RASOR ASSOCIATES, INC.

DOE/CE/40583--1

DE83 014656

THERMIONIC-COGENERATION-BURNER ASSESSMENT STUDY

SECOND QUARTERLY TECHNICAL PROGRESS REPORT

January - March, 1983

Prepared for

U.S. DEPARTMENT OF ENERGY
Contract No. DE-AC02-82CE40583

MASTER

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INTRODUCTION AND OBJECTIVES

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:

- The ability to deliver heat at temperatures sufficiently high for any industrial process, while providing energy savings of 10-20%.
- Modularity, permitting use over a range of installation sizes with staged introductions.
- Reliability, through inherent redundancy.
- Compatibility with existing furnaces.

The specific tasks of this study are to mathematically model the thermionic cogeneration burner, experimentally confirm the projected energy flows in a thermal mock-up, make a cost estimate of the burner, including manufacturing, installation and maintenance, review industries in general and determine what groups of industries would be able to use the electrical power generated in the process, select one or more industries out of those for an in-depth study, including determination of the performance required for a thermionic cogeneration system to be competitive in that industry.

Summary

Work during this period concentrated in two areas: a) finishing the development of the mathematical modeling program and beginning an initial parametric analysis; and b) completing the design and construction of the thermal mock-up experiment. The completion of the performance analysis program was critical as it will form the basis of the cost analysis, necessary in the evaluation of proposed burner designs, and it will also provide predicted operating parameters for the thermal burner experiment, necessary input in the choice of building materials. The thermal burner experiment itself will demonstrate the practicality of the high heat fluxes and temperatures thought necessary to make an economical thermionic cogeneration burner. The data and experience obtained from the experiment will also provide necessary input into any proposed burner designs.

The performance analysis work continued this quarter with the completion of the programming of the mathematical model and with the start of a series of parametric analyses. Initial studies predict that approximately 25-30% of the heat contained in the flue gas can be passed through the thermionic converters (TEC) and then be converted at 12-15% efficiency into electrical power. This results in up to 17 kWe per 1 million Btu/hr burner firing rate. This is a 4-10 percent energy saving over power produced at the utility.

The thermal burner design and construction have been completed, as well as initial testing on the furnace and preheat systems. The actual test runs are planned for early in the next quarter. When the experimental design is modeled as a zero-bypass single-ring burner, the resulting heat flux to the emitter plates is predicted to be in the range of 40 W/cm^2 (with $T_E=1700 \text{ K}$) and with a heat transfer rate from the flue gas to the emitter of approximately $0.027 \text{ W/cm}^2 \text{ K}$. The operating temperatures are proposed to be $\sim 2000\text{-}2400 \text{ K}$ for the flue gas, 1700 K for the emitter surfaces and 1000 K for the preheated air.

The following industries are still considered viable options for use of the thermionic cogeneration burner: chlor-alkali, alumina-aluminum, copper refining, steel and gray iron, industries using resistance heating,

electrolytic industries and electrochemical industries. Information gathered during the second quarter on these industries is presented in that portion of the quarterly report. The selected case study will begin after one or two industries are chosen for detailed analysis.

TASK I: THERMIONIC BURNER PERFORMANCE

I-1. Performance Analysis

Analytical Analysis - The objective of this task is to develop, program and apply an analytical engineering model of a thermionic cogeneration burner. This model must be capable of predicting flow rates, temperatures, output and overall performance of specific burner designs. A second part of this modeling procedure will be to develop a program capable of estimating the cost, maintenance, life cycle costs and return-on-investment for the proposed burner designs. Through these calculations, the applicability and benefits of the use of thermionic cogeneration burners in specific industries can be evaluated. These modeling techniques will also be used in predicting the expected operating parameters for the thermal burner experiment. Subsequent to operation of the thermal experiment, the data taken will be analyzed and used as input to the analytical engineering model.

Currently, the programming of the analytical model is complete and a variety of calculations testing the flexibility of the program have been done. Initial predictions for the expected operating parameters of the thermal burner have also been completed. The modeling of the cost and economics as well as more detailed assessment of various burners is underway and will be completed in the third and fourth quarters.

The organization of this section is first to review in general terms the program logic and methodology (the specific details of the program are given in Appendix A), second to discuss some of the initial parametric analyses which have been done and lastly to discuss the future course of action for this part of the burner analysis.

Program Organization - The mathematical model, on which the computer program is based, assumes a basic burner design, shown in Fig. 1. The burner design assumes: 1) that there are N coaxial rings of thermionic converters; 2) that the burning occurs in the center of these converters and part of the heat is then transferred by the use of cellular ceramics to the emitter side of the converters with the remainder of the heat (flue gas) exiting for use

1 2 3

1

as process gas; 3) that the converters convert some of this input heat to electrical power; 4) that the excess heat is then rejected by the collector side of the converters into the air stream; 5) and that this heated air is then used for burning and/or mixed with the exiting flue gas to adjust the process gas temperature. The energy balance for this entire system is treated in stages.

The first stage considered is the energy balance for a single ring of converters. This balancing involve four related calculations: a) the temperature of the flue gas in the zone, b) energy flow between the flue gas and the emitter, c) the electrical power generated by the thermionic converters, and d) the heat rejected by the collectors to the air stream for a single ring. When these values are converged, the resulting air and flue gas temperatures are then used as input for the next ring which is treated in a similar manner. This process is repeated until the individual heat flux, and temperatures (flue gas, emitter, collector and air) are converged for all rings. The amount of heat flux from the flue gas to the emitter and from the collector to the air can be controlled by two parameters: 1) the heat transfer coefficient and 2) the heat transfer surface to emitter or collector finning ratio. This second value will most likely vary from ring to ring and from the emitter to the collector, but not within a ring (see Fig. 2).

The overall energy balance for the N ring system is calculated from the total energy removed from the burner flue gas, the fuel supplied, and the assumed flue gas exit temperature. This balance results in a new exit flue gas temperature (the flue gas temperature at ring 1) and, if this is different from the value previously used to start the ring by ring energy balance, stages one and two are repeated. Once these values have converged and an overall energy balance for the entire burner system has been obtained, then the total burner power and efficiency can be calculated. The balancing described above is performed at a fixed voltage point. When a new voltage point is desired, other than the multi-stage balancing must be repeated.

The details of the program structure are shown in Fig. 3 with the specific details on the subroutines in Appendix A. The stage 1 (individual ring) energy balancing is accomplished by the following subroutines: TECMDL,

Fig. 2 Schematic representation of emitter and collector fins. Note that the fin ratio (area of the flow side/ A_E) of the emitter may be different from the collector. There are two main energy transfer methods across the emitter - collector gap : electron current and radiation.

ENERGY, NEW-TEMP and TEMPEC. ENERGY calculates the heat flux from the flue gas to the emitter and from the collector to the air. TECMDL calculates the heat flux in and out of the converters and the power generated. NEW-TEMP and TEMPEC update the emitter and collector temperatures using either a two-dimensional first order Newton Raphson procedure (NEW-TEMP) or, if far from convergence, a variable damping procedure. The convergence threshold is that relative difference in the heat fluxes as calculated from ENERGY and TECMDL are less than 0.001, which corresponds to converging the emitter and collector temperatures to approximately 1 degree. The stage 2 (overall burner) energy balance is handled by THERMBAL, which used the converter efficiencies as calculated by EFFSUB. THERMBAL calculates an energy balance for the flue gas of the Nring system based on the type of fuel burned, the burning ratio, (rich, stoichiometric or lean) the preheat air temperature, and the efficiency with which the flue gas is converted to DC electric power by the converters. From this calculation, the flue gas temperature at ring 1 is predicted. This value is then used to update the previously used value by a secant method. The flue gas temperature is considered to be converged when the relative difference is less than .005 (~1 degree). Once the heat fluxes for the entire burner system are converged, then the overall power and current can be calculated using the POWER subroutine. At this point the program can either calculate a new voltage point, using a linear extrapolation on the temperatures, EXTRPT, to obtain good starting guesses for the temperatures at the next point, or it can plot and analyze the previously obtained values. The various plotting choices are displayed by PLOTMENU, and then the actual plotting can either be displayed on the CRT or they can be done as hard copy. Variables calculated for the converter array are stored in multi-dimensional arrays (e.g., the collector temperatures are stored as $T_c(M,N)$ where M labels the voltage point and N is the ring number). The entire calculation is done on a per 10,000 Btu/hr basis, thus the results can be scaled to any size burner.

Initial Parametric Analysis

To test the flexibility of the program a wide variety of systems were considered, only a few of which will be discussed here. Investigated systems 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); 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.

Another area investigated was the convergence capability of the program. In particular, the effects of differing convergence thresholds on the overall calculation, and what the radius of convergence is for the iterations on the emitter, collector and flue gas temperatures, as well as the number of iterations necessary to reach convergence.

Preliminary findings are presented in this section. First, the convergence behavior of the program will be discussed, then results will be presented for a five-ring system, for the failure mode behavior of a five-ring system and finally for the predicted operating parameters of the thermal burner experiment.

Convergence Behavior

When beginning a new calculation, the choice of starting guesses for the flue gas, collector and emitter temperatures is 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.

Five-Ring System - Normal Operation Conditions

Results for an optimized five-ring burner are shown in the next two figures. Fig. 4 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 any more heat into the already hot air. When the bypass air ratio is increased to 1.0, this is no longer a problem as seen on Fig. 5, where the collector and emitter temperatures are now constant for all five rings. In both Figs. 4 and 5, the staggered values of the air and flue gas temperatures show the entrance and exit temperatures for that ring. In Fig. 4 the process gas temperature is the same as the exit flue gas temperature whereas in Fig. 5 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 the collectors reject heat into the air stream. 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. 6 shows a current-voltage (I-V) curve for the five-ring system (with 1.5 bypass) which has been scaled to represent a 1 M Btu/hr burner. This I-V curve is somewhat different from conventional I-V curves where the temperatures are held constant while the voltage varies. The current shown assumes all converters are connected in parallel. This is not a physically realistic system and future analyses will analyze a series-parallel ring of converters. In this case the system is rebalanced at each point and as such the temperatures change along the I-V curve. Fig. 7 shows the calculated TEC efficiencies as a function of voltage and the electrical-to-thermal power conversion ratio, which values have maxima at about 0.6 V, of 14% and 15 kWe/MBtu respectively. The thermionic converter efficiency is calculated as an optimized lead efficiency. The electrical-to-thermal power conversion ratio gives the amount of power produced per MBtu/hr burned fuel. This should not, however, be confused with the total burner efficiency which would have to take into account the potential of the process gas as well as the electrical power produced. In this case only ~30% of the heat from the

Fig. 4

Fig. 5

Fig. 6

Fig. 7

burner fuel passes through the converters, the remainder passes out of the system for use as process gas.

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

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 the flue gas temperature while the collector temperature begins to approach that of the air. However, these temperatures will never meet as there is still radiation occurring between the emitter and collector and as such some energy is still being transferred across the gap. The other rings, however, 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 and if the converters for each ring were connected in a series parallel array the net effect would be much smaller than the 20% shown here.

Fig. 8 RESULTANT TEMPERATURES ON FAILURE OF RING 1

Fig. 9

TABLE 2

Values Used for the System Parameters in the Failure Mode Calculations

BURNER

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 Temp (K)	575	575	575	575	575
Heat Transfer Coef. (W/cm ² 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

Modeling of Thermal Burner Experiment

Tables 3 and 4 show the predicted operating parameters for the thermal mock-up experiment. Two different fuel mixtures were considered, stoichiometric (Table 3) and 10% lean (Table 4). For both of these fuel mixtures burning rate of 0.8×10^6 Btu/hr was assumed, and the experimental plate area of 2000 cm² was used for the total emitter surface area. The

experimental set-up was modeled as a single ring burner, and with the preheat air temperature matched to the expected experimental operating value of 1000 K. The computed flue gas temperatures, emitter temperature, emitter side heat flux and heat transfer rates should agree well with the experimentally measured values. Other computed values such as the collector temperature, and collection side heat transfer coefficient will not be modeled by the thermal burner experiment. For either a stoichiometric or 5% lean mixture with a 0.8 MBtu/hr burning rate and with a 1000 K preheat, the heat flux was found to be approximately 27 W/cm^2 , the emitter side heat transfer coefficient was approximately $0.04 \text{ W/cm}^2 \text{ K}$, the emitter temperature was between 1700 K (5% lean) and 1760 K (stoi.) and the flue gas temperature was in the range between 2100-2700 K (5% lean) and 2200-2800 K (stoi.)

Summary

Several conclusions can be drawn from the parametric studies performed thus far, mainly dealing with heat transfer off the emitter and collector. Burner design for control of emitter and collector temperatures will depend critically on the heat transfer surface ratio (finning ratio) and may vary from ring to ring. This implies slightly different geometries for each ring of the burner. It will be important for the design to include the capability to modify that ratio between rings without major design changes.

Operation of the model has shown it is important to be able to have feedback control over the reservoir temperatures if changes in bypass are expected to be a normal operating condition, along with automatic control of the collector-air heat transfer.

The most important conclusion, however, is that the initial estimates of: a) flue gas exit temperature (1700+ K); b) energy flow through the converters (about 25-30%); and c) the heat transfer coefficients necessary to achieve those (about $.04 \text{ W/cm}^2 \text{ K}$) are being proved out in the more detailed analysis being done in this model. Also the earlier (equivalent) predictions of power generation per million Btu's (kWe/MBtu) are being substantiated.

Further analysis during the next quarter will look in greater depth at the implications of design features and especially at the cost per unit power figures.

TABLE 3

Single Ring, 0.8 M BTU Burner, 2000 cm² Total Area

TEMPERATURES

	T_E	1763 K
CONVERTER	T_C	1069 K
EFFICIENCY	T_F	2218 - 2780 K
11.5%	T_A	300 - 1057 K

HEAT TRANSFER

Emitter Side	h	0.04 W/cm ² K
	Ar	1:1
Collector Side	h	0.085 W/cm ² K
	Ar	1:1.6
Heat Flux In		28 W/cm ²

MASS FLOW RATES

M_{air}	7680 ft ³ /hr
M_{gas}	54,400 ft ³ /hr
Mixture	Stoichiometric

AIR PREHEAT POWER

49.6 kW

TABLE 4

Single Ring, 0.8 M BTU Burner, 2000 cm² Total AreaTEMPERATURES

	T_E	1701 K
CONVERTER	T_C	993 K
EFFICIENCY	T_F	2143 - 2660 K
12.6%	T_A	300 - 900 K

HEAT TRANSFER

Emitter Side	h	0.04 W/cm ² K
	Ar	1.1
Collector Side	h	0.085 W/cm ² K
	Ar	1:1.6
Heat Flux In		26.7 W/cm ²

MASS FLOW RATES

M_{air}	8064 ft ³ /hr
M_{gas}	56,900 ft ³ /hr
Mixture	5% lean

AIR PREHEAT POWER

46.7 kW

I-2. Thermal Burner Experiment

Experimental Design

The major goal of the thermal burner test is to experimentally measure the flame-to-emitter heat transfer coefficient at normal operating emitter temperatures and with normally attainable combustion air preheat. This goal can be accomplished by measuring the overall energy flow of energy passing into and out of the thermionic burner combustion chamber and from that calculating the energy flow. This entails the measurement of the temperatures and mass flow rates of the flue gas both into and out of the heat exchanger zone.

The temperature measurement of very hot gases represents a significant technical problem in that although thermocouples exist which can operate at the temperatures involved, they are made from refractory metals which cannot operate in the flue gas atmosphere. One way to use these thermocouples is to protect them from oxidation with a ceramic close-ended sheath and an inert gas blanket. Alumina sheaths of this type are generally used, however the temperatures expected in this test during operation will be so high that the melting temperature of alumina will be exceeded and the thermocouple will fail. Other ceramics which could stand the temperature (SiC) are not made in the appropriate shapes. Both the flue gas flowing into the emitter region and, in certain circumstances, the flue gas flowing out of the experiment are calculated to be above the melting point of alumina. The practical consequence of this is that the design for measurement of these temperatures has to rely on optical measurements of silicon carbide cellular ceramic parts that are in equilibrium with the flue gas streams. The analysis of the data to calculate the temperature of the flue gas stream will include corrections for the temperature difference between the SiC cellular ceramic and the flue gas stream. Details of the design and placement of these cellular ceramic blocks is given in the next section.

There are a number of other measurements which must be made in order to perform a detailed energy balance. They include:

- Air Mass Flow by:
 - Orifice pressure difference
 - Air temperature at that orifice
 - Air pressure at the orifice
- Preheat Energy Input by:
 - Current through the element
 - Voltage across the heater element
 - Energy loss off outside (calibration)
- Gas Combustion Energy Input by:
 - Flow meter
 - Gas pressure corrections
- Energy Losses, including:
 - Furnace exterior radiation and convection
 - Furnace water cooling
 - Furnace heat capacity
 - Radiation out the top of the system
- Calorimeter
 - Water mass flow
 - Temperature into and out of the system
- Flue Gas Energy Flow
 - Input Entrance Gas Temperature
 - Exit Gas Temperature

Most of the above measurements will be done by standard temperature and flow measurements. Data will be collected and analyzed on an HP-85 computer.

There are several crucial variables which must be calculated in this analysis: (1) the temperature difference between the flue gas and the SiC cellular ceramic, (2) the emissivity of the SiC plates acting as stand-ins for the emitter and (3) the thermal heat capacity of the furnace. Further work will be done during the next quarter to determine the overall energy balance.

Experimental Set-up

The thermal burner experiment, diagrammed in Fig. 10, consists of four major components: 1) an electric resistance air preheat system, 2) a gas burner and furnace with safety flame control device, 3) the heat exchanger/calorimeter assembly, and 4) a system of instrumentation and data storage. A description of each component follows.

Preheat System

To give flexibility in designing and operation of the thermal experiment, preheat of combustion air was accomplished with an electrical resistance heating element rather than with reject heat removed in the calorimeter. The power supply, called "AMPLE-AMP," has a maximum output of about 10 VDC and 10,000 amps. Since up to 60 kW of heat are needed, a heating element made of large section stainless steel tubing was selected to handle the 6000 amp electric current. Considerations of electrical resistance, heat transfer, and gas pressure drop through the pipe led to the use of two concentric pipes 14 ft. long with roughly equal electrical resistance (see Fig. 11). To equalize air flow down the annular space between the pipes and the central space, the central space was filled with an array of turbulence generators, the number of which was adjusted by experimentation. At 4 ft. intervals spacer bolts were installed to prevent the inner tube from sagging or warping. An expansion joint allows for some differential movement axially. The outer pipe temperature is monitored at three points along the pipe's length.

Fig. 10

SCHEMATIC OF THE THERMAL BURNER EXPERIMENT

Fig. 11

ELECTRICAL RESISTANCE AIR PREHEAT TUBE

Burner and Furnace

The gas burner and accessories (blower, gas valve, gas pressure regulators, and pilot assembly) were standard production parts from Eclipse, Inc. Protection Controls, Inc. supplied the U-V safety flame control device. The furnace is a refractory-lined steel can six feet high by three feet diameter. The internal volume of the furnace cavity is approximately 10 ft³. Fig. 12 shows a general view of the burner and furnace.

A cast refractory collar reduces the throat diameter to 9" (Fig. 13). This casting is equipped with four radial apertures for instrumentation penetration (windows, pressure measurement, etc.).

To measure the temperature of the gas leaving the furnace, a block of silicon carbide cellular ceramic is anchored to two 3/4" SiC support rods by means of male dovetails cut into the rods and female dovetails cut into the block (see Fig. 13). The rods are anchored to two aperture covers and the block is aligned so that a hohlraum punched through to the center of the block is visible at the instrumentation window. The hohlraum temperature will be measured with an optical photopyrometer.

Two shrouded thermocouples measure combustion air temperature at the burner air inlet and a third at the air flow measuring orifice. The furnace outside wall has thermocouples at the top and near the center to measure the temperature at, and therefore the energy loss from, the outside of the furnace.

A small water-supplied cooling system is built into the top of the furnace to prevent the top from "oil-canning" and moving the experiment during heat-up. The heat carried off is measured by thermocouples monitoring water temperature entering and leaving and by direct measurement of the water flow rate.

Heat Exchanger-Calorimeter

The calorimeter is the heart of the thermal burner experiment. Fig. 14 outlines the six stages of heat transfer taking place here. Silicon carbide

Fig. 12

GENERAL VIEW OF BURNER AND FURNACE

Fig. 13
REDUCING COLLAR AND INSTRUMENTATION PORTS

Fig. 14

**SCHEMATIC OF HEAT FLOW THROUGH
HEAT EXCHANGER/CALORIMETER ASSEMBLY**

cellular ceramic was chosen for removing heat from the low-luminosity furnace gases. This material, manufactured jointly by Corning and Carborundum, was expressly designed for this purpose. The cellular structures gives approximately a 40-fold increase in convection surface for the exchange of heat from the gases to the element. As the emissivity of SiC is about 0.8 and the tubes have a l/d ratio of about 10, the net emissivity of the cellular ceramic elements is close to 1. Fig. 15 shows the heat path through a single cellular ceramic element. The elements are built up in a cylindrical structure referred to as the "castle."

The silicon carbide "emitter" plates and the calorimeter shell form the thermal model of the thermionic array. At 1700 K radiation density from the plates is about 40 W/cm^2 , approximately as high as the heat flux encountered in thermionic converters; if the calorimeter shell is less than 400 K, reradiation is held to a negligible level. To allow variation of the heat flux (simulating a change in the electrical load on the thermionic converters), 12 movable shutters were installed in the calorimeter shell. These refractory boards have a low thermal conductivity and will reradiate a substantial (>50%) part of the heat back to the emitter plates.

Structurally, the heat exchanger-calorimeter consists of two subassemblies: the cellular ceramic castle/emitter plate assembly and the shutter/calorimeter assembly. The entire unit rests on a 1" silicon carbide base plate installed on the furnace with a thin gasket of alumina fibers (see Figs. 16-24).

Figs. 18 and 19 show the construction of the castle emitter assembly. Eighty-four cellular ceramic blocks are slotted on two sides. These slots correspond to rails on each side of the support rods. The rods are also slotted to retain the twelve "emitter" plates which are cut from the 1/4" crystal silicon carbide plates. The rods are cut from 3/4" silica-bonded silicon carbide plate. The castle elements form twelve columns 7 elements high. The entire assembly is 12.8" tall and approximately 11" in diameter.

The twelve support rods are prevented from collapsing inward by the cellular ceramic castle elements; outward displacement is prevented by twelve

Fig. 15
SCHEMATIC OF HEAT FLOW
THROUGH CELLULAR CERAMIC ELEMENTS

Fig. 17 SECTIONAL VIEW OF HEAT EXCHANGER/CALORIMETER

Fig. 18
HEAT EXCHANGER ASSEMBLY

INSIDE VIEW

Fig. 19

HEAT EXCHANGER ASSEMBLY

CELLULAR CERAMIC AND CHIMNEY BLOCKS REMOVED

Fig. 20
HEAT EXCHANGER WITH CALORIMETER SHELL REMOVED

Fig. 21
STAINLESS STEEL CHIMNEY

Fig. 22
CAST CERAMIC CHIMNEY

CLOSE-UP OF SHUTTER LINKAGE

Fig. 23
CALORIMETER HOUSING

LOWER ALUMINA SHAFT

SHUTTER

**SHUTTER WITH CUTAWAYS
FOR VIEWING EMITTER PLATE**

UPPER ALUMINA SHAFT

ARMS

SPACERS

LINKS

Fig. 24
PARTS FOR SHUTTER ASSEMBLY

tiles bonded to the base plate with high temperature adhesive (Fig. 19) and by twelve cast blocks which form a short chimney on top (Figs. 20 and 22). A refractory-lined stainless steel chimney (Fig. 21) sits on top of the cast chimney blocks. A lid, consisting of two 3/4" silica-bonded silicon carbide plates and a 6" high refractory casting, provides the weight necessary to force the gases through the castle elements. All ceramic cutting was done in-house with a diamond saw.

The calorimeter housing (Fig. 23) is made from .050 copper sheet; 1/4" copper tubes were soldered around the unit at about 1" intervals. Six portholes were soldered to the outside to allow photopyrometer readings of the "emitter" plates. The inside surface was sandblasted, etched with nitric acid and blackened with liver of sulfur to improve the absorbtivity. Pyrex windows were bonded to the portholes with high temperature RTV silicone rubber.

The shutters (Fig. 24) consist of double plates of Babcock & Wilcox Kaowool board (alumina fibers) bonded to alumina shafts; the lower parts of the shafts fit into holes in the tiles that locate the castle support rods, and the upper parts of the shafts protrude through holes in the calorimeter housing. These shafts were linked with a simple parallel motion linkage that allows all twelve shutters to work in synchrony. A lock and pointer with a scale allows the operator to return to a given position and hold the shutters at that position.

The calorimeter is cooled by 4 water circuits connected in parallel. Each circuit has a regulating valve, allowing the operator to adjust water flow to minimize condensation inside the calorimeter. The outlets of the 4 circuits join in a water-mixing cell.

To measure the output of the calorimeter, a Fischer-Porter rotameter is installed in the water line supplying the calorimeter; a thermocouple measures the temperature of the water going into the calorimeter and two thermocouples measure the temperature of the water leaving the mixing cell.

A cellular ceramic block is placed in the annular space between the castle lid and the stainless steel duct; three hohlraum holes allow temperature measurements with the photopyrometer.

Instrumentation

The focal point of the instrumentation system is a Hewlett-Packard 3497A data logger unit controlled by a Hewlett-Packard 85 computer. This device will monitor the following temperatures and voltages directly.

Port # Reading the:

1. Temperature of air at the air flow orifice.
2. Temperature of wall of the preheat tube at the hot end.
- 3-4. Temperature of air leaving preheat tube.
- 5-6. Temperature of wall of furnace.
7. Temperature of water going into cooling circuits
8. Temperature of water leaving furnace top cooling circuit.
- 9-10. Temperature of water from calorimeter mixing cell.
11. Voltage across preheat tube.
12. Voltage across AMPLE-AMP shunt (measures preheat tube current).

The remaining data must be measured by the operator and entered at the keyboard.

1. Air column across air flow orifice.
2. Air pressure at air flow orifice.
3. Gas flow at gas meter.
4. Water flow through calorimeter.
5. Water flow through furnace top cooling circuit.
6. Furnace throat hohlraum.
7. Three temperatures across an "emitter" plate (top, center, bottom).
8. Hottest temperature of chimney hohlraum.

A computer program will store this data at approximately half-hour intervals and will work out a preliminary heat balance. Supporting experiments will calibrate the preheat tube, air flow orifice, gas meter, viewport windows and water flow meter.

I-3. Cost Analysis

The total cost of the cogeneration burner system will be estimated, and the estimation method will be made a part of the computer program.

The program is being structured so that the operator will generate and investigate at will the operational parameters of the thermionic cogeneration burner, finally selecting a specific operating point. This operating point's parameters are then transferred over to the cost subroutine for use in calculation of the cost in \$/kWe. The operational parameters which will be passed include the efficiency, current density, thermal input power density, temperatures of the emitter and collector, and burner thermal size if specified. Note that all the data transferred to the cost program are specific variables; that is the geometrical arrangement of the converters is not specified until the cost subroutine is entered. At this point the actual dimensions are specified within the program and costs calculated. Collection of costs for building the cogeneration combustor will occur during the third and fourth quarters.

TASK II: THERMIONIC BURNER UTILIZATION

II-1. General Industry Survey

The purpose of this survey is to identify those industries which would provide a good thermal and electrical match for thermionic cogeneration with a minimum impact on the plant design, while using thermionic conversion to its best advantage. In previous reports several industries have been reported as looking attractive for thermionic cogeneration. They are:

1. Alumina-Aluminum refining
2. Chlor-Alkali production
3. Copper refining
4. Steel & gray iron production
5. Industries using resistance heating
6. Electrolytic industries in general
7. Electrochemical industries

The previous quarterly report outlined the major attributes of the industries listed above and gave details on the processes used, their thermal and electrical energy consumption, and any special safety or operational concerns.

One result of the parametric analysis of the burner performed during this quarter was the calculation of the process gas temperature as a function of the bypass air ratio as shown in Fig. 25. This calculation allowed correlation with some of the industries being considered and the resultant process temperatures are shown in Fig. 25.

The temperatures shown for the industries stated in Fig. 25 are the process temperatures reported in CTAS. It should be noted that the air supplied for combustion is 1.1 times stoichiometric, therefore the calculated process gas temperatures are lower than maximum theoretical temperatures. Further work in this area will be concentrated on determining in more detail the operating conditions in the industries.

Fig. 25

Work during this quarter was concentrated on the initial parametric analysis and designing and building the thermal burner experiment. The further investigation of the candidate processes will wait for results to be available from the thermal burner experiment and manpower to investigate those processes in more detail.

APPENDIX A

In the following pages the details on the individual subroutines are given. The following appendix includes for each subroutine: a) the purpose of the routine, b) the major equations used in the routine, c) the variables solved for by the routine (with units), d) the variables required as input to the routine (with units) and, if applicable, e) typical default values in the routines. The subroutines are described in the same order which they occur in the program.

Subroutine: Init(Tfp)

Purpose: Read in the initial variable values for operating the program and initialize any flags.

Equations:

$T_c(1,N)$ = initial values, $N=1$ to N_{ring}

$T_e(1,N)$ = initial values, $N=1$ to N_{ring}

$T_f(1,1)$ = initial value

$T_a(1,1)$ = ambient air temperature

Variables solved for:

<u>Symbol</u>	<u>Origin</u>	<u>Definition</u>	<u>Units</u>
$T_c(1,N)$	Init	collector temperature	K
$T_e(1,N)$	Init	emitter temperature	K
$T_f(1,1)=T_{fp}$	Init	flame temperature, first station	K
$T_a(1,1)$	Init	air temperature, ambient	K

Typical default values:

$T_c(1,N)$ = 850-950 K, 850-950 K, ...

$T_e(1,N)$ = 1700 K, 1700 K, ...

$T_f(1,1)$ = 2200-2600 K

$T_a(1,1)$ = 300 K

Subroutine: INDATA

Purpose: Input data from operator to program and set parameters for program operation. Also to provide a method to retain previous run data.

Equations:

$$\begin{aligned}Ma &= At * Ar \\Mg &= 100 * (100 - Ash) / Qf + Ma * (1.0 + Wa) \\Mb &= Bypass * At \\Mper &= 100 * (Ma * Wa + 100 * (8.94 + H_{2per} + H_{2Oper}) / Qf) / Mg \\Mt &= Mg + Mb \\Mpper &= [(Mper * Mg / 100) + Wa * Mb] * 100 / Mp\end{aligned}$$

Input Variables:

<u>Symbol</u>	<u>Origin</u>	<u>Definition</u>	<u>Units</u>
Phi-0	Indata	Bare emitter work function	eV
Vinit	Indata	Starting voltage for I-V curve calculation	V
Vfin	Indata	Ending voltage for I-V curve calculation	V
Vstep	Indata	Step voltage for I-V curve calculation	V
D	Indata	Emitter-collector gap	mils
He(n)	Indata	Emitter-flame convective heat transfer coefficient	W/cm ² K
Hc(n)	Indata	Collector-air convective heat transfer coefficient	W/cm ² K
Aer	Indata	Ratio of the emitter flame side surface to active emitter surface area	
Acr	Indata	Ratio of the collector air side surface area to collector (active) surface area	
Ae	Indata	Emitter area in each ring	cm ²

B	Indata	Bypass air ratio	
Tr(N)	Indata	Reservoir temperature	K
At	Indata	Theoretical air ratio - lbs. air to stoichiometrically produce 10,000 BTU	lb/10,000 BTU's combustion
Ar	Indata	Total air ratio	
Ash	Indata	% ash content in fuel by weight	%
Wa	Indata	Water content in air	lbH ₂ O/lb air
Q _F	Indata	Higher heating value of fuel being used	BTU/lb
H ₂ per	Indata	% H ₂ content in fuel by weight	%
H ₂ Oper	Indata	% H ₂ O content in fuel by weight	%

Typical default values:

Phi-0 = 4.9 eV
 Vinit = 0.02 V
 Vfin = 0.80 V
 Vstep = 0.02 V
 D = 20 mils
 He(N) = 0.085 W/cm² K - Jet Impingement
 Hc(N) = 0.0085 W/cm² K - Air Flow
 Aer(N) = 1.5-0.5
 Acr(N) = 2.0-0.5
 Ae(N) = 30/Nring cm²/10,000 BTU
 B = 1.5-0.0
 Tr(N) = 570-600 K

Fuel - Natural Gas

At = 7.2
 Ar = 1.1-1.0
 Ash = 0
 Wa = 0.013 lb H₂O/lb air
 Q_F = 22,000 Btu/lb
 H₂per = 10.35

$$H_2O_{per} = 0.0$$

Variables solved for:

Ma	Mass flow rate of air through collectors per 10,000 Btu burned	lb/10,000 Btu
Mg	Mass flow rate of flue gas per 10,000 Btu burned	lb/10,000 Btu
Mb	Bypass air mass flow rate per 10,000 Btu burned	lb/10,000 Btu
Mper	Percent moisture in the flue gas	%
Mt	Total gas flow rate, bypass & fluegas	lb/10,000 Btu
Mpper	Percent moisture in the process gas	%

Subroutine: TECMDL (V,N,M,Aflag-err(N))

Purpose: This subroutine is a variation on the phenomenological model of the ignited mode model described in Chapter 5, "Thermionic Energy Conversion," of the volume: Applied Atomic Collision Physics, Vol. 5. The chapter was written by Ned S. Rasor and contains a complete description of the model. As a consequence only the essentials of the model are included here.

Equations:

Work functions:

$$\text{Phi-e}(M,N) = 1.3 * [\text{Te}(M,N)/\text{Tr}(N)] - 0.628 * \text{Phi-0} + 1.6$$

$$\text{Phi-c}(M,N) = 4.394 - 3.197 * [\text{Tc}(M,N)/\text{Tr}(n)] + 0.8692 * [\text{Tc}(M,N)/\text{Tr}(N)]^2$$

(The use of different fits is currently under investigation.)

Other equations: See Dr. Rasor's article.

Variables solved for:

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
J(M,N)	Emitter to collector electron current flux (in Nth ring)	A/cm ²
Q _e (M,N)	Heat input to the emitter, per unit emitter surface area (Nth ring)	W/cm ²
P _e (M,N)	Power output from the converter, per unit emitter surface area (Nth ring)	W/cm ²
Q _c (M,N)	Reject heat from the the collector per unit emitter surface area (Nth ring)	W/cm ²
Phi-c(M,N)	Collector work function	eV
Phi-e(M,)	Emitter work function	eV
Aflag-err(N)	Flag to tell if any rings were solved using radiation default	

Variables Required as Input:

<u>Symbol</u>	<u>Origin</u>	<u>Description</u>	<u>Units</u>
$T_e(M,N)$	Init	Emitter temperature (Nth ring)	K
$T_c(M,N)$	Init	Collector temperature (Nth ring)	K
$T_r(N)$	Indata	Reservoir temperature (Nth ring)	K
Φ_0	Indata	Bare emitter work function	eV
D	Indata	Emitter-collector gap	mils
N		Ring number	
M		Mth voltage point	

Subroutine: ENERGY (N,M,Flag):

Purpose: To calculate emitter and collector heat transfer rates/unit area for the Nth ring and to calculate the flame and air temperature exiting the Nth ring. These values to be compared to those calculated in Tecmdl.

Equations:

$$Ta(M,N+1) = Tc(M,N) - Ta(M,N) * \exp[-Htc(N) * Ae(N) * Acr(N) / (Ma * Cpa(Ta(M,N)))]$$

$$Tf(M,N+1) = Te(M,N) - (Tf(M,N) - Te(M,N)) * \exp[Hte(N) * Ae(N) * Aer(N) / Mg * Cpf(Tf(M,N))]$$

$$Qcp(M,N) = (Ta(M,N+1) - Ta(M,N)) / (Ma * Cpa(Ta(M,N)) * Ae(N))$$

$$Qep(M,N) = (Tf(M,N+1) - Tf(M,N)) / (Mg * Cpf(Tf(M,N)) * Ae(N))$$

Variables solved for:

Qep(M,N)	emitter heat transfer rate/unit emitter area	W/cm ²
Qcp(M,N)	collector heat transfer rate/unit emitter area	W/cm ²
Ta(M,N+1)	air temperature leaving the Nth ring	K
Tf(M,N+1)	flame temperature leaving the Nth ring	K

Variables required:

<u>Symbol</u>	<u>Origin</u>	<u>Definition</u>	<u>Units</u>
Hte(N)	Indata	Emitter heat transfer coefficient	W/cm ² K
Htc(N)	Indata	Collector heat transfer coefficient	W/cm ² K
T _f (N)	Init	Flame temperature at Nth ring	K
Ta(N)	Init	Air temperature entering Nth ring	K
Te(N)	Init	Emitter temperature of Nth ring	K
Tc(N)	Init	Collector temperature of Nth ring	K
Aer	Indata	Ratio of total ring back emitter area to emitter area	
N		Ring number	

Flag		0 - update temperatures Ta, Tf 1 - hold temperatures as temporary values	
M		Mth voltage point	
Acr	Indata	Ratio of total ring back collector area to collector area	
Ma	Indata	Mass flow rate of air through collectors/10,000 Btu burned	lb/10,000 Btu
Mg	Indata	Mass flow rate of flue gas/ 10,000 Btu burned	lb/10,000 Btu
Cpa(Ta(M,N))	Function	Specific heat of air at temp. Ta(N)	W-hr/lb K
Cpf(Tf(M,N))	Function	Specific heat of gas at temp. Tf(N)	W-hr/lb K

Subroutine: New-temp (V,Qedif1,Qedif2,Qcdif1,Qcdif2,N,M,Flag-err)

Purpose: Update the emitter and collector temperatures via either a first order (coupled) Newton Raphson Technique or via a variable damping technique. The routine checks the magnitude of the differences in Qe and Qc and if small ≤ 15 uses Newton Raphson or if large > 15 uses damping.

The Newton Raphson technique calls Tecmdl and Energy twice to calculate the necessary partials to calculate new Te and Tc. The damping technique calls Tempec using a weighted average of the heat fluxes, Qe, Qep and Qc, Qcp to calculate new Te and Tc.

Equations:

Newton Raphson: Standard first order-Newton Raphson

$$\begin{pmatrix} T_e^{(i+1)}(M,N) \\ T_c^{(i+1)}(M,N) \end{pmatrix} = \begin{pmatrix} 2\Delta Q_e/2T_e & 2\Delta Q_e/2T_c \\ 2\Delta Q_c/2T_e & 2\Delta Q_c/2T_c \end{pmatrix}^{-1} \begin{pmatrix} T_e^i(M,N) \\ T_c^i(M,N) \end{pmatrix}$$

Damping:

$$Q_{e3} = (1.-Alph) * Q_{ep} + Alph * Q_e(M,N)$$

$$Q_{c3} = (1.-Alph) * Q_{cp} + Alph * Q_c(M,N)$$

Variables Solved for:

Newton Raphson:

Te(M,N) new emitter temperature of Nth ring K

Tc(M,N) new collector temperature of Nth ring K

Damping:

Qe3 weighted average emitter heat flux W/cm²

Qc3 weighted average collector heat flux W/cm²

<u>Symbol</u>	<u>Origin</u>	<u>Definition</u>	<u>Units</u>
<u>Newton Raphson/or Damping:</u>			
Te(M,N)	New-temp/Init	Emitter temperature of Nth ring last iteration)	K
Tc(M,N)	New-temp/Init	Collector temperature of Nth ring (last iteration)	K
Qediff2	Main	Qe(N)-Qep (this iteration)	W/cm ²
Qcdiff2	Main	Qc(N)-Qcp (this iteration)	W/cm ²

Newton Raphson: (for calls to Tecmdl:

V	---	Voltage	V
N	---	Ring number	
M	---	Mth voltage point	
Flag-err		Returned by call to Tecmdl	

Damping:

Qediff1	Main	Qe(M,N)-Qep (last iteration) (to check for divergence)	W/cm ²
Qcdiff1	Main	Qc(M,N)-Qcp (last iteration) (to check for divergence)	W/cm ²
Alph		Damping variable - can be varied from Alphmin to Alphmax	

Subroutine: TEMPEC (Qe3,Qc3,N,M)

Purpose: To calculate new collector and emitter temperature for Nth ring based on an energy balance between the converter internal energy and the heat transfer to and from the converter surfaces.

Equations:

$$T_c(M,N) = (T_a - \text{temp} - T_a(M,N) * \text{Exp-temp}) / (1.0 - \text{Exp-temp})$$

where

$$T_a - \text{temp} = Q_{c3} * M_a * C_{pa}(T_a(M,N) * A_e(N) + T_a(M,N))$$

$$\text{Exp-temp} = \exp(-1 * H_{tc}(N) * A_e(N) * A_{cr}(N) / [M_a * C_{pa}(T_a(M,N))])$$

$$T_e(M,N) = (T_f - \text{temp} - T_f(M,N) * \text{Exp-temp}) / (1.0 - \text{Exp-temp})$$

where

$$T_f - \text{temp} = Q_{e3} * M_g * C_{pf}[T_f(M,N)] * A_e(N) / [M_g * C_{pf}(T_f(M,N))]$$

$$\text{Exp-temp} = \exp(-1 * H_{te}(N) * A_e(N) * A_{er}(N) / [M_g * C_{pf}(T_f(M,N), M_{per})])$$

Variables solved for:

$T_e(M,N)$ emitter temperature of Nth ring K
 $T_c(M,N)$ collector temperature of Nth ring K

Variables required:

<u>Symbol</u>	<u>Origin</u>	<u>Definition</u>	<u>Units</u>
Aer(N)	Indata	Ratio of total ring back emitter area to emitter area	---
Acr(N)	Indata	Ratio of total ring back collector area to collector area	K
Ta(M,N)	Init/Tflame	Air temperature entering nth ring	K
Tf(M,N)	Init/Tflame	Flame temperature at nth ring	K

He(N)	Indata	Emitter heat transfer coefficient	$W/cm^2 K$
Hc(N)	Indata	Collector heat transfer coefficient	$W/cm^2 K$
Qe3	New-temp	Weighted average of Qe(N) + Qep	$W/cm^2 K$
Qc3	New-temp	Weighted average of Qc(N) + Qcp	$W/cm^2 K$
N		Ring number	
M		Mth voltage point	

Subroutine: EFFSUB (M)

Purpose: Calculate the efficiency of the system.

Equation:

$$\text{Eta(M)} = \frac{\sum_{N=1}^{\text{Nring}} \text{Pe(M,N)}}{\sum_{N=1}^{\text{Nring}} \text{Qe(M,N)}}$$

Variable Solved for:

Eta(M) = efficiency of the total system.

Variables Required:

<u>Symbol</u>	<u>Origin</u>	<u>Definition</u>	<u>Units</u>
Pe(M,N)	Tecmdl	Power/unit emitter area	W/cm ²
Qe(M,N)	Tecmdl	Emitter heat transfer rate/unit Emitter area	W/cm ²
M		Counter for voltage points	

Subroutine: Thermbal (Tfp,M)

Purpose: Calculate overall heat balance. Obtain new Tf(1) to be compared with value used at the start of the iteration, and obtain the process gas temperature, Tp.

Equations:

$$Ha = 1.033 \times 10^{-5} * (Ta(M,Nring+1))^2 + 0.2417 * Ta(M,Nring+1) - 20.5$$

$$P_{ti} = \left(\frac{Eta(M)}{1-Eta(M)} \right) * (Ma+Mb) * \left(\frac{Ha}{3415} \right)$$

$$H_f = \frac{10,000 - L + Ma * Ha - \frac{P_{ti} * (3415)}{Eta(M)} - 10.4 * Mg * Nper}{Mg}$$

$$H_p = \frac{H_f * Mg + Ha * Mb}{(Mg + Mb)}$$

Quadratic Equation for $T'_f(M,1)$: $aT'^2_f + bT'_f + c = 0$

$$a = (1.084 + 0.033 * Mper) * 10^{-5}$$

$$b = 0.2472 + 0.0013 * Mper$$

$$c = -1 * (0.13 * Mper + 22 + H_F)$$

Quadratic Equation for $T_p(M)$: $aT^2_p + bT_p + c = 0$

$$a = (1.084 + 0.033 * Mpper) * 10^{-5}$$

$$b = (0.2472 + 0.0018 * Mpper)$$

$$c = -1 * (0.13 * Mpper + 22 + H_p)$$

Variables Solved For:

H_a	Air enthalpy at last collector exit, just prior to burner	Btu/lb
P_{ti}	Thermionic power generation per 10,000 Btu burned	W/10K Btu
H_f	Flue gas enthalpy at burner exit, prior to mixing	Btu/lb
H_t	Enthalpy of flue gas at the point where bypass air has been rejoined with the flue gas.	Btu/lb
T_{fp}	= $T_f(M,1)$ Flame temperature at ring 1	K
T_p	Process gas temperature	K

Variables Required as Input:

<u>Symbol</u>	<u>Source</u>	<u>Description</u>	<u>Units</u>
M_{pper}	Indata	Percent moisture in process gas	lb/10,000 Btu
M_a	Indata	Air mass flow rate into the burner per 10,000 Btu burned	lb/10,000 Btu
M_b	Indata	Bypass air mass flow rate per 10,000 Btu burner	lb/10,000 Btu
M_g	Indata	Flue gas mass flow rate	lb/10,000 Btu
M_{per}	Indata	Percent moisture in the flue gas	%
M_t	Indata	Total gas flow rate, bypass + flue gas	lb/10,000 Btu
$T_c(n)$	Tempec	Collector temperature in nth ring	K
$E_{ta}(M)$	Tecmd1	Converter efficiency, nth ring	---
H_a	(Internal)	Total enthalpy change of air from ambient to exit of last collector	Btu/lb
L	Indata	Thermal losses in burner per 10,000 Btu of fuel	Btu
P_{ti}	(Internal)	Total thermionic output power	W
$T_a(M, N_{ring}+1)$	Tempec	Air temperature leaving last ring	K
M		Mth voltage point	

Subroutine: POWER (Vout, M)

Purpose: Calculate the total current and total power produced by all of the rings and store that data in an array to be assessed later.

Equations:

$$I_t(M) = \sum_{1}^{Nring} J(M,N) * Ae$$

$$P_t(M) = I_t(M) * Vout$$

Variables Solved For:

P_t	Total Power Output of the burner/10,000 Btu burned	W/10K Btu
I_t	Total current output of the burner/10,000 Btu burned	A/10K Btu

Variables Required as Input:

<u>Symbol</u>	<u>Origin</u>	<u>Description</u>	<u>Units</u>
J(M,N)	Tecmdl	Current flux output of the converter	A/cm ²
Ae	Indata	Emitter area per 10,000 Btu fuel burned	cm ² /10K Btu
Nring	Indata	Number of rings of converters	---
Vout	For-Next Loop	Output voltage of the converter	Volts
M		Mth voltage point	

Subroutine: EXTRPT (Tf1-1, Tf2-1, M)

Purpose: To perform a linear extrapolation of the temperatures, Tf, Ta, Te and Tc, to obtain a good starting guess for the (M+1)st voltage point on the I-V curve.

Equations:

$$Tf(M+1,1) = ABS(2*Tf2-1 - Tf1-1)$$

$$Ta(M+1,1) = Ta(M,1)$$

$$Te(M+1,N) = ABS[2*Te2(N)-Te1(N)], \quad N=1 \text{ to } Nring$$

$$Tc(M+1,N) = ABS[2*Tc2(N)-Tc1(N)], \quad N=1 \text{ to } Nring$$

Variables Solved for:

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
Tf(M+1,1)	Extrapolate exit flame temperature for the (M+1)st voltage point.	K
Ta(M+1,1)	Entrance air temperature for the (M+1)st voltage point.	K
Te(M+1,N)	Extrapolate Nth ring emitter temperature for the (M+1)st voltage point.	K
Tc(M+1,N)	Extrapolate Nth ring collector temperature for the (M+1)st voltage point	K

Variables Required as Input:

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
Tf2-1	Exit flame temperature for the Mth voltage point.	K
Tf1-1	Exit flame temperature for the (M-1)st voltage point.	K
Ta(M,1)	Entrance air temperature for the Mth voltage point.	K
Te2(N)	Nth ring emitter temperature for the Mth voltage point.	K
Te1(N)	Nth ring emitter temperature for the (M-1)st voltage point.	K
Tc2(N)	Nth ring collector temperature for the Mth voltage point.	K
Tc1(N)	Nth ring collector temperature for the (M-1)st voltage point.	K

Subroutine: MAXMIN

Purpose: To find the current-voltage characteristics at the point of maximum power output and the point of maximum efficiency.

Equations:

$$\text{Powmax} = \text{MAX} [P_{\text{total}}(M)]$$

$$\text{Effmax} = \text{MAX} [\text{Eff}(M)]$$

Variables Solved For:

Powmax	Maximum power produced over the I-V range
Effmax	Maximum efficiency produced over the I-V range
M_p	M index at which maximum power output occurs
M_e	M index at which maximum efficiency occurs

Variables Required at Input:

<u>Symbol</u>	<u>Origin</u>	<u>Description</u>	<u>Units</u>
P_t	Powert	Total burner Power output at Mth point on the I-V curve	W/10,000 Btu
Eff(M)	Effsub	Efficiency of the burner at the Mth point on the I-V curve	---

Subroutine: COSTECON

Purpose: Calculate the cost of a specific cogeneration burner based on the total emitter area, manufacturing and engineering estimates. Calculate the return-on-investment of the burner plus other analyses as may be appropriate.

Equations:

To be determined during the cost analysis phase.