Energy

CONSERVATION

DOE/CE/40583-3
(DE84002647)

THERMIONIC COGENERATION BURNER ASSESSMENT STUDY

Third Quarterly Technical Progress Report for April—June 1983

Work Performed Under Contract No. AC02-82CE40583

Rasor Associates, Inc.
Sunnyvale, California

Technical Information Center
Office of Scientific and Technical Information
United States Department of Energy

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Prepared for

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

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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

The thermal burner experiment was run during this quarter and the data analyzed. The data and analysis are presented in this quarterly report.

The heat transfer coefficient between the cellular ceramic and emitter plate was measured experimentally to be $0.035 \text{ W/cm}^2 \text{ K}$. This is higher than the previously used $0.025 \text{ W/cm}^2 \text{ K}$. It is expected that this heat transfer coefficient could have been higher than the measured value had more holes in the cellular ceramic been open later in the experiment when the flue gas temperatures were getting higher.

Excessive slag formed on the silicon carbide cellular ceramic during the test. This slag formation was greatly accelerated and enhanced by the presence of metal oxides including chromium, nickel, iron and copper oxides. A short test was performed which confirmed the effect these oxides have on silicon carbide.

The design of the thermal experiment was generally good, and with small modification the same arrangement can be used in a thermionic cogeneration burner.

The analytical analysis portion of this work found that the optimum emitter area ($\text{cm}^2/10,000 \text{ Btu}$) was a function of the heat transfer coefficients. This nominal optimum emitter area is defined as the area above which the marginal increase in power output per unit emitter area begins to drop sharply. The values are as follows:

Case	<u>Heat Transfer Coefficient</u>		Bypass Air Ratio	Optimum Active Emitter Area ($\text{cm}^2/10,000 \text{ Btu}$)
	Flue Gas - Emitter ($\text{W/cm}^2 \text{ K}$)	Collector-Air ($\text{W/cm}^2 \text{ K}$)		
1	.04	.085	0	20
2	.04	.085	.5	>25
3	.085	.085	.5	~25

I-1 Performance Analysis

Analytical Analysis

Most of the analytic analyses performed this quarter dealt with studies on the effects of the amount of active emitter surface area, the heat transfer methods and the use of bypass air on the overall burner performance. These studies will provide necessary input to any preliminary burner designs as well as to the cost analysis of these designs. The systems studied were all single ring systems, however, and with some exceptions the results should carry over to multi-ring systems as well.

Three different systems were studied; their operating parameters are given in Table 1. The first assumed that the heat transfer from the flue gas to the emitter was via cellular ceramic ($h = 0.04 \text{ W/cm}^2\text{K}$), from the collector to the air was jet impingement ($h = 0.085 \text{ W/cm}^2\text{K}$) and that there was no bypass air. The results as a function of active emitter area per 10,000 BTU are shown in Fig. 1. In the top graph the TEC efficiency and the thermal to electrical energy conversion ratio as a function of emitter area are shown. Both values drop off with larger areas. This fall-off is explained by the other two graphs on that page. These show the emitter and collector temperatures and the percent heat through the converters as a function of emitter area. It can be seen that as the area increases more heat is absorbed by the emitter, and it becomes impossible to reject enough heat off the collectors. Consequently the collector temperature rises. This combined with the lower TEC efficiency, reduces thermal to electric conversion at higher emitter areas. For this setup the optimal emitter area is $\sim 20 \text{ cm}^2/10,000 \text{ Btu}$. Beyond this value costs would increase with no appreciable gain, or even a loss in performance.

Fig. 1

TABLE 1

Operating Parameters for the Single Ring Burner Performance Studies

Fuel: Natural Gas

Burner Losses: 5%

Fuel Mixture: 5% lean

ConvertersBare Work Function, $\phi_0 = 4.9$ eV

Emitter-Collector Gap = 20 mils

Cesium Reservoir Temp. = 580 K

	<u>Heat Transfer Coefficient</u>		<u>Bypass Air Ratio</u>
	<u>Flue Gas-Emitter</u>	<u>Collector-Air</u>	
Run 1	$h \leq 0.04 \text{ W/cm}^2\text{K}$	$h \leq 0.085 \text{ W/cm}^2\text{K}$	0
Run 2	$h \leq 0.04 \text{ W/cm}^2\text{K}$	$h \leq 0.085 \text{ W/cm}^2\text{K}$	0.5
Run 3	$h \leq 0.085 \text{ W/cm}^2\text{K}$	$h \leq 0.085 \text{ W/cm}^2\text{K}$	0.5

To attempt to improve the performance at higher emitter areas, the problem of the collector heat rejection must be addressed. Two possibilities can be considered: 1) to improve the collector side heat transfer or 2) to introduce bypass air. It turns out that improving the heat transfer coefficient will not alleviate the problem as the collector-air temperature difference is already quite small and as such the air cannot absorb much more heat. The only alternative is to introduce bypass air. While alleviating the heat transfer problems. The reduction in thermal to electrical energy conversion at higher emitter areas is an artifact of the single ring calculation. It is not expected to carry over to systems with greater numbers of rings. The reason for this is as follows: the reduction in TEC efficiency is a consequence of increased collector temperatures. In a single-ring system the efficiency calculation is tied to the average collector temperature. In a multi-ring system the efficiency is dependently calculated for each ring, consequently the expectation is that the efficiency

of the last ring, with the hottest collector will drop, however the other rings efficiencies will be unaffected. Further calculations will be necessary to determine the true effect of the higher emitter areas in a multi-ring system. Other economic considerations which will need to be addressed in the cost analysis include: 1) the extra air volume may require increasing the blower size; and 2) the presence of bypass air will require extra ducting will need to be weighed against any increase in performance

The results for a system with a 0.5 bypass air ratio which uses cellular ceramic on the emitter side and jet impingement on the collector side is shown in Fig. 2. There is no longer a limit on collector heat rejection. At this point, the limiting factor of the performance is the ability to get heat into the emitters. This problem can be treated by using jet impingement on the emitter side, the results of which are shown in Fig. 3. Once again, the collector heat rejection problem for a larger emitter area returns. However, at $20 \text{ cm}^2/10,000 \text{ Btu}$, the thermal-to-electrical conversion ratios shown in Fig. 2 and Fig. 3 improve at higher emitter areas over the ratio shown in Fig. 1. Even though performance considerations are important, economic considerations will be the deciding factor as to which type design will prove to be the most advantageous; these considerations will be addressed in the last report.

In these three cases, the maximum thermal-to-electrical power conversion ratio is 4.1%. This value is the product of the TEC efficiency and the percent of heat passing through the converters. Using the cited heat transfer coefficients, the percent of the heat passing through the converters is ~30%. Calculations have shown that this number can be increased before the emitter-flue gas heat transfer pinch-point is reached. Another area where improvement can be expected is in the area of thermionic converter efficiencies. Fig. 4 shows some projected improved converter efficiencies. The model used in the program has maximum efficiencies of 15%; however, converters with efficiencies of >15% have already been demonstrated in laboratory situations. Thus, it is not overly optimistic to expect thermal-to-electrical conversion rates of 7-10% in the foreseeable future.

Fig. 2

Fig. 3

Fig. 4. Performance equivalent to ideal diode thermionic converter ($V_b = \phi_c$ for ideal diode). Solid lines are for maximum efficiency; dashed lines are for $J = 10 \text{ Amp/cm}^2$. *

*Figure taken from "Thermionic Energy Converter," chapter by Ned S. Rasor from Fundamentals Handbook of Electrical and Computer Engineering, Vol. II (S. L. Chang, Editor, John Wiley & Sons, 1983).

Series-Parallel Analysis

The output from a thermionic converter is typically 5 to 50 A/cm² of emitter area and 1 volt. This low voltage and high current output must be conducted to the next converter or to the power conditioning system. Keeping the bussing power losses low requires reducing the individual converter emitter area and increasing the number of converters. This can be done with the resultant output voltage being increased. However, placing the converters in a series string creates other problems caused by the effect of failure of converter on a string of converters. Failure to open circuit by a single converter reduces the electron cooling of the emitters in the string to zero and leads to emitter temperature increases to compensate for lost heat transfer. Arranging the converters in a series-parallel array allows the current from the other converters to continue to flow around the failed unit, as shown in Fig. 5. This arrangement provides a significant increase in reliability of the generator.

Power output, which is proportional to the heat flux input, can be effected by non-uniformities of heat flux into the emitter. Lower heat fluxes in one zone of a series-parallel array can lower the emitter temperatures changing the J-V characteristics of the converter and moving the optimum load-line for that converter. This reduces the power output of the overall array.

An analysis of the effects changes in power output have on the array can be made using a computer code developed here at Rasor Associates. Analysis of a 5x5 array is shown in Fig. 6. In this case, the heat flux varied from 20 to 40 W/cm² across the converter array in the parallel connection direction; in the second it varied that much in the series direction. A 20% reduction was seen in the case where heat flux varied in the series direction, and an 11% reduction was seen in the case where heat flux varied across the parallel direction in the array. The consequence of this analysis is that the design of the burner should take into account the effects resulting from non-uniform heat flux across the converter array.

Fig. 5

Fig. 6

Our design of the thermionic cogeneration burner includes arrangement of the converters in a series-parallel array where the converters are connected in parallel down the length of the axis of the burner. It also includes arrangement in series around the circumference of the burner since the circumferential variation in heat flux is expected to be small.

Fig. 7 shows the expected output of an array of 5x20 converters, with variation in the series and parallel directions of 50% as shown (20-40 W/cm², with 30 W/cm² the norm).

Results of this analysis have been integrated into the thermionic cogeneration burner design and are reflected in the bussing arrangements and voltage output connections.

FIG. 7

I-2 Thermal Burner Experiment

Test Goals and Arrangement

This experiment was designed and built to measure two important parameters in a thermionic cogeneration burner: the flue gas to emitter heat transfer coefficient, and the ability of the materials to withstand the environment. This was accomplished using the arrangement shown in Fig. 8.

Gas and heat flow in the experiment is as follows. The high temperature flue gases supplied from the furnace flows up and through the silicon carbide cellular ceramic elements, heating them. Flue gas exits from the system axially flowing up and into the chimney. The cellular ceramic elements radiate to silicon carbide plates which serves as the emitter-flame interface. Shutters are located between the emitter plates and calorimeter. The shutters allow adjustment of the emitter temperature over a small range. The calorimeter consists of a copper cylinder blackened on the inside and cooled on the outside by water. This arrangement is similar to what might be used in an operational design where the emitter plates would be replaced by rows of converters. Photos of the actual experimental parts were presented in the previous quarterly report.

Test Chronology

After several short test runs and calibrations, the thermal burner was operated for slightly longer than twelve hours. Data was collected and recorded directly on magnetic tape in a HP-85 computer/data logger as shown in Fig. 9. After the test, data taken was analyzed and some post-test recalibrations applied to the results.

Data and Results

Data collected during the experiment was analyzed immediately to track the overall energy balance and later reanalyzed with corrections for temperature reading variations and energy absorption by the furnace.

Fig. 8

SCHEMATIC OF HEAT FLOW THROUGH HEAT EXCHANGER/CALORIMETER ASSEMBLY

Fig. 9

SCHEMATIC OF THE THERMAL BURNER EXPERIMENT

Typical corrections involved window corrections (both taking into account the glass through which the optical pyrometer readings were taken as well as a film which formed on the windows during the course of the experiment); emissivity corrections (taking into account that the optical pyrometer readings were being taken of a material with emissivity less than 1.0); and estimates of the degree of non-equilibrium between the material and the flue gas. In particular the following readings needed to be corrected:

1) Furnace Throat:
[thermocouple T(15)]	- Window, Material Emissivity,
and Nonequilibrium with Gas
2) Emitter Plates:
[T(11), T(12), T(13)]	- Window, Material Emissivity
3) Chimney:
[T(14)]	- Nonequilibrium with Gas

The window corrections are determined by the calibration experiments performed subsequent to the burner experiment. The maximum deviations cited after the equations are the deviation of correction data from the correction curve fit equation, not the total figure to which these corrections are applied. Consequential overall deviations are small, less than 2%. Polynomial fits were made to the data resulting in correction factors (in degrees K) of:

Throat:

$$-320.9 + 0.4201 \cdot (T(15) - 273.15), \text{ max. dev. } 3.1\%$$

Emitter:

$$\text{Bottom: } 60.38 - 0.1062 \cdot (T(11) - 273.15) + 0.00008288 \cdot (T(11) - 273.15)^2 \text{ max. dev. } 21.0\%$$

$$\text{Middle: } 198.2 - 0.3496 \cdot (T(12) - 273.15) + 0.0001817 \cdot (T(12) - 273.15)^2 \text{ max. dev. } 15.4\%$$

$$\text{Top: } -94.29 + 0.1964 \cdot (T(13) - 273.15) + 0.00001848 \cdot (T(13) - 273.15)^2 \text{ max. dev. } 4.0\%$$

where the large error in the fits for the bottom and middle emitter plates corresponded to calibration points which were outside the range of experimental operating temperature. In the range of the experimental operating temperatures the correction fits were good to ~6% and the overall accuracy better than 2%. The data for emissivity temperature corrections were taken from standard tables. These corrections were applied to the

measured temperature plus the window correction. The polynomial fits used were:

Throat:

$$-69.74 + .0793 * (T(15) + \Delta T_{\text{window}} - 273.15) \text{ max. dev. } 0.5\%$$

Emitter:

(Bottom, middle and top:)

$$-23.75 + .0505 * (T(11) + \Delta T_{\text{window}} - 273.15) \text{ max. dev. } 4.4\%$$

The nonequilibrium correction (the difference between the cellular ceramic block being measured and the flue gas temperature passing through it was estimated to be 0 K for the block at the furnace throat and 150 K for the block in the chimney. These two correction factors are only rough estimates but it is impossible to obtain a more qualitative value for the correction factor during the test. Fig. 10 gives the corrected throat and chimney temperature readings.

In the following sections, the time-dependent behavior of some of the corrected measured temperatures will be discussed, followed by the calculated heat flux and heat transfer coefficients and finally the overall energy balance and energy balance error. The major changes seen in the time dependent plots are mostly related to the shutter changes and preheater adjustments. These changes along with the time at which they occurred are given in Table 2 and Fig. 11.

FURNACE - THROAT & CHIMNEY

Fig. 10

SYSTEM PARAMETERS

Fig. 11

TABLE 2

Changes in the Experimental Operating Conditions

<u>Time</u>	<u>Change</u>	<u>Effect</u>
5:00	Shutter setting = 11	Shutter closed
8:20	Shutter setting = 3.5	Emitter plate temp. drop
12:30	Back pressure building up	Air flow drop
13:00	Shutter setting = 7.0	Emitter plate temp. rises
14:00	More back pressure	Fuel consumption rises
15:00	Shutter setting = 10.0	Emitter plate temp. rises
16:00	Preheat setting changed	Preheat temp. drops

Emitter Plates

The three corrected emitter plate temperatures are shown as a function of time in Fig. 12. These values were extremely sensitive to the shutter settings as is evident from the plot. Also the crossing of the bottom and middle temperatures at 12:00 is most likely due to the plugging of the cellular ceramic by slag formation (see discussion under the experiment operation section).

The outer (cold side) temperatures of the emitter plates were measured, however, to calculate the heat transfer from the cellular ceramic to the emitter plates it is necessary to know the hot-side emitter plate temperature. This temperature can be determined by measuring the heat removal by the calorimeter and the cold side temperature:

$$T_{\text{hot}} = T_{\text{cold}} + q_{\text{cal}} * L/k$$

where q_{cal} = calorimeter heat removal per unit emitter area (W/cm^2)
 k = thermal conductivity = $0.19 \text{ W}/\text{cm-K}$
 L = plate thickness = 0.635 cm

EMITTER PLATES

Fig. 12

This hot side temperature is shown for the middle of the emitter plate in Fig. 13.

Furnace Wall Temperature

One major concern in running the experiment was whether or not equilibrium had been reached. To this end, two thermocouples were used to monitor the temperatures at the middle and the top of the outside of the furnace. The results of these measurements as a function of the time of day are shown in Fig. 14. (Note the initial, warm-up period between 5:00 a.m. and 8:00 a.m. is not shown.) Two things are clearly indicated by this plot: 1) even after ~12 hours of operation time the furnace body is still absorbing energy and 2) any calculations of the overall energy balance of the system will need to take into account both the energy being absorbed by the furnace itself as well as that being radiated by the outer walls.

Energy Balance

Using the flue gas temperatures, air mass flow rates, gas and air preheater energy input and furnace body temperature, an overall energy balance can be derived. The difference between input and output energy, the energy balance error, can be calculated from the overall energy balance. Fig. 15 presents energy balance error. It is noteworthy that the error was close to 1-2% about noon, in no cases was over 20%, and typically less than 10%.

Heat Flux

Fig. 16 shows the heat flux (W/cm^2), as a function of time, from the cellular ceramic to the emitter plates. The two curves shows the heat flux first calculated as being equal to the energy removed by the calorimeter and secondly corrected for the reradiation off the hot side of the emitter plate. The second term is the appropriate term to consider for heat transfer because the design used in an industrial application would not allow significant radiation streaming from the emitter surface.

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Heat Transfer Coefficient

Measuring the heat transfer coefficient is one of two main objectives of this work. Prior to this work, the heat transfer coefficient was assumed to be $0.025 \text{ W/cm}^2 \text{ K}$, a figure which was used to calculate the amount of energy that could be removed from the flue gas per unit area of emitter. The plot in Fig. 17 shows that $0.035 \text{ W/cm}^2 \text{ K}$ is a reasonable value to use for cellular ceramic heat transfer. The transfer coefficient has been calculated in three different manners, discussed below:

A. Method 1

The heat transfer coefficient is defined as:

$$h_1 = (q_{\text{cal}} + q_{\text{rad}})/(T_{\text{gas}} - T_{\text{hot}}),$$

where: $q_{\text{cal}} \text{ (W/cm}^2\text{)} = \text{heat per unit area removed by the calorimeter}$

$q_{\text{rad}} \text{ (W/cm}^2\text{)} = \text{radiation loss per unit area from the hot side of the emitter}$

$T_{\text{gas}} \text{ (K)} = \text{the corrected flue gas temperature}$

$T_{\text{hot}} \text{ (K)} = \text{the temperature of the hot side of the emitter plates (see the section on the emitter plates for a discussion of this value)}$

$A\text{-(cm}^2\text{)} = \text{area of the emitter plates (2000 cm}^2\text{)}$

$T_{\text{chimney}}\text{(-K)} = \text{corrected chimney temperature}$

and where T_{gas} and T_{hot} are calculated as described in Method 1.

Method 1, which gives a value of $0.035 \text{ W/cm}^2 \text{ K}$ is probably the most reliable of the three methods with Method 2 providing a lower bound to the value.

B. Method 2

The heat transfer coefficient is defined as

$$h_2 = q_{\text{cal}}/(T_{\text{gas}} - T_{\text{emitter}})$$

Fig. 17

where q_{cal} and T_{gas} are the same as used for Method 1; and

$T_{emitter}$ (K) = corrected measured emitter plate temperature
(The temperature of the middle of the emitter plates was used in these calculations)

C. Method 3

The heat transfer coefficient is defined as

$$h_3 = \frac{mC_p}{A} \frac{(T_{gas} - T_{chimney})}{(T_{gas} - T_{hot})}$$

where m (kg/hr) = mass flow rate of the flue gas; and

C_p (W/kg°K) = specific heat of the flue gas at temperature

Of the measurements used in these three calculations T_{gas} and $T_{chimney}$ are most poorly known and as such, Method 3, which depends the most heavily on these values, will have the largest uncertainty.

Thermal Test

The arrangement and survivability of the cellular ceramic in this application were two important results of this test. The arrangement proved to be workable, though some minor rearrangement of ceramic joints is necessary. The survivability of the SiC cellular ceramic was not as good as had been expected, and this portion of the report details the conditions found in the thermal experiment and subsequent auxiliary experiments.

After the furnace had cooled, it was disassembled and examined for physical changes. These will be discussed in order of disassembly; refer to Fig. 8 for location of parts.

The stainless steel chimney had lost its insulating liner near the bottom in several places. Apparently, the alumina (saffil) fibers had begun to melt, allowing the insulation board to shrink and pull away from the stainless steel wall. Where the chimney hohlraum block had been pressed

against it, the insulating boards were still in sound condition. Erosion of the stainless steel took place in areas where the lining was missing.

The upper part of the castle lid showed no signs of melting, although some cracks into the interior had formed. The lower parts of the lid, cut from silica-bonded silicon carbide, showed some collection of slag and appeared to be close to the melting point (of silica) near the center. The two slabs were securely fused together.

Fig. 18 shows a view into the interior of the heat exchanger. Three cellular ceramic blocks have been removed for examination. The silica-bonded, silicon carbide support rods had melted in several places, particularly at the flanges that located the silicon carbide cellular ceramic castle elements. Fig. 19 shows a support rod flange that failed, allowing the block on the left to be pushed outward by the pressure of the gases in the furnace. Fig. 20 shows a support rod that remained intact.

The cellular ceramic castle elements were all coated with large amounts of white slag (Figs. 18, 21-23). Additionally, it was evident that material had been eroded away from the inside surface, up to .25 inch in places. Moreover, upon removal of a castle block, it was apparent that the outside surface (outlet side) had a thick accumulation of grayish slag that partially blocked a large percentage of the tubes. Figs. 24 and 25 show the outlet side of a single block. This slag was presumably responsible for the decreased air flow into the furnace (due to back pressure) and as it was heavier near the top of the castle, and was responsible for the temperature inversion that took place at about 12:00.

An EDX analysis was performed on the slag to determine qualitatively what its constituents are. Fig. 26 shows the results of several analyses. The major peaks correspond to silicon, chromium, iron, nickel and copper. The presence of silicon is not surprising. Iron, nickel and chromium are all found in 304 stainless steel, from which the preheat tube was fabricated. It is not known where the copper may have come from.

Fig. 18

INSIDE VIEW OF HEAT EXCHANGER

CASTLE LID REMOVED

Fig. 19

**VIEW OF SUPPORT ROD SHOWING DETERIORATION
OF FLANGES SUPPORTING CELLULAR CERAMIC**

Fig. 20

VIEW OF SUPPORT ROD SHOWING NO DETERIORATION

CELLULAR CERAMIC ELEMENT

Fig. 21

HEAT EXCHANGER PARTS AFTER TEST

EROSION OF SIC MATERIAL

Fig. 22

INLET SIDE OF CELLULAR CERAMIC ELEMENT

Fig. 23

ENLARGED VIEW

Fig. 24

OUTLET SIDE OF CELLULAR CERAMIC ELEMENT

Fig. 25

ENLARGED VIEW

Fig. 26 RESULTS OF EDX ANALYSIS OF SLAG SAMPLES

Literature on the high-temperature behavior of silicon carbide indicates that in oxidizing atmospheres, oxidation takes place forming CO_2 gas and a liquid layer of silica. It is well-known that the presence of many substances, most notably alkali metals, greatly harm this protective layer of silica.

A simple experiment was performed to see if the presence of stainless steel may have contributed to the degradation of the silicon carbide castle elements. The temperatures of the preheat tube were sufficiently high that surface oxidation took place, and small bits of oxides may well have been carried up into the furnace by the combustion air stream.

The experimental set-up consisted of a rigidly-mounted "rosebud" oxy-acetylene torch that impinged upon a previously unused block of silicon carbide cellular ceramic. The block was brought closer to the tip over a 10-minute period until it had attained a temperature of 1800°C on the surface facing the torch. It was held in this position for another 10 minutes while the temperature stabilized at $1760\text{--}1800^\circ\text{C}$. Then the specimen was slowly backed away and the torch extinguished.

A second specimen was treated as above, with the exception that it was touched in several places with a thin piece of stainless steel welding rod, which left small quantities of burned steel on the hot surface.

Figs. 27 and 28 show the two experimental specimens. The block in Fig. 27 has a surface coating of shiny glaze. During the test some bubble formation was apparent and some very thin filmy bubbles were still visible after the block cooled.

When the second block (Fig. 28) was heated and exposed to stainless steel, large amounts of white slag were formed, eventually blocking some of the passages in the cellular ceramic. It seems apparent that the presence of metal oxides from the stainless steel preheat tube substantially hastened the degradation of the castle elements.

Fig. 27

**CELLULAR CERAMIC TEST BLOCK
EXPOSED TO CLEAN GASSES**

Fig. 28

**CELLULAR CERAMIC TEST BLOCK
EXPOSED TO SMALL AMOUNTS OF STAINLESS STEEL**

Conclusions

Several major conclusions were drawn from this test:

1. A heat transfer coefficient of $0.035 \text{ W/cm}^2 \text{ K}$ was measured. Higher coefficients may be possible with unfouled cellular ceramics.
2. Fouling of the silicon carbide cellular ceramic was accelerated by the presence of oxides of chromium, nickel, iron and copper. Further work will be performed with Carborundum Corporation to determine other possible failure mechanisms.
3. This design of the cogeneration burner, if modified to remove positions where steels are operated at high temperatures upstream of the cellular ceramics, is effective and efficient in heating the emitter surfaces.
4. A slight redesign of the cellular ceramic blocks would remove a major source of stress risers in them and reduce or eliminate failures by cracking.

Task II THERMIONIC BURNER UTILIZATION

II-1 General Industry Survey

The purpose of this portion of the study is to identify those industries which use high temperature flue gas and DC power. Subsequently, an economic analysis will be performed on applications of thermionic cogeneration burners to one of those industries. The general industry survey was performed, in part, by reviewing the following data bases searching for attractive energy requirement matches:

- DOE Energy Data Base
- Compendex Data Base
- Energyline Data Base
- NTIS Data Base

and in part by in-house reviews.

The search thus far has yielded the following candidate industries:

- Chlorine-Alkali
- Alumina-Aluminum
- Phosphate Production
- Copper Production
- Thermionic/Combined Cycle Low Power Units
- Steel Production

Work during this quarter concentrated on developing and operating the thermal test burner. The analysis of the above industries will be completed during the final phase of this contract.

APPENDIX A

Calibration Experiments

A series of calibration experiments were performed prior to and after the main experiment to interpret data from the experiment. These are briefly described below:

Water Flowmeter Calibration - The water flowmeter (Fischer-Porter 3500) was guaranteed by the manufacturer to be within 2% of full scale at any reading. This was checked by measuring the time required to flow a precisely-measured volume of water. All the data fell within the limits of the manufacturer's claim, and their calibration figures were used.

Gas Meter Calibration - Pacific Gas & Electric Company is required by the California Public Utilities Commission to maintain their instruments with 2% accuracy. It was therefore decided to rely on the utility gas meter for gas flow data. However, using previously calibrated Fischer-Porter rotometer, an independent check of the gas meter was performed.

Pressures at the gas meter and at the flowmeter were measured by means of a mercury manometer. Gas temperature at the flowmeter was also measured, and the figure for local gas density was obtained from the utility company. With these the flowmeter was corrected to standard conditions. The gas meter was corrected for over-pressure; no temperature correction was necessary, as delivery temperature was very close to 60°F.

The utility gas meter proved to read about 3% low.

Air Preheat Loss - The air preheat pipe loses some heat through its insulating jacket and by thermal conduction through the heavy copper leads. The following experiment was performed to confirm the value of the heat loss computation theoretically.

At combustion airflow of 8000 CFM, the preheat temperature was raised to 900 K and power readings from the Ample-Amp and the temperature of the pipe was recorded at three points. Then the blower was shut off and the power required to maintain these temperatures was measured. The heating efficiency was then calculated. This number agreed well with the theoretical model which was used to calculate the energy balance.

Air Flow Meter Calibration - In the thermal burner experiment, combustion air flow was measured by a water manometer across a fixed orifice with correction for temperature and pressure. In general, this type of measuring system can be read to within 2% accuracy if reasonable care is taken during fabrication and installation.

As a check on the accuracy of our system, the air mass flow was computed by measuring the temperature increase through the preheat tube at low preheat temperatures. Temperature increases of 10°C, 50°C, and 100°C were used, at different flow rates likely to be encountered. A correction was made for heat loss from the pipe through the leads and insulation; the mass flow was then computed from the electrical input.

The results from this experiment proved to be consistently lower than the flow rate measured by the orifice. A correction factor was applied to the value measured at the orifice, based on the results of the experiment.

APPENDIX B

Data Collection

The data acquisition for the thermionic cogeneration burner (TCB) experiment was controlled by a Hewlett-Packard 85 computer. The HP-85 was connected to a HP 3497A data logger which handled the automatic data acquisition from the thermocouples and voltage probes. The remaining measured data was input manually. The program which controlled the data acquisition was structured into four main sections: 1) ENTER: which controls the data acquisition, both automatic and manual, and displays the measured data; 2) EBALAN: which does a preliminary overall energy balance for the thermionic cogeneration burner to give the operator feedback on the progress of the experiment; 3) STORE: records the acquired data on tape; and 4) HEATUP: gives the operator an estimate of the length of time until thermal equilibrium of the furnace is reached (initially a great deal of energy is going into heating the furnace walls). Each of these four actions will be discussed briefly below. A listing of the complete program is given in this Appendix.

ENTER:

This section both records and displays the system parameters. The data acquisition is broken into two parts, those read automatically and those read and entered manually.

The system monitored the following temperature and voltages directly.

<u>Port #</u>	<u>Reading the</u>
---------------	--------------------

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 positions of these automatic readings are shown schematically in Fig. B-1. The subprograms of this section initialize the interface bus, make the thermocouple readings, convert them to the appropriate temperature units, make the voltmeter readings and warn the operation if any values are outside the normal range.

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

The variables which these are stored as, as well as their units are shown in Table B-1.

Fig. B-1

SCHEMATIC OF THE THERMAL BURNER EXPERIMENT

TABLE B-1

Thermionic Cogeneration Burner Parameters Recorded During the Experiment

Parameter	Variable Name	Units	Method of Measurement	Auto/Manual
Air Meter	T(1)	K	thermocouple	auto
Elbow	T(2)	K	thermocouple	auto
Nozzle	T(3)	K	thermocouple	auto
Ring Outlet	T(4)	K	thermocouple	auto
Preheat Tube	T(5)	K	thermocouple	auto
Water Outlet	T(6)	K	thermocouple	auto
Furnace Wall Middle	T(7)	K	thermocouple	auto
Water Inlet	T(8)	K	thermocouple	auto
Water Outlet	T(9)	K	thermocouple	auto
Furnace Wall Top	T(10)	K	thermocouple	auto
Ample-Amp V	V(0)	V	voltage probe	auto
Emitter Bottom	T1:T(11)	°C:K	optical pyrometer	manual
Emitter Middle	T2:T(12)	°C:K	optical pyrometer	manual
Emitter Top	T3:T(13)	°C:K	optical pyrometer	manual
Chimney	T4:T(14)	°C:K	optical pyrometer	manual
Furnace Throat	T5:T(15)	°C:K	optical pyrometer	manual
Water Flow	K0	%	meter	manual
Cooling Water	K1	gal/min	meter	manual
Air Flow	K2	in H ₂ O	meter	manual
Gas Flow	K3	sec/15 ft ³	meter/watch	manual
Air Gauge	G0	in H ₂ O	meter	manual
Preheat Tube Wall	T6:T(16)	°C:K	thermocouple	manual

EBALAN

This section performs a preliminary energy balance for the entire experiment. This balancing is performed in four stages: 1) preheater,

2) furnace, 3) cellular ceramic-emitter plate-calorimeter assembly and 4) overall. For each step the energy input and output are calculated and then the difference is computed and displayed. (The details of these balancing procedures are discussed in the section on the analysis of data.) For these preliminary calculations the values were all used in their raw (measured) form. (The corrections which need to be applied will be discussed later). This preliminary calculation gave the operation at feeling for the energy balance error.

STORE

This section of the program writes the measured data (both automatic and manual along with the time) onto tape. In this way the entire experiments data can be further analyzed at a future time. During the course of the experiment the data was recorded and stored approximately every half hour.

HEATUP

One of the major concerns with the experiment was whether or not an equilibrium had been reached. The portion of the experiment which took the longest to reach equilibrium was the furnace itself, due to the large thermal mass of the furnace walls. The time-temperature dependence is shown in the following equation:

$$R = \frac{-1}{\Delta(t)} \log \frac{T_t - T_x}{T_o - T_x}$$

and

$$T \text{ (minutes to equilibrium)} = \frac{-1}{R} \log \frac{T_f - T_x}{T_o - T_x}$$

where R = temperature rate-of-change coefficient

T_t = current temperature

T_o = initial body temperature

T_x = heat source temperature

T_f = final temperature (estimate)

Δt = elapsed time since startup

PROGRAM LISTING

Attached is a listing of the program used for data acquisition and analysis.


```

10 ! MOCKUP mk & 7. 5-13-83. INSTRUMENTATION FOR THERMAL MOCK-UP.
20 OPTION BASE 0
30 CLEAR
40 DISP TIMES$
50 DISP "IS THIS CORRECT(Y/N)?"
60 INPUT AS
70 IF AS="Y" THEN GOTO 160
80 DISP "ENTER THE CORRECT TIME IN HH:MM:SS"
90 INPUT TS
100 SETTIME HMS(TS),0
110 DISP TIMES$
120 DISP "IS THIS CORRECT(Y/N)?"
130 INPUT AS
140 IF AS="Y" THEN GOTO 160
150 GOTO 80
160 COM R(9,45),T(17),V(2),T(17),V(2),W(10)
170 ! SET ZERO AND DEFAULTS FOR THE VARIABLES
180 T1=0 @ T2=0 @ T3=0 @ T4=0 @ T5=0 @ T6=0
190 K0=0 @ K1=0 @ K2=0 @ K3=0 @ G0=0
200 T(11)=0 @ T(12)=0 @ T(13)=0 @ T(14)=0 @ T(15)=0
210 T(16)=0
220 DISP "ENTER THE FIRST RECORD TO BE WRITTEN"
230 INPUT Z9
240 GOSUB 2230
250 CLEAR
260 ON KEY# 1,"ENTER" GOSUB 350
270 ON KEY# 2,"EBALAN" GOSUB 1120
280 ON KEY# 3,"STORE" GOTO 1990
290 ON KEY# 4,"HEATUP" GOSUB 2140
300 ON KEY# 5,"" GOTO 300
310 ON KEY# 6,"" GOTO 310
320 ON KEY# 7,"" GOTO 320
330 ON KEY# 8,"" GOTO 330
340 KEY LABEL @ GOTO 260
350 T1$=TIMES$ ! READ CLOCK
360 CLEAR
370 DISP "--- PYROMETER READINGS ---:T1$
380 DISP USING 500 ; "1-FURN.THROAT T5 T(15) C",T5
390 DISP USING 500 ; "2-EMIT.BOTTOM T1 T(11) C",T1
400 DISP USING 500 ; " EMIT.MIDDLE T2 T(12) C",T2
410 DISP USING 500 ; " EMIT.TOP T3 T(13) C",T3
420 DISP USING 500 ; "3-CHIMNEY T4 T(14) C",T4
430 DISP "--- METER READINGS ---"
440 DISP USING 500 ; "4-WATER FLOW K0 Z",K0
450 DISP USING 500 ; "5-AIR FLOW K2 inH20",K2
460 DISP USING 500 ; " AIR GAUGE G0 inH20",G0
470 DISP USING 500 ; " TUBE WL TP. T6 T(16) C",T6
480 DISP USING 500 ; " GAS FLOW K3 s/15f3",K3
490 DISP USING 500 ; "6-COOLING H2O K1 gl/min",K1
500 IMAGE 24A,X,DDDD.DD
510 ON KEY# 1,"FURN" GOTO 610
520 ON KEY# 2,"EMITTR" GOTO 630
530 ON KEY# 3,"CHMNEY" GOTO 690
540 ON KEY# 4,"WATER" GOTO 710
550 ON KEY# 5,"AIR&GAS" GOTO 730
560 ON KEY# 6,"COOLING" GOTO 810
570 ON KEY# 7,"LOGGER" GOTO 830
580 ON KEY# 8,"RETURN" GOTO 250
590 KEY LABEL @ GOTO 590
600 ! ENTER MEASUREMENTS*****LIST 234

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610 CLEAR @ DISP "ENTER TEMPERATURE AT FURNACE THROAT, DEG C"
620 INPUT T5@ T(15)=T5+273.15 @ GOTO 360
630 CLEAR @ DISP "ENTER TEMPERATURE AT BOTTOM OF EMITTER PLATE, DEG C"
640 INPUT T1@ T(11)=T1+273.15
650 DISP "ENTER TEMPERATURE AT CENTER OF EMITTER PLATE, DEG C"
660 INPUT T2@ T(12)=T2+273.15
670 DISP "ENTER TEMPERATURE AT TOP OF EMITTER PLATE, DEG C"
680 INPUT T3@ T(13)=T3+273.15 @ GOTO 360
690 CLEAR @ DISP "ENTER CHIMNEY TEMPERATURE, DEG C"
700 INPUT T4@ T(14)=T4+273.15 @ GOTO 360
710 CLEAR @ DISP "ENTER WATER FLOW RATE,Z"
720 INPUT K0@ GOTO 360
730 CLEAR @ DISP "ENTER AIR FLOW RATE,INCHES OF H2O"
740 INPUT K2
750 DISP "AIR GAUGE PRESSURE, INOF H2O"
760 INPUT G0
770 DISP "TUBE WALL TEMP. C"
780 INPUT T6@ T(16)=T6+273.15
790 DISP "ENTER SECONDS PER 15 CU FT GAS FLOW"
800 INPUT K3@ GOTO 360
810 CLEAR @ DISP "ENTER COOLING RING WATER FLOW RATE, GAL/MIN"
820 INPUT K1@ GOTO 360
830 ! *****
840 CLEAR @ DISP " LOGGER READINGS ",HMS$(T(0))
850 IMAGE 22A,X,DDDD.DD
860 IMAGE 20A,X,D,DDDE
870 DISP USING 860 ; "AIR METER T(1) K",T(1)
880 DISP USING 860 ; "ELBOW T(2) K",T(2)
890 DISP USING 860 ; "NOZZLE T(3) K",T(3)
900 DISP USING 860 ; "PREHEAT TUE T(5) K",T(5)
910 DISP USING 860 ; "WATER INLET T(8) K",T(8)
920 DISP USING 860 ; "WATER OUTLET T(6) K",T(6)
930 DISP USING 860 ; "WATER OUTLET T(9) K",T(9)
940 DISP USING 860 ; "RING OUTLET T(4) K",T(4)
950 DISP USING 860 ; "FURNACE MIDL T(7) K",T(7)
960 DISP USING 860 ; "FURNACE TOP T(10) K",T(10)
970 DISP USING 860 ; "AMPLAMP V V(0) V",V(0)
980 DISP USING 860 ; "AMPLAMP I 200=V(1)kA",V(1)*200
990 ON KEY# 1,"ENTER" GOTO 350
1000 ON KEY# 2,"LOGDAT" GOTO 1080
1010 ON KEY# 3,"LOGGER" GOTO 830
1020 ON KEY# 4,"RETURN" GOTO 250
1030 ON KEY# 5,"" GOTO 1030
1040 ON KEY# 6,"" GOTO 1040
1050 ON KEY# 7,"" GOTO 1050
1060 ON KEY# 8,"" GOTO 1060
1070 KEY LABEL @ GOTO 1070
1080 ! BEGIN CALL TO DATA LOGGER
1090 GOSUB 2230 ! CALL DATA LOGGER
1100 ! PRINT "T(5)":T(5)
1110 IF T(5)<=1300 THEN GOTO 840
1120 BEEP 40,9999 @ DISP "HELP I AM TOO HOT" @ BEEP 40,9999 @ PAUSE
1130 GOTO 830
1140 ! *****
1150 CLEAR @ DISP " I AM BALANCING THE ENERGY" @ DISP " PLEASE BE PATIENT"
1160 ! BEGIN THE ENERGY BALANCING
1170 A0=(2.277/12)^2 ! ORIFICE AREA
1180 B=2.277/4 ! DIAMETER RATIO
1190 H0=.075*((G0*.03606+14.7)/14.7) ! DENSITY
1200 D2=4/12 ! PIPE DIAMETER
1210 V0=8000

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1220 M0=.0000432 ! LBM/FT-HR
1230 E=V0*D2*H0/(M0*32.2) ! REYNOLDS NUMBER
1240 C1=.7398*(B-.7)+1.6425*(B-.7)^2+1.3236*(B-.7)^3
1250 C0=1.0835-.1687*LGTE+(.0243*LGTE)^2-.0011*LGTE^3+C1
1260 Y=-(.3242-.2504*B+.4131*B*B)*(K2/G0))+1
1270 F0=Y*C0*A0*SQR(2*32.2*144*K2*.03606/(H0*293/T(1))) ! FLOW ft3/sec AT STP
1280 IF 3600*F0-V0<40 THEN GOTO 1310
1290 V0=3600*F0
1300 GOTO 1230
1310 M1=F0*H0*3600 ! LBM/HR AIR
1320 M2=M1/2.205 ! KG/HR
1330 M3=.0502*(14.7+15.95*.4921/2.54)*3600*15/(14.7*K3)
1340 M4=(M1*.013+M3*.92529)/(M1+M3) ! % MOISTURE
1350 E0=V(0)*V(1)*200*3415 ! PREHEATER BTU/HR
1360 E1=.1*E0 ! PREHEATER LOSSES
1370 IF T(2)>T(3) THEN D5=T(2)
1380 IF T(3)>T(2) THEN D5=T(3)
1390 PRINT D5
1400 ! CORRECT D5 FOR ERROR IN THERMOCOUPLE READING
1410 D7=.08586-.0001594*D5+.0000001505*D5*D5 ! DENSITY
1420 V1=M1/(3600*P1*(4/24)*D7) ! VELOCITY FT/S
1430 M5=.0000111+.00000001765*D5-3.972E-12*D5*D5 ! MU
1440 Z1=V1*D7*(1/(16*12))/M5 ! RENOLDS NUMBER
1450 J4=.01336+.00002045*D5-.00000002011*D5*D5 ! K
1460 IF Z1>4000 THEN H2=.000567*J4*.174*Z1*.618/(1/(16*12))
1470 IF Z1<4000 THEN H2=.000567*J4*.615*Z1*.466/(1/(16*12))
1480 J5=.4992+.0001406*D5
1490 D5=D5+J5*5.67E-12*(D5^4-T(16)^4)/H2+.207*.02*(D5-T(16))/(H2*.2*10)
1500 PRINT D5
1510 D2=.5*(T(1)+D5)*9/5-460
1520 C2=.2393+.00000642*D2+.0000000185*D2*D2
1530 E2=M1*C2*(T(1)-D5)*9/5
1540 E3=E2+E0-E1 ! QERR A TO B
1550 D3=.5*(D5+T(15))*9/5-460
1560 C3=(.1.084+.033*M4)*.00001*D3*D3+(.2472+.0018*M4)*D3-.13*M4)/D3
1570 E4=(M1+M3)*C3*(D5-T(15))*9/5 ! QB-QC
1580 E5=5000 ! Q PILOT EST 5 FT3/HR BURNED BY
1590 E6=M3*20054 ! GAS INPUT BTU/HR
1600 D3=(T(7)+T(10))*5+293)*.5*9/5-460
1610 N0=.721+.0000197*D3-.000000203*D3*D3 ! PRANDTL NUMBER
1620 N1=.01336+.00002045*D3-.00000002011*D3*D3 ! AIR CONDUCTION
1630 Z0=EXP(15.23-.008826*D3+.000004659*D3*D3)
1640 G1=6*6*(.5*(T(7)+T(10))-293)*9/5)*20 ! GRASSHOFF NO
1650 G2=G1*N0
1660 IF G2<10000000000 THEN H1=N1*.555*G2*.25/6
1670 IF G2>10000000000 THEN H1=N1*.021*G2*.4/6
1680 F7=H1*56.5*(.5*(T(7)+T(10))-293)*9/5 ! CONVECTIVE HEAT LOSS ON EXTERIOR

1690 E8=E4+E5+E6-E7 ! ENERGY ERROR THRU FURNACE
1700 D4=.5*(T(15)+T(14))*9/5-460
1710 C4=(.1.084+.033*M4)*.00001*D4*D4+(.2472+.0018*M4)*D4-.13*M4)/D4
1720 E9=(M1+M3)*C4*(T(15)-T(14))*9/5
1730 IF T(6)>T(9) THEN D6=T(6)
1740 IF T(9)>T(6) THEN D6=T(9)
1750 J0=6*60*8.34*K0*1*(D6-T(8))*9/5)/100 ! CALORIMETER ENERGY REMOVAL
1760 J1=8.34*60*K1*1*(T(4)-T(8))*9/5 ! COOLING RING LOSSES
1770 J2=E9-J0-J1 ! QERROR C TO D
1780 J3=J2+E8+E3 ! TOTAL ENERGY ERROR
1790 ! DISPLAY ENERGY BALANCE
1800 IMAGE 15A,6X,S7D.DD
1810 CLEAR

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1820 IMAGE 15A,X,S7D.DD
1830 DISP USING 1820 ; "PREHEATER E0",E0
1840 DISP USING 1820 ; "PREHEAT LOSS E1",E1
1850 DISP USING 1820 ; "QA-QB E2",E2
1860 DISP USING 1800 ; "-- Qerr A-B E3",E3
1870 DISP USING 1820 ; "QB-QC E4",E4
1880 DISP USING 1820 ; "Q PILOT E5",E5
1890 DISP USING 1820 ; "GAS INPUT E6",E6
1900 DISP USING 1820 ; "CONV.HEAT LS E7",E7
1910 DISP USING 1800 ; "-- Qerr Furn E8",E8
1920 DISP USING 1820 ; "QC-QD E9",E9
1930 DISP USING 1820 ; "CALOR.EN.RMV J0",J0 @ DISP USING 1820 ; "RING LOSSES J1",J1
1940 DISP USING 1800 ; "-- Qerr C-D J2",J2
1950 DISP USING 1800 ; "--TOTAL ERROR J3",J3
1960 PAUSE
1970 CLEAR
1980 RETURN
1990 ! *****
2000 ! HERE IS WHERE THE DATA WILL BE STORED
2010 ASSIGN# 1 TO "THMKDATA"
2020 DISP USING 2030 ; HMS$(T(0)),T(1),T(2),G0
2030 IMAGE 8A,X,4D.2D,X,4D.2D,X,4D.2D
2040 PRINT# 1,Z9 ; T(),V(),K0,K1,K2,K3,G0
2050 PRINT "RECORD ";Z9;" RECORDED ";HMS$(T(0))
2060 Z8=Z9
2070 DISP "ENTER THE RECORD NUMBER YOU WANT TO SEE"
2080 INPUT Z8
2090 READ# 1,Z8 ; T(),V(),U1,U2,U3,U4,U5
2100 DISP USING 2030 ; HMS$(T(0));T(1);T(2);G0
2110 ASSIGN# 1 TO *
2120 Z9=Z9+1
2130 RETURN
2140 ! *****
2150 CLEAR @ DISP "ENTER DEL-t (MIN)" @ INPUT W(0)@ W(0)-W(0)
2160 DISP "ENTER Tt" @ INPUT W(1)
2170 DISP "ENTER Tx" @ INPUT W(2)
2180 DISP "ENTER To" @ INPUT W(3)
2190 DISP "ENTER Tf" @ INPUT W(4)
2200 DISP "ENTER Ti" @ INPUT W(5)
2210 W(6)=-(1*(1/W(0))=LOG((W(1)-W(2))/(W(3)-W(2))))
2211 ! PRINT W(6)
2220 W(7)=-(1*(1/W(6))=LOG((W(4)-W(2))/(W(5)-W(2))))
2221 PRINT "THE HEAT UP TIME IS ";W(7);" MIN"
2222 PRINT "OR ";W(7)/60;" HOURS"
2223 RETURN
2230 ! *****
2240 TS=TIMES
2250 T(0)=HMS(Ts)
2260 ! READ TIME, 10 K-TYPE THER371 INPUT K2
2270 P1=3497
2280 GOSUB 2440 ! CALL Init
2290 GOSUB 3250 ! CALL Kcoef
2300 FOR I=9 TO 18
2310 P1=I @ Ps="K"
2320 GOSUB 3490 ! CALL Sc_deg
2330 J=I-R
2340 T(J)=P+273.15
2350 NEXT I
2360 TS=TIMES
2370 T(0)=HMS(Ts) ! CONVERT STRING TO SECONDS

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2380 FOR I=1 TO 2
2390 P1=I
2400 GOSUB 3940 ! CALL Dev
2410 V(I-1)=P
2420 NEXT I
2430 DISP "DONE" @ WAIT 1000 @ RETURN
2440 ! SUBPROGRAM Init Hp85
2450 ! QA 7/08/80 GAC
2460 ! P1=Dvmeter
2470 DIM Q7$(23) ! DEVICE NAMES
2480 !
2490 ! INITIALIZE DEVICE ADDRESSES
2500 !
2510 R0=709 ! 3497A SCANNER ADDRESS
2520 R1=722 ! 3456A DIGITAL VOLTMETER ADDRESS
2530 R2=724 ! 3437A SYSTEM VOLTMETER ADDRESS
2540 R3=0 ! ERROR FLAG
2550 R4=0 ! USED IN SUBROUTINE "Strip"
2560 O3=R0 DIV 100 ! INTEGER DIVIDE, i.e. Bus=IP(Scn/100)
2570 O4=R1
2580 R1$="0000000000000000"
2590 ON ERROR GOTO 3020 ! IF P1 HAS NOT BEEN DEFINED
2600 IF P1=3497 THEN R1=R0 ! PASS PARAMETER USED HERE
2610 IF P1<>3456 AND P1<>3497 THEN 3020 ! Abort
2620 OFF ERROR
2630 !
2640 !
2650 ! VERIFY THAT INTERFACE IS HP-IB
2660 !
2670 ON ERROR GOTO 2740
2680 STATUS O3,0 ! O6
2690 OFF ERROR
2700 !
2710 ! PRINT ERROR MESSAGE TO CRT IF NO INTERFACE OR NOT HP-IB INTERFACE.
2720 !
2730 IF O6=1 THEN 2840 ! OK
2740 OFF ERROR
2750 CLEAR
2760 DISP USING "/",K" ; "CAUTION: HP-IB INTERFACE #"&VAL$(O3)&" IS NOT PRESENT."
2770 DISP USING "/",K" ; " PROGRAM EXECUTION TERMINATED"
2780 BEEP
2790 STOP
2800 !
2810 ! INITIALIZE 82937A HP-IB INTERFACE, RESET INTERFACE
2820 !
2830 !
2840 ABORTIO O3 ! INITIALIZES INTERFACE AND BUS
2850 RESET O3 ! SENDS DEVICE CLEAR (DCL)
2860 !
2870 !
2880 ! CHECK FOR EQUIPMENT ON BUS AT ALL ADDRESSES AND PRINT DEVICE NAMES
2890 !
2900 !
2910 CLEAR @ DISP USING "/",2X,K,DD,/,/" ; "EQUIPMENT PRESENT ON BUS ";O3
2920 FOR O2=0 TO 30
2930 OUTPUT O3=100+O2 USING "#" ; ! ADDRESS DEVICE TO LISTEN
2940 RESUME O3 ! DROP ATN
2950 STATUS O3,2 ; O5 ! SEE IF IT LISTENED
2960 IF BINAND(O5,3)=0 THEN 2990 ! NOT THERE
2970 GOSUB 3080 ! CALL DEV_NAME
2980 DISP USING 3000 ; Q7$,O2
2990 NEXT O2
3000 IMAGE 37A," at address ",2Z
3010 GOTO 3060 ! EXIT
3020 OFF ERROR
3030 R3=2
3040 R$="Init"
3050 GOSUB 4200 ! CALL Warn
3060 RETURN
3070 ! SUBEND
3080 ! SUB DEV_NAME
3090 ! O7$=DEVICE NAME
3100 Q7$=""
3110 IF O2<>O4 MOD 100 THEN 3130
3120 Q7$="3456A Digital Voltmeter"
3130 IF O2<>R2 MOD 100 THEN 3150
3140 Q7$="3437A System Voltmeter"
3150 IF O2<>21 THEN 3170
3160 Q7$="hp85A System Computer"
3170 IF O2<>R0 MOD 100 THEN 3200
3180 Q7$="3497A Scanner,Timer"
3190 IF R1=R0 THEN Q7$=Q7$&"DVM"
3200 IF Q7$<>"" THEN 3220
3210 Q7$="Device Unknown" ! UNKNOWN DEVICE-ANY DEVICE WITH NO LABEL
3220 !
3230 RETURN
3240 ! SUBEND
3250 ! SUBPROGRAM Kcoef hp85
3260 ! QA 7/22/80 GAC
3270 ! NO PARAMETERS
3280 !
3290 RESTORE 3360
3300 O3=3
3310 FOR O1=0 TO 8 ! 8 SEGMENTS AND SC COEFFICIENTS
3320 FOR O2=1 TO 5 ! 5 COEFFICIENTS
3330 READ R(O3,5=O1+O2)
3340 NEXT O2
3350 NEXT O1
3360 ! TYPE K COEFFICIENTS
3370 DATA 1106070,-49675000000,1.14708E15,-.00645782,-270
3380 DATA 320939,-1834430000,6.17105E12,-.00643963,-259.411
3390 DATA 121274,-115989000,7823120000,-.00632268,-237.096
3400 DATA 58575,-11949600,2034670000,-.00578481,-193.25
3410 DATA 33405.4,-1689600,107971000,-.00382995,-109.209
3420 DATA 23862,117909,-2267120,.00196027,48.5292
3430 DATA 24662.4,-92361.8,2373410,.00909134,223.865
3440 DATA 25167.5,56158.1,2787480,.0377955,911.811
3450 ! S-C COEFFICIENTS
3460 DATA 6.65829E-8,.0000394486,.000000024541,-9.13087E-11,0
3470 RETURN
3480 ! SUBEND
3490 ! SUBPROGRAM Sc_deg hp85 rev A 1980/07/22
3500 ! P1=Chan, P5=Type$
3510 ! Q1,O2=Limits(1:9,1:2)
3520 Q4=0 ! SET LIMITS OF TEMPERATURE TO VOLTAGE CONVERSION (Deg C)
3530 Q5=70
3540 O1=IP(P1)
3550 O7=POS("EJKRSTBnn",P5(1,1))
3560 R3=2*(O1<0 OR O1>999) ! CHECK FOR PARAMETERS OUT OF RANGE
3570 R3=R3+4*(O7=0)
3580 IF R3<>0 THEN 3880 ! Abort

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3590 D2=19+01-01 MOD 20 ! MEASURE VOLTAGE AND REF. TEMP.
3600 P1=02 ! SETUP Dcv CALL
3610 GOSUB 3940 ! CALL Dcv
3620 Q3=10+P
3630 IF R3<>0 THEN P=9.E19 @ GOTO 3920
3640 P1=01 ! SETUP Dcv CALL
3650 GOSUB 3940 ! CALL Dcv
3660 Q8=P
3670 IF R3<>0 THEN P=9.E99 @ GOTO 3920
3680 P1=08 @ P2=Q3 ! P$=P$ :SETUP Sctemp CALL
3690 GOSUB 4910 ! CALL Sctemp
3700 RESTORE 3490 ! READ THIS SUB's DATA
3710 FOR Q9=1 TO Q7
3720 READ Q1,Q2
3730 NEXT Q9
3740 ! CONVERSION RANGE CHECK
3750 R3=128*(P<Q1 OR P>Q2)
3760 R3=R3+256*(Q3<Q4 OR Q3>Q5)
3770 IF R3<>0 THEN 3880 ! Abort
3780 GOTO 3920 ! P=P
3790 DATA -270,1000
3800 DATA -210,760
3810 DATA -270,1372
3820 DATA -50,1768
3830 DATA -50,1768
3840 DATA -270,400
3850 DATA 130,1820
3860 DATA 0,1300
3870 DATA -270,400
3880 ! Abort: Err$="Sc_deg"
3890 R$="Sc_deg"
3900 GOSUB 4200 ! CALL Warn
3910 P=9.E19 @ GOTO 3920
3920 RETURN
3930 ! SUBEND
3940 ! SUBPROGRAM Dcv hp85
3950 ! QA 7/10/80 GAC
3960 ! P1=Channel
3970 OUTPUT R1 USING "#"
3980 RESUME R1 DIV 100 ! DROP ATN
3990 STATUS R1 DIV 100,2 : Q2
4000 IF BINAND(Q2,3)=0 THEN Q2=1 ELSE Q2=0
4010 Q3=0 ! FLAG FOR PRESENCE OF SCANNER
4020 IF R1=R0 OR P1=-1 THEN GOTO 4070
4030 OUTPUT R0 USING "#"
4040 RESUME R0 DIV 100 ! DROP ATN
4050 STATUS R0 DIV 100,2 : Q3
4060 IF BINAND(Q3,3)=0 THEN Q3=1 ELSE Q3=0
4070 R3=2*((P1<0 OR P1>999) AND P1<>-1)+16*(Q3 OR Q2 AND R0=R1)
4080 R3=R3+32*(Q2 AND R0<>R1)
4090 IF R3 THEN GOTO 4150
4100 IF P1<>-1 THEN OUTPUT R0 USING "AA,DDD" ; "AC";INT(P1)
4110 IF R1=R0 THEN OUTPUT R1 ;"VR5VN1VA1VF1VD5VC0VS0VH0VT3" ! 3497 SETUP & TRG
4120 IF R1<>R0 THEN OUTPUT R1 ;"HIST16STGT3" ! 3456 SETUP & TRG
4130 ENTER R1 : P
4140 GOTO 4180 ! RETURN-RESULT IN P
4150 R$="Dcv"
4160 GOSUB 4200 ! CALL Warn
4170 P=9.E19
4180 RETURN
4190 ! SUBEND

4200 ! SUBPROGRAM Warn hp85
4210 ! QA 7/30/80 GAC
4220 ! R3=ERROR WORD
4230 ! R$=NAME OF CALLING ROUTINE
4240 DIM Q8$(100),Q6$(15)
4250 Q5=2 ! MAXIMUM NUMBER OF WARNINGS ON EACH ERROR ( <=9 )
4260 Q2=0 ! ERROR FLAG
4270 ON ERROR GOTO 4310
4280 R1$=R1$
4290 OFF ERROR
4300 GOTO 4330
4310 OFF ERROR
4320 R1$="0000000000000000" ! RESET ERRORS
4330 !
4340 FOR Q4=0 TO 14 ! ANY ERRORS THAT NEED WARNINGS?
4350 IF BIT(R3,Q4) AND VAL(R1$(Q4+1,Q4+1))<Q5 THEN Q2=Q2+2*Q4
4360 NEXT Q4 ! DUMMY INDEX
4370 IF Q2=0 THEN 4890 ! NO ERRORS...RETURN
4380 !
4390 Q6=0
4400 ON ERROR GOTO 4550
4410 IF R0=0 THEN 4550 ! Nodate; PRINT HEADING
4420 ON TIMEOUT R0 DIV 100 GOTO 4550
4430 SET TIMEOUT (R0 DIV 100);1000
4440 OUTPUT R0 USING "#"
4450 RESUME R0 DIV 100 ! DROP ATN
4460 STATUS R0 DIV 100,2 : Q3 ! FLAG FOR PRESENCE OF SCANNER
4470 OFF ERROR
4480 IF BINAND(Q3,3)=0 THEN 4550 ! Nodate
4490 OUTPUT R0 USING "2A" ; "TD"
4500 ENTER R0 : Q6$ ! Q6$=Date
4510 IF Q6$="01:01:00:00:00" THEN 4550 ! Nodate
4520 PRINT USING "/,K" ; "*****"
4530 PRINT USING " 3(K)" ; "==" ; "Date: "&Q6$(1,2)&"/"&Q6$(4,5)&" Time: "&Q6$(
,14)&"=="
4540 GOTO 4570
4550 OFF ERROR
4560 PRINT USING "/,K" ; "*****"
4570 PRINT USING "/,K/,K/,/" ; "WARNING: SUBPROGRAM "&R$&" WAS";" NOT
EXECUTED"
4580 ON ERROR GOTO 4600 ! IN CASE ISC IS UNDEFINED
4590 OFF TIMEOUT R0 DIV 100
4600 OFF ERROR
4610 RESTORE 4740
4620 FOR Q4=0 TO 14 ! IDENTIFY THE INDIVIDUAL ERRORS
4630 READ Q8$
4640 IF NOT BIT(Q2,Q4) THEN 4690 ! Next_indx
4650 R1$(Q4+1,Q4+1)=VAL(VAL(R1$(Q4+1,Q4+1))+1) ! INCREMENT
4660 Q6=Q6+1 ! NUMBER OF ERRORS
4670 PRINT Q8$ ! ERROR MESSAGE
4680 IF VAL(R1$(Q4+1,Q4+1))<Q5 THEN PRINT USING "K/,/" ; " -LAST WARNING FOR T
IS ERROR-"
4690 NEXT Q4
4700 IF Q6>-1 THEN PRINT USING "/,K" ; "SEE THE "&R$&" DOCUMENTATION TO"
4710 IF Q6=1 THEN PRINT "INTERPRET THIS ERROR"
4720 IF Q6>1 THEN PRINT "INTERPRET THESE ERRORS"
4730 PRINT "*****"
4740 DATA "ERROR 0: Passed array is dimen- sioned improperly"
4750 DATA "ERROR 1: First pass parameter out of range"
4760 DATA "ERROR 2: Second pass parameter out of range"

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4770 DATA "ERROR 3: Third pass parameter out of range"
4780 DATA "ERROR 4: 3497 scanner not found on bus"
4790 DATA "ERROR 5: 3456 DVM not found on bus"
4800 DATA "ERROR 6: 3437 system voltmeter not found on bus"
4810 DATA "ERROR 7: Thermocouple 'volt. to temp.' conversion out
of range"
4820 DATA "ERROR 8: Thermocouple 'temp. to volt.' conversion out
of range"
4830 DATA "ERROR 9: Xmin=Xmax or Ymin=Ymax"
4840 DATA "ERROR 10: Scaling value<=0 on a log axis"
4850 DATA "ERROR 11: Datapoint<=0 on a log axis"
4860 DATA "ERROR 12: Level crossing not found"
4870 DATA "ERROR 13: User defined error"
4880 DATA "ERROR 14: User defined error"
4890 RETURN
4900 ! SUBEND
4910 ! SUBPROGRAM Sctemp hp85 rev A 1980/07/22
4920 ! P1=Voltage,P$=Type$,P2=Ref_tmp
4930 Q3=POS("EJKRSTBN",P$)
4940 IF Q3=0 THEN P=9.E19 @ GOTO 5020
4950 Q1=P1+R(Q3,41)+P2*(R(Q3,42)+P2*(R(Q3,43)+P2*(R(Q3,44))))
4960 Q2=7
4970 IF Q1<R(Q3,4*5+4) THEN Q2=3
4980 IF Q1<R(Q3,(Q2-1)*5+4) THEN Q2=Q2-2
4990 IF Q1<R(Q3,Q2*5+4) THEN Q2=Q2-1
5000 Q4=Q1-R(Q3,5*Q2+4)
5010 P=R(Q3,5*Q2+5)+Q4*(R(Q3,5*Q2+1)+Q4*(R(Q3,5*Q2+2)+Q4*(R(Q3,5*Q2+3))))
5020 RETURN
5030 ! SUBEND

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