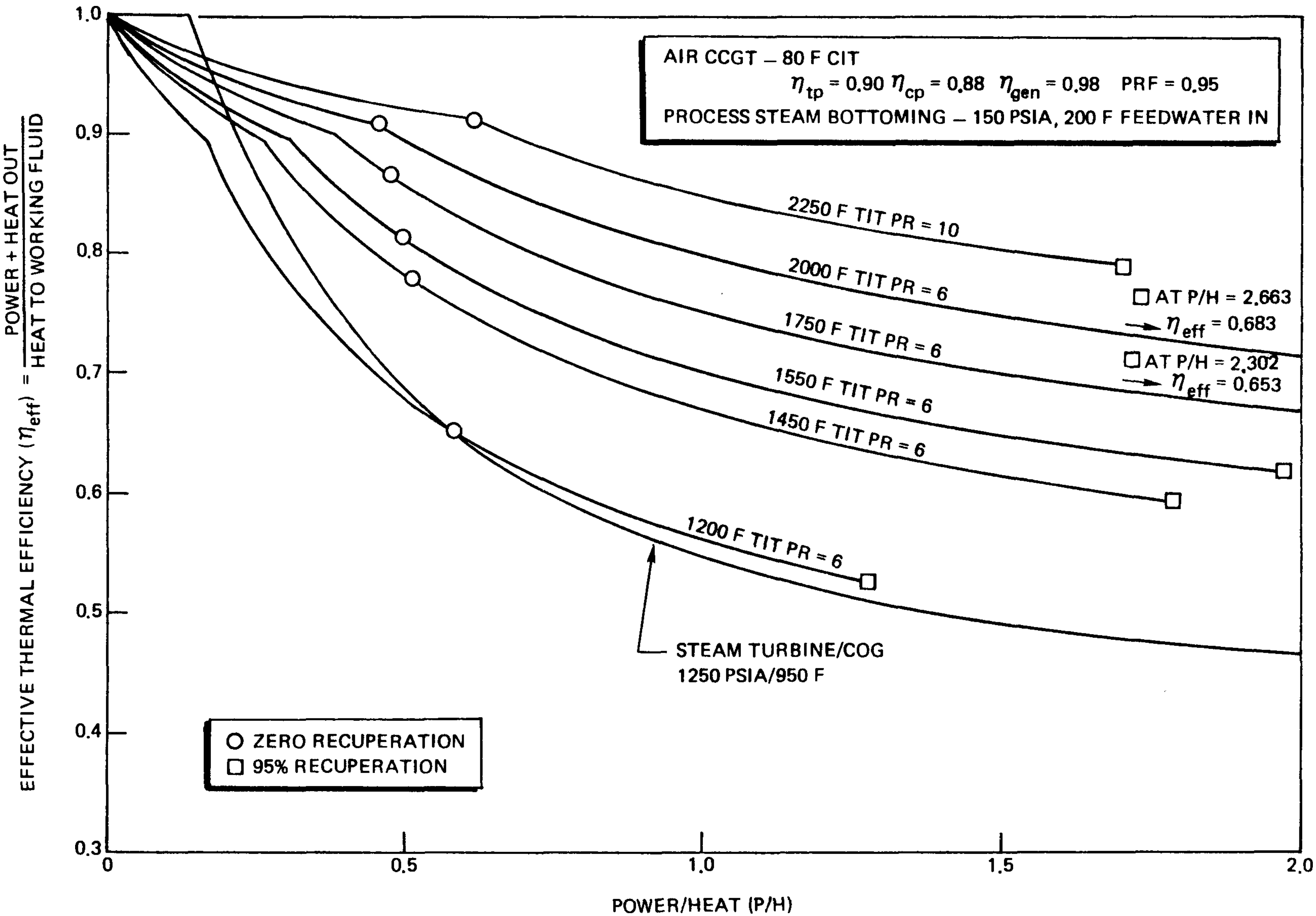


Figure 1. Performance of GT/Cogeneration Cycles (Varying Pressure Ratio and Turbine Inlet Temperature)

OBJECTIVES AND GROUND RULES

At the completion of the Phase I studies, the DOE funded Rocketdyne to conduct a Phase II R&D program on components and subassemblies of coal-fired heaters to service CCGT-based cogeneration systems. The size range was specified as that suitable for 25 to 50 MW of electrical power output. The contract specified that two different heater concepts were to be researched for the 1450 to 1550 F turbine inlet temperature range, and additionally, a heater concept employing ceramics was to be researched for the 1750 F or higher turbine temperature range. The DOE further established that none of the products of coal combustion were to be passed through a gas turbine.

Consultations with the DOE then established that the two fired heater module concepts that were to be researched for the 1450 to 1550 F working fluid temperature were the atmospheric fluidized bed (AFB) combustion system and the dry bottom pulverized coal (PC) combustion system. And the fired heater to be researched for the 1750 F working fluid service was the series atmospheric fluidized bed system.

PERIOD OF PERFORMANCE

The Phase II program covered in this report was performed during the period 13 February 1980 to 13 November 1983. A 1-year extension to the Phase II program was negotiated in November 1983. Work performed during the 1-year extension will be reported in a separate final report at the end of the extended contract period.

PROGRAM TEAM

The Rocketdyne Division of Rockwell International, as the prime contractor, directed the program and had prime contract responsibility. The other team members included:

- Battelle Columbus Laboratories, Columbus, OH
- Burns & Roe Pacific, Inc., Los Angeles, CA
- Solar Turbines International Division of Caterpillar Tractor, San Diego, CA

General Electric Company, Cincinnati, OH

General Atomic Company

Rockwell International, North American Aircraft Operations, El Segundo, CA

The Battelle Columbus Laboratories played an especially significant role in the conduct of the heater research. It participated in all aspects. The laboratories contract consumed about 25% of the resources.

PLAN OF THE PHASE II PROGRAM

The technical approach to the Phase II R&D effort was based upon (1) an analysis of the heater requirements for service in appropriately sized CCGT/cogeneration systems, (2) the selection of conceptual commercial heater designs for the service, (3) an analysis of the technical issues that require R&D in such heaters (to prepare for commercial development).

Baseline Thermodynamic Cycles

There is a wide variety of possible CCGT/cogeneration systems having the specified electrical power outputs. On the basis of Phase I studies, a generic family of CCGT/cogeneration cycles having the potential for a wide range of industrial cogeneration applications was selected to define the performance requirements of the conceptual commercial fired heater designs whose technology was to be developed during the Phase II program. One of the selected cycles is illustrated in Fig. 2.

The results of the 25 to 50 MWe CCGT/cogeneration cycle and applications studies indicated that such systems are most likely to be economically competitive when utilized in applications requiring a ratio of electrical power output to process heat output on the order of 0.5 to 1.5. Thus the probable range of heat outputs of fired heaters designed to service CCGT/cogeneration systems of 25 to 50 MWe electrical output will be equivalent to 100,000 to 600,000 pounds of steam per hour; i.e., equivalent in size to relatively large industrial boilers.

LOAD CONDITIONS

POWER, MW	25.1	24.4	13.6	14.9	24.9	14.2
HEAT, MW	23.3	23.33	20.16	19.11	21.10	21.78
P/H	1.079	1.046	0.675	0.780	1.180	0.652
	MAX P	MAX H	MIN P	MIN H	MAX P/H	MIN P/H

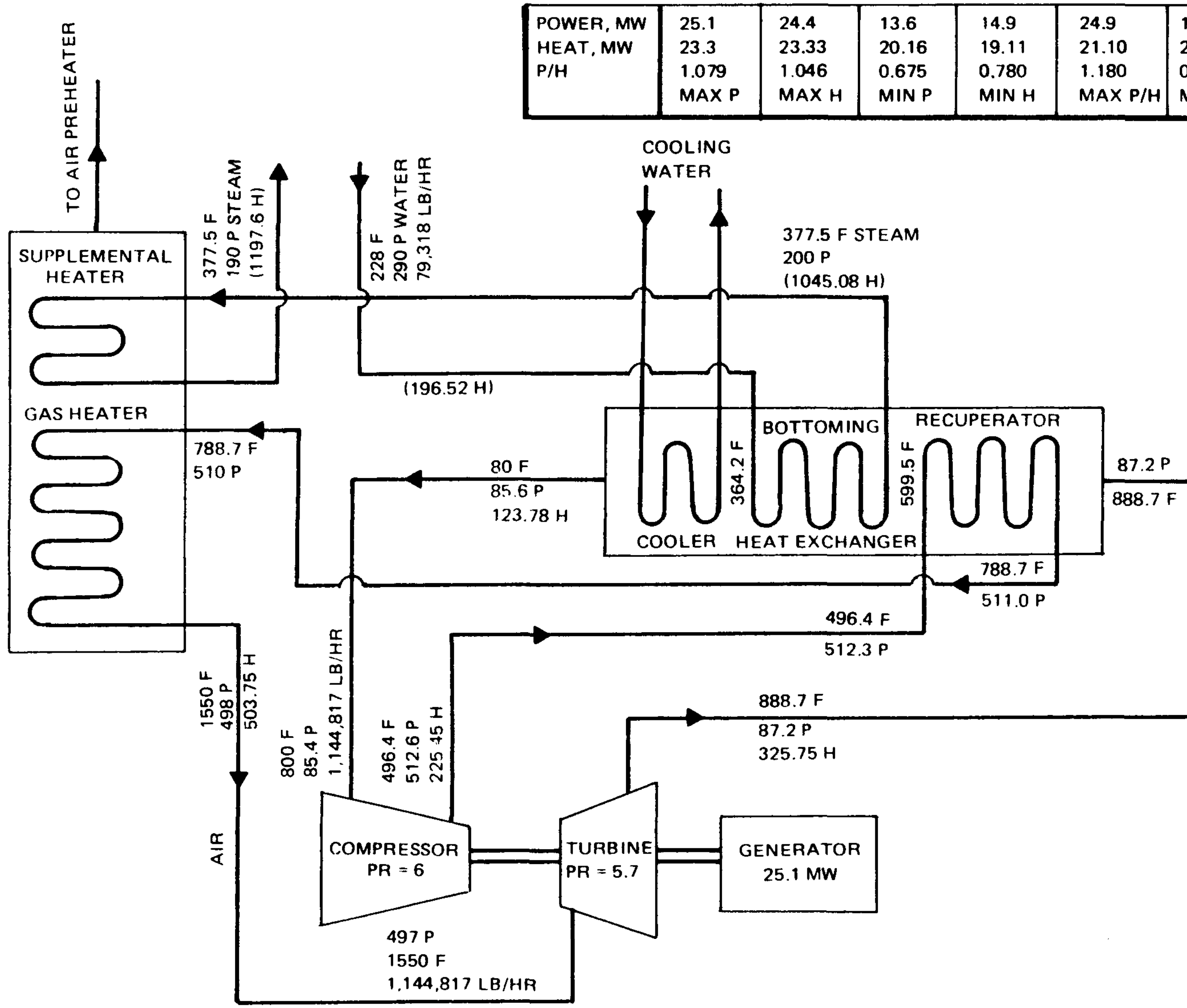


Figure 2. Generic CCGT/Cogeneration Air/Steam Cycle for AFB-Fired Heater Applications

Cycle Working Fluids

The gas turbine cycle working fluid choice affects the fired heater design and development in that it influences the heat transfer coefficients available on the working fluid side of the heat exchanger tubing, influences the heat exchanger working fluid flow area requirements and determines the corrosion/erosion environment on the working fluid side. For purposes of the Phase II research, it was decided to utilize an air working fluid for fluidized bed combustor concepts and a helium working fluid for pulverized coal-fired concepts. The greater working fluid side heat transfer coefficient available from helium (at the same $\Delta P/P$) was believed required with the PC fired heater concept to keep the furnace tube wall temperatures at an acceptable level.

Fired Heat Exchanger Conceptual Commercial Design Concepts

The three fundamental fired heater concepts that were the basis for the Phase II research are (1) dry bottom PC radiant furnace fired heater, (2) coal-fired AFB and, (3) coal-fired atmospheric fluidized beds, arranged in series, employing both a high operating temperature bed, 1850 to 2000 F, and an approximately 1650 F operating temperature bed. Each of these three concepts is consistent with the DOE instruction that none of the products of coal combustion be passed through the turbomachinery, and with the size requirement.

Dry Bottom Pulverized Coal (1450 to 1550 F Working Fluid). The conceptual commercial design of a 25 MWe dry bottom PC-fired heater is presented in Fig. 3. This concept is similar to that employed in many modern steam boilers. It differs principally in that the metal heating surface temperatures are much higher, and in that it utilizes very large quantities of exhaust gas recirculation (from the air heater inlet back to the burner windbox) in order to prevent the furnace heat flux from exceeding the capabilities of the turbine working fluid, which cools the furnace walls.

Atmospheric Fluidized Bed (1450 to 1550 F Working Fluid). The conceptual commercial design of the second 1450 to 1550 F working fluid temperature fired heater is presented in Fig. 4. This concept employs the combustion of crushed coal in a

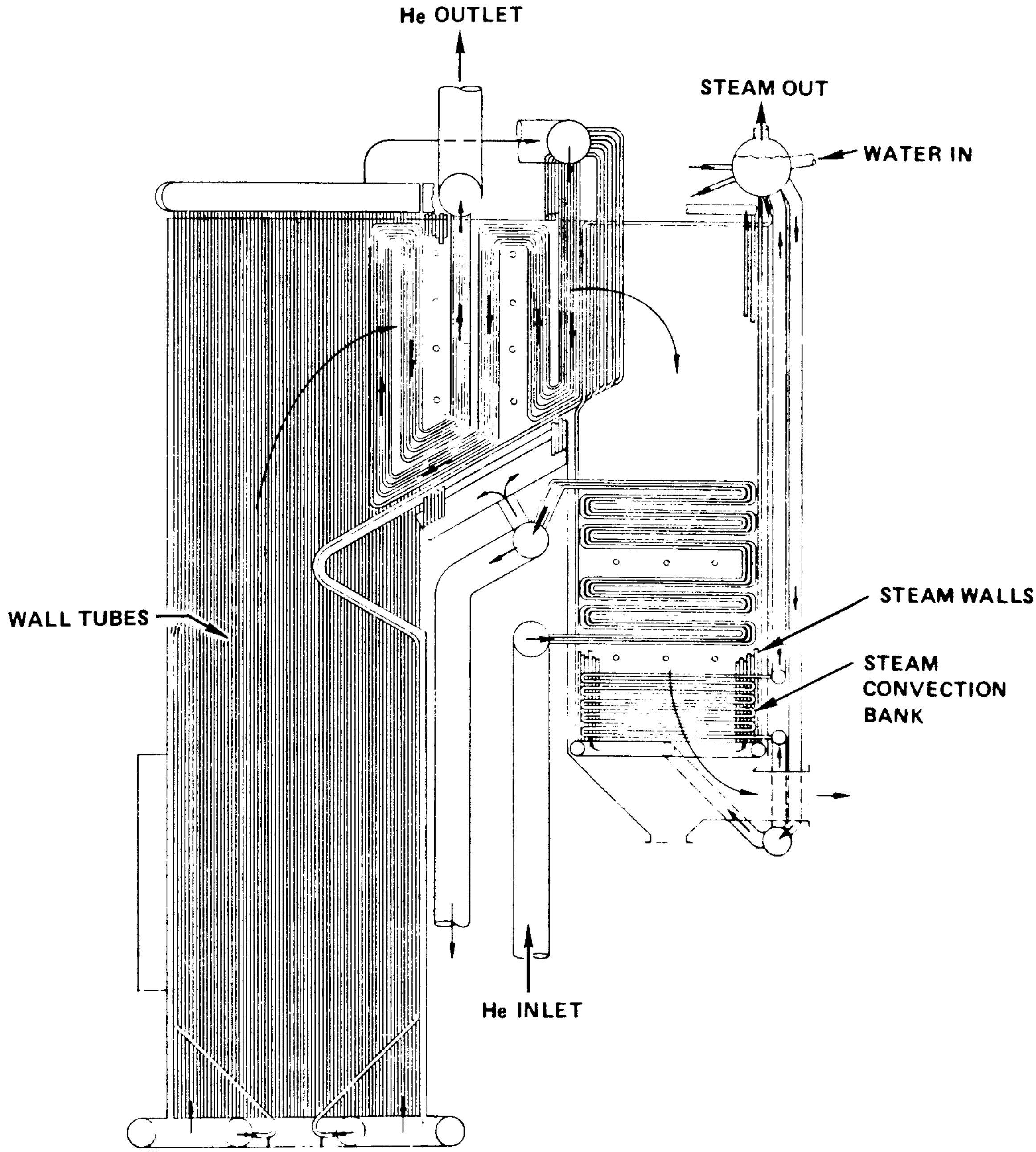


Figure 3. Conceptual Commercial Pulverized Coal-Fired CCGT Heater

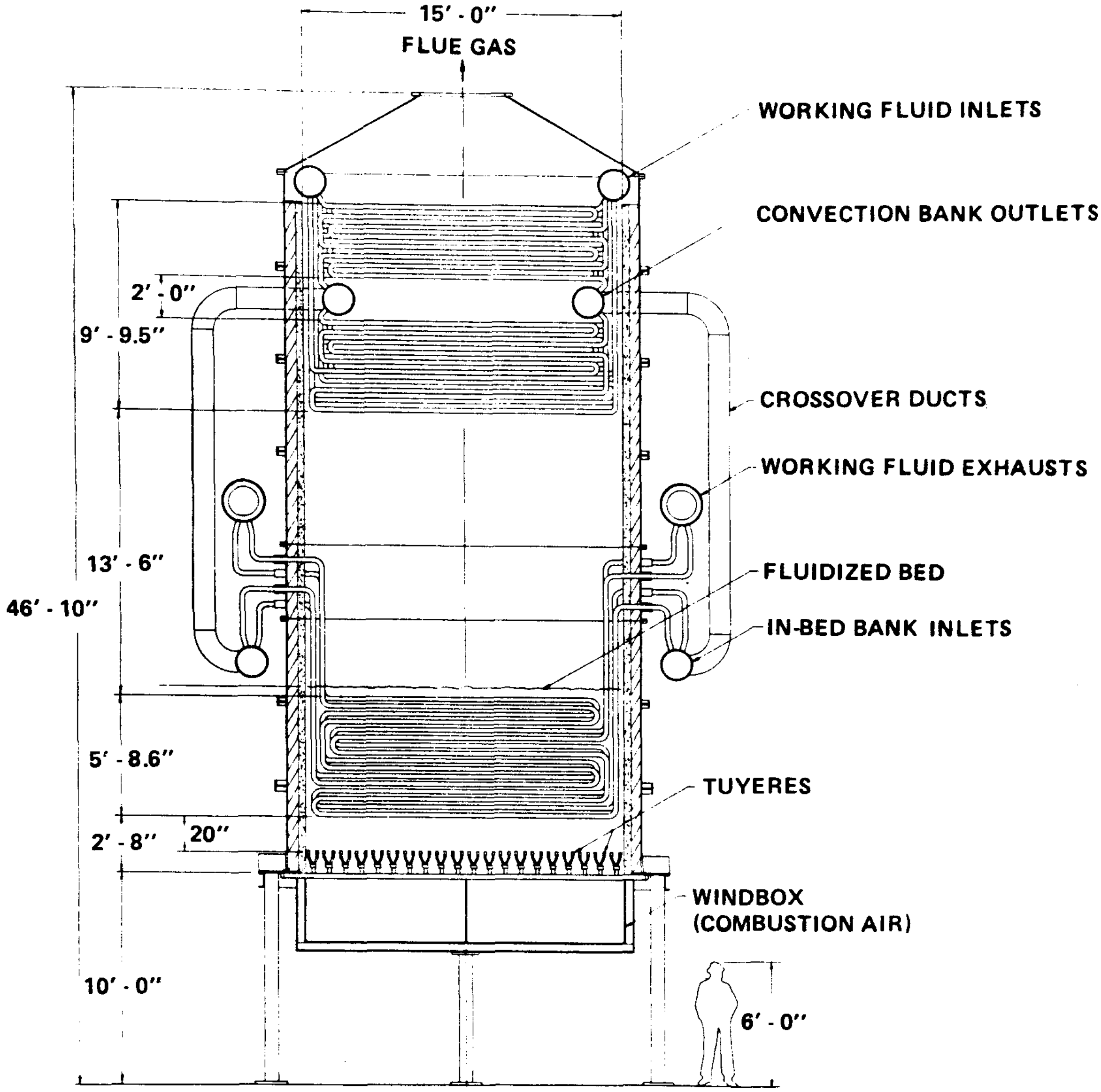


Figure 4. Conceptual Commercial CCGT Heater Fluidized Bed

fluidized bed containing limestone. Heat is transferred from the coal combustion products to the CCGT working fluid flowing through tubes within the fluidized bed and in convection surface above the fluidized bed. The design is similar to that being developed by several manufacturers for steam boiler service. The major differences derive from the much higher metal temperatures, and the nonboiling heat absorption character of the CCGT application.

Series Fluidized Beds (1750 F Working Fluid). The fired heater concept selected for development to supply a CCGT working fluid temperature of 1750 F is the series fluidized bed concept. A combustor/heat exchanger system employing this concept utilizes the fluidized bed system described above to raise the CCGT working fluid from the fired heater inlet temperature to the maximum temperature available from metallic exchanger surface (i.e., approximately 1550 F). The remainder of the heat addition required to attain the target 1750 F working fluid temperature is provided in a separate fluidized bed combustor, similar in basic operating principles to the previous combustor, but operating at a sufficiently high bed temperature to supply heat to the 1750 F working fluid, and employing ceramic materials for the heat exchanger surface. The operating temperature of this second high-temperature bed is so high that not enough of the gaseous sulfur compounds produced by the coal burned within it will be absorbed by the limestone bed material. Therefore, the exhaust gases from the high-temperature bed are routed to the inlet of the low-temperature bed to provide sufficient absorption of their sulfur oxides. A schematic of the flue gas routing is presented in Fig. 5. The conceptual commercial design of the 1750 F working fluid temperature fired heater concept is presented in Fig. 6.

PULVERIZED COAL-FIRED HEATER RESEARCH

The program for the PC-fired heater was organized to research two major technology needs:

1. Identification of alloy materials and design practices permitting the economically competitive design of fired heaters to withstand metal operating temperatures in the range of 1050 to 1600 F. This range of metal operating temperatures is seldom encountered in conventional PC-fired steam boiler systems

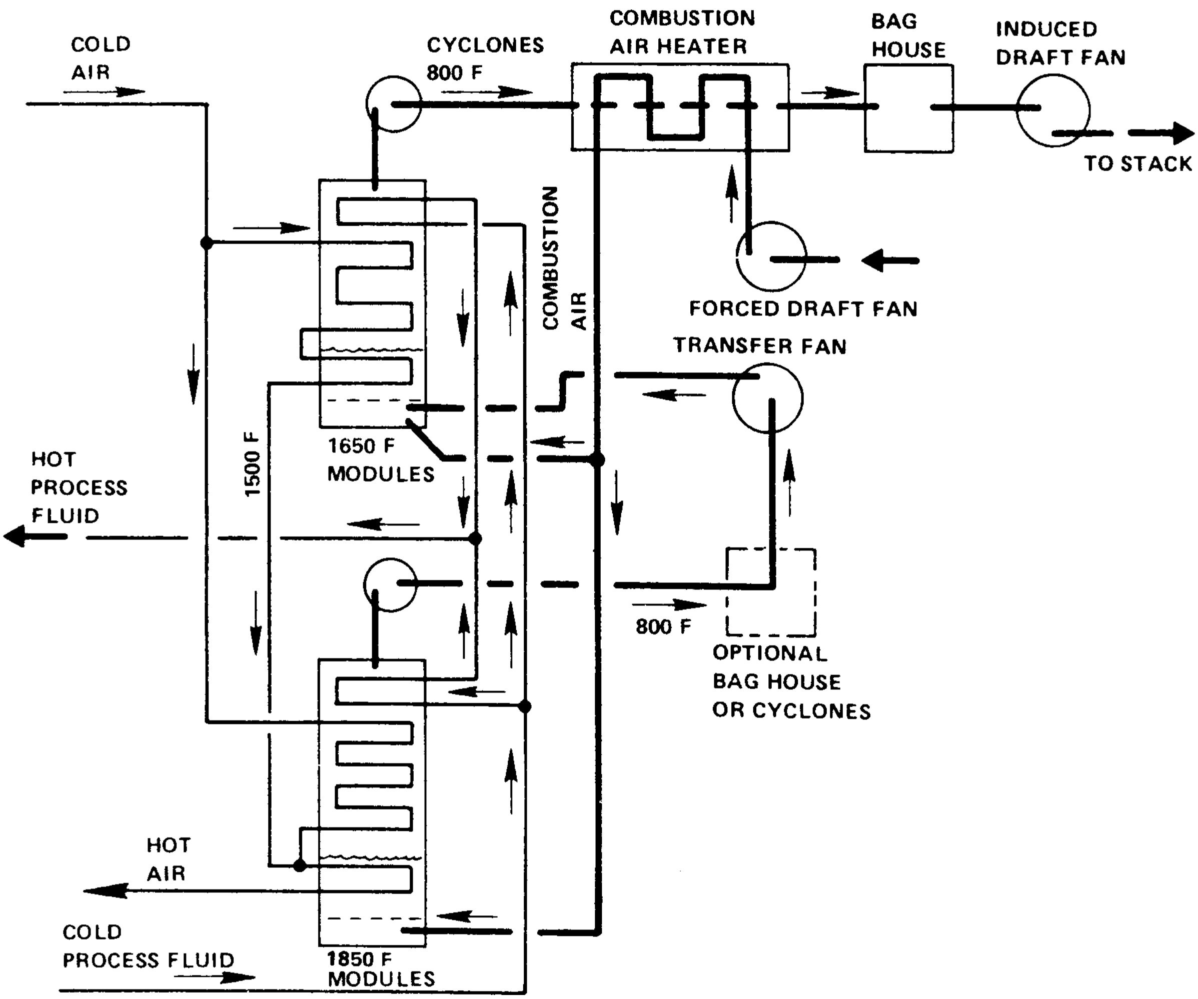


Figure 5. Series Bed-Flow Schematic

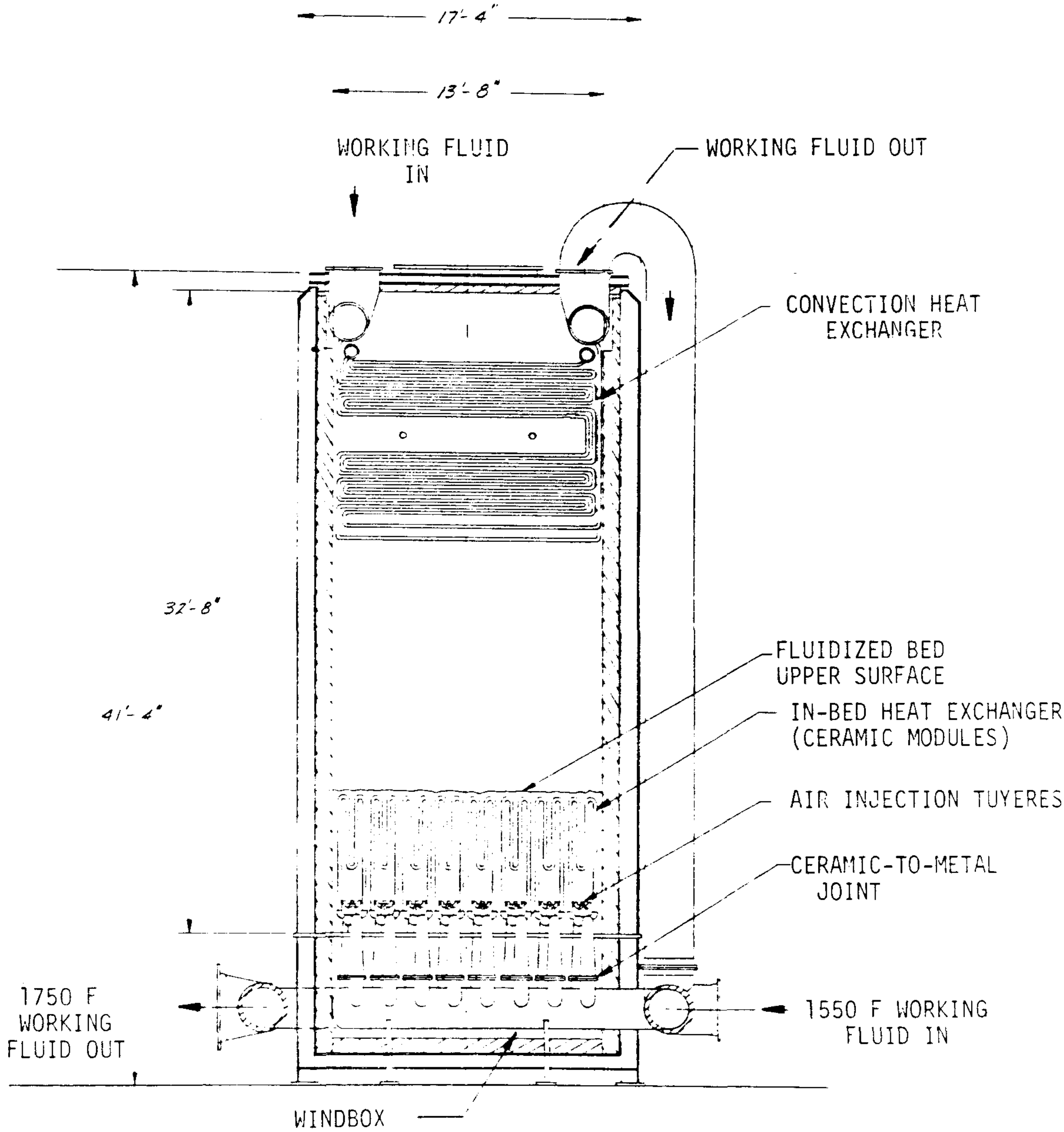


Figure 6. Conceptual Commercial Design, High-Temperature Series Bed

2. Development of design criteria to utilize flue gas recirculation and/or flue gas tempering to reduce, and to make acceptably uniform, the heat flux absorbed by the furnace walls from the PC flame. The object here is to permit the design of large, high-capacity furnaces while at the same time maintaining both peak and average heat flux rates within the absorption capabilities of furnace walls cooled by CCGT cycle working fluid

As a target for PC-fired CCGT heaters, it was desired to devise design techniques to limit the peak heat flux to less than 30,000 Btu/ft^2 hr and to limit the variation of heat flux to no greater than ±30% of average.

PC Fireside Corrosion Research

The corrosive conditions existing in present-day pulverized coal-fired boilers are understood partially. However, little information is available regarding corrosion of tube materials for service temperatures above 1350 F.

The requirements of CCGT heater service dictate that high-temperature/high-strength alloys be selected from a group of alloys (principally nickel based) for which there is scant information on corrosion resistance at the temperatures of concern. For this program, 12 alloys were selected for test as heat exchanger tube candidates, as listed in Table 1. These alloys then were tested over a range of temperatures in simulated corrosive environments in the metallurgical laboratory, and in the actual corrosive environment of operating utility boilers.

Pulverized Coal Laboratory Corrosion Tests

For the metal temperature range of 1050 to 1350 F, the susceptibility of the tube materials to sulfidation attack by an alkali iron trisulfate deposit was investigated. Test coupons were coated with an equimolar mixture of $Na_3Fe(SO_4)_3$ and $K_2Fe(SO_4)_3$, and subjected to corrosion in gas mixtures representative of the PC combustors. This particular salt composition was chosen because of its melting point (1020 F), which ensures that it will be molten at the four selected temperatures of exposure (1050, 1150, 1250, and 1350 F).

TABLE 1. COMPOSITION OF ALLOYS SELECTED FOR EVALUATION FOR PC SERVICE

ALLOY	COMPOSITION IN WEIGHT PERCENTAGE					TYPE OF SCALE
	Fe	Ni	Cr	Mo	OTHERS (Al, Ti, W, Si, Mn, C, ETC.)	
A106	98	0	0	0	BALANCE	OXIDES OF IRON
P22	94	0	2.25	1	BALANCE	OXIDES OF IRON
AISI 304	70	8	18	0	BALANCE	Cr_2O_3 + OXIDES OF IRON + NiO
AISI 347	68	10	18	0	BALANCE	Cr_2O_3 + OXIDES OF IRON + NiO
AISI 310	52	20	25	0	BALANCE	Cr_2O_3 + OXIDES OF IRON + NiO
INCONEL 671	0	53	46	0	BALANCE	Cr_2O_3
INCONEL 617	0	54	22	9.0	BALANCE	Cr_2O_3 + NiO
MINONIC 86	0	64	25	10.0	BALANCE	Cr_2O_3 + NiO
HASTELLOY X	19	47	22	9.0	BALANCE	Cr_2O_3 + NiO + OXIDES OF IRON
PE-13	19	47	22	9.0	BALANCE	Cr_2O_3 + NiO + OXIDES OF IRON
INCONEL 618E	16	55	23	0	BALANCE	Cr_2O_3 + NiO + OXIDES OF IRON
INCOLOY 800H	44	33	21	0	BALANCE	Cr_2O_3 + NiO + OXIDES OF IRON

The exposures were conducted with coupons approximately 2 by 1 by 0.2 cm in size. These were immersed in individual crucibles containing the appropriate salt mixtures. The exposures were carried out in a flue gas environment containing 3 vol % O_2, 10 vol % CO_2, 0.5 vol % SO_2, and the balance N_2. Exposure times were 100 to 500 hours. Tests were conducted at steady temperatures of 1050, 1150, 1250, and 1350 F in the alkali-iron-trisulfate deposite, and at 1650 F in a salt mixture consisting of 2 molar parts of Na_2SO_4; plus 1 molar part each of

K_2SO_4, $CaSO_4$, $MgSO_4$, and $BaSO_4$; plus .25 molar parts each of NaCl and KCl. Cycling temperature tests were conducted with the specimens exposed for alternating 12-hour periods at 1250 and 1650 F in a salt mixture initially composed of equimolar $Na_2Fe(SO_4)_3$ and $K_2Fe(SO_4)_3$. Corrosion effects were determined by cathodic descaling and weight loss measurements of selected specimens, and by metallographic examination of others.

Based on these laboratory investigations of the corrosion behavior of the commercial nickel-base and iron-base alloys in alkali salts under isothermal conditions (at 1650 F) and alkali-iron-trisulfate under both temperature cycling conditions (1250 to 1650 F) and steady-state conditions (1050-1350 F), the following conclusions are drawn:

- In these accelerated laboratory tests, all the alloys are susceptible to severe corrosion in both the salt environments.
- Corrosion in alkali-salt exposure at 1650 F appears, in terms of overall weight loss, to be less severe than in the cyclic salt exposure at 1250 to 1650 F and steady-state exposure at 1250 F. The chlorides present in the salt greatly influence the corrosion reaction (1) by cracking the external oxide scale leading to a "break-away" phenomenon and (2) by enhancing internal attack by void formation, oxidation, and sometimes sulfidation. For most of the alloys, the weight loss data in the alkali salt do not show a regular and monotonic increase with time of exposure. Instead, the weight-loss data indicate a "break-away" corrosion phenomenon. However, they are lower than the values in the alkali-iron-trisulfate salt.
- The weight losses observed in the alkali-iron-trisulfate salt at 1250 F (steady state) and at 1250 to 1650 F (cyclic exposure) have approximately the same range of values. For most of the alloys, the weight-loss data in the cyclic salt (1250 to 1650 F) show a monotonic increase with time of exposure. Fluxing by the salt at both 1250 and 1650 F contributes to corrosion. At 1250 F, fluxing occurs by the acidic alkali-iron-trisulfate salt. At 1650 F, in addition to fluxing by the alkali-sulfate salt, some internal sulfidation also occurs.

- All the alloys studied undergo corrosion in the 1050 to 1350 F steady-state alkali-iron-trisulfate salt mixture at rapid rates initially, which then decrease with time. All rates are unacceptably high. The alloys suffer corrosion by an "acidic-fluxing" mechanism. Inconel 671, an exclusive Cr_2O_3 scale former, is the only alloy that substantially resists the corrosive attack.
- Molybdenum-containing alloys suffer greater amounts of corrosion than molybdenum-free alloys in the alkali-iron-trisulfate. The volatile oxides of molybdenum enhance the cracking of oxide scales.
- The corrosion experienced in these runs was expected to be more severe than in actual heaters (due to the undiluted corrodents). The relative performance of the alloys, however, is of interest. Although all the alloys are corroded in both the salts, Inconel 671 appears to be capable of some level of corrosion resistance. AISI 310 suffered considerable external corrosion and internal attack in these tests, but it still may represent an economic choice because, of all the alloys investigated, it is the only one which has both the desired qualities of being high in chromium content and low in cost.

Corrosion Testing in Utility Boilers. The objective of this portion of the research program was to expose selected alloys, assembled in the form of corrosion probes, in utility boilers, and to collect data on metal wastage as a function of time, temperature, and composition of the alloys. Alloys tested included 304H, 310, 800H, Nimonic 86, Inco 617 and 618E, Inco 671, FeCrAlY.

Corrosion probes were exposed in three operating utility boilers. The selected sites were Bayshore Station, Toledo, OH (2000 hours), Tanner's Creek Station, Lawrenceburg, IN (2886 hours), and Mill Creek Station, Louisville, KY (1627 hours). The three stations were operating on different coals covering a range of sulfur content.

At each test site, corrosion probes were exposed in three locations in the boiler. Two sets of probes were located in the superheater section and another set was located in the furnace waterwall section.

Standard coal and ash analysis were performed on the fuels. The sulfur content ranged from less than 1% to just over 3%. None of the three coals would be considered significantly corrosive on the basis of the Corrosion Index Nomograph established by Combustion Engineering (Ref. 6). The Tanners Creek coal would be rated as unusually benign in terms of high-temperature corrosion.

The deposits that formed on the tubes were examined, weight-loss data was gathered on selected specimens, and other selected specimens were subjected to metallographic examinations. The results indicate no unusual corrosion problems for these alloys at the temperatures required in a CCGT/PC system.

The results indicate that (1) the alloys did not suffer accelerated corrosion and metal wastage up to 2000 hours of exposure. For the 2000-hour exposures, all alloys suffered weight losses much less than that frequently considered tolerable (300 milligrams per sq cm per 10,000 hours); (2) all the alloys formed protective oxide scales with no internal corrosion and/or sulfidation; (3) the deposits formed on the alloys consisted mainly of inert flyash silicates with minor amounts of salts; (4) the salts in the deposited material appeared to consist of a complex mixture of alkali and alkaline sulfates and chlorides; and (5) the salts did not appear to have been molten at the exposure temperature.

<u>Interpretation of PC Corrosion Research Results</u>. The laboratory investigations clearly show that all of the candidate heat exchanger metals are subject to an unacceptable rate of corrosion when exposed to the pure salts that are believed to consistute the corrosive medium in the actual heater environment. However, these same alloys did not encounter unacceptable corrosion rates when exposed for periods of up to 2000 hours in three pulverized coal-fired utility boilers. These somewhat conflicting results are believed due to the deposit environment in the particular utility boilers, which is very much diluted by inert materials from the coal ash, and thus low enough in corrosive content to avoid serious attack. It is understood that this behavior is not inconsistent with the behavior observed in a population of utility boilers. Many do not encounter excessive corrosion of high-temperature (1100 to 1200 F) superheater materials, while others, burning a different coal or having a different pattern of ash deposits, do encounter severe corrosion. The results of the current research indicate that

all of the candiate metals tested have a potential for encountering severe corrosion, depending principally upon the nature of the coal combusted and also upon the detailed design of the heater. There are methods for evaluating the corrosive potential of coals, and given a naturally well-behaved coal ash (or an adequate additive program), the current research indicates that it will be possible to provide a PC heater configuration, and a materials schedule, that will provide an acceptable life.

Research on PC Furnace Heat Flux Control

Design studies conducted during the Phase I effort indicated that adquate cooling of conventional 25 to 50 MWe pulverized coal furnaces can not be provided economically by a gas turbine-cycle working fluid. The conceptual commercial PC heater design, therefore, employs flue gas recirculation (FGR) on the order of 40% to reduce the peak furnace heat flux and to make it more uniform.

The Phase II research effort summarized herein included a modest program to evaluate furnace and burner concepts aimed at effectively employing FGR and furnace configuration to meet the heat flux targets. Because of resource allocations, the bulk of the research was conducted by cold flow studies of reduced scale models.

Burner Research. Flue gas recirculation (FGR) must be done in such a way that flame stability is not affected materially. Flame stability in a burner is attained aerodynamically by ensuring that hot burning gases are recirculated into an ignitable incoming mixture. Circular burner cold flow studies at 1/4 linear scale were used to provide a means for making an initial selection of FGR/burner configurations in which flame stability and ignition are not impaired seriously. The results of the tests established a burner geometry and range of operating conditions over which a well-defined flame stabilizing gas recirculation pattern may be maintained without FGR. In addition a configuration was defined whereby cool recirculated flue gas can be fed into the flame gases without significant detriment to flame stability. The essential features of the design are shown in Fig. 7.

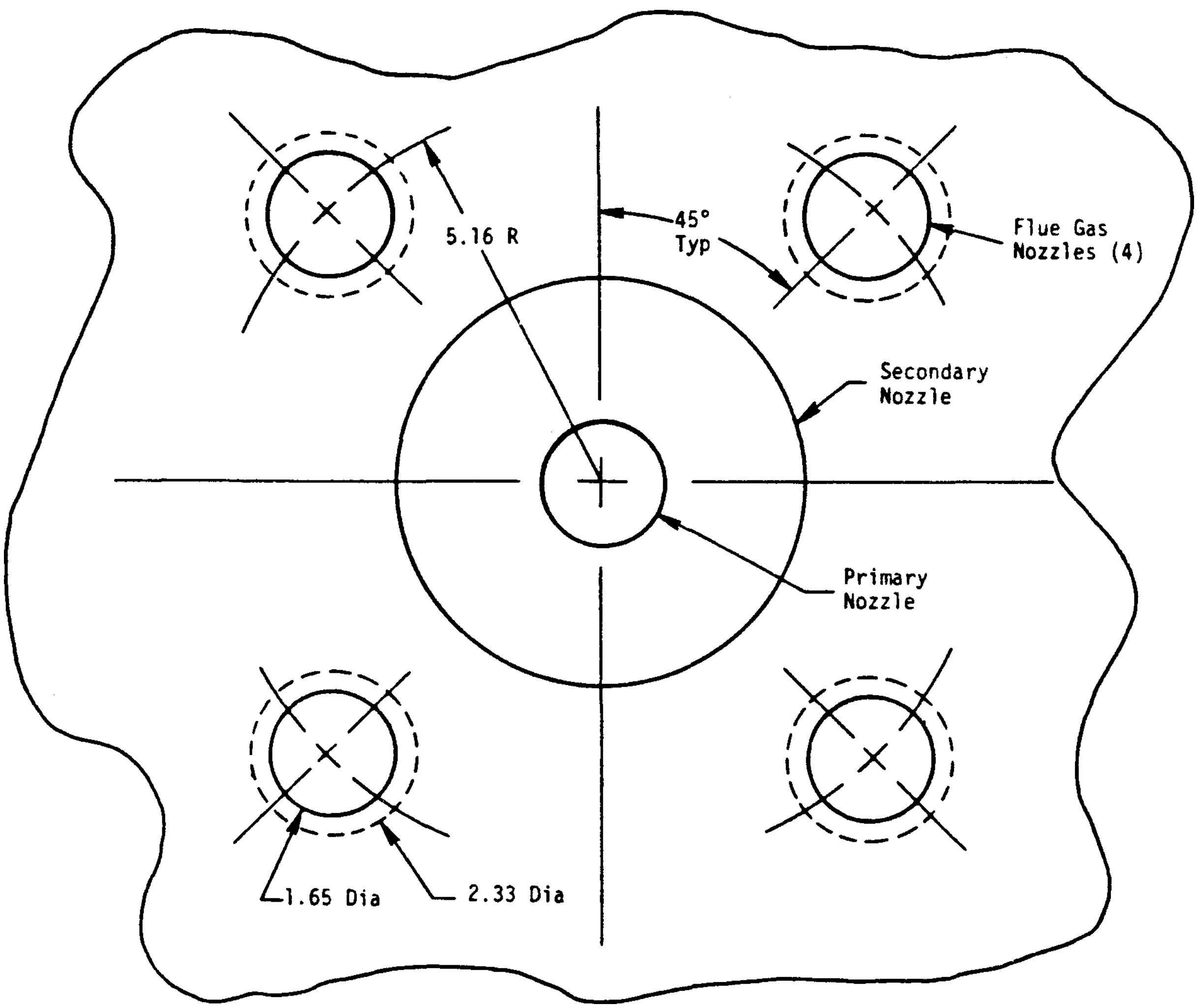


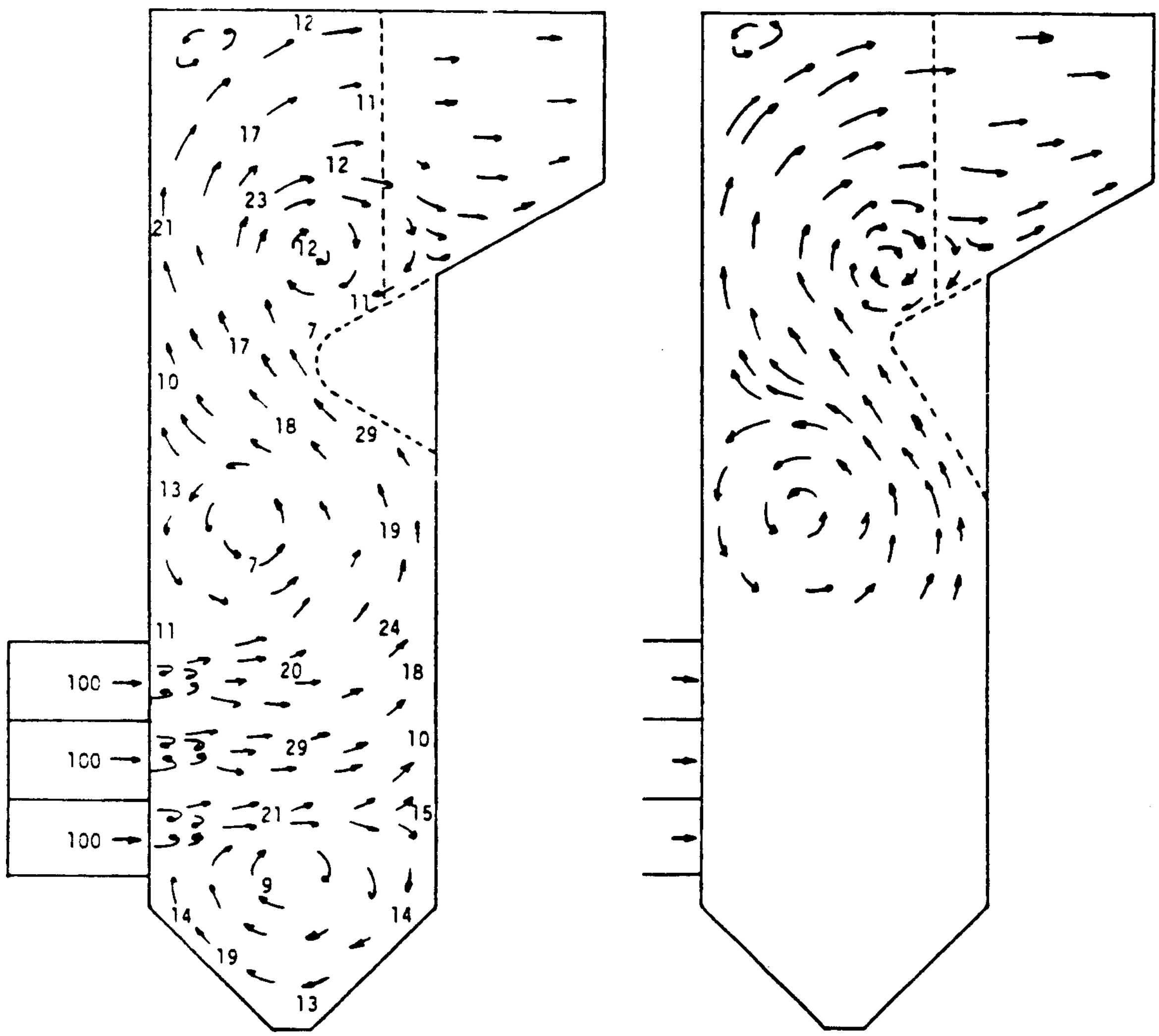
Figure 7. Four-Hole Flue Gas Injector
(Model Dimensions in Inches)

Hardware based on Fig. 7 was used as the basis for the circular burner tested in the combustion phase of the program. The combustion testing was performed to prove the validity of the design approach by demonstrating the flame stability and uniformity of flame temperature profiles generated by a working burner based on the aerodynamic model. The design of the hot-fire model burner closely followed the geometry of the cold-flow model, but was sized at 3/8 linear scale and had the important practical features of a water-cooled throat and front face, and an adjustable swirl vane mechanism. The primary coal/air feed pipe was designed to accommodate a central gas burner that was used to heat the furnace to its normal operating temperature. The burner was constructed of stainless steel and mounted to fire vertically downward in the test furnace. The combustion chamber consisted of a double-walled water-jacketed vessel with internal dimensions of 4-ft. diameter and 8-ft. long from the burner face to the center of the outlet duct, and 11 feet to the bottom of the ash hopper.

The FGR techniques examined in the cold- and hot-fire burner and furnace tests show that a uniform flame temperature can be obtained with this technique with very stable flame conditions. The technique is quite viable for use in PC burners and furnaces to provide heat flux control to the furnace wall and heat exchanger bank cooling tubes. This development opens the way for the design and evaluation of PC furnaces for the CCGT application using gaseous cooling by the working fluid with wall safety and design factors that are reasonable because the maximum wall temperature can be determined without having to protect against inadvertent hot spots due to uncontrolled flame temperatures.

Furnace Geometry Research. Cold-flow study techniques also were used to investigate the conceptual heater's furnace flow patterns and gas mixing. In order to simplify and reduce the cost of the study, the changes in fluid properties and characteristics (viscosity, density) that exist in an operating combustion system were not simulated. A linear scale of 0.15 was selected for the furnace flow models studied. Geometric similarity was attained, but since the only flow medium was air at ambient conditions, not all of the mass and momentum relationships of the full-scale unit could be attained on the model without distorting velocity relationships. These unavoidable differences are not different from those experienced in the past in other successful model studies. Velocity and direction of gas streams were measured. Gas stream mixing was measured via tracer gas techniques.

Studies of the flow patterns throughout the front fired heater arrangement similar to Fig. 3 showed these to be similar to those known to exist in boiler furnaces of similar shape and firing arrangement. Several modifications were explored to improve the distribution of heat to the heater enclosure and the leading tubes of the convection section. Flow patterns of the original and final configurations are shown in Fig. 8. The configuration arrived at showed a



FLOW PATTERNS IN ORIGINAL CONFIGURATION

NUMBERS INDICATE LOCAL
VELOCITIES AS PERCENT
OF NOZZLE VELOCITY

FLOW PATTERNS OBTAINED
WITH 33% NOSE LENGTH,
30 DEGREE APPROACH

Figure 8. Cold-Flow Patterns - Front Fired Heater

completely acceptable flow distribution throughout the furnace and across the entrance to the super-heater section. The burner arrays were operated with their 40% flue gas recirculation ports in full operation without indicating any undesirable effects on the overall mixing and flow patterns.

The axisymmetric heater design of Fig. 9 was evaluated for its potentially more uniform gas flow and heat transfer characteristics. A novel feature of the design is the offset furnace exit duct, which was adopted to improve the uniformity of flow across the width of the convective heat transfer section. This model was fitted with 12 simulated burners, which were arranged in four groups of three stacked vertically at every other corner of the eight-sided furnace. With the axisymmetric furnace, a configuration was developed providing uniform flow through the tube bank and moderate fluid velocities at the furnace walls. The measured mixing of flue gas within the heater shows that essentially uniform mixing existed throughout the volume above the burners. It was concluded regarding the axisymmetric heater design that (1) uniform velocities exist throughout the heater; (2) flue gas is well mixed immediately above the burners; (3) mixing at the burners appears sufficiently delayed to provide stable ignition; (4) no fluid recirculation occurs in the furnace or tube bank; and (5) uniform tube bank flow rates are achieved.

The results of heat flux control R&D were very encouraging. Both PC furnace configurations developed during the cold-flow testing appear suitable for development into furnaces whose heat flux is controlled adquately. The model circular burner testing additionally indicated that it will be possible to attain adequate flame stability with exhaust gas recirculation rates as high as 40%. In assessing program results, however, it should be recognized that many of the factors that interact to determine the heat flux impinging upon a given square foot of furnace wall surface require full-scale development. Additionally, the scale of the furnace will influence the peak heat flux. The resources and philosophy of the current program fell far short of what would have been required to conduct full-scale hot-fire experimentation. A fundamental problem with the PC heater concept is that the scale effects are so significant that only a very large and expensive installation can be expected to resolve the issues fully.

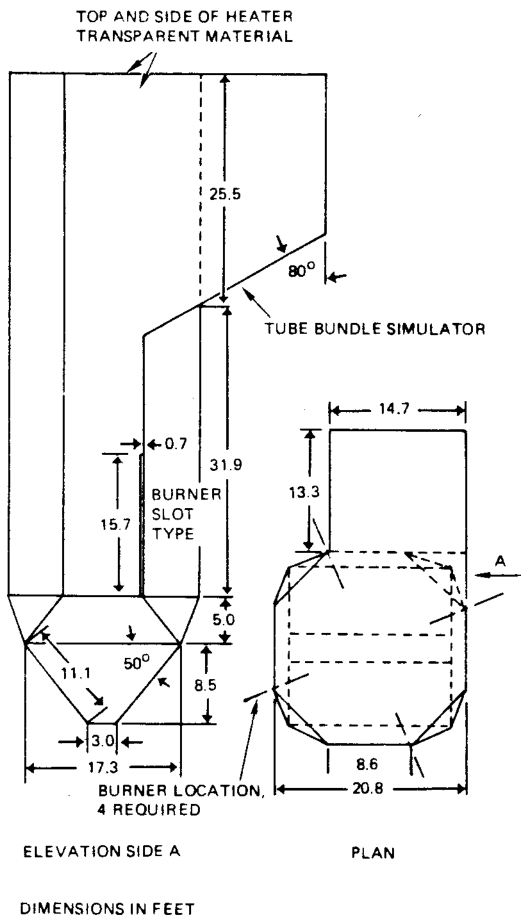


Figure 9. Axisymmetric Heater Model Showing Full-Size Furnace Dimensions

ATMOSPHERIC FLUIDIZED BED RESEARCH FOR 1450 TO 1550 F TURBINE INLET TEMPERATURE

Research on Atmospheric Fluidized Bed (AFB) combustion and heat transfer technology was the major task of the Phase II Program. The research undertaken was concerned principally with those technical issues involved in the application of the AFB concept to CCGT heaters, i.e., which differentiate the CCGT application from the steam boiler application. There was no attempt in this CCGT research program to address all of the issues inherent in AFB combustion.

The Phase II program concerned two major technical issues:

1. Because of the much higher heating surface metal temperatures that must be sustained in a CCGT heater as opposed to a steam boiler, the program endeavored to identify alloy materials and AFB design and operating practices that would permit the economically competitive design of heaters to withstand the AFB coal combustion environment. Principal attention was given to conditions in the fluidized bed itself but with additional research on the convection section.
2. The second major issue researched was the adaptation of the technology of fluidized bed combustion from steam boiler practice to the special needs of the CCGT-fired heater. Again, these special needs derive principally from the much higher operating temperatures of the heat transfer surfaces in the fluidized bed, and the substitution of an air working fluid for the steam and water fluids operative in a steam boiler. As coal-fired fluidized bed technology is much less developed than pulverized coal, the program included the design and operation of a complete AFB heater system to insure that the adaptation was adequate.

The Battelle effort included all the experimental laboratory corrosion research work, and test AFB operations with a 24-inch research AFB. The Rocketdyne work included designing of protctype commercial systems and the design, fabrication, erection, and operation of a 6 by 6-foot AFB air heater for operational and metallurgy research.

<u>AFB Corrosion Research</u>

This AFB program was directed toward identifying the most economical heat exchanger materials adequate for the intended service. The significant elements of the program were (1) the conduct of accelerated corrosion tests in controlled laboratory furnaces; (2) the development of an oxygen partial pressure probe for use in the fluidized bed environment; (3) the characterization of the AFB combustor environment in which the corrosion samples were to be exposed, and the development of coal and combustion air feed systems to minimize corrosion/erosion effects; and (4) the conduct of corrosion exposures of candidate metals in closely controlled, well-characterized AFBs.

Metals Evaluated. Design CCGT in-bed tube metal temperatures will fall in the 1200 to 1600 F range, ruling out the application of carbon and low alloy content steels. The in-bed metals chosen for evaluation in the metallurgical lab and 24 inch AFB are listed in Table 2. For the 6 by 6-foot AFB, Haynes 188, a cobalt-based alloy and HK40, a cast stainless, were added. Convection bank alloys per Table 3 were exposed in the 6 by 6-foot AFB.

TABLE 2. NOMINAL COMPOSITIONS OF THE SELECTED IN-BED ALLOYS

ALLOY	COMPOSITIONS IN WEIGHT PERCENT							
	Fe	Ni	Co	Cr	Mo	W	Al	OTHER
INCONEL 617	0.0	54.0	12.5	22.0	9.0	0.0	1.0	
INCONEL 618E	16.0	55.0	0.0	23.0	0.0	6.0	0.0	
HASTELLOY X	18.5	46.0	2.5	22.0	9.0	0.6	0.0	1 Mn, 1 Si
PE-13	18.5	46.0	2.5	22.0	9.0	0.0	0.0	
NIMONIC 86	0.0	64.0	0.0	25.0	10.0	0.0	0.0	0.03 Ce
INCOLOY 800H	44.0	33.0	0.0	21.0	0.0	0.0	0.35	0.35 Ti 0.75 Mn 0.5 Si
AISI 310	52.0	20.0	0.0	25.0	0.0	0.0	0.0	1.5 Mn 0.5 Si
AISI 347	BAL	10.0	0.0	18.0	0.0	0.0	0.0	(Nb+Ta)
AISI 304	BAL	10.0	0.0	18.0	0.0	0.0	0.0	
FeCrAly	BAL	0.0	0.0	15.0	0.0	0.0	4.0	0.5Y
FeCrAly	BAL	0.0	0.0	25.0	0.0	0.0	4.0	1.0Y

TABLE 3. CONVECTION BANK MATERIALS

AISI 1010	(CARBON STEEL)
ASTM A 213 T2 (1/2 Cr - 1/2 Mo STEEL)	
ASTM A 213 T22 (2-1/4 Cr - 1 Mo STEEL)	
ASTM A 213 T9 (9 Cr - 1 Mo STEEL)	
304H	STAINLESS STEEL

Metallurgical Laboratory Corrosion Research. An extensive laboratory investigation was conducted in which coupons of the alloys were exposed to simulated combustion gases, consisting of mixtures of CO, CO_2, SO_2, and air, and to simulated deposits of the bed materials, which comprised mixtures of CaO, CaS, and $CaSO_4$. All the experiments were performed at 1650 F, which corresponds to a maximum metal temperature. For the simulated combustion gas exposures, the oxygen partial pressures used were those actually measured in the BCL 24-inch diameter AFB, and the sulfur partial pressures corresponded to values calculated from equilibrium combustion and other thermodynamic considerations. Steady-state exposures (constant gas composition and constant temperature) were run to follow the development of corrosion morphologies as a function of time. In other experiments, the gas mixtures were oscillated between high PO_2, low PS_2 (excess air) and low PO_2, high PS_2 (substoichiometric) values to learn how the expected protective oxide films on the alloys were affected by periodic immersion in sulfidizing conditions.

The results indicated that:

1. a substoichiometric combustion gas environment was extremely agressive and induced sulfidation corrosion. In particular, the nickel-containing alloys were extremely susceptible to sulfidation, the degree increasing with nickel content. For the iron-base alloys, the progression of sulfidation attack was slower and decreased with increasing chromium content. The alumina scale-forming alloy investigated, FeCrAlY, exhibited some accelerated oxidation attack, forming thicker oxide scales than in simple air oxidation, but demonstrated extremely protective behavior in general.

2. In the oscillating oxygen content environment, when the alloys were first exposed to the substoichiometric environment, the alloys suffered sulfidation corrosion as expected from the steady-state experiments and the "re-oxidized" scale layers formed in the subsequent excess air cycle were not protective.
3. When exposed first to the excess air environment, the initially formed oxide scale layer was more protective on the high-chromium iron-base alloys AISI 310 and Incoloy 800 than on the lower chromium alloys AISI 304 and 347. Of the nickel-base alloys, the high-chromium alloy, Inconel 671, exhibited excellent protection; the lower chromium alloys which contained iron, Hasteloy X and Inconel 618E, also exhibited continued protective behavior. The iron-free alloy, Inconel 617, developed protective scales in a few special cases only.
4. In the simulated deposits, where the oxygen partial pressure was fixed by the equilibrium dissociation partial pressure of the powder mixture, so that the only source of sulfur was from dissociation of these solids, the mixture of $CaSO_4$ and CaO was found to be capable of initiating some sulfidation of the nickel-containing alloys. The CaS-CaO mixture was found to be significantly more aggressive, however, with the rates of corrosion some 50% higher than in the $CaSO_4$-CaO mixture. Again, iron-base and iron-containing alloys were much less and less susceptible, respectively, to this attack. For the 300-series stainless steels, the form of attack was essentially accelerated oxidation, with very little sulfur penetration.
5. While the corrosion in the simulated deposits exhibited a very similar morphology, for a given alloy, to that in the equivalent gaseous environment, the rate of attack was some order of magnitude slower in the deposits.
6. A significant reaction occurred between the CaO-CaS deposit and the protective chromia scales on some of the alloys. The formation of a layer of calcium chromate was observed, which suggests a possible mechanism for binding deposits to the scaled alloy surfaces.

It appears that all the alloys investigated are susceptible to some form of accelerated attack if subjected to the measured low PO_2 and expected high PS_2 gaseous environments encountered in substoichiometric regions of a coal-fired AFB. FeCrAlY is the least susceptible to attack while the 300-series stainless steels are quite tolerant to internal sulfidation, the susceptibility increasing with decreasing chromium content. Nickel-base alloys are prone to the initiation of sulfidation after only 15-minute exposure, then progress to the development of voluminous internal sulfides, and finally to the formation of liquid nickel sulfides becoming more rapid with increased nickel content.

The results of the oscillating gas mixture experiments suggest that, for all the alloys considered except Inconel 617, the oxide scales formed in the excess air cycles should afford good protection and that prolonged exposures of several minutes at a time to substoichiometric conditions would be required to initiate sulfidation. Inconel 617 appeared very sensitive to substoichiometric conditions. The danger of catastrophic corrosion of nickel-containing alloys through the formation of liquid nickel sulfide at temperatures in the range of 1460 to 1170 F should be borne in mind, however. This becomes more likely with prolonged exposure to substoichiometric conditions, and with increasing nickel content in the alloy.

Corrosion Research via AFB Testing. The Phase II program included test firings of a variety of AFB air heater configurations, under a variety of operating conditions, with the aim of researching their interrelationship with the corrosion/erosion behavior of the candidate tube metals. A diagnostic probe capable of measuring the instantaneous oxygen pressure at selected locations within the beds was utilized as a clue to the corrosive environment. The configuration of the coal and combustion air feed systems and the air-to-coal feed ratio were adjusted to provide bed environments believed to be "corrosive," or "noncorrosive," as desired for a particular test series. All testing was targeted for a 6 fps superficial bed velocity. All coal was Illinois No. 6, with 3 to 4% sulfur.

The heat transfer surface within the beds was composed of tubes with the same diameter and spacing as those of the conceptual commercial design. Corrosion probes, consisting of 1-inch long tubular sections of the candidate metals, arranged in series on air-cooled bayonet probes, were inserted at selected locations above, below, and in the midst of the tube bank. Corrosive/erosive effects were assessed by weight loss and photomicrography analysis of the controlled temperature specimens.

<u>24-Inch AFB Corrosion Research</u>. The Characterization testing was conducted in two series of runs in which (1) the unit's operation was characterized and (2) the influence of various design and operating parameters on the bed environment were investigated. In the course of this testing the oxygen partial pressure probe design and operation were verified as well as used to measure the fluidized bed environment. The characterization program consisted of 23 runs with an accumulated duration of 88 hours at stabilized conditions.

The characterization test series brought out several operational characteristics of the AFB, which are believed to affect its corrosion environment:

1. As illustrated in Fig. 10, the local indicated oxygen pressure at a given location in the bed varies cyclically (at about 1 cps) from oxidizing to reducing. By assigning values to the PO_2 levels considered oxidizing and reducing (in this case $PO_2 > 10^{-3.4}$Atm = oxidizing and $PO_2 < 10^{-12}$Atm = reducing) one is able to integrate the trace to determine the percentage of time at that location which is spent in the oxidizing, transition, and reducing regimes.
2. At any given location within the bed, the percentage of time spent in the oxidizing and reducing regimes is remarkably constant and repeatable from run to run, provided that configuration and operating parameters are unchanged. The oxidizing-reducing percentages are functions of configuration, coal sizing, coal volatiles, excess air, percentage primary air, etc.
3. The designer can exercise significant control over the oxygen environment by appropriate selection of configuration and operating parameters.

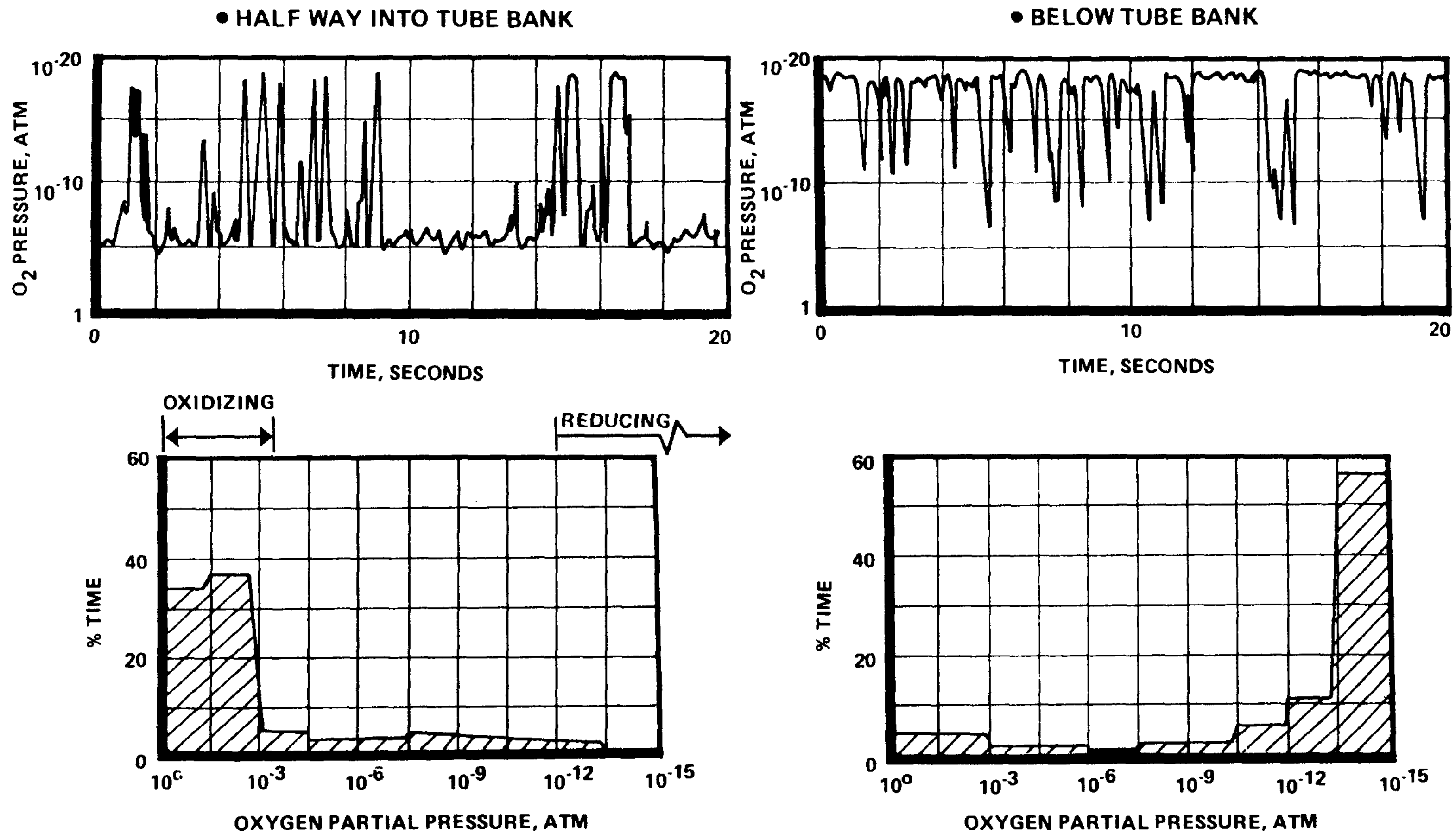


Figure 10. Measured Oxygen Concentrations ℄ of 24-Inch Dia AFB

On completion of the characterization testing described above, the 24-inch AFB with its "best" coal and air feed system was used for corrosion testing. Both oxidizing and reducing zones existed in the bed at 20% overall excess air. The coal was dried, crushed, and screened to -8 mesh, while the limestone was -8 +60 mesh. The average bed temperature was 1652 F, the superficial velocity was approximately 6 fps, and the bed depth was approximately 5 feet. The SO_2 content of the flue gas was maintained between 450 ppm and 550 ppm with a Ca/S ratio of approximately 3.2.

Corrosion and oxygen probe data were obtained during three separate 250-hour experiments, corresponding to conditions of 50, 20, and 0% excess air. Twenty-four specimens were used to construct each corrosion probe, which was designed to simulate a single tube in the heat-exchanger tube bundle. During the three 250-hour experiments, nine multialloy probes and nine binary probes (contained specimens of Incoloy 800 and AISI 304 only) were exposed to the fluidized bed environment, for a total of 18 corrosion probes. Six corrosion probes were exposed during each 250-hour experiment. The corrosion specimen exposure times were targeted for 100, 150, or 200 hours, depending on the type of probe and its location.

Descaling, weighing, and metallographic operations conducted on the exposed alloy specimens indicated two mechanisms of material degradation occurred. The first mechanism was alloy corrosion beneath an adherent deposit of bed material. All the alloys tested developed protective Cr_2O_3 scales (as expected) when exposed in areas of the bed where the probe indicated high oxygen partial pressures existed. However, some of the alloys, particularly the nickel-base alloys, experienced the early stages of sulfidation when exposed to low-oxygen partial pressures. This behavior would be expected to develop into serious corrosion problems during prolonged exposure under the same conditions.

The second mechanism, alloy corrosion/deposit formation followed by the mechanical removal of the deposit and corrosion products, was a significant form of material degradation observed in these tests. This coupled corrosion/erosion mode of attack was attributed to the vigorous motion of the bed constituents, and the maximum weight-loss values occurred on specimens located near the centerline of the bed.

The following conclusions can be drawn from the results of this program:

1. Persistent substoichiometric conditions promote accelerated oxidation and sulfidation attack of all the alloys studied.
2. The nickel-base alloys were the most prone to attack under substoichiometric conditions. In these limited time tests, only one case of catastrophic attack was observed, on Inconel 618E. In general, corrosion morphologies recognized as precursers to rapid sulfidation-related degradation were developed.
3. The FeCrAlY cladding alloy also suffered accelerated oxidation and oxidation-sulfidation in some cases, although the attack was quite uniform. Although it did prove to be the most resistant, the extent of attack was greater than anticipated, and suggests that the 25% Cr version of this alloy should be considered instead of the 15% version used here.
4. Of the iron-base alloys, AISI 304 exhibited accelerated oxidation attack, particularly in substoichiometric conditions. Its behavior in oxidizing conditions was as expected, and the rapid oxidation rates observed suggest a temperature limit in the 1400 F range.
5. AISI 347 and 310 exhibited quite acceptable behavior in general, with lower apparent rates than 304.
6. Incoloy 800H showed essentially good behavior in oxidizing (excess air) conditions, with a marked increase in corrosion in substoichiometric conditions. However, no indications were found in these tests that this alloy was susceptible to catastrophic attack; the corrosion morphologies were consistent with this alloy being intermediate in nickel content between the stainless steels and the nickel-base alloys.
7. A mechanical acceleration of the degradation process was observed to operate in the center region of the fluidized bed. Bed deposit formed on the specimens apparently was removed periodically, stripping protective oxide from the alloy surfaces and exposing them to the ambient gas. This was the most rapid form of degradation experienced in this program, and suggests that motion in the bed, and the deposit formation/removal phenomenon, are important factors that require further investigation.

8. In the absence of this mechanical interaction, excess air combustion conditions promoted the formation of apparently normal protective chromium oxide scales on all the alloys (except FeCrAlY).

9. The in-situ oxygen probe provided a reliable means of identifying local variations in the nature of the combustion environment, and identified regions of the bed with high corrosive potentials. Characteristic signals from such regions showed a prevailing low-oxygen partial pressure (10^{-12} atm).

10. Oxygen probe signals characteristic of excess air conditions (a prevailing oxygen partial pressure of 10^{-2} atm with excursions to lower values) are considered to indicate an environment in which the alloys tested will exhibit protective corrosive behavior. The boundary of these "safe" conditions appears to be where the oxygen probe indicates an exactly stoichiometric combustion condition, i.e., a signal continuously oscillating between limits of 10^{-2} and 10^{-12} atm.

6 by 6-Foot AFB Corrosion Research

Hardware

The 6 by 6-foot Atmospheric Fluidized Bed is an experimental facility (Fig. 11) for advancing the technology of CCGT heat exchangers operating in an AFB. The system is sized to allow research data from the other supporting Phase II test activities to be utilized in R&D hardware of a size approaching minimum demonstration dimensions. The 6 by 6-foot system was used for AFB operational experiments and for heat exchanger materials exposure data testing. The unit was designed to provide operating data over a wide range of conditions. This includes superficial bed velocities from 2 to 8 fps and ash recycle rates up to 3 times the coal feed rate. Sections through the 6 by 6-foot heater are shown in Fig. 12 and the design criteria are summarized in Table 4. The combustor was equipped with over 50 ports accepting corrosion or diagnostic probes. The diagnostic probes were used to characterize the bed-operating conditions and the corrosion probes were used to expose a variety of metal samples at different locations in the bed and convection bank. Numerous other ports were provided for pressure and temperature instrumentation, as well as inspection ports and manways.

Figure 11. 6 by 6-Foot AFB Experimental Facility

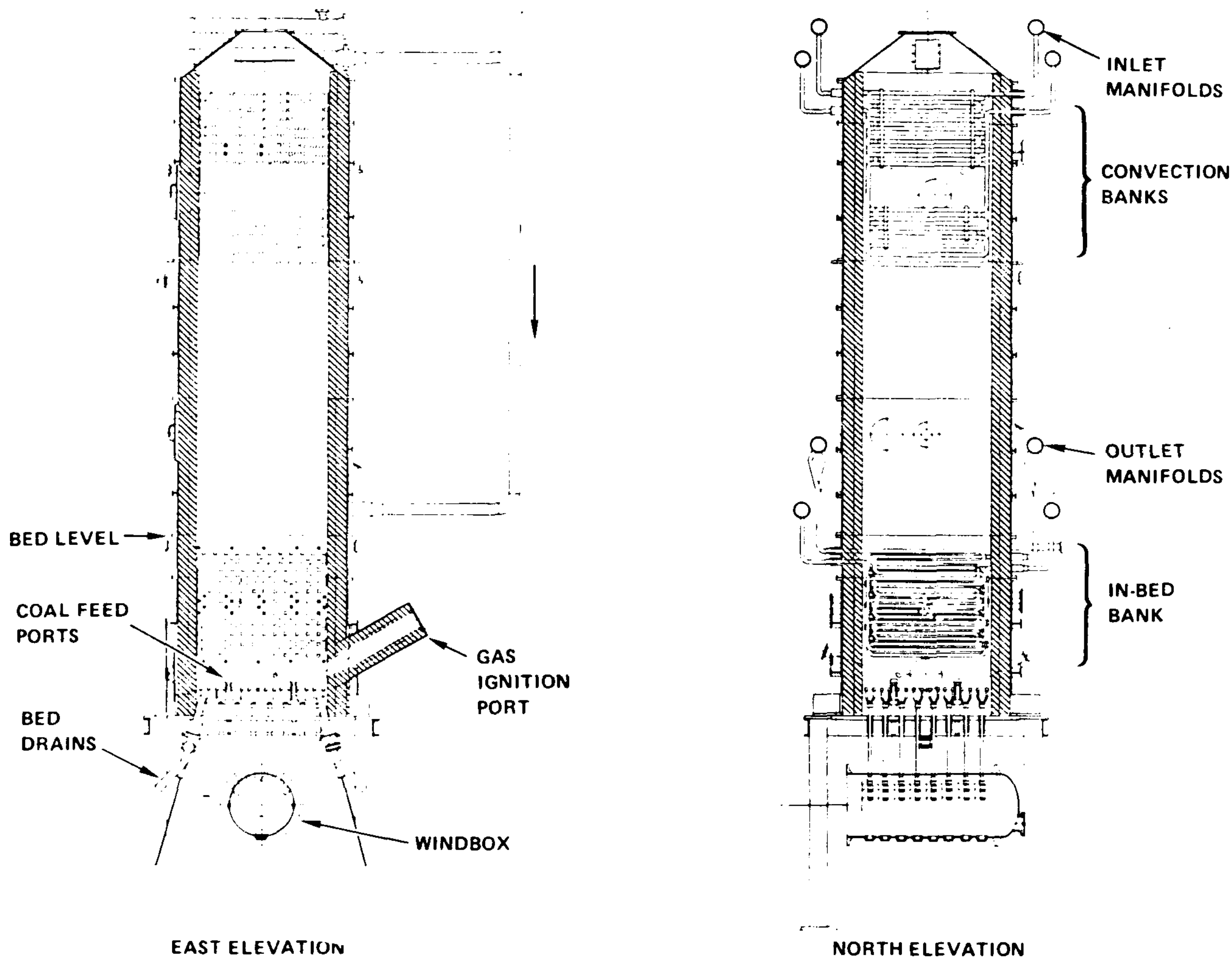


Figure 12. 6 by 6-Foot Overall Assembly

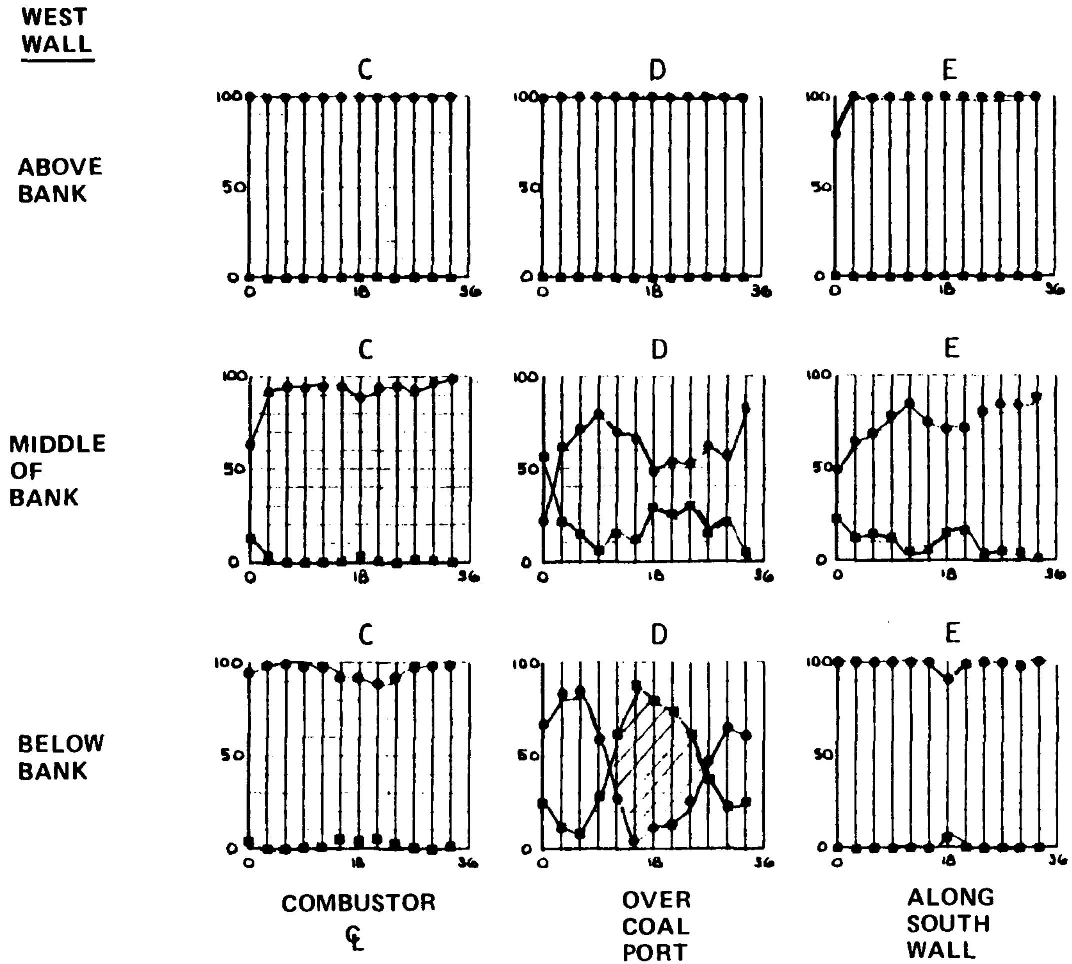
TABLE 4. 6 BY 6-FOOT AFB SIZE AND PERFORMANCE CRITERIA

• INSIDE PLAN DIMENSIONS	6 BY 6 FEET
• DISTRIBUTOR TO FIRST TUBE ROW	18 INCHES
• FREEBOARD HEIGHT	13 FEET
• SUPERFICIAL VELOCITY	2 TO 8 FT/SEC 6 FT/SEC NOMINAL
• NOMINAL BED TEMPERATURE	1500 TO 1650 F
• NOMINAL COAL FLOW/SIZE	1370 LB/HR, UNDER 4 MESH
• EXCESS AIR	20% TO 50%
• COMBUSTION AIR TEMPERATURE	620 F NOMINAL
• CALCIUM/SULFUR MOL RATIO	2 TO 4
• LIMESTONE SIZE	-8 +20 MESH
• WORKING FLUID (TUBE COOLANT)	AIR
• OUTLET TEMPERATURE	1450 TO 1550 F
• OUTLET PRESSURE	UP TO 200 PSIG
• ASH RECYCLE RATE	0 TO 3 TIMES COAL FLOW RATE

Testing

A characterization and development test series consisting of six runs with an accumulated duration of 238 hours at design bed temperature was first conducted.

In the early runs, the partial pressure probe was used to characterize the in-bed environments provided by the as built coal and combustion air feed configurations. Figure 13 illustrates the probe traverse results typical for each of the four quadrants when operating at an overall excess air of 20%. For this figure, oxygen probe traverses were made through nine ports in the west wall of the combustor. Starting at the west wall, readings were taken at 3-inch intervals until an insertion depth of 33 inch was attained. In the as-built configuration, coal is introduced through four ports, each located at the center of the four 3 by 3-foot quadrants, which make up the 6 by 6-foot plan area. About 10% of total combustion air flow is used as "primary air" to blow in the coal. The remaining "secondary air" is distributed uniformly.



● % OF TIME WHEN O_2 PRESSURE $>10^{-3.4}$ ATM

■ % OF TIME WHEN O_2 PRESSURE $<10^{-12}$ ATM

Figure 13. As-Built Oxygen Signature, 20% Excess Air

The O_2 traverses of Fig. 13 indicate that above each coal feed port a plume exists in which reducing conditions obtain far more than 50% of the time. This plume penetrates partially into the tube bank but does not reach the top row (the tube bank is 59 inches deep).

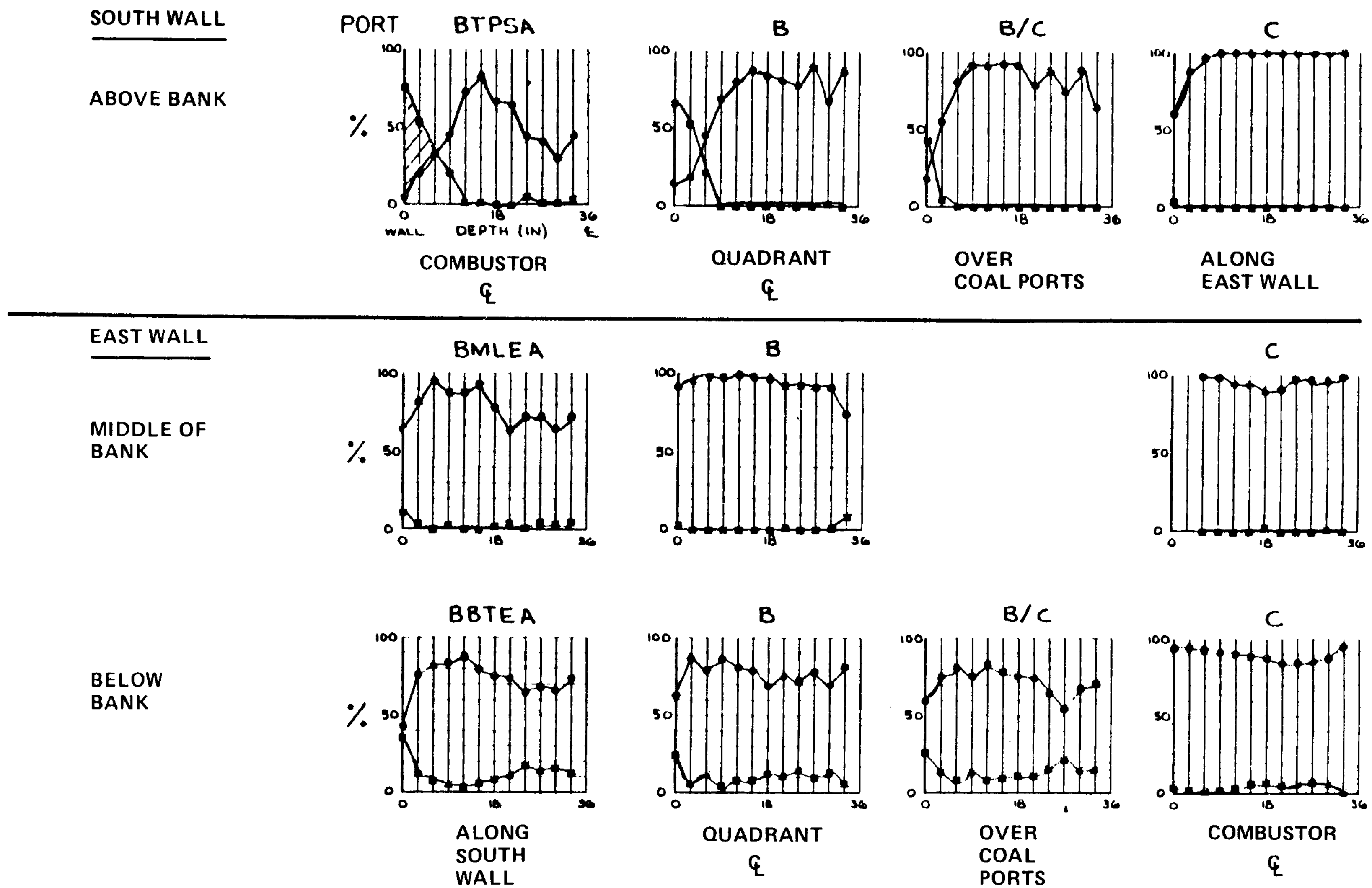
On the basis of the experience with the 24-inch AFB, it was felt that the tube environment provided in the plume above each coal feed port by the as-built configuration would be excessively harsh.

Several modifications to the coal and combustion air feed configurations were tested. In each case, the total coal and air fed to each quadrant remained equal, and at least one quadrant retained the as-built configuration. For the configurations evaluated, there was little cross-talk between quadrants, i.e., the traverses of the as-built quadrant showed little change.

Traverse results with a modification applied in the southeast quadrant are provided in Fig. 14. For this run, the single-coal feed port was replaced with four ports, each at the center of an 18 by 18-inch square. Secondary air distribution was unchanged. This mod essentially eliminated the plume over the coal feed ports.

At the conclusion of the characterization series, four types of coal feed ports were selected for the material specimen exposure series. The aim was to permit comparisons of the behavior of the candidate alloys in environments having a range of hostility. The configurations selected included:

1. Reference Quadrant: The southwest quadrant had the original coal port design, which was one port per quadrant (9 sq ft) and even distribution of secondary air from the distributor plate. This system is similar to that which has been employed in AFB steam boilers, and as discussed above, produces a reducing zone plume above the coal feed port.
2. Four Coal Ports Quadrant: The southeast quadrant had four coal ports (one port per 2.25 sq ft) and even distribution of the secondary air. As described in Fig. 14 this arrangement had a near-perfect oxidizing environment throughout the bed heat exchanger region, including above



● % OF TIME WHEN O_2 PRESSURE $>10^{-3.4}$ ATM

■ % OF TIME WHEN O_2 PRESSURE $<10^{-12}$ ATM

Figure 14. Modified Coal Ports Oxygen Signature, 20% Excess Air (Four Coal Feed Ports in S.E. Quadrant)

the coal feed ports. Also, the coal and primary air are distributed more evenly, perhaps with beneficial erosive effects. However, the configuration has the disadvantage of requiring many coal feed ports.

3. Augmented Air: The northwest and northeast quadrants had one coal port per quadrant (the same as the original coal port), but additional air was injected above the coal port splash plate. There are small design differences between the two quadrants. This augmented air amounted to about 12% of the total combustion air flow to each quadrant. The flow area of the secondary air tuyeres of these quadrants was reduced so that total combustion air flow remained unchanged. Development testing of this augmented air configuration had produced traverses judged to be not quite as good as that of the four coal port quadrant plotted in Fig. 14. Also, there was some apprehension that the concentration of combustion air at the coal port might increase the erosion effects. However, the coal feed system is much simplified, so a trial was made.

The material specimen exposure (erosion/corrosion) test series consisted of two runs with an accumulated duration of 371 hours at operating conditions. Twenty-nine corrosion probes (both cooled and uncooled) containing a large number of candidate tube and hanger material specimens were exposed in both the fluidized bed and convection region. Almost all of the operation was at the nominal conditions of 6 fps superficial velocity, 1650 F bed temperature, 25% excess air, and 90% sulfur capture. Ash recycle was used throughout the operation with a recycle rate of about two times the coal feedrate. A limited amount of oxygen pressure probing was conducted to verify that the condition of the bed environment remained constant. As the exposure testing was completed an extension to the program to add 650 hours of testing was negotiated. As a consequence, only one corrosion probe was removed for metallurgical analysis. The results of this analysis are not yet available.

The following conclusions can be drawn from the 6 by 6-foot AFB Corrosion Research effort to date:

1. The 6 by 6-foot AFB development test program results reinforce those of the 24-inch AFB. The 6 by 6-foot AFB was fitted initially with a typical state-of-the-art coal and combustion air distribution system as

employed in AFB steam boiler practice. Diagnostic results showed bed zones having a substoichiometric combustion environment, with very low average oxygen pressures, and presumably thereby, high sulphur pressures and high potential for corrosive attack. Other zones in the state-of-the-art bed provided high-combustion stoichiometry and presumably relatively benign conditions with respect to corrosion of metals. These results tend to explain the wide scatter in corrosion results obtained by previous investigators.

2. The 6 by 6-foot AFB test program also demonstrated that the bed environment can be controlled to provide an essentially oxidizing condition in all zones of the bed by means of appropriate design of the means for coal and combustion air introduction. Two different coal and air introduction schemes having a similar result were devised. Further, the 6 by 6-foot AFB testing again demonstrated the constancy of average oxygen partial pressure at each location within the bed, provided only that the configuration and operating conditions remain unchanged.

<u>AFB Airheater Operations Research</u>

As an adjunct to the 24-inch and 6 by 6-foot AFB test operations for corrosion research (as described above), it was necessary to resolve many issues inherent in the operation of AFBs for air heater purposes. The following conclusions may be drawn from these efforts:

1. The in-bed heat transfer coefficient correlation must incorporate a radiation component that contributes substantially to the overall coefficient. At the high metal temperature experienced in CCGT heaters, the total bedside coefficient is on the order of $75 BTU/ft^2 hr F$ as compared to about 45 for boiler surface.
2. The combination of the relatively deep bed required for CCGT service and the flyash recycle system is sufficient to provide a combustion efficiency of 98+%. The demonstrated combustible loss is easily acceptable economically. The incorporation of ash recycle in commercial installations is necessary for economic operation.

3. The tuyere-style air distribution system is basically trouble free. Air distribution is uniform and unaffected by the passage of time. The distributor support plate is insulated adequately by the inert bed material, so it needs no expansion joints at its connection to the containment walls.
4. The emissions of sulphur oxides can be controlled readily within new source performance standards.
5. The emissions of nitrogen oxides are about 20% of that permitted by new-source performance standards.
6. The in-bed tube bank support system is adequate to accommodate the differential thermal expansions.
7. The tubular combustion air heater and the multicyclone dust separator tend to accumulate loosely agglomerated dust deposits that interfere with acceptable operation. These deposits are readily prevented by periodic blowing of an acoustic horn.
8. The back spacings of the convection bank tubes tend to accumulate a loosely agglomerated dust deposit, which to date has not interfered with operation. Some form of soot blowing, perhaps the acoustic horn concept, appears appropriate for the convection bank.
9. The ash recycle system is effective in controlling unburned combustible loss and minimizing the calcium-to-sulphur ratio.
10. The thermal inertia of the tubes and inert bed material is so great that the working fluid exit temperature changes vary slowly with abrupt changes in operating conditions. Combustion control is adequate if coal and combustion air flow are proportioned to working fluid flow, with only a slow-acting trim adjustment to coal and air flow on the basis of working fluid exit temperature.
11. The large thermal inertia of in-bed tubes and inert bed material, taken together with the small quantity of combustible material present in the bed at any given time, permit a safe response (without tube overheating) to such emergencies as failure of the cooling air supply to the tubes, i.e., a turbine trip. In such cases, it is possible to shut off the coal but continue the combustion air flow so as to burn out the combustibles in the bed before slumping. This avoids shutting down with hot tubes in a reducing environment.

12. The coal feed system distribution piping is trouble free provided that extraneous contaminants, such as nails and pieces of weld wire, are screened out carefully before the coal is admitted to the system. It is possible to unplug a given distribution line while the unit is operating.

In summation, the research program has served to validate many of the details of the conceptual commercial CCGT design.

SERIES AFBs FOR 1750 F TURBINE INLET TEMPERATURE

The conceptual commercial fired heater concept chosen as the basis for research at the 1750 F turbine inlet temperature incorporates fluidized beds operating in series. The combustion and heat transfer technology is basically the same as that employed in the 1450 to 1550 F AFB fired heater. The technical issues lie principally in the use of ceramic materials for the heat exchanger in the high-temperature bed and in the effects of the high bed temperature on emissions and operability.

Research on Silicon Carbide for Heat Exchanger Tubes and Manifolds

The hottest tubes and manifolds in the series bed heater will operate at about 1800 F. The contract specifically required that ceramic materials of heat exchanger construction be researched for this application. It is recognized that there are no metals available with sufficient strength for CCGT applications at that temperature.

All of the ceramic research conducted was with the silicon carbide family of materials and was concerned largely with their durability when exposed in a high-temperature coal-fired fluidized bed. Because the strength of ceramic materials is strongly dependent upon their flaw content, the assessment of silicon carbide degradation in the hot fluidized bed was based upon evaluations of material recession (if any) and of the average strength of exposed specimens versus those of a control group of unexposed specimens.

A small (4 by 6-inch plan area) AFB test unit was designed and built specifically for the SiC tube sample exposure. Fluidizing air was supplied by a facility compressor and electrically powered air heater. The desired 1800 F bed temperature was obtained by injecting a small amount of methane above the distributor plate. The resultant bed environment is highly oxidizing. Three 100-hour test runs were made at oxidizing conditions at superficial velocities of 6, 12, and 18 ft/sec. A fourth 100-hour run was made at reducing conditions and 6 ft/sec velocity (by using nitrogen, excess methane and enough oxygen to achieve a bed temperature of 1800 F).

Three types of SiC tube materials were tested. They included Norton Company siliconized (NC430), SiC, Carborundum sintered alpha SiC, and Materials Technology Corp. chemical vapor desposited (CVD) SiC. One-third of the siliconized SiC samples had a ceramic-to-ceramic joint at the center of the tube length. The number of samples ordered was sufficient to provide baseline (unexposed) and exposed burst test data.

A total of 26 samples were exposed during the oxidizing condition runs. Most of the tubes were exposed to a single 100-hour run. However, 8 tubes were left in for the full 300 hours. No erosion or corrosion was observed on any of the exposed samples. Instead, each tube was coated completely with a thin (1 mil) uniform layer of material. The coating was primarily CaO with secondary compositions of $CaCO_3$, $CaSO_4$, and $Ca(OH)_2$.

No erosion or corrosion was observed on any of the tubes exposed during the reducing condition tests. The thin layer of CaO formed on tubes during the oxidizing condition tests was not present on the tubes exposed to reducing conditions.

The burst test data for tubes exposed during the testing is presented in Table 5, along with data for the as-received condition. While there is considerable scatter in the data, it is concluded that the 4 by 6-inch AFB exposure, either oxidizing or reducing, did not degrade the strength of SiC tubes.

TABLE 5. SUMMARY OF 4 BY 6-INCH AFB SiC BURST TESTS

SiC MATERIAL (1)	NO. OF SAMPLES	EXPOSURE (2)	AVERAGE HOOP (3) TENSILE STRENGTH (ksi)	
			VALUE	RANGE
NC430	7	NONE	16.5	10.9-18.9
NC430	7	OXID.	15.9	11.8-20.5
NC430	2	RED.	15.2	14.0-16.4
NC430+J	7	NONE	10.1	4.4-11.8
NC430+J	4	OXID.	13.9	12.8-15.9
NC430+J	2	RED.	15.2	14.9-15.5
ALPHA	8	NONE	30.8	20.9-37.5
ALPHA	5	OXID.	28.5	15.8-38.0
ALPHA	2	RED.	17.8	17.1-18.5
CVD	9	NONE	23.8	6.3-37.3
CVD	5	OXID.	19.8	16.6-37.9
CVD	2	RED.	13.9	8.5-19.2

1. NC430 = SILICONIZED SiC, TYPE NC430
   ALPHA = SINTERED ALPHA SiC
   CVD = CHEMICAL VAPOR DEPOSITED SiC
   +J = WITH JOINT
2. OX. = OXIDIZING
   RED. = REDUCING
   NONE= = NO EXPOSURE, CONTROL SAMPLES
3. BASED ON AVERAGE WALL THICKNESS

SiC tube specimens were exposed in the 24-inch AFB during the testing conducted at about 1650 F bed temperature for metal specimen exposures. They were uncooled and were inserted horizontally into the heat exchanger tube array. A total of eight tubes, each 1.0-inch O.d x approximately 30-inch long, were exposed for up to 750 hours in three 250-hour runs. Two types of SiC material were evaluated, NC430 siliconized silicon carbide from Norton Company and chemical vapor deposited (CVD) silicon carbide from Syntax Company.

Visual and microscopic evaluations of the exposed tubes showed them to be coated with the fluidized bed material. This coating was porous and generally less than 120 microns thick.

A thin, dense glassy coating was present between the SiC tube and the porous fluidized bed coating. In thin areas (2 to 3 microns), it contained 96 to 100% silicon; in thicker areas (5 to 8 microns), between 30 and 60% silicon. The other constituent of the coating was calcium. It is thought that a silica layer formed as a result of oxidation of the silicon and/or SiC. This reacted with the lime of the fluidized bed to form glassy calcium silicates. Although the oxygen partial pressures measured in the bed were periodically as low as 10^{-16} atmospheres, the tubes were capable of forming a protective passive oxide layer.

The comparative evaluation of the burst strength, Table 6, of the SiC tubes before and after exposure to the 24-inch AFB indicates that there is essentially no degradation in strength.

Ceramic-to-Metal Joint

Any fired CCCT heater employing ceramic heating surface will require joints between ceramic ducts and internally insulated metal ducts. The conceptual commercial heater concept locates these joints in the windbox, beneath the AFB. Personnel are thus protected from harm in the event of ceramic fracture. And small leaks at the joints can be tolerated, as the leakage is confined and joins the combustion air.

Detail design studies were made in the area of the windbox, tuyeres and ceramic heat exchanger manifolding to allow for assembly access and servicing of the components. The basic approach to building this ceramic heater is the use of shop-fabricated modules. Field assembly uses mechanical joints. The modules are field-replaceable without the need to make ceramic joints. The ceramic heat

TABLE 6. SUMMARY OF 24-INCH AFB SiC BURST TESTS

SiC MATERIAL	NO. OF SAMPLES	EXPOSURE (HOURS)	AVERAGE HOOP (1) TENSILE STRENGTH (ksi)	
			VALUE	RANGE
NC430	7	NONE (2)	16.5	10.9-18.9
1/8-INCH WALL	6	NONE (3)	7.8	6.1-10.0
	3	500	6.4	3.4- 9.2
	5	750	13.0	11.1-14.2
NC430	10	NONE (3)	11.6	4.9-13.7
1/4-INCH WALL	4	250	11.9	10.8-13.4
	8	500	12.6	10.5-15.2
NC430	23	NONE (2)(3)	11.8	4.9-18.9
COMBINED	20	250,500,750	11.6	3.4-15.2
CVD	9	NONE (2)	23.8	6.3-37.3
CVD	10	NONE (3)	22.1	4.2-39.4
CVD	3	250	21.4	16.3-29.1

1. BASED ON AVERAGE WALL THICKNESS
2. ROCKETDYNE 4 BY 6-INCH AFB CONTROL SAMPLES
3. NEW BATTELLE CONTROL SAMPLES
4. NC430 = SILICONIZED SiC
   CVD = CHEMICAL VAPOR DEPOSITED SiC

exchanger module is shown in Fig. 15. It contains eight parallel, four pass tube circuits for a total of 32 vertical runs. Tubes are 2 1/2 inches OD on 5-inch centers. Thus, the module occupies a 20 by 40-inch plan area. Each module contains ceramic inlet and outlet flanges, conical transition sections, and manifolds connecting to the eight tube circuits. The ceramic module is entirely shop fabricated of several subassemblies with presently available ceramic to ceramic joint technology. The module would be inspected completely and proof tested prior to shipment. The module is installed from the top, inserting the inlet and outlet ducts through the distributor plate. Makeup of the seal to the distributor plate and ceramic to metal joint is from the windbox side.

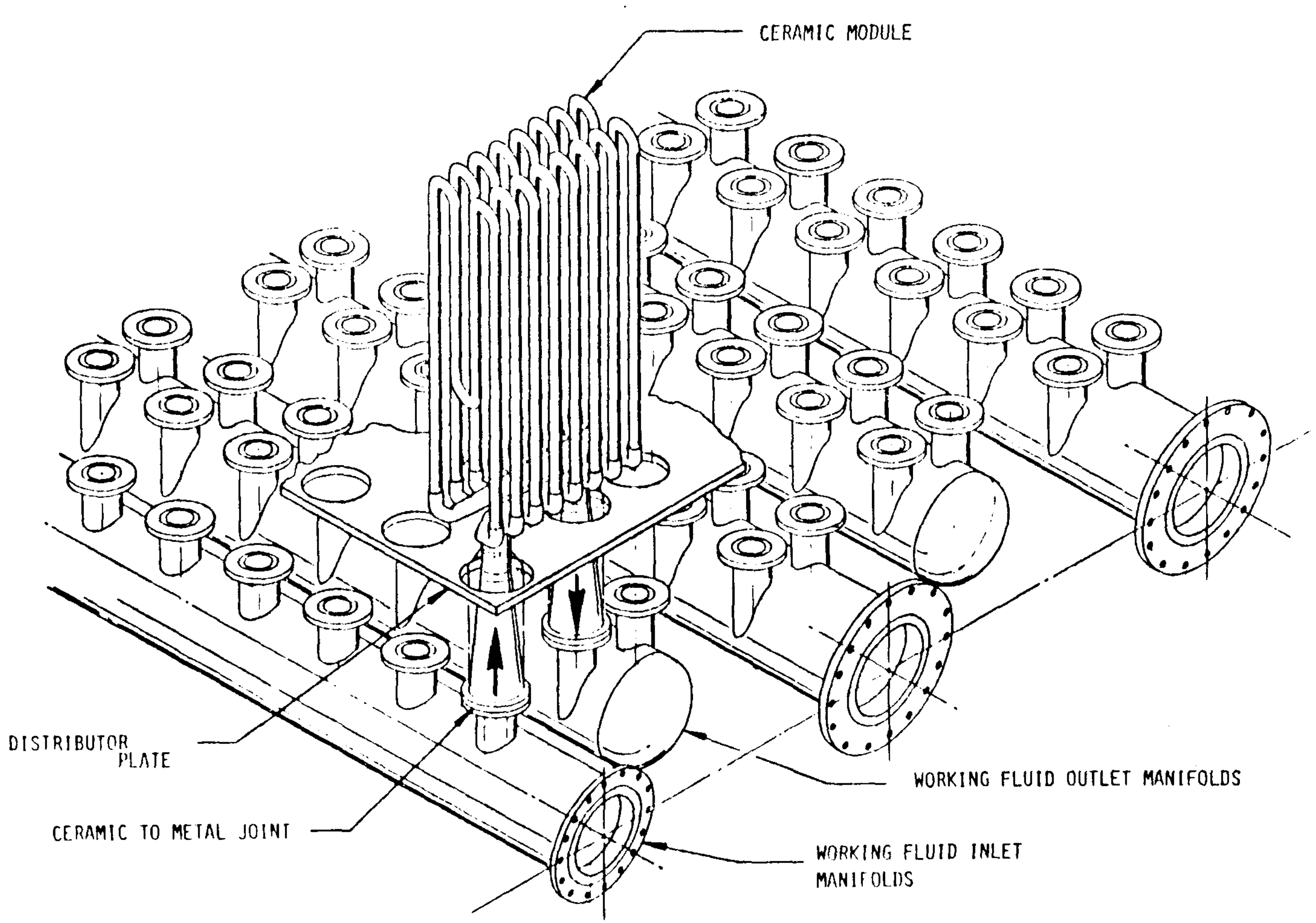


Figure 15. Ceramic Module and Working Fluid Manifolds

Between the ceramic manifold and the ceramic-to-metal joint lies the transition duct. The function of this section of the module, shown in Fig. 16, is to provide a gradual transition between the externally insulated manifold running at the 1750 F working fluid temperature and the internally insulated joint running at 700 F. Since this transition is made in the ceramic part, care must be taken to avoid high local stresses. This transition is performed in a gradual conical section of duct with both inner and outer insulation tapering over its full length. In this way, a gradual longitudinal temperature change and reasonable thermal stresses are achieved.

The ceramic-to-metal joint design is shown in Fig. 17. The design must minimize the stresses, complexity, and mass of the ceramic component to be practical. For this reason, clamp rings are used instead of a more conventional integral flange. Several other features are employed to accommodate the low thermal expansion and lack of ductility of the ceramic part. Compliant material is used at every ceramic to metal interface to prevent locally high contact stresses. Finite element stress analysis techniques were used to identify local highly stressed areas and refine the configuration. Based on the expected SiC material properties and the predicted stresses, the probability of failure of the ceramic flange is approximately 1 in 10,000.

Radial thermal expansion mismatch is handled in two ways. Low-expansion Incoloy 903 is used for the metal flange and ceramic clamp ring to minimize radial mismatch. In addition, the grafoil material used for the gasket and compliant layer has a sufficiently low coefficient of friction to allow sliding and, thus, limit shear loads into the ceramic to a reasonable value.

Axial thermal expansion mismatch, which would cause changes in joint preload, is eliminated by a careful selection of low- and intermediate-expansion metal alloys.

Testing of a full-size ceramic-to-metal joint will be conducted using a test setup designed to simulate the joint operating conditions. Included in the test fixture is a section of externally insulated SiC duct, the SiC transition section between the externally insulated and internally insulated portions, the ceramic-to-metal joint, and a short section of internally insulated metal duct.

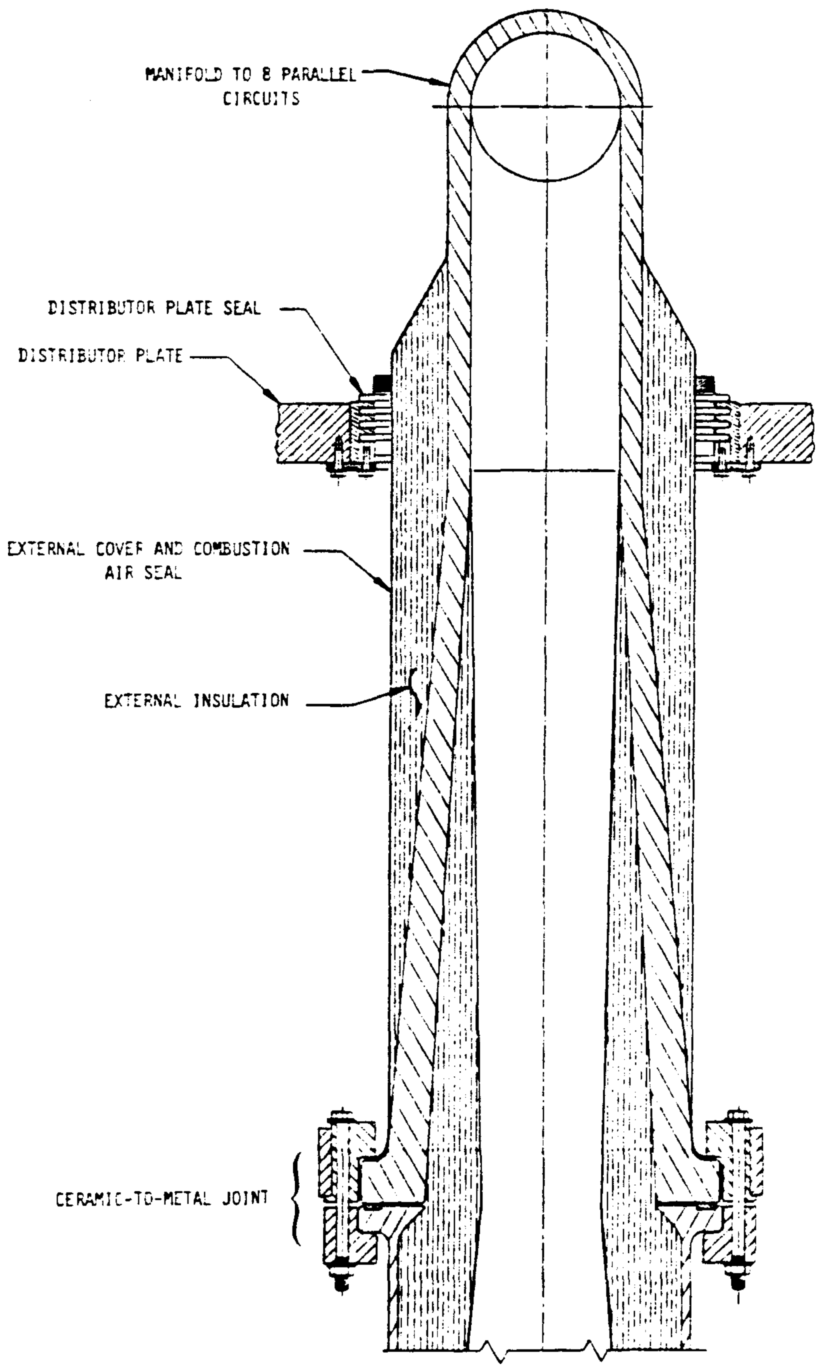


Figure 16. Ceramic Transition Section

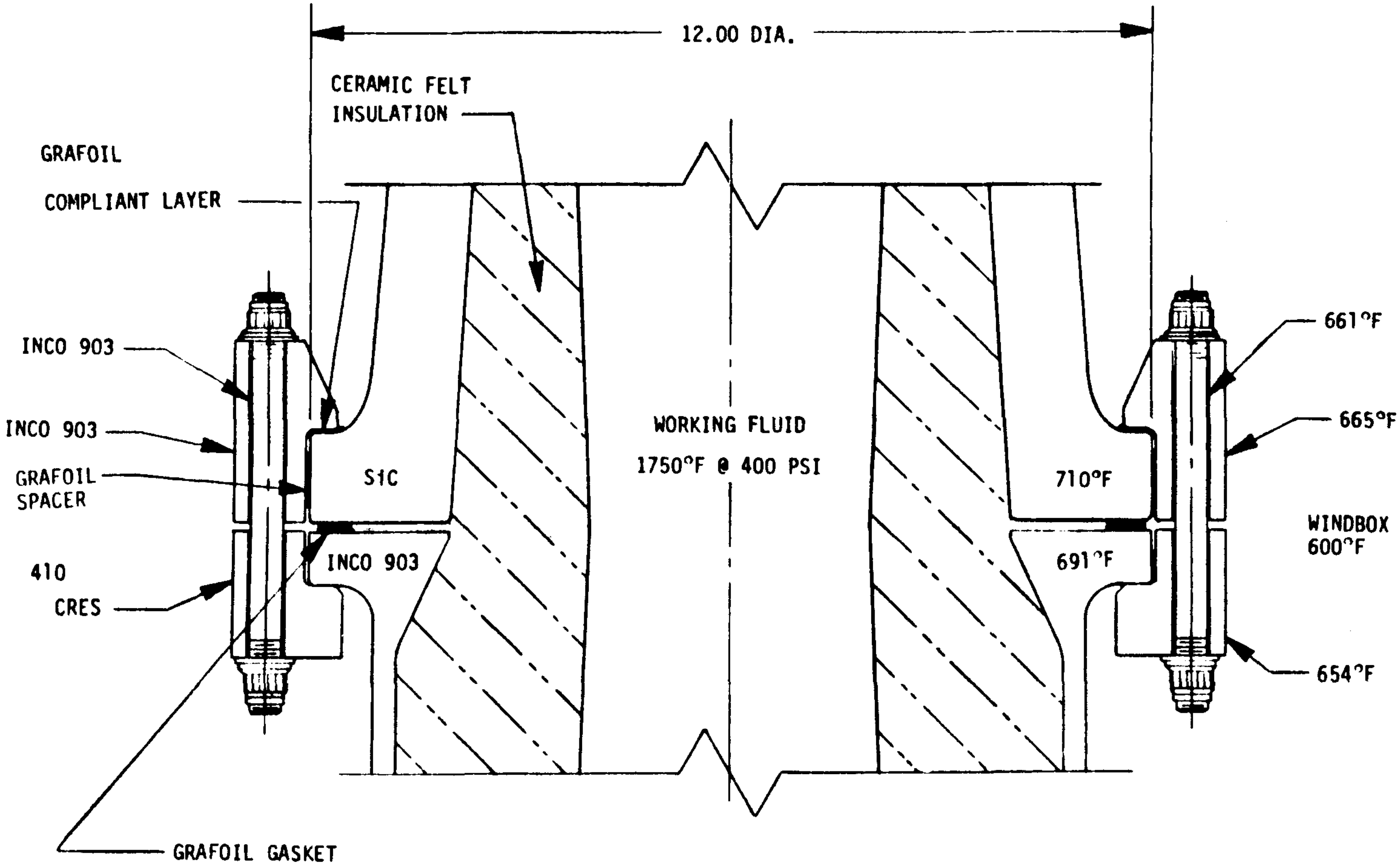


Figure 17. Ceramic-to-Metal Joint Materials and Temperatures

Fabrication of the test components and setup of the test equipment has been completed. Delays in the test schedule were caused by problems in fabrication of the ceramic test piece and a resultant interference with the 350-hour erosion/corrosion tests on the 6 by 6 combustor. As a result, testing of the ceramic-to-metal joint has been rescheduled. Testing will take place during the early part of the Phase III add-on. The results will be reported in the final report of that contract.

Series Bed Combustion Operations

Two experiments were conducted to evaluate the combustion aspects of the series bed concept.

The 24-inch AFB was used in a 3-hour run to simulate the downstream, 1650 F bed of a series bed arrangement and to measure sulfur recovery performance. To accomplish this, a sulfur-containing flue gas was synthesized by adding SO_2 to the combustion air plenum with the ignition burner in operation. The ignition burner heated the incoming combustion air to 940 F. At a 940 F temperature, about 4.0 scfm of natural gas was used. This is the equivalent of 22 lbs/hr of coal or 15% of the fuel. Sulfur dioxide was added at the rate of 2.6 lb/hr to the plenum, the equivalent of 6% sulfur coal. The Ca/S ratio required for acceptable sulfur emissions was 4.1, the highest of any experiments. However, the scatter in the Ca/S ratio needed for adequate sulfur control is large, and while the average Ca/S at 1650 F bed temperature was about 3.3, there were runs requiring 3.9 and 4.0. This experiment shows that the two beds in series can be used, but that somewhat more limestone may be required to control sulfur emissions.

The 24-inch AFB also was used to simulate the upstream, 1850 F bed. No operating difficulties were experienced at 1850 F. NO_x concentrations in the exhaust gas were minimal at 1850 F bed temperature and are compared with 1650 F bed results in Table 7.

TABLE 7. NO_x EXPERIMENTS

NO_x ppm READING	NORMALIZED*	TEMPERATURE, F	EXCESS AIR %	VELOCITY FT/SEC
380	485	1650	50	6
420	425	1650	20	6
85	72	1650	0	6
540	550	1850	20	6.6
*NORMALIZED TO 18% EXCESS AIR				

The one experiment at 1850 F showed that NO_x emissions increased by about 25% as the combustion temperature is increased from 1650 F to 1850 F. However, only 15 to 20% of the coal will be burned in the 1850 F bed, and additionally, the use of SiC tubes in the bed permits operation at or below stoichiometric. The series beds NO_x missions are not expected to be a problem.

WORKING FLUID SIDE CORROSION

Corrosion of the heat transfer materials by the working fluid is a secondary consideration compared to the fireside corrosion problem, but is nevertheless important in view of the extreme application intended.

Iron-base alloys that contain insufficient chromium to form a continuous protective thermal oxide film of Cr_2O_3 form scales containing proportions of Fe_2O_3, Fe_3O_4, and possibly F_eO, depending on alloy and temperature. These iron-base scales are often friable and easily detached, and therefore pose a potential source of erodent if they spall and become entrained in the high-velocity gas stream. Erosion problems could be encountered by the first-stage vanes and blades of the turbine.

In high velocity gas flow situations, even the usually protective Cr_2O_3 scales may be degraded by oxidation to the volatile CrO_3, which has been observed at temperatures above about 1470 F.

A special laboratory test rig was designed for the program. This apparatus simulated the metal temperature, gas velocity, gas temperature, and composition that may exist inside the AFB heat exchanger tubes.

The corrosion flow loop consisted of a 2-inch OD tubing system with two electrical furnaces to accommodate the test specimens, and a heat sink to cool the air before it passed through the blower. The specimens were in the form of rings cut from 2-inch OD tube stock, with chamfered edges to promote good sealing when several were stacked together to form a section of the tube system. In operation, cooled air leaving an air/water heat sink passed through a two-stage blower, through a series of internally wound air heaters that heated it to approximately 1000 F, and into the first specimen furnace, where the tube/specimen metal temperature was maintained at approximately 1100 F. From this furnace, the air was heated further to approximately 1500 F by internally wound heaters before it entered the second specimen furnace, where the tube/specimen temperature was maintained at approximately 1650 F. After this furnace, the air passed through an unlagged, unheated tube to the heat sink to complete the cycle. The system pressure, and gas and specimen temperatures were monitored throughout the runs. Table 8 summarizes the test conditions used.

TABLE 8. WORKING FLUID CORROSION RESULTS

NO.	GAS VELOCITY (FT/SEC)	DURATION (HR)	COMMENTS
1	120/146[A]	441	TERMINATED BECAUSE OF AIR LEAKS
2	200/243	120	--
3	200/243	1000	DISASSEMBLY PROBLEM
4	0	1000	BASELINE RUN
A: HIGHER VELOCITY IN LOWER-TEMPERATURE FURNACE			

Two groups of alloys were tested, corresponding to those suitable for application at approximately 1100 F and at approximately 1650 F in the heat exchanger cycle. These are listed in Table 9.

TABLE 9. SPECIMEN ALLOYS USED IN WORKING FLUID CORROSION TESTS

ALLOY	NOMINAL COMPOSITION	DENSITY (G/CM^3)	COEFF. OF THERMAL EXP. (IN/IN F BY 10^6)	EXPOSURE TEMP. (F)
INCONEL 617	Ni-12 Co-9 Mo-22 Cr	8.37	8.7 (1600)	1650
INCONEL 618E	Ni-15 Fe-6 W-23 Cr	8.56	8.91 (1600)	1050
HASTELLOY X	Ni-17 Fe-8 Mo-21 Cr	8.23	9.0 (1600)	1650
NIMONIC 86	Ni-10 Mo-25 Cr	8.54	8.6 (1560)	1650
INCOLOY 800	Fe-32 Ni-20 Cr	7.95	10.0 (1600)	1650
AISI 347	Fe-8 Ni-18 Cr-Nb	8.03	10.86 (1000) 10.35 (1000)	1650 1100
AISI 304	Fe-8 Ni-18 Cr	8.03	10.1 (1000)	1100
AISI 310	Fe-20 Ni-25 Cr	8.03	9.5 (1000)	1100
A335	Fe-1 Mo-2.25 Cr		7.8 (1000)	1100
A106	LOW-CARBON STEEL		7.97 (1000)	1100

Specimen analysis was conducted by descaling and weighing, and by electron probe microanalysis to measure the chromium profile of the corroded surfaces. The interpretation of test results was complicated by the condition that corrosion occurred on both inner and outer surfaces of the specimens, and by experimental difficulties.

Comparisons of the metal loss (determined by measuring chromium profiles) from the inside surface of the specimens (flowing air at 1550 F) with that from the outside surface (furnace at 1650 F) showed no significant or consistent difference for any of the alloys. Additionally, comparisons made of weight loss measurements of specimens run under flowing air conditions with a set run in the same apparatus under stagnant conditions generally gave weight loss results of a similar order, up to 10 times greater than those from chromium profile measurements. Although neither method of analysis provided data of the precision or ease of interpretation expected, the data from the chromium profile measurements are considered most likely to be realistic. The values obtained were some two orders of magnitude lower than the calculated maximum possible losses by vaporization. Hence, the conclusions for high-temperature materials are that:

1. There is no significant change in oxidation rate by the gas flow on the working fluid side of the tubes
2. That the likely rate of metal loss from oxidation on the working fluid side is approximately 0.6 mil/yr

For specimens exposed at the lower temperature (1100 F), only weight-change data were gathered. These indicated very large weight losses, equivalent to 10 mil/yr loss per wall for static conditions, and 30 mil/yr per wall for flowing conditions for the low-alloy steels. These results confirm that these low alloy steels should not be used at this temperature. Similar data for the 300-series stainless steels also indicated increased losses in flowing conditions at 1100 F, but these were nevertheless very small, suggesting a wastage rate of approximately 0.1 mil/yr.

OVERALL CONCLUSIONS AND RECOMMENDATIONS

The analyses conducted in the current and previous phases of this program leave no doubt that closed-cycle gas turbine based cogeneration systems have the potential for displacing oil and gas as fuels in many industries. The thermodynamic efficiency benefits provided by the gas turbine/cogeneration cycle result in significant fuel savings as compared with the competitive steam turbine-based cogeneration cycle, which for the same power and heat output is expected to have approximately the same capital costs. The competitive position of CCGT/cogeneration systems, versus oil and gas-fired cogeneration or noncogeneration systems, depends on the relative costs of coal versus the clean fuels. Present-day fuel cost differentials are sufficient to favor the CCGT/cogeneration installation in many cases. The future cost differentials are predicted to increase, with a resulting increase in the percentage of cases favoring CCGT/cogeneration.

System Demands Upon the Fired Heater

The thermodynamic efficiency of the CCGT/cogeneration system is a strong function of the turbine inlet temperature. At low temperatures, in the 1200 F region, the efficiency potentials are not sufficient to be competitive with alternative systems (or indeed, to meet the Federal Energy Regulating Commission rule on qualifying cogeneration systems). Turbine inlet temperatures in the 1450 to 1550 F range are sufficiently high to provide competitive thermodynamic efficiencies, and as temperatures are increased to the 1750 to 2250 F range, very significant increases in efficiency are obtained. It is clear that if CCGT/cogeneration systems are to be used, it will be necessary as a minimum to develop fired heater technology to supply the 1450 to 1550 F turbine inlet temperature, and desirable to attain higher temperatures. The developed CCGT/technology must cope with the materials and heater operability challenges posed by the required turbine inlet temperatures, which are much higher than those currently in use with steam turbine-based systems.

The ground rules of the current research required that the heater R&D be conducted with raw coal, i.e., coal not modified or processed (beneficiated) to improve its interactions in the fired heater. The anticipated future cost differentials between oil and gas versus coal are expected to be large enough to support some beneficiation of the coal, if that processing results in either cheaper fired heaters or higher attainable turbine inlet temperatures. Consideration of coal modifications is recommended for future study.

Heater Development, 1450 to 1550 F Heaters

The program's studies and test efforts indicate that both the fluidized bed and pulverized coal heater concepts researched for the 1450 to 1550 F turbine inlet temperature application are technically feasible. However, for a variety of reasons the fluidized bed concept appears more attractive for a wide range of industrial applications, and additionally is expected to be less costly to develop. The major technical issue requiring continuing development is the durability of metals in the AFB environment. It is recommended that this technology be pursued through continued testing of the 6 by 6-foot AFB.

1750 F and Higher Turbine Inlet Temperature Heaters. The potential for sizable efficiency gains due to turbine inlet temperatures higher than those attainable with metal heat exchangers favors continued development effort on heater concepts employing ceramic surfaces. The series bed heater concept, while limited to about 1750 F by bed operability considerations when burning raw coal, can be continued in development at very modest expense as an adjunct of the 1450 to 1550 F AFB development program recommended above. Such continued development is recommended. For higher turbine inlet temperature, in the 2000 to 2250 F temperature range, added studies of alternative heater concepts, both with and without coal beneficiation, are recommended.

REFERENCES

1. Advanced Coal-Fired Combustor/Heat Exchanger Technology Study, Final Report, RI/RD78-212, Rocketdyne Division, Rockwell International, Canoga Park, CA.
2. Closed-Cycle Gas Turbine Heater Program, Final Report for U.S. Department of Energy, Contract EF-77-C-01-2611, AiResearch Manufacturing Company of Arizona.
3. Advanced Coal-Fueled Combustor/Heat Exchanger Technology Study - Cogeneration Applications, Final Report, RI/RD79-199, Rocketdyne Division, Rockwell International, April 1979.
4. Final Report, Cogeneration Applications Study, Contract EF-77-C-01-2611, Mod., AiResearch Manufacturing Company of Arizona, 6 April 1979.
5. Borio et al: "Improved Thermal Efficiency by Control of Factors Affecting Metal Wastage in Pulverized Coal-Fired Steam Generators", in "Ash Deposits and Corrosion Due to Impurities in Combustion Gases", Hemisphere Publishing Company, 1978.

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