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OPTIMUM DRY-COOLING SUB-SYSTEMS FOR A SOLAR AIR CONDITIONER

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SUMMARY

Dry-cooling sub-systems for residential solar-powered Rankine-compression air conditioners have been economically optimized and compared with the cost of a wet cooling tower. Results in terms of yearly incremental busbar cost due to the use of dry-cooling have been presented for Philadelphia and Miami. With input data corresponding to local weather, energy rate and capital costs, condenser surface designs and performance, the computerized optimization program yields design specifications of the sub-system which has the lowest annual incremental cost.

INTRODUCTION

Air conditioners reject waste heat to the environment through evaporative (wet) cooling towers or air (dry) coolers. The loss of water from the former to the local atmosphere is quite extensive. A three-ton-solar-powered air conditioner equipped with flat plate collectors vaporizes approximately 41.3 kilograms (91 lb) of water per hour, based upon an overall coefficient of performance of 0.65 of the machine. During the summer months in an urban center, the addition of water vapor to the ambient air is often environmentally objectionable. It is also known that the increase of moisture in air causes low thermal efficiency of the collector. Furthermore, the circulating water is chemically treated for anti-corrosion and anti-freezing, and the discharge of such water for maintenance may overburden our existing water treatment plants in many metropolitan areas.

The dry-cooling system has four outstanding advantages: (a) no harmful or visible pollution discharge, (b) practically maintenance free, (c) no requirement for a water treatment plant, and (d) the elimination of make-up water supply.

Because of these considerations, solar-driven air conditioners designed for wide-spread residential utilization may be required to use dry-cooling. It is noted that the current design of the commercial lithium bromide-water absorption air conditioners is not suitable for using dry-cooling due to possible LiBr crystallization in the absorber at high ambient air temperatures. This problem must be solved before dry-cooling can be adapted to the air conditioner. Recent studies of solar absorption air-conditioning systems have been concerned with those equipped with wet-cooling towers (refs. 1 and 2). In this study the dry-cooling is proposed for a solar-powered Rankine-compression air conditioner.

As compared to wet-cooling, a possible disadvantage associated with dry-cooling is that the latter system requires higher capital and operating costs (although little maintenance cost is involved). The heat transfer by air is much less effective than by water. In addition, the overall coefficient of performance of an air conditioner equipped with nonconcentrating solar collectors is quite low and it rejects as much as twice the amount of heat as a conventional vapor compression machine does. Thus, an unoptimized dry sub-system may be very costly.

The objective of this study is to economically optimize the dry-cooling sub-system for a solar-powered Rankine-compression air conditioner. The computerized program selects the best possible dry-cooling sub-system design by optimizing the heat transfer and thermodynamic relations with economic trade-offs.

ECONOMIC OPTIMIZATION

The economic analysis is based on the capital and operating costs of the solar-powered system which incorporates the Rankine-vapor compression cooling sub-system. Optimization is based on minimizing the annual total cost increment between dry-cooling and wet-cooling.

System Description

The schematic assembly of the solar-powered Rankine-compression air conditioner along with its thermodynamic pressure-enthalpy diagram for the working fluid is shown in figure 1. Only the cooling mode of the machine is considered in this study. Although heating can be accomplished with this system, it is not considered in this report. The working fluid chosen is Freon-12 (R-12). This does not rule out the use of other fluids. The effect of the thermodynamic properties of potential working fluids on the performance of a solar-driven heat pump has been analyzed in reference 3. The system is designed to provide three tons of air conditioning at temperatures of 10° C (50° F) in the evaporator and 94.5° C (202° F) in the boiler. The condensing temperature of the working fluid in the air-cooled condenser is one of the four system variables which will be discussed in a later section. A single fluid (R-12) is utilized for both Rankine and Compression cycles for simplified equipment design, although the use of different fluids (one for Rankine cycle and the other for the compression cycle) may yield better overall efficiencies.

The working fluid is vaporized by the heat supplied by the hot water from collector or storage tank (not shown in fig. 1), and then expands in the expander to provide the power for both compressor and pump. The exhaust vapor from the expander and the compressed vapor leaving the compressor are condensed in the air-cooled condenser. An appropriate amount of the condensate is pumped to the boiler for vaporization while the remaining liquid (the two mass flow rates are among the outputs of the design program) is adiabatically expanded through the expansion valve to the evaporator pressure.

The thermal efficiency of the Rankine cycle, η_r, is

$$\eta_r = \frac{W_e - W_p}{Q_b} \qquad (1)$$

where

W_e = power produced by the expander, kW (Btu/hr)
W_p = power for the pump, kW (Btu/hr)
Q_b = heat rate to the boiler supplied by solar collector-storage unit, kW (Btu/hr)

The coefficient of performance, COP, of the compression cycle is,

$$COP = \frac{Q_e}{W_c} \qquad (2)$$

where

Q_e cooling capacity of the air conditioner, kW (Btu/hr)
W_c power for the compressor, kW (Btu/hr)

With $W_e = W_p + W_c$, the overall coefficient of performance, OCOP, is

$$OCOP = \frac{Q_e}{Q_b} = \eta_r \cdot COP \qquad (3)$$

Equations (1) to (3) for various condensing temperatures of R-12 are plotted in figure 2, where

T_e evaporator temperature, ^oC (^oF)
T_b boiler temperature, ^oC (^oF)
E_{exp} expander efficiency, dimensionless
E_p pump efficiency, dimensionless
E_{comp} compressor efficiency, dimensionless

Computerized Optimization Program

The program for the computer was written to carry out the minimization of the total annual cost increment. The same guidelines were applied for both dry-cooling and wet-cooling when determining system constraints, conditions, and the state of the art. The program assumptions, input data requirements, system variables, cost equations, and procedures are outlined below:

Assumptions. - The program assumptions are the following:

1. The air conditioner performance varies with condensing temperature in accordance with the data given in figure 2.

2. The baseline solar collectors considered herein are selectively coated (such as black chrome) and have two glass covers which deliver 0.252 kW/m^2 (80 $Btu/hr\text{-}ft^2$) of heat to the boiler.

3. The percentages of the cooling loads in various sites are based on the data reported in reference 4. Two cases considered herein are 77 percent of the total load for Philadelphia and 49 percent for Miami.

4. The air-cooled condenser is a single pass cross-flow type with both fluids (air side and Freon side) unmixed.

5. The air side pressure drop across the condenser is to be kept above a minimal value (9.76 kg/m^2, or 2 lb/ft^2) in order to overcome a pressure differential caused by wind.

6. Condenser tubes are thin and their thermal resistance is negligible as compared to air film resistance.

7. The fixed charge rate is 10.2 percent on the basis of 8 percent interest on the capital cost for 20 years.

Input data. - Input data include air conditioner performance (fig. 2), solar heat collected and delivered to the boiler, percentage of cooling load supplied by solar, heat exchanger surface and its performance, minimum air side pressure drop of the condenser, rated cooling capacity of the air conditioner, boiler temperature, evaporator temperature, weather data (temperature) of the site, properties of the working fluid and air, design condensing temperature of wet-cooling system, thermal efficiencies of equipment components (expander, compressor, pump, fan, etc.), fixed charge rate, and costs of electricity, solar collector, heat exchanger surface, electric motor, and fan blades. These input parameters can be readily changed so as to allow the program to be quite general and adaptable to local conditions.

System variables. - With the input and parameters, the thermofluid, heat transfer and cost equations of the system can be written in terms of four variables which can be varied independently and which must be optimized to yield the least cost of the system.

The four variables are: (a) initial temperature difference (ITD), which is defined as the temperature difference between the working fluid entering the condenser and the ambient air, (b) condensing temperature of the working fluid, (c) number of tube banks in the direction of air flow, and (d) mass velocity ratio of the working fluid and the air.

Cost equations. - The increased cost due to the use of dry-cooling includes incremental capital cost, operating cost, and penalty cost due to decreased thermal efficiency and idled solar equipments whenever the ambient temperature is higher than the design condition.

The cost of the wet-cooling tower and the wet-condenser for the conventional system is estimated at \$700. The maintenance cost of the wet-cooling system, which might be significant, is not included in the analysis due to lack of data in the field.

The incremental capital costs are broken down into:

1. Cost of solar collector: $y_1 = C_1(A_1 - A_2)$, where C_1 is the cost per square foot of collector, A_1 the collector area required in dry-cooling and A_2 in wet-cooling.

2. Cost of hot water storage tank: $y_2 = \$0.75\ (A_1 - A_2)$; see reference 5.

3. Cost of condenser surface and header: $y_3 = C_2A_3$, where C_2 is the cost per unit condenser surface area installed, and A_3 the condenser surface area.

4. Cost of motors for fan and pump: $y_4 = C_3(P_1 + P_2)$, where C_3 is the cost of motors for the fan and pump per horsepower; P_1 is the power required for the fan and P_2 the power for the pump.

5. Cost of fan blades: $y_5 = C_4A_4$, where C_4 is the cost of fan blades per unit area covered, and A_4 is the frontal area of the condenser.

Thus, the annual total incremental capital cost, y_c, is

$$y_c = (y_1 + y_2 + y_3 + y_4 + y_5 - 700)f_c \tag{4}$$

where f_c is the fixed charge rate or capital-recovery factor.

The operating cost is for electricity to power the fan and is computed by

$$y_o = C_5KH \tag{5}$$

where C_5 is the electricity cost per KWh, K the power for the fan, and H the total operating hours of the fan per year.

When the ambient air temperature is higher than design temperature, the thermal efficiency decreases. To meet the designed cooling load, conventional energy (electricity) is required to make up the deficit. The cost, y_e, is the electrical energy penalty cost. Also, the decrease in capacity due to higher ambient air temperatures penalizes capital investment because of the partially or entirely idled solar collector-storage unit. The capacity penalty cost, y_f, is computed on the basis of yearly lost capacity of the solar unit.

Thus, the yearly incremental cost of the solar-powered Rankine-compression air conditioner with dry-cooling is

$$y = y_c + y_o + y_e + y_f \tag{6}$$

Procedures. - The procedure is to minimize the annual total cost of the system for using dry-cooling for given values of condensing temperature of the working fluid and compare costs. The minimization method applied herein is Rosenbrock's constrained hill climbing procedure (ref. 6). Four constraints are imposed on the system: (a) air velocity is to be kept below 45.7 m/sec (150 ft/sec), (b) condensing temperature is in the range of 37.8° C (100° F) and 54.4° C (130° F), (c) the minimum allowable air pressure drop across the condenser is 9.76 kg/m^2 (2 lb/ft^2), and (d) the lower bound and upper bound of the mass velocity ratio of entering vapor and air are functions of number of tube banks, air velocity, and air side pressure drop.

Once the dry-cooling system has been designed for a given ITD, its performance is evaluated at ambient air temperatures representative of local yearly fluctuations. For this design ITD, a fixed air-cooled condenser size, fan and pump power are assumed. Thus, when the condensing temperature is higher than the design value due to high ambient air temperature, the cost of both energy and capacity penalties is then computed for this ambient temperature and multiplied by the percent of the year this temperature is experienced at the site.

The output of the program is the annual total incremental cost (between dry cooling and wet-cooling), the design ITD, number of tube banks, condenser size, mass flow rates of working fluid and air, and other optimum design specifications.

The flow diagrams of the computer design program is displayed in appendix A. The input data requirement, notation and listing of the program are presented in appendix B. A sample design output for use in Philadelphia is given in appendix C.

RESULTS AND DISCUSSION

Figures 3(a) and (b) shows the annual incremental cost due to the use of dry-cooling in Philadelphia and Miami for using two different condenser surfaces, which are taken from reference 7. Surfaces A and B respectively refer to figures 10-83 and 10-84 in that reference.

The curves along with the values shown indicate the percentage of cooling load supplied by solar energy. For a large condenser (small ITD), the capital and operating incremental costs are high, but little or no cooling capacity is lost (thus little or no energy and capital penalty cost is involved) at high ambient air temperatures. To meet the same percentages of the yearly cooling load (49 percent for Miami and 77 percent for Philadelphia when a wet-cooling system is used), the incremental cost for adapting a dry-cooling system is quite high.

It is noted that each point on the curve is a minimal optimum point corresponding to that design ITD, and hence the true optimum for the dry-cooling subsystem is that design ITD which yields the least cost. Each point also identifies the percentage of the cooling load provided by solar energy. Since there is a unique value of solar percentage for each point along the curve, the curve can be interpreted on the basis of solar percentage of the cooling load as well as the ITD. The curves are fairly smooth and consistent except a few points which fluctuate along the curves. This is believed to be the consequence of specific design requirements such as the number of tube banks having to be an integer and the imposed allowable minimum air pressure drop across the condenser.

The curves in figure 3(a) and (b) result in definite minimum values of the cost increment. In all cases, the cost increment is quite sensitive to the solar percentage of the cooling load - particularly that portion of the curve with solar percentages higher than at the minimum cost point. For surface A under Miami conditions, the cost increment is approximately 200 percent greater for a decrease in solar percentage of 3 percent. Although the cost increment also rises as the solar percentage drops below the optimum point, it increases only approximately 15 percent for solar percentage decrease of 8 percent. Results are similar for the other 3 cases.

The significance of the condenser surface design is seen by a comparison at the optimum points. Use of surface B would cost $50 per year more compared to surface A, to meet 73 percent of the cooling load in Philadelphia.

Figure 4 illustrates the itemized annual incremental cost for using a dry-cooling system in Philadelphia. The contributions of capital, operating, and penalty costs to the total incremental cost are clearly shown. The shaded area indicates the capital savings at those design ITD's corresponding to relatively small condensers. Figure 5 shows the effect of number of tube banks on the incremental cost. The dashed lines are used to indicate only the general trend since the number of tube banks must be an integer.

The highlight of the optimum design specifications for Philadelphia and Miami is tabulated in Table I. The breakdown of costs is also given therein. A sample output of the design program is given in appendix C.

SUMMARY OF RESULTS

An optimum design procedure has been developed to estimate the annual incremental cost for a three-ton solar-powered Rankine-compression air conditioner equipped with a dry-cooling condenser over that with a wet-cooling tower. Conclusions may be made as follows:

1. The sensitivity of the cost increment between the two cooling systems illustrates the need for an optimization program when considering a dry-cooling solar system.

2. Within the conditions and guidelines stated within the report, it was concluded that -

a. The cost increment was significantly higher (a greater penalty) when values of solar percentage of the cooling load (an input parameter) was greater than at the optimum point compared to when the values were smaller than optimum.

b. Dry-cooling is economically competitive with conventional wet-cooling whenever the maintenance cost of the latter (which is ignored in this study) is in the range of $100 to $200 per year, or greater.

c. The optimization program has proved to be adaptable to various locales and design requirements.

3. The dry-cooling solar system, which eliminates water vapor in the atmosphere, offers a better environment with a slightly higher or no additional cost as compared to the wet-cooling tower system.

Some significant remaining problems or questions are as follows:

1. Absorption air conditioning has not yet been considered in a dry cooling system due to the crystallization of the working fluid at high ambient temperatures. If this problem can be addressed and solved, the benefits of dry cooling would be applicable for such units.

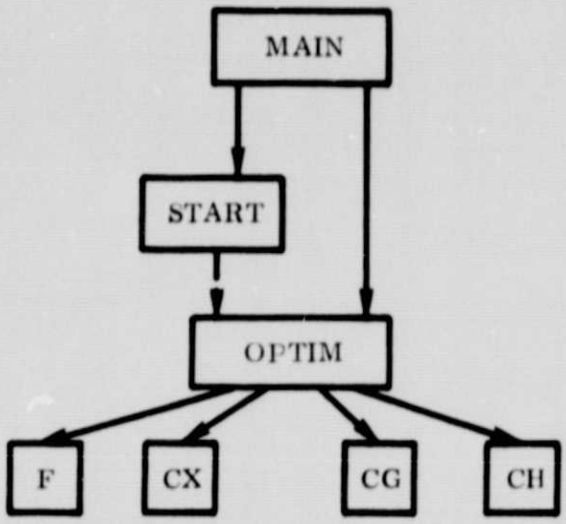
2. Maintenance cost for water treatment of the wet-cooling tower used for solar-driven residential air conditioners.

3. Cost of heat exchangers for rejecting waste heat to ambient air, as required by dry cooling.

APPENDIX A

FLOW DIAGRAMS

Flow Diagram of Subroutine calling



MAIN Main program.

START Finds starting values of variables such that they satisfy both the explicit and implicit constraints and do not lie within any boundary zone.

OPTIM Seeks minimum by means of constrained Rosenbrock method.

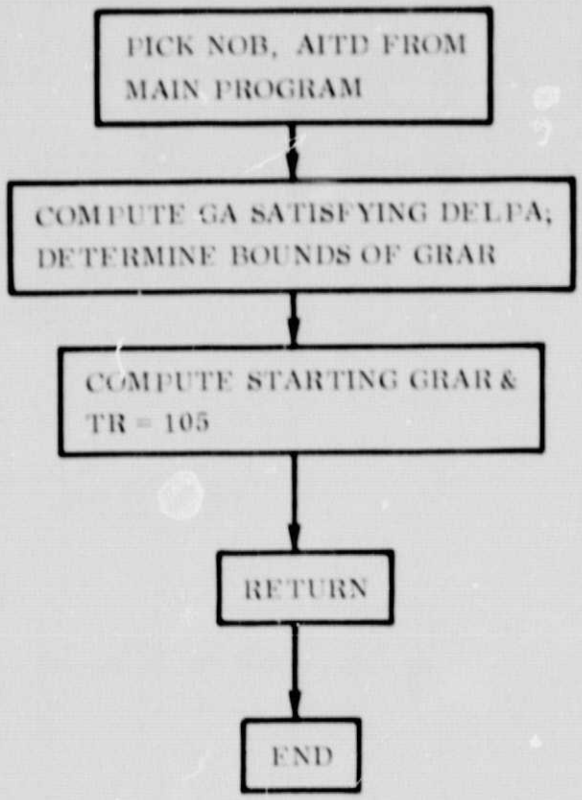
F Objective function of the total yearly bus-bar costs.

CX Constraint functions.

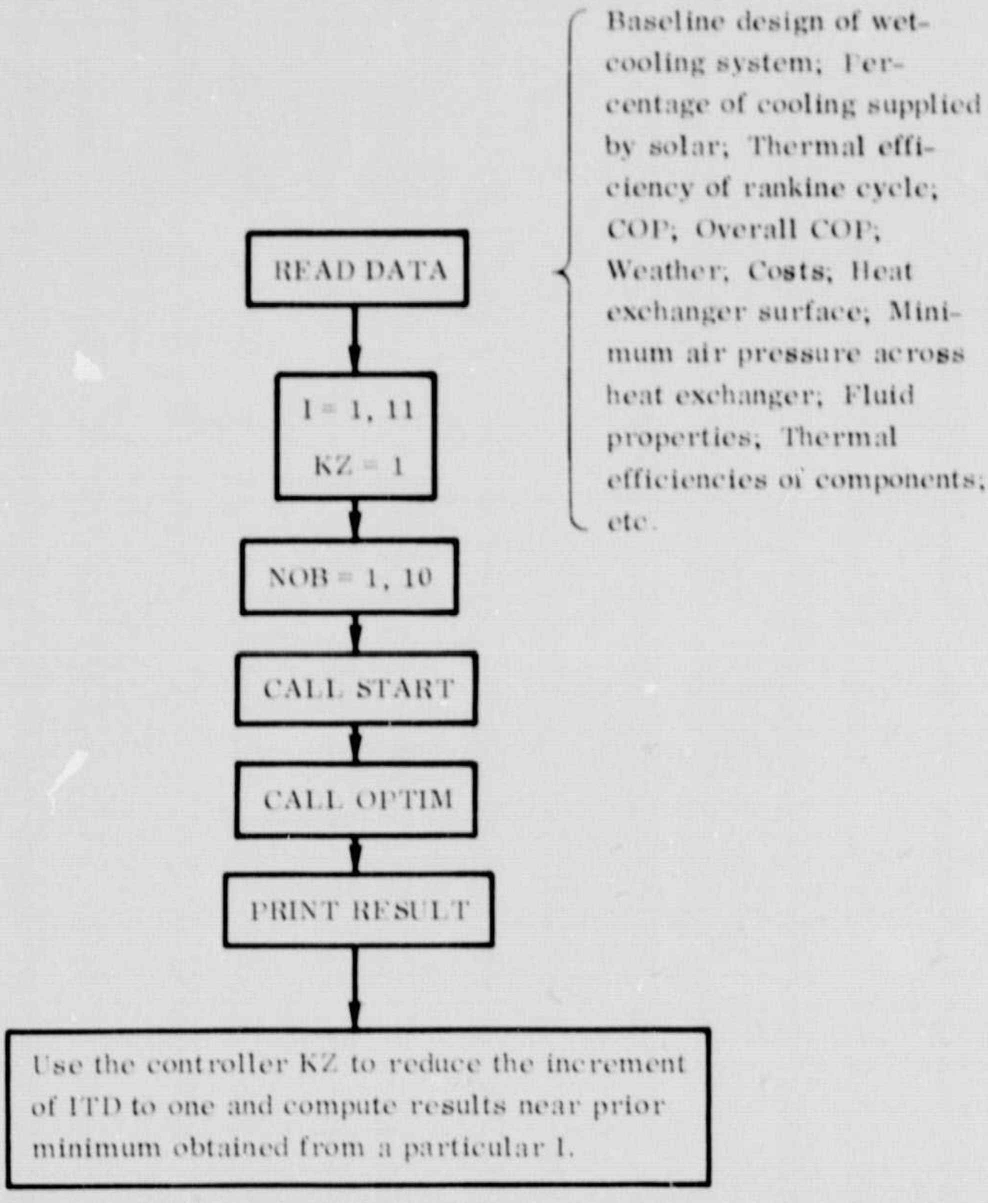
CG Lower bounds of CX.

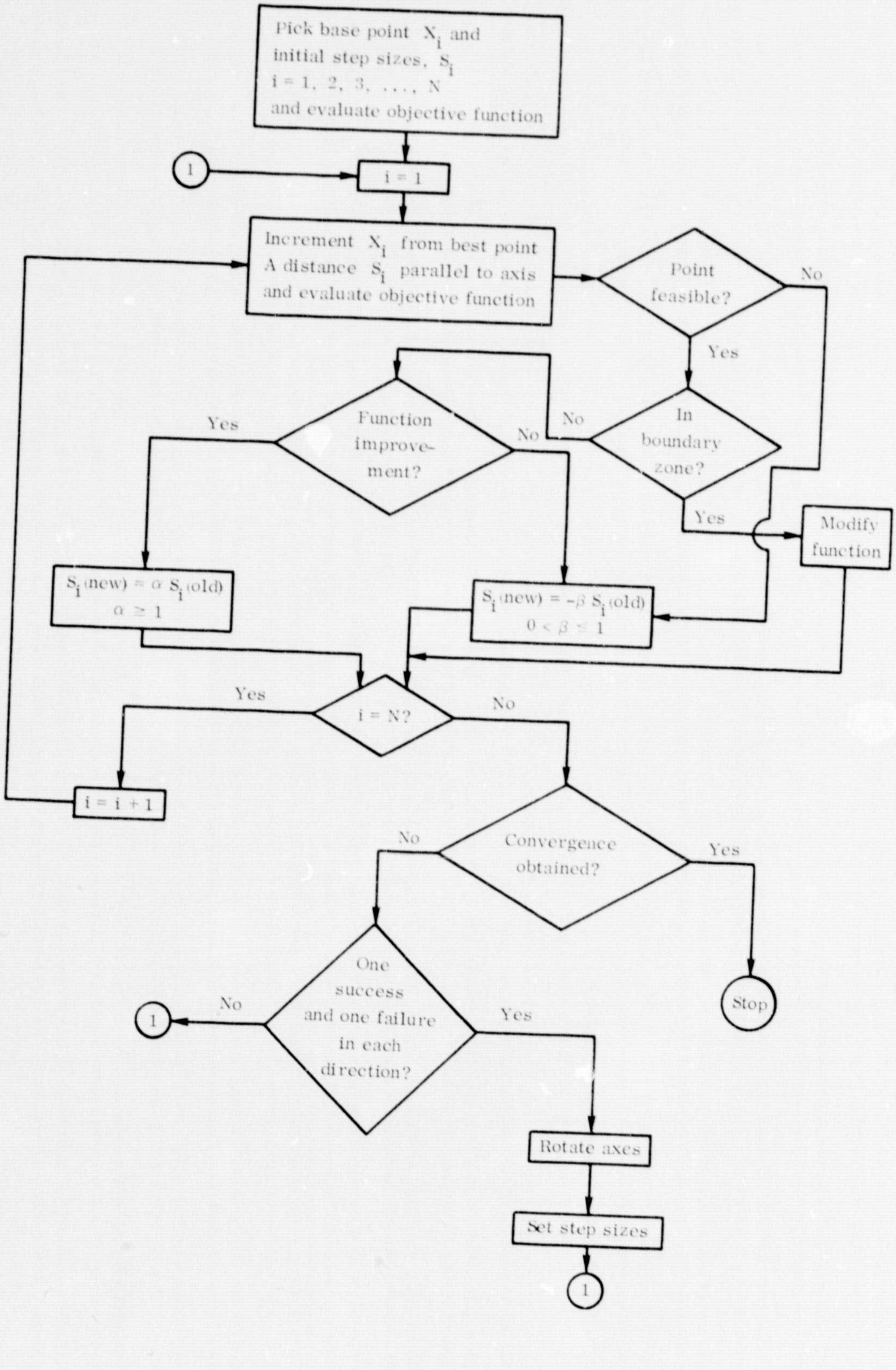
CH Upper bounds of CX.

Subroutine Start

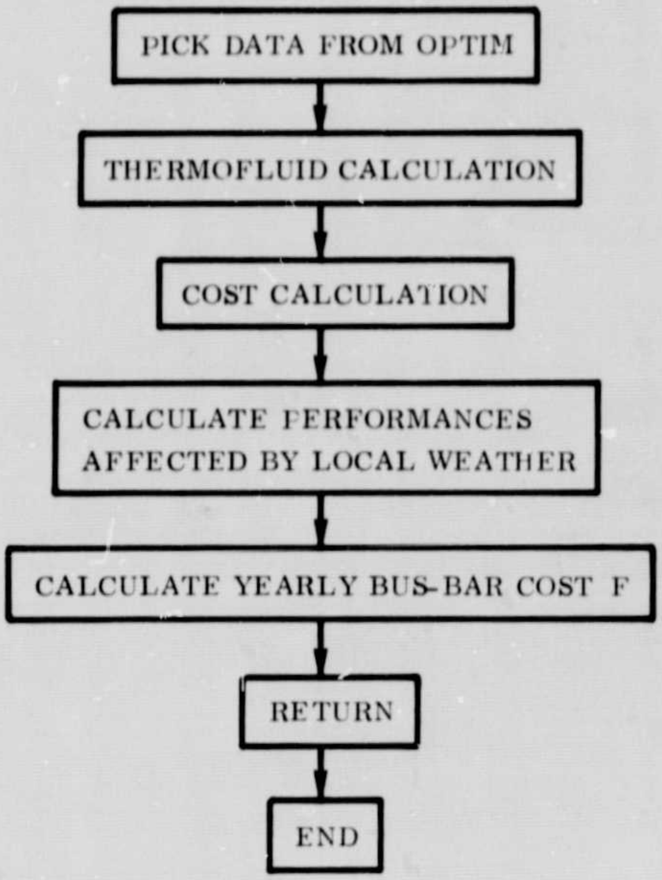


Main Program

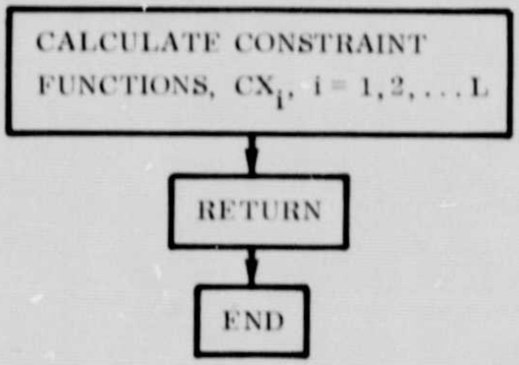



Pick base point X_i and
initial step sizes, S_i
$i = 1, 2, 3, \ldots, N$
and evaluate objective function
1
i = 1
Increment X_i from best point
A distance S_i parallel to axis
and evaluate objective function
Point
feasible?
No
Yes
In
boundary
zone?
No
Yes
Modify
function
Function
improve-
ment?
Yes
No
$S_i(\text{new}) = \alpha\, S_i(\text{old})$
$\alpha \geq 1$
$S_i(\text{new}) = -\beta\, S_i(\text{old})$
$0 < \beta \leq 1$
i = N?
Yes
No
i = i + 1
Convergence
obtained?
No
Yes
Stop
One
success
and one failure
in each
direction?
No
1
Yes
Rotate axes
Set step sizes
1

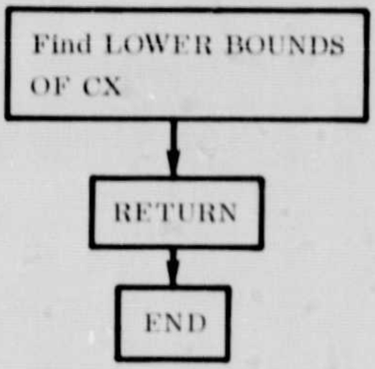
Function F


PICK DATA FROM OPTIM
THERMOFLUID CALCULATION
COST CALCULATION
CALCULATE PERFORMANCES AFFECTED BY LOCAL WEATHER
CALCULATE YEARLY BUS-BAR COST F
RETURN
END

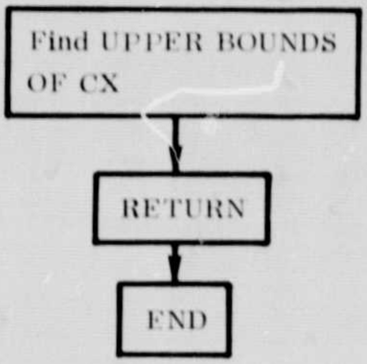
Function CX



Function CG



Function CH



APPENDIX B

PROGRAM INPUT DATA, NOTATION, AND LISTING

Input Data

AITD	Initial temperature difference (temperature difference between the condensing R-12 and the ambient air), (F)
AKA	Thermal conductivity of air (Btu/hr-ft-F)
AKRL	Thermal conductivity of liquid R-12 (Btu/hr-ft-F)
ALPHA	Ratio of total transfer area of air-side of heat exchanger to total exchanger volume
AMUA	Dynamic viscosity of air (lb/hr-ft)
AMURG	Dynamic viscosity of R-12 vapor (lb/hr-ft)
AMURL	Dynamic viscosity of liquid R-12 (lb/hr-ft)
C1 - C2	Coefficients of curve fit for Rankine cycle efficiency
C3 - C5	Coefficients of curve fit for compression cycle COP
C6 - C8	Coefficients of curve fit for enthalpy of R-12 vapor
C9 - C11	Coefficients of curve fit for enthalpy of R-12 liquid
C12 - C13	Coefficients of curve fit saturation pressure of R-12
C14 - C15	Curve fit constants for dimensionless heat transfer coefficients for heat exchanger surface
C16 - C17	Curve fit constants for friction factor for heat exchanger surface
C18 - C20	Coefficients of curve fit for specific volume of R-12 liquid
C21 - C23	Coefficients of curve fit for specific volume of R-12 vapor
COSEM	Cost of electric motor (\$/HP)
COSFB	Fan blade cost per area covered (\$/ft^2)
CPA	Specific heat of air (Btu/lb-F)
CPRL	Specific heat of liquid R-12 (Btu/lb-F)
CTPEA	Cost of cooling tower per unit total area of exchanger (\$/ft^2)
COSPW	Cost of electricity (\$/KWH)
COSTC	Cost of Solar collector (\$/ft^2)
DEQ	Hydraulic diameter = 4 × flow passage hydraulic radius (ft)

DITCH	Number of fins per foot (fins/ft)
EFFAN	Fan efficiency
EFP	Pump efficiency
FCR	Fixed-charge rate (percent/100)
FERC	Recoverable energy factor for moving air (percent/100)
FTHK	Fin thickness of exchanger (ft)
OD	Tube diameter of heat exchanger (ft)
PAI	Entering pressure of air (lb/ft^2)
PERSS	Percentage of cooling load supplied by solar
PRA	Prandtl number of air
PRRL	Prandtl number of liquid R-12
QE	Cooling capacity of the unit (Btu/hr)
RFATA	Ratio of fin area to total are of the air side of exchanger
RHOA	Density of air (lb/ft^3)
RHOR	Density of liquid R-12 (lb/ft^3)
SIGMA	Ratio of free-flow to frontal area of air side of exchanger
SLF	Fin height of exchanger (ft)
TAI1(I)	Ambient air temperatures used in evaluating dry-cooling tower performances (F)
TCB	Condensing temperature of R-12 of baseline design wet cooling system (F)
TEB	Fluid temperature in the evaporator (F)
TINXB	Temperature of fluid entering the expander (F)
TKF	Thermal conducitivity of fin material of exchanger (Btu/hr-ft-F)
TPER1(I)	Fraction of year TAI1(I) experienced
VADF	Velocity of air delivered by fan (ft/sec)
XD	Longitudinal tube spacing (depth pitch) of exchanger (ft)
XW	Transverse tube spacing (width pitch) of exchanger (ft)
WETC	Cost of wet-cooling tower and "wet-condensers" ($)

Notation

A	Total heat transfer area of air-side of heat exchanger (ft^2)±
ACCL	Annual penalty capital and operating costs due to ambient air temperatures above design temperature ($/yr)
ACOS	Total annual bus-bar cost of the system ($/yr)
ACPC	Annual penalty capital cost due to ambient air temperatures above design temperature ($/yr)
AEPC	Annual penalty operating cost due to ambient air temperatures above design temperature ($/yr)
AFR	Frontal area of heat exchanger (ft^2)
ALMTD	Log-mean temperature difference (F)
ALT	Tube length of exchanger (ft)
AMC	Mass flow rate of R-12 in the compression cycle (lb/hr)
AMP	Mass flow rate of R-12 in the Rankine cycle (lb/hr)
ANTU	Number of transfer unit of exchanger
ATUB	Total area of tubes of exchanger (ft^2)
COP	Coefficient of performance of compression cycle
DA	General storage vector
DELPA	Air pressure drop across echanger (lb/ft^2)
DELPR	R-12 pressure drop inside tube (lb/ft^2)
DELTA	Temperature increase of air across exchanger (F)
DELY	Difference between current value and previous stage value of objective function ($/yr)
DEP	Depth of exchanger (ft)
E	Vector of initial step sizes
EFF	Fin efficiency of exchanger (percent/100)
EFFP	Thermal efficiency of the Rankine cycle (percent/100)
EFZ	Temperature effectiveness of exchanger fin (percent/100)
EPS	Heat exchanger effectiveness (percent/100)
FAIR	Friction factor of air across exchanger
FR	Friction factor of R-12 flowing inside of tube

GA	Mass velocity of air (lb/hr-ft^2)
GM	Mean mass velocity of R-12 vapor (lb/hr-ft^2)
GRAR	Mass velocity ratio of vapor R-12 to air
HA	Mean air-film conductance of a finned exchanger (Btu/hr-ft^2-F)
HPA	Fan power for air (HP)
HPR	Pump power for R-12 (HP)
HR	Mean R-12 film conductance in a pipe (Btu/hr-ft^2-F)
K	Point index
L	Number of variables plus number of constraints
LOCA	Number used to identify weather station
LOOPY	Maximum number of stages to be calculated
M	Optimization controller; +1 for maximization, -1 for minimization
N	Dimension limit in subfunctions F, CX, CG and CH
ND	Storage controller; 1 for storage in DA, 0 for no storage
NDATA	Number of data points to be stored in DA
NHXS	Number used to identify heat exchanger surface
NOB	Number of tube banks parallel to direction of air flow
NPAR	Dimension limit in subfunctions F, CX, CG, and CH
NSTEP	Control of step sizes for each rotation; 0 for original step size, 1 for step size from previous rotation of axes
OCOP	Overall coefficient of performance of the air conditioner (= EFFP × COP)
OLHX	Overall length of the air-cooled condenser (ft)
OWHX	Overall width of the air-cooled condenser (ft)
P	Number of variables
PFKW	Fan power for air (KW)
PRKW	Pump power for R-12 (KW)
PR	Printing controller (number of stages between outputs)
QB	Solar energy collected by the collector (Btu/hr)
QBB	Solar energy collected by the collector for the baseline design unit (Btu/hr)

QRC	Heat rejection from the compression cycle (Btu/hr)
QRJ	Heat rejection through the air-cooled condenser (Btu/hr)
QRP	Heat rejection from the Rankine cycle (Btu/hr)
REA	Reynolds number of air flow
RER	Reynolds number of R-12 flow
RTAIA	Ratio of air-side area to R-12 side area of exchanger
SS	Fraction of cooling load supplied by solar energy
STPR	Product of Stanton number and Prandtl number to the 2/3 power
SVRG	Specific volume of R-12 vapor (ft^3/lb)
SVRL	Specific volume of liquid R-12 (ft^3/lb)
TAI	Temperature of air entering the condenser (F)
TAO	Temperature of air leaving the condenser (F)
TR	Design condensing temperature of R-12 (F)
U	Overall heat transfer coefficient based on air-side area ($Btu/hr\text{-}ft^2\text{-}F$)
UITA	Overall heat transfer coefficient based on R-12 side area ($Btu/hr\text{-}ft^2\text{-}F$)
V	Direction vector
VA	Air velocity (ft/sec)
VOL	Volume of heat exchanger (ft^3)
VRI	Velocity of R-12 vapor entering the condenser (ft/sec)
WA	Mass flow rate of air (lb/hr)
WCOMP	Power required by the compressor (Btu/hr)
WEXP	Power generated by the expander (Btu/hr)
WPUHP	Power required by the pump (HP)
WR	Total mass flow rate of R-12 (lb/hr)
X	Independent variables
XI	Area of solar collector (ft^2)
YC	Total annual bus-bar capital cost ($/yr)
YC1	Capital cost of solar collector and storage tank ($)
YC2	Capital cost of air-cooled condenser ($)
YC3	Capital cost of electric motors ($)

YC4	Capital cost of fan blades ($)
YCO	YC + YO
YO	Annual bus-bar operating cost ($/yr)

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APPENDIX C

SAMPLE OF PROGRAM OUTPUT

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C       ************************************************************
C       *                                                          *
C       *                                                          *
C       *  OPTIMUM DRY COOLING SYSTEMS FOR A SOLAR AIR CONDITIONER *
C       *                                                          *
C       *                                                          *
C       ************************************************************
C
C
C       MAIN PROGRAM
C
        DIMENSION DIT(15),DA(70),EE(3),XX(3),TC(2),Z(20),WW(50)
        COMMON ACB,AITD,AKA,AKRL,ALPHA,AMUA,AMURG,AMURL,C1,C2,C3,C4,
       1C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15,C16,C17,C18,C19,C20,
       2C21,C22,C23,COPB,COSEM,COSFB,COSPW,COSTC,CPA,CPRL,CTPEA,DEQ,
       3DITCH,EFFAN,EFFPB,EFP,FCR,FERC,FTHK,HYR,KOUNT,OD,P2,PA1,PRA,
       4PRRL,QE,QBB,RFATA,RHOA,RHOR,RTATA,SIGMA,SLF,TAI1(15),TCB,TEB,
       5TINXB,TKF,TPER1(15),VADF,WETC,XD,XW,XZ,H6,PERSS,Z1
        INTEGER XZ
        READ (5,001) QE,TCB,TINXB,TEB
        READ (5,901) AMUA,AKA,CPA,PRA,RHOA,RHOR
        READ (5,002) (TAI1(I),I=1,5)
        READ (5,002) CPRL,AMURL,AMURG,AKRL,PRRL
        READ (5,002) COSTC,CTPEA,COSEM,COSFB,FCR
        READ (5,002) VADF,PA1,EFP,FERC,EFFAN
        READ (5,003) LOCA,(TPER1(I),I=1,5)
        READ (5,004) NHXS,OD,RFATA,DEQ,SIGMA,ALPHA,XW
        READ (5,004) NHXS,XD,FTHK,DITCH,TKF,SLF,HYR
        READ (5,005) C1,C2,C3,C4,C5
        READ (5,006) C6,C7,C8,C9,C10,C11,C12,C13
        READ (5,007) C14,C15,C16,C17
        READ (5,008) C18,C19,C20,C21,C22,C23
        READ (5,009,END=999) WETC,COSPW,PERSS
    001 FORMAT (F10.3,3F10.4)
    002 FORMAT (5F10.4)
    003 FORMAT (I5,5F5.2)
    004 FORMAT (I10,6F10.5)
    005 FORMAT (5F10.6)
    006 FORMAT (8F10.4)
    007 FORMAT (4F10.4)
    008 FORMAT (F10.5,2F20.15,3F10.6)
    009 FORMAT (3F10.2)
    901 FORMAT (6F10.4)
        NDATA=50
        Z1=TPER1(1)+TPER1(2)+TPER1(3)+TPER1(4)+TPER1(5)
        P2=EXP(C12+C13/(TINXB+460.))
        H6=C6+C7*TEB+C8*TEB*TEB
        TR=TCB
        EFFP=C1+C2*TR
        COP=C3+C4*TR+C5*TR*TR
        OCOP=EFFP*COP
        QBB=QE/OCOP
        ACB=QBB/80.
        DA(51)=24.**(2.*C17)
        DA(63)=(1.-FTHK*DITCH)/(1.-RFATA)
        DA(64)=0.0108765*CPRL/SQRT(PRRL)*(AMURG/OD)**0.1
        DA(65)=4./(3.1416*OD*OD)
```

```
      DA(66)=2.0
      DA(67)=16.1*3600.**2*DEQ*(AMUA/DEQ)**C17/(C16*XD)
      DA(70)=1./(2.*C17)
      RTAIA=DA(63)
      DIT(1)=10.
      DO 200 IID=1,10
      DIT(IID+1)=DIT(IID)+5.0
  200 CONTINUE
C
C     *** CALCULATE MAX. AND MIN. MASS FLOW RATE WR ***
C
      TC(1)=100.
      TC(2)=130.
      DO 102 K=1,2
      TR=TC(K)
      EFFP=C1+C2*TR
      COP=C3+C4*TR+C5*TR*TR
      OCOP=EFFP*COP
      QB=QE/OCOP
      QRP=(1.-EFFP)*QB
      HG=C6+C7*TR+C8*TR*TR
      HF=C9+C10*TR+C11*TR*TR
      AMP=QRP/(HG-HF)
      AMC=QE/(HG-HF)
      WR=AMP+AMC
      DA(K+60)=WR
  102 CONTINUE
      WRITE(6,001) QE,TCB,TINXB,TEB
      WRITE(6,901) AMUA,AKA,CPA,PRA,RHOA,RHOR
      WRITE(6,002) (TAI1(I),I=1,5)
      WRITE(6,002) CPRL,AMURL,AMURG,AKRL,PRRL
      WRITE(6,002) COSTC,CTPEA,COSEM,COSFB,FCR
      WRITE(6,002) VADF,PA1,EFP,FERC,EFFAN
      WRITE(6,003) LOCA,(TPER1(I),I=1,5)
      WRITE(6,004) NHXS,OD,RFATA,DEQ,SIGMA,ALPHA,XW
      WRITE(6,004) NHXS,XD,FTHR,DITCH,TKF,SLF,HYR
      WRITE(6,005) C1,C2,C3,C4,C5
      WRITE(6,006) C6,C7,C8,C9,C10,C11,C12,C13
      WRITE(6,007) C14,C15,C16,C17
      WRITE(6,008) C18,C19,C20,C21,C22,C23
      WRITE(6,009) WETC,COSPW,PLRSS
      WRITE (6,3000) DA(61),DA(62),DA(63),DA(64),DA(65),DA(66),DA(67),
     1DA(70)
 3000 FORMAT (8E12.5/)
      KZ=1
      DO 100 I=1,11
      AITD=DIT(I)
  114 DO 110 NOB=1,10
      DA(2)=NOB
C
C     FIND STARTING VALUES WITHIN CONSTRAINTS
C
      CALL START (XX,DA)
      GO TO (100,31),KZ
   31 EE(1)=1.5
      EE(2)=2.0
      DO 101 J=3,NDATA
```

```
      DA(J)=0.0
  101 CONTINUE
      CALL OPTIM(XX,EE,DA)
      YCO=DA(34)+DA(35)
      ACOS=YCO+DA(50)
      WRITE (6,1006)
 1006 FORMAT  (' ************************************************************
     1*****************************************')
      WRITE (6,1007)
 1007 FORMAT (' *                                                           ',
     1'                                      *')
      WRITE (6,1004)  NHXS,AITD,DA(2),DA(1),XX(1),XX(2),DA(52)
 1004 FORMAT (' * NHXS='I2,    '    AITD='F5.1,'    NOB='F4.1,'    DEP='
     1F7.3,'   GRAR='E14.7,'   TR='F7.3,'  SS='F5.2,'     *')
      WRITE (6,1008) DA(34),DA(35),YCO,DA(50),ACOS
 1008 FORMAT (' * YC='E11.4,'    YO='E11.4,'    YCO='E11.4,'    ACCL='
     1E11.4,'   ACOS='E11.4,'         *')
      WRITE (6,1007)
      WRITE (6,1006)
      Z(NOB)=ACOS
      IF (NOB.EQ.1) GO TO 110
      IF (Z(NOB)-Z(NOB-1)) 110,110,111
  111 GO TO (112,113,115,999),KZ
  112 WW(I)=Z(NOB-1)
      IF (I.EQ.1) GO TO 100
      IF (WW(I).LE.WW(I-1)) GO TO 100
      KZ=2
      AITD=DIT(I-1)-1.0
      GO TO 114
  113 AITD=AITD-1.0
      IF (AITD.GT.DIT(I-2)) GO TO 114
      KZ=3
      AITD=DIT(I-1)+1.0
      GO TO 114
  115 AITD=AITD+1.0
      IF (AITD.LT.DIT(I)) GO TO 114
      KZ=4
      AITD=DIT(I+1)
      GO TO 114
  110 CONTINUE
  100 CONTINUE
  999 STOP
      END
```

```
      SUBROUTINE START (X,DA)
      DIMENSION X(3),DA(70)
      COMMON ACB,ALTD,AKA,AKRL,ALPHA,AMUA,AMURG,AMURL,C1,C2,C3,C4,
     1C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15,C16,C17,C18,C19,C20,
     2C21,C22,C23,COPB,COSEM,COSFB,COSFW,COSTC,CPA,CPRL,CTPFA,DEQ,
     3DITCH,EFFAN,EFFPB,EFP,FCR,FERC,FTHK,HYR,KOUNT,OD,PZ,PA1,PRA,
     4PRRL,QE,QPB,RFATA,RHOA,RHOR,RTAIA,SIGMA,SLF,TAIL(15),TCB,TEB,
     5TINXB,TKF,TPERI(15),VADF,WETC,XD,XW,XZ,H6,PERSS,Z1
      INTEGER XZ
      DA(1)=DA(2)*XD
      VAMAX=120.
      XIMIN=DA(65)*DA(61)/(3600.*RHOA*DA(2)*VAMAX)
      GAMIN=(DA(67)*DA(66)/DA(2)*RHOA)**DA(70)*1.05
      XIMAX=DA(65)*DA(62)/(GAMIN*DA(2))
      DA(68)=XIMIN
      DA(69)=XIMAX
      VA=GAMIN/(RHOA*3600.)
      IF (VA-5.) 16,17,17
   17 X(1)=XIMAX*DA(61)/DA(62)
      X(2)=105.
      XZ=2
      WRITE (6,15) X(1),GAMIN,XIMIN,XIMAX
   15 FORMAT (4E15.7/)
      GO TO 13
   16 XZ=1
   13 RETURN
      END
```

```
      SUBROUTINE OPTIM (X,E,DA)
      DIMENSION X(3), E(3), V(3,3), SA(3), D(3), H(6), AL(6),
     1PH(6), B(6,6), BX(6),  VV(6,6), EINT(3), DA(70)
      COMMON ACB,AITD,AKA,AKRL,ALPHA,AMUA,AMURG,AMURL,C1,C2,C3,C4,
     1C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15,C16,C17,C18,C19,C20,
     2C21,C22,C23,COPB,COSLM,COSFB,COSPW,COSTC,CPA,CPPL,CTPEA,DEC,
     3DITCH,EFFAN,EFFPB,EFP,FCR,FERC,FTHK,HYR,KOUNT,OD,P2,PA1,PRA,
     4PRRL,QE,QBB,RFATA,RHOA,RHOR,RTAIA,SIGMA,SLF,TAI1(15),TCB,TEB,
     5TINXB,TKF,TPER1(15),VADF,WETC,XD,XW,XZ,H6,PERSS,Z1
      INTEGER C,P,PR,R,XZ
      REAL LC
      M=-1
      P=2
      L=4
      LOOPY=250
      PR=LOOPY
      ND=1
      NDATA=70
      NSTEP=0
      WRITE (6,013)
  013 FORMAT (/' ***** SUBROUTINE OPTIM DATA *****')
C
   30 LAP=PR-1
      LOOP=0
      ISW=0
      INIT=0
      KOUNT=0
      TERM=0.
      DELY=1.0E-10
      F1=0.0
      NPAR=NDATA
      N=L
      DO 40 K=1,L
   40 AL(K)=(CH(X,DA,N,NPAR,K)-CG(X,DA,N,NPAR,K))*.0001
      DO 60 I=1,P
      DO 60 J=1,P
      V(I,J)=0.0
      IF (I-J) 60,61,60
   61 V(I,J)=1.0
   60 CONTINUE
      DO 65 KK=1,P
      EINT(KK)=E(KK)
   65 CONTINUE
C
 1000 DO 70 J=1,P
```

```
      IF (NSTEP.EQ.0) E(J)=EINT(J)
      SA(J)=2.0
   70 D(J)=0.0
      FBEST=F1
   80 I=1
      IF (INIT.EQ.0) GO TO 120
   90 DO 110 K=1,P
  110 X(K)=X(K)+E(I)*V(I,K)
      IF (X(K).GT.0.) GO TO 501
      WRITE (6,502) K,I,E(I),V(I,K),X(K)
  502 FORMAT ('  K='I3,'  I='I3,3F15.7)
  501 CONTINUE
      DO 50 K=1,L
   50 H(K)=F0
C
  120 F1=F(X,DA,N,NPAR)
      F1=M*F1
      IF (ISW.EQ.0) F0=F1
      ISW=1
      IF (ABS(FBEST-F1)-DELY) 122,122,125
  122 TERM=1.0
      GO TO 450
  125 CONTINUE
C
      J=1
C
  130 XC=CX(X,DA,N,NPAR,J)
      LC=CG(X,DA,N,NPAR,J)
      UC=CH(X,DA,N,NPAR,J)
      IF (XC.LE.LC) GO TO 420
      IF (XC.GE.UC) GO TO 420
      IF (F1.LT.F0) GO TO 420
      IF (XC.LT.LC+AL(J)) GO TO 140
      IF (XC.GT.UC-AL(J)) GO TO 140
      H(J)=F0
      GO TO 210
  140 CONTINUE
      BW=AL(J)
      IF (XC.LE.LC.OR.UC.LE.XC) GO TO 150
      IF (LC.LT.XC.AND.XC.LT.LC+BW) GO TO 160
      IF (UC-BW.LT.XC.AND.XC.LT.UC) GO TO 170
      PH(J)=1.0
      GO TO 210
  150 PH(J)=0.0
      GO TO 190
  160 PW=(LC+BW-XC)/BW
      GO TO 180
  170 PW=(XC-UC+BW)/BW
  180 PH(J)=1.0-3.0*PW+4.0*PW*PW-2.0*PW*PW*PW
  190 F1=H(J)+(F1-H(J))*PH(J)
  210 CONTINUE
      IF (J.EQ.L) GO TO 220
      J=J+1
      GO TO 130
  220 INIT=1
      IF (F1.LT.F0) GO TO 420
      D(I)=D(I)+E(I)
```

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```
      E(I)=3.0*E(I)
      FO=F1
      IF (SA(I).GE.1.5) SA(I)=1.0
  230 DO 240 JJ=1,P
      IF (SA(JJ).GE.0.5) GO TO 440
  240 CONTINUE
C     AXES ROTATION
C
      DO 250 R=1,P
      DO 250 C=1,P
  250 VV(C,R)=0.0
      DO 260 R=1,P
      KR=R
      DO 260 C=1,P
      DO 265 K=KR,P
  265 VV(R,C)=D(K)*V(K,C)+VV(R,C)
  260 B(R,C)=VV(R,C)
      BMAG=0.0
      DO 280 C=1,P
      BMAG=BMAG+B(1,C)*B(1,C)
  280 CONTINUE
      BMAG=SQRT(BMAG)
      BX(1)=BMAG
      DO 310 C=1,P
  310 V(1,C)=B(1,C)/BMAG
      DO 390 R=2,P
      IR=R-1
      DO 390 C=1,P
      SUMVM=0.0
      DO 320 KK=1,IR
      SUMAV=0.0
      DO 330 KJ=1,P
  330 SUMAV=SUMAV+VV(R,KJ)*V(KK,KJ)
  320 SUMVM=SUMAV*V(KK,C)+SUMVM
  390 B(R,C)=VV(R,C)-SUMVM
      DO 340 R=2,P
      BBMAG=0.0
      DO 350 K=1,P
  350 BBMAG=BBMAG+B(R,K)*B(R,K)
      BBMAG=SQRT(BBMAG)
      DO 340 C=1,P
  340 V(R,C)=B(R,C)/BBMAG
      LOOP=LOOP+1
      LAP=LAP+1
      IF (LAP.EQ.PR) GO TO 450
      GO TO 1000
  420 IF (INIT.EQ.0) GO TO 450
      DO 430 IX=1,P
  430 X(IX)=X(IX)-E(I)*V(I,IX)
      E(I)=-0.5*E(I)
      IF (SA(I).LT.1.5) SA(I)=0.0
      GO TO 230
  440 CONTINUE
      IF (I.EQ.P) GO TO 80
      I=I+1
      GO TO 90
  450 WRITE (6,003)
```

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```
003 FORMAT ( /,2X,5HSTAGE,8X,8HFUNCTION,12X,8HPROGRESS,9X,
   116HLATERAL PROGRESS)
    WRITE  (6,004) LOOP,FO,PMAG,BBMAG
004 FORMAT (1H,I5,3E20.8)
    WRITE  (6,014) KOUNT
014 FORMAT (  2X,33HNUMBER OF FUNCTION EVALUATIONS =  ,I8)
    WRITE  (6,005)
005 FORMAT (  2X,25HVALUES OF X AT THIS STAGE)
C     PRINT CURRENT VALUES OF X
    WRITE  (6,006) (JM, X(JM), JM=1,P)
006 FORMAT (  2X,5(2HX(,I2,4H) = ,1PE14.6,4X))
    LAP=0
    IF (INIT.EQ.0) GO TO 470
    IF (TERM.EQ.1.0) GO TO 480
    IF (LOOP.GE.LOOPY) GO TO 480
    GO TO 1000
470 WRITE  (6,007)
007 FORMAT (///,2X,61HTHE STARTING POINT MUST NOT VIOLATE THE CONSTRAI
   INTS.  IT APPEARS TO HAVE DONE SO.)
480 CONTINUE
    WRITE (6,019)
019 FORMAT (/' ***** OPTIMUM DESIGN SPECIFICATIONS *****'/)
    WRITE (6,015) DA(3),DA(4),DA(5),DA(6),DA(7)
    WRITE (6,016) DA(8),DA(9),DA(10),DA(11),DA(12)
    WRITE (6,017) DA(13),DA(14),DA(15),DA(16),DA(17)
    WRITE (6,018) DA(18),DA(19),DA(20),DA(21),DA(22)
    WRITE (6,020) DA(23),DA(24),DA(25),DA(26),DA(27)
    WRITE (6,021) DA(28),DA(29),DA(30),DA(31),DA(32)
    WRITE (6,022) DA(33),DA(36),DA(37),DA(38),DA(39)
    WRITE (6,023) DA(40),DA(41),DA(42),DA(43),DA(44)
    WRITE (6,024) DA(45),DA(46),DA(47),DA(48),DA(49)
    WRITE (6,025) DA(53),DA(54),DA(55)
015 FORMAT  ('  VA='E10.3,'  EPS='E10.3,'  A='E14.7,'  DEP='E12.5,
   1'  AFR='E14.7)
016 FORMAT  ('  ALT='E12.5,'    AM='E12.5,'  ATUB='E14.7,'  U='E12.5,
   1'  PEKW='E12.5)
017 FORMAT  ('  GA='E12.5,'  GM='E12.5,'  VR1='E12.5,'  REA='E12.5,
   1'  RER='E12.5)
018 FORMAT  ('  WA='E14.7,'  WR='E14.7,'  TAO='E12.5,'  DELTA='E12.5,
   1'  ALMTD='E12.5)
020 FORMAT  ('  DELPA='E12.5,'  HPA='E14.5,'  DELPR='E12.4,'  HPR='
   1E12.5,'  QRJ='E14.7)
021 FORMAT  ('  QB='E14.7,'  EFFP='E12.5,'  OWHX='E12.5,'  OLHX='
   1E12.5,'  EFZ='E12.5)
022 FORMAT ('  AA2='E12.5,'  COP='E12.5,'  OCOP='E12.5,'  WCOMP='
   1E12.5,'  QRP='E12.5)
023 FORMAT ('  QRC='E12.5,'  AMP='E12.5,'  AMC='E12.5,'  WPUMP='
   1E12.5,'  WEXP='E12.5)
024 FORMAT ('  X1='E12.5,'  YC1='E12.5,'  YC2='E12.5,'  YC3='
   1E12.5,'  YC4='E12.5)
025 FORMAT ('  ALPC='E11.4,'  ACPC='E11.4,'  DA(55)='E11.4/)
473 RETURN
    END
```

```
      FUNCTION F (X,DA,N,NPAR)
      DIMENSION X(N), DA(NPAR)
      COMMON ACB,ATTD,AKA,AKRL,ALPHA,AMUA,AMURG,AMURL,C1,C2,C3,C4,
     1C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15,C16,C17,C18,C19,C20,
     2C21,C22,C23,COPB,COSEM,COSFB,COSPW,COSTC,CPA,CPRL,CTPEA,DEQ,
     3DITCH,EFFAN,EFFPB,EFP,FCR,FERC,FTHK,HYR,KOUNT,OD,P2,PA1,PRA,
     4PRRL,QE,QBB,RFATA,RHOA,RHOR,RTATA,SIGMA,SLF,TAI1(15),TCB,TEB,
     5TINXB,TKF,TPER1(15),VADF,WETC,XD,XW,XZ,H6,PERSS,Z)
      GRAR=X(1)
      IF (X(1).GT.0.) GO TO 501
      WRITE (6,001) X(1)
  001 FORMAT (E15.7)
  501 CONTINUE
      TR=X(2)
      EFFP=C1+C2*TR
      COP=C3+C4*TR+C5*TR*TR
      OCOP=EFFP*COP
      QB=QE/OCOP
      QRP=(1.-EFFP)*QB
      HG=C6+C7*TR+C8*TR*TR
      HF=C9+C10*TR+C11*TR*TR
      AMP=QRP/(HG-HF)
      AMC=QE/(H6-HF)
      WR=AMP+AMC
      QRJ=(1.+1./OCOP)*QE
      WCOMP=QE/COP
      QRC=QRJ-QRP
      P1=EXP(C12+C13/(TR+460.))
      WPU=AMP*(P2-P1)*144./(RHOR*EFP*778.)
      WPUKW=WPU*2.928E-4
      WPUHP=WPU*3.927E-4
      WEXP=WCOMP+WPU
      SVRL=C18+C19*TR+C20*TR*TR
      SVRG=C21+C22*TR+C23*TR*TR
      GR1=DA(65)*WR/DA(2)
      GM=0.58*GR1
      GA=GR1/GRAR
      VA=GA/(3600.*RHOA)
      REA=DEQ*GA/AMUA
      STPR=C14*REA**C15
      FAIR=C16*REA**C17
      HA=CPA*GA*STPR/PRA**0.667
      AM=SQRT(2.*HA/(TKF*FTHK))
      EFF=TANH(AM*SLF)/(AM*SLF)
      EFZ=1.-RFATA*(1.-EFF)
      AA2=DA(64)*SQRT(SVRG/SVRL)
      HR=AA2*GM**0.9
      U=1./(1./(EFZ*HA)+RTATA/HR)
      UITA=1./(1./(RTATA*EFZ*HA)+1./HR)
      ANTU=ALPHA*DA(1)*U/(SIGMA*CPA*GA)
      EPS=1.-EXP(-ANTU)
      DELTA=EPS*ATTD
      WA=QRJ/(CPA*DELTA)
      AFR=WA/(SIGMA*GA)
      ALT=AFR/XW
      RER=OD*GM/AMURG
```

```
      VR1=GR1*SVRG/3600.
      FR=0.056/PER**0.2
      CMIN=CPA*WA
      A=ANTU*CMIN/U
      VOL=A/ALPHA
      DEP=VOL/AFR
      TAO=TR-AITD*(1.-EPS)
      TAI=TR-AITD
      SVAI=53.3*(TAI+460.)/PAI
      RSV21=(TAO+460.)/(TAI+460.)
      RSVM1=((TAO+TAI)/2.+460.)/(TAI+460.)
      DELPA=(GA/3600.)**2*SVAI/64.4*((1.+SIGMA**2)*(RSV21-1.)+FAIR*DEP
     1*4./DEQ*RSVM1)
      DELPR=2./32.2*ALT/GD*SVRG*(GM/3600.)**2*FR
      HPR=DELPR*WR*SVRL/(3600.*550.)
      PPKW=HPR/(1.341*EFP)
      HPA=WA*(DELPA/RHOA+VA**2/(64.4*(1.-FERC)))/(3600.*550.)
      PFKW=HPA/(1.341*EFFAN)
      ATUB=A/RTATA
      ALMTD=QRJ/(U*A)
      NW=AFR**0.5/XW
      OWHX=NW*XW
      OLHX=AFR/OWHX
      X1=QB/QBB*ACB
      YC1=X1*(0.75+COSTC)
      YC2=A*CTPEA
      YC3=(HPA+WPUMP)*COSEM
      YC4=VA*AFR*COSFB/VADF
      YC=(YC1+YC2-KETC+YC3+YC4-ACB*(0.75+COSTC))*FCR
      YO=Z1*87.60*PFKW*COSPW
      DA(3)=VA
      DA(4)=EPS
      DA(5)=A
      DA(6)=DEP
      DA(7)=AFR
      DA(8)=ALT
      DA(9)=AM
      DA(10)=ATUB
      DA(11)=U
      DA(12)=PFKW
      DA(13)=GA
      DA(14)=GM
      DA(15)=VR1
      DA(16)=REA
      DA(17)=RER
      DA(18)=WA
      DA(19)=WR
      DA(20)=TAO
      DA(21)=DELTA
      DA(22)=ALMTD
      DA(23)=DELPA
      DA(24)=HPA
      DA(25)=DELPR
      DA(26)=HPR
      DA(27)=QRJ
      DA(28)=QB
      DA(29)=EFFP
```

```
      DA(30)=QWHX
      DA(31)=QLHX
      DA(32)=EFZ
      DA(33)=AA2
      DA(34)=YC
      DA(35)=YO
      DA(36)=COP
      DA(37)=OCOP
      DA(38)=WCOMP
      DA(39)=QRP
      DA(40)=QRC
      DA(41)=AMP
      DA(42)=AMC
      DA(43)=WPUMP
      DA(44)=WEXP
      DA(45)=X1
      DA(46)=YC1
      DA(47)=YC2
      DA(48)=YC3
      DA(49)=YC4
C
C     ***AMBIENT AIR TEMPERATURE EFFECT***
C
      AEPC=0.
      ACPC=0.
      TPSS=0.
      COPB=COP
      DO 100 K=1,5
      TRR=AITD+TAI1(K)
      EFFP=C1+C2*TRR
      COP=C3+C4*TRR+C5*TRR*TRR
      WCOMP=QE/COP
      QRP=QRJ-WCOMP-QE
      QB=QRP/(1.-EFFP)
      WM=WCOMP-EFFP*QB
      IF (WM.LE.0.) GO TO 100
      PERWM=WM/WCOMP
      TPERW=PERWM*TPER1(K)/Z1
      TPSS=TPSS+TPERW
      EPC=WM*2.928E-4*TPER1(K)*87.6*COSPW
      CPC=WM/QL*COPB*YC1*FCR*TPER1(K)/Z1
      AEPC=AEPC+EPC
      ACPC=ACPC+CPC
      ACCL=AEPC+ACPC
  100 CONTINUE
      DA(50)=ACCL
      DA(52)=PERSS-TPSS
      DA(53)=AEPC
      DA(54)=ACPC
      DA(55)=YC+YO+ACPC
      F=YC+YO+ACCL
      KOUNT=KOUNT+1
      RETURN
      END
```

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```
      FUNCTION CX (X,DA,N,NPAR,K)
      DIMENSION X(N), DA(NPAR)
      IF (K.GE.3) GO TO 1
      CX=X(K)
      GO TO 5
    1 KK=K-2
      GO TO (4,2),KK
    2 CX=DA(3)
      GO TO 5
    4 CX=DA(23)
    5 RETURN
      END
```

```
      FUNCTION CG (X,DA,N,NPAR,K)
      DIMENSION X(N), DA(NPAR)
      GO TO (2,3,4,6),K
    2 CG=DA(68)
      GO TO 9
    3 CG=100.
      GO TO 9
    4 CG=DA(66)
      GO TO 9
    6 CG=4.0
    9 RETURN
      END
```

```
      FUNCTION CH (X,DA,N,NPAR,K)
      DIMENSION X(N), DA(NPAR)
      GO TO (2,3,4,6),K
    2 CH=DA(69)
      GO TO 9
    3 CH=130.
      GO TO 9
    4 CH=DA(51)*DA(66)
      GO TO 9
    6 CH=130.
    9 RETURN
      END
```

```
***** SUBROUTINE OPTIM DATA *****

STAGE        FUNCTION              PROGRESS            LATERAL PROGRESS
  1        -.12414439+03         .60827625+01           .98639392+00
NUMBER OF FUNCTION EVALUATIONS =          6
VALUES OF X AT THIS STAGE
X( 1) =    5.405688+01    X( 2) =    1.040000+02     X(

STAGE        FUNCTION              PROGRESS            LATERAL PROGRESS
  42       -.76558565+02         .25463106-02           .95367425-06
NUMBER OF FUNCTION EVALUATIONS =       1599
VALUES OF X AT THIS STAGE
X( 1) =    5.093055+01    X( 2) =    1.000001+02     X(

***** OPTIMUM DESIGN SPECIFICATIONS *****

VA=   .716+02  EPS=   .660+00  A=   .6998009+03  DEP=   .43320+00  AFR=   .9024705+01
ALT=   .10830+03   AM=   .16773+02  ATUB=   .6794917+02  U=   .10172+02  PFKW=   .78464+00
GA=   .56671+04  GM=   .16799+06  VR1=   .24909+02  REA=   .15064+04  RER=   .17866+06
WA=   .2740705+05  WR=   .1531786+04  TAO=   .93194+02  DELTA=   .13194+02  ALMTD=   .12240+02
DELPA=   .20626+01  HPA=   .89437+00  DELPR=   .6750+03  HPR=   .66595-02  QRJ=   .6678841+05
QR=   .5078841+05  EFFP=   .95060-01  OWHX=   .30000+01  OLHX=   .30082+01  EFZ=   .95031+00
AA2=   .68897-02  COP=   .74566+01  OCOP=   .70682+00  WCOMP=   .48279+04  ORP=   .45960+05
ORC=   .40828+05  AMP=   .82486+03  AMC=   .70693+03  WPUMP=   .33845+00  WEXP=   .56898+04
X1=   .63486+03  YC1=   .40758+04  YC2=   .69980+03  YC3=   .61641+02  YC4=   .13020+02
AEPC=   .4028+01  ACPC=   .2130+02  DA(55)=   .7253+02

**************************************************************************************
*                                                                                    *
* NHYS= 1   AITD= 20.0   NOB= 6.0   DEP=   .433   GRAF=   .5093055+02   TR=100.000  SS=  .73  *
* YC=   .7596+01   YO=   .4363+02   YCO=   .5123+02   ACCL=   .2533+02   ACOS=   .7656+02   *
*                                                                                    *
**************************************************************************************
```

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TABLE I. - OPTIMUM DESIGN SPECIFICATIONS OF DRY-COOLING SYSTEMS FOR A SOLAR-POWERED THREE-TON RANKINE-COMPRESSION AIR CONDITIONER

	Philadelphia	Miami
Heat exchanger surface	A	A
Optimum ITD, ^{o}C (^{o}F)	11.1 (20)	11.1 (20)
Number of tube banks	6	7
Depth, m (ft)	0.132 (0.433)	0.154 (0.505)
Overall width, m (ft)	0.915 (3.0)	0.915 (3.0)
Overall lengtl., M (ft)	0.915 (3.0)	0.915 (3.0)
Air side area, m^2 (ft^2)	65.0 (700)	76.8 (827)
Frontal area, m^2 (ft^2)	0.84 (9.03)	0.85 (9.14)
Air flow rate, kg/hr (lb/hr) $\times 10^{-5}$	0.124 (0.274)	0.113 (0.25)
Flow rate (Rankine), kg/hr (lb/hr)	383 (825)	383 (825)
Flow rate (compression), kg/hr (lb/hr)	321 (707)	321 (707)
Air velocity, m/sec (ft/sec)	6.6 (21.6)	5.9 (19.5)
Vapor velocity, m/sec (ft/sec)	7.6 (24.9)	6.5 (21.4)
Air pressure drop, kg/m^2 (lb/ft^2)	10.06 (2.06)	9.76 (2.00)
Inside pressure drop, kg/m^2 (lb/ft^2)	3295 (675)	2529 (518)
Fan power, kW	0.785	0.631
Solar collector area, m^2 (ft^2)	59 (635)	59 (635)
Incremental costs, \$/yr.:		
Capital	7.6	19.6
Operating	43.6	133.0
Energy penalty	4.0	10.9
Capacity penalty	21.3	15.1
Total	76.5	178.6

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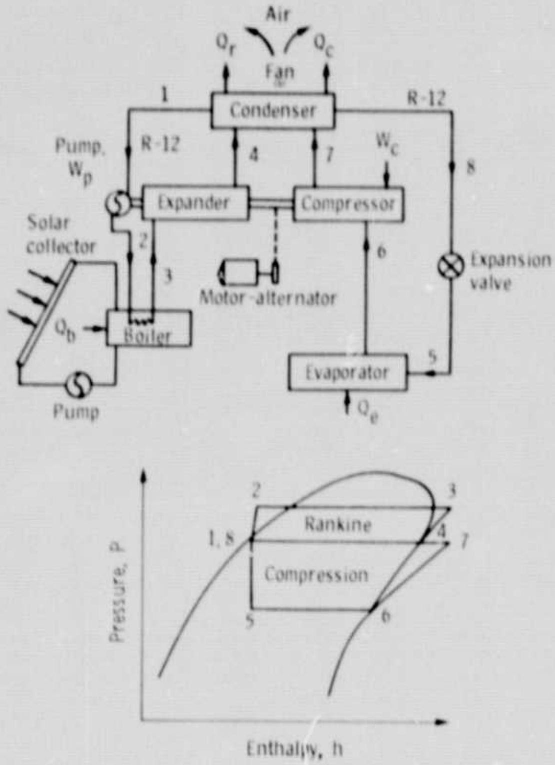

Figure 1. - Schematic solar Rankine-compression air conditioner with P-h diagram for R-12.

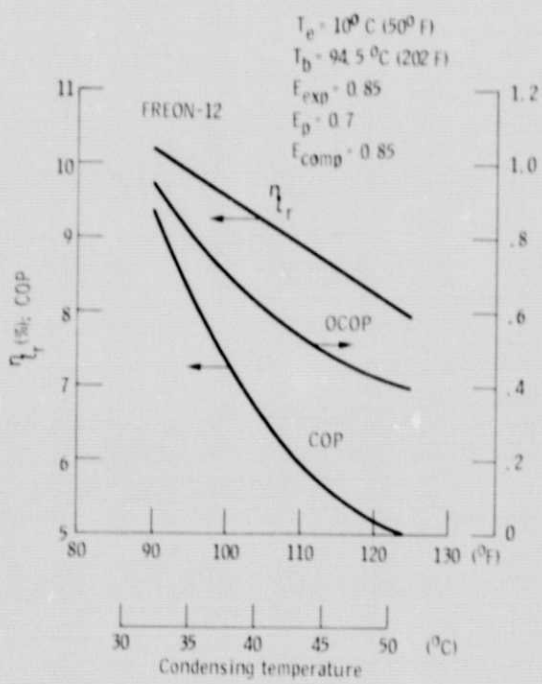

Figure 2. - Rankine-compression system performance.

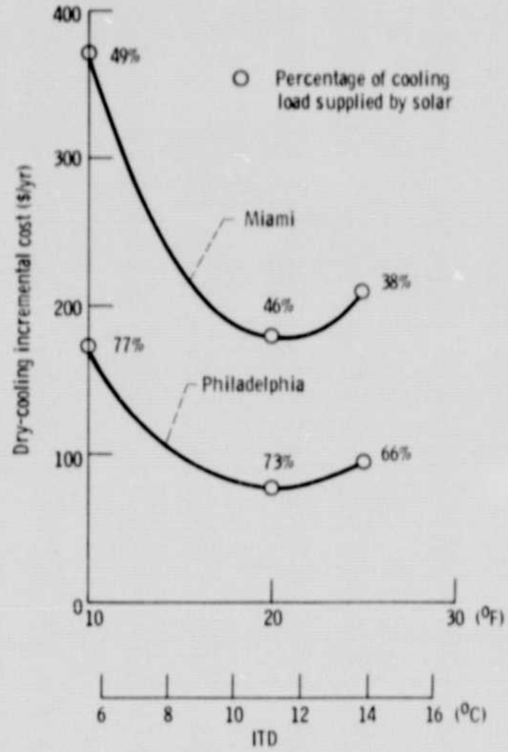

Figure 3a. - Annual incremental cost of the dry-cooling system with heat exchanger surface A.

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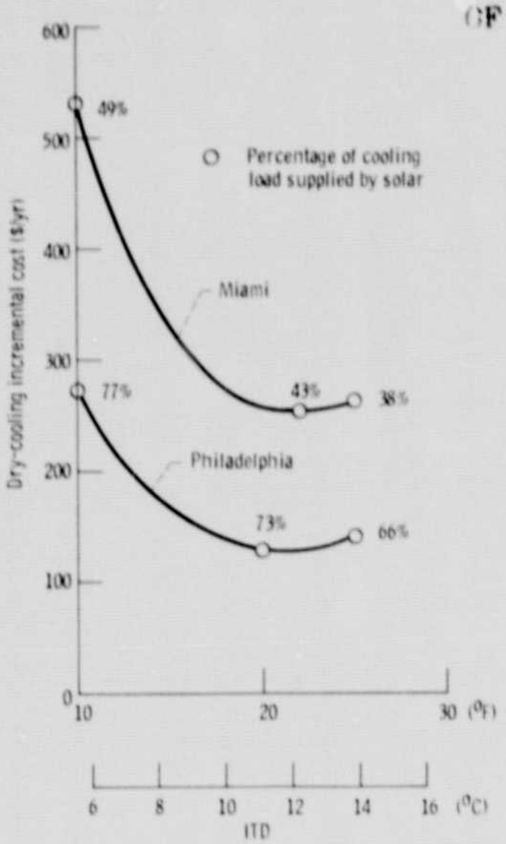

Figure 3b. - Annual incremental cost of the dry-cooling system with heat exchanger surface B.

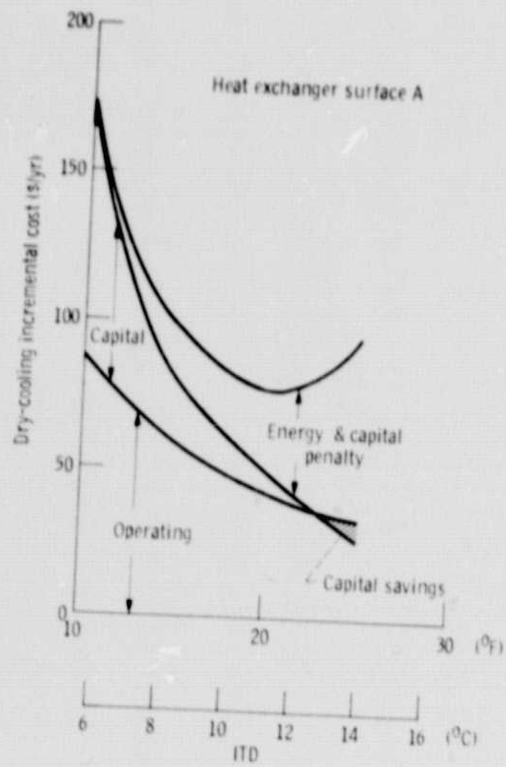

Figure 4. - Itemized annual incremental cost of the dry-cooling system in philadelphia.

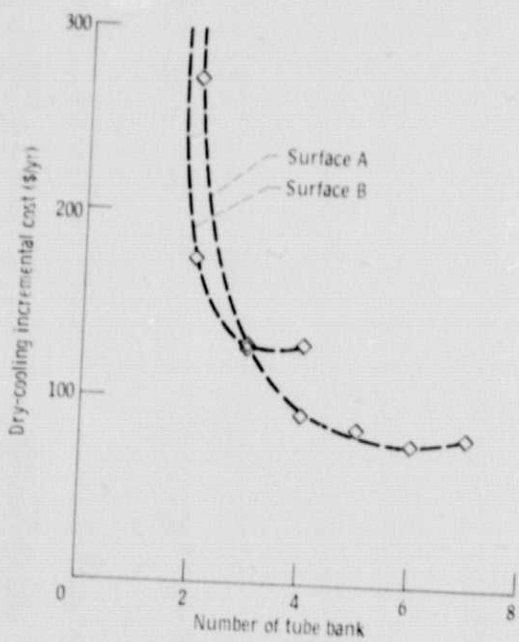

Figure 5. - Effect of number of heat exchanger tubes on cost in phildelphia.