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ENERGY RECOVERY IN AIR-CONDITIONING SYSTEMS

by

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B.S., Al-Mustansiriyah University, 1972

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

1978

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NOMENCLATURE

Symbol	Significance	Units
A	Total exposed surface of fins and tubes	ft^2
A_o	Total outside bare-tube surface	ft^2
APD	Air pressure drop through air-fin coil	Inch of water
AV	Actual air velocity	ft/min
a_s	Flow area a cross bundle	ft^2
cfme	Exhaust air flow capacity	ft^3/min
cfms	Supply air flow capacity	ft^3/min
C_{pa}	Specific heat of air at constant pressure	Btu/lbm-^oF
DI	Inside diameter of air-fin coil	ft
D_v	Equivalent diameter for air-side pressure drop in air-fin coil	ft
f	Friction factor for air side of air-fin coil	dimensionless
FN	Fin spacing	Fins/inch
FNV	Air net free volume over air-fin coil	ft^3
FRS	Frictional area surface for one row for air-fin coil	ft^2
F_s	Air flow correction factor	dimensionless
FTK	Fin wall thickness of air coil	ft
GPM	Flow rate	gal/min
G_i	Heat capacity at various points	Btu/hr ^oF
G_s	Mass velocity	lbm/ft^2-hr
H	Job site elevation	ft
h_ℓ	Head loss	ft of water

Symbol	Significance	Units
K	Loss coefficient for minor losses	dimensionless
L_p	Length of Gross-flow path	ft
OD	Outside diameter of air coil tube	ft
OFD	Outside diameter of air coil fin	ft
PEG	Pressure drop of the ethylene glycol through the coil	ft of water
q_e	Heat gained from the exhaust air	Btu/hr
$q_{e.g.}$	Heat transferred by the ethylene glycol between exhaust and make up air coils	Btu/hr
Q_i	Mass flow rate at various points	lb_m/hr
q_s	Heat picked by make up air coil	Btu/hr
R_a	Recovery factor for smaller air flow	dimensionless
R_b	Recovery factor for larger air flow	dimensionless
R_e	Reynolds number	dimensionless
RN	Number of rows of tubes high	dimensionless
S	Specific gravity	dimensionless
S_f	Fins area of air-fin coil	ft^2/ft length
S_h	Center-to-center distance between tubes in a row of a cross-flow tube bank	ft
S_ℓ	Center-to-center longitudinal distance in the direction of flow	ft
S_o	Bare tube area of air-fin coil	ft^2/ft length
T_i	Temperatures at various points	^oF
TK	Tube wall thickness of air-coil	ft
U	Overall heat transfer coefficient for air coils (referred to outside bare tube surface area A)	Btu/hr ft^2 ^oF
VA	Air side face velocity	ft/min
VEG	Ethylene glycol velocity	ft/sec

Symbol	Significance	Units
V_m	Maximum air velocity at minimum cross section in a tube row	ft/min
VS	Standard air velocity	ft/min
W	Number of rows of tubes deep	dimensionless
X	Percentage of ethylene glycol by weight	dimensionless
Z	Coil tube length	ft

Greek Letters

μ	Viscosity at the caloric temperature	lb_m/ft-hr
μ_W	Viscosity at the tube-wall temperature	lb_m/ft-hr
ρ	Density of air	lb_m/ft^3
ρ_S	Density of ethylence glycol and water mixture	lb_m/ft^3
Φ_S	Viscosity correction for heating/or cooling	dimensionless

CHAPTER 1

INTRODUCTION

Energy conservation is an important item for consideration to all, building designers, developers, owners and managers. Air-to-air heat recovery, through processed air with energy recovered from exhaust air, is one area of investigation for potential energy and cost savings.

Although ideally suited for hospitals, office buildings, apartments, hotels, schools, auditoriums and factories, air-to-air heat recovery equipment is applicable to almost any commercial, institutional, or industrial facility. Therefore, it should be carefully considered wherever wasted energy is discharged from a process or building.

While the reserve of energy sources is not unlimited, it is being wasted in enormous quantities.

But wherever energy is wasted, there is an opportunity to recover some portion for some useful purposes. This was the theme of a paper presented by P. C. Greiner, Edison Electric Institute, New York at the recent National Electric Heating Conference held in Cincinnati [1]*. Very simply, he says, "Don't buy energy twice".

Heat-loss through air change represents, in general, some 30 percent of the overall heat loss in a multiple-dwelling building and approximately 20 percent of such loss in a single family house [2].

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*Number in brackets designate references in the list of References.

VARIOUS HEAT-RECOVERY SYSTEMS CURRENTLY AVAILABLE FOR DOMESTIC USE:

Existing heat recovery systems are surveyed by examining the advantages and disadvantages of each from various points of view, particularly:

- that of efficiency, which is obviously of capital importance;
- that of pressure loss, which increases ventilation costs and make acoustic problems more difficult to resolve;
- that of frost occurrence, which affects efficiency;
- that of sanitation: the forced-air intake must not be polluted by the exhausted air.

1. Systems Based on the Thermal Capacity of a Material:

Figure (1a) represents a rotary system, the most typical type of these systems. Recirculation of a volume of gas occurs at the time of air-current inversion or reversal. This disadvantage can be minimized by purging the heat recovery system at the time of reversal, employing some additional apparatus. In addition, the heat recovery system may gradually become fouled and clogged. This problem can be overcome either by using a washing device or by fitting filters; however, both solutions have some disadvantages.

The rotary heat recovery system consists of a porous wheel which rotates about an axis parallel to two gaseous streams. The streams are separated by a wall that diametrically intersects the wheel. With this apparatus, the air streams follow a fixed course, and the collector (accumulating) material passes from one stream to another at variable speed. This system under proper conditions is 80 percent efficient [2] and has the same disadvantages as the stationary porous system. A purger permits limiting the recirculation of stale air at the point where the wheel crosses

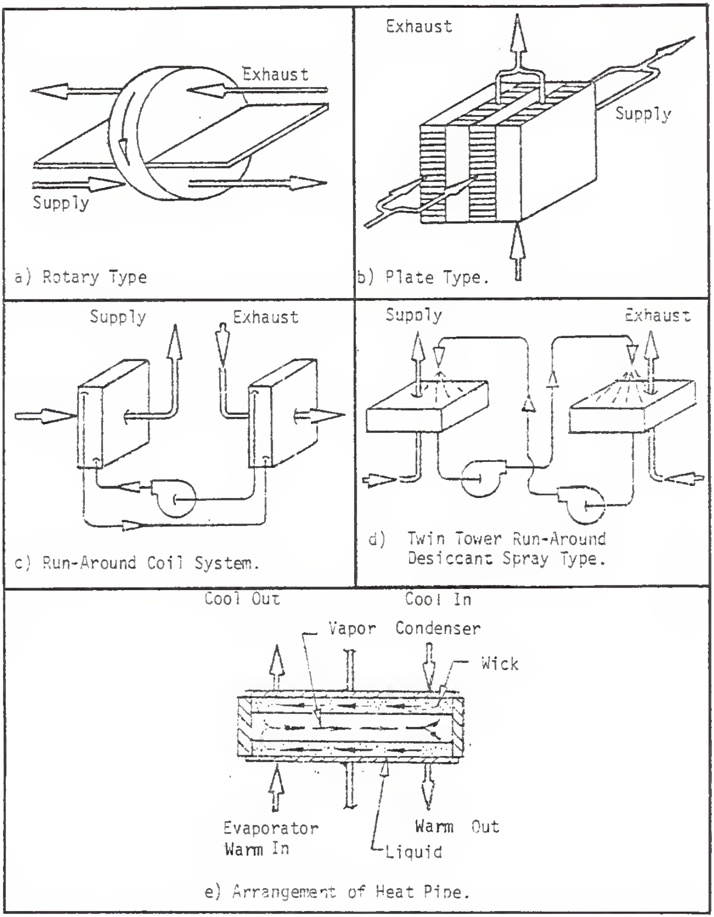

Figure 1. Schemes of Several Principles of Air-to-Air Heat Exchangers.

the boundary within the stream of exhausted air and fresh air. But there is a risk of recirculation on a level with the seal between the rotating part and the barrier separating the two streams. This risk can usually be limited if the pressure of the fresh air exceeds the exhausted air.

If the moist exhaust air is below 32^{0}F, as it passes over that part of the system material whose temperature is close to the outside temperature, frost is apt to form within these heat recovery systems. This condition can be improved by use of a pre-heating system or by shutting the system off below a certain outside temperature. Unfortunately, these remedial steps decrease the systems efficiency.

Typical recovery efficiencies for non-hygroscopic rotary are 70-80 percent sensible heat [3].

2. Systems using Direct Heat Transfer:

Figure (1b). These type of exchangers may be of metal, plastic, or combined fiber materials. Air flow is usually either cross or counter flow. Counter flow provides the greatest temperature difference for maximum heat transfer, and cross flow can allow more convenient air connections. The usual plate exchangers transfer only sensible heat, when the temperature of one air stream is lower than the dew point of the other, and direct condensation occurs. Preheating to avoid condensation could prevent unusually high pressure drop, corrosion, or freeze-up due to presence of water on the surfaces. As desired, recovery may be limited and controlled by having a portion of the supply air by-pass the exchanger by means of dampers. There is no leakage between exhaust and supply air if air passages are sealed. Usual recovery efficiencies are 40 to 60 percent sensible heat [3].

3. Systems Employing an Intermediary Energy-Carrying Fluid:

(Run-Around System)

Figure (1c). This system consists of an energy-carrying fluid circulating between two finned tube coils, one set within the warm-air stream, the other within the cold air stream. A pump serves to circulate this fluid.

This system offers significant advantage over the previous one:

- exhaust ducts and forced-air intake ducts may be placed at some distance from each other,
- contamination of bad odors is not likely to occur.

Frost problems and fouling difficulties are resolved as in the first system.

4. Run-Around, Multiple Tower, Desiccant Spray Exchanger:

Figure (1d). This system is similar to the run-around, coil and pump system. An extended packed surface is substituted for the cooling coils, such as cooling tower fill. A liquid absorbent (usually a solution of the halogen group such as lithium chloride/water) is substituted for the water/anti-freeze circulating liquid. Another difference is that the absorbent liquid is sprayed counter flow to the air streams through the extended packed surface. This necessitates two solution pumps to complete the run-around circuit.

This system provides total heat transfer as the solution absorbs (or desorbs) heat and water vapor from the exhaust air stream. Moreover, by circulation and contact the circulating liquid with the system, the supply air stream is preconditioned to approach the system's temperature and vapor-pressure difference. The system is also reversible because of its nature of action, similar to the hygroscopic rotary recovery system. It will pre-cool and dehumidify in the summer and will preheat and humidify in the winter.

5. Heat Pipe Air-to-Air Heat Transfer System:

Figure (1e). In this system, the ducts are arranged such that inlet air stream flows through one side of the unit, and the outlet air stream flows through the opposite side. Heat is thus transferred from one stream to another stream.

The unit is constructed of a series finned tubes. Each tube consists of an envelop (the tube), a wick, and a working fluid and is sealed at both ends. These tubes are the actual heat pipes. Heat applied to one end of the unit evaporates the working fluid from the wick. The vapor then flows to the cold end of the tube, where it is condensed and returned by the wick to the hot end for re-evaporation, thus completing the cycle.

The heat pipe is a completely reversible, essentially iso-thermal device. When a section of the envelop is exposed to a temperature gradient with respect to another section, the cycle commences seizing the existing gradient.

Advantages:

1. Manufacturers claim up to 68% efficiency [4].
2. No cross contamination of air streams occurs.
3. The leaving air temperature may be controlled by tilting the coil.

Disadvantages:

1. The units are costly [4].
2. Side-by-side air discharge and intake is required, which necessitates expensive duct work to bring the supply and exhaust air to the equipment room for processing. Some disadvantage exists for all but run-around.
3. The units are reportedly limited to a maximum length of 8 ft [4].
4. A preheating coil is required for temperatures below 32 ^{o}F outside temperature to prevent the exhaust air condensate from freezing.

In this study, the purpose is to develop a technical and economic analysis of the Run-Around Coil System and Heat Pipe System heat exchanger types used in exhaust air heat recovery.

These two are typical of all types available. The analysis of the heat pipe system depends on performance data reported by manufacturer except for the "run-around" system. The "run around" system is a "built-up" system of standard components available from different manufacturers.

CHAPTER 2

"RUN-AROUND COIL SYSTEM"

General Description

Figure (1c). With the standard extended surface, finned-tube water coils may be used with a circulation pump for recovery of sensible heat from exhaust air. One coil is located in the exhaust air stream and the other in the supply air stream. A pump circulates water or a water-antifreeze solution between the coils, transferring energy from the exhaust recovery coil to the supply air coil. The direction of the flow of solution to the air is usually counter for maximum heat transfer.

The system is seasonally reversible (i.e., the air to be pre-conditioned by the supply air coil will reflect an approach to the solution temperature from the exhaust air coil, thereby preheating when the outdoor air is cooler than the exhaust and precooling when the outdoor air is warmer than the exhaust).

This system operates generally for sensible heat recovery only, except when the temperature of one air stream is lower than the dew point temperature of the other, and direct condensation occurs. Preheating the lower air stream to avoid condensation will prevent unusually high pressure drop, corrosion, or freeze-up due to water on the surfaces. When required, recovery may be limited and controlled through the use of face and by-pass dampers. Components are usually selected for ratings that will achieve recovery efficiencies of 40 to 60 % sensible heat [3].

Typical Applications

Comfort	Industrial/Process
Offices	Paint Booths
Laboratories	Animal Care Facilities
Schools	Grain Drying
Plants	Heat Treating
Recreational Facilities	General Drying
Hospitals	Sewage Plants
Hotels	Kitchens
Restaurants	Laundries

Theory and Modeling Equations

Heat Balance and Transfer Equations

The heat transfer and balance equations for this system were written as (see notation of Figure 2):

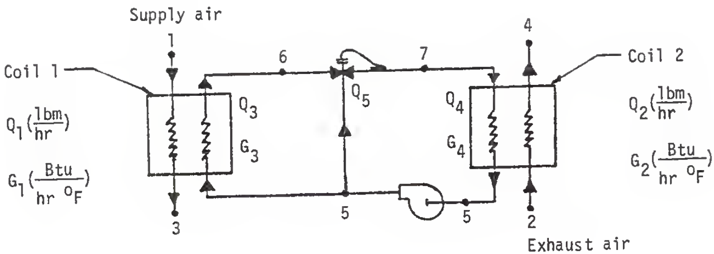

Figure (2) Arrangement of Run-Around Coil System.

$$q_e = q_{e.g.} = q_s \tag{1}$$

$$Q_2 \cdot C_{pa} (T_2-T_4) = U_2A_2 \frac{(T_5-T_2) - (T_7-T_4)}{\ln[(T_5-T_2)/(T_7-T_4)]}$$

$$= U_1A_1 \frac{(T_5-T_3) - (T_6-T_1)}{\ln[(T_5-T_3)/(T_6-T_1)]}$$

$$= Q_1 \cdot C_{pa} (T_3-T_1) \qquad \text{(Winter operation)} \tag{2}$$

assuming counter-flow operation

$$Q_3 + Q_5 = Q_4 \tag{3}$$

$$G_3T_6 + G_5T_5 = G_4T_7 \tag{4}$$

By trial-and-error, given values of T_1, T_2, G_1, G_2, U_1 and U_2, a balance case can be obtained and T_5, T_6, T_7, T_3 and T_4 can be determined. Details for their determination are given in Appendix A.

Frost Control Determination

Frost control is needed only during winter operation. If $T_7 < 32\ ^oF$, Q_5 may be selected to require $T_7 = 32\ ^oF$. More details are given in Appendix A.

Make up and Exhaust Air Coils

The U value of the coil based on outside (air-side) area:

$$\frac{1}{U} = \frac{2.75}{VA^{0.58}} + 0.0183 + \frac{1.975\ FN + 1.05}{166\ VEG^{0.8}} \tag{5}$$

The air pressure drop:

$$APD = 27.69 \times \frac{f G_s^2 L_p}{(5.22 \times 10^{10})\ D_v S \Phi_s} \left(\frac{D_v}{S_h}\right)^{0.4} \left(\frac{S_\ell}{S_h}\right)^{0.6} \qquad (6)$$

The pressure drop of the ethylene glycol:

$$PEG = 1.495 \left(\frac{VEG}{3}\right)^{1.75} [0.0039\ WZ + 0.0875\ (W-1) + 0.3] + 35.78\ \frac{(VEG)^2}{64.4} \qquad (7)$$

Equation (5) is that developed by Stoecker [5]. Details of determination of equations (6) and (7) are given in Appendix A.

Ethylene Glycol

The mass flow rate and heat capacity are:

$$Q = 176431.84\ VEG\ DI^2\ (1+0.1X) \qquad (8)$$

$$G = (1-0.398\ X)\ Q \qquad (9)$$

Details of development of equations (8) and (9) are given in Appendix A.

Energy Recovered

The system is built for sensible heat transfer in which no moisture is exchanged between air streams. The sensible heat gain by the outside air is:

$$q = 1.08\ cfms\ (T_3 - T_1) \qquad (10)$$

Regarding the sensible-heat recovered per season, information from figures (3), (4), (5) and (6), which gives temperature frequency during heating and cooling seasons for an area averaging 4000 to 5000 and 5500 to 6500 degree days respectively, have been used.

Operating Energy

The energy required to operate the fans and pump is

Fan:

$$q = \frac{0.4003876 \text{ cfm} \times \text{APD}}{\text{Eff.}} \tag{11}$$

Pump:

$$q = \frac{0.642676 \text{ GPM} \times \text{S} \times \text{PEG}}{\text{Eff.}} \tag{12}$$

Development of equations (11) and (12) are in Appendix A.

Net Energy Recovered

$$q = q \text{ (energy recovered)} - q \text{ (operating energy for fans and pump)} \tag{13}$$

CHAPTER 3

THE COST EQUATIONS

To determine:

<u>The Initial Cost for</u>

Coil

$$\text{cost (\$/sq.ft.)} = \frac{19.1 - 0.083\ Z}{W^{1/3}\ (A_0/1000)^{0.13}} \tag{14}$$

Estimated cost for standard air-coil exchanger in \$/sq.ft. of bare-tube surface as formulated by Edward [8].

<u>The Total Initial Cost</u>

$$\text{cost (\$)} = \sum \text{cost (coils + pump + labor + ethylene glycol + fans)} \tag{15}$$

<u>The Operating Energy Cost for</u>

Fan

$$\text{cost (\$/year)} = \text{(Fan BHP)} \times 0.746\ \frac{KW}{BHP} \times \frac{\$}{KW\text{-}HR}\ \text{(Elec. Cost)} \times \frac{HRS}{YEAR} \tag{16}$$

Pump

$$\text{cost (\$/year)} = \text{(Pump BHP)} \times \frac{0.746\ KW}{BHP} \times \frac{\$}{KW\text{-}HR}\ \text{(Elec. Cost)} \times \frac{HRS}{YEAR} \tag{17}$$

<u>The Total Operating Energy Cost</u>

$$\begin{aligned}\text{cost (\$/year)} = {} & \text{Fans operating energy cost (\$/year)} + \\ & \text{Pump operating energy cost (\$/year)}\end{aligned} \tag{18}$$

The Capital Equipment Reduction for

Boiler

$$\text{cost (\$)} = \frac{\text{Btuh energy recovered in winter}}{\text{100000 Btuh/Therm}} \times \frac{\$}{\text{Therm}} \text{ Average equipment cost} \tag{19}$$

Chiller

$$\text{cost (\$)} = \frac{\text{Btuh energy recovered in summer}}{\text{12000 Btuh/Ton}} \times \frac{\$}{\text{Ton}} \text{ Average equipment cost} \tag{20}$$

The Total Capital Equipment Reduction:

$$\text{cost (\$)} = \text{\$ Boiler} + \text{\$ Chiller} \tag{21}$$

The Energy Gross Recovery:

Winter

$$\text{savings (\$/year)} = \frac{\text{Btuh energy recovered in winter}}{\text{100000 Btuh/Therm}} \times \frac{\$}{\text{Therm}} \text{ Heating Cost} \tag{22}$$

Summer

$$\text{savings (\$/year)} = \frac{\text{Btuh energy recovered in summer}}{\text{12000 Buth/Ton}} \times \frac{\$}{\text{Ton}} \text{ Cooling Cost} \tag{23}$$

The Total Energy Gross Recovery:

$$\text{savings (\$/year)} = \text{Winter G.R. (\$/year)} + \text{Summer G.R. (\$/year)} \tag{24}$$

The Net Energy Gross Recovery:

$$\text{savings (\$/year)} = \text{Total G.R. (\$/year)} - \text{Total operating (\$/year)} \tag{25}$$

The Years of Pay Back:

$$\text{Pay back (yrs.)} = \frac{\text{\$ Total Initial Cost} - \text{\$ Total Capital Reduction}}{\text{Net Gross Recovery (\$/Yrs)}} \tag{26}$$

Details of equations (14 to 26) are given in Appendix A.

Calculational Scheme

A computer program (shown in Appendix B) was written which, by inputting the coil descriptions, air flow rates, air temperatures, fan efficiencies, pump efficiency, initial system's component cost, unit heating and cooling energy cost, and an optional water antifreeze solution percentage and velocity, allows the design engineer to estimate the net energy recovered and the pay back period. The program iterates between the make up and exhaust coils of the system until the antifreeze solution temperatures (T_5, T_6 and T_7) balance. At this condition all energy and dollar quantities are calculated.

The program determines the specifications for controlling condensate frosting at the design outside air temperature and calculates the resulting capacity with frost control operating.

CHAPTER 4

SPECIFIC SYSTEM ANALYSIS

Results and Discussion

The potential savings can be evaluated for a heat recovery system. An optimum system consists of the most favorable combination of the following variables:

1. Length of the coil, Z.
2. Height (or number of tubes high) of coil, HT.
3. Number of rows of tubes deep (parallel to the path of air flow), W.
4. Fin spacing, FN.
5. Glycol flow rate, VEG.

The qualitative effects of the previously mentioned five variables are as follows:

Increasing the length or number of tubes high, increases the heat transfer area but also increases the cost. Furthermore, increasing the length or the number of tubes high not only increases the cross-sectional area for air flow, reducing the velocity and decreasing the air-side heat transfer coefficient, but also decreases the power required for the fan. The first and second above variables, were combined as a function of one variable, air face velocity (VA) as shown:

$$VA = \frac{CFM}{HT \times Z}$$

Increasing the number of rows of tubes deep increases the heat transfer area, but also increases the initial cost of the coil as well as the cost of pumping both air and ethylene glycol.

Spacing the fins closer together increases the cost of the coil and the air pressure drop, but also increases the heat-transfer area.

Finally, a high flow rate of the ethylene glycol increases the glycol side heat-transfer coefficient, but also increases the pumping cost.

Values of fin spacing, face velocity, ethylene glycol velocity and coil depth, were selected for the application considered here to be 10 fins per inch, 500 fpm, 8 fps and 4 rows respectively.

These four parameters were chosen to study the individual effects on the system by subjecting each parameter to a variation while keeping the other parameters at their standard values.

The effect of the fin spacing (FN) variation on annual energy recovered, net annual energy recovered cost and pay back periods, are shown in figures 7, 8 and 9 respectively. The optimum and/or economic value of fin spacing in all these figures is 10 fins per inch.

In figure 7, total recovery unit area (A) curve shows a gradual increase as the number of fins per inch increases. The reason is that the total recovery unit area is directly proportional to the number of fins per inch.

Total annual operating energy (TAOE) curve shows a gradual increase as the number of fins per inch increases. The reason is that total annual operating energy is directly proportional to air pressure drop (APO) and the air pressure drop is directly proportional to the number of fins per inch.

Total annual gross recovery (TAGR) curve shows a gradual increase until it reaches the optimum value of the number of fins per inch. Further increases in the number of fins per inch shows a small response. The reason is that, total annual gross recovery is a function of overall heat transfer coefficient (U) and total recovery unit area. Overall heat transfer coefficient is inversely proportional to the number of fins per inch as shown in equation (5). The rate of decreases in overall heat transfer coefficient is proportionally much smaller than the increase in total recovery unit area. However, the numerical results show that the by-pass was open for preventation of frost formation. This limited total annual gross recovery, as noted in the figure by reducing the ethylene flow through the make up coil.

Total annual net gross recovery (TANGR) is the difference between the total annual gross recovery and the total operating energy, as is shown in the curve.

Figure 8, shows the effect of annual net energy recovered cost for the oil, gas, and electric system (if it is used for heating) with respect to the variation of the fin spacing.

The annual net energy cost recovered is directly proportional to the total energy gross recovered cost (TGR) and inversely proportional to total operating energy cost (TOE). Total energy gross recovered cost for oil, gas, and electric are functions of the total annual gross recovery and heating costs of oil, gas, and electric. The total operating energy cost is a function of the total annual operating energy and the electric operating costs.

The annual net energy recovered cost for oil curve shows an increase until the number of fins per inch value equal to 10. Further increase in the number of fins per inch value results in an appreciable drop in the annual net energy recovered cost for oil. The behavior of the curve is the difference between the total annual gross recovered multiplied by oil heating cost (taken 0.26 $/Therm) and the total annual operating energy multiplied by electric operating cost (taken 0.025 $/KW-HR).

There is an overall decrease in the annual net energy cost recovered curve by increasing the number of fins per inch. However, up to the fin spacing value equal to 10, the decrease is more gradual than for higher values of the fin spacing. The behavior shown in the curve is due to low gas heating cost (taken 0.13 $/Therm).

There is a noticeable increase in the value of the annual net energy cost recovered for electric up to the fin spacing equal to 10. For values of the fin spacing greater than 10, a very small increase is seen as evident from the curve. That is due to high electric heating cost (taken 0.73 $/Therm).

The noticeable difference in the slopes of the annual net energy recovered cost for oil, gas and electric curves, with respect to the variation of the fin spacing, are due to lowest heating cost for gas and oil, and the highest heating cost for electricity.

The pay back period is directly dependent on initial costs (EIC), and is inversely proportional to total capital equipment reduction (TECR) and net energy recovered costs. The pay back for oil, gas, and electric (PAYBO, PAYBG, and PAYBE) curves are represented in figure 9. As is evident from these curves, the minimum pay back period occurs at the fin spacing value of 10 fins per inch.

Figures 10 and 11 represent the relation between the total annual gross recovered, total annual net gross recovered, total recovery unit area, total annual operating energy, the annual net energy cost recovered for oil, gas and electric against the face velocity (VA).

The total recoveryunit area decreases as the face velocity increases, as is evident from the graph. The total recovery unit area is directly proportional to the length of the coil. The face velocity is inversely proportional to the product of the height and the length of the coil. Keeping the height constant, the length decreases as the face velocity increases, hence the above result between the total recovery unit area and the face velocity.

The total annual operating energy increases as the face velocity increases. The total annual operating energy is directly proportional to the pressure drop. The face velocity is directly proportional to the pressure drop. This makes a noticeable increase in the total annual operating energy as the face velocity increases.

The total annual gross recovery decreases as the face velocity increases. The total annual gross recovery is directly proportional to the product of the overall heat transfer coefficient and the total recovery unit area. The overall heat transfer coefficient is directly proportional to the fractional power of face velocity ($VA^{0.58}$) and the total recovery unit area is inversely proportional to the face velocity. Hence UA decreases as VA increases and thus the behavior is seen in the curve for total annual gross recovery.

The total annual net gross recovered decreases as the face velocity increases. The total annual net gross recovered is the difference between the total annual gross recovered and the total annual operating energy.

The annual net energy cost recovered for oil, gas and electric curves decreases as the face velocity increases. The annual net energy cost recovered is directly proportional to the total energy gross recovered cost and inversely proportional to the total operating energy cost. The total energy gross recovered cost is function of the product of the total annual gross recovered and heating cost. The total operating energy cost is the function of the product of the total annual operating energy and the electric operating costs.

The noticeable difference in slopes of the annual net energy cost recovered for oil, gas and electric is due to different oil, gas, and electric heating costs.

From the above curves, it is seen that the best value of the face velocity is between 400 to 600 fpm. 500 fpm was selected for a standard run.

Figure 12 shows that the total recovery unit area is constant as the ethylene glycol velocity increases because the total recovery unit area is not dependent on the ethylene glycol velocity.

The total annual operating energy increase as the ethylene glycol velocity increases. The reason is that the total annual operating energy is directly proportional to the pressure drop in ethylene glycol (PEG). The pressure drop in ethylene glycol is dependent on the ethylene glycol velocity (VEG^2 and $VEG^{1.75}$) as shown in equation (7), hence the above result between the total annual operating energy and the ethylene glycol velocity.

The total annual gross recovered increases as the ethylene glycol velocity increases. The total annual gross recovery is directly proportional to the product of the overall heat transfer coefficient and the total recovery unit area. The total recovery unit area is constant, and the overall heat transfer coefficient is directly proportional to a fractional power of the ethylene glycol velocity ($VEG^{0.8}$) as shown in (5), hence the above result is satisfied.

The total annual net gross recovered increase as the ethylene glycol velocity increases. The total annual net gross recovered is the difference between the total annual gross recovered and the total annual operating energy.

The ethylene glycol velocity equal to 8 is considered as the maximum ethylene velocity for the system to run under low pressure. The ethylene glycol velocity equal to 8 is taken as the standard value for the system. Above this velocity, the system is considered working under high pressure which requires high cost fabrication and components.

Figure 13 shows that the total annual gross recovered increases as the number of rows in coil depth increases, because the total recovery unit area increases the number of rows in coil depth increases. However, the numerical results show that the by-pass was open for preventation of frost formation. This limited the total annual gross recovered, as noted in the figure, by reducing the ethylene glycol flow through the make up coil.

The total annual operating energy curve shows that it increases as the number of rows in coil depth increases, because the total annual operating energy depends on the air pressure drop and the air pressure drop depends on the number of rows in coil depth.

The total annual net gross recovered curve shows an increase until the number of rows in coil depth equal to 4, then decreases as the number of rows increases beyond 4. The reason is that the total annual net gross recovered is directly proportional to the total annual gross recovered and inversely proportional to the total annual operating energy. The magnitude of the total annual operating energy gradually increases until the number of rows equal to 4; for values of the number of rows greater than 4, the increase is much steeper. For this reason, the value of the total annual net gross recovered tends to decrease after the number of rows equal to 4.

Figure 14 shows the effect of the number of rows in coil depth variation on the annual net energy cost recovered. The annual net energy cost recovered for oil, gas and electric curves increase until the number of rows equal to 4. Further increase in the number of rows results in fall of the above values. This is because the annual net energy cost recovered is directly proportional to the total energy gross recovered cost and inversely to the total operating energy cost, as already explained in the discussion of figure 8. The significant effect of the total operating energy cost on these curves produces this result.

Figure 15 shows the effect of the number of rows on the payback period. Because the payback is inversely proportional to the capital equipment reduction cost, the total annual net energy cost recovered and directly proportional to the total initial cost, these curves increase with different slopes.

In short, figures 13 to 15 indicate that the highest annual net energy recovered and the highest annual net energy cost recovered are obtained for the number of rows equal to 4, and the quickest pay back period results for the number of rows equal to 2. Hence the value of the number of the rows equal to 4 is selected as standard coil dimension.

Figures 7 through 15 are based on a geographic area with 4000 to 5000 degree days.

Figures 16 to 24 demonstrate also the standard values of the fin spacing, face velocity, ethylene glycol velocity and coil depth for a geographic area with 5500 to 6500 degree days. This set of conditions shows the same results regarding the four parameters as in the first set of degree days.

The only difference between the two sets is that the annual net energy recovered and the annual net energy cost recovered have greater values in the second set than in the first set and the pay back periods have lower values in the second set than in the first set. This occurs because the total annual net gross recovered is directly proportional with the degree days. The same influence is noted on the annual net energy cost recovered for oil, gas and electric. The pay back periods are inversely proportional to the annual net energy cost recovered which is directly proportional with the degree days.

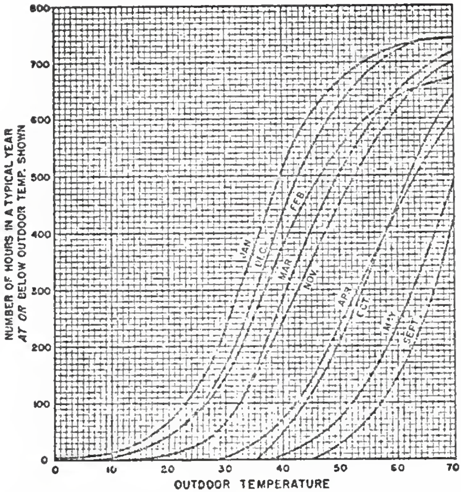

Figure 3. Climatological Data for an Area with 4000 to 5000 Degree Days. The outdoor temperatures are related to the hours of occurrence of the different months of the heating season. After U.S. Dept. of Commerce Weather Bureau, Asheville, N.C.

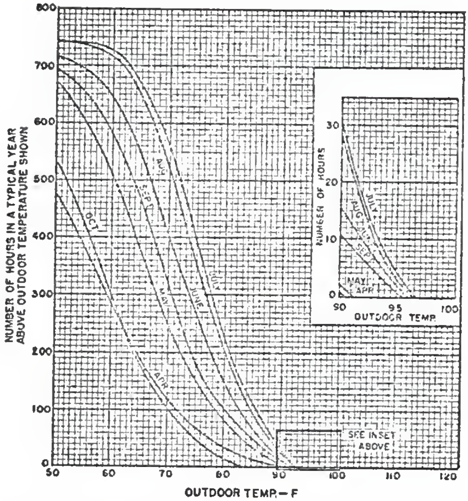

Figure 4. Climatological Data for an Area with 4000 to 5000 Degree Days. The outdoor temperatures are related to the hours of occurrence of the different months of the cooling season. After U.S. Dept. of Commerce Weather Burea, Asheville, N.C.

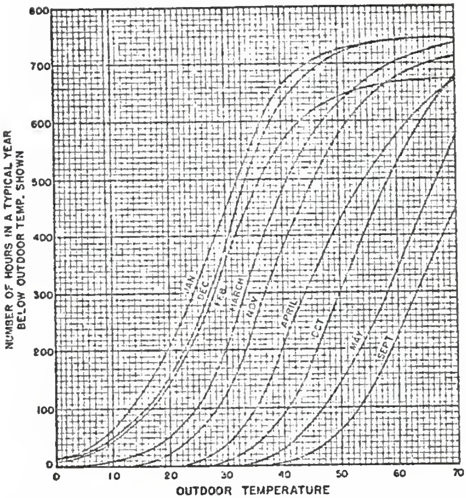

Figure 5. Climatological Data for an Area with 5500 to 6500 Degree Days. The outdoor temperatures are related to the hours of occurrence for the different months of the heating season. After U.S. Dept. of Commerce Weather Bureau, Asheville, N.C.

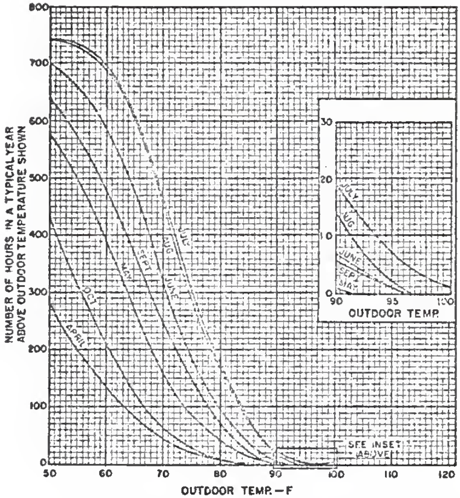

Figure 6. Climatological Data for an Area with 5500 to 6500 Degree Days. The outdoor temperatures are related to the hours of occurrence of the different months of the cooling season. After U.S. Deot. of Commerce Weather Burea, Asheville, N.C.

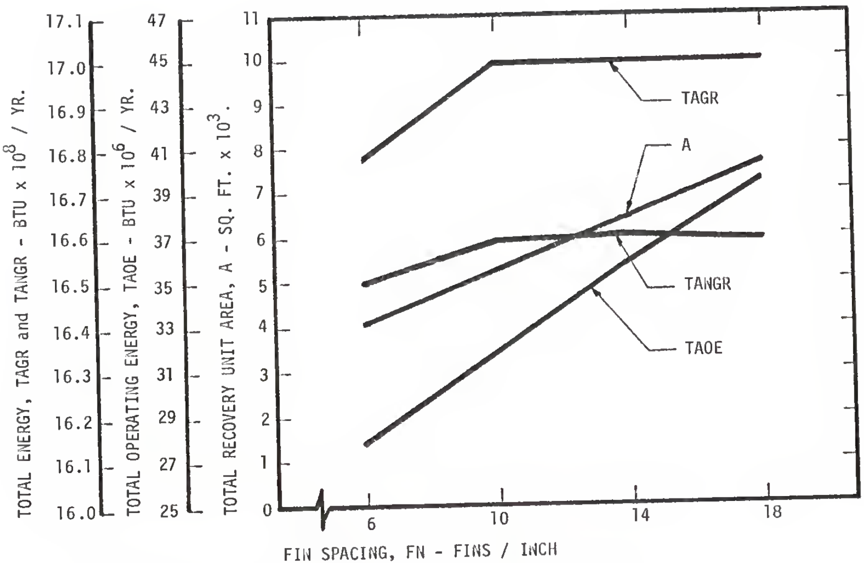

Figure 7. Effects of Fin Spacing on the Energy Recovered for an Area of 4000 to 5000 Degree Days.

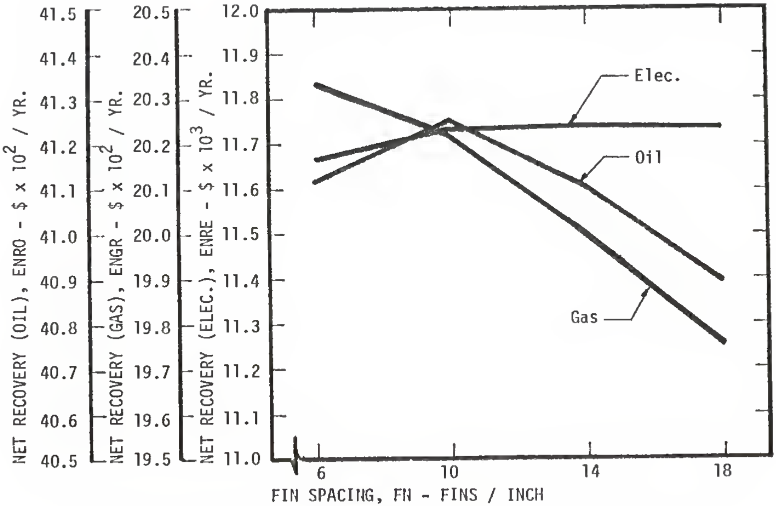

Figure 8. Effects of Fin Spacing on the Cost of Energy Recovered for an Area of 4000 to 5000 Degree Days.

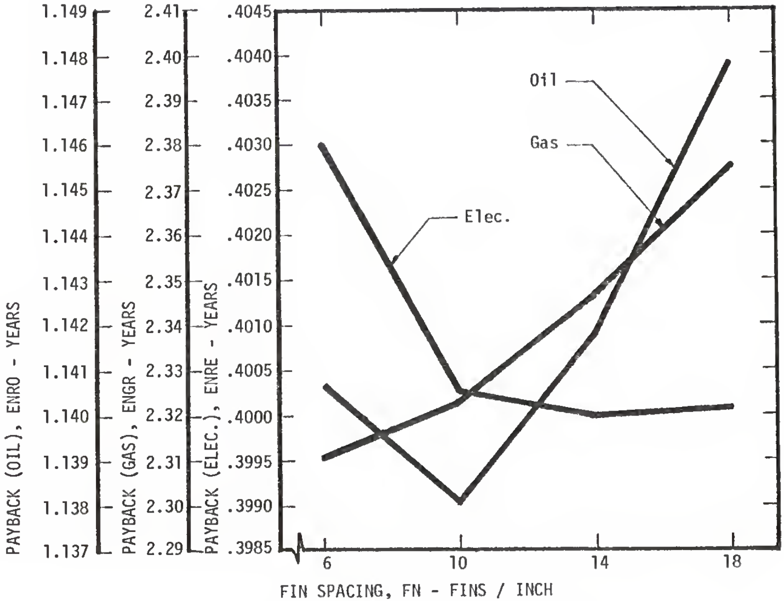

Figure 9. Effects of Fin Spacing on the Years Payback for an Area of 4000 to 5000 Degree Days.

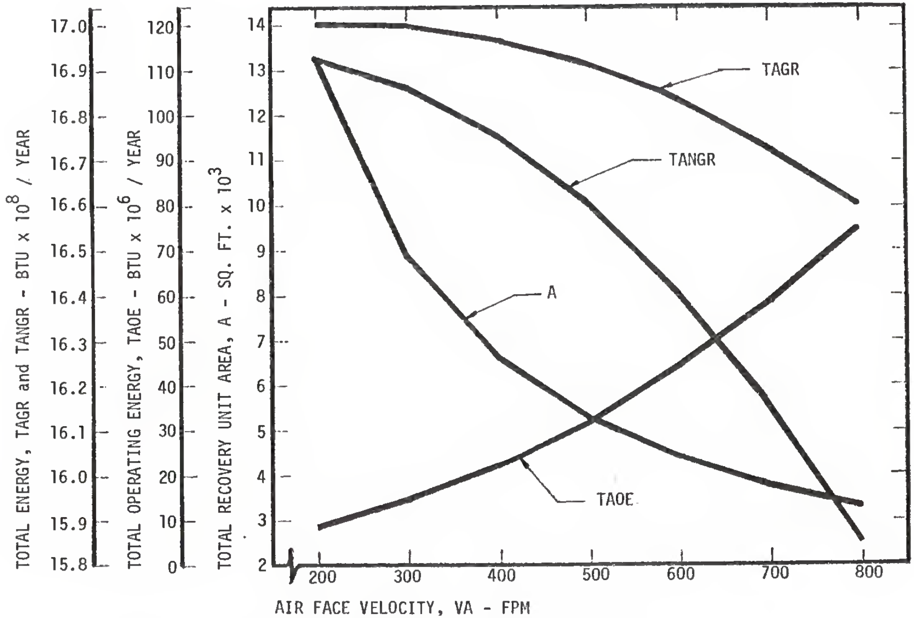

Figure 10. Effects of Air Face Velocity on Energy Recovered for an Area of 4000 to 5000 Degree Days.

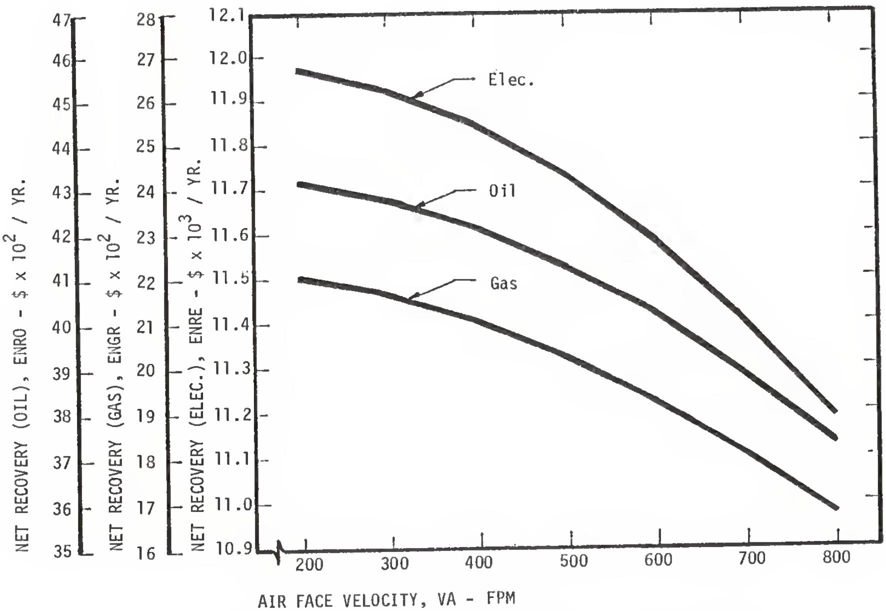

Figure 11. Effects of Air Face Velocity on the Cost of Energy Recovered for an Area of 4000 to 5000 Degree Days.

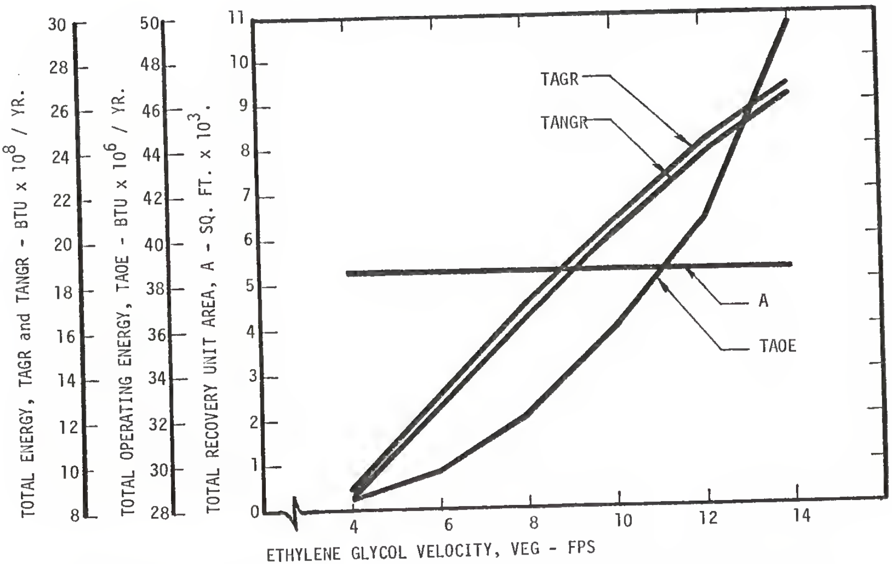

Figure 12. Effects of Ethylene Glycol Velocity on the Energy Recovered for an Area of 4000 to 5000 Degree Days.

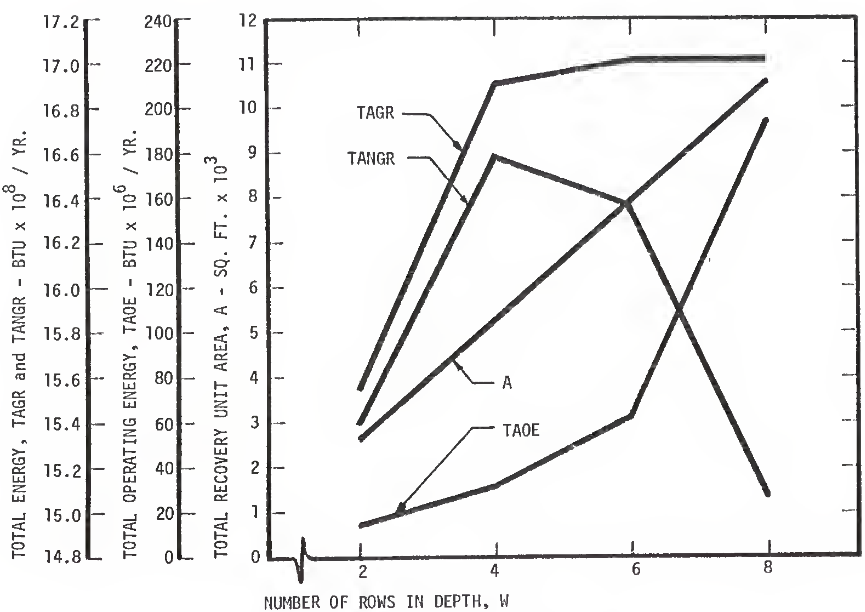

Figure 13. Effects of No. of Rows in Depth on Energy Recovered for an Area of 4000 to 5000 Degree Days.

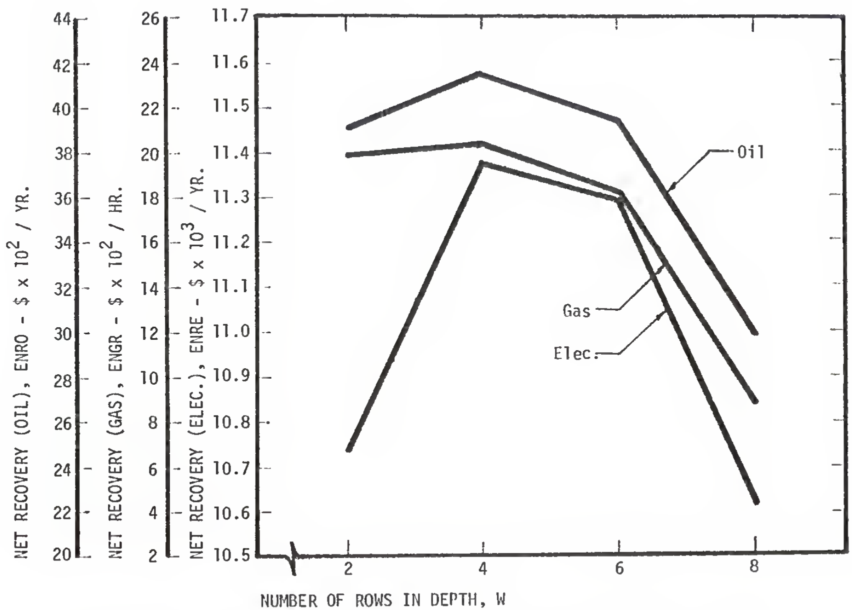

Figure 14. Effects of No. of Rows in Depth on the Cost of Energy Recovered for an Area of 4000 to 5000 Degree Days.

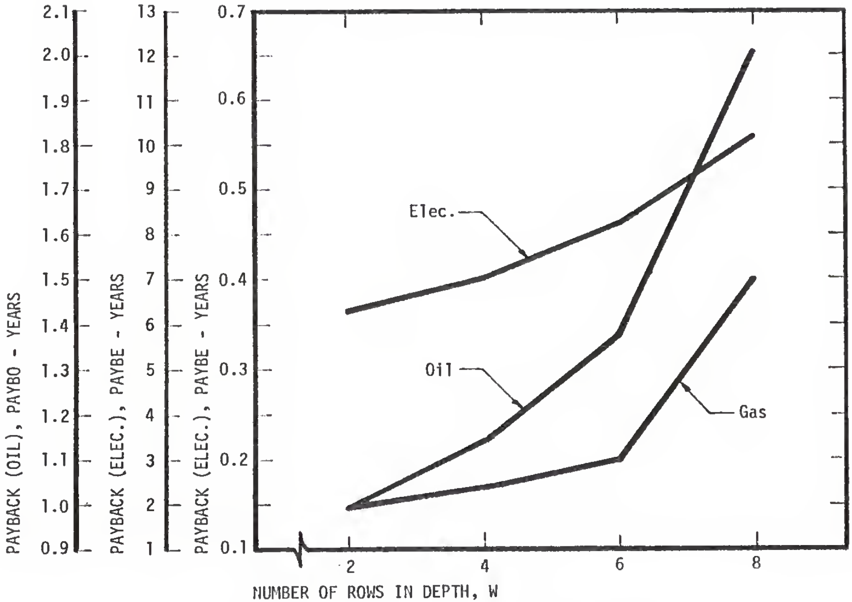

Figure 15. Effects of No. of Rows in Depth on the Years Payback for an Area of 4000 - 5000 Degree Days.

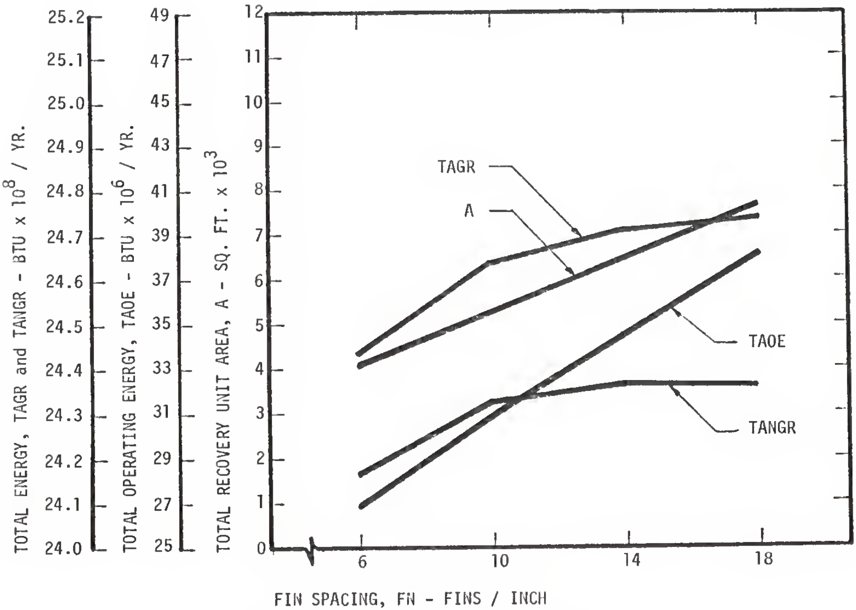

Figure 16. Effects of Fin Spacing on the Energy Recovered for an Area of 5500 to 6500 Degree Days.

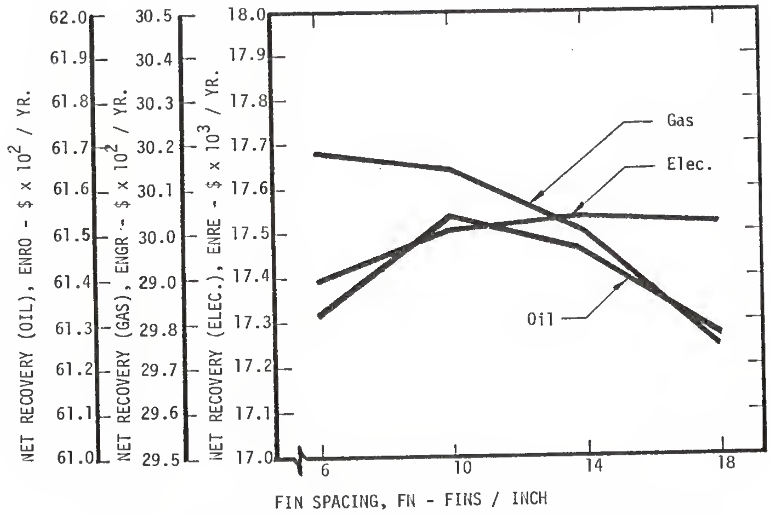

Figure 17. Effects of Fin Spacing on the Cost of Energy Recovered for an Area of 5500 to 6500 Degree Days.

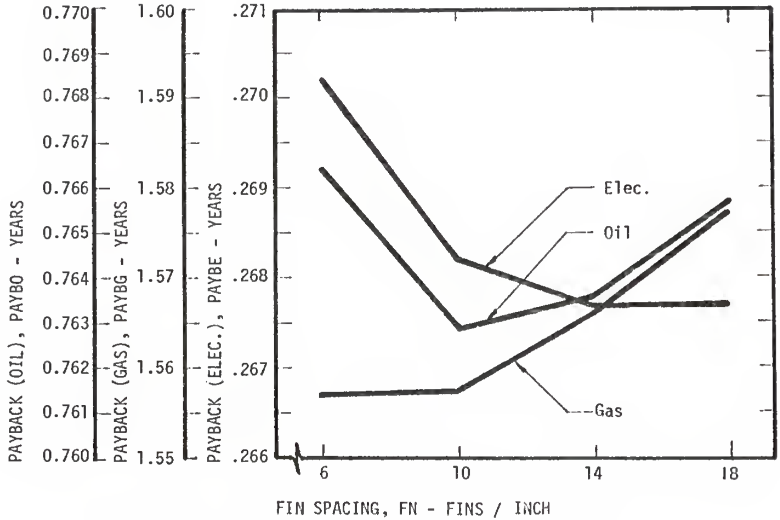

Figure 18. Effects of Fin Spacing on the Years Payback for an Area of 5500 to 6500 Degree Days.

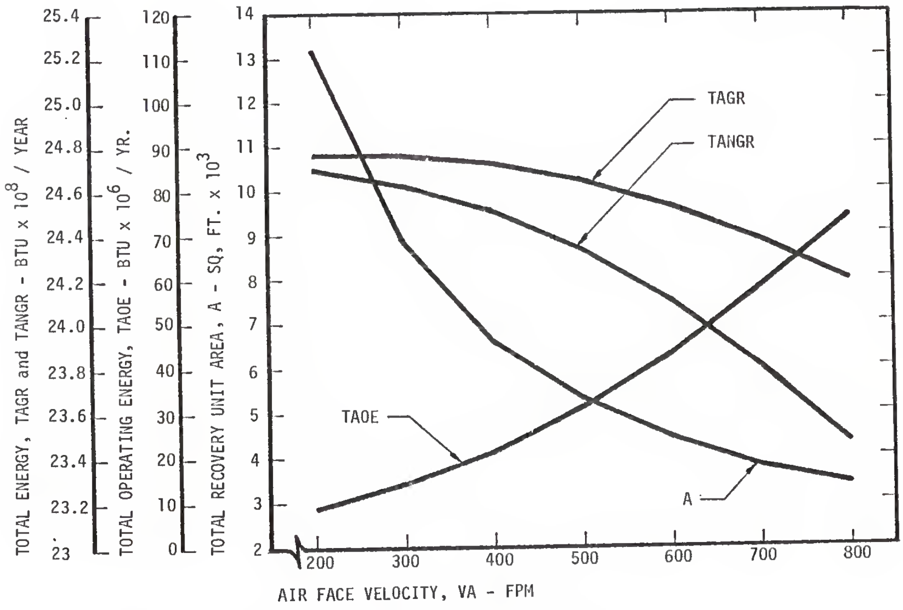

Figure 19. Effects of Air Face Velocity on Energy Recovered for an Area of 5500 to 6500 Degree Days.

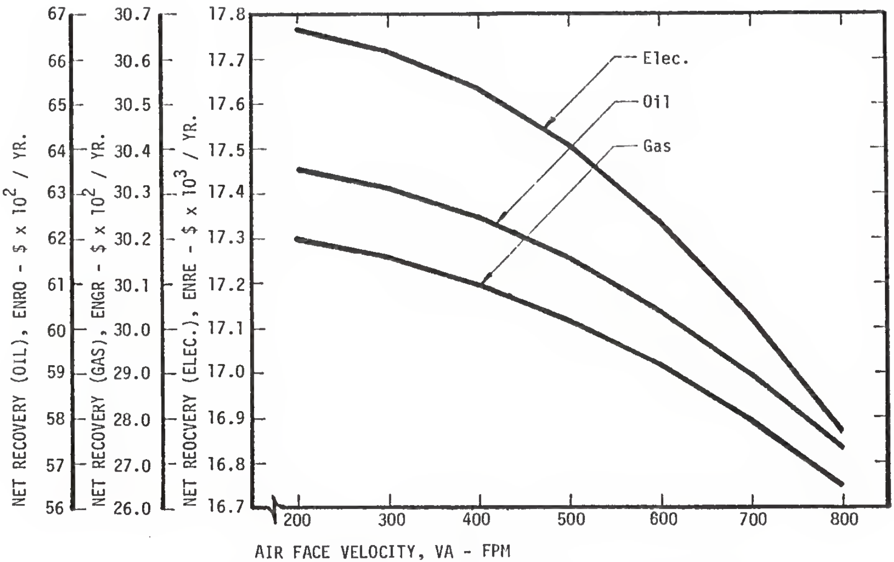

Figure 20. Effects of Air Face Velocity on the Cost of Energy Recovered for an Area of 5500 to 6500 Degree Days.

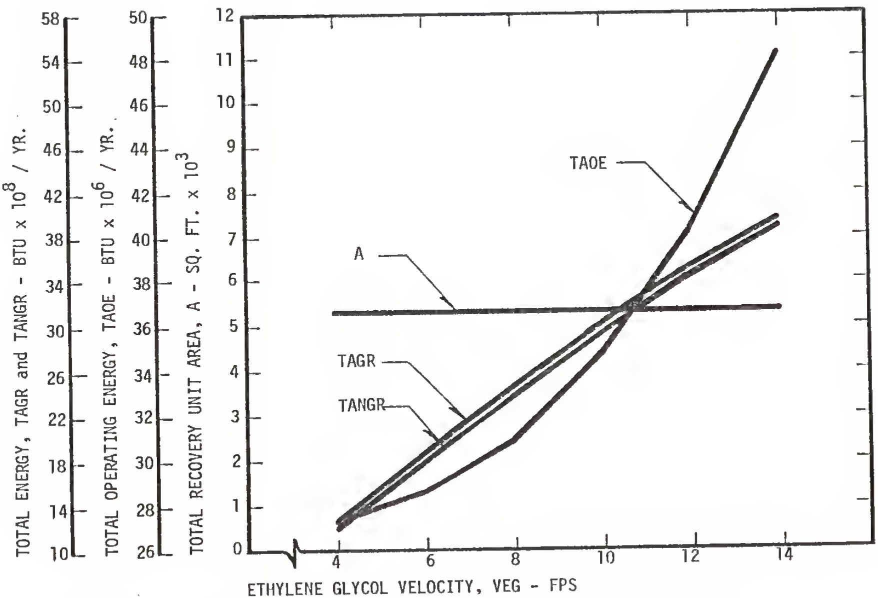

Figure 21. Effects of Ethylene Glycol Velocity on the Energy Recovered for an Area of 5500 to 6500 Degree Days.

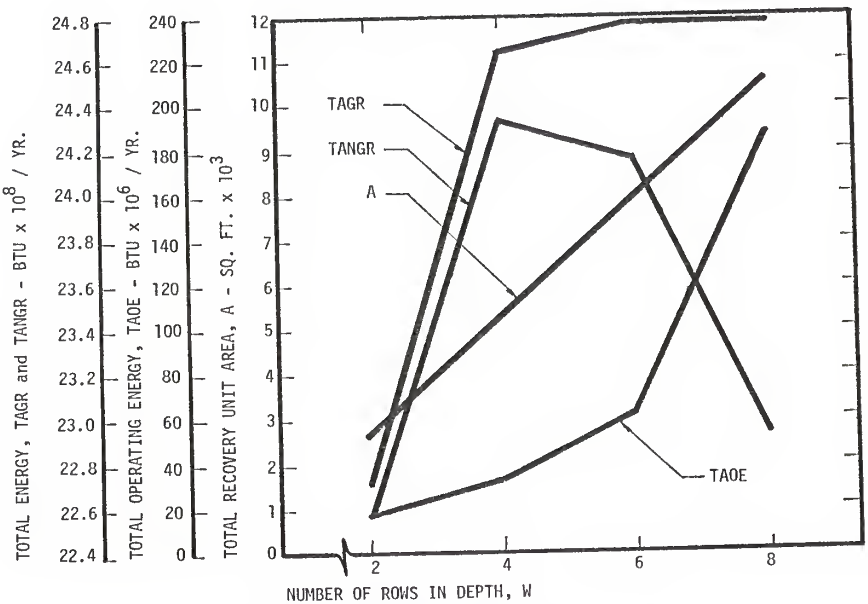

Figure 22. Effects of No. of Rows in Depth on Energy Recovered for an Area of 5500 - 6500 Degree Days.

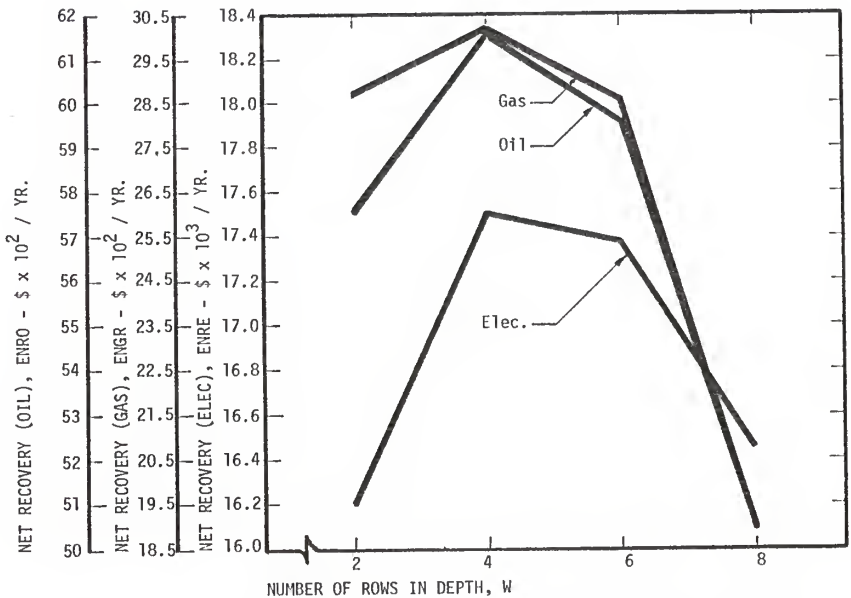

Figure 23. Effects of No. of Rows in Oepth on the Cost of Energy Recovered for an Area of 5500 to 6500 Oegree Days.

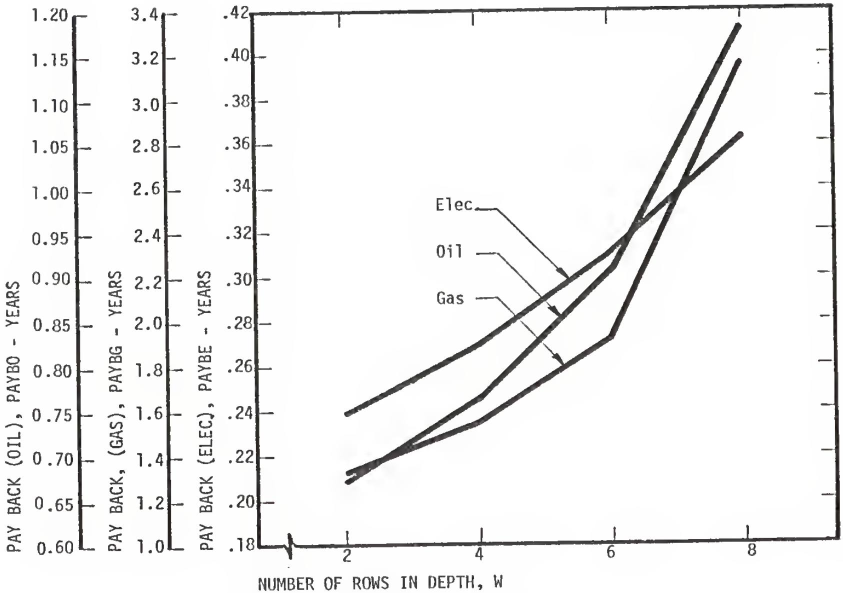

Figure 24. Effects of No. of Rows in Depth on the Years Pay Back for an Area of 5500 to 6500 Degree Days.

CHAPTER 5

"HEAT PIPE RECOVERY UNIT"

General Description

Figure 25 shows the typical ventilation system using the heat pipe recovery unit.

The efficiency of a "heat pipe" thermal recovery unit is the measure of its ability to recover thermal energy from one air stream and to transfer

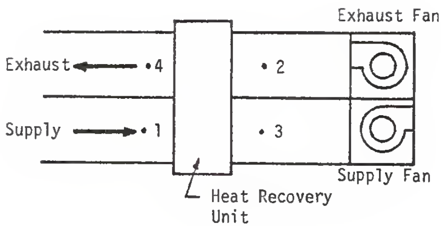

Figure 25. Arrangement of Heat Pipe Recovery Unit.

it into another air stream flowing in the opposite direction. The recovery factor (R) is the percentage of available sensible thermal energy that is recovered. The recovery factors are based on sensible heat transfer only, even though latent heat is transferred when condensation occurs on the unit.

The required information for analysis is supplied by the manufacturer of the unit. The data used here is from Q-DOT, but it is typical of other manufacturers of heat pipe units and even of data for other types of exchangers (heat wheel, recuperator, etc.)

The recovery factor of a unit varies with the geometry of the unit. For the heat pipe type the variables are the number of fins per inch, the number of rows of heat pipes, the mass flow ratio of the two streams, and the air density.

The pressure drop across each side of a thermal recovery unit is dependent upon the number of fins per inch, the number of rows of heat pipe, the air velocity, and the air density.

Analysis can be made by using characteristic curves. For this analysis characteristic curves for Q-PIPE thermal recovery units produced by Q-DOT CORPORATION [13] were chosen.

Air density corrections due to temperature and moisture variations are negligible. Altitude density corrections are significant and are included. Temperature and moisture density corrections must be considered for applications other than those within the comfort range.

No control is required for summer-winter switch over. Because the heat pipe units are bidirectional, transferring heat from the high temperature side to the other side, they automatically switch to the precooling mode whenever the exhaust becomes cooler than the air in the supply duct.

Theory and Modeling Equations

Heat Balance and Transfer Equations

The heat transfer and balance equations for this system were written as (see figure 25):

$$q_e = q_s \tag{27}$$

$$T_3 = T_1 + [R_a(T_2-T_1)] \tag{28}$$

$$T_4 = T_2 - [R_b(T_2-T_1)] \tag{29}$$

$$T_3 = T_1 + [R_b(T_2-T_1)] \tag{28a}$$

$$T_4 = T_2 - [R_a(T_2-T_1)] \tag{29a}$$

Equations 28 and 29 are used when supply air flow is smaller than exhaust flow. Equations 28a and 29a are used when supply air flow is larger than exhaust flow. If air flows are equal ($R_a = R_b$), any of these equations may be used.

The theory presented is that developed by Isothermics, Inc. [14]. Details of determination of R_a and R_b are given in Appendix C.

Frost Control Determination

The heat pipe units are easily adapted to face-and-by pass control, for frost prevention and temperature control, as shown in figure 26.

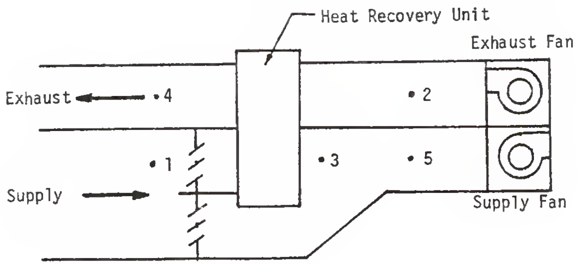

Figure 26. Schematic Diagram for Frost Control.

The preceding schematic diagram is followed to prevent frost in the exhaust air side. If the exhaust air temperature $T_4 < 32\ ^oF$, part of air supply is bypassed; this option is built in the program.

Another possibility to prevent frost is to pre-heat the supply air before it enters the recovery unit. This was not considered here because of its high initial and operation cost.

Characteristics Curves

A 6 row unit, 14 fins per inch, is chosen for this analysis. The performance curves are shown in figures 27, 28, and 29, and table 1. The general form of these curves was found as:

$$VS = [-7.3041216 + 1.027933\ AV - 0.253238 \times 10^{-4}\ AV^2] + [0.5277119 \times 10^{-2} - 0.6327463 \times 10^{-4}\ AV + 0.280454 \times 10^{-7}\ AV^2]\ H + [-0.6582271 \times 10^{-6} + 0.3537444 \times 10^{-8}\ AV - 0.3220021 \times 10^{-11}\ AV^2]\ H^2 \quad (30)$$

$$R = [0.4819098 + 0.3368778\ G - 0.6189942 \times 10^{-1}\ G^2] + [-0.366823 \times 10^{-3} + 0.1159242 \times 10^{-3}\ G - 0.87691 \times 10^{-4}\ G^2]\ VS + [0.2868927 \times 10^{-6} - 0.2522431 \times 10^{-6}\ G + 0.1094314 \times 10^{-6}\ G^2]\ VS^2 \quad (31)$$

$$APD = [-0.7787704 \times 10^{-1} - 0.1196548 \times 10^{-4} H + 0.1090248 \times 10^{-8} H^2] + [0.8309141 \times 10^{-3} + 0.9480123 \times 10^{-7} H - 0.6518396 \times 10^{-11} H^2] VS + [0.1757011 \times 10^{-5} - 0.2584665 \times 10^{-10} H + 0.1227925 \times 10^{-13} H^2] VS^2 \quad (32)$$

$$F_s = 1.08 - 3.825 \times 10^{-5} H + 3.75 \times 10^{-10} H^2 \quad (33)$$

Details of equations 30, 31, 32, and 33 are given in Appendix C.

Energy Equations

Energy savings at design temperature may be calculated as follows, assuming 100 percent energy utilization efficiency:

$$q = 1.08 \text{ cfms} \times F_s \times (T_3 - T_1) \quad (34)$$

Regarding the energy recovered per season, data from figures 3, 4, 5, and 6 have been used in the calculational program.

The fan operating energy is as in equation 11, and the net energy recovered is

$$q = q \text{ (energy recovered)} - q \text{ (operating energy for fans)} \quad (35)$$

The Cost Equations - Heat Pipe Units

To determine:

The Total Initial Cost:

$$\text{cost (\$)} = \sum \text{cost (Heat pipe unit + Labor + Fans)} \quad (36)$$

The Fan Operating Energy Cost:

$$\text{cost (\$)} = (\text{Fan BHP}) \times 0.746 \times \frac{\$}{\text{KW-HR}} (\text{Elec. cost}) \times \frac{\text{HRS}}{\text{YEAR}} \qquad (16)$$

The Total Capital Equipment Reduction

Equations 19, 20 and 21 are also used.

The Total Energy Gross Recovery:

Equations 22, 23 and 24 are also used.

The Net Energy Recovery Cost:

Equation 25 is used.

The Years of Pay Back:

Equation 26 is used.

The initial cost was selected on the basis of existing data, and may be changed for more recent information.

Calculational Scheme

A computer program (shown in Appendix D) was written for finding the equations of each curve in figures (27), (28), and (29). By selecting any three arbitrary points on these curves, R = f(VS), VS = f(H), and APD = f(VS) are obtained. The same program was then used to find the general equation of these curves as function of both variables for each figure (i.e., equations 30, 31, and 32).

A computer program (shown in Appendix E) was written which by inputting equations 30, 31, and 32, air flow rates, air temperatures, fan efficiencies, system's component cost, and unit heating and cooling costs, allowed calculation of R_a and R_b. With R_a and R_b known, the program then determined T_3 and T_4 as in equations (28) and (29) or (28-a) and (29-a). The program, using the selected input values, determines if the resulting T_4 is below 32 ^oF.

If T_4 is below 32 ^oF, the program option is selected which allows part of the supply air (as shown in figure 26) to be by-passed; then by fixing T_4 to be equal to 32 ^oF, T_3 and then T_5 were found.

The program then determines the energy recovered per season, the operating energy, the cost results, and the pay back period.

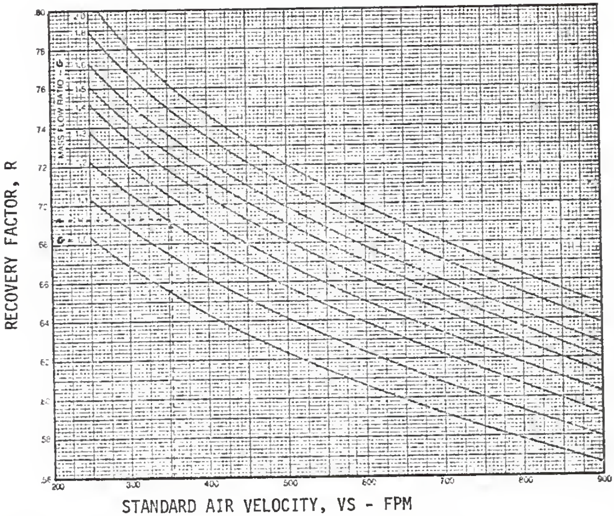

Figure 27. Recovery Performance for 6 Row Heat Pipe Recovery Unit, 14 Fins Per Inch.

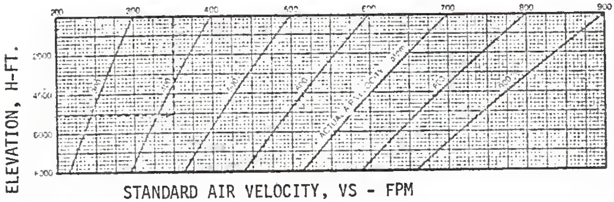

Figure 28. Elevation Correction for 6 Row Heat Pipe Recovery Unit, 14 Fins Per Inch.

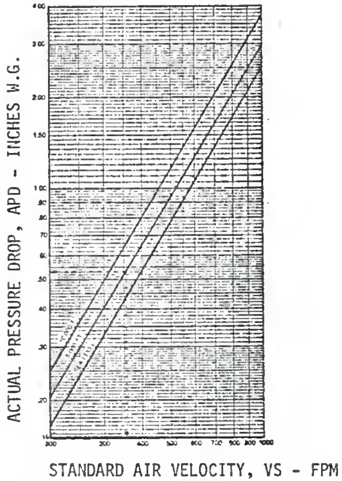

Figure 29. Air Friction for 6 Row Heat Pipe Recovery Unit, 14 Fins Per Inc.

ELEVATION	F_x	ELEVATION	F_x
Sea Level	1.080	5000 ft.	0.899
2000 ft.	1.005	6000 ft.	0.863
4000 ft.	0.934	8000 ft.	0.798

Table 1. Air Flow Correction Factor.

CHAPTER 6

SPECIFIC SYSTEM ANALYSIS

Results and Discussion

For the heat pipe system, the effect of air flow velocities on the system performance has been studied.

Figure 30, which based on an geographic location with 4000 to 5000 degree days, shows the effect of variation on the air face velocity (V) on the total annual gross recovered (TAGR), the total annual net gross recovered (TANGR), the total annual operating energy consummed for the fans (TAOE) and the face area of the recovery unit.

The total annual gross recovered decreases as the air face velocity increases, because the total annual gross recovered depends on the inlet and outlet air fresh temperature T_1 and T_3 correspondingly, provided T_1 is given (constant). T_3 is variable and depends upon recovery factor (R). The recovery factor decreases as the air face velocity increases, because of smaller area (see figure 27; recovery performance) for constant air flow capacity.

The total annual operating energy curve shows an increase as the air face velocity increases, due to air pressure drop (APO).

The total annual net energy recovered curve decreases as the air face velocity increases, because it depends upon the total annual energy recovered and inversely dependent on the total annual operating energy.

Recovery unit face area curve shows a decrease as the air face velocity increases, if the air flow capacity is constant.

The economical range of velocities is in between 400 to 600 fpm.

The total annual gross recovered, the total annual net gross recovered, and the recovery unit face area are higher at low air face velocity which means more expensive recovery unit but the total annual operating energy is low; however the reverse is true at higher velocity.

Figure 31, which based on an geographic location with 5500 to 6500 degree days, give the same result and conclusion.

The main difference between set 1 and set 2, degree days is that the total annual gross recovered and the total annual net gross recovered are directly proportional to the degree days.

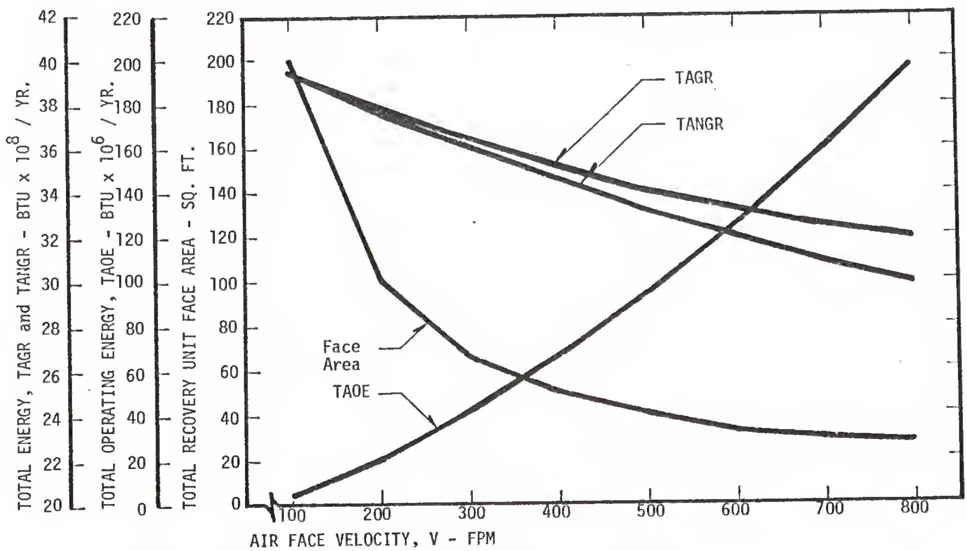

Figure 30. Effects of Air Face Velocity on the Energy Recovered for an Area of 4000 to 5000 Degree Days

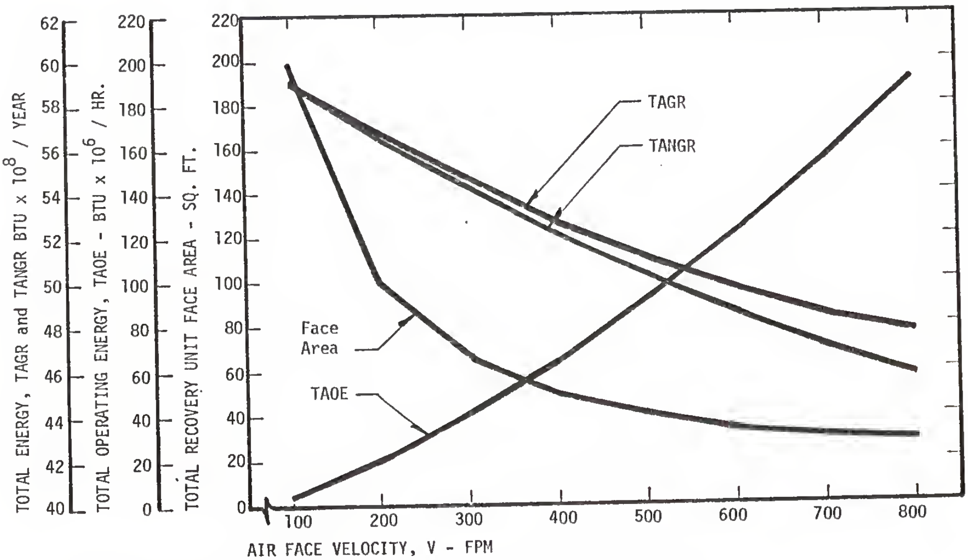

Figure 31. Effects of Air Face Velocity on the Energy Recovered for an Area of 5500 to 6500 Degree Days.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to analyze two heat recovery units, in order to determine the influence of specific parameters on the energy recovered. Thereafter, it was to decide the best system suited for a specific purpose in order to conserve some energy being wasted.

The basic equations describing the two systems, run-around coil system and heat-pipe recovery unit, were developed and the economic considerations were investigated.

The reason for selecting these two types was to provide analysis for two basically different systems as shown below;

A. Run-Around Coil System:

1. It is indirect heat transfer system.
2. Several coil parameters were varied and subjected to the study. Those coil parameters which cause the variation of heat transfer area.

B. Heat Pipe Recovery Unit:

1. It is direct heat transfer system.
2. The characteristic curves of this type, which were submitted by the manufacturer, was subject for the study (no parameters were selected, i.e. fixed coil dimensions).
3. According to the study of this type same can be applied for Rotary and Plate recovery types using characteristic curves from the manufacturer.

The study for run-around coil system was done by "built up" system of standard components available from a variety of manufacturers and notice the effect of variation of each parameter, keeping the others constant, on the net energy recovered (savings) and the coil size (initial cost) and repeat it for all the parameters.

The analysis for heat-pipe recovery unit depends on performance data reported by manufacturer. The effect of air flow velocity variation on the net energy recovered (saving) and the coil size (initial cost) was studied.

The study for the run-around coil system shows that:

1. Increasing the number of coil tubes or decrease the fin spacing leads to increase in coil cost and the pressure drop. It increases the heat transfer area (increase in initial coil cost). For this reason energy recovered increases but the net energy recovered (saving) shows maximum value for a specified values of the parameter.

2. Increasing the air flow velocity decreases the energy recovered and increases the pressure drop. The reduced coil size needed for the specified air flow quantity reduces the net energy recovered.

3. Increase in the ethylene glycol velocity increases the heat transfer coefficient. This increases the energy recovered, and increase glycol pumping cost (operating energy cost) which shows that effect on the net energy recovered (saving). A noticeable increase in net energy recovered (saving) was shown but glycol velocity is limited to 8 fps for the system to be operative under low pressure.

The study for heat-pipe recovery shows that the energy recovered decreases as the air flow velocity increases. A decrease in face coil area causes an increase in the operating energy. Thus a decrease in net energy recovered was noticed.

The problem can be extended in different directions. The effect of latent heat was not considered because the sensible heat-gain is much greater than the latent heat gain for most applications. The initial cost of the systems and their accessories, the heating and cooling cost were selected to be reasonable and maybe changed to reflect further increase. The additional cost necessary for pump and fan size increases was not considered here. This should be added in a more detailed analysis. No maintenance cost is included. It varies considerably with the unit size, proficiency of the servicing organization and the operating hours. Maintenance cost should be included if it is available.

The economic feasibility of inserting a unit in an existing system depends primarily on the savings in operating costs. These savings are dependent on the required volume and temperature delivered to the system, the volume and temperature of the exhaust, hours of operation, cost of energy, and the local design temperature.

From these calculations, it can be seen that either of the two heat recovery systems can be installed with a little or no extra cost. If savings in heating and cooling plants costs are taken into account, considerable savings could be availed in operating costs.

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APPENDIX A

Appendix A

Derivation of Heat Balance and Transfer Equations

The terms which are used in equation (2) are

Q_1 = 4.5 cfms

Q_2 = 4.5 cfme

$G_1 = C_{pa} \cdot Q_1$ = 0.24 x 4.5 cfms = 1.08 cfms

$G_2 = C_{pa} \cdot Q_2$ = 0.24 x 4.5 cfme = 1.08 cfme

From equation 2

$$G_3 (T_5-T_6) = G_1 (T_3-T_1) \qquad \text{(A-1)}$$

$$= U_1A_1 \frac{(T_5-T_3) - (T_6-T_1)}{\ell n[(T_5-T_3)/(T_6-T_1)]} \quad \text{for counter flow} \qquad \text{(A-2)}$$

Solving for T_3 in equation (A-1), and substituting into equation (A-2). The corresponding value of T_6 is

$$T_6 = T_5 - (T_5-T_1)\left(\frac{1-e^{D_1}}{RM_1-e^{D_1}}\right) \qquad \text{(A-3)}$$

where

$$D_1 = U_1A_1 \; [1/G_3 - 1/G_1]$$

and

$$RM1 = G_3/G_1$$

If T_5 is an estimated value to start the iteration, its new value after finding T_6 in equation (A-3) is,

$$T_5 = T_6 - (T_6-T_2)\left(\frac{1-e^{D_2}}{RM2-e^{D_2}}\right) \qquad \text{(A-4)}$$

where

$$D_2 = U_2A_2\ [1/G_4 - 1/G_2]$$

and

$$RM_2 = G_4/G_2$$

Equation (A-4) is used to iterate on T_5 if the by-pass value is not open. If not,

$$T_5 = T_7 - (T_7-T_2)\left(\frac{1-e^{D_2}}{RM_2-e^{D_2}}\right) \qquad \text{(A-5)}$$

Iteration is continued until a temperature balance is reached, so that from equation (2),

$$T_3 = T_1 + (T_5-T_6)\ RM_1, \qquad \text{(A-6)}$$

$$T_4 = T_2 - (T_5-T_6)\ RM_2 \quad \text{if by pass value is closed,} \qquad \text{(A-7)}$$

and

$$T_4 = T_2 - (T_5-T_7)\ RM_2 \quad \text{if by pass value is on.} \qquad \text{(A-8)}$$

Frost Control Determination

The program runs the selection and checks to see if the resulting T_7 is below 32 ^{o}F as follows:

Since the study is to find a maximum heat recovery as in equation (A-1), by analyzing the left term it is found that T_5 is constant. For a maximum heat recovery T_6 is selected to be equal to T_1, as initial value for the iteration, in order to keep a maximum value for the left term of equation (A-1), and start with T_7 = 32 ^{o}F.

Development of Make up and Exhaust Air Coils Equation

The circuiting coil is chosen of vertical headers feeding horizontal tube circuits in parallel, as shown in figure A-1. The flow of ethylene glycol through the U bends is counter to the flow of air. Pure counter flow was assumed in the coils

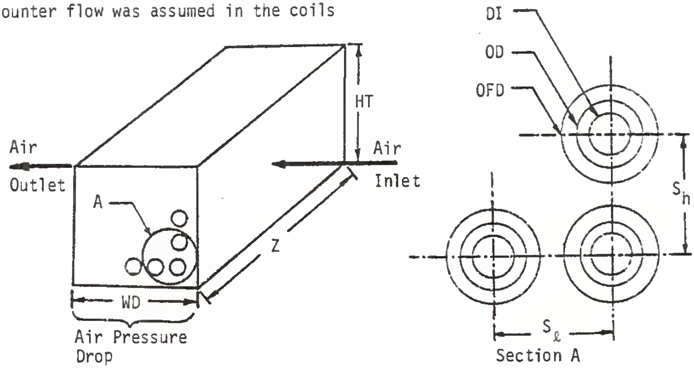

Figure A-1. Schematic Diagram for Run-Around Coil Concern

Further assumptions are

$$OD = \frac{5}{8}" = 0.052 \text{ ft.}$$

$$TK = 0.017" = 0.0014 \text{ ft.}$$

$$S_h = 1\frac{5}{8}" = 0.135 \text{ ft.}$$

$$S_\ell = 1\frac{5}{8}" = 0.135 \text{ ft.}$$

$$OFD = 2.44 \times OD = 0.127 \text{ ft.}$$

$$FTK = 0.014" = 0.0011 \text{ ft.}$$

The values of OD, TK, S_h and S_ℓ were selected from [5] consistent with equations 5 and 7.

The values of OFD and FTK were selected to maintain clearance of 0.1 inch between every two adjacent fins [8].

One of the most important steps in the study of heat transfer is to estimate the pressure drop and the rate of heat transfer for turbulent flow across tube bundles. But before such an estimation can be made, the Reynolds number must be determined. There are cases where laminar or transition flow takes place in the passage between tubes. In most actual applications, however, the flow is turbulent.

The tubes may be arranged either in staggered form or in in-line form; only the latter one is considered here. To achieve more generality, it is considered that there is no change in the tube diameter or the spacing from one bundle to another.

From equation (6), the pressure drop in cross flow was

$$APD = \frac{f\, G_s^2\, L_p}{(5.22x10^{10})\, D_v S\, \Phi_s} \left(\frac{D_v}{S_h}\right)^{0.4} \left(\frac{S_\ell}{S_h}\right)^{0.6} \quad lb/in^2 \qquad (A-9)$$

developed by Gunter and Shaw [9] and presented by Kern and Kraus [10]. The numerical factor (27.69) in equation (6) is to convert the dimensions to inches of water. The main terms in equation (A-9) can be found by

$$D_v = \frac{4\ FNV}{FRS}$$

where

$$FNV = [S_\ell \ x\ HT\ x\ Z - \frac{\pi}{4} OD^2\ x\ Z\ x\ RN\ x\ W - \frac{\pi}{4}(OFD^2 - OD^2)\ x\ FTK\ x\ RN\ x\ W]$$

$$FRS = (S_f + S_o)\ RN\ x\ Z$$

$$S_f = 6\pi(OFD^2 - OD^2)\ FN$$

$$S_o = 12\pi\ (1 - FN\ x\ FTK)\ OD$$

$$Z = CFM\ /\ (HT\ x\ VA)$$

$$G_s = \frac{Q}{a_s}$$

where

$$a_s = [HT - \{OD - (OFD-OD)\ FTK\ x\ FN\}\ RN]\ Z$$

$$S = \frac{\rho}{62.4} = \frac{0.635978195}{T_a}$$

where

$$\rho = \frac{14.7\ x\ 144}{53.3\ x\ T_a}$$

$$L_p = S_\ell \times W$$

$$\phi_s = (\mu / \mu_s)^{0.14}$$

ϕ_s can be considered to be 1, because the viscosity variation between the caloric temperature and the tube-wall temperature is small enough in the application considered here that it can be neglected.

To find the friction factor for air side (f), it is necessary to evaluate

$$R_e = \frac{\rho V_m D_v}{\mu} = \frac{G_s D_v}{\mu}$$

Figure A-2, shows correlations presented by Kern and Kraus [10]. The equation of the line is

$$f = 0.0025288 - 4.115 \times 10^{-9} R_e$$

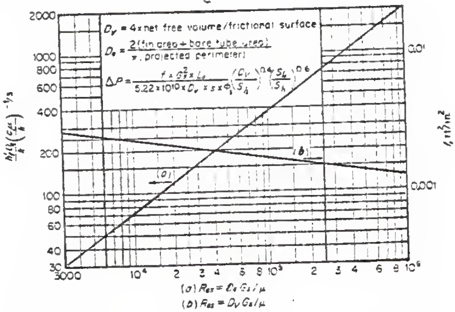

Figure A-2. Transverse-Fin Heat Transfer and Pressure Drop. (a) Jameson [Trans. ASME, 67:623-642 (1945)]; (b) Gunter and Shaw [Trans. ASME, 67: 643 (1945)].

Equation (7), the ethylene glycol pressure drop was

$$PEG = 1.495 \left(\frac{VEG}{3}\right)^{1.75} [0.0039\ WZ + 0.0875\ (W-1) + 0.3] \qquad \text{(A-10)}$$

as given by Stoecker [5]. Stoecker [5] recommends addition of 5 ft. of water head for interconnecting piping, when a glycol velocity varies from 1 to 6 fps. Since the head loss for steady, incompressible, constant-area flow is

$$h_{\ell} = f \frac{Z}{DI} \frac{VEG^2}{2g} = K \frac{VEG^2}{2g} \qquad \text{(A-11)}$$

by considering 3 fps glycol velocity in equation (A-11), K becomes equal to 35.78 and the head loss in equation (7) is equivalent to 5 ft water.

Derivation of Ethylene Glycol Equations

If the ethylene glycol with following physical properties (specific heat and specific gravity)

$$C_p = 0.602$$

$$S = 1.1$$

is mixed with water by X percent by weight, so the mixture physical properties is

$$C_p = (1 - 0.398\ X)$$

$$S = (1 + 0.1\ X)$$

$$\rho_{\underline{S}} = 62.4\ (1 + 0.1\ X)$$

then these relationships lead directly to equations (8) and (9).

Derivations of Operating Energy

$$\text{Fan BHP} = \frac{62.3 \times \text{CFM} \times \text{APD}}{12 \times 33000 \times \text{Eff.}}$$

$$= \frac{0.000157 \times \text{CFM} \times \text{APD}}{\text{Eff.}} \qquad \text{(A-12)}$$

Fan operating energy

$$= (\text{fan BHP}) \times 2545$$

$$\text{Pump BHP} = \frac{\text{GPM} \times S \times 8.333 \times \text{PEG}}{33000 \times \text{Eff.}}$$

$$= \frac{\text{GPM} \times S \times \text{PEG}}{3960 \times \text{Eff.}} \qquad \text{(A-13)}$$

Pump operating energy

$$= (\text{Pump BHP}) \times 2545$$

Equation (A-12) is developed by [11] and equation (A-13) is developed by [12].

Derivations of the Cost Equations

Equation (14) is based on weight of coil materials as presented by Edward [8]. A multiple of this cost is necessary to accomodate material cost increases. A factor of 8 greater than Edwards value was used for the results presented here. However, the multiple may be changed to reflect further increases or more accurate cost information.

Initial costs for pump, labor, ethylene, glycol and fans in equation (15) were selected to be reasonable and may be changed to reflect further increase.

The cost recovery and operation cost of the system, as in equations from 16 to 26, were based on the following:

a) Heating costs

It is assumed that as in [7] that

oil cost = 0.3 \$/gallon and its heating eff. = 0.82

gas cost = 1.05 \$/1000 ft^3 and its heating eff. = 0.8

electric cost = 0.025 \$/Kw-hr and its heating eff. = 1.0

Then

oil heating cost = 0.26 \$/Therm

gas heating cost = 0.13 \$/Therm

electric heating cost = 0.73 \$/Therm

b) Cooling Costs

Refrigeration system, (i.e. chiller) so

$$\text{Electric cooling costs} = 0.025 \frac{\$}{\text{Kw-hr}} \times 1 \frac{\text{Kw-hr}}{\text{Ton}}$$

$$= 0.025 \frac{\$}{\text{Ton}}$$

c) Working hours

Working hours values were taken from figures (3) and (4) for 4000 to 5000 degree days and from figures (5) and (6) for 5500 to 6500 degree days.

d) Average equipment costs

At design outside temperature (boiler for winter, chiller for summer), the average equipment cost is considered 125 $\frac{\$}{\text{Therm}}$ for boiler, and 90 $\frac{\$}{\text{Ton}}$ for chiller.

The values in sections a, b and d, above are as given by Trane Bulletin [7], but may be changed for more accurate cost information.

APPENDIX B

```
$JOB
C     ******************************************************************
C     *            -(( RUN-AROUND COIL SYSTEM   ))-                      *
C     *                                                                  *
C     * CFMS= SUPPLY AIR FLOW IN CFM                                     *
C     * CFME= EXHAUST AIR FLOW  IN CFM                                   *
C     *   WT= WINTER TEMPERATURE IN DEGREE FAH.                          *
C     *   ST= SUMMER TEMPERATURE IN DEGREE FAH.                          *
C     *    X= % OF THE ETHYLENE GLYCOL BY WEIGHT.                        *
C     *  VEG= ETHYLENE GLYCOL VELOCITY IN FPS.                           *
C     *   VA=AIR SIDE FACE VELOCITY IN FPM.                              *
C     *   OD= OUT-SIDE COIL TUBE DIAMETER IN FEET.                       *
C     *   FN= COIL FIN SPACING IN  FINS/INCH .                           *
C     *   RN= NO. OF ROWS IN HEIGHT                                      *
C     *    W= NO. OF ROWS IN DEEP                                        *
C     *  PEG= ETHYLENE GLYCOL PRESSURE DROP IN (FT. OF H2O )             *
C     *   FE= FAN EFFICIENCY IN (%)                                      *
C     *   PE= PUMP EFFICIENCY IN (%)                                     *
C     *  OEC= OPERATING ENERGY COST FOR THE FAN IN ($)                   *
C     *  OEP= OPERATING ENERGY COST FOR THE PUMP IN ($)                  *
C     *   GR= ENERGY GROSS RECOVERD IN BTUH.                             *
C     * WEFL= WINTER EQUIVALENT HEATING LOAD IN (HRS./YR.)               *
C     * SEFL= SUMMER EQUIVALENT COOLING LOAD IN (HRS./YR.)               *
C     *  OOT= OIL HEATING COST IN ($/THERM)                              *
C     *  OGT= GAS HEATING COST IN ($/THERM)                              *
C     *  OET= ELEC. HEATING COST IN ($/THERM)                            *
C     * OPKW= OPERATING ENERGY COST (ELEC.) IN ($/KW-HR.)                *
C     * OPTR= OPERATING ENERGY COST (ELEC.) IN ($/TON OF REFRIGERATION)*
C     * OCHT= BOILER CAPITAL EQUIPMENT REDUCTION IN ($/THERM)IGERATION)*
C     * OCCT= CHILLER CAPITAL EQUIPMENT REDUCTION IN ($/THERM)           *
C     * ENRO= NET RECOVERY (OIL) IN ($/YR.)                              *
C     * ENRG= NET RECOVERY (GAS) IN ($/YR.)                              *
C     * ENRE= NET RECOVERY (ELEC.) IN ($/YR.)                            *
C     * TGRO= TOTAL GROSS RECOVERED (OIL) IN ($/YR.)                     *
C     * TGRG= TOTAL GROSS RECOVERED (GAS) IN ($/YR.)                     *
C     * TGRE= TOTAL GROSS RECOVERED (ELEC.) IN ($/YR.)                   *
C     *  TOE= TOTAL OPERATING ENERGY COST IN ($/YR.)                     *
C     * TCRB= BOILER CAPITAL REDUCION IN ($)                             *
C     * TCRC= CHILLER CAPITAL REDUCION IN ($)                            *
C     * EICL= LABOR INITIAL COST IN ($)                                  *
C     * EICF= FANS INITIAL COST IN ($)                                   *
C     * TCER= TOTAL CAPITAL EQUIPMENT REDUCTION IN ($)                   *
C     *  EIC= TOTAL INITIAL COST IN ($)                                  *
C     * TAOE= TOTAL ANNUAL OPERATING ENERGY IN (BTU/YR.)                 *
C     *TAHGR= TOTAL ANNUAL HEATING GROSS RECOVERY IN (BTU/YR.)           *
C     *TACGR= TOTAL ANNUAL COOLING GROSS RECOVERY IN (BTU/YR.)           *
C     * TAGR= TOTAL ANNUAL GROSS RECOVERY IN (BTU/YR.)                   *
C     *TANGR= TOTAL ANNUAL NET GROSS RECOVERY IN (BTU/YR.)               *
C     *PAYBO= PAYBACK (IN CASE OIL USED FOR HEATING) IN (YRS.)           *
C     *PAYBG= PAYBACK (IN CASE GAS USED FOR HEATING) IN (YRS.)           *
C     *PAYBE= PAYBACK (IN CASE ELEC. USED FOR HEATING) IN (YRS.)         *
C     ******************************************************************
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 LP1,LP2
      DIMENSION OLDT(50),OLDH(50),RNEWT(50),RNEWH(50)
      REAL WTII/0.0/,STII/95.0/
      MM=1
      READ(5,44) KK
      READ(5,*)     CFMS,CFME,WT2,ST2,X,OD1,OD2,TK1,TK2,SH1,SH2,
     *              SL1,SL2,RN1,RN2,FTK1,FTK2,FE1,FE2,PE,WEFL,SEFL,
     *              EICP,EICPI,EICL,EICG,EICF,OOT,OGT,OET,OPKW,
```

```
     *                  OPTR,OCHT,DCCT,VIS1,VIS2
   5 READ(5,*)          VEG,VA1,VA2,FN1,FN2,W1,W2
     WT1=WT11
     ST1=ST11
     IF(MM.EQ.1.AND.MM.LT.2) GO TO 8
     IF(MM.EQ.2.AND.MM.LT.3) GO TO 9
     IF(MM.EQ.3.AND.MM.LT.4) GO TO 10
     IF(MM.EQ.4.AND.MM.LT.5) GO TO 11
     IF(MM.EQ.5.AND.MM.LT.6) GO TO 13
     IF(MM.EQ.6.AND.MM.LT.7) GO TO 46
     IF(MM.EQ.7.AND.MM.LT.8) GO TO 48
     IF(MM.EQ.8.AND.MM.LT.9) GO TO 53
   8 WRITE(6,28)
     GO TO 35
   9 WRITE(6,29)
     GO TO 35
  10 WRITE(6,34)
     GO TO 35
  11 WRITE(6,50)
     GO TO 35
  13 WRITE(6,51)
     GO TO 35
  46 WRITE(6,49)
     GO TO 35
  48 WRITE(6,52)
     GO TO 35
  53 WRITE(6,54)
  35 PRINT 19
     PRINT 22
     PRINT 19
     WRITE(6,299) CFMS,CFME,WT1,WT2,ST1,ST2,VEG,X,DD1,DD2,VA1,VA2,
C                 FN1,FN2,SH1,SH2,SL1,SL2,RN1,RN2,W1,W2,FE1,FE2,PE,
C                 WEFL,SEFL,EICP,EICPI,EICL,EICG,EICF,TK1,TK2,DDT,
C                 DGT,DET,DPKW,DPTR,DCHT,DCCT,VIS1,VIS2,FTK1,FTK2
     DI1=DD1-2.*TK1
     DI2=DD2-2.*TK2
     OFD1=2.44*DD1
     OFD2=2.44*DD2
     HT1=SH1*RN1
     HT2=SH2*RN2
     Z1=CFMS/(HT1*VA1)
     Z2=CFME/(HT2*VA2)
     WD1=SL1*W1
     WD2=SL2*W2
     AO1=(11.*DD1*Z1*RN1*W1)/(42.0)
     AO2=(11.*DD2*Z2*RN2*W2)/(42.0)
     FRS1=((132.0*Z1*RN1)/(7.0))*(FN1*((OFD1**2)-(DD1**2))
    1 +2.*DD1*(1.-FN1*FTK1))
     FRS2=((132.0*Z2*RN2)/(7.0))*(FN2*((OFD2**2)-(DD2**2))
    1 +2.*DD2*(1.-FN2*FTK2))
     A1=FRS1*W1
     A2=FRS2*W2
     Q1=4.5*CFMS
     Q2=4.5*CFME
     G1=1.08*CFMS
     G2=1.08*CFME
     TAHGR=0.0
     TACGR=0.0
     NSET=1
     LL=1
```

```
      LLL=1
  997 READ(5,1) INDEX
      READ (5,1) N
      DO 12 I=1,N
   12 READ (5,3) OLDT(I),OLDH(I)
      IF(INDEX.EQ.1)GO TO 999
      NMAX=1
   89 CONTINUE
      IF(STLL-OLDT(NMAX)) 999,999,79
   79 NMAX=NMAX+1
      GO TO 89
  999 CONTINUE
      VEG2=VEG
      GPM2=352.5338*VEG2*(DI2**2)
      U2=1.D/((2.75/(VA2**0.58))+(0.0183)+((1.975*FN2+1.05)/
     *(166.0*(VEG2**0.8))))
      UA2=U2*A2
      Q4=176431.8434*VEG2*(DI2**2)*(1.+0.1*X)
      G4=Q4*(1.-0.398*X)
      D2=UA2*(1.0/G4-1.0/G2)
      RM2=G4/G2
      FNV1=((SL1*HT1*Z1)-((11.*(OD1**2)*Z1*RN1*W1)/14.)-((11.*FTK1*RN1*
     1 W1*((OFD1**2)-(OD1**2)))/14.))
      FNV2=((SL2*HT2*Z2)-((11.*(OD2**2)*Z2*RN1*W2)/14.)-((11.*FTK2*RN2*
     1 W2*((OFD2**2)-(OD2**2)))/14.))
      DV1=4.*FNV1/FRS1
      DV2=4.*FNV2/FRS2
      AS1=Z1*(HT1-RN1*OD1-RN1*FN1*FTK1*(OFD1-OD1))
      AS2=Z2*(HT2-RN2*OD2-RN2*FN2*FTK2*(OFD2-OD2))
      GS1=Q1/AS1
      GS2=Q2/AS2
      RE1=DV1*GS1/VIS1
      RE2=DV2*GS2/VIS2
      F1=D.0025288-(4.115/(1D.**9))*RE1
      F2=D.0025288-(4.115/(1D.**9))*RE2
      LP1=SL1*W1
      LP2=SL2*W2
      VEG1=GPM2/(352.5338*(DI1**2))
      GPM1=352.5338*VEG1*(DI1**2)
      U1=1.0/((2.75/(VA1**D.58))+(0.0183)+((1.975*FN1+1.05)/
     *(166.0*(VEG1**0.8))))
      UA1=U1*A1
      Q3=176431.8434*VEG1*(DI1**2)*(1.+0.1*X)
      G3=Q3*(1.-D.398*X)
      D1=UA1*(1.0/G3-1.0/G1)
      RM1=G3/G1
      IF(INDEX.EQ.2) GO TO 45
      IF(WT1.NE.WT11) WT1=WT1OLD
      WET5=0.5*(WT1+WT2)
   27 WT6=WET5-(WET5-WT1)*((1.D-DEXP(D1))/(RM1-DEXP(D1)))
      WT5=WT6-(WT6-WT2)*((1.-DEXP(D2))/(RM2-DEXP(D2)))
      IF(DABS(WET5-WT5)-(1.0D-9).LE.0) GO TO 222
      WET5=WT5
      GO TO 27
  222 WT3=WT1+(WT5-WT6)*RM1
      WT4=WT2-(WT5-WT6)*RM2
      IF(WT6-32.0) 767,221,221
  767 WT7=32.0
      WT6=WT1
      WT55=WT7-(WT7-WT2)*((1.-DEXP(D2))/(RM2-DEXP(D2)))
```

```
757 VEG1=((WT55-WT7)*VEG2*(DI2**2))/((WT55-WT6)*(DI1**2))
    GPM1=352.5338*VEG1*(DI1**2)
    U1=1.0/((2.75/(VA1**0.58))+(0.0183)+((1.975*FN1+1.05)/
   *(166.0*(VEG1**0.8))))
    UA1=U1*A1
    Q3=176431.8434*VEG1*(DI1**2)*(1.+0.1*X)
    G3=Q3*(1.-0.398*X)
    O1=UA1*(1.0/G3-1.0/G1)
    RM1=G3/G1
    WT6=WT55-(WT55-WT1)*((1.0-DEXP(O1))/(RM1-DEXP(O1)))
    WT7=((Q3*WT6)+(Q4-Q3)*WT55)/Q4
    WT5=WT7-(WT7-WT2)*((1.-DEXP(O2))/(RM2-DEXP(O2)))
    IF(DABS(WT55-WT5)-(1.0D-9).LE.0) GO TO 223
    WT55=WT5
    GO TO 757
223 WT3=WT1+(WT5-WT6)*RM1
    WT4=WT2-(WT5-WT7)*RM2
221 IF(WT1.NE.WT11) GO TO 47
    Q5=Q4-Q3
    WVEG1=VEG1
    WVEG2=VEG2
    WWT1=WT1
    WWT2=WT2
    WWT3=WT3
    WWT4=WT4
    WWT5=WT5
    WWT6=WT6
    WWT7=WT7
    GPM11=GPM1
    U11=U1
    UA11=UA1
    RM11=RM1
    D11=O1
    Q11=Q1
    G11=G1
    Q22=Q2
    G22=G2
    Q33=Q3
    G33=G3
    Q44=Q4
    G44=G4
    Q55=Q5
    GPM22=GPM2
    U22=U2
    UA22=UA2
    RM22=RM2
    WTA1=(0.5*(WWT1+WWT3)+460.)
    WTA2=(0.5*(WWT2+WWT4)+460.)
 45 CONTINUE
    IF(ST1.NE.ST11) ST1=ST1OLO
    SET5=0.5*(ST1+ST2)
 39 ST6=SET5-(SET5-ST1)*((1.0-DEXP(O1))/(RM1-DEXP(O1)))
    ST5=ST6-(ST6-ST2)*((1.0-DEXP(O2))/(RM2-DEXP(O2)))
    IF(DABS(SET5-ST5)-(1.0D-9).LE.0) GO TO 225
    SET5=ST5
    GO TO  39
225 ST3=ST1+(ST5-ST6)*RM1
    ST4=ST2-(ST5-ST6)*RM2
    IF(ST1.NE.ST11) GO TO 47
    SVEG1=VEG1
```

```
      SVEG2=VEG2
      SST1=ST1
      SST2=ST2
      SST3=ST3
      SST4=ST4
      SST5=ST5
      SST6=ST6
      STA1=(0.5*(SST1+SST3)+460.)
      STA2=(0.5*(SST2+SST4)+460.)
   47 CONTINUE
C
      CALL HOURS (INOEX,WT1,WT3,ST1,ST3,N,OLOT,OLOH,RNEWT,RNEWH,TAHGR,
     1            TACGR,CFMS,LL,LLL,WT1OLO,ST1OLO,NMAX )
C
      IF(INOEX.EQ.2) GO TO 111
      IF(WT1.LE.70.0.AND.WT1.LE.WT2) GO TO 999
      GO TO 113
  111 IF(ST1.GE.50.0.AND.ST1.GE.ST2) GO TO 45
  113 CONTINUE
      NSET=NSET+1
      IF(NSET-2) 997,997,1000
 1000 CONTINUE
      WDEN1=39.685/WTA1
      WDEN2=39.685/WTA2
      WS1=WDEN1/62.4
      WS2=WDEN2/62.4
      WAPO1=(F1*LP1*(GS1**2)*((OV1/SH1)**0.4)*((SL1/SH1)**0.6)*27.6923)
     1 /(OV1*WS1*(5.22*(10.**10)))
      WAPO2=(F2*LP2*(GS2**2)*((OV2/SH2)**0.4)*((SL2/SH2)**0.6)*27.6923)
     1 /(OV2*WS2*(5.22*(10.**10)))
      WGRD= TAHGR*DDT/100000.
      WGRG= TAHGR*DGT/100000.
      WGRE= TAHGR*DET/100000.
      WOEC1=(0.746*OPKW *CFMS*WAPO1)*WEFL/(6356.0*FE1)
      WOEC2=(0.746*OPKW *CFME*WAPO2)*WEFL/(6356.0*FE2)
      WGR1=1.08*CFMS*(WWT3-WWT1)
      WGR2=1.08*CFME*(WWT2-WWT4)
      WPEG1=(1.495)*((WVEG1/3.0)**1.75)*(1.+0.1*X)*(0.0039*W1*Z1*12+
     * 0.0875*(W1-1.0)+0.3)+((35.78/64.4)*(WVEG1**2))
      WPEG2=(1.495)*((WVEG2/3.0)**1.75)*(1.+0.1*X)*(0.0039*W2*Z2*12+
     * 0.0875*(W2-1.0)+0.3)+((35.78/64.4)*(WVEG2**2))
      WPEG=2.0*WPEG2
      WOEP=(0.746*GPM2*WPEG*OPKW )*WEFL/(3960*PE)
      SDEN1=39.685/STA1
      SDEN2=39.685/STA2
      SS1=SDEN1/62.4
      SS2=SDEN2/62.4
      SAPO1=(F1*LP1*(GS1**2)*((OV1/SH1)**0.4)*((SL1/SH1)**0.6)*27.6923)
     1 /(OV1*SS1*(5.22*(10.**10)))
      SAPO2=(F2*LP2*(GS2**2)*((OV2/SH2)**0.4)*((SL2/SH2)**0.6)*27.6923)
     1 /(OV2*SS2*(5.22*(10.**10)))
      SGR= TACGR*DPTR/12000.
      SGR1=1.08*CFMS*(SST1-SST3)
      SGR2=1.08*CFME*(SST4-SST2)
      SOEC1=(0.746*OPKW *CFMS*SAPO1)*SEFL/(6356.0*FE1)
      SOEC2=(0.746*OPKW *CFME*SAPO2)*SEFL/(6356.0*FE2)
      SPEG1=(1.495)*((SVEG1/3.0)**1.75)*(1.+0.1*X)*(0.0039*W1*Z1*12+
     * 0.0875*(W1-1.0)+0.3)+((35.78/64.4)*(WVEG1**2))
      SPEG2=(1.495)*((SVEG2/3.0)**1.75)*(1.+0.1*X)*(0.0039*W2*Z2*12+
     * 0.0875*(W2-1.0)+0.3)+((35.78/64.4)*(WVEG2**2))
```

```
      SPEG=SPEG1+SPEG2
      SOEP=(0.746*GPM2*SPEG*OPKW )*SEFL/(3960*PE)
      TGRO=WGRO+SGR
      TGRG=WGRG+SGR
      TGRE=WGRE+SGR
      TOE=WOEC1+SOEC1+WOEC2+SOEC2+WOEP+SOEP
      TAOE=TOE*3413.0/0.025
      ENRO=TGRO-TOE
      ENRG=TGRG-TOE
      ENRE=TGRE-TOE
      EICC1=8.0*AO1*((19.1-0.083*Z1)/((W1**0.333)*((AO1/1000.)**0.13)))
      EICC2=8.0*AO2*((19.1-0.083*Z2)/((W2**0.333)*((AO2/1000.)**0.13)))
      TCRB=OCHT *WGR1/100000.0
      TCRC=OCCT*SGR1/12000.0
      TCER=TCRB+TCRC
      EIC=EICC1+EICC2+EICP+EICPI+EICL+EICG+EICF
      A=A1+A2
      TAGR=TAHGR+TACGR
      TANGR=TAGR-TAOE
      TGRPA=TAGR/A
      PAYBO=(EIC-TCER)/ENRO
      PAYBG=(EIC-TCER)/ENRG
      PAYBE=(EIC-TCER)/ENRE
      PRINT 19
      PRINT 101
  101 FORMAT('*',20X,' (WINTER RESULT ) ')
      PRINT 19
      WRITE(6,102) WWT3,WWT4,WWT5,WWT6,GPM11,GPM22,Q11,Q22,Q33,Q44,Q55,
     *             G11,G22,G33,G44,O11,O2,U11,U22,UA11,UA2,RM11,RM22,
     *             WVEG1,WVEG2,WPEG1,WPEG2,WPEG,WAPO1,WAPO2,WOEP,WGR1,
     *             WGR2,WGRO,WGRG,WGRE,WOEC1,WOEC2,WWT7
      IF(Q5.GT.0.0) GO TO 107
  107 WRITE(6,108)
      PRINT 19
      PRINT 103
  103 FORMAT('*',20X,' (SUMMER RESULT ) ')
      PRINT 19
      WRITE(6,104) SST3,SST4,SST5,SST6,GPM1,GPM2,Q1,Q2,Q3,Q4,
     *             SDEN1,G1,G2,G3,G4,O1,O2,U1,U2,UA1,UA2,RM1,
     *             RM2,SVEG1,SVEG2,SPEG1,SPEG2,SPEG,SAPO1,
     *             SAPO2,SOEP,SGR1,SGR2,SOEC1,SOEC2,SGR
      PRINT 19
      PRINT 105
  105 FORMAT('*',20X, '(COMMON AND CONCLUSION RESULTS)')
      PRINT 19
      WRITE(6,106) HT1,HT2,WO1,WO2,Z1,Z2,TGRO,TGRG,TGRE,TAOE,ENRO,
     *             ENRG,ENRE,TCRB,TCRC,TCER,EIC,TAHGR,TACGR,TAGR,
     *             TGRPA,PAYBO,PAYBG,PAYBE,TANGR,A
      PRINT 19
    1 FORMAT(I3)
    3 FORMAT(F7.1,F8.1)
   19 FORMAT('*',  80('*'))
   22 FORMAT('*', 20X,'( INPUT DATA )')
   28 FORMAT('1',10X,'THIS CASE FOR  AIR VELOCITY (V)=100 FPM ')
   29 FORMAT('*',10X,'THIS CASE FOR  AIR VELOCITY (V)=200 FPM ')
   34 FORMAT('*',10X,'THIS CASE FOR  AIR VELOCITY (V)=300 FPM ')
   50 FORMAT('*',10X,'THIS CASE FOR  AIR VELOCITY (V)=400 FPM ')
   51 FORMAT('*',10X,'THIS CASE FOR  AIR VELOCITY (V)=500 FPM ')
   49 FORMAT('*',10X,'THIS CASE FOR  AIR VELOCITY (V)=600 FPM ')
   52 FORMAT('*',10X,'THIS CASE FOR  AIR VELOCITY (V)=700 FPM ')
```

```
 54 FORMAT('*',10X,'THIS CASE FOR  AIR VELOCITY (V)=800 FPM ')
 44 FORMAT(I4)
299 FORMAT(   /,9X,'CFMS  =',E12.5,5X,'CFME  =',E12.5,5X,'WT1   =',E12.5,
   *          /,9X,'WT2   =',E12.5,5X,'ST1   =',E12.5,5X,'ST2   =',E12.5,
   *          /,9X,'VEG   =',E12.5,5X,'X     =',E12.5,5X,'OD1   =',E12.5,
   *          /,9X,'OD2   =',E12.5,5X,'VA1   =',E12.5,5X,'VA2   =',E12.5,
   *          /,9X,'FN1   =',E12.5,5X,'FN2   =',E12.5,5X,'SH1   =',E12.5,
   *          /,9X,'SH2   =',E12.5,5X,'SL1   =',E12.5,5X,'SL2   =',E12.5,
   *          /,9X,'RN1   =',E12.5,5X,'RN2   =',E12.5,5X,'W1    =',E12.5,
   *          /,9X,'W2    =',E12.5,5X,'FE1   =',E12.5,5X,'FE2   =',E12.5,
   *          /,9X,'PE    =',E12.5,5X,'WEFL  =',E12.5,5X,'SEFL  =',E12.5,
   *          /,9X,'EICP  =',E12.5,5X,'EICPI =',E12.5,5X,'EICL  =',E12.5,
   *          /,9X,'EICG  =',E12.5,5X,'EICF  =',E12.5,5X,'TK1   =',E12.5,
   *          /,9X,'TK2   =',E12.5,5X,'DOT   =',E12.5,5X,'DGT   =',E12.5,
   *          /,9X,'DET   =',E12.5,5X,'DPKW  =',E12.5,5X,'DPTR  =',E12.5,
   *          /,9X,'DCHT  =',E12.5,5X,'DCCT  =',E12.5,5X,'VIS1  =',E12.5,
   *          /,9X,'VIS2  =',E12.5,5X,'FTK1  =',E12.5,5X,'FTK2  =',E12.5)
102 FORMAT(   /,9X,'T3    =',E12.5,5X,'T4    =',E12.5,5X,'T5    =',E12.5,
   *          /,9X,'T6    =',E12.5,5X,'GPM1  =',E12.5,5X,'GPM2  =',E12.5,
   *          /,9X,'O1    =',E12.5,5X,'O2    =',E12.5,5X,'O3    =',E12.5,
   *          /,9X,'O4    =',E12.5,5X,'O5    =',E12.5,5X,'G1    =',E12.5,
   *          /,9X,'G2    =',E12.5,5X,'G3    =',E12.5,5X,'G4    =',E12.5,
   *          /,9X,'D1    =',E12.5,5X,'D2    =',E12.5,5X,'U1    =',E12.5,
   *          /,9X,'U2    =',E12.5,5X,'UA1   =',E12.5,5X,'UA2   =',E12.5,
   *          /,9X,'RM1   =',E12.5,5X,'RM2   =',E12.5,5X,'VEG1  =',E12.5,
   *          /,9X,'VEG2  =',E12.5,5X,'PEG1  =',E12.5,5X,'PEG2  =',E12.5,
   *          /,9X,'PEG   =',E12.5,5X,'APD1  =',E12.5,5X,'APD2  =',E12.5,
   *          /,9X,'OEP   =',E12.5,5X,'GR1   =',E12.5,5X,'GR2   =',E12.5,
   *          /,9X,'GRO   =',E12.5,5X,'GRG   =',E12.5,5X,'GRE   =',E12.5,
   *          /,9X,'OEC1  =',E12.5,5X,'OEC2  =',E12.5,5X,'T7    =',E12.5)
108 FORMAT('*',8X,'(THE BY-PASS VALVE IS OPEN  IN WINTER OPERATION)')
104 FORMAT(   /,9X,'T3    =',E12.5,5X,'T4    =',E12.5,5X,'T5    =',E12.5,
   *          /,9X,'T6    =',E12.5,5X,'GPM1  =',E12.5,5X,'GPM2  =',E12.5,
   *          /,9X,'O1    =',E12.5,5X,'O2    =',E12.5,5X,'O3    =',E12.5,
   *          /,9X,'O4    =',E12.5,5X,'OEN1  =',E12.5,5X,'G1    =',E12.5,
   *          /,9X,'G2    =',E12.5,5X,'G3    =',E12.5,5X,'G4    =',E12.5,
   *          /,9X,'D1    =',E12.5,5X,'D2    =',E12.5,5X,'U1    =',E12.5,
   *          /,9X,'U2    =',E12.5,5X,'UA1   =',E12.5,5X,'UA2   =',E12.5,
   *          /,9X,'RM1   =',E12.5,5X,'RM2   =',E12.5,5X,'VEG1  =',E12.5,
   *          /,9X,'VEG2  =',E12.5,5X,'PEG1  =',E12.5,5X,'PEG2  =',E12.5,
   *          /,9X,'PEG   =',E12.5,5X,'APD1  =',E12.5,5X,'APD2  =',E12.5,
   *          /,9X,'OEP   =',E12.5,5X,'GR1   =',E12.5,5X,'GR2   =',E12.5,
   *          /,9X,'OEC1  =',E12.5,5X,'OEC2  =',E12.5,5X,'GR    =',E12.5)
106 FORMAT(   /,9X,'HT1   =',E12.5,5X,'HT2   =',E12.5,5X,'WD1   =',E12.5,
   *          /,9X,'WD2   =',E12.5,5X,'Z1    =',E12.5,5X,'Z2    =',E12.5,
   *          /,9X,'TGRO  =',E12.5,5X,'TGRG  =',E12.5,5X,'TGRE  =',E12.5,
   *          /,9X,'TAOE  =',E12.5,5X,'ENRO  =',E12.5,5X,'ENRG  =',E12.5,
   *          /,9X,'ENRE  =',E12.5,5X,'TCRB  =',E12.5,5X,'TCRC  =',E12.5,
   *          /,9X,'TCER  =',E12.5,5X,'EIC   =',E12.5,5X,'TAHGR=',E12.5,
   *          /,9X,'TACGR=',E12.5,5X,'TAGR  =',E12.5,5X,'TGRPA=',E12.5,
   *          /,9X,'PAYBO=',E12.5,5X,'PAYBG=',E12.5,5X,'PAYBE=',E12.5,
   *          /,9X,'TANGR=',E12.5,5X,'A     =',E12.5)
    MM=MM+1
    IF(MM-KK) 5,5,7
  7 CONTINUE
    STOP
    END
C   ***********************************************************************
C   *  THIS SUBROUTINE HOURS USED FOR TABULATING NEW ARRAY OF TEMPS.     *
C   *  AND ARRAY OF CORRESPONDING HOURS.                                 *
```

```
C     ****************************************************************
      SUBROUTINE HOURS(INDEX,WT1,WT3,ST1,ST3,N,OLDT,OLDH,RNEWT,RNEWH,
     1               TAHGR,TACGR,CFMS,LL,LLL,WT1OLD,ST1OLD,NMAX)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION OLDT(50),OLDH(50),RNEWT(50),RNEWH(50)
      IF(INDEX.EQ.2) GO TO 31
      TMIN=WTI
      TMAX=WT3
      GO TO 32
   31 TMIN=ST3
      TMAX=STI
   32 CONTINUE
      NK=N-1
      DO 200 I=1,NK
      J=I+1
      IF (TMIN.GE.OLOT(I).AND.TMIN.LE.OLOT(I+1) ) GO TO 14
      IF (TMAX.GE.OLDT(J-1).AND.TMAX.LE.OLDT(J)) GO TO 15
      GO TO 200
   14 KK1=I
      HMIN=(OLDH(KK1+1)-OLDH(KK1))/(OLDT(KK1+1)-OLDT(KK1))*
     1 (TMIN-OLDT(KK1))+OLDH(KK1)
   15 KK2=J-1
      HMAX=(OLDH(KK2+1)-OLDH(KK2))/(OLDT(KK2+1)-OLDT(KK2))*
     1 (TMAX-OLDT(KK2))+OLDH(KK2)
  200 CONTINUE
      DO 100 I=1,NK
      J=I+1
      IF(INDEX.EQ.2) GO TO 41
      IF(HMIN.GE.OLDH(I).AND.HMIN.LE.OLDH(1+1)) GO TO 40
      IF(HMAX.GE.OLDH(J-1).AND.HMAX.LE.OLDH(J)) GO TO 30
      GO TO 100
   41 CONTINUE
      IF(HMIN.LE.OLOH(I).AND.HMIN.GE.OLDH(I+1)) GO TO 40
      IF(HMAX.LE.OLDH(J-I).AND.HMAX.GE.OLDH(J)) GO TO 30
      GO TO 100
   40 KI=I
   30 K2=J-I
  100 CONTINUE
      NN=K2-K1
      NN1=NN+I
      NN2=NN+2
      RNEWH(I)=HMIN
      RNEWH(NN2)=HMAX
      RNEWT(1)=TMIN
      RNEWT(NN2)=TMAX
      DO 80 L=2,NN1
      RNEWH(L)=OLOH(K1+L-I)
      RNEWT(L)=OLDT(KI+L-1)
   80 CONTINUE
      L=1
      IF(INDEX.EQ.2) GO TO 95
      HGR=(1.08*CFMS)*(TMAX-RNEWT(L))*RNEWH(L)
      WT1=RNEWT(L+1)
      WT1OLD=WTI
      TAHGR=TAHGR+HGR
      LL=LL+1
      GO TO 97
   95 J=L-1
      CGR=1.08*CFMS*(RNEWT(NN2-J)-TMIN)*RNEWH(NN2-J)
      ST1=OLOT(NMAX-LLL)
```

```
      ST1OLD=ST1
      TACGR=TACGR+CGR
      LLL=LLL+1
   97 CONTINUE
      RETURN
      END
$ENTRY
```

APPENDIX C

Appendix C

Determination of VS

The equations of the curves in figure 28 were determined by the computer program (shown in Appendix D) as shown

$$VS = (298.9753 - 11.59322 \times 10^{-3} H + 0.1449816 \times 10^{-6} H^2) \quad \text{for } AV = 300$$

$$VS = (399.9628 - 15.44916 \times 10^{-3} H + 0.2769957 \times 10^{-6} H^2) \quad \text{for } AV = 400$$

$$VS = (499.7739 - 18.673 \times 10^{-3} H + 0.192449 \times 10^{-6} H^2) \quad \text{for } AV = 500$$

$$VS = (600.0673 - 22.18371 \times 10^{-3} H + 0.250031 \times 10^{-6} H^2) \quad \text{for } AV = 600$$

$$VS = (699.8415 - 25.33304 \times 10^{-3} H + 0.2520391 \times 10^{-6} H^2) \quad \text{for } AV = 700$$

$$VS = (800.0952 - 29.20782 \times 10^{-3} H + 0.336966 \times 10^{-6} H^2) \quad \text{for } AV = 800$$

$$VS = (896.5751 - 27.84579 \times 10^{-3} H - 0.219282 \times 10^{-6} H^2) \quad \text{for } AV = 900$$

But since VS = f(H,AV), the above coefficients were used as input in the same computer program, and equation 30 was found. With H and AV (input data) known, VS is determined.

A smaller value of VS corresponds to smaller air flow rate and a large value of VS corresponds to a larger air flow rate. VS was calculated by equation 30.

Determination of R

The equations of the curves in figure 27 were determined by a computer program (shown in Appendix D) as shown.

$$R = (0.75771719 - 0.33494178 \times 10^{-3} VS + 0.13688623 \times 10^{-6} VS^2) \quad \text{for } G=1.0$$

$$R = (0.77299494 - 0.35435311 \times 10^{-3} VS + 0.16081322 \times 10^{-6} VS^2) \quad \text{for } G=1.1$$

$$R = (0.79764146 - 0.3404084 \times 10^{-3}\ VS + 0.12507371 \times 10^{-6}\ VS^2) \quad \text{for } G=1.2$$

$$R = (0.81985146 - 0.37411135\ \ 10^{-3}\ VS + 0.14926809 \times 10^{-6}\ VS^2) \quad \text{for } G=1.3$$

$$R = (0.83567923 - 0.38196915 \times 10^{-3}\ VS + 0.15071691 \times 10^{-6}\ VS^2) \quad \text{for } G=1.4$$

$$R = (0.84511191 - 0.38216077 \times 10^{-3}\ VS + 0.14893794 \times 10^{-6}\ VS^2) \quad \text{for } G=1.5$$

$$R = (0.86138093 - 0.40705432 \times 10^{-3}\ VS + 0.16623653 \times 10^{-6}\ VS^2) \quad \text{for } G=1.6$$

$$R = (0.88449264 - 0.44027995 \times 10^{-3}\ VS + 0.18759965 \times 10^{-6}\ VS^2) \quad \text{for } G=1.8$$

$$R = (0.91029024 - 0.48727333 \times 10^{-3}\ VS + 0.220064 \times 10^{-6}\ VS^2) \quad \text{for } G=2$$

Since R = f(VS, G), the coefficients in the above equations were used as input in the computer program (see Appendix O), and equation 31 was found. Parameter VS was taken from equation 30, and parameter G can be determined as

$$G = \frac{\text{Larger air flow}}{\text{Smaller air flow}} \geq 1$$

The smaller value of VS with G value were substituted in equation 31, and R_a was found.

Then,

$$R_b = R_a/G$$

Oetermination of APO

The computer program shown in Appendix D was used to find the equation of APO for a specific value of H, by selecting three arbitrary points on each curve in figure 29.

$$APO = (-.7787674 \times 10^{-1} + 0.830931 \times 10^{-3}\ VS + 0.1757019 \times 10^{-5}\ VS^2)$$

$$\text{for } H = 0 \text{ ft}$$

$$APD = (-.1104487 + 0.1141962 \times 10^{-3}\ VS + 0.1934748 \times 10^{-5}\ VS^2)$$

for $H = 5 \times 10^3$ ft

$$APD = (-.8850657 \times 10^{-1} + 0.1127086 \times 10^{-3}\ VS + 0.2726474 \times 10^{-5}\ VS^2)$$

for $H = 10^4$ ft

As

APD = f(H, VS), the coefficients in the above equation were used as input in the computer program (see Appendix D), and equation 32 was found.

Determination of F_s

Table 1 represents the relationship between F_s and H. Three arbitrary values were selected from the table to form three simultaneous equations. These equations were solved for the coefficients. The equation of F_s becomes as in (33).

APPENDIX D

```
$JOB
C     *****************************************************************
C     *       -(CURVE FITTING BY LEAST SQUARE POLYNOMIAL METHOD)-       *
C     *     N= THE NUMBER OF DATA POINTS.                               *
C     *     M= THE DEGREE OF THE POLYNOMIAL TO BE FITTED.               *
C     *     L= NO. OF AC-VALUES WHICH CORRESPOND TO EACH H(I)           *
C     *    MM= AN INDEX TO READ DATA POINTS.                            *
C     *    LL= THE NO. OF POLYS. OF DIFFERENT DEGREES TO BE FITTED.     *
C     * H(I)= THE VALUE OF H AT I-TH DATA POINT.                        *
C     * W(I)= THE WEIGHT OF THE I-TH DATA POINT. IF ALL POINTS ARE      *
C     *       TREATED EQUALLY. W(I)=1.                                  *
C     *AC(I)= THE J-TH VALUE OF AC AT THE I-TH DATA POINT.              *
C     *****************************************************************
      DIMENSION A(30,30),B(30,30),H(30),AC(30,4),W(30),C(30,30)
      MM=0
      READ(5,100) LL
    5 IF(MM.GE.LL) GO TO 1000
   10 READ (5,200) N,M,L
      IF(MM.NE.0) GO TO 25
   15 WRITE(6,400)
      DO 20 I=1,N
      READ (5,300)  H(I),W(I),( AC(I,J),J=1,L)
      DO 20 J=1,L
   20 WRITE (6,500)  H(I),W(I), AC(I,J)
C
C     .. FOLLOW 11 STATEMENTS TO FORM THE COEFFICIENT MATRIX OF THE
C     .. NORMAL EQUATIONS
C
   25 DO 30 I=1,N
   30 C(I,1)=1.0
      MP1=M+1
      DO 35 J=2,MP1
      DO 35 I=1,N
   35 C(I,J)=C(I,J-1)* H(I)
      DO 40 I=1,MP1
      DO 40 J=1,MP1
      A(I,J)=0.0
      DO 40 K=1,N
   40 A(I,J)=A(I,J)+C(K,I)*C(K,J)*W(K)
C
C     .. FOLLOWING 5 STATEMENTS TO FORM THE CONSTANT MATRIX OF THE
C     .. NORMAL EQUATIONS
C
      DO 45 J=1,L
      DO 45 I=1,MP1
      B(I,J)=0.0
      DO 45 K=1,N
   45 B(I,J)=B(I,J)+C(K,I)*AC(K,J)*W(K)
C
C     .. CALL SURROUTINE CHAPB TO SOLVE THE NORMAL EQUATIONS
C
      CALL CHAPB(A,MP1,B,L,DET)
      WRITE(6,600)N
      WRITE(6,700) M
      DO 50 J=1,L
      DO 50 I=1,MP1
      II=I-1
   50 WRITE(6,800) II,B(I,J)
      WRITE(6,900)
      MM=MM+1
```

```
      GO TO 5
  100 FORMAT(I4)
  200 FORMAT(3I4)
  300 FORMAT(2F10.6,F10.5)
  400 FORMAT('1',14X,'H',20X,'WEIGHT',22X,'AC'//)
  500 FORMAT(8X,E12.6,12X,F12.6,13X,E15.6/)
  600 FORMAT (///,' NUMBER OF GIVEN DATA POINTS = ',I2)
  700 FORMAT(/7X,'DEGREE OF POLYNOMIAL = ',I2,///)
  800 FORMAT(5X,I2,' DEGREE COEFFICIENT = ',E18.8,/)
  900 FORMAT(/,10H - - - - -,///)
 1000 STOP
      END
C
      SUBROUTINE CHAPR (A,MP1,B,L,DET)
C     THIS SUBPROGRAM IS FOR MATRIX INVERSION AND SIMUL.LINEAR EQS.
      DIMENSION A(30,30),B(30,30),IPVOT(30),INDEX(30,2),PIVOT(30)
      COMMON IPVOT,INDEX,PIVOT
      EQUIVALENCE (IROW,JROW),(ICOL,JCOL)
C
C     FOLLOWING 3 STATEMENTS FOR INITIALIZATION
C
   57 DET=1.
      DO 17 J=1,MP1
   17 IPVOT(J)=0
      DO 135 I=1,MP1
C
C     FOLLOWING 12 STATEMENTS FOR SEARCH FOR PIVOT ELEMENT
C
      T=0.
      DO 9 J=1,MP1
      IF (IPVOT(J).EQ.1) GO TO 9
   13 DO 23 K=1,MP1
      IF (IPVOT(K)-1) 43,23,81
   43 IF(ABS(T).GE.ABS(A(J,K))) GO TO 23
   83 IROW=J
      ICOL=K
      T=A(J,K)
   23 CONTINUE
    9 CONTINUE
      IPVOT(ICOL)=IPVOT(ICOL)+1
C
C     FOLLOWING 15 STATEMENTS TO PUT PIVOT ELEMENT ON DIAGONAL
C
      IF (IROW.EQ.ICOL) GO TO 109
   73 DET=-DET
      DO 12 M=1,MP1
      T=A(IROW,M)
      A(IROW,M)=A(ICOL,M)
   12 A(ICOL,M)=T
      IF (L.LE.0) GO TO 109
   33 DO 2 M=1,L
      T=B(IROW,M)
      B(IROW,M)=B(ICOL,M)
    2 B(ICOL,M)=T
  109 INDEX(I,1)=IROW
      INDEX(I,2)=ICOL
      PIVOT(I)=A(ICOL,ICOL)
      DET=DET*PIVOT(I)
C
C     FOLLOWING 6 STATEMENTS TO DIVIDE PIVOT ROW BY PIVOT ELEMENT
```

```
C
      A(ICOL,ICOL)=1.
      DO 205 M=1,MP1
  205 A(ICOL,M)=A(ICOL,M)/PIVOT(I)
      IF(L.LE.0) GO TO 347
   66 DO 52 M=1,L
   52 B(ICOL,M)=B(ICOL,M)/PIVOT(I)
C
C     FOLLOWING 10 STATEMENTS TO REDUCE NON-PIVOT ROWS
C
  347 DO 135 LI=1,MP1
      IF(LI.EQ.ICOL) GO TO 135
   21 T=A(LI,ICOL)
      A(LI,ICOL)=0.
      DO 89 M=1,MP1
   89 A(LI,M)=A(LI,M)-A(ICOL,M)*T
      IF(L.LE.0) GO TO 135
   18 DO 68 M=1,L
   68 B(LI,M)=B(LI,M)-B(ICOL,M)*T
  135 CONTINUE
C
C     FOLLOWING 11 STATEMENTS TO INTERCHANGE COLUMNS
C
  222 DO 3 I=1,MP1
      M=MP1-I+1
      IF (INDEX(M,1).EQ.INDEX(M,2)) GO TO 3
   19 JROW=INDEX(M,1)
      JCOL=INDEX(M,2)
      DO 549 K=1,MP1
      T=A(K,JROW)
      A(K,JROW)=A(K,JCOL)
      A(K,JCOL)=T
  549 CONTINUE
    3 CONTINUE
   81 RETURN
      END
$ENTRY
```

APPENDIX E

```
$JOB
C      ****************************************************************
C      *            -((  O-PIPE THERMAL RECOVRY UNIT ))-              *
C      *     H= JOB SITE ELEVATION IN FEET                            *
C      * CFMS= SUPPLY AIR FLOW IN CFM                                 *
C      * CFME= EXHAUST AIR FLOW  IN CFM                               *
C      *   FA= FACE AREA (ONE SIDE OF PARTITION) IN SQ.FT.            *
C      *  AVS= ACTUAL AIR SUPPLY VELOCITY IN FPM.                     *
C      *  AVE= ACTUAL AIR EXHAUST VELOCITY IN FPM.                    *
C      *    G= MASS FLOW RATIO OF THE TWO AIR STREAMS (LARGER/SMALLER) *
C      *  VS1= STANDARD AIR VELOCITY OF SMALLER CFM                   *
C      *  VS2= STANDARD AIR VELOCITY OF LARGER CFM                    *
C      *   RA= RECOVERY FACTOR OF SMALLER AIR FLOW                    *
C      *   RB= RECOVERY FACTOR OF LARGER AIR FLOW                     *
C      * APD1= ACTUAL PRESSURE DROP FOR SMALLER AIR FLOW  IN INCH W.G. *
C      * APD2= ACTUAL PRESSURE DROP FOR  LARGER AIR FLOW  IN INCH W.G. *
C      *   FS= AIR FLOW CORRECTION FACTORARGER AIR FLOW IN INCH W.G.  *
C      *   WT= WINTER TEMPERATURE IN DEGREE FAH.                      *
C      *   ST= SUMMER TEMPERATURE IN DEGREE FAH.                      *
C      *   FE= FAN EFFICIENCY IN (%)                                  *
C      * EICU= INITIAL COST OF THE O-PIPE THERMAL RECOVERY UNIT IN ($) *
C      * EICL= LABOR INITIAL COST IN ($)                              *
C      * EICF= FANS INITIAL COST IN ($)                               *
C      *   GR= ENERGY GROSS RECOVERD IN BTUH.                         *
C      *CFMS1= AIR SUPPLY BY-PASSED IN CFM.                           *
C      * TGRO= TOTAL GROSS RECOVERED (OIL) IN ($/YR.)                 *
C      * TGRG= TOTAL GROSS RECOVERED (GAS) IN ($/YR.)                 *
C      * TGRE= TOTAL GROSS RECOVERED (ELEC.) IN ($/YR.)               *
C      *  TOE= TOTAL OPERATING ENERGY COST IN ($/YR.)                 *
C      * TAOE= TOTAL ANNUAL OPERATING ENERGY IN (BTU/YR.)             *
C      * ENRO= NET RECOVERY (OIL) IN ($/YR.)                          *
C      * ENRG= NET RECOVERY (GAS) IN ($/YR.)                          *
C      * ENRE= NET RECOVERY (ELEC.) IN ($/YR.)                        *
C      * TCRB= BOILER CAPITAL REDUCION IN ($)                         *
C      * TCRC= CHILLER CAPITAL REDUCION IN ($)                        *
C      * WEFL= WINTER EQUIVALENT HEATING LOAD IN (HRS./YR.)           *
C      * SEFL= SUMMER EQUIVALENT COOLING LOAD IN (HRS./YR.)           *
C      *  OOT= OIL HEATING COST IN ($/THERM)                          *
C      *  OGT= GAS HEATING COST IN ($/THERM)                          *
C      *  OET= ELEC. HEATING COST IN ($/THERM)                        *
C      * OPKW= OPERATING ENERGY COST (ELEC.) IN ($/KW-HR.)            *
C      * OPTR= OPERATING ENERGY COST (ELEC.) IN ($/TON OF REFRIGERATION)*
C      * OCHT= BOILER CAPITAL EQUIPMENT REDUCTION IN ($/THERM)IGERATION)*
C      * OCCT= CHILLER CAPITAL EQUIPMENT REDUCTION IN ($/THERM)        *
C      *   OE= OPERATING ENERGY COST IN ($)                           *
C      * TCER= TOTAL CAPITAL EQUIPMENT REDUCTION IN ($)               *
C      *  EIC= TOTAL INITIAL COST IN ($)                              *
C      *TAHGR= TOTAL ANNUAL HEATING GROSS RECOVERY IN (BTU/YR.)       *
C      *TACGR= TOTAL ANNUAL COOLING GROSS RECOVERY IN (BTU/YR.)       *
C      * TAGR= TOTAL ANNUAL GROSS RECOVERY IN (BTU/YR.)               *
C      *TANGR= TOTAL ANNUAL NET GROSS RECOVERY IN (BTU/YR.)           *
C      *PAYBO= PAYBACK (IN CASE OIL USED FOR HEATING) IN (YRS.)       *
C      *PAYBG= PAYBACK (IN CASE GAS USED FOR HEATING) IN (YRS.)       *
C      *PAYBE= PAYBACK (IN CASE ELEC. USED FOR HEATING) IN (YRS.)     *
C      ****************************************************************
       IMPLICIT REAL*8(A-H,O-Z)
       DIMENSION OLDT(50),OLDH(50),RNEWT(50),RNEWH(50)
       REAL WT11/0.0/,ST11/95.0/
       MM=1
       READ(5,44) KK
```

```
      READ(5,*)      H,CFMS,CFME,WT2,ST2,FE1,FE2,WEFL,SEFL,EICU,
     *               EICL,EICF,OOT,OGT,OET,OPKW,OPTR,OCHT,OCCT
    5 READ(5,*) V
      WT1=WT11
      ST1=ST11
      IF(MM.EQ.1.AND.MM.LT.2) GO TO 8
      IF(MM.EQ.2.AND.MM.LT.3) GO TO 9
      IF(MM.EQ.3.AND.MM.LT.4) GO TO 10
      IF(MM.EQ.4.AND.MM.LT.5) GO TO 11
      IF(MM.EQ.5.AND.MM.LT.6) GO TO 13
      IF(MM.EQ.6.AND.MM.LT.7) GO TO 46
      IF(MM.EQ.7.AND.MM.LT.8) GO TO 48
      IF(MM.EQ.8.AND.MM.LT.9) GO TO 53
    8 WRITE(6,28)
      GO TO 35
    9 WRITE(6,29)
      GO TO 35
   10 WRITE(6,34)
      GO TO 35
   11 WRITE(6,50)
      GO TO 35
   13 WRITE(6,51)
      GO TO 35
   46 WRITE(6,49)
      GO TO 35
   48 WRITE(6,52)
      GO TO 35
   53 WRITE(6,54)
   35 PRINT 19
      PRINT 22
      PRINT 19
      WRITE(6,299) H,CFMS,CFME,WT1,ST1,WT2,ST2,FE1,FE2,WEFL,SEFL,EICU,
     C              EICL,EICF,OOT,OGT,OET,OPKW,OPTR,OCHT,OCCT,V
      CFMS1=0.0
      TAHGR=0.0
      TACGR=0.0
      NSET=1
      LL=1
      LLL=1
  997 READ(5,1) INDEX
      READ (5,1) N
      DO 12 I=1,N
   12 READ (5,3) OLOT(I),OLOH(I)
      CFMS11=CFMS
      IF(CFME.GT.CFMS11) GO TO 700
      FA=CFMS11/V
      G=CFMS11/CFME
      GX=G+1.0D-9
      M=GX
      GO TO 701
  700 FA=CFME/V
      G=CFME/CFMS11
      GX=G+1.0D-9
      M=GX
  701 AVS=CFMS11/FA
      AVE=CFME/FA
      VS01=(-7.304216+1.027933*AVS-0.0000253223B*AVS**2)+(0.005277119-
     10.6327463*10**(-4)*AVS+0.2804574*10**(-7)*AVS**2)*H+(-0.6582271*
     210**(-6)+0.3537444*10**(-8)*AVS-0.3220021*10**(-11)*AVS**(2))*
     3H**(2)
```

```
      VS02=(-7.304216+1.027933*AVE-0.0000253223B*AVE**2)+(0.005277119-
     10.6327463*10**(-4)*AVE+0.2804574*10**(-7)*AVE**2)*H+(-0.6582271*
     210**(-6)+0.3537444*10**(-8)*AVE-0.3220021*10**(-11)*AVE**(2))*
     3H**(2)
      IF (AVS.GT.AVE) GO TO 702
      VS1=VS01
      VS2=VS02
      GO TO 703
  702 VS1=VS02
      VS2=VS01
  703 RA=(0.48190998+0.3368778*G-0.06189942*(G**2))+(-0.366823/(10**3)+
     C(.1159242/(10**3))*G-(.87691/(10**4))*(G**2))*VS1+(((.2868927/
     C(10.**6))-(0.2522431/(10.**6))*G+(.1094314/(10.**6))*(G**2)))*
     C(VS1**2)
      RB=RA/G
      AP01=(-0.7787704D-1-0.1196548D-4*H+0.1090248D-8*H**2)+
     C(0.8309141D-3+0.9480123D-7*H-0.6518396D-11*H**2)*VS1+
     C(0.1757011D-5-0.2586650D-10*H+0.1227925D-13*H**2)*VS1**2
      APD2=(-0.7787704D-1-0.1196548D-4*H+0.1090248D-8*H**2)+
     C(0.8309141D-3+0.9480123D-7*H-0.6518396D-11*H**2)*VS2+
     C(0.1757011D-5-0.2586650D-10*H+0.1227925D-13*H**2)*VS2**2
      FS=(1.08-(3.825*10.0**(-5)*H)+(3.75*10.0**(-10)*(H**2)))
      IF(INOFX.EQ.1) GO TO 999
      NMAX=1
   89 CONTINUE
      IF(ST11-OLDT(NMAX)) 999,999,79
   79 NMAX=NMAX+1
      GO TO 89
  999 IF(INDEX.EQ.2) GO TO 45
      IF(WT1.NE.WT11) WT1=WT1OLD
      IF(CFMS11.LE.CFME) GO TO 704
      WT3=WT1+(RB*(WT2-WT1))
      WT4=WT2-(RA*(WT2-WT1))
      GO TO 705
  704 WT3=WT1+(RA*(WT2-WT1))
      WT4=WT2-(RB*(WT2-WT1))
  705 IF(WT4-32.0) 721,722,722
  721 WT4=32.0
      CFMS=CFME*(WT2-WT4)/(WT3-WT1)
      CFMS1=CFMS11-CFMS
      WT5=((CFMS*WT3)+(CFMS1*WT1))/CFMS11
  722 IF(WT1.NE.WT11) GO TO 47
      WWT1=WT1
      WWT2=WT2
      WWT3=WT3
      WWT4=WT4
      WWT5=WT5
      WRA=RA
      WRB=RB
      CFMSS=CFMS
      CFMS01=CFMS1
      AVS1=AVS
   45 IF(ST1.NE.ST11) ST1=ST1OLD
      IF(CFMS.LE.CFME) GO TO 706
      ST3=ST1+(RB*(ST2-ST1))
      ST4=ST2-(RA*(ST2-ST1))
      GO TO 707
  706 ST3=ST1+(RA*(ST2-ST1))
      ST4=ST2-(RB*(ST2-ST1))
  707 CONTINUE
```

```
      IF(ST1.NE.ST11) GO TO 47
      SST1=ST1
      SST2=ST2
      SST3=ST3
      SST4=ST4
      SRA=RA
      SRB=RB
      AVS2=AVS
      CFMSE=CFMS
   47 CONTINUE
C     ******************************************************************
      CALL HOURS (INDEX,WT1,WT3,ST1,ST3,N,OLOT,OLOH,RNEWT,RNEWH,TAHGR,
     1          TACGR,CFMS,LL,LLL,WT1OLO,ST1OLD,NMAX,FS,CFMS11)
C     ******************************************************************
      IF(INDEX.EQ.2) GO TO 111
      IF(WT1.LE.70.0.AND.WT1.LE.WT2) GO TO 999
      GO TO 113
  111 IF(ST1.GE.50.0.AND.ST1.GE.ST2) GO TO 999
  113 CONTINUE
      NSET=NSET+1
      IF(NSET-2) 998,998,1000
  998 CFMS=CFMS11
      GO TO 997
 1000 CONTINUE
      WGRO=TAHGR*OOT/100000.
      WGRG=TAHGR*DGT/100000.
      WGRE=TAHGR*OET/100000.
      SGR=TACGR*DPTR/12000.
      IF(CFME.GT.CFMS) GO TO 714
      WOE1=(0.746*DPKW*CFMS*APO1)*WEFL/(6356.*FE1)
      WOE2=(0.746*OPKW*CFME*APO2)*WEFL/(6356.*FE2)
      GO TO 710
  714 WOE1=(0.746*DPKW*CFMS*APO2)*WEFL/(6356.*FE1)
      WOE2=(0.746*DPKW*CFME*APO1)*WEFL/(6356.*FE2)
  710 WGR1=1.08*CFMSS*FS*(WWT3-WWT1)
      WGR2=1.08*CFME*FS*(WWT2-WWT4)
      SGR1=1.08*CFMSS*FS*(SST1-SST3)
      SGR2=1.08*CFME*FS*(SST4-SST2)
      IF(CFME.GT.CFMS11) GO TO 711
      SOE1=(0.746*DPKW*CFMSS*APO1)*SEFL/(6356.*FE1)
      SOE2=(0.746*OPKW*CFME*APO2)*SEFL/(6356.*FE2)
      GO TO 712
  711 SOE1=(0.746*OPKW*CFMSS*APO2)*SEFL/(6356.*FE1)
      SOE2=(0.746*DPKW*CFME*APO1)*SEFL/(6356.*FE2)
  712 TGRO=WGRO+SGR
      TGRG=WGRG+SGR
      TGRE=WGRE+SGR
      TOE=WOE1+SOE1+WOE2+SOE2
      ENRO=TGRO-TOE
      ENRG=TGRG-TOE
      ENRE=TGRE-TOE
      TCRB=DCHT *WGR1/100000.0
      TCRC=OCCT*SGR1/12000.0
      TCER=TCRB+TCRC
      EIC=EICU+EICL+EICF
      TAOE=TOE*3413./0.025
      TAGR=TAHGR+TACGR
      TANGR=TAGR-TAOE
      PAYBO=(EIC-TCER)/ENRO
      PAYBG=(EIC-TCER)/ENRG
```

```
      PAYBE=(EIC-TCER)/ENRE
      PRINT 19
      PRINT 101
  101 FORMAT('*',20X,' (WINTER RESULT )')
      PRINT 19
      WRITE(6,102) WWT3,WWT4,WWT5,AVS1,AVE,VS1,VS2,WGRO,WGRG,WGRE,APO1,
     *             APO2,WRA,WRB,WOE1,WOE2,WGR1,WGR2,CFMSS,CFMSO1,FA
      IF(CFMS1.GT.0.0) GO TO 723
  723 PRINT 724
  724 FORMAT('*',10X, ' (THE BY-PASS IS ON ) ')
      PRINT 19
      PRINT 103
  103 FORMAT('*',20X,'  (SUMMER RESULT)   ')
      PRINT 19
      WRITE(6,104) SST3,SST4,AVS2,AVE,FA,VS1,VS2,SGR,SGR1,SGR2,
     *             APD1,APO2,SRA,SRB,SOE1,SOE2,G,CFMSE,CFME
      PRINT 19
      PRINT 105
  105 FORMAT('*',20X, ' (COMMON AND CONCLUSION RESULTS)')
      PRINT 19
      WRITE(6,106) TGRO,TGRG,TGRE,TOE,TAOE,ENRO,ENRG,ENRE,TCRB,TCRC,
     *             TCER,EIC,TAHGR,TACGR,TAGR,TANGR,PAYBO,PAYBG,PAYBE
      PRINT 19
    1 FORMAT(I3)
    3 FORMAT(F7.1,F8.1)
   19 FORMAT('*',     80('*'))
   22 FORMAT('*', 20X,' (  INPUT  DATA  )  ')
   28 FORMAT('1',10X,'THIS CASE FOR  AIR VELOCITY (V)=100 FPM ')
   29 FORMAT('1',10X,'THIS CASE FOR  AIR VELOCITY (V)=200 FPM ')
   34 FORMAT('1',10X,'THIS CASE FOR  AIR VELOCITY (V)=300 FPM ')
   50 FORMAT('1',10X,'THIS CASE FOR  AIR VELOCITY (V)=400 FPM ')
   51 FORMAT('1',10X,'THIS CASE FOR  AIR VELOCITY (V)=500 FPM ')
   49 FORMAT('1',10X,'THIS CASE FOR  AIR VELOCITY (V)=600 FPM ')
   52 FORMAT('1',10X,'THIS CASE FOR  AIR VELOCITY (V)=700 FPM ')
   54 FORMAT('1',10X,'THIS CASE FOR  AIR VELOCITY (V)=800 FPM ')
   44 FORMAT(I4)
  299 FORMAT(    /,9X,'H    =',E12.5,5X,'CFMS =',E12.5,5X,'CFME =',E12.5,
     *           /,9X,'WT1  =',E12.5,5X,'ST1  =',E12.5,5X,'WT2  =',E12.5,
     *           /,9X,'ST2  =',E12.5,5X,'FE1  =',E12.5,5X,'FE2  =',E12.5,
     *           /,9X,'WEFL =',E12.5,5X,'SEFL =',E12.5,5X,'EICU =',E12.5,
     *           /,9X,'EICL =',E12.5,5X,'EICF =',E12.5,5X,'OOT  =',E12.5,
     *           /,9X,'DGT  =',E12.5,5X,'OET  =',E12.5,5X,'OPKW =',E12.5,
     *           /,9X,'OPTR =',E12.5,5X,'DCHT =',E12.5,5X,'OCCT =',E12.5,
     *           /,9X,'V    =',E12.5)
  102 FORMAT(    /,9X,'T3   =',E12.5,5X,'T4   =',E12.5,5X,'T5   =',E12.5,
     *           /,9X,'AVS  =',E12.5,5X,'AVE  =',E12.5,5X,'VS1  =',E12.5,
     *           /,9X,'VS2  =',E12.5,5X,'GRO  =',E12.5,5X,'GRG  =',E12.5,
     *           /,9X,'GRE  =',E12.5,5X,'APO1 =',E12.5,5X,'APO2 =',E12.5,
     *           /,9X,'RA   =',E12.5,5X,'RB   =',E12.5,5X,'OE1  =',E12.5,
     *           /,9X,'OE2  =',E12.5,5X,'GR1  =',E12.5,5X,'GR2  =',E12.5,
     *           /,9X,'CFMS =',E12.5,5X,'CFMS1=',E12.5,5X,'FA   =',E12.5)
  104 FORMAT(    /,9X,'T3   =',E12.5,5X,'T4   =',E12.5,5X,'AVS  =',E12.5,
     *           /,9X,'AVE  =',E12.5,5X,'FA   =',E12.5,5X,'VS1  =',E12.5,
     *           /,9X,'VS2  =',E12.5,5X,'GR   =',E12.5,5X,'GR1  =',E12.5,
     *           /,9X,'GR2  =',E12.5,5X,'APO1 =',E12.5,5X,'APO2 =',E12.5,
     *           /,9X,'RA   =',E12.5,5X,'RB   =',E12.5,5X,'OE1  =',E12.5,
     *           /,9X,'OE2  =',E12.5,5X,'G    =',E12.5,5X,'CFMS =',E12.5,
     *           /,9X,'CFME =',E12.5)
  106 FORMAT(    /,9X,'TGRO =',E12.5,5X,'TGRG =',E12.5,5X,'TGRE =',E12.5,
     *           /,9X,'TOE  =',E12.5,5X,'TAOE =',E12.5,5X,'ENRO =',E12.5,
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     *          /,9X,'ENRG =',E12.5,5X,'ENRE =',E12.5,5X,'TCRB =',E12.5,
     *          /,9X,'TCRC =',E12.5,5X,'TCER =',E12.5,5X,'EIC  =',E12.5,
     *          /,9X,'TAHGR=',E12.5,5X,'TACGR=',E12.5,5X,'TAGR =',E12.5,
     *          /,9X,'TANGR=',E12.5,5X,'PAYBO=',E12.5,5X,'PAYBG=',E12.5,
     *          /,9X,'PAYBE=',E12.5)
      MM=MM+1
      IF(MM-KK) 5,5,7
    7 CONTINUE
      STOP
      END
C     ******************************************************************
C     *  THIS SUBROUTINE HOURS USED FOR TABULATING NEW ARRAY OF TEMPS. *
C     *  AND ARRAY OF CORRESPONDING HOURS.                              *
C     ******************************************************************
      SUBROUTINE HOURS(INDEX,WT1,WT3,ST1,ST3,N,OLOT,OLOH,RNEWT,RNEWH,
     1           TAHGR,TACGR,CFMS,LL,LLL,WT1OLO,ST1OLO,NMAX,FS,CFMS11)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION OLOT(50),OLOH(50),RNEWT(50),RNEWH(50)
      IF(INDEX.EQ.2) GO TO 31
      TMIN=WT1
      TMAX=WT3
      GO TO 32
   31 TMIN=ST3
      TMAX=ST1
   32 CONTINUE
      NK=N-1
      DO 200 I=1,NK
      J=I+1
      IF (TMIN.GE.OLOT(I).AND.TMIN.LE.OLOT(I+1) ) GO TO 14
      IF (TMAX.GE.OLOT(J-1).AND.TMAX.LE.OLOT(J)) GO TO 15
      GO TO 200
   14 KK1=I
      HMIN=(OLOH(KK1+1)-OLOH(KK1))/(OLOT(KK1+1)-OLOT(KK1))*
     1 (TMIN-OLOT(KK1))+OLOH(KK1)
   15 KK2=J-1
      HMAX=(OLOH(KK2+1)-OLOH(KK2))/(OLOT(KK2+1)-OLOT(KK2))*
     1 (TMAX-OLOT(KK2))+OLOH(KK2)
  200 CONTINUE
      DO 100 I=1,NK
      J=I+1
      IF(INDEX.EQ.2) GO TO 41
      IF(HMIN.GE.OLOH(I).AND.HMIN.LE.OLOH(I+1)) GO TO 40
      IF(HMAX.GE.OLOH(J-1).AND.HMAX.LE.OLOH(J)) GO TO 30
      GO TO 100
   41 CONTINUE
      IF(HMIN.LE.OLOH(I).AND.HMIN.GE.OLOH(I+1)) GO TO 40
      IF(HMAX.LE.OLOH(J-1).AND.HMAX.GE.OLOH(J)) GO TO 30
      GO TO 100
   40 K1=I
   30 K2=J-1
  100 CONTINUE
      NN=K2-K1
      NN1=NN+1
      NN2=NN+2
      RNEWH(1)=HMIN
      RNEWH(NN2)=HMAX
      RNEWT(1)=TMIN
      RNEWT(NN2)=TMAX
      DO 80 L=2,NN1
      RNEWH(L)=OLOH(K1+L-1)
```

```
      RNEWT(L)=OLDT(K1+L-1)
   80 CONTINUE
      L=1
      IF(INDEX.EQ.2) GO TO 95
      HGR=(1.08*CFMS11*FS)*(TMAX-RNEWT(L))*RNEWH(L)
      WT1=RNEWT(L+1)
      WT1OLD=WT1
      TAHGR=TAHGR+HGR
      LL=LL+1
      GO TO 97
   95 J=L-1
      CGR=1.08*CFMS*FS *(RNEWT(NN2-J)-TMIN)*RNEWH(NN2-J)
      ST1=OLDT(NMAX-LLL)
      ST1OLD=ST1
      TACGR=TACGR+CGR
      LLL=LLL+1
   97 CONTINUE
      RETURN
      END
$ENTRY
```

ACKNOWLEDGEMENTS

In recognition of his continual support and guidance, suggestions and comments throughout the solution of the problem and in the preparation of this thesis, I would like to express my gratitude to Professor Robert L. Gorton, my major advisor.

Thanks are also due to the other members of my committee, Dr. J. E. Kipp and Dr. T. W. Lester.

I would also like to thank the Iraqi Ministry of Higher Education and Scientific Research for granting me a state scholarship.

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ENERGY RECOVERY IN AIR-CONDITIONING
SYSTEMS

by

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B.S., Al-Mustansiriyah University, 1972

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

1978

ABSTRACT

Energy conservation is now an integral part of good planning, for efficient use, and systems are being recognized which are economically and technically feasible. Energy conservation may therefore become compulsory.

Heat lost by natural ventilation cannot be recovered, and the only energy saving possibility is to reduce the rate to the unnecessary wastage due to structural design, such as the use of windows with controlled crackage.

For mechanically-ventilated buildings however, using inlet and exhaust systems, a number of techniques exist. It is possible to save at least half of the heat lost in the exhaust air. These techniques generally involve use of heat recovery devices of some type.

Heat recovery systems can be grouped basically into direct, and indirect heat transfer apparatus. In the direct system, the warm exhaust air and the incoming cold air pass through the same heat exchanger unit. The transfer between the two air streams are either by conduction or by regenerative process as in the thermal wheel.

In the indirect system, a secondary medium is used to transfer heat from the exhaust and cold air streams. This has the advantage that the two air streams do not have to be brought together.

Two systems which are typical of other types, run-around coil system and a heat-pipe recovery unit were selected for study. These were selected for analysis because of their highest net energy recovered with respect to a reasonable heat recovery unit size which involves optional initial cost.

Effects of different parameters, glylcol ethyene and air flow velocities for the run-around coil system, and the effect of change in air flow velocities for heat-pipe recovery unit were studied for highest net energy saved and pay back time.

It was noticed that the energy recovered increases as the heat transfer area increases, thus increasing initial cost. This caused an increase in the operating energy cost affecting net energy saved. The net energy saved reaches a maximum limit with respect to the parameter affecting the change in the heat transfer area and then tends towards a decrease.

Energy saved and pay back time depends on the initial costs and on heating and cooling costs. For this study these costs were selected at current levels and may be altered in order to assess the cost involved for a localized area.

Keeping other parameters constant but varying only one at the same time resulted in the highest net energy saving for a specific value of that parameter. The same result was obtained for a range of velocity with respect to the selected values and the local design temperature.