ABSTRACT

M. KUDRET SELCUK

Ph.D Agricultural Engineering

OPTIMIZATION OF SOLAR POWER PRODUCTION USING HEAT ENGINES

The research is directed towards the study of the production of mechanical power from solar radiation based upon the criterion of economic performance.

An analysis of combinations of various categories of cycle, collector, engine, storage system and sink has been made. The study was first applied to a steady state model, then an unsteady state analysis was also included for feasible locations in terms of the seasonal variation of solar radiation. The influence of design parameters upon the cost of the power produced was examined. Optimum design and operating conditions for various combinations were determined and computer programmes were developed for the analysis of various systems. Margins of improvement were indicated and attention was directed towards areas displaying possibilities for reduction in the cost of the power produced. The results of the analyses and conclusions reached have been arranged in the form of reference material for easy accessibility.

OPTIMIZATION OF
SOLAR POWER PRODUCTION

M.K. Selçuk

OPTIMIZATION OF SOLAR POWER PRODUCTION USING HEAT ENGINES

by

M. Kudret Selçuk

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirement for the degree of Doctor of Philosophy

Department of Agricultural Engineering
Macdonald College
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Montreal

March 1969

This thesis is dedicated
to my father

ASIM SELÇUK (1899-1954)

whose support and encouragement have
inspired me throughout my work

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NOMENCLATURE

Symbol		Units	Fortran Notation
A	Area of collector normal to radiation input	sq.ft.	AREA
A'	Area normal to flow of working fluid	sq.ft.	
A_{app}	Approximate collector area	sq.ft.	AREAPP
$a_{n,r}$	Annuity (economic analysis)	dimensionless	ANNUTY
B	Collector width	ft.	
C_p	Specific heat at constant pressure	$Btu/lb_m\,^oF.$	
C	Cost (economic analysis)	U.S. $	
C_{cond}	Cost of the condenser	U.S. $	SININV
$C_{cond.tu}$	Cost of the condenser tubing	U.S.$/sq.ft.	PRCOTU
$C_{tot.tur}$	Cost of the turbine	U.S. $	TURINV
C_{cont}	Cost of the control system	U.S. $	COTINV
$C_{kw.hr}$	Cost of the power produced	U.S.$/kw.hr.	FINCOS
C_{shell}	Cost of the condenser shell	U.S. $	PRCOSH
c	Constant (convection between glass sheets)	dimensionless	CEAIR
F'	Factor for collector fin efficiency and bond resistance	dimensionless	EFPRIM
F''	Collector flow factor	dimensionless	FLOFAC
F_r	Flow factor = $F' \times F''$	dimensionless	FR

Symbol		Units	Fortran Notation
G	Flow per unit area	lb./hr.sq.ft.	G
H_f	Enthalpy of saturated liquid	Btu/lb.	HFL
H_g	Enthalpy of saturated vapour	Btu/lb.	HV
H_x	Enthalpy of the mixture	Btu/lb.	HX
h	Convective film coefficient from wall to working fluid	Btu/hr.sq.ft$^{\circ}$F	FILMIN
h_c	Convective heat transfer coefficient	" "	
h_o	Convective film coefficient from collector to surroundings	" "	FILMOU
h_r	Equivalent radiant heat transfer coefficient	" "	HRAD
I_o	Solar radiation intensity outside atmosphere (solar constant)	Btu/hr.sq.ft.	SOLCON
I	Solar radiation intensity normal to the collector surface	" "	RADTIN
I_{HD}	Direct horizontal radiation intensity	" "	
I_{Hd}	Diffuse horizontal radiation intensity	" "	RAHODI
I_{Ht}	Total horizontal radiation intensity	" "	RADHOT
I_{tot}	Total solar radiation (hemispherical) intensity	" "	
$I_{tot.day}$	Daily total radiation (horizontal)	Btu/day.sq.ft.	DAYTOT
I_d	Diffuse solar radiation (hemispherical) intensity	Btu/hr.sq.ft.	
I_{DN}	Direct solar radiation (normal beam) intensity	" "	RADDIR

Symbol		Units	Fortran Notation
I_{av}	Average solar radiation intensity over a time period	Btu/hr.sq.ft.	AVERAD
I_c	Critical solar radiation intensity	" "	RADCRT
i	Angle of incidence	Degrees	
i	Rate of interest (economic analysis)	per cent	ENTRS
Kw	Power rating	Kilowatts	POWER
k	Thermal conductivity	Btu/hr.sq.ft.	
k_i	Thermal conductivity of rear insulation	Btu/hr.ft.^oF	CONINS
k_t	Condenser tube thermal conductivity	" "	TUBCND
L	Length	ft.	
LMTD	Logarithmic mean temperature difference	^oF	ELEMTD
m	Mirror boost factor	Dimensionless	BOOSMI
m	Gradient of the cost function	Dimensionless	EM
n	Number of Glass Sheets	"	GLANUM
n	Period (in economic analysis)	years	EXPLIF
O	Operation expenses (as a fraction of the total yearly expenses)	Dimensionless	OPERTN
p	Power consumed	KW	CONSUM
p	Pressure	Psi	P
Q_{tot}	Total heat input	Btu/hr.	QTOT
Q_{ADD}	Heat added	Btu/lb.	QADD
Q_{REJ}	Heat rejected	Btu/$lb._m$	QREJ

Symbol		Units	Fortran Notation
Q_u	Useful heat	Btu/hr.	QUSEF
q	Heat flux	Btu/hr.sq.ft.	
q''_i	Radiant heat flux	" "	RADTIN
R	Orientation factor	Dimensionless	ORFAC
R_f	Capital recovery factor	Dimensionless	CAREFC
r	Reflectivity	Dimensionless	
r_h	Hourly/daily total solar radiation	Dimensionless	FRAD
S	Surface area of the condenser tubing	sq.ft.	CONSUR
S	Entropy	Btu/lb_m ^oR	
S_f	Entropy of saturated liquid	"	SFL
S_g	Entropy of vapour	"	SV
S_x	Entropy of the working substance after isentropic expansion	"	SX
S	Amount of stored energy	Btu/kw.hr	STOR
T	Temperature measured above ambient	^oF	
T_1	$t_1 - t_a$, boiler temperature above ambient	^oF	
T_2	$t_2 - t_a$, condenser temperature above ambient	^oF	
T'	Absolute temperature (t+460)	^oF	
t	Temperature (standard scale)	^oF	
t_a	Ambient temperature	^oF	TAMBI
t_1	Temperature of the boiler	^oF	T1
t_2	Temperature of the condenser	^oF	T2
t_c	Collector plate temperature	^oF	

Symbol		Units	Fortran Notation
U	Universal heat transfer coefficient	Btu/hr.sq.ft°F	UNIVER
U_f	Use factor	Dimensionless	USEFAC
U_L	Upward heat loss coefficient from a solar collector	Btu/hr.sq.ft°F	
U_{LC}	Total heat loss coefficient from a solar collector	" "	ULC
U_{rear}	Rear heat loss coefficient	" "	
V	Velocity of the working substance	ft./sec.	
v	Specific volume	$ft^3/lb._m$	
Y	Distance between collector plates	ft	
W_{oa}	Actual work output	Btu/lb_m	WOUA
W_{oi}	Ideal work output	"	WOUI
W_p	Ideal pump work	"	WPUMP
W_{pa}	Actual pump work	"	WPUMPA
X	Quality of the fluid-vapour mixture at the turbine outlet	Dimensionless	X
Z	Zenith angle	Degrees	ZEN

Greek Symbols		Units	Fortran Notation
α	Absorptivity	Dimensionless	
α_c	Absorptivity of the collector plate	Dimensionless	ALFA
α_g	Absorptivity of glass plate		
β	Collector tilt	Degrees	BETA
Δ	Difference		DIFFER
δ	Declination	Degrees	DECLIN
δ_i	Insulation thickness	Ft.	DELINS
δ_t	Condenser tube thickness	Ft.	TUBTHK
ε	Emissivity	Dimensionless	
ε_c	Collector plate emissivity	Dimensionless	
ε_g	Glass plate emissivity	Dimensionless	
ϕ	Utilizability	Dimensionless	UTIL
ξ	Solar hour angle (15^{o}= 1 hr)	Degrees	SUNANG
ξ_s	Sunset hour angle	Degrees	SUNSET
σ	Stephan-Bolzmann constant	Btu/hr.sq.ft.$^{o}R^{4}$	
η	Over-all efficiency	Dimensionless	EF
η_c	Collector efficiency	Dimensionless	ETACOL
η_t	Turbine efficiency	Dimensionless	ETATUR
η_s	System efficiency (except collector)	Dimensionless	
η_m	Mechanical efficiency	Dimensionless	
η_R	Rankine cycle efficiency	Dimensionless	ETARAN
τ	Transmissivity	Dimensionless	TAU
$\tau_{atm.}$	Atmospheric transmissivity	Dimensionless	
ρ	Density	$lb._m/ft.^3$	
ϕ	Latitude	Degrees	PARLEL
λ	Wavelength	Microns	
ω	Mass flow rate	$lb._m/hr.$	FLOW
ω_s	Mass flow rate per unit width	$lb._m/hr.ft$	
ψ	Consumption pattern (fraction of the maximum rating)	Dimensionless	F1 F2 ⋮

Subscripts

a	:	air, ambient
atm	:	atmosphere
abs	:	absorbed
b	:	boiler
c,col	:	collector
cg	:	collector (absorber) to glass
con	:	condenser
cont	:	control
conv	:	convection
cwi	:	cooling water inlet
cwo	:	cooling water outler
dif	:	diffuse
dir	:	direct
g	:	glass
ga	:	glass to air
i	:	inner
lat	:	latent
o	:	outer, initial
out	:	outlet
rad	:	radiation
sen	:	sensible
tot	:	total

I. INTRODUCTION

I.1. A brief historical summary of solar power production

Although the inherent potential in solar radiation was realized by Archimedes over 2000 years ago when he utilized it to burn the boats of the Roman fleet by means of focussed sunlight upon their sails, no subsequent attempts were recorded until 1615 when Solomon de Caux of France succeeded in raising water by expanding air heated by solar radiation. Another Frenchman, August Mouchot, pioneered efforts in solar energy utilization in the 19th century by constructing solar steam engines in 1866 to 1872 and 1878. Messrs. Adel Pifre and C. L. A. Telliers have also been cited in the literature, which describes their solar engines operated with steam and ammonia vapour.(1)

John Ericsson of New York was a pioneer in the field of solar mechanical power production in the United States. He constructed several solar engines operated by steam or hot air between 1868 and 1883. During the early years of the 20th century, from 1901 to 1904, A. G. Eneas constructed some truncated cone-type solar collectors which successfully produced steam, but these were not actually used for driving a steam engine. However, in 1901, he succeeded in building another of truncated cone design which was utilized in supplying steam to a compound condensing engine which actually produced $4\frac{1}{2}$ h.p. H. E. Willsie and John Boyle Jr., from 1902 to 1908, constructed various solar engines which operated with steam, ammonia or sulphur dioxide, the working fluid being heated and vaporized in Flat Plate collectors.

Frank Shuman operated two solar engines in Tacony, Pennsylvania in 1907 and 1911, the first with a horizontal glass-topped water-box, the second incorporating trough-type collectors.

One of the greatest achievements in solar power production was the 100 h.p. steam engine employing parabolic troughs designed and built by F. Shuman and C. V. Boys and installed in Meadi, Egypt, in 1913. However, the rapid advent of the internal combustion engine served to discourage further attempts to produce mechanical power from the sun.

During the period from 1920 to 1950, work in this area was relatively dormant, but subsequently increased interest in spacecraft power schemes opened a new era in solar energy utilization.

Limited power requirements as well as unlimited financial resources enabled researchers to investigate every conceivable method of solar energy utilization from silicon cells to thermionics or from inflatable paraboloidal concentrators to thermoelectric conversion. Many significant developments and devices emerged from these liberally financed research programmes. Silicon solar cells have already been accepted as almost the standard power supply for spacecraft and satellites. A recent project, "Apollo Telescope Mount," employing 100 m^2 of silicon solar cells to deliver 7200 watts at peak load at 24-30 volts DC rating for a maximum duration of six months, is estimated to cost $4,000,000![2]

In such projects aimed at producing power in space, the performance criteria are assessed in terms of the power-to-weight ratio rather than the power-to-cost ratio.

On the other hand, the production of mechanical power from solar radiation for terrestrial applications has been given considerable attention in a number of countries during recent years. H. Tabor of Israel has successfully constructed a solar power unit which was demonstrated in Rome during the "United Nations Conference on New Sources of Energy" in 1961.[3]

Soviet scientists have been working independently on various aspects of solar energy utilization both in Moscow and in Tashkent. Direct energy conversion utilizing silicon cells, thermoelectric and thermionic converters have been analysed and the resultant devices reported. A large-scale application proposed in 1958,(4) which consisted of a field of mirrors placed on railway tracks with a power rating of 1600 Kw, does not appear to have produced concrete results since they have not yet been reported in the literature.

An account of recent developments in the Soviet Union is given in Reference (5). It is not possible to comment on the feasibility of their achievements since no cost figures have been reported for an existing solar power plant.

The French team, formerly based in Algeria, has been working mainly at the University of Marseilles where direct energy conversion problems as well as thermal utilization of solar energy in the form of high temperature steam production have been studied.

Other individual attempts such as those of Professor Masson of Senegal(7) and the Italian Somor solar pump(8) must be mentioned as significant achievements in the production of mechanical power from solar radiation.

One of the most notable developments among solar power schemes is the project undertaken by Professor

Francia. His power plant has been assembled at St. Ilario, Genoa,[9] and is aimed at generating steam employing a sun tracking field of mirrors and a honeycomb type "non radiating" absorber. The implications of this project, which is still in progress, will be discussed in the relevant section of this thesis, especially insofar as it modifies the economic significance of solar power.

In addition to the above projects, which have been specifically aimed at producing mechanical work from solar radiation, there has been considerable research to improve the performance of the various individual component parts of such power plants. This is exemplified by a series of investigations comprising theoretical analyses of flat plate[10, 11, 12] and concentrating[13, 14, 15] type collectors, the use of selective surfaces[16, 17] and honeycomb structures[18, 19] and the improvement of turbine performance using various working substances.[20]

However, all of these individual efforts for separately optimizing the performance of each component of a solar thermal power plant are not likely to yield the best possible over-all arrangement since the change of some variables adversely affects the effectiveness of various components. The following example illustrates this.

An improved cycle efficiency is attained at elevated ceiling temperatures, whereas the collector efficiency is reduced. Therefore, the maximization of the cycle efficiency or collector efficiency alone would not maximize the power output or minimize the cost per unit output. Instead, a compromise may lie at a condition yielding neither the best collector nor best cycle efficiency.

I.2. Philosophical basis of the feasibility study of Solar Power Production

Almost without exception, all attempts which have been made to produce cheap mechanical power from solar radiation by means of heat engines have failed to yield an economical solution. The prime reason for this has been the limitation of each of these studies to the analysis of a single system with predetermined specification; for example, some investigations have confined their attention to flat plate collectors while others have examined hot air engines or concentrating collectors.

Up to the present, no fundamental investigation has been attempted with the objective of determining the optimum system, and the details of its design and performance, from the various possible alternative arrangements of components. In fact, it would have been advisable to have completed such a study prior to the construction and performance evaluation of any specific solar power producing system. This would have resulted in substantial savings in the time and energy which have been consumed in previous endeavours to produce cheap power from solar radiation in the absence of a clear understanding of the effects of the various design and performance parameters in the definition of regions of feasibility.

In addition to the above reasons, the previous ten years' experience of the author in solar energy studies and the unique research facility in solar science and engineering available at the Brace Research Institute provided a cogent motive for the former to select this topic for his doctoral dissertation.

The purpose of the present fundamental study is to provide a rational basis for the comparison of alternative methods of solar power production and to specify feasible margins for improvement as a guide to promising areas of future research. Indeed, the originality of the work lies in this aspect.

The following can, therefore, be stated as contributions to knowledge in the field of mechanical power production from solar radiation using heat engines under the economic performance criterion.

I.3. Contributions to knowledge

A systematic study has been made of all conceivable combinations of energy collection and conversion mechanism for the production of power from solar radiation by means of heat engines.

A generalized model has been devised which embraces the full range of collectors, thermodynamic cycles and ancillaries.

A detailed survey of the possible combinations has been made to isolate those feasible for practical realization.

Solutions to mathematical models of the latter have been developed and their implications discussed.

Analyses of typical models have been presented in detail in the appendices.

The system has been optimized in both the steady and unsteady states.

The degree of improvement in performance which can be obtained from the optimization of the various parameters according to the current state of the art has been discussed and areas indicated where future investment in fundamental and applied research would be most effective in improving the thermo-economics of the system.

A collection of reference material for the guidance of future designers of solar power plants in various localities has been compiled and presented.

I.4. Definition of the problem and objectives

Although the title of the thesis implies that a feasibility study will be made, it is necessary to define the basic criterion. Economic performance will be the criterion of this study. Therefore the important consideration in the optimization has to be the minimization of the cost of power produced at a given rating irrespective of the maximum thermal efficiencies and perfected design and operating conditions. There would be no justification for improving any component of the solar power system beyond proper margins, after which the increased initial investment would outweight the expected increase in the power output.

The parameters involved in the analysis are too many for handling in a single relation capable of differentiation in order to provide maxima or minima by simple mathematical operations. Therefore, systematic analysis of the components, by establishing all of the mathematical correlations and constraints, becomes a necessity. The following resumé outlines the methods employed in tackling the problem and the various assumptions made in the analysis.

The basic pattern of the analysis is as represented in Figure 1. Necessary adjustments have to be made for various combinations of the cycle, collector, engine, sink, and where required, a heat storage system. Therefore, this work aims to:

1. set up theoretical relations and define marginal characteristics and properties;
2. examine each component and establish mathematical models and equations from thermodynamic heat transfer and economic points of view;
3. solve those mathematical models using digital computer techniques, defining the range of optimum performance for each component and comparing the various possible combinations using economic performance criteria;
4. extend the study of those parameters promising improvement and suggest a combination of components to yield minimum cost under the present status of technology and science;
5. find out breakthroughs for guiding future investigators;
6. summarize and compile the findings of the mathematical analysis to facilitate the selection of the best combination of components to design a solar power system for a given locality, climatic conditions and power rating.

II. MATHEMATICAL MODELS FOR THE PROBLEM

II.1. General comments on the formulation of the problem

The kernel of the analysis is the optimization of the variables influencing the unit cost of the power produced.

There have been many proposals and applications of solar power production via thermal engines. This analysis will not be confined to a single type system of given design. Instead, various possible combinations of the components will be tried to obtain the system yielding the best optimum, such as steam Rankine cycle, flat plate collector, turbine with condenser or Rankine cycle with an organic fluid, concentrating collector, with storage, reciprocating engine, etc.

The variation of a parameter may only be influential on a single component, such as the circulation water inlet temperature at the condenser which affects the condenser performance only, or alternatively it might be effective in more than one or even in all of the components, such as in the case of the peak temperature. The latter is involved in the cycle efficiency, collector performance, storage system specifications, etc. Therefore, the information flow must be so arranged that the performance of components should match with each other. Common parameters should be varied simultaneously to obtain the optimum from the economic performance point of view.

Formulation of steady state performance

In carying out the analysis, the following assumptions were made in order to represent the performance of each element and of the complete system, respectively.

The radiation intensity I is constant. This assumption has to be modified in the unsteady state analysis to represent the actual performance, since the solar radiation intensity at the earth's surface is a function of the following variables:

$$I = I(I_o, \tau_{atm}, \phi, \beta, \delta, \xi) \qquad (2.1)$$

The properties of the working fluid such as enthalpy, entropy and specific volume are invariant. These properties have to be modified only when the substance itself is changed. The thermal cycle relations yield the net ideal work W_i, heat rejected from the system Q_R, and heat added to the working substance in the collector Q_A per unit mass of fluid circulated. The actual work is some fraction of the ideal work $W_{oa} = \eta W_{oi}$

where $\eta = \eta_t \eta_m$, the product of the efficiencies due to fluid friction and mechanical friction. The efficiency due to irreversible fluid friction, η_t, is defined as:

$$\eta_t = (H_1-H_2')/(H_1-H_2) \tag{2.2}$$

for an irreversible isentropic expansion. Subscripts refer to the simple Rankine cycle which is outlined in Fig. 2. The point 1 represents the state at the turbine entry, 2 represents the state after isentropic expansion and 2' after irreversible isentropic expansion. The arithmetic values employed have been based on previous experience with systems possessing similar ranges of operation and comparable size and design features.

The heat to be supplied by the collector, Q_A, in the actual case must be a function of time. For the sake of obtaining some preliminary information on the prospective ranges of optimum performance, Q_A will be assumed constant. This assumption implies that the solar radiation intensity, I, is also constant.

The demand for power may be a function of time depending on the location or purpose of utilization. If the power is continually demanded, a storage system is necessary to supply the energy deficit or to store the excess.

Since the steady state analysis assumes that supply is equal to demand, no storage will be needed. In cases of immediate consumption of the energy supplied, such as pumping water whenever the sun shines and storing the water in an elevated tank, no thermal storage would be required. However, the optimization of a system with variable energy supply is very difficult if not totally impossible. This alternative will be treated later when the average performance optimum for the system is investigated.

The following summarizes the above discussions on the formulation of the problem. The performance of the system is such that the energy supply and consumption are identical, no storage being required. The system is of the simplest form but does not represent the actual performance since in practice neither the supply, which is the radiant energy incident on the collector plane, nor the consumption would be constant. However, this analysis has been carried out as the first step in order to locate the regions of interest before attempting to optimize the solar power plant under variable radiation input and consumption conditions.

Formulation of unsteady state performance

Since a constant energy supply or consumption is not expected, the system has to be operated under varying radiant heat flux and power consumption conditions. The two possible ways of attacking the problem might be the following:

(a) To set up the system for optimum performance at the average input and power consumption conditions and observe the performance variation. The performance could be somehow improved by adjusting the operating conditions such as the pressure and flow rate.

(b) To set up the system so flexibly that some of the components, depending on the demand or supply, could be added to or removed from the system. For example, boosters could be used to raise the temperature of the working substance to a level which would yield acceptable efficiencies in the case of deficient energy supply.

Both suggestions have their own drawbacks which will be examined at length whenever the related topics are treated.

The information flow for both models has been visualized in Figure 3. Depending on the amount of the energy excess or deficit, the storage system's size and performance can be determined. The formulation of each component of the solar power plant will later be described in detail.

The calculation of the solar radiation intensity $I = I(t)$, and the history of power consumption $KW = KW(t)$, where (t) refers to a time variable, provides the information necessary for sizing the heat storage system. The storage systems will be studied in a separate chapter. The formulation and solution of the performance of other components of the system such as the CYCLE, COLLECTOR, ENGINE and SINK remain the same both in the steady state and the unsteady state analyses.

II.2. Possible combinations of the elements ofthe Solar Power System

Various devices can be used for collecting solar radiation and converting it into mechanical work, as illustrated in Figure 4. Taking one component at a time from five basic elements, namely, CYCLE, COLLECTOR, SINK, TURBINE and CONTROL SYSTEM, it is evident that one hundred and fifty different combinations can be obtained.

However, further examination of this large number of possible combinations enables a substantial section to be excluded from further consideration on feasibility grounds and thus considerably reduces the time and effort necessary for analysis. The following section has, therefore, been presented with the aim of formulating and solving various aspects of solar power production more effectively.

II.3. Elimination of unrealistic combinations of components

Figure 4, which presents a list of possible combinations of components of the solar power plant, reveals how tedious it would be to analyze the 150 cases proposed. However, in the present section, which comprises a general survey of the possible combinations of components, attempts have been directed towards eliminating some of the less promising cases such as the Stirling engine combined with the Flat Plate collector. Of the remainder, some are introduced in the form of a parametric study of the relevant factors, such as the effect of selective surfaces on the flat plate collector performance or the influence of the working substance on the cycle efficiencies.

Study of the cycles proposed

The cycles proposed are essentially of three types, the Rankine, Brayton, and Stirling cycles.

Proposals of the Rankine-steam and the Rankine-organic fluid cycles will be combined in one typical case. Since only Vapour Enthalpy-Entropy-Temperature data change between various working substances, cases 1 and 2 in Figure 4 can be examined by running the same computer programme with different data.

The Stirling cycle operates at high temperatures and the proposals and realizations are all based on a double piston-reciprocating engine with a sun-tracking concentrating collector, since high temperatures of the order of $1250^{o}F$[21] can only be obtained using a concentrator. In this way several of the combinations using this cycle are eliminated and the study confined to one combination only, namely, the Stirling cycle-reciprocating engine-concentrating type, sun-tracking collector.

The Brayton cycle. Though theoretically the Brayton cycle could be employed in a solar power plant, because of the reduced efficiencies at low temperatures, only concentrating type collectors, which are also required for the Stirling engine, may be used. The Brayton cycle analysis is, therefore, also limited to the sun-tracking concentrator - turbine and a sink. The inert gas and air cycles can be compared by supplying the corresponding physical properties into the programme. In the case of the air-Brayton cycle the atmosphere acts as a natural sink; the sink therefore can be omitted. The inert gas Brayton cycle on the other hand needs a heat sink to recirculate the working substance. The systems combining the sun tracking concentrator, air Brayton cycle and turbine, and sun tracking concentrator, inert gas Brayton cycle and turbine with radiator, respectively, are the only two feasible alternatives for a solar power plant operating with the Brayton cycle.

The use of an air or water cooled condenser or a radiator depends solely on the availability of cooling water in enough quantities. In many cases, such as a plant used for water pumping purposes, enough circulation can always be maintained using water pumped out from a well. Even when an air-cooled condenser is employed to eliminate the circulation pump the feasible region is not much affected. When the air or water-cooled condenser is used, instead of there being a change in the feasible region, it is rather the absolute cost figure which changes.

The water-cooled condenser has been chosen as the standard type for all the cycles and vapours, since it allows the maintenance of lower condenser temperatures due to the higher film conductance experienced at the cooling medium and the tube of the condenser. The possibility of using an air-cooled condenser has been eliminated from the detailed studies and treated as a parameter depending on the locality. In locations where the cooling water is scarce the air-cooled condenser or water cooling tower is suggested.

Figure 5 outlines the remaining feasible combinations after the above-mentioned simplifying assumptions have been made.

Basic typical analyses are as follows:

(a) Rankine cycle - flat plate collector - condenser - turbine, where the parameters are:

working substance

selective surfaces

convection suppressors (honeycomb, etc.)

mirror boosters

(b) Rankine cycle - concentrating collector - condenser - rotary engine, where the parameters are:

concentration ratio

sun tracking system or fixed orientation

(c) Brayton cycle - concentrating collector - turbine, where the parameters are:

working substance

heat rejection system: radiator (or natural sink in case of air - Brayton cycle)

(d) Stirling cycle - concentrating collector - reciprocating engine, where the parameters are:

working substance

heat rejection system: radiator (or natural sink in case of air - Stirling cycle)

III. STEADY STATE ANALYSIS

III.1. Solution of a Typical Case: Flat Plate Collector - Steam Rankine Cycle - Turbine

Relations and Constraints

The steady state analysis is based upon the Information Flow Chart presented in Figure 3. Possible combinations of various components have been indicated in Figure 4. Those combinations have been further simplified in Figure 5 as has already been discussed.

The complete set of equations describing the performance and facilitating the cost calculations is given. Other combinations which have been tested in computer programmes are presented in the appendices.

As a typical combination the following has been chosen:

Steam Rankine Cycle (Saturated)

The effect of superheating can be easily introduced by inserting the corresponding enthalpy and entropy values for the state corresponding to the superheated steam.

Storage is eliminated since the supply is assumed to be consumed immediately.

Collector

The collector is assumed to be a typical flat-plate type. The influences of various design parameters are included by testing different arrangements of the transparent covers and ordinary black or selective surfaces.

Engine

A steam turbine has been selected as the basic prime mover. The relative effect upon the engine cost of the inlet and discharge steam temperatures and pressures is far greater than that of the number of stages and operating speed in the range of power ratings from 10 to 20 Kw. forming the subject of this study. In such small turbines, the cost of the turbine rotors and nozzles is small compared with that of the casing, bearings, seals, valves and other essential auxiliaries. During the first series of approximate calculations the turbine cost has, therefore, been assumed to be a function of the inlet and outlet steam temperatures, t_1 and t_2, only. This facilitates the calculation of the region of operation at minimum total cost for the complete solar power plant and also simplifies the application of the various mathematical techniques available for computing the optimum operating conditions. Once the region of minimum cost has been identified as a function of the boiler and condenser temperatures, a more refined technique can be used to investigate it in detail.

Sink

A steam condenser is to be utilized for heat rejection. Depending on the availability of the circulation water, either a water-cooled or an air-cooled condenser could be employed. In the case of a solar power plant for water-pumping purposes, the water to be pumped out could also be used in the cooling circuit. If water is unavailable or only available in limited quantities, either a cooling tower or an air-cooled condenser could be proposed. The air-cooled condenser would be more expensive as the convective heat transfer coefficient, h_c, to air is at least an order of magnitude lower than in the case of water. The addition of finned surfaces would improve the performance; however, the cost would still be high.

Therefore, in this typical combination of the system, a shell-and-tube type water-cooled condenser is employed.

The working formulae for the Steam-Rankine Cycle

The cycle efficiency, amounts of heat added, Q_{ADD}, and rejected, Q_{REJ}, per pound of working substance are given by the following formulae: States refer to Figure 2.

$$Q_{ADD} = H_{g1} - H_{f2} \quad (3.1)$$

$$Q_{REJ} = H_{X2} - H_{f2} \quad (3.2)$$

$$W_{oi} = Q_{ADD} - Q_{REJ} \quad (3.3)$$

The numerical values of the properties of state required for the analysis of the Rankine cycle can either be obtained from steam tables accurate to five significant figures or some approximation can be employed to express them in terms of the boiler and condenser temperatures. In the case of the numerical analysis carried out on the digital computer, the most accurate available figures for state points at ten Fahrenheit degree intervals were fed into the computer memory and linear interpolation used for intermediate values. However, in order to explore the variation of energy cost using mathematical optimization techniques it was found advantageous to express the derived properties of state as linear functions of temperature which could be readily differentiated. Thus, the amounts of heat added and rejected and the cycle efficiency could be expressed as functions of the boiler and condenser temperatures. In the expected range of operation the temperature margins have been set as:

$$212 < t_1 < 300^{\circ}F \tag{3.4}$$

$$80 < t_2 < 130^{\circ}F \tag{3.5}$$

The following approximate relations have been obtained by assuming linear variation of entropy and enthalpy of the saturated liquid and vapour with temperature. Should it become necessary to extend the range of operation beyond that specified above, similar relations would still be applicable with modified constants.

Linear approximations

Enthalpies:

$$H_{f2} = t_2 - 32 \qquad H_{f2}: Btu/lb_m \tag{3.6}$$

$$H_{g1} = 1150.4 + 0.333\ (t_1 - 212) \qquad 212 < t_1 < 300 \tag{3.7}$$

$$H_{g2} = 1096.6 + 0.425\ (t_2 - 80) \qquad 80 < t_2 < 130 \tag{3.8}$$

Entropies:

$$S_{g1} = 1.7566 - 0.00139\ (t_1 - 212) \qquad 212 < t_1 < 300 \tag{3.9}$$

$$S_{g2} = 2.0360 - 0.00142\ (t_2 - 80) \qquad 80 < t_2 < 130 \tag{3.10}$$

$$S_{f2} = 0.0932 - 0.00177\ (t_2 - 80) \qquad 80 < t_2 < 130 \tag{3.11}$$

Quality of steam after isentropic expansion from the saturated steam state:

$$X_2 = (S_{g1} - S_{f2})/(S_{g2} - S_{f2}) \tag{3.12}$$

Substituting (3.9), (3.10) and (3.11) into (3.12)

The enthalpy of steam at state X_2

$$H_{X2} = H_{f2} - X_2(H_{g2} - H_{f2}) \tag{3.13}$$

$$= t_2 - 32 + \left(\frac{1.8165 - 0.00139t_1 - 0.00177t_2}{1.9148 - 0.0035t_2}\right)$$

$$\left[1096.6 + 0.425(t_2 - 80)(t_2 - 32)\right]$$

Simplifying:

$$H_{X2} = t_2 - 32 + \left(\frac{1.8165 - 0.00139t_1 - 0.00177t_2}{1.9148 - 0.0035t_2}\right)$$

$$(1094.6 - 0.575t_2) \qquad (3.14)$$

Ideal Work Output

$$W_{oi} = H_{g1} - H_{X2} \qquad (3.15)$$

From (3.7 and (3.13):

$$W_{oi} = 1150.4 + 0.333\,(t_1 - 212) - (t_2 - 32) +$$

$$\left[\frac{1.8165 - 0.00139t_1 - 0.00177t_2}{1.9148 - 0.0035\,t_2}\right](1094.6 - 0.575t_2) \qquad (3.16)$$

Actual Work Output

$$W_{oa} = W_{oi} \cdot \eta \qquad (3.17)$$

Simplifying (3.16):

$$W_{oa} = \eta \Big[1112.0 + 0.333t_1 - t_2 +$$

$$\left(\frac{1.8165 - 0.00139t_1 - 0.00177t_2}{1.9148 - 0.0035t_2}\right)(1094.6 - 0.575t_2)\Big] \qquad (3.18)$$

Heat Added:

Substituting (3.6) and (3.7) into (3.1)

$$Q_{ADD} = 1150.4 + 0.333\,(t_1 - 212) - (t_2 - 32) \qquad (3.19)$$

Simplifying:

$$Q_{ADD} = 1112 + 0.333t_1 - t_2 \qquad (3.20)$$

Heat Rejected

Inserting (3.13) and (3.6) into (3.2):

$$Q_{REJ} = \left(\frac{1.8165-0.00139t_1-0.00177t_2}{1.9148-0.0035\ t_2}\right)(1094.6-0.575t_2) \tag{3.21}$$

The amounts of heat added and rejected as well as the work output are defined per pound of steam circulated. The steam rate can be calculated from:

$$\omega = \frac{KW}{W_{oa}} \tag{3.22}$$

where KW is the power rating in kilowatts.

From (3.17) and (3.22):

$$\omega = \frac{KW}{1112+0.333t_1-t_2-\left(\frac{1.8165-0.00139t_1-0.00177t_2}{1.9148-0.0035\ t_2}\right)(1094.6-0.575t_2)} \tag{3.23}$$

The Flat Plate Collector performance

The collector performance should match the cycle specifications; therefore, water entering at t_2 at a rate of w should be heated to t_1. It is possible either to employ a single stage heater or to split the heating process into several parts such that the working fluid is heated during successive stages, using the type of collector yielding the best efficiency for each of the given temperature ranges. This concept[22] is illustrated in Figure 6. Styrocel, a transparent large-celled plastic foam used by the author in pursuit of high efficiencies at temperatures around boiling point of water, is a promising material provided that some precautions against excessive heating and softening of the plastic are taken.[23]

Heating from ambient to A would occur in collector (1), possessing a single transparent Tedlar or glass cover. This would provide the highest efficiency owing to the small excess operating temperature above the surroundings. For temperatures between A and B, $A < t_1 < B$ a single glass cover with selectively coated collector plates operates most effectively.

This stepwise heating of the working substance would result in the collector cost being a minimum. The total amount of heat collected would be obtained from

$$Q_{tot} = Q_{add} \cdot w \qquad \text{Btu/hr} \tag{3.24}$$

$$Q_{tot} = \sum_{i=1}^{n} A_i \eta_{ci} I \tag{3.25}$$

Equating (3.24) and (3.25) and using (3.20):

$$Q_{tot} = w(1112+0.333t_1-t_2) = I \sum_{i=1}^{n} A_i \eta_{ci} \tag{3.26}$$

The amount of heat collected in each portion of the collector must be summed to find the total heat collected. The heat collected can also be represented by the enthalpy rise.

$$Q_{tot} = Q_{tot1} + Q_{tot2} + \cdot \cdot \cdot + Q_{tot.n} + Q_{tot.b} \quad (3.27)$$

But during the heating process, first the saturation point is reached, then boiling occurs at constant temperature.

$$Q_{sat} = \sum_{i=1}^{n} Q_{tot_i} = w\, Cp\, (t_1 - t_2) \quad (3.28)$$

$$Q_{tot_1} = w\, Cp\, (t_{out_{c1}} - t_2) \quad (3.28.1)$$

$$Q_{tot_2} = w\, Cp\, (t_{out_{c2}} - t_{in_{c2}}) \quad (3.28.2)$$

$$Q_{tot_n} = w\, Cp\, (t_1 - t_{in_{cn}}) \quad (3.28.n)$$

t_{out_c} and t_{in_c} refer to outlet and inlet temperatures of each section of the collector. The number of stages can be increased if t_1 is too high or t_2 is too low. The final stage has to operate at constant temperature.

$$Q_{tot.b} = w(H_{g1} - H_{f1})$$

The most reasonable assumptions for t_{out_c} and t_{in_c} values would be the intersection points of the $(t_c - t_a)$ vs. η_c curves in Figure 6.

Having substituted the inlet and outlet temperatures of the working fluid it is then possible to obtain corresponding collector areas. For example, for the first stage heater:

$$Q_{tot_1} = I A_1 \eta_{c1} = w\, Cp\, (t_{out_{c1}} - t_{in_{c1}}) \quad (3.29)$$

$$A_1 = \frac{w\, Cp(t_{outc1} - t_{inc1})}{I \eta_{c1}} \quad (3.30)$$

η_{c1} must be taken as the efficiency of the collector for the given range of temperature.

The efficiency of the Flat-Plate Solar Water Heater is derived in the appendix 3-a.

The collector efficiency is expressed by:

$$\eta_c = \frac{Fr(I\tau\alpha - U_{lc}(t_1-t_a))}{I} \qquad (3.31)$$

where:

$$F_r = \left(1 - \frac{e^{-\frac{U_{lc}}{GC_p}}}{\frac{U_{lc}}{GC_p}}\right) F'$$

Referring to equation (3.30), the surface area of each collector stage may then be written as

$$A_1 = \frac{wC_p(t_{outc1}-t_2)}{Fr_1[I\tau_1\alpha - U_{lc_1}(t_2-t_a)]} \qquad (3.32)$$

Similarly

$$A_2 = \frac{wC_p(t_{outc2}-t_{inc2})}{Fr_2[I\tau_2\alpha - U_{lc2}(t_{inc2}-t_a)]} \qquad (3.32.1)$$

$$A_n = \frac{wC_P(t_1-t_{incn})}{Fr_n[I\tau_n\alpha - U_{lc_n}(t_1-t_a)]} \qquad (3.32.n)$$

In the final stage, boiling of the fluid occurs at the constant saturation temperature t_1.
It must be noted that t_{inc} is equal to t_2, the sink temperature, and t_{outcn} is equal to t_1, the ceiling temperature. Also, as the final stage collector operates at constant

temperature, the convective film coefficient, h_b, and heat removal efficiency factor, F_{rb}, must be evaluated at the constant temperature. Referring all temperatures to the datum of the ambient temperature, t_a:

$$T = t-t_a \tag{3.33}$$

$$(t_{out_c}-t_{in_c}) = (t_{out_c}-t_a) - (t_{in_c}-t_a) \tag{3.34}$$

$$(t_{out_c}-t_{in_c}) = T_{out_c} - T_{in_c} \tag{3.35}$$

Equations (32.1) to (32.n) can then be rewritten

$$A_1 = \frac{\omega Cp(T_{out_{c1}}-T_{in_{c1}})}{Fr_1[I\tau_1\alpha-U_{lc_1}T_{in_{c1}}]} \tag{3.36.1}$$

$$A_n = \frac{\omega Cp(T_{outcn}-T_{incn})}{Fr_n[I\tau_n\alpha-U_{lc_n}T_{in_{cn}}]} \tag{3.36.n}$$

For the collector section in which saturated water boils at the constant temperature t_1

$$A_b = \frac{\omega(H_{g1}-H_{f1})}{Fr_b(I\tau_b\alpha-U_{lc_b}T_1)} \tag{3.37}$$

The appropriate number of stages to be employed in heating the working substance depends upon the values of t_1, t_2, and t_a, where the ceiling and sink temperatures, measured above the ambient, are represented by:

$$t_1-t_a = T_1 \tag{3.38}$$

$$t_2-t_a = T_2 \tag{3.39}$$

The optimum types of collector for the initial and final stages can be selected from Figure 6 by finding the points where the ordinates through t_1 and t_2 intersect the curve of maximum efficiency. The latter curve can also be used in the selection of the number of intermediate collector stages and their respective inlet and outlet temperatures.

It must be noted, however, that the efficiencies of flat-plate collectors at high temperatures are relatively low and very sensitive to the influence of the over-all heat transfer coefficient, U_{lc}, therefore it must be determined with considerable precision as is outlined in the following section.

The Universal Heat Transfer Coefficient
(Collector Heat Losses)

The losses of heat upwards from the collector plate through the glass cover to the environment were first studied in detail by Hottel and Woertz,[24] whose work was later extended by Tabor.[25]

The upward heat loss per unit area may be expressed:

$$q_L = \frac{t_c - t_a}{\dfrac{n}{c\,\sqrt[4]{(t_c - t_a)/(n+f)}} + \dfrac{1}{hw}} + \frac{\sigma\,(T_c'^4 - T_a'^4)}{\dfrac{1}{\varepsilon_c} + \dfrac{2n+f-1}{\varepsilon_g} - n} \qquad (3.40)$$

where T' refers to the absolute temperature.

t_c Collector plate temperature (Average)

c is a constant for calculating the convective heat transfer between parallel plates. Hottel and Woertz recommend a value of 0.126 for vertical plates and from 0.139 to 0.195 for horizontal plates. In the light of

Tabor's work the most reliable figure for the range of design and operating temperatures considered in the present analysis is 0.21.[25]

ε_c is the emissivity of the blackened collector surface, a value of 0.93 being used for matt black paint.

ε_g is the emissivity of the glass sheet. The figure of 0.88 has been used, suggested by Tabor.[25] However, hemispherical emissivity may be taken as 0.83 according to Yellott.[26] The variation of ε_g with temperature has not been considered, due to the limited temperature range.

n is the number of glass sheets.

f is the ratio of thermal resistance of the outer glass sheet to that of an inner sheet, a value of 0.36 being employed for a wind velocity of 10 mph.[22]

Substitution of the above values in equation (3.40) leads to:

$$q_L = \frac{(t_c - t_a)}{\dfrac{n}{0.21\sqrt[4]{(t_c - t_a)/(n+0.36)}} + \dfrac{1}{4.07}} + \frac{(T_c'^4 - T_a'^4)}{\dfrac{1}{0.93} + \dfrac{2n-0.64}{0.83} - n} \qquad (3.41)$$

Introducing the equivalent radiative coefficient h_r, where

$$h_r = \frac{(T_c'^4 - T_a'^4)}{(t_c - t_a)} \qquad (3.42)$$

simplification gives

$$q_l = (t_c - t_a)\left[\frac{1}{\dfrac{n}{0.21\sqrt[4]{(t_c-t_a)/(n+0.36)}} + 0.246} + \frac{h_r}{0.29 + 1.4n}\right] \quad (3.43)$$

Comparing this with the expression for the heat lost through the transparent cover used in the heat balance, equation (1.1) of Appendix 3.a, that is:

$$q_l = U_l(t_c - t_a)$$

the over-all heat transfer coefficient for upward losses becomes:

$$U_l = \frac{1}{\dfrac{n}{0.21\sqrt[4]{(t_c-t_a)/(n+0.36)}} + 0.246} + \frac{h_r}{0.29+1.4n} \quad (3.44)$$

Assuming that the collector is so designed that the combined rear and edge losses amount to ten per cent of the upward losses, which is generally accepted as good practice,[25]

$$U_{lc} = 1.1\left[\frac{1}{\dfrac{n}{0.21\sqrt[4]{(t_c-t_a)/(n+0.36)}} + 0.246} + \frac{h_r}{0.29+1.4n}\right] \quad (3.45)$$

The above equation permits the accurate estimation of the over-all heat loss transfer coefficient U_{lc}, for substitution in equations (3.32.1) to (3.32.n) and (3.36.1) to (3.36.n) in order to evaluate the areas of each collector stage of the optimum heat collector assembly for operation between the given temperatures t_1 and t_2.

The maximum temperature that can be attained in a flat-plate collector is termed the equilibrium temperature. Each particular design of collector is associated with an equilibrium temperature of a particular value. When a collector is operating at its equilibrium temperature, the whole of the heat absorbed is required to offset the outward heat losses and the efficiency is zero. Hence, the higher engine efficiencies associated with higher boiler temperatures close to the equilibrium temperature are of no effect.

Conversely, the advantages obtained from high collector efficiencies when operating with an outlet temperature close to ambient are nullified by the engine efficiency approaching zero at the environmental temperature. Somewhere between these two extremes there are likely to exist unique sets of optimum values of boiler and condenser temperatures which yield maximum over-all efficiency and minimum over-all cost per unit of power produced respectively. This optimization study aims to obtain the optimum operating temperatures for a variety of systems using various designs of collector and types of heat engine.

Sink

In the first combination to be studied, that of a flat-plate solar heat collector coupled to a steam turbine, the heat from the cycle is rejected through a condenser. In the case of a gas cycle the condenser would be replaced by a radiator. The major parameter controlling the performance of the condenser is the temperature of the surroundings or the cooling medium. The cooling medium will be water available either at ambient temperature or somewhat below this in the case of a deep well.

The condenser cost will be strongly dependent upon the extent of the condensing surface, S, which can be calculated as follows:

$$Q_{rej.tot} = LMTD.S.U \tag{3.46}$$

where

$$LMTD = \frac{\Delta Tmax - \Delta Tmin}{\ln \frac{\Delta Tmax}{\Delta Tmin}} \tag{3.47}$$

$$\Delta Tmax = T_2 - T_{cwi} \tag{3.48}$$

$$\Delta Tmin = T_2 - T_{cwo} \tag{3.49}$$

t_2 = condensing steam temperature which is equal to turbine exhaust temperature.

Substituting from (3.48) and (3.49) into (3.47):

$$LMTD = \frac{T_{cwo} - T_{cwi}}{\ln (T_2-T_{cwi})/(T_2-T_{cwo})} \tag{3.50}$$

Also, the universal heat transfer coefficient is given by:

$$U = \frac{1}{\frac{1}{hi} + \frac{1}{ho} + \frac{\delta_t}{k_t}} \quad \text{(Btu/hr sq ft } ^oF) \tag{3.51}$$

where hi is the convective heat transfer coefficient inside the tubes.

ho is the convective heat transfer coefficient for condensing steam outside the tubes.

δ_t is the thickness of the tube wall.

k_t is the thermal conductivity of the tube wall.

However, since the conductances of the liquid film and the tube wall material are negligible compared with that of the condensing steam, the following simplification may be made:

$$U \cong hi \tag{3.52}$$

Substituting for U and LMTD from equations (3.52) and (3.50) respectively into equation (3.46) and rearranging:

$$S = \frac{Q_{rej.tot}}{hi(T_{cwo}-T_{cwi})/\ln (T_2-T_{cwi})/(T_2-T_{cwo})} \tag{3.53}$$

Furthermore, the quantity of heat rejected may be obtained from equation (3.21), while noting that:

$$Q_{rej.tot} = \varpi\, Q_{rej} \tag{3.54}$$

Thus, the surface area of the condenser tube array is given:

$$S = \frac{\varpi \left(\frac{1.8165-0.00139t_1-0.00177t_2}{1.9148-0.0035\ t_2}\right)(1094.6-0.575t_2)}{hi(T_{cwo}-T_{cwi})/\ln (T_2-T_{cwi})/(T_2-T_{cwo})} \tag{3.55}$$

The total cost of the condenser is then:

$$C_{cond} = C_{cond.tu.}S + C_{shell} \tag{3.56}$$

where $C_{con.tu}$ is the cost of condenser tubing per unit condensing surface, and C_{shell} is the total fixed cost of the condenser shell.

Turbine

The steam turbine performance has already been described in the cycle analysis. The usable power produced by the turbine will be W_{oa}, given by equation (3.17).

The turbine cost is assumed as a first approximation to be independent of T_1 and T_2. In the later sections this assumption will have to be modified. For a small range (10-20 kw) the same turbine may be used by changing the number of nozzles. In the case of operation at a pressure below atmospheric, for example assumed to be 10 psia. boiler pressure, to a lower vacuum, continual operation of a vacuum pump is required. This has been added to the cost of the turbine.

$$C_{tot.turb} = \text{Constant for above atmospheric pressures} \tag{3.57}$$

$$C_{tot.turb} = C_{turb} + C_{vacuum\ pump} \tag{3.58}$$

Pump cost (C_{pump}) is assumed to be a constant value, since the size would not change appreciably within the power range studied, i.e., 10 to 20 kw.

Control, Structures and Auxiliaries

The essential part of the system, the governor performance, is not dependent on the cycle's ceiling and sink temperatures. Instead, it is more dependent on the driven speed. Therefore, the final term in the cost relation (C_{cont}) should vanish when differentiated with respect to T_1 and T_2, though it should stand in the absolute cost figure.

The STORAGE system and DEMAND function are of no interest in the STEADY STATE PERFORMANCE analysis, since the system is assumed to operate whenever the radiation is above a predetermined level. The power produced will, therefore, be consumed without any storage.

Since the problem of optimization in solar power production comprises many separate phases, and different aspects have to be formulated in separate chapters, only a general chapter has been devoted to the techniques of the solution. However, results obtained in each stage with reference to the solution methods are to be presented immediately after the formulation of the problem. It is believed that this arrangement maintains continuity of the text and eliminates jumping back and forth among chapters.

Conclusions drawn from the computer results for the Flat Plate Solution

Results of the flat plate collector - Steam Rankine cycle and turbine analysis - lead one to the following conclusions which should help to simplify the analysis of other alternatives in the rest of the text and confine the survey to a restricted region (see Table 1).

1. The condenser temperature is not significant in reducing the collector cost. Lowering the condenser temperature from 110°F to 90°F only reduces the cost of the power produced from 45 cents/kw hr to 41 cents/kw hr. In fact, when the condenser is matched to the turbine for a given set of environmental conditions, i.e., temperature of ambient air and cooling medium, which will normally be water, the condensate temperature remains within closer limits. Therefore, not much improvement is to be expected by perfecting the condenser, since neither ambient temperature nor a cooling medium inlet temperature can be controlled. Therefore, in the rest of the analysis the condenser cost is regarded as a fixed figure which does not affect the optimum point.

2. The turbine cost is almost invariant for the fixed power rating and for varying boiler and condenser temperatures since the casing, rotor, nozzles, blades, gears and other mechanical devices have to be used and their cost would not change much with its shape and size.

3. Increasing the number of glass cover plates beyond 3 would not reduce the cost of the power produced, since radiation intensities above 300 Btu/hr ft^2 are needed to attain a better efficiency. At lower radiation intensities

4 or more glass plates are not able to collect more heat than 3 or 2 covers, which then are obviously cheaper in cost.

4. The collector cost is the most significant term in the final cost figure. For the optimum design condition some typical numerical values are presented below:

$t_{cond} = 81^{o}F$, $n = 3$ Glass, $I = 220$ Btu/hr ft^2,

$C_{kwhr} = 39$ cents, $t = 180^{o}F$, $C_{tot} = \$29279$,

$C_{coll} = \$21597$, $C_{coll}/C_{tot} = 0.74$

This shows that even under a favourable radiation input condition the collector cost is three quarters of the total cost of the system. Therefore, maximum emphasis has to be placed on reducing the collector cost or increasing its efficiency to reduce the area required. The following section goes into a more detailed study of the collector performance.

III.1.1. The influence of various design parameters on the collector performance

From results obtained from the previously analysed Basic Feasibility Study and listed in Table 1 for the flat-plate collector, it can be concluded that even under the most optimistic assumptions, such as constant radiation flux as high as 220 Btu/hr ft^2 available for 2400 hours in a year, the cost per kw hr always stays around 40 cents. Therefore, it becomes evident that there is a greater need to investigate margins of improvement in the flat plate collector performance and search for a solution in regard to that.

Considering equation (3.31) which describes the flat plate collector performance

$$q_{useful} = F_r \left[I\tau\alpha - U_{lc} (t_l - t_a) \right] \qquad \text{Repeated} \qquad (3.31)$$

q_{useful} can be increased by increasing τ, α, F_r and I and reducing U_{lc} since t_a cannot be controlled and t_l is the independent variable which is also related to the thermal cycle. The first parameter F_R is the product of F' and F". F' can be separately optimized from the point of view of design since the factors involved, such as collector plate thermal conductivity, fin efficiency, tube size and spacing and material cost are independent of other terms in equation (3.31).

F", the flow factor is given by

$$F'' = \frac{1 - e^{-\frac{U_{lc}}{GC_p}}}{\frac{U_{lc}}{GC_p}} \qquad (3.59)$$

F" can be increased by increasing the flow rate and reducing the heat losses. C_p which is a property of the working substance, also enters into it. Since a separate section has been devoted to the influence of the working substance, we shall consider only G and U_{1c} here.

$G = \frac{w}{A}$: Flow per unit area depends on the temperature rise in the sensible heat collector. The greater portion, around 90 per cent, of the collector area should operate at constant boiler temperature. F" which has been derived in Appendix 3-a, from a physical point of view takes care of the variation of collector plate and fluid temperatures. In the boiler section, F" has to be unity which corresponds to the fictitious case of $G = \infty$.

Whenever $G \to \infty$, $F'' \to 1$.

$$\lim_{G \to \infty} F'' = \left. \frac{1 - e^{-\frac{U_{1c}}{GC_p}}}{\frac{U_{1c}}{GC_p}} \right|_{G = \infty} = \frac{1 - e^{-0}}{0} = \frac{0}{0} = ? \quad \text{Indeterminate} \tag{3.60}$$

Using l'Hospital rule[28]

$$\lim_{G \to \infty} F'' = \lim \left\{ \frac{\frac{d}{dG}\left(1 - e^{-\frac{U_{1c}}{GC_p}}\right)}{\frac{d}{dG}\left(\frac{U_{1c}}{GC_p}\right)} \right\}_{G = \infty} \tag{3.61}$$

$$= \left. \frac{\left(-e^{-\frac{U_{1c}}{GC_p}}\right)\left[-\frac{1}{G^2}\left(\frac{U_{1c}}{C_p}\right)\right]}{\left[-\frac{1}{G^2}\left(\frac{U_{1c}}{C_p}\right)\right]} \right|_{G = \infty} \tag{3.62}$$

$$F'' = e^{-\frac{U_{lc}}{GC_p}}\Big|_{G=\infty} = 1 \qquad (3.63)$$

This then confirms the above statement. Consequently F' and F" will not be considered in the parametric study of the flat plate collector efficiency.

(I), Incident radiation intensity on the collector plane can be increased to increase the amount of the useful heat collected. This can be maintained by employing additional reflecting surfaces (Mirror boosters) around the collector. However, the additional expenses involved in using the mirror boosters must not exceed the gains in efficiency. Increased radiation intensity also results in increased collector plate temperatures; hence losses are increased. Since an optimum lies between the mirror size and the efficiency increase, Section III.1.4 has been devoted to the subject.

(τ), Transmissivity of the transparent cover and (α), absorptivity of the collector plate surface also need to be increased.

τ is the total transmission of the incoming beam through a number of parallel sheets under the consideration of multiple reflections between those plates. For a given number of transparent covers the total transmission could be improved by

a. using a cover material having a higher transmissivity. In case of glass, clear glass with high transmissivity (Lustraglass, Pyrex, etc.) could be used. However, the gain in the collected heat due to the increased transmissivity is of the order of 5 to 8 per cent whereas the cost increase is much beyond that amount. A square foot of Pyrex glass costs about $8.50 whereas ordinary glass costs only $0.4.(27) The plastic films such as weatherable Mylar and Tedlar improve the transmissivity have been used in many designs.(28,29) However, those plastic films do not have a sharp long wave cut-off point as glass, on the contrary they transmit the Infrared Radiation to certain extent.(30)
Thus, a greater portion of the long wave radiation will be transmitted, therefore, causing an increase in losses. Current prices of Tedlar (30 cents/ft^2) when compared with glass (40 cents/ft^2) as well as some operational experience, indicate that plastics cannot seriously compete with glass. The more frequent need of replacements in plastic films compared with glass would bring up the price to the same level.

b. The heat losses from the glass cover to the ambient occur through the direct transmission of the thermal radiation, which is a very small fraction for the temperatures experienced at the collector plate. Since glass is

practically opaque to thermal radiation with wave lengths longer than 3 μ and since more than 98 per cent of the radiation emitted from a black body at $700^{o}R$ is at wave-lengths greater than 3 μ, therefore all long wave radiation will be absorbed by the glass plate. Heat absorbed in the glass plate results in increased glass temperature which in turn increases the convection heat transfer from the glass cover to the surrounding.
The glass temperature stops increasing as soon as the heat absorbed from the incoming solar radiation and long wave radiation emission of the collector plate, equals the losses from the plate by means of convection to an ambient and radiation to sky.

Further detailed analysis of the heat losses through the transparent cover to surroundings with special reference to selective surface follows.

III.2 Selective Surfaces - The Energy Balance on the Unit Collector for the Glass Cover

Applying the 1st Law of Thermodynamics to the glass cover:

For the steady state:

$$q_{rad.cg} + q_{conv.cg} + q_{abs.sol} = q_{rad.gs} + q_{conv.ga} \tag{3.64}$$

where

$q_{rad.cg}$ = net radiant heat transfer from the absorber plate to glass cover

$q_{conv.cg}$ = convective H.T from collector plate to the glass cover

$q_{abs.sol}$ = solar radiation absorbed by the glass cover

$q_{rad.gs}$ = heat lost by radiation from the glass cover to sky

$q_{conv.ga}$ = heat lost by convection from the glass cover to the ambient air

(3.64) can be written as

$$\int_0^\infty \frac{1}{\frac{1}{\varepsilon_{\lambda c}} + \frac{1}{\varepsilon_{\lambda g}} - 1} (e_{b\lambda c} - e_{b\lambda g})\, d\lambda + h_{c,cg}(t_c - t_g) + \int_0^\infty I_\lambda \alpha_\lambda \, d\lambda = \varepsilon_g \sigma (T_g'^4 - T_{sky}'^4) + h_{c,ga}(t_g - t_a) \tag{3.65}$$

where

$$\varepsilon_g = \frac{\int_0^\infty \varepsilon_\lambda e_{b\lambda}\, d\lambda}{\int_0^\infty e_{b\lambda}\, d\lambda} = \frac{\pi \int_0^\infty \varepsilon_\lambda i_{bn\lambda}\, d\lambda}{\pi \int_0^\infty i_{bn\lambda}\, d\lambda} \tag{3.66}$$

and $e_{b\lambda}$ = Monochromatic total hemispherical emissive power of a black body

$i_{bn\lambda}$ = Intensity of monochromatic normal radiation from a black body.

There have been numerous investigations on the spectral radiation characteristics of selective surfaces.[31,32,33,34] However, this type of detailed study is considered beyond the scope of the present work. Rather, this work outlines principles in improving the collector performance by the use of selective surfaces which possess high short wave absorption and low long wave emittance.

The solar radiation at the ground level is already attenuated in the long wave components. Less than 19.8 per cent of the total irradiation lies at wavelengths greater than 1 μ, and less than 2.1 per cent lies at wavelengths greater than 3 μ. If the plate temperature is higher, a greater fraction of the thermal radiation will be of shorter wavelengths.[37]

At 150^{o}F plate temperature, 0.03 per cent of the emissive power lies in the range of greater than 3 μ.

At 200^{o}F plate temperature 0.09 per cent of the emissive power lies in the range of greater than 3 μ.

At 300^{o}F plate temperature 0.25 per cent of the emissive power lies in the range of greater than 3 μ.

This indicates the inherent advantage of selective coatings, which possess low emissivity, disappears as the plate temperature increases. Ideally, different selective surfaces are required for different boiler temperatures. Since it is impractical to change surfaces for varying radiant flux input, the selective surface prepared for a specific temperature has to operate in a range which does not yield the ideal performance. In the case of the flat plate, this variation of range is unimportant. Though there have been some selective surfaces which proved to be successful in the laboratory, not many have been commercially successful.[35] However, one of the best commercially available selective surfaces produced in accordance with the process developed by C S I R O of Australia[36] is reported to have an emissivity of 0.2 for wavelengths greater than 3 μ and an absorptivity of 0.9 for wavelengths less than 3 μ. The performance of a solar power plant using flat plate collectors which utilize this type of a selective surface was analyzed and the computer results are presented and compared with ordinary black painted collectors. All the working formulae have been kept the same as in the previous treatment. It will be recalled that the energy balance for the black painted surface is:

$$q_{useful} = \left[I\tau\alpha - U_{lc}(t_c - t_a) \right] \qquad (3.67)$$

Energy balance for any collector:

$$q_{useful} = q_{abs} - q_{lost.col} \tag{3.68}$$

However, if the absorber plate absorbs selectively at different wavelengths

$$q_{abs} = q_{abs,0-\lambda_c} + q_{abs,\lambda c-3\mu} + q_{abs,3\mu-\infty} \tag{3.69}$$

Equation (3.69) gives the heat absorbed by the collector plate due to its selective absorptivity and heat absorbed by the glass cover due to selective transmissivity of glass.

Where

$q_{abs,0-\lambda c}$: Heat absorbed from 0 to λ_c, the transient wavelength of the ideal selective surface at which the absorptivity suddenly changes.

$q_{abs,\lambda c-3\mu}$: Heat absorbed from (λc) to 3 μ (glass cut-off

$q_{abs,3\mu-\infty}=0$: Since no radiation is transmitted through glass beyond 3μ.

The first term in equation (3.67) : $I\tau\alpha = q_{abs}$ (3.70)

$$q_{abs} = I\left[\left(\frac{I_{o-\lambda c}}{I_{o-\infty}}\right)\tau_{o-\lambda c}\,\alpha_{o-\ c} + \left(\frac{I_{\lambda c-3}}{I_{o-\infty}}\right)\tau_{\lambda c-3\mu}\,\alpha_{\lambda c-3\mu}\right] \tag{3.71}$$

The fraction of the solar radiation intensity falling within the ranges of $(0-\lambda_c)$, microns and $(\lambda_{c-3\mu})$ can be obtained from the spectral solar radiation data available for various air masses.(37)

The amount of heat lost due to the selective emissivity of the absorber plate must be calculated to obtain the useful heat from equation (3.68).

q_{lost}, the heat loss from the collector as previously discussed, is composed of front (glass cover) and rear and edge losses. It was mentioned that $U_{Lc} \cong 1.1 U_{L}$ applies to most of the practical cases. Therefore, it must be possible to calculate the losses in terms of front losses as follows:

$$q_{lost} = 1.1\ q_{lost,front} \quad (3.72) \text{ in Btu/hr ft}^2$$

$$q_{lost,front} = h_{c,cg}(t_c - t_g) + \int_0^{\lambda_c} \frac{1}{\frac{1}{\varepsilon_{\lambda,c}} + \frac{1}{\varepsilon_{\lambda,g}} - 1} (e_{b\lambda,c} - e_{b\lambda,g})\, d\lambda$$

$$+ \int_{\lambda_c}^{\infty} \frac{1}{\frac{1}{\varepsilon_{\lambda,c}} + \frac{1}{\varepsilon_{\lambda,g}} - 1} (e_{b\lambda,c} - e_{b\lambda,g})\, d\lambda \quad (3.73)$$

Though it should be possible to insert (3.73) into (3.72) then (3.71) and (3.72) into (3.68) and solve for q_{useful}, it is difficult to integrate (3.73), especially if ($\varepsilon_{\lambda,c}$) and ($\varepsilon_{\lambda,g}$) are not constants or simple functions. Therefore, the following simplifications will be applied for the sake of obtaining an equation that can be easily solved. For the example presented, λ_c happens to be 3μ, which automatically drops one of the terms ($I_{\lambda,c-3}$) in equation (3.71). Although there is a gradual change of absorptivity from 3μ to 9μ, a step change at 3μ has been assumed. With the ranges of $0-3\mu$ and 3μ to ∞ gray body relations can be used. $\alpha_{0-3\mu} = \varepsilon_{0-3\mu} = 0.9 \quad \alpha_{3\mu-\infty} = \varepsilon_{3\mu-\infty} = 0.2$ figures will be used.

Equation (3.71) can be rewritten.

$$q_{abs} = I\left[\left\{\frac{I_{0-3\mu}}{I_{0-\infty}}\right\}_{T=10600^\circ R} \tau_{0-3\mu}\alpha_{0-3\mu} + \left\{\frac{I_{3\mu-\infty}}{I_{0-\infty}}\right\}_{T=10600^\circ R} \tau_{3\mu-\infty}\,\alpha_{3\mu-\infty}\right] \tag{3.74}$$

Similarly (3.73) can be simplified.

Using the averaged collector plate temperature and assuming the heat lost from the absorber plate is the same as the collector front losses for the unit collector area:

$$q_{lost.front} = \left\{h_{c.cg}(t_c - t_g) + q_{rad.net,selective,cg}\right\} \tag{3.75}$$

Some simplification will be applied to calculate

$(q_{rad.net,selective,cg})$

From Radiation Functions[38] at $T_c = 300^0F = 760^0R$

The fraction of the emitted radiation from a black body below and above 3μ:

$$\left\{\frac{I_{0-3\mu}}{I_{0-\infty}}\right\}_b = 0.0025 \quad \text{and} \quad \left\{\frac{I_{3\mu-\infty}}{I_{0-\infty}}\right\}_b = 0.9975$$

For the glass plate, which is at a still lower temperature, all the radiation emitted lies at wavelengths greater than 3μ.

$$\varepsilon_g = \varepsilon_{g,3\mu-\infty} = 0.83 \quad \text{and} \quad \varepsilon_c = \varepsilon_{c,3\mu-\infty} = 0.2$$

$$q_{lost.col} = 1.1\left\{h_{c,cg}(t_c-t_g) + (T_c'^4-T_g'^4)\left[\frac{1}{\frac{1}{\varepsilon_g}+\frac{1}{\varepsilon_c}-1}\right]\right\} \quad (3.76)$$

$$q_{lost.col} = 1.1\left\{h_{c,cg}(t_c-t_g) + (T_c'^4-T_g'^4)0.192\right\} \quad (3.77)$$

Similarly (3.71) may be simplified:

For solar radiation at sea level and air mass of (2)

$\frac{I_{3\mu-\infty}}{I_{0-\infty}} < 0.01$ may be ignored, $\lambda_c = 3\mu$

Therefore

$$\frac{I_{0-3\mu}}{I_{0-\infty}} \cong 1.0$$

$$q_{abs} = I\,\tau_{0-3\mu}\cdot\alpha_{0-3\mu} \quad (3.78)$$

for the selective surface employed $\alpha_{0-3\mu} = 0.9$

$$q_{abs} = 0.9(I\cdot\tau_{0-3\mu}) \quad (3.79)$$

Substituting (3.79) and (3.77) into (3.68)

$$q_{useful} = 0.9\ I\tau_{0-3\mu} - 1.1\left\{h_{c,cg}(t_c-t_g) + 0.192\ (T_c'^4-T_g'^4)\right\} \quad (3.80)$$

Equation (3.80) can be directly employed provided that both t_c and t_g are known. Although t_c can be approximated from the fluid temperature (t), the determination of t_g is more involved.

In the case of ordinary black paint which is assumed to have constant emissivity and absorptivity $\alpha_{0-\infty} = \varepsilon_{0-\infty} = 0.93$, the heat losses were calculated utilizing a working formula, but in the case of varying absorptivity and emissivity it becomes essential to determine t_c and t_g.

Reconsidering the heat losses from the collector plate to the glass cover, since no heat is stored for the steady state operation, the heat lost to the ambient from the glass cover is equal to the heat transferred from the collector plate to the glass cover,

$$q_{lost.ga} = h_{c.ga}(t_g - t_a) + (T_g'^4 - T_{sky}'^4)\ \varepsilon_g \tag{3.81}$$

Therefore, equation (3.75) equals equation (3.81).

Equation (3.75) and (3.81) can be solved simultaneously to obtain t_g if t_a and t_c, t_{sky} are assumed. $t_{sky} = t_a - 20^{\circ}F$ for clear sky conditions. It must be noted that the collector plate temperature is assumed constant.

$$t_c = t + \Delta t_f \tag{3.82}$$

Δt_f is the temperature difference between the fluid and the tube wall in heat transfer from plate to the fluid. Δt_f can be closely estimated employing h_c inside the collector tubes as suggested by Iqbal[39] and Baker.[40] Since t is specified by the cycle requirements, t_c can be solved.

This analysis becomes more complicated when more than one glass plate is used. There exists for an (n) glass plate collector, n glass temperatures. With the collector plate temperature altogether (n+1) unknowns exist. Writing the energy balance equations for n glass plates and one for the absorber plate, (n+1) simultaneous equations are obtained. Then the energy balance equation for the collector gives the amount of the useful heat once the unknown temperatures have been determined.

$$q_{useful} = q_{abs} - q_{lost} = fnc \left[I, t_c, t_{g1}, t_{g2}, \ldots t_{gn}, t_a \right] \tag{3.83}$$

A similar case for a non selective absorber plate is detailed in Reference (24). Further developments in the properties of the selective surface might help to reduce the cost of the power produced. At the present time almost all of the selective surfaces do not have the abrupt change of characteristics at a transition wavelength. Therefore, actual efficiencies are likely to be less than expected.

Although the performance of flat plate collectors with selectively absorbing surfaces could be theoretically calculated as outlined above, it would be more reliable if the analyses were based upon the actually constructed and tested units.

Therefore, the efficiency figures of an actually constructed land tested collector of selective surface[17] have been used in the cost optimization study. The computer programme No.01 was run for a flat plate collector with the absorptivity, transmissivity and over-all heat loss coefficients, corresponding to the characteristics of the above-mentioned collector. These coefficients were: $\alpha_{sw} = 0.9$, $\tau = 0.78$ and $U_{lc} = 0.6$. Australian prices of material, workmanship and interest rates were used in the analyses. Table 2 gives the figures obtained from Programme No. 01.

As a final comment on the selective coating the following can be mentioned:

Though the reduction of the emissivity of the surface at longer wavelengths would increase the collector plate temperature, and hence increase efficiency, the convective heat loss would also increase. This problem is not encountered in space solar power systems or if the space between the glass plate and the collector is evacuated. Because of the size of general installations employed this is impossible. Increased convection losses, together with an increase in long wavelength emission by the selective surface at elevated temperatures, combined with increase in direct transmission of heat I.R. from the transparent cover, limit the prospects of application of the selective surface for high temperature solar power plants.

Therefore, a system which would suppress the convection as well as increase the short wave absorption and decrease long wave emission, is requisite. One is led then to conceive a honeycomb structure. This will be the subject matter of section III.1.3.

III.1.3 Honeycomb Structures on Flat Plate Collectors

The use of honeycomb structures as radiation absorbing devices which may ideally have zero emissivity and unit absorptivity, has been proposed by G. Francia in his classic paper.[41] The honeycomb structures are used mainly in two ways.

1. As large cells with a length/width ratio greater than 25 for intense flux absorption purposes, as experienced in the focal plane of concentrating type collectors.
2. As smaller length/width ratio cells around 4-6, for convection suppressors over the flat plate absorber sheets.

The concentrating type collectors with long cells will be examined in Chapter III.2. Convection suppressing cells form the subject of this chapter.

The square, circular, or hexagonal shaped honeycombs have been examined[42,43] for their theoretical performance and also some experimental results have been reported.[44]

For basic materials Hollands has proposed thin glasses (0.01" thick) and the University of Marseilles team has used plastic films. Both types are made from transparent materials which transmit a high percentage of the solar radiation, especially for angles of incidence of less than 45^0. Hollands reports[45] an equivalent transmissivity, theoretically calculated, as 0.95, for $\delta = 0.01"$, $i = 45^0$ and glass with extinction coefficient of k = 0.8 per inch.

On the other hand, for properly dimensioned cells, convection can be eliminated if the temperature difference between the top and the base of the cell remains below $\Delta T_{critical}$. As long as the actual temperature rise of the collector plate remains below $\Delta T_{critical}$ the heat lost from the plate to the ambient will be composed of only direct radiant exchange between the plate and the sky and conduction through the cell walls and the stagnant air inside the cells. This corresponds to a case where Nu = 1. Owing to the low thermal conductivity of the air inside the cells, heat losses will be significantly reduced. Direct long wave emission from the base of the cell to the opening depends on the honeycomb depth/width ratio. The equivalent shape factors in radiant heat exchange F for a cell with black faces and F' for gray faces have been calculated and reported by Hottel and Keller.[46] If F and F' are substituted into the equations (3.84) and (3.85) respectively, the radiant heat loss can be calculated from

$$q_r = F \quad (T_c^4 - T_g^4) \tag{3.84}$$

$$q_r' = F' \quad (T_c^4 - T_g^4) \tag{3.85}$$

where

T_c = Collector temp.

T_g = Cover glass temp.

$\varepsilon_c, \varepsilon_g$ = Emissivities

ρ_c, ρ_g = Reflectances

$$\frac{1}{F'} = \frac{1}{F} + \frac{\rho_c}{\varepsilon_c} + \frac{\rho_g}{\varepsilon_g}$$

Although F could be reduced by increasing the length/width ratio, reduction of the plate emissivity using selective coatings is also very effective. The theoretical prediction by Hollands suggests a reduction of U_1 from 0.625 to 0.423 by using a selective coating on the absorber plate.(45) The present cheap methods of producing selective coatings encourage the use of both the honeycomb and the selective surfaces together. Another recent survey dealing with honeycombs(47) treats the problem from a slightly different point of view. H. Buchberg and his collaborators made honeycomb cells from surfaces which specularly reflect the visible (short wave) radiation, whereas they absorb the long wave infra-red emission from the absorber plate. The cells opening width to breadth ratio was kept small and the longer axis of the rectangular openings was directed E-W to maintain higher transmission of direct solar radiation at larger angle of incidences. Various depth:breadth:width ratios, and various reflecting surfaces obtained firstly by means of vacuum deposition of aluminum on kraft paper cells and secondly by bonding aluminized Mylar on the cell, were examined by Buchberg et al. and an optimization study was done based on the available and projected cost figures.[48]

In this survey, transparent cells need to be examined since existing industrial experience in manufacturing hexagonal honeycomb cells has already been adapted to the manufacture of transparent cells and cost figures as well as flat plate collector performance characteristics[49] are available.

In view of the problems involved in the manufacture of rectangular cells of 0.5 mil. thick cardboard with vacuum deposited or specularly reflecting cells bonded without spoiling the high reflectivity required, the cost of this type of cells will likely be higher than the transparent hexagonal ones. Therefore, the cost optimization for the flat plate collector with transparent square or hexagonal honeycomb cells only will be examined. The hexagonal cells can be formed easily[50] and suppress convection ideally.

The rectangular specularly reflecting cell can be examined applying the same method of analysis once the actual cost of the honeycomb panel is available. The efficiency has to be worked out for the specific geometry and surface properties employed in the proposed design, based on the relations given in Reference 48.

Computer programmes used in the steady state analysis were modified to include the effect of both the honeycombs and the use of selective surfaces. Programme No. 02 allows one to analyze a square honeycomb with a selective absorber. The following working formulae were employed in the optimization study. Improved understanding of the physical phenomena occurring in the honeycomb, improvements in performance and reduction in manufacturing costs are expected to reduce the cost of the power produced.

Honeycomb cell + Black absorber

$$q_u = F_P \left[I \tau_{honey} \alpha - U_L (t_f - t_a) \right] \qquad (3.86)$$

$U_{L_{Black}} = 0.62 \quad \alpha_{sw} = 0.93$

Honeycomb cell + Selective

$U_{L_{Select}} = 0.42 \quad \alpha_{sw} = 0.9$

Emissivity of the selective surface, $\varepsilon_{lw} = 0.15$, is included in ($U_{L_{Selective}}$). $\tau_{Honeyc.} = 0.8$

Results of this analysis are presented in Table 3.

As another alternative, flat plate collectors with an ordinary black painted absorber surface, plastic "Melinex" hexagonal honeycomb cells with h/d ratio of 5 and an opening of 1 cm. which have been tested and actual performance data reported, are also considered for the optimization study.

The performance curves representing the insolation rate, the plate temperature and efficiency relations were transformed into the following working formulae which were used in the computer programmes.

$$q_{useful} = \eta_{(I)} \cdot I \qquad (3.87)$$

where

$\eta(I)$ = overall efficiency which is a function of the insolation rate

also

$$q_{useful} = \frac{\eta(I)}{\eta(1000)} \cdot \eta(1000) \cdot I \qquad (3.88)$$

where

$\eta_{(1000)}$ = efficiency for I = 1000 watts/m^2

$\eta(1000)$ and $\eta_{(I)}/\eta(1000)$ were taken from Reference 49 and fitted to the following relations:

$$\eta_{(1000)} = 0.46 - ((t_c - t_a) - 85)0.0072 \qquad (3.89)$$

$$\frac{\eta(I)}{\eta(1000)} = 1.0 - 0.00128(1000-I) - 2.95(1000-I)^2\ 10^{-6} \qquad (3.90)$$

where

t_c = collector temperature in ^oC

t_a = ambient temperature in ^oC

I = radiation intensity in watts/m^2

For consistency in units radiation intensities and temperatures used in the optimization study were converted from British Engineering units to M.K.S. units, then inserted into equations (3.89) and (3.90).

Computer programme No. 03 was written to analyze the above described flat plate collector with plastic honeycombs. Results are summarized in Table 4.

Honeycomb cells remain one of the few promising aspects of the solar power cost minimization studies deserving further careful attention.

The optimum operation temperature for the flat plate collector equipped with honeycomb cell and selective absorber plate, Turbine-condenser assembly using steam as a working substance, was found to be 236^{o}F for a radiation flux of 220 Btu/hr/ft^2.

The corresponding cost of the power produced under the conditions pertaining at Alice Springs in arid central Australia was found to be about 27 cents per Kw hr. The use of another working substance is not attractive as long as higher temperatures suitable for a more efficient turbine design could be attained using selective coatings and honeycombs. Therefore, this alternative is not included in this section, but in another chapter (III.1.5).

III.1.4 The Use of Mirror Boosters to improve the flat plate Collector Performance

Additional reflecting surfaces directed towards the collector surface increase the output per unit area for a given insolation rate. It has already been demonstrated that the increase of (I) in equation (3.31) would increase the useful heat collection.

The use of side mirrors to reflect radiation from areas bordering the collecting surface dates back to Schuman[1] who used them in a solar power plant constructed in Meadi, Egypt. In this significant attempt, the output per unit collector area was increased by means of mirrors attached to the south and north ends of the collectors.

A survey of mirror boosters reported by Dr. Tabor and his collaborators,[51] describes possible combinations of the side mirrors and analyzes the performance of a flat plate collector with north-south or east-west end mirrors as well as a mirror system reflecting both from east-west and north-south edges. Transposition of mirrors from morning to afternoon operation can be maintained by linking the pair of mirrors together or using a truncated pyramid type of mirror arrangement pivoted about a point.

Figure 7 illustrates the basic types of mirror boosters. The radiation intensity incident upon a plane parallel to the collector surface can not be varied since it is determined by the solar constant, the atmospheric transmittance and the orientation factor. However, the heat which can be collected based upon the intensity measured on the absorber plate surface can be increased by mirror boosters. Since the relative cost of the mirror surfaces and the framework needed to support them, is at least an order of magnitude lower than the cost of a 3 or 4 glass cover collector, it is worthwhile to use mirror boosters provided that their area is carefully determined and the booster mirrors do not cast shadows on the main collecting surfaces early in the morning or late in the afternoon. The angle ψ between the collector plane and the mirror plane, the mirror length and its position can be separately optimized for maximum heat collection during a given period of time. The addition of side mirrors necessitates the separating of individual collector units in order to avoid shading. This increases the length of the piping connecting the collectors and the area of land needed to install them. This will naturally involve additional expenditure.

In the steady state analysis treated in Chapter III it is not possible to include the study of a mirror booster optimization because the system is optimized for a fixed radiation intensity. The mirror position and mirror size must be optimized for the day-long operation. A mirror system reducing the radiation incident on the absorber plate during early hours may further increase the collection around noon, thus increasing the daily collection. In other words a compromise must be sought for the maximum output during a period in which the solar radiation intensity is above the critical radiation intensity. Thus the cost of the power produced in the long run would be minimized. A combination of mirrors must be continuously rotated to attain the highest possible boost and its length must be adjusted to attain the full coverage of the collector surface at various angles of incidence.

Figure 7 illustrates this important effect of the change of the angle of incidence which results in the reduction of the LHS mirror size, and in an increased angle of ψ. On the other hand an increased RHS mirror size leads to a decrease in the angle of ψ for the afternoon operation and vice versa during the morning. During the late afternoon operation, the west side mirror and during the early morning operation the east side mirror are inefficient.

However, from the point of view of practical operation and in order to eliminate expensive sun tracking mirror control systems, some departure has to be accepted from the most efficient boosting condition.

Since the objective of the research is to optimize a number of combinations of a solar power plant's components and not to perfect any single element, an ingenious mirror booster system proposed and tested by Tabor is taken as a basis for this study. Some other mirror boosters proposed[52] are more like low concentration type collectors rather than a set of mirrors arranged to increase the output of a flat plate collector. Therefore, these will not be treated here.

It is believed that further complications in the mirror system create a hybrid design between the flat plate collector and the concentrating type collector. The latter will be examined in a separate chapter. Some further analytical and conceptual reasoning will be outlined where needed. The useful operation period of a flat plate collector for production of steam at a temperature of the order of $212^{o}F$ which has been found necessary from the steady state analysis outlined in Chapter III.1 requires intensities above 220 $Btu/hr/ft^2$ which is available only for 3 hours on either side of noon. However, through the use of a properly designed mirror system, the flux on the collector plane can be increased and the operation period can be extended. But this requires continuous adjustment which means extra operational costs or a complicated tracking system. Although it has been mentioned that the optimization of the mirror boosters dimensions and positions cannot be included in the steady state analysis the flat plate collector equipped with a properly selected mirror booster can be analyzed for obtaining the minimum cost of the power produced.

Since the steady state analysis is based upon the averaged radiation intensity over an extended period there are no reasons not to average the mirror factor (M) which is defined as "the ratio of the filtered (i.e., transmitted through the transparent cover and absorbed by the collector plate) incident radiation with mirror booster to the intensity without mirror booster."

This ratio is reported to be 2.0 for a single set of mirrors transposed from east to west daily and from south to north at the solstices.[51] A truncated pyramid type mirror assembly increases the mirror factor to 2.4 while requiring twice as much mirror surface and still needing adjustment once a day.

The cost optimization study was repeated for a flat plate collector equipped with a transposable single mirror system and for a 200 per cent increase in the insulation rate and a mirror area about the same as the collector, i.e., 5 per cent more than the collector area to allow for edge losses. The cost of the power produced based upon Australian prices[36] is presented in Table 5.

III.1.5 The Influence of the Working Substance on the Flat Plate Collector

The Rankine cycle efficiency as well as the collector efficiency depend upon the boiling point of the working substance. The latent heat of evaporation also differs markedly from substance to substance.

Water has been extensively used in all large scale power plants. Although mercury and kerosine were tested, their use was not widespread. There have, however, been attempts to find other suitable working substances for terrestrial solar power plants and small scale power units for space applications. Sulphur dioxide was used in the Somor engine,[8] Professor Masson of Senegal tested a range of Freons,[7] and Dr. Tabor used Monochloro Benzine after examining various organic fluids[20] for use in his successful solar power scheme. The basic criterion for using a working substance other than water is to see whether a larger power output can be obtained for a given collector area or the cost of the power produced lessened. The latter, in fact, is the objective of this research. Larger power output may not necessarily yield the lesser cost since this may necessitate increased investment for equipment, and the working substance itself, unlike water, would be an added expense. A working substance possessing a heavy molecular weight was looked for, since this reduces the discharge velocity from the nozzle for a given mass flow rate. Reducing the full admission nozzle exit velocities allows lower turbine shaft speeds to be used. A hermetically sealed turbine generator assembly developed in the National Physical Laboratory of Israel is a significant achievement in the production of mechanical energy from solar radiation.

Although this unique development has its own feature of increasing the turbine efficiency - by reducing the dimensions and employing only one moving shaft, that combines the turbine and generator rotors - it aims to improve only one component of the solar power plant. Having acknowledged the merits of a Monochlorobenzine turbine, some other alternatives will also be examined. Among the working substances proposed for use in solar power plants are Freon, Sulphur dioxide and some organic fluids such as the Fluorochemicals suggested by Ray and Moss[53] and Halogenized Hydrocarbons investigated by Tabor.

In this research the effect of the working substance on the over-all performance of the solar plant operating on the Rankine cycle has been discussed.

The efficiency of the Monochloro Benzene turbine for full and partial admission has been reported by Tabor.[20] Efficiencies predicted for Fluorochemicals in Reference 52 indicate 35%, 67%, 62% and 74% for fluids of Molecular weight of 186, 219, 416 and 462, respectively. Except for FC.75 which has an efficiency of 62% and molecular weight of 416, the trend of efficiency follows the trend of the molecular weight. Volatility is said to be responsible for the reduction of efficiency using FC.75. It is, therefore, reasonable to predict the turbine efficiencies assuming them to be proportional to the Molecular weight of the working substance.

There are many practical difficulties associated with some of the many working substances other than water since the positive slope of the T-S diagram necessitates the use of a feed-back heat exchanger. Special attention should be paid to the turbine design and manufacture as these factors are responsible for increased costs, especially if the units are manufactured in small quantities. In the case of loss of the working substance due to leakage it becomes difficult to supply for rural applications.

The use of honeycombs and selective surfaces permit higher boiler temperatures which tend to improve the cycle efficiency. Unless a separate theoretical analysis and experimental verification is completed, new working substances cannot be proposed for use on a solar power plant nor can they be discarded completely.

In looking forward to some reduction in the price of the newly introduced fluorochemicals and improvement in performance of the special turbines, it can only be concluded that other working substances may have some chance of application. The optimization methods developed in this research are directly applicable to the analysis of any such system. Any cost and efficiency prediction of other working fluids would not be accurate enough to reach concrete conclusions. Instead, the promises of organic fluids will be indicated and future developmental studies on the new substances will be suggested as topics for further research.

III.2 Concentration

The maximum temperature attainable in a flat plate collector is limited due to the increasing heat losses at elevated temperatures. It has already been indicated that for every design, i.e., for a given combination of transparent covers, absorber surface properties and insulation thicknesses, there is an equilibrium temperature above which the useful heat collection of q_u falls to zero. Since the efficiency is too low at temperatures near the equilibrium temperature, more collector areas will be needed, thereby increasing investment and thus causing high costs per Kw hr produced.

The optimum outlet temperature for a 3 glass cover collector with ordinary black absorber plate was found to be $211^{o}F$ for a radiation intensity of 300 Btu/hr ft^2. The equilibrium temperature corresponding to this optimum temperature is calculated from

$$t_{equil} = t_a + \frac{I\tau\alpha}{U_{Lc}} \quad (3.91)$$

i.e., for an ambient temperature of $75^{o}F$, the same collector has an equilibrium temperature around $350^{o}F$. Honeycomb structures and selective coatings, as already demonstrated, help to increase the collector efficiency at elevated temperatures, while at the same time causing the equilibrium temperature to rise.

The useful heat collected for unit area:

$$q_u = q_{abs} - q_{lost} \quad (3.91)$$

for any collector. If the collection area is A_c, and the area from which the heat is lost is A_{lost}:

$$Q_u = A_c \cdot q_{abs} + A_{lost} \cdot q_{lost} \quad (3.92)$$

The total collection can be increased by increasing the first term and/or decreasing the second.

For the flat plate collector "except for mirror boosters"

$$A_c < A_{lost} \text{ where } A_{lost} = A_{rear} + A_{edges}$$

since $A_{rear} \cong A_c$.

Therefore, the area from which the heat is lost is greater than the collection area. The collection area can be increased by using concentration methods, though the total increase in the heat collected will not be as large as the increase in area because of reflectance losses and the inclination of the reflecting surface in relation to the incoming solar beam. Figure 8 illustrates some basic types of concentrators.

The following equation shows the energy balance on the receiver of a concentrating type collector. The dimensions and symbols refer to Figure 9. Applying the First Law of Thermodynamics to the system enclosing the receiver for any concentrator, for steady state performance:

$$w(H_{out}-H_{in}) = \iint I(x,y)dx.dy - q_{lost,receiver} \quad (3.93)$$

where $I(x,y)$ is the radiation intensity normal to the receiver plane.

The equation (3.93) is valid as long as perfect sun tracking is maintained since all of the incident radiation reflected by the concentrating mirror is assumed to be intercepted by the receiver plate. The sun tracking can be maintained by moving the concentrator and receiver assembly, in which case, however, many practical difficulties are involved for large collectors. Heliostats would appear to provide a better alternative. The double reflections from the heliostat and the concentrating mirror can be reduced to a single reflection using a set of adjustable mirrors. These mirrors concentrate the beam on the focal plane as a linear strip or spot image, as well as tracking the sun.

The variation of the flux intensity on the receiver surface has been studied by various researchers.[54,55] The spatial distribution of direct incoming radiant flux to the receiver, measured at the receiver inlet I(x,y), is closely related to the precision of manufacture of the concentrating mirror as well as to its alignment.[56] It has no direct bearing on this study since the integrated value can also be used:

$$I_n r_1 r_2 A_n \eta_{mir} = \iint I(x,y)dx.dy \tag{3.94}$$

where I_n indicates the normal beam intensity, A_n the projected area of the mirror measured on the plane perpendicular to the beam I_n; r_1 and r_2 reflectivities of the heliostat and the concentrating mirrors; and η_{mir} a factor describing the precision of the mirror. Detailed examination of the heat losses from the receiver is as follows:

Expressing the receiver losses as:

$$q_{lost,receiver} = q_{lost,rear} + q_{lost,front} \qquad (3.95)$$

$$q_{lost.front} = q_{emitted} + q_{convected}.$$

$q_{emitted}$ may be minimized by using cavity type absorbers.[57] This type, however, should have a very small opening which needs high concentrations and requires very precise tracking. It may easily come off focus which would destroy other parts of the receiver. Convection can be reduced by confining the air space to smaller cells.

Long cell honeycombs have the merit of combining these two. The incoming beam is almost completely absorbed after a few reflections, and the space is finely divided into convection cells. The performance of the long cell honeycomb cavity approaches the performance of a "Hohlraum" which has an absorptivity of 1.0. Temperatures above the melting point of the absorber plates in the case of cells from which no heat has been withdrawn, have been reported by Francia,[41] who used this principle in developing an efficient absorber (boiler) in his sun tracking mirror field system.

$$q_{lost,\ rear} = A_{rear,receiv.} \quad U_{lreceiver} \ (t_l - t_a) \qquad (3.96)$$

Since also $A_{rear,receiv.} \ll A_{col}$ the losses will be much less.

The thermal analysis of the receiver and the prediction of the collection temperatures and the receiver efficiencies, cannot be done as accurately as for the flat plate, unless the geometry of the receiver, absorbing elements, heat transfer surfaces, insulation type and constructional techniques are all specified. The receiver easily delivers superheated steam since temperatures of the order of $550^{o}C$ at 150 atmosphere[58] can be obtained. Proportioning of the superheater and evaporator surfaces, and the exact theoretical determination of the heat transfer coefficients are omitted from the present work. The reported efficiency values will be used in the cost analysis.

The system is made up of the following components:

i. mirror field
ii. control mechanism to track the sun
iii. supporting structure for the mirror
iv. boiler assembly
v. boiler support
vi. steam and feed water piping
vii. pumps and controls
viii. turbine
ix. condenser

A few advantages of the Francia system can be outlined as follows:

a. Mirrors are individually adjusted and controlled. Thus the breakage of some of the mirrors cannot stop the solar plant.

b. Mirrors are supported on the low framework and less subject to wind forces since individual element areas are less than $1m^2$.

c. The inverted bell type receiver is more advantageous from the point of view of reduced convection and radiation losses.

d. The boiler (receiver) is fixed and therefore no flexible steam couplings are required. However, the boiler may burn out if the water circulation fails, so safety devices have to be installed to prevent such an event.

e. The boiler supporting column also serves as the casing of the feed and steam outlet piping.

f. Owing to the high temperatures attained, the design of the steam turbine offers no difficulties. However, some of the problems that could be involved require discussion.

Firstly, the system cannot operate under diffuse radiation. Secondly, the design of the mirror tracking system requires very precise engineering. The construction of the boiler tracking and other elements necessitates precision workmanship, which is not available in underdeveloped countries. Thirdly, the importing of mechanical equipment results in increased transportation costs and customs duty which may prove prohibitive. Finally the operational temperature of the plants is very sensitive to the changes of radiation intensity. This may cause some inefficient operation and mechanical troubles with varying insolation.

A thermal flywheel proposed by Francia which smooths over the irregularities, would also increase the cost. The concentrating steam generating plant can be approximately calculated from:

$$C_{tot.boiler} = A_{mir}\left[C_{mir} + C_{frm} + C_{cont.}\right] + C_{struct} + C_{boiler} \qquad (3.97)$$

Mirror costs and the supporting frame are proportional to the mirror surface. The boiler cost, although related to the total collection area, depends mainly upon the concentration area ratio and a number of other design features. Individual examples constructed to date are either on a laboratory scale or produced in very small numbers. It is difficult, therefore, at this stage, to obtain a cost figure for possible production in large numbers.

The most authoritative cost estimate available has been given by G. Francia[58] where a total cost of $\$30/m^2$ has been predicted. Although the mirror areas and costs can be closely calculated, the cost of the other components cannot be predicted any better than the above figure unless a careful engineering analysis supported by experimental evidence is made. For these reasons, $\$30/m^2$ is to be used as a preliminary cost estimate. However, the validity of this assumption will be discussed at length in Chapter VII.

The conversion efficiency from solar radiation to the steam produced in boiler is reported as 50 per cent for a linear boiler and better than 70 per cent for a point focussing boiler.(49) In addition, for an operating pressure of 150 Atm (150 x 14.7 = 2200 psi) and about $900^{\circ}F$, condenser temperature of $95^{\circ}F$, the Rankine efficiency would be:

$$\eta_{Rankine,ideal} = \frac{H_{g1} - H_{x2} - W_p}{H_{g1} - H_{f1} - W_p} = 0.43 \qquad (3.98)$$

The steam at high pressure and temperature available from the concentrating boiler has the advantage of being directly useable in an industrially manufactured efficient turbine.

Taking $\eta_t = 0.80$ as turbine efficiency, the Rankine cycle's efficiency is obtained as

$$\eta_{Rankine.actual} = 0.8 \times 0.43 = 0.345 = 34.5\%$$

using the collection efficiency figure from the solar radiation to steam as 70 per cent.

$$KW = I.A_{mir}.0.70\eta_m.\eta_{Ran.act}/3413 \qquad (3.99)$$

where I measured in $Btu/hr\ ft^2$

$$KW = I.A_{mir}.0.70\eta_m.\eta_{Ran.act} \qquad (3.100)$$

where I measured in Kw/m^2

12 Kw output would necessitate a collection area of:

$$A = \frac{KW}{0.7\eta_m \cdot \eta_{Ran.act}\ I} \qquad (3.101)$$

The previous data would yield for I = 0.8 Kw/m^2 = 253 Btu/hr ft^2

$$A = \frac{12}{0.7(0.95)(0.345)0.8} = 50\ m^2$$

The total cost of the boiler system can therefore be expected to be $C_{tot.boil}$ = 50 x 30 = $1500 for the boiler part of the system.

The cost of the plant is calculated from:

$$C_{tot.plant} = C_{tot.boil} + C_{turb.} + C_{cond.} + C_{pump} \qquad (3.102)$$

The cost prediction of $30/$m^2$ by Francia, although not a commercial figure for the installed plant, which would also include the transportation and profits, may be used as a starting point. The turbine cost for a pressure of 150 atm. and 900^{o}F is expected to be no less than $2500 owing to the leakage sealing problems involved and the increased heat losses. The condenser cost is about the same as that of the flat plate system but larger heads are needed for the feed pump. Taking C_{cond} = $250, C_{pump} = $100, and allowing $150 for piping and insulation, the total cost for the system will be:

$$C_{tot.plant} = 50 \times 30 + 2500 + 250 + 100 + 250 = \$4500$$

The lifetime of the concentrating system is expected to be lower than the flat plate since high temperatures are employed.

Also the moving parts, which form the mirror control mechanism will wear and the surface properties of reflecting surfaces change. For a lifetime of 10 years, the total yearly expenditure is obtained from:

$$E_{tot} = (C_{tot.plant} + C_{operator})(R_f + r) \qquad (3.103)$$

where $C_{operator}$ = yearly expenses for operator

R_f = capital recovery factor

$$R_f = \frac{i(i+1)^n}{(1+1)^n - 1} \qquad (3.104)$$

(See also Appendix 1 for R_f)

Operation and repair costs will be higher for this unit than for the flat plate collector since it is not possible to operate such a system without supervision. The salary of a man needed for this supervision could run as high as $20/day in Australia, although for many underdeveloped countries this figure would be too high. Total annual expenses would then be, assuming 6% for repairs, 5% for interest on capital, and annual salary being $7200:

$$R_f = \frac{0.05(1+0.05)^{10}}{(1+0.05)^{10} - 1} = 0.13$$

$$E_{tot} = (4500 + 7200)(0.13 + 0.05) = \$2106$$

The yearly production based on 8 hours of daily output for 300 days a year at rated power is:

$$W_{tot.year} = 8 \times 300 \times 12 = 28800 \text{ Kw hrs}$$

cost of power produced

$$C_{kwh} = (2106/28800) \times 100 = 7.1 \text{ cents/kwh}$$

This figure is largely affected by the local labour costs and the amount of expenditure on the repair and interest rates and may, therefore, vary widely. A further discussion of these important aspects and the comparison with the equivalent flat plate collector will be postponed until Chapter VII.

III.3 Brayton-Cycle Concentrating type collector - Sink and Turbine

The Brayton cycle for air and other inert fases has recently gained in importance in space programmes and with gas cooled Nuclear Reactors.

The Brayton Cycle using fossil fuels as a heat source, has been used extensively in turbojet engines where the power/weight ratio is important. The cost of power produced is still higher than for the conventional Diesel Engine. A Brayton cycle unit for Satellite power applications, employing a solar heat source has also been proposed.[59]

The Brayton Cycle is outlined in Figure 10. At low maximum cycle temperatures, the net output of the cycle is too low to justify its operation for useful power production, since most of the power produced is consumed in the compressor work.

The ideal work produced is obtained from

$$W_i = (H_3 - H_4) - (H_2 - H_1) \tag{3.105}$$

The actual work will be reduced due to the irreversible adiabatic compression and expansion processes marked as (1-2') and (3-4'). If the fluid flow had occurred at no pressure drop through the "Heat Addition" and "Heat Rejection" processes, then the net actual work would have been

$$W_{oa} = (H_3 - H_{4'}) - (H_{2'} - H_1) \tag{3.106}$$

The pressure drops in the processes of heat addition and rejection further reduces the net work produced to

$$W_{oa} = (H_{3''} - H_{4''}) - (H_{2'} - H_1) \tag{3.107}$$

The exact amount of work can be determined only if all of the pressure drops are known. A solar power plant employing a Brayton cycle will suffer excessive pressure drops in the heater and in the sink, if used as a closed cycle unit using an inert gas as a working substance.

A study of the Brayton - Argon Cycle[60] indicates that temperatures of the order of 1400°F must be used to attain an optimum combination of collector turbine and radiator. An efficiency of 23 per cent has been predicted. Since the above-mentioned research does not aim at producing low cost power, but, rather to reduce the weight per unit power output, the cost optimization was not considered.

The temperatures needed for useful operation of the Brayton cycle can only be obtained using a concentrating type collector. The point focussing receiver described in section III.2 of this chapter is suitable. However, the rate of heat transferred from the collector absorbing surface to the gaseous working substance circulated, is of the order of 5 to 10 Btu/hr ft^2 deg F; wherease it is 50-100 for water in convective heating, and up to 10,000 Btu/hr ft^2 deg F in boiling water. This indicates the need for larger heat transfer surfaces. The tube wall temperature will be much higher, the yield strength of the tube material will be reduced at elevated temperatures and higher pressure drops required will necessitate the use of heavier tube walls to withstand higher pressure. An air heater operating at 1400°F, even if a practical possibility would turn out to be very inefficient. An exact performance-analysis of such a heater for heating gas to temperatures of the order of 1400°F cannot be undertaken unless the actual model with dimensions and material properties are specified.

Considering the practical difficulties involved in operating a concentrating collector, incorporating air-cooling operating at 1400°F, low receiver efficiencies, and high costs of construction and increased pumping losses to improve heat transfer characteristics of the receiver, the Brayton Cycle with solar heat source will not be further examined as an alternative cheap source of power.

III.4 Stirling Cycle - Concentrating Collector - Sink - Reciprocating Engine

The two-piston, closed cycle engine, named after its inventor Robert Stirling, was first constructed in 1816. However, no substantial record of its application and development was maintained for more than 100 years, until 1938, when N. V. Philips Gloeilampenfabrichen initiated a research and development programme. In 1944 the first air Stirling engine was operated successfully.

After 1948, similar studies were started in the U.S.A. where the problem was treated from a different angle, incorporating solar and other energy sources.

The basic advantages of the Stirling engines are thermal efficiencies as high as 45 per cent(61) and silent operation. In space applications the solar-operated Stirling engine is claimed to have low weight/power ratios. Independent work has been carried out in the Allison Division of General Motors Corp. in Indianapolis,(62) Battelle Memorial Institute in Columbus, Ohio,(63) and the University of Florida in Gainsville(64) on solar-operated Stirling engines. The heat sources of some Stirling engines have been Diesel fuel fired[65] for U.S. Army specified power units where compactness and continuous operation have been the main requirements.[66] Very large engines, up to 360 Hp,[67] have also been constructed and have been successfully run.

The Stirling engine with a transparent quartz window at the cylinder head, was patented by Professor Farrington Daniels and Dr. Theodor Finkelstein.[68] Solar Stirling engines have been constructed at the Battelle Memorial Institute[63] and at the University of Florida in fractional HP ranges.[64] The paraboloid type of concentrating collector was employed to attain temperatures in the order of 1400^{o}F. Besides the precise tracking requirement, the present cost estimate which is about $470 for a 50-watt unit indicates the economical drawback. The power range projected, 12 Kw requires 240 such units which would cost approximately $120,000. This is an order of magnitude larger than the cost of a flat plate collector steam Rankine cycle - Turbine system and therefore does not meet the economical performance criteria. A single concentrator would still not lower the cost to an acceptable level.

Some other operational features, design considerations and proposals such as NaK eutectic alloy and LiH, for the heat transfer fluid and storage purposes, would not further reduce the cost of the power produced, but on the contrary, lead to an increase.

The above considerations and other problems involved in the Solar Stirling Engine resulted in research activities being discontinued in some institutions.[69] Instead, a Stirling Engine with conventional fuel operation is gaining interest. Development is still continuing[65] for units ranging from a few horsepower to several hundred horsepower.

Therefore, the concentrating type of collector with air or other fluid as the working substance for a Stirling engine combination will no longer be examined. In addition, the solar collector design does not show promise. The main reason for this is the reduced collector efficiencies at elevated temperatures, and the low heat transfer rates for gases which are usually used as the working substance.

IV. UNSTEADY STATE ANALYSIS

IV.1. General Discussion on the Variation of Design and Input Parameters

In the analyses that have already been outlined, a constant radiation intensity has been assumed to occur throughout all the sunny days experienced during the year. This simplifying assumption, however, is only true in the special case of a sun-tracking satellite power system. In all terrestrial applications, the intensity of solar radiation incident upon a horizontal or tilted plane varies both with time and with atmospheric conditions. As a consequence of this variation, since it causes a change in the output of the power plant and the operating conditions, the cost figures previously obtained for the constant intensity case are no longer applicable.

Unsteady state regimes for the solar power plant may be considered to fall within the following categories:

1. The collector area is fixed for average operating conditions, while the power output alters with the radiant flux change; but no heat or electrical work storage, using storage batteries, is taken into account.
2. There is a time dependent demand for the power. In other words, consumption of the power produced must follow a

definite pattern depending upon the hour of the day and the month of the year. This would appear to be the most realistic approach since there is very little or no consumption to be expected after midnight in farms, whereas irrigation and other mechanical work requirements would increase the power demanded during the day time.

3. A special case for consideration in power demand could be a constant consumption at nominal rating. This case, however, can be easily handled once the problem with the arbitrary power demand pattern is solved. Since a constant power demand is not likely to occur and the maintenance of such a performance would require unnecessarily large storage systems, this case in the Unsteady Analysis will not be unduly emphasized.

Preliminary results obtained from the steady state analysis without a storage system indicate costs, even under the most optimistic conditions, to be above 10 cents/kw hr. Addition of a storage system would obviously raise this figure. Unless a careful determination of the essential power needs is made and power consumption limited to considerably shorter periods especially during the winter and rainy seasons, the increased cost of storage could easily bring the cost per kw hr up to a prohibitive level.

The output of the plant may be varied in order to satisfy a variable demand by either of the following methods:

A. By varying the collection area depending on the power demanded. This would imply that the system would have to be constructed conforming to the maximum power requirement. Therefore, some portion of the collector will normally remain unused. The cost of the power produced would obviously be increased.

B. By varying the flow rate of the working substance in phase with the variation of the solar radiation intensity. This apertains to the first case where the Demand Function follows identically the supply function, and no storage is required. No changes occur in turbine performance as a result of variations in operating temperatures since constant output temperature (t_1) can be maintained by changing the flow rate and the condenser temperature is also fixed. The system can be equipped with automatic control of the flow rate, while a shut-off device similar to the one developed by Neeman[70] can be added for those periods during which the radiation intensity is below a predetermined value. This intensity is usually referred to as: "The Critical Radiation Intensity." In cases where the power demanded is more than that supplied through the collector, the deficit has to be made up. Therefore the energy must be stored at a higher temperature in order to overcome irreversibilities inherent in the heat transfer processes and permit efficient operation during overcast periods or at night. Storage of energy for future use will be discussed in length in the related chapter.

Since the energy input, solar Radiation Intensity, which has been called "Disturbance" in optimization studies, is time dependent, it has to be formulated and available radiant flux on the collector plane must be known for every hour during a year's period.

Though many proposals have been suggested[71,72] for predicting the solar radiation intensity, it is more reliable to base the analyses upon the measured radiation flux for a given locality.

In almost every solar radiation measuring station, the total radiation intensity is measured on the horizontal plane. For some selected stations, diffuse and direct beam radiation measurements are also available.[73] This chapter gives the basic conversion formulae for calculating the solar radiation intensity on a tilted plane if the "total" solar radiation or the "total and diffuse" solar radiation intensities are given. It must be pointed out, however, that the best approach is that of carrying out actual measurements at the site on the tilted plane long enough to get a statistical average rather than that of approximating it through calculations. Particularly in the case of intensities converted from a horizontal to a tilted plane, there would be inaccuracies wherever diffuse measurements were not available.

It is to be noted, however, that the measured radiation intensity for a given locality does not imply that the variation will remain similar for all years to come. Hence, accuracy in calculating the radiant flux on the tilted plane would not appear to be too significant in a final analysis of the aims of optimization studies.

IV.2. Solar Radiation Intensity and its Determination

The reliability of any optimization study of solar power production at any chosen locality is dependent upon the accuracy of the prediction of the solar radiation intensity throughout the expected lifetime of the plant. It is obvious that exact prediction is impossible. However, long periods of sunshine hour measurements provide a relatively dependable measure of the probability of sunshine. Many empirical relations have been suggested to correlate sunshine hour measurements with the daily total, and hourly distribution from the daily total, for selected climatic conditions. These data, however, give an over-all picture of the possibility of utilization of solar radiation, rather than any assistance in designing a system. Measured values of solar radiation intensity for extended periods, of course, are the most dependable source of information. Unfortunately precise radiation data are available at only a few locations, from among those where solar power production shows some prospects of economic application.

Production of mechanical power from solar radiation can be conceived at localities enjoying extensive periods of sunshine and at which competitive sources of energy are too expensive or inconvenient for some reason or other.

A world-wide survey completed by a University of Wisconsin team gives a list of stations in which Radiation Measurements are carried out as well as giving isopleths (constant solar radiation intensity curves) all over the world for every month of the year.[(74)] A careful study of this excellent survey gives a sound idea regarding the localities in which solar energy utilization shows promise. The essential requirement for any solar power application is of course a steady supply of solar radiation throughout the year. Some specific applications, however, may permit some overcast periods in summer time, such as in the case of space heating with solar radiation, or in the winter, if, for instance, refrigeration or air-conditioning in the summer is desired.

Though it is theoretically possible to store energy for future use for an extended period of as long as several months, the increased cost of storage, especially at high temperatures around 200°F, makes it impractical. Therefore, it is necessary to limit consideration of solar power production to localities possessing more than 3000 sunshine hours per year relatively uniformly distributed throughout the seasons. Unfortunately, such locations are rare on the earth. Most of them lie between 15° and 35° north or south of the equator. They include the southwestern USA and some parts of Mexico, the North African desert, the Middle East, Central Iran, Turkestan, Uzbekistan, some parts of Pakistan in the Northern hemisphere; and the Atacama desert of Chile, Argentina, Brazil, the Kalahari desert of southern Africa and the Australian dry arid regions in the Southern hemisphere.

For the basis of comparison, Alice Springs in Australia (133° 53' East meridian, 23°48' South Latitude) has been selected, since dependable radiation data[75] based on long-term observations were readily available and local material and workmanship costs* were kindly supplied by Mr. R. V. Dunkle of the Solar Energy Group, CSIRO of Australia.[36]

Because there is a well-developed, competitive solar collector industry as well as an evident enthusiasm for utilizing solar energy in arid parts of Australia, it is a

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*Figures for this example have been expressed in Australian dollars, whereas for other sections in U.S. dollars.

suitable area in which to consider the application of solar power. It is to be noted that there may exist many other localities with enough sunshine and where fuel costs are high or in which other sources of energy are not available. However, the project aims to set up some techniques which may be utilized in the case of any place of promise for solar power production. Therefore, one example is considered to be sufficient to demonstrate the method. Since sample computer programmes are presented in the Appendix, the only requirement for the optimization study in a new location is the relevant radiation and cost data.

The radiation intensity, I, used in the computation is the total radiation intensity on the collector plane. Since almost all of the radiation data available refer to a horizontal plane, the intensity on a tilted plane must be calculated by the steps outlined below. A similar extensive survey and an automatic programme to calculate the radiation intensities on tilted planes of any orientation has been developed in the Geography Department of McGill University by Professor B. Garnier and Mr. Atsumu Ohmura and must be referred to[76] by those who require to calculate the intensity more precisely.

The unsteady state analysis covering a year's period, devised for testing various collector areas and boiler temperatures, in itself takes a long time and requires 220 k cores, even on an IBM 360-75 which is a fast modern computer. The additional computation time required to search for the best orientation for every day of the year in order to obtain a few per cent increase in the solar radiation intensity incident on the collector plane, is not justified due to the excessive increase in computation expenses.

Instead, an optimum orientation will be selected as described in the next chapter. Having previously calculated the radiation intensity on the tilted plane in a separate subprogramme, the main optimization programme will be considerably simplified and computation time reduced.

Although the collector must track the sun for maximum possible collection, not much will be lost by orienting the collector towards the Equator, with the N-S line coinciding with the collector axis. Especially in the case of a power application in which high temperatures are needed for turbine operation, collection has to be confined to the eight-hour period symmetrically spaced about solar noon. During short periods the total radiant energy received by the inclined plane does not differ markedly from that of the sun tracking system. Therefore, in the Northern Hemisphere a southward facing collector orientation is preferable. The degree of tilt can be varied daily to maintain normal incidence at noon for maximum collection for a southward facing collector. If this adjustment creates operational troubles and design difficulties, then it is recommended that a battery of collectors, connected to each other by condensate feeding and steam headers, be tilted to a fixed orientation, to give maximum output either throughout the whole year or during the preferred season. The degree of tilt is also a function of the latitude.

For places away from the Equator, the more the collector is tilted towards the Equator, the more heat is obtained. Even on the Equator, a $\pm$ 23°27' tilt is needed to collect maximum radiant flux to cope with the changing declination. For localities as far as 40° north or south latitudes the gain by orienting the collector to optimum tilt, could be as high as 30 per cent,[77] for a year.

The solar radiation intensity on the tilted plane may be calculated by following the steps described below:

The direct horizontal radiation

$$I_{HD} = I_{Ht} - I_{Hd} \tag{4.1}$$

Direct normal beam

$$I_{HD}/\text{Cos}\,i = I_{DN} \tag{4.2}$$

Total radiation intensity on the inclined plane

$$I = I_{DN}.\text{Cos}\,i + I_{dif} \tag{4.3}$$

The diffuse radiation intensity on the inclined plane has been assumed to be the same as on the horizontal plane.

$$I = I_{HD} \cdot \frac{\text{Cos}\, i}{\text{Cos}\, z} + I_{dif} \qquad (4.4)$$

$$I = (I_{Ht} - I_{Hd}) \cdot \frac{\text{Cos}\, i}{\text{Cos}\, z} + I_{dif} \qquad (4.5)$$

$$I_{dif} = I_{Hd}$$

$$I = I_{Ht} \cdot \frac{\text{Cos}\, i}{\text{Cos}\, z} + I_{Hd} \left(1 - \frac{\text{Cos}\, i}{\text{Cos}\, z} \right) \qquad (4.6)$$

At noon for the optimum oriented plant: $\text{Cos}\, i = 1$

During the useful collection period: $\frac{\text{Cos}\, i}{\text{Cos}\, z} > 1$

$\frac{\text{Cos}\, i}{\text{Cos}\, z}$: is also called "The Orientation Factor, R"

Whenever I_{Ht} and I_{Hd} measurements are available, the radiation intensity, I, on the inclined collector plane can be obtained from (4.6).

If only I_{Ht} measurements are given for dry arid regions with mostly clear sky conditions, $I_{Hd} \cong 0.1\, I_{Ht}$

$$I = I_{Ht} \frac{\text{Cos}\, i}{\text{Cos}\, z} + 0.1\, I_{Ht} \left(1 - \frac{\text{Cos}\, i}{\text{Cos}\, z}\right) \qquad (4.7)$$

$$I = 0.9\, I_{Ht} \frac{\text{Cos}\, i}{\text{Cos}\, z} + 0.1\, I_{Ht} \qquad (4.8)$$

Equation (4.8) gives the radiation intensity on the inclined plane for the case in which only total horizontal measurements are available.

Optimum orientation at noon if the plane is tilted from the horizontal by β degrees

$$\phi - \beta = \delta \quad \text{or} \quad \beta = \phi - \delta \quad , \text{then } i = 0^{\circ} \quad \text{for} \quad \xi = 0$$

$$\mathrm{Cos}\, i = \mathrm{Sin}\,(\phi - \beta).\mathrm{Sin}\,\delta + \mathrm{Cos}\,(\phi - \beta)\,\mathrm{Cos}\,\delta\,.\mathrm{Cos}\,\xi \tag{4.9}$$

The equation (4.9) gives the angle of incidence at any time measured from noon, for a plane facing the equator, tilted β degrees.

Substituting $(\phi - \beta) = \delta$

$$\mathrm{Cos}\, i = \mathrm{Sin}^2\,\delta + \mathrm{Cos}^2\delta\,.\mathrm{Cos}\,\xi \tag{4.10}$$

for the horizontal $\beta = 0 \qquad i = z$

$$\mathrm{Cos}\, z = \mathrm{Sin}\,\phi\,.\mathrm{Sin}\,\delta + \mathrm{Cos}\,\phi\,.\mathrm{Cos}\,\delta\,.\mathrm{Cos}\,\xi \tag{4.11}$$

This gives the zenith angle in terms of Latitude ϕ , Declination δ and the Hour angle ξ .

Whenever exact determinations are needed, one should know the I_{dif} or calculate it from Equation (4.6). If this is not available, then Equation (4.8) provides values accurate enough for the current optimization studies.

A computer programme has been written and presented in detail in Appendix 2-c, in which the total solar radiation intensity on the plane tilted towards the equator is calculated. Although, for the maximum energy collection, the tilt must be adjusted every day, it would also be possible to limit the adjustment to once per month at the cost of a small reduction in performance. The programme has been set to consider monthly adjustments for the declination to maintain normal incidence at noon.

To be able to calculate the radiation intensity on the tilted collector plane, it is necessary to know the horizontal total and/or total + diffuse measurements for every hour of the year. Unfortunately, this kind of extensive information is not available for many localities. Instead, daily totals are reported in most of the publications. In cases where daily total horizontal measurements are available, the computer programme outlined in Appendix 2c can be run to obtain the hourly distribution of the daily total horizontal solar radiation. The method based on curves developed by A. Whillier[78] is adapted for use in latitudes between 35^{o}N and 35^{o}S. The radiation intensity on the inclined collector plane can be obtained by applying the previously described technique.

IV.3. Influence of the Radiation Intensity on the Performance of the Flat Plate Collector

The flat plate collector performance is represented by equation (3.31), derived and discussed previously. The effect of increased radiant flux using mirror boosters has been considered in Chapter III.1.4. For moderate temperatures the mirror booster proves to be a significant factor in reducing the cost. It should yield a better optimum for the solar power plant employing flat plate collectors, after a careful design analysis considering the cost of the mirror system as well as increased maintenance costs.

In this chapter the variation of radiation intensity will be examined from a different point of view. Instead of treating the radiation intensity, I, as a parameter and testing various designs for an optimum solution, the performance variation of a fixed combination of components, optimized for a given temperature and averaged radiation intensity, will be considered.

IV.4. Demand for Power

IV.4.1 Demand always equal to the supply

The first stage solution will be based upon fixed boiler and condenser temperatures. At a later stage various boiler temperatures will be tested in search of a better optimum. The condenser temperature will be assumed as invariant, due to its relative unimportance, which was previously emphasized in Chapter III.1.

The following sequence of formulation and solution applies to the Fortran Programme No. 1 presented in Appendix 2b.

Step 1. Set a boiler temperature within the feasible region which was obtained from the steady state analysis. Recalling the relation giving the useful heat collected per unit area which is, for the boiler operating at constant temperature

$$q_u = F_{rb} \left[I\tau\alpha - U_{lc} (t_l - t_a) \right] \quad (4.12)$$

below the Critical Radiation intensity,

$$q_u = 0, \; F_{rb} \neq 0$$

therefore:

$$I\tau\alpha - U_{lc} (t_l - t_a) = 0 \quad (4.13)$$

$$I_{crt} = 1.05 \frac{U_{lc} (t_l - t_a)}{\tau\alpha} \quad (4.14)$$

Realizing that at least some useful conversion, say 5%, be necessary to justify the operation of the solar power plant, a factor of 1.05 has been used.

Equation 4.14 gives the critical intensity in terms of boiler temperature since the other parameters are invariant for a given design.

The collection should be attempted for those days during which

$$I < I_{crt}$$

Step 2. The amount of heat which can be collected is

$$\sum_{1}^{n} q_u = F_{rb} \sum_{1}^{n} \left[I \tau\alpha - U_{1c} \, (t_1 - t_a) \right] \tag{4.15}$$

But

$$U_{1c} \, (t_1 - t_a) = I_{crt} \tag{4.16}$$

Substituting from (4.16) into (4.15)

$$\sum_{1}^{n} q_u = F_{rb} \sum_{1}^{n} (I - I_{crt}) \tag{4.17}$$

Adding only those intensities $I > I_{crt}$ for (n) days the average amount of heat collectable is given by

$$\frac{1}{n} \sum_{1}^{n} q_u = F_{rb} \frac{1}{n} \sum_{1}^{n} (I - I_{crt})^{+} \tag{4.18}$$

Dividing and multiplying RHS by I_{av} , this gives

$$\frac{1}{n} \sum_{1}^{n} q_u = F_{rb} \, I_{av} \frac{1}{n} \sum_{1}^{n} \left(\frac{I - I_{crt}}{I_{av}}\right)^{+} \tag{4.19}$$

The Utilizability factor is given by:

$$\phi = \frac{1}{n}\sum_{I}^{n} \frac{I - I_{crt}}{I_{av}} \tag{4.20}$$

Thus

$$q_{u\ aver} = F_{rb} \cdot I_{av}\, \tau\alpha\phi \tag{4.21}$$

The usual procedure as applied by Whillier(79) has been to plot the frequency distribution of solar radiation and obtain ϕ vs (I/I_{av}) curves for a given locality.

In this research a more direct approach will be utilized taking advantage of the powerful computational capabilities of modern digital computers.

Step 3. The yearly average of the solar radiation will be obtained by summing up I (i,j,k) for those hours during which $I\ (i,j,k) > I_{crt}$ or $[I\ (i,j,k) - I_{crt}]^+$ and dividing the result by the total number of sunshine hours.

$$q_{tot} = \sum_{i=1}^{12} \sum_{j=1}^{31} \sum_{-\xi}^{+\xi} I\ (i,j,k) \tag{4.22}$$

$$q_{av.year} = \frac{\sum_{i=1}^{12} \sum_{j=1}^{31} \sum_{-\xi}^{+\xi} I\ (i,j,k)}{\sum (i,j,k)} \tag{4.23}$$

where

$\sum (i,j,k)$ = total sunshine hours

It must be noted that the total number of hours is always less than (i.j.k).

Step 4. Since the collector area of the solar power plant will be constant, it is most reasonable to assume the area to correspond to the average radiation intensity for the year. Since a programme has been developed to optimize the solar power plant with flat plate collector operating under constant radiation intensity. This programme should be utilized to obtain an area and a cost per kw hr figure.

Step 5. The next step is to obtain the actual amount of work produced by calculating the exact amount of work produced during each hour and summing up throughout the year. This would allow one to obtain a more reliable cost figure than in the previous step.

$$Q_{tot.year} = \sum_{i=1}^{12} \sum_{j=1}^{31} \sum_{k=-\xi}^{+\xi} I\,(i,j,k)\ A.\ \eta\,(i,j,k) \tag{4.24}$$

where

$\eta(i,j,k)$ is the hourly efficiency for constant boiler and condenser temperatures.

$$W_{tot.year} = \frac{Q_{tot.year}}{3413} \tag{4.25}$$

Step 6. Since the frequency distribution of the solar radiation is not usually a straight line, the numbers of days during which the intensity is above and below the average are not equal. It may happen that the area based on the yearly average does not in fact yield the maximum collection and minimum power cost. Therefore, various areas must be tested. Seventy-five per cent and 125 per cent of the original areas were also used in the analysis by repeating steps 4 and 5 for each area. It is to be noted, however, that the power production at any instant and in any area must remain below the rated power; e.g., if the power produced is greater than the rating, the excess will be wasted. In computer programming, the hourly work was calculated for the given area and radiation intensity. If this figure turned out to be greater than the rated power, the output was equated to the maximum rated power. This allows one to choose a more correct collecting surface than the surface based on the average radiation.

Step 7. Different boiler temperatures may be tested repeating steps 1 to 6 for values around the feasible optimum predicted.

The Fortran programme No. 1 presented in Appendix 2-c has been run and the following results presented in Table 6 have been obtained. It must be noted that this survey is valid only for the given radiant flux input and the cost figures. One of the important conclusions reached from the computer analysis is that, if an area which is greater than the average is used, the effective operational period is extended. One has to decide on a separate basis the total amount to be invested as well as the sacrifice of production for some overcast periods. If the total investment allocated is limited and some interruption in power supplies is justified, then collector areas may be reduced.

IV.4.2 Time-Dependent Power Demand

In the most general case of solar power production both the power consumption and the radiant flux vary with time. This case also represents most closely the actual performance of a solar power plant in the field.

The pattern of power consumption depends, of course, upon the pattern of use. A typical pattern ψ(i,j,k), is presented in Figure 11). Though this specific pattern has been employed in the computer analysis, the Fortran programme is arranged to accept any conceivable pattern which might be encountered in different localities and climatic regimes as well as types of use. In this representation indices i,j,k represent month, day, and hour, respectively. Figure 12. graphically illustrates the variation of power demanded, consumption and the storage for a week's period. Two and one half days of initial storage and a maximum of two overcast days were assumed.

The unsteady state analysis is carried out as described below:

1. The consumption function, $P(i,j,k)$ is defined for the whole year from the previously defined consumption pattern. $\psi(i,j,k)$ can be obtained from

   $$P(i,j,k) = \psi(i,j,k).Kw$$

   For the sake of simplicity the consumption pattern is assumed to be the same for every day of the year. This reduces $\psi(i,j,k)$ to $\psi(k)$ and

   $$P(i,j,k) = \psi(k).Kw$$

2. The production of power is obtained for a constant collector area which is calculated on the basis outlined in the "no storage" analysis which was described in the previous section. The power produced at any instant can be calculated by multiplying the incident solar radiation by the over-all conversion efficiency from solar radiation to shaft horsepower output of the turbine.

It is obvious that the power produced will be zero all the time when $I(i,j,k) < I_{crt}$. Yet its value, even if it is zero, must be calculated for every hour of the year to enable the energy excess or deficit to be calculated, since there is some consumption every hour even though there is no production.

3. In order that the power plant may operate, it is assumed that a storage material is available within a reasonable price range which can be utilized in storing and recovering energy at the constant boiler temperature.

The similarity between the trends of the power demand and the solar radiation supply curves indicates that the greater portion of the power is consumed whenever the solar radiation intensity is at its peak. This, of course, reduces the need of extra storage. However, an initial storage is assumed to overcome the deficit in the supply during the overcast days.

This minimum reserve capacity, which is a climatological factor, has to be carefully determined, other wise there might either be a lack of supply of power or the cost of the power produced would be higher than it need be due to excessive investment in the storage system. This is contrary to the main aim of the analysis which is to minimize the cost of the power produced. Since hourly net production was W(i,j,k), and hourly net consumption was P(i,j,k), the difference gives the excess power produced, if it is a positive quantity; or deficit in supply, if the difference is a negative quantity.

$$\Delta = W(i,j,k) - P(i,j,k)$$

If Δ is converted into energy units and added to the initial stored energy, it yields the remaining stored heat, Q_{stor} (i,j,k), at any hour. $Q_{stor}(i,j,k) = Q_{initial} + (W(i,j,k) - P(i,j,k))$.

The system keeps on running as long as the remaining stored energy is positive or in other words the temperature of the storage medium remains at/or above the minimum acceptable level. A fusion process is needed to store and recover the energy at constant temperature. As soon as more energy than the stored is extracted, the temperature of the storage medium will start dropping. Also the sensible heat (also called Liquid Enthalpy, h_f) will be recovered which is only a small fraction of the latent heat (also called Fusion Enthalpy) per lb_m of the material.

The power production is stopped as soon as the initial storage is exhausted. No power will then be supplied until the production exceeds the consumption. As it has been noted, the period of interruption permitted, although a factor related to the sunshine availability of the location is really the decisive factor. It may on one hand increase the cost to an undesirably high level, or on the other, reduce it and make it feasible. In order to guarantee the supply, the storage capacity should be larger. This important aspect needs special consideration for every locality with different climatic regimes. The next step in the unsteady analysis would be to test the following in search of a better optimum:

a. Different collector areas, say 75 per cent, 125 per cent, 150 per cent and 200 per cent, of the average area as well as 100 per cent, the rated area based on the average yearly radiation.

b. Different boiler temperatures.

c. Different initial storage capacities.

Some numerical results obtained through the computer programme No. 2 for a set of assumptions are tabulated in Table 7.

IV.4.3 Time-Independent Power Demand

When the power demand curve defined in Section IV.4.2 is a straight horizontal line, in other words, when KW is constant, the same method of analysis as in the variable power demand case, can still be employed. The elements of the consumption matrix must all be equal to the rated power.

$$P(i,j,k) = \text{Rating for all } i,j,k.$$

It is obvious that even for a locality with a maximum sunshine possibility, excessive storage capacity will be required, because of the continuous demand during the night hours as well as in the daytime.

The computer programme No. 2 devised for the Unsteady state, with variable demand performance analysis with storage yielded cost figures greater than 50 cents/kwhr. In the case of constant power demand, the cost of the power produced will be in excess of the above amount. Since the exact cost figures could easily be verified running programme No. 2 with $\psi(k) = 1$ for $k = 1, 2, \ldots n$, further detailed study of the constant power consumption has been omitted.

V. STORAGE OF THERMAL ENERGY

V.1 Criteria for Storage Requirements

The need for storing energy has already been outlined and methods of calculation of its quantity have been described, in section IV.4. In that chapter, an arbitrary power consumption pattern was assumed and the storage capacity needed to supply this demand was calculated. This way of tackling the problem although mathematically viable, does not answer all the possible arguments which may arise.

The objective of the research is to find optimum solutions to various alternative proposals for producing cheap mechanical power from solar radiation. Thus it would be unreasonable to start by making a decision to install a solar power plant in any locality first and then after that to optimize the design features and operating conditions. Rather one should start with an investigation of the possibilities of installing such a plant in a given locality. The requirement should first be satisfied and then if the preliminary survey shows promise, further optimization methods described for various systems of solar power production should be analyzed with regard to the specified conditions and the given locality.

The following are therefore the basic criteria in deciding whether to install solar power plants or use conventional supplies.

a. The availability of solar radiation.

b. The required minimum sunshine hours or minimum radiation intensity which should be available. These, however, do not indicate by themselves that there will be an optimum. The cost figures of materials, workmanship and interest rates on the capital invested, which vary from locality to locality, must be taken into account.

c. The other alternatives available in power supplies must be well examined before proposing a solar power system. Comparative studies of solar power production have been treated in numerous articles and books.[80,81,82] Most of these references usually compare solar and conventional power supplies and end up with some conclusions indicating the advantages and promises of solar power schemes. Since the present study as a whole covers all conceivable methods of solar power production, it allows one to obtain a dependable cost figure per Kw hr produced, provided that accurate radiation and cost data are supplied.

Cost figures of other alternative power supplies such as Diesel engines and small sized steam boiler engine (or turbine) assemblies are commercially available in almost any country. Diesel engines, particularly, are extensively used for small scale power needs such as irrigation and electrical projects in small villages. There should be enough evidence to justify changing already established systems in favour of solar power. It is necessary to have assurance of a cheap and dependable supply.

Once the decision has been made to install a solar plant, the former being justified by both the sunshine regime and the excessive costs of alternative power sources, one comes to the important question of whether to install a storage system or not.

It has already been demonstrated that, in the case of the installation including a storage system, especially in those places where the overcast periods exceed 2 1/2 days, the cost of power produced becomes more than 50 cents per Kw hr. Since the interruption in the radiant supply cannot be predicted exactly, it is not possible to assure fully that the solar plant will supply the demand. It would be wiser to discontinue the operation if the interruption is longer than a predetermined period. The extent of this period is best determined by the climatic regime and the specific requirements of the consumer. With regard to applications, such as in the case of unattended pumping stations, where the total amount pumped is of greater importance than actual pumping time, such a lack of continuity would be justified. The demand function which is proportional to the radiant supply due to the increased irrigation requirements in sunny periods even eliminates the heat storage system. This may well be replaced with a storage tank or pool which stores the pumped water. It must be noted, however, that the energy storage allows the system to operate at higher efficiencies and maintains smoother operation, especially for those localities having bright periods intermingled with frequent cloudy periods, as is experienced in the tropics.

Therefore, additional engineering analysis of solar power supply systems in the light of the methods described is necessary with regard to a specific locality, to determine whether the use of a storage system is necessary or not. Further treatment of the subject from a design point of view is beyond the scope of this study.

V.2 Discussions on the Storage of Energy at High Temperatures

The storage of energy at the optimum boiler temperature for a solar power plant is essential as long as a continuous supply to satisfy any demand pattern is desired. Storage methods are usually grouped under two main categories: (1) Sensible heat storage (Enthalpy Storage); and (2) Latent heat storage (Fusion Enthalpy Storage).

(1) Sensible heat storage has been attempted especially for space heating purposes and proved to be effective in the case of low temperature applications.[83, 84] This has been achieved through storage of hot water[85] or by storing energy by means of hot air heating rock piles from which the energy is recuperated by a counter flow of air.[86]

Whenever the storage of energy at high temperatures is required for production of steam above 200°F maintained over long periods, then enthalpy storage creates many problems. The permissible temperature drop has to be kept small enough to secure efficient operation of the turbine. The transfer of heat from the rock piles to the working fluid gives rise to many difficulties. The storage of energy in the soil or in the sea at high temperatures and recovery for future use still remain as proposals and no concrete solution has been found to date.

Compressed water, at temperatures higher than the boiler temperatures, which is flashed into steam, has been proposed as an alternative method of thermal enthalpy storage.[87] The computer results for unsteady state operation without storage yield costs of around 27 cents per Kw hr for Alice Springs, which has high average radiation intensities. Any additional investment in the storage system contributes to increase the cost of the complete installation. Since the principle of flashing steam and the analysis of the Rankine Cycle operating with flashed steam is well known, further derivation of the relations is omitted.

However, it can be well concluded that in addition to the technical problems remaining, such as the construction of large pressurized vessels and their insulation to retain heat for months on end to ensure continuous operation, the economic limitations set by the greatly increased cost figures inhibit further consideration of enthalpy storage.

(2) Latent heat storage. The unique feature of materials with congruent melting points is that the energy can be stored and recovered at a constant temperature, thus facilitating the efficient operation of a solar power plant. The reduction in the amount of heat added to the working substance may result in increased wetness-of steam even though the steam may be at the saturation temperature. Excess moisture in the exhaust steam, therefore, causes blade erosion. Latent heat storage allows the maintenance of a constant temperature difference between the working substance and the storage medium. This maximizes the effectiveness of the Heat Exchanger and reduces the increase in unavailable energy.

Some cheap storage materials are available, such as Glauber Salt - $Na_2SO_4 \cdot 10\ H_2O$ - which has a melting point of 90^oF and 1 lb_m of it can store 104 Btu's of energy. Both Glauber Salt and many other storage materials suggested for house heating purposes[88, 89] have fusion temperatures below 140^oF, which is still lower than the temperature recommended by the steady state optimization analysis. Some crystalline salts have been examined as energy storage materials for space heating purposes by Whillier.[79] $Na_2HPO_4 \cdot 12\ H_2O$ Disodium phosphate dodecahydrate did not prove to be a suitable material for repeated cyclic fusion and solidification, since stratification occurred due to separation into two other hydrates - $Na_2HPO_4 \cdot 7\ H_2O$ and $Na_2HPO_4 \cdot 2\ H_2O$. Glauber salt also exhibited insufficient dissolving of the anhydrous Na_2SO_4 in the saturated solution in the absence of perfect mechanical mixing. In addition to the above disadvantages, other known fusion salts have low melting points. Other fusion salts originally developed for the constant temperature storage and transportation of delicate instruments, patented by Melpar Inc. under the trade mark "Transit-Heet," exhibit interesting physical properties. A series of substances having fusion temperatures up to 300^oF have been reported.[90]

The composition of the materials has not been disclosed as they are still protected by patents. However, it is certain that such materials are available. The fusion heat storage system requires a container which also acts as the heat exchanger from the fluid heated in the collector to molten salt and from molten salt to the working substance. The transient heat transfer analysis of the exchanger has not been possible since exact physical properties have not yet been reported. However, an analysis based on the approximate properties(91) is presented below.

The heat storage material can be supplied for a temperature range of 150^{o}-$250^{o}F$ which is acceptable for flat plate collectors. For cheaper material costing 5 cents per pound and a storage capacity of 150 Btu per pound, the cost is estimated at about $5.00 per cubic foot of storage volume. The combined cost of the heat storage material, the heat exchanger including the filling and sealing expenses, is predicted to be at least $1.00 per 1000 Btu of stored energy. Additional insulation costs and controls required would, however, raise this figure. Allowing 50 per cent for these items, a total of $1.50 per 1000 Btu can be expected. A plant rated at 12 Kw at full capacity is expected to produce in accordance with the pattern of Figure 11

$$\sum_{k=1}^{24} \psi(k).Kw = 8 \times 12 = 96 \text{ Kw hr/day} \qquad (5.1)$$

For a boiler temperature of $240^{o}F$ and condenser temperature of 95^{o}F the Rankine Cycle efficiency would become 19.4 per cent

If η_t = 0.60 and η_m = 0.95

$$\eta_s = 0.194(0.60)(0.95) = 0.11$$

The amount of heat to be stored then would be

$$Q_{stor} = (96/0.11) \quad 3413$$

$$= 3{,}000{,}000 \text{ Btu/day}$$

The additional expenses together with the above assumed cost figure of $1.5/1000 Btu, would eventually become (3,000,000/1000)1.5, i.e., $4500 more. The storage of heat for two and a half days of demand would need $11250, which is the same order of magnitude as the cost of the flat plate collector system.

In fact, in the unsteady state analysis made using the computer programme No. 2, it has been found that even storage of heat for 2 1/2 days is not sufficient for continuous operation for Alice Springs, which was chosen as a typical locality. The collection area was taken to be twice as much, i.e., 200 per cent of the area based on the yearly average radiation. This reduces the amount of initial storage needed to maintain continuous operation but increases the investment needed for the collectors. Although the cost of power produced is reduced from 150 cents per Kw hr to 50 cents, it is still too high to justify any attempt to introduce storage systems.

This figure is far beyond that of the cost of power using alternative sources. The highest cost known to the author is that of the small town diesel powered electric supplies being 7.5 cents, which, however, assures 24 hours of dependable supply.

Therefore, in the context of the present cost figures and lack of experimental evidence, the use of the fusion process would still be premature. However, it is quite probable that further developments in the technique of more economical heat storage may lead to the project being more viable.

VI. FORMULATION AND SOLUTION

VI.1 Fortran Programming and Solution of Models

The optimization studies covered by this research did not yield a single mathematical model with an objective function and a number of constraining relations. This solution would allow one to obtain a single point. In other words, there is no single set of values which can be regarded as the answer to the optimization problem. Since the present study aims at treating a number of different systems such as the flat plate collector - turbine - condenser combination, for various design parameters of the collector, such as selective surfaces, honeycomb structures, or for different working substances; or concentrating type collectors, Stirling and Brayton Cycles, it is not possible to arrange for a single model. Therefore, the Fortran programming had to be carried out in different steps.

Basically, the programming was applied to both the steady and unsteady cases. The basis of the analyses and the Fortran programmes have already been referred to in the chapters concerned. The following is a list of those programmes and describes their features:

VI.1.1 Steady State Analysis

The steady state analysis was applied to models listed below:

A. Flat plate - steam Rankine - Turbine Condenser

A.1 Same as above only selective surfaces used

A.2 " " " " an ideal glass Honeycomb structure was laid over the selective absorber plate

A.3 Same as above only an actual plastic honeycomb structure was laid over the absorber plate

A.4 Same as above only mirror booster and selective surfaces

Three solution methods proposed are described below. Reference was made to the specific method used for the various models in the related chapter.

In determining the optimum point of design one of the following methods can be used.

a. Exhaustive enumeration

b. Mapping

c. Steepest descent

These methods are outlined in Appendix 4. Out of these 3 methods, the exhaustive enumeration was employed as the first survey on the subject. As long as the range of variation of variables and number of trials are small, this method is acceptable, otherwise the evaluation of results becomes too tedious. On the other hand a direct optimization technique such as the steepest descent is started at a feasible point and independent variables are changed in appropriate steps to reach the optimum. This method, however, is not suitable for functions like Rosenbrock's[92] and others[93] which have steep valleys. Iteration may start shooting around optimum and computation time may be too lengthy. Many other methods are available which converge much faster. Some of them are in ready access in McGill Computer Centre's SSP (Scientific Subroutine Package) programmes such as Fletcher and Powell method "Subroutine FMFP," conjugate gradients "Subroutine FMCG."

The use of built-in library programmes of the computers eliminates writing a separate programme and rather a main programme which calls the Subroutine FMFP or FMCG would readily allow one to reach the minimum cost figure.

However, even a rapidly converging programme enabling one to locate the minimum, would not still give much idea about the region in neighbourhood of the optimum which is of interest to us. The solar plant as outlined in fine detail in previous chapters, operates under varying radiation intensity and therefore a steady state analysis although yielding a single optimum does not represent the actual performance. For these reasons, the direct search techniques, though powerful, are not found to be illustrative.

Instead, a two-dimensional mapping which is explained in Appendix 4b was preferred to other methods, since this allows one to examine the neighbourhood of the optimum and gives a better idea of what happens if the optimum operation conditions are not satisfied. Also, some discontinuities such as change of the number of collector glass plates at definite prefixed temperatures, can be better treated. Discontinuities in the Direct Search Techniques might create irrelevant results, therefore it may be necessary to add further constraint relations for such a discontinuity or to confine the search to more restricted regions.

VI.1.2 Unsteady State Analysis

A. Main Programmes. The analysis was applied to the unsteady state performance without storage and the unsteady state analysis with variable power demand and storage. The formulation of both analyses was explained in detail in chapter IV

B. A subprogramme was prepared to calculate the radiation intensities required in the main programmes. A year's radiation data for a horizontal plane at hourly intervals during an 8-hour period, i.e., $\pm$ 4 hours around noon were fed through punched cards. The programme calculated the radiation intensity on the tilted collector plane for a year's period and produced a deck of punched cards which were later used as data cards for the main programme. Similarly, the average radiation for every month, the yearly total and the yearly average radiation intensities were also calculated and obtained as punched cards. Although two programmes might be combined in one where both the radiation intensity calculations on the inclined collector plane and optimization of the solar power plant can be covered within the same programme, the work was split into two, since the memory requirements had exceeded the installed capacity of the McGill Computer Centre's 360-75 computer which has 330 K Dynamic Cores. It was thus possible to execute it in this way.

VII DISCUSSION AND CONCLUSIONS

This chapter is devoted to the extension of the analysis presented in the earlier sections of the thesis and to the presentation of conclusions based upon the numerical results obtained. The discussion has been divided into two parts, the first relating to the steady state analysis and the second to the performance of a system under varying radiation input. This is in order to facilitate a comparison between the various systems, outlining the advantages of each proposal as well as its drawbacks. Consideration is then given to the determination of the actual power output in the context of the most promising combination, from which eventually an accurate cost figure is obtained.

Steady State Analysis - the Flat Plate Collector

The heat transfer relations describing the performance of the ordinary flat plate collector are the most accurate of the several assemblies studied. The numerical results indicate that the ordinary black-painted collector is inferior to the collector with a selective coating. The optimum design and operating condition for the collector with the selectively coated absorber plate depends upon the insolation rate. Although the steady state analysis has been applied to a large range of radiation inputs, extending from 180 Btu/hr ft^2 to 330 Btu/hr ft^2, cost figures corresponding to the higher rates are unlikely to be of practical importance due to the rarity of their occurrence under natural conditions. In Chapter IV.1 the radiation availability at various localities was discussed. A sample was presented for Alice Springs in Australia which averages the high insolation rate of 214 Btu/hr ft^2 with a reasonably uniform seasonal distribution. The period for which this average is computed is that during which the radiation intensity on the collector plane remained above the critical value, i.e., 139 Btu/hr ft^2. This duration was found to be 1770 hours. The average radiation intensity of 214 Btu/hr ft^2 during this period was far lower than the high rate of 330 Btu/hr ft^2, i.e., the maximum considered in the computer analysis.

The comparison of cost figures was therefore based on a radiation intensity of 220 Btu/hr ft^2. However, within the range between 180 and 230 Btu/hr ft^2 commonly encountered in practise, the numerical value of the radiation intensity is not significant, whenever all of the systems are compared for the same radiation intensity. The condenser temperature was also kept invariant owing to the reasons stated in the related chapter.

The flat plate collector with three glass covers and ordinary black paint yielded a cost figure of 46 cents/kw hr, for an average radiation intensity of 220 Btu/hr ft^2, a condenser temperature of 95°F, and a duration of 2400 hours/year.

Material cost figures and other assumptions concerning the operation are tabulated together with the list of physical properties in Appendix 2a.

The selective black painted flat-plate collector with two glass covers is an improvement on the simple flat plate collector discussed above. The cost figure for this combination was reduced to 40 cents/kw hr for a radiation intensity of 220 Btu/hr ft^2. This figure, however, is still too high to be accepted for practical application.

The flat plate collector with glass honeycombs and selective surface yielded a cost as low as 27 cents for an insolation rate of 220 Btu/hr ft^2. The cost of the honeycomb pane had to be assumed at $1/ft^2 since no such structures are commercially available.

The flat plate collector with plastic honeycombs and black painted surface, as developed and tested in the University of Marseilles, gave a cost figure of 50 cents/ft^2 at an average intensity of 220 Btu/hr ft^2.

Although collectors incorporating plastic honeycombs are much more expensive than those with glass honeycombs when operating at radiation intensities of 220 Btu/hr ft^2, they compare favourably with the latter at high intensities. For example, at a radiation intensity of 300 Btu/hr ft^2 plastic honeycombs yielded a cost of 14 cents/kw hr as compared with 15 cents/kw hr for glass honeycombs.

The flat plate collector equipped with a plastic honeycomb is more sensitive to changes in radiation intensity than the collector with the glass honeycomb. The reduced direct transmission at increased angles of incidence, corresponding to lower radiation intensities, may be responsible for the increased losses in the case of the plastic honeycombs. This comparison, however, cannot be considered fair until experimental evidence on the performance of the selective absorber - glass honeycomb system is available. This should not preclude the fact that honeycombs, both glass and plastic, deserve more careful attention since considerable reductions in the cost of the power produced are possible. Further development of honeycomb manufacturing techniques and reduction in cost as well as a better understanding of honeycomb performance are therefore essential. This aspect, which may demonstrate a breakthrough in solar radiation technique, is recommended for future investigation.

The flat plate collector with selective surfaces and mirror boosters yielded the lowest cost within the range of radiation intensities considered. A transposable mirror system on the East or West side of the collector, while doubling the average radiation intensity, with a mirror panel costing about $\$1/ft^2$, reduces the cost of the power produced to 14 cents/kw hr. In calculating this cost, additional operating expenses were not considered on the presumption that the mirrors would only have to be adjusted once per day. If there were no adjustments, the shadows cast in the morning or afternoon would reduce the output. The maintenance of high reflectivity of the mirror surfaces throughout their lifetime and protection against wind, hailstones and other natural hazards, are some engineering problems still to be considered.

The optimum cost figures obtained throughout the steady state analyses are summarized and plotted against the radiation intensity for various flat plate collectors in Figure 13 to facilitate their intercomparison. The optimum operating temperatures are not indicated since these are not of primary concern, the objective being to obtain the minimum cost regardless of the temperature. If lower boiler temperatures are used, boiler pressures will be correspondingly lower. In the case of ordinary black collectors, pressures below atmospheric are required to operate the system most economically. This creates many practical problems on the operational level, as well as necessitating the use of additional costly vacuum pumps.

By using honeycomb cells, the temperature can be raised above 212^{o}F which would eliminate the need for a vacuum pump.

The use of both honeycombs and mirror booster panels to increase the collector efficiency is an interesting combination deserving further study. Since exact relations describing the performance of such a system are not available, its analysis is not included in this optimization study. Noting the problems involved in operating honeycombs, especially plastic ones, at high temperatures, and the difficulties of mirror panel operations, one cannot immediately conclude that the honeycomb and mirror booster combination would be practical to use.

After solutions to these practical problems are obtained, the use of honeycomb + mirror boosters should be the most promising approach. They are, therefore, recommended for future investigation. The material and workmanship cost figures and radiation data were taken from Australian sources. The cost of the power produced was based on these data. The collector cost, which is the basic item in the system's cost, was \$5.5/ft^2. On the other hand, the collector cost in France is only \$2.5/ft^2 as noted in Reference (49). Although this reduction in the collector cost should influence the final cost per kw hr, it does not affect the cost of the various designs of collectors incorporating honeycombs, selective surfaces, mirror boosters, etc., relative to each other. Therefore, reported cost figures for various flat plate collectors are typical values for an appropriate location, but not necessarily the best obtainable in the world.

Radiation availability is another important factor influencing the cost of the power produced. The typical location selected for the example presented was Alice Springs in Australia. The total sunshine hours available in the selected locality together with the cost figures of material, are the decisive factors in selecting the appropriate power plant. Unless the final cost turns out to be less than that using alternative power sources, no immediate attempt to apply solar power in practice should be expected. Therefore, places enjoying the highest number of sunshine hours will not necessarily be associated with the lowest power costs since many components of the power plant may have to be imported from industrialized countries, and therefore suffer from inflated material prices, heavy transportation costs and import duties.

The methods outlined in this thesis are applicable to any locality and sample computer programmes are easily adaptable to any situation currently envisaged.

Concentrating Type Collectors. The most promising development, which is outlined in Chapter III.2 - the "Francia" system, incorporating a suntracking field of mirrors and honeycomb cell absorber, was calculated to yield a cost of 7.1 cents/kw hr. This figure was based upon the cost of the boiler plant as predicted by Francia himself, the remaining cost figures being appropriate to Australian conditions as for the flat plate collectors. The major item was found to be the expense of maintaining a full-time operator, the cost of which may vary widely from one location to another. Owing to the extreme influence of operation cost on the cost of the power produced, it is recommended that special attention be paid to this factor. Cost predictions for the mirrors, control mechanism, and the boiler (receiver) have not yet been realized in practice. Unless large-scale production can be achieved, the assumed prices are likely to be unduly optimistic. Since some development is underway in the Francia design, certain technical and commercial details have not been disclosed, due to the requirements of the sponsors. It is therefore too early to reach a final conclusion on this design. Nevertheless, this system shows the greatest promise of all the combinations considered for application in locations subject to high intensities of solar radiation with a large direct solar radiation component. This system does not have good prospects in the tropics where diffuse radiation comprises a substantial proportion of the global solar radiation.

Unsteady State Analysis

Since the steady state analysis of the performance of solar power plants has indicated that the honeycomb and selective surface combination yields the lowest cost, and the honeycomb + mirror booster combination was not considered in this section due to reasons already outlined, the unsteady state analysis without storage was carried out for the flat plate collector with honeycombs and selective surface absorber only. The cost figure per kw hr produced is in close agreement with the result from the steady state analysis which was reported as 27 cents. This cost is very little influenced by the area employed since both the output and the total cost are proportional to the area. This fact has been presented in Figure 14. The resulting figure is too high for any immediate application. However, honeycombs with mirror boosters should reduce this cost to a figure even lower than 16 cents/kw hr, the figure which was reported as a result of the steady state analysis for collector with selective surfaces and mirror boosters, but without honeycombs. This unsteady state analysis, however, may be used to yield accurate cost figures for any specific locality rather than to compare two different systems.

The unsteady state analysis with storage verifies the fact demonstrated in Chapter V which concluded with the high costs of storage of thermal energy for future use. The cost figure was searched first without any maximum power limitations, which implies larger amounts of power could be produced and consumed. This case yielded cost figures descending even after 300 per cent of the rated area was used. Since the turbine has to be designed to operate at the rated power and the power which cannot be consumed is effectively wasted, this case is not representative.

The second case limiting the maximum power to the nominal rating, i.e., 12 kw, yielded a cost figure of 53 cents/kw hr. Therefore, a large increase of the collector area to reduce the initial storage required and to make up the deficit in overcast periods (and at night) is not a feasible solution since large storage capacities and larger collector areas are both items increasing the cost of the power produced.

Economical power production with storage still requires further developments in the storage materials as outlined in Chapter V. Even the cost obtained for a case without any storage is not competitive with conventional energy sources. Therefore, it is recommended that initial attempts to produce solar power should exclude storage owing to the high cost figures and complications in the system resulting from the addition of an extra heat exchanger and necessary circulation of the secondary fluid.

In conclusion it must be emphasized that the current research is intended to serve as a foundation stone, upon which further research and development may be built. All the analyses have either comprised investigations into the interrelationships between the various parameters influencing performance or systems analyses of individual components. With the exception of the flat plate collector analysis, which was made in considerable detail, none of the individual components was made the subject of specific studies in order to achieve the optimum in individual efficiency and performance. Instead, the effect of feasible margins of improvement in the individual components upon the economics of the integrated power plant have been investigated. Methods of analysis have been developed from which further verification of the cost of the power produced can be extended to any locality for both systems with and without storage.

Although the projected improvements which have been suggested may take a considerable period to be realized in practice, there are no reasons why solar power plants should not become competitive with alternative methods of small-scale power production in localities where they enjoy special geographical or environmental advantages. The two configurations showing the most promise are the concentrating type with sun tracking field of mirrors and the flat plate collector incorporating honeycombs and mirror boosters.

Further engineering analysis should be useful in reducing the cost of the manufacture of individual components. Furthermore, a national or international policy decision to embark upon quantity production would place solar power in a much more favourable competitive position relative to alternative methods.

LIST OF REFERENCES

1. Jordan, Richard C., Ibele, Warren E. Mechanical Energy from Solar Energy. Proceedings World Symposium on Applied Solar Energy, Phoenix, 1955, pp. 81-101.

2. Adkisson, W. B., Dietrich, J. P. Solar Energy Conversion System for Apollo Telescope Mount. Proceedings Solar Energy Society Annual Meeting, 1968, Palo Alto, California.

3. Anon. Solar Power Generator at Rome, The Sun at Work. Third quarter, 1961, pp. 9.

4. Baum, V. A., Aparasi, R. R., Garf, B. A. High Power Solar Installations. Jnl. Solar Energy, Vol. 1, No. 1, 1957, pp. 6-12.

5. Anon. All Union Conference on the Utilization of Solar Energy. Applied Solar Energy (English Translation of Geliotekhnika), Vol. 1, No. 6, Nov.-Dec., 1965, pp. 37-40.

6. Bulletin d'Information, Université d'Alger, Institut de l'Energie Solaire, No. 6, Mar. 1962.

7. Masson, H., Girardier, J. P. Solar Motors with Flat Plate Collectors. Jnl. Solar Energy, Vol. 10, No. 4, 1966, pp. 165-169.

8. Ward, G. T. Possibilities for the Utilization of Solar Energy in Underdeveloped Rural Areas. FAO, Informal Working Bulletin 16, Rome, 1960, pp. 46-47.

9. Francia, G. Installation Pilotes pour Centrales Solaires. Comples Bulletin 14, July 1968, pp. 57-73.

10. Bliss, R. W. Jr. The Derivations of Several "Plate-Efficiency Factors" Useful in the Design of Flat-Plate Solar Heat Collectors. Jnl. Solar Energy, Vol. 3, No. 4, pp. 55-64.

11. Hottel, H. C., Whillier, A. Evaluation of Flat-Plate Solar Collector Performance, Transactions of the Conference on the Use of Solar Energy: Scientific Basis, II. Part I, Section A, pp. 74-104 (1955).

12. Liu, Y. H., Benjamin, and Jordan, R. C. A Rational Procedure for Predicting the Long-term Average Performance of Flat Plate Solar Energy Collectors, Jnl. Solar Energy, Vol. 7, No. 2, 1963, pp. 53-74.

13. Duffie, J. A., Löf, G. O. G. Focusing Solar Collectors for Power Generation. Sixth World Power Conference, Melbourne, 1962, Paper No. 207 - III 7/5, pp. 1-27.

14. Tabor, H., Zeimer, H. Low Cost Focussing Collector for Solar Power Units. Jnl. Solar Energy, Vol. 6, No. 2, April-June, 1962, pp. 55-59.

15. Liu, Y. H., Jordan, R. C. Performance and Evaluation of Concentrating Solar Collectors for Power Generation. ASME Paper No. 63-WA-114.

16. Tabor, H. Solar Energy Collector Design, with special reference to selective radiation. Trans. of Conf. on the use of Solar Energy, The Scientific Basis, Tucson, Ariz., Oct. 31 - Nov. 1, 1955, Vol. 2, pp. 1-23.

17. Close, D. J. Flat Plate Solar Absorbers: The Production and Testing of a Selective Surface for Copper Absorber Plates. C.S.I.R.O. Engineering Section, Rep. E-D-7, Melbourne, June, 1962.

18. Buchberg, H., Lalude, O., Edwards, K. Performance Characteristics of Rectangular Honeycomb Solar-Thermal Converters. Proceedings Solar Energy Society Annual Meeting, 1968, Palo Alto, Calif.

19. Perrot, M., Desautel, J., Peri, G., Gallet, P., Bouthier, M. Essais d'Utilisation de Cellule Antirayonnantes au chauffage à basse et moyenne temperatures. Comples Bulletin No. 10, pp. 91-97, 1966.

20. Tabor, H., Bronicki, L. Small Turbine for Solar Energy Power Package. United Nations Conference on New Sources of Energy. Rome, 1961, Paper No. E/Conf. 35/5/54.

21. Anon. Technical Proposal for Design and Development of Flight Type Advanced Stirling Engine. Allison Division, General Motors Corporation, April 6, 1959, EDR 1401.

22. Whillier, A. Lecture notes on the Engineering Utilization of Solar Energy; Graduate Diploma Course, Brace Research Institute of McGill University, 1962-1963.

23. Selcuk, M. K. Flat-plate solar collector performance at high temperatures. Jnl. Solar Energy, Vol. 8, No. 2, 1964, pp. 57-62.

24. Hottel, H. C., Woertz, B. B. The performance of flat plate solar heat collectors. Transactions of A.S.M.E. Feb. 1942, pp. 91-104.

25. Tabor, H. Radiation convection and conduction coefficients in solar collectors. Bulletin of Res. Counc. of Israel, Vol. 6c, No. 3, Aug. 1958.

26. Yellott, J. I. Calculation of solar heat gain through single glass. Jnl. Solar Energy, Vol. 7, No. 4, 1963, pp. 167-175.

27. Anon. Glass color filters, Price list CF300. April 1, 1968, Corning Glass Works, Corning, N.Y.

28. Andrassy, S. Solar water heaters. U.N. Conf. on New Sources of Energy. Paper No. E/Conf. 35/S/96. Rome, 1961.

29. Whillier, A. Plastic covers for solar collectors. Jnl. Solar Energy, Vol. 7, No. 3, 1963, pp. 148, 151.

30. Edlin, F., Willauer, D. Plastic Films for solar energy applications. United Nations Conference on New Sources of Energy, Rome 1961, Paper No. E/Conf. 35/15/33.

31. Edwards, D. K., Gier, J. T., Nelson, K. E., Roddick, R. D. Spectral and directional thermal radiation characteristics of selective surfaces for solar collectors. United Nations Conference on New Sources of Energy. Rome 1961, Paper No. E/Conf. 35/S/43.

32. Tabor, H., Harris, J., Weinberger, H., and Boron, B. Further studies on selective black coatings. U.N. Conf. on New Sources of Energy. Paper No. E/Conf. 35/S/46, Rome 1961.

33. Gier, J. T., Dunkle, R. V. Selective Spectral Characteristics as an important factor in the efficiency of solar collectors. Transactions of the Conference on the use of Solar Energy, Vol. 2, 1955, pp. 41-45.

34. Kokoropulos, P., Salam, E., and Daniels, F. Selective radiation coatings, preparation and high temperature stability. Jnl. Solar Energy, Vol. 3, pp. 19-23, 1959.

35. Whillier, A., Saluja, G. Effect of Materials and construction details on the thermal performance of solar water heaters. Jnl. Solar Energy, 9, No. 1, 1965, pp. 21-26.

36. Dunkle, R. V. Private communication. Dec. 16, 1968. C.S.I.R.O., Australia.

37. Moon, P. Proposed standard solar radiation curves for engineering use. J. Franklin Institute, Philadelphia, U.S.A.? Vol. 230, pp. 583-617, 1940.

38. Dunkle, R. V. Thermal radiation tables and applications. A.S.M.E. Paper 53-A-220, 1953.

39. Iqbal, M. Free convection effects inside tubes of flat plate solar collectors. Jnl. Solar energy, Vol. 10, No. 4, 1966, pp. 207-211.

40. Baker, L. H. Film heat-transfer coefficients in solar collector tubes at low Reynolds Numbers. Jnl. Solar Energy, Vol. 11, No. 2, pp. 78-84, 1967.

41. Francia, G. A new collector of solar radiant energy - Theory and experimental verification. United Nations Conference on New Sources of Energy, Rome 1961, Paper No. E/Conf./35/S/71.

42. Hollands, K. G. T. Natural convection in a horizontal layer of air with internal constrains. Ph.D. Thesis McGill University, 1966.

43. Perrot, M., Gallet, G. Structure anti rayonnantes de G. Francia. Comples Bulletin No. 6, 1964, pp. 64-71.

44. Perrot, M., Gallet, P., Peri, G. Ropke, A., Coulet, M. Realisation et étude pratique de different types de structures cellulaires anti rayonnants. Comples Bulletin No. 10, 1966, pp. 83-89.

45. Hollands, K. G. T. Honeycomb devices in flat plate solar collectors. Jnl. Solar Energy, Vol. 9, No. 3, 1965, pp. 159-164.

46. Hottel, H. C., Keller, J. D. Effect of reradiation on heat transmission in furnaces and through openings. Trans. A.S.M.E. IS-55-6, 1933.

47. Buchberg, H., Lalude, O., and Edwards, D. K. Performance characteristics of rectangular honeycomb solar thermal converters. Proceedings Solar Energy Society Annual Meeting, Palo Alto, 1968.

48. Buchberg, H., Edwards, D. K., Lalude, O. Design considerations for cellular solar collectors. A.S.M.E. Winter Annual Meeting, 1968.

49. Peri, G. Private communication. Jan. 24, 1969. Faculty of Science, University of Marseilles.

50. Gier, J. T., Dunkle, R. V., and Roddick, R. D. U.S. Patent No. 3,136,674, June 9, 1964.

51. Tabor, H. Z. Mirror boosters for solar collectors. Jnl. Solar Energy, Vol. 10, No. 3, 1966, pp. 111-118.

52. Merchant, D. L., and Cobble, M. H. Mirror solar panels. Jnl. Solar Energy, Vol. 10, No. 3, 1966, pp. 150-152.

53. Ray, S. K., and Moss, G. Fluorochemicals as working fluids for small Rankine cycle power units. Advanced Energy Conversion, Vol. 6, 1966, pp. 89-102.

54. Lof, G. O. G., Fester, D. A., Duffie, J. A. Energy Balances on a parabolic cylinder solar collector. Jnl. Engineering for Power, Jan. 1962, pp. 24-32.

55. Powell, C. E., Gerber, W. O. Experimental characterization of parabolic solar concentrator performance. Proceedings, Solar Energy Society Annual Meeting, 1968, Palo Alto, Calif.

56. Lof, G. O. G., Duffie, J. A. Optimization of focussing solar collector design. II. Effects of misalignment. Solar Energy Laboratory, University of Wisconsin, Nov. 18, 1963.

57. Laszlo, T. S. New techniques and possibilities in solar furnaces. United Nations Conference on New Sources of Energy, Paper No E/Conf.35/S/5, Rome 1961.

58. Francia, G. Pilot plants of solar steam generating stations. Jnl. Solar Energy, Vol. 12, No. 1, pp. 51-64.

59. Glassman, A. J., and Stewart, W. I. A look at the thermodynamic characteristics of Brayton cycles for space power. AIAA Preprint 63-218, June 17, 1963.

60. Huffman, G. D., Hedgepeth, L. M., Ostdiek, F. R. Performance and weight comparison for solar dynamic conversion systems. Research and Technology Briefs, Vol. 4, No. 2, Feb. 1966, pp. 1-14.

61. Heffner, F. E. Highlights from 6500 hours of Stirling Engine operation. SAE, International Automotive Engineering Congress, Detroit, Michigan, January 11-15 1965, Paper No. 949D.

62. Welsh, H. W., Monson, D. S. Allison adapting Stirling Engine to 1-year-in-space operation. SAE Journal, Vol. 70, 1962, pp. 44-51.

63. Trayser, D. A., Eibling, J. A. A 50 watt portable generator employing a solar powered Stirling Engine. Jnl. Solar Energy, Vol. 11, No. 3-4, 1967, pp. 153-

64. Farber, E., Prescott, F. L. Closed cycle solar hot-air engines. Part I. A 1/4 HP engine. Part II. A 1/3 HP pressurized engine. Jnl. Solar Energy, Vol. 9, No. 4 pp. 170-182.

65. Flynn, G. Jr., Percival, W. H., Heffner, F. E. GMR Stirling thermal engine. SAE Transactions, Vol. 68 1960, pp. 665-684.

66. Lienesch, J. H., Wade, W. R. Stirling engine progress report. Smoke, odor, noise and exhaust emissions. SAE, Automotive Engineering.

67. Heffner, F. E. Highlights from 6500 hours of Stirling engine operation. SAE Transactions, Vol. , 1966, pp. 48-54.

68. Daniels, F., Finkelstein, T. Thermodynamic reciprocating apparatus. U.S. Patent 3117414, July 14, 1961, Assigned to Wisconsin Alumni Research Foundation.

69. Heffner, F. E. Private communication, Jan. 16, 1969. General Motors Research Laboratories, Warren, Mich.

70. Robinson, N., Neeman, Eliyahu. "The Solar Switch; an automatic device for economizing auxiliary heating of solar water heaters." United Nations Conference on New Sources of Energy, Paper No. E/Conf. 35/S/31, Rome 1961.

71. Page, John, K. The estimation of monthly values of daily total short wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40°North - 40°South. United Nations Conference on New Sources of Energy, Paper No. E/Conf. 35/S/98, Rome 1961.

72. Fritz, S. Solar radiation during cloudless days. Heating Ventilating, Vol. 46, No. 1, 1949.

73. Black, J. N. The distribution of solar radiation over the earth's surface. Archiv fur Meteorologie, Geophysik und Bioklimatologie, Vol. 7, No. 2, 1956.

74. Lof, G. O. G., Duffie, J. A., World Distribution of solar radiation. Engineering Experiment Station Report No. 21, University of Wisconsin, July 1966.

75. Maher, J. V. Private communication, Feb. 7th, 1969. Bureau of Meteorology, Melbourne.

76. Garnier, B. J., Ohmura, A. A method of calculating the direct short wave radiation income of slopes. Journal of Applied Meteorology, Vol. 7, No. 5, 1968, pp. 769-800.

77. Morse, R. N., Czarnecki, J. I. The effect of an incident radiation of inclination and orientation. Australian CSIRO Report ED6, Aug. 1958.

78. Whillier, A. Solar radiation graphs. Jnl Solar Energy, Vol. 9, No. 3, 1965, pp. 164-165.

79. Whillier, A. Solar energy and its utilization for house heating. Sc.D. Thesis Mech. Eng. M.I.T. 1953.

80. Saif-Ul-Rehman, M. Solar energy utilization in developing countries. Jnl. Solar Energy, Vol. 11, No. 2, pp. 98-107.

81. Golding, E. W. Power supplies, A development pamphlet. The Overseas Development Institute, London, England.

82. Putnam, P. C. Energy in the Future. Van Nostrand Co., 556 pp., 1953.

83. Engebretson, C. D. The use of solar energy for space heating M.I.T. Solar House IV. United Nations Conference on New Sources of Energy, Paper No.E/Conf. 35/S/67, Rome 1961.

84. Fukuo, N., et al. Installations for solar space heating in girin., United Nations Conference on New Sources of Energy, Paper No. E/Conf. 35/S/112, Rome 1961.

85. Bliss, R. W. The performance of an experimental system using solar energy for heating and night radiation for cooling a building. United Nations Conference on New Sources of Energy, Paper No. E/Conf. 35/S/30, Rome 1961.

86. Lof, G. O. G. Design and performance of domestic heating system employing solar heated air. United Nations Conference on New Sources of Energy. Paper No. E/Conf. 35/S/114, Rome 1961.

87. Hirschmann, J. G. A solar energy pilot plant for Northern Chile. Jnl. Solar Energy, V: 37-43, 1961.

88. Telkes, M. III. Solar House Heating, A Panel. Proceedings World Symposium on Applied Solar Energy, Phoenix 1955, pp. 147-150.

89. Dietz, A. G. H. Weather and Heat Storage Factors, Space Heating with Solar Energy. Proceedings of a Course Symposium, M.I.T., 1954, pp. 122-131.

90. Anon, New Melpar System Protects Missile Hardware from Heat, Technology week (Aerospace Technology), Jul. 3, 1967.

91. Telkes, M. Private Communication, Jan. 24, 1969.

92. Rosenbrock, H. H. An automatic method for finding the greatest or least value of a function. The Comp. Jnl., 3: 175, 1960.

93. Lasdon, L. S., A. D. Waren. Mathematical Programming for Optimal Design. Electro-Technology, Nov. 1967, pp. 53-70.

TABLE 1. Summary of the computer results: cost of the power produced (cents/kw hr), steady state, flat plate collector, ordinary black-painted absorber

Programme No. 0 - Constant radiation intensity
$I = 220$ Btu/hr ft^2

		Glass covers		
		2	3	4
Condenser temperature	110	> 50	48	45
	105	> 50	47	43
	100	> 50	45	41
	95	50	43	40.9
	90	48	40	40.8
	85	46	39.1	40.6

Programme No. 00 - Constant condenser temperature
$t_2 = 95^oF$

		Glass covers		
		2	3	4
Radiation intensity	320	24	23	24
	300	27	25.2	26.5
	280	31	28.8	30
	260	36	33	34
	240	42	38	40
	220	49	45.6	47
	200	50	50	50

TABLE 2. Summary of the computer results: cost of the power produced (cents/kw hr), steady state, flat plate collector, selective absorber

Programme No. 01 - Constant condenser temperature
$t_2 = 95^oF$

Radiation intensity	Btu/hr ft^2	320	300	280	260	240	220	200
Cost of power	cents/kw hr	19.0	21.1	24.0	27.8	33.0	40.0	49
Boiler temp. at min. cost	^oF	240	234	227	220	211	200	189

TABLE 3. Summary of the computer results: cost of the power produced (cents/kw hr), steady state, flat plate collector, honeycomb, selective absorber

Programme No. 02 - Constant condenser temperature
$t_2 = 95^oF$

Radiation intensity	Btu/hr ft^2	320	300	280	260	240	220	200
Cost of power	cents/kw hr	15.0	16.1	18.0	20.3	23.0	27.1	32.0
Boiler temp. at min. cost	^oF	260	259	258	256	254	245	236

TABLE 4. Summary of the computer results: cost of the power produced (cents/kw hr), steady state, flat plate collector, plastic honeycomb, ordinary black absorber

Programme No. 03 - Constant condenser temperature
$t_2 = 95^oF$

Radiation intensity	Btu/ hr ft2	320	300	280	260	240	220	200
Cost of power	cents/ kw hr	14.0	15.8	18.0	22.2	29.7	49	> 50
Boiler temp. at min. cost	^oF	213	210	209	208	207	205	

TABLE 5. Summary of the computer results: cost of the power produced (cents/kw hr), steady state, flat plate collector, selective absorber, mirror boosters

Programme No. 04 - Constant condenser temperature
$t_2 = 95^oF$

Radiation intensity	Btu/ hr ft2	320	300	280	260	240	220	200
Cost of power	cents/ kw hr	9.0	9.5	10.0	10.8	11.0	11.9	14.0
Boiler temp. at min. cost	^oF	260	259	258	257	256	255	254

TABLE 6. Summary of the computer results: cost of the power produced (cents/kw hr), unsteady state, no storage, flat plate collector with honeycomb and selective absorber

Programme No. 1

		Per Cent of the rated area			
		50	75	100	125
Boiler temperature in degrees F	210	28.7	26.9	26.8	27.9
	220	28.1	26.4	26.4	27.6
	230	28.1	26.4	26.4	27.6
	240	28.4	26.7	26.8	28.1
	250	29	27.2	27.3	28.6

The radiation data used is for Alice Springs, Australia

Condenser temperature = $90^{O}F$

TABLE 7. Summary of the computer results: cost of the power produced (cents/kw hr), unsteady state, with storage, flat plate collector with honeycomb and selective absorber

Programme No. 2

		Per cent of the rated area						
		75	100	125	150	200	250	300
Case 1 - No maximum power limitation, all power produced is consumed								
Boiler temperature degrees F	210	211	143	103	79	52.8	37.5	28.2
	250	250	164	124	92	61.5	44	34
Case 2 - Maximum power limited to 12 kw								
Boiler temperature degrees F	210	250	153	115	96.7	74.5	61.7	53.5
	250	250	171	134.5	113	90.6	77.5	67.7

Condenser temperature constant $t_2 = 90^{\circ}F$

Demand Pattern $\psi(k)$

Hour	8am-11am	11am-2pm	2pm-5pm	5pm-8pm	8pm-11pm	11pm-2am	2am-5am	5am-8am
Consumption (k) Per cent of the maximum rating	0.4	0.6	1.0	0.3	0.2	0.2	0.2	0.2
k	1	2	3	4	5	6	7	8

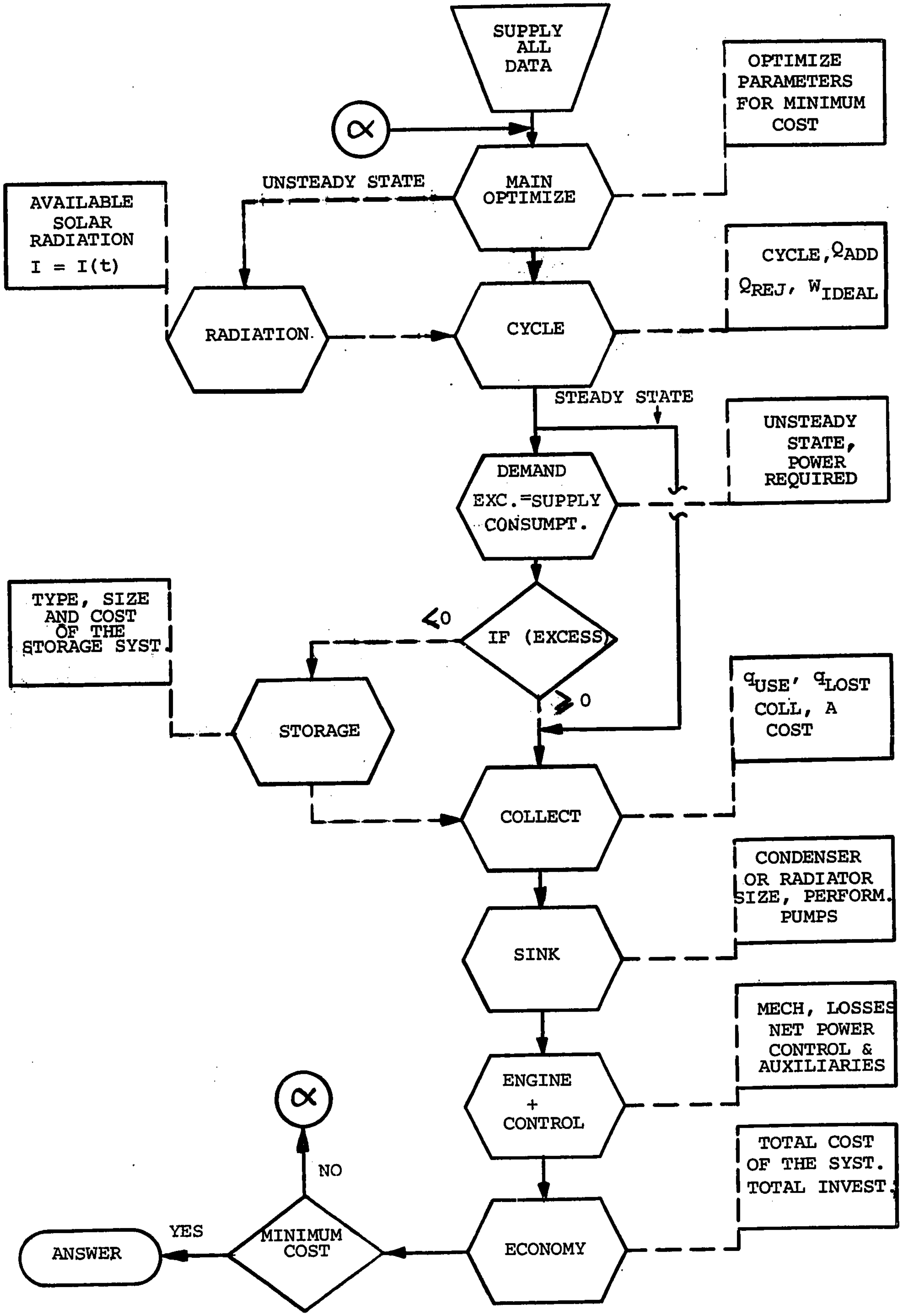


FIG. 1) . BASIC SCHEME OF ANALYSIS

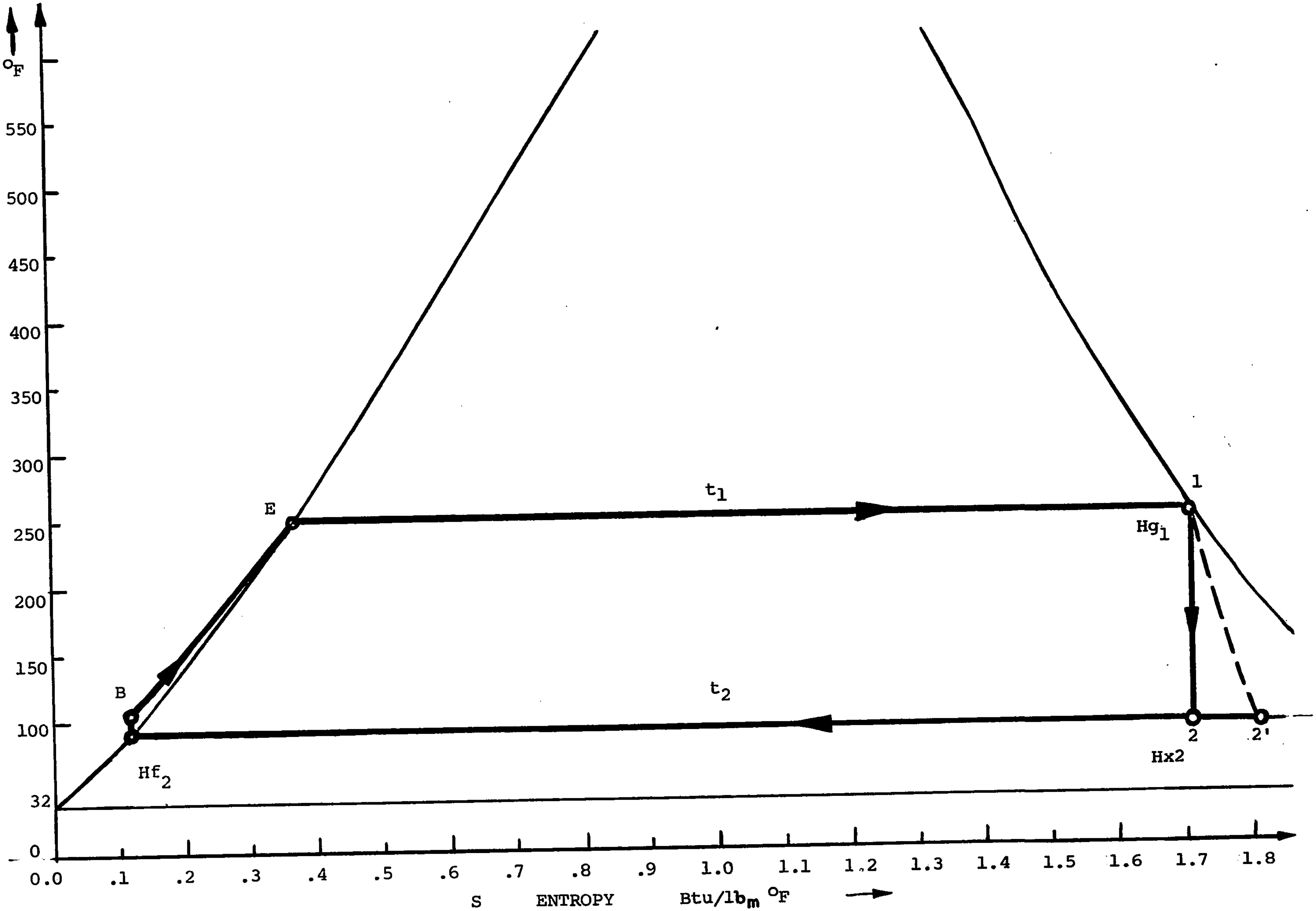


FIG. 2) TEMPERATURE - ENTROPY DIAGRAMME FOR STEAM-RANKINE CYCLE

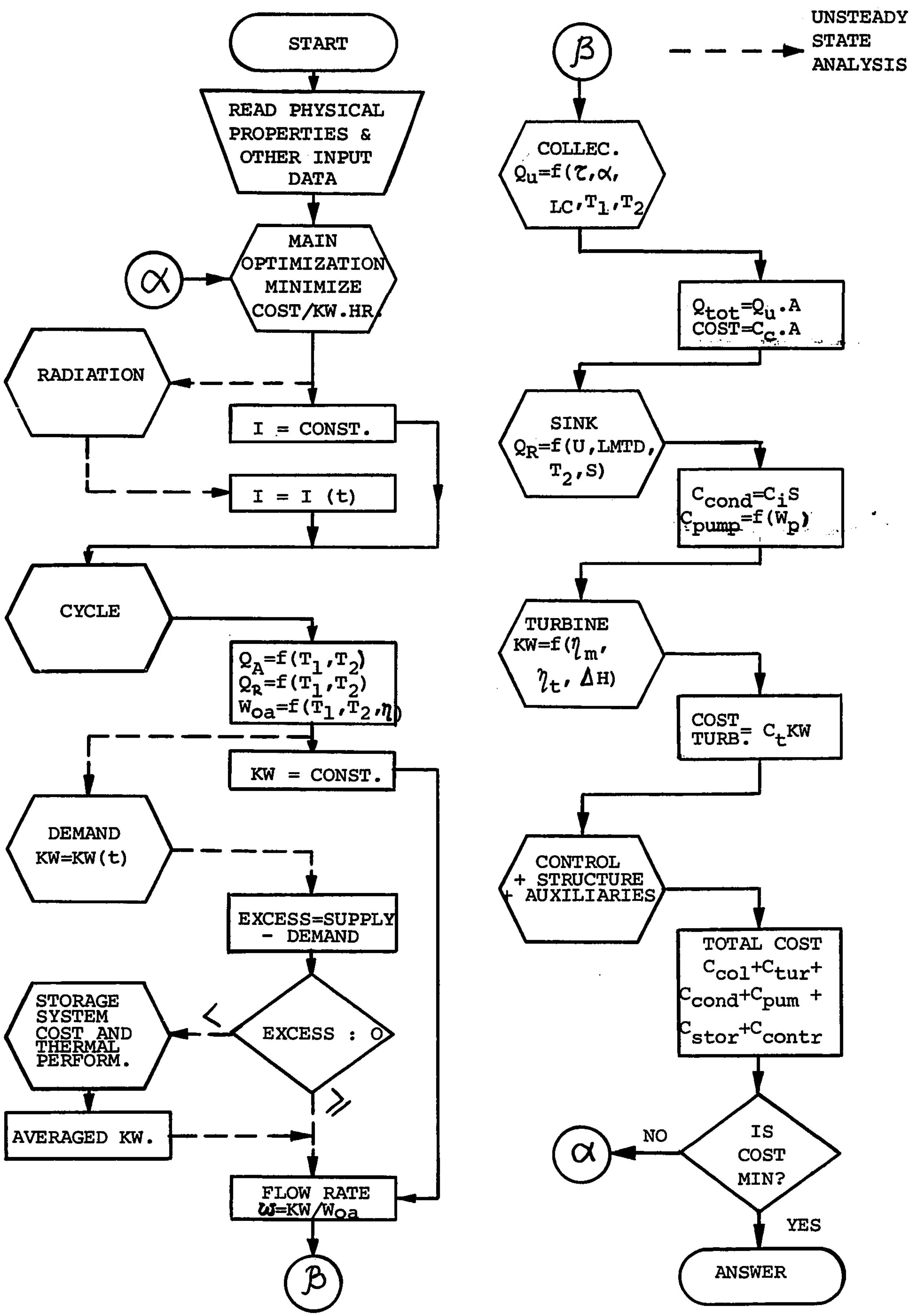
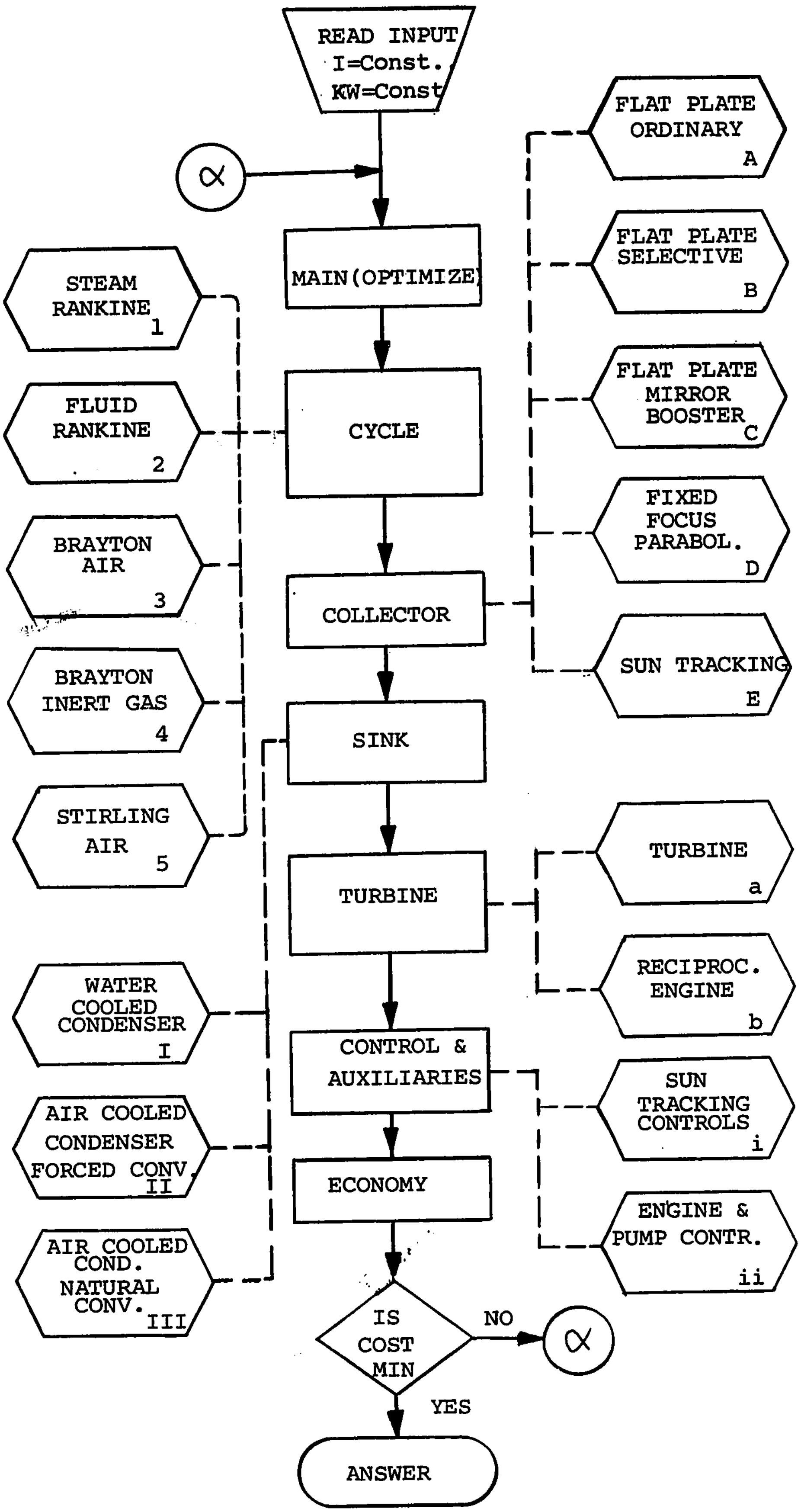


FIG. 3 STEADY AND UNSTEADY STATE INFORMATION FLOW CHART



1	A	I	a	ii
1	A	I	b	ii
1	A	II	a	ii
1	A	II	b	ii
1	A	III	a	ii
1	A	III	b	ii
1	B	I	a	ii
1	B	I	b	ii
1	B	II	a	ii
1	B	II	b	ii
1	B	III	a	ii
1	B	III	b	ii
1	C	I	a	ii
1	C	I	b	ii
1	C	II	a	ii
1	C	II	b	ii
1	C	III	a	ii
1	C	III	b	ii
1	D	I	a	ii
1	D	I	b	ii
1	D	II	a	ii
1	D	II	b	ii
1	D	III	a	ii
1	D	III	b	ii
1	E	I	a	i+ii
1	E	I	b	i+ii
1	E	II	a	i+ii
1	E	II	b	i+ii
1	E	III	a	i+ii
1	E	III	b	i+ii

30 COMBINATIONS

REPEATED FOR OTHER

4 CYCLES

30 x 5 = 150

POSSIBLE

COMBINATIONS

FIGURE 4) STEADY STATE ANALYSIS

POSSIBLE COMBINATIONS

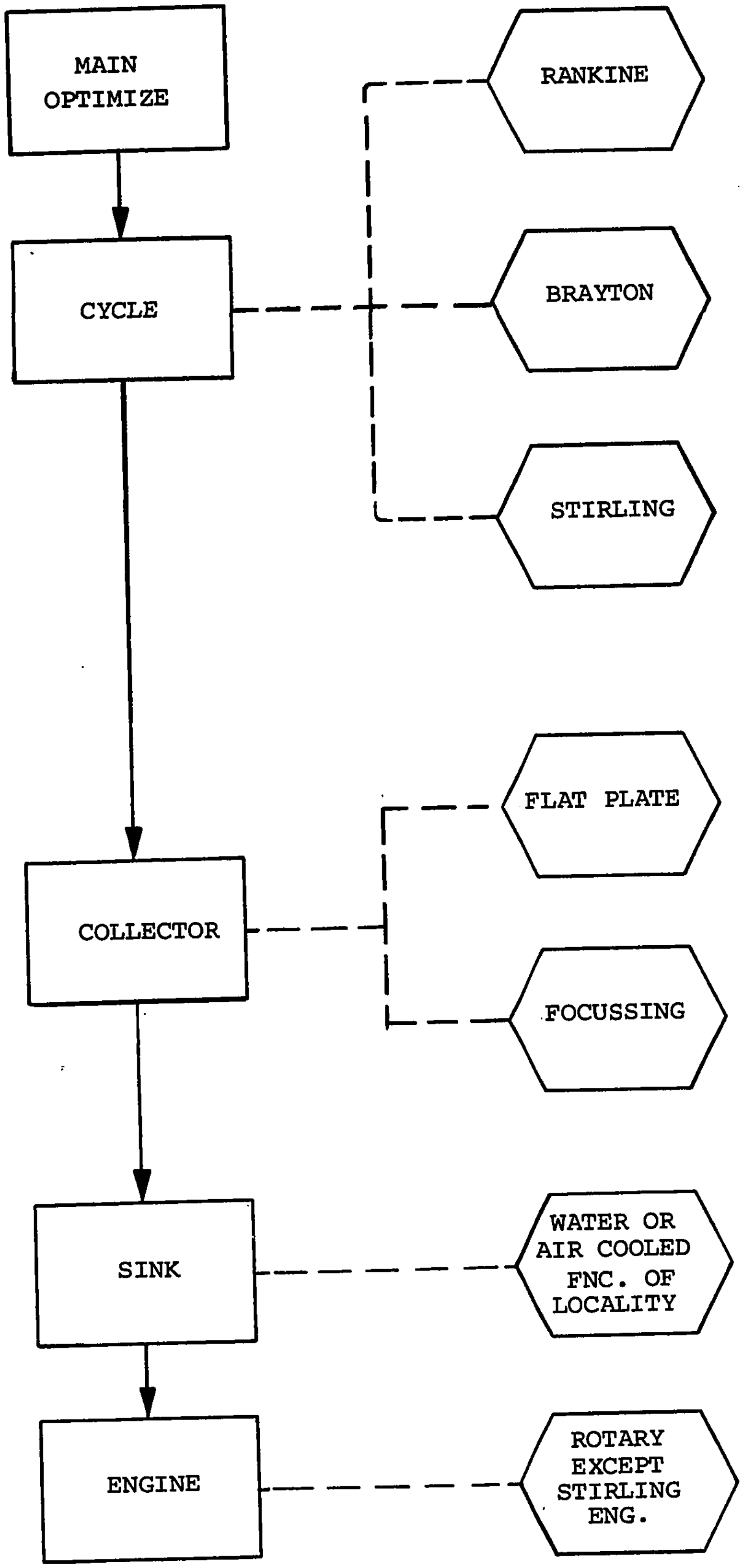


FIG. 5) SIMPLIFICATIONS OVER THE COMBINATIONS PROPOSED IN FIG. 4

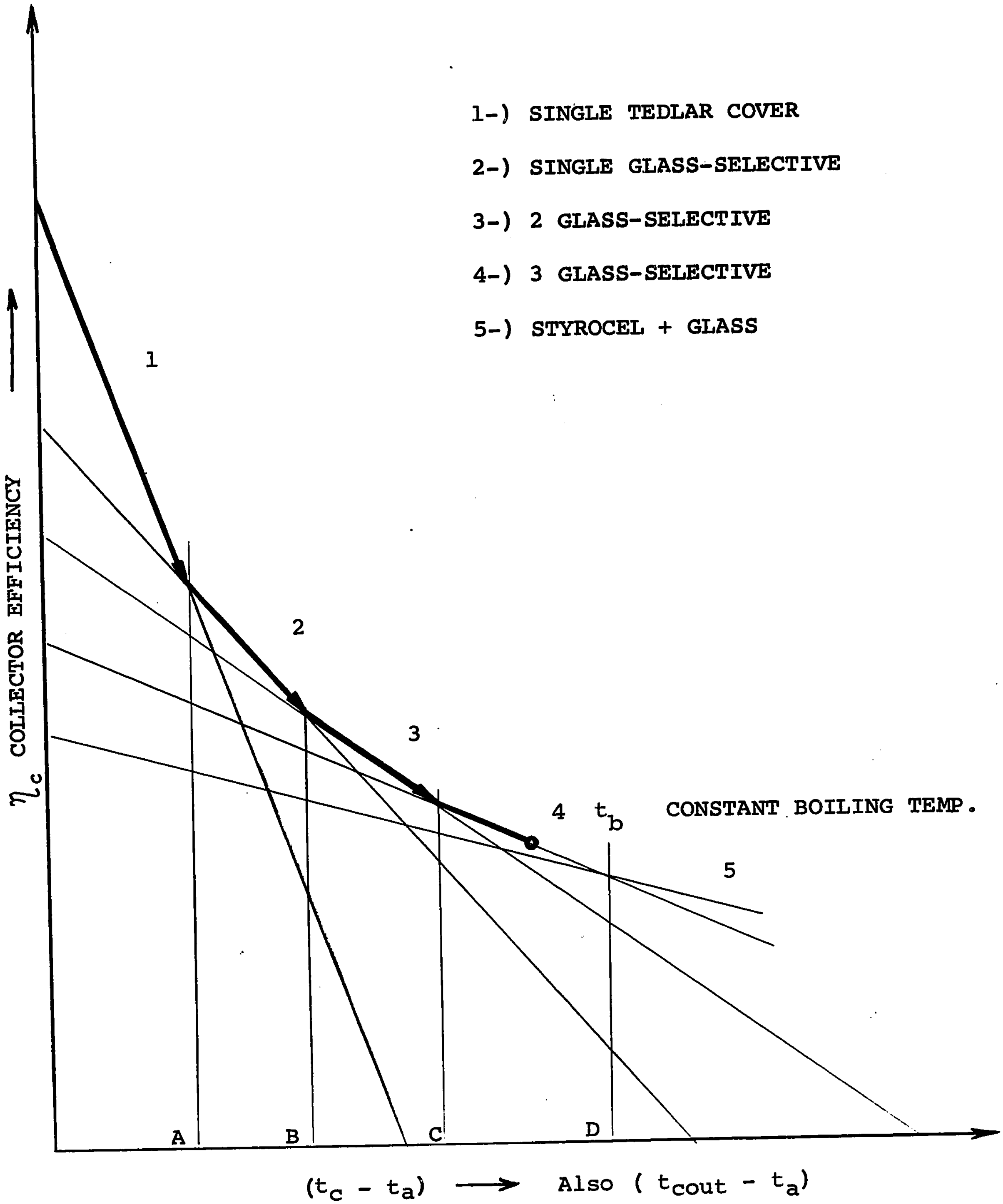
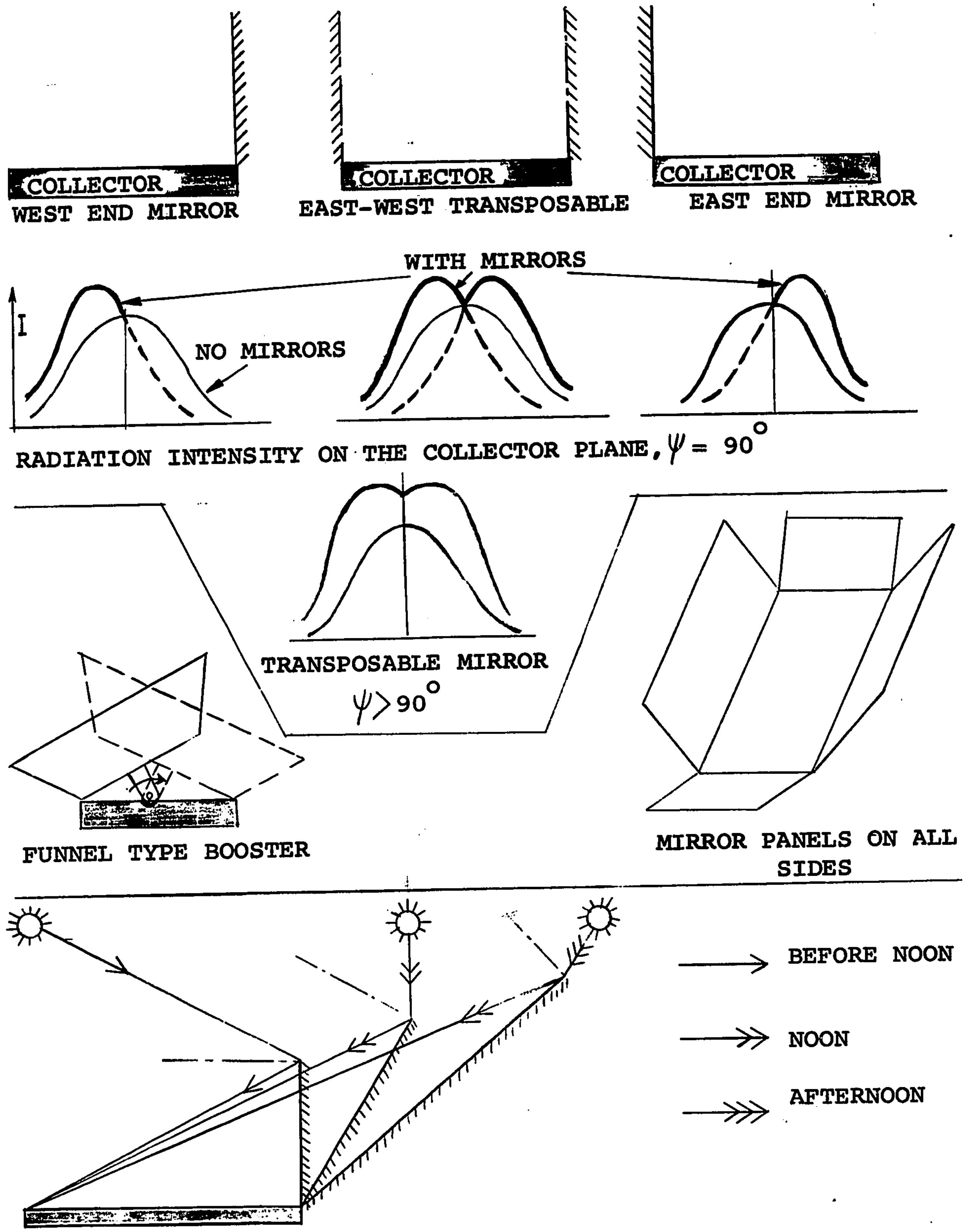


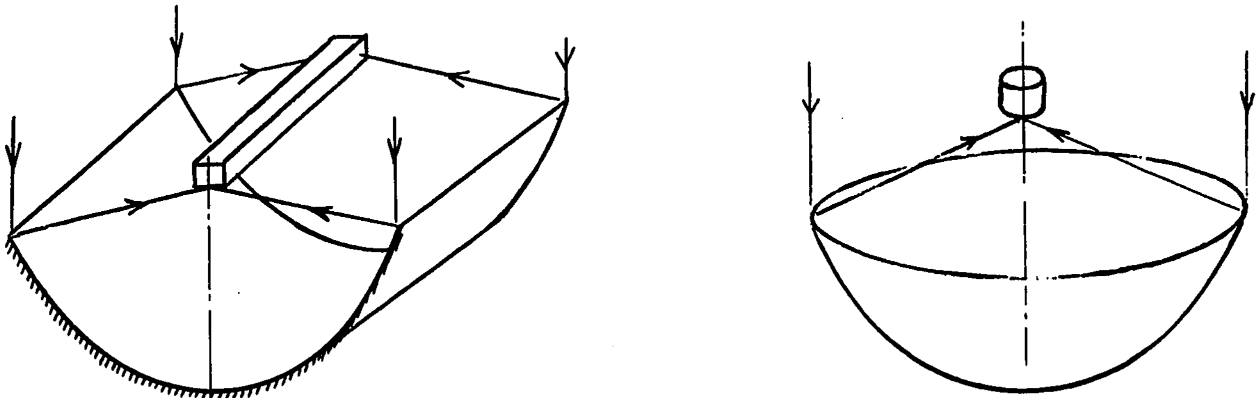
FIG. 6) TRENDS OF COLLECTOR EFFICIENCY VS TEMPERATURE CURVES

Note : FOR A WELL DESIGNED COLLECTOR $(t_{cout} - t_a)$ AND $(t_c - t_a)$ CURVES DIFFER SLIGHTLY

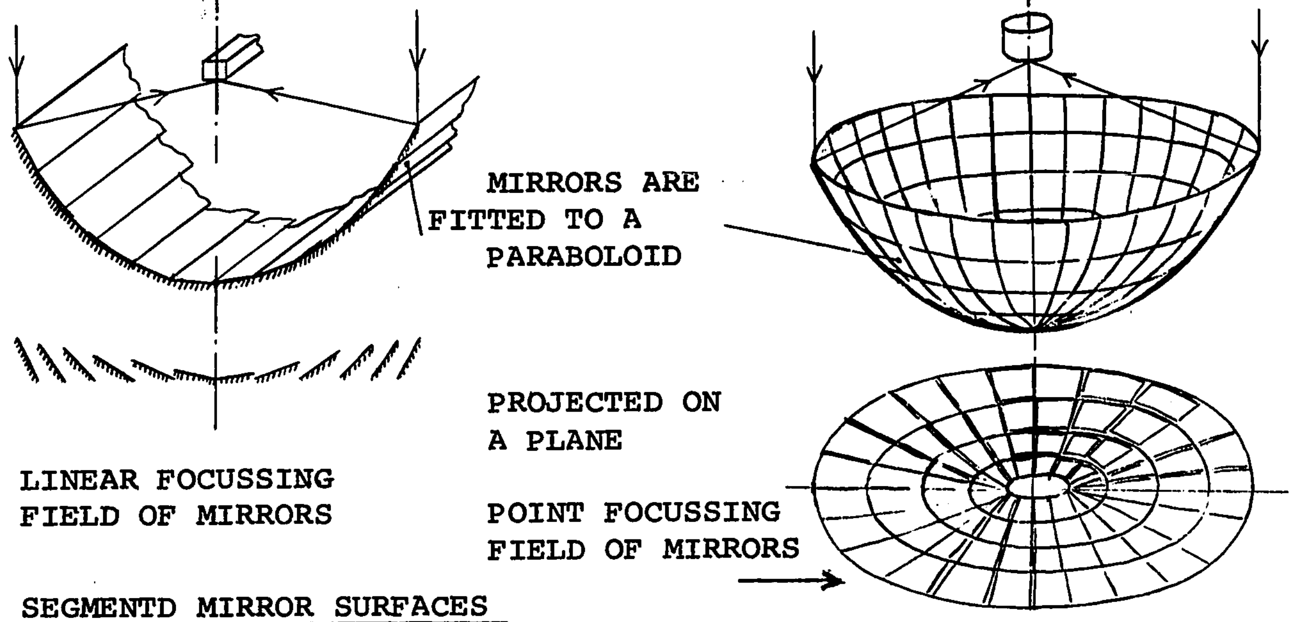


VARIATION OF THE MIRROR TILT AND LENGTH(L) REQUIRED FOR THE FULL COVERAGE OF COLLECTOR SURFACE

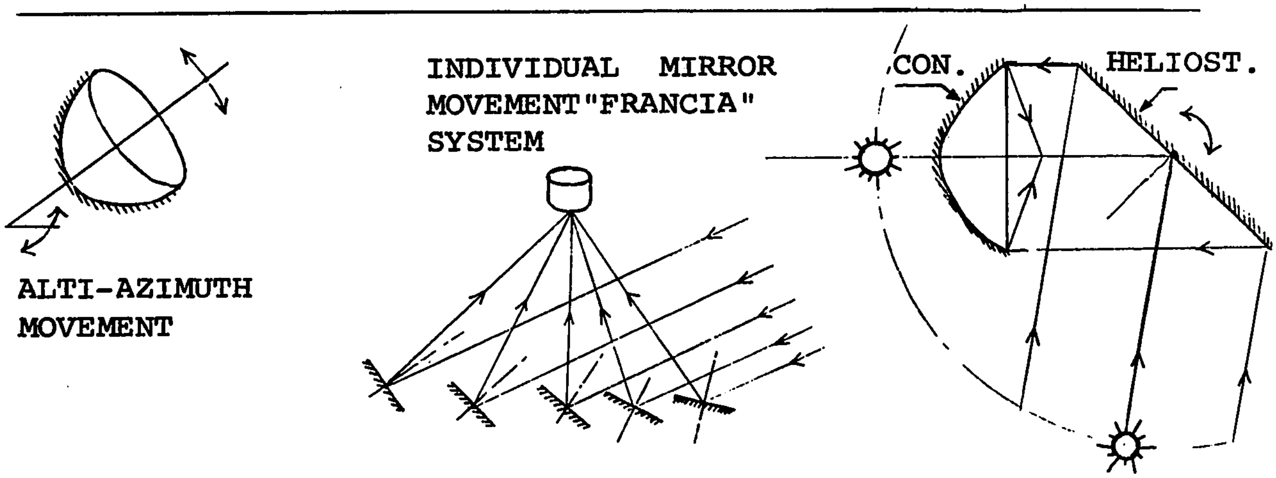
FIG. 7) DESIGN AND PERFORMANCE OF MIRROR BOOSTERS
(ADAPTED FROM REFERENCE 51)



PRECISION CONCENTRATORS WITH SMOOTH SURFACES

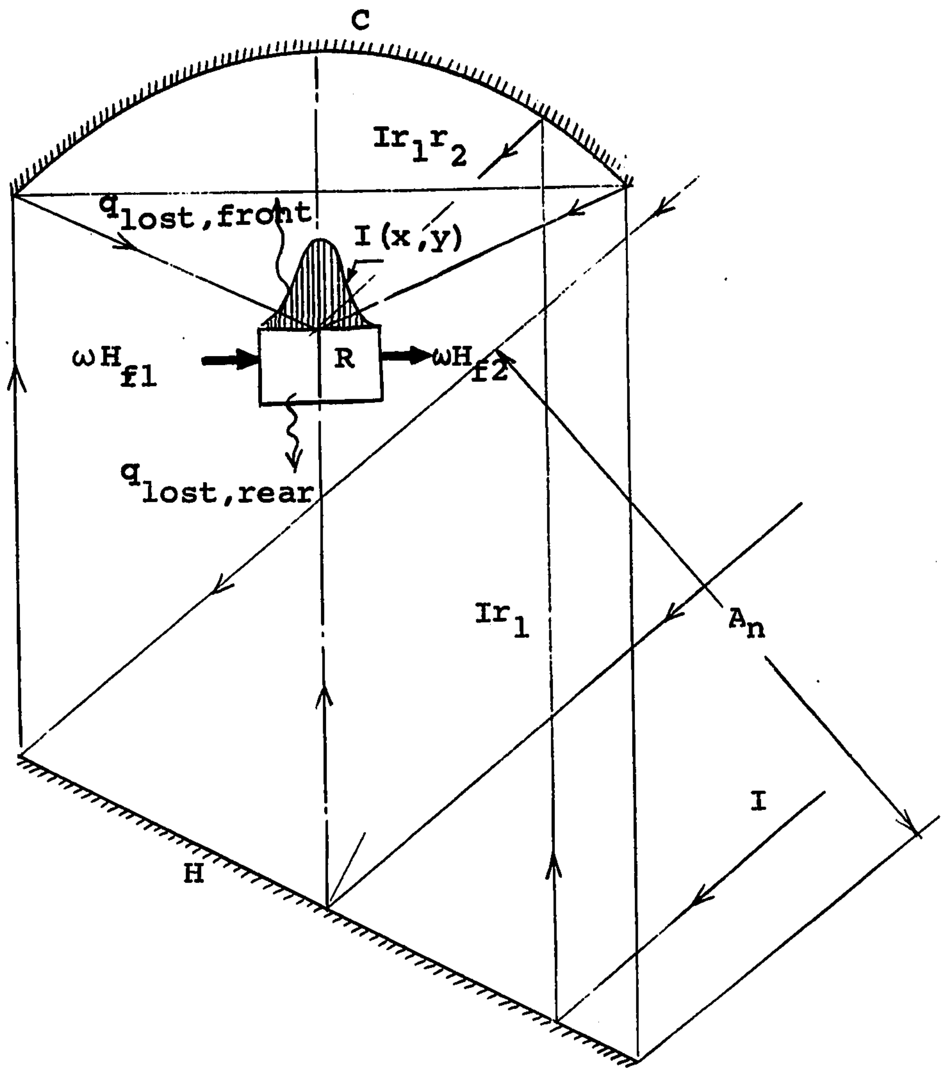


SEGMENTD MIRROR SURFACES



SUN TRACKING SYSTEMS

FIG.-8) CONCENTRATING TYPE COLLECTORS



R : RECEIVER

H : HELIOSTAT

C : CONCENTRATING MIRROR

A_n: AREA PERPENDICULAR TO DIRECTION OF THE SOLAR BEAM

I : INTENSITY OF THE SOLAR RADIATION ON THE PLANE (A_n)

I(x,y) : " " " " " " " RECEIVER

FIG.-9) ENERGY BALANCE FOR A CONCENTRATING COLLECTOR

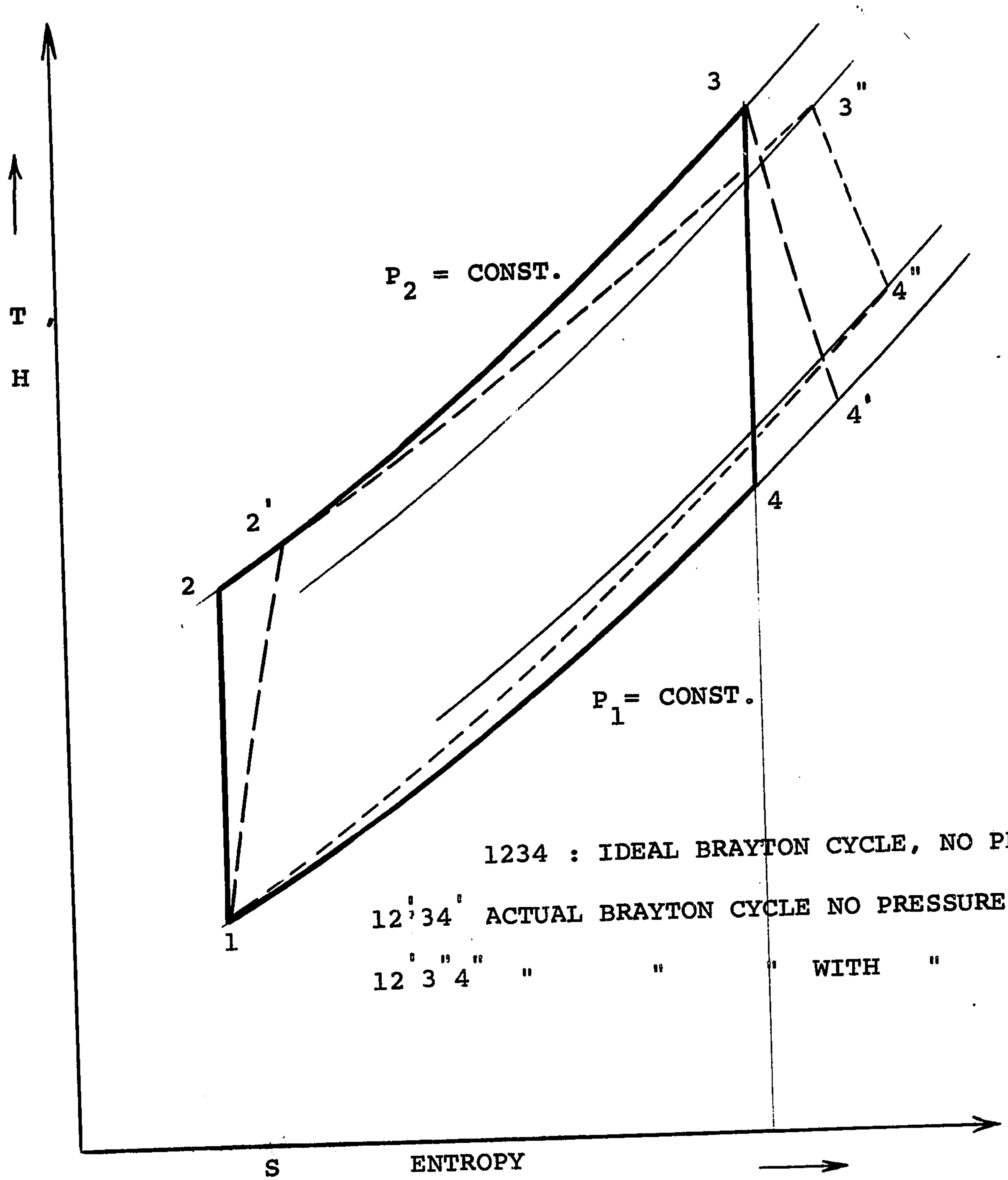
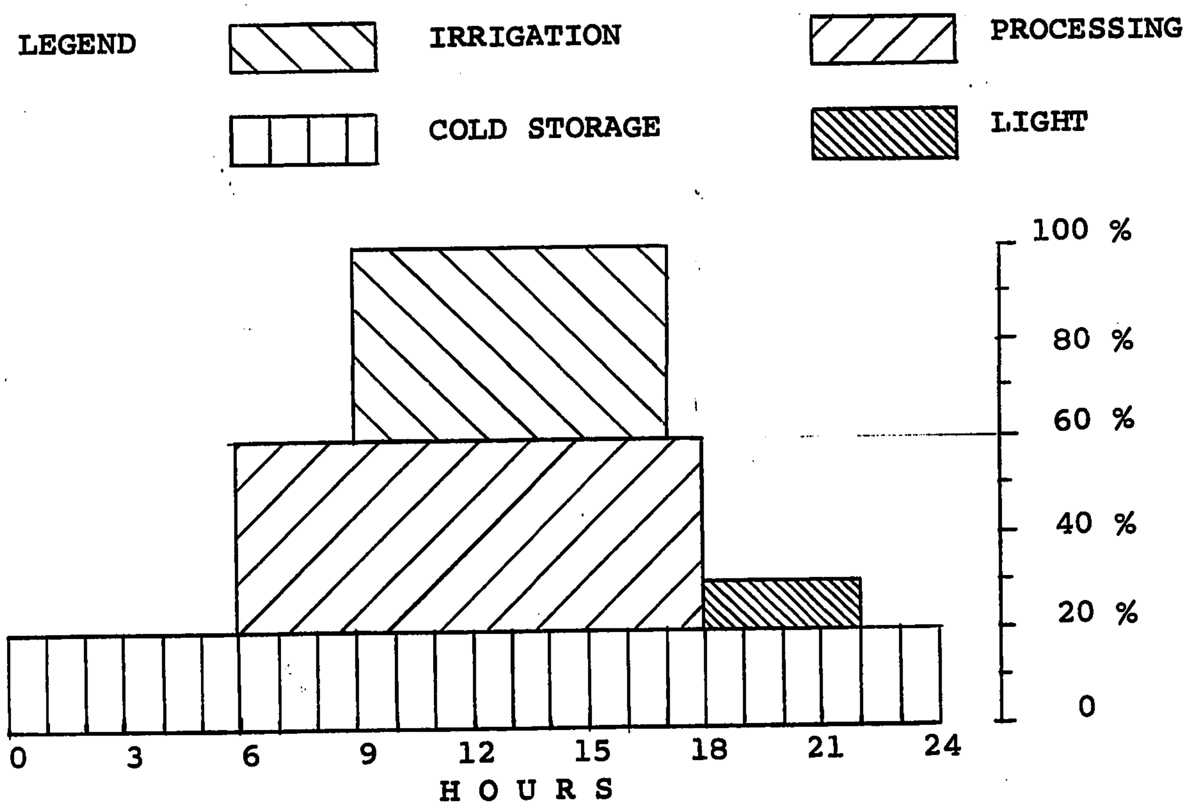
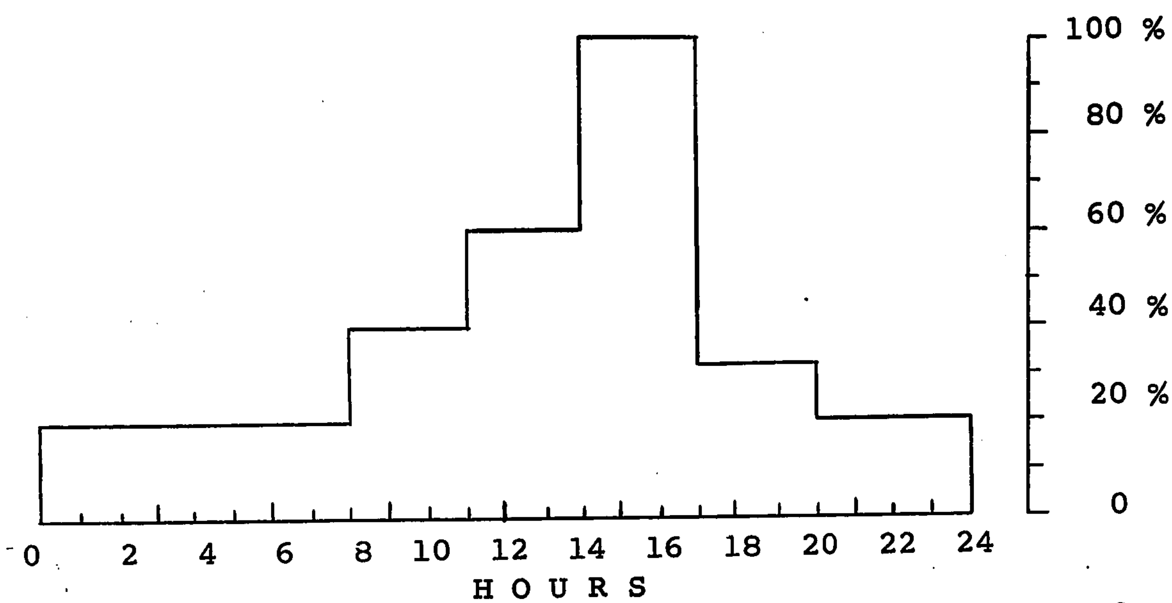


FIG. 10) BRAYTON CYCLE WITH AND WITHOUT PRESSURE DROP



A TYPICAL PATTERN FOR A SMALL FARM



THE SAMPLE PATTERN USED IN THE COMPUTER PROGRAMME No. 2

FIG.11) CONSUMPTION PATTERN $\psi(K)$ = FNC. (TIME)

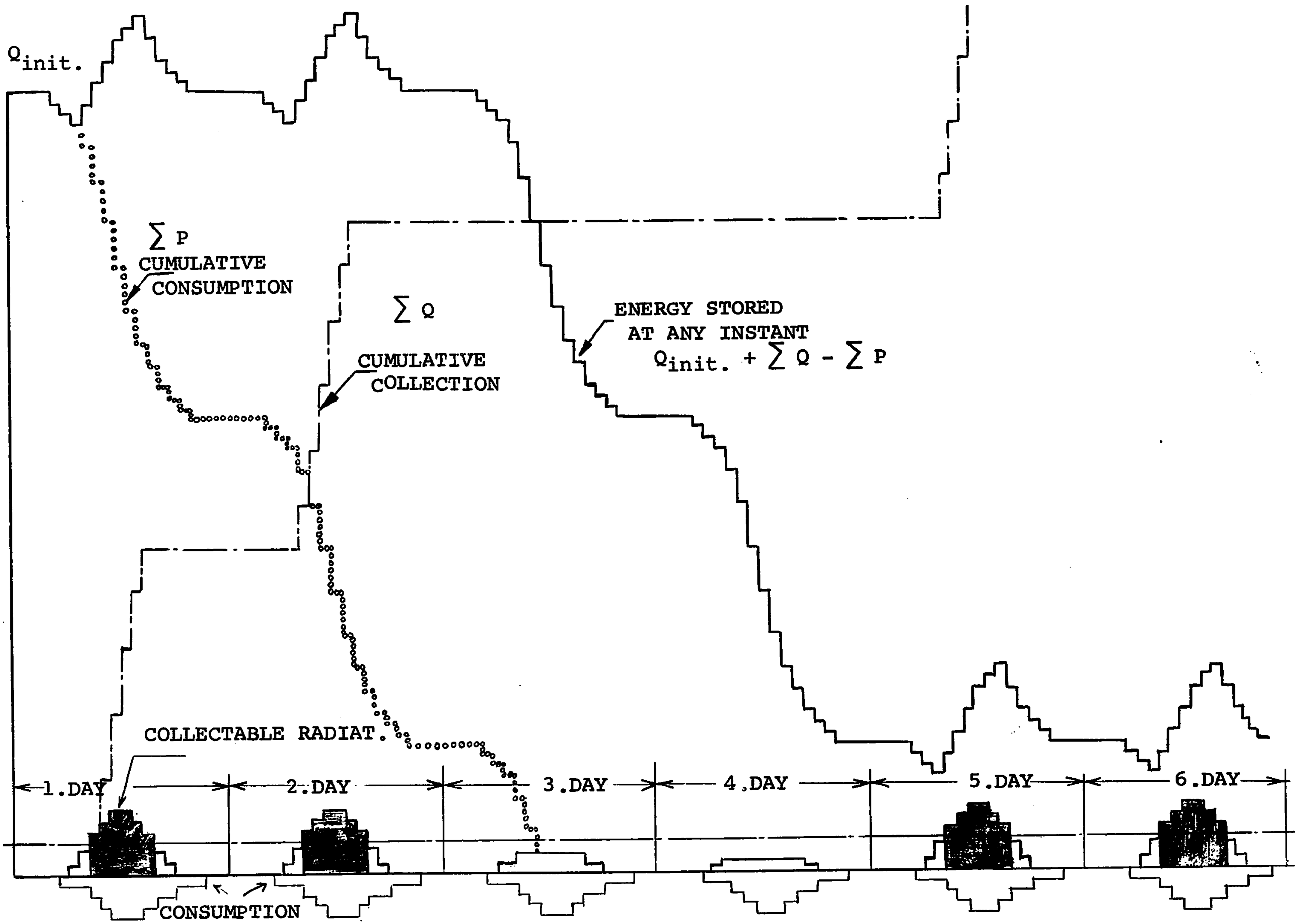


FIG. 12) UNSTEADY STATE WITH STORAGE, VARIATION OF COLLECTION AND STORED ENERGY WITH TIME

CONDENSER TEMPERATURE= 90°F

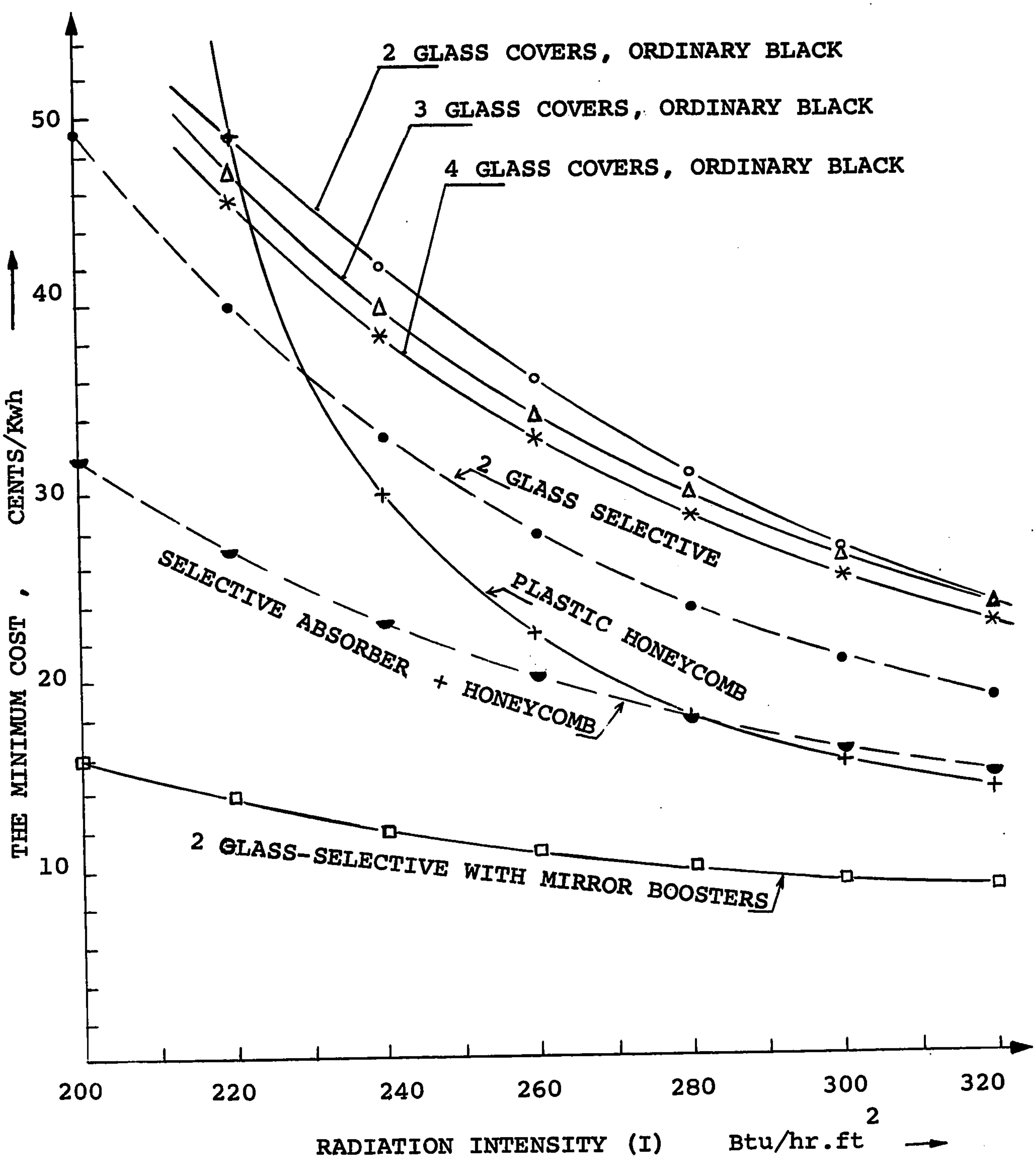


FIG.13) MINIMUM COST IN CENTS/Kwh VS RADIATION INTENSITY CURVES FOR VARIOUS FLAT PLATE COLLECTORS, STEADY STATE ANALYSIS

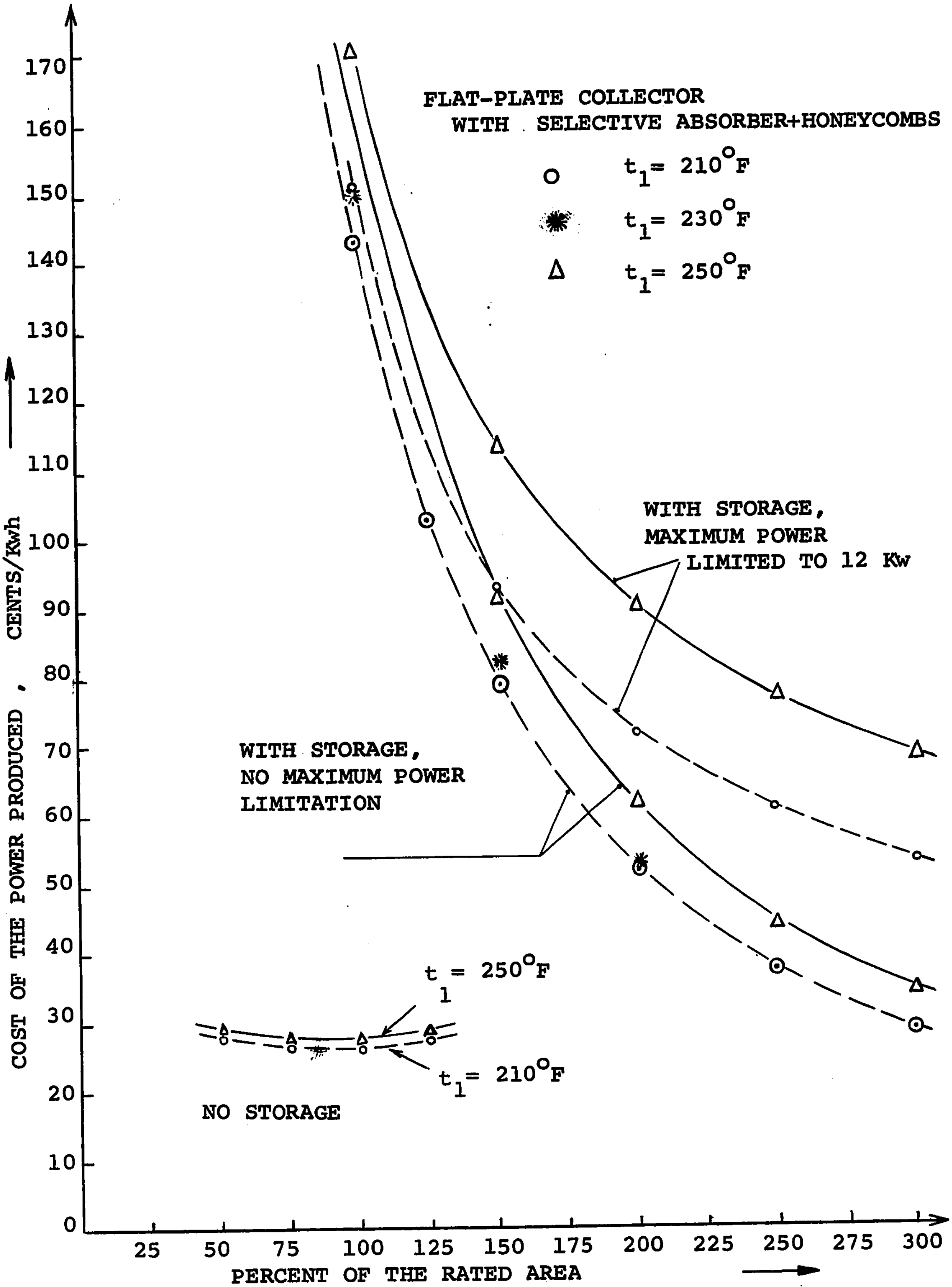


FIG.14) COST OF THE POWER PRODUCED VS PERCENT OF THE RATED AREA, UNSTEADY STATE ANALYSIS.

Appendix 1

CALCULATIONS OF THE COST OF THE POWER PRODUCED IN CENTS/KW. HR. AND TECHNIQUES FOR MINIMIZING IT

Once the combination of components which would yield maximum thermal efficiency or work output for a given set of input data is known it is possible to calculate the necessary capital investment. Together with the operation and maintenance costs it is possible to calculate the "fixed annual charges." The amount of energy collectable for a given locality is determined by the geographic position as well as by environmental climatic conditions such as cloudiness, industrial atmospheric dust, etc. The cost of the power produced may be calculated by dividing the fixed annual charges by the total kw.hr. produced within a year.

The cost of the power produced, corresponding to a set of conditions yielding the maximum thermal efficiency, may not necessarily be the lowest cost attainable with the given combination. Since the criterion is to obtain the minimum cost, once the cost function can be expressed implicitly in terms of independent or dependent variables, it is possible to arrive at the minimum value using one of the following techniques.

1. Classical Differential Approach

   a. Unconstrained minimum by taking the partial derivatives and equating them to zero.

   b. Using Lagrange Undetermined Multipliers for the constrained minima.

2. Exhaustive Enumeration

This is a straightforward method of testing all possible combinations of the variables. It is satisfactory provided that the number of variables is confined to two or three and the range of study, i.e., "feasible region," is small enough to enable the survey to be executed using one of the high speed computers available.

This method may be attempted in the following sections as a preliminary survey to obtain the regions of promise and the computer programme's operation stay within reasonable time limits.

3. Direct Minimizing

One of the sophisticated processes, such as the one suggested by Fletcher and Powell's* or Fiacco-McCormic,** may be used. Since steepest descent method*** is applicable

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*R. Fletcher and M. J. D. Powell. A Rapidly Convergent Descent Method for minimization. Computer Journal, 6 (1963), 163-168.

**A. V. Fiacco and G. P. McCormick. Extensions of SUMT for Nonlinear Programming. Management Science, 12 (July, 1966), 816-828.

***L. S. Lasdon and A. D. Waren. Mathematical Programming for optimal design. Electro Technology, Nov. 1967, pp. 53-70.

to a function with only the two independent variables, T_1 and T_2, it is preferred to the Fletcher-Powell or Fiacco-McCormic methods. The cost evaluation and its minimization are detailed below.

The total investment in the solar power plant is obtained from

$$C_{tot} = \sum_{i=1}^{n} A_{col.i} C_{col.i} + C_{con.tu} S + C_{shell} + C_{turb} + C_{pump} + C_{contr.} \qquad (1)$$

The fixed annual charges may be calculated on the equivalent annual costs* based on the benefit cost ratio and compound interests.

The Capital Recovery Factor is given by

$$R_f = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (2)$$

where

i = interest

n = expected lifetime

The total expenses on a yearly basis

$$E_{tot} = C_{tot} (R_f + r + o) \qquad (3)$$

In dollars

r = repair costs as per cent

*Anon. Cost Benefit Evaluations as Applied to Aid Financed water or Related Land Use Projects. Supplement No. 1, May 31, 1963. Department of State Agency for International Development Office of Engineering.

o = operating costs as per cent

The yearly amount of work produced in kw. hours

$$W_{year} = 2 \sum_{i=1}^{\xi} \sum_{j=1}^{30} \sum_{k=1}^{12} \sum_{m=1}^{n} A_{col.m}\, C_{col.m}\, I(i,j,k)\, \phi(i,j,k)\, U_f(i,k)\, \eta_s(T_1,T_2,I)/3413 \qquad (4)$$

where

U_f = use factor

$$\phi = \frac{1}{n} \sum_{1}^{n} \left(\frac{I_n - I_c}{I_{av}}\right)^{+} \qquad (5)$$

= Utilizability, a climatic factor.

$\eta_s(T_1, T_2, I(i,j,k))$ = efficiency of conversion from radiation to mechanical work, is a function of the radiation intensity, T_1, T_2.

$$C_{kw.hr.} = \left(\frac{100\ E_{tot}}{W}\right) \text{ in } \left(\frac{\text{cents}}{\text{kw.hr}}\right) \qquad (6)$$

The cost of the power produced which must be minimized.

$$C_{kw.hr.} = \frac{\left(\sum_{m=1}^{n} A_{col.m} C_{col.m} + C_{con.tu} \cdot S + C_{shell} + C_{turb} + C_{pump} + C_{cont.}\right)(R_f + o + r)}{2 \sum_{i=1}^{\xi} \sum_{j=1}^{30} \sum_{k=1}^{12} \sum_{m=1}^{n} A_{col.m} C_m I(i,j,k)\, \phi(i,j,k)\, \eta_s (T_1, T_2, I(i,j,k))\, U_f(i,k)} \qquad (7)$$

The system's efficiency: η_s =

$$\frac{W_{oa}\cdot w}{I(i,j,k)A_{coll}} = \frac{\text{Useful Work}}{\text{Incident energy}} = \frac{KW}{I(i,j,k)A_{coll}} = \eta_s \quad (8)$$

The optimization has to be carried out for an averaged radiation intensity (I) but the actual output will vary due to the change of (I) with time. Therefore,

η_s = fnc $(T_1, T_2, I(i,j,k))$ must be determined. Since

$$Q_{sens}(T_1,T_2) = 0.1\ Q_{latent}(T_1) \quad (9)$$

The variation of collector efficiency for different transparent covers may be ignored and a single relation can be used for $Q_{sensible}(T_1,T_2)$. This allows the collector area to be calculated in two steps. One from (T_1,T_2), the other at T_1 (for boiling)

$$\eta_s = (T_1,T_2,I(i,j,k)) =$$

$$\frac{W_{oa}\cdot w}{I\ (i,j,k)\left[\frac{w c_p(T_1-T_2)}{F_r(\bar{I}\tau\alpha-U_{1c}T_2)} + \frac{w(H_{g_1}-H_{f_2})}{F_{rb}(\bar{I}\tau_1\alpha_1-U_{1c_1}T_1)}\right]} \quad (10)$$

Care should be exercised in using equation (10) such that the term $(\bar{I}\tau_1\alpha_1-U_{1c}T_1)$ should always be positive

$$\bar{I}_{min}\tau_1\alpha_1-U_{1c}T_1 = 0 \quad (11)$$

$$\bar{I}_{min} = \frac{U_{1c}T_1}{\tau_1\alpha_1} \quad (12)$$

Therefore $\bar{I} > \bar{I}_{min}$ should be maintained.

This also implies that the Utilizability factor ϕ sums up only the radiation intensities above I_{min}. Substituting η_s into (4)

$$C_{kwh} =$$

$$\frac{A_{col.sen.}C_{col.sen.}+A_{col.b.}C_{col.b}+C_{shell}+C_{con.tu}+\ldots)(R_f+O+r)3413}{2\sum_{i=1}^{\xi}\sum_{j=1}^{30}\sum_{k=1}^{12}(A_{col.sen}+A_{col.b})\,\phi(i,j,k)\frac{W_{oa}\cdot\varpi}{(A_{col.sen}+A_{col.b})I(i,j,k)}I(i,j,k)U_f(i,k)}$$

where : ξ sunset hour measured from noon

from $W_{oa}\varpi = Kw$

$$C_{kwh} =$$

$$\frac{(A_{col.sen.}C_{col.sen} + A_{col.b}C_{col.b} + C_{shell} + \ldots)(R_f+O+r)3413}{2\sum_{i=1}^{\xi}\sum_{j=1}^{30}\sum_{k=1}^{12}\phi(i,j,k)\ U_f(i,k)\ KW} \tag{13}$$

In minimizing the cost, the significant variables are T_1 and T_2. Although some of the terms are functions of other variables such as speed, size, pressure, etc., as a first step they will be considered as invariants.

Minimizing the Cost Function using the Differential Approach

It is well known that any dependent function, if expressed as an implicit function of two independent variables, represents a surface in three dimensional space or, extending this concept to N variables, the dependent function is a surface in the (N + 1) dimensional space.

The maximum or minimum value of the function within the region of study satisfies the condition of having the tangent plane as horizontal, which means

$$\left.\frac{\partial F}{\partial x_1}\right|_* = 0 \qquad \left.\frac{\partial F}{\partial x_2}\right|_* = 0 \qquad (14)$$

or in general $\left.\dfrac{\partial F}{\partial x_n}\right|_* = 0$

However, the reverse of this statement is not correct since at inflexion points, saddle points and flat parts of a surface the condition (14) is satisfied but the points are not maxima or minima. Therefore, the procedure must be utilized with precaution. An attempt which has been made to minimize the cost function by the differential approach is presented below.

To obtain the minimum cost, the partial derivatives of $C_{kw\ hr}$ with respect to T_1 and T_2 must be obtained. Then using the classical indirect method† and solving the two simultaneous equations, the local optimum can be obtained. However, the necessary condition for a maximum or minimum of a function specified in Reference†† has to be satisfied: $f_{xx}(a,b) < 0$ or $f_{xx}(a,b) > 0$, $D = f_{xy}^2(a,b) - f_{xx}(a,b)f_{yy}(a,b) < 0$

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†D. J. Wilde and C. S. Beightler. Foundations of Optimization. Prentice Hall, 1967.

†† I. S. Sokolnikoff, R. M. Redheffer. Mathematics of Physics and Modern Engineering. McGraw-Hill Co., New York, 1966.

Let:

$$\mathrm{M} = \frac{(R_f + 0 + r)\ 3413}{2 \sum\sum\sum \phi(i,j,k)\ U_f(i,k)\ KW} \quad (15)$$

then M : independent of T_1, T_2

$C_{kw\ hr}$ =

$$\mathrm{M}(A_{coll.}\ C_{coll} + C_{con.tu}\ S + C_{shell} + C_{pump} + C_{contr} + C_{turb}) \quad (16)$$

C_{tur}, C_{shell} C_{pump} and $C_{control}$ may well be assumed as independent of T_1 and T_2 for the power ratings and the temperature ranges employed.

$$\frac{\partial C_{kwh}}{\partial T_1} = \mathrm{M}\ \frac{\partial}{\partial T_1}\ (\sum_{m=1}^{n} A_{col.m}\ C_{col.m} + C_{con.tu}\ S) \quad (17)$$

$$\frac{\partial C_{tur}}{\partial T_1},\quad \frac{\partial C_{shell}}{\partial T_1},\quad \frac{\partial C_{pump}}{\partial T_1},\quad \frac{\partial C_{cont}}{\partial T_1}$$

all are zero since those variables are assumed as independent of T_1.

Similarly $\frac{\partial C_{tur}}{\partial T_2}$, $\frac{\partial C_{shell}}{\partial T_2}$, $\frac{\partial C_{pump}}{\partial T_2}$, $\frac{\partial C_{cont}}{\partial T_2}$ are also zero.

$$\frac{\partial C_{kwh}}{\partial T_2} = \mathrm{M}\frac{\partial}{\partial T_2}\ (\sum_{m=1}^{n} A_{col.m} C_{col.m} + C_{con.tu}\cdot S) \quad (18)$$

These parital derivatives must vanish at the optimum.

$$\frac{\partial C_{kwh}}{\partial T_1} = 0 \quad (19)$$

$$\frac{\partial C_{kwh}}{\partial T_2} = 0 \quad (20)$$

$C_{coll,i}$ is a function of T_1 (maximum cycle temperature) but it is not a continuous function since the basic difference among various types of collectors is the number of transparent glazings which can only be digits such as 1, 2, 3, 4, etc., glass or plastic (Tedlar) sheets. (C_{coll} vs T_1) will be a Discrete Function. For the sake of introducing C_{coll} as a temperature dependent term, as a first approximation, the following can be written:

$$C_{coll} = C_{frame} + C_{ins,\Delta T} \cdot T_1 + C_{glaze} \cdot T_1 \qquad (21)$$

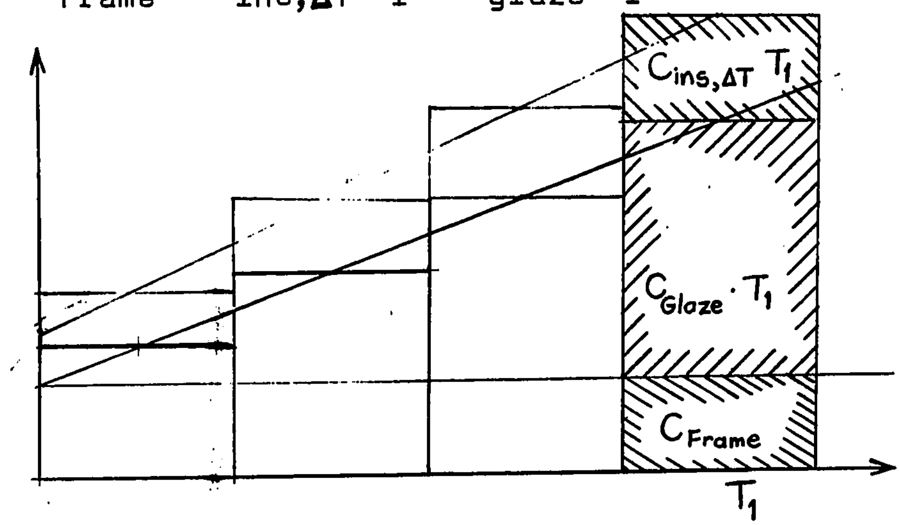

Figure 1. Collector cost vs Outlet Temperature measured above ambient.

where $C_{ins,\Delta T}$: cost of the insulation per °F measured above the ambient, per sq. ft. The rear losses are assumed to be about 10% of the upward losses through the transparent glazing

C_{glaze} : Approximated cost for glazing

$C_{ins,\Delta T}$ = cost of insulation per ^{o}F temperature rise from the ambient;

C_{glaze} = cost of glazing per sp. ft. as obtained from Figure 1.

$$C_{col} = C_{frame} + (C_{ins,\Delta T} + C_{glaze})T_1 \qquad (22)$$

or letting

$$C_{ins,\Delta T,glaze} = C_{ins,\Delta T} + C_{glaze} \qquad (23)$$

$$C_{col} = C_{frame} + C_{ins,\Delta T,glaze}T_1$$

Substituting (23) into (17) and dropping M

$$\frac{\partial}{\partial T_1}\left(\sum_{m=1}^{n} A_{col.m}(C_{frame} + C_{ins,\Delta T,glaze}T_1) + C_{con.tu}\ S\right) = 0 \qquad (24)$$

$$\frac{\partial}{\partial T_2}\left(\sum_{m=1}^{n} A_{col.m}(C_{frame} + C_{ins,\Delta T,glaze}T_1) + C_{con.tu}\ S\right) = 0 \qquad (25)$$

Following the simplification applied to equation (10), only a two-stage collector will be considered.

Taking (A_{coll}) from (3.36) and (3.37), changing the subscript as required since only two steps are employed, and using (3.55) for S, equations (24) and (25) could be written:

$$\frac{\partial}{\partial T_1}\left\{\left(\frac{\omega cp(t_1-t_2)}{F_r(\bar{I}\tau\alpha-U_{1c}T_2)} + \frac{\omega(H_{g1}-H_{f1})}{F_{r1}(\bar{I}\tau_1\alpha_1-U_{1c1}T_1)}\right)(C_{frame}+C_{ins,\Delta T,glaze}T_1)\right.$$

$$\left. + \frac{\omega\left(\frac{1.8165-0.00139t_1-0.00177t_2}{1.9148-0.0035\ t_2}\right)(1094.6-0.575t_2)}{hi\left[\frac{t_{cwo}-t_{cwi}}{\ln\left(\frac{t_2-t_{cwi}}{t_2-t_{cwo}}\right)}\right]}\right\} \qquad (26)$$

$$\frac{\partial}{\partial T_2}\left\{ \qquad \right\} \tag{27}$$

ϖ : can be taken as a function of (T_1, T_2, η and Kw) from (3.23).

Substituting (3.23) into (26) and (27) and expressing $H_{g1}-H_{f1}$ as a function of T_1:

$$\begin{aligned} H_{g1}-H_{f1} &= 11.50.4 + 0.333\,(T_1-212) - (T_1-32) \\ &= 1112 - 0.666T_1 \end{aligned} \tag{28}$$

$$\frac{\partial}{\partial T_1}\left\{\frac{KW}{\eta(1112+0.333t_1-t_2-(\frac{1.8165-0.00139t_1-0.00177t_2}{1.9148-0.0035t_2})\cdot(1094.6-0.575t_2))}\right.$$

$$\left.\frac{Cp(t_1-t_2)}{F_r(\overline{I}\tau\alpha-U_{1c}t_2)}\right\}C_{frame}+\frac{\partial}{\partial T_1}\left\{ \quad \right\}C_{ins,\Delta T,glaze}+\frac{\partial}{\partial T_1}\left\{\frac{KW}{\eta(1112+0.333t_1-t_2}\right.$$

$$\left.\frac{(1112-0.666t_1)}{F_{r1}(\overline{I}\tau_1\alpha_1-U_{1c1}T_1)}\right\}C_{frame} + \frac{\partial}{\partial T_1}\left\{ \quad \right\}C_{ins,\Delta T,glaze} + \frac{\partial}{\partial T_1}\left[\right.$$

$$\left.\frac{KW}{(1112+0.333t_1-t_2)} \quad \frac{(1.8165-0.00139t_1-0.00177t_2)}{1.9148-0.0035t_2}\right]$$

$$\left\{\frac{(1094.6-0.575t_2)\,\ln(\frac{t_2-t_{cwi}}{t_2-t_{cwo}})}{hi(t_{cwo}-t_{cwi})}\right\}C_{con.tu} = 0 \tag{29}$$

$$\frac{\partial}{\partial T_2}\left\{\,.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\,\right\} = 0 \tag{30}$$

Equations (29) and (30) could also be used for examining the influence of other parameters such as (η), U_{1c}, τ, α when they could be expressed in the form of a continuous function. However, this possibility will not be examined now since these are not continuous functions and a few possible combinations can always be considered separately, which is much simpler than going into tedious differentiations.

The minimum point must be obtained by solving two non-linear (29) and (30) simultaneous equations utilizing any technique. One of the widely used techniques, Newton-Raphson method, would still require the second derivatives for solving the equations.

Due to the lengthy relations and non-warranted convergence, it has been decided another method had to be tried in obtaining the optimum point since the differential approach would be further complex in the case of an increased number of dependent variables.

Appendix 2

SOURCE PROGRAMMES IN FORTRAN IV AND SOME TYPICAL RESULTS

2a. Steady State Analysis

The following sample computer programmes and some typical results are presented. Typical input data, which are common to all programmes, are presented on page 1.

Programme No. 00: Mapping the cost function against (T_1 and T_2) for ordinary black-painted flat plate collector.

: Sample maps for 2, 3 and 4 glass cover collectors.

Programme No. 0 : Mapping the cost function against (T_1 and I) for ordinary black-painted flat plate collector.

: Sample maps for 2, 3 and 4 glass cover collectors.

Programme No. 01: Same as 0, above, only for selective absorber plate and 2 glass covers. Main programme and subroutine (Collec) are represented.

: Sample map.

Programme No. 02: Main programme the same as 01, only subroutine (Collec) for selective absorber + honeycomb is presented.

: Sample map.

Programme No. 03: Main programme the same as 01, only subroutine (Collec) for ordinary black-painted absorber + plastic honeycombs is presented.

: Sample map.

Programme No. 04: Main programme the same as 01, only subroutine (Collec) for selective absorber plate and 2 glass plates with mirror boosters is presented.

: Sample map.

2b. Unsteady State Analysis

Programme 1: This programme calculates the hourly work produced and energy consumed without storage. Production above the rated power (12 Kw in the sample run) is not utilized. Radiation data for a typical year at Alice Springs, Australia, was supplied by means of the deck of cards obtained from Programme No. 3 (presented in Appendix 2c). Yearly total work produced and cost of the power, in cents per Kw hr, are obtained for various boiler temperatures and various collector areas.

Programme 2: Unsteady state performance with storage is analyzed for one year. A typical varying consumption pattern is assumed and radiation data for Alice Springs is used. The critical intensity is dependent on the assumed boiler temperature. The average radiation has been calculated for intensities above the critical intensity and these results are supplied from Programme 3.

Various areas, 100%, 150%, 200%, 250% and 300% of the area calculated for the yearly average radiation intensity are used in calculations and various boiler temperatures are tested. The storage capacity required for continuous operation and the cost of the power produced in cents/Kw hr are also computed.

2c. Calculation of the radiation intensity on the collector plane

A computer programme for the calculation of the hourly total radiation from the daily total horizontal radiation.

The method presented by A. Whillier* is applicable for localities between 50°N and 50°S latitude and gives the hourly totals from the daily total. The examples covered, however, require intensities which normally occur between 8 a.m. and 4 p.m. within latitudes 35°N and 35°S. The curves shown in Figure 2 of the article are approximated with

*A. Whillier. Solar Radiation Graphs, Jnl. Solar Energy, 9, No. 3 (1965), 164, 165.

straight lines within a range of times of the setting of the sun, which correspond to the range expected between the above latitudes.

The change of declination is considered by the values for the mid-month as an average.

The following values of declination have been used as monthly averages:

Declination in degrees (January through December, respectively):

-21.1, -12.6, -4.1, 9.8, 18.9, 23.3, 21.5, 14.0, 3.0, -8.6, -18.5, 023.3

Sunset hour for Alice Springs, Australia, 23°48'S p.m.

(January through December, respectively);

6.40, 6.32, 6.10, 5.43, 5.25, 5.15, 5.23, 5.55, 6.15, 6.35, 6.45.

The sunset hours must be determined for each hour from Figure 1. An example is given for Alice Springs in Australia 23°48'S latitude. Hourly/daily total radiation is obtained from the following relation. Minutes are expressed as a percentage.

11-12 a.m. or 12- 1 p.m.	$rh_1 = 0.162 - (\xi_s - 5.00)\ 0.02$	(1)
10-11 a.m. or 1- 2 p.m.	$rh_2 = 0.142 - (\xi_s - 5.00)\ 0.015$	(2)
9-10 a.m. or 2- 3 p.m.	$rh_3 = 0.111 - (\xi_s - 5.00)\ 0.004$	(3)

8- 9 a.m. or 3- 4 p.m. $\quad rh_4 = 0.063 + (\xi_s - 5.00)\, 0.006$ (4)

7- 8 a.m. or $\quad rh_5 = 0.02 + (\xi_s - 5.00)\, 0.016$ (5)

The maximum hourly fractions from 12 to 4 p.m. are observed during the Winter Solstice. The fraction incident from 8 a.m. to 4 p.m. is

$$2(0.162+0.142+0.111+0.065+0.022) = 0.996$$

This differs from the daily total by less than 1/2 per cent.

The summer operation is different from that of the winter. The fraction incident from 8 a.m. to 4 p.m. is

$$2(0.123+0.115+0.10+0.08) = 0.836$$

About 16.4% will be lost if the collection is confined to the hours between 8 a.m. and 4 p.m..

Collection from 7 a.m. to 5 p.m. yields

$$2(0.123+0.115+0.10+0.08+0.05) = 0.936$$

However, the intensity between 7 a.m. and 8 a.m. and 4 p.m. and 5 p.m. is still too low to yield the desired temperature for $I_{tot.day} = 700 \frac{\text{Cal}}{\text{cm}^2\text{day}}$

$$I_{tot.h} = 700 \times 0.05 = 35 \text{ cal/hr cm}^2$$

$$= \frac{35}{60} \times 221.2 = 130 \text{ Btu/hr ft}^2$$

For a 2 glass cover, flat plate collector,

$\tau = 0.78$ and $\alpha = 0.93$, giving $U_{lc} = 0.7(\text{Btu/hr ft}^2 \text{ deg F})$, if steam at 212°F is desired.

The critical intensity allowing a 5% surplus is:

$$I_{crit} = 1.05\ \frac{U_{Lc}(t_1 - t_a)}{\tau\alpha} = 1.05\left[\frac{0.7(212-75)}{(0.78)(0.93)}\right] = 139 \text{ Btu/hr ft}^2$$

Thus the temperature desired cannot be maintained and hence a range from 8 a.m. to 4 p.m. can be regarded as the maximum period available for collection.

The hourly intensities can therefore be calculated from

$$I_{th} = I_{tot.day} \cdot r_h \qquad (6)$$

The following sample programme 31 is arranged to calculate the hourly total horizontal radiation from the daily total.

Programme 31. The first step is to calculate the hourly total radiation intensity on the horizontal plane from the daily total on horizontal plane using Whillier's method as described above. Secondly, the hourly total intensity on the tilted collector plane, facing south, is calculated from the total horizontal using the conversion formulae (4.8), (4.9) and (4.11). Results are printed and also a deck of cards is produced for use in Programme No. 1 and Programme No. 2.

Programme 3. If the hourly total horizontal measurements are available, hourly total radiation intensity on the tilted collector plane is calculated without carrying out step 1. Results are printed and also a deck of cards is produced for use in Programme No. 1 and Programme No. 2.

BOILER PRESSURES IN PSIA

4.74	5.99	7.51	9.34	11.25	14.12	17.19	20.78	24.97	29.82

CONDENSER PRESSURES IN PSIA

1.69	1.27	0.95	0.67	0.51	0.36	0.0	0.0	0.0	0.0

BOILER TEMPERATURES IN %F<

160.00	170.00	180.00	190.00	200.00	210.00	220.00	230.00	240.00	250.00

CONDENSER TEMPERATURES IN %F<

120.00	110.00	100.00	90.00	80.00	70.00	0.0	0.0	0.0	0.0

ENTHALPIES BTU/LB

1130.20	1134.20	1138.10	1142.00	1145.90	1149.70	1153.40	1157.00	1160.50	1164.00
1113.70	1109.50	1105.20	1100.90	1096.60	1092.30	0.0	0.0	0.0	0.0
127.89	137.90	147.92	157.95	167.99	178.05	188.13	198.23	208.34	218.48
87.92	77.94	67.97	57.99	48.02	38.04	0.0	0.0	0.0	0.0

ENTROPIES BTU/LB.F

1.8485	1.8293	1.8109	1.7932	1.7762	1.7598	1.7440	1.7288	1.7140	1.6998
1.9339	1.9577	1.9826	2.0087	2.0360	2.0647	0.0	0.0	0.0	0.0
0.2311	0.2472	0.2630	0.2785	0.2938	0.3090	0.3239	0.3387	0.3531	0.3675
0.1645	0.1471	0.1295	0.1115	0.0932	0.0745	0.0	0.0	0.0	0.0

TURBINE EFFICIENCIES
0.60

PUMP EFFICIENCIES
0.75

ABSORPTIVITIES
0.93

POWER RATING IN KW
12.00

TRANSMISSIVITIES
0.88

OVERALL HEAT LOSS COEFFICIENT
0.70

ALL PRICES IN DOLLARS

WOOD PRICE	GLASS PRI.	TEDLARP.	SHEET IRON	GLASWOOL	TUR.PRI.	CIRC.PUM.	FEED PUM.
5.50	0.37	0.30	0.20	0.10	180.00	150.00	100.00

PIPE PRICE	GOVER.PRI.	COND.TUBE	COND.SHELL	REPAIR	OPERATION	INTEREST	LIFETIME,YEARS
0.20	100.00	0.20	200.00	0.02	0.05	0.06	15.00

USE FACTOR	AMBIENT T	COOL W I	COOL W O	PIPE HEATLOSS
1.00	75.00	75.00	79.00	0.02

```
             C      OPTIMIZATION IN SOLAR POWER PRODUCTION
             C      USING HEAT ENGINES
             C      ORDINARY BLACK PAINTED FLAT PLATE COLLECTOR WITH  2 , 3 AND 4
             C      GLASS COVERS
             C      COST OF THE POWER PRODUCED FOR VARIOUS CONDENSER TEMPERATURES
             C      M.KUDRET SELCUK
             C      MAIN PROGRAMME
 0001               DIMENSION IPRINT(101),ISIGN(51),FINCOS(4002),EF(12,6)
 0002               DIMENSION  P1(11),P2(11),T1(11),T2(11),HV1(11),HV2(11),HFL1(11),
                   1HFL2(11),SV1(11),SFL1(11),SFL2(11),SX1(11),SX2(11),SV2(11),
                   2HX1(11),HX2(11),RADION(12,8),X1(11),X2(11),ETACOL(5),ETATUR(5),
                   3VOL1(11),VOL2(11),ULC(5),TAU(5),POWER(5),ALFA(5),ETAPUM(5)
 0003               COMMON  P1,P2,T1,T2,HV1,HV2,HFL1,HFL2,SV1,SV2,SFL1,SFL2,SX1,SX2,
                   1HX1,HX2,RADION,X1,X2,ETACOL,ETATUR,VOL1,VOL2,ULC,TAU,POWER,ALFA,
                   2ETAPUM,FLOW,PIPLOS,FRICLS,QADD,QREJ,CONSUR,TCWI,TCWO,UTIL,SUMRAD,
                   3AREA,COLINV,STOINV,SININV,TURINV,COTINV,REPAIR,OPERTN,ENTRS,EXPLIF
 0004               COMMON  I,J,K,L,M,N,II,JJ,KK,LL,MM,NN,IJ,IK,IL,IM,IN
 0005               COMMON ETARAN,TAMBI,EF
 0006               COMMON  PRWOOD,PRGLAS,PRTEDL,PRSTEL,PRFIBG,PRTUR,PRCIPU,PRFEPU,
                   1PRPIPE,PRGOVR,PRCUTU,PRCOSH,EFOVER,USEFAC,TOTINV,TOTEXP
 0007             1 FORMAT(10F8.2)
 0008             2 FORMAT(10F8.4)
 0009             3 FORMAT(5F10.2)
 0010             4 FORMAT(2F10.2)
 0011             5 FORMAT(  12F6.1 )
 0012             6 FORMAT(8F10.2)
 0013             7 FORMAT(12F6.2)
 0014             8 FORMAT(E12.6,15X,E12.6)
 0015             9 FORMAT(F 10.2)
 0016            10 FORMAT(6F12.4)
 0017            11 FORMAT(I6,10F10.2)
 0018            16 FORMAT(10(4X,A1))
 0019            17 FORMAT(4X,A1)
 0020            19 FORMAT(83H THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS
                  1  A#1 C/KWHR  Z#50 C/KWHR      )
 0021            20 FORMAT(10(F5.0,5X))
 0022            21 FORMAT(50(1X,A1))
 0023            22 FORMAT(F9.2,46H IS THE MIN COST REPRESENTED BY(A),RADIATION# F6.0,
                  15H ULC# F4.2,5H TAU# F4.2,6H ALFA# F4.2,9H GLAS.NU#  F4.0   //    )
 0024            23 FORMAT(1X,100A1)
 0025            25 FORMAT(1X,100A1,I5)
 0026            24 FORMAT(1X,100A1 /////)
 0027            26 FORMAT(1H1)
 0028            27 FORMAT(53H FIG   < CONDENSER TEMPERAT. -BOILER TEMP. VS COST      )
 0029            29 FORMAT(5I10)
 0030            30 FORMAT(27H BOILER PRESSURES IN PSIA       )
 0031            31 FORMAT(30H CONDENSER PRESSURES IN PSIA     )
 0032            32 FORMAT(28H BOILER TEMPERATURES IN %F<    )
 0033            33 FORMAT(31H CONDENSER TEMPERATURES IN %F<     )
 0034            34 FORMAT(20H ENTHALPIES BTU/LB       )
 0035            35 FORMAT(24H ENTROPIES BTU/LB.F         )
 0036            36 FORMAT(22H TURBINE EFFICIENCIES        )
 0037            37 FORMAT(19H PUMP EFFICIENCIES        )
 0038            38 FORMAT(16H ABSORPTIVITIES     )
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0039        40 FORMAT(20H POWER RATING IN KW    )
0040       140 FORMAT(18H TRANSMISSIVITIES      )
0041       141 FORMAT(33H OVERALL HEAT LOSS COEFFICIENT          )
0042       145 FORMAT(23H ALL PRICES IN DOLLARS       )
0043       146 FORMAT(83H WOOD PRICE GLASS PRI.TEDLARP.  SHEET IRON GLASWOOL  TUR
          1.PRI. CIRC.PUM.  FEED PUM.       )
0044       147 FORMAT(90H PIPE PRICE GOVER.PRI.COND.TUBE  COND.SHELL REPAIR   OPE
          1RATION INTEREST  LIFETIME,YEARS                    )
0045       148 FORMAT(54H USE FACTOR AMBIENT T COOL W I COOL W O PIPE HEATLOSS  )
0046           READ(5,16)(ISIGN(KK),KK=1,50)
0047           READ (5,17)IEMPTY
0048           READ(5,17)IBLANK
0049      1001 READ (5,29)NN,IJ,IK,IL,IM
0050           READ (5,1)(P1(M),M=1,10)
0051           READ (5,1)(P2(M),M=1,10)
0052           READ (5,1)(T1(M),M=1,10)
0053           READ (5,1)(T2(M),M=1,10)
0054           READ (5,1)(HV1(M),M=1,10)
0055           READ (5,1)(HV2(M),M=1,10)
0056           READ (5,1)(HFL1(M),M=1,10)
0057           READ (5,1)(HFL2(M),M=1,10)
0058           READ (5,2)(SV1(M),M=1,10)
0059           READ (5,2)(SV2(M),M=1,10)
0060           READ (5,2)(SFL1(M),M=1,10)
0061           READ (5,2)(SFL2(M),M=1,10)
0062           READ (5,10)P1(11),T1(11),HV1(11),SV1(11),HFL1(11),SFL1(11)
0063           READ (5,9)ETATUR(1)
0064           READ (5,9)ETAPUM(1)
0065           READ (5,9)ALFA(1)
0066           READ (5,9)POWER(1)
0067           READ (5,9)TAU(1)
0068           READ (5,9)ULC(1)
0069           READ (5,6)PRWOOD,PRGLAS,PRTEDL,PRSTEL,PRFIBG,PRTUR,PRCIPU,PRFEPU
0070           READ (5,6)PRPIPE,PRGOVR,PRCOTU,PRCUSH,REPAIR,OPERTN,FNTRS,EXPLIF
0071           READ (5,3)USEFAC,TAMBI,TCWI,TCWO,PIPLOS
0072           WRITE(6,26)
0073           WRITE(6,30)
0074           WRITE(6,1)(P1(M),M=1,10)
0075           WRITE(6,31)
0076           WRITE(6,1)(P2(M),M=1,10)
0077           WRITE(6,32)
0078           WRITE(6,1)(T1(M),M=1,10)
0079           WRITE(6,33)
0080           WRITE(6,1)(T2(M),M=1,10)
0081           WRITE(6,34)
0082           WRITE(6,1)(HV1(M),M=1,10)
0083           WRITE(6,1)(HV2(M),M=1,10)
0084           WRITE(6,1)(HFL1(M),M=1,10)
0085           WRITE(6,1)(HFL2(M),M=1,10)
0086           WRITE(6,35)
0087           WRITE(6,2)(SV1(M),M=1,10)
0088           WRITE(6,2)(SV2(M),M=1,10)
0089           WRITE(6,2)(SFL1(M),M=1,10)
0090           WRITE(6,2)(SFL2(M),M=1,10)
```

```
      WRITE(6,36)
      WRITE(6,9)ETATUR(1)
      WRITE(6,37)
      WRITE(6,9)ETAPUM(1)
      WRITE(6,38)
      WRITE(6,9)ALFA(1)
      WRITE(6,40)
      WRITE(6,9)POWER(1)
      WRITE(6,140)
      WRITE(6,9)TAU(1)
      WRITE(6,141)
      WRITE(6,9)ULC(1)
      WRITE(6,145)
      WRITE(6,146)
      WRITE(6,6)PRWOOD,PRGLAS,PRTEDL,PRSTEL,PRFIBG,PRTUR,PRCIPU,PRFEPU
      WRITE(6,147)
      WRITE(6,6)PRPIPE,PRGOVR,PRCOTU,PRCOSH,REPAIR,OPERTN,ENTRS,EXPLIF
      WRITE(6,148)
      WRITE(6,3)USEFAC,TAMBI,TCWI,TCWO,PIPLOS
      WRITE(6,26)
      DO 150 MTK=1,3
      K=1
      L=1
      MM=1
      II=1
      JJ=1
      JLM=1
      KJ=1
      LM=1
C     INTERPOLATION OF PHYSICAL PROPERTIES
      DO 200 J=2,4
      TN2=T2(J)
      PN2=P2(J)
      HVN2=HV2(J)
      SVN2=SV2(J)
      HFLN2=HFL2(J)
      SFLN2=SFL2(J)
      TINT2=T2(J+1)-T2(J)
      PINT2=P2(J+1)-P2(J)
      HVINT2=HV2(J+1)-HV2(J)
      SVINT2=SV2(J+1)-SV2(J)
      HFINT2=HFL2(J+1)-HFL2(J)
      SFINT2=SFL2(J+1)-SFL2(J)
      NNI=0
   73 ANNI=NNI
      PAT=ANNI/10.
      T2(J)=(    TINT2      )*PAT+TN2
      P2(J)=(  PINT2        )*PAT+PN2
      HV2(J)=(  HVINT2        )*PAT+HVN2
      SV2(J)=(    SVINT2       )*PAT+SVN2
      HFL2(J)=(  HFINT2           )*PAT+HFLN2
      SFL2(J)=(     SFINT2         )*PAT+SFLN2
      DO 100 I=1,10
      NI=0
```

```
0144          TN1=T1(I)
0145          PN1=P1(I)
0146          HVN1=HV1(I)
0147          SVN1=SV1(I)
0148          HFLN1=HFL1(I)
0149          SFLN1=SFL1(I)
0150          TINT1=T1(I+1)-T1(I)
0151          PINT1=P1(I+1)-P1(I)
0152          HVINT1=HV1(I+1)-HV1(I)
0153          SVINT1=SV1(I+1)-SV1(I)
0154          HFINT1=HFL1(I+1)-HFL1(I)
0155          SFINT1=SFL1(I+1)-SFL1(I)
0156       63 ANI=NI
0157          RAT=ANI/10.
0158          T1(I)=(   TINT1   )*RAT+TN1
0159          P1(I)=(   PINT1   )*RAT+PN1
0160          HV1(I)=(   HVINT1   )*RAT+ HVN1
0161          SV1(I)=(   SVINT1   )*RAT+ SVN1
0162          HFL1(I)=(   HFINT1    )*RAT+HFLN1
0163          SFL1(I)=(   SFINT1    )*RAT+SFLN1
        C     RANKINE CYCLE FOR SATURATED STEAM
        C     ISENTROPIC EXPANSION FROM THE SATURATED VAPOUR STATE
        C     X2   IS THE QUALITY OF STEAM AFTER ISENTROPIC EXPANSION
0164          X2(J)=(SV1(I)-SFL2(J))/(SV2(J)-SFL2(J))
0165          HX2(J)=HFL2(J)+X2(J)*(HV2(J)-HFL2(J))
        C     IDEAL WORK
0166          WOUI=HV1(I)-HX2(J)
        C     ACTUAL WORK
0167          WOUA=WOUI*ETATUR(K)
0168          QADD=HV1(I)-HFL2(J)
        C     PUMP WORK
0169          WPUMP=0.00298*(P1(I)-P2(J))
0170          ACRATE=POWER(L)*(1.+PIPLOS)
0171          WPUMPA=WPUMP/ETAPUM(K)
0172          WNETT=WOUA-WPUMPA
0173          ETARAN=WNETT/QADD
0174          QREJ=HX2(J)-HFL2(J)
0175          QTOT=ACRATE*3413.
0176          FLOW=QTOT/(QADD-QREJ)
        C     FLAT PLATE COLLECTOR PERFORMANCE,AREA ,COST CALCULATIONS
0177          QUSEF=QADD*(1.+PIPLOS)*FLOW
0178          JMN=1
0179          ETACOL(K)=0.20
0180          IF(MTK-1      )611,611,612
0181      611 GLANUM=2.
0182          GO TO 619
0183      612 IF(MTK-2      )613,613,614
0184      613 GLANUM=3.
0185          GO TO 619
0186      614 IF(MTK-3      )615,615,616
0187      615 GLANUM=4.
0188          GO TO 619
0189      616 IF(MTK-4      )617,617,619
0190      617 GLANUM=5.
```

```
0191      619 TAU(K)=0.88**GLANUM
        C     HOTTEL AND WOERTZ EQUATION FOR THE COLLECTOR HEAT LOSSES
0192          HRAD=0.1714E-08*((T1(I)+460.)**4.-(TAMBI+460.)**4.)/(T1(I)-TAMBI)
0193          ULC(K)=1.1*(1./(GLANUM/(0.21*((T1(I)-TAMBI)/(GLANUM+0.36))**0.25)
             1+2.46)+HRAD/(0.347+1.27*GLANUM))
0194          EFPRIM=0.9
0195          RADION(II,JJ)=220.
0196          CHECK=RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*(T1(I)-TAMBI)
0197       39 IF(CHECK)47,47,41
0198       41 AREAPP=QUSEF/(RADION(II,JJ)*ETACOL(K))
0199          G=FLOW/(0.1*AREAPP)
0200      520 EXPON=EFPRIM*ULC(K)/G
0201          IF(EXPCN-100.)522,522,523
0202      522 FLOFAC=(1.-(1./(2.718**EXPON)))/EXPON
0203          GO TO 526
0204      523 FLOFAC=0.01
0205      526 FR=FLOFAC*EFPRIM
0206          ARESEN=0.1*QUSEF/(FR*(RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*
             1(T2(J)-TAMBI)))
0207          ARELAT=0.9*QUSEF/(EFPRIM*(RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*
             1(T1(I)-TAMBI)))
0208          AREA=ARESEN+ARELAT
0209          G=FLOW/ARESEN
0210          JMN=JMN+1
0211          ETACOL(K)=FR*CHECK/RADION(II,JJ)
0212          IF(JMN-2)520,520,45
0213       45 EF(II,JJ)=ETARAN*ETACOL(K)
0214          IF(EF(II,JJ))47,47,48
0215       47 EF(II,JJ)=0.
0216          TOTWRK=1.0
0217          GO TO 51
0218       48 TOTHOU=2400.
0219          TOTWRK=AREA*EF(II,JJ)*USEFAC*RADION(II,JJ)*TOTHOU/3413.
0220       51 COLCOS=(5.5+(GLANUM-2.0)*1.2*PRGLAS)*AREA
0221          ASSEM=1.2
0222          COLINV=COLCOS*ASSEM
        C     NO STORAGE SYSTEM IS REQUIRED
0223          STOINV=0.
        C     TEMPERATURE AND AUTOMATIC CONTROLS COST
0224          COTINV=250.
        C     TURBINE PERFORMANCE AND AND COST ANLYSIS
        C     IF THE SYSTEM SHOULD OPERATE BELOW 212  DEG.F. A VACUUM PUMP
        C     MUST BE USED
0225          IF(T1(I)-212.)54,54,56
0226       54 PRVAPU=250.
0227          TURINV=PRTUR*POWER(K)+PRCIPU+PRFEPU+PRVAPU
0228          GO TO 57
0229       56 TURINV=PRTUR*POWER(K)+PRCIPU+PRFEPU
        C     CONDENSER PERFORMANCE ,CONDENSING SURFACE REQUIREMENTS AND COST
0230       57 QREJTO=FLOW*QREJ
0231          FILMIN=1000.
0232          FILMOU=50.
0233          TUBTHK=0.001
0234          TUBCND=100.
```

```
            UNIVER=1./(1./FILMOU+1./FILMIN+TUBTHK/TUBCND)
            ELEMTD=T2(J)-(TCWO+TCWI)/2.
            CONSUR=QREJTO/(ELEMTD*UNIVER)
            SININV=CONSUR*PRCOTU+PRCOSH
C           FINAL COST CALCULATIONS,COST PER KWHR
            TOTINV=COLINV+STOINV+SININV+TURINV+COTINV
            CAREFC=ENTRS*(1.+ENTRS)**EXPLIF/((1.+ENTRS)**EXPLIF-1.)
            TOTEXP=TOTINV*(CAREFC+REPAIR+OPERTN)
            FINCOS(MM)=TOTEXP/TOTWRK
            IF(FINCOS(MM)-0.40)177,177,178
        177 WRITE(6,11)MM,T1(I),T2(J),TOTINV,TOTEXP,FINCOS(MM),AREA,COLCOS,
           1RADION(II,JJ) ,ETACOL(K),EF(II,JJ)
        178 CONTINUE
C           GENERATING THE MATRIX  FINCOS%3000< TO STORE COST FIGURE FOR
C           ALL COMBINATIONS OF T1 AND T2
            MM=MM+1
            NI=NI+1
         59 IF(NI-10)63,61,100
         61 T1(I)=TN1
            P1(I)=PN1
            HV1(I)=HVN1
            SV1(I)=SVN1
            HFL1(I)=HFLN1
            SFL1(I)=SFLN1
        100 CONTINUE
            NNI=NNI+1
            IF(NNI-9)83,81,200
         81 CONTINUE
         83 IF(MM-3000)93,93,200
         93 GO TO 73
        200 CONTINUE
C           MAXIMUM COST WITHIN THE RANGE OF PARAMETERS VARIATION
            COSMIN=FINCOS(1)
            COSMAX=FINCOS(1)
            KL=1
        201 IF(FINCOS(KL)-COSMAX)204,204,203
        203 COSMAX=FINCOS(KL)
        204 IF(FINCOS(KL)-COSMIN)207,207,205
        207 COSMIN=FINCOS(KL)
        205 KL=KL+1
            IF(KL-MM)201,208,208
        208 WRITE(6,26)
            DO 210 IM=1,100
        210 IPRINT(IM)=IBLANK
            WRITE(6,24)(IPRINT(IM),IM=1,100)
            LINE=0
            LM=1
            ELM=LM
C           MAPPING THE COST FUNCTION AGAINST T1 AND T2, COST#FNC%T1,T2<
C           SET THE MATRIX INTO A BLANK SPACE% -  IS USED FOR BLANKS<
        211 DO 215 KIL=1,100
        215 IPRINT(KIL)=IBLANK
        213 KK=FINCOS(LM)*100. +1.0
            IF(KK-50)91,91,90
```

```
0282          90 KK=50
0283          91 AMM=FLOAT(LM)/100.+1.
0284             NMM=AMM
0285             CMM=NMM
0286             IF(AMM-CMM)214,219,214
0287         214 IKI=(AMM-CMM)*99.+1.
0288             IPRINT(IKI)=ISIGN(KK)
0289             LM=LM+1
0290             IF(LM-3000)218,218,219
0291         218 GO TO 213
0292         219 IPRINT(100)=ISIGN(KK)
        C        PLOTTING THE RESULTS FOR ONE FIXED CONDENSER TEMPERATURE&T2<
0293             LINE=LINE+1
0294             NLINE =111 -LINE
0295             KLINE=(NLINE/10)*10-NLINE
0296             IF(KLINE)222,224,222
0297         222 WRITE(6,23)(IPRINT(LKL),LKL=1,100)
0298             GO TO 226
0299         224 WRITE(6,25)(IPRINT(LKL),LKL=1,100),NLINE
        C        PRINT LINES FOR ALL T2 UNTIL THE RANGE IS COVERED
0300         226 IF(LM-3000)212,217,217
0301         212 LM=LM+1
0302             GO TO 213
0303         217 DO  231 JLM=1,100
0304         231 IPRINT(JLM)=IBLANK
0305             DO  235 JLM=5,100,5
0306         235 IPRINT(JLM)=ISIGN(42)
0307             WRITE(6,23)(IPRINT(JLM),JLM=1,100)
0308             WRITE(6,20)(T1(I),I=1,10)
0309             WRITE (6,19)
0310             WRITE(6,21)(ISIGN(KJ),KJ=1,50)
0311             COCENT=COSMIN*100.
0312             WRITE(6,22)COCENT,RADION(II,JJ),ULC(L),TAU(L),ALFA(L),GLANUM
0313             WRITE(6,27)
0314             WRITE(6,26)
0315         150 CONTINUE
0316             IF(NN-1)999,1001,999
0317         999 CALL EXIT
0318             DEBUG SUBCHK
0319             END
```

TOTAL MEMORY REQUIREMENTS 0083D8 BYTES

SAMPLE RESULTS OF PROGRAMME: OO

1817	176.00	83.00	29948.89	5180.05	0.40	3737.63	22216.45	220.00	0.27	0.02
1818	177.00	83.00	29886.61	5169.28	0.40	3729.15	22166.05	220.00	0.26	0.02
1819	178.00	83.00	29828.35	5159.20	0.40	3721.23	22118.98	220.00	0.26	0.02
1820	179.00	83.00	29774.68	5149.92	0.40	3713.95	22075.71	220.00	0.26	0.02
1821	180.00	83.00	29725.01	5141.33	0.40	3707.23	22035.75	220.00	0.26	0.02
1822	181.00	83.00	29685.77	5134.54	0.40	3701.95	22004.41	220.00	0.26	0.02
1909	168.00	82.00	30349.39	5249.32	0.40	3786.49	22506.91	220.00	0.28	0.02
1910	169.00	82.00	30245.55	5231.37	0.40	3772.29	22422.51	220.00	0.28	0.02
1911	170.00	82.00	30146.33	5214.20	0.40	3758.73	22341.91	220.00	0.28	0.02
1912	171.00	82.00	30061.54	5199.54	0.40	3747.18	22273.23	220.00	0.28	0.02
1913	172.00	82.00	29981.14	5185.63	0.40	3736.23	22208.16	220.00	0.27	0.02
1914	173.00	82.00	29905.13	5172.48	0.40	3725.90	22146.73	220.00	0.27	0.02
1915	174.00	82.00	29833.52	5160.10	0.40	3716.17	22088.91	220.00	0.27	0.02
1916	175.00	82.00	29765.94	5148.41	0.40	3707.01	22034.43	220.00	0.27	0.02
1917	176.00	82.00	29702.44	5137.43	0.40	3698.40	21983.31	220.00	0.27	0.02
1918	177.00	82.00	29643.39	5127.21	0.40	3690.42	21935.87	220.00	0.26	0.02
1919	178.00	82.00	29588.32	5117.69	0.40	3683.00	21891.72	220.00	0.26	0.02
1920	179.00	82.00	29537.66	5108.93	0.40	3676.18	21851.20	220.00	0.26	0.02
1921	180.00	82.00	29490.97	5100.85	0.40	3669.92	21813.97	220.00	0.26	0.02
1922	181.00	82.00	29454.43	5094.53	0.40	3665.06	21785.12	220.00	0.26	0.02
1923	182.00	82.00	29422.08	5088.94	0.40	3660.79	21759.74	220.00	0.25	0.02
1924	183.00	82.00	29393.52	5084.00	0.40	3657.05	21737.49	220.00	0.25	0.02
1925	184.00	82.00	29368.77	5079.71	0.40	3653.83	21718.39	220.00	0.25	0.02
1926	185.00	82.00	29348.13	5076.14	0.40	3651.19	21702.68	220.00	0.25	0.02
1927	186.00	82.00	29331.36	5073.25	0.40	3649.09	21690.18	220.00	0.24	0.02
1928	187.00	82.00	29318.34	5070.99	0.40	3647.51	21680.78	220.00	0.24	0.02
1929	188.00	82.00	29309.56	5069.47	0.40	3646.52	21674.89	220.00	0.24	0.02
2005	164.00	81.00	30545.88	5283.31	0.40	3804.61	22614.59	220.00	0.29	0.02
2006	165.00	81.00	30426.73	5262.70	0.40	3788.38	22518.11	220.00	0.29	0.02
2007	166.00	81.00	30312.46	5242.94	0.40	3772.82	22425.65	220.00	0.29	0.02
2008	167.00	81.00	30203.05	5224.02	0.40	3757.94	22337.18	220.00	0.29	0.02
2009	168.00	81.00	30098.57	5205.94	0.40	3743.74	22252.77	220.00	0.28	0.02
2010	169.00	81.00	29998.77	5188.68	0.40	3730.18	22172.20	220.00	0.28	0.02
2011	170.00	81.00	29903.55	5172.21	0.39	3717.26	22095.40	220.00	0.28	0.02
2012	171.00	81.00	29822.29	5158.16	0.39	3706.28	22030.10	220.00	0.28	0.02
2013	172.00	81.00	29745.37	5144.85	0.39	3695.89	21968.36	220.00	0.28	0.02
2014	173.00	81.00	29672.73	5132.29	0.39	3686.09	21910.14	220.00	0.27	0.02
2015	174.00	81.00	29604.34	5120.46	0.39	3676.89	21855.43	220.00	0.27	0.02
2016	175.00	81.00	29539.93	5109.32	0.39	3668.24	21804.00	220.00	0.27	0.02
2017	176.00	81.00	29479.52	5098.87	0.39	3660.14	21755.85	220.00	0.27	0.02
2018	177.00	81.00	29423.43	5089.17	0.39	3652.64	21711.27	220.00	0.26	0.02
2019	178.00	81.00	29371.20	5080.14	0.39	3645.67	21669.87	220.00	0.26	0.02
2020	179.00	81.00	29323.29	5071.85	0.39	3639.30	21632.02	220.00	0.26	0.02
2021	180.00	81.00	29279.30	5064.24	0.39	3633.48	21597.41	220.00	0.26	0.02
2022	181.00	81.00	29245.22	5058.34	0.39	3629.03	21570.97	220.00	0.26	0.02
2023	182.00	81.00	29215.28	5053.17	0.39	3625.16	21547.95	220.00	0.25	0.02
2024	183.00	81.00	29189.02	5048.62	0.39	3621.80	21527.95	220.00	0.25	0.02
2025	184.00	81.00	29166.51	5044.73	0.39	3618.95	21511.06	220.00	0.25	0.02
2026	185.00	81.00	29148.05	5041.54	0.40	3616.68	21497.52	220.00	0.25	0.02
2027	186.00	81.00	29133.37	5039.00	0.40	3614.92	21487.09	220.00	0.24	0.02
2028	187.00	81.00	29122.38	5037.10	0.40	3613.68	21479.70	220.00	0.24	0.02
2029	188.00	81.00	29115.56	5035.92	0.40	3613.02	21475.77	220.00	0.24	0.02
2030	189.00	81.00	29112.43	5035.38	0.40	3612.87	21474.88	220.00	0.24	0.02
2031	190.00	81.00	29113.49	5035.56	0.40	3613.30	21477.46	220.00	0.24	0.02
2032	191.00	81.00	29123.97	5037.37	0.40	3615.04	21487.81	220.00	0.23	0.02
2104	163.00	80.90	30644.62	5300.39	0.40	3816.94	22687.98	220.00	0.29	0.02
2105	164.00	80.90	30521.00	5279.01	0.40	3800.10	22587.80	220.00	0.29	0.02
2106	165.00	80.90	30402.29	5258.48	0.40	3783.95	22491.77	220.00	0.29	0.02

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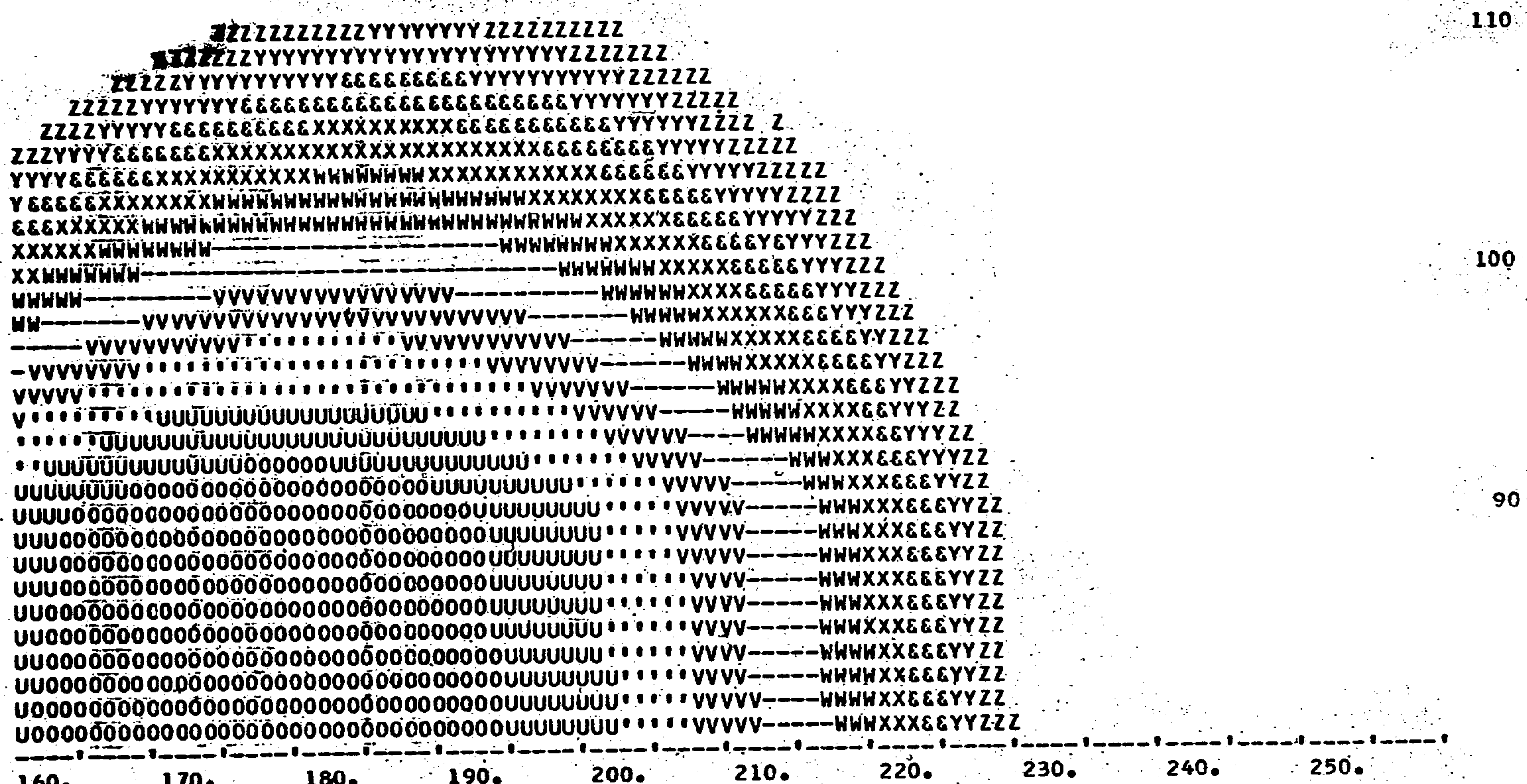
                                                                                                                    100



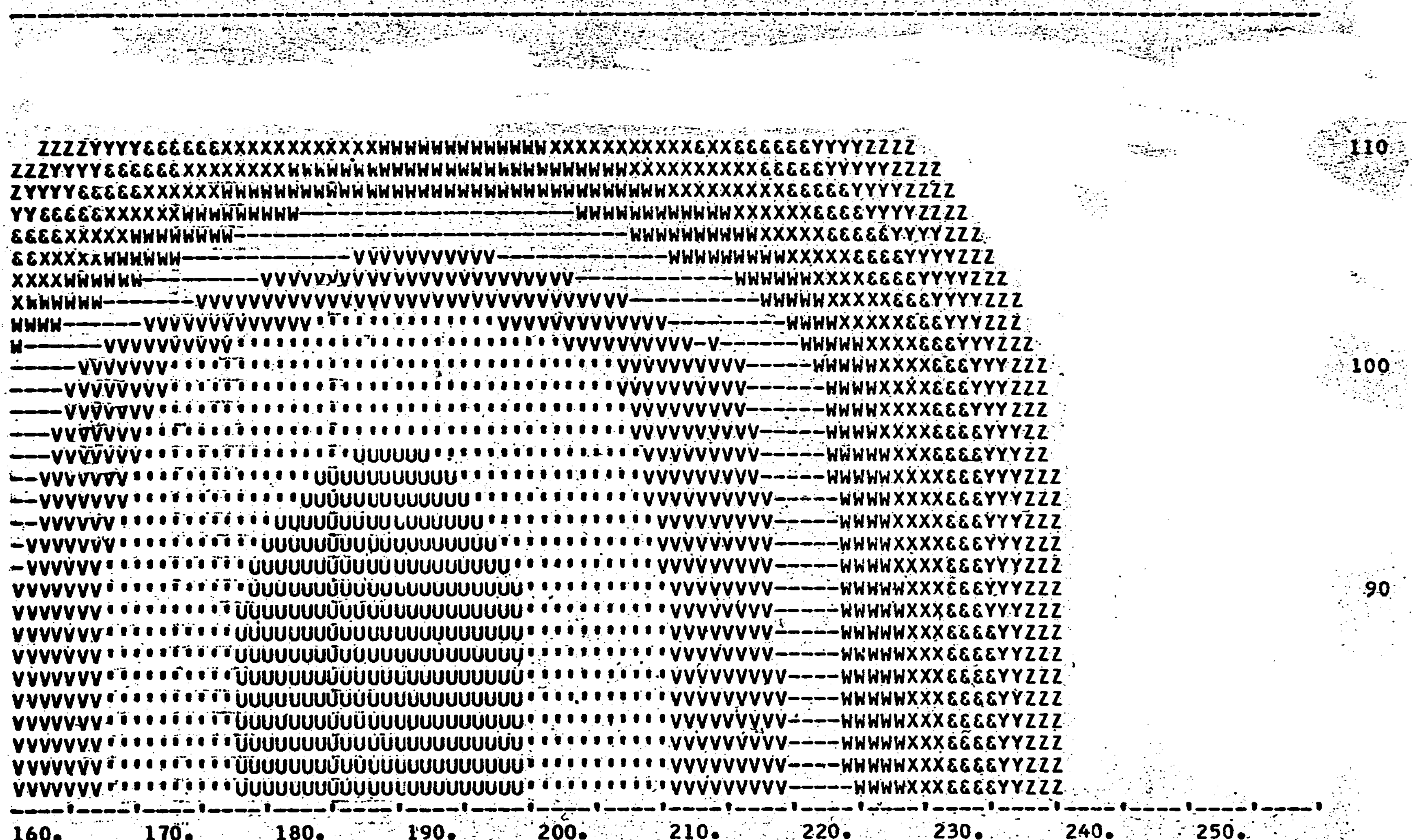

ZZZZZZZZZZZZZZZZZ                                                                                                    90
ZZZYYYYYYYYYZZZZZZZZZ
YYYYYYYYYYYYYYYYYYZZZZZZ
&&&&&&&&&&&&&YYYYYYYZZZZZZ
&&&&&&&&&&&&&&&&&&YYYYYYZZZZ
XXXXXXXXXXXXX&&&&&&&YYYYYZZZZ
XXXXXXXXXXXXXXXXXX&&&&&&YYYYZZZ
WWWWWWWWWWWWWWWXXXXXXX&&&&YYYZZZZ
W----WWWWWWWWWWWWWXXXXX&&&&YYYYZZZ
-------------WWWWWWWXXXXX&&&&YYYZZZ
----------------WWWWWWXXXXX&&&YYYZZZ
VVVVVVVVVVV---------WWWWWXXXX&&&YYYZZZ
----!-----!-----!-----!-----!-----!-----!-----!-----!-----!-----!-----!-----!-----!-----!-----!-----!-----!-----!
160.      170.      180.      190.      200.      210.      220.      230.      240.      250.
THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS    A#1 C/KWHR  Z#50 C/KWHR
A % B = C + D , E $ F * G / H < I 0 J . K 1 L 2 M 3 N 4 O 5 P 6 Q 7 R 8 S 9 T 0 U ' V - W X & Y Z
   42.64 IS THE MIN COST REPRESENTED BY(A),RADIATION#   220. ULC#0.85 TAU#0.77 ALFA#0.93 GLAS.NU#  2.

FIG   < CONDENSER TEMPERAT. -BOILER TEMP. VS COST
```



THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS A#1 C/KWHR Z#50 C/KWHR
A % B = C + D , E $ F * G / H < I 0 J . K 1 L 2 M 3 N 4 O 5 P 6 Q 7 R 8 S 9 T 0 U ' V - W X & Y Z
39.10 IS THE MIN COST REPRESENTED BY(A),RADIATION# 220. ULC#0.60 TAU#0.68 ALFA#0.93 GLAS.NU# 3.

FIG < CONDENSER TEMPERAT. -BOILER TEMP. VS COST



THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS A#1 C/KWHR Z#50 C/KWHR
A % B = C + D , E $ F * G / H < I 0 J . K 1 L 2 M 3 N 4 O 5 P 6 Q 7 R 8 S 9 T 0 U ' V - W X & Y Z
40.67 IS THE MIN COST REPRESENTED BY(A),RADIATION# 220. ULC#0.46 TAU#0.60 ALFA#0.93 GLAS.NU# 4.

FIG < CONDENSER TEMPERAT. -BOILER TEMP. VS COST

PROGRAMME : O

```
             C      OPTIMIZATION IN SOLAR POWER PRODUCTION
             C      USING HEAT ENGINES
             C      ORDINARY BLACK PAINTED FLAT PLATE COLLECTOR WITH  2 , 3 AND 4
             C      GLASS COVERS
             C      COST OF THE POWER PRODUCED FOR VARIOUS CONDENSER TEMPERATURES
             C      M.KUDRET SELCUK
             C      MAIN PROGRAMME
0001                DIMENSION IPRINT(101),ISIGN(51),FINCOS(4002),EF(12,6)
0002                DIMENSION  P1(11),P2(11),T1(11),T2(11),HV1(11),HV2(11),HFL1(11),
                   1HFL2(11),SV1(11),SFL1(11),SFL2(11),SX1(11),SX2(11),SV2(11),
                   2HX1(11),HX2(11),RADION(12,8),X1(11),X2(11),ETACOL(5),ETATUR(5),
                   3VOL1(11),VOL2(11),ULC(5),TAU(5),POWER(5),ALFA(5),ETAPUM(5)
0003              1 FORMAT(10F8.2)
0004              2 FORMAT(10F8.4)
0005              3 FORMAT(5F10.2)
0006              4 FORMAT(2F10.2)
0007              5 FORMAT(  12F6.1 )
0008              6 FORMAT(8F10.2)
0009              7 FORMAT(12F6.2)
0010              8 FORMAT(E12.6,15X,E12.6)
0011              9 FORMAT(F10.2)
0012             10 FORMAT(6F12.4)
0013             11 FORMAT(I6,10F10.2)
0014             16 FORMAT(10(4X,A1))
0015             17 FORMAT(4X,A1)
0016             19 FORMAT(83H THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS
                   1  A#1 C/KWHR  Z#50 C/KWHR      )
0017             20 FORMAT(10(F5.0,5X))
0018             21 FORMAT(50(1X,A1))
0019             22 FORMAT(F9.2,46H IS THE MIN COST REPRESENTED BY(A),COND.TEMP= F6.0,
                   15H ULC# F4.2,5H TAU# F4.2,6H ALFA# F4.2,9H GLAS.NU#  F4.0   //    )
0020             23 FORMAT(1X, 90A1)
0021             24 FORMAT(1X,100A1 /////)
0022             25 FORMAT(1X, 90A1,I4)
0023             26 FORMAT(1H1)
0024             27 FORMAT(53H FIG   < RADIATION INTENSITY -BOILER TEMP. VS COST      )
0025             29 FORMAT(5I10)
0026             30 FORMAT(27H BOILER PRESSURES IN PSIA       )
0027             31 FORMAT(30H CONDENSER PRESSURES IN PSIA      )
0028             32 FORMAT(28H BOILER TEMPERATURES IN %F<     )
0029             33 FORMAT(31H CONDENSER TEMPERATURES IN %F<     )
0030             34 FORMAT(20H ENTHALPIES BTU/LB       )
0031             35 FORMAT(24H ENTROPIES BTU/LB.F          )
0032             36 FORMAT(22H TURBINE EFFICIENCIES        )
0033             37 FORMAT(19H PUMP EFFICIENCIES       )
0034             38 FORMAT(16H ABSORPTIVITIES      )
0035             40 FORMAT(20H POWER RATING IN KW     )
0036            140 FORMAT(18H TRANSMISSIVITIES      )
0037            141 FORMAT(33H OVERALL HEAT LOSS COEFFICIENT          )
0038            145 FORMAT(23H ALL PRICES IN DOLLARS  -    )
0039            146 FORMAT(83H WOOD PRICE GLASS PRI.TEDLARP.  SHEET IRON GLASWOOL  TUR
                   1.PRI. CIRC.PUM.  FEED PUM.      )
0040            147 FORMAT(90H PIPE PRICE GOVER.PRI.COND.TUBE  COND.SHELL REPAIR   OPE
                   1RATION INTEREST  LIFETIME,YEARS            )
```

```
  149 FORMAT(54H USE FACTOR AMBIENT T COOL W I COOL W O PIPE HEATLOSS  )
      READ(5,16)(ISIGN(KK),KK=1,50)
      READ (5,17)IEMPTY
      READ(5,17)IBLANK
 1001 READ (5,29)NN,IJ,IK,IL,IM
      READ (5,1)(P1(M),M=1,10)
      READ (5,1)(P2(M),M=1,10)
      READ (5,1)(T1(M),M=1,10)
      READ (5,1)(T2(M),M=1,10)
      READ (5,1)(HV1(M),M=1,10)
      READ (5,1)(HV2(M),M=1,10)
      READ (5,1)(HFL1(M),M=1,10)
      READ (5,1)(HFL2(M),M=1,10)
      READ (5,2)(SV1(M),M=1,10)
      READ (5,2)(SV2(M),M=1,10)
      READ (5,2)(SFL1(M),M=1,10)
      READ (5,2)(SFL2(M),M=1,10)
      READ (5,10)P1(11),T1(11),HV1(11),SV1(11),HFL1(11),SFL1(11)
      READ (5,9)ETATUR(1)
      READ (5,9)ETAPUM(1)
      READ (5,9)ALFA(1)
      READ (5,9)POWER(1)
      READ (5,9)TAU(1)
      READ (5,9)ULC(1)
      READ (5,6)PRWOOD,PRGLAS,PRTEDL,PRSTEL,PRFIBG,PRTUR,PRCIPU,PRFEPU
      READ (5,6)PRPIPE,PRGOVR,PRCOTU,PRCOSH,REPAIR,OPERTN,ENTRS,EXPLIF
      READ (5,3)USEFAC,TAMBI,TCWI,TCWO,PIPLOS
      WRITE(6,26)
      WRITE(6,30)
      WRITE(6,1)(P1(M),M=1,10)
      WRITE(6,31)
      WRITE(6,1)(P2(M),M=1,10)
      WRITE(6,32)
      WRITE(6,1)(T1(M),M=1,10)
      WRITE(6,33)
      WRITE(6,1)(T2(M),M=1,10)
      WRITE(6,34)
      WRITE(6,1)(HV1(M),M=1,10)
      WRITE(6,1)(HV2(M),M=1,10)
      WRITE(6,1)(HFL1(M),M=1,10)
      WRITE(6,1)(HFL2(M),M=1,10)
      WRITE(6,35)
      WRITE(6,2)(SV1(M),M=1,10)
      WRITE(6,2)(SV2(M),M=1,10)
      WRITE(6,2)(SFL1(M),M=1,10)
      WRITE(6,2)(SFL2(M),M=1,10)
      WRITE(6,36)
      WRITE(6,9)ETATUR(1)
      WRITE(6,37)
      WRITE(6,9)ETAPUM(1)
      WRITE(6,38)
      WRITE(6,9)ALFA(1)
      WRITE(6,40)
      WRITE(6,9)POWER(1)
```

```
0095          WRITE(6,140)
0096          WRITE(6,9)TAU(1)
0097          WRITE(6,141)
0098          WRITE(6,9)ULC(1)
0099          WRITE(6,145)
0100          WRITE(5,146)
0101          WRITE(6,6)PRWOOD,PRGLAS,PRTEDL,PRSTEL,PRFIBG,PRTUR,PRCIPU,PRFEPU
0102          WRITE(6,147)
0103          WRITE(6,5)PRPIPE,PRGOVR,PRCOTU,PRCOSH,REPAIR,OPERTN,ENTRS,EXPLIF
0104          WRITE(6,148)
0105          WRITE(5,3)USEFAC,TAMBI,TCWI,TCWO,PIPLOS
0106          WRITE(6,26)
0107          J=3
      C       INTERPOLATION OF PHYSICAL PROPERTIES
0108          TN2=T2(J)
0109          PN2=P2(J)
0110          HVN2=HV2(J)
0111          SVN2=SV2(J)
0112          HFLN2=HFL2(J)
0113          SFLN2=SFL2(J)
0114          TINT2=T2(J+1)-T2(J)
0115          PINT2=P2(J+1)-P2(J)
0116          HVINT2=HV2(J+1)-HV2(J)
0117          SVINT2=SV2(J+1)-SV2(J)
0118          HFINT2=HFL2(J+1)-HFL2(J)
0119          SFINT2=SFL2(J+1)-SFL2(J)
0120          PAT=0.5
0121          T2(J)=(   TINT2      )*PAT+TN2
0122          P2(J)=(  PINT2       )*PAT+PN2
0123          HV2(J)=(  HVINT2       )*PAT+HVN2
0124          SV2(J)=(    SVINT2       )*PAT+SVN2
0125          HFL2(J)=(  HFINT2          )*PAT+HFLN2
0126          SFL2(J)=(     SFINT2        )*PAT+SFLN2
0127          DO 150 MTK=1,3
0128          K=1
0129          L=1
0130          MM=1
0131          II=1
0132          JJ=1
0133          JLM=1
0134          KJ=1
0135          LM=1
0136          DO 250 KJK=1,30
0137          RADION(II,JJ)=335.-5.*FLOAT(KJK)
0138          DO 100 I=1,10
0139          NI=0
0140          TN1=T1(I)
0141          PN1=P1(I)
0142          HVN1=HV1(I)
0143          SVN1=SV1(I)
0144          HFLN1=HFL1(I)
0145          SFLN1=SFL1(I)
0146          TINT1=T1(I+1)-T1(I)
0147          PINT1=P1(I+1)-P1(I)
```

```
0148          HVINT1=HV1(I+1)-HV1(I)
0149          SVINT1=SV1(I+1)-SV1(I)
0150          HFINT1=HFL1(I+1)-HFL1(I)
0151          SFINT1=SFL1(I+1)-SFL1(I)
0152       63 ANI=NI
0153          RAT=ANI/10.
0154          T1(I)=(   TINT1    )*RAT+TN1
0155          P1(I)=(   PINT1    )*RAT+PN1
0156          HV1(I)=(   HVINT1    )*RAT+ HVN1
0157          SV1(I)=(   SVINT1    )*RAT+ SVN1
0158          HFL1(I)=(   HFINT1     )*RAT+HFLN1
0159          SFL1(I)=(   SFINT1     )*RAT+SFLN1
        C     RANKINE CYCLE FOR SATURATED STEAM
        C     ISENTROPIC EXPANSION FROM THE SATURATED VAPOUR STATE
        C     X2   IS THE QUALITY OF STEAM AFTER ISENTROPIC EXPANSION
0160          X2(J)=(SV1(I)-SFL2(J))/(SV2(J)-SFL2(J))
0161          HX2(J)=HFL2(J)+X2(J)*(HV2(J)-HFL2(J))
        C     IDEAL WORK
0162          WOUI=HV1(I)-HX2(J)
        C     ACTUAL WORK
0163          WOUA=WOUI*ETATUR(K)
0164          QADD=HV1(I)-HFL2(J)
        C     PUMP WORK
0165          WPUMP=0.00298*(P1(I)-P2(J))
0166          ACRATE=POWER(L)*(1.+PIPLOS)
0167          WPUMPA=WPUMP/ETAPUM(K)
0168          WNETT=WOUA-WPUMPA
0169          ETARAN=WNETT/QADD
0170          QREJ=HX2(J)-HFL2(J)
0171          QTOT=ACRATE*3413.
0172          FLOW=QTOT/(QADD-QREJ)
        C     FLAT PLATE COLLECTOR PERFORMANCE,AREA ,COST CALCULATIONS
0173          QUSEF=QADD*(1.+PIPLOS)*FLOW
0174          JMN=1
0175          ETACOL(K)=0.20
0176          IF(MTK-1      )611,611,612
0177      611 GLANUM=2.
0178          GO TO 619
0179      612 IF(MTK-2      )613,613,614
0180      613 GLANUM=3.
0181          GO TO 619
0182      614 IF(MTK-3      )615,615,616
0183      615 GLANUM=4.
0184          GO TO 619
0185      616 IF(MTK-4      )617,617,619
0186      617 GLANUM=5.
0187      619 TAU(K)=0.88**GLANUM
        C     HOTTEL AND WOERTZ EQUATION FOR THE COLLECTOR HEAT LOSSES
0188          HRAD=0.1714E-08*((T1(I)+460.)**4.-(TAMBI+460.)**4.)/(T1(I)-TAMBI)
0189          ULC(K)=1.1*(1./(GLANUM/(0.21*((T1(I)-TAMBI)/(GLANUM+0.36))**0.25)
         1+2.46)+HRAD/(0.347+1.27*GLANUM))
0190          EFPRIM=0.9
0191          CHECK=RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*(T1(I)-TAMBI)
0192          RADCRT=1.05*ULC(K)*(T1(I)-TAMBI)/(TAU(K)*ALFA(K))
```

```
0193          IF(RADION(II,JJ)-RADCRT)47,47,39
0194       39 IF(CHECK)47,47,41
0195       41 AREAPP=QUSEF/(RADION(II,JJ)*ETACOL(K))
0196          G=FLOW/(0.1*AREAPP)
0197      520 EXPON=EFPRIM*ULC(K)/G
0198          IF(EXPON-100.)522,522,523
0199      522 FLOFAC=(1.-(1./(2.718**EXPON)))/EXPON
0200          GO TO 526
0201      523 FLOFAC=0.01
0202      526 FR=FLOFAC*EFPRIM
0203          ARESEN=0.1*QUSEF/(FR*(RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*
         1(T2(J)-TAMBI)))
0204          ARELAT=0.9*QUSEF/(EFPRIM*(RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*
         1(T1(I)-TAMBI)))
0205          AREA=ARESEN+ARELAT
0206          G=FLOW/ARESEN
0207          JMN=JMN+1
0208          ETACOL(K)=FR*CHECK/RADION(II,JJ)
0209          IF(JMN-2)520,520,45
0210       45 EF(II,JJ)=ETARAN*ETACOL(K)
0211          IF(EF(II,JJ))47,47,48
0212       47 EF(II,JJ)=0.000001
0213          TOTWRK=0.000001
0214          GO TO 51
0215       48 TOTHOU=2400.
0216          TOTWRK=AREA*EF(II,JJ)*USEFAC*RADION(II,JJ)*TOTHOU/3413.
0217       51 COLCOS=(5.5+(GLANUM-2.0)*1.2*PRGLAS)*AREA
0218          ASSEM=1.2
0219          COLINV=COLCOS*ASSEM
        C     NO STORAGE SYSTEM IS REQUIRED
0220          STOINV=0.
        C     TEMPERATURE AND AUTOMATIC CONTROLS COST
0221          COTINV=250.
        C     TURBINE PERFORMANCE AND AND COST ANLYSIS
        C     IF THE SYSTEM SHOULD OPERATE BELOW 212  DEG.F. A VACUUM PUMP
        C     MUST BE USED
0222          IF(T1(I)-212.)54,54,56
0223       54 PRVAPU=250.
0224          TURINV=PRTUR*POWER(K)+PRCIPU+PRFEPU+PRVAPU
0225          GO TO 57
0226       56 TURINV=PRTUR*POWER(K)+PRCIPU+PRFEPU
        C     CONDENSER PERFORMANCE AND COST
0227       57 SININV=PRCOSH+100.
        C     FINAL COST CALCULATIONS,COST PER KWHR
0228          TOTINV=COLINV+STOINV+SININV+TURINV+COTINV
0229          CAREFC=ENTRS*(1.+ENTRS)**EXPLIF/((1.+ENTRS)**EXPLIF-1.)
0230          TOTEXP=TOTINV*(CAREFC+REPAIR+OPERTN)
0231          FINCOS(MM)=TOTEXP/TOTWRK
0232          IF(FINCOS(MM)-0.20)177,177,178
0233      177 WRITE(5,11)MM,T1(I),T2(J),TOTINV,TOTEXP,FINCOS(MM),AREA,COLCOS,
         1RADION(II,JJ) ,ETACOL(K),EF(II,JJ)
0234      178 CONTINUE
        C     GENERATING THE MATRIX  FINCOS%3000< TO STORE COST FIGURE FOR
        C     ALL COMBINATIONS OF T1 AND T2
```

```
          MM=MM+1
          NI=NI+1
       59 IF(NI-10)63,61,100
       61 T1(I)=TN1
          P1(I)=PN1
          HV1(I)=HVN1
          SV1(I)=SVN1
          HFL1(I)=HFLN1
          SFL1(I)=SFLN1
      100 CONTINUE
      250 CONTINUE
C         THE MINIMUM COST WITHIN THE RANGE OF VARATION OF PARAMETERS
          COSMIN=FINCOS(1)
          COSMAX=FINCOS(1)
          KL=1
      201 IF(FINCOS(KL)-COSMAX)204,204,203
      203 COSMAX=FINCOS(KL)
      204 IF(FINCOS(KL)-COSMIN)207,207,205
      207 COSMIN=FINCOS(KL)
      205 KL=KL+1
          IF(KL-MM)201,208,208
      208 WRITE(6,26)
          DO 210 IM=1,100
      210 IPRINT(IM)=IBLANK
          WRITE(6,24)(IPRINT(IM),IM=1,100)
          LINE=0
          LM=1
          ELM=LM
C         MAPPING THE COST FUNCTION AGAINST T1 AND T2, COST=FNC*T1,T2<
C
C         SET THE MATRIX INTO A BLANK SPACE* -  IS USED FOR BLANKS<
      211 DO 215 KIL=1,100
      215 IPRINT(KIL)=IBLANK
      213 KK=FINCOS(LM)*100. +1.0
       82 IF(KK)90,90,89
       89 IF(KK-50)91,91,90
       90 KK=50
       91 AMM=FLOAT(LM)/100.+1.
          NMM=AMM
          CMM=NMM
          IF(AMM-CMM)214,219,214
      214 IKI=(AMM-CMM)*99.+1.
          IPRINT(IKI)=ISIGN(KK)
          LM=LM+1
          IF(LM-3000)218,218,219
      218 GO TO 213
      219 IPRINT(100)=ISIGN(KK)
C         PLOTTING THE RESULTS FOR ONE FIXED CONDENSER TEMPERATURE*T2<
          LINE=LINE+1
          NLINE=335-5*LINE
          KLINE=(NLINE/20)*20-NLINE
          IF(KLINE)222,224,222
      222 WRITE(6,23)(IPRINT(LKL),LKL=1,90 )
          GO TO 226
```

```
0284          224 WRITE(6,25)(IPRINT(LKL),LKL=1,90 ),NLINE
            C     PRINT LINES FOR ALL T2 UNTIL THE RANGE IS COVERED
0285          226 IF(LM-3000)212,217,217
0286          212 LM=LM+1
0287              GO TO 213
0288          217 DO  231 JLM=1,100
0289          231 IPRINT(JLM)=IBLANK
0290              DO  235 JLM=5,100,5
0291          235 IPRINT(JLM)=ISIGN(42)
0292              WRITE(6,23)(IPRINT(JLM),JLM=1, 90)
0293              WRITE(6,20)(T1(I),I=1,10)
0294              WRITE (6,19)
0295              WRITE(6,21)(ISIGN(KJ),KJ=1,50)
0296              COCENT=COSMIN*100.
0297              WRITE(6,22)COCENT,T2(J)          ,ULC(L),TAU(L),ALFA(L),GLANUM
0298              WRITE(6,27)
0299              WRITE(6,26)
0300          150 CONTINUE
0301              IF(NN-1)999,1001,999
0302          999 CALL EXIT
0303              DEBUG SUBCHK
0304              END
```

TOTAL MEMORY REQUIREMENTS 008A0C BYTES

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--------------------------------------------------------------------------------------------------------------------



3MMMMMM2222222222222LLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLL2222222222MMMMMMM333333NNNNN
33333MMMMMMMM2222222222222222222222222222222222222222222222MMMMMMMM3333333NNNNNN44440
NN33333333MMMMMMMMMMMMMM22222222222222222222MMMMMMMMMMMMMMMMMM33333333NNNNNN4444000055  320
NNNNNN3333333333MMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM33MMM333333333NNNNNNN44444000005555PPP
4444NNNNNNNN3333333333333333333333333333333333333333NNNNNNNN444444000055555PPPP666Q
004444444NNNNNNNNNNNNNNN333333333NNNNNNNNNNNNNNNNNNNNNN44444440000055555PPPP6666QQQ777
00C00004444444444444NNNNNNNNNNNNNNNNNNN44444444444444440000000055555PPPPP6666QQQ777RRR88  300
55555000000000004444444444444444444444444000000000000000555555PPPPPP6666QQQQ777RRR88SSS99
PPPP55555555550000000000000000000000000000555555555555PPPPPPP66666QQQQ777RRRR88SSS99TT00U
666PPPPPPPPP555555555555555555555555555PPPPPPPPP66P666666QQQQ77777RRR888SSS99TTT00UU'VV
QQQ666666666PPPPPPPPPPPPPPPPPPPPPPPPPP66666666666QQQQQQQ77777RRRR888SSS999TTT00UU''V  WWX  280
777CQQQQQQQ6666666666666666666666660QQQQQQQQ77777777RRRR8888SSSS999TT000UU''VV WWX&&YZ
RRR777777777QQQQQQQQQQQQQQQQQQQ777777777777RRRRRR888888SSSS9999TTT00UUU''VV  WXX&YYZ
88888RRRRRRRRRRRRR7777777RRRRRRRRRRRRR8888888SSSSS999999TTT000UUU''VV  WWXX&&YZ
SSSSSSS88888888888888888888888888888SSSSSSS999999TTTT00000UUU''VVV  WWXX&&YZZ             260
T99999999SSSSSSSSSSSSSSSSSS999999999TTTTTT00000UUUU''''VVV  WWXX&&YYZZ
00000TTTTTTTTTTTTTTTTTTTTTTTTTTT0000000UUUUU''''VVVV    WWXX&&YYZZ
'UUUUUUUUU00000000000000UUUUUUUUUU''''''VVVV   WWWXXX&&&YYZZ
VVVVVVV''''''''''''''''VVVVVVVVV    WWWWXXX&&&YYYZZ                                       240
WWWWW                     WWWWWWWXXXXX&&&&YYYZZZ
&&&&&XXXXXXXXXXXXXXX&&&&&&&&YYYYZZZZ
ZZZZZZZZYYYYYYZZZZZZZZZZ
                                                                                          220



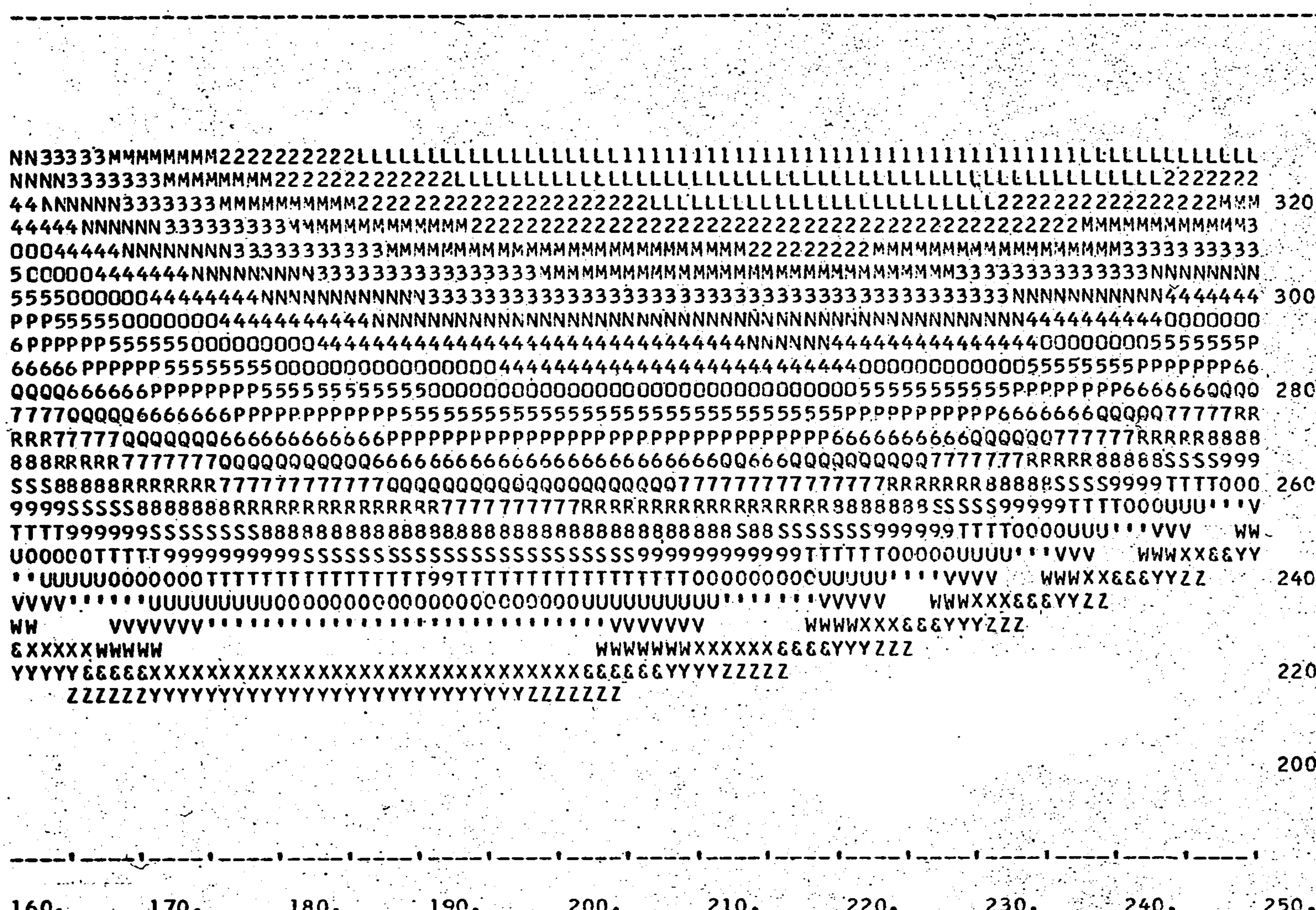
                                                                                          200



----'----'----'----'----'----'----'----'----'----'----'----'----'----'----'----'----'----'----.

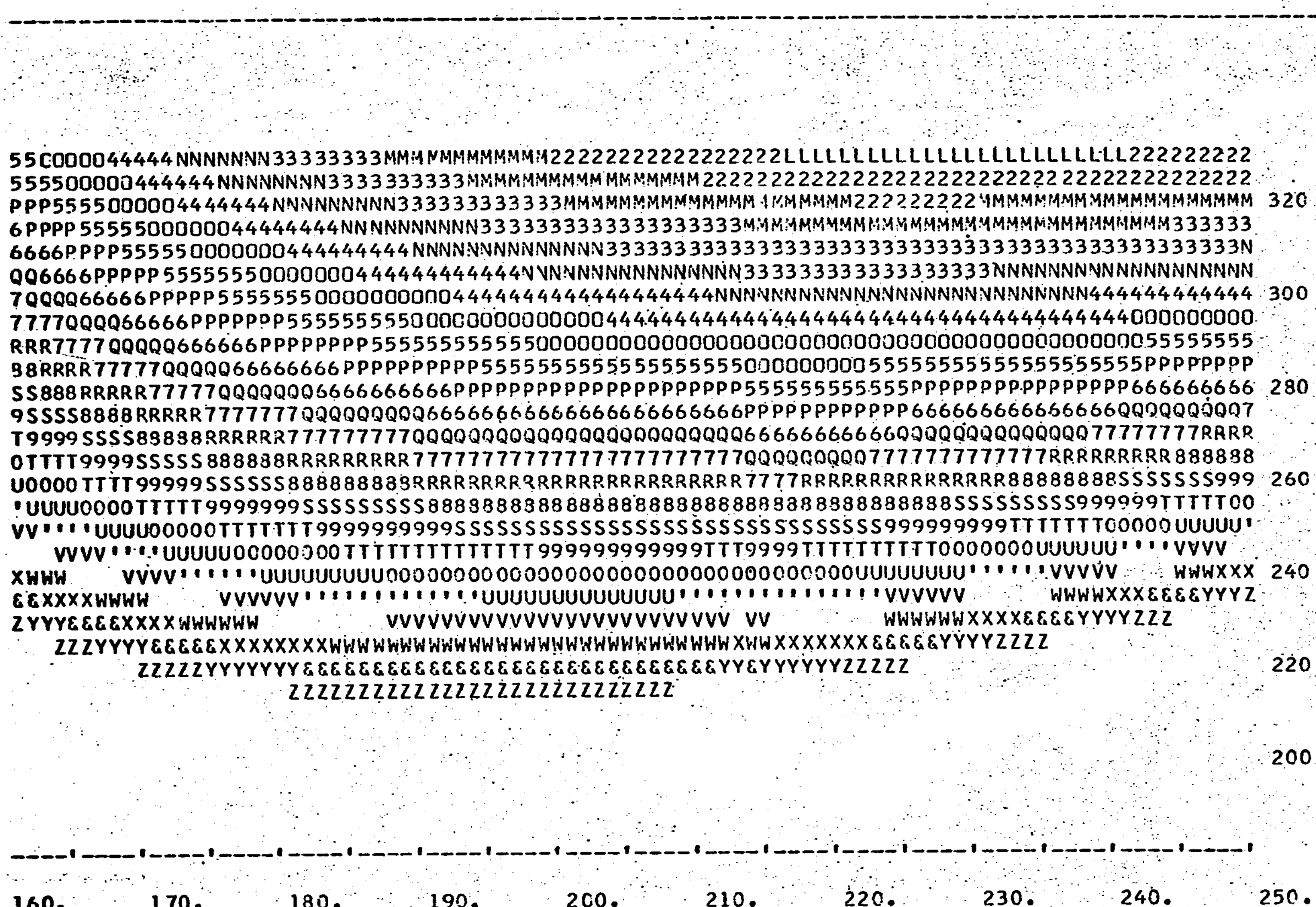
160.      170.      180.      190.      200.      210.      220.      230.      240.      250.
THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS    A#1 C/KWHR  Z#50 C/KWHR
A % B = C + D , E $ F * G / H < I O J . K I L 2 M 3 N 4 O 5 P 6 Q 7 R 8 S 9 T O U ' V   W X & Y Z
   22.57 IS THE MIN COST REPRESENTED BY(A),COND.TEMP=    95. ULC#0.85 TAU#0.77 ALFA#0.93 GLAS.NU#  2.

FIG   < RADIATION INTENSITY -BOILER TEMP. VS COST
```



THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS A#1 C/KWHR Z#50 C/KWHR
A % B = C + D , E $ F * G / H < I 0 J . K 1 L 2 M 3 N 4 0 5 P 6 Q 7 R 8 S 9 T 0 U ' V W X & Y Z
21.54 IS THE MIN COST REPRESENTED BY(A),COND.TEMP= 95. ULC#0.60 TAU#0.68 ALFA#0.93 GLAS.NU# 3.

FIG < RADIATION INTENSITY -BOILER TEMP. VS COST



THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS A#1 C/KWHR Z#50 C/KWHR

A % B = C + D , E $ F * G / H < I O J . K 1 L 2 M 3 N 4 O 5 P 6 Q 7 R 8 S 9 T O U ' V W X & Y Z

22.86 IS THE MIN COST REPRESENTED BY(A),COND.TEMP= 95. ULC#0.46 TAU#0.60 ALFA#0.93 GLAS.NU# 4.

FIG < RADIATION INTENSITY -BOILER TEMP. VS COST

MAIN PROGRAMME FOR :
01 - 02 - 03 - 04

```
          C      OPTIMIZATION IN SOLAR POWER PRODUCTION
          C      USING HEAT ENGINES
          C      M.KUDRET SELCUK
          C      MAIN PROGRAMME
0001             DIMENSION IPRINT(101),ISIGN(51),FINCOS(3002),EF(12,6)
0002             DIMENSION  P1(11),P2(11),T1(11),T2(11),HV1(11),HV2(11),HFL1(11),
                1HFL2(11),SV1(11),SFL1(11),SFL2(11),SX1(11),SX2(11),SV2(11),
                2HX1(11),HX2(11),RADION(12,8),X1(11),X2(11),ETACOL(5),ETATUR(5),
                3ULC(5),TAU(5),POWER(5),ALFA(5),ETAPUM(5)
0003             COMMON  P1,P2,T1,T2,HV1,HV2,HFL1,HFL2,SV1,SV2,SFL1,SFL2,SX1,SX2,
                1HX1,HX2,RADION,X1,X2,ETACOL,ETATUR,          ULC,TAU,POWER,ALFA,
                2ETAPUM,FLOW,PIPLOS,FRICLS,QADD,QREJ,CONSUR,TCWI,TCWO,UTIL,SUMRAD,
                3AREA,COLINV,STOINV,SININV,TURINV,COTINV,REPAIR,OPERTN,ENTRS,EXPLIF
0004             COMMON  I,J,K,L,M,N,II,JJ,KK,LL,MM,NN,IJ,IK,IL,IM,IN
0005             COMMON ETARAN,TAMBI,EF,OUSEF,TOTHOU,TOTWRK
0006           1 FORMAT(10F8.2)
0007           2 FORMAT(10F8.4)
0008           3 FORMAT(5F10.2)
0009           4 FORMAT(2F10.2)
0010           5 FORMAT(  12F6.1 )
0011           6 FORMAT(8F10.2)
0012           7 FORMAT(12F6.2)
0013           8 FORMAT(E12.6,15X,E12.6)
0014           9 FORMAT(F10.2)
0015          10 FORMAT(6F12.4)
0016          11 FORMAT(I5,2F6.0,2F8.0,F9.2,2F8.0,F5.0,2F8.2)
0017          14 FORMAT(85H ITER. T1     T2  TOTAL.INV TOT.EXP.COST C/KWH  AREA  COL
                1.INV RAD. COL.EF. OVER.EF.                         ///)
0018          16 FORMAT(10(4X,A1))
0019          17 FORMAT(4X,A1)
0020          19 FORMAT(63H THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS
                1  A#1 C/KWHR  Z#50 C/KWHR      )
0021          20 FORMAT(10(F5.0,5X))
0022          21 FORMAT(50(1X,A1))
0023          22 FORMAT(F9.2,46H IS THE MIN COST REPRESENTED BY(A),COND.TEMP= F6.0,
                15H ULC# F4.2,5H TAU# F4.2,6H ALFA# F4.2,15H SELECT BLACK   F4.0//)
0024          23 FORMAT(1X,100A1)
0025          24 FORMAT(1X,100A1 /////)
0026          25 FORMAT(1X,100A1,I5)
0027          26 FORMAT(1H1)
0028          27 FORMAT(53H FIG   < RADIATION INTENSITY-BOILER TEMP. VS COST       )
0029          29 FORMAT(5I10)
0030          30 FORMAT(27H BOILER PRESSURES IN PSIA       )
0031          31 FORMAT(30H CONDENSER PRESSURES IN PSIA     )
0032          32 FORMAT(28H BOILER TEMPERATURES IN %F<     )
0033          33 FORMAT(31H CONDENSER TEMPERATURES IN %F<     )
0034          34 FORMAT(20H ENTHALPIES BTU/LB      )
0035          35 FORMAT(24H ENTROPIES BTU/LB.F        )
0036          36 FORMAT(22H TURBINE EFFICIENCIES       )
0037          37 FORMAT(19H PUMP EFFICIENCIES        )
0038          38 FORMAT(16H ABSORPTIVITIES      )
0039          40 FORMAT(20H POWER RATING IN KW     )
0040         140 FORMAT(18H TRANSMISSIVITIES      )
0041         141 FORMAT(33H OVERALL HEAT LOSS COEFFICIENT        )
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0042          145 FORMAT(23H ALL PRICES IN DOLLARS       )
0043          146 FORMAT(83H WOOD PRICE GLASS PRI.TEDLARP.  SHEET IRON GLASWOOL  TUR
                 1.PRI. CIRC.PUM.  FEED PUM.      )
0044          147 FORMAT(90H PIPE PRICE GOVER.PRI.COND.TUBE  COND.SHELL REPAIR   OPE
                 1RATION INTEREST  LIFETIME,YEARS             )
0045          148 FORMAT(54H USE FACTOR AMBIENT T COOL W I COOL W O PIPE HEATLOSS  )
0046              READ(5,16)(ISIGN(KK),KK=1,50)
0047              READ (5,17)IEMPTY
0048              READ(5,17)IBLANK
0049         1001 READ (5,29)NN,IJ,IK,IL,IM
0050              READ (5,1)(P1(M),M=1,10)
0051              READ (5,1)(P2(M),M=1,10)
0052              READ (5,1)(T1(M),M=1,10)
0053              READ (5,1)(T2(M),M=1,10)
0054              READ (5,1)(HV1(M),M=1,10)
0055              READ (5,1)(HV2(M),M=1,10)
0056              READ (5,1)(HFL1(M),M=1,10)
0057              READ (5,1)(HFL2(M),M=1,10)
0058              READ (5,2)(SV1(M),M=1,10)
0059              READ (5,2)(SV2(M),M=1,10)
0060              READ (5,2)(SFL1(M),M=1,10)
0061              READ (5,2)(SFL2(M),M=1,10)
0062              READ (5,10)P1(11),T1(11),HV1(11),SV1(11),HFL1(11),SFL1(11)
0063              READ (5,3)(ETATUR(M),M=1,5)
0064              READ (5,3)(ETAPUM(M),M=1,5)
0065              READ (5,3)(ALFA(M),M=1,5)
0066              READ (5,3)(POWER(M),M=1,5)
0067              READ (5,3)(TAU(M),M=1,5)
0068              READ (5,3)(ULC(M),M=1,5)
0069              READ (5,6)PRWOOD,PRGLAS,PRTEDL,PRSTEL,PRFIBG,PRTUR,PRCIPU,PRFEPU
0070              READ (5,6)PRPIPE,PRGOVR,PRCOTU,PRCOSH,REPAIR,OPERTN,ENTRS,EXPLIF
0071              READ (5,3)USEFAC,TAMBI,TCWI,TCWO,PIPLOS
0072              WRITE(6,26)
0073              WRITE(6,30)
0074              WRITE(6,1)(P1(M),M=1,10)
0075              WRITE(6,31)
0076              WRITE(6,1)(P2(M),M=1,10)
0077              WRITE(6,32)
0078              WRITE(6,1)(T1(M),M=1,10)
0079              WRITE(6,33)
0080              WRITE(6,1)(T2(M),M=1,10)
0081              WRITE(6,34)
0082              WRITE(6,1)(HV1(M),M=1,10)
0083              WRITE(6,1)(HV2(M),M=1,10)
0084              WRITE(6,1)(HFL1(M),M=1,10)
0085              WRITE(6,1)(HFL2(M),M=1,10)
0086              WRITE(6,35)
0087              WRITE(6,2)(SV1(M),M=1,10)
0088              WRITE(6,2)(SV2(M),M=1,10)
0089              WRITE(6,2)(SFL1(M),M=1,10)
0090              WRITE(6,2)(SFL2(M),M=1,10)
0091              WRITE(6,36)
0092              WRITE(6,9)ETATUR(1)
0093              WRITE(6,37)
```

```
      WRITE(6,9)ETAPUM(1)
      WRITE(6,38)
      WRITE(6,9)ALFA(1)
      WRITE(6,40)
      WRITE(6,9)POWER(1)
      WRITE(6,140)
      WRITE(6,9)TAU(1)
      WRITE(6,141)
      WRITE(6,9)ULC(1)
      WRITE(6,145)
      WRITE(6,146)
      WRITE(6,6)PRWOOD,PRGLAS,PRTEDL,PRSTEL,PRFIBG,PRTUR,PRCIPU,PRFEPU
      WRITE(6,147)
      WRITE(6,6)PRPIPE,PRGCVR,PRCOTU,PRCOSH,REPAIR,OPERTN,ENTRS,EXPLIF
      WRITE(6,148)
      WRITE(6,3)USEFAC,TAMBI,TCWI,TCWO,PIPLOS
      WRITE(6,26)
      WRITE(6,14)
      J=3
      K=1
      L=1
      MM=1
      II=1
      JJ=1
      JLM=1
      KJ=1
      LM=1
      TN2=T2(J)
      PN2=P2(J)
      HVN2=HV2(J)
      SVN2=SV2(J)
      HFLN2=HFL2(J)
      SFLN2=SFL2(J)
      TINT2=T2(J+1)-T2(J)
      PINT2=P2(J+1)-P2(J)
      HVINT2=HV2(J+1)-HV2(J)
      SVINT2=SV2(J+1)-SV2(J)
      HFINT2=HFL2(J+1)-HFL2(J)
      SFINT2=SFL2(J+1)-SFL2(J)
      DO 250 KJK=1,30
      AKJK=KJK
      RADION(II,JJ)=335.0-5.0*AKJK
C     INTERPOLATION OF PHYSICAL PROPERTIES
   73 ANNI=NNI
      PAT=0.5
      T2(J)=(   TINT2     )*PAT+TN2
      P2(J)=(  PINT2      )*PAT+PN2
      HV2(J)=(  HVINT2      )*PAT+HVN2
      SV2(J)=(    SVINT2      )*PAT+SVN2
      HFL2(J)=(  HFINT2         )*PAT+HFLN2
      SFL2(J)=(     SFINT2       )*PAT+SFLN2
      DO 100 I=1,10
      NI=0
      TN1=T1(I)
```

```
      PN1=P1(I)
      HVN1=HV1(I)
      SVN1=SV1(I)
      HFLN1=HFL1(I)
      SFLN1=SFL1(I)
      TINT1=T1(I+1)-T1(I)
      PINT1=P1(I+1)-P1(I)
      HVINT1=HV1(I+1)-HV1(I)
      SVINT1=SV1(I+1)-SV1(I)
      HFINT1=HFL1(I+1)-HFL1(I)
      SFINT1=SFL1(I+1)-SFL1(I)
   63 ANI=NI
      RAT=ANI/10.
      T1(I)=(   TINT1   )*RAT+TN1
      P1(I)=(   PINT1   )*RAT+PN1
      HV1(I)=(   HVINT1   )*RAT+ HVN1
      SV1(I)=(   SVINT1   )*RAT+ SVN1
      HFL1(I)=(   HFINT1    )*RAT+HFLN1
      SFL1(I)=(   SFINT1    )*RAT+SFLN1
C     RANKINE CYCLE FOR SATURATED STEAM
C     ISENTROPIC EXPANSION FROM THE SATURATED VAPOUR STATE
C     X2   IS THE QUALITY OF STEAM AFTER ISENTROPIC EXPANSION
      X2(J)=(SV1(I)-SFL2(J))/(SV2(J)-SFL2(J))
      HX2(J)=HFL2(J)+X2(J)*(HV2(J)-HFL2(J))
C     IDEAL WORK
      WOUI=HV1(I)-HX2(J)
C     ACTUAL WORK
      WOUA=WOUI*ETATUR(K)
      QADD=HV1(I)-HFL2(J)
C     PUMP WORK
      WPUMP=0.00298*(P1(I)-P2(J))
      ACRATE=POWER(L)*(1.+PIPLOS)
      WPUMPA=WPUMP/ETAPUM(K)
C     NET WORK
      WNETT=WOUA-WPUMPA
C     RANKINE CYCLE EFFICIENCY
      ETARAN=WNETT/QADD
      QREJ=HX2(J)-HFL2(J)
      QTOT=ACRATE*3413.
      FLOW=QTOT/(QADD-QREJ)
C     FLAT PLATE COLLECTOR PERFORMANCE,AREA ,COST CALCULATIONS
C     TOTAL HEAT WHICH MUST BE COLLECTED
      QUSEF=QADD*(1.+PIPLOS)*FLOW
      CALL CCLLEC
C     NO STORAGE SYSTEM IS REQUIRED
      STOINV=0.
C     TEMPERATURE AND AUTOMATIC CONTROLS COST
      COTINV=250.
C     TURBINE  PERFORMANCE AND COST
C     IF THE SYSTEM SHOULD OPERATE BELOW 212  DEG.F. A VACUUM PUMP
C     MUST BE USED
      IF(T1(I)-212.)54,54,56
   54 PRVAPU=250.
      TURINV=PRTUR*POWER(K)+PRCIPU+PRFEPU+PRVAPU
```

```
0186          GO TO 57
0187       56 TURINV=PRTUR*POWER(K)+PRCIPU+PRFEPU
        C     THE CONDENSER TEMPERATURE IS FIXED AT 95 DEG. F
        C     THE CONDENSER COST TOO IS FIXED
0188       57 SININV=300.
        C     FINAL COST CALCULATIONS,COST PER KWHR
0189          TOTINV=COLINV+STOINV+SININV+TURINV+COTINV
0190          CAREFC=ENTRS*(1.+ENTRS)**EXPLIF/((1.+ENTRS)**EXPLIF-1.)
0191          TOTEXP=TOTINV*(CAREFC+REPAIR+UPERTN)
0192          FINCOS(MM)=TOTEXP/TOTWRK
0193          IF(FINCOS(MM)-0.20)177,177,178
0194      177 WRITE(6,11)MM,T1(I),T2(J),TOTINV,TOTEXP,FINCOS(MM),AREA,COLINV,
         1RADIUN(II,JJ) ,ETACOL(K),EF(II,JJ)
0195      178 CONTINUE
        C     GENERATING THE MATRIX  FINCOS%3000< TO STORE COST FIGURE FOR
        C     ALL COMBINATIONS OF T1 AND T2
0196          MM=MM+1
0197          NI=NI+1
0198       59 IF(NI-10)63,61,100
0199       61 T1(I)=TN1
0200          P1(I)=PN1
0201          HV1(I)=HVN1
0202          SV1(I)=SVN1
0203          HFL1(I)=HFLN1
0204          SFL1(I)=SFLN1
0205      100 CONTINUE
0206      250 CONTINUE
        C     MINIMUM COST WITHIN THE RANGE OF PARAMETERS VARIATION
0207          COSMIN=FINCOS(1)
0208          COSMAX=FINCOS(1)
0209          KL=1
0210      201 IF(FINCOS(KL)-COSMAX)204,204,203
0211      203 COSMAX=FINCOS(KL)
0212      204 IF(FINCOS(KL)-COSMIN)207,207,205
0213      207 COSMIN=FINCOS(KL)
0214      205 KL=KL+1
0215          IF(KL-MM)201,208,208
0216      208 WRITE(6,26)
0217          DO 210 IM=1,100
0218      210 IPRINT(IM)=IBLANK
0219          WRITE(6,24)(IPRINT(IM),IM=1,100)
0220          LINE=0
0221          LM=1
0222          ELM=LM
        C     MAPPING THE COST FUNCTION AGAINST T1 AND I, COST#FNC%T1,I<
        C     SET THE MATRIX INTO A BLANK SPACE% -  IS USED FOR BLANKS<
0223      211 DO 215 KIL=1,100
0224      215 IPRINT(KIL)=IBLANK
0225      213 KK=FINCOS(LM)*100. +1.0
0226       82 IF(KK)90,90,89
0227       89 IF(KK-50)91,91,90
0228       90 KK=50
0229       91 AMM=FLOAT(LM)/100.+1.
0230          NMM=AMM.
```

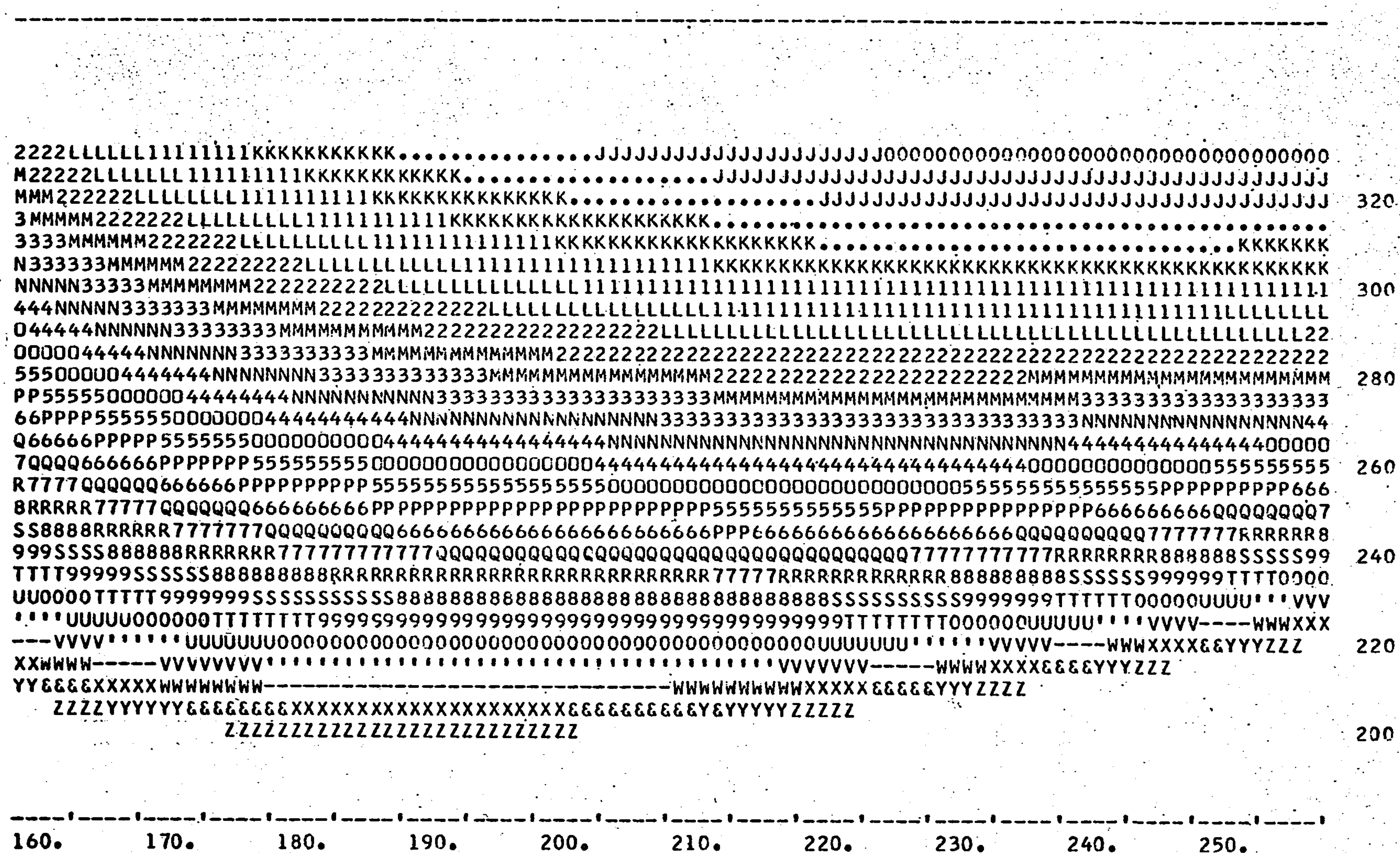
```
0231           CMM=NMM
0232           IF(AMM-CMM)214,219,214
0233       214 IKI=(AMM-CMM)*99.+1.
0234           IPRINT(IKI)=ISIGN(KK)
0235           LM=LM+1
0236           IF(LM-3000)218,218,219
0237       218 GO TO 213
0238       219 IPRINT(100)=ISIGN(KK)
         C     PLOTTING THE RESULTS FUR ONE FIXED CONDENSER TEMPERATURE%T2<
0239           LINE=LINE+1
0240           NLINE=335-5*LINE
0241           KLINE=(NLINE/20)*20-NLINE
0242           IF(KLINE)222,224,222
0243       222 WRITE(6,23)(IPRINT(LKL),LKL=1,100)
0244           GO TC 226
0245       224 WRITE(6,25)(IPRINT(LKL),LKL=1,100),NLINE
         C     PRINT LINES FOR ALL T2 UNTIL THE RANGE IS COVERED
0246       226 IF(LM-3000)212,217,217
0247       212 LM=LM+1
0248           GO TO 213
0249       217 DO  231 JLM=1,100
0250       231 IPRINT(JLM)=IBLANK
0251           DO  235 JLM=5,100,5
0252       235 IPRINT(JLM)=ISIGN(42)
0253           WRITE(6,23)(IPRINT(JLM),JLM=1,100)
0254           WRITE(6,20)(T1(I),I=1,10)
0255           WRITE (6,19)
0256           WRITE(6,21)(ISIGN(KJ),KJ=1,50)
0257           COCENT=CCSHIN*100.
0258           GLANUM=2.
0259           WRITE(6,22)COCENT,T2(J),ULC(1),TAU(1),ALFA(1),GLANUM
0260           WRITE(6,27)
0261           WRITE(6,26)
0262       150 CONTINUE
0263           IF(NN-1)999,1001,999
0264       999 CALL EXIT
0265           DEBUG SUBCHK
0266           END
```

TOTAL MEMCRY REQUIREMENTS 006C4C BYTES

```
0001          SUBROUTINE COLLEC
        C     COLLECTOR WITH SELECTIVE ABSORBING SURFACE AND TWO GLASS COVERS
0002          DIMENSION IPRINT(101),ISIGN(51),FINCOS(3002),EF(12,6)
0003          DIMENSION  P1(11),P2(11),T1(11),T2(11),HV1(11),HV2(11),HFL1(11),
             1HFL2(11),SV1(11),SFL1(11),SFL2(11),SX1(11),SX2(11),SV2(11),
             2HX1(11),HX2(11),RADION(12,8),X1(11),X2(11),ETACOL(5),ETATUR(5),
             3ULC(5),TAU(5),POWER(5),ALFA(5),ETAPUM(5)
0004          COMMON  P1,P2,T1,T2,HV1,HV2,HFL1,HFL2,SV1,SV2,SFL1,SFL2,SX1,SX2,
             1HX1,HX2,RADION,X1,X2,ETACOL,ETATUR,          ULC,TAU,POWER,ALFA,
             2ETAPUM,FLOW,PIPLOS,FRICLS,QADD,QREJ,CONSUR,TCWI,TCWO,UTIL,SUMRAD,
             3AREA,COLINV,STOINV,SININV,TURINV,COTINV,REPAIR,OPERTN,ENTRS,EXPLIF
0005          COMMON  I,J,K,L,M,N,II,JJ,KK,LL,MM,NN,IJ,IK,IL,IM,IN
0006          COMMON ETARAN,TAMBI,EF,QUSEF,TOTHOU,TOTWRK
0007          JMN=1
0008          GLANUM=2.
0009          ETACOL(K)=0.35
0010          TAU(K)=0.88**GLANUM
0011          ALFA(K)=0.9
0012          ULC(K)=0.6
0013          EFPRIM=0.9
0014          CHECK=RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*(T1(I)-TAMBI)
0015          RADCRT=1.05*ULC(K)*(T1(I)-TAMBI)/(TAU(K)*ALFA(K))
0016          IF(RADION(II,JJ)-RADCRT)47,47,39
0017       39 IF(CHECK)47,47,41
0018       41 AREAPP=QUSEF/(RADION(II,JJ)*ETACOL(K))
0019          G=FLOW/(0.1*AREAPP)
0020      520 EXPON=EFPRIM*ULC(K)/G
0021          IF(EXPON-100.)522,522,523
0022      522 FLOFAC=(1.-(1./(2.718**EXPON)))/EXPON
0023          GO TO 526
0024      523 FLOFAC=0.01
0025      526 FR=FLOFAC*EFPRIM
0026          ARESEN=0.1*QUSEF/(FR*(RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*
             1(T2(J)-TAMBI)))
0027          ARELAT=0.9*QUSEF/(EFPRIM*(RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*
             1(T1(I)-TAMBI)))
0028          AREA=ARESEN+ARELAT
0029          G=FLOW/ARESEN
0030          JMN=JMN+1
0031          ETACOL(K)=FR*CHECK/RADION(II,JJ)
0032          IF(JMN-2)520,520,45
0033       45 EF(II,JJ)=ETARAN*ETACOL(K)
0034          IF(EF(II,JJ))47,47,48
0035       47 EF(II,JJ)=0.
0036          TOTWRK=1.0
0037          GO TO 51
0038       48 TOTHOU=2400.
0039          TOTWRK=AREA*EF(II,JJ)*RADION(II,JJ)*TOTHOU/3413.
0040       51 COLCOS=5.5*AREA
0041          ASSEM=1.2
0042          COLINV=COLCOS*ASSEM
0043          RETURN
0044          END
```

SAMPLE RESULTS FOR PROGRAMME : 01

ITER.	T1	T2	TOTAL.INV	TCT.EXP.COST	C/KWH	AREA	COL.INV	RAD.	COL.EF.	OVER.EF.
30	189.	95.	16980.	2937.	0.20	2086.	13770.	330.	0.37	0.03
31	190.	95.	16906.	2924.	0.20	2075.	13696.	330.	0.36	0.03
32	191.	95.	16838.	2912.	0.20	2065.	13628.	330.	0.36	0.03
33	192.	95.	16771.	2901.	0.20	2055.	13561.	330.	0.36	0.03
34	193.	95.	16706.	2889.	0.20	2045.	13496.	330.	0.36	0.03
35	194.	95.	16642.	2878.	0.20	2035.	13432.	330.	0.36	0.03
36	195.	95.	16579.	2868.	0.20	2026.	13369.	330.	0.36	0.03
37	196.	95.	16516.	2857.	0.19	2016.	13308.	330.	0.36	0.03
38	197.	95.	16459.	2847.	0.19	2007.	13249.	330.	0.35	0.03
39	198.	95.	16401.	2837.	0.19	1999.	13191.	330.	0.35	0.03
40	199.	95.	16344.	2827.	0.19	1990.	13134.	330.	0.35	0.03
41	200.	95.	16288.	2817.	0.19	1982.	13078.	330.	0.35	0.03
42	201.	95.	16237.	2808.	0.19	1974.	13027.	330.	0.35	0.03
43	202.	95.	16187.	2800.	0.19	1966.	12977.	330.	0.35	0.03
44	203.	95.	16139.	2791.	0.19	1959.	12929.	330.	0.35	0.03
45	204.	95.	16091.	2783.	0.19	1952.	12881.	330.	0.34	0.03
46	205.	95.	16045.	2775.	0.19	1945.	12835.	330.	0.34	0.03
47	206.	95.	15999.	2767.	0.19	1938.	12789.	330.	0.34	0.03
48	207.	95.	15955.	2760.	0.19	1931.	12745.	330.	0.34	0.03
49	208.	95.	15912.	2752.	0.19	1925.	12702.	330.	0.34	0.03
50	209.	95.	15870.	2745.	0.19	1918.	12660.	330.	0.34	0.03
51	210.	95.	15829.	2738.	0.19	1912.	12619.	330.	0.34	0.03
52	211.	95.	15791.	2731.	0.19	1906.	12581.	330.	0.33	0.03
53	212.	95.	15755.	2725.	0.19	1901.	12545.	330.	0.33	0.03
54	213.	95.	15470.	2676.	0.18	1895.	12510.	330.	0.33	0.03
55	214.	95.	15435.	2670.	0.18	1890.	12475.	330.	0.33	0.03
56	215.	95.	15402.	2664.	0.18	1885.	12442.	330.	0.33	0.03
57	216.	95.	15369.	2658.	0.18	1880.	12409.	330.	0.33	0.03
58	217.	95.	15337.	2653.	0.18	1875.	12377.	330.	0.33	0.03
59	218.	95.	15306.	2647.	0.18	1871.	12346.	330.	0.33	0.03
60	219.	95.	15276.	2642.	0.18	1866.	12316.	330.	0.32	0.03
61	220.	95.	15246.	2637.	0.18	1862.	12286.	330.	0.32	0.03
62	221.	95.	15220.	2633.	0.18	1858.	12260.	330.	0.32	0.03
63	222.	95.	15195.	2628.	0.18	1854.	12235.	330.	0.32	0.03
64	223.	95.	15171.	2624.	0.18	1850.	12211.	330.	0.32	0.03
65	224.	95.	15147.	2620.	0.18	1846.	12187.	330.	0.32	0.03
66	225.	95.	15124.	2616.	0.18	1843.	12164.	330.	0.32	0.03
67	226.	95.	15102.	2612.	0.18	1840.	12142.	330.	0.31	0.03
68	227.	95.	15080.	2608.	0.18	1836.	12120.	330.	0.31	0.03
69	228.	95.	15059.	2605.	0.18	1833.	12099.	330.	0.31	0.03
70	229.	95.	15039.	2601.	0.18	1830.	12079.	330.	0.31	0.03
71	230.	95.	15020.	2598.	0.18	1827.	12060.	330.	0.31	0.03
72	231.	95.	15003.	2595.	0.18	1825.	12043.	330.	0.31	0.03
73	232.	95.	14986.	2592.	0.18	1822.	12026.	330.	0.31	0.03
74	233.	95.	14971.	2589.	0.18	1820.	12011.	330.	0.30	0.03
75	234.	95.	14956.	2587.	0.18	1818.	11996.	330.	0.30	0.03
76	235.	95.	14941.	2584.	0.18	1815.	11981.	330.	0.30	0.03
77	236.	95.	14928.	2582.	0.18	1813.	11968.	330.	0.30	0.03
78	237.	95.	14915.	2580.	0.18	1811.	11955.	330.	0.30	0.03
79	238.	95.	14902.	2578.	0.18	1809.	11942.	330.	0.30	0.03
80	239.	95.	14890.	2575.	0.18	1808.	11930.	330.	0.30	0.03
81	240.	95.	14879.	2574.	0.18	1806.	11919.	330.	0.30	0.03
82	241.	95.	14870.	2572.	0.18	1805.	11910.	330.	0.29	0.03
83	242.	95.	14862.	2571.	0.18	1803.	11902.	330.	0.29	0.03



THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS A#1 C/KWHR Z#50 C/KWHR

A % B = C + D , E $ F * G / H < I 0 J . K 1 L 2 M 3 N 4 O 5 P 6 Q 7 R 8 S 9 T 0 U ' V - W X & Y Z

17.83 IS THE MIN COST REPRESENTED BY(A),COND.TEMP= 95. ULC#0.60 TAU#0.77 ALFA#0.90 SELECT BLACK 2.

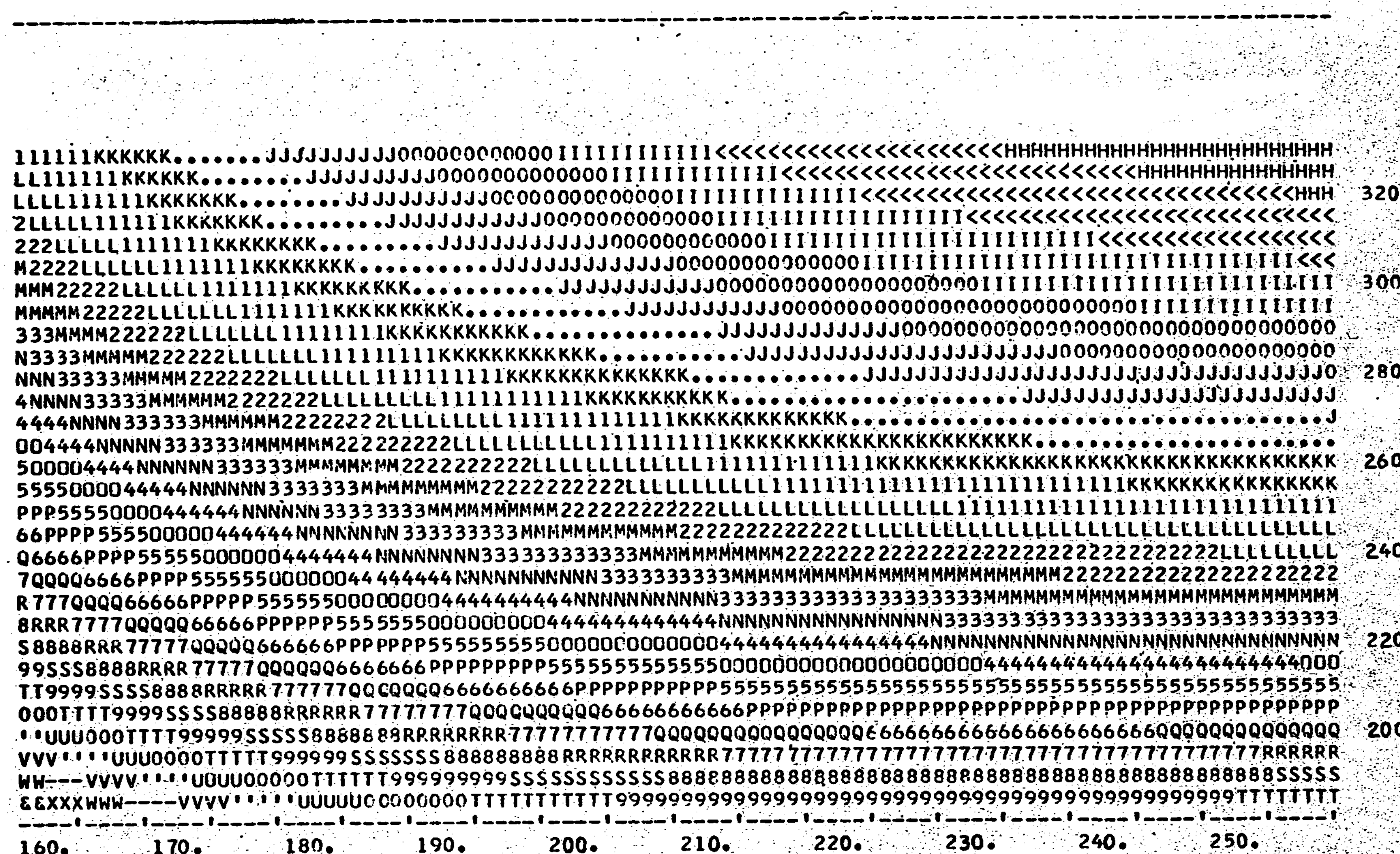
FIG < RADIATION INTENSITY-BOILER TEMP. VS COST

```
      SUBROUTINE COLLEC
C     FLAT PLATE COLLECTOR PERFORMANCE  WITH HONEYCOMB CONVECTION
C     SUPPRESSORS AND SELECTIVE ABSORBEING SURFACE
C     HONEYCOMB CELLS AND THEIR CHARACTERISTIC FIGURES AS SUGGESTED
C     BY T.HOLLANDS
      DIMENSION IPRINT(101),ISIGN(51),FINCOS(3002),EF(12,6)
      DIMENSION  P1(11),P2(11),T1(11),T2(11),HV1(11),HV2(11),HFL1(11),
     1HFL2(11),SV1(11),SFL1(11),SFL2(11),SX1(11),SX2(11),SV2(11),
     2HX1(11),HX2(11),RADION(12,9),X1(11),X2(11),ETACOL(5),ETATUR(5),
     3ULC(5),TAU(5),POWER(5),ALFA(5),ETAPUM(5)
      COMMON  P1,P2,T1,T2,HV1,HV2,HFL1,HFL2,SV1,SV2,SFL1,SFL2,SX1,SX2,
     1HX1,HX2,RADION,X1,X2,ETACOL,ETATUR,ULC,TAU,POWER,ALFA,
     2ETAPUM,FLOW,PIPLOS,FRICLS,QADD,QREJ,CONSUR,TCWI,TCWO,UTIL,SUMRAD,
     3AREA,COLINV,STOINV,SININV,TURINV,COTINV,REPAIR,OPERTN,ENTRS,EXPLIF
      COMMON  I,J,K,L,M,N,II,JJ,KK,LL,MM,NN,IJ,IK,IL,IM,IN
      COMMON ETARAN,TAMBI,EE,QUSEF,TOTHOU,TOTWRK
      JMN=1
      ETACOL(K)=0.40
      ULC(K)=0.423
      ALFA(K)=0.9
      TAU(K)=0.83
      EFPRIM=0.9
      CHECK=RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*(T1(I)-TAMBI)
      RADCRT=1.05*ULC(K)*(T1(I)-TAMBI)/(TAU(K)*ALFA(K))
      IF(RADION(II,JJ)-RADCRT)47,47,39
   39 IF(CHECK)47,47,41
   41 AREAPP=QUSEF/(RADION(II,JJ)*ETACOL(K))
      G=FLOW/(0.1*AREAPP)
  520 EXPON=EFPRIM*ULC(K)/G
      IF(EXPON-100.)522,522,523
  522 FLOFAC=(1.-(1./(2.718**EXPON)))/EXPON
      GO TO 526
  523 FLOFAC=0.01
  526 FR=FLOFAC*EFPRIM
      ARESEN=0.1*QUSEF/(FR*(RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*
     1(T2(J)-TAMBI)))
      ARELAT=0.9*QUSEF/(EFPRIM*(RADION(II,JJ)*TAU(K)*ALFA(K)-ULC(K)*
     1(T1(I)-TAMBI)))
      AREA=ARESEN+ARELAT
      G=FLOW/ARESEN
      JMN=JMN+1
      ETACOL(K)=FR*CHECK/RADION(II,JJ)
      IF(JMN-2)520,520,45
   45 EF(II,JJ)=ETARAN*ETACOL(K)
      IF(EF(II,JJ))47,47,48
   47 EF(II,JJ)=0.000001
      TOTWRK=0.000001
      GO TO 51
   48 TOTHOU=2400.
      TOTWRK=AREA*EF(II,JJ)*RADION(II,JJ)*TOTHOU/3413.
   51 COLCOS=6.5*AREA
      ASSEM=1.2
      COLINV=COLCOS*ASSEM
      RETURN
      END
```

TOTAL MEMORY REQUIREMENTS 0036AE BYTES

76	235.00	95.00	13676.45	2365.52	0.15	1373.90	10716.45	330.00	0.44	0.05
77	236.00	95.00	13642.97	2359.73	0.15	1369.61	10682.97	330.00	0.43	0.05
78	237.00	95.00	13609.97	2354.02	0.15	1365.36	10649.97	330.00	0.43	0.05
79	238.00	95.00	13577.46	2348.40	0.15	1361.21	10617.46	330.00	0.43	0.05
80	239.00	95.00	13545.45	2342.86	0.15	1357.11	10585.45	330.00	0.43	0.05
81	240.00	95.00	13513.92	2337.41	0.15	1353.07	10553.92	330.00	0.43	0.05
82	241.00	95.00	13484.48	2332.32	0.15	1349.29	10524.48	330.00	0.43	0.05
83	242.00	95.00	13455.47	2327.30	0.15	1345.57	10495.47	330.00	0.43	0.05
84	243.00	95.00	13426.90	2322.36	0.15	1341.91	10466.90	330.00	0.43	0.05
85	244.00	95.00	13398.74	2317.49	0.15	1338.30	10438.74	330.00	0.43	0.05
86	245.00	95.00	13371.00	2312.69	0.15	1334.74	10411.00	330.00	0.42	0.05
87	246.00	95.00	13343.68	2307.97	0.15	1331.24	10383.68	330.00	0.42	0.05
88	247.00	95.00	13316.75	2303.31	0.15	1327.79	10356.75	330.00	0.42	0.05
89	248.00	95.00	13290.23	2298.72	0.15	1324.39	10330.23	330.00	0.42	0.05
90	249.00	95.00	13264.11	2294.20	0.15	1321.04	10304.11	330.00	0.42	0.05
91	250.00	95.00	13238.38	2289.75	0.15	1317.74	10278.38	330.00	0.42	0.05
92	251.00	95.00	13214.77	2285.67	0.15	1314.71	10254.77	330.00	0.42	0.05
93	252.00	95.00	13191.50	2281.64	0.15	1311.73	10231.50	330.00	0.42	0.05
94	253.00	95.00	13168.59	2277.68	0.15	1308.79	10208.59	330.00	0.42	0.05
95	254.00	95.00	13146.01	2273.78	0.14	1305.90	10186.01	330.00	0.42	0.05
96	255.00	95.00	13123.80	2269.93	0.14	1303.05	10163.80	330.00	0.41	0.05
97	256.00	95.00	13101.91	2266.15	0.14	1300.25	10141.91	330.00	0.41	0.05
98	257.00	95.00	13080.35	2262.42	0.14	1297.48	10120.35	330.00	0.41	0.05
99	258.00	95.00	13059.14	2258.75	0.14	1294.76	10099.14	330.00	0.41	0.05
100	259.00	95.00	13038.24	2255.14	0.14	1292.08	10078.24	330.00	0.41	0.05
186	245.00	95.00	13595.25	2351.48	0.15	1363.49	10635.25	325.00	0.42	0.05
187	246.00	95.00	13567.86	2346.74	0.15	1359.98	10607.86	325.00	0.42	0.05
188	247.00	95.00	13540.88	2342.07	0.15	1356.52	10580.88	325.00	0.42	0.05
189	248.00	95.00	13514.31	2337.48	0.15	1353.12	10554.31	325.00	0.42	0.05
190	249.00	95.00	13488.15	2332.95	0.15	1349.76	10528.15	325.00	0.42	0.05
191	250.00	95.00	13462.39	2328.50	0.15	1346.46	10502.39	325.00	0.42	0.05
192	251.00	95.00	13438.79	2324.42	0.15	1343.44	10478.79	325.00	0.41	0.05
193	252.00	95.00	13415.55	2320.40	0.15	1340.46	10455.55	325.00	0.41	0.05
194	253.00	95.00	13392.68	2316.44	0.15	1337.52	10432.68	325.00	0.41	0.05
195	254.00	95.00	13370.14	2312.54	0.15	1334.63	10410.14	325.00	0.41	0.05
196	255.00	95.00	13347.98	2308.71	0.15	1331.79	10387.98	325.00	0.41	0.05
197	256.00	95.00	13326.15	2304.93	0.15	1328.99	10366.15	325.00	0.41	0.05
198	257.00	95.00	13304.65	2301.22	0.15	1326.24	10344.65	325.00	0.41	0.05
199	258.00	95.00	13283.52	2297.56	0.15	1323.53	10323.52	325.00	0.41	0.05
200	259.00	95.00	13262.70	2293.96	0.15	1320.66	10302.70	325.00	0.41	0.05
298	257.00	95.00	13539.14	2341.77	0.15	1356.30	10579.14	320.00	0.40	0.05
299	258.00	95.00	13518.11	2338.13	0.15	1353.60	10558.11	320.00	0.40	0.05
300	259.00	95.00	13497.40	2334.55	0.15	1350.95	10537.40	320.00	0.40	0.05

SAMPLE RESULTS OF PROGRAMME : 02



THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS A#1 C/KWHR Z#50 C/KWHR

A % B = C + D , E $ F * G / H < I O J . K 1 L 2 M 3 N 4 O 5 P 6 Q 7 R 8 S 9 T O U ' V - W X & Y Z $

14.38 IS THE MIN COST REPRESENTED BY(A),COND.TEMP= 95. ULC#0.42 TAU#0.83 ALFA#0.90 SEL.HONEYCOMB 1.

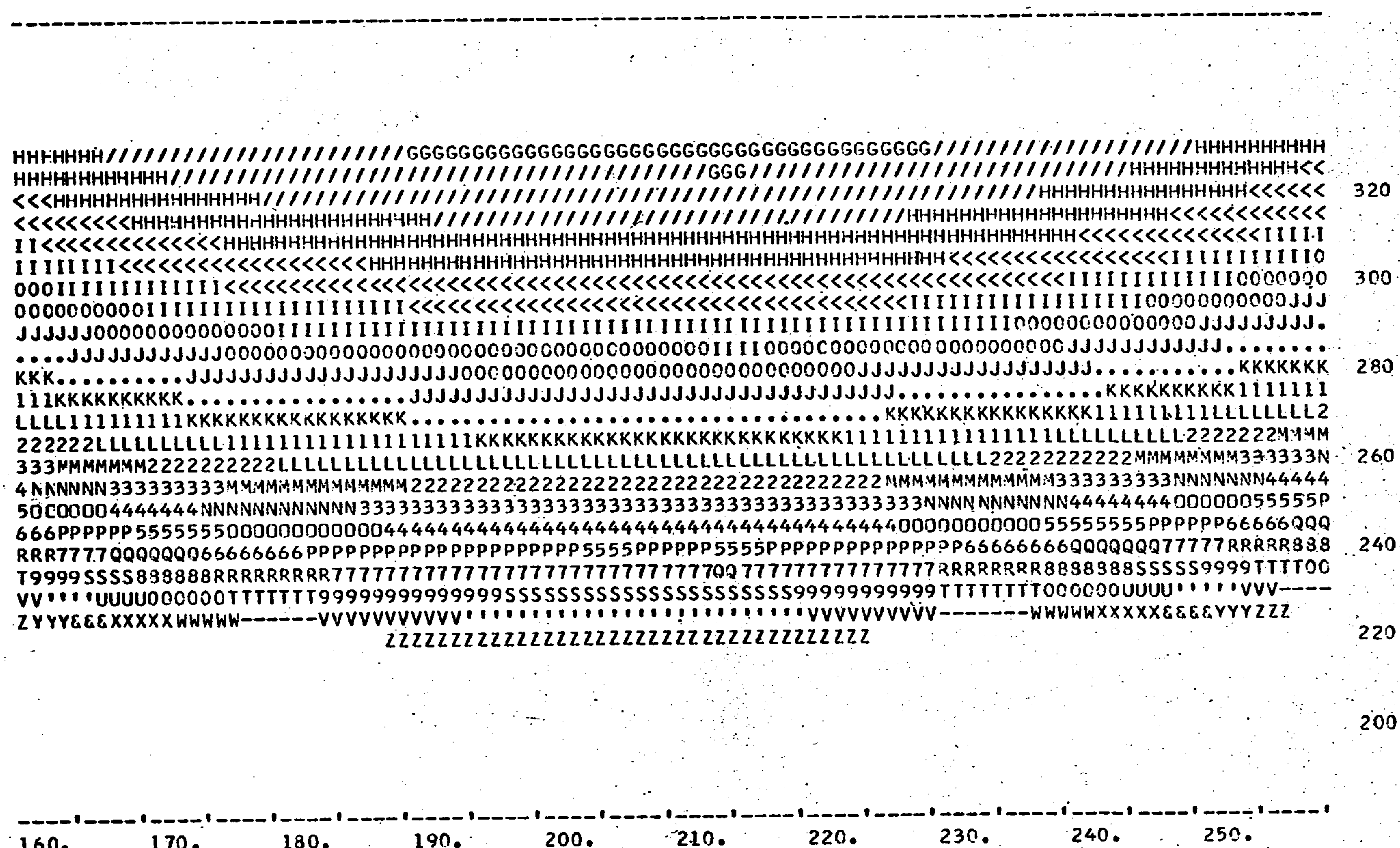
FIG < RADIATION INTENSITY-BOILER TEMP. VS COST

```
0001          SUBROUTINE COLLEC
         C    HONEYCOMB CELLS MADE FROM MELINEX PLASTIC FILM  H/D=5 , D=1 CM. ,
         C    ORDINARY BLACK PAINTED, DATA COURTESY OF G.PERI , UNIVERSITY OF
         C    MARSEILLE
0002          DIMENSION IPRINT(101),ISIGN(51),FINCOS(3002),EF(12,6)
0003          DIMENSION  P1(11),P2(11),T1(11),T2(11),HV1(11),HV2(11),HFL1(11),
             1HFL2(11),SV1(11),SFL1(11),SFL2(11),SX1(11),SX2(11),SV2(11),
             2HX1(11),HX2(11),RADION(12,8),X1(11),X2(11),ETACOL(5),ETATUR(5),
             3ULC(5),TAU(5),POWER(5),ALFA(5),ETAPUM(5)
0004          COMMON  P1,P2,T1,T2,HV1,HV2,HFL1,HFL2,SV1,SV2,SFL1,SFL2,SX1,SX2,
             1HX1,HX2,RADION,X1,X2,ETACOL,ETATUR,             ULC,TAU,POWER,ALFA,
             2ETAPUM,FLOW,PIPLOS,FRICLS,QADD,QREJ,CONSUR,TCWI,TCWO,UTIL,SUMRAD,
             3AREA,COLINV,STOINV,SININV,TURINV,COTINV,REPAIR,OPERTN,ENTRS,EXPLIF
0005          COMMON  I,J,K,L,M,N,II,JJ,KK,LL,MM,NN,IJ,IK,IL,IM,IN
0006          COMMON ETARAN,TAMBI,EF,QUSEF,TOTHOU,TOTWRK
0007          TCEN1=(T1(I)-32.)*0.555
0008          TAMCEN=(TAMBI-32.)*0.555
0009          ETANOM= 0.46- (TCEN1-TAMCEN-85.)*0.0072
0010          RADMET=RADION(II,JJ)*3.17
0011          ETRAFC=1.0-0.00129*(1000.-RADMET)-0.00000295*((1000.-RADMET)**2)
0012          ETACOL(K)=ETANOM*ETRAFC
0013          IF(ETACOL(K))42,42,44
0014       42 ETACOL(K)=0.000001
0015       44 AREA=QUSEF/(ETACOL(K)*RADION(II,JJ))
0016       45 EF(II,JJ)=ETARAN*ETACOL(K)
0017          IF(EF(II,JJ))47,47,48
0018       47 EF(II,JJ)=0.
0019          TOTWRK=1.0
0020          GO TO 51
0021       48 TOTHOU=2400.
0022          TOTWRK=AREA*EF(II,JJ)*RADION(II,JJ)*TOTHOU/3413.
0023       51 COLCOS=6.0*AREA
0024          ASSEM=1.2
0025          COLINV=COLCOS*ASSEM
0026          RETURN
0027          END
```

TOTAL MEMORY REQUIREMENTS 0034C4 BYTES

SAMPLE RESULTS OF PROGRAMME:o3

1	160.00	95.00	15041.87	2601.69	0.14	1643.32	11831.87	330.00	0.77	0.05
2	161.00	95.00	14953.07	2586.33	0.14	1630.98	11743.07	330.00	0.77	0.05
3	162.00	95.00	14867.37	2571.51	0.14	1619.08	11657.37	330.00	0.76	0.05
4	163.00	95.00	14784.61	2557.19	0.14	1607.58	11574.61	330.00	0.76	0.05
5	164.00	95.00	14704.75	2543.38	0.14	1596.49	11494.75	330.00	0.75	0.05
6	165.00	95.00	14627.66	2530.05	0.14	1585.79	11417.66	330.00	0.75	0.05
7	166.00	95.00	14553.19	2517.17	0.14	1575.44	11343.19	330.00	0.75	0.05
8	167.00	95.00	14481.37	2504.74	0.14	1565.47	11271.37	330.00	0.74	0.05
9	168.00	95.00	14412.04	2492.75	0.14	1555.84	11202.04	330.00	0.74	0.05
10	169.00	95.00	14345.18	2481.19	0.14	1546.55	11135.18	330.00	0.73	0.05
11	170.00	95.00	14280.63	2470.02	0.14	1537.59	11070.63	330.00	0.73	0.05
12	171.00	95.00	14223.07	2460.07	0.14	1529.59	11013.07	330.00	0.72	0.05
13	172.00	95.00	14167.59	2450.47	0.14	1521.39	10957.59	330.00	0.72	0.05
14	173.00	95.00	14114.09	2441.22	0.14	1514.46	10904.09	330.00	0.72	0.05
15	174.00	95.00	14062.59	2432.31	0.14	1507.30	10852.59	330.00	0.71	0.05
16	175.00	95.00	14012.99	2423.73	0.13	1500.42	10802.99	330.00	0.71	0.05
17	176.00	95.00	13965.22	2415.47	0.13	1493.78	10755.22	330.00	0.70	0.05
18	177.00	95.00	13919.32	2407.53	0.13	1487.41	10709.32	330.00	0.70	0.05
19	178.00	95.00	13875.13	2399.89	0.13	1481.27	10665.13	330.00	0.70	0.05
20	179.00	95.00	13832.74	2392.56	0.13	1475.38	10622.74	330.00	0.69	0.05
21	180.00	95.00	13792.02	2385.51	0.13	1469.73	10582.02	330.00	0.69	0.05
22	181.00	95.00	13755.91	2379.27	0.13	1464.71	10545.91	330.00	0.68	0.05
23	182.00	95.00	13721.35	2373.29	0.13	1459.91	10511.35	330.00	0.68	0.05
24	183.00	95.00	13688.27	2367.57	0.13	1455.32	10478.27	330.00	0.67	0.05
25	184.00	95.00	13656.73	2362.11	0.13	1450.94	10446.73	330.00	0.67	0.05
26	185.00	95.00	13626.61	2356.90	0.13	1446.75	10416.61	330.00	0.67	0.05
27	186.00	95.00	13597.96	2351.95	0.13	1442.77	10387.96	330.00	0.66	0.05
28	187.00	95.00	13570.70	2347.23	0.13	1438.99	10360.70	330.00	0.66	0.05
29	188.00	95.00	13544.85	2342.76	0.13	1435.40	10334.85	330.00	0.65	0.05
30	189.00	95.00	13520.36	2338.52	0.13	1431.99	10310.36	330.00	0.65	0.05
31	190.00	95.00	13497.20	2334.52	0.13	1428.78	10287.20	330.00	0.64	0.05
32	191.00	95.00	13478.00	2331.20	0.13	1426.11	10268.00	330.00	0.64	0.05
33	192.00	95.00	13460.05	2328.09	0.13	1423.62	10250.05	330.00	0.64	0.05
34	193.00	95.00	13443.39	2325.21	0.13	1421.30	10233.39	330.00	0.63	0.05
35	194.00	95.00	13427.91	2322.53	0.13	1419.16	10217.91	330.00	0.63	0.05
36	195.00	95.00	13413.70	2320.08	0.13	1417.18	10203.70	330.00	0.62	0.05
37	196.00	95.00	13400.65	2317.82	0.13	1415.37	10190.65	330.00	0.62	0.05
38	197.00	95.00	13388.82	2315.77	0.13	1413.73	10178.82	330.00	0.62	0.05
39	198.00	95.00	13378.19	2313.93	0.13	1412.25	10168.19	330.00	0.61	0.05
40	199.00	95.00	13368.72	2312.30	0.13	1410.93	10158.72	330.00	0.61	0.05
41	200.00	95.00	13360.45	2310.87	0.13	1409.78	10150.45	330.00	0.60	0.05
42	201.00	95.00	13355.86	2310.07	0.13	1409.15	10145.86	330.00	0.60	0.05
43	202.00	95.00	13352.41	2309.47	0.13	1408.67	10142.41	330.00	0.59	0.05
44	203.00	95.00	13350.06	2309.07	0.13	1408.34	10140.06	330.00	0.59	0.05
45	204.00	95.00	13348.83	2308.86	0.13	1408.17	10138.83	330.00	0.59	0.05
46	205.00	95.00	13348.71	2308.84	0.13	1408.16	10138.71	330.00	0.58	0.05
47	206.00	95.00	13349.67	2309.00	0.13	1408.29	10139.67	330.00	0.58	0.05
48	207.00	95.00	13351.75	2309.36	0.13	1408.58	10141.75	330.00	0.57	0.05
49	208.00	95.00	13354.95	2309.91	0.13	1409.02	10144.95	330.00	0.57	0.05
50	209.00	95.00	13359.23	2310.66	0.13	1409.62	10149.23	330.00	0.56	0.05
51	210.00	95.00	13364.64	2311.59	0.13	1410.37	10154.64	330.00	0.56	0.05
52	211.00	95.00	13373.52	2313.13	0.13	1411.60	10163.52	330.00	0.56	0.05
53	212.00	95.00	13383.48	2314.85	0.13	1412.98	10173.48	330.00	0.55	0.05
54	213.00	95.00	13144.51	2273.52	0.13	1414.52	10184.51	330.00	0.55	0.05
55	214.00	95.00	13156.66	2275.62	0.13	1416.20	10196.66	330.00	0.54	0.05
56	215.00	95.00	13169.92	2277.91	0.13	1418.04	10209.92	330.00	0.54	0.05
57	216.00	95.00	13184.27	2280.39	0.13	1420.04	10224.27	330.00	0.54	0.05
58	217.00	95.00	13199.73	2283.07	0.13	1422.19	10239.73	330.00	0.53	0.05



THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS A#1 C/KWHR Z#50 C/KWHR
A % B = C + D , E $ F * G / H < I 0 J . K 1 L 2 M 3 N 4 O 5 P 6 Q 7 R 8 S 9 T O U ' V - W X & Y Z
12.65 IS THE MIN COST REPRESENTED BY(A),COND.TEMP= 95. ULC#0.70 TAU#0.88 ALFA#0.93 PLAS.HONEYC. 1.

FIG < RADIATION INTENSITY-BOILER TEMP. VS COST

```
0001          SUBROUTINE COLLEC
         C    MIRROR BOOSTERS ARE ADDED TO ENHANCE THE RADIATION INTENSITY
         C    EACH COLLECTOR IS EQUIPPED WITH TRANSPOSABLE SIDE MIRRORS
         C    THE MIRROR AREA IS ABOUT 5 PERCENT MORE THAN THE COLLECTOR AREA
         C    TO COMPENSATE THE INCREASED EDGE LOSSES
0002          DIMENSION IPRINT(101),ISIGN(51),FINCOS(3002),EF(12,6)
0003          DIMENSION  P1(11),P2(11),T1(11),T2(11),HV1(11),HV2(11),HFL1(11),
             1HFL2(11),SV1(11),SFL1(11),SFL2(11),SX1(11),SX2(11),SV2(11),
             2HX1(11),HX2(11),RADION(12,8),X1(11),X2(11),ETACOL(5),ETATUR(5),
             3ULC(5),TAU(5),POWER(5),ALFA(5),ETAPUM(5)
0004          COMMON  P1,P2,T1,T2,HV1,HV2,HFL1,HFL2,SV1,SV2,SFL1,SFL2,SX1,SX2,
             1HX1,HX2,RADION,X1,X2,ETACOL,ETATUR,            ULC,TAU,POWER,ALFA,
             2ETAPUM,FLOW,PIPLOS,FRICLS,QADD,QREJ,CONSUR,TCWI,TCWO,UTIL,SUMRAD,
             3AREA,COLINV,STOINV,SININV,TURINV,COTINV,REPAIR,OPERTN,ENTRS,EXPLIF
0005          COMMON  I,J,K,L,M,N,II,JJ,KK,LL,MM,NN,IJ,IK,IL,IM,IN
0006          COMMON ETARAN,TAMBI,EF,QUSEF,TOTHOU,TOTWRK
         C    THE MIRROR BOOST FACTOR FOR DAY LONG OPERATION IS TAKEN AS  2
0007          BOOSMI=2.0
         C    ACTUAL AVERAGE RADIATION INTENSITY ON THE ABSORBER PLATE
0008          RACONC=RADION(II,JJ)*BOOSMI
0009          JMN=1
0010          ETACOL(L)=0.30
0011          ULC(K)=0.62
0012          ALFA(K)=0.9
0013          TAU(K)=0.78
0014          EFPRIM=0.9
0015          CHECK=RACONC*TAU(K)*ALFA(K)-ULC(K)*(T1(I)-TAMBI)
0016          RADCRT=1.05*ULC(K)*(T1(I)-TAMBI)/(TAU(K)*ALFA(K))
0017          IF(RACONC-RADCRT)47,47,39
0018       39 IF(CHECK)47,47,41
0019       41 AREAPP=QUSEF/(RACONC*ETACOL(K))
0020          G=FLOW/(0.1*AREAPP)
0021      520 EXPON=EFPRIM*ULC(K)/G
0022          IF(EXPON-100.)522,522,523
0023      522 FLOFAC=(1.-(1./(2.718**EXPON)))/EXPON
0024          GO TO 526
0025      523 FLOFAC=0.01
0026      526 FR=FLOFAC*EFPRIM
0027          ARESEN=0.1*QUSEF/(FR*(RACONC*TAU(K)*ALFA(K)-ULC(K)*
             1(T2(J)-TAMBI)))
0028          ARELAT=0.9*QUSEF/(EFPRIM*(RACONC*TAU(K)*ALFA(K)-ULC(K)*
             1(T1(I)-TAMBI)))
0029          AREA=ARESEN+ARELAT
0030          G=FLOW/ARESEN
0031          JMN=JMN+1
0032          ETACOL(K)=FR*CHECK/RACONC
0033          IF(JMN-2)520,520,45
0034       45 EF(II,JJ)=ETARAN*ETACOL(K)
0035          IF(EF(II,JJ))47,47,48
0036       47 EF(II,JJ)=0.
0037          TOTWRK=1.0
0038          GO TO 51
0039       48 TOTHOU=2400.
0040          TOTWRK=AREA*EF(II,JJ)*RACONC*TOTHOU/3413.
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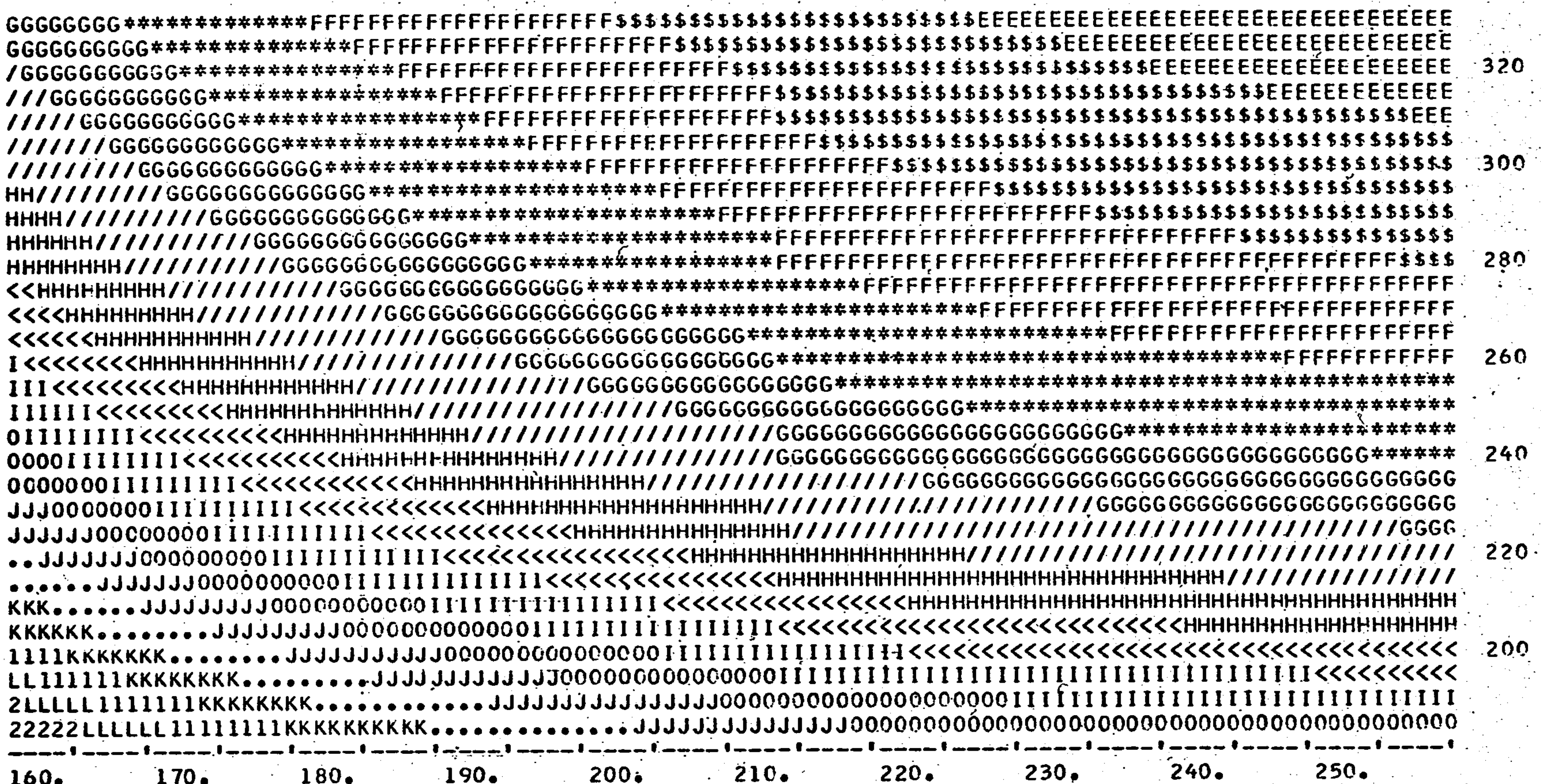
```
0041        AMIRR=1.05*AREA
0042        COSMIR=0.6
0043        COSFRM=0.4
0044     51 COLCOS=5.5*AREA+AMIRR*(COSMIR+COSFRM)
0045        ASSEM=1.2
0046        COLINV=COLCOS*ASSEM
0047        RETURN
0048        END
```

TOTAL MEMORY REQUIREMENTS 0036A0 BYTES

SAMPLE RESULTS OF PROGRAMME: 04

67	226.00	95.00	8479.99	1466.73	0.09	702.29	5519.99	330.00	0.46	0.05
68	227.00	95.00	8456.71	1462.70	0.09	699.33	5496.71	330.00	0.46	0.05
69	228.00	95.00	8433.75	1458.73	0.09	696.41	5473.75	330.00	0.46	0.05
70	229.00	95.00	8411.10	1454.81	0.09	693.53	5451.10	330.00	0.46	0.05
71	230.00	95.00	8388.76	1450.95	0.09	690.68	5428.76	330.00	0.46	0.05
72	231.00	95.00	8367.52	1447.27	0.09	687.98	5407.52	330.00	0.46	0.05
73	232.00	95.00	8346.56	1443.65	0.09	685.31	5386.56	330.00	0.46	0.05
74	233.00	95.00	8325.87	1440.07	0.09	682.68	5365.87	330.00	0.46	0.05
75	234.00	95.00	8305.45	1436.54	0.09	680.08	5345.45	330.00	0.46	0.05
76	235.00	95.00	8285.28	1433.05	0.09	677.52	5325.28	330.00	0.45	0.05
77	236.00	95.00	8265.38	1429.61	0.09	674.99	5305.38	330.00	0.45	0.05
78	237.00	95.00	8245.73	1426.21	0.09	672.49	5285.73	330.00	0.45	0.05
79	238.00	95.00	8226.33	1422.85	0.09	670.02	5266.33	330.00	0.45	0.05
80	239.00	95.00	8207.18	1419.54	0.09	667.58	5247.18	330.00	0.45	0.05
81	240.00	95.00	8188.29	1416.27	0.09	665.18	5228.29	330.00	0.45	0.05
82	241.00	95.00	8170.43	1413.18	0.09	662.91	5210.43	330.00	0.45	0.05
83	242.00	95.00	8152.79	1410.13	0.09	660.66	5192.79	330.00	0.45	0.05
84	243.00	95.00	8135.37	1407.12	0.09	658.45	5175.37	330.00	0.45	0.05
85	244.00	95.00	8118.16	1404.14	0.09	656.26	5158.16	330.00	0.45	0.05
86	245.00	95.00	8101.17	1401.20	0.09	654.09	5141.17	330.00	0.45	0.05
87	246.00	95.00	8084.39	1398.30	0.09	651.96	5124.39	330.00	0.45	0.05
88	247.00	95.00	8067.81	1395.43	0.09	649.85	5107.81	330.00	0.45	0.05
89	248.00	95.00	8051.43	1392.60	0.09	647.77	5091.43	330.00	0.44	0.05
90	249.00	95.00	8035.26	1389.80	0.09	645.71	5075.26	330.00	0.44	0.05
91	250.00	95.00	8019.27	1387.04	0.09	643.67	5059.27	330.00	0.44	0.05
92	251.00	95.00	8004.34	1384.46	0.09	641.77	5044.34	330.00	0.44	0.05
93	252.00	95.00	7989.57	1381.90	0.09	639.90	5029.57	330.00	0.44	0.05
94	253.00	95.00	7974.99	1379.38	0.09	638.04	5014.99	330.00	0.44	0.05
95	254.00	95.00	7960.57	1376.89	0.09	636.21	5000.57	330.00	0.44	0.05
96	255.00	95.00	7946.34	1374.42	0.08	634.39	4986.34	330.00	0.44	0.05
97	256.00	95.00	7932.25	1371.99	0.08	632.60	4972.25	330.00	0.44	0.06
98	257.00	95.00	7918.34	1369.58	0.08	630.83	4958.34	330.00	0.44	0.06
99	258.00	95.00	7904.60	1367.20	0.08	629.08	4944.60	330.00	0.44	0.06
100	259.00	95.00	7891.01	1364.85	0.08	627.36	4931.01	330.00	0.44	0.06
101	160.00	95.00	12249.72	2118.75	0.13	1150.09	9039.72	325.00	0.51	0.03
102	161.00	95.00	12145.31	2100.69	0.13	1136.81	8935.31	325.00	0.51	0.03
103	162.00	95.00	12043.72	2083.12	0.13	1123.88	8833.72	325.00	0.51	0.03
104	163.00	95.00	11944.77	2066.01	0.13	1111.30	8734.77	325.00	0.51	0.03
105	164.00	95.00	11848.45	2049.34	0.12	1099.04	8638.45	325.00	0.51	0.03
106	165.00	95.00	11754.57	2033.11	0.12	1087.10	8544.57	325.00	0.51	0.03
107	166.00	95.00	11663.05	2017.28	0.12	1075.45	8453.05	325.00	0.51	0.03
108	167.00	95.00	11573.87	2001.85	0.12	1064.11	8363.87	325.00	0.51	0.03
109	168.00	95.00	11486.88	1986.81	0.12	1053.04	8276.88	325.00	0.51	0.03
110	169.00	95.00	11402.06	1972.14	0.12	1042.25	8192.06	325.00	0.50	0.03
111	170.00	95.00	11319.27	1957.82	0.12	1031.71	8109.27	325.00	0.50	0.03
112	171.00	95.00	11241.87	1944.43	0.12	1021.87	8031.87	325.00	0.50	0.04
113	172.00	95.00	11166.27	1931.35	0.12	1012.25	7956.27	325.00	0.50	0.04
114	173.00	95.00	11092.36	1918.57	0.12	1002.85	7882.36	325.00	0.50	0.04
115	174.00	95.00	11020.13	1906.08	0.12	993.66	7810.13	325.00	0.50	0.04
116	175.00	95.00	10949.50	1893.86	0.12	984.67	7739.50	325.00	0.50	0.04
117	176.00	95.00	10880.41	1881.91	0.11	975.88	7670.41	325.00	0.50	0.04
118	177.00	95.00	10812.85	1870.23	0.11	967.28	7602.85	325.00	0.50	0.04
119	178.00	95.00	10746.70	1858.78	0.11	958.87	7536.70	325.00	0.50	0.04
120	179.00	95.00	10682.01	1847.59	0.11	950.64	7472.01	325.00	0.50	0.04
121	180.00	95.00	10618.68	1836.64	0.11	942.58	7408.68	325.00	0.50	0.04
122	181.00	95.00	10558.72	1826.27	0.11	934.95	7348.72	325.00	0.50	0.04
123	182.00	95.00	10499.98	1816.11	0.11	927.48	7289.98	325.00	0.49	0.04
124	183.00	95.00	10442.40	1806.15	0.11	920.15	7232.40	325.00	0.49	0.04
125	184.00	95.00	10385.99	1796.39	0.11	912.98	7175.99	325.00	0.49	0.04



THE FOLLOWING GIVES A LIST IN ASCENDING ORDER SUCH AS A#1 C/KWHR Z#59 C/KWHR
A % B = C + D , E $ F * G / H < I 0 J . K 1 L 2 M 3 N 4 O 5 P 6 Q 7 R 8 S 9 T 0 U ' V - W X & Y Z
8.44 IS THE MIN COST REPRESENTED BY(A),COND.TEMP= 95. ULC#0.62 TAU#0.78 ALFA#0.90 MIRROR BOOST 2.

FIG < RADIATION INTENSITY-BOILER TEMP. VS COST

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            C      OPTIMIZATION IN SOLAR POWER PRODUCTION
            C      USING HEAT ENGINES
            C      M.KUDRET SELCUK
            C      UNSTEADY STATE ANALYSIS OF THE SOLAR POWER PLANT
            C      FLAT PLATE COLLECTOR ,NO STORAGE,CONSTANT AREA
            C      MAIN PROGRAMME
 0001              DIMENSION FINCOS(50),EFFIC(40),RADIAT(40),RADTIN(12,31,8),
                  1ENDAY(12,8),WRKMON(12,8) ,AVERAD(12,8),MONTH(12),EF(12,8)
 0002              DIMENSION VAFLOW(40)
 0003              DIMENSION  P1(11),P2(11),T1(11),T2(11),HV1(11),HV2(11),HFL1(11),
                  1HFL2(11),SV1(11),SFL1(11),SFL2(11),SX1(11),SX2(11),SV2(11),
                  2HX1(11),HX2(11),RADION(12,8),X1(11),X2(11),ETACOL(5),ETATUR(5),
                  3VOL1(11),VOL2(11),ULC(5),TAU(5),POWER(5),ALFA(5),ETAPUM(5)
 0004            1 FORMAT(10F8.2)
 0005            2 FORMAT(10F8.4)
 0006            3 FORMAT(5F10.2)
 0007            4 FORMAT(2F10.2)
 0008            5 FORMAT(  12F6.1 )
 0009            6 FORMAT(8F10.2)
 0010            7 FORMAT(12F6.2)
 0011            8 FORMAT(E12.6,15X,E12.6)
 0012            9 FORMAT(F10.2)
 0013           10 FORMAT(6F12.4)
 0014           11 FORMAT(I6,2F10.0,F8.2,2F10.0,14H BOILER TEMP.#   F5.0,
                  118H CONDENSER TEMP.#      F5.0  /)
 0015           18 FORMAT(8F8.0,2X, A4,2I4)
 0016           19 FORMAT(12(2X,A4))
 0017           26 FORMAT(1H1)
 0018           27 FORMAT(35H FLOW FACTOR  LESS THAN  1 PERCENT      )
 0019           29 FORMAT(5I10)
 0020           30 FORMAT(27H BOILER PRESSURES IN PSIA       )
 0021           31 FORMAT(30H CONDENSER PRESSURES IN PSIA      )
 0022           32 FORMAT(28H BOILER TEMPERATURES IN %F<     )
 0023           33 FORMAT(31H CONDENSER TEMPERATURES IN %F<     )
 0024           34 FORMAT(20H ENTHALPIES BTU/LB      )
 0025           35 FORMAT(24H ENTROPIES BTU/LB.F        )
 0026           36 FORMAT(22H TURBINE EFFICIENCIES       )
 0027           37 FORMAT(19H PUMP EFFICIENCIES       )
 0028           38 FORMAT(16H ABSORPTIVITIES      )
 0029           40 FORMAT(20H POWER RATING IN KW    )
 0030           60 FORMAT(16H COLLECTOR AREA#     F12.0)
 0031           65 FORMAT(2X,8F8.0,2X,A4,2X,'RAD.a)
 0032           66 FORMAT(2X,8F8.0,2X,A4,2X,'SUN.a)
 0033           67 FORMAT(26H TOTAL YEARLY RADIATION#  F16.0)
 0034           68 FORMAT(27H YEARLY AVERAGE RADIATION  F6.0 /)
 0035           69 FORMAT(2X,10F6.0,10H RADIATION       /)
 0036           70 FORMAT(2X,10F6.3,11H EFFICIENCY      ///)
 0037           71 FORMAT(2X,10F6.0,10H FLOWRATE         ///)
 0038           72 FORMAT(8F8.0,5X,16H TOTAL WORK FOR , A4)
 0039           76 FORMAT(15H COST PER KWH#   F8.6,12H COLL.AREA#    F8.2, 8H TRIAL#
                  1  I4)
 0040          140 FORMAT(18H TRANSMISSIVITIES      )
 0041          141 FORMAT(31H OVERALL HEAT LOSS COEFFICIENT          )
 0042          143 FORMAT(22H UTILIZABILITY FACTOR          )
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0043       145 FORMAT(23H ALL PRICES IN DOLLARS       )
0044       146 FORMAT(83H WOOD PRICE GLASS PRI.TEDLARP.  SHEET IRON GLASWOOL  TUR
              1.PRI. CIRC.PUM.  FEED PUM.      )
0045       147 FORMAT(90H PIPE PRICE GOVER.PRI.COND.TUBE  COND.SHELL REPAIR   OPE
              1RATION INTEREST  LIFETIME,YEARS            )
0046       148 FORMAT(54H USE FACTOR AMBIENT T COOL W I COOL W O PIPE HEATLOSS  )
0047       149 FORMAT(53H *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-  )
0048      1001 READ (5,29)NN,IJ,IK,IL,IM
0049           READ (5,1)(P1(M),M=1,10)
0050           READ (5,1)(P2(M),M=1,10)
0051           READ (5,1)(T1(M),M=1,10)
0052           READ (5,1)(T2(M),M=1,10)
0053           READ (5,1)(HV1(M),M=1,10)
0054           READ (5,1)(HV2(M),M=1,10)
0055           READ (5,1)(HFL1(M),M=1,10)
0056           READ (5,1)(HFL2(M),M=1,10)
0057           READ (5,2)(SV1(M),M=1,10)
0058           READ (5,2)(SV2(M),M=1,10)
0059           READ (5,2)(SFL1(M),M=1,10)
0060           READ (5,2)(SFL2(M),M=1,10)
0061           READ (5,3)(ETATUR(M),M=1,5)
0062           READ (5,3)(ETAPUM(M),M=1,5)
0063           READ (5,3)(ALFA(M),M=1,5)
0064           READ (5,3)(POWER(M),M=1,5)
0065           READ (5,3)(TAU(M),M=1,5)
0066           READ (5,3)(ULC(M),M=1,5)
0067           READ (5,6)PRWOOD,PRGLAS,PRTEDL,PRSTEL,PRFIBG,PRTUR,PRCIPU,PRFEPU
0068           READ (5,6)PRPIPE,PRGOVR,PRCOTU,PRCOSH,REPAIR,OPERTN,ENTRS,EXPLIF
0069           READ (5,3)USEFAC,TAMBI,TCWI,TCWO,PIPLOS
0070           READ (5,19)(MONTH(L),L=1,12)
0071           DO 168 L=1,12
0072           GO TO(101,102,101,103,101,103,101,101,103,101,103,101),L
0073       101 MX=31
0074           GO TO 104
0075       102 MX=28
0076           GO TO 104
0077       103 MX=30
0078       104 CONTINUE
0079           DO 168 M=1,MX
0080       168 READ (5,18)(RADTIN(L,M,N),N=1,8),MONTH(L),IDAY,IMON
0081           WRITE(6,26)
0082           WRITE(6,30)
0083           WRITE(6,1)(P1(M),M=1,10)
0084           WRITE(6,31)
0085           WRITE(6,1)(P2(M),M=1,10)
0086           WRITE(6,32)
0087           WRITE(6,1)(T1(M),M=1,10)
0088           WRITE(6,33)
0089           WRITE(6,1)(T2(M),M=1,10)
0090           WRITE(6,34)
0091           WRITE(6,1)(HV1(M),M=1,10)
0092           WRITE(6,1)(HV2(M),M=1,10)
0093           WRITE(6,1)(HFL1(M),M=1,10)
0094           WRITE(6,1)(HFL2(M),M=1,10)
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```
0095            WRITE(6,35)
0096            WRITE(6,2)(SV1(M),M=1,10)
0097            WRITE(6,2)(SV2(M),M=1,10)
0098            WRITE(6,2)(SFL1(M),M=1,10)
0099            WRITE(6,2)(SFL2(M),M=1,10)
0100            WRITE(6,36)
0101            WRITE(6,9)ETATUR(1)
0102            WRITE(6,37)
0103            WRITE(6,9)ETAPUM(1)
0104            WRITE(6,38)
0105            WRITE(6,9)ALFA(1)
0106            WRITE(6,40)
0107            WRITE(6,9)POWER(1)
0108            WRITE(6,140)
0109            WRITE(6,9)TAU(1)
0110            WRITE(6,141)
0111            WRITE(6,9)ULC(1)
0112            WRITE(6,145)
0113            WRITE(6,146)
0114            WRITE(6,6)PRWOOD,PRGLAS,PRTEDL,PRSTEL,PRFIRG,PRTUR,PRCIPJ,PRFEPU
0115            WRITE(6,147)
0116            WRITE(6,6)PRPIPE,PRGOVR,PRCOTU,PRCOSH,REPAIR,OPERTN,ENTRS,EXPLIF
0117            WRITE(6,148)
0118            WRITE(6,3)USEFAC,TAMBI,TCWI,TCWO,PIPLOS
0119            DO 100 I=6,10
0120            WRITE(6,26)
0121            K=1
0122            II=1
0123            JJ=1
0124            J=4
0125            TOTDAY=0.
          C     THERMODYNAMICAL ANALYSIS OF THE CYCLE
          C     RANKINE CYCLE FOR SATURATED STEAM
          C     ISENTROPIC EXPANSION FROM THE SATURATED VAPOUR STATE
          C     X2   IS THE QUALITY OF STEAM AFTER ISENTROPIC EXPANSION
0126            X2(J)=(SV1(I)-SFL2(J))/(SV2(J)-SFL2(J))
0127            HX2(J)=HFL2(J)+X2(J)*(HV2(J)-HFL2(J))
          C     IDEAL WORK
0128            WOUI=HV1(I)-HX2(J)
          C     ACTUAL WORK
0129            WOUA=WOUI*ETATUR(K)
0130            QADD=HV1(I)-HFL2(J)
          C     PUMP WORK
0131            WPUMP=0.00298*(P1(I)-P2(J))
0132            WPUMPA=WPUMP/ETAPUM(K)
          C     NET  WORK
0133            WNETT=WOUA-WPUMPA
          C     RANKINE CYCLE EFFICIENCY
0134            ETARAN=WNETT/QADD
0135            QREJ=HX2(J)-HFL2(J)
0136            ALFA(K)=0.9
0137            TAU(K)=0.83
0138            ULC(K)=0.423
          C     CRITICAL RADIATION INTENSITY BELOW WHICH NO USEFUL HEAT COLLECTION
```

```
C      SHOULD BE ATTEMPTED
       RADCRT=1.05*ULC(K)*(T1(I)-TAMBI)/(TAU(K)*ALFA(K))
       DO 285 L=1,12
       GO TO(301,302,301,303,301,303,301,301,303,301,303,301),L
   301 MV=31
       GO TO 304
   302 MV=28
       GO TO 304
   303 MV=30
   304 CONTINUE
       DO 285 N=1,8
       DAYCOU=0.
       SUMRAD=0.
       DO 185 M=1,MV
C      COMPARING THE HOURLY RADIATION INTENSITY WITH THE CRITICAL
       IF(RADTIN(L,M,N)-RADCRT)185,185,184
   184 SUMRAD=SUMRAD+RADTIN(L,M,N)
       DAYCOU=DAYCOU+1.
   185 ENDAY(L,N)=DAYCOU
       IF(ENDAY(L,N))186,186,187
   186 AVERAD(L,N)=0.
       GO TO 285
   187 AVERAD(L,N)=SUMRAD/ENDAY(L,N)
C      EQUATE THE HOURLY RADIATION INTENSITY TO MONTHLY AVERAGE
   285 RADION(L,N)=AVERAD(L,N)
C      PRINT A LIST OF RADIATION INTENSITIES AND NUMBER OF DAYS
C      ENCOUNTERED WITHIN THE CORRESPONDING MONTH
       DO 288 L=1,12
       WRITE(6,65)(RADION(L,N),N=1,8),MONTH(L)
       WRITE(6,66)( ENDAY(L,N),N=1,8),MONTH(L)
   288 CONTINUE
       TOYERA =0.
C      OBTAIN THE YEARLY TOTAL RADIATION
       DO 289 L=1,12
       DO 289 N=1,8
   289 TOYERA=TOYERA+AVERAD(L,N)*ENDAY(L,N)
       WRITE(6,67)TOYERA
       DO 291 L=1,12
       DO 291 N=1,8
   291 TOTDAY=TOTDAY+ENDAY(L,N)
C      OBTAIN THE YEARLY AVERAGE RADIATION
       AVERYE=TOYERA/TOTDAY
       WRITE(6,68)AVERYE
       WRITE(6,149)
   311 RADION(II,JJ)=AVERYE
C      FLAT PLATE COLLECTOR PERFORMANCE,AREA ,COST CALCULATIONS
       RATING=12.
       ACRATE=RATING*(1.+PIPLOS)
       QTOT=ACRATE*3413.
       FLOW=QTOT/(QADD-QREJ)
C      TOTAL HEAT WHICH MUST BE COLLECTED
       QUSEF=QADD*(1.+PIPLOS)*FLOW
       JMN=1
C      FLAT PLATE COLLECTOR PERFORMANCE  WITH HONEYCOMB CONVECTION
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C     SUPPRESSORS AND SELECTIVE ABSORBING SURFACE
C     HONEYCOMB CELLS AND THEIR CHARACTERISTIC FIGURES AS SUGGESTED
C     BY T.HOLLANDS
      ETACOL(K)=0.40
      EFPRIM=0.9
      CHECK=AVERYE*TAU(K)*ALFA(K)-ULC(K)*(T1(I)-TAMBI)
      IF(AVERYE-RADCRT)47,47,39
   39 IF(CHECK)47,47,41
   41 AREAPP=QUSEF/(AVERYE*ETACOL(K))
      G=FLOW/(0.1*AREAPP)
  520 EXPON=EFPRIM*ULC(K)/G
      IF(EXPON-100.)522,522,523
  522 FLOFAC=(1.-(1./(2.718**EXPON)))/EXPON
      GO TO 526
  523 FLOFAC=0.01
  526 FR=FLOFAC*EFPRIM
      ARESEN=0.1*QUSEF/(FR*(AVERYE*TAU(K)*ALFA(K)-ULC(K)*
     1(T2(J)-TAMBI)))
      ARELAT=.9*QUSEF/(EFPRIM*(AVERYE*TAU(K)*ALFA(K)-ULC(K)*
     1(T1(I)-TAMBI)) )
      AREA=ARESEN+ARELAT
      G=FLOW/ARESEN
      JMN=JMN+1
      ETACOL(K)=FR*CHECK/AVERYE
      IF(JMN-2)520,520,45
   45 EF(II,JJ)=ETARAN*ETACOL(K)
      OAREA=AREA
      IF(EF(II,JJ))47,47,48
   47 EF(II,JJ)=0.000001
   48 CONTINUE
      DO 450 KAR=3,5
      AKAR=KAR
      AREA=0.25*OAREA*FLOAT(KAR)
      WRITE(6,60)AREA
  312 DO 340 KMK=1,20
      RADIAT(KMK)=330.-10.*FLOAT(KMK)
      IMN=1
  322 CONTINUE
      WRKHOU=.1*AREA*FR*(RADIAT(KMK)*TAU(K)*ALFA(K)-ULC(K)*(T2(J)-TAMBI)
     1)/3413.+.9*AREA*EFPRIM*(RADIAT(KMK)*TAU(K)*ALFA(K)-ULC(K)*(T1(I)-
     2TAMBI))/3413.
      WRKHOU=WRKHOU*ETARAN
      EFFIC(KMK)=WRKHOU*3413./(AREA*RADIAT(KMK))
C     CORRECT THE FLOW RATE TO MAINTAIN CONSTANT OUTPUT TEMPERATURE
      VAFLOW(KMK)=AREA*RADIAT(KMK)/(HV1(I)-HFL2(J))
      G=VAFLOW(KMK)/(0.1*AREA)
 1520 EPOWR=EFPRIM*ULC(K)/G
      IF(EPOWR-100.)1522,1522,1523
 1522 FLOFAC=(1.-(1./(2.718**EPOWR)))/EPOWR
      GO TO 1526
 1523 FLOFAC=0.01
 1526 FR=FLOFAC*EFPRIM
      IMN=IMN+1
      IF(IMN-2)322,322,340
```

```
0229        340 CONTINUE
0230            WRITE(6,9)T1(I)
0231            WRITE(6,69)(RADIAT(KMK),KMK=1,10)
0232            WRITE(6,70)(EFFIC(KMK),KMK=1,10)
0233            WRITE(6,71)(VAFLOW(KMK),KMK=1,10)
0234            WRITE(6,69)(RADIAT(KMK),KMK=11,20)
0235            WRITE(6,70)(EFFIC(KMK),KMK=11,20)
0236            WRITE(6,71)(VAFLOW(KMK),KMK=11,20)
0237            TOTWRK=0.
0238            DO 375 II=1,12
0239            DO 375 JJ=1,8
0240            DO 191 KMK=1,20
0241            RADIAT(KMK)=330.-10.*FLOAT(KMK)
0242            IRADI=RADION(II,JJ)
0243            ROURAD=(IRADI/10)*10
0244            IF(ROURAD-RADIAT(KMK))191,193,191
0245        191 CONTINUE
0246        193 WRKMON(II,JJ)=AREA*EFFIC(KMK)*RADION(II,JJ)*USEFAC/3413.
0247            IF(WRKMON(II,JJ)-RATING)195,194,194
0248        194 WRKMON(II,JJ)=12.
0249        195 CONTINUE
0250            TOTWRK=TOTWRK+WRKMON(II,JJ)*ENDAY(II,JJ)
0251        375 CONTINUE
0252            DO 385 II=1,12
0253        385 WRITE(6,72)(WRKMON(II,JJ),JJ=1,8),MONTH(II)
0254         51 COLCOS=6.5*AREA
0255            ASSEM=1.2
0256            COLINV=COLCOS*ASSEM
          C     NO STORAGE SYSTEM IS REQUIRED
0257            STOINV=0.
          C     TEMPERATURE AND AUTOMATIC CONTROLS COST
0258            COTINV=250.
          C     TURBINE  PERFORMANCE AND COST
          C     IF THE SYSTEM SHOULD OPERATE BELOW 212  DEG.F. A VACUUM PUMP
          C     MUST BE USED
0259            IF(T1(I)-212.)54,54,56
0260         54 PRVAPU=250.
0261            TURINV=PRTUR*POWER(K)+PRCIPU+PRFEPU+PRVAPU
0262            GO TO 57
0263         56 TURINV=PRTUR*POWER(K)+PRCIPU+PRFEPU
          C     THE CONDENSER TEMPERATURE IS FIXED AT 90 DEG. F
          C     THE CONDENSER COST TOO IS FIXED
0264         57 SININV=300.
          C     FINAL COST CALCULATIONS,COST PER KWHR
          C     FINAL COST CALCULATIONS,COST PER KWHR
0265            TOTINV=COLINV+STOINV+SININV+TURINV+COTINV
0266            CAREFC=ENTRS*(1.+ENTRS)**EXPLIF/((1.+ENTRS)**EXPLIF-1.)
0267            TOTEXP=TOTINV*(CAREFC+REPAIR+OPERTN)
0268            FINCOS(I)=TOTEXP/TOTWRK
0269            COCENT=FINCOS(I) *100.
0270            WRITE(6,76)FINCOS(I),AREA,KAR
0271            WRITE(6,11)I,TOTINV,TOTEXP,COCENT,AREA,COLCOS,T1(I),T2(J)
0272            WRITE(6,149)
0273            WRITE(6,26)
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0274          459 CONTINUE
0275          100 CONTINUE
0276              IF(NN-1)999,1001,999
0277          999 CALL EXIT
0278              END
```

TOTAL MEMORY REQUIREMENTS 0065C8 BYTES

COLLECTOR AREA# 2485.
230.00

320.	310.	300.	290.	280.	270.	260.	250.	240.	230.	RADIATION
0.057	0.057	0.056	0.055	0.055	0.054	0.053	0.052	0.051	0.050	EFFICIENCY
724.	701.	678.	656.	633.	611.	588.	565.	543.	520.	FLOWRATE
220.	210.	200.	190.	180.	170.	160.	150.	140.	130.	RADIATION
0.048	0.047	0.046	0.044	0.042	0.040	0.038	0.035	0.032	0.029	EFFICIENCY
498.	475.	452.	430.	407.	384.	362.	339.	317.	294.	FLOWRATE

6.	10.	11.	12.	12.	11.	10.	6.	TOTAL WORK FOR JAN.
3.	7.	9.	10.	10.	9.	7.	3.	TOTAL WORK FOR FEB.
3.	7.	9.	10.	10.	9.	7.	3.	TOTAL WORK FOR MAR.
2.	5.	6.	8.	8.	6.	5.	2.	TOTAL WORK FOR APR.
0.	3.	4.	5.	5.	4.	3.	0.	TOTAL WORK FOR MAY.
0.	2.	3.	4.	4.	3.	2.	0.	TOTAL WORK FOR JUN.
0.	2.	3.	5.	5.	3.	2.	0.	TOTAL WORK FOR JUL.
2.	4.	6.	7.	7.	6.	5.	2.	TOTAL WORK FOR AUG.
3.	6.	7.	9.	9.	7.	6.	3.	TOTAL WORK FOR SEP.
3.	6.	7.	8.	8.	7.	5.	3.	TOTAL WORK FOR OCT.
2.	5.	6.	7.	7.	6.	5.	2.	TOTAL WORK FOR NOV.
2.	3.	5.	6.	6.	4.	3.	2.	TOTAL WORK FOR DEC.

COST PER KWH# 0.264108 COLL.AREA# 2485.43 TRIAL# 3
8 22346. 3865. 26.41 2485. 16155. BOILER TEMP.# 230. CONDENSER TEMP.# 90.

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COLLECTOR AREA# 3314.
230.00

320.	310.	300.	290.	280.	270.	260.	250.	240.	230.	RADIATION
0.057	0.057	0.056	0.055	0.055	0.054	0.053	0.052	0.051	0.050	EFFICIENCY
965.	935.	905.	874.	844.	814.	784.	754.	724.	694.	FLOWRATE
220.	210.	200.	190.	180.	170.	160.	150.	140.	130.	RADIATION
0.048	0.047	0.046	0.044	0.042	0.040	0.038	0.035	0.032	0.029	EFFICIENCY
663.	633.	603.	573.	543.	513.	482.	452.	422.	392.	FLOWRATE

8.	12.	12.	12.	12.	12.	12.	8.	TOTAL WORK FOR JAN.
4.	9.	11.	12.	12.	11.	9.	4.	TOTAL WORK FOR FEB.
4.	9.	11.	12.	12.	11.	9.	4.	TOTAL WORK FOR MAR.
3.	6.	8.	10.	10.	8.	6.	3.	TOTAL WORK FOR APR.
0.	4.	5.	7.	7.	5.	3.	0.	TOTAL WORK FOR MAY.
0.	3.	4.	5.	5.	4.	3.	0.	TOTAL WORK FOR JUN.
0.	3.	5.	6.	6.	5.	3.	0.	TOTAL WORK FOR JUL.
3.	6.	8.	10.	10.	8.	6.	3.	TOTAL WORK FOR AUG.
3.	7.	10.	11.	11.	10.	7.	3.	TOTAL WORK FOR SEP.
3.	7.	9.	11.	11.	9.	7.	3.	TOTAL WORK FOR OCT.
3.	7.	8.	10.	10.	8.	6.	3.	TOTAL WORK FOR NOV.
3.	5.	6.	7.	7.	6.	5.	3.	TOTAL WORK FOR DEC.

COST PER KWH# 0.264762 COLL.AREA# 3313.91 TRIAL# 4
8 28808. 4983. 26.48 3314. 21540. BOILER TEMP.# 230. CONDENSER TEMP.# 90.

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COLLECTOR AREA# 4142.
230.00

320.	310.	300.	290.	280.	270.	260.	250.	240.	230.	RADIATION
0.057	0.057	0.056	0.055	0.055	0.054	0.053	0.052	0.051	0.050	EFFICIENCY
1206.	1168.	1131.	1093.	1055.	1018.	980.	942.	905.	867.	FLOWRATE
220.	210.	200.	190.	180.	170.	160.	150.	140.	130.	RADIATION
0.048	0.047	0.046	0.044	0.042	0.040	0.038	0.035	0.032	0.029	EFFICIENCY
829.	792.	754.	716.	678.	641.	603.	565.	528.	490.	FLOWRATE

9.	12.	12.	12.	12.	12.	12.	11.	TOTAL WORK FOR JAN.
5.	11.	12.	12.	12.	12.	11.	5.	TOTAL WORK FOR FEB.
5.	11.	12.	12.	12.	12.	11.	5.	TOTAL WORK FOR MAR.
4.	8.	11.	12.	12.	11.	8.	4.	TOTAL WORK FOR APR.
0.	4.	7.	9.	9.	7.	4.	0.	TOTAL WORK FOR MAY.
0.	4.	5.	6.	6.	5.	4.	0.	TOTAL WORK FOR JUN.
0.	4.	6.	8.	8.	6.	4.	0.	TOTAL WORK FOR JUL.
4.	7.	10.	12.	12.	10.	8.	4.	TOTAL WORK FOR AUG.
4.	9.	12.	12.	12.	12.	9.	4.	TOTAL WORK FOR SEP.
4.	9.	11.	12.	12.	11.	9.	4.	TOTAL WORK FOR OCT.
4.	8.	10.	12.	12.	10.	8.	4.	TOTAL WORK FOR NOV.
4.	6.	8.	9.	9.	7.	6.	4.	TOTAL WORK FOR DEC.

COST PER KWH# 0.276911 COLL.AREA# 4142.38 TRIAL# 5
8 35271. 6101. 27.69 4142. 26925. BOILER TEMP.# 230. CONDENSER TEMP.# 90.

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      C     M.KUDRET SELCUK
      C     UNSTEADY STATE ANALYSIS WITH VARIABLE POWER DEMAND
      C     USING HEAT ENGINES
      C.    MAIN PROGRAMME
0001        DIMENSION FINCOS(50),WRKHOU(12,31,24),RADTIN(12,31,24),
           1ENDAY(12,12),FF(12,12)     ,AVERAD(12,12),MONTH(12)
0002        DIMENSION UTIL(12),DECLIN(12),CONSUM(12,31,24),STOR(12,31,24)
0003        DIMENSION  P1(11),P2(11),T1(11),T2(11),HV1(11),HV2(11),HFL1(11),
           1HFL2(11),SV1(11),SFL1(11),SFL2(11),SX1(11),SX2(11),SV2(11),
           2HX2(11),HX1(11),RADION(12,12),X1(11),X2(11),ETACOL(5),ETATUR(5),
           3ULC(5),TAU(5),POWER(5),ALFA(5),ETAPUM(5)
0004      1 FORMAT(10F8.2)
0005      2 FORMAT(10F8.4)
0006      3 FORMAT(5F10.2)
0007      4 FORMAT(2F10.2)
0008      5 FORMAT(  12F6.1 )
0009      6 FORMAT(8F10.2)
0010      7 FORMAT(12F6.2)
0011      8 FORMAT(F12.6,15X,F12.6)
0012      9 FORMAT(F10.2)
0013     10 FORMAT(5F12.4)
0014     11 FORMAT(I6,2F10.0,F8.2,2F10.0,14H BOILER TEMP.#    F5.0,
           118H CONDENSER TEMP.#       F5.0  /)
0015     12 FORMAT(12F6.1)
0016     17 FORMAT(2F16.0)
0017     18 FORMAT(8F8.0,2X,A4,2I4)
0018     19 FORMAT(12(2X,A4))
0019     26 FORMAT(1H1)
0020     27 FORMAT(35H FLOW FACTOR. LESS THAN  1 PERCENT      )
0021     29 FORMAT(F110)
0022     30 FORMAT(27H BOILER PRESSURES IN PSIA       )
0023     31 FORMAT(30H CONDENSER PRESSURES IN PSIA      )
0024     32 FORMAT(28H BOILER TEMPERATURES IN %F<    )
0025     33 FORMAT(31H CONDENSER TEMPERATURES IN %F<     )
0026     34 FORMAT(20H ENTHALPIES BTU/LB       )
0027     35 FORMAT(24H ENTROPIES BTU/LB.F          )
0028     36 FORMAT(22H TURBINE EFFICIENCIES        )
0029     37 FORMAT(19H PUMP EFFICIENCIES        )
0030     38 FORMAT(16H ABSORPTIVITIES      )
0031     40 FORMAT(20H POWER RATING IN KW  . )
0032     60 FORMAT(16H COLLECTOR AREA#       F12.0)
0033     61 FORMAT(26H INITIAL STORAGE IN KWH#        F12.0   //)
0034     65 FORMAT(2X,8F8.0,2X,A4,2X,'RAD.0)
0035     66 FORMAT(2X,8F8.0,2X,A4,2X,'SUN,0)
0036     67 FORMAT(26H TOTAL YEARLY RADIATION#  F16.0)
0037     68 FORMAT(27H YEARLY AVERAGE RADIATION  F6.0//)
0038     69 FORMAT(4X,20F4.0,10H RADIATION   /)
0039     70 FORMAT(4X,20F4.2,11H EFFICIENCY  /)
0040     71 FORMAT(4X,20F4.0,10H FLOW RATE    //)
0041     72 FORMAT(8F8.0,5X,16H TOTAL WORK FOR ,2A2)
0042     76 FORMAT(15H COST PER KWH#  F16.6,12H COLL.AREA#  F16.2, 9H TOTAL#
           1  I4)
0043     77 FORMAT(20H HOURLY STORAGE#        F16.0)
0044     78 FORMAT(27H SUPPLEMENT NEEDED IN KWH#      F12.0,
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                 129H HOUR WITHOUT POWER SUPPLY#      I6,4X,A6,I3)
0045          79 FORMAT(22H MINIMUM HEAT STORED#   F16.0,22H MAXIMUM HEAT STORED#
                1  F16.0 /)
0046          80 FORMAT(42H LARGEST STORAGE CAPASITY NEEDED IN BTU #       F12.0)
0047         140 FORMAT(18H TRANSMISSIVITIES      )
0048         141 FORMAT(31H OVERALL HEAT LOSS COEFFICIENT          )
0049         145 FORMAT(23H ALL PRICES IN DOLLARS        )
0050         146 FORMAT(83H WOOD PRICE GLASS PRI.TEDLARP.  SHEET IRON GLASWOOL  TUR
                1.PRI. CIRC.PUM.  FEED PUM.      )
0051         147 FORMAT(90H PIPE PRICE GOVER.PRI.COND.TUBE  COND.SHELL REPAIR   OPE
                1RATION INTEREST  LIFETIME,YEARS                 )
0052         148 FORMAT(54H USE FACTOR AMBIENT T COOL W I COOL W O PIPE HEATLOSS  )
0053         149 FORMAT(53H ***    ***    ***  ***    ***    ***    ***    ***     )
0054         151 FORMAT(53H THE FRACTION OFTHE RATED POWER CONSUMED#3 HOURLY<      )
0055        1001 READ (5,29)NN,IJ,IK,IL,IM
0056             READ (5,29)NJAN,NFEB,NJUN,NJULY,NAUG
0057             READ (5,1)(P1(M),M=1,10)
0058             READ (5,1)(P2(M),M=1,10)
0059             READ (5,1)(T1(M),M=1,10)
0060             READ (5,1)(T2(M),M=1,10)
0061             READ (5,1)(HV1(M),M=1,10)
0062             READ (5,1)(HV2(M),M=1,10)
0063             READ (5,1)(HFL1(M),M=1,10)
0064             READ (5,1)(HFL2(M),M=1,10)
0065             READ (5,2)(SV1(M),M=1,10)
0066             READ (5,2)(SV2(M),M=1,10)
0067             READ (5,2)(SFL1(M),M=1,10)
0068             READ (5,2)(SFL2(M),M=1,10)
0069             READ (5,3)(ETATUR(M),M=1,5)
0070             READ (5,3)(ETAPUM(M),M=1,5)
0071             READ (5,3)(ALFA(M),M=1,5)
0072             READ (5,3)(POWER(M),M=1,5)
0073             READ (5,3)(TAU(M),M=1,5)
0074             READ (5,3)(ULC(M),M=1,5)
0075             READ (5,4)PARLEL,BETA
0076             READ (5,6)PRWOOD,PRGLAS,PRTEDL,PRSTEL,PRFIBG,PRTUR,PRCIPJ,PRFEPU
0077             READ (5,6)PRPIPE,PRGOVR,PRCOTU,PRCOSH,REPAIR,OPERTN,ENTRS,EXPLIF
0078             READ (5,3)USEFAC,TAMBI,TCWI,TCWO,PIPLOS
0079             READ (5,19)(MONTH(L),L=1,12)
0080             READ (5,4)RATING,RESDAY
0081             READ (5,6)F1,F2,F3,F4,F5,F6,F7,F8
           C     READ THE RADIATION INTENSITY ON THE  TILTED COLLECTOR
           C     PLANE  OBTAINED FROM  A SUBROUTINE
0082             DO 168 L=1,12
0083             GO TO (101,102,101,103,101,103,101,101,103,101,103,101),L
0084         101 MV=NJAN
0085             GO TO 104
0086         102 MV=NFEB
0087             GO TO 104
0088         103 MV=NJUN
0089         104 CONTINUE
0090             DO 168 M=1,MV
0091         168 READ (5,18)(RADTIN(L,M,N),N=1,8),MONTH(L),IDAY,IMON
0092             WRITE(6,26)
```

```
      WRITE(6,30)
      WRITE(6,1)(P1(M),M=1,10)
      WRITE(6,31)
      WRITE(6,1)(P2(M),M=1,10)
      WRITE(6,32)
      WRITE(6,1)(T1(M),M=1,10)
      WRITE(6,33)
      WRITE(6,1)(T2(M),M=1,10)
      WRITE(6,34)
      WRITE(6,1)(HV1(M),M=1,10)
      WRITE(6,1)(HV2(M),M=1,10)
      WRITE(6,1)(HFL1(M),M=1,10)
      WRITE(6,1)(HFL2(M),M=1,10)
      WRITE(6,35)
      WRITE(6,2)(SV1(M),M=1,10)
      WRITE(6,2)(SV2(M),M=1,10)
      WRITE(6,2)(SFL1(M),M=1,10)
      WRITE(6,2)(SFL2(M),M=1,10)
      WRITE(6,36)
      WRITE(6,9)ETATUR(1)
      WRITE(6,37)
      WRITE(6,9)ETAPUM(1)
      WRITE(6,38)
      WRITE(6,9)ALFA(1)
      WRITE(6,40)
      WRITE(6,9)POWER(1)
      WRITE(6,140)
      WRITE(6,9)TAU(1)
      WRITE(6,141)
      WRITE(6,9)ULC(1)
      WRITE(6,145)
      WRITE(6,146)
      WRITE(6,6)PRWOOD,PRGLAS,PRSTEL,PRSTEL,PREIBG,PRTUP,PRCIPU,PREEPU
      WRITE(6,147)
      WRITE(6,6)PRPIPE,PRGOVR,PRCOTU,PRCOSH,REPAIR,OPERTN,ENTRS,EXPLIF
      WRITE(6,148)
      WRITE(6,3)USEFAC,TAMBI,TCHI,TCWO,PIPLOS
      WRITE(6,151)
      WRITE(6,6)F1,F2,F3,F4,F5,F6,F7,F8
      WRITE(6,26)
        DO 100 I=8,10,2
C     READ A LIST OF AVERAGED RADIATION INTENSITIES OBTAINED  BY MEANS
C     OF A SUBROUTINE  CALCULATING MONTHLY AVERAGES OF THE RADIATION
C     FROM  A YEARS  DATA
C     DUE TO THE EASE OF COMPUTATION DAY IS STARTED AT 8 AM
C     N#1 REPRESENTS 8 AM ,  N#8 REPRESENTS 4 PM ETC
C     RADIATION AFTER THE FIRST 8 HOURS IS ASSUMED TO BE ZERO
  163 DO 167 L=1,12
      READ (5,65)(RADION(L,N),N=1,8),MONTH(L)
      READ (5,66)( ENDAY(L,N),N=1,8),MONTH(L)
  167 CONTINUE
C     READ THE YEARLY TOTAL AND YEARLY AVERAGE RADIATION
      READ (5,17)TOYERA,AVERYE
      DO 288 L=1,12
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```
0140            WRITE(6,65)(RADION(L,M),M=1,8),MONTH(L)
0141            WRITE(6,66)(ENDAY(L,M),M=1,8),MONTH(L)
0142        230 CONTINUE
0143            WRITE(6,17)TOYERA,AVERYE
0144            DO 161 L=1,12
0145            GO TO(201,202,201,203,201,203,201,201,203,201,203,201),L
0146        201 MV=NJAN
0147            GO TO 204
0148        202 MV=NFEB
0149            GO TO 204
0150        203 MV=NJUN
0151        204 CONTINUE
0152            DO 161 M=1,MV
0153            DO 161 N=9,24
0154        161 RADTIN(L,M,N)=0.
0155            ASSEM=1.2
0156            K=1
0157            II=1
0158            JJ=1
0159            J=4
0160            TOTDAY=0.
          C     THERMODYNAMICAL ANALYSIS OF THE CYCLE
          C     RANKINE CYCLE FOR SATURATED STEAM
          C     ISENTROPIC EXPANSION FROM THE SATURATED VAPOUR STATE
          C     X2   IS THE QUALITY OF STEAM AFTER ISENTROPIC EXPANSION
0161            X2(J)=(SV1(I)-SFL2(J))/(SV2(J)-SFL2(J))
0162            HX2(J)=HFL2(J)+X2(J)*(HV2(J)-HFL2(J))
          C     IDEAL WORK
0163            WOUI=HV1(I)-HX2(J)
          C     ACTUAL WORK
0164            WOUA=WOUI*ETATUR(K)
0165            QADD=HV1(I)-HFL2(J)
          C     PUMP WORK
0166            WPUMP=0.00299*(P1(I)-P2(J))
0167            WPUMPA=WPUMP/ETAPUM(K)
          C     NET  WORK
0168            WNETT=WOUA-WPUMPA
          C     RANKINE CYCLE EFFICIENCY
0169            ETARAN=WNETT/QADD
0170            QREJ=HX2(J)-HFL2(J)
          C     CRITICAL RADIATION INTENSITY BELOW WHICH NO USEFUL HEAT COLLECTION
          C     SHOULD BE ATTEMPTED
0171            ULC(K)=0.423
0172            ALFA(K)=0.9
0173            TAU(K)=0.83
0174            RADCRT=1.05*ULC(K)*(T1(I)-TAMBI)/(TAU(K)*ALFA(K))
0175        311 RADION(II,JJ)=AVERYE
          C     FLAT PLATE COLLECTOR PERFORMANCE,AREA ,COST CALCULATIONS
0176            RATING=12.
0177            ACRATE=RATING*(1.+PIPLOS)
0178            QTOT=ACRATE*3413.
0179            FLOW=QTOT/(QADD-QREJ)
          C     TOTAL HEAT WHICH MUST BE COLLECTED
0180            QUSEF=QADD*(1.+PIPLOS)*FLOW
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            JMN=1
C     FLAT PLATE COLLECTOR PERFORMANCE  WITH HONEYCOMB CONVECTION
C     SUPPRESSORS AND SELECTIVE ABSORBING SURFACE
C     HONEYCOMB CELLS AND THEIR CHARACTERISTIC FIGURES AS SUGGESTED
C     BY T.HOLLANDS
            ETACOL(K)=0.40
            EFPRIM=0.9
            CHECK=AVERYE*TAU(K)*ALFA(K)-ULC(K)*(T1(I)-TAMBI)
            IF(AVERYE-RADCRT)47,47,39
         39 IF(CHECK)47,47,41
         41 AREAPP=QUSEF/(AVERYE*ETACOL(K))
            G=FLOW/(0.1*AREAPP)
        520 EXPON=EFPRIM*ULC(K)/G
            IF(EXPON-100.)522,522,523
        522 FLOFAC=(1.-(1./(2.718**EXPON)))/EXPON
            GO TO 526
        523 FLOFAC=0.01
        526 FR=FLOFAC*EFPRIM
            ARESEN=0.1*QUSEF/(FR*(AVERYE*TAU(K)*ALFA(K)-ULC(K)*
           1(T2(J)-TAMBI)))
            ARFLAT=.9*QUSEF/(EFPRIM*(AVERYE*TAU(K)*ALFA(K)-ULC(K)*
           1(T1(I)-TAMBI)))
            AREA=ARESEN+ARFLAT
            G=FLOW/ARESEN
            JMN=JMN+1
            ETACOL(K)=FR*CHECK/AVERYE
            IF(JMN-2)520,520,45
         45 FF(II,JJ)=ETAPAN*ETACOL(K)
            WRITE(6,60)AREA
            OAREA=AREA
            IF(FF(II,JJ))47,47,48
         47 FF(II,JJ)=0.000001
         48 CONTINUE
        312 CONTINUE
            DO 450 KAR=6,8,2
            NIK=0
            AREA=OAREA*0.25*FLOAT(KAR)
            WRITE(6,60)AREA
C     THE INITIAL STORAGE CAPASITY MAY BE SELECTED FOR A NUMBER OF
C     RESERVE DAYS
            STOR(1,1,1)=RESDAY*RATING*3.*(F1+F2+F3+F4+F5+F6+F7+F8)/FF(II,JJ)
        471 FIRSTO=STOR(1,1,1)
            FIRSTO=STOR(1,1,1)
        475 OLDSTO=STOR(1,1,1)
            WRITE(6,61)OLDSTO
C     GENERATE THE CONSUMPTION MATRIX CONFORMING THE GIVEN PATTERN
            DO 581 L=1,12
            GO TO(501,502,501,503,501,503,501,501,503,501,503,501),L
        501 MX=NJAN
            GO TO 505
        502 MX=NFEB
            GO TO 505
        503 MX=NJUN
        505 DO 581 M=1,MX
```

```
0226            DO 571 N=1,3
0227        571 CONSUM(L,M,N)=F1*RATING
0228            DO 572 N=4,6
0229        572 CONSUM(L,M,N)=F2*RATING
0230            DO 573 N=7,9
0231        573 CONSUM(L,M,N)=F3*RATING
0232            DO 574 N=10,12
0233        574 CONSUM(L,M,N)=F4*RATING
0234            DO 575 N=13,15
0235        575 CONSUM(L,M,N)=F5*RATING
0236            DO 576 N=16,18
0237        576 CONSUM(L,M,N)=F6*RATING
0238            DO 577 N=19,21
0239        577 CONSUM(L,M,N)=F7*RATING
0240            DO 578 N=22,24
0241        578 CONSUM(L,M,N)=F8*RATING
0242        581 CONTINUE
0243            LACHOU=0
0244            TOTWRK=0.001
0245            DO 900 L=1,12
0246            GO TO(601,602,601,602,601,603,601,601,603,601,603,601),L
0247        601 MY=NJAN
0248            GO TO 605
0249        602 MY=NFEB
0250            GO TO 605
0251        603 MY=NJUN
0252        605 CONTINUE
0253            DO 800 M=1,MY
0254            DO 800 N=1,24
0255            IF(RADTIN(L,M,N)-RADCRT)320,320,321
0256        320 WRKHOU(L,M,N)=0.
0257            GO TO 340
0258        321 IMN=1
0259        322 WRKHOU(L,M,N)=.1*AREA*FR*(RADTIN(L,M,N)*TAU(K)*ALFA(K)-ULC(K)*
               1(T2(J)-TAMBI))/3413.+.9*AREA*EFPRIM*(RADTIN(L,M,N)*TAU(K)*ALFA(K)-
               2ULC(K)*(T1(I)-TAMBI))/3413.
0260            WRKHOU(L,M,N)=WRKHOU(L,M,N)*ETARAN
0261            EFICI=WRKHOU(L,M,N)/(AREA*RADTIN(L,M,N)/3413.)
0262            FLOWRA=AREA*RADTIN(L,M,N)* EFICI/(HV1(I)-HFL2(J))
0263            G=FLOWRA/(.1*AREA)
0264       1520 EPOWR=EFPRIM*ULC(K)/G
0265            IF(EPOWR-100.)1522,1522,1523
0266       1522 FLOFAC=(1.-(1./(2.718**EPOWR)))/EPOWR
0267            GO TO 1526
0268       1523 FLOFAC=0.01
0269       1526 FR=FLOFAC*EFPRIM
0270            IMN=IMN+1
0271            IF(IMN-2)322,322,340
0272        340 CONTINUE
0273            DIFFER=WRKHOU(L,M,N)-CONSUM(L,M,N)
0274            STOR(L,M,N)=OLDSTO+DIFFER
0275        344 BTUSTO=STOR(L,M,N)*3413.
0276        343 IF(STOR(L,M,N))591,593,593
0277        591 BOOST=-STOR(L,M,N)
```

```
        LACHOU=LACHOU+1
        NLACK=(LACHOU/24)*24
        IF(LACHOU-NLACK)590,592,590
  592   WRITE(6,78)COOST,LACHOU,MONTH(L),M
        GO TO 590
  593   LACHOU=0
        COOST=0.
  590   TOTWRK=TOTWRK+WRKHOU(L,M,N)
        OLDSTO=STOR(L,M,N)
  900   CONTINUE
C       FINDING MAXIMUM OR MINIMUM STORAGE CAPACITY
        STOMAX=STOR(1,1,1)
        DO 900 L=1,12
        GO TO(901,902,901,903,901,903,901,901,903,901,903,901),L
  901   MW=NJAN
        GO TO 905
  902   MW=NFEB
        GO TO 905
  903   MW=NJUN
  905   DO 900 M=1,MW
        DO 900 N=1,24
        IF(STOMAX-STOR(L,M,N))910,910,909
  909   STOMIN=STOR(L,M,N)
        GO TO 900
  910   STOMAX=STOR(L,M,N)
  900   CONTINUE
        WRITE(6,79)STOMIN,STOMAX
        STOR(1,1,1)=OLDSTO-STOMIN
        BIGSTO=(STOMAX-STOMIN)*3413.
        WRITE(6,80)BIGSTO
   51   COLCOS=6.5*AREA
        COLINV=COLCOS*ASSEM
C       COST OF THE STORAGE SYSTEM BASED ON 1000 .BTU
        COSTOR=1.5
        STOINV=COSTOR*BIGSTO/1000.
C       TEMPERATURE AND AUTOMATIC CONTROLS COST
        COTINV=250.
C       TURBINE PERFORMANCE AND COST ANALYSIS
C       IF THE SYSTEM SHOULD OPERATE BELOW 212  DEG.F. A VACUUM PUMP
C       MUST BE USED
        IF(T1(I)-212.)54,54,56
   54   PRVAPU=250.
        TURINV=PRTUR*POWER(K)+PRCIPU+PRFEPU+PRVAPU
        GO TO 57
   56   TURINV=PRTUR*POWER(K)+PRCIPU+PRFEPU
C       THE CONDENSER TEMPERATURE IS FIXED AT 90 DEG. F
C       THE CONDENSER COST IS ALSO FIXED
   57   SININV=300.
C       FINAL COST CALCULATIONS,COST PER KWHR
        TOTINV=COLINV+STOINV+SININV+TURINV+COTINV
        CAREFC=ENTRS*(1.+ENTRS)**EXPLIF/((1.+ENTRS)**EXPLIF-1.)
        TOTEXP=TOTINV*(CAREFC+REPAIR+OPERTM)
        FINCOS(I)=TOTEXP/TOTWRK
        COCENT=FINCOS(I) *100.
```

```
0323              WRITE(6,76)FINCOS(I),AREA,KAR
0324              WRITE(6,11)I,TOTINV,TOTEXP,COCENT,AREA,COLCOS,T1(I),T2(J)
            C     OR THE STORAGE CAPASITY MAY BE CHOSEN TO SUPPLY THE NEEDS
            C     THROUGHOUT A YEAR, RESULTS OF A PREVIOUS ANALYSIS GIVING THE
            C     MAXIMUM DEFICIT IN ENERGY  MAY BE USED
0325              STOR(1,1,1)=BIGSTO/3413.
0326              NIK=NIK+1
0327              IF(NIK-1)471,471,450
0328          450 CONTINUE
0329          100 CONTINUE
0330          999 CALL EXIT
0331              DEBUG SUBCHK
0332              END

 TOTAL MEMORY REQUIREMENTS 023298 BYTES
```

SAMPLE RESULTS OF PROGRAMME NO: 2

193.	260.	231.	257.	305.	292.	263.	189.	JAN.	RAD.
29.	30.	31.	31.	31.	31.	30.	29.	JAN.	SUN.
140.	207.	237.	262.	262.	237.	206.	139.	FEB.	RAD.
28.	28.	28.	28.	28.	28.	28.	28.	FEB.	SUN.
135.	203.	232.	265.	265.	238.	203.	135.	MAR.	RAD.
30.	31.	31.	31.	31.	31.	31.	30.	MAR.	SUN.
106.	168.	199.	220.	220.	193.	168.	106.	APR.	RAD.
25.	27.	29.	30.	30.	29.	27.	25.	APR.	SUN.
0.	127.	153.	177.	177.	157.	125.	0.	MAY.	RAD.
0.	25.	26.	27.	27.	26.	25.	0.	MAY.	SUN.
0.	104.	134.	150.	150.	132.	102.	0.	JUN.	RAD.
0.	26.	27.	29.	29.	27.	25.	0.	JUN.	SUN.
0.	116.	147.	169.	169.	146.	114.	0.	JUL.	RAD.
0.	30.	31.	31.	31.	31.	30.	0.	JUL.	SUN.
103.	162.	191.	213.	213.	191.	164.	102.	AUG.	RAD.
21.	27.	30.	31.	31.	30.	26.	20.	AUG.	SUN.
124.	181.	212.	238.	238.	212.	181.	124.	SEP.	RAD.
24.	29.	30.	30.	30.	30.	29.	24.	SEP.	SUN.
123.	180.	207.	230.	230.	207.	180.	122.	OCT.	RAD.
27.	30.	31.	31.	31.	31.	30.	27.	OCT.	SUN.
116.	171.	193.	214.	214.	192.	168.	113.	NOV.	RAD.
26.	28.	29.	29.	29.	29.	28.	26.	NOV.	SUN.
110.	149.	165.	183.	183.	163.	146.	107.	DEC.	RAD.
16.	27.	30.	30.	30.	30.	27.	13.	DEC.	SUN.

469834. 185.

COLLECTOR AREA# 3307.

COLLECTOR AREA# 4960.

INITIAL STORAGE IN KWH# 6922.

SUPPLEMENT NEEDED IN KWH#	75.	HOUR WITHOUT POWER SUPPLY#	24	JUL. 15
SUPPLEMENT NEEDED IN KWH#	151.	HOUR WITHOUT POWER SUPPLY#	48	JUL. 16
SUPPLEMENT NEEDED IN KWH#	226.	HOUR WITHOUT POWER SUPPLY#	72	JUL. 17
SUPPLEMENT NEEDED IN KWH#	297.	HOUR WITHOUT POWER SUPPLY#	96	JUL. 18
SUPPLEMENT NEEDED IN KWH#	367.	HOUR WITHOUT POWER SUPPLY#	120	JUL. 19
SUPPLEMENT NEEDED IN KWH#	437.	HOUR WITHOUT POWER SUPPLY#	144	JUL. 20
SUPPLEMENT NEEDED IN KWH#	499.	HOUR WITHOUT POWER SUPPLY#	168	JUL. 21
SUPPLEMENT NEEDED IN KWH#	579.	HOUR WITHOUT POWER SUPPLY#	192	JUL. 22
SUPPLEMENT NEEDED IN KWH#	659.	HOUR WITHOUT POWER SUPPLY#	216	JUL. 23
SUPPLEMENT NEEDED IN KWH#	736.	HOUR WITHOUT POWER SUPPLY#	240	JUL. 24
SUPPLEMENT NEEDED IN KWH#	812.	HOUR WITHOUT POWER SUPPLY#	264	JUL. 25
SUPPLEMENT NEEDED IN KWH#	886.	HOUR WITHOUT POWER SUPPLY#	288	JUL. 26
SUPPLEMENT NEEDED IN KWH#	960.	HOUR WITHOUT POWER SUPPLY#	312	JUL. 27
SUPPLEMENT NEEDED IN KWH#	1033.	HOUR WITHOUT POWER SUPPLY#	336	JUL. 28
SUPPLEMENT NEEDED IN KWH#	1112.	HOUR WITHOUT POWER SUPPLY#	360	JUL. 29
SUPPLEMENT NEEDED IN KWH#	1180.	HOUR WITHOUT POWER SUPPLY#	384	JUL. 30
SUPPLEMENT NEEDED IN KWH#	1248.	HOUR WITHOUT POWER SUPPLY#	408	JUL. 31
SUPPLEMENT NEEDED IN KWH#	1301.	HOUR WITHOUT POWER SUPPLY#	432	AUG. 1
SUPPLEMENT NEEDED IN KWH#	1375.	HOUR WITHOUT POWER SUPPLY#	456	AUG. 2
SUPPLEMENT NEEDED IN KWH#	1421.	HOUR WITHOUT POWER SUPPLY#	480	AUG. 3
SUPPLEMENT NEEDED IN KWH#	1466.	HOUR WITHOUT POWER SUPPLY#	504	AUG. 4
SUPPLEMENT NEEDED IN KWH#	1512.	HOUR WITHOUT POWER SUPPLY#	528	AUG. 5
SUPPLEMENT NEEDED IN KWH#	1549.	HOUR WITHOUT POWER SUPPLY#	552	AUG. 6
SUPPLEMENT NEEDED IN KWH#	1596.	HOUR WITHOUT POWER SUPPLY#	576	AUG. 7
SUPPLEMENT NEEDED IN KWH#	1653.	HOUR WITHOUT POWER SUPPLY#	600	AUG. 8
SUPPLEMENT NEEDED IN KWH#	1746.	HOUR WITHOUT POWER SUPPLY#	624	AUG. 9
SUPPLEMENT NEEDED IN KWH#	1852.	HOUR WITHOUT POWER SUPPLY#	648	AUG. 10
SUPPLEMENT NEEDED IN KWH#	1895.	HOUR WITHOUT POWER SUPPLY#	672	AUG. 11

SAMPLE RESULTS OF PROGRAMME NO: 2

```
SUPPLEMENT NEEDED IN KWH#        7[illegible].  HOUR WITHOUT POWER SUPPLY#   [illegible]    DEC. 30
SUPPLEMENT NEEDED IN KWH#        7552.  HOUR WITHOUT POWER SUPPLY#   [illegible]    DEC. 31
MINIMUM HEAT STORED#          -8014.  MAXIMUM HEAT STORED#            7996.

LARGEST STORAGE CAPASITY NEEDED IN BTU #     546[illegible].
COST PER KWH#          0.828766 COLL.AREA#          4960.19 TRIAL#     [illegible]
    8   123[illegible].    21380.    82.8[illegible]     4960.     32241. BOILER TEMP.# 230. CONDENSER TEMP.#   90.
------------------------------------
INITIAL STORAGE IN KWH#        16009.

MINIMUM HEAT STORED#             1062. MAXIMUM HEAT STORED#          17[illegible].

LARGEST STORAGE CAPASITY NEEDED IN BTU #     54677[illegible].
COST PER KWH#          0.829146 COLL.AREA#          4960.19 TRIAL#     6
    8   123665.    21390.    82.91     4960.     32241. BOILER TEMP.# 230. CONDENSER TEMP.#   90.
________________________________________________________________________
COLLECTOR AREA#        6614.
INITIAL STORAGE IN KWH#         6922.

MINIMUM HEAT STORED#              580. MAXIMUM HEAT STORED#          11053.

LARGEST STORAGE CAPASITY NEEDED IN BTU #     35744144.
COST PER KWH#          0.543878 COLL.AREA#          6613.59 TRIAL#     8
    8   103162.    18708.    54.39     6614.     42983. BOILER TEMP.# 230. CONDENSER TEMP.#   90.

INITIAL STORAGE IN KWH#        10473.

MINIMUM HEAT STORED#             4124. MAXIMUM HEAT STORED#          14604.

LARGEST STORAGE CAPASITY NEEDED IN BTU #     35767600.
COST PER KWH#          0.544055 COLL.AREA#          6613.59 TRIAL#     8
    8   108197.    18714.    54.41     6614.     42988. BOILER TEMP.# 230. CONDENSER TEMP.#   90.
```

 PROGRAMME NO: 3

```
      C     SUBROUTINE FOR CALCULATING THE RADIATION INTENSITY ON
      C     THE TILTED COLLECTOR PLANE
      C     M.KUDRET SELCUK
      C     HORIZONTAL TOTAL OR DIRECT AND DIFFUSE  INTENSITIES
      C     SHOULD BE AVAILABLE
      C     IN CASE OF ONLY TOTAL HORIZONTAL IS AVAILABLE  DIFFUSE
      C     IS ASSUMED TO BE 10 PERCENT OF THE TOTAL
            DIMENSION  RADHOT(12,31,24),RAHODI(12,31,24),RADTIN(12,31,24),
           1RAHDIR(12,31,24),DECLIN(12),AVERAD(12,12),ENDAY(12,12)
            DIMENSION MONTH(12)
            DIMENSION  P1(11),P2(11),T1(11),T2(11),HV1(11),HV2(11),HFL1(11),
           1HFL2(11),SV1(11),SFL1(11),SFL2(11),SX1(11),SX2(11),SV2(11),
           2HX2(11),HX1(11),RADION(12,12),X1(11),X2(11),ETACOL(5),ETATUR(5),
           3ULC(5),TAU(5),POWER(5),ALFA(5),ETAPUM(5)
          1 FORMAT(10F8.2)
          2 FORMAT(10F8.4)
          3 FORMAT(5F10.2)
          4 FORMAT(2F10.2)
          6 FORMAT(8F10.2)
          8 FORMAT(5F16.6)
         10 FORMAT(12F6.1)
         12 FORMAT(12F6.0)
         13 FORMAT(12F6.0,A4,    I4)
         15 FORMAT(45H TOTAL HORIZONTAL RADIATION AVAILABLE ONLY        /)
         16 FORMAT(40H HORIZONTAL TOTAL AND DIFFUSE AVAILABLE       /)
         17 FORMAT(2F16.0)
         18 FORMAT(8F8.0,2X,A4,2I4)
         19 FORMAT(12(2X,A4))
         26 FORMAT(1H1)
         29 FORMAT(5I10)
         65 FORMAT(2X,8F8.0,2X,A4,2X,'RAD.@)
         66 FORMAT(2X,8F8.0,2X,A4,2X,'SUN.@)
         67 FORMAT(26H TOTAL YEARLY RADIATION=  F16.0)
         68 FORMAT(27H YEARLY AVERAGE RADIATION  F6.0//)
       1001 READ (5,29)NN,IJ,IK,IL,IM
            READ (5,29)NJAN,NFEB,NJUN
            READ (5,1)(P1(M),M=1,10)
            READ (5,1)(P2(M),M=1,10)
            READ (5,1)(T1(M),M=1,10)
            READ (5,1)(T2(M),M=1,10)
            READ (5,1)(HV1(M),M=1,10)
            READ (5,1)(HV2(M),M=1,10)
            READ (5,1)(HFL1(M),M=1,10)
            READ (5,1)(HFL2(M),M=1,10)
            READ (5,2)(SV1(M),M=1,10)
            READ (5,2)(SV2(M),M=1,10)
            READ (5,2)(SFL1(M),M=1,10)
            READ (5,2)(SFL2(M),M=1,10)
            READ (5,3)(ETATUR(M),M=1,5)
            READ (5,3)(ETAPUM(M),M=1,5)
            READ (5,3)(ALFA(M),M=1,5)
            READ (5,3)(POWER(M),M=1,5)
            READ (5,3)(TAU(M),M=1,5)
            READ (5,3)(ULC(M),M=1,5)
```

```
      READ (5,3)USEFAC,TAMBI,TCWI,TCWO,PIPLOS
      READ (5,4)PARLEL,BETA
      READ (5,10)(DECLIN(L),L=1,12)
      READ (5,19)(MONTH(L),L=1,12)
      PARLEL=PARLEL*0.0174
      DO 171 L=1,12
      GO TO(101,102,101,103,101,103,101,101,103,101,103,101),L
  101 MZ=NJAN
      GO TO 104
  102 MZ=NFEB
      GO TO 104
  103 MZ=NJUN
  104 CONTINUE
      DO 170 M=1,MZ
C     DUE TO THE EASE OF COMPUTATION DAY IS STARTED AT 8 AM
C     N#1 REPRESENTS 8 AM , N#8 REPRESENTS 4 PM ETC.
      READ (5,18)(RADHOT(L,M,N),N=1,8),MONTH(L),IDAY,IMON
  170 CONTINUE
  171 CONTINUE
      DO 175 L=1,12
      GO TO(111,112,111,113,111 ,113,111,111,113,111,113,111),L
  111 MZ=NJAN
      GO TO 114
  112 MZ=NFEB
      GO TO 114
  113 MZ=NJUN
  114 CONTINUE
      DELTA=DECLIN(L) *0.01714
      ARGUM=(PARLEL-DECLIN(L))*0.0174
      DO 175 M=1,MZ
      DO 175 N=1,8
      SUNANG=(FLOAT(N)-4.30)*0.2618
      COSINC=SIN(ARGUM)*SIN(DELTA)+COS(ARGUM)*COS(DELTA)*COS(SUNANG)
      COSZEN=SIN(PARLEL)*SIN(DELTA)+COS(PARLEL)*COS(DELTA)*COS(SUNANG)
      IF(COSZEN)116,115,116
  115 COSZEN=0.000001
  116 ORFAC=COSINC/COSZEN
      IF(NN-1)176,173,176
  173 RADTIN(L,M,N)=RADHOT(L,M,N)*ORFAC*0.9
      GO TO 175
  176 RADTIN(L,M,N)=RADHOT(L,M,N)*ORFAC+RAHODI(L,M,N)*(1.-ORFAC)
  175 CONTINUE
      DO 180 L=1,12
      GO TO(201,202,201,203,201,203,201,201,203,201,203,201),L
  201 MY=NJAN
      GO TO 204
  202 MY=NFEB
      GO TO 204
  203 MY=NJUN
  204 CONTINUE
      DO 180 M=1,MY
      WRITE(7,18)(RADTIN(L,M,N),N=1,8),MONTH(L),M,L
C     THE RADIATION INTENSITY AFTER  FIRST 8 HOURS  IS ASSUMED
C     BELOW THE CRITICAL THEREFORE TAKEN AS ZERO
```

```
0094            DO 179 N=9,24
0095        179 RADTIN(L,M,N)=0.
0096        180 CONTINUE
0097            DO 100 I=7,9,2
0098            K=1
0099            II=1
0100            JJ=1
0101            J=4
0102            MTK=1
0103            WRITE(6,26)
0104            TOTDAY=0.
          C     THERMODYNAMICAL ANALYSIS OF THE CYCLE
0105            X2(J)=(SV1(I)-SFL2(J))/(SV2(J)-SFL2(J))
0106            HX2(J)=HFL2(J)+X2(J)*(HV2(J)-HFL2(J))
0107            WOUI=HV1(I)-HX2(J)
0108            WOUA=WOUI*ETATUR(K)
0109            QADD=HV1(I)-HFL2(J)
0110            WPUMP=0.00298*(P1(I)-P2(J))
0111            WPUMPA=WPUMP/ETAPUM(K)
0112            WNETT=WOUA-WPUMPA
0113            ETARAN=WNETT/QADD
0114            QREJ=HX2(J)-HFL2(J)
0115            IF(MTK-1)611,611,612
0116        611 GLANUM=3.
0117            GO TO 619
0118        612 IF(MTK-2)619,613,613
0119        613 GLANUM=4.
0120        619 TAU(K)=0.88**GLANUM
0121            HRAD=0.1714E-08*((T1(I)+460.)**4.-(TAMBI+460.)**4.)/(T1(I)-TAMBI)
0122            ULC(K)=1.1*(1./(GLANUM/(0.21*((T1(I)-TAMBI)/(GLANUM+0.36))**0.25)
               1+2.46)+HRAD/(0.347+1.27*GLANUM))
          C     CRITICAL RADIATION INTENSITY BELOW WHICH NO USEFUL HEAT COLLECTION
          C     SHOULD BE ATTEMPTED
0123            RADCRT=1.05*ULC(K)*(T1(I)-TAMBI)/(TAU(K)*ALFA(K))
0124            DO 285 L=1,12
0125            DO 285 N=1,8
0126            DAYCOU=0.
0127            SUMRAD=0.
0128            GO TO(301,302,301,303,301,303,301,301,303,301,303,301),L
0129        301 MV=NJAN
0130            GO TO 304
0131        302 MV=NFEB
0132            GO TO 304
0133        303 MV=NJUN
0134        304 CONTINUE
0135            DO 185 M=1,MV
          C     COMPARING THE HOURLY RADIATION INTENSITY WITH THE CRITICAL
0136            IF(RADTIN(L,M,N)-RADCRT)185,185,184
0137        184 SUMRAD=SUMRAD+RADTIN(L,M,N)
0138            DAYCOU=DAYCOU+1.
0139        185 ENDAY(L,N)=DAYCOU
0140            IF(ENDAY(L,N))186,186,187
0141        186 AVERAD(L,N)=0.
0142            GO TO 285
```

```
0143          187 AVERAD(L,N)=SUMRAD/ENDAY(L,N)
            C     EQUATE THE HOURLY RADIATION INTENSITY TO MONTHLY AVERAGE
0144          285 RADION(L,N)=AVERAD(L,N)
            C     PRINT A LIST OF RADIATION INTENSITIES AND NUMBER OF DAYS
            C     ENCOUNTERED WITHIN THE CORRESPONDING MONTH
0145              DO 288 L=1,12
            C     PUNCH A DECK OF CARDS LISTING THE AVERAGE RADIATION
0146              WRITE(7,65)(RADION(L,N),N=1,8),MONTH(L)
            C     PUNCH A DECK OF CARDS LISTING NUMBER OF DAYS DURING WHICH
            C     THE RADIATION INTENSITY IS GREATER THAN THE CRITICAL
0147              WRITE(7,66)( ENDAY(L,N),N=1,8),MONTH(L)
0148          288 CONTINUE
0149              TOYERA =0.
            C     OBTAIN THE YEARLY TOTAL RADIATION
0150              DO 289 L=1,12
0151              DO 289 N=1,8
0152          289 TOYERA=TOYERA+AVERAD(L,N)*ENDAY(L,N)
0153              WRITE(6,67)TOYERA
0154              DO 291 L=1,12
0155              DO 291 N=1,8
0156          291 TOTDAY=TOTDAY+ENDAY(L,N)
            C     OBTAIN THE YEARLY AVERAGE RADIATION
0157              AVERYE=TOYERA/TOTDAY
0158              WRITE(6,68)AVERYE
0159              WRITE(7,17)TOYERA,AVERYE
0160              IF(IJ-1)999,1001,999
0161          100 CONTINUE
0162          999 CALL EXIT
0163              DEBUG SUBCHK
0164              END
```

TOTAL MEMORY REQUIREMENTS 025C36 BYTES

DAILY TOTALS IN LANGLEYS FOR ALICE SPRINGS ,AUSTRALIA

JAN.	294.	710.	739.	594.	651.	617.	617.	696.	688.	696.	718.	685.	388.	207.	679.
733.	719.	707.	707.	702.	651.	594.	594.	427.	481.	665.	679.	676.	657.	628.	538.
FEB.	680.	684.	693.	661.	535.	621.	661.	674.	696.	718.	674.	693.	529.	583.	595.
605.	646.	699.	706.	658.	636.	627.	658.	636.	627.	658.	652.	650.			
MAR.	502.	348.	631.	647.	634.	654.	692.	638.	660.	644.	560.	609.	641.	631.	625.
612.	612.	634.	599.	573.	544.	547.	547.	560.	576.	580.	541.	557.	470.	431.	518.
APR.	520.	540.	452.	540.	572.	564.	548.	520.	456.	500.	552.	528.	376.	536.	560.
492.	448.	268.	200.	500.	500.	508.	488.	456.	476.	480.	480.	456.	300.	252.	
MAY.	235.	183.	257.	407.	341.	470.	536.	448.	541.	437.	418.	492.	484.	462.	484.
459.	440.	448.	389.	367.	367.	367.	407.	411.	363.	422.	415.	349.	73.	110.	150.
JUN.	300.	389.	421.	474.	405.	397.	360.	417.	397.	385.	405.	271.	413.	405.	389.
397.	397.	401.	390.	377.	377.	385.	389.	405.	381.	263.	223.	373.	405.	389.	
JUL.	361.	376.	427.	365.	388.	400.	416.	388.	306.	404.	439.	435.	412.	412.	427.
423.	427.	447.	451.	455.	486.	412.	400.	419.	427.	431.	431.	439.	412.	459.	463.
AUG.	464.	376.	488.	488.	488.	519.	480.	445.	302.	232.	503.	511.	464.	248.	577.
554.	546.	565.	522.	522.	542.	542.	561.	573.	557.	557.	546.	581.	283.	224.	286.
SEP.	491.	503.	358.	511.	523.	503.	358.	436.	358.	472.	582.	601.	601.	597.	601.
593.	511.	582.	582.	578.	589.	546.	240.	275.	334.	464.	554.	589.	580.	554.	
OCT.	432.	448.	554.	563.	467.	365.	544.	486.	458.	500.	595.	570.	352.	512.	563.
576.	592.	390.	256.	589.	614.	541.	544.	544.	605.	608.	576.	624.	541.	614.	640.
NOV.	607.	539.	371.	539.	283.	647.	546.	202.	431.	502.	607.	654.	694.	671.	728.
634.	644.	522.	583.	650.	519.	600.	657.	691.	698.	674.	607.	590.	596.	539.	
DEC.	523.	605.	640.	645.	675.	733.	795.	760.	541.	367.	438.	426.	462.	517.	568.
443.	371.	470.	285.	339.	472.	497.	590.	640.	684.	689.	763.	573.	723.	758.	677.

88.	121.	134.	146.	147.	135.	123.	91.	JAN.	1	1
213.	293.	323.	353.	354.	325.	296.	220.	JAN.	2	1
222.	305.	336.	368.	368.	338.	308.	229.	JAN.	3	1
178.	245.	270.	296.	296.	272.	248.	184.	JAN.	4	1
195.	269.	296.	324.	324.	298.	272.	202.	JAN.	5	1
185.	255.	281.	307.	308.	282.	258.	191.	JAN.	6	1
185.	255.	281.	307.	308.	282.	258.	191.	JAN.	7	1
209.	287.	317.	346.	347.	318.	291.	216.	JAN.	8	1
207.	284.	313.	342.	343.	315.	287.	213.	JAN.	9	1
209.	287.	317.	346.	347.	318.	291.	216.	JAN.	10	1
216.	296.	327.	357.	358.	329.	300.	223.	JAN.	11	1
206.	283.	312.	341.	341.	313.	286.	212.	JAN.	12	1
116.	160.	177.	193.	193.	178.	162.	120.	JAN.	13	1
62.	85.	94.	103.	103.	95.	86.	64.	JAN.	14	1
204.	280.	309.	338.	338.	311.	283.	210.	JAN.	15	1
220.	302.	334.	365.	365.	335.	306.	227.	JAN.	16	1
216.	297.	327.	358.	358.	329.	300.	223.	JAN.	17	1
212.	292.	322.	352.	352.	323.	295.	219.	JAN.	18	1
212.	292.	322.	352.	352.	323.	295.	219.	JAN.	19	1
211.	290.	320.	349.	350.	321.	293.	218.	JAN.	20	1
195.	269.	296.	324.	324.	298.	272.	202.	JAN.	21	1
178.	245.	270.	296.	296.	272.	248.	184.	JAN.	22	1
178.	245.	270.	296.	296.	272.	248.	184.	JAN.	23	1
128.	176.	194.	213.	213.	195.	178.	132.	JAN.	24	1
144.	198.	219.	239.	240.	220.	201.	149.	JAN.	25	1
200.	274.	303.	331.	331.	304.	278.	206.	JAN.	26	1
204.	280.	309.	338.	338.	311.	283.	210.	JAN.	27	1
203.	279.	308.	336.	337.	309.	282.	210.	JAN.	28	1
197.	271.	299.	327.	327.	301.	274.	204.	JAN.	29	1
189.	259.	286.	313.	313.	287.	262.	195.	JAN.	30	1
162.	222.	245.	268.	268.	246.	225.	167.	JAN.	31	1

193.	260.	281.	307.	308.	282.	263.	199.	JAN.	RAD.
29.	30.	31.	31.	31.	31.	30.	29.	JAN.	SUN.
140.	207.	237.	262.	262.	237.	206.	139.	FEB.	RAD.
28.	28.	28.	28.	28.	28.	28.	28.	FEB.	SUN.
135.	203.	238.	265.	265.	238.	203.	135.	MAR.	RAD.
30.	31.	31.	31.	31.	31.	31.	30.	MAR.	SUN.
106.	168.	199.	220.	219.	198.	168.	105.	APR.	RAD.
25.	27.	29.	30.	30.	29.	27.	25.	APR.	SUN.
0.	127.	158.	177.	177.	157.	125.	0.	MAY.	RAD.
0.	25.	26.	27.	27.	26.	25.	0.	MAY.	SUN.
0.	104.	134.	150.	150.	132.	101.	0.	JUN.	RAD.
0.	26.	27.	29.	29.	27.	25.	0.	JUN.	SUN.
0.	116.	147.	168.	168.	146.	114.	0.	JUL.	RAD.
0.	30.	31.	31.	31.	31.	30.	0.	JUL.	SUN.
104.	163.	191.	213.	213.	191.	164.	102.	AUG.	RAD.
21.	27.	30.	31.	31.	30.	26.	20.	AUG.	SUN.
124.	181.	212.	238.	238.	212.	181.	123.	SEP.	RAD.
24.	29.	30.	30.	30.	30.	29.	24.	SEP.	SUN.
123.	180.	207.	230.	230.	207.	180.	122.	OCT.	RAD.
27.	30.	31.	31.	31.	31.	30.	27.	OCT.	SUN.
116.	171.	193.	214.	214.	195.	168.	113.	NOV.	RAD.
26.	28.	29.	29.	29.	28.	28.	25.	NOV.	SUN.
112.	149.	165.	183.	183.	163.	146.	107.	DEC.	RAD.
15.	27.	30.	30.	30.	30.	27.	13.	DEC.	SUN.

TOTAL YEARLY RADIATION# 469543.

YEARLY AVERAGE RADIATION 185.

PROGRAMME NO: 31

```
                C      SUBROUTINE FOR CALCULATING THE RADIATION INTENSITY ON
                C      THE TILTED COLLECTOR PLANE
                C      M.KUDRET SELCUK
                C      HORIZONTAL TOTAL OR DIRECT AND DIFFUSE  INTENSITIES
                C      SHOULD BE AVAILABLE
                C      IN CASE OF ONLY TOTAL HORIZONTAL IS AVAILABLE  DIFFUSE
                C      IS ASSUMED TO BE 10 PERCENT OF THE TOTAL
 0001                  DIMENSION RADHOT(12,31,24),RADTIN(12,31,24),DECLIN(12),MONTH(12),
                      1AVERAD(12,12),ENDAY(12,12),DAYTOT(12,31),SUNSET(12)
 0002                  DIMENSION  P1(11),P2(11),T1(11),T2(11),HV1(11),HV2(11),HFL1(11),
                      1HFL2(11),SV1(11),SFL1(11),SFL2(11),SX1(11),SX2(11),SV2(11),
                      2HX2(11),HX1(11),RADION(12,12),X1(11),X2(11),ETACOL(5),ETATUR(5),
                      3ULC(5),TAU(5),POWER(5),ALFA(5),ETAPUM(5)
 0003                1 FORMAT(10F6.2)
 0004                2 FORMAT(10F8.4)
 0005                3 FORMAT(5F10.2)
 0006                4 FORMAT(2F10.2)
 0007                6 FORMAT(8F10.2)
 0008                8 FORMAT(5F16.6)
 0009                9 FORMAT(1X,A4,15F5.0/16F5.0)
 0010               10 FORMAT(12F6.1)
 0011               11 FORMAT(12F6.2)
 0012               12 FORMAT(12F6.0)
 0013               13 FORMAT(12F6.0,A4,    I4)
 0014               14 FORMAT(54H DAILY TOTALS IN LANGLEYS FOR ALICE SPRINGS ,AUSTRALIA )
 0015               15 FORMAT(45H TOTAL HORIZONTAL RADIATION AVAILABLE ONLY         /)
 0016               16 FORMAT(40H HORIZONTAL TOTAL AND DIFFUSE AVAILABLE       /)
 0017               17 FORMAT(2F16.0)
 0018               18 FORMAT(8F8.0,2X,A4,2I4)
 0019               19 FORMAT(12(2X,A4))
 0020               26 FORMAT(1H1)
 0021               29 FORMAT(5I10)
 0022               65 FORMAT(2X,8F8.0,2X,A4,2X,'RAD.@)
 0023               66 FORMAT(2X,8F8.0,2X,A4,2X,'SUN.@)
 0024               67 FORMAT(26H TOTAL YEARLY RADIATION#  F16.0)
 0025               68 FORMAT(27H YEARLY AVERAGE RADIATION   F6.0//)
 0026             1001 READ (5,29)NN,IJ,IK,IL,IM
 0027                  READ (5,29)NJAN,NFEB,NJUN
 0028                  READ (5,1)(P1(M),M=1,10)
 0029                  READ (5,1)(P2(M),M=1,10)
 0030                  READ (5,1)(T1(M),M=1,10)
 0031                  READ (5,1)(T2(M),M=1,10)
 0032                  READ (5,1)(HV1(M),M=1,10)
 0033                  READ (5,1)(HV2(M),M=1,10)
 0034                  READ (5,1)(HFL1(M),M=1,10)
 0035                  READ (5,1)(HFL2(M),M=1,10)
 0036                  READ (5,2)(SV1(M),M=1,10)
 0037                  READ (5,2)(SV2(M),M=1,10)
 0038                  READ (5,2)(SFL1(M),M=1,10)
 0039                  READ (5,2)(SFL2(M),M=1,10)
 0040                  READ (5,3)(ETATUR(M),M=1,5)
 0041                  READ (5,3)(ETAPUM(M),M=1,5)
 0042                  READ (5,3)(ALFA(M),M=1,5)
 0043                  READ (5,3)(POWER(M),M=1,5)
```

```
0044          READ (5,3)(TAU(M),M=1,5)
0045          READ (5,3)(ULC(M),M=1,5)
0046          READ (5,3)USEFAC,TAMBI,TCWI,TCWO,PIPLOS
0047          READ (5,4)PARLEL,BETA
0048          READ (5,10)(DECLIN(L),L=1,12)
0049          READ (5,19)(MONTH(L),L=1,12)
0050          READ (5,11)(SUNSET(L),L=1,12)
0051          WRITE(6,14)
0052          DO 171 L=1,12
0053          GO TO(101,102,101,103,101,103,101,101,103,101,103,101),L
0054      101 MZ=NJAN
0055          GO TO 104
0056      102 MZ=NFEB
0057          GO TO 104
0058      103 MZ=NJUN
0059      104 CONTINUE
        C     DUE TO THE EASE OF COMPUTATION DAY IS STARTED AT 8 AM
        C     N=1 REPRESENTS 8 AM , N=8 REPRESENTS 4 PM ETC.
0060          READ (5,9)MONTH(L),(DAYTOT(L,M),M=1,MZ)
0061          WRITE(6,9)MONTH(L),(DAYTOT(L,M),M=1,MZ)
0062      171 CONTINUE
0063          WRITE(6,26)
        C     FROM THIS STATEMENT TO  170 CONTINUE INCLUSIVE CALCULATES THE
        C     HOURLY TOTALS FROM THE DAILY TOTALS USING WHILLIERS METHOD
0064          DO 170 L=1,12
0065          GO TO (211,212,211,213,211,213,211,211,213,211,213,211),L
0066      211 MZ=NJAN
0067          GO TO 214
0068      212 MZ=NFEB
0069          GO TO 214
0070      213 MZ=NJUN
0071      214 CONTINUE
0072          DO 169 M=1,MZ
0073          DAYTOT(L,M)=DAYTOT(L,M)*3.68
0074          RADHOT(L,M,1)=(0.063+(SUNSET(L)-5.00)*0.006)*DAYTOT(L,M)
0075          RADHOT(L,M,2)=(0.111-(SUNSET(L)-5.00)*0.004)*DAYTOT(L,M)
0076          RADHOT(L,M,3)=(0.142-(SUNSET(L)-5.00)*0.015)*DAYTOT(L,M)
0077          RADHOT(L,M,4)=(0.162-(SUNSET(L)-5.00)*0.020)*DAYTOT(L,M)
0078          RADHOT(L,M,5)=RADHOT(L,M,4)
0079          RADHOT(L,M,6)=RADHOT(L,M,3)
0080          RADHOT(L,M,7)=RADHOT(L,M,2)
0081          RADHOT(L,M,8)=RADHOT(L,M,1)
0082      169 CONTINUE
0083      170 CONTINUE
0084          DO 175 L=1,12
0085          GO TO(111,112,111,113,111 ,113,111,111,113,111,113,111),L
0086      111 MZ=NJAN
0087          GO TO 114
0088      112 MZ=NFEB
0089          GO TO 114
0090      113 MZ=NJUN
0091      114 CONTINUE
0092          PARLEL=PARLEL*0.0174
0093          DELTA=DECLIN(L) *0.01714
```

```
0094           ARGUM=(PARLEL-DECLIN(L))*0.0174
0095           DO 175 M=1,MZ
0096           DO 175 N=1,8
0097           SUNANG=(FLOAT(N)-4.30)*0.2618
0098           COSINC=SIN(ARGUM)*SIN(DELTA)+COS(ARGUM)*COS(DELTA)*COS(SUNANG)
0099           COSZEN=SIN(PARLEL)*SIN(DELTA)+COS(PARLEL)*COS(DELTA)*COS(SUNANG)
0100           IF(COSZEN)116,115,116
0101       115 COSZEN=0.000001
0102       116 ORFAC=COSINC/COSZEN
0103       173 RADTIN(L,M,N)=RADHOT(L,M,N)*ORFAC*0.9
0104       175 CONTINUE
0105           DO 180 L=1,12
0106           GO TO(201,202,201,203,201,203,201,201,203,201,203,201),L
0107       201 MY=NJAN
0108           GO TO 204
0109       202 MY=NFEB
0110           GO TO 204
0111       203 MY=NJUN
0112       204 CONTINUE
0113           DO 179 M=1,MY
0114           WRITE(6,18)(RADTIN(L,M,N),N=1,8),MONTH(L),M,L
         C     THE RADIATION INTENSITY AFTER  FIRST 8 HOURS  IS ASSUMED
         C     BELOW THE CRITICAL THEREFORE TAKEN AS ZERO
0115           DO 179 N=9,24
0116       179 RADTIN(L,M,N)=0.
0117           WRITE(6,26)
0118       180 CONTINUE
0119           DO 100 I=6,10,2
0120           K=1
0121           II=1
0122           JJ=1
0123           J=4
0124           TOTDAY=0.
0125           ULC(K)=0.423
0126           ALFA(K)=0.9
0127           TAU(K)=0.83
         C     CRITICAL RADIATION INTENSITY BELOW WHICH NO USEFUL HEAT COLLECTION
         C     SHOULD BE ATTEMPTED
0128           RADCRT=1.05*ULC(K)*(T1(I)-TAMB)/(TAU(K)*ALFA(K))
0129           DO 285 L=1,12
0130           DO 285 N=1,8
0131           DAYCOU=0.
0132           SUMRAD=0.
0133           GO TO(301,302,301,303,301,303,301,301,303,301,303,301),L
0134       301 MV=NJAN
0135           GO TO 304
0136       302 MV=NFEB
0137           GO TO 304
0138       303 MV=NJUN
0139       304 CONTINUE
0140           DO 185 M=1,MV
         C     COMPARING THE HOURLY RADIATION INTENSITY WITH THE CRITICAL
0141           IF(RADTIN(L,M,N)-RADCRT)185,185,184
0142       184 SUMRAD=SUMRAD+RADTIN(L,M,N)
```

```
0143             DAYCOU=DAYCOU+1.
0144         185 ENDAY(L,N)=DAYCOU
0145             IF(ENDAY(L,N))186,186,187
0146         186 AVERAD(L,N)=0.
0147             GO TO 285
0148         187 AVERAD(L,N)=SUMRAD/ENDAY(L,N)
          C      EQUATE THE HOURLY RADIATION INTENSITY TO MONTHLY AVERAGE
0149         285 RADION(L,N)=AVERAD(L,N)
          C      PRINT A LIST OF RADIATION INTENSITIES AND NUMBER OF DAYS
          C      ENCOUNTERED WITHIN THE CORRESPONDING MONTH
0150             DO 288 L=1,12
          C      PUNCH A DECK OF CARDS LISTING THE AVERAGE RADIATION
0151             WRITE(6,65)(RADION(L,N),N=1,8),MONTH(L)
0152             WRITE(7,65)(RADION(L,N),N=1,8),MONTH(L)
          C      PUNCH A DECK OF CARDS LISTING NUMBER OF DAYS DURING WHICH
          C      THE RADIATION INTENSITY IS GREATER THAN THE CRITICAL
0153             WRITE(6,66)( ENDAY(L,N),N=1,8),MONTH(L)
0154             WRITE(7,66)( ENDAY(L,N),N=1,8),MONTH(L)
0155         288 CONTINUE
0156             TOYERA =0.
          C      OBTAIN THE YEARLY TOTAL RADIATION
0157             DO 289 L=1,12
0158             DO 289 N=1,8
0159         289 TOYERA=TOYERA+AVERAD(L,N)*ENDAY(L,N)
0160             WRITE(6,67)TOYERA
0161             DO 291 L=1,12
0162             DO 291 N=1,8
0163         291 TOTDAY=TOTDAY+ENDAY(L,N)
          C      OBTAIN THE YEARLY AVERAGE RADIATION
0164             AVERYE=TOYERA/TOTDAY
0165             WRITE(6,68)AVERYE
0166             WRITE(7,17)TOYERA,AVERYE
0167         100 CONTINUE
0168             IF(IJ-1)999,1001,999
0169         999 CALL EXIT
0170             DEBUG SUBCHK
0171             END
```

TOTAL MEMORY REQUIREMENTS 014070 BYTES

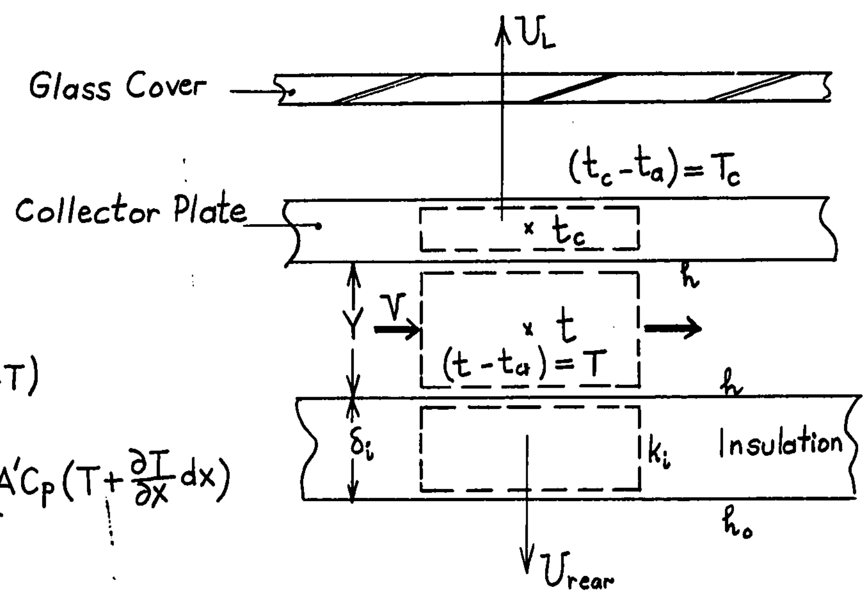
Appendix 3

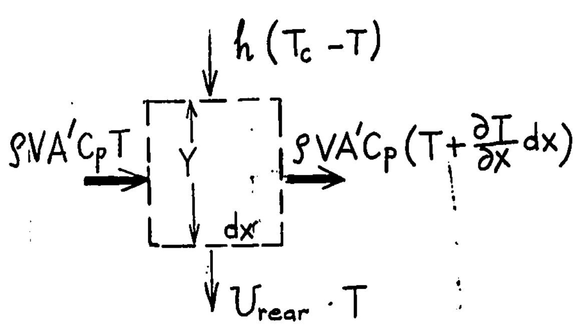
DERIVATION OF THE FLAT PLATE COLLECTOR EFFICIENCY

The derivation of the flat plate collector efficiency is presented below

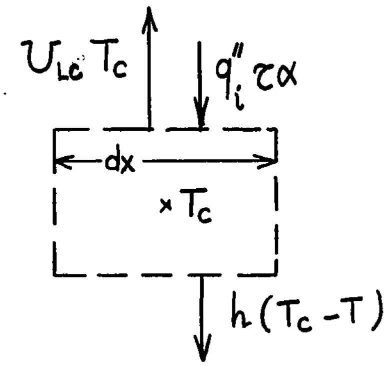
The Flat Plate Solar Heat Collector Steady State Performance

The analysis is made for the two-dimensional case, all temperatures being referred to a datum at the temperature of the surroundings. A system of unit width is examined, the flow rate $w_s = \frac{w}{B}$ where B is the collector width.





Control Volume, Fluid Stream



Collector Plate (no conduction)

Energy Balance on the
Collector Plate

Axial conduction neglected, for unit collector area

$$q_i'' \tau\alpha = U_L T_c + hT_c - T.h \qquad (1)$$

where

$U_L T_c = q_l$ Upward heat loss

$h(T_c - T)$: Heat transferred to fluid

rearranging

$$(U_L + h)T_c - hT = q_i'' \tau\alpha$$

or, using the notation I for radiation intensity

$$(U_L + h)T_c - hT = I\tau\alpha \qquad (2)$$

Energy Balance on the
Control Volume

Assuming unit width, B = 1

$$\rho VA'CpT - \rho VA'Cp(T + \frac{\partial T}{\partial x} dx) + h(T_c-T)\, dx - U_{rear}Tdx = 0 \qquad (3)$$

where

$$U_{rear} = \frac{1}{(1/h + \delta i/ki + 1/h_o)} \quad (4)$$

$$-\rho VA'Cp \frac{\partial T}{\partial x} + h(T_c - T) - U_{rear}T = 0 \quad (5)$$

$A' = Y.B$, and for unit width $A' = Y$.

Also $\frac{\partial T}{\partial x} = \frac{dT}{dx}$, since T is a function of x only.

$VA' = w$ and for unit width $\rho VY = w_s$

$$-w_s \, Cp \frac{dT}{dx} + h(T_c - T) - U_{rear}T = 0$$

$$\frac{dT}{dx} + \left(\frac{h + U_{rear}}{w_s Cp}\right) T - \frac{h}{w_s Cp} T_c = 0 \quad (6)$$

Solving T_c from (2) and substituting into (6)

$$T_c = \frac{I\tau\alpha + hT}{U_L + h} \quad (7)$$

$$\frac{dT}{dx} + \left(\frac{h + U_{rear}}{w_s Cp}\right) T - \frac{h}{w_s Cp}\left(\frac{I\tau\alpha + hT}{U_L + h}\right) = 0 \quad (8)$$

Rearranging

$$\frac{dT}{dx} + \left(\frac{h + U_{rear}}{w_s Cp} - \frac{h^2}{w_s Cp(U_L + h)}\right) T = \frac{hI}{w_s Cp(U_L + h)} \quad (9)$$

This is a first order first degree differential equation of the form

$$\frac{dT}{dx} + KT = D \quad (10)$$

subject to boundary conditions

$$T(0) = T_{in} = t_{in} - ta$$

The complimentary solution for the homogeneous part

$$\frac{dT}{dx} - KT = 0 \qquad (11)$$

Case 1. $K = 0$ and $\frac{dT}{dx} = 0$.

The homogeneous solution, $T = C$, has no physical significance as $Q_{gain} = Q_{loss}$ and the enthalpy rise of the working fluid is zero.

Case 2. $K > 0$. The solution is of the form $T = Me^{-Kx}$ (12)

where M is a constant and

$$K = \frac{1}{\varpi_s Cp}\left\{h + U_{rear} - \frac{h^2}{U_1 + h}\right\} > 0 \qquad (13)$$

For most practical purposes

$$\frac{U_{rear}}{U_L} = 0.1 \qquad (14)$$

Substituting 14 in 13 and factoring by h

$$K = \frac{h}{\varpi_s Cp}\left\{1 + 0.1\frac{U_L}{h} - \frac{1}{(U_L/h+1)}\right\} \qquad (15)$$

Since $\frac{1}{(U_L/h-1)} < 1$, it is unnecessary to try the case where $K < 0$.

Let us try the particular solution.

Let $T = DN$ (16)

where N is a constant be a solution, substituting in differential equation (10)

$$\frac{d(DN)}{dx} + KDN = D \tag{17}$$

In the case of the particular solution $N = \frac{1}{K}$,

$$T = \frac{D}{K} \tag{18}$$

In the case of the general solution

$$T = Me^{-kx} + \frac{D}{K} \tag{19}$$

From the boundary condition

$$T(0) = T_{in},\ T_{in} = M + \frac{D}{K},\ \text{and } M = T - \frac{D}{K} \tag{20}$$

hence

$$T = (T_{in} - \frac{D}{K})e^{-kx} + \frac{D}{K} \tag{21}$$

If $T_{in} \neq 0$, then

$$T = \frac{D}{K} \quad 1-e^{-kx} \quad + T_{in}e^{-kx} \tag{22}$$

If $T_{in} = 0$, then

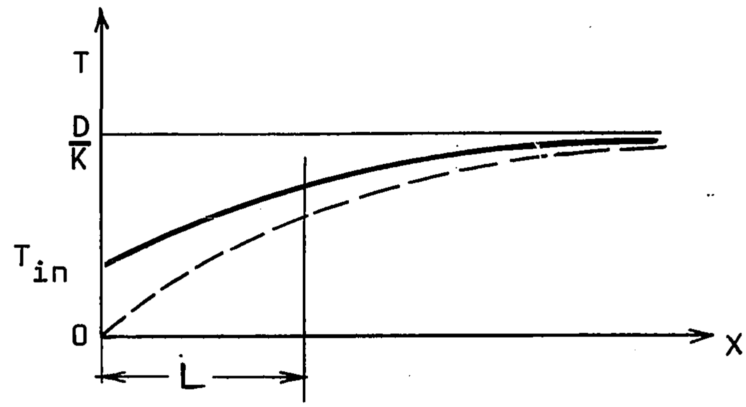
$$T = \frac{D}{K}(1-e^{-kx}) \tag{23}$$

In both cases, at $X = \infty$

$$T = \frac{D}{K} = \frac{\dfrac{hI\tau\alpha}{\varpi_s Cp(U_1+h)}}{\dfrac{h+U_{rear}}{\varpi_s CP} + \dfrac{h^2}{\varpi_s Cp(U_1+h)}}$$

$$= \frac{hI\tau\alpha}{(h+U_{rear})(U_1+h)-h^2} \tag{24}$$

The temperature of the fluid therefore varies from T_{in} at entry to a value approaching $\frac{D}{K}$ asymptotically at $X = \infty$, according to the diagram.



The fluid exit temperature can be obtained by setting X = L,

$$T(L) = T_{out} = \frac{D}{K}\left(1-e^{-kl}\right) + T_{in}e^{-kl} \tag{25}$$

Constants K and D are too unwieldy for use in the analysis of collector performance over a large range of operating conditions. However, as the convective film coefficient, h, is at least fifty times the magnitude of the over-all heat transfer coefficient for upward heat loss, U_1, in a well-designed heat collector, the following simplification may be applied to both constants, using the binomial expansion and neglecting second order terms,

$$\frac{1}{U_1/h+1} = 1 - \frac{U_1}{h} \tag{26}$$

Hence, from equation (15),

$$K = \frac{h}{\varpi_s Cp} \quad 1 + 0.1\frac{U_l}{h} \ (1 - \frac{U_l}{h}) \tag{27}$$

which reduces to

$$K = \frac{1.1U_l}{\varpi_s Cp} \tag{28}$$

Also, from equation (26),

$$D = \frac{I\tau\alpha}{\varpi_s Cp(1+U_l/h)} = \frac{I\tau\alpha}{\varpi_s Cp}\ (1 - \frac{U_l}{h}) \tag{29}$$

Substituting for K and D from equations (27) and (29) into equation (25),

$$T_{out} = \frac{I\tau\alpha(1-U_l/h)}{1.1U_l}\left\{1-e^{-\frac{1.1U_l}{\varpi_s Cp}\cdot L}\right\} + T_{in}e^{-\frac{1.1(U_l L)}{\varpi_s Cp}} \tag{30}$$

Equation (30) can be rewritten in terms of the mass flow rate of working fluid, based on unit area of collector surface exposed to solar radiation as follows:

$$G = \frac{\varpi}{A} = \frac{\varpi}{BL} = \frac{\varpi_s}{L} \tag{31}$$

hence

$$T_{out} = \frac{I\tau\alpha}{1.1}(\frac{1}{U_l} - \frac{1}{h})\left\{1-e^{-\frac{1.1U_l}{GCp}}\right\} + T_{in}e^{-\frac{1.1U_l}{GCp}} \tag{32}$$

The term $\frac{U_l}{GCp}$ is a dimensionless parameter which is termed the Number of Transfer Units, NTU, in most of the heat transfer texts.

Therefore

$$T_{out} = \frac{I\tau\alpha}{1.1}\left(\frac{1}{U_L} - \frac{1}{h}\right)\left\{1 - e^{-1.1NTU}\right\} + T_{in}e^{-1.1NTU} \qquad (33)$$

Since (h) is relatively large in the case of boiling water and water near saturation, compared with the coefficient U_L, its reciprocal may be neglected, hence

$$T_{out} = \frac{I\tau\alpha}{1.1U_l} + e^{-1.1NTU}\left\{T_{in} - \frac{I\tau\alpha}{1.1U_L}\right\} \qquad (34)$$

In the case of $T_{in} = 0$ which implies $t_{in} = t_{amb}$

$$T_{out} = \frac{I\tau\alpha}{1.1U_L}\left\{1 - e^{-1.1NTU}\right\} \qquad (35)$$

Equation (35) can also be obtained directly from equation (23).

The enthalpy rise of the fluid

$$\Delta H = wCp\left(T_{out} - T_{in}\right) \qquad (36)$$

$$\Delta H = wCp\left[\frac{I\tau\alpha}{1.1U_L}(1 - e^{-1.1NTU}) - T_{in}(1 - e^{-1.1NTU})\right]$$

$$\Delta H = wCp\left[1 - e^{-1.1NTU} \quad \left(\frac{I\tau\alpha}{1.1U_L} - T_{in}\right)\right] \qquad (37)$$

Factoring by $1.1U_L$

$$\Delta H = \frac{wCp}{1.1U_L}\left[1 - e^{-1.1NTU}\right]\left(I\tau\alpha - 1.1T_{in}U_l\right) \qquad (38)$$

The collector efficiency is

$$\eta_c = \frac{Q_{useful}}{\text{Radiation input}} = \frac{\Delta H}{AI}$$

$$\eta_c = \frac{1}{\frac{1.1U_l}{GCp}\, I}\left(1 - e^{-1.1NTU}\right)\left(I\tau\alpha - 1.1T_{in}U_l\right) \qquad (39)$$

By defining the "flow factor"

$$F'' = \frac{1 - e^{-1.1NTU}}{1.1NTU} \qquad (40)$$

the expression for the collector efficiency reduces to

$$\eta_c = \frac{F''}{I}\left(I\tau\alpha - 1.1\ T_{in}U_l\right) \qquad (41)$$

The latter is in agreement with A. Whillier* who arrived at the following equation after a detailed analysis of a flat-plate solar water heater.

$$\eta_c = \frac{F_r}{I}\left(I\tau\alpha - T_{in}U_{lc}\right) \qquad (42)$$

where the "heat removal efficiency," F_r, is the product of F" and a second factor, F', termed the "collector efficiency factor." F' accounts for the resistance to heat transfer of the boundary layer at the fluid-tube interface, the wall of the tube, the bond between the tube and the plate and the fin effect of the flat plate. Its numerical value, therefore, depends upon the detailed construction of the collector.

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*A. Whillier. Solar Energy and Its Utilization for House Heating, Sc.D. Thesis, Mechanical Engineering, M.I.T., 1953.

Since the present analysis aims to optimize the over-all performance of the complete solar power plant, rather than to investigate the detailed design parameters of a single component, the collector efficiency factor, F', has been taken as a constant. For a well-designed collector using metals of high thermal conductivity and with efficient bonding between the tube and the plate, this would be approximately unity. Furthermore, even in a relatively inexpensive and less efficient collector the value of F' would be a constant exceeding 0.9. Hence, as the collector plate design is relatively independent of the operating temperatures employed, the locations of the optimum operating points would not be affected.

It is convenient at this stage to define a new over-all heat transfer coefficient, U_{lc}, to include the effects of rear and edge losses as well as that of the transparent glazing, as discussed in connection with equation 14.

$$U_{lc} = 1.1U_l \tag{43}$$

Since $T_{in} = t_{inc} - t_a$, the relation for the collector efficiency becomes:

$$\eta_c = \frac{F_r\ (I\tau\alpha - U_{lc}(t_{inc}-t_a))}{I} \tag{44}$$

Appendix 4

METHODS OF COMPUTATION

a. Exhaustive Enumeration

This is a straightforward method easily applicable in this case where there are only two independent variables. It may be utilized to determine regions of interest as a first step in obtaining a complete solution to the problem. This method is preferable to the differential approach and to the direct minimizing techniques in the case of two or three independent variables since it would be too tedious to minimize the complex non-linear cost function by an exact mathematical procedure such as differentiation. This has been demonstrated already. However, whenever the number of independent variables exceeds four or five, then the number of trials necessary would be so great that it would not be feasible to obtain the minimum cost due to the vast amount of data and the excessive demands upon computer time.

The two most important variables, T_1 (boiler) and T_2 (condenser temperatures), have been varied in the proposed range and results have been directly compared in the programme. Also an automatic programme to find the minimum value of the cost has been devised and results are directly printed in cents/kw. hour.

This approach has been found most efficient since the cost function was, whenever expressed in a single equation, too lengthy but the number of iteration and computer memory requirements were within the capacity of the IBM 360/75 computer of McGill University's Computer Centre.

b. Mapping

The computer results were also presented in the form of a two-dimensional field plot. The two independent variables, namely T_1 and T_2, were represented by the X and Y axes, whereas the corresponding cost figures were printed in symbols, each symbol representing the cost function as a percentage of the range of maximum variation. This presentation enables one to visualize the variation of the function in three dimensional space since all points represented by the same symbols would yield the contours on the Z = fnc (X, Y) surface when they are joined together.

The shift of the valley of the cost function could readily be observed by stepwise changing of some invariants which might be introduced as variables in the analysis in further stages. The character of the surface, such as <u>unimodality</u> or <u>multimodality</u> may also be visualized. This approach confines the study to a narrower region and saves computation time.

The results of various runs have been compared and some of the typical runs are presented in Appendix 2.a)

c. Steepest Descent Method

One of the Direct minimizing techniques, which can easily be applied to a problem with two independent variables is the "Steepest Descent Method."* The following gives an outline of the steps to be followed in minimizing the cost function by giving finite increments to both independent variables, T_1 and T_2.

(a) A feasible starting point is chosen within the region of interest ,(Fig. A4.1)

$\bar{X}_o(T_{1,o}, T_{2,o})$

(b) The cost function is calculated at this point

$F(T_{1,o}, T_{2,o})$

(c) One of the variables, $T_{1,o}$, is increased by a significant amount T_1, and the cost function is re-evaluated at

$X_{1,o}(T_{1,o} + \Delta T_1, T_{2,o})$ as $F(T_{1,o} + \Delta T_1, T_{2,o})$

(d) The gradient (m_1) in the T_1 direction is obtained from

*D. J. Wilde, and C. S. Beightler. Foundations of Optimization. Prentice Hall 1967.

$$m_1 = \frac{F(T_{1,o} + \Delta T_1, T_{2,o}) - F(T_{1,o}, T_{2,o})}{\Delta T_1}$$

(e) Now $T_{2,o}$ is increased by a significant amount ΔT_2 while $T_{1,o}$ is kept constant and the cost function is re-evaluated at

$X_{2,o}(T_{1,o}, T_{2,o} + \Delta T_2)$ as $F(T_{1,o}, T_2 + \Delta T_2)$

(f) The gradient (m_2) in the T_2 direction is obtained from

$$\frac{F(T1,o,T2,o + \Delta T2) - F(T1,o,T2,o)}{\Delta T_2}$$

(g) The direction of steepest descent is obtained from

$T_{1,1} = (T_{1,o} + \Delta T_1)$, $T_{2,1} = (T_{2,o} + \frac{m2}{m_1} \Delta T_1)$

(h) The increment of the function between $(T_{1,o}, T_{2,o})$ and $(T_{1,1}, T_{2,1})$ is tested. If it is positive, T_1 and T_2 are replaced by $-T_1$ and $-T_2$ respectively.

(i) The optimization procedure is converted into one dimensional quasilocal minimum search. The steepest descent direction is followed until the function stops decreasing and starts increasing. This process will reduce the additional computation time spent for finding $F(T_1 + \Delta T_1, T_2)$ and $F(T_1, T_2 + \Delta T_2)$ and will instead involve direct calculation of $F(T_1 + \Delta T_1, T_2 + \Delta T_2)$. Additionally quadratic or cubic interpolation techniques* may be utilized to accelerate the convergence to the quasi local minimum.

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*L. S. Lasdon, and A. D. Waren. Mathematical programming for Optimal Design. Electro-Technology, Nov. 1967, pp. 53-70.

(j) Once the quasi local minimum on the steepest descent direction is found, a new direction of steepest descent is searched for by repeating the steps suggested from (a) to (h), assuming the quasi local minimum as the new starting point.

(k) The search is continued until the following stop criterion is satisfied.

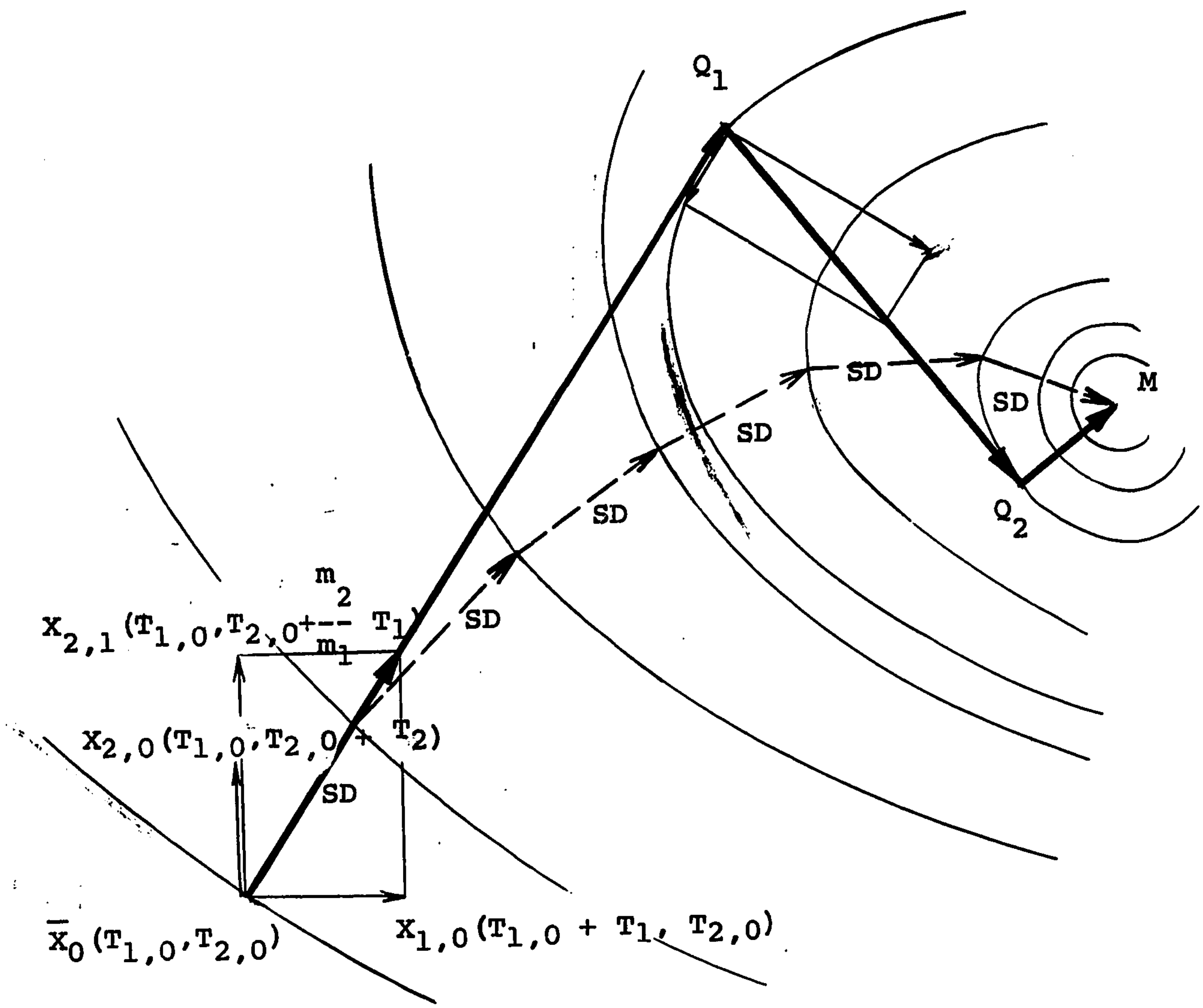
$$\left| F_{i+1} - F_i \right| < \varepsilon$$

where

F_{i+1} = (i+1)th iteration

F_i = ith iteration

ε = A predetermined positive constant small enough to yield the local minimum within the desired accuracy.



PATH DESCRIBED IN THE TEXT WHICH UTILIZES QUASI-LOCAL MINIMUM (Q). THE DIRECTION OF STEEPEST DESCENT IS SEARCHED ONLY AT X_0 , Q_1 , Q_2 ETC.

ALTERNATIVE PATH. THE STEEPEST DESCENT DIRECTION IS SEARCHED AT EVERY ITERATION

CONTOURS

FIG.A4-1) REPRESENTATION OF THE STEEPEST DESCENT METHOD IN 3 DIMENSIONAL SPACE. RESPONCE SURFACE , $z=f(x,y)$ CORRESPONDS TO $Cost=f(T_1,T_2)$