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CONSERVATION

THERMIONIC COGENERATION BURNER ASSESSMENT STUDY
PERFORMANCE ANALYSIS RESULTS

Topical Report

December 1983

Work Performed Under Contract No. AC02-82CE40583

Rasor Associates, Inc.
Sunnyvale, California

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THERMIONIC COGENERATION BURNER ASSESSMENT STUDY
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TOPICAL REPORT

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Prepared For
U.S. Department of Energy
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SUMMARY

Cogeneration in general has the objective of the simultaneous production of useful heat for an industrial (or other) process and, from the same heat source, the generation of electrical power. Many energy conversion systems are able to do this, but most systems produce hot water or steam in spite of the fact that more than 60% of industrial energy consumed in the U.S. is used as high temperature gases ($>1000^{\circ}\text{F}$, $>537^{\circ}\text{C}$).

The thermionic cogeneration burner was conceived to supply the requisite high temperature gases and to generate electrical power simultaneously. Its attributes include:

- o The ability to deliver heat at temperatures sufficiently high for any industrial process, while providing energy savings of 3-20%.
- o Modularity, permitting use over a range of installation sizes with staged introduction.
- o Reliability, through inherent redundancy.
- o Compatibility with existing furnaces.

The purpose of this contract was to 1) test and evaluate two of the more important engineering aspects of designing and building thermionic cogeneration burners (TCB's); 2) make a cost and performance estimate of the TCB; and identify and evaluate industries where TCB's could be installed and where that the electrical power (DC) produced by the TCB's would be used directly in the process.

This Topical Report details the results of the performance analysis. In particular this part of the overall program yielded the following conclusions:

- A computer program was developed which predicts TCB performance based on data from the thermal simulation experimental and normal operationally controlled parameters (such as air/fuel ratio and cesium reservoir temperature).

- Power output of the TCB will vary between 8 and 15⁺kWe/MBtu/hr depending on the condition of combustion at the industrial site.
- Power output at the high end of the 8-15 kWe/MBtu/hr range is achieved by increasing the amount of cooling air used in the collectors and then by passing the excess air around the combustion chambers and directly into the furnace or boiler.
- Federal Energy Regulatory Commission (FERC) efficiency for the TCB will be about 52% in a standard industrial furnace.
- Temperature of the exhaust gas from the TCB will range from 2200⁺ K with zero bypass to 1200 K with 1.5 bypass. The bypass ratio is the ratio of air passing through the collectors and going into the furnace to the air passing through the collectors and being used as combustion air. This temperature range covers industries from steel to chlorine-alkali plants.
- A trade-off analysis shows 20-30 cm²/MBtu/hr to be the optimum area of emitters per unit burner size.
- A failure analysis was performed. Failure of individual converters due to open circuit will decrease the power by about 1%. Converters can be designed with a fuse to fail to open circuit rather than closed circuit. If an entire ring fails due to absence of a fuseable link, about 20% of the power output will be lost.

THERMIONIC BURNER ANALYSIS

1.0 COMPUTATIONAL MODEL

A mathematical model of the burner was developed and incorporated in a computer program which was used to predict the engineering and economic attributes of a wide range of thermionic cogeneration burner designs. Also, for a given set of design parameters, the program is able to calculate the efficiency and power output, and through these predict an ideal operating range. Based on an initial set of design parameters and constraints, a current-voltage (I-V) curve and other burner attributes are calculated and then used in the evaluation of that specific design. The calculations are performed by first choosing a voltage, and then setting the initial parameters. Next the resulting converter and burner parameters are calculated. Various constraints are placed on the system as the calculation proceeds, these included:

- maintaining conservation of energy, both for the individual converter-burner rings and for the overall burner (see Fig. II-1)
- keeping the heat transfer coefficients and surface areas within acceptable bounds
- restricting all temperatures to acceptable operating ranges.

The calculations were done for a nominal 10,000 Btu burner, but the design values could be scaled for any size industrial burner.

The mathematical model used assumes a basic burner arrangement, shown in Fig. 1. For this design there are N rings of thermionic converters, arranged sequentially down the barrel of the burner, with the gas flow moving axially from zone (ring) to zone (ring). Each of the zones has a specific amount of emitter area. It is important to realize, however, that the program does not assign this cylindrical geometry, but instead allows the energy balance to proceed independent of any geometrical constraints. The assignment of a specific geometry is dependent on the required flame-to-emitter and collector-to-air heat transfer. These heat transfer

THERMIONIC COMBUSTOR

Fig. 1 Thermionic Combustor Schematic Flow diagram. Note that the calculational sequence starts from gas exit at $T_f(1)$ and proceeds upstream.

coefficients are assigned parameters which are set by the operator during program initialization based on experience and calculations.

The program proceeds by first calculating an energy balance on a single ring of converters. The various sources of energy flow which need to be balanced for a single ring are shown in Fig. 2. Once the energy balance for this ring is obtained, converged attributes, (e.g. emitter and collector temperatures, and heat flow in and out of the converter), are known and can be used to find the flame and air temperature for the next ring. This calculation of parameters for each new ring is continued until an energy balance has been obtained for each ring in the system using the previous ring's converged parameters as input. A schematic of this ring to ring energy balance is shown in Fig. 3. Once the converged parameters have been obtained for all the rings, an overall energy balance for the entire burner, shown in Fig. 1 is calculated. If an energy balance has not been obtained, the initial flame temperature is updated and the entire balancing procedure is repeated. The total burner energy balance is driven by the choice of the voltage. The voltage is stepped and for each new voltage the entire energy balancing procedure is repeated until a current voltage (I-V) curve has been calculated.

The flow diagram shown in Fig. 4 gives the calculational sequence followed by the program. The entire program has been adapted to a Hewlett-Packard 9816 computer. Typically a standard I-V curve will take 3-5 minutes to calculate, once a stable range of temperatures and heat transfer surface areas have been found. Details of the program can be found in Appendix A and the Second Quarterly Report of this contract.

2.0 COMPUTATIONAL RESULTS

2.1 Computer Program

As with a physical system, the computer model is controlled by the following variables:

Fig. 2 Single Ring Energy Balance - Adjust the emitter and collector temperatures to achieve energy balance between internal converter energy transfer and external thermal energy transfer

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Fig. 4 Flow diagram for the thermionic cogeneration burner program

- Air/fuel ratio
- Bypass air ratio
- Cesium reservoir temperature
- Emitter area and heat transfer coefficient
- Collector area and heat transfer coefficient

The air/fuel ratio is the ratio of combustion air to fuel introduced into the combustion chamber. This ratio effects output by two mechanisms: changing the temperature of the flame, and changing the amount of air available for converter heat rejection. Typical industry standards call for 20-30% excess air over stoichiometric, in most applications, to maintain complete combustion in the furnace. Any less air often leads to fouling of the furnace. Excess air above stoichiometric reduces the flame temperature, and as a consequence, it is kept to a minimum, usually 20-30%.

The bypass air ratio is the amount of air, beyond stoichiometric which is put into the collector cooling channels, but which will bypass the combustion chamber and mix with the flue gas stream as it exits the burner. Bypass air is useful because it allows extra air for collector cooling without reducing the flame temperature. However, it does reduce flue gas temperature once it exits the burner.

The cesium reservoir temperature controls the cesium pressure in the system. Typically it is best to optimize this after other controls are optimized to reduce system perturbation.

The emitter area and heat transfer coefficient are mentioned together because, in the governing equations for these systems, they always occur as a product. As the emitter area to thermal output ratio increases, the benefit of increased emitter area is limited by the ability of the added converters to reject heat off their collectors. As will be shown later, the increased emitter area yields more output with each increment until the collector cooling air reaches its temperature difference pinch point, at which time the collector temperature of the new ring starts rising and the output of that ring drops below the previous ring. Consequently, the incremental power output increase with added emitter area starts to level off.

The collector area and collector heat transfer coefficient are like the emitter in that they occur together in the governing equations. The effect of increases in the collector area are also discussed in the body of the following portion of the report.

To test the flexibility of the program a wide variety of systems were considered, only a few of which will be discussed here. Systems investigated included those with a varying number of rings (1 through 5), with varying heat transfer coefficients and finning ratios, with varying amounts of bypass air (0 through 2, bypass to stoichiometric), and with varying amounts of emitter (active) surface area. The effect of different emitter and collector bare work functions were also investigated, as well as the effects of the failure of an entire ring on the overall burner performance.

2.2 Convergence Behavior

When beginning a new calculation, the choice of starting guesses for the flue gas, collector and emitter temperatures are rather important. In particular, if the guess for the flue gas temperature is too high then the program may be unable to converge. However, with a reasonably good starting guess (within approximately 100 degrees of the exact answer) the emitter and collector temperatures are usually converged in 3 or 4 iterations and the flame temperature on 4 or 5 iterations. Once the program begins to calculate its own temperatures (i.e., in the moves from ring to ring or to a new voltage point) then these iteration counts drop to 1 or 2. When converged the temperatures are good to approximately ± 1 K. The time per full iteration (single ring burner) is approximately 10 seconds on an HP 9816.

2.3 Five-Ring System - Normal Operation Conditions

Results for an optimized five-ring burner are shown in the next two figures. Fig. 5 shows the various temperatures obtained with zero bypass air. The increase in the collector and emitter temperatures for the last ring (ring 5, hot end) is due to the inability of the system to reject heat, which adds heat to the already hot air. When the bypass air ratio is increased to 1.0, this is no longer a problem as seen in Fig. 6, where the

Fig. 5

Fig. 6

collector and emitter temperatures are now constant for all five rings. In both Figs. II-5 and 6, the staggered values of the air and flue gas temperatures show the entrance and exit temperatures for that ring. In Fig. II-5, the process gas temperature is the same as the exit flue gas temperature. In Fig. 6, it is less than the flue gas temperature due to mixing with the cooler bypass air. For both cases the flue gas temperature decreases from the entrance (ring 5) to the exit (ring 1) due to the energy being removed by the converter rings. On the other hand, the air, which enters at room temperature at ring 1, steadily rises as it absorbs heat from the collectors. The burner parameters for the 1.0 bypass case are given in Table 1. The parameters are approximately those used for all of the calculations discussed in this section.

Fig. 7 shows the calculated TCB efficiencies as a function of voltage and the electrical-to-thermal power conversion ratio. The values have maxima of 14%, and 15 kWe/MBtu respectively. The thermionic converter efficiency is calculated assuming an optimized lead. This should not, however, be confused with the total burner efficiency which would have to take into account the energy of the process gas as well as the electrical power produced. In this case ~30% of the heat from the burner fuel passes through the converters, the remainder passes out of the system for use as process gas, and is not wasted. The electrical-to-thermal power conversion ratio gives the amount of power produced per million Btu/hr (MBtu/hr) burned fuel.

TABLE 1

Values used for the System Parameters in the Five-Ring Burner Calculations

BURNERS

Fuel:	Natural gas
Mixture:	10% lean
Flue Gas Flow Rate:	8.478 lb/10,000 Btu
Air Flow Rate:	7.920 lb/10,000 Btu
Losses:	0
Bypass Air Ratio:	1.0

THERMIONIC CONVERTERS

Bare Work Function:	4.9 eV
Gap:	20 mils

RING	1	2	3	4	5
Reservoir Temp. (K)	575	575	575	575	575
Heat Transfer Coef. ($\text{W}/\text{cm}^2 \text{ K}$)	0.085	0.085	0.085	0.085	0.085
Finning Ratios					
Emitter	1.29	0.89	0.67	0.54	0.45
Collector	0.55	0.68	0.85	1.14	1.73

3.0 SYSTEM DESIGN TRADE-OFF

Part of the design criteria are based on failure modes, failure effects, and system integration effects. These effects include: single component failure, non-uniform heat flux, entire ring failure, bypass air changes, and increased emitter area. A number of these failure modes and system integration effects were investigated using the computer model. The following sections deal with the conclusions from each of those areas.

Single converter failure is of concern in a system because failure of a single converter to open circuit will significantly reduce the electron cooling of the other converters in the series. The solution to this problem is to arrange the converters in a series-parallel array, so that current sharing can mitigate the effect of single converter failure. Arrangement of the converters in a series-parallel array introduces the question of how the output of an array will be affected by variation in heat flux.

An analysis was performed on the effect of non-uniform heat flux on a series-parallel array of converters. With uniform heat flux to all converters there is no difference between the output of the array and the output of a single converter with the same area as the array. However, if there is a 50% variation in the series-connected direction across an array there is a 20% reduction in output; and an 11% reduction in output if the variation is in the parallel connection direction.

3.1 Ring Failure Effect

Figs. 8 and 9 show the effects of failure of a converter ring in a multi-ring system. This analysis was done on a five-ring system where the converters are assumed to be connected in series around the ring and in parallel from ring to ring. The system parameters are given in Table 2. To simulate a failure, the cesium reservoir temperature in ring 1 was set to zero. Fig. 8 shows the resulting temperatures (air, collector, emitter and flue gas). Once the cesium pressure is lost, ring 1 ceases to produce current and the emitter temperature begins to approach flue gas temperature.

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Fig. 8 Resultant Temperatures on Failure of Ring 1

Fig. 9

The other rings remain relatively unaffected. Fig. 9 shows the effect on the total thermionic converter efficiency and on the thermal to electrical power conversion. In both cases the failure has approximately a 20% effect. However, in an actual burner design, the more probable failure would be in a single converter. If the converters for each ring were internally connected in a series-parallel array, the net effect would be much smaller than the 20% shown here, probably more like 1-5%. Since closed circuit failure of a single converter would short out all the converters in parallel, which could mean a much larger power loss than failure of a single converter to open circuit, it is advantageous to design the converter to fail to open circuit, if failure occurs. This can be accomplished by the inclusion of a fuseable link in each converter which is calibrated to fail at 2 times the maximum load current. Current from the other converters operating in parallel would melt the link and open the circuit.

TABLE 2

Values Used for the System Parameters in the Failure Mode CalculationsBurner:

Fuel:	Natural Gas
Mixture:	10% Lean
Flue Gas Flow Rate:	8.478 lb/10,000 Btu
Air Flow Rate:	7.920 lb/10,000 Btu
Losses:	0
Bypass Air Ratio:	0.5

Thermionic Converters

Bare Work Function:	4.9 eV
Gap:	20 mils

RING	1	2	3	4	5
Reservoir Temperature (k)	575	575	575	575	575
Heat Transfer Coeff. ($\text{W}/\text{cm}^2\text{K}$)	0.085	0.085	0.085	0.085	0.085
Finning Ratios:					
Emitter	1.05	0.75	0.55	0.42	0.28
Collector	0.63	0.86	1.15	1.83	2.00

3.2 Bypass Air

Bypass air is that air which is introduced into the collector cooling channel above and beyond the air required for combustion, and which subsequently bypasses the combustion chamber and mixes with the flue gas as it exits the combustion chamber. The practical effect of the introduction of the bypass air is to increase collector cooling without decreasing the flame temperature. The effect on standard converters is shown in Fig. 10. The flue gas exit temperature (after mixing with bypass air) is shown in Fig.

11. The obvious conclusion is that the amount of bypass air should be maximized consistent with the needs of the industry.

3.3 Emitter Area Trade-off

The total emitter area in a burner obviously determines the power output. The ratio of emitter area to thermal capacity of the (10,000 Btu/hr) burner will be a major factor in determining the overall energy output and the emitter and collector temperatures. To get a rough feeling for the trade-offs, one can imagine a 10,000 Btu/hr burner with a single, very small converter. The amount of power produced would be very small, and the impact on the burner preheat small also. As the area of converters increased, assuming a constant (maximum) heat transfer coefficient, the power output would increase. Eventually the temperature difference between the optimum collector and the cooling air, or the optimum emitter and the flame will drop to the point that addition of emitter surface area to this burner will require either increased heat transfer, raising the collector temperature, or lowering the emitter temperature. We assumed maximum heat transfer prior to beginning this exercise, so the remaining question becomes how far off optimum is it reasonable to take the emitter and collector temperatures? One way to analyze this question is to calculate and plot the conversion efficiency and electrical to thermal ratio as a function of emitter area per 10,000 Btu/hr. This was done for a single ring case and is shown in Fig.

12. As shown in the figure, the electrical to thermal ratio stops increasing at about $22 \text{ cm}^2/10,000 \text{ Btu/hr}$. This calculation was done with a single ring model. This analysis is limited because it takes the average emitter and collector temperatures and applies those to what would be an entire array of converters, many of which would be operating at optimum temperatures, and a minority of which would be operating at off-optimum temperatures. It is possible to perform an analysis of this condition by increasing the number of rings, changing the conditions at each ring to suit the flame and cooling air temperature. However, the calculation is difficult and time consuming and has been left to future analyses.

Fig. 10

Fig. 11

Fig. 12

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