AN EVALUATION OF THE ENERGY CONSUMPTION OF AUTOMOBILE PAINT-DRYING OVENS

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Symbol	Meaning
T_A	Oven air temperature (°F)
T_m	Air temperature leaving the burner (°F)
T_O	Fresh air temperature entering the burner (°F)
$T_{W1} \rightarrow T_{W5}$	Oven wall temperatures (°F)
$T_{D1} \rightarrow T_{D5}$	Air duct wall temperatures (°F)
T_S	Internal oven steel temperature (°F)
T_T	Body carrying truck temperature (°F)
T_B	Car body temperature (°F)
T_p	Ambient plant air temperature (°F)
$\dot{m}_{tt}$	Solvent evaporation rate $\left(\frac{lb}{Hr}\right)$
h_{fg}	Heat of solvent vaporization $\left(\frac{Btu}{lb.}\right)$
$\dot{m}_O$	Mass flow rate fresh air $\left(\frac{lb}{Hr}\right)$
$\dot{m}_R$	Mass flow rate return air $\left(\frac{lb}{Hr}\right)$
$\dot{m}_m$	Mass flow rate supply air $\left(\frac{lb}{Hr}\right)$
$\dot{m}_E$	Mass flow rate exhaust air $\left(\frac{lb}{Hr}\right)$
m_A	Mass of air in the oven (lb)
m_B	Mass of car body (lb)
$m_{W1} \rightarrow m_{W5}$	Mass of oven wall layers (lb)
$m_{D1} \rightarrow m_{D4}$	Mass of ductwork segments (lb)
m_T	Mass of body carrying trucks (lb)
m_S	Mass of internal oven steel (lb)
C_p	Specific heat of air (Btu/lb-°F)
$C_{D1} - C_{D4}$	Specific heat of ductwork (Btu/lb-°F)
$C_{W1} - C_{W5}$	Specific heat of wall layers (Btu/lb-°F)

LIST OF SYMBOLS (Cont'd)

Symbol	Meaning
C_T	Specific heat of body truck (Btu/lb-°F)
C_S	Specific heat of oven steel (Btu/lb-°F)
C_B	Specific heat of car body (Btu/lb-°F)
K	Fiberglass insulation resistance (Btu-in/hr-°F-ft^2)
ΔX	Wall layer thickness (inches)
A_W	Surface area of oven walls, floor and ceiling (ft^2)
A_S	Surface area of internal oven steel (ft^2)
A_T	Surface area of body carrying truck (ft^2)
A_B	Surface area of car body (ft^2)
$A_{D1} \rightarrow A_{D4}$	Surface area of ductwork (ft^2)
	Avg. convective heat transfer coefficients (Btu/ft^2-°F-hr)
$\bar{h}_1$	Oven wall coefficient (inside oven)
$\bar{h}_2$	Oven wall coefficient (plant side)
$\bar{h}_{D1} \rightarrow \bar{h}_{D4}$	Ductwork coefficients (inside duct)
$\bar{h}'_{D2}$	Supply duct coefficient (plant side)
$\bar{h}'_{D4}$	Return duct coefficient (plant side)
$\bar{h}_S$	Internal steel coefficient
$\bar{h}_B$	Body coefficient
$\bar{h}_T$	Body carrying truck coefficient
U_W	Overall wall heat transfer coefficient (Btu/hr-ft^2-°F)
U_{D2} & U_{D4}	Overall ductwork (outside the oven) heat transfer coefficients (Btu/hr-ft^2-°F)
$\dot{E}$	Burner energy rate (Btu/hr)
$\dot{E}_{SS}$	Steady-state burner energy rate (Btu/hr)
θ	Time (hours)
DT	Time interval of integration (hours)

Chapter I

INTRODUCTION

> In the last two years, we have witnessed a tremendous outcry over the United States' current 'energy crisis'. We have not witnessed a corresponding out pour of concrete solutions to the problem, however, and perhaps the time has come to begin work in the direction of some solution."[1]

It seems rare for a day to pass without being confronted with some form of news about the "energy crisis" such as that presented above. The disheartening fact is that at present there appears to be little hope for recovery in the immediate future. Society today is organized around energy. Unfortunately, energy management and conservation has been severely lacking in the past. Today, however, society is taking a look back over its shoulder and re-examining some of its past mistakes in energy use and is attempting to correct them for the future.

Without a doubt, industry is the United States largest single user of all forms of energy. Consequently, it is the hardest hit by the energy pinch [1]*. Recognizing the impending energy shortage, large scale re-evaluations of energy uses within industry are being made at the present time.

The evaluation not only examines the future energy needs of industry; but it also re-examines past and present energy consuming processes, with the hope of eliminating or reducing the amount of energy they require.

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[1]D. Deyoe, "Heat Recovery--How Can the Heat Ripe Help?" <u>ASHRAE Journal</u>, April, 1973, p. 35.

*Numbers in [ ] refer to references in Selected References.

The Fisher Body Division of General Motors Corporation is very much involved in the re-evaluation process. One plant in particular, Flint Fisher Body No. 1, is deeply concerned with the predicted energy shortage. The plant has three basic manufacturing functions: 1) Metal stamping and assembly, 2) Body-in-white assembly, 3) Body painting and trim. Due to the nature of the plant's operations a great deal of energy is required to maintain its production and to supply the related process equipment. A typical process, which is representative of many energy consuming processes being re-evaluated, is body paint drying. Every body that is painted in the plant requires oven drying to cure and reflow the acrylic paints. The curing and reflow processes require an air (oxygen) supply and a temperature of 315°F for approximately eleven minutes. The ovens used to dry the bodies are heated by gas-fired, forced-air, burners located on the roof of the plant.

In the past, with unlimited, low-cost energy available, there appeared to be little need for controlling the ovens' energy consumption to the fullest extent. Now, however, the situation has drastically changed. The gas suppliers are cutting back on the amounts of process gas sold and in some areas are putting industrial users on standby service. Needless to say, shutdowns are costly and every means available is being employed to prevent them.

The need for reducing the energy consumption in every phase of plant operation is what prompted the writing of this thesis. The paint-drying ovens were chosen as a typical example of an energy consuming operation which deserves the attention of analysis for purposes of detection and possible improvement in energy consumption characteristics.

Unfortunately, most of the design work on the ovens has been done by experiment and experience. Little or no data has been written regarding their operation or thermal response characteristics. Therefore, much of the background information for this thesis has been acquired through observation and personal communications with those directly involved with the ovens' operation and maintenance.

Chapter II

MINIMIZATION OF ENERGY CONSUMPTION

In the last decade great strides have been made in optimization theory and technique. Most of this work has been performed by Chemical and Industrial Engineers and Mathematicians. Only recently has the Mechanical Engineer become involved (mainly in the aerospace industry), which made it necessary to start this evaluation from basic heat transfer relationships for the oven and develop a technique suitable for conserving energy in their operation.

The first part in the evaluation was to determine a relationship between the energy required to maintain the ovens at steady-state and the energy required to cool and then reheat the ovens. This was done to determine if any energy savings would result from shutting the ovens down during periods when the paint lines were not running.

During steady-state operation the losses from the ovens will be at a maximum. This is due to the fact that the energy loss rate is highest when the driving potential (temperature difference) is at its maximum (which occurs at steady-state). This can be shown by the following equation:

$$E_{SS} = \int_0^{\theta} \sum_{i=1}^{n} U_i A_i (T_A - T_p) d\theta \qquad (1)$$

In other words the steady-state energy input into an oven is equal to the summation of all the component losses in the system integrated over the interval being considered. This integral has maximum value when the difference $(T_A - T_p)$ is a maximum, i.e., when T_A is maximum.

Now consider a cooling and heating cycle for the oven of the same time duration as the steady-state case. The oven will cool during the interval $\theta = 0$ to $\theta = \theta_1$, and then be reheated back to steady-state during the time period θ_1 to θ. During the cool down cycle the losses from the oven will start out at their maximum steady-state rate, but will decrease with time as T_A decreases. This is due to the fact that T_p is almost completely time independent. This can be expressed by the following relationship:

$$E_{\substack{loss \\ \text{Cool Down}}} = \int_0^{\theta_1} \sum_{i=1}^{n} U_i A_i (T_A(\theta) - T_p) d\theta \qquad (2)$$

The energy required to heat up the oven is also a function of time and temperature. The loss rate is at a minimum when the oven is cold ($T_A = T_p$) and increases to its maximum when the oven reaches steady-state. This relationship can be expressed by the following equation:

$$E_{\substack{Heat \\ Up}} = \int_{\theta_1}^{\theta} \sum_{i=1}^{n} U_i A_i (T_A(\theta) - T_p) d\theta + E_{\substack{loss \\ \text{Cool Down}}} \qquad (3)$$

The value E_{SS} obtained from equation (1) is the amount of energy required to make up the losses from the oven during a set time interval. If the time interval is divided into two phases the equation becomes the following:

$$E_{SS} = \int_0^{\theta_1} \sum_{i=1}^{n} U_i A_i (T_A - T_p) d\theta + \int_{\theta_1}^{\theta} \sum_{i=1}^{n} U_i A_i (T_A - T_p) d\theta \qquad (1')$$

Now recognizing the fact that $E_{Heat-up}$ is the energy required to re-supply the energy lost from thermal, heat storage during cool-down ($\theta = 0$ to $\theta = \theta_1$) plus the energy required to overcome the losses from the oven during re-heat ($\theta = \theta_1$ to $\theta = \theta$) it becomes apparent that the cool-down, reheat cycle requires less energy than is needed for the steady state operation. This is because $\int_0^{\theta_1} \sum_{i=1}^{n} U_i A_i (T_A - T_p) d\theta$ is always greater than $\int_0^{\theta_1} \sum_{i=1}^{n} U_i A_i (T_A(\theta) - T_p) d\theta$; since $(T_A(\theta) - T_p)$ is always less than $(T_A - T_p)$ after cool down has been initiated. Also $\int_{\theta_1}^{\theta} \sum_{i=1}^{n} U_i A_i (T_A - T_p) d\theta$ is always greater than $\int_{\theta_1}^{\theta} \sum_{i=1}^{n} U_i A_i (T_A(\theta) - T_p) d\theta$; since $(T_A - T_p)$ is always greater than $(T_A(\theta) - T_p)$ until steady state is reached when $T_A = T_A(\theta)$. Therefore the following inequality is obtained:

$$E_{SS} \Big|_0^{\theta} > E_{heat-up} \Big|_{\theta_1}^{\theta} \qquad (4)$$

The inequality states that the energy required to hold the ovens at steady-state, for any time interval, is always greater than the energy required to reheat them after shut down (for the same time interval). This can be seen graphically in Figure 1.

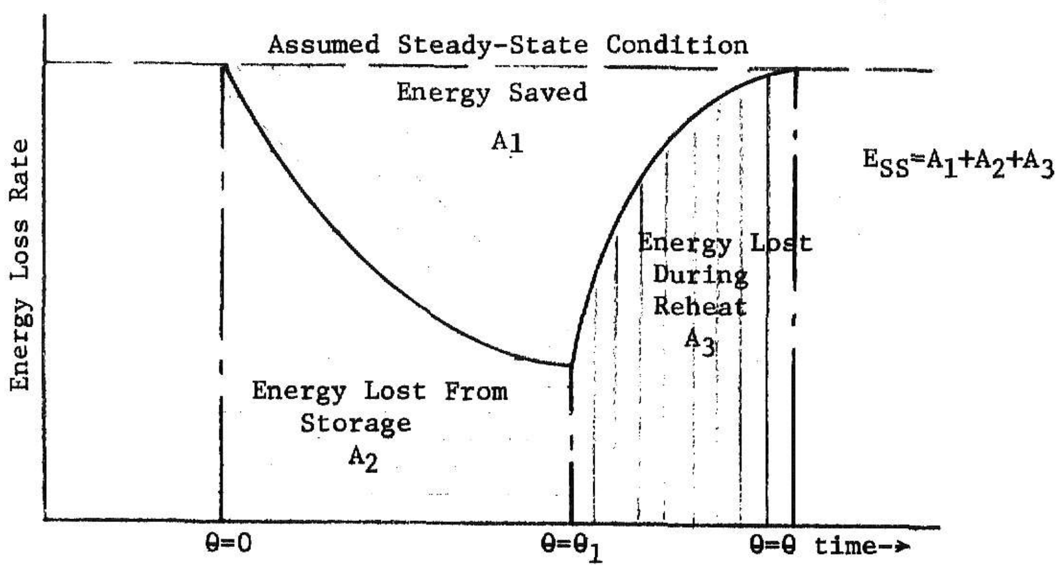

Fig. 1. The Energy Inequality

It can be deduced from the above figure that the savings will be greatest by keeping the interval from θ_1 to θ at its minimum possible value. In other words to minimize the ovens' energy consumption, turn the burner on at the last possible moment, for the interval being considered, to its maximum allowable rate. The above scheme is often referred to as bang-bang control and is commonly employed to minimize fuel consumption for rockets and missiles [2], [3], [4].

Another possible area of energy savings to be considered is the use of the waste heat from the oven exhausts. Volitile solvents are released during the paint drying process and if proper exhaust rates are not maintained an explosive condition in the ovens can result. At present approximately twenty-four percent of the total flow is continually exhausted from the ovens. However, due to the nature of the exhaust system, this flow drops by approximately one-half when the recirculating air system is shut off during cool down periods. When the ovens are in operation the exhaust air quantity results in a load of 2,082,024 Btu/hour per zone on the burner, a factor which cannot be overlooked.

It is important to note that the exhaust air must be made up by an equal amount of fresh air to prevent infiltration from the plant and to supply the necessary oxygen for drying. At present the air is taken from outside the plant and must be heated before entering the oven. Thus another avenue opens up for conserving energy: waste heat utilization for preheating the supply air. This technique is becoming very common in industry today and will be investigated in this thesis as a means of using the available energy from the exhaust air.

The next sections of this thesis cover the methods used in determining the proper bang-bang control sequence, the feasibility of waste heat utilization from the exhaust gases, and recommendations based on the findings.

Chapter III

DATA COLLECTION TECHNIQUE

There are two techniques which can be used to obtain the type of data necessary to evaluate the energy savings resulting from bang-bang control and waste heat utilization. One method of course is simply to run many physical tests on the ovens and record the thermal response curves and energy requirements for varying outdoor conditions. This method is very costly, time consuming, and would be of little value in evaluating future ovens or similar processes. The second method and the one preferred here is to develop a mathematical model of the ovens' thermal response and use a computer to compress the time factor so that the necessary information can rapidly be obtained. The model will also be useful in evaluating future processes with only minor modifications.

Chapter IV

MODEL FORMULATION

The first step in the development of any model is to get an understanding of the physical system the model is to represent. To accomplish this the blueprints of a typical oven were carefully analyzed. Figure 3 is a schematic of a typical oven zone, i.e., a segment of the total, continuous oven which is heated by an individual burner. The number of zones an oven contains may vary from two to four depending on the period of heating required.

The first zone in the ovens is a heat-up zone. It is within this zone that the bodies are elevated from their entering temperature to the operating temperature of the oven, which in this case is 315°F. Due to the transient nature of the body temperatures in this zone, it will not be considered in this analysis.

The bodies upon leaving zone one are held at 315°F for approximately eleven minutes. If the line were run continually, 24 hours per day, seven days a week, the burners would, of course, have to be left on full time. However, due to frequent production and line stoppages this is not the case. The shut down periods provide the avenue for energy reduction using the bang-bang control scheme. Due to the non-steady-state conditions developed by this type control scheme, a transient, thermal model is required for the evaluation.

The ovens can be modeled by writing a set of linear differential equations for the temperature changes occurring in the components within them (see Figure 2 for the total flow circuit schematic). The oven and

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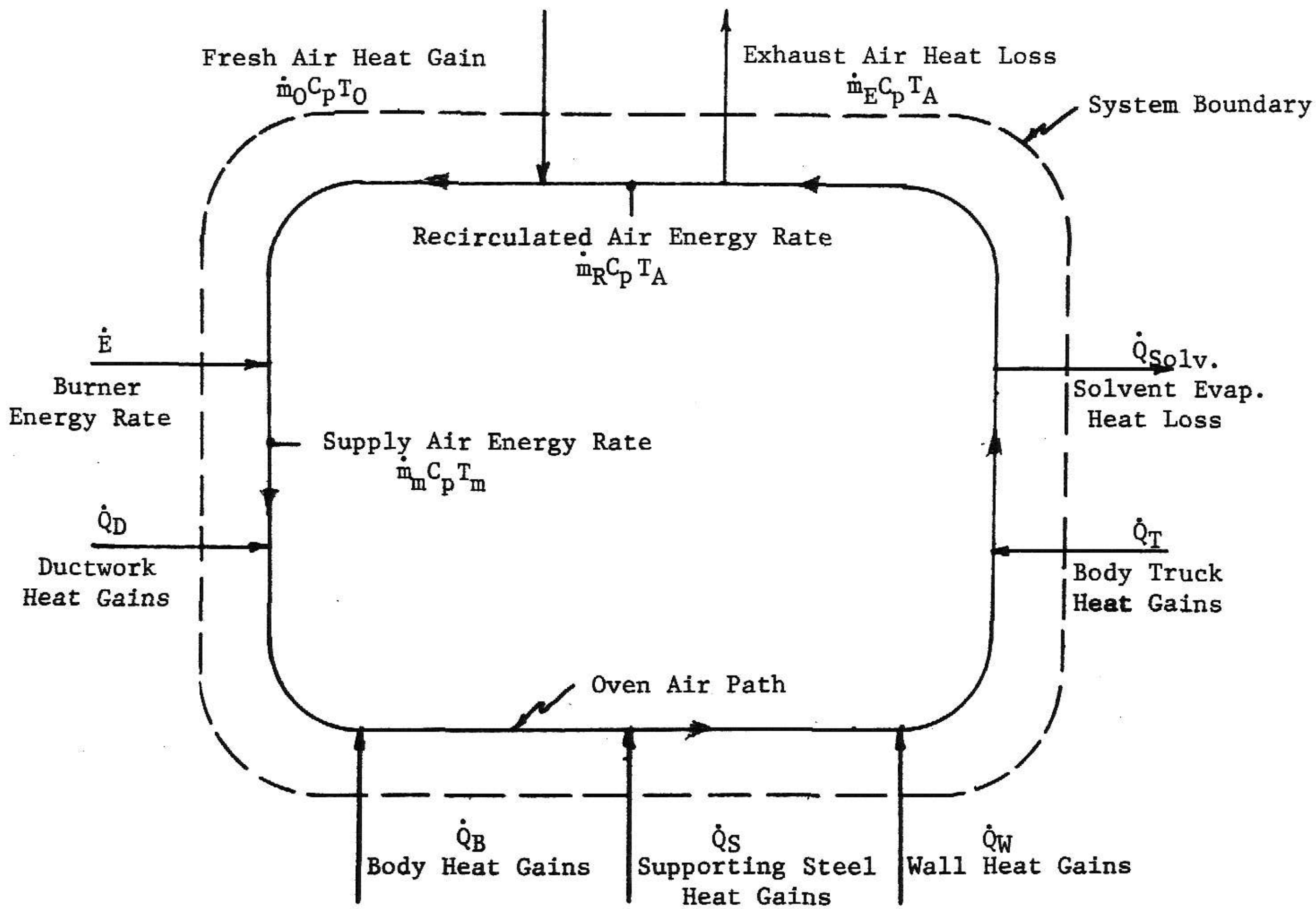


Figure 2. Total Air Flow Schematic

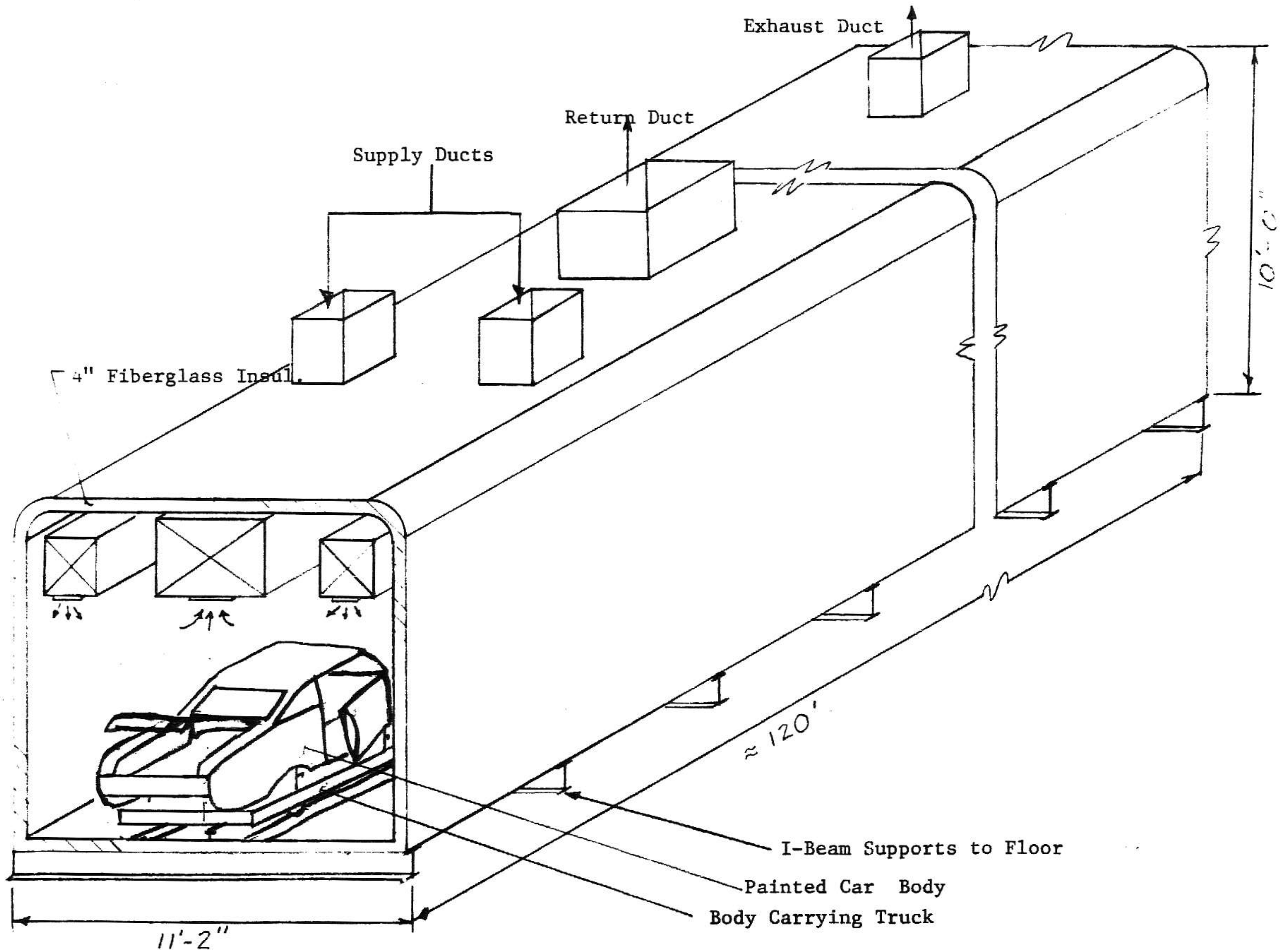


Figure 3. Typical Oven Zone Layout

its contents were separated into thirteen characteristic temperatures each with an equation to represent each time rate of change. The equations for each component are of the form:

$$\underbrace{m_x\, C_x\, \frac{dT_x}{d\theta}}_{\text{Energy storage rate}} = \underbrace{\bar{h}_x\, A_x (\Delta T)}_{\text{Convective heat transfer rate}} + \underbrace{\frac{K}{\Delta x}\, A_x (\Delta T)}_{\text{Conductive heat transfer rate}} \tag{5}$$

For the supporting steel track and track plates within the ovens (see Figure 3),

$$m_S\, C_S\, \frac{dT_S}{d\theta} = \bar{h}_S A_S (T_A - T_S) \quad . \tag{6}$$

For the bodies in the oven (Figure 3),

$$m_B\, C_B\, \frac{dT_B}{d\theta} = \bar{h}_B A_B (T_A - T_B) \quad . \tag{7}$$

For the body trucks which carry the bodies through the oven. (Fig. 3),

$$m_T\, C_T\, \frac{dT_T}{d\theta} = \bar{h}_T A_T (T_A - T_T) \quad . \tag{8}$$

The ductwork connecting air distribution systems to the heater houses on the roof was divided into four segments. Segment 1 represents the supply ductwork inside the oven; segment 2 represents the supply duct from the heater house to the oven; segment 3 represents the return air ductwork inside the oven; and segment 4 represents the return ductwork from the oven to the heater house.

The following equations represent the energy transfer for the four segments:

Segment 1: $$m_{D1} C_{D1} \frac{dT_{D1}}{d\theta} = \bar{h}_{D1} A_{D1} (T_m - T_{D1}) + \bar{h}'_{D1} A_{D1} (T_A - T_{D1}) \tag{9}$$

Segment 2: $$m_{D2} C_{D2} \frac{dT_{D2}}{d\theta} = \bar{h}_{D2} A_{D2} (T_m - T_{D2}) + \bar{h}'_{D2} A_{D2} (T_P - T_{D2}) \tag{10}$$

Segment 3. $$m_{D3}C_{D3}\frac{dT_{D3}}{d\theta} = \bar{h}_{D3}A_{D3}(T_A - T_{D3}) \tag{11}$$

Segment 4. $$m_{D4}C_{D4}\frac{dT_{D4}}{d\theta} = \bar{h}_{D4}A_{D4}(T_A - T_{D4}) + \bar{h}'_{D4}A_{D4}(T_p - T_{D4}) \tag{12}$$

The equations for the walls, floor, and ceiling of the oven required inclusion of internal conduction terms because of spatial temp-variation through their thickness. The conduction of energy through the wall was determined by using a finite difference technique. The wall was divided into five segments as shown in Figure 4.

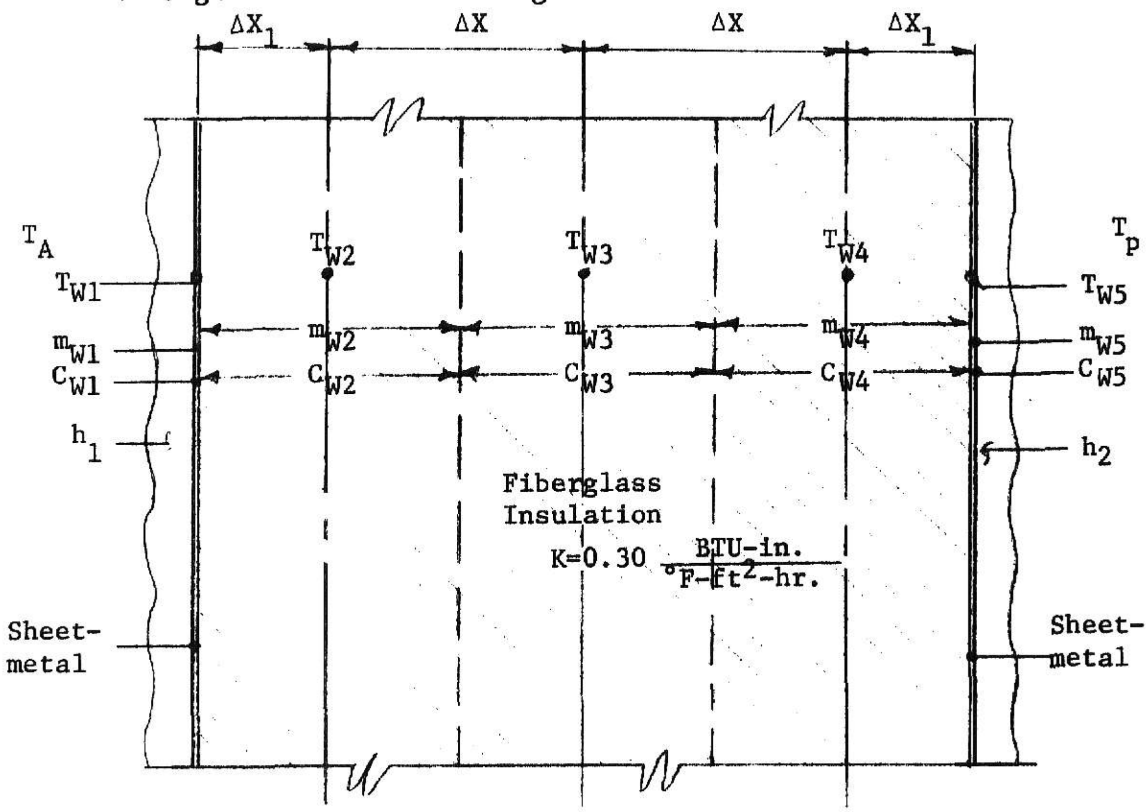


Fig. 4. Oven Wall Section

Five temperature nodes in the wall were chosen, one at the center of each segment. The two sheet metal layers were treated as though they had mass, and thermal capacity, but no resistance (due to their high conductivity and thin gage).

The electrical analogy shown in Figure 5 illustrates the thermal characteristics of the above walls more clearly. It can be utilized in obtaining the flux and storage equations for the walls.

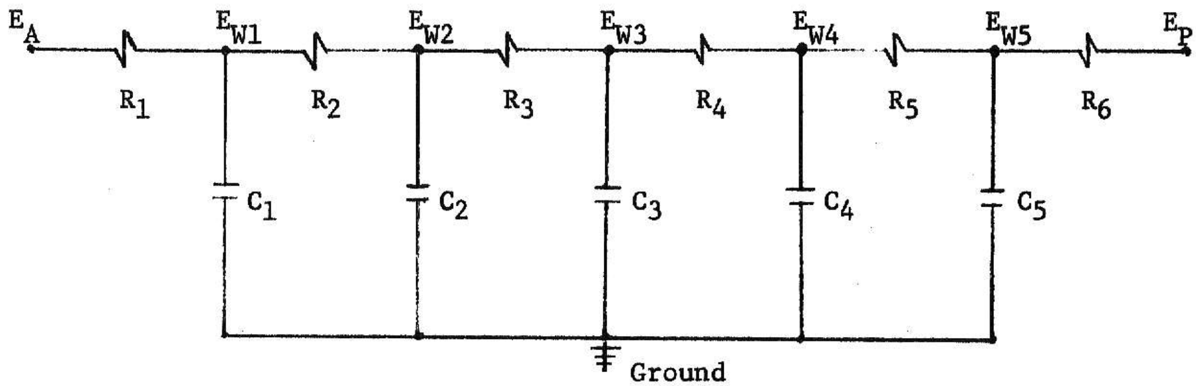


Fig. 5. Oven Wall Electrical Analogy

Using the notation of Figure 5, the analog circuit equations are the following:

$$C_1 \frac{dE_{W1}}{d\theta} = \frac{1}{R_1}(E_A - E_{W1}) + \frac{1}{R_2}(E_{W2} - E_{W1}) \quad (13)$$

$$C_2 \frac{dE_{W2}}{d\theta} = \frac{1}{R_2}(E_{W1} - E_{W2}) + \frac{1}{R_3}(E_{W3} - E_{W2}) \quad (14)$$

$$C_3 \frac{dE_{W3}}{d\theta} = \frac{1}{R_3}(E_{W2} - E_{W3}) + \frac{1}{R_4}(E_{W4} - E_{W3}) \quad (15)$$

$$C_4 \frac{dE_{W4}}{d\theta} = \frac{1}{R_4}(E_{W3} - E_{W4}) + \frac{1}{R_5}(E_{W5} - E_{W4}) \quad (16)$$

$$C_5 \frac{dE_{W5}}{d\theta} = \frac{1}{R_5}(E_{W4} - E_{W5}) + \frac{1}{R_6}(E_p - E_{W5}) \quad (17)$$

By letting the electrical values for E, C and R be replaced by their thermal equivalents, the equations become:

$$m_{W1}C_{W1}\frac{dT_{W1}}{d\theta} = \bar{h}_1 A_W(T_A - T_{W1}) + \left(\frac{K}{\Delta X_1}\right) A_W(T_{W2} - T_{W1}) \tag{18}$$

$$m_{W2}C_{W2}\frac{dT_{W2}}{d\theta} = \left(\frac{K}{\Delta X_1}\right) A_W(T_{W1} - T_{W2}) + \left(\frac{K}{\Delta X}\right) A_W(T_{W3} - T_{W2}) \tag{19}$$

$$m_{W3}C_{W3}\frac{dT_{W3}}{d\theta} = \left(\frac{K}{\Delta X}\right) A_W(T_{W2} - T_{W3}) + \left(\frac{K}{\Delta X}\right) A_W(T_{W4} - T_{W3}) \tag{20}$$

$$m_{W4}C_{W4}\frac{dT_{W4}}{d\theta} = \left(\frac{K}{\Delta X}\right) A_W(T_{W3} - T_{W4}) + \left(\frac{K}{\Delta X_1}\right) A_W(T_{W5} - T_{W4}) \tag{21}$$

$$m_{W5}C_{W5}\frac{dT_{W5}}{d\theta} = \left(\frac{K}{\Delta X_1}\right) A_W(T_{W4} - T_{W5}) + \bar{h}_2 A_W(T_p - T_{W5}) \tag{22}$$

To determine the burner exit air temperature, T_m, an energy and mass balance was written for the system as drawn in Figure 6.

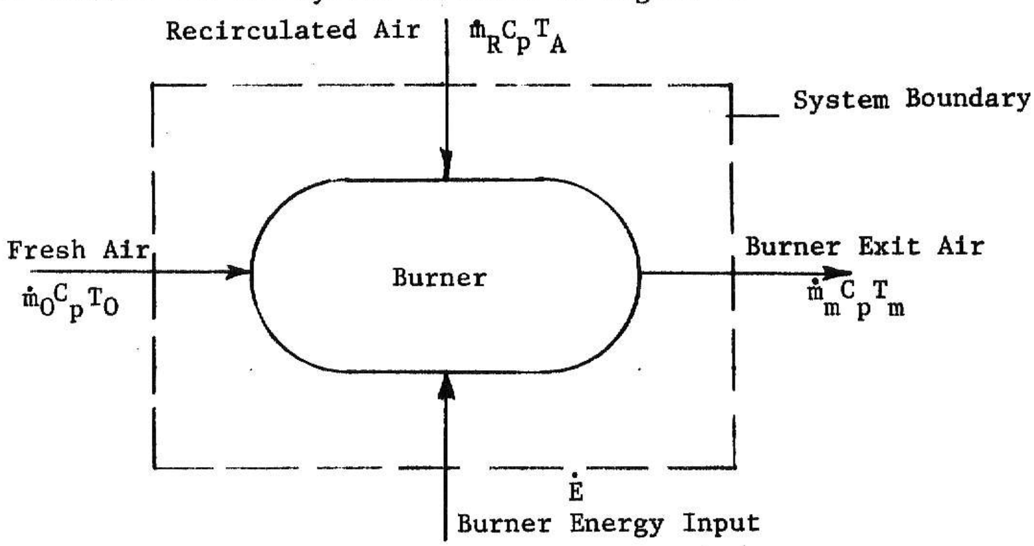


Fig. 6. Burner System

The mass balance is expressed by the following equation:

$$\dot{m}_O + \dot{m}_R = \dot{m}_m \tag{23}$$

The energy balance is written (assuming $C_p \approx$ const),

$$\dot{m}_O C_p T_O + \dot{m}_R C_p T_A + \dot{E} = \dot{m}_m C_p T_m \ . \tag{24}$$

Solving for T_m yields:

$$T_m = \frac{\dot{m}_O C_P T_O + \dot{m}_R C_P T_A + \dot{E}}{\dot{m}_m C_p}$$

The fresh air fraction in the ovens is maintained at 24% $\dot{m}_m$ (when the burners are on) and the recirculated air percent is 76% of $\dot{m}_m$; with these substitutions, the expression for T_m becomes

$$T_m = 0.24\ T_O + 0.76\ T_A + \frac{\dot{E}}{\dot{m}_m C_p} \quad . \tag{26}$$

For the time rate of change of the air temperature in the oven an energy balance was written for the system shown in Figure 7 (assuming complete mixing and no property gradients in the oven).

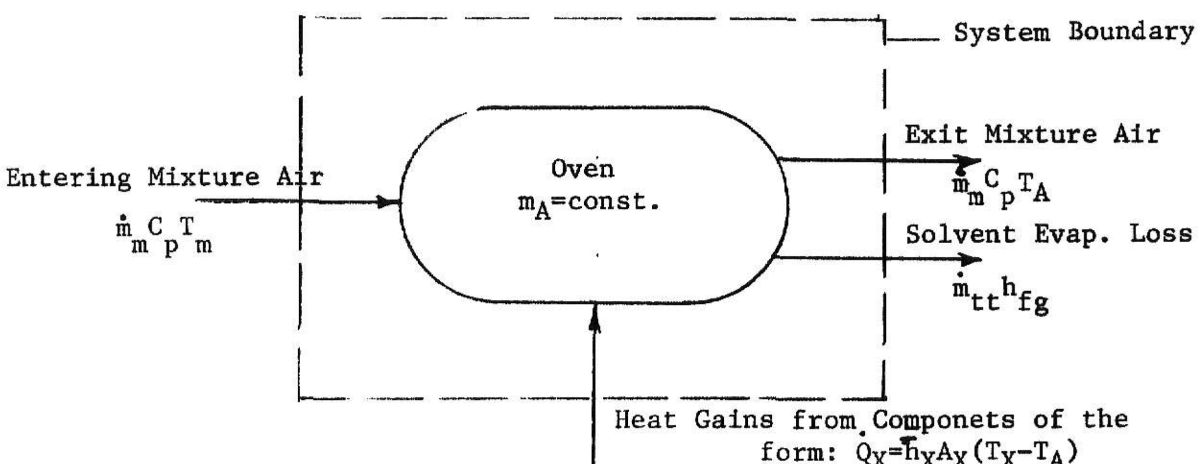


Fig. 7. Transient Oven System

The transient energy balance is the following:

$$\begin{aligned} m_A C_p \dot{T}_A = {} & \dot{m}_m C_p T_m - \dot{m}_m C_p T_A + \bar{h}_B A_B (T_B - T_A) + \bar{h}_S A_S (T_S - T_A) \\ & + \bar{h}_{D1} A_{D1} (T_{D1} - T_m) + \bar{h}_{D2} A_{D2} (T_{D2} - T_m) + \bar{h}_{D3} A_{D3} (T_{D3} - T_A) \\ & + \bar{h}_{D4} A_{D4} (T_{D4} - T_A) + \bar{h}_1 A_W (T_{W1} - T_A) + \bar{h}_T A_T (T_T - T_A) \\ & - \dot{m}_{tt} h_{fg} \end{aligned} \tag{27}$$

The above equations represent the energy transfers occurring in the ovens during any time period. In addition to this it is necessary to have an equation from which the steady-state energy rate can be computed for specific values of plant and outside air temperatures. The form of the equation was chosen to make dual calculations of $\dot{E}_{SS}$, the steady-state energy requirements, for comparison to actual operating data.

Figure 8 depicts the steady-state operation of the ovens.

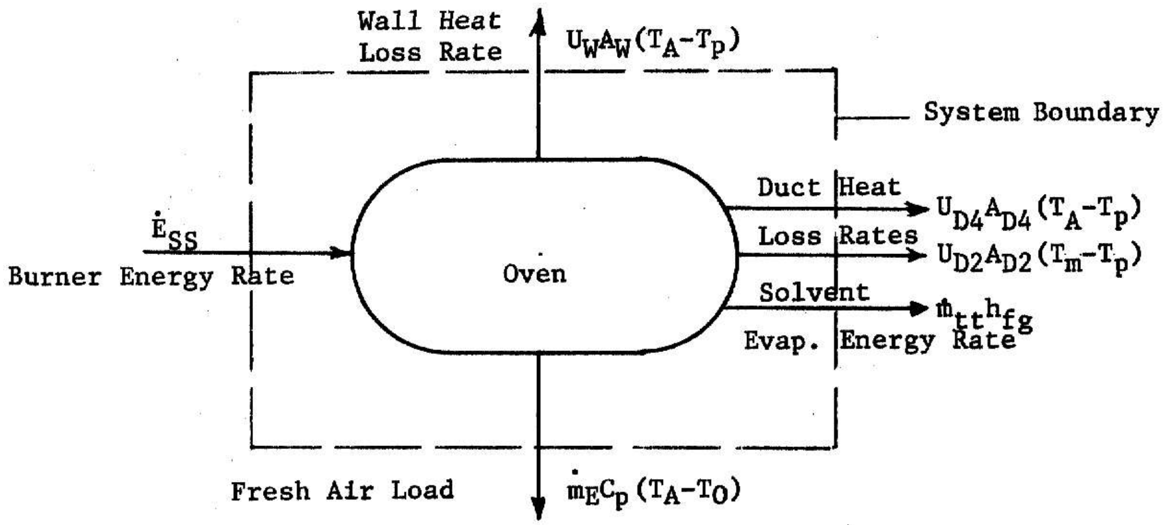


Fig. 8. Steady-State Oven System

The steady-state energy balance is

$$\dot{E}_{SS} = U_W A_W (T_A - T_P) + U_{D2} A_{D2} (T_m - T_P) + U_{D4} A_{D4} (T_A - T_P)$$

$$+ \dot{m}_{tt} h_{fg} + \dot{m}_E C_p (T_A - T_O) \quad . \tag{28}$$

The values for the masses and areas in the model are given in Appendix A. The values for the average convective heat transfer coefficients, thermal capacities, mass flow rates, and resistances are given in Appendix A.

Finite difference equations of the form $\frac{dT}{d\theta} = \frac{T^{+} - T}{\Delta\theta}$ were substituted into the model equations and a simple, total-step, iteration, procedure for calculation was used in the computer program presented in Appendix B. The results were checked for stability and accuracy by a trial run comparison to IBM's Subroutine HPCL. The comparisons revealed only a maximum difference of 3°F.

The next step in the model development was to verify the model results by comparison to actual measured data. This is done in the next chapter.

Chapter V

VERIFICATION OF THE MODEL

After the basic modeling equations were completed, it was necessary to check the accuracy of its results with real data. To do this a test was set up at Fisher Body Flint Plant No. 1. The center zone of a typical reflow oven was selected as the test location to eliminate any end effects in the oven from the plant. The fresh air temperature was recorded and then the burner was shut down simultaneously with the paint line. (Note the exhaust fans are left on to prevent explosive conditions from accumulation of evaporated solvent in the oven). The oven air temperature then was recorded against time, on a Honeywell recorder.

After the oven cooled down for approximately four hours it was reheated. The reheat procedure was to turn the recirculating fans and burners on to their maximum rates simultaneously. The outdoor air temperature entering the burner was recorded and the oven air temperature was again recorded against time.

With the same conditions for T_0 and T_p input into the equations representing the cool down operation, results from the modeling routine were obtained. The measured results and the computed results are presented in Figure 9. The computed results showed reasonable agreement with the experimental data. The greatest deviation being about 9.0°F at 2.3 hours.

The model was also tested for the heat-up conditions used in the plant's test run. The measured and computed results are compared in Figure 10. Again the comparison of results show reasonable agreement. The greatest difference between experimental and model data was 15°F.

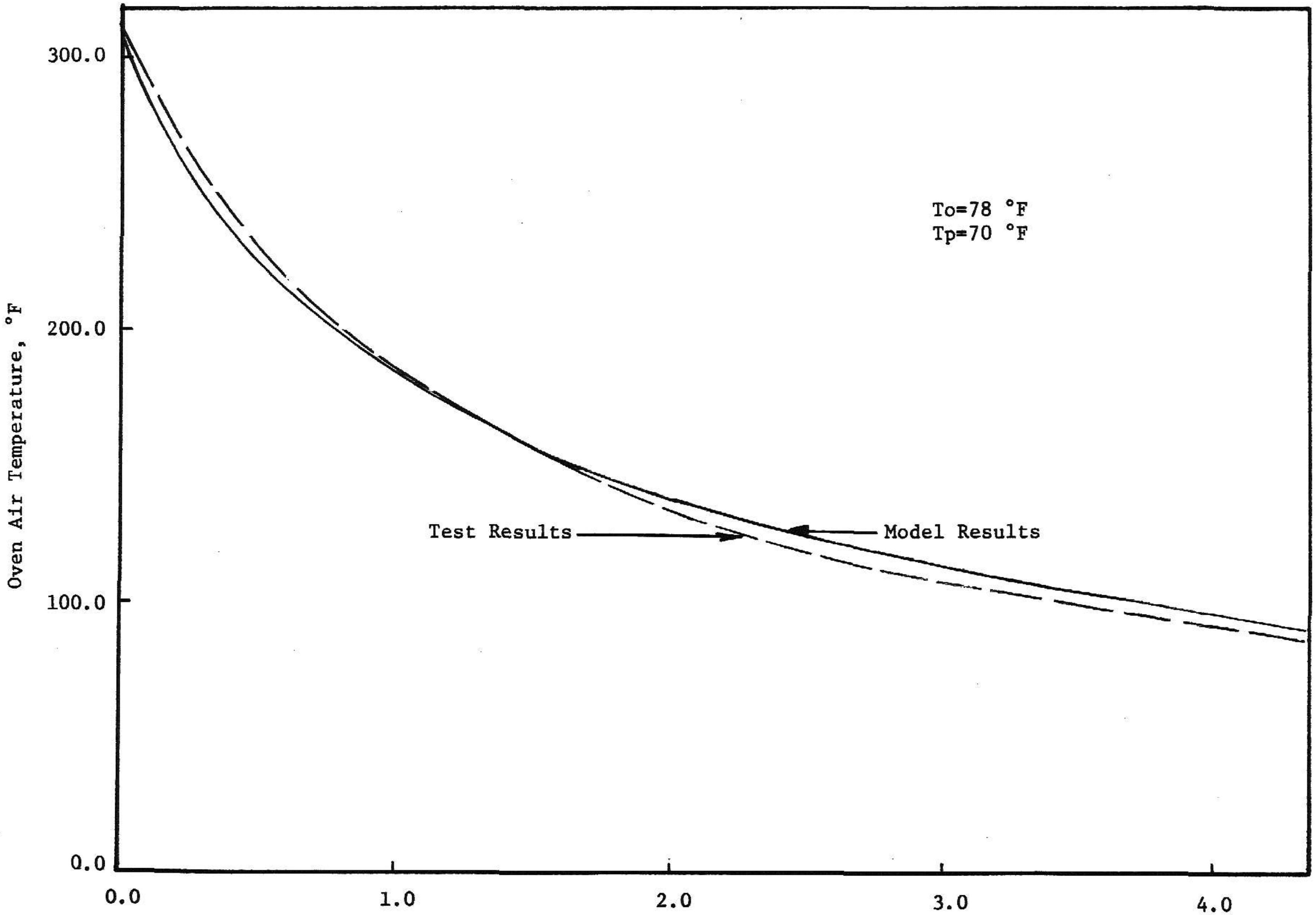


Figure 9. Oven Air Cool-Down Curves

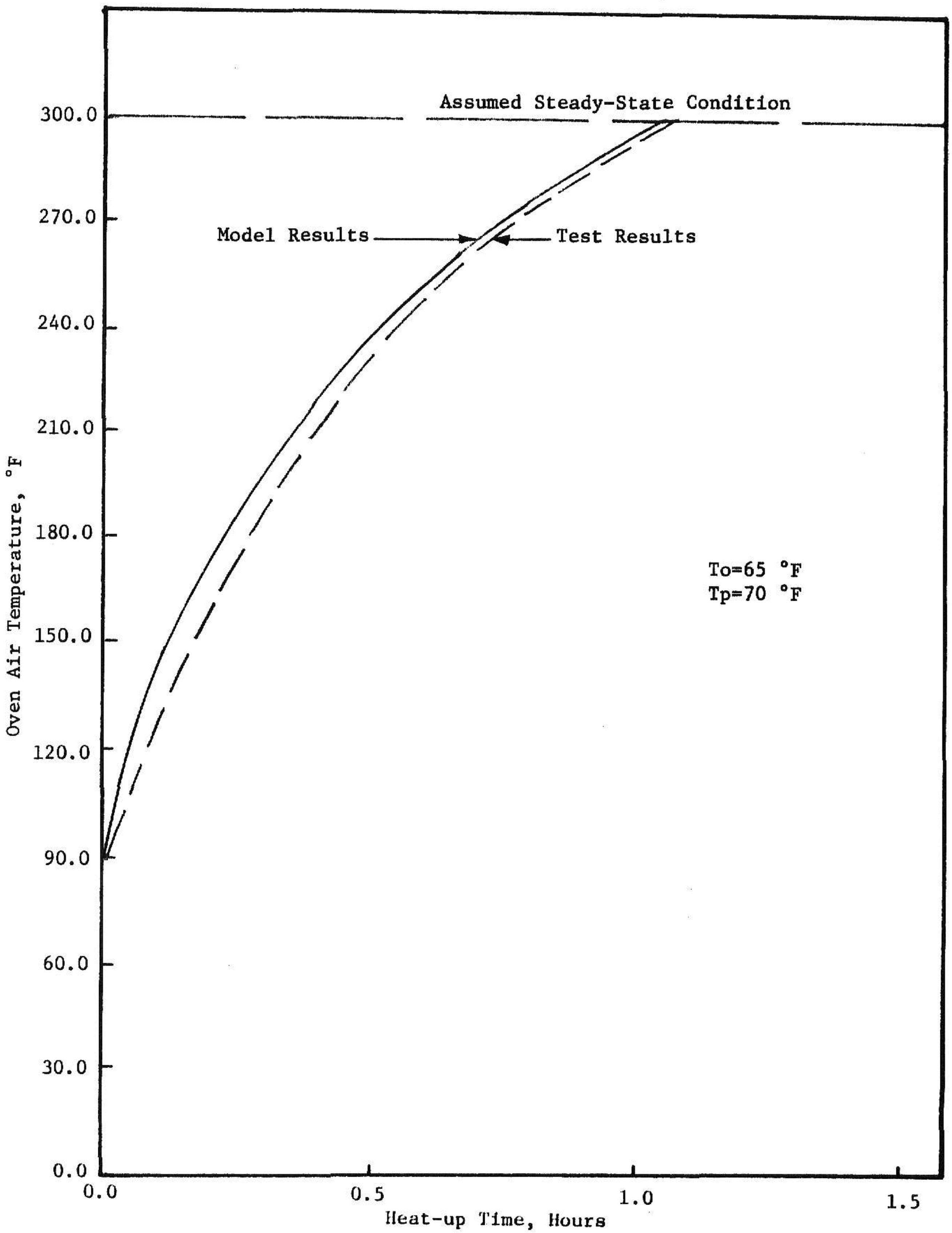


Figure 10. Oven Air Heat-Up Curves

Because of the close comparison of the model results to the measured results, the model and program can now be used with some confidence. The computer model was used to determine the proper time intervals for burner firing and shut off to achieve the minimum energy use during paint line shut down periods. The next chapter of this thesis contains a presentation of the proper control sequence for various outdoor conditions.

Chapter VI

BANG - BANG CONTROL SAVINGS

The model was used for the determination of the proper oven firing rates under a bang-bang control scheme. The first step in the procedure was to determine the appropriate outdoor temperature ranges to be applied. Reasonable time intervals to leave the ovens shut down were also specified.

In Flint, Michigan, the plant location, the outdoor design dry-bulb conditions are -1°F winter and 89°F summer [5]. To effectively cover this entire range, six values of outdoor temperatures were selected: 0°F, 20°F, 40°F, 60°F, 80°F, 100°F.

The burners, at the present time, are manually shut down and fired, even though the operating temperature level is controlled by a proportional, burner, control system. Because of this, the minimum time allowable for a complete shut down was selected as one-half hour. This allows time for the operator to reach the burners from the maintenance shop and have the necessary time to fire an entire oven.

The program was run for two classes of shut downs. In the first class the time duration of shut down is less than one shift (8 hrs); in the second class the shut down period is of sufficient duration for the oven to come to steady-state equilibrium with plant temperature.

The first class of shut downs are short enough to require that the exhaust fans remain on during the entire cool down period. The computer model is applicable exactly as it was written for this type of shut down. For the second class of shut down a modification was made in the program to reduce computer time required for solution. Instead of running the cool down routine to equilibrium (plant conditions) and then reheating, the plant equilibrium temperatures were input as initial conditions into the heat-up routine and it was run separately to the assumed line start-up temperature of 300°F where the proportional controller takes over.

Class I Shut Downs

For the first class of shut downs, time intervals for burner shutdown were selected as 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 hours. The model was run for the six outdoor temperatures selected and the results are presented in Figures 11 and 12.

Figure 11 shows the proper burner down times for maximum energy savings for specified fresh air temperatures. It contains burner shut down time specifications for production line down-periods of up to five hours.

Figure 12 represents the dollar savings gained under the same burner down condition as used in Figure 11. These savings were computed on a basis of 65.8 cents per million BTU of natural gas [6]. Total savings also include the savings in electrical power resulting from shutting down the recirculating fan during periods of burner shut down. This figure can be utilized by the oven maintenance operator to determine if the predicted savings are great enough to justify the manpower required to kill and re-fire the burners.

Class II Shut Downs

The savings from shutting down the burners are plotted in Figure 13 as a function of outside air temperature and the total time the line is shut off. The resulting savings are also based on a energy cost of 65.8

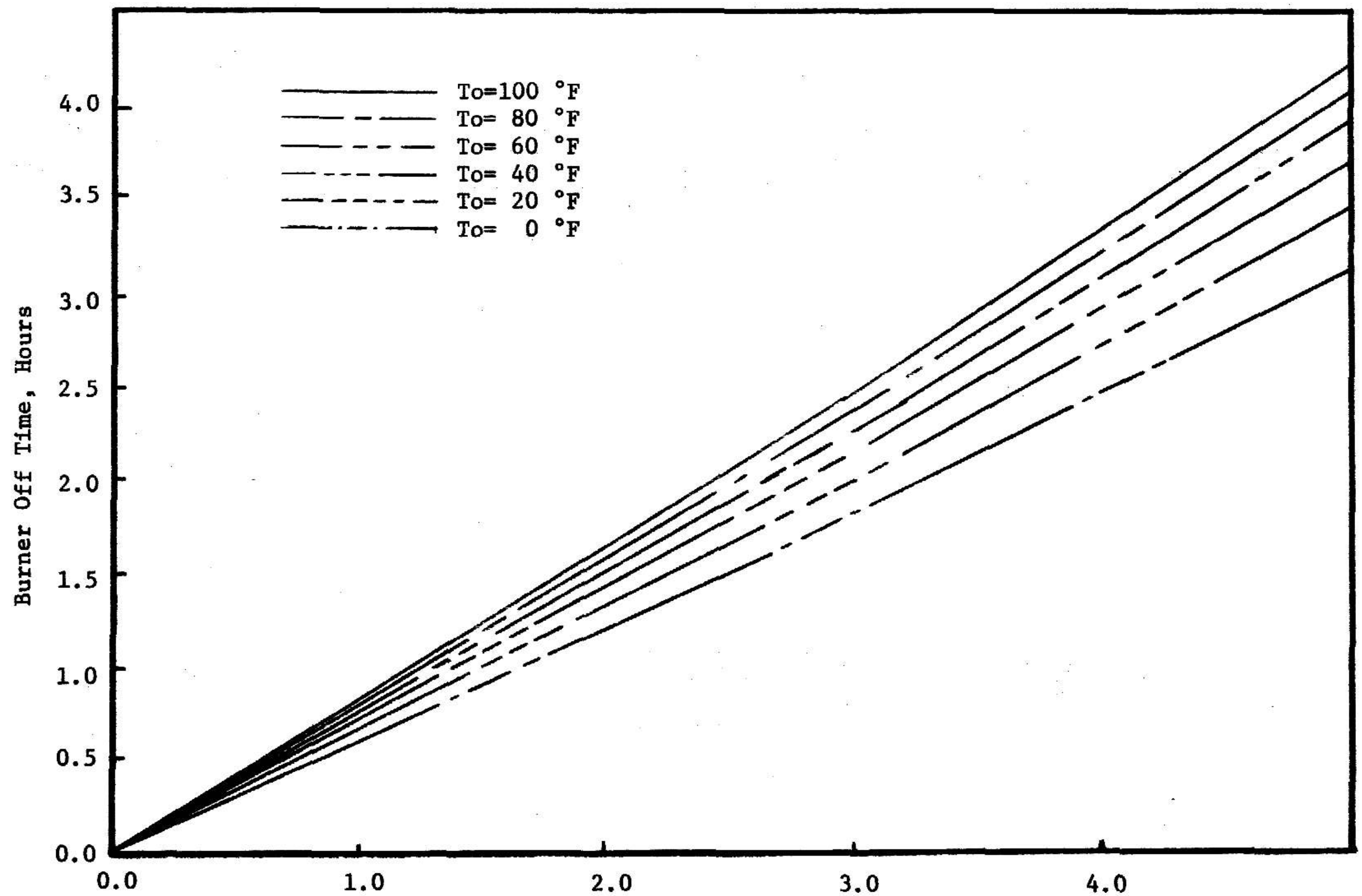


Figure 11. Class I Shut-Down Times

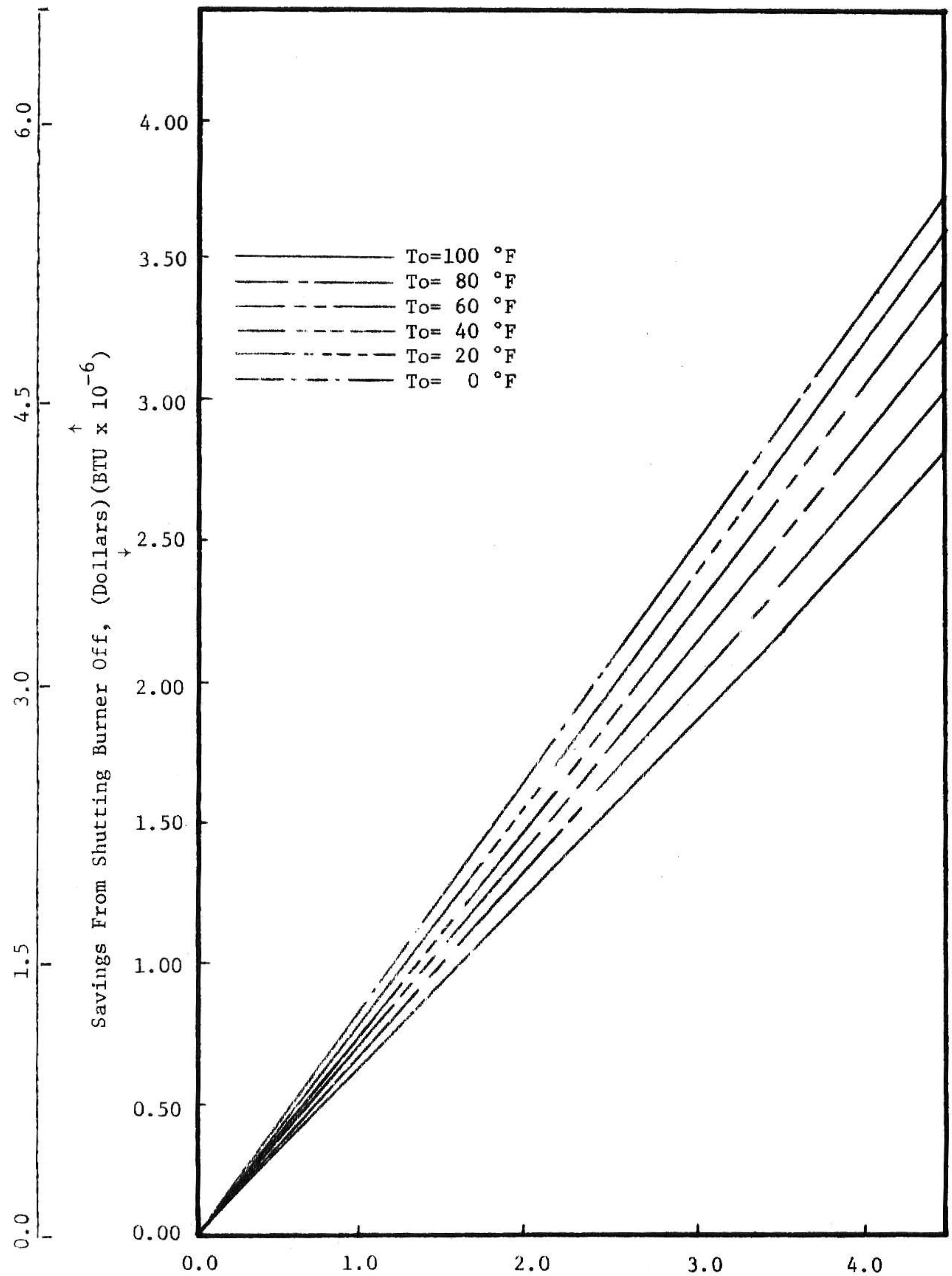


Figure 12. Class I Shut-Down Savings

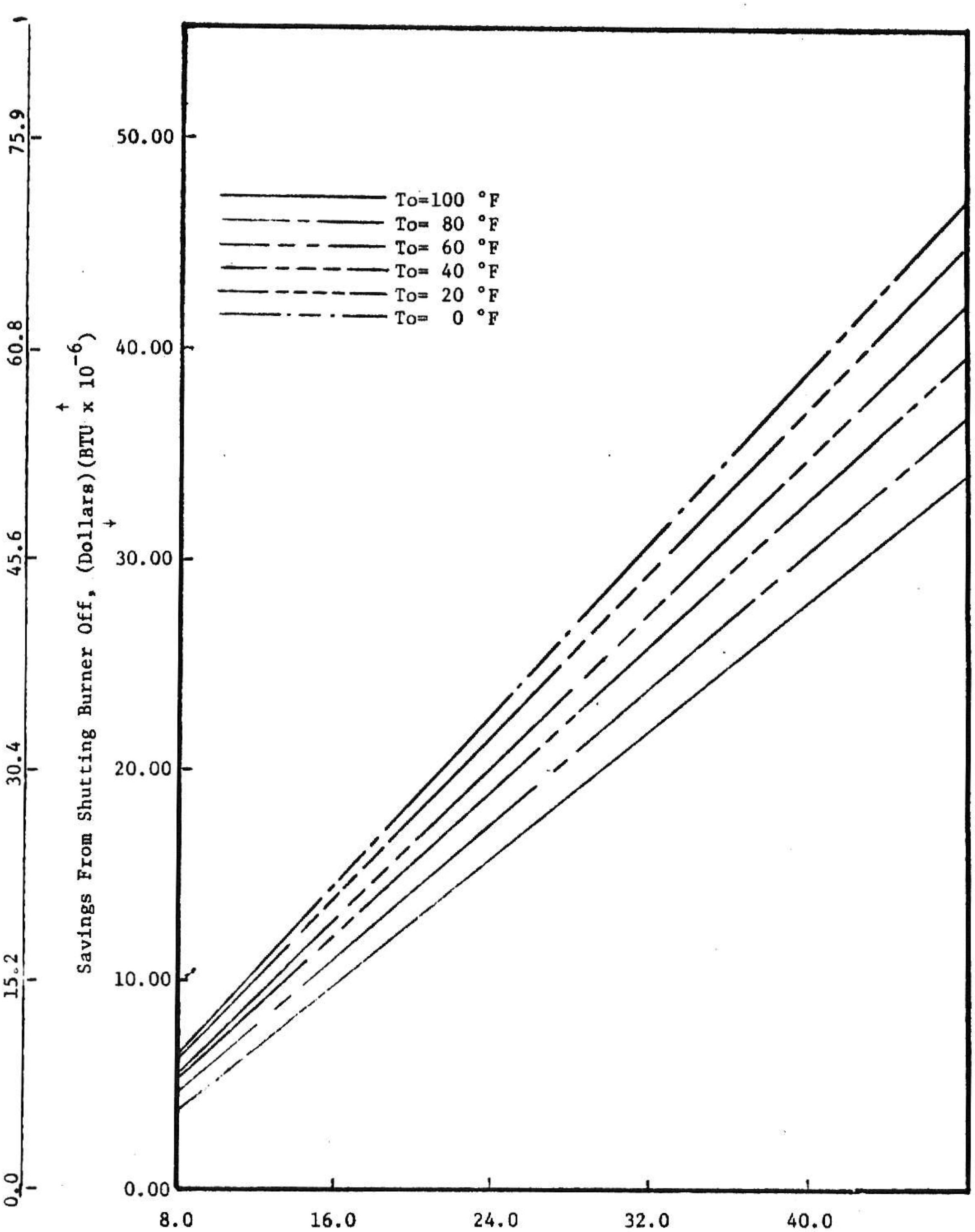


Figure 13. Class II Shut-Down Savings

cents per million BTU's and are expressed as dollar savings over leaving the ovens running at steady-state. The large savings are due to the long time periods of shut down and short periods of heat-up as shown in Figure 14.

To get some idea of the magnitude of the savings involved, the case of one eight hour shutdown per day was considered. Using a base of 234 working days per year and a savings of five dollars per day per burner, the yearly savings amounts to $1,170. This represents an energy savings of 1,778 million BTU of fuel.

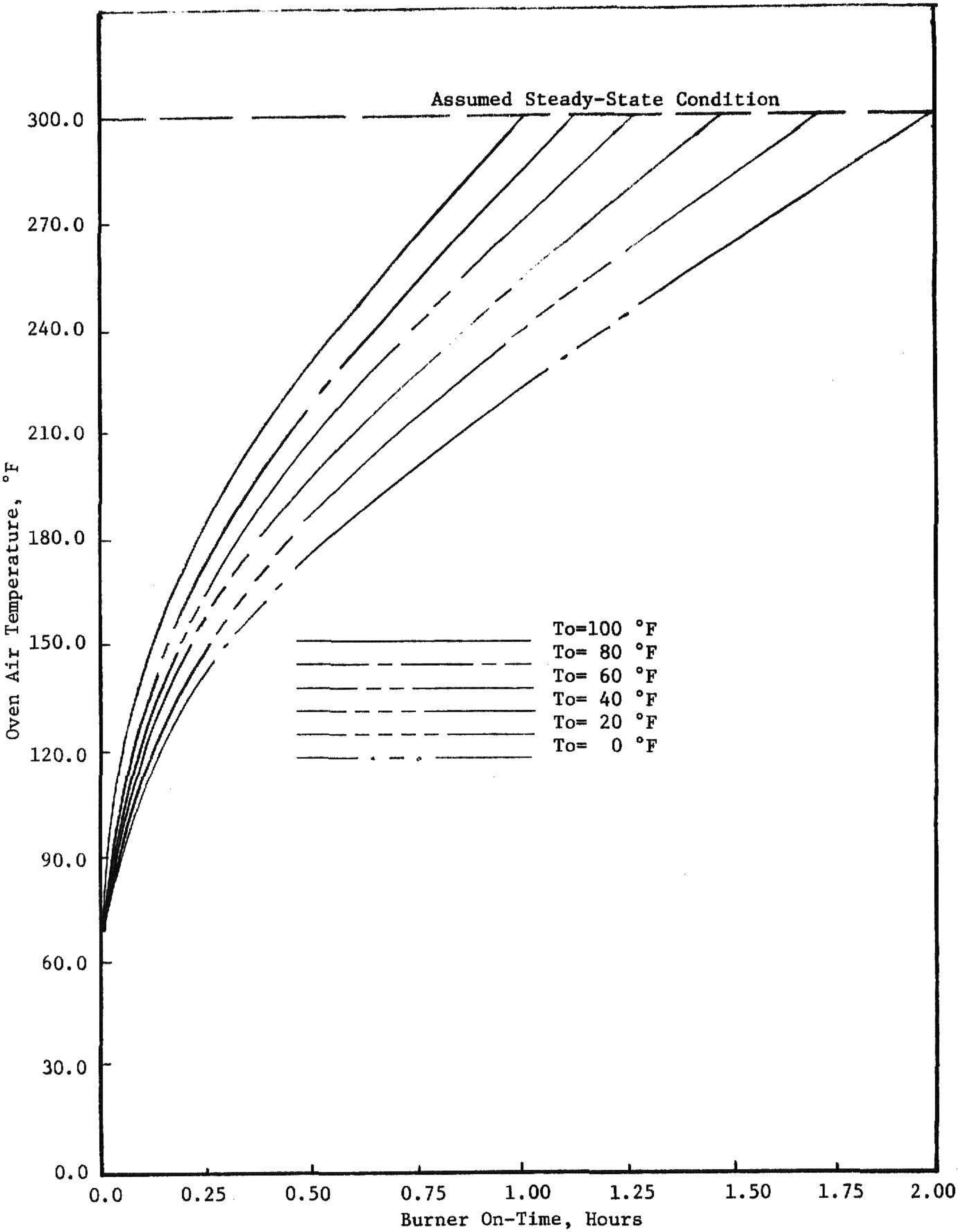


Figure 14. Class II Heat-Up Times

Chapter VII

WASTE HEAT RECOVERY

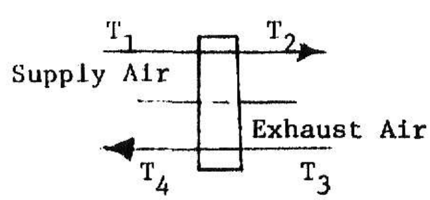
The feasibility of saving energy by using waste heat recovery is determined primarily by three factors. First, the cost of buying the heat exchangers, revising the existing ductwork, and increasing fan static pressure must be evaluated. Secondly, the chemical nature of the exhaust gases and their condensation properties must be examined to determine if any scrubbing is necessary. Finally, the yearly energy savings due to recovery must be computed and compared to the cost of the first two factors to make certain that an economic benefit results.

Rotary regenerative equipment was chosen for evaluation of the heat reclaim process. The rotary equipment generally has a lower initial cost than a heat pipe system [7] and its operational characteristics are suitable for the service contemplated here.

Each zone in the oven, when operating at steady-state, has an exhaust air rate of approximately 5000 cfm at 315°F. No latent heat transfer was considered due to the low moisture content of the air at this temperature. Typically a nonhygroscopic, metallic regenerator for this quantity of air will be approximately five feet square by two feet deep, and weighs around 2500 pounds [7].

To operate at maximum efficiency, the units are set-up for counter flow heat transfer. In the counter flow arrangement, efficiencies usually fall in the range of 65 to 85% [7]. Regenerator efficiency is defined in the following manner:

$$N = \frac{(T_1 - T_2)}{(T_1 - T_3)} \; ; \quad \text{where} \qquad (30)$$



The pressure drop across the exchanger was also included in the evaluation. For air velocities of 500 fpm the pressure drop across the units will generally range from 0.5 to 0.8 inches of water [7].

It was necessary to find average monthly temperature values for use in computing an average monthly savings gained by using the regenerators. The data in Table 1 represents the average degree days for the area, per month, which were used in the calculations [8].

Table 1. Average monthly degree day values.

Jan.	Feb.	March	April	May	June
1218	1080	861	531	259	73

July	Aug.	Sept.	Oct.	Nov.	Dec.
73	95	95	337	712	1116

With the information above, the average monthly temperature values were computed by the following formula and are presented in Table 2.

$$t\ avg = 65. - \frac{DD}{DM} \tag{31}$$

where DD = degree days
DM = days in the month
t avg = average temperature for the month

Using the average outdoor temperature values in equation 28, which gives the steady-state energy requirements without regeneration, the average monthly burner energy costs were calculated. The results are presented in Table 2.

Table 2. Average Monthly Energy Savings Per Zone with Waste Heat Utilization

Month	Avg. T_O No Preheat °F	$\hat{E}_{SS}$ x 10^{-6} Btu/hr	Btu/mo. x 10^{-6}	Dollar Cost	Avg. T_O Preheat °F	$\hat{E}_{SS}$ x 10^{-6} Btu/hr	Btu/mo. x 10^{-6}	Dollar Cost	Monthly Savings $
January	25.7	1.42	545.3	$ 358	242.6	.68	261.1	$ 172	$ 186
February	26.4	1.42	447.6	314	242.8	.68	228.5	150	164
March	37.2	1.37	526.1	346	245.5	.66	253.4	167	179
April	41.3	1.32	485.8	320	248.1	.65	239.2	157	163
May	56.5	1.28	491.5	323	250.4	.63	241.9	159	164
June	62.5	1.26	463.7	305	251.8	.62	228.2	150	155
July	62.6	1.26	483.8	318	251.9	.62	238.1	157	161
August	61.9	1.26	483.8	318	251.7	.62	238.1	157	161
September	61.8	1.26	463.7	305	251.6	.62	228.2	150	155
October	54.1	1.29	495.4	326	249.7	.63	241.9	159	167
November	41.2	1.35	496.8	327	246.5	.66	242.8	159	168
December	29.0	1.41	541.4	356	243.5	.66	253.4	167	189
				$3916				$1904	

Total Avg. Year Savings = $2012

Base 384 Hrs/31 day mo.
368 hrs/30 day mo.
336 hrs/28 day mo.

Assume 16 hour/day operation

Using a regenerator efficiency of 75% and equation 30, the preheated outdoor air temperatures were calculated for the design temperatures from Table 2. These are presented in Table 2.

The steady state energy requirements were determined by using the preheated outdoor air temperatures in equation 28. These are also presented in Table 2. The difference between the two steady-state energy requirements represents the savings by using regeneration for each zone in the oven. Using a value of 65.8 cents per million BTU's the dollar savings were computed and are presented in Table 2. The total annual savings amounted to $2,012 (3057 million BTU's per year).

Extensive ductwork revision must be undertaken for inclusion of regenerators in the existing ovens. These revisions are impossible to estimate without being able to obtain local conditions and local costs. However, for complete economic justification, these capital costs must be less than the anticipated fuel savings.

It is important to remember that inclusion of the heat recovery system will modify the response times calculated earlier for the various outside air temperatures. Because of regenerator use, the fresh air temperature would increase at a rate proportional to the increase in oven air temperature. With the increased fresh air temperature faster rise in oven air temperature would occur. This would reduce the length of heat-up interval, which according to equation 4, would cause the system to move to a higher level of energy savings. Determination of these savings and of the modified oven response were not treated numerically in this study.

Chapter VIII

RECOMMENDATIONS AND CONCLUSION

It has been shown that substantial energy savings will result from the proper use of oven on-off sequences and from waste heat utilization. The dollar savings based on a single zone, obtained by shutting down the burner during line shut downs, were found to be rather low, ranging up to $3.50 for 4 hour burner off times. The shut off procedures do, however, provide a means of reducing the amount of fuel required. This is becoming a critical factor for an industry faced with fuel rationing.

Application of the waste heat recovery system was shown to result in significant dollar savings. Again there is a need to emphasize the fact that the fuel savings by the regenerators may be offset to some extent by the capital investment to buy and install the equipment, plus a small expenditure to operate its control and power system. These two factors do not, however, rule out its future potential. As in the case of oven on-off control the increasing cost of fuel is not the only factor to be considered. The availability of heating fuel is decreasing rapidly, and all possible measures should be used to reduce its consumption.

The "energy crisis" is very real and its presence is being felt more and more everyday. A strong effort needs to be put forth to reduce energy consumption by all segments of society.

This thesis represents an example of the type of analysis of past practice which will be required of all energy consuming processes. The total energy savings are shown to be relatively small because total energy use is small for this system. The techniques of analysis and modeling, however, are appropriate to similar systems, regardless of size for future analysis purposes.

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APPENDICES

Appendix A

NUMERICAL PARAMETER VALUES

VALUES OF MODEL PARAMETERS PER 120 FEET OVEN ZONE

The following values for the masses of the oven and its components were calculated from specifications on the construction prints of the ovens. All values used in the program are based on a typical zone 120 feet long. All masses were calculated with the following equation:

$$m = \rho V \text{ ; where } \quad \rho = \text{density of component } (lb/ft^3)$$
$$V = \text{volume of component } (ft^3)$$

For the steel components $\rho = 489.\ lb/ft^3$ [9]. For air the density was calculated as a function of air temperature with a base temperature of 315°F $\rho_A = .075\ lb/ft^3 \left(\frac{775.}{TA + 460.}\right)$. For the fiberglass in the walls the density was given by the manufacturer, $\rho_f = 9.0\ lb/ft^3$.

$m_A = \left(\frac{467,261.25}{TA + 460.}\right)$ lb

$m_{W1} = m_{W5} = 7768.$ lb

$m_{W2} = m_{W3} = m_{W4} = 4750.$ lb

$m_{D1} = 2136.$ lb

$m_{D2} = 396.$ lb

$m_{D3} = 1962.$ lb

$m_{D4} = 234.$ lb

$m_T = 10,702.$ lb

$m_S = 10,469.$ lb

$m_B = 5189.$ lb

The mass flow rate of the outdoor air which is equal to the mass flow rate of the exhaust air from the oven has a different value for heat-up and cool-down conditions. This is due to the change in system resistance the exhaust fan experiences when the recirculating fan is on.

The following figure shows the system resistance curves for the two cases mentioned above.

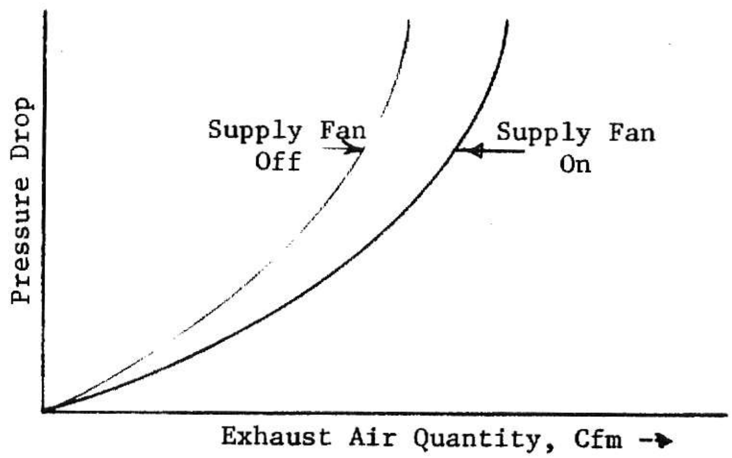

Fig. 15. Exhaust System Resistance Curves

Both curves show the same characteristic parabolic shape. The value for the exhaust air flow rates are determined by superimposing the proper fan characteristic curve over the two resistance curves. The ratio of mass flow rate for outside air can vary from ≃ 1:1 to 3:1 (supply fan on $\dot{m}_o$:supply fan off $\dot{m}_o$) depending the exact system operating point on the fan curve. The value selected for this thesis was 2:1. The results obtained agree reasonably well with experimental data thereby providing some justification for its use.

The surface areas for the various oven components were taken off the construction prints from a typical oven and are listed below:

1) $A_w = 4902.\ ft^2$
2) $A_{D1} = 1428.\ ft^2$
3) $A_{D2} = 264.\ ft^2$
4) $A_{D3} = 1308.\ ft^2$
5) $A_{D4} = 156.\ ft^2$
6) $A_B = 4790.\ ft^2$
7) $A_S = 1098.\ ft^2$
8) $A_T = 909.\ ft^2$

The values for the specific heats of the oven components were obtained from reference [10]. The specific heat of the air at constant pressure Cp = 0.24 Btu/lb-°F. The values of specific heat for the metallic oven components were found to be C = 0.12 Btu/lb-°F. The value of the specific heat for the fiberglass layers in the walls of the oven was given by the manufacturer C_f = 0.24 Btu/lb-°F. Also included from the manufacturer was the thermal resistance value for the fiberglass rated from 200°F to 400°F which was K_f = 0.30 Btu-in/hr-°F-ft^2.

The average heat transfer coefficients were determined for the components exposed to the oven air with recirculating fans on and again with the recirculating fans turned off. With the fans turned off the values for the components in the oven were selected at 1.1 Btu/hr-°F-ft^2. This is a value typical for combined forced and free convection from flat plates for very low velocities [11].

The value selected for the condition when the recirculating fans were on was 3.3 Btu/hr-ft^2-°F. Again in this case an actual value would be practically impossible to determine because of the complex component shapes and air flow patterns. This value is however, reasonable when compared to the value at the lower flow rate and typical values listed in reference [11]. Some justification of the choice is provided by the fact that the chosen values caused the model to fit the actual data very closely.

The average heat transfer coefficients for the surfaces exposed to plant air were chosen at the still air value of 1.65 Btu/hr-ft^2-°F as given in reference [11].

Appendix B

COMPUTER PROGRAM AND SAMPLE OUTPUT

ILLEGIBLE DOCUMENT

THE FOLLOWING DOCUMENT(S) IS OF POOR LEGIBILITY IN THE ORIGINAL

THIS IS THE BEST COPY AVAILABLE

```
$JOB            ,TIME=45
C     THIS PROGRAM  IS A SIMULATION OF THE TRANSIENT THERMAL HEAT
C     RESPONSE IN THE HEAT-UP AND COOL DOWN OF A MODERN GAS FIRED
C     AUTOMOBILE BODY PAINT DRYING OVEN.  THE HEAT INPUT IS SET BY
C     OPERATOR AND CAN BE VARIED BY MEANS OF AN INTERNAL ROUTINE
C     IN THE MAIN PROGRAM.  THE PROGRAM UTILIZES THE NUMERICAL
C     INTEGRATION TECHNIQUE FOR SOLVING A SET OF THIRTEEN SIMULTANEOUS
C     LINEAR DIFFERENTIAL EQUATIONS WITH CONSTANT COEFFICIENTS.
      WRITE(6,200)
  200 FORMAT('1',T4,'TB',T12,'TW1',T20,'TW2',T28,'TW3',T36,'TW4',T44,
     1'TW5',
     1T52,'TS',T60,'TD1',T68,'TD2',T76,'TD3',T84,'TD4',T92,'TT',T100,
     1'TA',
     1T108,'TP',T116,'TIME')
C     SET THE VARIABLE DT TO ANY VALUE LESS THAN 1/300. THIS IS THE
C     INTEGRAL STEP SIZE.
      DT=1./1000.
C     X IS THE TIME COUNTER IN THE PROGRAM.
      X=1.
C     R IS A DUMMY VARIABLE TO TELL THE PROGRAM WHEN TO PRINT.
      R=0.0
C     NOW INPUT THE INITIAL CONDITIONS FOR THE BEGINING OF THE RUN.
      TIME=0.
      S=1.
      TP=70.
      TO=40.
C     THE NEXT STATEMENT COMPUTES THE STEADY-STATE ENERGY VALUE.
      EDSS=1538482.-4518.*TO
      ED=2100000.
      TA=315.
      TW1=306.51688
      TW2=268.90655
      TW3=193.5069
      TW4=118.1038
      TW5=80.49547
      X3=ED/27540.+.76*TA+.24*TO
      TM=X3
      TD1=TM-.5*(TM-TA)
      TD2=TM-.55303*(TM-TP)
      TD3=315.
      TD4=315.
      TS=315.
      TT=315.
      TB=315.
      ED=0.
C     THE NEXT SET OF VARIABLES REPRESENT THE VARIOUS HEAT TRANSFER
C     COEFFIENTS IN THE OVEN THESE SHOULD NOT BE CHANGED.
C     HB IS THE VALUE FOR THE BODY FILM COEFFICIENT.
      HB=1.1
C     HS IS THE COEFFICIENT FOR THE INTERNAL SUPPORTING STEEL.
      HS=1.1
C     HT IS THE COEFFICIENT FOR THE BODY-CARRYING TRUCKS.
      HT=1.1
C     HI IS THE COEFFICIENT FOR THE INTERIOR OF THE WALLS.
      HI=1.1
C     HD1 IS THE COEFFICIENT FOR THE SUPPLY DUCT IN THE OVEN.
      HD1=1.1
C     HD2 IS THE COEFFICIENT FOR THE SUPPLY DUCT IN THE PLANT.
      HD2=1.1
C     HD3 IS THE COEFFICIENT FOR THE RETURN DUCT IN THE OVEN.
```

```
      HD3=1.1
      AB=4709.2
      WB=5189.1
      CB=.12
      R2=.30
      AW=4902.
      CW1=.12
      T1=1.33/2.
      WW1=7768.5
      CW2=.24
      WW2=4750.
      T=1.33
      H2=1.65
      AS=1098.
      WWS=10469.
      AD1=1428.
      WD1=2136.
      AD2=264.
      WD2=346.
      HD2P=1.65
      AD3=1308.
      WD3=1962.
      AT=909.1
      WT=10702.
      CP=.24
      AD4=156.
    2 A1=((HB*AB)/(WB*CB))*DT
      A3=((R2*AW)/(CW1*T1*WW1))*DT
      A4=((H1*AW)/(WW1*CW1))*DT
      A5=((R2*AW)/(T1*CW2*WW2))*DT
      A7=((R2*AW)/(T*CW2*WW2))*DT
      A9=((H2*AW)/(WW1*CW1))*DT
      A10=((HS*AS)/(WWS*CW1))*DT
      A11=((HD1*AD1)/(WD1*CW1))*DT
      A13=((HD2*AD2)/(WD2*CW1))*DT
      A14=((HD2P*AD2)/(WD2*CW1))*DT
      A15=((HD3*AD3)/(WD3*CW1))*DT
      A16=((HT*AT)/(WT*CW1))*DT
      A12=A13+A14
      A8=A9+A3
      A6=A5+A7
      A2=A3+A4
C     THE FOLLOWING THIRTEEN EQUATIONS ARE THE MODEL  FOR THE OVEN.
      WRITE(6,150)TB,TW1,TW2,TW3,TW4,TW5,TS,TD1,TD2,TD3,TD4,TT,TA,TM,
     1 TIME
  150 FORMAT(15F8.3)
   20 TBN=A1*TA-(A1-1.)*TB
      TZ=TA+460.
      WA=467261.25/TZ
      A17=WA*CP
      WOD=14596200./TZ
      WOD=WOD/2.
      TM=TO
      TW1N=-(A2-1.)*TW1+A3*TW2+A4*TA
      TW2N=A5*TW1-(A6-1.)*TW2+A7*TW3
      TW3N=A7*TW2-(A5-1.)*TW3+A7*TW4
      TW4N=A7*TW3-(A6-1.)*TW4+A5*TW5
      TW5N=A3*TW4-(A8-1.)*TW5+A9*TP
      TSN=-(A10-1.)*TS+A10*TA
      TD1N=-(A11*2.-1.)*TD1+A11*TM+A11*TA
```

```
      TD2N=-(A12-1.)*TD2+A13*TM+A14*TP
      TD3N=-(A15-1.)*TD3+A15*TA
      TD4N=-(A12-1.)*TD4+A13*TA+A14*TP
      TTN=-(A16-1.)*TT+A16*TA
      TNA=(DT/A17)*(HB*AB*TB+H1*AW*TW1+HS*AS*TS+HD1*AD1*TD1+
     1HD2*AD2*TD2+HD3*AD3*TD3+HD2*AD4*TD4+HT*AT*TT)
     1+DT*((WOD/VA)*TO-3.05*126.)
     1+(1./A17)*ED*DT-(A11+A13)*TM-(((WOD*CP+H1*AW+HB*AB+HS*AS+
     1HD3*AD3+HD2*AD4+HT*AT)*(DT/A17))-1.)*TA
      TM=TO
      R=1.+R
      X=1.+X
      TIME=DT*X
C     THE NEXT IF STATEMENT SETS THE NUMBER OF HEAT-UP RUNS IN THE
C     PROGRAM.  THESE ARE TO BE SET BY THE OPERATOR.
      IF(S-11.)9,10,10
    9 IF(TIME-.5*S)3,6,6
C     NOW THE HEAT-UP ROUTINE IN THE PROGRAM BEGINS.
    6 Y2=TBN
      Y1=TIME
      Y3=TW1N
      Y4=TW2N
      Y5=TW3N
      Y6=TW4N
      Y7=TW5N
      Y8=TSN
      Y9=TD1N
      Y10=TD2N
      Y11=TD3N
      Y12=TD4N
      Y13=TTN
      Y14=TNA
      Y15=X
      Y16=TM
      Y17=TO
      Y18=TP
      Y19=R
      Y30=H1
      Y31=HB
      Y32=HS
      Y35=HD1
      Y36=HD3
      Y37=HT
      Y38=HD2
      WRITE(6,300)TBN,TW1N,TW2N,TW3N,TW4N,TW5N,TSN,TD1N,TD2N,TD3N,TD4N,
     1TTN,TNA,TM,TIME
  300 FORMAT(15F8.3)
      WRITE(6,160)
  160 FORMAT('0',T40,'HEAT-UP BEGINS HERE')
C     THE VALUE FOR ED IS SET BY THE OPERATR AND MAY BE A FUNCTION OF
C     TIME.
      ED=2100000.
      HB=3.3
      HS=3.3
      H1=3.3
      HD1=3.3
      HD2=3.3
      HD3=3.3
      HT=3.3
      A1=((HB*AB)/(WB*CB))*DT
```

```
      A3=((R2*AW)/(CW1*T1*W1))*DT
      A4=((H1*AW)/(W1*CW1))*DT
      A5=((R2*AW)/(T1*CW2*W2))*DT
      A7=((R2*AW)/(T*CW2*W2))*DT
      A9=((H2*AW)/(W1*CW1))*DT
      A10=((HS*AS)/(WS*CW1))*DT
      A11=((HD1*AD1)/(WD1*CW1))*DT
      A13=((HD2*AD2)/(WD2*CW1))*DT
      A14=((HD2P*AD2)/(WD2*CW1))*DT
      A15=((HD3*AD3)/(WD3*CW1))*DT
      A16=((HT*AT)/(WT*CW1))*DT
      A12=A13+A14
      A8=A9+A3
      A6=A5+A7
      A2=A3+A4
      R=0.
    4 TA=TAN
      TW1=TW1N
      TW2=TW2N
      TW3=TW3N
      TW4=TW4N
      TW5=TW5N
      TS=TSN
      TD1=TD1N
      TD2=TD2N
      TD3=TD3N
      TD4=TD4N
      TT=TTN
      TA=TNA
      TZ=TA+460.
      WA=46721.25/TZ
      A17= A*CP
      WOD=145262.0/TZ
      TAN=A1*TA-(A1-1.)*TA
      TM=E0/WOD+.76*TA+.24*TU
      TW1N=-(A2-1.)*TW1+A3*TW2+A4*TA
      TW2N=A5*TW1-(A6-1.)*TW2+A7*TW3
      TW3N=A7*TW2-(A5-1.)*TW3+A7*TW4
      TW4N=A7*TW3-(A6-1.)*TW4+A5*TW5
      TW5N=A3*TW4-(A8-1.)*TW5+A9*TP
      TSN=-(A10-1.)*TS+A10*TA
      TD1N=-(A11*2.-1.)*TD1+A11*TM+A11*TA
      TD2N=-(A12-1.)*TD2+A13*TM+A14*TP
      TD3N=-(A15-1.)*TD3+A15*TA
      TD4N=-(A12-1.)*TD4+A13*TA+A14*TP
      TTN=-(A16-1.)*TT+A16*TA
      TNA=(DT/A17)*(HB*AB*TB+H1*AW*TW1+HS*AS*TS+HD1*AD1*TD1+
     1HD2*AD2*TD2+HD3*AD3*TD3+HD2*AD4*TD4+HT*AT*TT)
     1+DT*((WOD/WA)*T0-3.05*126.)
     1+(1./A17)*E0*DT-(A11+A13)*TM-(((WOD*CP+H1*AW+HB*AB+HS*AS+
     1HD3*AD3+HD2*AD4+HT*AT)*(DT/A17))-1.)*TA
      R=1.+R
      X=1.+X
      TIME=DT*X
C     TEST IF THE OVEN HAS REACHED THE DESIRED HEAT-UP CONDITION.
      IF(TNA-300.)69,8,8
   69 IF(R-100.)4,5,5
    5 WRITE(6,900)TAN,TW1N,TW2N,TW3N,TW4N,TW5N,TSN,TD1N,TD2N,TD3N,TD4N,
     1TTN,TNA,TM,TIME
  900 FORMAT(15F8.3)
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```
      R=0.
      GO TO 4
C     COMPUTE THE COST TO HEAT THE OVEN UP AND ALSO THE COST TO
C     HOLD THE OVEN AT THE STEADY-STATE CONDITION.
    8 WRITE(6,900)TBN,TW1N,TW2N,TW3N,TW4N,TW5N,TSN,TD1N,TD2N,TD3N,TD4N,
     1TTN,TNA,TM,TIME
      BTUH=ED*(TIME-Y1)
      BTUR=EDSS*TIME+50902.*TIME
      SAVE=BTUR-BTUH
      SAVP=(SAVE/BTUR)*100.
      WRITE(6,220)SAVP
  220 FORMAT('0',T4,'THE PERCENT STEADY-STATE ENERGY SAVED=',F7.2)
      WRITE(6,210)BTUH,BTUR,SAVE
  210 FORMAT('0',T4,'BTUS TO HEAT-UP=',E16.8,T45,'BTUS TO HOLD=',
     1E16.8,T80,'BTUS SAVED=',E16.8)
C     COMPUTE THE PERCENT SAVINGS TO  SHUT DOWN THE OVEN.
      DOLS=.658*(SAVE/1000000.)
      WRITE(6,290)DOLS
  290 FORMAT('0',T4,'THE SAVINGS BY COOLING DOWN THE OVEN=$',F10.2)
C     RESET THE INITIAL CONDIONS IN THE PROBLEM TO THE VALUE THEY
C     WERE WHEN HEAT-UP WAS STARTED.
      ED=0.
      TIME=Y1
      TB=Y2
      TW1=Y3
      TW2=Y4
      TW3=Y5
      TW4=Y6
      TW5=Y7
      TS=Y8
      TD1=Y9
      TD2=Y10
      TD3=Y11
      TD4=Y12
      TT=Y13
      TA=Y14
      X=Y15
      TM=Y16
      TO=Y17
      TR=Y18
      R=Y19
      H1=Y30
      HA=Y31
      HS=Y32
      HD1=Y35
      HD3=Y36
      HT=Y37
      HD2=Y38
      S=S+1.
      WRITE(6,140)S
  140 FORMAT('1',T40,'RETURN TO COOLING',T65,'S=',F5.2)
      WRITE(6,400)
  400 FORMAT('0',T4,'TB',T12,'TW1',T20,'TW2',T28,'TW3',T36,'TW4',T44,
     1'TW5',
     1T52,'TS',T60,'TD1',T68,'TD2',T76,'TD3',T84,'TD4',T92,'TT',T100,
     1'TA',
     1T108,'TM',T116,'TIME')
      GO TO 2
    3 IF(R-100.)140,50,50
   50 WRITE(6,100)TBN,TW1N,TW2N,TW3N,TW4N,TW5N,TSN,TD1N,TD2N,TD3N,TD4N,
```

```
     1TTW,TWA,TM,TIME
 100 FORMAT(15F8.3)
     R=0.
  40 TW=TWN
     TW1=TW1N
     TW2=TW2N
     TW3=TW3N
     TW4=TW4N
     TW5=TW5N
     TS=TSN
     TD1=TD1N
     TD2=TD2N
     TD3=TD3N
     TD4=TD4N
     TT=TTN
     TA=TNA
C    TEST IF THE OVEN HAS COOLED PAST THE DESIRED STOPPING POINT.
     IF(TA-70.)10,10,20
  10 CONTINUE
     STOP
     END

$ENTRY
```

SAMPLE OUTPUT

TB	TW1	TW2	TW3	TW4	TW5	TS	TD1	TD2	TD3	TD4	TT	TA	TM	TIME
315.000	306.517	268.908	193.506	118.104	80.495	315.000	322.526	166.236	315.000	315.000	315.000	315.000	330.052	0.000
300.648	293.648	267.825	193.472	115.106	80.383	312.820	217.546	91.786	305.622	191.081	313.217	278.631	60.000	0.1[illegible]1
282.360	279.148	264.594	193.249	118.086	80.344	308.822	179.539	71.529	287.602	158.000	309.918	261.029	60.000	0.2[illegible]1
265.644	265.924	259.803	192.701	118.034	80.326	303.748	163.009	67.185	271.784	146.093	305.685	246.958	60.000	0.3[illegible]1
251.187	254.175	254.076	191.774	117.931	80.309	297.956	153.703	66.253	257.357	139.573	300.805	235.109	60.000	0.4[illegible]1
238.727	243.691	247.855	190.468	117.754	80.282	291.686	147.132	66.053	244.531	134.762	295.462	224.791	60.000	0.5[illegible]1
HEAT-UP BEGINS HERE														
274.969	266.868	244.126	188.888	117.493	80.241	286.465	303.758	234.021	271.262	204.596	290.287	269.281	341.782	0.6[illegible]1
287.870	279.853	244.307	188.297	117.370	80.223	287.343	317.778	248.065	283.629	215.094	290.668	300.091	351.593	0.6[illegible]0

THE PERCENT STEADY-STATE ENERGY SAVED= 65.41

BTUS TO HEAT-UP= 0.29189990E 06 BTUS TO HOLD= 0.84397030E 06 BTUS SAVED= 0.55207040E 06

THE SAVINGS BY COOLING DOWN THE OVEN=$ 0.36

RETURN TO COOLING S= 2.00

TW	TW1	TW2	TW3	TW4	TW5	TS	TD1	TD2	TD3	TD4	TT	TA	TM	TIM
238.727	243.691	247.855	190.468	117.754	80.232	291.686	147.132	66.053	244.531	134.762	295.462	224.791	60.000	0.501
239.611	243.592	247.791	190.453	117.752	80.282	291.621	147.074	66.052	244.410	134.719	295.405	224.694	60.000	0.502
227.750	234.111	241.339	188.794	117.498	80.240	285.050	141.757	66.010	233.039	130.676	289.732	215.506	60.000	0.602
218.121	225.432	234.839	186.828	117.129	80.181	278.242	137.140	66.001	222.892	127.095	283.829	207.178	60.000	0.702
209.454	217.408	228.401	184.602	116.672	80.101	271.346	132.992	65.999	213.755	123.846	277.770	199.534	60.000	0.802
201.549	209.930	222.090	182.160	116.117	80.001	264.467	129.195	65.999	205.445	120.858	271.614	192.443	60.000	0.902
194.325	202.984	216.003	179.574	115.477	79.881	257.546	125.716	65.999	197.885	118.108	265.468	185.677	60.000	1.001

HEAT-UP BEGINS HERE

238.035	232.412	212.918	176.909	114.749	79.741	251.693	269.683	213.517	233.251	180.892	258.883	253.742	339.640	1.101
269.940	250.464	215.643	174.655	113.969	79.586	255.872	304.745	239.902	265.526	203.905	260.811	280.347	333.779	1.201
292.238	281.281	221.568	173.131	113.200	79.422	264.652	321.038	253.608	288.937	218.688	267.054	299.987	351.574	1.301
292.431	281.463	221.637	173.120	113.193	79.420	264.753	321.215	253.724	289.139	218.816	267.130	300.162	351.732	1.302

THE PERCENT STEADY-STATE ENERGY SAVED= 63.18

BTUS TO HEAT-UP= 0.63209910E 06 BTUS TO HOLD= 0.17169510E 07 BTUS SAVED= 0.10848510E 07

THE SAVINGS BY COOLING DOWN THE OVEN=$ 0.71

RETURN TO COOLING S= 3.00

TB	TW1	TW2	TW3	TW4	TW5	TS	TD1	TD2	TD3	TD4	TT	TA	TM	TIM
194.325	202.964	216.003	179.574	115.477	79.831	257.546	125.710	65.999	197.885	118.108	265.468	185.677	60.000	1.0 1
194.254	202.916	215.943	179.547	115.471	79.880	257.477	125.676	65.999	197.811	118.081	265.405	185.613	60.000	1.0 2
187.463	196.300	209.976	176.800	114.739	79.740	250.610	122.335	65.999	190.737	115.479	259.180	179.571	60.000	1.1 2
181.092	170.031	204.197	173.951	113.931	79.582	243.620	119.287	65.999	184.130	113.026	252.977	173.663	60.000	1.2 2
175.079	184.069	198.607	171.029	113.056	79.406	237.125	116.354	65.999	177.918	110.701	246.819	168.048	60.000	1.3 2
169.375	178.480	193.201	168.058	112.123	79.219	230.540	113.565	65.999	172.045	108.489	240.712	162.691	60.000	1.4 2
163.995	172.991	193.024	165.088	111.151	79.021	224.144	110.930	65.999	166.522	106.398	234.730	157.617	60.000	1.5 1

HEAT-UP BEGINS HERE

TB	TW1	TW2	TW3	TW4	TW5	TS	TD1	TD2	TD3	TD4	TT	TA	TM	TIM
210.365	204.625	185.559	162.161	110.132	78.810	219.766	243.664	198.005	205.177	163.009	228.837	226.459	284.975	1.601
242.914	233.436	189.638	159.756	109.106	78.593	225.170	275.089	223.696	238.367	185.932	231.411	253.494	309.502	1.7 1
265.551	254.708	196.367	158.166	108.136	78.377	234.972	295.676	237.541	262.202	200.911	238.238	273.413	327.554	1.8 1
283.188	271.557	204.461	157.440	107.279	78.176	246.760	311.933	248.087	280.571	212.557	247.357	289.613	342.219	1.901
294.282	282.243	210.733	157.421	106.753	78.044	255.953	322.269	254.729	291.990	219.904	254.834	300.093	351.702	1.974

THE PERCENT STEADY-STATE ENERGY SAVED= 61.84

BTUS TO HEAT-UP= 0.99329900E 06 BTUS TO HOLD= 0.26031190E 07 BTUS SAVED= 0.16098190E 07

THE SAVINGS BY COOLING DOWN THE OVEN=$ 1.06

RETURN TO COOLING S= 4.00

TF	TW1	TW2	TW3	TW4	TW5	TG	TD1	TD2	TD3	TD4	TT	TA	TI	TIM
163.935	172.991	188.024	165.088	111.151	79.021	224.144	110.933	65.999	166.522	106.398	234.730	157.617	60.000	1.501
163.942	172.936	187.973	165.058	111.141	79.013	224.080	110.904	65.999	166.467	106.377	234.670	157.566	60.000	1.502
158.752	167.719	182.916	162.046	110.119	78.808	217.751	108.357	65.999	161.151	104.355	228.704	152.652	60.000	1.602
153.730	162.706	178.022	159.034	109.066	78.588	211.562	105.915	65.999	156.067	102.415	222.825	147.930	60.000	1.702
149.008	157.863	173.284	156.035	107.987	78.362	205.535	103.569	65.999	151.195	100.551	217.039	143.388	60.000	1.802
144.420	153.236	168.694	153.056	106.891	78.131	199.614	101.312	65.999	146.516	98.756	211.353	139.013	60.000	1.902
140.047	148.799	164.291	150.140	105.795	77.698	193.917	99.159	65.999	142.060	97.045	205.825	134.837	60.000	2.001

HEAT-UP BEGINS HERE

TF	TW1	TW2	TW3	TW4	TW5	TG	TD1	TD2	TD3	TD4	TT	TA	TI	TIM
197.353	181.936	165.057	147.317	104.682	77.661	191.534	227.780	185.345	182.462	148.427	201.290	204.596	264.761	2.101
226.643	211.102	167.489	145.062	103.594	77.424	198.409	253.929	210.337	216.038	171.116	204.965	231.296	283.457	2.201
243.461	232.519	174.945	143.651	102.589	77.195	209.376	274.656	224.227	240.073	186.180	212.694	251.375	307.631	2.301
261.247	249.689	183.462	143.121	101.720	76.986	222.096	291.058	234.865	258.608	197.929	222.560	257.725	322.414	2.401
276.323	264.272	192.531	143.401	101.030	76.807	235.454	305.127	243.898	274.102	207.921	233.537	282.012	335.362	2.501
289.858	277.440	201.686	144.385	100.542	76.666	248.844	317.976	252.040	287.901	216.929	245.067	295.125	347.222	2.601
294.917	282.330	205.243	144.936	100.409	76.622	254.035	322.622	255.063	292.992	220.273	249.643	300.034	351.662	2.640

THE PERCENT STEADY-STATE ENERGY SAVED= 61.45

BTUS TO HEAT-UP= 0.13418990E 07 BTUS TO HOLD= 0.34813770E 07 BTUS SAVED= 0.21394780E 07

THE SAVINGS BY COOLING DOWN THE OVEN=$ 1.41

RETURN TO COOLING S= 5.00

TB	TW1	TW2	TW3	TW4	TW5	[illegible]	TD1	TD2	TD3	TD4	[illegible]	T4	TM	TIM
140.047	148.799	164.291	150.140	105.795	77.898	193.917	99.159	65.999	142.069	97.045	205.825	134.837	60.000	2.0 1
140.003	148.755	164.247	150.111	105.783	77.896	193.860	99.137	65.999	142.016	97.028	205.770	134.795	60.000	2.0 2
135.747	144.430	159.936	147.199	104.559	77.658	188.154	97.041	65.999	137.683	95.361	200.296	130.726	60.000	2.1 2
131.643	140.252	155.755	144.328	103.552	77.419	182.796	95.019	65.999	133.596	93.752	194.933	126.799	60.000	2.2 2
127.681	136.215	151.699	141.502	102.436	77.180	177.464	93.066	65.999	129.478	92.200	189.652	123.006	60.000	2.3 2
123.857	132.311	147.764	138.725	101.329	76.942	172.317	91.180	65.999	125.590	90.700	184.545	119.341	60.000	2.4 2
120.199	128.573	143.982	136.025	100.239	76.706	167.345	89.377	65.999	121.872	89.265	179.573	115.836	60.000	2.5 1

HEAT-UP BEGINS HERE

TB	TW1	TW2	TW3	TW4	TW5	[illegible]	TD1	TD2	TD3	TD4	[illegible]	T4	TM	TIM
169.052	162.870	143.427	133.442	99.151	76.470	166.904	205.158	174.764	163.521	136.243	176.611	185.392	247.854	2.601
202.008	192.360	148.485	131.446	98.103	76.239	175.303	236.213	199.156	197.361	158.717	181.543	212.718	272.643	2.701
224.972	214.083	155.368	130.304	97.151	76.019	187.425	257.082	213.094	221.559	173.859	195.299	232.946	290.973	2.801
242.915	231.350	165.436	130.043	96.347	75.821	201.050	273.625	223.821	240.253	185.710	201.009	249.453	305.917	2.901
258.154	246.130	174.898	130.587	95.729	75.656	215.105	287.843	232.949	255.912	195.807	212.687	263.398	318.988	3.001
271.858	259.478	184.401	131.828	95.320	75.530	229.089	300.731	241.179	269.853	204.913	224.803	277.148	330.972	3.1 1
284.662	271.954	193.799	133.659	95.128	75.447	242.787	312.621	248.876	282.795	213.428	237.071	289.673	342.298	3.201
295.222	282.255	201.765	135.630	95.135	75.413	254.282	322.820	255.229	293.431	220.457	247.627	300.080	351.708	3.287

THE PERCENT STEADY-STATE ENERGY SAVED= 61.92

BTUS TO HEAT-UP= 0.16506000E 07 BTUS TO HOLD= 0.43345780E 07 BTUS SAVED= 0.26839780E 07

THE SAVINGS BY COOLING DOWN THE OVEN=$ 1.77

RETURN TO COOLING S= 6.00

TI	TW1	TW2	TW3	TW4	TW5	TS	TO1	TO2	TO3	TO4	TT	TA	TF	TIME
120.199	126.573	143.922	136.025	100.239	76.706	167.343	89.377	65.999	121.872	89.265	179.573	115.856	60.000	2.5 1
120.153	126.536	143.945	135.998	100.228	76.703	167.294	89.359	65.999	121.835	89.251	179.524	115.801	60.000	2.5 2
116.594	124.953	140.236	133.323	99.135	76.457	162.412	87.599	65.999	116.209	87.851	174.628	112.379	60.000	2.6 2
113.145	121.349	136.641	130.763	98.061	76.234	157.669	85.895	65.999	114.755	86.498	169.827	109.07_	60.000	2.7 2
109.811	117.929	133.149	128.139	96.999	76.003	153.064	84.254	65.999	111.318	65.193	165.152	105.874	60.000	[illegible]
106.589	114.619	129.757	125.630	95.953	75.776	148.592	82.665	65.999	105.046	83.926	160.591	102.784	60.000	2.9 2
103.505	111.447	126.501	123.272	94.934	75.554	144.294	81.144	65.999	104.913	82.716	156.188	99.825	60.000	3.0 1

HEAT-UP BEGINS HERE

TI	TW1	TW2	TW3	TW4	TW5	TS	TO1	TO2	TO3	TO4	TT	TA	TF	TIME
153.236	146.799	126.529	120.901	93.926	75.333	145.688	190.334	165.863	147.590	125.992	154.820	169.654	233.6_7	3.1 1
185.353	176.564	132.131	117.195	92.965	75.119	155.480	221.335	159.765	181.670	148.302	161.050	197.122	25_.5_5	[illegible]
209.472	198.492	140.485	113.344	92.135	74.918	168.685	242.346	203.759	206.033	163.530	170.828	217.510	277.0_9	[illegible]
227.531	215.957	149.563	118.371	91.397	74.740	183.159	259.055	214.594	224.893	175.491	182.398	234.186	292.116	3.4 1
242.987	230.931	159.788	119.194	90.879	74.595	197.893	273.425	223.812	240.720	185.699	194.791	248.795	305.335	3.5 1
256.956	244.463	169.617	120.704	90.571	74.471	212.427	286.462	232.138	254.829	194.910	207.506	262.200	317.459	3.6 1
269.796	257.116	179.312	122.792	90.460	74.430	226.573	298.687	239.921	267.911	203.521	220.279	274.660	328.908	3.7 1
282.151	269.192	188.833	125.361	90.604	74.415	240.279	310.391	247.359	280.362	211.750	232.975	287.036	339.9_7	3.8 1
294.141	280.899	196.182	128.329	90.932	74.446	253.557	321.754	254.570	292.399	219.726	245.523	298.892	350.6_5	3.9 1
295.323	282.054	199.109	128.646	90.976	74.451	254.863	322.876	255.282	293.586	220.515	246.769	300.064	35_.695	3.9 1

THE PERCENT STEADY-STATE ENERGY SAVED= 62.95

BTUS TO HEAT-UP= 0.19109990E 07 BTUS TO HOLD= 0.51574490E 07 BTUS SAVED= 0.32464500E 07

THE SAVINGS BY COOLING DOWN THE OVEN=$ 2.14

RETURN TO COOLING S= 7.00

TB	TW1	TW2	TW3	TW4	TW5	TS	TD1	TD2	TD3	TD4	TT	TA	TM	TIME
103.505	111.447	126.501	123.262	94.924	75.554	144.294	81.144	65.999	104.913	82.716	156.188	99.525	60.000	3.0.1
103.474	111.415	126.469	123.178	94.924	75.551	144.252	81.128	65.999	104.882	82.704	156.145	99.796	60.000	3.0.2
100.464	108.314	123.275	120.783	93.914	75.331	140.040	79.643	65.999	101.624	81.522	151.811	96.908	60.000	3.1.2
97.553	105.313	120.176	118.445	92.923	75.115	135.954	78.209	65.999	98.868	80.380	147.590	94.116	60.000	3.2.2
94.739	102.407	117.168	116.163	91.952	74.902	131.991	76.820	65.999	96.011	79.276	143.479	91.417	60.000	3.3.2
92.020	99.596	114.249	113.958	91.001	74.694	128.148	75.478	65.999	93.249	78.209	139.477	88.808	60.000	3.4.2
89.416	96.901	111.446	111.891	90.080	74.493	124.459	74.194	65.999	90.605	77.187	135.622	86.311	60.000	3.5.1

HEAT-UP BEGINS HERE

TB	TW1	TW2	TW3	TW4	TW5	TS	TD1	TD2	TD3	TD4	TT	TA	TM	TIME
139.917	133.216	111.985	109.774	89.173	74.293	127.502	177.855	158.369	134.170	117.361	135.777	156.432	2[illegible].676	3.6.1
173.202	163.250	118.076	105.356	88.315	74.101	136.555	208.639	181.877	168.463	139.554	143.213	184.632	246.7[illegible]3	3.7.1
196.450	185.361	126.856	107.792	87.560	73.922	152.742	229.[illegible]	195.9[illegible]7	193.016	154.674	154.015	204.564	265.334	3.8.0
214.757	203.043	136.710	108.099	86.958	73.766	167.996	246.870	206.861	212.045	166.946	166.413	221.431	280.566	3.9.1
230.333	218.209	146.572	109.194	86.546	73.644	183.356	261.405	216.191	228.042	177.267	179.498	236.208	293.956	4.0.1
244.362	231.920	157.007	110.965	86.344	73.563	198.399	274.5[illegible]	224.612	242.311	186.584	192.794	249.765	306.219	4.1.1
257.454	244.739	166.961	113.3[illegible]4	86.358	73.525	212.454	286.947	232.482	255.549	195.291	206.057	262.565	317.793	4.2.1
269.939	256.972	175.753	116.112	85.584	73.552	227.015	298.771	239.997	268.123	203.605	219.166	274.060	328.9[illegible]	4.3.1
282.016	268.790	186.341	119.307	87.012	73.584	240.576	310.224	247.267	280.263	211.648	232.056	286.802	339.7[illegible]8	4.4.1
293.809	280.328	195.751	122.823	87.629	73.679	253.700	321.415	254.366	292.096	219.502	244.738	298.496	350.279	4.5.1
295.325	281.813	196.963	123.301	87.722	73.695	255.377	322.855	255.279	293.617	220.512	246.368	300.002	35[illegible].641	4.5.4

THE PERCENT STEADY-STATE ENERGY SAVED= 64.26

BTUS TO HEAT-UP= 0.21272990E 07 BTUS TO HOLD= 0.59526270E 07 BTUS SAVED= 0.38253280E 07

THE SAVINGS BY COOLING DOWN THE OVEN=$ 2.52

RETURN TO COOLING S= 6.00

TI	TW1	TW2	TW3	TW4	TW5	TO	TO1	TO2	TO3	TO4	T1	T4	TP	TIME
89.416	96.901	111.446	111.741	90.080	74.495	124.459	74.194	65.999	90.605	77.187	135.622	86.311	60.000	3.5 1
89.391	96.874	111.418	111.769	90.071	74.491	124.423	74.181	65.999	90.579	77.177	135.583	86.286	60.000	3.5 2
86.950	94.241	108.670	109.656	89.162	74.291	120.811	72.926	65.999	87.998	76.180	131.795	83.849	60.000	3.6 2
84.394	91.693	106.006	107.536	88.274	74.097	117.311	71.717	65.999	85.503	75.216	128.112	81.494	60.000	3.7 2
82.020	89.227	103.421	105.594	87.406	73.906	113.920	70.546	65.999	83.093	74.285	124.531	79.218	60.000	3.8 2
79.726	86.842	100.916	103.643	86.560	73.720	110.635	69.414	65.999	80.765	73.385	121.050	77.016	60.000	3.9 2
77.532	84.557	98.510	101.764	85.745	73.541	107.454	66.332	65.997	78.534	72.524	117.702	74.914	60.000	4.0 1

HEAT-UP BEGINS HERE

139.717	131.749	99.502	100.217	84.941	73.364	111.986	167.561	151.066	121.575	110.101	119.767	145.[illegible]	[illegible]	4.1 1
162.156	152.342	106.031	96.871	84.180	73.194	124.160	198.357	175.254	157.414	132.213	127.842	173.039	236.793	4.2 1
185.531	174.569	115.197	98.577	83.536	73.036	139.226	219.665	189.387	182.123	147.627	139.578	193.770	255.558	4.3 1
204.342	192.219	125.394	99.146	83.041	72.905	155.179	236.659	200.466	201.306	159.806	152.750	210.782	270.958	4.4 1
219.790	207.557	135.866	100.496	82.733	72.805	171.104	251.382	209.835	217.465	170.236	166.460	225.719	284.474	4.5 1
233.965	221.451	146.262	102.513	82.633	72.746	186.609	264.709	218.349	231.690	179.655	180.320	239.425	296.872	4.6 1
247.145	234.425	156.515	105.085	82.748	72.730	201.555	277.197	226.303	245.268	188.455	194.045	252.357	308.566	4.7 1
259.537	246.799	166.529	108.117	83.072	72.759	215.923	289.136	233.891	257.975	196.849	207.541	264.768	319.768	4.8 1
271.958	258.749	176.331	111.525	83.595	72.832	229.750	300.687	241.224	270.216	204.962	220.772	276.808	330.673	4.9 1
283.857	270.377	185.940	115.243	84.303	72.947	243.091	311.952	248.371	282.133	212.870	233.722	288.572	341.308	5.0 1
295.383	281.671	195.291	119.174	85.170	73.100	255.862	327.897	255.311	293.692	220.548	246.278	300.020	351.658	5.100

THE PERCENT STEADY-STATE ENERGY SAVED= 65.66

BTUS TO HEAT-UP= 0.23078990E 07 BTUS TO HOLD= 0.67253890E 07 BTUS SAVED= 0.44174900E 07

THE SAVINGS BY COOLING DOWN THE OVEN=$ 2.91

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AN EVALUATION OF THE ENERGY CONSUMPTION OF AUTOMOBILE PAINT-DRYING OVENS

by

Rodney Alan Walsh

B.S., General Motors Institute, 1973

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1973

ABSTRACT

The energy shortage presently facing this nation has caused a great deal of alarm and concern to all portions of society. The automobile industry, a major energy consumer, is attempting to reduce the amount of energy it consumes in an effort to lessen the energy shortage. Large scale energy evaluations of past and present processes are being conducted to see if any reduction in energy consumption can be obtained. One such process, automobile paint drying, was evaluated in this thesis.

The evaluation was conducted in three segments. The first segment was concerned with developing various schemes to reduce the energy consumption in the ovens. Two methods were determined to lower their energy requirements. The first method involves the shutting down of the ovens during periods when the paint lines are not running. It was found that the use of bang-bang control would minimize the energy consumed during the down time intervals. The second method proposed was the use of the waste heat from the ovens' exhaust gases. The use of rotary regenerative equipment was selected to obtain the heat recovery.

The second segment of the evaluation was to develop a transient, thermal model of the ovens. The model was used to obtain the information necessary for selecting the proper bang-bang control sequences which minimized the ovens' energy consumption. The model developed represents the thermal characteristics of the ovens' components with a set of linear first-order differential equations. A computer program was written which uses a finite difference technique to obtain the solutions to the model equations.

The final segment of the evaluation was concerned with the resultant savings from the two proposed methods for energy reduction. It was found that the bang-bang control scheme and the regenerative equipment both substantially reduced the energy-consumption of the ovens. The magnitude of the monetary savings from the reduction schemes was small because of the relatively small size of the burners being evaluated. However, with the availability of fuel decreasing rapidly, the fuel consumption savings are sure to increase in their significance.

VITA

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Master of Science

Thesis: AN EVALUATION OF THE ENERGY CONSUMPTION OF AUTOMOBILE PAINT DRYING OVENS

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