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SEPARATELY-FIRED AIR HEATERS FOR MHD/STEAM POWER PLANTS

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ABSTRACT

This paper presents the results of a study that examined technical and economic issues associated with the evolution of MHD plant design from oxygen-enriched configurations to separately-fired air heater designs.

A preliminary concept of a 500 MWe oxygen-enriched, early commercial MHD/steam combined cycle power plant with a low temperature oxidant heater was developed and used as the baseline plant for this study. This baseline plant concept was then modified to represent plant designs that employ natural gas-fired high temperature air heaters in place of low temperature oxidant heaters; the air heater parameters were selected to be consistent with the findings of a literature review on the state of air heater technology. Efficiencies, capital costs, and operating costs of the separately-fired plants were determined and compared with those of the oxygen-enriched plant.

The major conclusions reached in this study are that clean fuel-fired air heater technology is sufficiently advanced to allow design and operation of an MHD power plant using a separately-fired air heater, but that the capital cost and COE of a separately-fired plant would both be higher than those of an oxygen-enriched plant.

INTRODUCTION

Commercial, mature-design MHD power plants will probably utilize direct-fired, regenerative air heaters for preheating the air to the MHD combustor. Several studies have indicated that direct-fired MHD systems offer higher efficiency than the oxygen-enriched designs that have been proposed for retrofits and for early-commercial plants. One possible intermediate step between oxygen-enriched plants and direct-fired designs is the use of a separately-fired air preheater, where the regenerative air heater modules are fired with a clean fuel, such as natural gas or distillate oil.

High temperature (4200 °F and above) combustion is a requisite for efficient open-cycle MHD power generation. This is because the high temperature causes thermal ionization in the seeded plasma that in turn provides the high plasma electrical conductivity needed for MHD power production. The possible methods of achieving this high combustion temperature include enriching lower temperature (1200 °F) combustion air with oxygen, or using combustion air preheated to the higher temperatures of 2500 °F to 3000 °F.

Coal-fired production of high temperature air preheat, either separately- or direct-fired, is a developmental issue, and significantly more technically challenging than the expedient of oxygen enrichment, which is well within current design capability. The major technical issues in the design of direct-fired air heaters are the ability of the ceramic materials used in the air heater matrix and pressure vessel linings to survive the erosive and corrosive conditions found in MHD diffuser discharge gas, the operation of valves in this environment, and the control of slag formation and seed condensation in the air heater. Present U.S. coal-fired MHD facility testing therefore uses oxygen enrichment, as do conceptual designs for early commercial coal-fired MHD retrofit and new plant applications.

In the Soviet Union and India, MHD development has focused on natural gas-fired MHD power production. With a "clean" fuel, such as natural gas, high temperature air heater development is much closer to the design experience for high temperature blast furnace heaters. In these international development programs, clean-fuel separately-fired air heater systems have been tested and used.

This paper summarizes the results of a study[1] that evaluated two potential configurations for 500 MWe output coal-fired early commercial MHD/steam power plants. One configuration uses oxygen-enriched air to achieve high combustion temperatures, the other uses natural gas-fired air heaters to obtain the high combustion temperatures required for efficient open-cycle MHD power production. Each MHD/steam plant design incorporates a similar MHD topping cycle and steam bottoming cycle, using conditions that have been projected for early commercial MHD/steam power plants.

This study began with a review of the literature available on separately-fired and direct-fired air heaters for MHD applications. Based on the air heater state-of-the-art reported in the literature, conceptual designs for two separately-fired 500 MWe MHD/steam power plants, corresponding to two different preheat temperatures, were developed. Performance, capital cost, and cost of electricity were determined for these separately-fired plants and compared with similar data for a 500 MWe oxygen-enriched plant.

LITERATURE REVIEW

The literature on clean fuel-fired air heaters was reviewed to ascertain the state-of-the-art for these components. This review included not only studies that deal specifically with MHD but also studies that address other applications, such as air heaters in the primary metals industries.

This review indicates that fixed bed, regenerative, separately-fired air heaters have demonstrated the capability of delivering air at temperatures up to 3635 °F at the U-02 facility in the USSR[2,3], and mass flow rates up to 95 lb/sec have been demonstrated at the U-25 facility[2]. A design for a cored brick heater with a design point of 440 lb/sec air flow at 3092 °F has been developed, but this unit has not been demonstrated.

The conclusion reached from the literature review is that fixed bed, regenerative, separately-fired air heaters are technically feasible, and that their performance has been demonstrated in small scale facilities. There is a need for demonstration of their operation and durability at the large scales (500 lb/sec air output) needed for an MHD/steam power plant with a commercial size rating (500 MWe or greater). This demonstration is not expected in the near future. The Ryazan pilot MHD power plant[4], which is based on an air heater rated for 470 lb/sec at 2600 °F, had been under construction, but this project has been postponed indefinitely.

BASELINE PLANT DESIGN

A preliminary concept of a 500 MWe oxygen-enriched, early commercial MHD/steam combined cycle power plant, with a low temperature oxidant heater was developed and used as the baseline plant for this study. The plant design is scaled up from the 220 MWe NASA Engineering Test Facility (ETF) design[5]. Table 1 shows the major design parameters and the performance for the baseline plant.

The plant was designed to burn Illinois No. 6 coal, a high sulfur bituminous coal, and to meet the present New Source Performance Standards (NSPS) for atmospheric emissions. The standards that apply to this plant are 90 percent capture of SO_2, resulting in an emission rate of 0.60 lb/million Btu, and emissions of NO_x and particulates of 0.60 and 0.03 lb/million Btu, respectively. The seed used to capture sulfur in the MHD combustor and to provide ionization was a mixture of K_2CO_3, K_2SO_4, Na_2CO_3, and Na_2SO_4. The seed was assumed to be regenerated by the TRW Econoseed process[6]; the seed regeneration system is at the power plant site, but is not integrated to the power plant cycle.

Table 1

BASELINE PLANT CHARACTERISTICS

OVERALL PLANT PERFORMANCE	
POWER SUMMARY, kWe	
MHD DC Power	245,370
Steam Turbine Power	377,695
GROSS POWER, kWe	623,065
COAL THERMAL INPUT, MWt	1,160.0
NET PLANT EFFICIENCY (HHV), %	43.26
MHD TOPPING CYCLE DESIGN PARAMETERS	
Maximum Magnetic Field Strength, Tesla	6.0
Maximum Axial Voltage Gradient (Ex), V/m	2,500
Maximum Current Density (Jy), A/cm²	0.589
Maximum Hall Parameter	3.60
Oxygen Enrichment, Volume %	30.0
Oxidant Preheat, °F	1,200
Channel Connection	Faraday
Channel Inlet Mach Number	0.95
Channel Exit Mach Number	0.80
Diffuser Exit Temperature, °F	3,500
STEAM BOTTOMING CYCLE DESIGN PARAMETERS	
Throttle Pressure, psig	2,400
Throttle Temperature, °F	1,000
Reheat Temperature, °F	1,000
Condenser Pressure, "HgA	2.5

AIR HEATER DESIGN CHARACTERISTICS

A conceptual design for the separately-fired air heater modules was developed for this study. The fuels considered for firing the air heater were natural gas, distillate oil, and residual oil. Natural gas was selected as the air heater fuel. The historical and projected fuel prices for natural gas are lower than those of the other two candidates, and the consumption of natural gas by electrical generating plants is considerably higher than that of the other two fuels. In addition, residual oil typically has a sulfur content that would require SO_2 emissions control equipment on the air heater combustion products.

Reaching the 2500 to 3000 °F air temperatures considered by this study requires flame temperatures in the 2800 to 3300 °F range. These temperatures are readily achievable with a natural gas-fired combustor, but a conventional combustor design that operates with a greater-than-stoichiometric amount of combustion air would have an unacceptable amount of NO_x in its flue gas. Under the present federal NSPS, only the total plant emissions are regulated; the total NO_x emissions permitted are 0.6 lb/million Btu of coal input plus 0.2 lb/million Btu of natural gas input. It is desirable to operate the air heater combustor at a NO_x emission rate of 0.2 lb/million Btu or less so as to not make the NO_x control requirement in the coal-fired portion of the plant more severe. Figure 1 shows the equilibrium NO_x emissions predicted for a gas-fired combustor; from this figure, it can be seen that operation of the combustor at a fuel-rich condition is needed to keep NO_x emissions under the 0.2 lb/million Btu threshold. It was assumed for this study that the air/fuel stoichiometric ratio for the air heater would be set at 98 percent, and that the flue gases from the air heater would be ducted to the afterburner section of the MHD HRSR to complete combustion and to mix with the combustion products from the MHD topping cycle.

Figure 2 shows the configuration of the air heater module selected for this study. The design is similar to the one developed by the USSR[7] for a 500 MWe natural gas-fired MHD power plant. The combustion products flow downward through the cored brick matrix, and are split at the lower end of the air heater module, with one stream going to the afterburning section in the HRSR, and the remaining stream providing a recirculation flow of flue gas to limit and control the flame temperature in the combustor section.

A detailed analysis of heat transfer characteristics, utilizing the differential equations employed for single-blow regenerator models, was performed for the 2500 °F air heater design. Table 2 shows the overall performance and physical parameters that were calculated for both air heater configurations.

SEPARATELY FIRED PLANT DESIGNS

The baseline plant conceptual design was modified and the coal feed down-sized to represent a plant design that employs the natural gas-fired high temperature air heaters described above in place of low temperature oxidant heaters. Two separately-fired plants were considered--one with a preheat temperature of 2500 °F, and the other with 3000 °F air preheat.

Since power plant performance and economics are dependent upon component size, plant output was kept similar; each plant produces a net output of about 500 MWe. The oxygen-enriched plant therefore has a larger coal thermal input than the plants with the separately-fired air heaters. Each power plant was designed with a similar steam bottoming cycle, which was rated for main steam at 2400 psig and 1000 °F, with a single reheat to 1000 °F.

Table 3 compares the performance and major cycle features of each of the three MHD/steam plant designs. The overall thermal efficiency (based on the combined thermal inputs for coal and natural gas) of the

Table 2

TIME-AVERAGED SEPARATELY FIRED AIR HEATER PERFORMANCE

Air Heater Air Delivery Temperature, °F	2500	3000
Net Heat to MHD Combustion Air, MWt	294.2	323.1
Natural Gas HHV Input, MWt	395.6	447.2
Air Heater Efficiency, % (HHV)	74.35	72.25
Air Heater Efficiency, % (LHV)	81.92	79.60
Auxiliary Loads, kWe		
Forced Draft Fan	1,500	1,696
Gas Recirculation Fan	1,244	415
Total Auxiliaries, kWe	2,744	2,111
Number of Operating/Spare Modules	6/1	6/1
Module Inside Diameter, ft	18	
Matrix Height, ft	115	

2,500 °F separately-fired configuration is about 0.2 percentage points lower than that of the oxygen-enriched baseline plant, while the 3,000 °F configuration shows an efficiency improvement of 0.7 percentage points relative to the baseline. The gross power outputs of the two separately-fired configurations are both about five percent less than that of the baseline plant, but elimination of the air separation unit, which consumes 27.4 MWe in auxiliary power, results in the separately-fired configurations having virtually the same net output as the oxygen-enriched case.

Table 4 compares the changes in performance requirements for some of the major power plant systems. Most of the major plant components have lower capacity requirements for the separately-fired configurations; this is due primarily to the lower thermal input to the MHD combustor for the separately-fired plants, which results in reduced requirements for topping-cycle related systems as well as reductions in thermal duty in the heat recovery and seed recovery system.

Table 3

OVERALL POWER PLANT PERFORMANCE FOR 500 MWE OXYGEN-ENRICHED AND SEPARATELY-FIRED PREHEATER CONFIGURATIONS

PLANT TYPE:	Oxygen-Enriched Baseline	2,500 °F Air Heater	3,000 °F Air Heater
POWER SUMMARY, kWe			
MHD DC Power, kWe	245,370	218,270	239,410
Steam Turbine Power, kWe	377,695	370,556	351,172
Gross Power, kWe	623,065	588,826	590,582
Air Separation Unit, kWe	-27,371	-	-
Other Auxiliaries, kWe	-93,907	-87,071	-90,932
Net Power, kWe	501,787	501,755	499,650
Net Efficiency, % Total HHV	43.26%	43.05%	43.94%
Net Total Heat Rate, Btu/kWh (HHV)	7,889	7,928	7,768
CONSUMABLES			
As-Rec'd Coal Feed, pph [Incl. 12.0% Moisture]	352,179	233,775	209,486
Coal Feed, Millions Btu/hr	3,958.8	2,627.9	2,354.8
SFAH Natural Gas Feed, Millions Btu/hr	0	1,350.2	1,526.2
Total Power Plant Thermal Input, Millions Btu/hr	3,958.8	3,978.1	3,881.1
Total Seed Feed, pph	64,296	42,680	38,245
Air Separation Unit Product, pph	377,176	0	0
MHD Combustor Coal Thermal Input, MWt	1,160.0	770.0	690.0
SFAH Natural Gas Input, MWt	-	395.6	447.2
Total Plant Thermal Input, MWt	1,160.0	1,165.6	1,137.2
Overall Plant NO_x Limit, lb/Million Btu	0.600	0.464	0.443

Notes:

Performance represents time-averaged values.

NO_x limit based on present NSPS for mixed-fuel plants, 0.600 lb/Million Btu for coal input, and 0.199 lb/Million Btu for natural gas input.

Table 4

CHANGES IN EQUIPMENT CAPACITIES OR DUTIES

Changes in Capacities
Relative to Baseline Plant, Percent

Air Heater Air Delivery Temperature, °F	2,500	3,000
Main Oxidant Compressor		
Mass Flow Rate	-4.3	-14.2
Power Consumption	-7.9	+1.3
MHD Channel		
Output Power	-11.0	-2.4
Channel Length	-0.6	+1.8
Heat Recovery/Seed Recovery System		
Total Heat Exchanger Duty	-10.2	-16.2
Radiant Boiler Gas Mass Flow	-10.0	-19.3
Convective Section Gas Mass Flow	+1.5	-1.7
Steam Turbine-Generator		
Main Steam Flow	-3.3	-8.6
Output Power	-1.9	-7.0

Notes:

Coal Thermal Input Sized for 500 MWe Net Plant Output.

Channels designed for minimum diffuser exit temperature of 2,200 K (3,500 °F) or for maximum length of 17.0 m.

Channel inlet/exit Mach numbers = 0.95 & 0.80.

Seed feed rate set for 90 % sulfur capture.

Table 5 compares the MHD topping cycles for each of the three plant configurations. The topping cycles for the separately-fired plants have substantially lower coal thermal inputs to the MHD combustor. Combustor oxidant and exit massflows are also reduced for the separately-fired configurations, in spite of the fact that the oxidant is non-enriched air. Combustor exit pressures are comparable for the oxygen-enriched and the 2500 °F preheat plants; the 3000 °F preheat plant operates with a combustor exit pressure 27 percent higher than that of the baseline because the high plasma conductivity resulting from that temperature allows a greater expansion ratio, and hence more power extraction.

ECONOMIC COMPARISON

Capital and operating costs were estimated for the oxygen-enriched baseline plant and for the separately-fired plant. These costs are compared to determine the benefits or penalties of using separately fired air heaters in an MHD plant relative to the oxygen-enriched plant configurations expected for early commercial MHD plants.

Table 6 shows the changes in Total Plant Cost (TPC) between each of the separately-fired configurations and the oxygen-enriched baseline plant; these changes are expressed as a percentage of the TPC for the baseline plant. The major changes in TPC arising from designing a separately-fired plant are the cost of the air heater itself, the omission of the Air Separation Unit (ASU), and a change in the cost of the seed injection and regeneration system. For both air delivery temperatures, every cost category decreases except for the air heater cost itself. For the 2500 °F configuration, the TPC increases by 8.8 percent relative to the oxygen-enriched baseline; for the 3000 °F configuration, the TPC increase relative to the baseline is smaller, at 3.4 percent.

Table 7 shows changes in the components that make up the levelized Cost of Electricity (COE). The COE values are levelized over a period of thirty years, and are based on first-year fuel costs of 1.68 and 2.25 \$/million Btu for coal and natural gas, respectively. The natural gas price was assumed to escalate at the same rate as the coal price; this assumption would favor the separately-fired configurations, since most forecasts call for natural gas to escalate at a higher rate than coal. The changes in COE are expressed as a percentage of the COE for the oxygen-enriched baseline plant.

For the 2500 °F configuration, the largest change in COE is a 7.3 percent decrease in coal cost, reflecting the smaller coal feed rate of the separately-fired configuration. This is offset by a 5.5 percent increase in "Natural Gas & Other Consumables", which reflects the natural gas that fires the air heater minus savings in natural gas from regeneration of a smaller quantity of seed. The third largest change is due to the difference in capital costs; the 8.8 percent increase in TPC results in a 4.5 percent increase in COE; other changes in COE components are relatively minor. The total increase in levelized COE relative to the baseline plant is 6.2 percent; this amount is almost entirely accounted for by the increase in "Natural Gas & Other Consumables".

The 3000 °F configuration showed better economics than the 2500 °F case. The 3000 °F plant had a decrease in coal charges of 8.7 percent, which was offset by 6.0 and 1.9 percent increases in "Natural Gas & Other Consumables" and "Capital Recovery", respectively, and minor increases in the other components. The total increase in levelized COE is 2.0 percent relative to the oxygen-enriched baseline plant.

Comparing the economics of the two air heater delivery temperatures indicates that the higher air temperature is favored. Higher temperature results in a smaller and more efficient MHD topping cycle, which tends to reduce the capital cost of the power plant. The reduction in air flow rate due to the smaller topping cycle partially offsets the increased thermal duty and natural gas cost needed to produce the higher air delivery temperature.

The air heater configurations considered showed penalties in not only TPC but also in COE relative to the baseline plant. In addition, the COE penalties for the separately-fired configurations would likely be larger than those shown in Table 7, since it is likely that the price of natural gas will escalate at a higher rate than that of coal.

CONCLUSIONS

The results of this study show that there are no major technological barriers in designing an MHD power plant based on separately-fired air heaters. The delivery temperatures needed for an MHD topping cycle have been demonstrated in several facilities, while the flow rates required for a commercial-scale MHD plant have been demonstrated in air heaters used in the metals industry. The primary technological barrier to the implementation of a separately-fired air heater is that there has been no demonstration of a heater that simultaneously satisfies the flow rate, pressure, and air temperature requirements of a commercial-scale MHD/steam power plant.

Although this study showed that there is no technological barrier to the separately-fired air heater, a power plant based on separately-fired technology has no economic advantages over an oxygen-enriched plant. Capital cost and levelized cost of electricity were both higher than those of the oxygen-enriched plant for each of the configurations considered.

Table 5

EFFECT OF SEPARATELY-FIRED PREHEATERS ON MHD TOPPING CYCLE PARAMETERS

Configuration	Oxygen-Enriched Baseline	2500 °F Air Heater	3000 °F Air Heater
MHD Combustor Coal Thermal Input, MWt	1160.0	770.0	690.0
Combustor Exit Total Pressure, atm	5.99	5.61	7.63
Seed, % Potassium	1.352	1.000	1.000
Combustor Exit Flow, kg/sec	283.85	255.47	228.93
Combustor Exit Total Temperature, K	2,733	2,745	2,864
MHD Combustor Oxidant Flow, kg/sec	237.12	224.46	201.14
Channel Inlet Conditions			
Static Temperature, K	2,582	2,581	2,699
Static Pressure, atm	3.62	3.38	4.60
Conductivity, mho/m	5.93	6.47	8.76
Channel Exit Conditions			
Static Temperature, K	2,141	2,133	2,163
Static Pressure, atm	0.77	0.77	0.77
Conductivity, mho/m	1.56	1.54	1.86
Channel Length, m	16.7	16.6	17.0
Inlet Area, m^2	0.640	0.622	0.421
Exit Area, m^2	3.414	3.130	2.809
Channel Length/Diameter Ratio	18.5	18.7	23.2
Channel Cooling Duty, MWt	46.6	40.0	49.4
Diffuser Exit Temperature, K	2,200	2,200	2,222
Maximum Ex, V/m	2,500	2,500	2,500
Maximum Ey, V/m	3,912	3,981	4,069
Maximum Jy, A/cm^2	0.589	0.640	0.884
Maximum Hall Parameter	3.60	3.86	3.87
DC Power Output, MWe	245.37	218.27	239.41
Enthalpy Extraction Ratio, %	21.2	21.9	24.8

Table 6

CAPITAL COST DIFFERENTIALS FOR SEPARATELY-FIRED AIR HEATERS

Account Number	Item/Description	2500 °F Heater TPC Increase, % of Baseline TPC	3000 °F Heater TPC Increase % of Baseline TPC
311	STRUCTURES & IMPROVEMENTS	-0.22	-0.42
312	BOILER PLANT EQUIPMENT	-1.22	-2.46
314	TURBOGENERATOR UNITS	-0.14	-0.52
315	ACCESSORY ELECTRIC EQUIPMENT	-0.52	-0.43
316	MISC. POWER PLANT EQUIPMENT	-0.07	-0.07
317	MHD TOPPING CYCLE EQUIPMENT		
317.2 & 3	Generator & Magnet	-0.41	-1.17
317.52	Separately-Fired Air Heater	+21.0	+18.9
317.6	Seed System	-2.44	-2.98
317.7	Air Separation Unit	-5.85	-5.85
	Other Topping Cycle Equipment	-1.65	-1.67
Total		+8.75	+3.37

Note: Total Plant Cost (TPC) increase is relative to the oxygen-enriched Baseline Plant.

Table 7

CHANGES IN LEVELIZED COST OF ELECTRICITY COMPONENTS FOR SEPARATELY-FIRED AIR HEATERS

Increase in Levelized COE Component, % of Baseline COE		
Air Heater Air Delivery Temperature, °F	2,500	3,000
Capital Recovery	+4.5	+1.9
Fixed O & M	+1.6	+1.1
Variable O & M	+0.9	+0.6
Coal Cost	-7.3	-8.7
Natural Gas & Other Consumables	+5.5	+6.0
Byproduct Credits	+1.0	+1.2
Total Increase in COE, mills/kWh	+6.2	+2.0

Notes:

Cost of Electricity (COE) increase is relative to the oxygen-enriched Baseline Plant.

Based on first-year fuel costs of 1.68 $/million Btu for coal and 2.25 $/million Btu for natural gas.

Natural gas and coal are assumed to escalate at the same rate.

The scenario used to evaluate the economics of the separately-fired configurations assumed that natural gas would escalate at the same rate as coal. However, a more likely scenario is one where natural gas escalates at a higher rate than coal. In that scenario, there would be an even larger COE penalty for the separately-fired configurations.

ACKNOWLEDGEMENT

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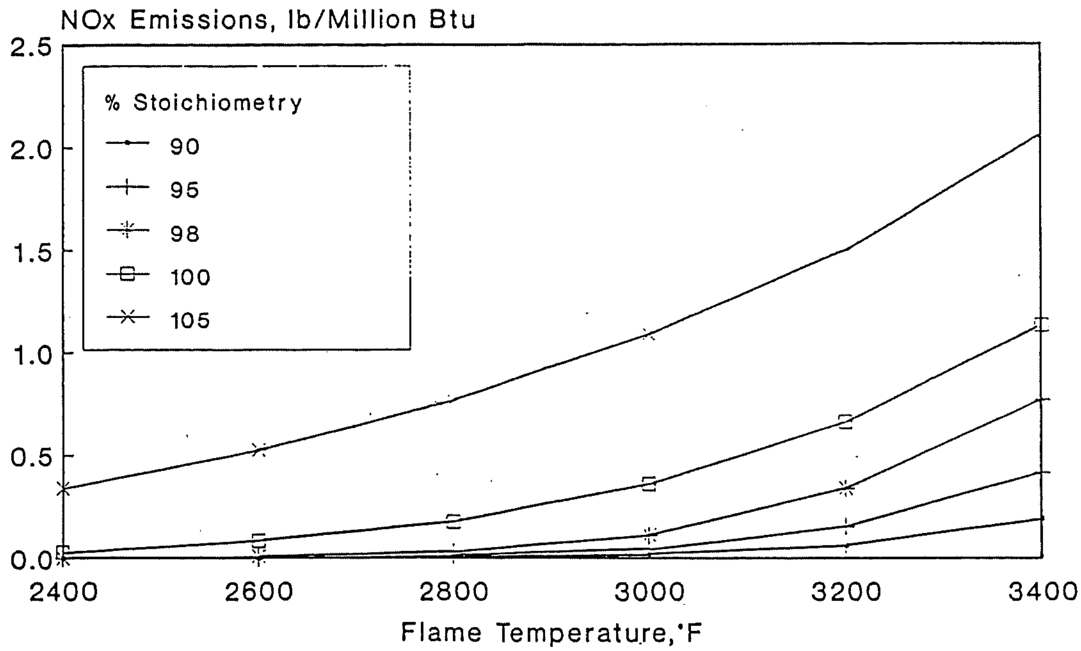

Figure 1
Equilibrium NOx Emissions for Natural Gas-Fired Air Heaters

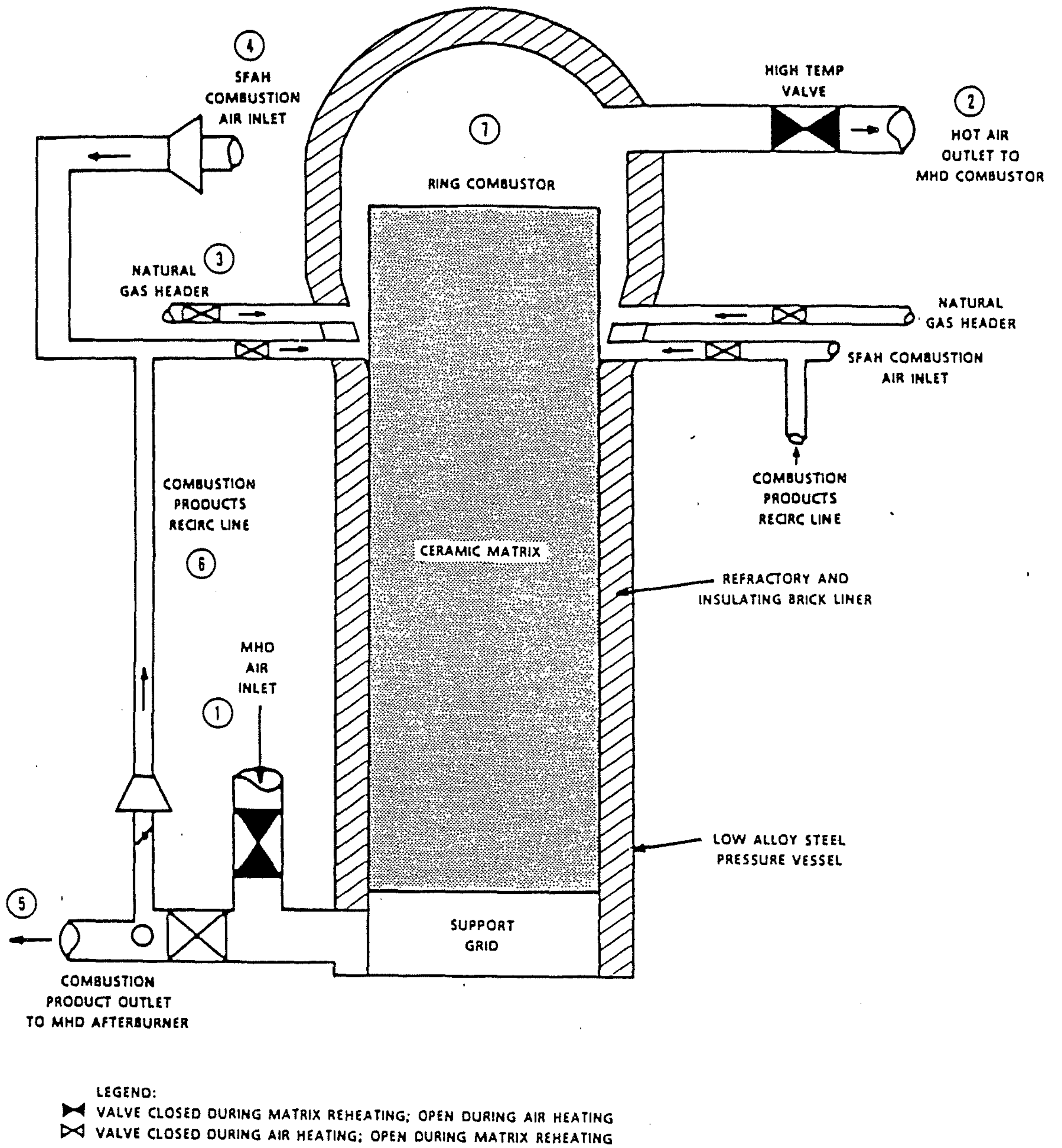

Figure 2
Separately-Fired Air Heater Configuration