ENGINEERING AND ECONOMIC EVALUATION OF SOLAR DISTILLATION FOR SMALL COMMUNITIES

by

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ABSTRACT

Solar distillation has been examined and evaluated as a means of providing fresh water for small communities in arid regions.

A solar sea water distillation plant supplying fresh water to a small island in the Eastern Caribbean has been assessed technically and economically. The process appears feasible, though the cost of the water produced is somewhat expensive.

A simple method for the testing of the solar still performance has been presented and several experimental verification trials were conducted.

The operation and economics of the solar plant have been compared with those of the island's rainfall collection system.

In general, the characteristics of solar distillation are ideally suited to small communities as the local inhabitants can build, repair, operate and manage these installations.

In order to render solar distillation economically more attractive, it is essential to quantify all the benefits resultant from the capital investment, including those stemming from its effect on the local economy.

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A_B - area of solar still evaporator basin -- sq. ft.

A_C - area of solar still transparent cover -- sq. ft.

A_G - area of ground beneath the basin and the edges of the solar still -- sq. ft.

A_H - area of horizontal projection of solar still transparent cover -- sq. ft.

B - mass of rejected concentrated brine from a solar still bay -- pounds

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C' - constant in convection heat transfer equation -- Btu/hr.,sq. ft.,(deg.F)

C''- constant in evaporation heat transfer equation -- pound, deg.F/Btu, psia

C_p - specific heat of humid air at constant pressure -- Btu/pound, deg. F.

C_{wg}- thermal capacity of water, still, ground -- Btu/sq. ft., deg. F.

dT_b/dt - change of basin temperature with time -- deg. F./hr.

D - coefficient of diffusion -- sq. ft./hr.

D_w - fresh water distilled from solar still bay -- pounds

f - correction factor used in the determination of sky temperatures

F_s - total amount of sea water in a solar still bay -- pounds

g - acceleration due to gravity -- ft./sec.^{2}

h - hour angle -- degrees

h_c or h_c' - convection heat transfer coefficient -- Btu/hr., sq. ft., deg. F.

$h_{c,ca}$ - convection heat transfer coefficient, cover to environment -- Btu/hr., sq. ft., deg. F.

h_{fg}- latent heat of vapourization of sea water -- Btu/pound

h_m - mass transfer coefficient -- pounds/hr., sq. ft.

h_r - equivalent radiative coefficient for radiant heat transfer

$h_{r,bs}$-between the basin surface and the environment -- Btu/hr., sq. ft.,deg.F.

$h_{r,ca}$-between the still cover and the environment -- Btu/hr.,sq. ft., deg.F.

H_b - absolute humidity of moist air at basin surface -- pounds water vapour/pound dry air

H_c - absolute humidity of moist air at the condensing cover -- pounds water vapour/pound dry air

i - angle of incidence of solar radiation on the transparent cover -- degrees

I_d - diffuse solar radiation intensity on a horizontal surface -- Btu/hr., sq. ft.

I_D - direct solar radiation intensity on a horizontal surface -- Btu/hr., sq. ft.

I_H - total solar radiation intensity on a horizontal surface -- Btu/hr., sq.ft.

k_f - thermal conductivity of humid air within the still -- Btu/hr., ft., deg.F.

k_s - thermal conductivity of the soil beneath the stills -- Btu/hr.,ft., deg.F.

K - extinction coefficient of the transparent cover film -- inches^{-1}

L - path length of solar radiation in transparent film -- inches

L' - mean beam length of long-wave radiation within the solar still -- inches

L_a - latitude -- degrees

L_B - leakage of brine from a solar still bay into the ground -- pounds

L_e - effective spacing between the basin surface and the condensing cover -- inches

L_{sw} - least width dimension of the solar still -- feet

m_{fw} - total mass flux of water vapour evaporating from the basin surface -- pounds/hr., sq. ft.

$N_{Gr,f}$ - dimensionless group -- Grashof number -- $\frac{x^3 g \rho_f^2 \Delta t \beta_f}{\mu_f^2}$ evaluated at film conditions

N_{Le} - dimensionless group -- Lewis number -- D/α

$N_{Pr,f}$ - dimensionless group -- Prandtl number -- $\left(C_p\, \mu / k\right)_f$ evaluated at film conditions

P - total pressure of the humid air within the solar still -- psia

p_b - partial pressure of water vapour in the saturated air within the solar still at the basin surface -- psia

p_c - partial pressure of water vapour in the saturated air within the solar still at the condensing cover -- psia

p_{wa} - vapour pressure of the water vapour in the ambient air above the solar stills -- inches Hg

q - heat transfer rates -- Btu/hr., sq.ft.

- q_b - by conduction from solar still basin to the ground, including edge losses
- q_c - by convection
- $q_{c,bc}$ - by convection from the basin surface to the cover of the solar still
- $q_{c,ca}$ - by convection from the solar still cover to the environment
- q_e - by evaporation from the basin surface
- q_{ls} - by leakage from the seams of the solar still cover
- $q_{r,bc}$ - by radiation from the basin surface to the cover
- $q_{r,ca}$ - by radiation from the solar still cover to the environment
- $q_{r,lt}$ - net amount of long-wave radiation emitted from the basin surface and transmitted by the wet transparent cover

r_{bl} - reflectivity of the basin liner of the solar still

r_d - reflectivity of the transparent cover for diffuse solar radiation

r_D - reflectivity of the transparent cover for direct solar radiation

r_o - reflectivity of the floating wick on the basin surface

r_s - reflectivity of the basin surface within the solar still

R_{BL} - amount of incident solar radiation, reflected from the basin liner, which is transmitted outwards through the brine and reaches the environment -- Btu/hr., sq.ft.

R_S - amount of incident solar radiation which is reflected from the basin surface to the environment -- Btu/hr., sq.ft.

R_O - amount of incident solar radiation which is reflected from the floating wick to the environment -- Btu/hr., sq.ft.

S_s - shape factor, for use in calculating the heat loss to the ground

t - temperatures associated with the solar stills, in lower case letters -- deg. F.; in capital letters -- deg. Rankine.

- t_a - ambient air above the stills
- t_b - saline water in the basin of the solar still
- t_c - transparent cover of the solar still
- t_f - "film" temperature at the brine surface, which is approximately equivalent to t_b
- t_s - outer border of the boundary layer film
- t_{sk} - effective sky temperature
- t_w - wall or evaporating surface

V' - velocity of wind over the still -- mph

V_L - amount of water vapour lost through leakage from the seams of the transparent cover of a solar still bay -- pounds

V_{LC} - amount of water vapour permeating through the transparent cover of a solar still bay -- pounds

w - mass fraction of water vapour in the air within the solar still -- pounds water vapour / pound of humid air

- w_b - at the brine-air interface
- w_c - at the condensing cover
- w_s - at the outer border of the boundary layer
- w_w - at the wall

x - effective spacing between parallel plates, i.e. the basin surface and the transparent cover -- feet

Greek Alphabet:

α - thermal diffusion coefficient -- sq.ft./hr.

α_c - absorptivity of solar radiation by the transparent cover

α_o - absorptivity of solar radiation by the floating Orlon mat

α_{wb} - absorptivity of water vapour for grey radiation at temperature T_b

α_{wc} - absorptivity of water vapour for grey radiation at temperature T_c

β - solar altitude above the horizon -- degrees

β_f - coefficient of volumetric expansion of humid air within the still -- deg. $F.^{-1}$

δ - solar declination -- degrees

Δt - temperature difference -- F. deg.

$\Delta t'$ - equivalent temperature difference between basin surface and transparent cover -- F. deg.

ϵ_{air} - emissivity of air

ϵ_b - emissivity of basin surface

ϵ_{ca} - emissivity of outer surface of transparent cover towards the environment

ϵ_{cb} - emissivity of wet, inner surface of the transparent cover towards the basin surface

μ_f - viscosity of humid air within the still -- pounds/hr., ft.

ρ_f - density of humid air in the still -- pounds/cu.ft.

σ - Stephan-Boltzmann radiation constant -- Btu/hr.,sq.ft., deg. $R.^4$

τ_A - transmittance of solar radiation through the transparent cover allowing for absorption losses only

τ_{bs} - transmittance of solar radiation through brine

τ_D - transmittance of direct solar radiation through transparent cover

τ_d - transmittance of diffuse solar radiation through transparent cover

τ_{wl} - transmittance of long-wave radiation from the basin to the environment through the wet transparent cover

τ_{wv} - transmittance of long-wave radiation through the water vapour saturated atmosphere within the solar still.

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Introduction

Purpose of Study: This thesis has resulted from a project undertaken by the author, while employed as a development officer with the Brace Research Institute of McGill University, to investigate a solar distillation plant which provides fresh water for a small island in the Caribbean.

Since 1961, the Brace Research Institute has been examining various methods of saline water conversion for the provision of fresh water. One aspect to which considerable attention has been given is that of solar distillation, in particular the development of a simple, locally fabricated, easily operable still for use by peasants or small communities in the emergent areas of the world.[1, 2] Intermittently, during the period 1965 to 1968, this work has progressed, based on the general design of the Institute's Do-It-Yourself Leaflet No. 1.[3] This work has yet to be published and is to some extent,still continuing..

In March, 1967, contact was first made with the directors of Petit St. Vincent Limited, who had earlier received this leaflet and other sources of information on solar distillation. They were proceeding with the construction of a large-scale plant to provide fresh water for a hotel development project on a remote, uninhabited island, Petit St. Vincent, the Grenadines, St. Vincent, West Indies. Upon further careful examination, it was decided that it would be mutually advantageous to enter into a program of cooperation with this firm. The main reasons for our interest could be listed as follows:

1) These solar distillation units embody some of the features of our later model stills and hence, in some respects, constitute an extension of the practical application of our work.

2) Owing to the particular location and climatic conditions appertaining to Petit St. Vincent, our preliminary estimates and studies indicated that solar distillation might constitute a technically feasible and economically viable method of supplying fresh water for the community.

3) The introduction and use of this new technology in the Grenadines should catalyze the propagation of beneficial assistance to other development projects and isolated small communities in the area.

4) The development of the tourist industry in the Grenadines will radically change the economy of the islands. Increased investment should raise the gross regional income, resulting in an improvement of the economic well-being of the local communities.

5) It is well known that these islands suffer from a chronic insufficiency of potable water. Hence, the procurement of fresh water using local resources, such as solar and wind energy, and labour, should greatly improve their overall domestic economic situation and their attractiveness to outside investors. The use of these energies for saline water conversion is precisely the area of application to which we of the Brace Research Institute have been devoting its time and effort for the past eight years.

It was felt that our presence would hasten the effects of this development, especially through our experience and contacts with the principal authorities and participating agencies in the region.

6) Finally, the existence of a solar distillation plant contributing to the fresh water supplies of a remote community provides an excellent field laboratory for the study of the suitability of this process. The precise amount of water produced and consumed on the island can be tallied. A proper engineering and economic evaluation can be undertaken to determine the most effective and efficient manner of construction and operation of solar distillation units under typical field conditions. In addition, the feasibility of this type of water supply technology can be ascertained and compared with that of other possible alternative systems. As the success of the development is directly dependent on the supply of fresh water, it will be possible to quantify, at some future time, the benefits resulting from the investment in the water works.

It was therefore concluded that a study should be undertaken to investigate the engineering and economic suitability of solar distillation for small communities and this constitutes the main theme of the thesis. It was decided to consider in detail the island of Petit St. Vincent as a laboratory model containing all the prerequisites necessary for a proper scientific assessment of the question of water supply. Thereby, the experimental results are not only directly applicable for the benefit of the island itself, but are also of value in resolving the problems of other similar communities.

Boundary Conditions: The boundary conditions of the study are as follows:

1) Petit St. Vincent is a specific case from which results can be related to isolated communities in general.

2) The overall resultant water demand is taken as being representative of any indigenous group in a similarly arid region.

3) The solar distillation plant in use on the island is regarded as the one under study. The rain water collection system, which forms the other part of the local water supply, is also regarded as under study.

4) The composite water system is not considered as a static installation, but rather as a normal village water works continually undergoing modification, repairs and improvement.

5) It is appreciated that several years of evaluation will be necessary before positive and conclusive predictions can be made. Nevertheless, it is assumed that the data accumulated over these one and one-half years will suffice to give an indication of the trend which these assessments will take.

Subsequently, it is hoped that these results will serve as an index of reference for small communities experiencing similar water shortages. Although conditions in other areas might be somewhat different, it is felt that enough information will be applicable to serve as a guide in the evaluation of solar distillation as a practical tool in water supply engineering.

Solar Distillation Productivity and Costs: Currently, two methods of fresh water provision are in use on Petit St. Vincent - solar distillation and rainfall collection from roofs and the solar still covers. One of the principal objectives of these investigations is to determine where solar distillation units fit into a system of fresh water supply in a small isolated community. This involves ascertaining the full technical characteristics of the solar stills so as to be able to understand the processes of mass and energy exchange involved. A technical examination of this type of solar still, incorporating some of the constructional details of the earlier Brace Research Institute prototypes and a low arc-to-chord ratio cover[4] has hitherto never been satisfactorily reported in the literature. The test method formulated has been prepared to satisfy the requirements of a small community in assessing the performance of their solar stills. The instrumentation and evaluating techniques used are relatively simple.

The data collected has resulted in the establishment of a series of operating lines, indicating the expected output from the stills as a function of the incident solar radiation. Combined with a thermodynamic analysis of the process, this should provide a clear understanding of the effects of the parameters involved and facilitate the prediction of the diurnal and annual variations in distillate production. In this manner, a total average output of fresh water has been determined. Concurrently, a detailed cost analysis of the solar still construction, coupled with expenditures on all factors of production, charges for maintenance, amortization of the capital investment, etc., has been collated so that it has been possible to calculate a specific cost of solar distilled water. A portion of the latter has been attributed to the cost of the storage, pumping and distribution systems.

The surfaces of the solar stills effectively act as a rainfall catchment area. The rain water collected can be added to the distillate, thus reducing the unit cost of the water produced.

Rainfall Collection and Costs Incurred: The other half of the fresh water collection and distribution system involves the use of the roofs of buildings as rainfall catchments. Rainfall collection constitutes one of the most common forms of fresh water supply in arid areas. This necessitates added expense to the building structure for adequate retrieval, along with storage cisterns, pipe lines, pumping facilities, filtration and treatment plants. The annual average amount of rain water collected can be predicted from climatological data and specific measurement. For this purpose and the engineering evaluation of the solar stills, a rudimentary meteorological station has been established on Petit St. Vincent (generally abbreviated to P.S.V. in the text). The total collection areas of different buildings have been assessed as potential rainfall catchments along with estimates of the variation in their annual output. The annual costs involved include maintenance, operating charges, the amortization of the capital investment reduced to an equivalent annual basis, etc. Hence it has been possible to determine the cost of the collected rain water being used in the water supply system.

Combined Fresh Water System: Certain costs, such as those relating to the distribution system, storage, chlorination and supervision, have been proportioned between both sources of supply. The solar distillation plant and the rainfall collection system, have been examined with a view to determining how effective and economic each is in fulfilling the fresh water demand. As in any community, expansion of the facilities on Petit St.

Vincent is bound to be made in time to come. It is only with the availability of data of this nature that predictions as to the areas of future water supply plant investment can be wisely determined. Therefore, if these analyses show that rain water collection is substantially cheaper than solar distillation, it would be far more sensible to apply future investment to the construction of additional rainfall catchments. Under these conditions, the marginal physical output per additional dollar invested in rainfall collection media would exceed that of solar distillation equipment, and logically future investments would be encouraged along these lines. Naturally, this will only be undertaken if all other factors are equal. The effects of these considerations, such as annual rainfall distribution, can often pose serious consequences which tend to necessitate an individual examination of each particular community's water supply problems.

Suitable climatological records and a careful tally of expenditures over a period of time will indicate the desirability of either of these methods of fresh water provision. Hence, as indicated earlier, it might be a few years before specific predictions can be firmly established. In the interval, this study can serve as a model to assist many categories of isolated communities in making policy decisions regarding the most economical form of fresh water supply for their particular needs.

Format of the Thesis: The central theme of this study is contained in the main section that follows as Chapters 1 to 5. The figures, tables, and a list of references relating to this part have all been placed at the end of the conclusions. A considerable amount of supporting information has been formulated into separate appendices at the end of the report. These data elucidate certain features of the study for a fuller comprehension of the problems involved. Each of these appendices has its own separately numbered pages, diagrams, tables and a list of references.

<u>References</u>: The body of the thesis and the appendices each have their own list of references enumerating the journals, books, or other sources of information cited in the text. The method of physical presentation of bibliographical entries varies considerably in academic reports. As a result, it has been decided to follow as closely as possible the examples given by Roy M. Wiles in his publication <u>Scholarly Reporting in the Humanities</u>, Third Edition, University of Toronto Press, pages 49-50. As no footnotes have been used, the following additional procedures have been adopted:

Where reference is made to an entire article, the entry in the List of References is followed by the page numbers at the beginning and end of the article.

Where reference is made to information contained on a specific page or section of a report, this page number is listed at the end of the entry.

Where a reference is referred to on more than one occasion in the text, the reference number is superscribed as usual, and the page number of the text is added immediately following, as in the example [24, p.375]. In this case, the entry in the List of References contains the page numbers of the entire article as listed above.

<u>Definitions of Terminology</u>: In order that there be no confusion regarding the subject chosen for study, the following terms have been defined:

<u>Solar distillation</u>: refers to a process whereby energy in the form of solar radiation is used to distil fresh water from saline water.

Small community: in the arid and semi-arid regions of the world, there are many small hamlets and villages, with a population of one to two thousand inhabitants, whose water supplies are either inadequate or unsuitable, and where a source of saline water is available. Frequently, there are communities among these, which would respond favourably to an increase in fresh water supply which would contribute to a positive raising of their standard of living. It is for this group that it is hoped the information presented here will be of some definite assistance.

Saline water: will be taken as any water source with a total dissolved solids content of over 1,000 ppm (parts per million). Sea water generally contains about 35,000 ppm of total dissolved solids.[5]

Fresh water: will be defined as water suitable for drinking purposes as set out by the Ontario Water Resources Commission[6], the U.S. Public Health Service[7], and the World Health Organization[8]. The total allowable solids content is 500 ppm, which will be considered the maximum desirable level in this study. It is recognized, however, that in certain cases, water of higher salinity can be tolerated.

Water supply system: includes the works and auxiliaries for collection, treatment, storage and distribution of the water from the sources of supply to the buildings or other designated areas of use. In this instance, it does not include the internal piping leading to the free-flowing outlets of the ultimate consumers.

CHAPTER 1

THEORETICAL EVALUATION OF THE SOLAR DISTILLATION PROCESS AND ITS EXPERIMENTAL VERIFICATION

Introduction: Although the literature is prolific with reports on the design and practical testing of solar stills, very few workers have attempted detailed thermodynamic analyses of the mechanisms of heat and mass transfer controlling the distillation process. Current understanding of the physical interaction of the parameters is by no means complete.

Dr. V.A. Baum[9] has undertaken elaborate tests to determine the interaction between heat and mass transfer within a simple hot-box type solar still. He studied the patterns of motion of the vapour-air mixtures within the still and developed correlations for the prediction of evaporation and condensation which have been verified experimentally. He found that the resistances to heat and mass transfer are confined to the boundary layers at the evaporating and condensing surfaces, which vary from several millimeters to a few centimeters in thickness. Several other individuals have contributed to the theory of the thermodynamics of solar distillation and have derived mathematical relations which can be used for the prediction of the performance of solar stills of the roof and deep-basin types.[10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]

Most of the former, however, have confined their attention to glass-covered stills and little consideration has been given to plastic-covered stills which form the subject of the present study. A historical review of the science of solar distillation is presented in Appendix A.

This chapter has been divided into three parts:

a) A theoretical presentation outlining the principal heat and mass transfer equations which can be used to estimate the performance of these air-inflated, plastic covered solar stills.

b) A discussion of the various parameters involved and the physical properties of the fluids under consideration and their use in the solution of the design performance equations.

c) Owing to the narrow operating range over which solar stills function, it was possible to quantify the heat and mass transfer equations into a series of simple charts. These permit the operators of similar type stills to estimate these flows from the measurements of solar radiation, windspeed, ambient air temperature, and the average cover and basin temperatures etc. A specific case has been worked out from experimental data and is discussed later.

The performance conditions of solar stills are reasonably similar and generally do not fluctuate over a wide operating range. Hence these charts are fairly flexible and can be used for the evaluation of a number of similar-type stills. Severe imbalance in the assessment of the heat and mass loads might be indicative of an equipment fault which would require further investigation on the part of the operator.

<u>The Air-Inflated Plastic Covered Solar Still</u>: The solar still which forms the subject of the present study is described in detail in Appendix C.

S E C T I O N I

THEORETICAL ANALYSIS OF THE SOLAR DISTILLATION PROCESS

Thermodynamic Assessment of the Solar Still Operation: The principle of operation of a solar still is quite simple. Sea water is fed into shallow basins formed by placing black, impervious sheets on the ground. The basins are covered by a transparent canopy supported by a small positive air pressure maintained by an electric blower. The short-wave radiation from the sun is transmitted through the cover, which is nearly opaque to the long-wave radiation re-emitted by the heated surfaces within the still. The solar radiation is absorbed by the basin liner which in turn heats up the saline water. The cover is securely fastened to the edges of the basin, thus a reasonably air tight compartment is formed. As the saline water heats up, the enclosed air between the basin and the canopy is eventually saturated with water vapour. Concurrently, the transparent cover is cooled by convection due to the effect of the wind and the lower ambient air temperatures and by direct radiation to the environment. In time, the film of moist air immediately beneath the cover reaches its dew point and condensation occurs on the underside of the canopy. The fresh water condensate flows off to the gutters on either side of the basin. The main components of the solar still are illustrated in Fig. No. C - 1.

Overall Energy Balance on the Solar Still: An overall heat balance has been set up on the still. This comprises a continual series of energy transfers into and out of the still, illustrated in Fig. No. 1, and given in equation No 1:

$$I_H = I_D + I_d = r_D I_D + r_d I_d + q_{r,ca} + q_{c,ca} + q_b + q_{1s} + q_{r,1t} + R_{BL} + R_S + C_{wg} (dT_b / dt) \quad \text{.....................(1)}$$

Equating all items on a basis of equal area, i.e. of the horizontal projection of the transparent cover, equation No. 1 becomes,

$$I_H = r_D I_D + r_d I_d + (A_C/A_H)(q_{r,ca} + q_{c,ca} + q_{1s}) + (A_G/A_H) q_b + (A_B/A_H)(q_{r,1t}) + R_{BL} + R_S + C_{wg}(dT_b/dt) \quad \ldots (2)$$

It has been suggested by Morse and Read[22] that a storage term, C_{wg}, would take care of the variation of the temperature of the still, including the heat build-up in the brine, the structural components of the still and the ground beneath the basin, from one time interval to another. This approach follows that of Ward[24] who used a similar term in evaluating unsteady state conditions of solar water heaters. In assessing area correction factors for terms dealing with incident solar radiation, it has been assumed that the radiation is incident on the surface A_H. This is particularly advantageous in avoiding complications with the reflected fractions of the radiation. The physical properties of the basin are assumed to apply to the structural sections included in A_H as the impervious liner covers all internal surfaces within the still. These sections amount to 5.3 % of A_H and the error introduced should be negligible.

This analysis has been formulated for a free sea water surface in the basin. Most of the stills on Petit St. Vincent (PSV) incorporate a black wick, floating on the brine surface. In this case, the analysis must be altered to take the effect of the wick into account. This has been done on page 15.

<u>Energy balance on the transparent cover of a solar still</u>: An energy balance on the cover of the still, taking into account inputs of energy to the still and cooling heat losses, is set out in equation No. 3 and illustrated in Fig. No. 2

$$q_{r,bc} + q_{c,bc} + q_e + \alpha_c I_D + \alpha_c I_d = q_{r,ca} + q_{c,ca} + q_{ls} \quad \ldots\ldots\ldots (3)$$

Normalizing these transfers on an equivalent area basis, equation No. 3 becomes

$$(A_B / A_H)(q_{r,bc} + q_{c,bc} + q_e) + \alpha_c I_D + \alpha_c I_d$$

$$= (A_C / A_H)(q_{r,ca} + q_{c,ca} + q_{ls}) \quad \ldots\ldots\ldots (4)$$

Energy balance on the solar still basin: A heat balance on a solar still basin has been illustrated in Fig. No. 2. This is represented in equation No. 5. It has been assumed that there is negligible short-wave radiation absorption by the still atmosphere.

$$\tau_D I_D + \tau_d I_d = q_{r,bc} + q_{c,bc} + q_{r,lt} + q_e + q_b + R_{BL} + R_S + C_{wg}(dT_b/dt)$$

$$\ldots\ldots\ldots (5)$$

By reducing all factors to a common area basis, equation No. 5 becomes

$$\tau_D I_D + \tau_d I_d = (A_B / A_H)(q_{r,bc} + q_{c,bc} + q_{r,lt} + q_e) + (A_G / A_H)(q_b)$$

$$+ R_{BL} + R_S + C_{wg}(dT_b / dt) \quad \ldots\ldots\ldots\ldots (6)$$

Reflectivity of Solar Radiation Within the Still: Solar radiation is reflected from the brine surface of the evaporator as well as from the basin liner. This has been illustrated diagrammatically in Fig. No. 3. The surface reflectivity can be estimated as follows

$$R_S = r_s(\tau_D I_D + \tau_d I_d) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

In addition, the reflectivity from the basin liner, R_{BL} , can be calculated

$$R_{BL} = r_{bl} (\tau_{bs})^2 (\tau_D I_D + \tau_d I_d - R_S) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

In the case where a floating mat is provided, the changes in reflection losses are illustrated in Fig. No. 3. The terms R_{BL} and R_S must be deleted from both equations Nos. 2 and 6. In their place must be added the reflectivity term, R_O, which can be estimated as follows:

$$R_0 = r_o (\tau_D I_D + \tau_d I_d) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

It is assumed that R_S and R_{BL}, or alternatively R_O, pass directly out of the solar still cover without further interactions, etc.

Convection Heat Transfer from the Basin Surface to the Transparent Cover:

For air enclosed between horizontal parallel plates, with heat flow upwards, McAdams (25, p. 182) has given the following relationship valid for Grashof numbers from 3.2 x 10^5 to 10^7.

$$\frac{h_c' \, x}{k_f} = 0.075 \left[\frac{x^3 \cdot \rho_f^2 \cdot g \cdot \beta_f \cdot \Delta t'}{\mu_f^2} \quad \frac{(C_p \mu)_f}{(k)_f} \right]^{1/3} \quad \ldots\ldots\ldots (10)$$

In this case, the effect of the spacing, x, between the plates, cancels out and the equation is reduced to that for single, heated plates, facing upwards in air. This can be assumed to hold by considering the basin surface and the transparent canopy as two horizontal parallel plates.

$$h_c' = 0.075 \, k_f \left[\frac{\rho_f^2 \cdot g \cdot \beta_f \cdot \Delta t'}{\mu_f^2} \quad \frac{(C_p \mu)_f}{(k)_f} \right]^{1/3} \quad \ldots\ldots\ldots (11)$$

Dunkle[21] has defined $\Delta t'$ as an equivalent temperature difference which includes the molecular weight difference in evaluating the buoyancy effect, and for the air-water system this is given by

$$\Delta t' = \left[t_b - t_c + \left(\frac{p_b - p_c}{39 - p_b} \right) T_b \right] \quad \text{..................... (12)}$$

Rearranging equation No. 11, the convective heat transfer coefficient can be written as

$$h_c' = C' \, (\Delta t')^{1/3} \quad \text{................. (13)}$$

The rate of heat transfer from the basin surface to the transparent canopy can then be estimated using equation No. 14.

$$q_{c,bc} = C' \, (\Delta t')^{1/3} \, (T_b - T_c) \quad \text{................. (14)}$$

Evaporation from the Brine: It is possible to utilize information on heat transfer phenomena for the estimation of mass transfer owing to the similarity of these transport processes. It has been showed by Eckert[26] that the relationship between convective (and conductive) heat transfer, from a wall or surface, and mass transfer can be written as

$$q_c / m_{fw} = C_p \, (t_w - t_s) / (w_w - w_s) \quad \text{............... (15)}$$

Heat transfer by convection can also be set down as

$$q_c = h_c' \, (t_w - t_s) \quad \text{................................(16)}$$

In a similar manner, mass transfer processes are described by a mass transfer coefficient

$$m_{fw} = h_m \, (w_w - w_s) \quad \text{..............................(17)}$$

Combining equations 15, 16 and 17, a simple relationship is obtained between the heat and mass transfer coefficients, known as the Lewis relation.

$$h_m = h_c' / C_p \quad \text{............................. (18)}$$

This is valid provided that the fluid mixture has a Lewis number equal to or close to unity. Several observers[26, 27] in this field, feel that the Lewis number for water vapour diffusing into air is sufficiently close to unity for the relationship to apply. Substituting, equation 16 in equation 15

$$m_{fw} = (h_c' / C_p)(w_w - w_s) \quad \text{.............................} \quad (19)$$

In addition, the values of w_b and w_c can be substituted respectively for w_w and w_s, as the limits of the evaporative and boundary layer phases.

$$m_{fw} = (h_c' / C_p)(w_b - w_c) \quad \text{.............................} \quad (20)$$

For small values of the mass fraction, w, it can be assumed that this differs little from the absolute humidity, H. Hence equation 20 becomes

$$m_{fw} = (h_c' / C_p)(H_b - H_c) \quad \text{.............................} \quad (21)$$

From the definition of absolute humidity, it is known that

$$H_b = \left(\frac{18}{29}\right)\left(\frac{p_b}{P - p_b}\right) \quad \text{.....} \quad (22) \quad \text{and} \quad H_c = \left(\frac{18}{29}\right)\left(\frac{p_c}{P - p_c}\right) \quad \text{....} \quad (23)$$

Assuming that the partial pressures, p_b and p_c are small relative to the total pressure, P, and that they are of the same order of magnitude, it is possible to factor out a term, 18/29 $(P - p_{ave})$, where p_{ave} is the average of p_b and P_c.

Hence a general relationship for mass transfer can be formulated thus

$$m_{fw} = C'' h_c' (p_b - p_c) \quad \text{.................................} \quad (24)$$

where the constant $C'' = 18/29\,(P - p_{ave})\,C_p$ .... (25)

A similar mass transfer equation has been given by Dunkle in equation No. 26(21,p.897)

$$m_{fw} = 0.198\, h_c' (p_b - p_c) \quad \text{.................................} \quad (26)$$

The heat used for evaporation can then be estimated as

$$q_e = C'' h_c' \ (p_b - p_c) \ h_{fg} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (27)$$

Substituting equation 13 in equation 27, the evaporative heat transfer can be written as

$$q_e = C'' C' (\Delta t')^{1/3} \ (p_b - p_c) \ h_{fg} \quad \ldots\ldots\ldots\ldots\ldots\ldots (28)$$

Radiative Heat Losses from the Basin Surface to the Transparent Cover:

Measurements have shown that little carbon dioxide is present within the solar still(20, p. 60). Hence long-wave radiation absorption is effectively due to the water vapour present in the saturated air space. The radiative heat transfer between two parallel planes enclosing an absorbing gas has been given by Meghreblian[28] as

$$q_{r,bc} = \frac{\sigma.\epsilon_b.\epsilon_{cb}(1-\alpha_{wb})\,T_b^4 - \sigma.\epsilon_b.\epsilon_{cb}(1-\alpha_{wc})\,T_c^4}{1-(1-\alpha_{wb})(1-\alpha_{wc})(1-\epsilon_b)(1-\epsilon_{cb})} \quad \ldots (29)$$

Long - Wave Radiation Energy Transmitted Through the Transparent Cover:

The polyvinyl fluoride film used as the transparent cover condensing film is not entirely opaque to long-wave radiation, i.e. in the range from 3 to 20 microns[29]. Hence it becomes necessary to make an allowance for this radiation transfer from the basin to the environment. Naturally this will be affected by the absorption of radiation by water vapour within the still atmosphere, and by the water film on the underside of the condensing cover. The net exchange can be estimated as follows

$$q_{r,lt} = \epsilon_b.\tau_{wl}.\tau_{wv}.\ h_{r,bs}(T_b - T_{sk}) \quad \ldots\ldots\ldots\ldots (30)$$

Radiation Heat Loss from the Still Cover: The solar still cover radiates heat to the sky. In this regard it becomes necessary to estimate the sky temperature, T_{sk}. For clear skies, Parmelee and Aubele[30] have found that the ratio of radiation received from the sky, R_{sk} to that from a black body at air temperature, R_a, varied according to the expression

$$f^4 = 0.55 + 0.33 \sqrt{p_{wa}} \qquad (31)$$

In addition

$$R_a = \epsilon_{sky} \cdot \sigma \cdot T_{sk}^4 \qquad (32)$$

and

$$R_a = \epsilon_{air} \cdot \sigma \cdot T_a^4 \qquad (33)$$

Therefore

$$T_{sk}^4 = (0.55 + 0.33 \sqrt{p_{wa}})\ T_a^4 \qquad (34)$$

and

$$T_{sk} = \left(0.55 + 0.33 \sqrt{p_{wa}}\right)^{1/4} (T_a) \qquad (35)$$

The radiative heat transfer loss from the canopy surface can then be computed from the standard formula

$$q_{r,ca} = \epsilon_{ca} \cdot h_{r,ca} \cdot (t_c - t_{sk}) \qquad (36)$$

Heat Loss Through Leakage from the Transparent Cover Seams: It is very difficult to quantify the leakage of water vapour and air escaping owing to the imperfect sealing of the cover clamps. The loss term is represented in the energy balances by q_{ls}. No equations have been given for its computation. Dzhubalieva[31] has put forward a method whereby this heat loss can be estimated.

Convection Heat Losses from the Solar Still Cover: The convection heat loss from the cover to the atmosphere is directly proportional to the windspeed and is affected by the air temperature. It can be represented as follows:

$$q_{c,ca} = h_{c,ca} (T_c - T_a) \quad \text{.............................} \quad (37)$$

The value of the heat transfer coefficient, $h_{c,\ ca}$, can be estimated using the Jurges formula, as given by McAdams[25, p. 249]

$$h_{c,ca} = a_1 + b_1 (V')^n \quad \text{.............................} \quad (38)$$

where a_1, b_1, and n are constants.

Heat Loss Through the Ground: The loss of heat through conduction from the evaporator basin into the ground beneath the stills can be obtained through the use of equation No. 39

$$q_b = \frac{S_s k_s (t_b - t_a)}{L_{sw}} \quad \text{.............................} \quad (39)$$

Storage of Heat In Distiller: The variation in the heat content of the unit can be estimated from the storage term

$$C_{wg} (d T_b / dt) \quad \text{.............................} \quad (40)$$

Basis of Factor Balances: When setting up a series of heat and mass balances on the solar stills, it is necessary to establish a basis of operation. With regard to both heat and mass balances, it was decided that the transfers should be rated per unit of the projected transparent cover area. This brings the calculations in line with those of other workers, Howe[33], Morse[22], etc. In this respect, A_H, the horizontal projection area of the canopy has been assigned the value 1, and calculations have been undertaken to determine the values of the other areas.

The ratios of these areas relative to A_H are:

$A_C / A_H = 1.015$

$A_B / A_H = 0.947$

$A_G / A_H = 1.8$

The term A_G takes into account all the bottom and edge losses of the stills. As the periphery of the stills is not a uniform rectangle, but is indented, the edge losses tend to be greater.

The logical temperature datum is the ambient air temperature, which varies very little for the location under study. Early in the morning, this differs little from the average basin temperature. This permits the estimation of heat losses from the still.

SECTION II

REVIEW OF PARAMETERS USED IN THE THEORETICAL COMPUTATIONS

Analysis of the Role of Solar Radiation in the Distillation Process: The energy input to the still comes from the incident solar radiation. This can be divided into two types of radiant energy, the direct beam radiation of the sun and a diffuse component. The latter results from the complex processes of absorption, reflection and multiple scattering of the solar beam by the atmospheric constituents. The direct component is treated as a single radiation beam. The angle at which this beam strikes a horizontal plane during the day is well known and can be estimated at any time by equation No. 41.

$$\sin\beta = \sin(L_a)\sin(\delta) + \cos(L_a)\cos(\delta)\cos(h) \quad \ldots (41)$$

Thus, knowing the latitude, declination and hour angle, the solar altitude can be calculated. This forms the complement of the angle of incidence of the beam to the horizontal plane.

The diffuse radiation, on the other hand, approaches the horizontal plane from all points of the hemispherical sky vault. As the diffuse component results directly from the depletion of the beam, generally, during periods of high insolation and clear skies the diffuse fraction is a small portion of the total. The reverse is true during overcast periods.

In practice, when undertaking engineering evaluations, only the total radiation on the horizontal, I_H, is measured. Where

$$I_H = I_D + I_d \quad \ldots\ldots\ldots\ldots\ldots\ldots (42)$$

In this particular case it has been decided to estimate the diffuse component by spot readings of the instantaneous diffuse radiation intensity, as measured by shielding the radiation sensor. Also, Parmelee[34] has published a series of charts valid for cloudless skies which give the diffuse radiation on the horizontal from a knowledge of the solar altitude and the total radiation on the surface. This can be used to verify the field measurements. In addition, the recently published work of Sharma and Pal[35] gives a satisfactory method of determining direct and diffuse radiation from total radiation readings,formulated specifically for the tropics,which can be used to verify these estimates. Finally, this can further be confirmed by applying the measured total radiation readings to the graphs of Liu and Jordan[36].

It has been found by Hottel and Woertz[37, p. 98], and also by Parmelee[38], that the diffuse component can be assumed to act as a single beam striking the surface at an angle of incidence of 58 degrees. This assumption, which has been used by Hodges[39], Baum[40, p. 8], and others, greatly simplifies the problem of calculating the input energy to the solar still. A variation in the angle from 56 to 69 degrees was noted by Parmelee. In this study, an angle of 61 degrees has been used.

Estimation of the Solar Geometry: In order to determine the input energy to the solar stills on Petit St. Vincent, latitude 12° 32' North, during any time period, the annual variation of the solar altitude has been calculated for every day and every hour from 0800 hours to 1600 hours. This is plotted in Fig. No. 4. For this location, all local times must be corrected to true solar time as indicated in Fig. No. 5. The solar altitude can then be determined using averages for the hourly periods $\pm\frac{1}{2}$ hours to $\pm 3\frac{1}{2}$ hours from solar noon.

The altitude is the compliment of the angle of incidence on a horizontal surface. As a result it was possible to determine the angles of incidence at all points on the cover surface. These were combined and weighted according to incident area, and an average angle of incidence thereby determined. These have been plotted in Fig. No. 6 for both direct and diffuse solar radiation. For direct radiation, the average angle of incidence equals the angle of incidence on the horizontal as the surface is aligned on a North-South axis, symmetrical and very nearly horizontal.

<u>Transmittance of Radiation Through the Transparent Cover</u>: The best available data on the transmittance of 4 mil Tedlar film has been published by Edlin[41, p. 26]. The variation of the transmissivity with angle of incidence is illustrated in Fig. No. 7. Recently, however, Grange[42] measured a transmittance of 92 % for normal incidence solar radiation passing through a treated, wettable 4 mil Tedlar with a water film on the underside. Assuming the shape of the earlier data of Edlin to be valid, a new transmittance curve for the treated Tedlar was constructed using as one point on the curve, 92 % transmittance at an angle of incidence of zero degrees. This has also been represented in Fig. No. 7 and repeated in Fig. No. 8.

It is possible through the use of Fig. No. 8 to determine τ_d and τ_D for the diffuse and direct components of the incident solar radiation.

Edlin[41, p. 25] has also measured the reflectivity of the Tedlar film which is likewise represented in Fig. No. 7. Combining the data from Fig. Nos. 7 and 8, it has been possible to construct a chart to give an estimate of the division of the direct component of the solar radiation incident on a wet, treated Tedlar surface, which is shown in Fig. No. 9. The data of Edlin for reflectivity have been used in the absence of any published information giving the reflectance of radiation from a treated

Tedlar surface with a water film on the underside. The absorptivity of the Tedlar-water film layers has been calculated from the relationship,

$$\tau_D + a_c + r_D = 1 \quad \text{.............................} \quad (43)$$

Edlin's earlier published figure on absorptivity of Tedlar film is 0.003 per mil, as a fraction of the incident radiation(41, p. 26). This is for dry, untreated film. In this case, it was felt that the absorptivity might be higher due to the sandblasting of the cover surface to produce wettability and the presence of the water film. Attempts were made to determine the thickness of this film, experimentally, and a value of 2 mils was noted. The method used in estimating the film thickness was not very accurate, but nonetheless calculations were undertaken using equation No. 44.

$$\tau_a = e^{-KL} \quad \text{.............................} \quad (44)$$

The results were uncertain, but did indicate that absorptivities of the order of magnitude shown in Fig. No. 9 are possible.

The substantial difference between the KL values for the water and Tedlar films, the difficulty in relating the two together and the uncertainty of the thickness of the water film, all support the decision to estimate the Tedlar film properties as shown in Fig. No. 9.

It should be noted, however, that the reflection losses are greater than the absorption losses over most of the range of angles of incidence.

Radiation Input Investigations: Practical engineering evaluations in the solar energy field generally entail the measurement of I_H only. In this particular installation on Petit St. Vincent, where the variation in the angle of incidence is small, it seemed logical to set out a series of typical conditions to ascertain what the percentage error in overall transmitted radiation would be, if I_D were assumed equal to I_H. This was undertaken for varying diffuse fractions of I_H, i.e. ratios of I_d / I_H, These results are noted in Fig. No. 10. The transmittances for various percentages of diffuse and direct radiation were estimated from Fig. Nos. 6 and 8. Estimates were made of the actual radiation transmitted for various percentages of the diffuse component. The deviation error, considering all the intensity, I_H, as being equivalent to I_D,was plotted against the angle of incidence of the solar beam. The basis of this error was taken as the actual radiation, separated into fractions as above.

It is interesting to note that for all angles of incidence below 60^o, the maximum error in this assumption is -9% for the extreme case of 100% diffuse radiation. Considering more typical values of diffuse radiation of less than 40% for clear, partly cloudy days, the error reduces to less than -3.5% for angles of incidence below 60^o. This should apply generally for all effectively horizontal surfaces. For Petit St. Vincent, the angle of incidence throughout the year is always less than 60^o from 0900 to 1500 hours and for 0800 to 1600 hours from April to September. As most of the radiation intensity comes during this period in the day, the substitution of I_D for I_H does not appear to introduce a substantial error.

Computation of Solar Radiation Components: On the basis of the data presented earlier, it was possible to construct charts which would separate various intensities of direct and diffuse solar radiation into the portions transmitted, reflected or absorbed by the film. This has been done in Fig. Nos. 11 and 12 for the direct and diffuse components respectively.

Reflection of Solar Radiation from Within the Solar Still: Solar radiation is reflected from the brine surface and the basin liner as represented in equations Nos. 7 and 8. The reflectivity of the brine surface for various angles of incidence, has been taken from the Smithsonian Tables[43]. Reasonably similar values have been given in the Handbook of Meteorology[44]. It was then possible to set up a chart, Fig. No. 13, showing the variation with angle of incidence of energy reflected from a plane brine surface.

In order to estimate the amount of energy reflected from the basin liner, it is necessary to determine the amount of the solar beam which is absorbed during its passage through the brine layer. Sverdrup gives the transmissivity of solar radiation through different categories of sea water as a function of depth[(5, p. 107)]. For the nominal two inch depth of the PSV stills, it was possible to give the variation of transmittance of this brine τ_{bs} as a function of angle of incidence in Fig. No. 14. The absorptivity of the liner can be approximated using the chart given by Hottel and Woertz for a blackened surface for artificial sunlight transmitted through glass[(37, p. 97)]. In this manner, it is possible to estimate in Fig. No. 15 the fraction of the transmitted energy which is reflected from the basin liner.

If a floating wick is used on the brine surface, equation No. 9 would apply. The values of R_0 can be estimated from the results of the reflectivity of the mat published by Edlin and illustrated in Fig. No. 7[(41, p.25)]. This is shown to be fairly constant at between 4 and 5 per cent. According to additional data supplied from Edlin's report, and also illustrated in Fig. No. 7, from a reflectivity point of view, it would seem to be better to have the mat floating on the surface than to have it covered by a water layer[(41, p. 25)].

Convection Heat Transfer from Basin Surface to Transparent Cover: The Grashof Numbers, $N_{Gr,\ f}$, were calculated for temperature levels representative of typical operating cover and basin temperatures found in solar stills. These have been listed in Table No. 1. It is evident that most of these results fall below the upper limit of 10^7 given by McAdams[25, p. 181]. Consequently, equation No. 11 was rearranged and values for the various parameters entered so that a relationship similar to the one given by Dunkle was established. Also listed in Table No. 1 are the values of the equation constant C' which corroborate Dunkle's value of 0.128[21,p.897].

Owing to the limited temperature variation of most solar stills, it is possible to set up charts to determine the equivalent temperature difference $\Delta t'$, which are valid for typical operating conditions. On PSV, the ambient air temperature rarely falls below 70° F., which further limits the range of temperature variation of the solar stills. Hence charts were constructed for basin temperatures varying from 90°F to 150° F. and for cover temperatures from 70° F. to 130° F. for fresh water, and for sea water, at normal, double, and triple concentrations. These are illustrated in Fig. Nos. 16, 17, 18, and 19 respectively. Hence, it was possible to indicate on Table No. 1 values for the heat transfer coefficient h'_c and for the rate of convection heat transfer, $q_{c,\ bc}$, valid for sea water at normal concentration.

In order to estimate the Grashof numbers, it was necessary to determine precise properties of the moist air under the conditions of operation. Extensive literature searches indicate that there is a dearth of information on the properties of humid air, considering how frequently this mixture is encountered in scientific investigations. One of the best references is the excellent book of Dorsey[45].

The following graphs were used in the estimation of all moist air properties in this report:

Fig. No. 20 - Density

Fig. No. 21 - Viscosity

Fig. No. 22 - Specific Heat and Coefficient of Volumetric Expansion

Fig. No. 23 - Thermal Conductivity

Fig. No. 24 - Prandtl Number

The acceleration due to gravity, g, was corrected for latitude as outlined in the Handbook of Meteorology[44, p. 90].

Values of the density of sea water and the vapour pressure variation with concentration and temperature were taken from the U.S. Office of Saline Water, Saline Water Conversion Engineering Data Book[46].

With regard to vapour pressures of sea water solutions, the vapour pressure at the brine surface, p_b, was taken as that corresponding to the particular brine solution at that temperature. It is surprising that several investigations[20, 22] have used values of fresh water when determining p_b. Although the vapour pressure depression is not great, in principle it is wrong to substitute fresh water vapour pressure values. In all cases, unless otherwise specified, values for p_b have been taken as those of normal sea water.

Radiation Heat Transfer from the Basin Surface to the Transparent Cover: The long-wave radiation absorption is effectively due to the water vapour present in the saturated air space separating the basin surface and the transparent canopy. Values of the water vapour emissivity or absorptivity for an effective spacing of 8.3 inches, have been estimated from the data of Perry[47], and are shown in Fig. No. 25.

They take into account deviations from ideal conditions. The mean beam length, L', is taken as equal to 1.8 Le, the effective spacing, following the recommendations of Perry, in this section. The value of ϵ_{cb} was taken as 0.90 to allow for the effect of the water layer on the underside of the film. Results for the rate of radiation heat transfer as outlined in equation No. 29 have been tabulated in Table No. 2. The net exchange has been calculated considering the presence of an enclosed absorbing gas, and again recalculated, not allowing for the gas. The latter case is 30% to 75% greater than the former.

Long-Wave Radiation Energy Transmittance Through the Transparent Cover:

Whillier[48] has calculated the long-wave radiation transmittance of dry, untreated 4 mil Tedlar and found it to be of the order of 30 per cent. Edlin has measured the transmittance through wet and dry Tedlar films of long-wave radiation from radiators at various temperatures[41, p. 27]. These results are shown in Fig. No. 26. A portion of the long-wave radiation emitted by the basin surface is transmitted through the Tedlar. The potential radiation exchange between the basin and the sky, i.e. the net amount of long-wave radiation transmitted by an exposed basin surface to the environment is

$$q_{r,lt} = \epsilon_b . h_{r,bs} . (T_b - T_{sk}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (45)$$

Water vapour present in the air enclosed in the still absorbs some of this energy. The absorptivity is given in Fig. No. 25. According to McAdams[25, p. 106], the transmittance of the radiant energy through the gas is $(1 - \alpha_{gas})$ The data in Fig. No. 25 are very close to those given by the Battelle Memorial Institute in a recent publication[20, p. 65].

Hence, taking into account the transmittance of the wet Tedler cover, the long-wave radiation transfer becomes equation 46, which has been presented earlier as equation No. 30

$$q_{r,lt} = \epsilon_b \cdot \tau_{wl} \cdot \tau_{wv} \cdot h_{r,bs} \; (T_b - T_{sk}) \quad \ldots\ldots\ldots\ldots\ldots \; (46)$$

It has been possible to quantify all the factors in equation No. 46, and to set up a plot of radiative heat exchange between the basin surface and the sky for typical operating conditions in Fig. No. 27.
The values for the emissivity of water have been taken from the American Institute of Physics Handbook[49]. The work of Erb[50], on the absorptivity of long-wave radiation in water films on solar distiller canopies, essentially confirms these measurements of Edlin.

The spectral transmission for infra-red radiation at 9.25 microns through various thicknesses of water film was estimated by Erb[(50, p.p. 10 - 13)] who indicated that any film thicker than 35 microns will absorb more than 90 per cent of the radiation energy. He states that the water film on the condensing surface has substantially black body behaviour absorbing most of the infra-red radiation before it reaches the reflecting surface. Drawing on earlier data given by Dorsey[45], he notes that the reflectivities from the surface only amount to 1 or 2 per cent. In addition, Dorsey[(45, p. 333)] gives the transmission of long-wave radiation through a water film 0.05 cm. thick as being 2.9 per cent from a radiator at 300^{o} C. and 4.0 per cent from a radiator at 370^{o} C.

Radiation Heat Loss From the Solar Still Cover: It is possible to determine the sky temperature from equation 35. It can be seen that the correction factor, f, is a function of the relative humidity. Hence a chart was set up relating relative humidity and air temperature, to determine the correction factor, Fig. No. 28. This can then be used in Fig. No. 29 to obtain the effective sky temperature.

For these particular stills, it then becomes possible to calculate the radiative heat loss through the quantification of the terms of equation No. 36. The heat transfer coefficient, $h_{r,ca}$, can be determined from Fig. No. 30 which is a plot of data earlier presented by Whillier[48]. The radiative heat losses can then be estimated directly using Fig. No. 31.

Convection Heat Loss from the Solar Still Cover: The coefficient of convective heat transfer, as given in equation No. 38 has been set down in Fig. No. 32. These values were corrected according to the method recommended by Schack[(25, p. 250)] for differences in the air temperature from 70° F. The windspeed, V', was multiplied by the ratio $(t_a + 460)/(t + 460)$ where t represents the actual air temperature. The coefficient of heat transfer can then be determined directly from the measured windspeed and air temperature.

The convection heat loss is then obtained directly from a knowledge of the air and cover temperatures using Fig. Nos. 33, 34 and 35, where plots of equation No. 37 have been constructed for typical operating values.

Evaporative Heat and Mass Transfer in the Stills: As the range of operating conditions of these solar stills is limited, it was possible to quantify the various parameters which make up the heat and mass transfer flows. The constant C", as set out in equation No. 25, was calculated for various basin temperatures and is shown in Fig. No. 36. In conjunction with data of $\Delta t'$ from Fig. No. 17 and vapour pressure values for the basin and cover temperature conditions, it was possible to estimate the mass transfer flux given in equation No. 26. This has been represented in Fig. No. 37. The equivalent heat transfer due to evaporation as shown in equation No. 28, is illustrated in Fig. No. 38.

Heat Loss Through Ground: The question of the flow of heat from solar distillers to the ground beneath them is a complex one. Considerable effort has gone into these investigations at the Office of Saline Water's Daytona Beach, Florida, research station. Temperature profiles of the soil beneath the evaporators were measured[51]. Some of the principal findings given by these sources are:

a) "For a large, uninsulated basin-type solar still, the net loss of heat into the ground is negligible"[(20, p. 45)].

b) At a depth of 1.6 feet, most of the temperature variation should be gone.[(20, p. 45)]

c) Bloemer et al also suggest that the method of Keller[32] be applied in this case in the estimation of ground losses. This investigated the flow of heat through furnace hearths.

   It forms the basis of equation No. 39.

For these particular stills, Fig. No. 39 has been plotted indicating the variation of heat loss through the ground based on equation No. 39.

Estimation of Storage Term: In large, uninsulated solar stills, the hourly change in the still temperature is moderated by changes in the heat stored within the unit. In deep basin stills, the thermal capacity term C_{wg} is far greater than in stills of this type. The water depth in this still is 2". Allowing for heating up 8" of soil below the ground, and distributing the thermal capacity effect of the concrete curbwalls per square foot of receiving area, a storage term of 27 Btu/hr., sq. ft. has been estimated. However, it must be stressed that there is close to 2400 sq. ft. of open surface on the footwall structure between adjacent plastic covers which receives solar radiation. This will reduce heat loss from these surfaces and undoubtedly cut down the size of the storage term. The value used in some of the stills in Australia is 16 Btu/hr., sq. ft. (22, p. 4). These stills do not incorporate concrete foundation walls and operate with a lower basin water depth.

<u>Mass Balances on Stills - on Petit St. Vincent</u>: Having examined the various sections of the heat transfer relationships, the mass transfer formulae are relatively straightforward.

The salt water feed, F_s is generally charged into the stills on a batch basis. For a basin depth of 2 inches, this constitutes a still capacity of 1500 U.S. gallons, approximately 12,500 pounds of sea water.

A mass balance on the still can be written as follows:

$$\Delta F_s = B + D_w + V_{LC} + V_L + L_B \quad \text{.............................} \quad (47)$$

The brine from the stills flows out in a small but continuous stream, especially in the period immediately following the filling of a bay. This is most probably due to a capillary action by the Orlon matting which effectively siphons brine from one pond to the next. The saline water eventually leaves from the overflow on the lower end of the bay. Estimates have been made for the average daily amount of this brine waste. Its specific gravity is generally measured to determine the degree of concentration of the sea water within the evaporators.

The fresh water product, D_w, flows into a measuring tank and is tallied daily.

Water vapour permeability through the Tedlar cover has been measured by Edlin[41, p. 16] and additional data have been supplied by the DuPont Company[52]. The quantity of water vapour lost ranges from 0.14 lbs./hr. per bay (75° F.) to 0.47 lbs./hr. per bay (150° F.). Edlin claims the loss is negligible - of the order of 1 to 2 per cent[41, p. 6]. However, it would appear here that these losses are even less than this. It must be recalled, however, that no permeability data are available for the treated Tedlar. Hence, the published data on normal Tedlar have been used. It is also noteworthy that the permeability rates for oxygen and nitrogen are 0.3 and 0.02 gms./100m^2/hour/mil.[29] As they are so insignificant, they can be neglected.

Additional water vapour and air losses can occur through leaks in the Tedlar covering. As the inflation pressure is generally maintained at about ¼" water gauge, leaks are possible and they do occur. The airflow through the fans, providing the makeup to the system, can be measured. However, the volumes involved are quite small. If V_L is negligible, as it should be, the fans should just operate against the back pressure of the system, so as to maintain the required degree of inflation. Theoretically the only losses which must be made up are V_{LC}, but in practice there are, generally, some leaks along the seams.

Leakage from the basin liner, L_B, should not happen in a well-built still. However, it is possible that perforations can occur in the butyl rubber lining resulting in leaks which cannot be measured. Hence, as ΔF_s can be accurately estimated, any substantial imbalance in equation No. 47 can be attributed to L_B, and V_{LC}.

SECTION III

PROCEDURE FOR EVALUATING SOLAR STILL PERFORMANCE

Through the use of this series of graphs, calculated for typical values of the parameters, and given measurements of solar radiation intensity, relative humidity, wind speed, ambient air temperature, average basin and cover temperatures, it is possible to assess the heat balance of the solar stills which can be verified in practice through measurement of the quantity of distillate and the change in basin temperature. It must be assumed that there will be a degree of hold up in the distillate gutters so that there cannot be perfect balance.

The principal objective of these thermodynamic analyses is to determine and evaluate the disposition of the radiant input energy so that a theoretical evaluation of the production operating line can be established. In order that the solar still be viable in use as a fresh water supply source, the operator must be able to verify, from measured operating parameters, that the fresh water output is compatible with the solar radiation intensity. Concurrently, the quality of the fresh water produced must also be up to standard.

In this study, it has been decided to treat the interchange of energy as being similar to the case of 'unsteady state with constant flow' studied by Ward[24]. The basic principles involved are that the average incident energy received during any time period equals the average heat loss plus the heat stored in the evaporated water plus the heat stored in the solar still. Clearly then, the storage term C_{wg} becomes most important in this series of heat balances. Attempts were made, unsuccessfully, to measure this using electrical energy, and will continue till this term can be more properly quantified.

It is possible, therefore, to use these charts to obtain a good engineering evaluation of the solar still performance. The parameters which must be measured are the:

1. ambient air temperature;
2. average relative humidity of the ambient air;
3. total solar radiation intensity on horizontal surface on an hourly basis;
4. average windspeed over the stills;
5. average cover temperature of the still;
6. average basin temperature of the still;
7. the distillate production on an hourly basis.

All calculations have been based on one square foot of A_H, as defined earlier. The fraction of diffuse radiation can either be obtained by measurement or through the use of charts as recommended earlier.

Derived Data

Item	Fig. No. Used
Solar time	5
Solar altitude	4
Angle of incidence on cover of the solar stills	6
Transmissivity, reflectivity and absorptivity of cover film	9
Reflectivity of floating mat	7
Effective sky temperature	28 and 29
Coefficient of convective heat transfer	32

Calculated Data

Item	Fig. No. Used
Components of I_D	11
Components of I_d	12
Reflectance from floating mat	By calculation
Radiation heat loss from the still	31
Convection heat loss from the still	33, 34, 35
Radiation from basin to sky	27
Evaporative heat transfer	38
Heat loss to ground	39

Internal Flows

Convection from basin to cover	Table No. I
Radiation from basin to cover	Table No. II

Two heat balances are recommended; the overall balance as set out in Equation No. 2 and the balance on the basin as set out in Equation No. 6.

Experimental Verification: A series of tests was undertaken to verify this method of solar still evaluation and to ascertain the feasibility of undertaking this kind of measurement at a typical field site. The instrumentation used has been described in detail in Appendix D. This equipment was quite unsophisticated as one would anticipate finding in an outlying region. Hence the degree of accuracy is not what would be expected under more controlled laboratory conditions. Nonetheless, the percentage of unaccounted losses was only 2.8%, on the overall balance, for the test of 24 May, 1968. The experimental readings and calculations for this test have been listed in Appendix E.

These results have been represented graphically in Fig. No. 40 to enable the reader to get a first hand impression of the distribution of the heat losses, a summary of which is given below.

Test of 24 May 1968 - Solar Still No. 5

Plastic Covered, 10 feet x 150 feet , effective evaporating area , 1285 sq.ft.

	Quantity Btu per sq.ft., day	Percent of Input Energy
Solar Radiation Input	2227.3	100.0
Reflection Loss from Transparent Cover	144.6	6.5
Radiation and Convection Heat loss from the transparent cover	1572.8	70.7
This includes the useful heat, i.e. for evaporation.	799.1	35.6
Direct radiation loss from Basin Surface to the Environment	50.1	2.2
Reflectance from Floating Wick	99.2	4.4
Heat Loss to Ground	262.0	11.8
Increase in Enthalpy of Still	35.0	1.6
Unaccounted for Losses	63.6	2.8

Observations

1. The apparent efficiency of operation during the test was 35.6 per cent.
2. There were several leaks in the cover seams and one known leak in the butyl rubber lining, during the tests.
3. The orders of magnitude of the following are very small relative to the main heat transfer streams: $q_{r,1t}$, $q_{c,bc}$, $q_{r,bc}$, and R_0. In addition q_b is not very large. However, they require close scrutiny.
4. The three principal streams are q_e, $q_{c,ca}$, $q_{r,ca}$ and their estimation deserves the greatest attention.
5. Much difficulty was experienced in measuring, under somewhat primitive conditions, the temperature of the transparent cover. As a result, it was necessary to work out an approximate cover temperature using Fig. No. 37, the average basin temperature, and the distillate produced during the time interval. It is interesting to note that the cover temperature did coincide more closely with these readings during night time hours than during the daytime.
6. The basin temperature varies along the width of the solar still bay and had to be averaged for each hour of the day. This has been represented in Fig. No. E - 1. The average basin temperature is listed in Table No. E -5a, and the temperature increment, dT_b/dt, has been calculated from this.
7. The heat balances were used to estimate a value for the storage term, C_{wg}. It will be noted that these figures vary somewhat from the calculated value of 27 Btu/sq.ft., deg. F. However, the overall average of 24.5 is remarkably close considering the conditions of the test. Also it must be remembered that a deviation of even up to 10 Btu on the C_{wg} reading might only mean a total imbalance of 30 to 50 Btu, depending on the hour under consideration.

Percentagewise, the imbalance is particularly bad during the first three hours of the test, i.e. till 0900 hours. Again in the late afternoon, the imbalance becomes large. This could very well mean that the measurement of temperatures was not too accurate. Holdups in the flow of distillate from the stills might partially explain these discrepancies.

8. It must be stressed that the most accurate measurements were those of solar radiation intensity and windspeed. The latter has only a second order effect. Hence, the input readings are reasonable, but the greatest possible discrepancy and error arises from the reading of the temperature measurements and the distillate measurement, both of which were somewhat crude due to the primitive conditions at the site.

9. The internal balance on the basin was not so satisfactory. Further verification of the temperatures, reduction of the vapour and brine leaks, which affects q_e, and a closer look at $q_{r,bc}$ and $q_{c,bc}$ should cast more light on this problem.

10. This test has been repeated on several occasions and the results corroborate those quoted quite closely. The percentage of unaccounted losses was 1.8% for the test of 9 May, and 3.7% for the test of 16 May.

Summary of Section: The method presented for the evaluation of solar stills under actual field conditions seems reasonable, taking all factors into account. Further work is needed to improve the testing techniques, using unsophisticated equipment. Eventually a simple system could be established to determine the effectiveness of the performance of solar distillation units in the production of fresh water for small communities.

CHAPTER 2

ESTIMATION OF THE ANNUAL FRESH WATER PRODUCTION OF THE SOLAR STILLS

Determination of Operating Lines: The long term evaluation of a solar distillation plant can be summarized through the correlation of two parameters - the solar radiation intensity and the distillate production.

The solar radiation intensities measured on P.S.V. during the period Dec. '67 to June '68 are listed in Table No. E-1. The monthly averages for the site have been compared with those measured at Barbados and listed in Table No. B-2. The monthly means for the two sites check out reasonably for the period December to March. However, the recorded insolation for P.S.V. was of the order of 15 per cent higher for the months of April and May. This may well be explained by the fact that rain fell on twice the number of days at the Barbados location. In addition, it must not be overlooked that the records in Table No. B-2 are for a different time period, 1963 and 1964. The validity of the measurements on P.S.V. will be verified by means of an annual instrument recalibration scheduled for December, 1968. The instrument was purchased new from the suppliers in December, 1967. All instrumentation used in P.S.V. has been described in Appendix D.

Average productivities, in U.S. gal. per square foot per day, have been given in Table No. E-6. These have been determined by dividing the total number of gallons of fresh water produced per bay by the effective evaporating area per bay, A_H, which amounts to 1,285 sq. ft. It would be somewhat laborious to reproduce all the readings which have been taken to determine these productivities. The system of measurement of the distillate production has been described in Appendix D, and is currently being improved. Towards the end of May, steps were taken to prevent rain water from pouring off the canopy into the distillate tanks. This was done for the first five bays only. In all earlier readings, the distillate production had to be disregarded on all days with a measurable rainfall. In the initial months of operation, considerable difficulties were experienced with the deflation of the solar still transparent covers due to problems with the electricity supply to the blowers. In addition, the productivity was reduced through leaks in the clamping system and basin liner, etc. In deciding on the suitability of a particular distillate reading, reference also had to be made to the daily log to ascertain whether operating difficulties had been noted for that day. As a result, where reasonable agreement was obtained between the productivities of three or four bays on the same day, these outputs were averaged and have been enumerated in Table No. E-6. The above problems are typical of those which can be expected when working in an isolated area in the complete absence of normal scientific laboratory facilities. In many respects, this also affects the measurement of the other parameters, outlined in Tables E-2 to E-4. Recently, the quality of the measurements has definitely improved as the staff becomes more adept in handling the scientific equipment.

The distillate productivities in Table No. E-6 have been compared to the insolation corresponding to each specific day. Using the method of least squares as outlined by Kosakiewicz,[53] the regression line equations for each month have been computed using an IBM-1620 computer. This has given a series of operating lines which are listed in Table No. 3. The equations for the average productivities of the solar still bays have been plotted in Fig. No. 41 along with the points from Table No. E-6.

In order to estimate the annual production from a solar still bay, the following method was employed:

A) As no insolation readings were taken for the period June to November, the regression line equation, corresponding to the month where the mean solar altitudes are approximately the same, was used. In this manner, the equation of January has been used for December and November, that of February for October, March for September, April for August, and May for June and July.

B) In order to estimate the insolation for these months, reference was made to the records for Barbados, given in Table No. B-2. As there are distinctive seasons, allowance for variation of the solar radiation intensity was made by taking the ratio of the corresponding months in Barbados, and using this ratio to modify the measured intensity data of P.S.V. For example, the monthly mean insolation for March for P.S.V. was multiplied by the ratio of the insolation means of September to March for Barbados, in order to determine the average solar radiation intensity for September for P.S.V.

This method should be valid as a first approximation of the distillate production. The true output of the units will only be known after several years when a detailed assessment of the variation of productivity with insolation will be possible. This will lead to more representative regression line equations than those cited in Table No. 3, which are based on records for a single month in each case.

There are a number of qualifications to these results which must be added:

(1) These productivities represent distillate outputs with and without the use in the stills of floating wicks, thus representing a lower than average expected performance.

(2) As specified earlier, the clamping system has not yet been perfected, resulting in a number of leaks from the solar stills which has had a definite effect on the overall productivity. It is certainly expected that new and better construction techniques recently instituted will also improve the output of these units.

In this respect, it has been noticed that solar still bay No. V outperformed, on most occasions, the other stills. This should be due to the fact that the clamping system and the construction of the concrete rails have been revised and improved. As the spacing between the rails is far more precise along the length of the bay , the cover on this bay assumes a very smooth shape upon being inflated, unlike the other units where wrinkles in the transparent cover definitely reduce the production of distillate. As all the bays will eventually be reconstructed to incorporate these modifications, a separate study of the productivity of bay No. V has been undertaken. The regression line equations have been calculated as before, the results are listed in Table No. 3 and plotted along with the productivity data in Fig. No. 42.

As only two bays were operating during the month of January, separate regression line equations were calculated and are listed in Table No. 3. The results, illustrated in Fig. No. 43, show a difference in productivity variation which may be attributed either to the effect of the floating wick or to the insulating value of the coral layer which underlies bay No. I.

Estimation of the Annual Production of Distillate: On the basis of the data listed above, an estimate of the annual production of distillate from a solar still bay was made as follows:

Method No. 1: Regression line equations for Bay No. II for January, and for the average productivities of all the bays for February to May as listed in Table No. 3 , gave an annual distillate production per bay of 31,085 U.S. gallons. Five days down time were allowed for repairs and maintenance.

Method No. 2: Owing to the improvements which have been undertaken on the more recently completed bays, it was also decided to estimate the annual production of distillate using the figures obtained for bay No. V, along with the average productivity regression line equation for February and the regression line equation for bay No. I for January. This results in a value for distillate production which will be much more compatible with the expected output. This has been estimated at 32,885 U.S. gallons per bay per year. Again 5 days have been left for repairs to the bay, where no production is anticipated.

This latter method seems far more representative of the distillate production which should be used in the economic analysis in Chapter 3. The prospects of even greater annual outputs of fresh water are very good as more improvements are instituted.

It is not the purpose of this study to compare the output of these stills to those cited by others. A standardized method of comparison should be evolved to take into account all factors in order that satisfactory comparisons can be undertaken.

<u>Experimental Results</u>: All tests outlined in Chapter 1 were undertaken on Bay No. V due to its superior performance. The results of three of these trials have been plotted in Fig. No. 42. On each of these days the theoretical analysis procedure presented earlier was able to account for 96.3 to 98.2 per cent of the input energy. These points agree very well with the regression line equation for solar still Bay No. V for the month of May. It is hoped that future work will analyse points at various positions along these lines so that they can be used with confidence by the operator. When sufficient points along the length of an operating line have been experimentally verified in this manner, it then becomes possible to use this line as a gauge of the performance of the solar still units during that time period. In this manner, the still operator can verify the potential unit production and so be in a position to detect equipment faults, rationally. In addition, if expansion of the facilities is being contemplated, these lines give a good estimate of the expected output which can be used in the design of the size of the added sections.

CHAPTER 3

ECONOMICS OF THE OPERATION OF THE SOLAR STILLS

Introduction: As no standard method has been established to date whereby the size, productivity, capital costs and annual operating charges for various solar stills could be easily compared, it was necessary to set up a procedure for use in evaluating the P.S.V. installation. The following conditions have been utilized:

A) The size of a solar still bay has been taken as the horizontal projection of the transparent canopy in square feet.

B) The productivity of the stills, in U.S. gallons per square foot per day, as defined in Chapter 2, has been taken as the number of U.S. gallons of fresh water produced per bay, per 24 hour day, divided by the area as specified in (A).

C) The capital charges for the solar stills cover all expenditures necessary to set up the water works including the land, site preparation, materials and labour for the construction of the stills, pumps, piping, storage reservoirs, electrical installation, etc.

D) The annual operating charge includes all expenses attributable to the still such as operating labour, materials and supplies, fuel for pumps, amortization of the equipment reduced to an equivalent annual basis, maintenance, etc.

It is not expected, nor is it necessarily advocated, that a small community would build its solar distillation plant identically to the one on P.S.V. What has been presented is a detailed analysis of the solar still construction costs and estimated annual operating charges so that they can be compared realistically with the productivity. This has not necessarily been the method of approach of some earlier workers in the field. Often a review of their claims reveals an optimism which stems from the failure to incorporate all these items into a true cost picture and from an over-estimation of the productivity based on tests carried out under the most favourable climatic conditions. These results were sometimes misleading and often must have confused the observer in the developing country.

Finally, it must be remembered that the solar stills described in this report are providing water for an exclusive hotel catering to a high priced tourist market. The benefits derived are dependent upon a satisfactory supply of fresh water. Hence, the plant has been adequately and substantially equipped, for the investment has a potentially high benefit-cost ratio. This is not the case in an isolated village, where it will be necessary to reduce expenditures to a minimum in order to achieve a similar output of fresh water, and still realize a viable investment.

Criteria for Estimating the Efficiency of Water Supply Investment: There are three methods proposed for evaluating investment calculations:[54,p.152]

(1) Present-Value Rule calls for the adoption of any project for which the present value of the associated stream of net benefits or net receipts, discounted at the appropriate rate of interest, is greater than zero.

(2) Internal-Rate-of-Return Rule calls for the adoption of any project whose internal rate of return, i.e. the discount rate that makes the present value of the cost stream equal to the

present value of the receipts stream, is greater than the appropriate rate of interest.

(3) Annual-Net-Benefits Rule calls for the adoption of any project for which the annual net benefit is greater than zero when computed at the appropriate rate of interest.

There seems to be some controversy on the use of these methods. Hirshleiffer[54,p.154] favours method 1 and recommends that method 2 should not be used. On the other hand, Edge[55,p.7] writes favourably about this latter method. He does, however, propose a fourth procedure based on equivalent annual costs which seems most appropriate when considering an isolated community such as P.S.V. Only costs are taken into account. Capital expenditures are converted to equivalent annual charges and added to the operating costs. In these communities, it is somewhat difficult to quantify the benefits. For example, in P.S.V. what should be the charge for water be? Therefore, it is easier, at this stage, to examine the relative costs of alternative methods. In many cases, the benefits will themselves accrue to the well-being of the society, regardless of the source of the fresh water. Once the comparative costs have been estimated, they can be assessed in the light of their effect on the overall economy of the community and the region as a whole.

Determination of the Costs of Solar Distillation Plants: In order that the costs of the solar stills be normalized, and hence comparable to other installations, several standard costing outlines for desalination plants and water supply systems were studied.[56, 57, 58] As a result, a composite cost procedure has been developed which it is hoped will assist communities in analyzing the charges attributable to their solar distillation plants.

In the specific case of P.S.V., capital investment charges and annual operating expenses have been determined for the following three facets of the water supply system: the solar distillation plant, the rain water collection system and the combined fresh water reticulation system.

It must be noted that all currencies quoted in this section are in U.S. dollars. All volumetric quantities of fresh or sea water cited are in U.S. gallons. This has been done in order that the results might be more easily understood and appreciated by the reader.

Construction Cost Analysis - Solar Stills: A materials specifications list has been set up in Table No. 4 indicating a description and the quantities of the components needed to construct one nominal 10 ft. x 150 ft. bay as described in Appendix C.

The explicit cost of these materials, taken from landed costs in P.S.V., has been given in Table No. 5 along with the estimates of the amount of labour and wages required for the construction of one solar still bay. These were derived from discussions with the designers, builders and foremen on the site. The rates of pay are for local unskilled labour, with allowance for skilled labour where required. It must be stressed that the results of these analyses are only preliminary estimates computed from materials used and from certain measurements of labour requirements taken on the site. Generally, they are reasonably accurate. Nonetheless, they will be continuously modified as the equipment is improved and altered in the course of time.

An attempt was also made to obtain an approximate assessment of the cost of auxiliaries needed for the functioning of the solar distillation plant. These have been listed in Table No. 6. However, a number of points require clarification, and these will serve as well in the reckoning of the annual charges:

(1) Each solar still bay is apportioned twice the land surface of its effective evaporating area.

(2) Alternating current electricity is available at 3 cents per kw. hr. This price has been calculated following a recent study of the existing power station equipment, consisting of twin 40 kw. diesel-electric generators. This charge agrees with studies undertaken earlier by the author on the operation of this type of equipment in isolated areas such as these.[59]

(3) The water works includes a sea water intake and piping layout through which water is pumped to the tanks feeding the solar stills.

(4) On the site, there is a distillate and rain water storage capacity of 7,600 gallons. In addition, it has been assumed that one compartment, or 60,000 gallons, of the large low level cistern will be levied to the plant accounts. This gives a total storage capacity of 67,600 gallons for the entire plant, which is equivalent to about 35 days' distillate production under maximum output conditions.

(5) Fresh water is pumped from the plant site to the large cistern. This piping has been charged to the plant, and has been indicated on Map No. 2. Both the piping and storage portions of the water works are oversized relative to the production capacity of the

solar stills. It would appear, therefore, that the marginal cost of any additional production from the plant, due to possible future expanded solar still capacity, should be less than that indicated currently.

(6) An estimate of $2,000 has been made for the initial design work which must go into the construction of any solar still of this type at this time. To some extent, most solar distillation units are still experimental, involving testing and verification of components and techniques.

(7) The contingency allowance permits the inclusion of a number of items including fencing around the stills, etc. The actual cost of the stills in P.S.V. exceeds the figures quoted here. As a detailed accounting system has yet to be introduced there, it is impossible to ascertain just what the precise charges amount to. Realistically, the actual cost should only be of interest to this development. If available, however, it would be of interest to other entrepreneurs who undertake this type of venture.

The importance of the study of this system of water supply is to present a reasonable appraisal of what is necessary in the way of plant equipment and how much investment this requires under actual field conditions. It is fully expected that these preliminary estimates will approximate these costs.

Land Costs: Many observers do not consider the cost of land as a factor in the economic assessment of this process. In reality, what must be considered is the opportunity cost of this land. On P.S.V., the site is attractively situated on the leeward side of the island. However, the location is rather sheltered from the wind and, according to the project architect, it is not particularly suited to the siting of beach houses or other buildings of the development. Hence, the charge for the land included in the cost analysis was directly prorated from the purchase price of the island. On P.S.V., the land could also have been used for agricultural purposes to grow market garden crops for the development. This would require water for increased yields and the economics of this alternative has not been fully explored. Land costs are generally very small and should not add much to the total investment charges of a community's water supply system, provided the land has no alternative productive use.

Annual Operating Costs: It is difficult to predict exactly what the anticipated life of the solar still components will be over the period of the economic life of the plant. It is only possible to make reasonable estimates and to base these predictions on past experience.

The longest lived still on record, that at Las Salinas, Chile,[60, 61] was not well documented or studied to provide information on long term material evaluation and operating costs. A report published in 1961 in California, described a solar still which had been operating for seven years, although again an economic evaluation of the installation was not given in detail.[14] Nonetheless, the following guide lines have been set out for this analysis:

(1) A plant life of 20 years has been taken. It is not sensible to make predictions for a period longer than the expected economic life.

(2) In allowing for the replacement of certain components during this interval, account must be taken of:

(a) variations in the price of this material with time;

(b) technological change which should improve its characteristics and performance;

(c) new materials which might have a longer useful life at the same cost.

Hence, although similar costs have been used, the anticipated life of various components have been adjusted to allow for possible future alterations.

(3) It must not be overlooked that in the field of desalination where rapid technological change is occurring all the time, the unit might become obsolete in a few years.

(4) In setting up a cost analysis over a span of 20 years, it must be stressed that the purchasing power of the unit of currency used will be continually fluctuating, depending on whether an inflationary or deflationary cycle is dominant. In isolated rural areas, prices often do not tend to change quite so rapidly due to lower economic activity.

(5) The simplified method of discounting a replacement component has been used in the cost assessment.[58,p.9] It is assumed that replacements occur in an even number of multiples during the overall time interval, i.e. twenty years in this case.

(6) The interest rate has been taken as eight per cent bearing in mind the recent increases in rates. Edge also feels this is a reasonable rate of return, after taxes, to investors for low risk

projects.[55,p.8]

7) Based on the experience with these stills on P.S.V. and earlier installations studied, an average operating and maintenance labour requirement of one attendant, with a weekly wage of about $20, appears to be reasonable.

8) To simplify the analysis, no allowance has been made for the salvage value of the existing equipment.
In addition, no allowance has been made for the following items:
   (a) On-the-site technical supervision.
   (b) Interest on working capital - in this particular case, the units have been built very slowly and over reasonably extended periods of time. It has been mainly the imported materials, such as the transparent cover and the basin liner sheets, which have been in stock for some time. These have tied up some capital.
   (c) Performance testing - a solar still is such a simple piece of equipment that fresh water of good quality can be obtained shortly after commencing operations.
   (d) Taxes - generally water supply plants are exempt from governmental taxation. This eliminates the need for capital cost allowances for taxation purposes.

Although these costs have not been included in this analysis, it may well be that they should be tabulated when appraising the economics of other stills, where they might be applicable.

The annual charges are summarized in Table No. 7. The cost per 1,000 gallons of fresh water is calculated using predicted distillate production quantities as outlined in Chapter 2. The total amount of potential fresh water production, including collected rain water, and the final estimated costs of this water, are also given.

<u>Discussion of Results</u>: Upon initial examination, these costs might appear to be quite expensive. A closer look will indicate that they are not quite so unrealistic. A number of factors must be considered:

1) As stated earlier, the plant could be expanded without greatly increasing the investment in auxiliaries which should result in cheaper unit water costs. Currently, these are high because the amount of water produced is small. In any low capacity system, relatively high unit costs must be envisaged.

2) Nearly forty per cent of the annual charges are for the amortization of the plant equipment. Most of the auxiliaries and about forty per cent of the investment in the solar still bays should be amortized over a forty year period. This would reduce these amortization charges by about ten per cent. Also, there is definitely a salvage value in some of the equipment at the end of the twenty year time interval, but its value is rather difficult to quantify, and it has therefore not been considered.

3) In running these units, every effort must be made to reduce the amount of labour required for operation and maintenance of the equipment. This has been a matter of prime concern in the design and later modifications of this plant.

4) The estimates have allowed seventeen per cent of the annual charges for maintenance, administration and miscellaneous expenses. Any improvements in operation and organization will reduce these amounts. Following the institution of a proper accounting system, these figures can be analysed more closely and their absolute values determined precisely. In the hotel industry, these costs are higher than what one might expect to find in a small village.

5) About one-third of the annual charges come in the payment of replacement components of the stills. The life of these components has been determined from averages of claims set forth by the suppliers of the materials and from the experience of the author and others working in this field. In particular, the cost of the clamping system, one fifth of the total annual charges, has been determined from direct measurements taken on this installation. The current investment in the canopy clamp is one half that of the cost of the original design formulated in late 1966. Continual improvements brought about this reduction in expenditure. Current investigations on this system should extend the life considerably and reduce this charge. In general, new advances in solar still technology will continually lower these expenditures so that the future prospects are for reduced costs, disregarding inflationary trends.

6) With proper maintenance, many items and components of the system will last longer than 20 years. Hence, realistically, this will again tend to reduce annual disbursements. Improvements in solar still technology are already increasing the yields of these stills and will continue to do so in the future.

7) A significant amount, nearly thirty per cent, of the annual charges is made in payment for local goods and services. For the small community, this constitutes a decided advantage as these expenditures will be a form of transfer payment rather than direct leakage from the area.

These tables serve only to indicate the general orders of magnitude of the costs involved. The small community can build its stills and auxiliaries far more modestly and hence anticipate reductions in the cost of water produced. The decision as to the type of distillation plant and its manner of operation can only be made at the individual community level to best satisfy the existing water demand with the resources the community has available.

Projections of These Costs to the Requirements of Small Communities: The analyses dealt with in this chapter have examined the accounting costs of the solar distillation plant. The absolute value of these charges is very important. However, the interpretation of these costs and their second order effects are equally significant in considering the impact of an investment on a developing area whose resources are not fully utilized. This effect has been noted in Appendix I. A project employing local labour and materials stimulates the regional economy far more than one where a prefabricated plant, purchased in an area remote from the region, is simply installed on the site. In the latter case, not only is there a transfer of capital directly out of the region, but the community also faces an obligation in the form of annual payments for the energy needed to operate these units. This does not apply solely in the comparison of industrially developed and emerging nations. It is equally significant within the boundaries of a single country where there exists areas of economic disparity. A solar distillation plant constructed in one of these depressed areas will not only contribute to the local water supply but will stimulate second order benefits whose effects might change the entire complexion regarding the suitability of alternative investments.

Finally, a close look at the percentage distribution of the annual expenditures outlined in Table No. 7, shows the following pattern:

	Per cent of Annual Charges
Investment Amortization Costs	41
Replacement Amortization Charges	34
Labour Costs	8
Operating, Maintenance and Administration Charges	17

Many of the communities are too destitute to ever be able to install their own desalination plants, and must rely on donations of materials and supplies from abroad for the execution of these projects. Solar distillation technology is ideally suited to this role as the local community can contribute its labour for the construction of the plant, if the materials are supplied by some outside agency. Experience on P.S.V. has proven quite conclusively that the native population, notwithstanding their relatively low level of education, can build solar stills and even improve the design of some of the components. From the list of annual charges, it can be seen that if the community did not have to bear the initial capital investment, nearly sixty per cent of the annual operating charges would no longer apply, assuming that they themselves ran the plant. The bulk of the remaining annual disbursements would be to cover the replacement costs of the still components. It must not be overlooked that a portion of these are also labour charges. Considerable attention is being devoted to reducing these expenditures and it is expected that significant improvements should be forthcoming. When these factors are considered, solar distillation appears to be a reasonable method for the partial solution of the chronic water problems of the world's arid zones. It must be recalled that solar distillation would probably be most competitive in sizes of under 5000 gallons distillate produced per day. It is not however, the object of this study to set an upper economic limit on the size of solar distillation plants. This aspect certainly requires study and verification. Results from the larger solar distillation plants which have recently been built will shed more light on this question.

If a solar distillation system such as that on P.S.V. were installed in a peasant community, the cost estimates could be revised as follows:

A) Assuming the community provided the labour and administration for the construction of the plant, the solar still investment charges would reduce to about $1,700 per bay.

B) The cost of the auxiliaries, built more modestly than those on P.S.V., could be reduced to $400 per bay.

C) This would make the plant investment charges total to about $31,500 or roughly one half the cost listed here.

Assuming a similar distillate production to that indicated in Chapter 2, and an average per capita consumption of water of 2.5 U.S. gallons per day, as outlined in Appendix I, a solar distillation plant of this size could supply a peasant community of 500 to 550 persons, solely from the distillate production.

Depending on the rainfall intensity, the size of the community serviced could be increased up to one hundred per cent. Hence, it appears possible to install a solar distillation plant for a cost of $25 to $40 per inhabitant. The annual operating charges, as outlined in Table No. 7, would reduce to $6 to $9 per inhabitant per year. The majority of these charges would be for the amortization of the installation and replacement components, and for maintenance and operating expenses. These figures would need confirmation by means of a study of an actual installation in a small community. However, they should be indicative of the order of magnitude of the charges involved.

The rather high unit capital costs of the P.S.V. solar stills reflects the use of Tedlar, the cost of which is $ 0.40 per square foot. It is possible to construct glass covered solar stills , utilizing glass at $0.09 per square foot, which results in a cheaper unit cost. (64,p. 73)

CHAPTER 4

THE ECONOMICS OF THE RAINFALL COLLECTION AND RETICULATION SYSTEMS

Introduction: The rainfall collection system installed on P.S.V. has been described in Appendix G. In order to determine the cost of the collected rain water, a number of tables have been set out describing the system and the financial investment entailed. The rainfall catchments on the island have been listed in Table No. G-1. In estimating the costs of this system, the solar still catchment area must be deleted. This amounts to 36 per cent of the total area under consideration.

Table No. 8 lists the principal storage cisterns which have been built on P.S.V. The high level cistern and one half of the low level cistern have been allotted to the reticulation system. One quarter of the low level cistern has been charged to the solar distillation plant, leaving therefore a storage capacity of 138,300 gallons in the rainfall collection system. For an annual precipitation of 35 inches, these reservoirs would be able to store 25 per cent of the probable total collection of fresh water.

Table No. 9 deals with the cost of the rain water piping system, also known as the "wallaba water" system. This covers the capital investment dealing with the collection of the rain water at the various catchment areas, its delivery to the treatment plant and the lines leading to the storage reservoirs of the reticulation system.

Table No. 10 outlines the cost of the gutters installed on the roof catchment areas specified in Table No. G-1. In addition, the capital investment charges for the rain water collection system are enumerated. The equipment costs were determined from the landed costs of materials on P.S.V. as in the case of the solar distillation plant. Labour charges were calculated by the builders on the basis of performance records in this type of construction. These costs apply equally to the erection of the storage cisterns. All anticipated construction projects scheduled up to the end of 1968 have been included in these figures. In all cases, allowance has been made for administration and contingency charges in order to present a more accurate picture of the true costs involved. It must nevertheless be reiterated that these are only estimates which have been formulated in the absence of a proper system of accounts. Hence, while these estimates might entail some errors, they should not be excessive.

Table No. 11 gives the anticipated annual charges that would be incurred in the operation of this system. The same conditions of cost estimation used for the solar distillation plant have been applied here. Assumptions on the expected rain water collection efficiencies have been based on the data given in Appendix F.

As the rainfall intensity might range from 20 to 50 inches per annum, variation of the resultant cost per 1000 gallons has been calculated for each case. Finally, allowance has been made for the addition of the rain water not requiring precipitation treatment, which reduces the overall cost per 1000 gallons.

Table B-1 gives the average rainfall for the region at 46.3 inches per year. The current measurements of rainfall on P.S.V. are indicated in Table No. E-4 and these are in reasonable agreement with this long term average. Based on this figure, an approximate cost of rain water would be about $6.45 per 1000 gallons.

<u>Discussion of the Results</u>: A few observations should help clarify the situation and place these cost figures in the right perspective.

(1) The annual charges quoted in Table No. 11 are only valid provided that the technical difficulties regarding the precipitation of the wallaba water stain are resolved, as has been outlined in Appendix G. Where the consumer is dependent on high quality water for the operation of a commercial venture, as in the case of a hotel development, the production of a discoloured effluent to a great extent nullifies the effects of the effort and financial committment of the project. The wallaba water is not injurious to the health of the community. In fact, in this region, it is consumed in its raw form quite extensively. However, its colour is by no means attractive and this would have a detrimental effect upon an unconditioned consumer. Early attempts at precipitation of the staining ingredients were not overly successful, and efforts to dilute the clear, yellow tainted effluent with solar still distillate only produced a discoloured product which was also unacceptable. In this case, the danger of not overcoming this problem can be quite serious when one considers that these two fresh water streams will eventually be combined to feed the reticulation system. This must be given serious consideration in view of the high cost of both the rain water and the solar still distillate. The entire effect of the high quality distillate might be cancelled out by its combination with the discoloured rain water. The problem of contamination of rain water by natural sources must be carefully studied in any small community project such as this.

(2) The stain from the wallaba shingles should stop bleeding in about three years in areas with annual rainfalls of this order

of magnitude. However, in order to pressurize and chlorinate the fresh water, the project directors still foresee the use of the wallaba water system, as outlined, with only the elimination of the treatment phase of the process. This would hardly affect the annual charges, although a reduction in the supervision, labour and administration costs might be envisaged.

(3) The charges are again quite high primarily because the scale of the entire operation is small. Extra catchment areas could be built and fitted into the existing system with a reduction in the overall cost of the water produced.

(4) It is important to note that the annual rainfall is relatively unpredictable in any area. An analysis of the sources used to provide the precipitation data tabulated in Appendix B indicates that the annual variation can be as much as 20 inches in this region. At one site in Carriacou in 1966, just over 2 per cent of the annual rainfall fell in amounts of less than 0.05 inch per day. An analysis of the precipitation records for Waterford, Barbados, for the period 1963 to 1965 indicate that this figure is more like 5 to 7 per cent for that site.[62] As a result, any community contemplating installing a rainfall collection system as a fresh water supply source, must study carefully the intensity distribution pattern for its region in order that a satisfactory basis for technical design considerations can be formulated.

<u>Economics of the Operation of the Fresh Water Reticulation System</u>: The fresh water circulation system is described briefly in Appendix G and is illustrated on Map No. 2. A breakdown of the piping costs is listed in

Table No. 12. The principal investment charges of the system are listed in Table No. 13 as well as estimates of the annual operating charges. These have been calculated for a daily average fresh water demand of 4400 gallons. This is a weighted average determined from an anticipated daily demand of 5000 gallons during the winter months, and a modified summer demand of 4000 gallons. It will be noted, however, that the absolute value of the total amount of water pumped will not vary the annual charges considerably as the majority of the charges stem from the amortization of the investment expenditures and not from the handling costs. The circulation cost should be charged to the solar distillation plant and the rainfall collection system in direct proportion to the amount of fresh water produced annually from each source.

These costs again seem somewhat high. The reasons for this are:

(a) the small scale of the installation under study.

(b) the fact that the investment of the system has been amortized over 20 years. In this particular case, it is very difficult to predict just what the state of the hotel development will be 20 years hence. Undoubtedly it will be quite modified if in fact it exists as a commercial enterprise at all. It is therefore mere conjecture to set up estimates for longer periods of time. In the case of a small community, there is no question of doubt of the permanence of the installation. Under these conditions, amortizing the investment over 40 years, reduces the circulation costs by about $0.20 per 1000 gallons. Of course, the expected demand for fresh water will change as well over the years altering the price of the water.

The cost of labour is also a major expenditure. If the opportunity cost of this labour is nil, and the small community really desires a satisfactory water system, it must contribute the one resource with which it is so abundantly endowed - the labour of its inhabitants. The lesser developed regions of the world will only increase their standards of living through self-help, and this is one area in which they can make a positive contribution. This has been outlined more fully in Appendix I.

CHAPTER 5

COMPARISON OF THE TWO WATER SUPPLY SYSTEMS

Discussion of Results: The performance of the two systems of water supply on P.S.V. depends on meteorological phenomena. In this respect they are complementary. In the consideration of a solar distillation plant, allowance for rainfall collection seems quite logical as the extra effort and expenditure entailed is minimal. The solar stills constitute a convenient catchment area, which should not be left unexploited.

The collection of rain water has been practiced for centuries and it is unlikely that there will be any reduction in this process in the future, particularly in the small communities under consideration.

It becomes important to decide when a desalination system should be incorporated, as well, into the existing rainfall collection system. This must be determined by the frequency distribution patterns of the rainfall over the year. Clearly, if no rain falls for four to six months, then the community must build large reservoirs and must be prepared to drink water of at least that age. Without proper care, contamination can be severe as has been cited in Appendix F.

Again, if the annual rainfall intensity is known to be cyclical, during a dry year insufficient production would result in a water shortage.

The solar still appears then to be a logical buffer against the 'dry spell' which is so much a part of these arid zones. It has been noticed on P.S.V. during this last winter (dry) season, that the solar stills assured the project of a dependable, daily supply of water. This is, of course, one of the prime advantages of solar distillation.

One possible alternative to the use of either of these water supply systems, the importation of fresh water from some of the neighbouring islands, has been outlined in Appendix H. The current prospects for P.S.V. do not appear to be too encouraging along these lines. Nonetheless, this alternative should be explored fully, notwithstanding the many difficulties inherent in any possible scheme of this type.

The criteria for determining water policies in small communities has been set out in Appendix I. The advantages and disadvantages of solar distillation are clearly enumerated.

The characteristics of these two systems in use on P.S.V. have been outlined in Table No. 14. The results listed here can also be applied to small communities. In comparing these systems with other possible alternatives, a number of points should be stressed.

(1) The small communities generally have access to capital at lower rates of interest, e.g. from federal sources or through foreign aid loans, etc., which will reduce the annual charges and cost of the output water.[58, 63]

(2) The life of the water works should be extended in both cases to forty years in a small community.

(3) Both these systems are labour-intensive, utilizing local resources, as outlined in Appendix I. Many solar stills incorporate a transparent cover of glass which is being manufactured increasingly on a universal scale.

(4) In time the development of locally produced materials should reduce completely the necessity to import certain components of the solar stills.

Notwithstanding the apparent disparity in the accounting costs of fresh water produced by each system, the problem of whether to recommend that future investments be applied to one or the other is not so clear-cut. Sections of the solar distillation plant have been functioning for one and one half years giving a much clearer idea of their performance potential as compared to that of the rainfall collection system which is just beginning operations. Hence, it is desirable to proceed slowly in order to appreciate both systems, following a period of study and observation into the characteristics of their performance.

As indicated in the introduction, this report gives more of an indication of the trend of future investment patterns rather than a precise definition of the pattern itself. If cost is to be the only criterion in the application of future water supply investments, then clearly additional rainfall catchment areas should be considered initially. If the construction of new buildings is scheduled, then the roofs should be fitted with guttering systems and the collection cisterns should be connected to the rain water piping system. This appears to offer the least expensive solution to the problem of water supply. The directors of the project on P.S.V. have decided against building rainfall catchment areas directly on the ground for aesthetic reasons. This does not apply to the solar distillation plant which has proven so reliable in supplying the island with water for the past 18 months. Also, the plant has turned out to be a good attraction, which is continuously being visited by a stream of tourists and travellers. If no additional buildings will be erected in the near future, the most logical way to satisfy an increased demand for fresh water would be in the extension of the solar distillation plant with its built-in rainfall catchment area. As specified earlier, it would not be necessary to modify the auxiliaries as they are already overdesigned. Expanding the plant facilities would reduce the overall cost of the fresh water effluent as outlined in Chapter 3.

The results of these investigations are in general agreement with the findings of Morse on the question of the level of rainfall intensity above which solar distillation is no longer competitive with rainfall collection. He feels that the break even point is about 18 inches rainfall per annum.[64] In the case of P.S.V., it has been shown that the anticipated average precipitation should be two and one half times this figure. Consequently, the choice of incorporating a solar distillation plant in the rain water collection system in this area is one of expediency. The other factors listed in Table No. 14 have monetary equivalents as well, but these are not quite so simple to quantify as the accounting costs of the investment and operating charges listed in Chapters 3 and 4.

It must not be overlooked that the solar distillation plant combined with the rainfall collection system, assures the development on P.S.V. of two distinct fresh water supply sources. This creates a safety factor for a remote community. In the case of a complete breakdown of one system, the other will be able to satisfy at least part of the demand for fresh water.

The use of solar distillation in a rainfall catchment system reduces the amount of storage capacity required. The resultant savings in the cost of cistern capacity can be written off against the investment expenditure in the solar distillation plants. This has been mentioned in Appendix F. Again it is necessary to study the merits of the economics in each case separately as these are dependent on the rainfall intensity and distribution frequency, the solar radiation intensity and distribution frequency, the cost of the cisterns and the cost of the solar stills all of which vary from one location to another. Certainly this point deserves attention in planning any installation of this type. Unfortunately, the installations on P.S.V. were not designed with these factors specifically in mind so that it becomes more difficult to extract this information from the investment costs.

Finally, it cannot be overemphasized that the conservation of fresh water in these areas is of prime importance as the cost of its procurement will always be high. Wherever possible, saline water should be used for sanitary purposes. A study undertaken ancillary to these investigations has shown that a sea water circulation system for P.S.V. could be operated inexpensively. The water cost should be between $0.30 and $0.50 per 1000 gallons.[65] This would reduce the load on the fresh water supply systems and free any surplus water for gardening and other uses. The entire question of water use is one of equal importance to that of water supply - the two cannot be separated.

RECOMMENDATIONS FOR FUTURE RESEARCH

This study has examined the process of solar distillation with special reference to its suitability for the provision of fresh water for small communities. During the course of the work, a number of questions have arisen which are beyond the scope of this preliminary report. These require further investigation if solar distillation is ever to have widespread application.

1. A comprehensive study must be made of the economic ramifications of the installation of a solar distillation plant for the provision of fresh water to a small community in a developing area. Details of the costs and of the primary and secondary benefits should be estimated so as to establish a true picture of the economic impact of the investment.

2. A detailed inquiry into the technical and economic characteristics of the water supply system on Petit St. Vincent, over a period of several years, would yield invaluable information on their suitability under actual field conditions, while extending the work which has been initiated in these investigations.

In addition, the following studies should be pursued:

a) a comparison of the performance of insulated solar still bays with those currently in operation.

b) an examination of the feasibility of using surplus electricity from the power station to preheat the sea water feed to the solar stills, in order to extend their period of useful production each day.

c) a solution of the difficulties experienced with the flocculation of rain water collected from wallaba-shingled roofs. Although this is not a universal problem, these roofs are used extensively in this region and the results of this research would improve the quality of the water consumed by the local inhabitants.

3. A standard method should be formulated for the testing and evaluation of solar stills operating under field conditions in small communities. The instrumentation and techniques employed should be simple so as to permit their extensive utilization. In particular, the measurement of the solar still basin and cover temperatures deserves attention.

4. A standard procedure for setting out the costs of solar distillation plants must be established. In addition, the expenditures involved in the collection and storage of rain water must be clearly defined and quantified. The utilization of this information would reveal to the small community the level of rainfall intensity below which they should give serious consideration to the installation of a solar distillation plant.

5. In order to assist the observer in the developing area to make proper decisions on water supply problems, a comparative study of existing large scale solar still installations, outlining construction techniques, technical characteristics and economic considerations, would be most useful. This should be coupled with an examination of:

a) the potential for the increase of solar still productivities
b) all relevant factors which will advise the small community as to the optimum sizes of plants for efficient and economic operation in various environments.

6. If polyvinyl fluoride film (Tedlar) continues to be used extensively for transparent covers of solar stills, then the following properties, both for wet and for dry film which have been treated to produce surface wettability, should be measured in laboratory experiments:

a) the emissivity and absorptivity

b) the transmissivity for solar radiation at different angles of incidence

c) the reflectivity for solar radiation at different angles of incidence

d) the transmissivity for long-wave radiation from radiators at temperatures of up to two hundred degrees Fahrenheit.

7. In order to extend the theoretical evaluation of the internal heat transfers within the solar stills, a detailed study should be made of the radiation heat transfer from the basin surface to the cover and to the environment. The effect of the water layer lining the transparent canopy on these radiation heat flows and the manner in which this influences the heat balances must be explored. Also it is necessary to examine the relative humidity of the air enclosed within the solar stills and its role in the determination of heat transfer. The influence of these factors must be considered at all hours of the day and night in order to establish their significance.

8. A study of the performance of the floating wicks, and the problems of scaling and its detrimental effects on the output of the stills, should be undertaken. The question of the economics of the use of this component in solar stills should be examined critically.

CONCLUSIONS

The results of this study can be summarized as follows:

1. Solar distillation constitutes a technically feasible method of providing fresh water for a small community.

2. Experience with the installations on Petit St. Vincent has demonstrated that the units can be built quite satisfactorily using local labour and resources.

3. A method has been formulated for testing and evaluating the performance of the solar stills under field conditions using simple instrumentation and techniques.

4. The combination of the solar distillation plant and the rainfall collection system, comprising the water works on this island, has proven to be dependable because of the complementary natures of the two components.

5. Notwithstanding current operational difficulties, and considering annual charges only, the rainfall collection system on Petit St. Vincent produces water at a cheaper rate than the solar distillation plant.

6. One advantage of solar distillation is that some fresh water is always available owing to the daily output of the units.

7. Solar distillation is admirably suited for use by small communities as it provides them with an independent source of fresh water supply which is within their capacity to build, repair, operate and manage.

8. Judging strictly from accounting charges, the solar distillation units studied in this report produce water at a relatively high cost. An analysis of these expenses has indicated, however, that this process constitutes a suitable investment for water supply systems in developing regions. This arises from the high proportion of local services and materials in the

expenditures. Potentially, the capital investment in this system has a low foreign exchange requirement ratio. The economic consequences resultant from this investment, incorporating all benefits, primary, secondary and others, will have to be examined when comparisons are made with alternative means of fresh water supply.

9. Finally, it should be recognised that assistance in the establishment of systems of fresh water supply for the thousands of small communities in the developing areas of the world is really an international social cost, which the wealthier nations and regions must bear. The provision of certain basic materials for solar still construction is a humanitarian gesture which deserves serious attention. It is evident that the solar distillation process belongs to that type of intermediate technology which will enable small communities to help themselves to increase their standard of living and economic well-being.

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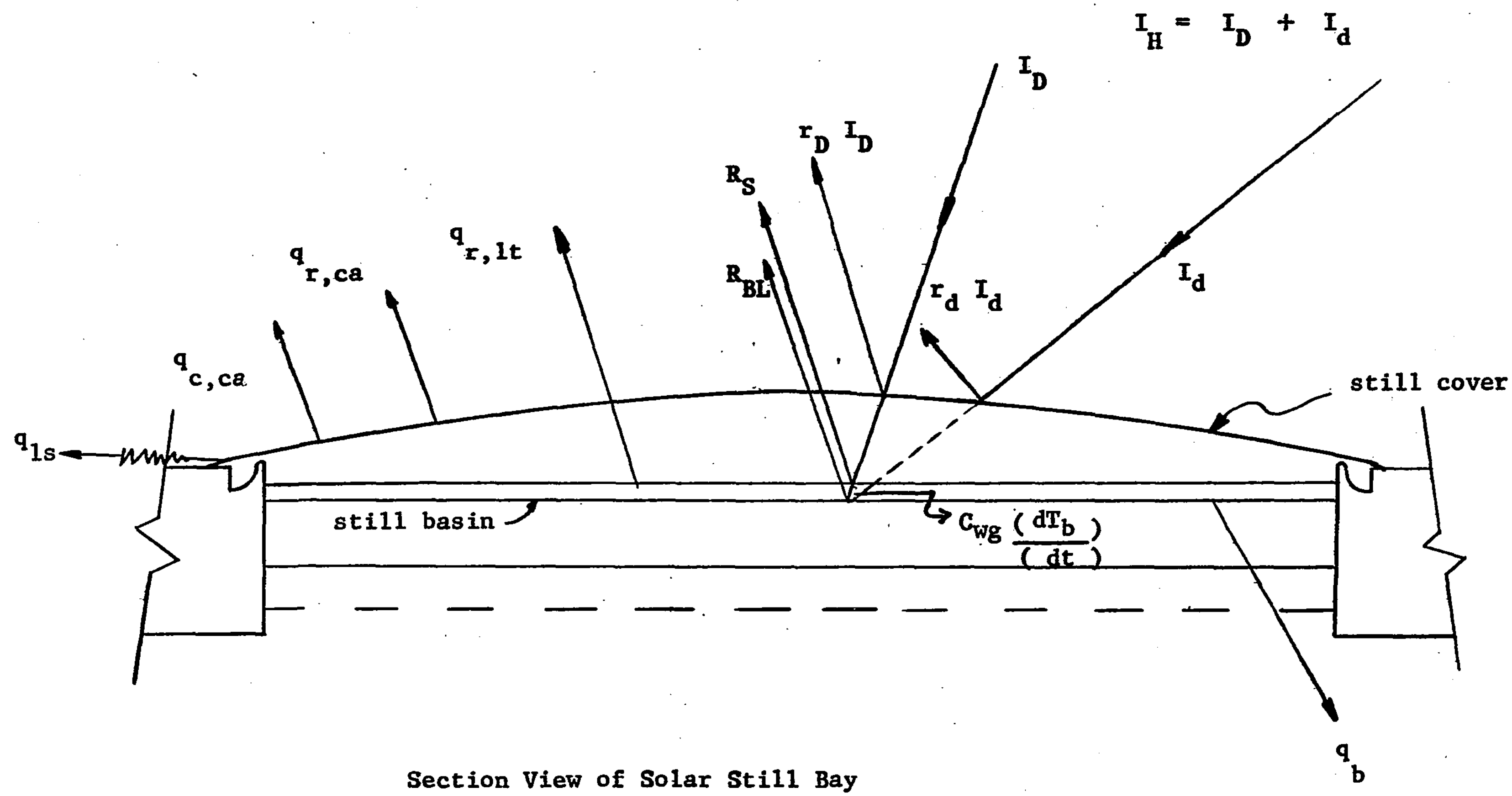
OVERALL HEAT BALANCE ON A SOLAR STILL BAY

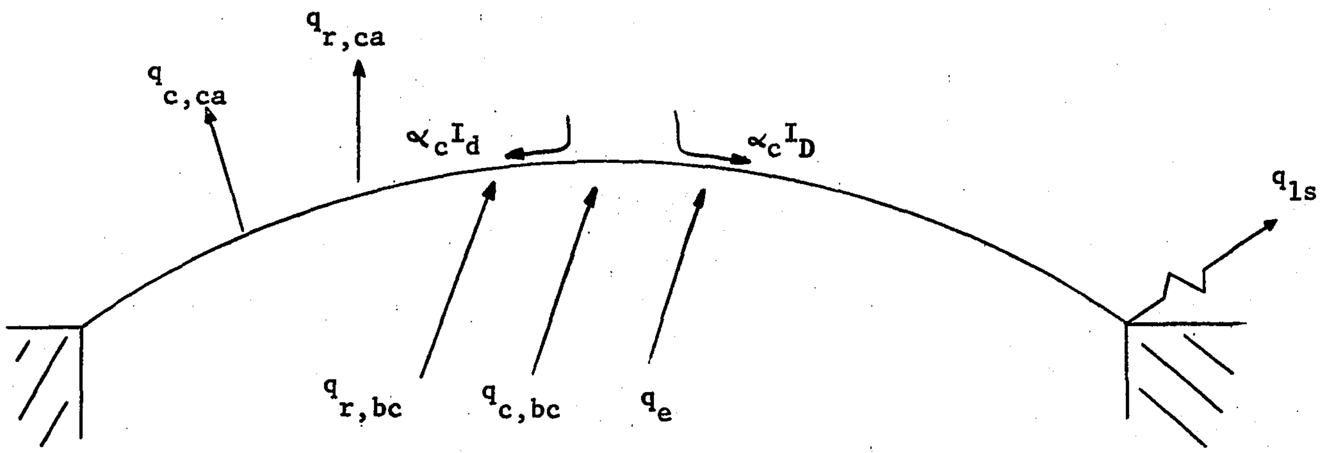
Figure No.1



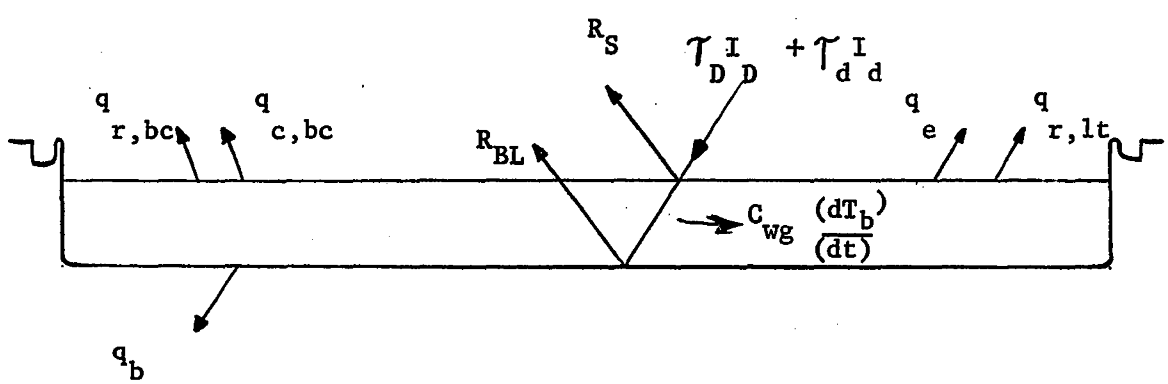
Section View of Solar Still Bay

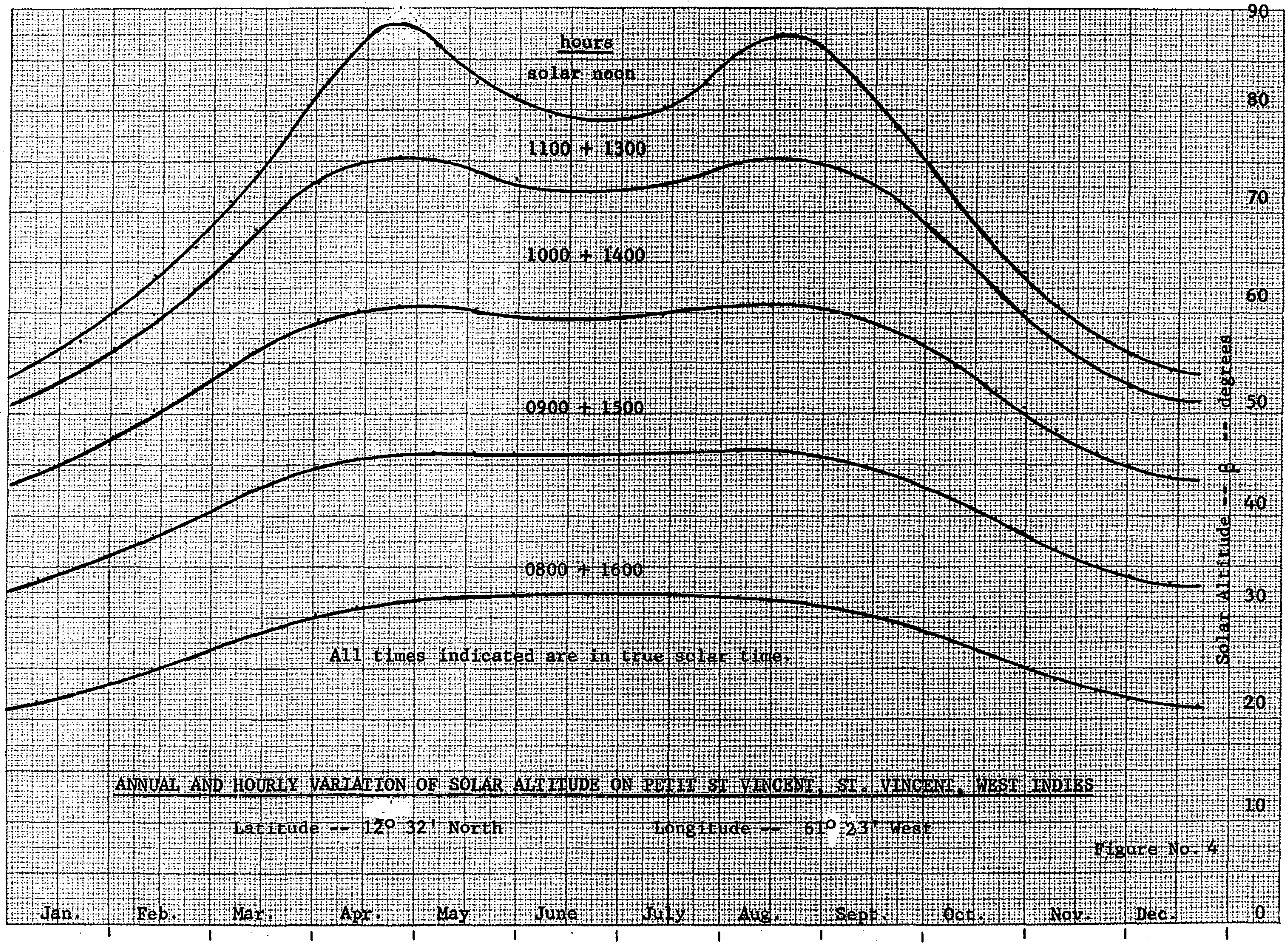
Not to Scale

HEAT BALANCE ON THE SOLAR STILL TRANSPARENT COVER

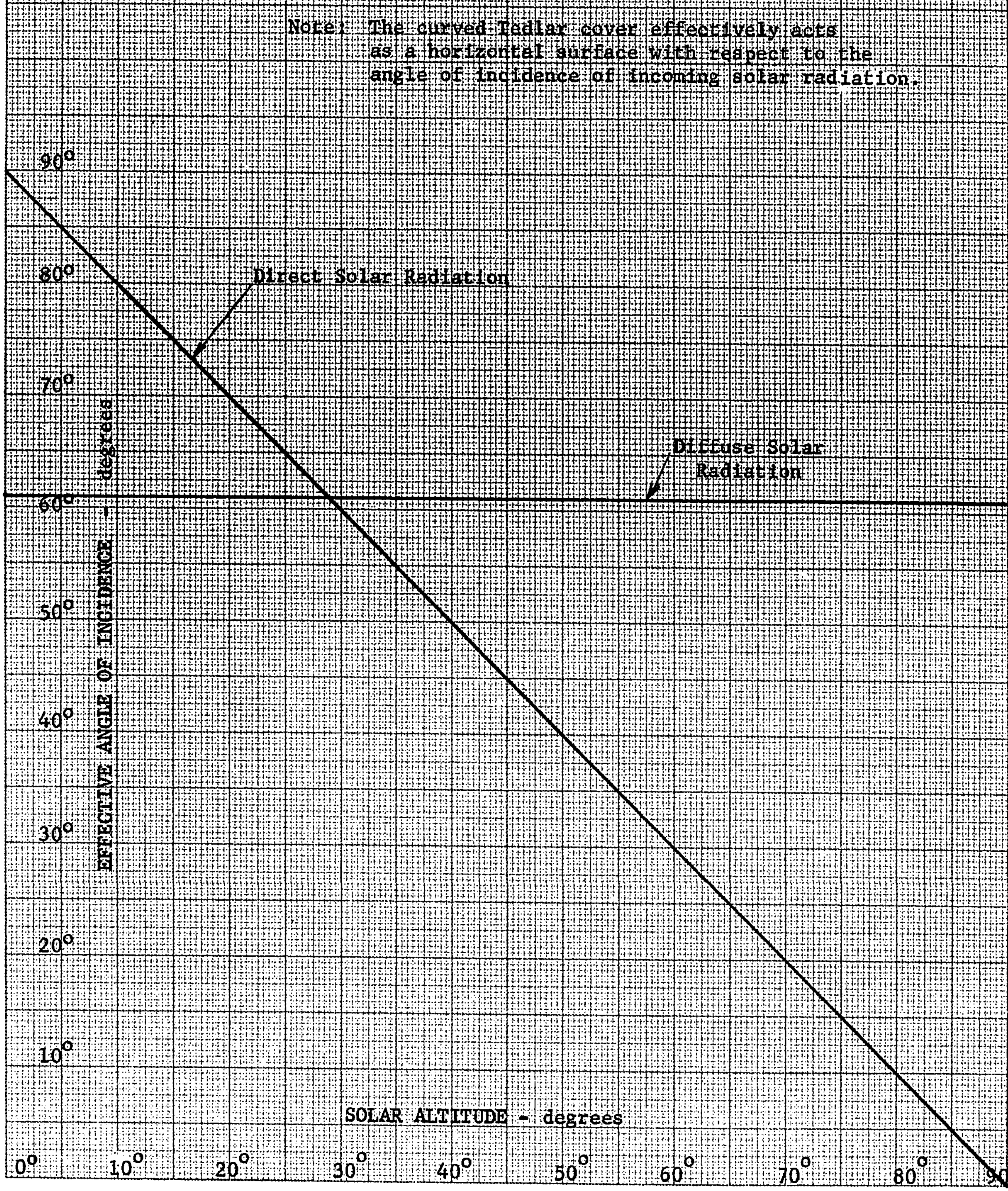


HEAT BALANCE ON THE SOLAR STILL EVAPORATOR BASIN




hours
solar noon
1100 + 1300
1000 + 1400
0900 + 1500
0800 + 1600
All times indicated are in true solar time.
ANNUAL AND HOURLY VARIATION OF SOLAR ALTITUDE ON PETIT ST VINCENT, ST. VINCENT, WEST INDIES
Latitude -- 12° 32' North
Longitude -- 61° 23' West
Solar Altitude -- β -- degrees
90
80
70
60
50
40
30
20
10
0
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
Figure No. 4

VARIATION OF THE EFFECTIVE ANGLE OF INCIDENCE OF SOLAR RADIATION ON THE TEDLAR COVER OF THE SOLAR STILLS AT DIFFERENT SOLAR ALTITUDES



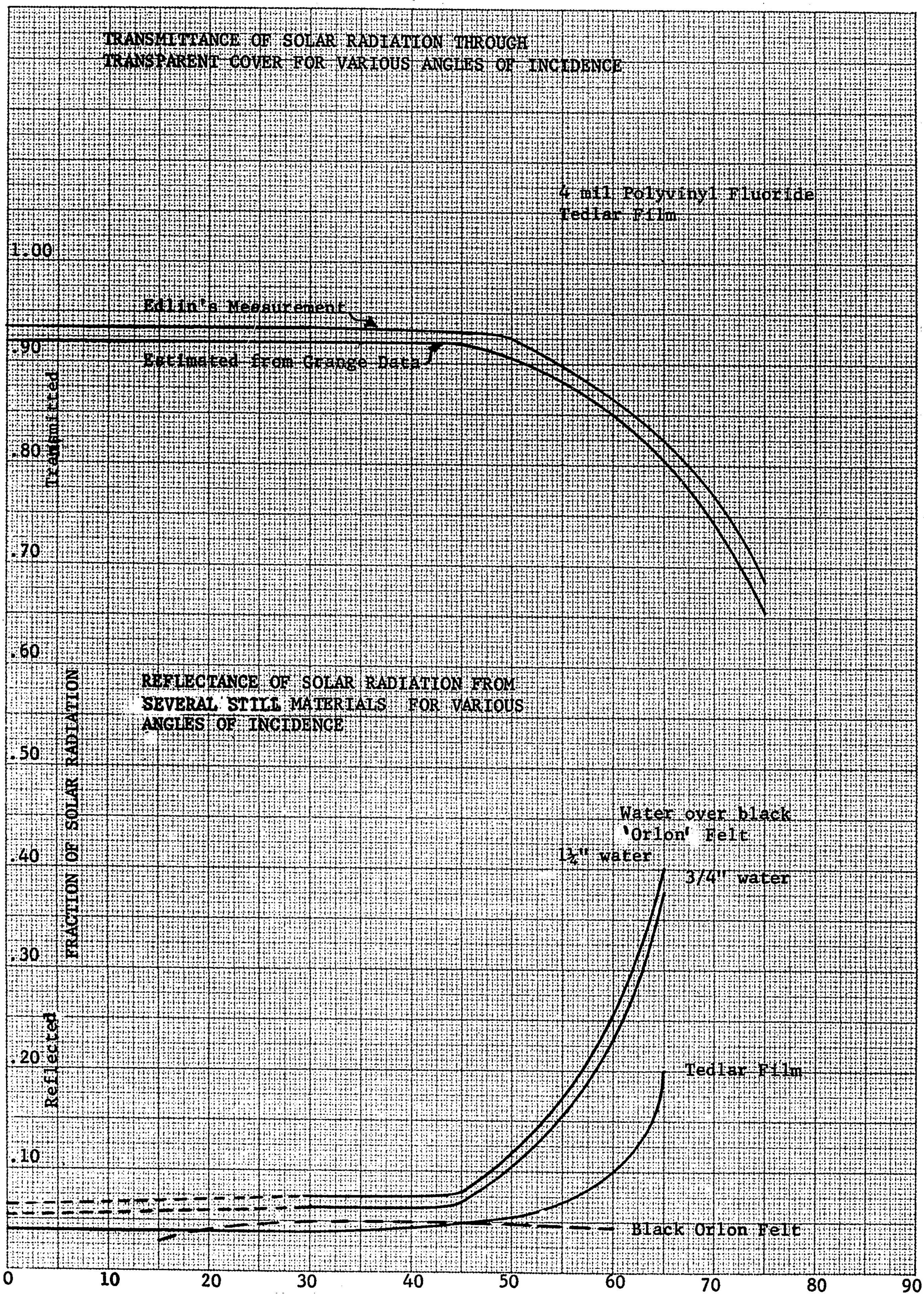
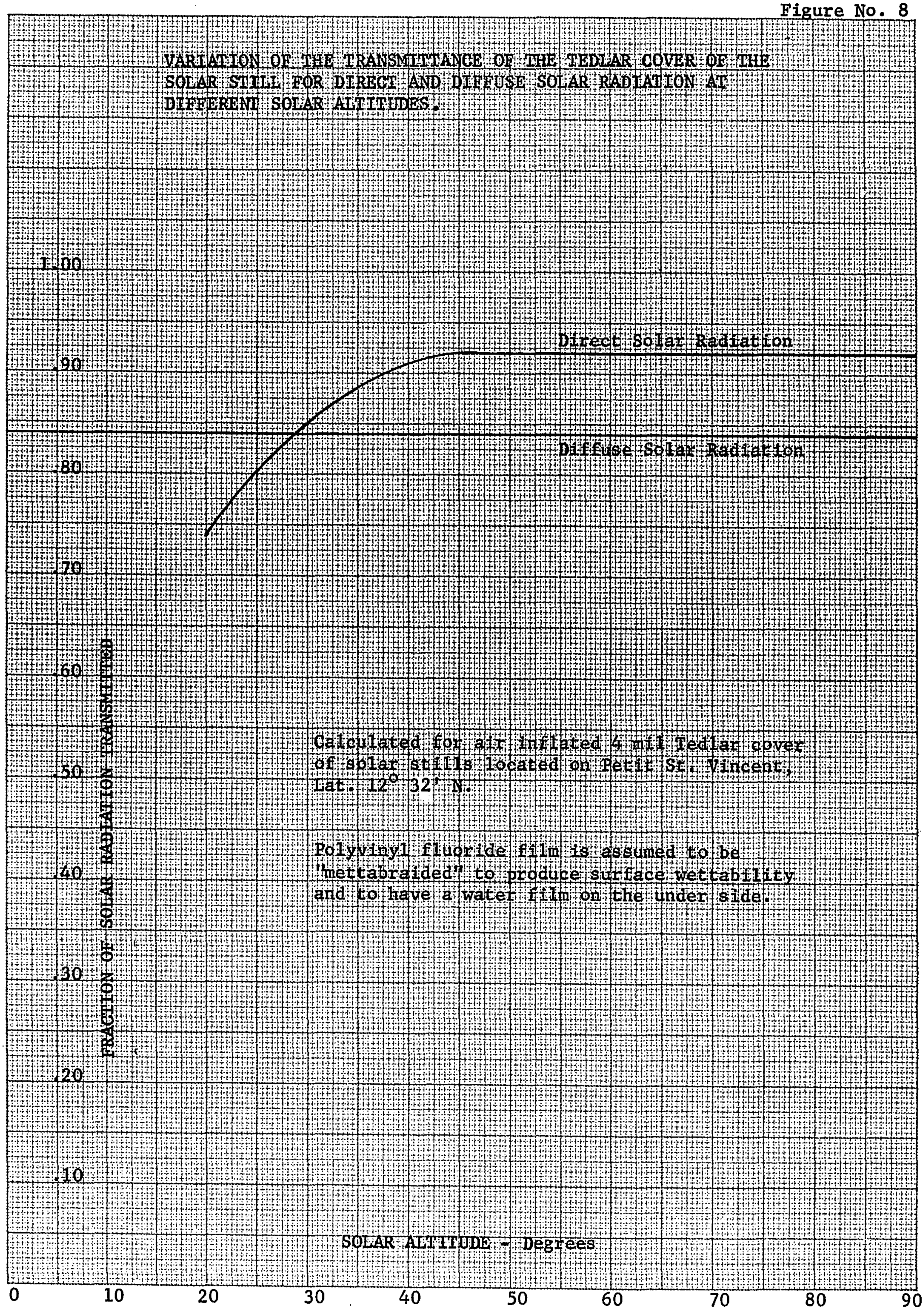
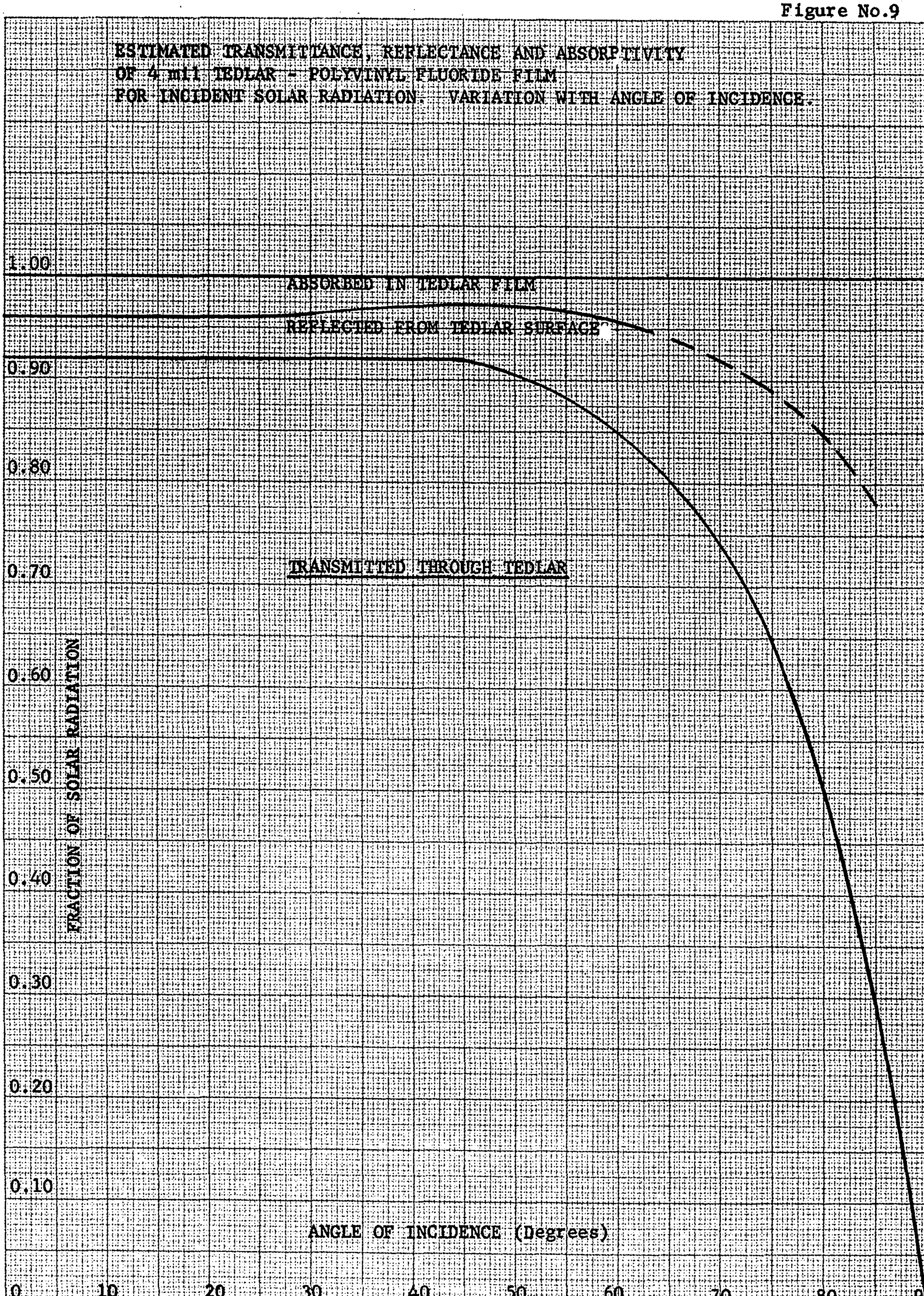

TRANSMITTANCE OF SOLAR RADIATION THROUGH TRANSPARENT COVER FOR VARIOUS ANGLES OF INCIDENCE
4 mil Polyvinyl Fluoride Tedlar Film
Edlin's Measurement
Estimated from Grange Data
REFLECTANCE OF SOLAR RADIATION FROM SEVERAL STILL MATERIALS FOR VARIOUS ANGLES OF INCIDENCE
Water over black 'Orlon' Felt
1¼" water
3/4" water
Tedlar Film
Black Orlon Felt
FRACTION OF SOLAR RADIATION
Transmitted
Reflected
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
10
20
30
40
50
60
70
80
90

Figure No. 8

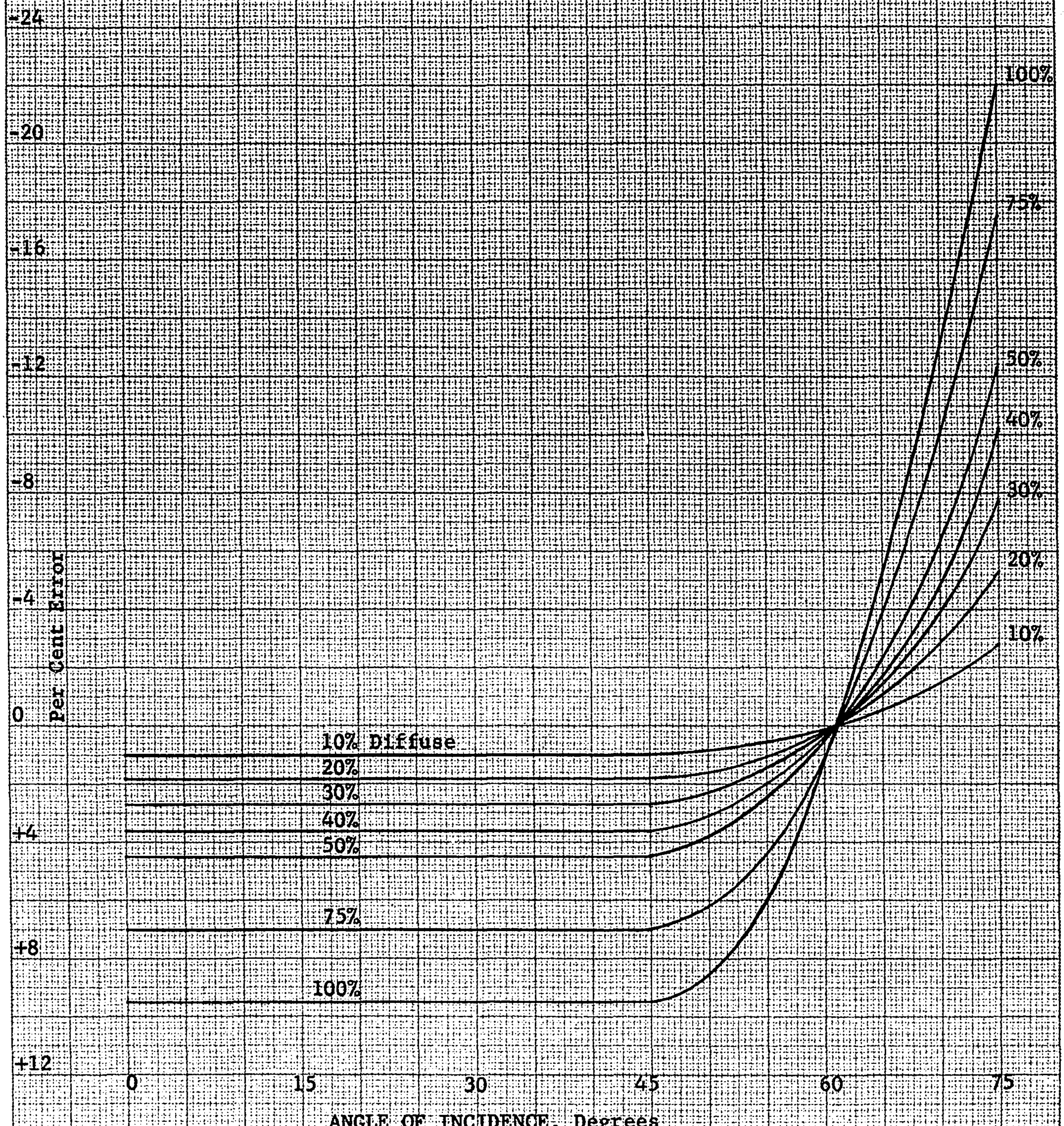

VARIATION OF THE TRANSMITTANCE OF THE TEDLAR COVER OF THE SOLAR STILL FOR DIRECT AND DIFFUSE SOLAR RADIATION AT DIFFERENT SOLAR ALTITUDES.
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
FRACTION OF SOLAR RADIATION TRANSMITTED
Direct Solar Radiation
Diffuse Solar Radiation
Calculated for air inflated 4 mil Tedlar cover of solar stills located on Petit St. Vincent, Lat. 12° 32' N.
Polyvinyl fluoride film is assumed to be "mettabraided" to produce surface wettability and to have a water film on the under side.
SOLAR ALTITUDE - Degrees
0
10
20
30
40
50
60
70
80
90

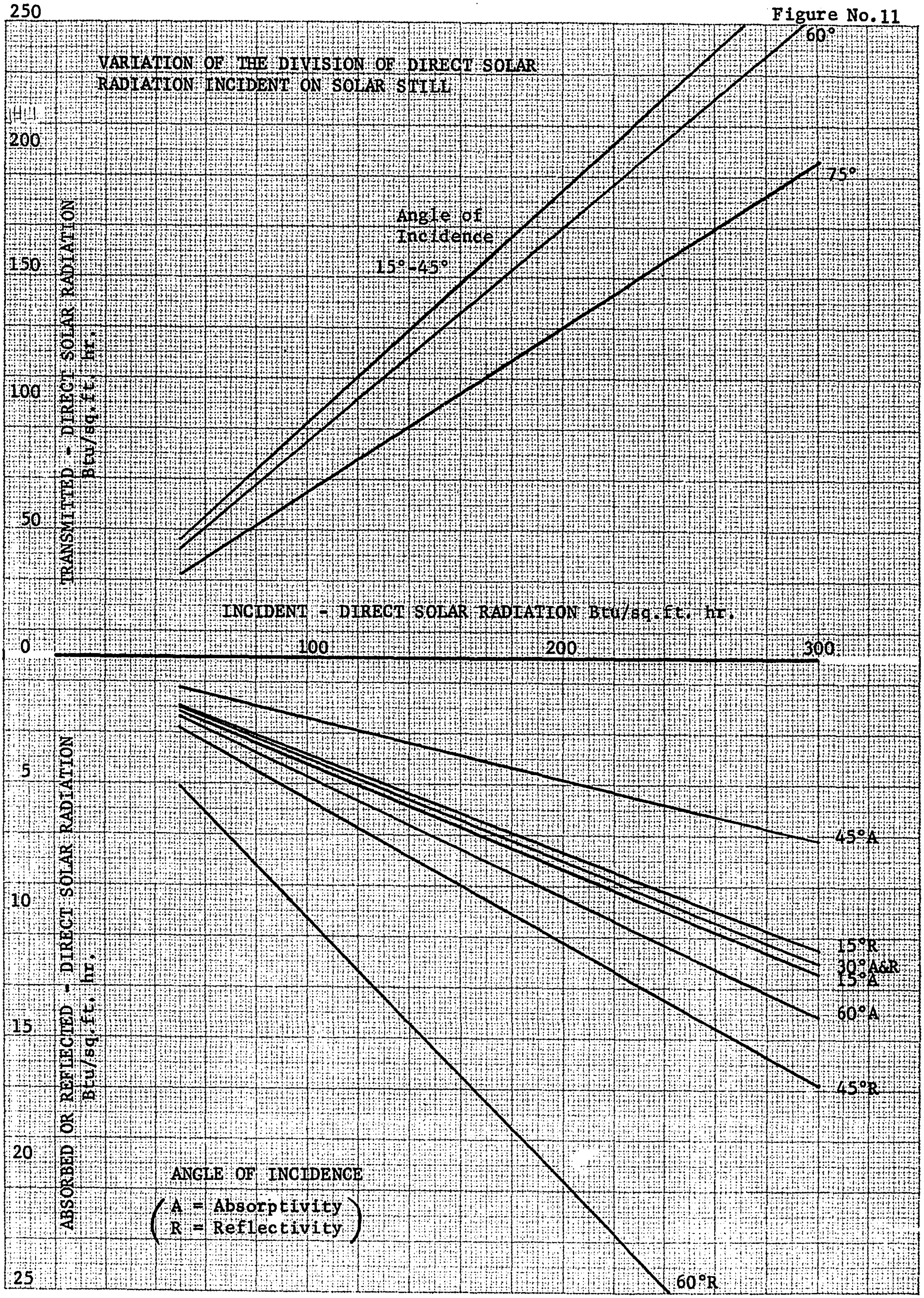

ESTIMATED TRANSMITTANCE, REFLECTANCE AND ABSORPTIVITY
OF 4 mil TEDLAR - POLYVINYL FLUORIDE FILM
FOR INCIDENT SOLAR RADIATION. VARIATION WITH ANGLE OF INCIDENCE.
ABSORBED IN TEDLAR FILM
REFLECTED FROM TEDLAR SURFACE
TRANSMITTED THROUGH TEDLAR
FRACTION OF SOLAR RADIATION
ANGLE OF INCIDENCE (Degrees)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0
10
20
30
40
50
60
70
80
90

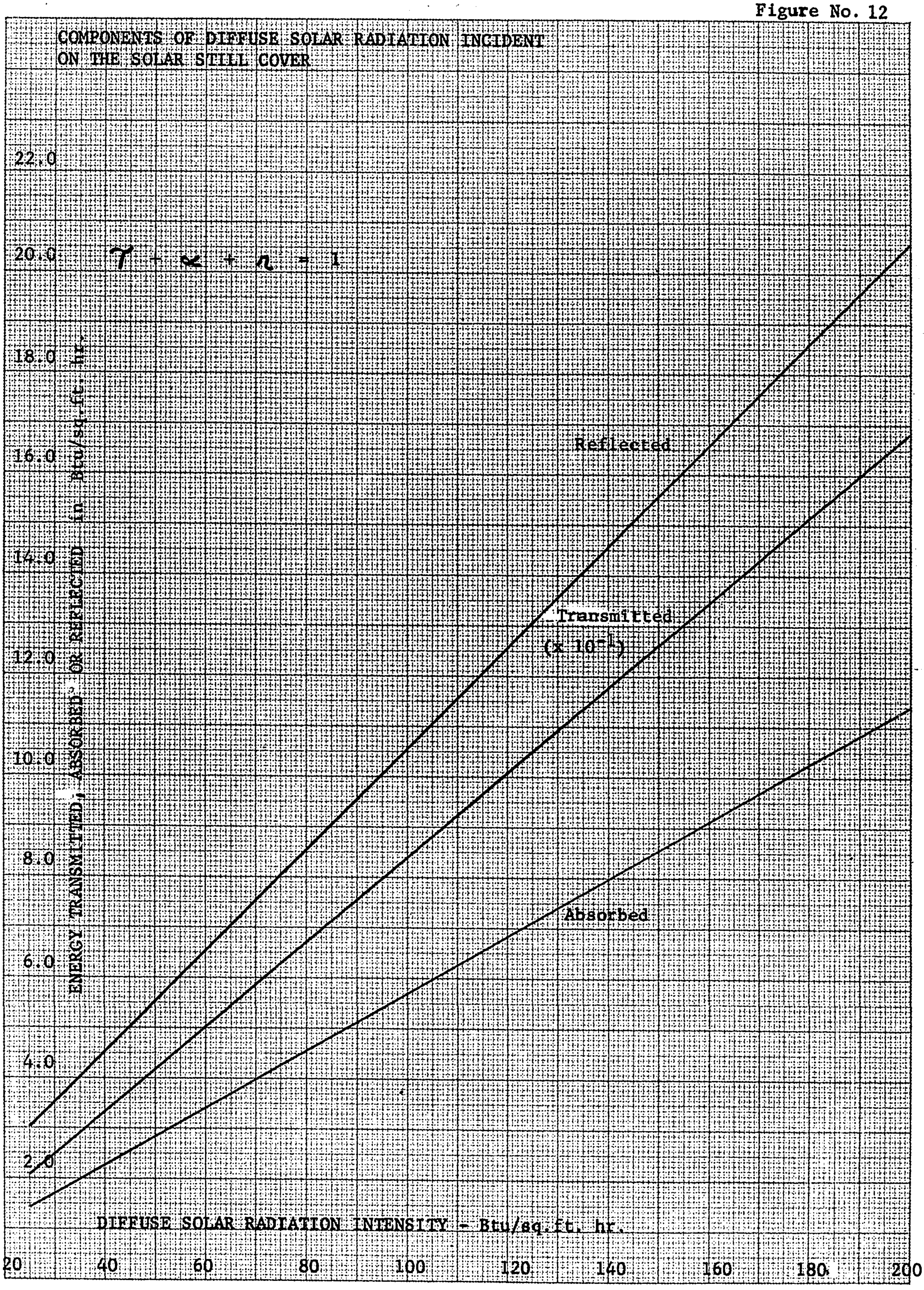
DEVIATION OF ASSUMPTION OF TOTAL RADIATION INCIDENT ON SOLAR STILLS TAKEN AS BEING EQUIVALENT TO DIRECT RADIATION: VARIATION OF RELATIVE AMOUNT OF ENERGY TRANSMITTED THROUGH COVER AS A FUNCTION OF ANGLE OF INCIDENCE.

Per cent Deviation is calculated as $\frac{A - B}{B}$

where: A = total radiation, all assumed direct.
B = total radiation, direct & diffuse components.




VARIATION OF THE DIVISION OF DIRECT SOLAR RADIATION INCIDENT ON SOLAR STILL
TRANSMITTED - DIRECT SOLAR RADIATION Btu/sq.ft. hr.
ABSORBED OR REFLECTED - DIRECT SOLAR RADIATION Btu/sq.ft. hr.
INCIDENT - DIRECT SOLAR RADIATION Btu/sq.ft. hr.
250
200
150
100
50
0
5
10
15
20
25
100
200
300
Angle of Incidence
15°-45°
60°
75°
45°A
15°R
30°A&R
15°A
60°A
45°R
60°R
ANGLE OF INCIDENCE
A = Absorptivity
R = Reflectivity


COMPONENTS OF DIFFUSE SOLAR RADIATION INCIDENT ON THE SOLAR STILL COVER
τ + α + ρ = 1
Reflected
Transmitted (x 10⁻¹)
Absorbed
ENERGY TRANSMITTED, ABSORBED OR REFLECTED in Btu/sq.ft. hr.
DIFFUSE SOLAR RADIATION INTENSITY - Btu/sq.ft. hr.
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
20
40
60
80
100
120
140
160
180
200

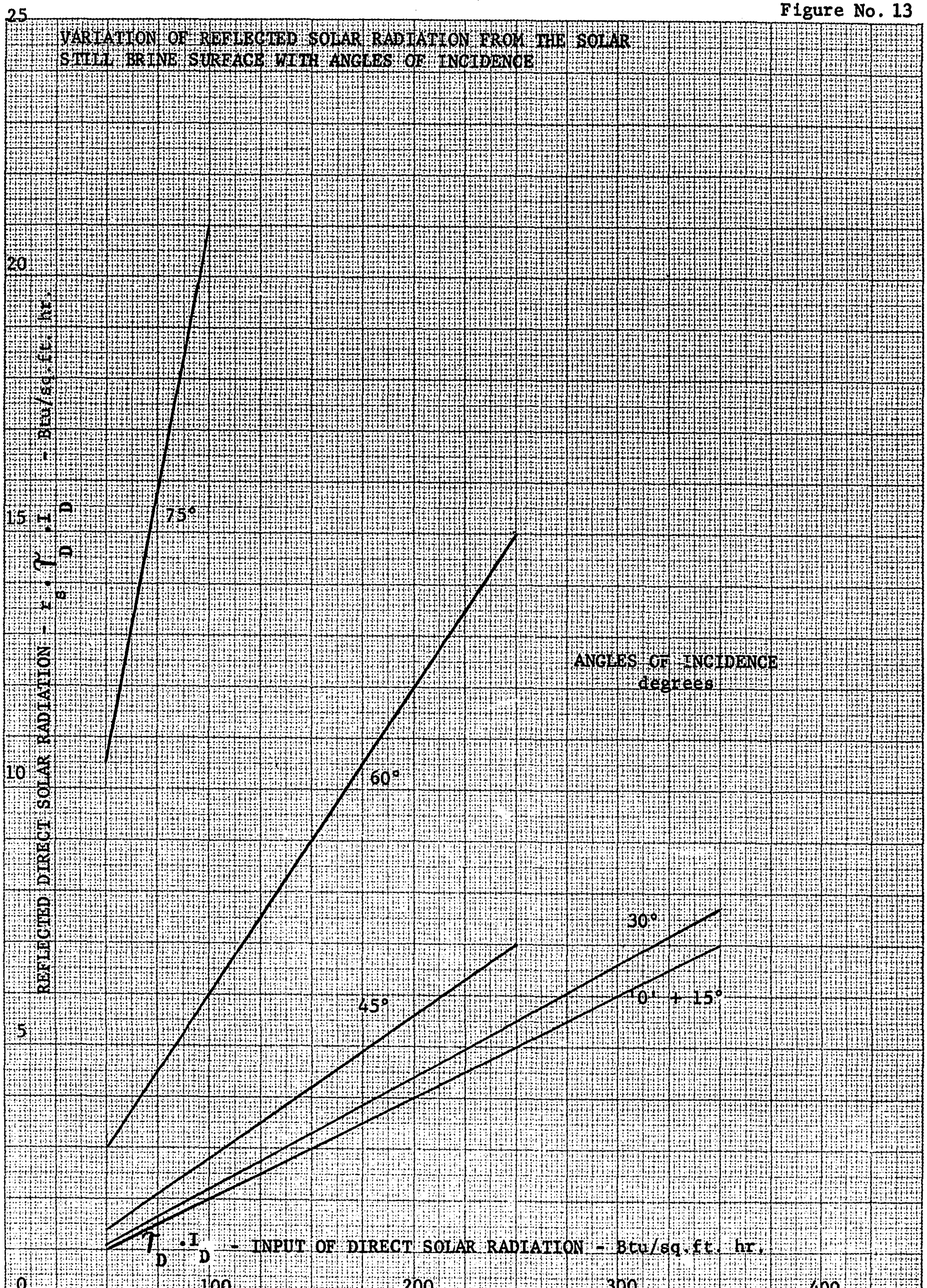

VARIATION OF REFLECTED SOLAR RADIATION FROM THE SOLAR STILL BRINE SURFACE WITH ANGLES OF INCIDENCE
REFLECTED DIRECT SOLAR RADIATION - r · τ · I - Btu/sq.ft. hr.
τ · I - INPUT OF DIRECT SOLAR RADIATION - Btu/sq.ft. hr.
ANGLES OF INCIDENCE
degrees
75°
60°
45°
30°
0° + 15°
0
5
10
15
20
25
100
200
300
400

Figure No. 14

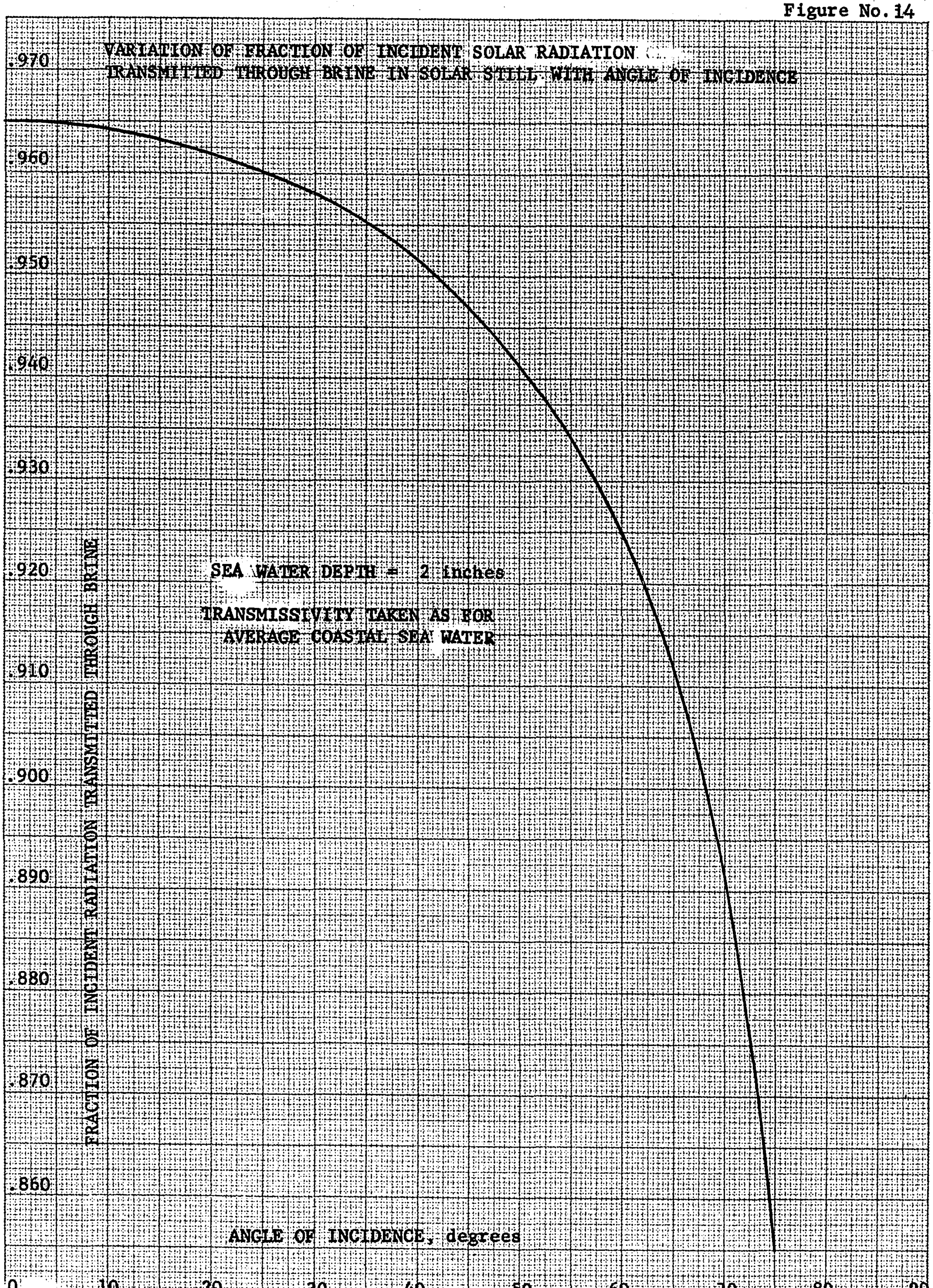

VARIATION OF FRACTION OF INCIDENT SOLAR RADIATION
TRANSMITTED THROUGH BRINE IN SOLAR STILL WITH ANGLE OF INCIDENCE
SEA WATER DEPTH = 2 inches
TRANSMISSIVITY TAKEN AS FOR
AVERAGE COASTAL SEA WATER
FRACTION OF INCIDENT RADIATION TRANSMITTED THROUGH BRINE
ANGLE OF INCIDENCE, degrees
.970
.960
.950
.940
.930
.920
.910
.900
.890
.880
.870
.860
0
10
20
30
40
50
60
70
80
90

Figure No. 15

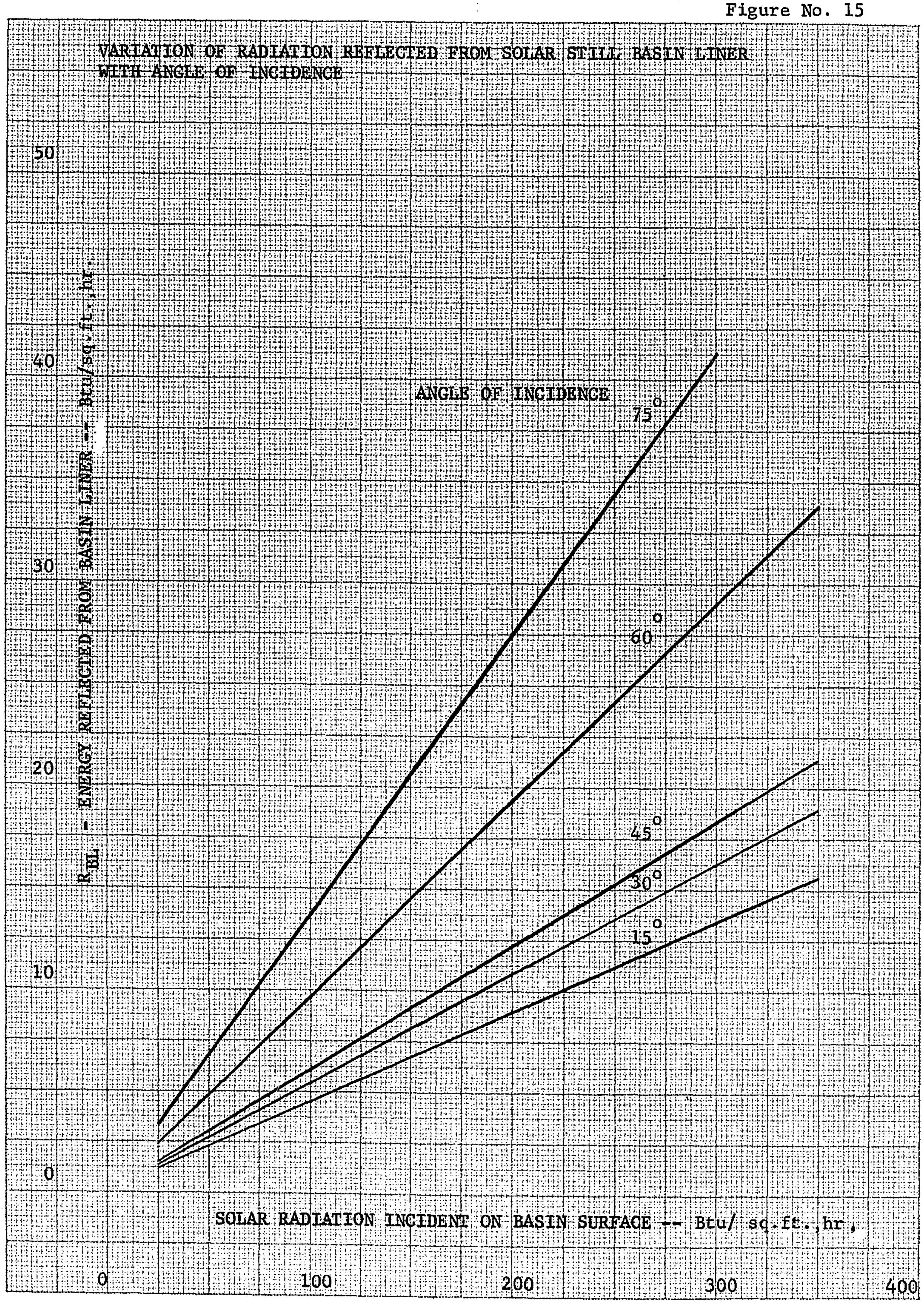

VARIATION OF RADIATION REFLECTED FROM SOLAR STILL BASIN LINER
WITH ANGLE OF INCIDENCE
ANGLE OF INCIDENCE
75°
60°
45°
30°
15°
R_{BL} - ENERGY REFLECTED FROM BASIN LINER -- Btu/sq.ft.,hr.
SOLAR RADIATION INCIDENT ON BASIN SURFACE -- Btu/ sq.ft.,hr,
50
40
30
20
10
0
0
100
200
300
400

Figure No. 16

THE EQUIVALENT TEMPERATURE DIFFERENCE FOR - FRESH WATER

ESTIMATION OF THE EQUIVALENT TEMPERATURE DIFFERENCE FOR USE IN THE CALCULATION OF CONVECTIVE HEAT TRANSFER FROM SOLAR STILL BRINE TO THE COVER AND FOR CALCULATING THE HEAT TRANSFER FOR EVAPORATION AS A FUNCTION OF BASIN AND COVER TEMPERATURES.

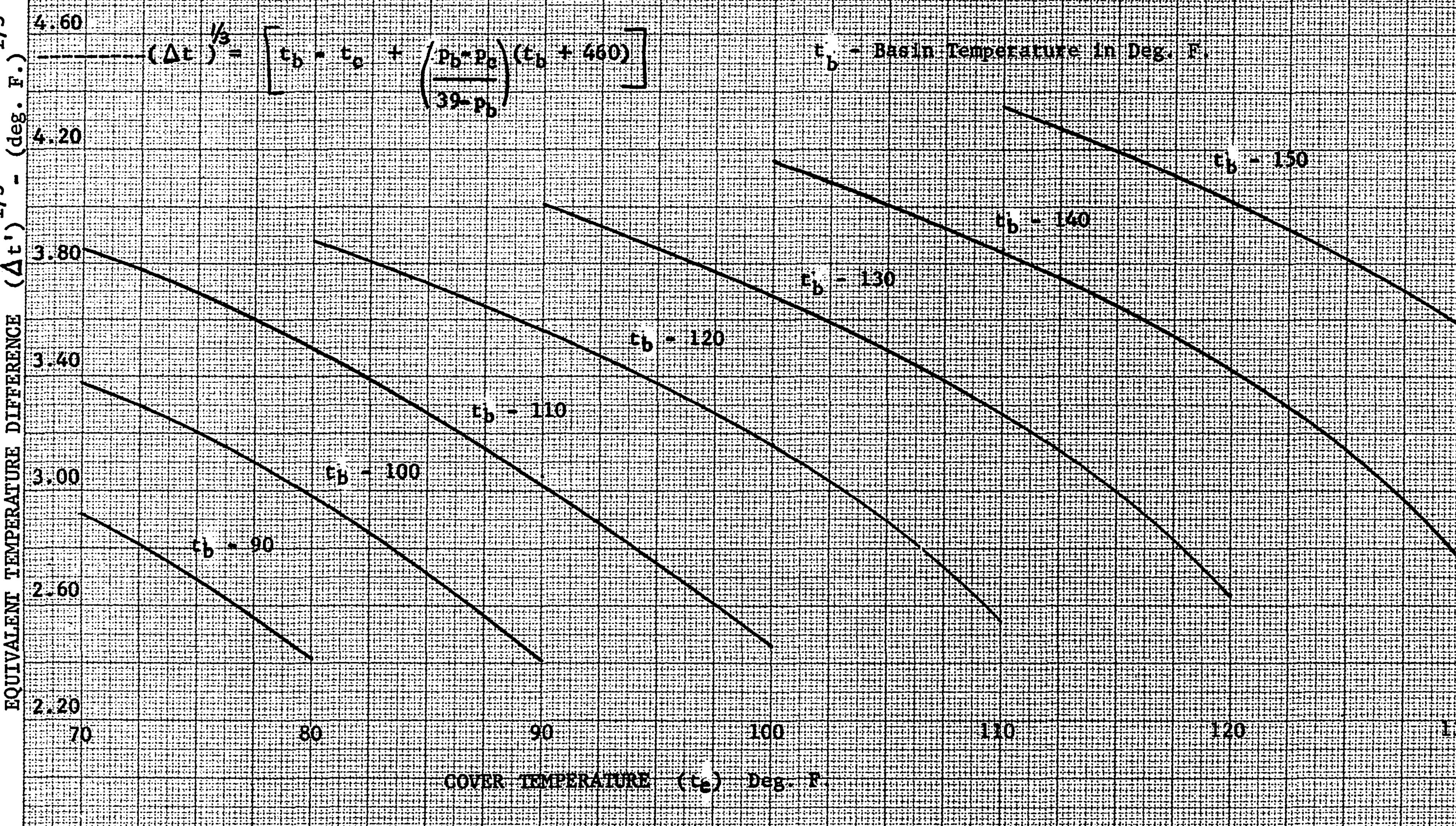


Figure No. 17

THE EQUIVALENT TEMPERATURE DIFFERENCE FOR NORMAL SEA WATER

ESTIMATION OF THE EQUIVALENT TEMPERATURE DIFFERENCE FOR USE IN THE CALCULATION OF CONVECTIVE HEAT TRANSFER FROM SOLAR STILL BRINE TO THE COVER AND FOR CALCULATING THE HEAT TRANSFER FOR EVAPORATION AS A FUNCTION OF BASIN AND COVER TEMPERATURES.

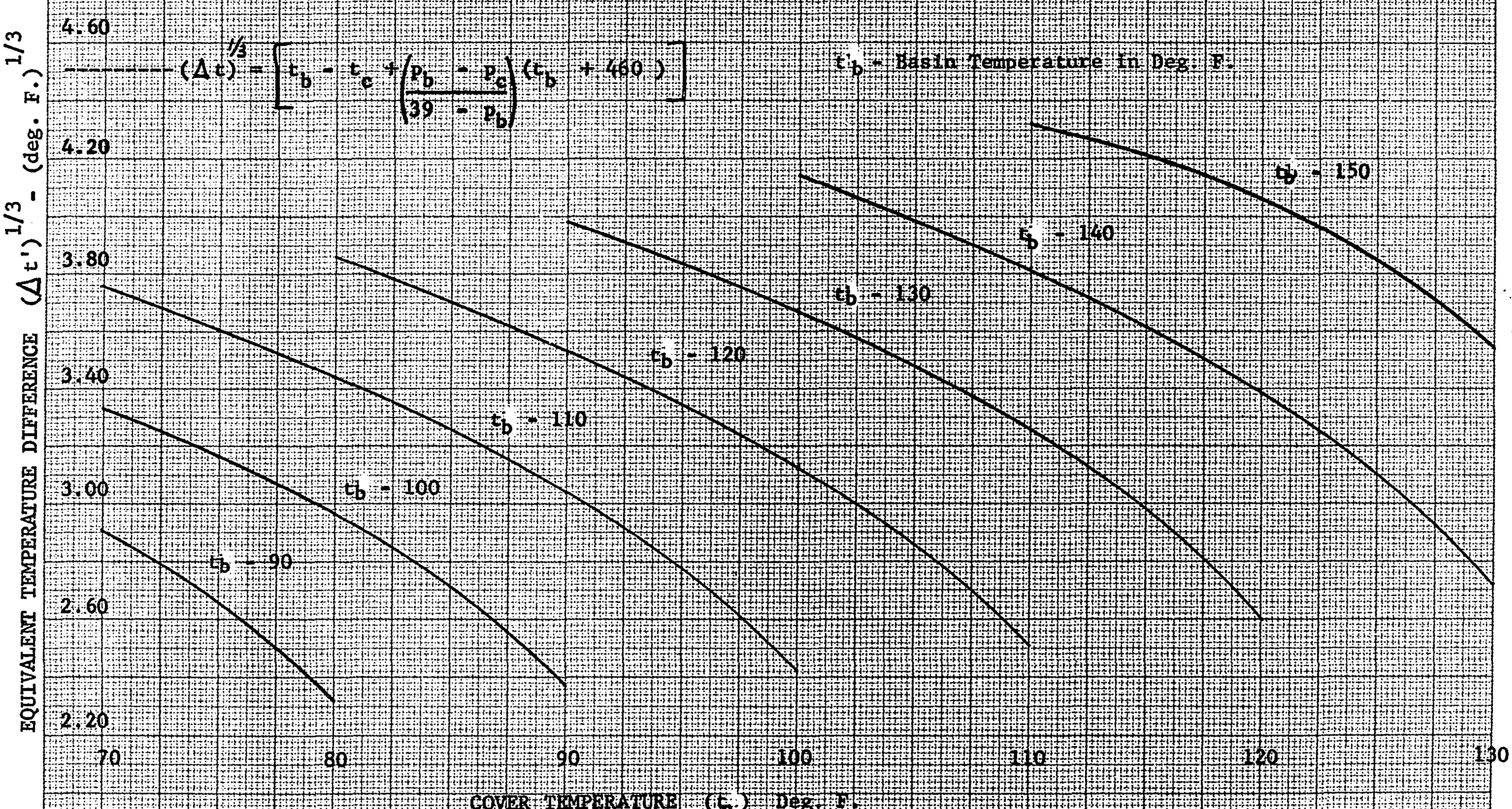
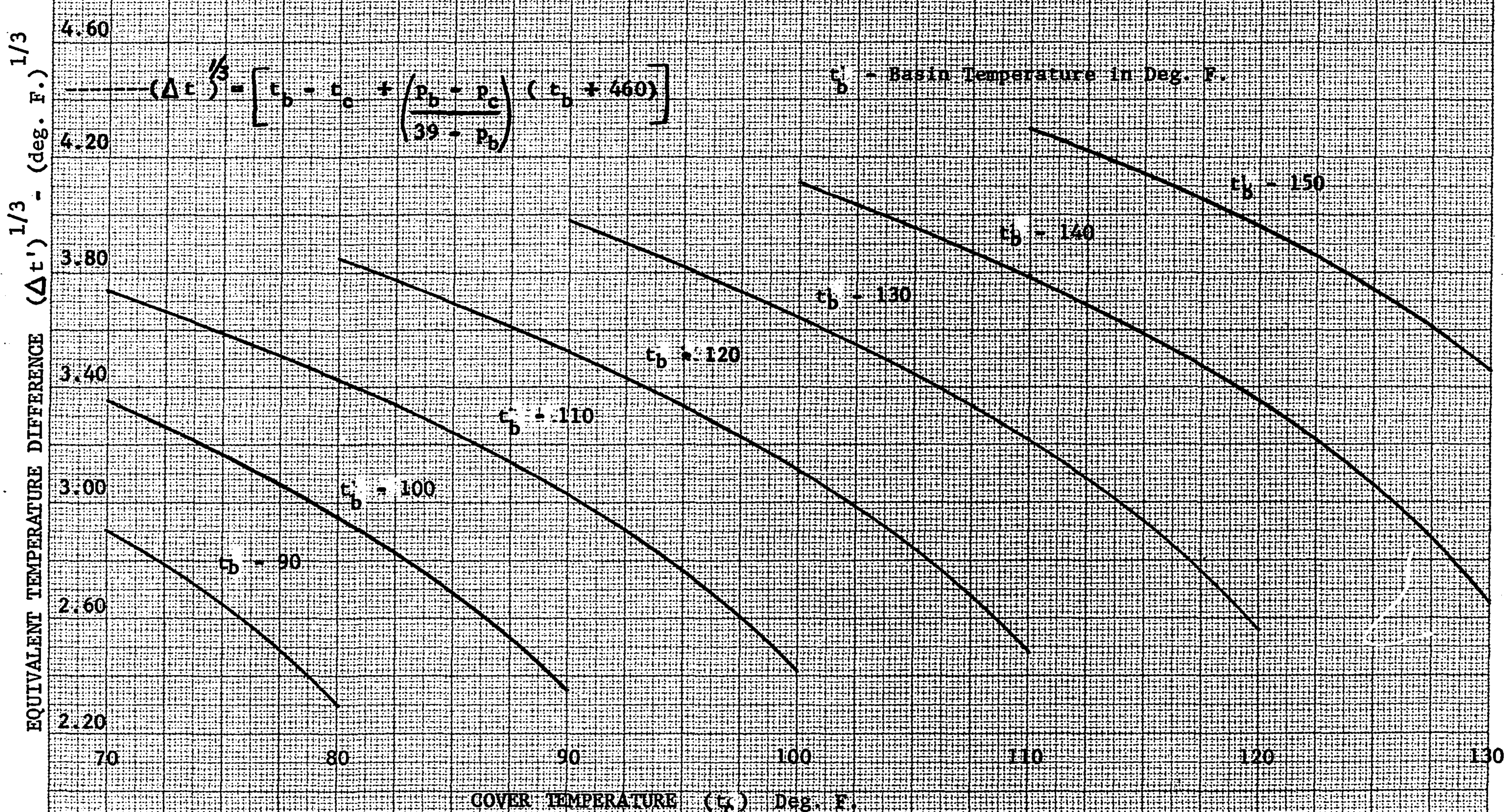


Figure No. 18

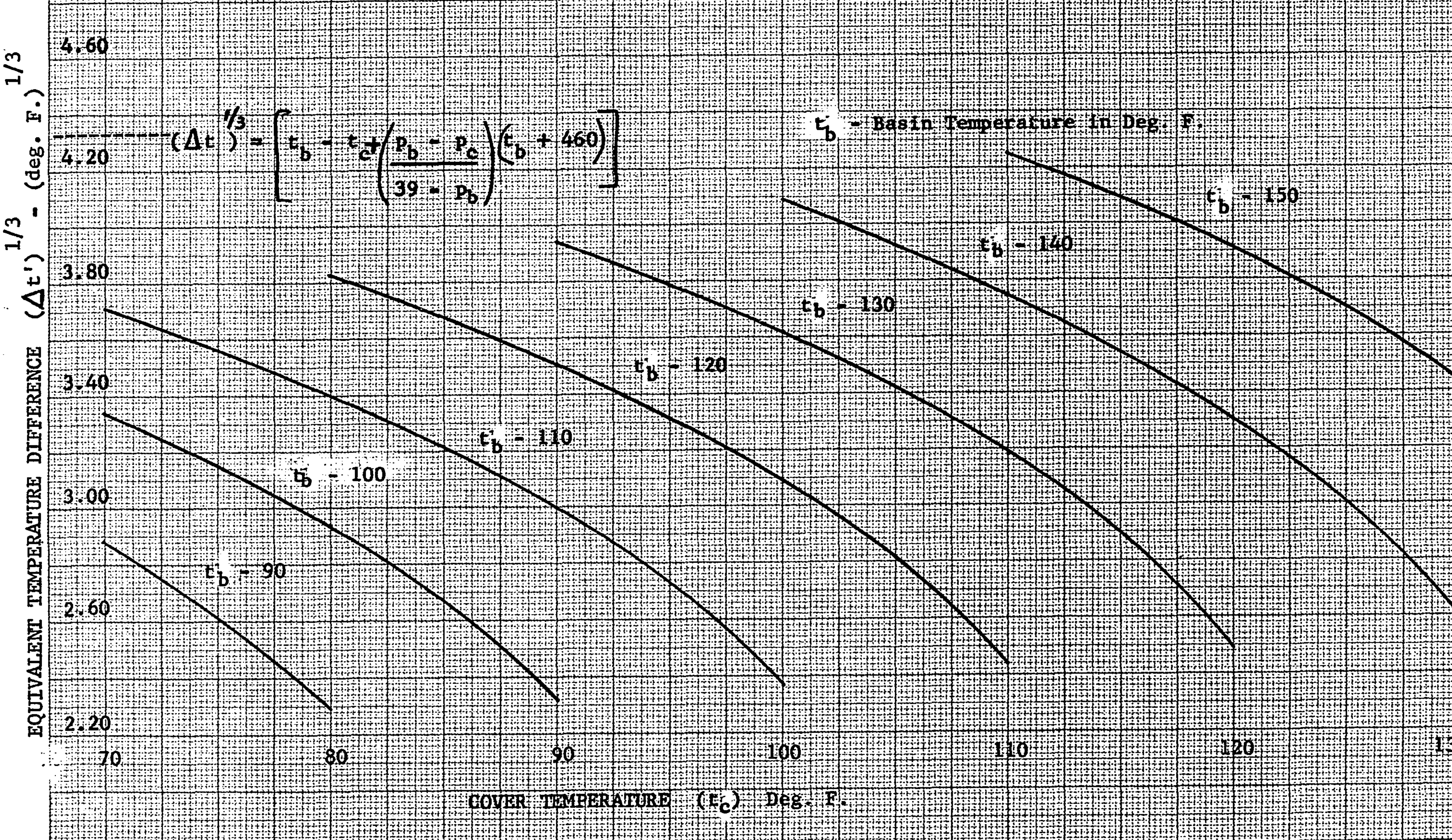
THE EQUIVALENT TEMPERATURE DIFFERENCE FOR DOUBLE CONCENTRATED SEA WATER

ESTIMATION OF THE EQUIVALENT TEMPERATURE DIFFERENCE FOR USE IN THE CALCULATION OF CONVECTIVE HEAT TRANSFER FROM SOLAR STILL BRINE TO THE COVER AND FOR CALCULATING THE HEAT TRANSFER FOR EVAPORATION AS A FUNCTION OF BASIN AND COVER TEMPERATURES.



THE EQUIVALENT TEMPERATURE DIFFERENCE FOR TRIPLE CONCENTRATED SEA WATER

ESTIMATION OF THE EQUIVALENT TEMPERATURE DIFFERENCE FOR USE IN THE CALCULATION OF CONVECTIVE HEAT TRANSFER FROM SOLAR STILL BRINE TO THE COVER AND FOR CALCULATING THE HEAT TRANSFER FOR EVAPORATION AS A FUNCTION OF BASIN AND COVER TEMPERATURES.



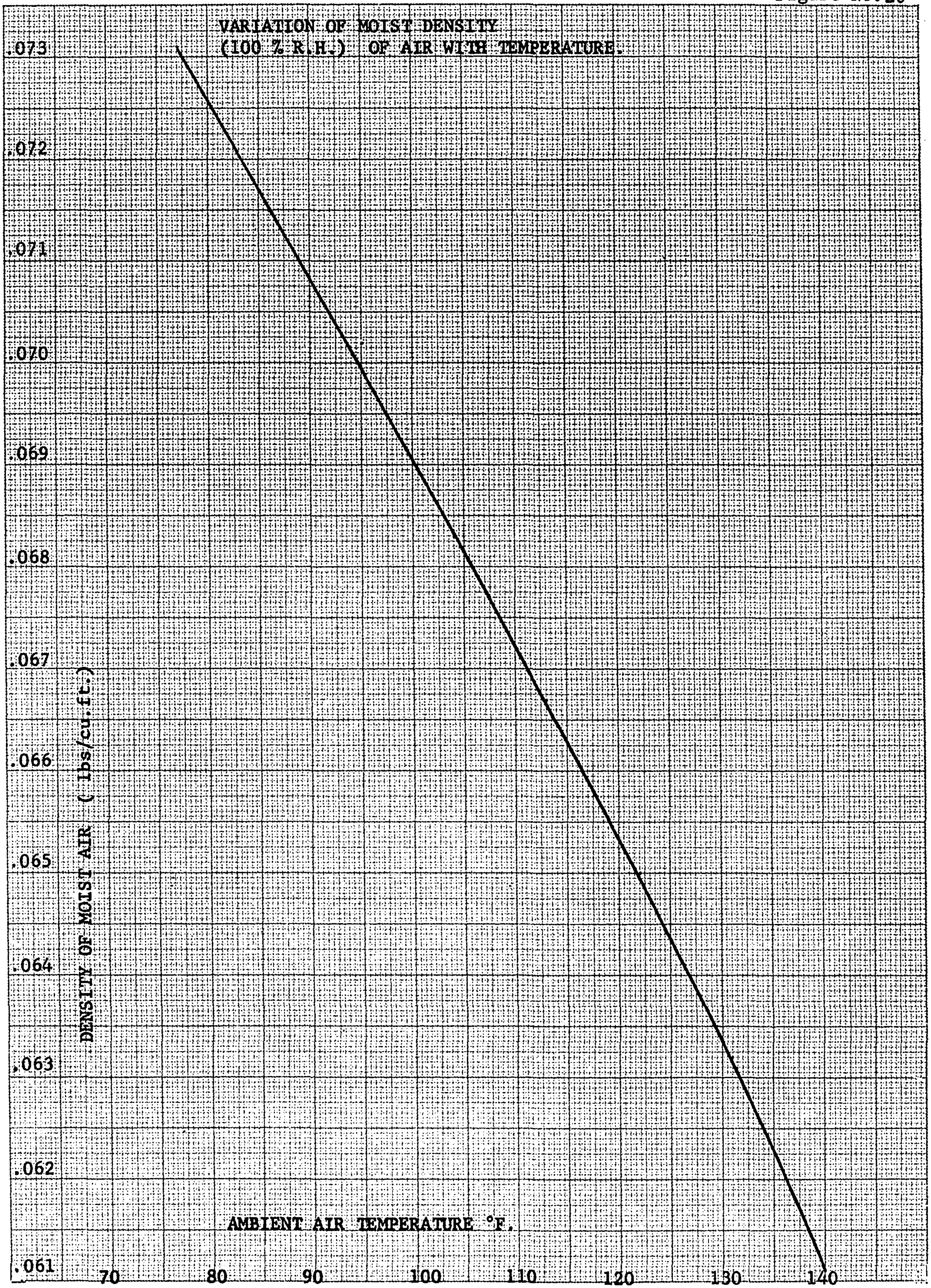
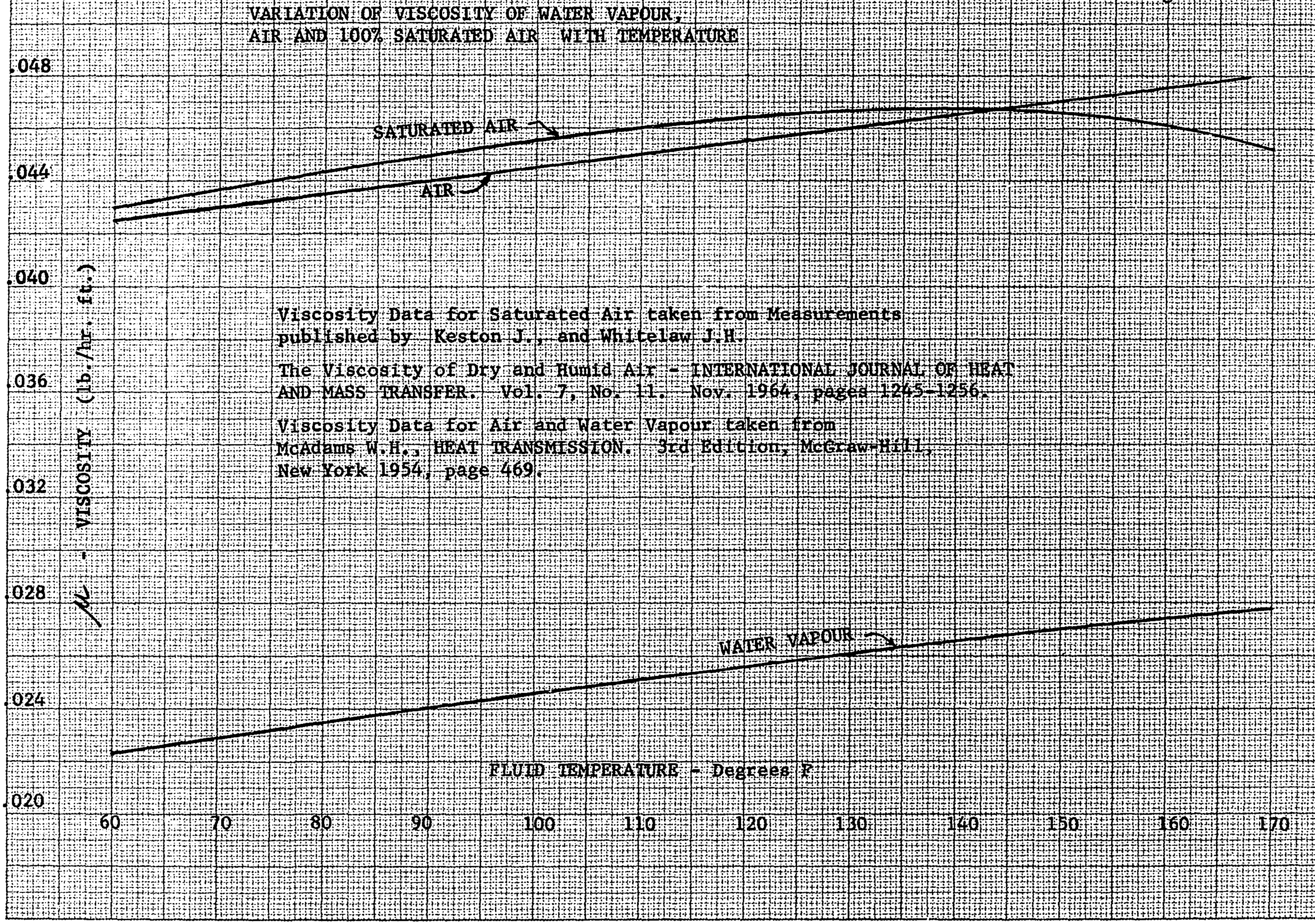
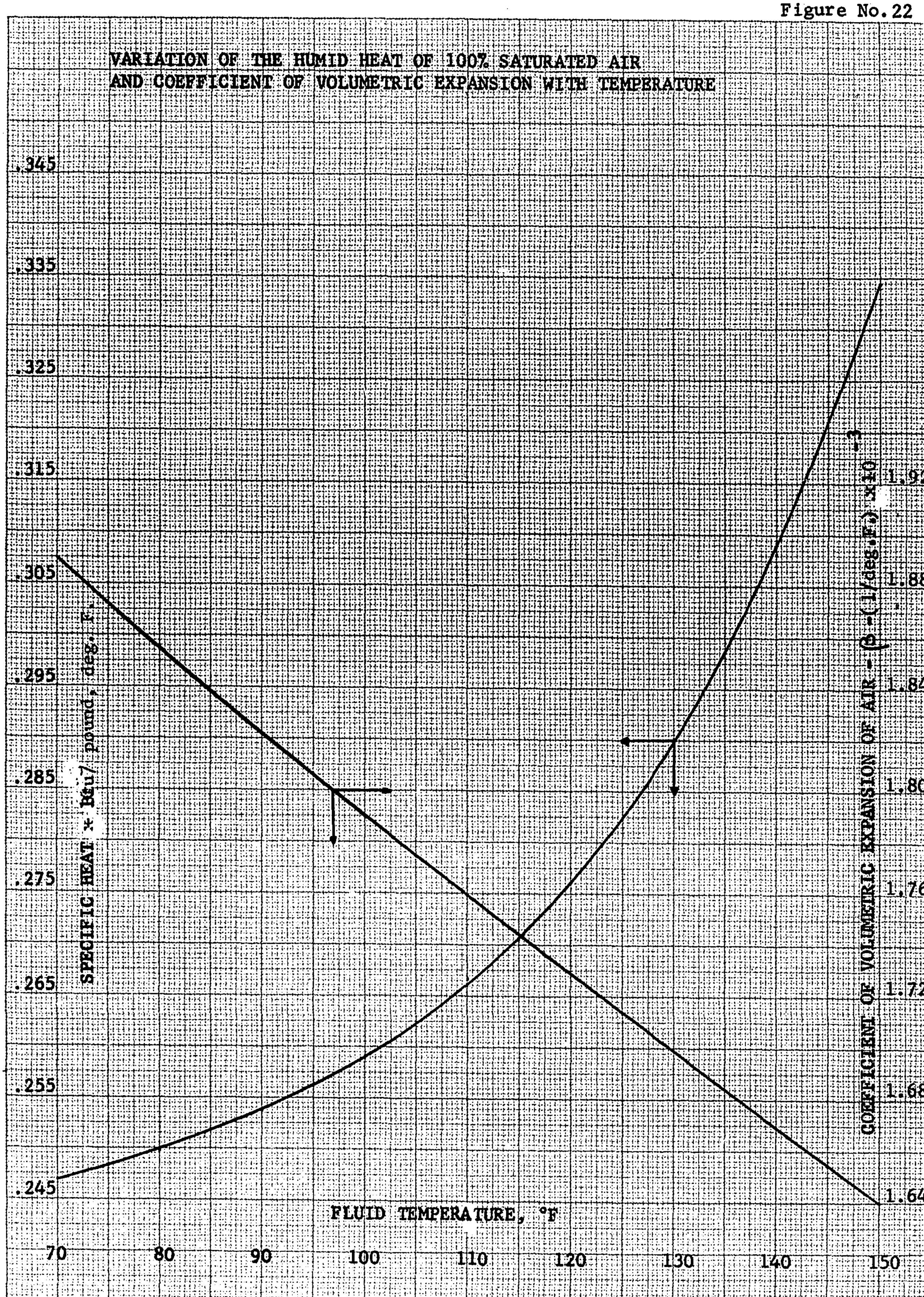

VARIATION OF MOIST DENSITY
(100 % R.H.) OF AIR WITH TEMPERATURE.
DENSITY OF MOIST AIR (lbs/cu.ft.)
.073
.072
.071
.070
.069
.068
.067
.066
.065
.064
.063
.062
.061
AMBIENT AIR TEMPERATURE °F.
70
80
90
100
110
120
130
140

Figure No. 21


VARIATION OF VISCOSITY OF WATER VAPOUR,
AIR AND 100% SATURATED AIR WITH TEMPERATURE
SATURATED AIR
AIR
WATER VAPOUR
Viscosity Data for Saturated Air taken from Measurements
published by Keston J., and Whitelaw J.H.
The Viscosity of Dry and Humid Air - INTERNATIONAL JOURNAL OF HEAT
AND MASS TRANSFER. Vol. 7, No. 11. Nov. 1964, pages 1245-1256.
Viscosity Data for Air and Water Vapour taken from
McAdams W.H., HEAT TRANSMISSION. 3rd Edition, McGraw-Hill,
New York 1954, page 469.
μ - VISCOSITY (lb./hr. ft.)
.048
.044
.040
.036
.032
.028
.024
.020
FLUID TEMPERATURE - Degrees F
60
70
80
90
100
110
120
130
140
150
160
170


VARIATION OF THE HUMID HEAT OF 100% SATURATED AIR
AND COEFFICIENT OF VOLUMETRIC EXPANSION WITH TEMPERATURE
SPECIFIC HEAT - Btu/ pound, deg. F.
COEFFICIENT OF VOLUMETRIC EXPANSION OF AIR - β - (1/deg.F.) x10^-3
FLUID TEMPERATURE, °F
.345
.335
.325
.315
.305
.295
.285
.275
.265
.255
.245
1.92
1.88
1.84
1.80
1.76
1.72
1.68
1.64
70
80
90
100
110
120
130
140
150

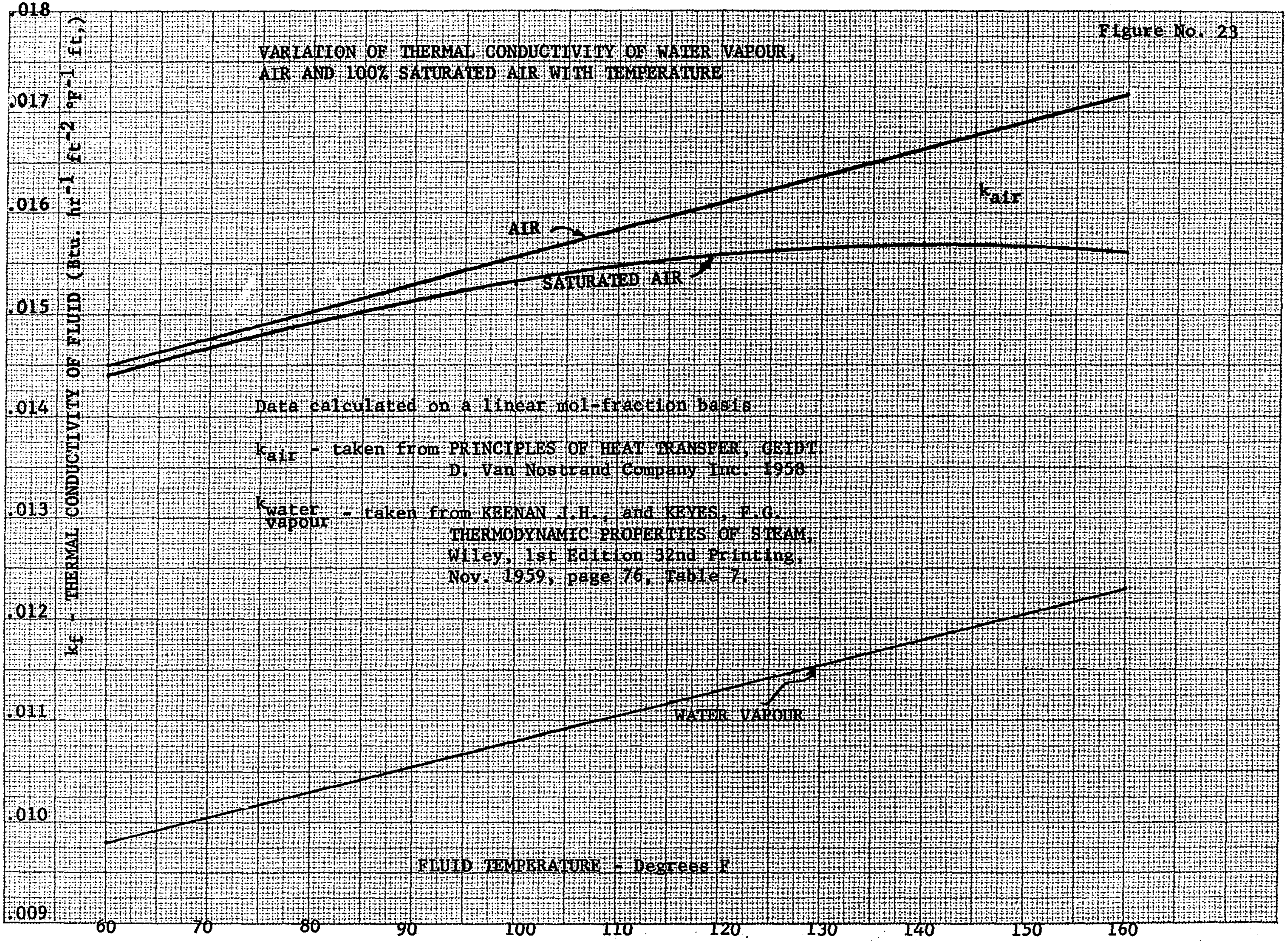
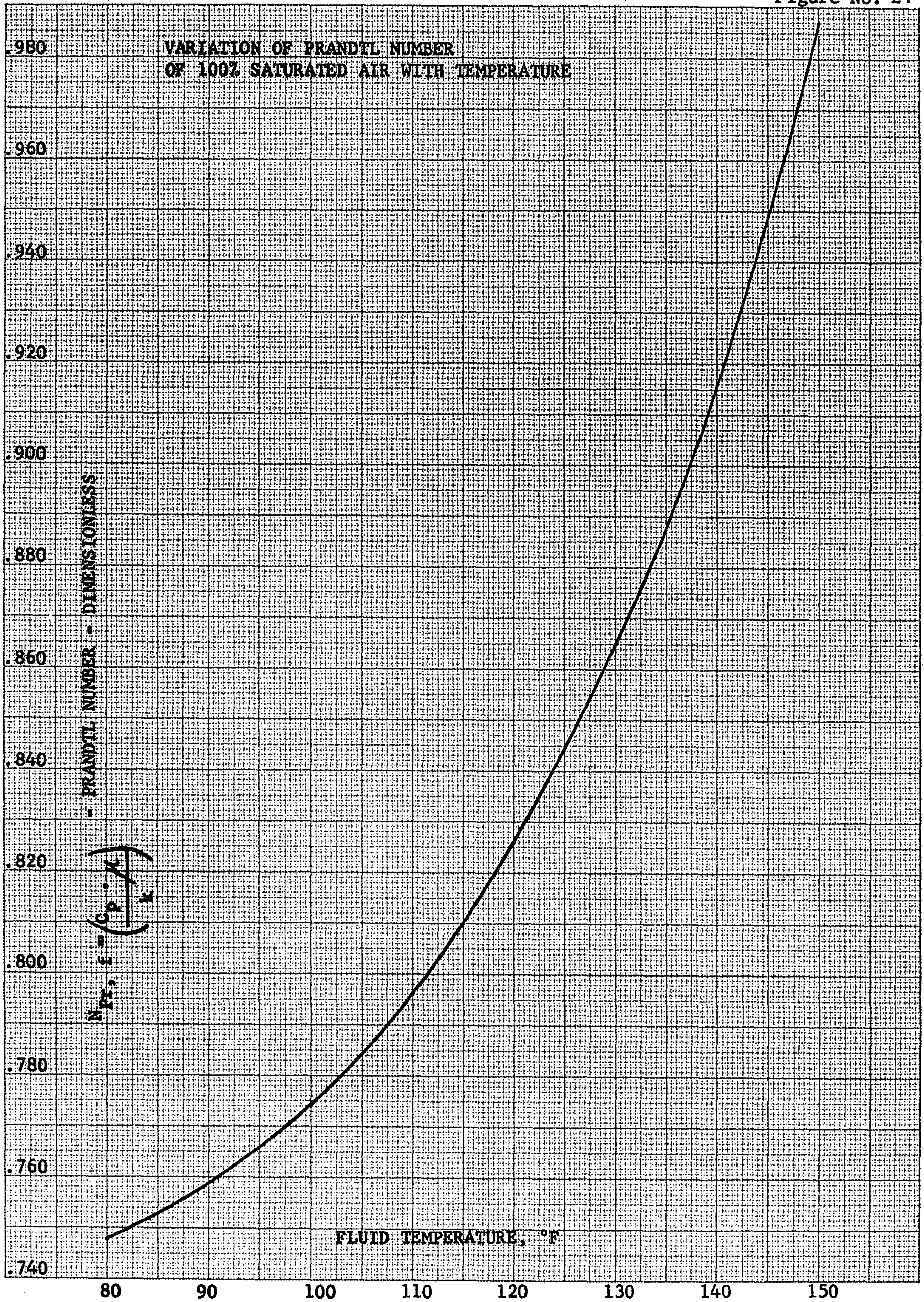
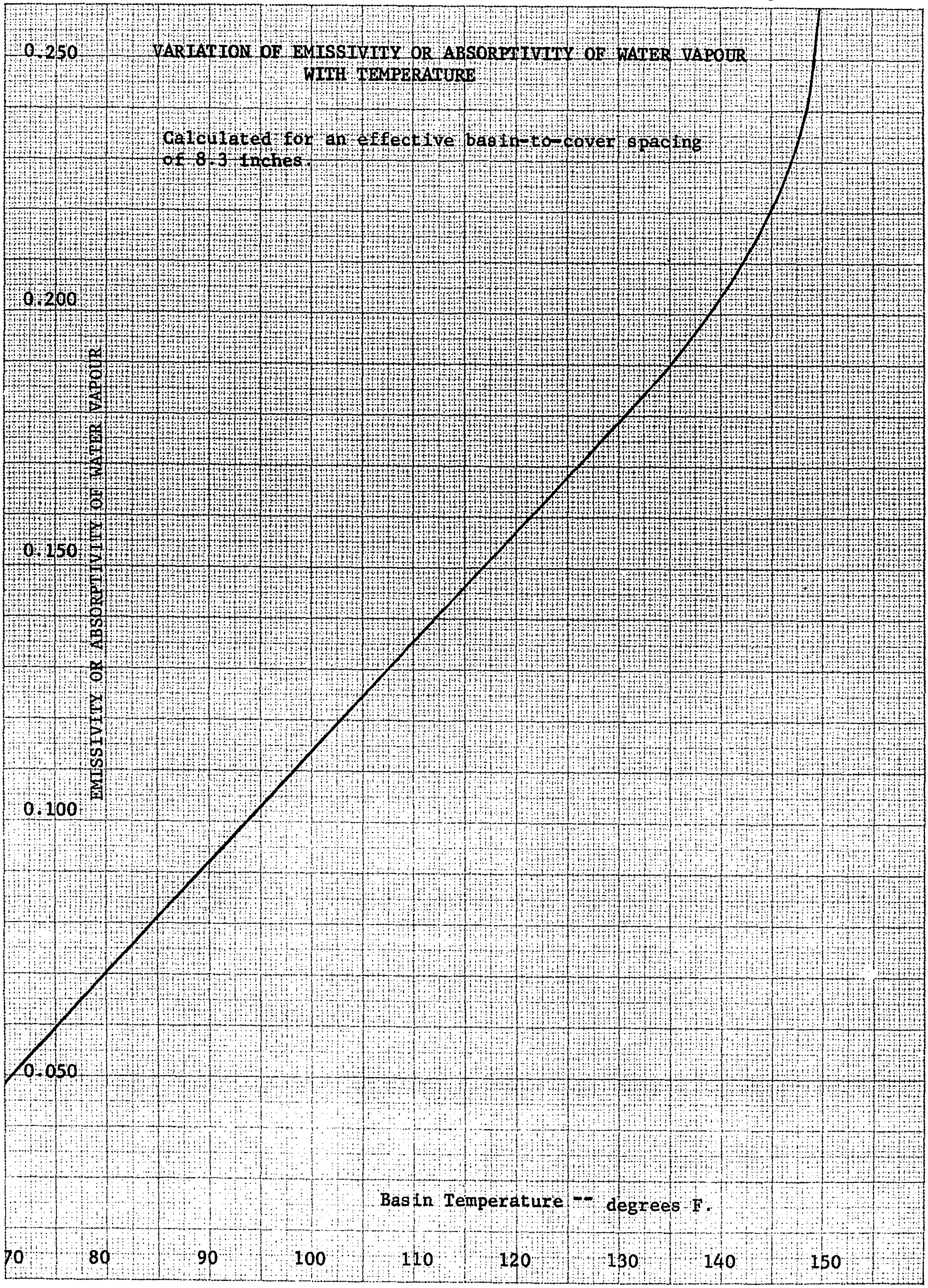
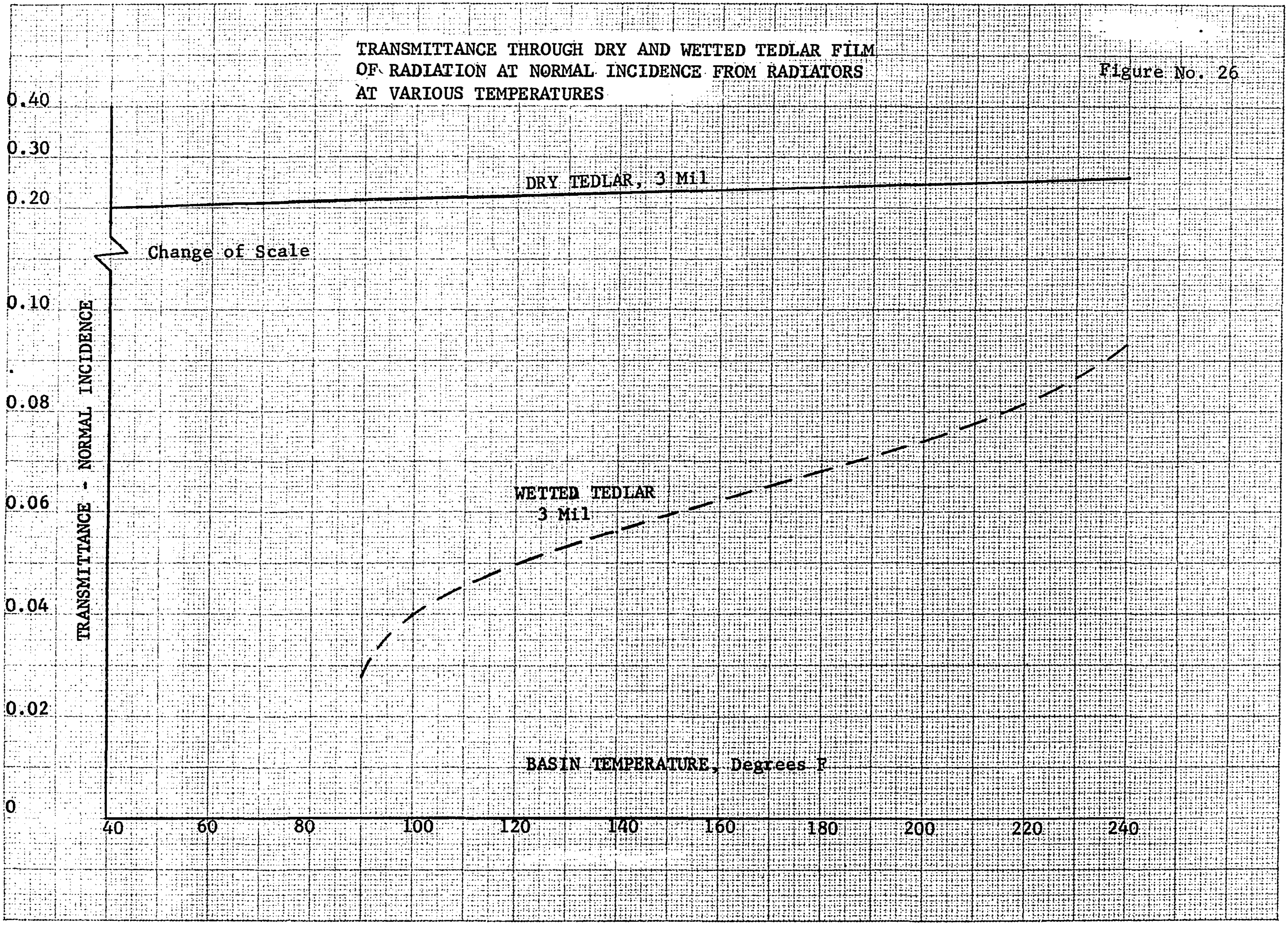


Figure No. 23
VARIATION OF THERMAL CONDUCTIVITY OF WATER VAPOUR,
AIR AND 100% SATURATED AIR WITH TEMPERATURE
AIR
SATURATED AIR
k air
Data calculated on a linear mol-fraction basis
k air - taken from PRINCIPLES OF HEAT TRANSFER, GEIDT.
D. Van Nostrand Company Inc. 1958
k water vapour - taken from KEENAN J.H., and KEYES, F.G.
THERMODYNAMIC PROPERTIES OF STEAM,
Wiley, 1st Edition 32nd Printing,
Nov. 1959, page 76, Table 7.
WATER VAPOUR
FLUID TEMPERATURE - Degrees F
k f - THERMAL CONDUCTIVITY OF FLUID (Btu. hr-1 ft-2 °F-1 ft.)
.018
.017
.016
.015
.014
.013
.012
.011
.010
.009
60
70
80
90
100
110
120
130
140
150
160

Figure No. 24


VARIATION OF PRANDTL NUMBER
OF 100% SATURATED AIR WITH TEMPERATURE
.980
.960
.940
.920
.900
.880
.860
.840
.820
.800
.780
.760
.740
$N_{Pr}, \epsilon = \left(\frac{C_p \cdot \mu}{k}\right)$ - PRANDTL NUMBER - DIMENSIONLESS
FLUID TEMPERATURE, °F
80
90
100
110
120
130
140
150


0.250
VARIATION OF EMISSIVITY OR ABSORPTIVITY OF WATER VAPOUR
WITH TEMPERATURE
Calculated for an effective basin-to-cover spacing
of 8.3 inches.
0.200
0.150
0.100
0.050
EMISSIVITY OR ABSORPTIVITY OF WATER VAPOUR
Basin Temperature -- degrees F.
70
80
90
100
110
120
130
140
150



TRANSMITTANCE THROUGH DRY AND WETTED TEDLAR FILM OF RADIATION AT NORMAL INCIDENCE FROM RADIATORS AT VARIOUS TEMPERATURES
Figure No. 26
DRY TEDLAR, 3 Mil
Change of Scale
WETTED TEDLAR 3 Mil
TRANSMITTANCE - NORMAL INCIDENCE
BASIN TEMPERATURE, Degrees F
0.40
0.30
0.20
0.10
0.08
0.06
0.04
0.02
0
40
60
80
100
120
140
160
180
200
220
240

Figure No. 27

VARIATION OF RADIATION HEAT TRANSFER
FROM SOLAR STILL BASIN TO SKY.

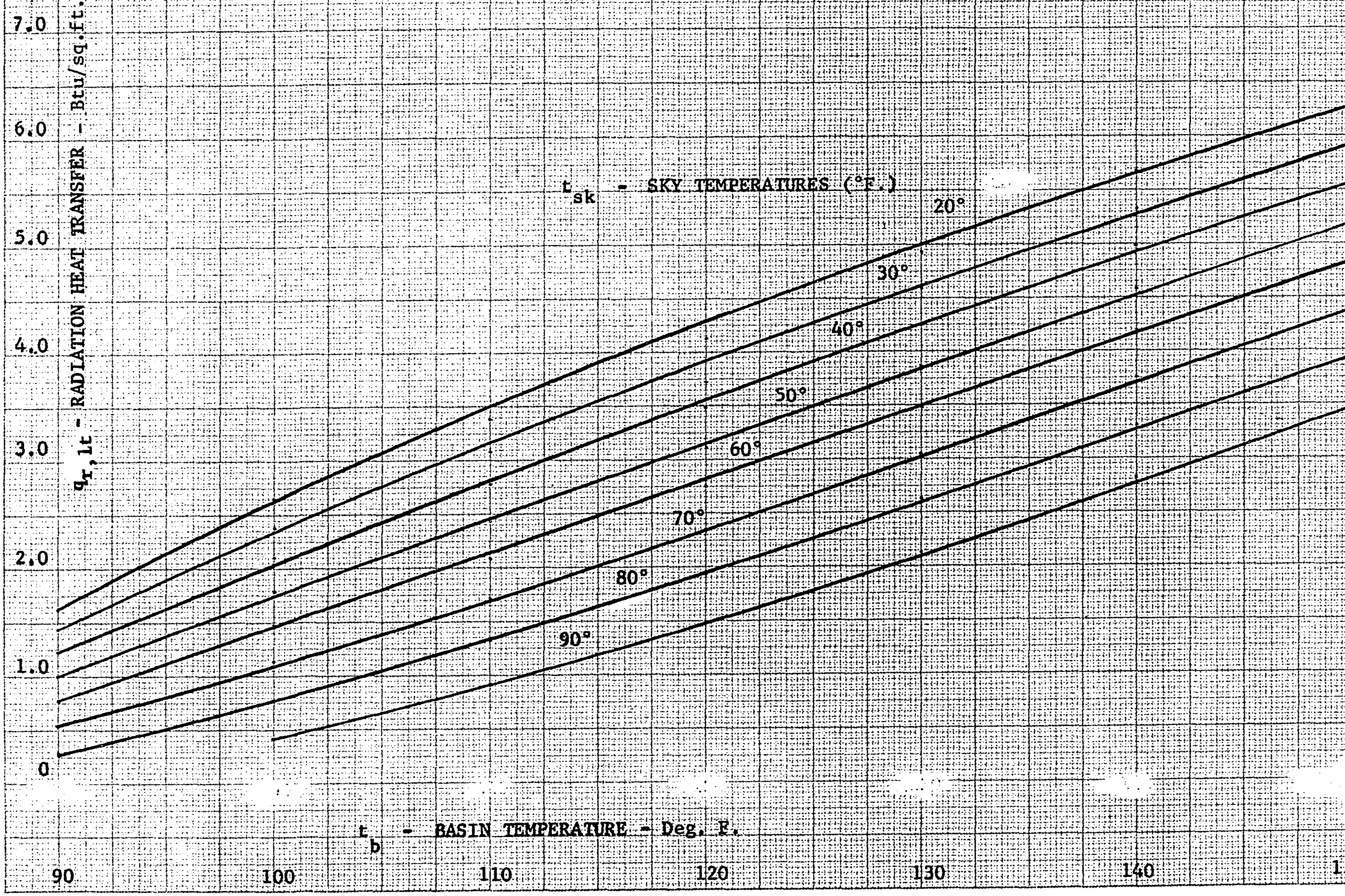
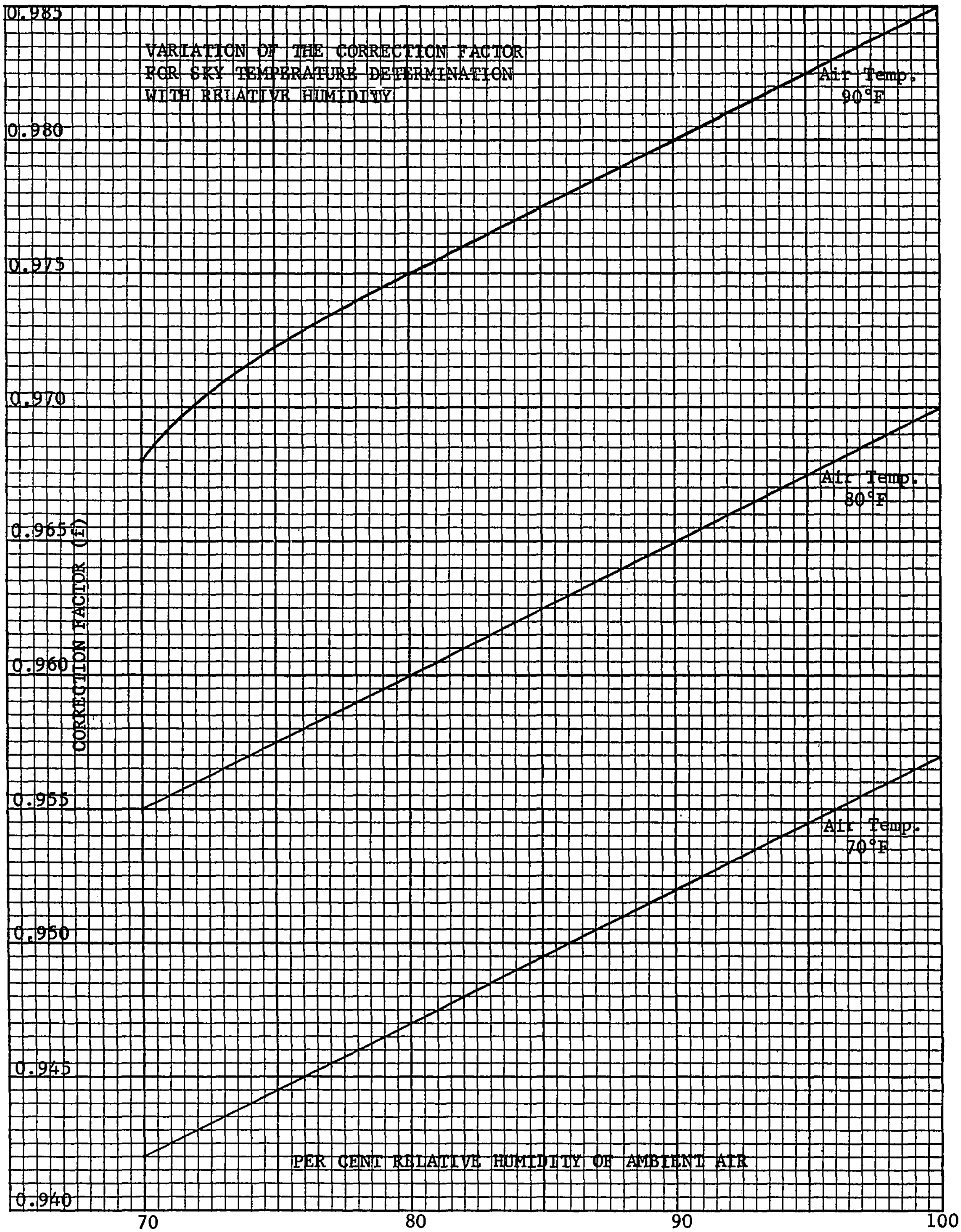
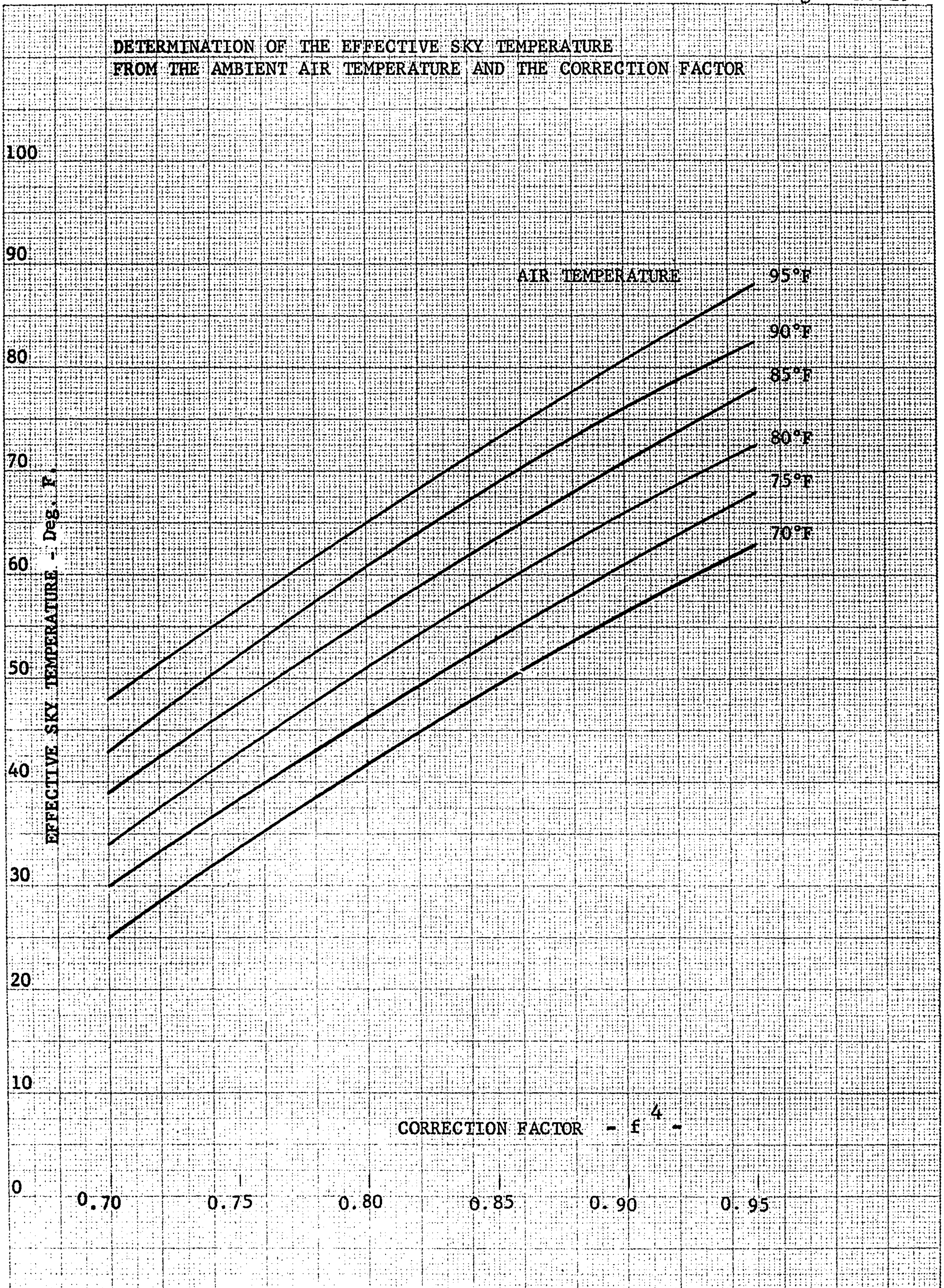


Figure No. 28


VARIATION OF THE CORRECTION FACTOR
FOR SKY TEMPERATURE DETERMINATION
WITH RELATIVE HUMIDITY
Air Temp.
90°F
Air Temp.
80°F
Air Temp.
70°F
CORRECTION FACTOR (f)
PER CENT RELATIVE HUMIDITY OF AMBIENT AIR
0.985
0.980
0.975
0.970
0.965
0.960
0.955
0.950
0.945
0.940
70
80
90
100


DETERMINATION OF THE EFFECTIVE SKY TEMPERATURE
FROM THE AMBIENT AIR TEMPERATURE AND THE CORRECTION FACTOR
EFFECTIVE SKY TEMPERATURE - Deg. F.
100
90
80
70
60
50
40
30
20
10
0
AIR TEMPERATURE
95°F
90°F
85°F
80°F
75°F
70°F
CORRECTION FACTOR - f4 -
0.70
0.75
0.80
0.85
0.90
0.95

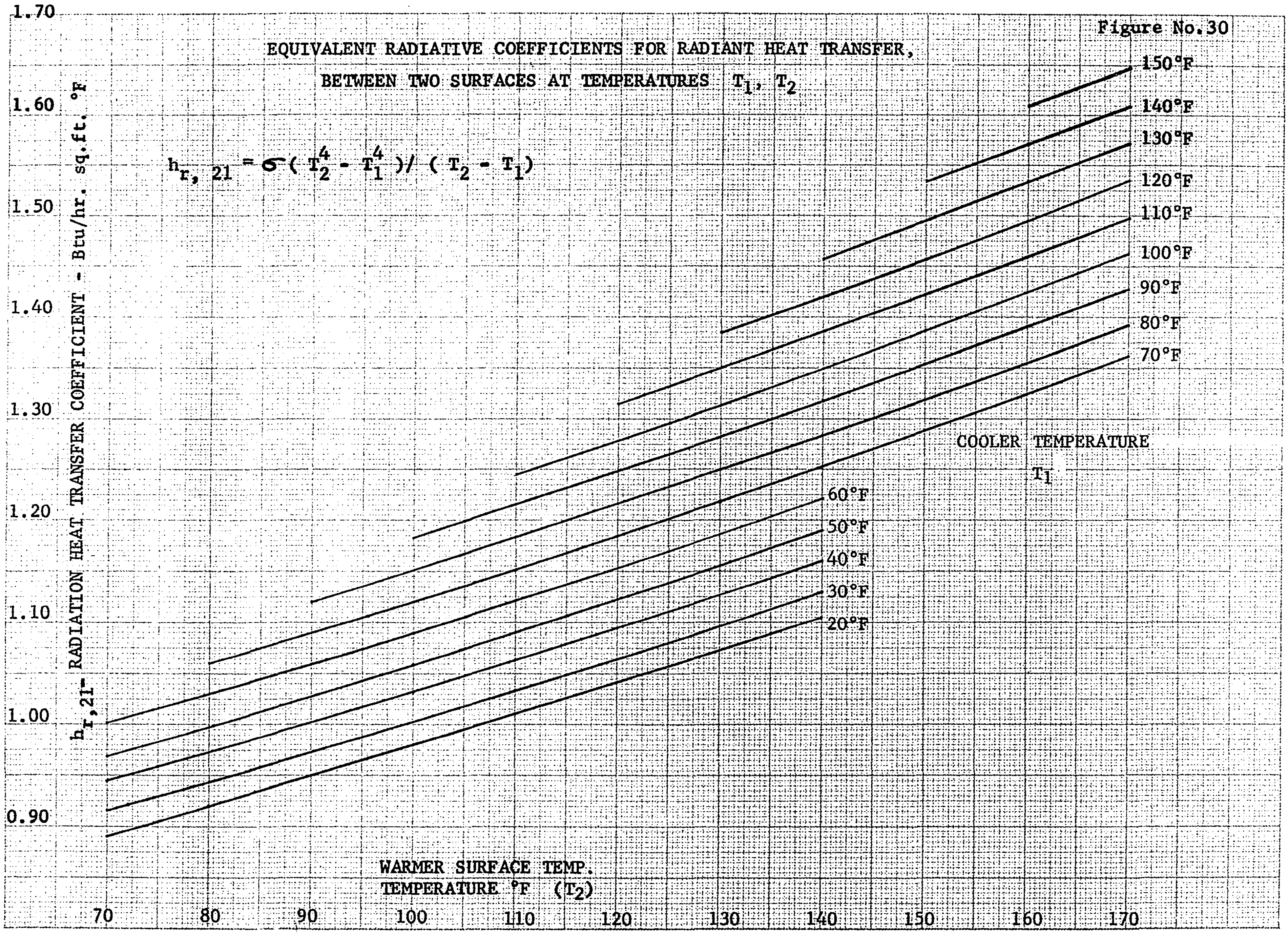


Figure No. 30
EQUIVALENT RADIATIVE COEFFICIENTS FOR RADIANT HEAT TRANSFER,
BETWEEN TWO SURFACES AT TEMPERATURES T_1, T_2
$h_{r,21} = \sigma(T_2^4 - T_1^4)/(T_2 - T_1)$
$h_{r,21}$ - RADIATION HEAT TRANSFER COEFFICIENT - Btu/hr. sq.ft. °F
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
150°F
140°F
130°F
120°F
110°F
100°F
90°F
80°F
70°F
60°F
50°F
40°F
30°F
20°F
COOLER TEMPERATURE
T_1
WARMER SURFACE TEMP.
TEMPERATURE °F (T_2)
70
80
90
100
110
120
130
140
150
160
170

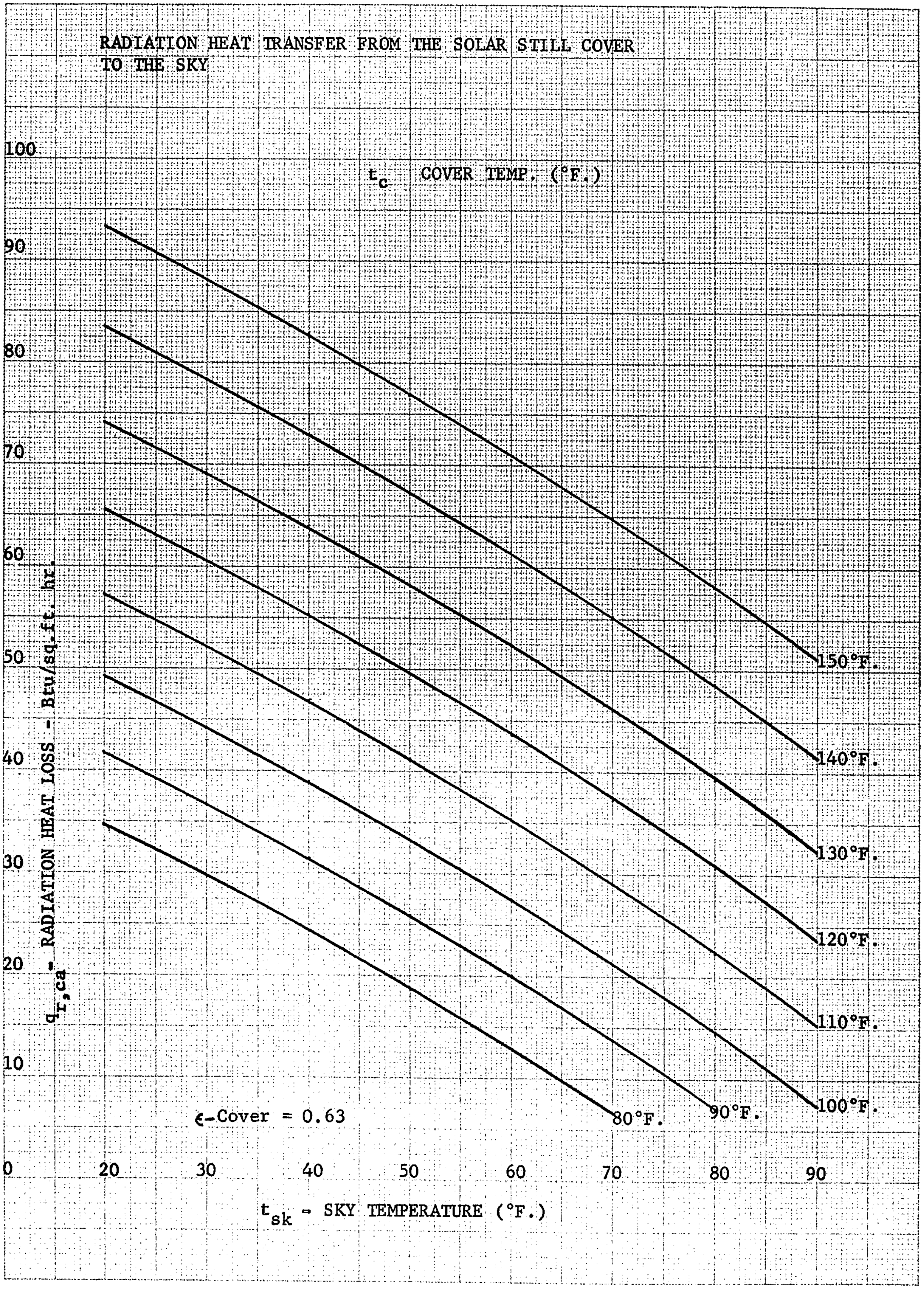
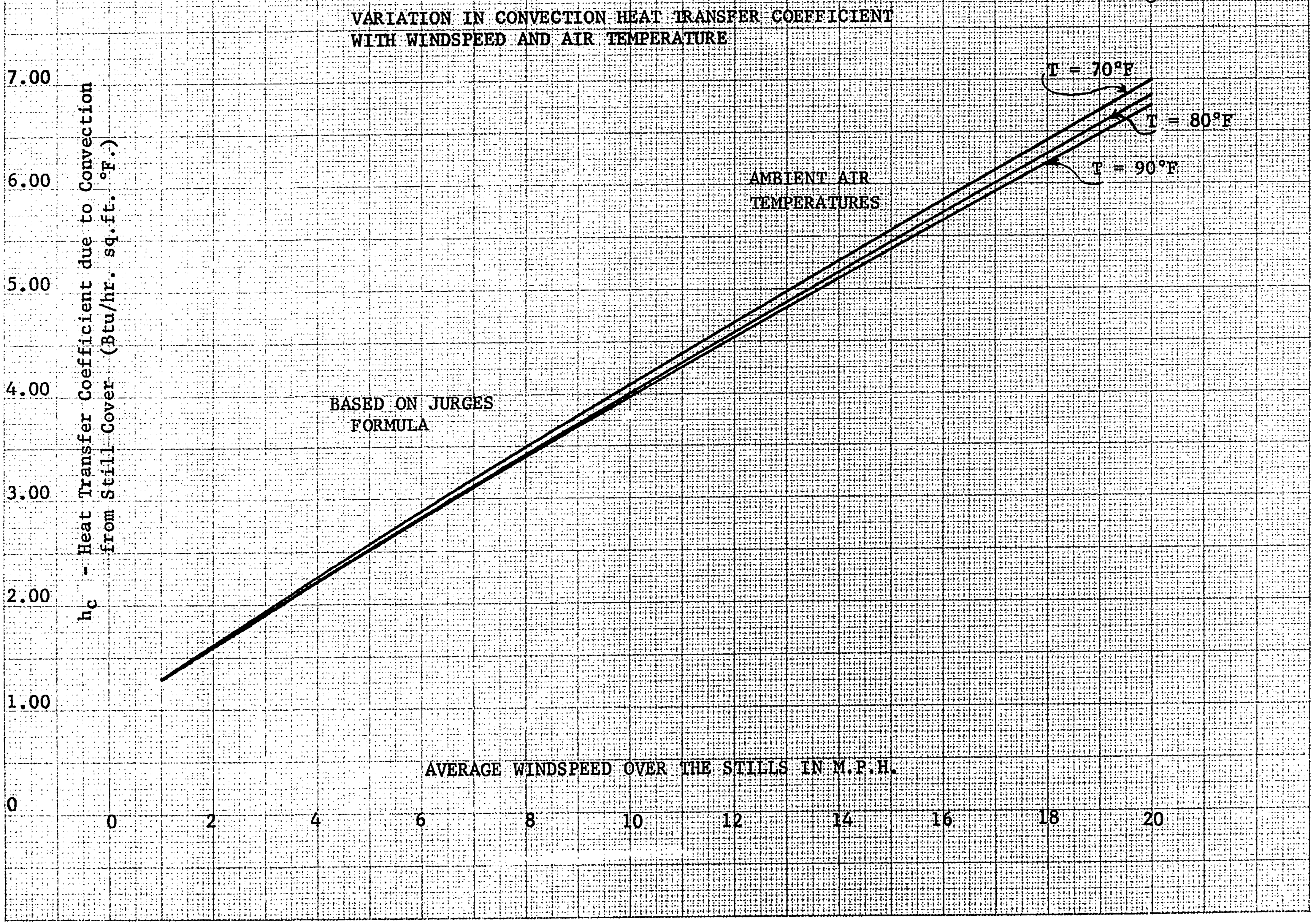
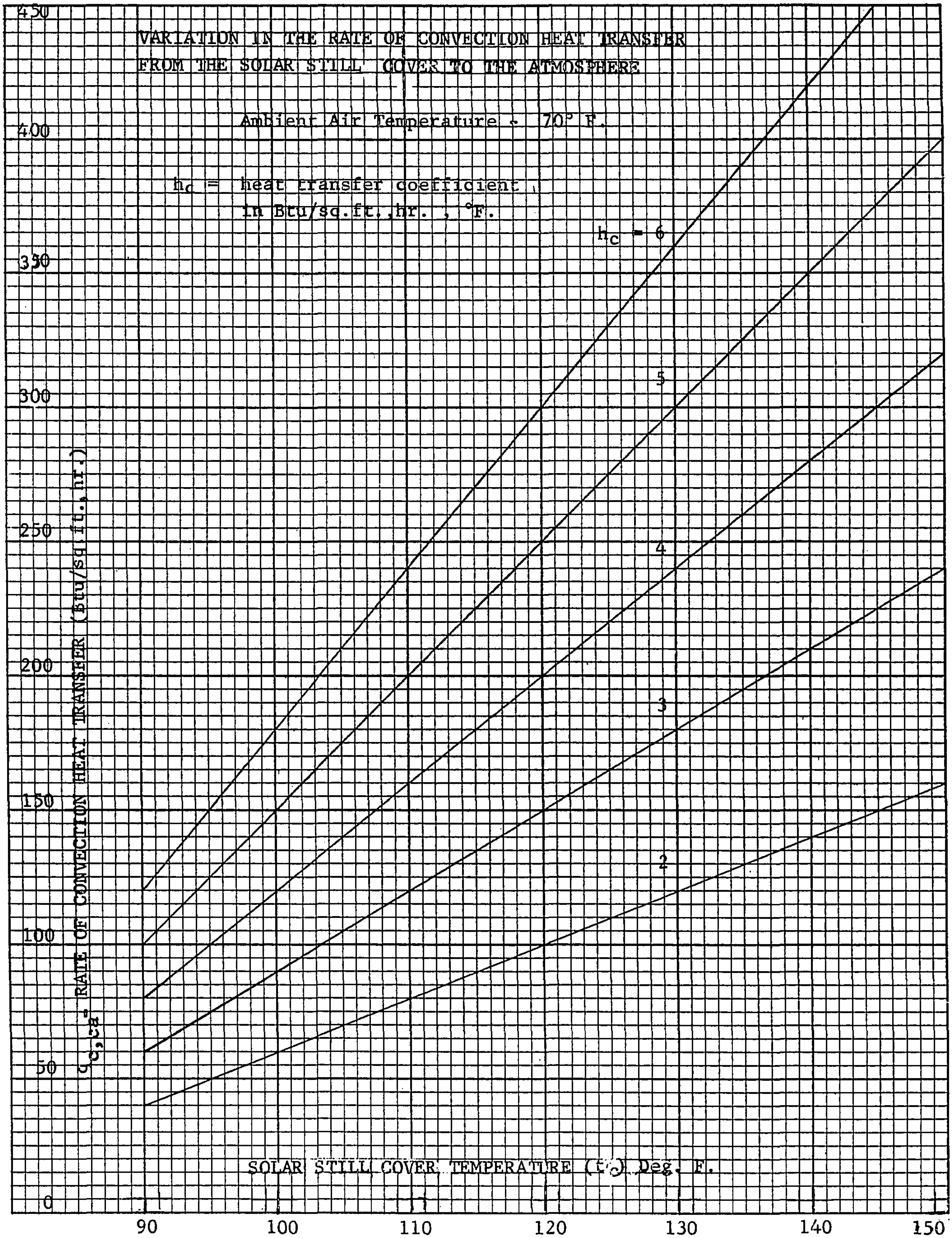
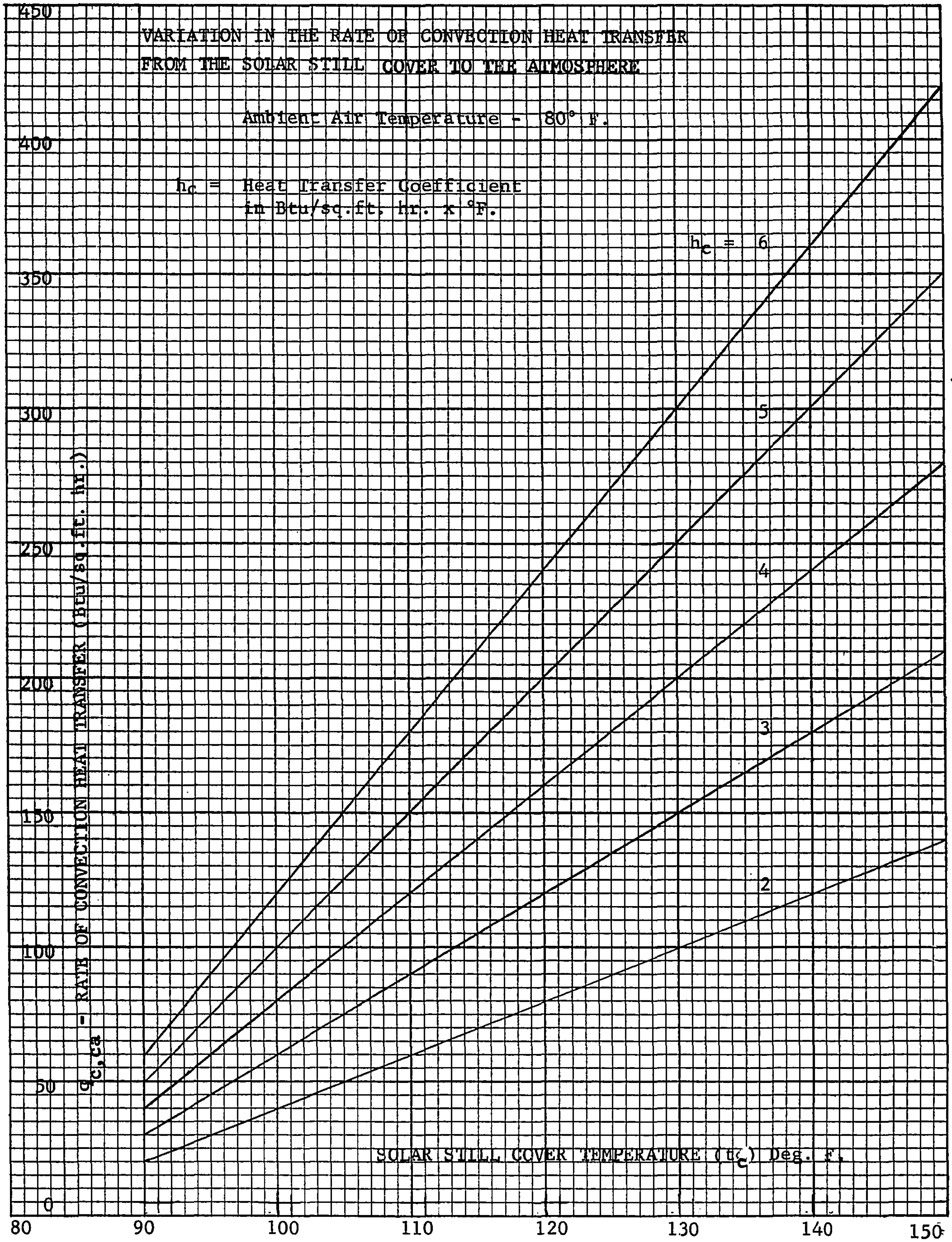

RADIATION HEAT TRANSFER FROM THE SOLAR STILL COVER TO THE SKY
t_c COVER TEMP. (°F.)
150°F.
140°F.
130°F.
120°F.
110°F.
100°F.
90°F.
80°F.
ϵ-Cover = 0.63
$q_{r,ca}$ - RADIATION HEAT LOSS - Btu/sq.ft. hr.
0
10
20
30
40
50
60
70
80
90
100
t_{sk} - SKY TEMPERATURE (°F.)

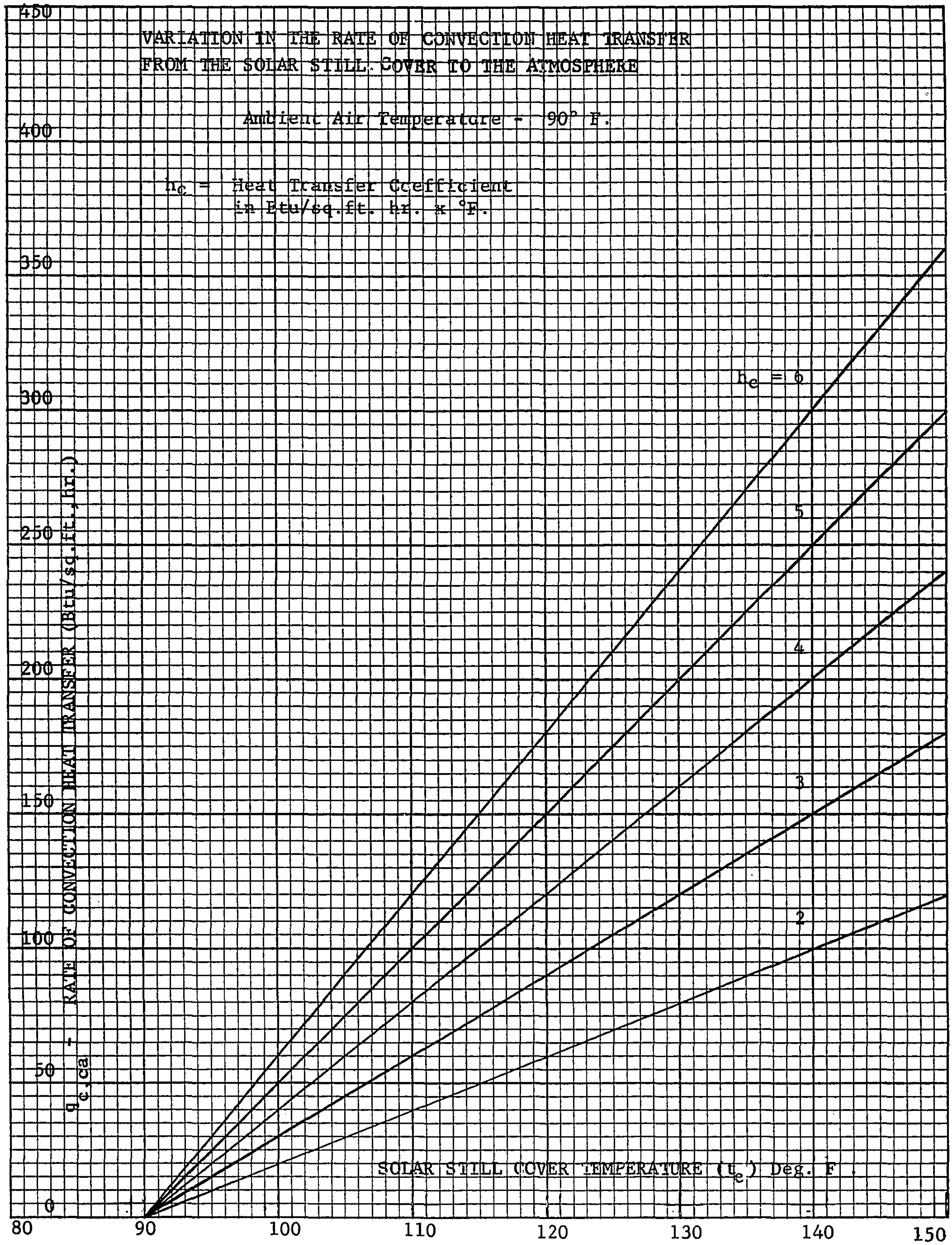
Figure No. 32



VARIATION IN CONVECTION HEAT TRANSFER COEFFICIENT
WITH WINDSPEED AND AIR TEMPERATURE
T = 70°F
T = 80°F
T = 90°F
AMBIENT AIR
TEMPERATURES
BASED ON JURGES
FORMULA
h_c - Heat Transfer Coefficient due to Convection
from Still Cover (Btu/hr. sq.ft. °F.)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0
AVERAGE WINDSPEED OVER THE STILLS IN M.P.H.
0
2
4
6
8
10
12
14
16
18
20


VARIATION IN THE RATE OF CONVECTION HEAT TRANSFER
FROM THE SOLAR STILL COVER TO THE ATMOSPHERE
Ambient Air Temperature - 70° F.
h_c = heat transfer coefficient
in Btu/sq.ft.,hr., °F.
h_c = 6
5
4
3
2
$q_{c,ca}$ - RATE OF CONVECTION HEAT TRANSFER (Btu/sq ft.,hr.)
SOLAR STILL COVER TEMPERATURE (t_c) Deg. F.
0
50
100
150
200
250
300
350
400
450
90
100
110
120
130
140
150


VARIATION IN THE RATE OF CONVECTION HEAT TRANSFER
FROM THE SOLAR STILL COVER TO THE ATMOSPHERE
Ambient Air Temperature - 80° F.
h_c = Heat Transfer Coefficient
in Btu/sq.ft. hr. x °F.
h_c = 6
5
4
3
2
$q_{c,ca}$ - RATE OF CONVECTION HEAT TRANSFER (Btu/sq.ft. hr.)
SOLAR STILL COVER TEMPERATURE (t_c) Deg. F.
450
400
350
300
250
200
150
100
50
0
80
90
100
110
120
130
140
150


VARIATION IN THE RATE OF CONVECTION HEAT TRANSFER
FROM THE SOLAR STILL COVER TO THE ATMOSPHERE
Ambient Air Temperature - 90° F.
h_c = Heat Transfer Coefficient in Btu/sq.ft. hr. x °F.
h_c = 6
5
4
3
2
$q_{c,ca}$ - RATE OF CONVECTION HEAT TRANSFER (Btu/sq.ft.,hr.)
SOLAR STILL COVER TEMPERATURE (t_c) Deg. F
0
50
100
150
200
250
300
350
400
450
80
90
100
110
120
130
140
150

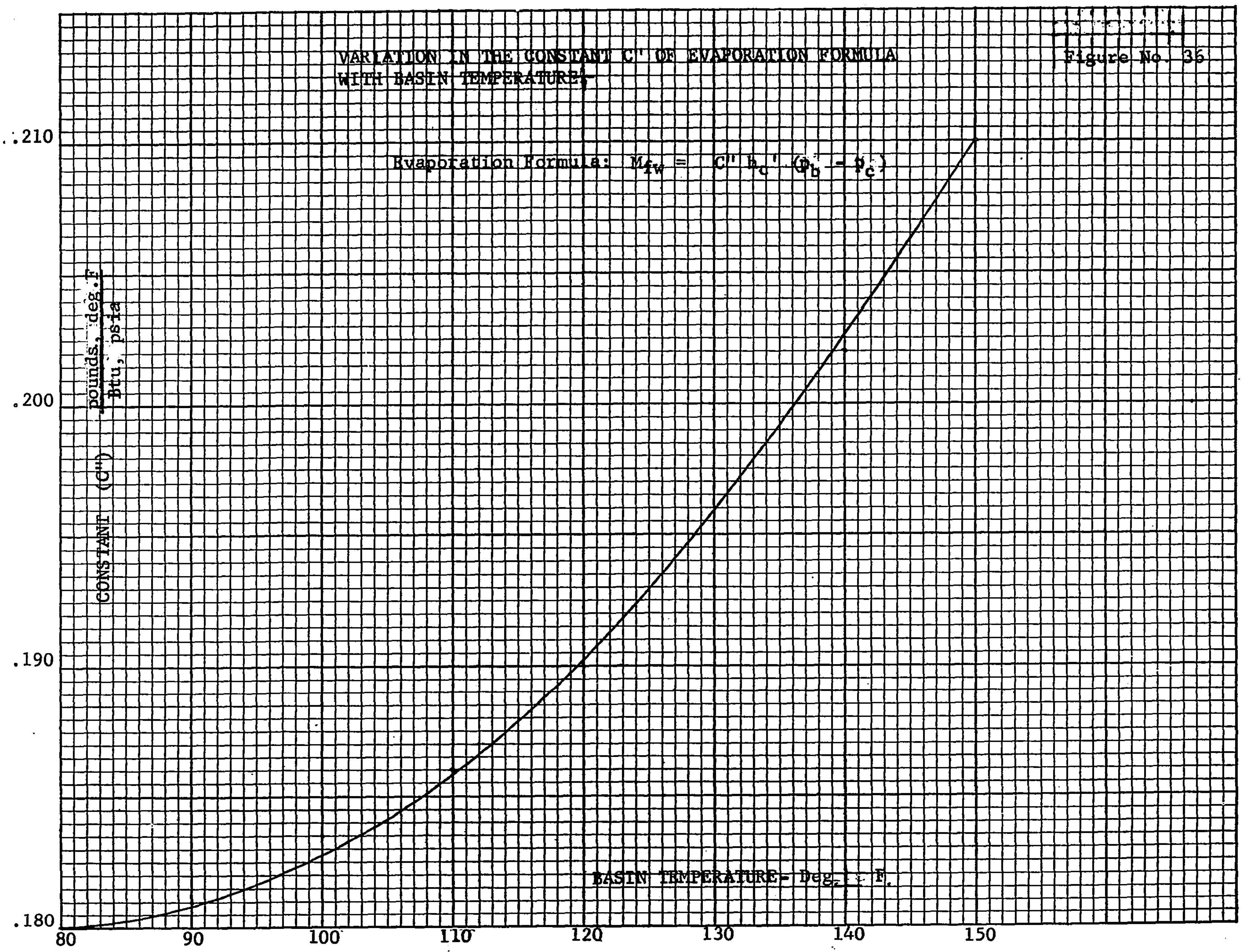


Figure No. 36
VARIATION IN THE CONSTANT C'' OF EVAPORATION FORMULA WITH BASIN TEMPERATURE
Evaporation Formula: M_fw = C'' h_c' (p_b - p_c)
CONSTANT (C'') pounds, deg. F / Btu, psia
.210
.200
.190
.180
80
90
100
110
120
130
140
150
BASIN TEMPERATURE - Deg. F.

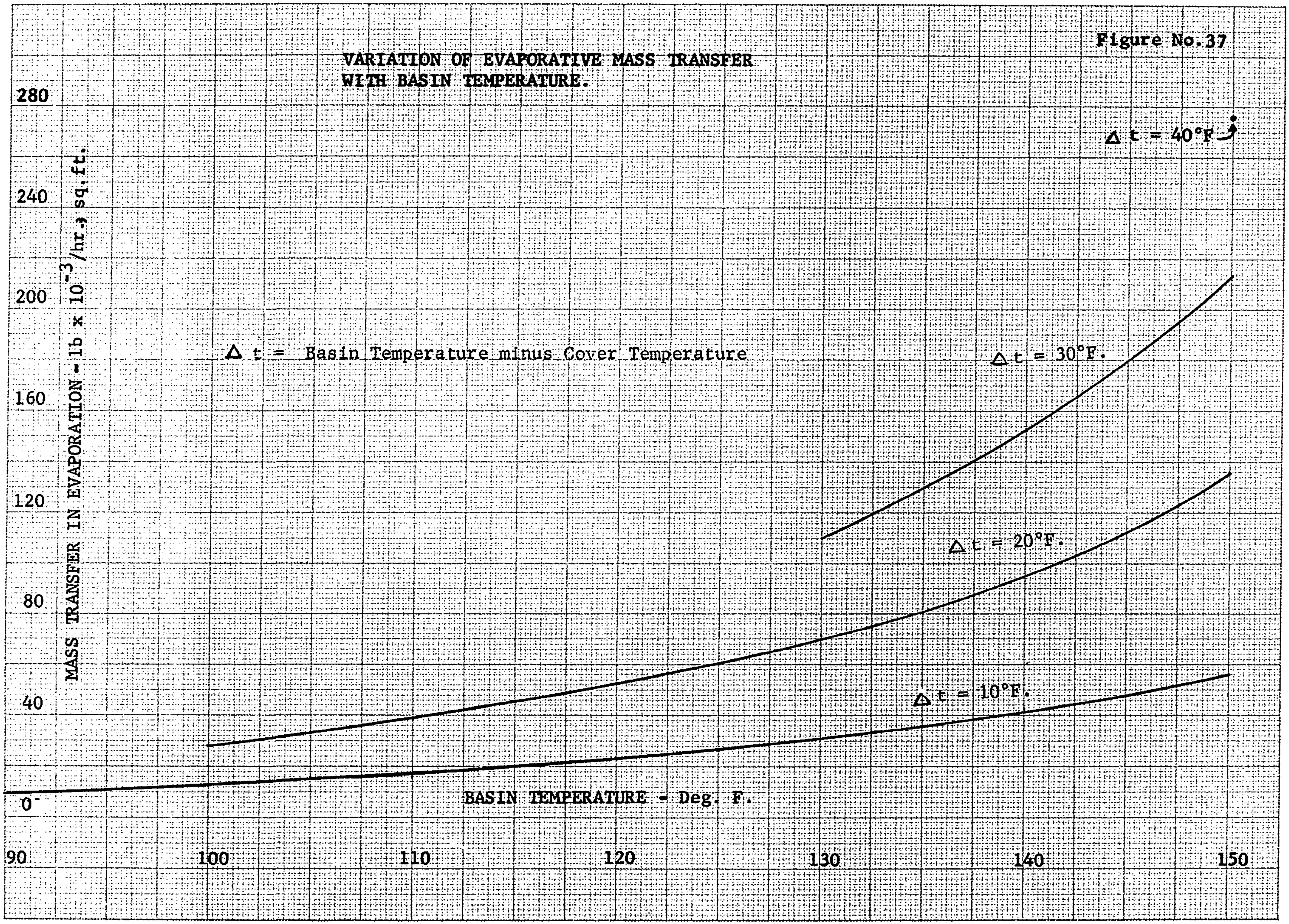


Figure No.37
VARIATION OF EVAPORATIVE MASS TRANSFER
WITH BASIN TEMPERATURE.
MASS TRANSFER IN EVAPORATION - lb x 10^-3/hr., sq.ft.
280
240
200
160
120
80
40
0
Δ t = 40°F
Δ t = Basin Temperature minus Cover Temperature
Δ t = 30°F.
Δ t = 20°F.
Δ t = 10°F.
BASIN TEMPERATURE - Deg. F.
90
100
110
120
130
140
150

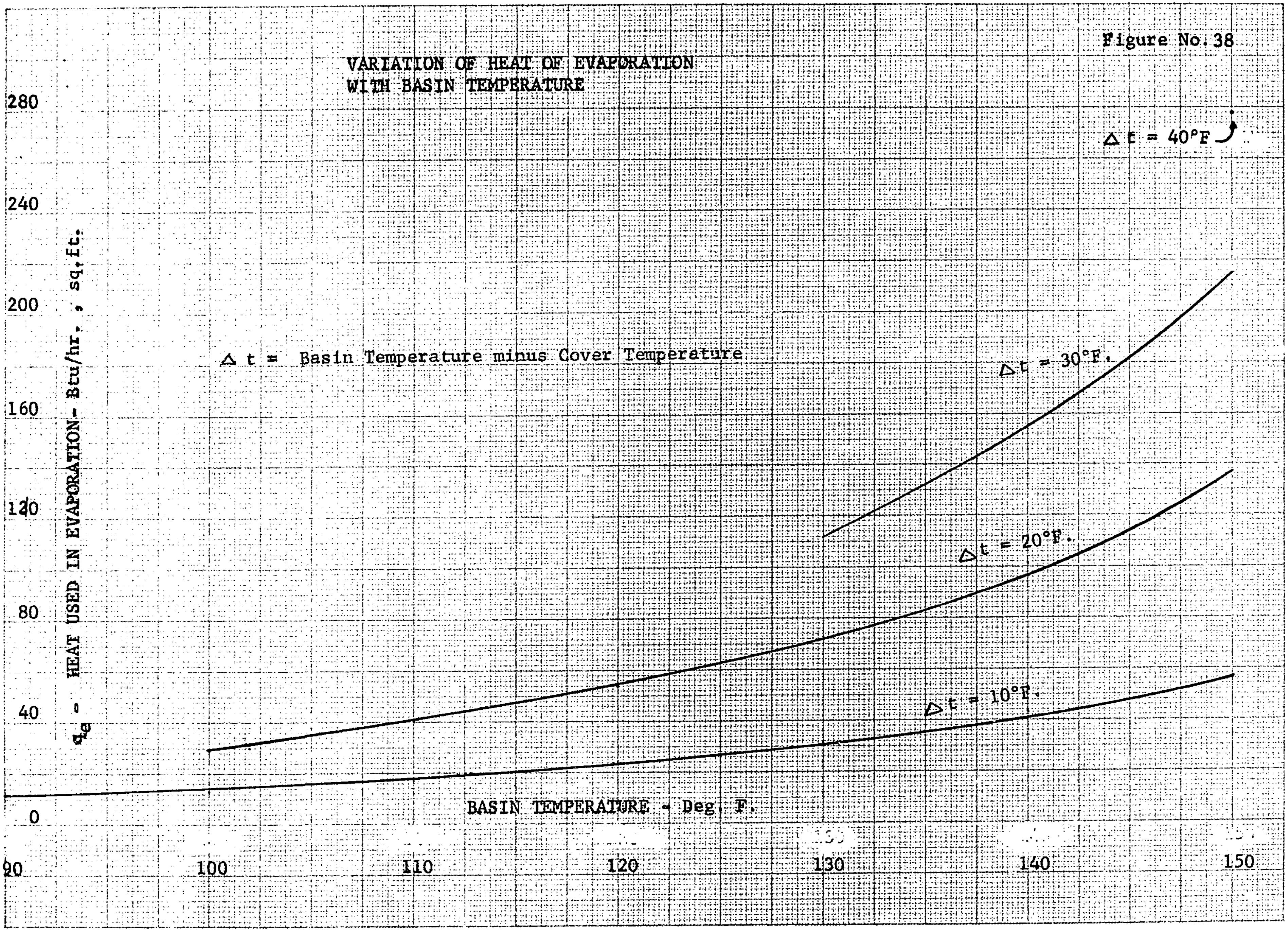
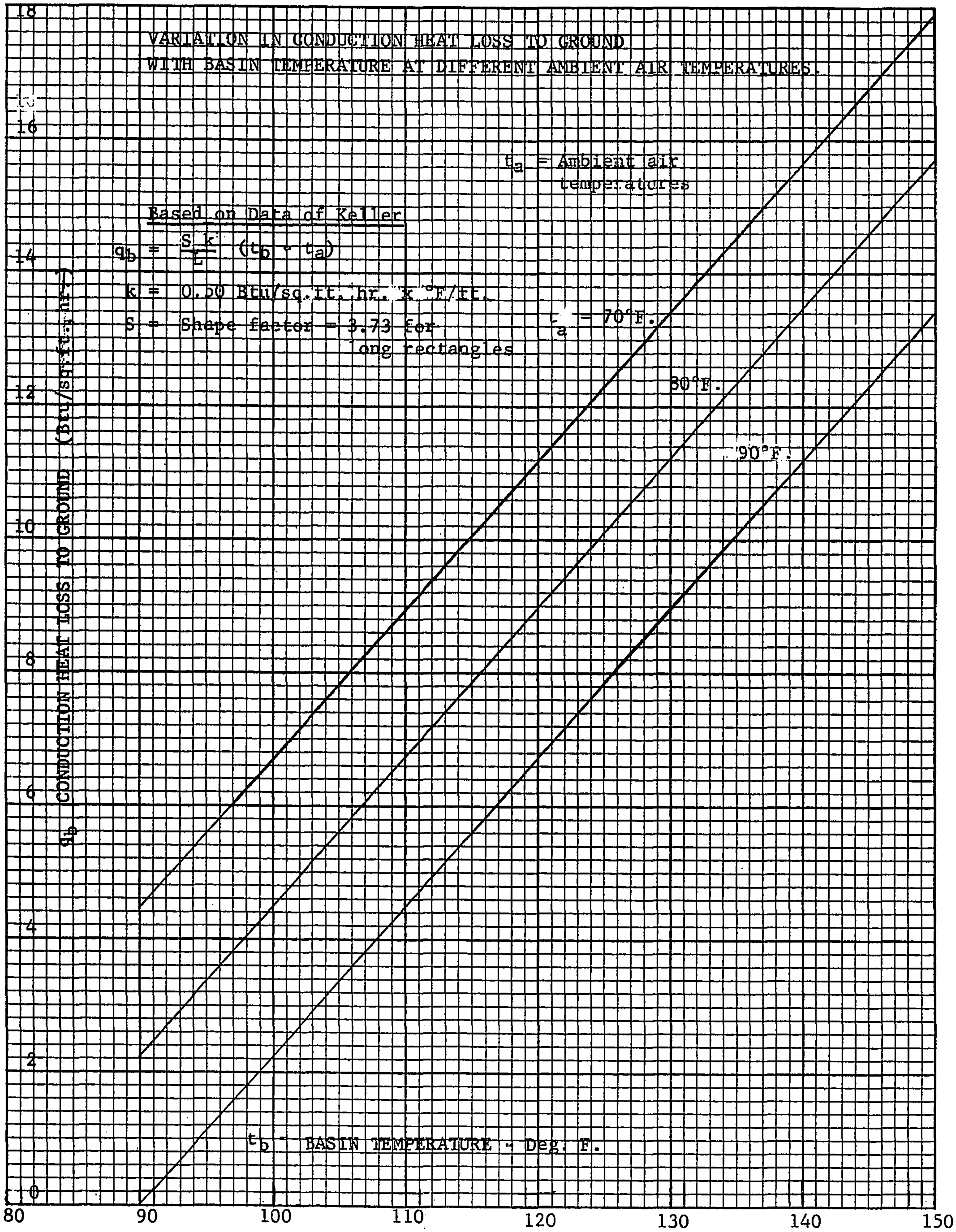
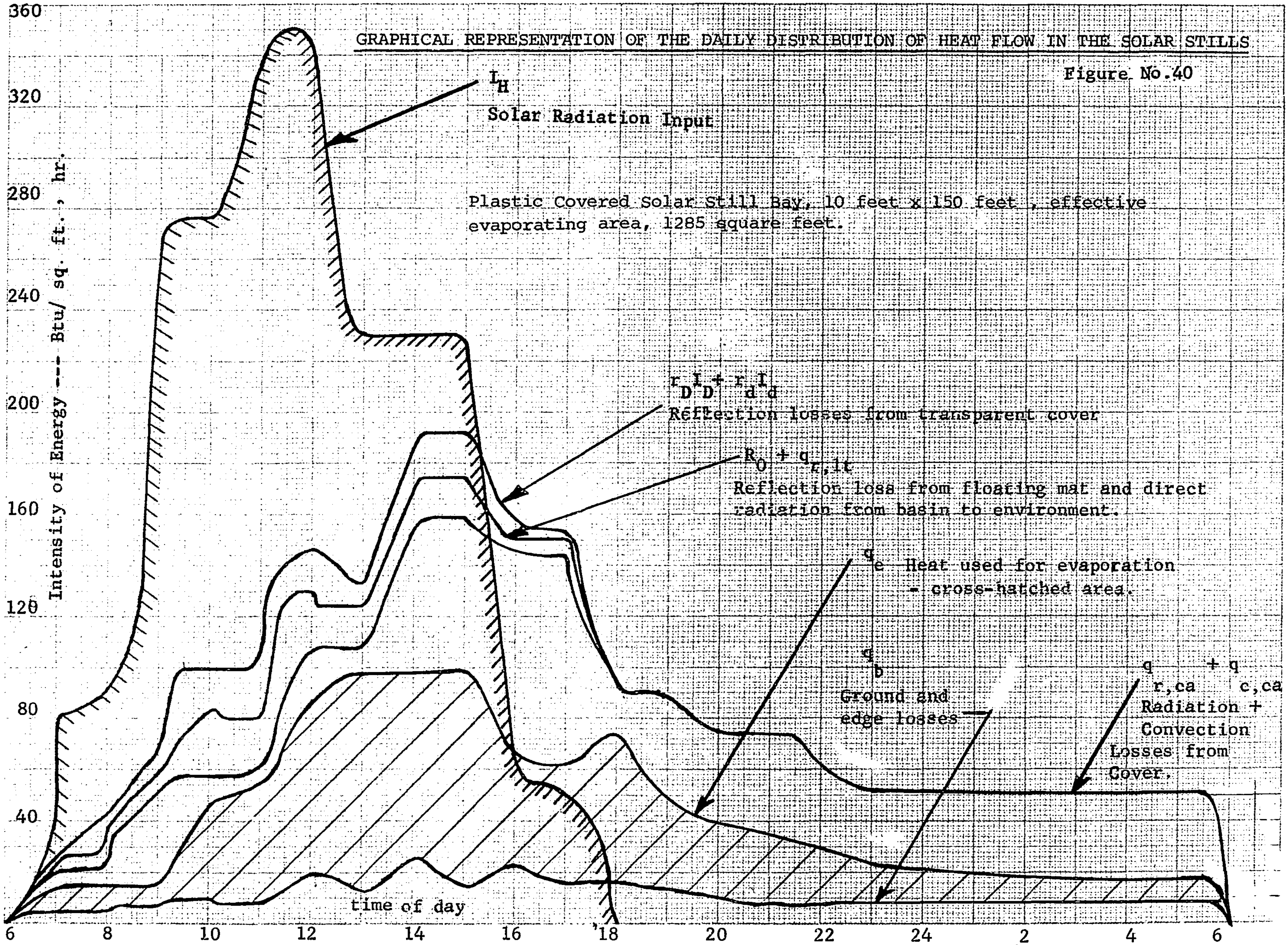


Figure No. 38
VARIATION OF HEAT OF EVAPORATION
WITH BASIN TEMPERATURE
Δ t = 40°F
Δ t = Basin Temperature minus Cover Temperature
Δ t = 30°F.
Δ t = 20°F.
Δ t = 10°F.
q_e = HEAT USED IN EVAPORATION - Btu/hr., sq. ft.
BASIN TEMPERATURE - Deg. F.
280
240
200
160
120
80
40
0
90
100
110
120
130
140
150

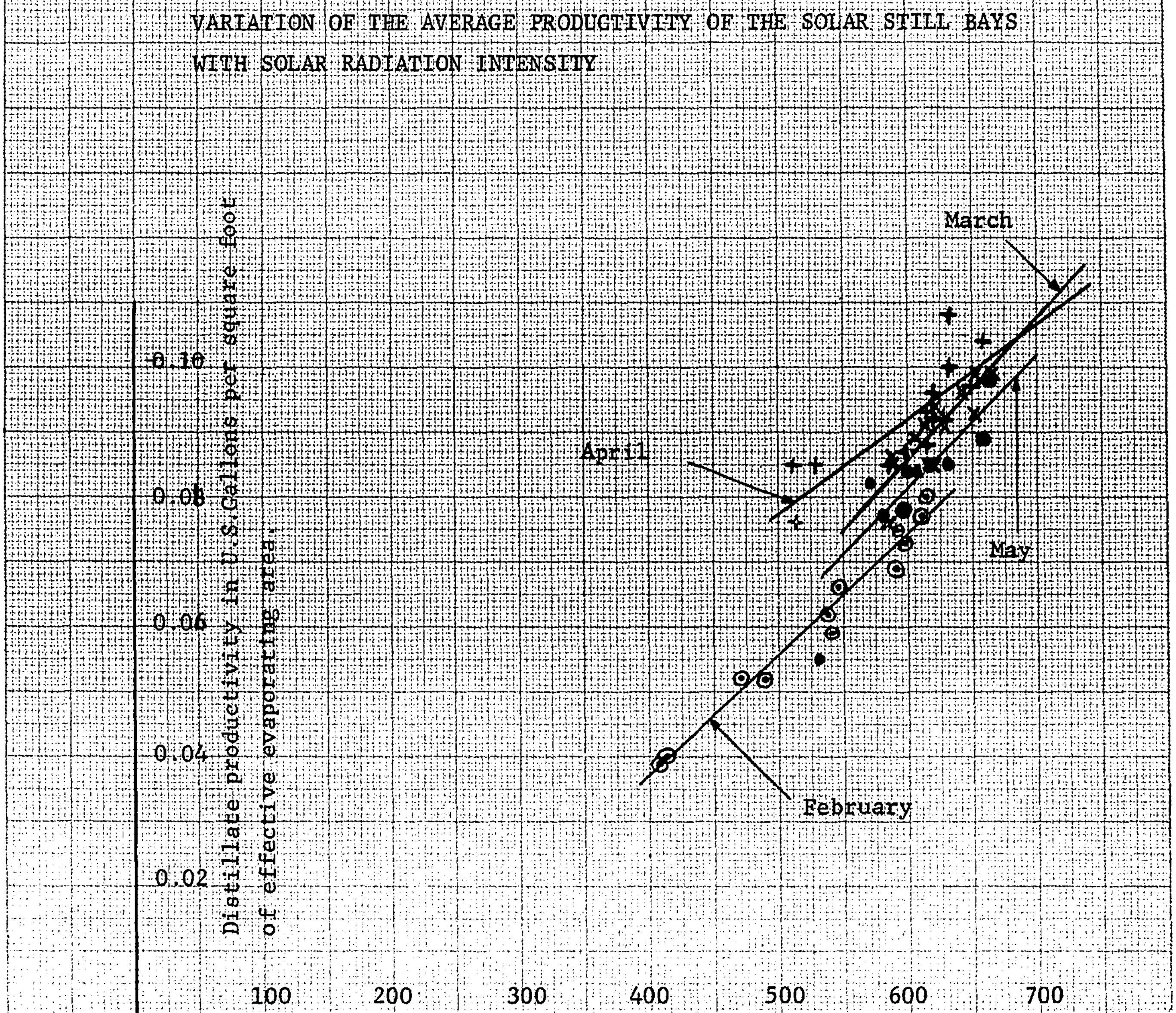
Figure No. 39


VARIATION IN CONDUCTION HEAT LOSS TO GROUND
WITH BASIN TEMPERATURE AT DIFFERENT AMBIENT AIR TEMPERATURES.
t_a = Ambient air temperatures
Based on Data of Keller
$q_b = \frac{S\ k}{L} (t_b - t_a)$
k = 0.50 Btu/sq.ft. hr. x °F/ft.
S = Shape factor = 3.73 for long rectangles
t_a = 70°F.
80°F.
90°F.
q_b CONDUCTION HEAT LOSS TO GROUND (Btu/sq.ft., hr.)
t_b - BASIN TEMPERATURE - Deg. F.
0
2
4
6
8
10
12
14
16
18
80
90
100
110
120
130
140
150



GRAPHICAL REPRESENTATION OF THE DAILY DISTRIBUTION OF HEAT FLOW IN THE SOLAR STILLS
Figure No.40
I_H
Solar Radiation Input
Plastic Covered Solar Still Bay, 10 feet x 150 feet , effective evaporating area, 1285 square feet.
$r_D I_D + r_d I_d$
Reflection losses from transparent cover
$R_0 + q_{r,1t}$
Reflection loss from floating mat and direct radiation from basin to environment.
q_e Heat used for evaporation - cross-hatched area.
q_b
Ground and edge losses
$q_{r,ca} + q_{c,ca}$
Radiation + Convection Losses from Cover.
Intensity of Energy --- Btu/ sq. ft. , hr.
360
320
280
240
200
160
120
80
40
time of day
6
8
10
12
14
16
18
20
22
24
2
4
6

Figure No. 41.



I_H - Solar Radiation Intensity on Horizontal Surface -- langleys / day.

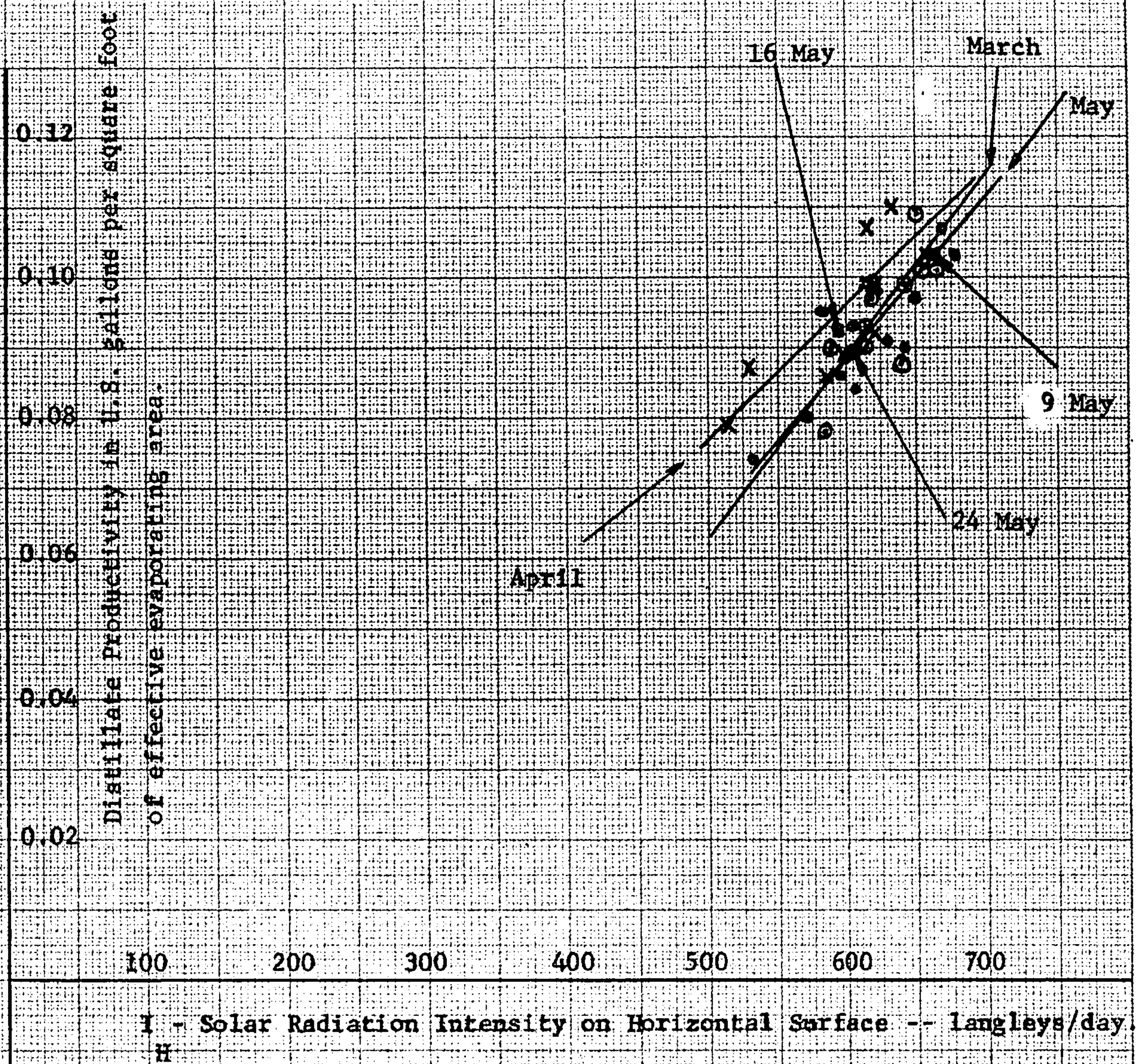
Results shown are for February, March, April, May, 1968.

Regression Lines have been drawn for each month.

Average productivities selected from Bays I to V on days when outputs of several individual bays were in reasonable agreement.

⊙ Data for February
× Data for March
+ Data for April
● Data for May

VARIATION OF PRODUCTIVITY OF SOLAR STILL BAY NO.V
WITH SOLAR RADIATION INTENSITY

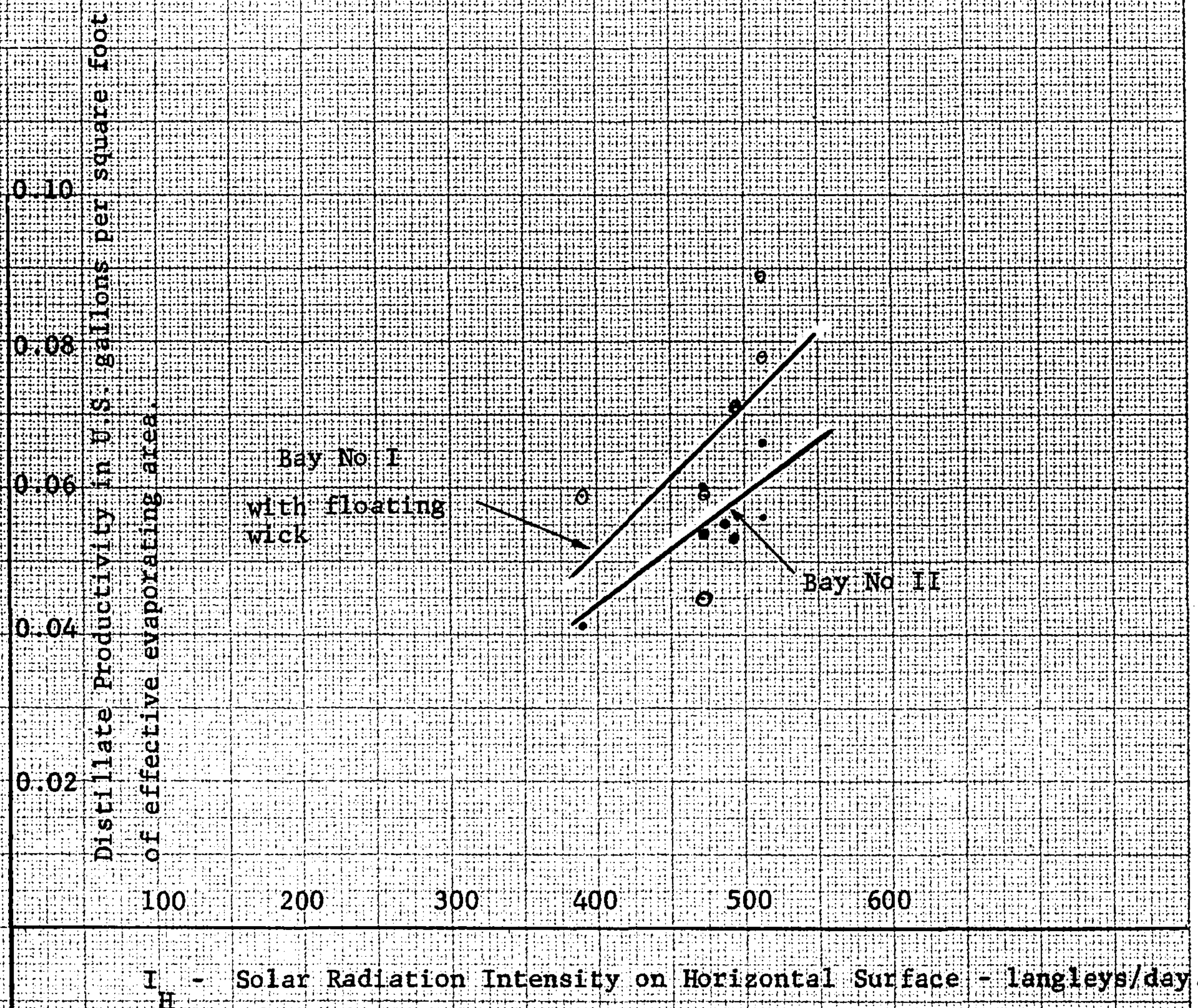


Regression lines have been drawn for March, April and May, 1968.

Results of the three test runs have been indicated.

⊙ Data for March
✕ Data for April
• Data for May

VARIATION OF PRODUCTIVITY OF SOLAR STILL BAY NOS. I AND II WITH SOLAR RADIATION INTENSITY



Results shown are for January, 1968.

Regression lines have been drawn for each bay.

o Bay No. I

• Bay No. II

TABLE No. 1

VARIATION OF CONVECTION HEAT TRANSFER FROM BASIN SURFACE TO TRANSPARENT COVER OF SOLAR STILL

Average Basin Temperature t_b °F	Average Cover Temperature t_c °F	Grashof Number N_{Gr} (Dimensionless) x 10^6	Convection Coefficient C' Btu/hr, sq.ft, $°F^{4/3}$	Corrected Temp. Difference $\Delta t'$ °F	Convection Heat Transfer Coefficient $h_{c,bc}$ Btu/hr, sq.ft., °F	Convection Heat Transfer Brine to Cover $q_{c,bc}$ Btu/hr, sq.ft., °F
90	80	6.44	0.1288	12.5	0.299	3.0
100	80	11.88	0.1278	23.2	0.364	7.3
	90	5.94		13.2	0.302	3.0
110	90	11.10	0.1270	27.8	0.385	7.7
	100	5.55		14.4	0.309	3.1
120	100	10.30	0.1265	30.3	0.395	7.9
	110	5.15		15.8	0.318	3.2
130	100	14.85		49.0	0.467	14.0
	110	9.90	0.1275	34.0	0.413	8.3
	120	4.95		17.6	0.331	3.3
140	110	14.14		56.2	0.488	14.7
	120	9.24	0.1275	40.0	0.436	8.7
	130	4.71		20.2	0.347	3.5
150	110	18.06		80.4	0.553	22.2
	120	13.55	0.1282	66.9	0.520	15.6
	130	9.03		44.3	0.453	9.1
	140	4.52		20.8	0.353	3.5

TABLE No. 2

RADIATION HEAT TRANSFER FROM BASIN SURFACE TO TRANSPARENT COVER OF SOLAR STILL

Basin Temp. °F	Cover Temp. °F	$q_{r,1t}$ Radiation Heat Transfer - Btu/hr,sq.ft.		Per cent decrease in radiation heat transfer due to effect of enclosed gas
		Not allowing for absorption by enclosed gas	Allowing for absorption by enclosed gas	
90	70	18.4	11.3	38
	80	9.2	5.06	45
100	80	19.0	11.2	41
	90	9.8	6.1	34
110	90	20.9	12.4	41
	100	11.1	6.25	44
120	100	22.6	14.15	37
	110	11.5	7.9	31
130	100	34.0	19.5	43
	110	22.9	13.25	42
	120	11.4	5.36	53
140	110	35.7	18.5	48
	120	29.1	10.6	56
	130	12.7	5.2	59
150	120	37.3	9.4	75
	130	25.9	4.0	85

TABLE NO. 3

REGRESSION LINE EQUATIONS RELATING SOLAR STILL PRODUCTIVITY TO INSOLATION

Time Period 1968	Source of Data Solar Stills	Equation	Number of Points Used	Correlation Coefficient
January	Bay No. I	$D_w/A_H = 0.000201\ I_H - 0.029$	6	0.59
January	Bay No. II	$D_w/A_H = 0.000150\ I_H - 0.016$	7	0.83
February	Average Bays I to IV	$D_w/A_H = 0.000186\ I_H - 0.037$	12	0.99
March	"	$D_w/A_H = 0.000218\ I_H - 0.045$	13	0.86
April	"	$D_w/A_H = 0.000147\ I_H + 0.004$	14	0.81
May	"	$D_w/A_H = 0.000204\ I_H - 0.041$	9	0.92
March	Bay No. V	$D_w/A_H = 0.000260\ I_H - 0.067$	12	0.85
April	Bay No. V	$D_w/A_H = 0.000194\ I_H - 0.020$	11	0.81
May	Bay No. V	$D_w/A_H = 0.000235\ I_H - 0.051$	12	0.77

where D_w/A_H is the productivity in U.S. Gal./sq.ft., day and I_H is the insolation in langleys/ day.

TABLE No. 4

MATERIALS SPECIFICATIONS LIST OF THE SOLAR STILLS ON PETIT ST. VINCENT

No.	Function	Specification	Quantity Used	Estimated Useful Life - Years
1.	Transparent Cover	4 mil polyvinyl fluoride film 'mettabraided' on one side+	10 ft. x 150 ft.	5
2.	Basin and distillate trough liner	30 mil, black, butyl rubber sheet	11.2 ft. x 152 ft.	20
3.	Floating absorbent layer	Black, non-woven wick of poly-acrylonitrile fibres* 2.25 ounces/sq.yd.	8.7 ft. x 150 ft.	4
4.	Clamp for transparent cover attachment	Weatherproof plywood 3/4" thick	0.5 ft. x 350 ft.	2
5.	Clamp for transparent cover attachment	Oval shaped electrical conduit 3/8" wide x 7/8" long	1300 feet	2
6.	Clamp attachment to curb walls	Nickel-plated concrete anchor bolts 3/8" x 3-3/4"	1.5 feet spacing 220 required	2
7.	Adhesive to fix rubber sheet to curb wall	Butyl rubber adhesive	6 gallons	2
8.	Tape to cover clamp edge	Butyl rubber pressure-sensitive adhesive tape - 2" wide	325 feet	2
9.	Weedicide for site preparation	Dieldren type	2 gallons	20
10.	Sand	Beach sand	625 cu.ft.	20
11.	Polyethylene film	4 mil thick, damp proof course	10 ft. x 150 ft.	20
12.	Basin forms	Pine boards	500 lineal ft.	
13.	Concrete curb walls	1:3:5 cement: sand: stone non-reinforced concrete mixture	18.5" wide x 15" to 24" deep x 180' long	20
14.	Plastic pipe and fittings Miscellaneous, fasteners	1-1/2" diameter for distillate 3" diameter air blower inlet and brine outlet systems		20

+ Trade name registered with the U.S. Patent Office - Tedlar

* Trade name registered with the U.S. Patent Office - Orlon

TABLE NO. 5

P R E L I M I N A R Y   E S T I M A T E S - June, 1968

CONSTRUCTION COST ANALYSIS OF A SOLAR STILL BAY

Effective area = 1,285 sq. ft.

ITEM	Material Spec. Number	Material Costs US $	Required labour hrs.	Labour Cost US $	% of Total Cost
Transparent cover	1	570	40	20	24.5
Basin liner	2	400	75	38	22.3
Floating layer	3	100			
Clamping system	4,5,6,7,8	363	208	104	19.4
Still foundations	9,10,11	70	240	50	5.0
Curb walls & end walls *	12,13	115	1,085	313	17.8
Fittings	14	70	48	24	3.9
Supervision - 20%			340	170	7.1
		1,688	2,036	719	100.0
Adding 20% to materials for administration		337			
		2,025			
Cost per sq. ft. of solar still		1.58	1.6 hrs.	0.56	
Cost materials and labour		2.14			
Cost per bay		2,750			
Cost per 15 bays		41,250			

N.B. The labour charges are variable and have been taken from measurements and estimates. Allowance has been made for the differential in labour skills.

* Each bay is charged 17/15 rails to allow for the extra rails.

TABLE No. 6

P R E L I M I N A R Y E S T I M A T E S - June, 1968

Costs of Solar Sea Water Distillation Plant Components

(based on Plant in PSV of 15 bays)

ITEM	US $	
Land	430	Taken pro rata from the island purchase price
Clearing of site	200	
Site survey	175	
Preliminary design	2,000	Estimated
Sea water pumps and installation	1,000	
Reservoir - sea water	1,260	
Sea water lines	175	
Distillate pumps and installation	600	
Distillate measurement tanks	600	
On site piping and misc.	1,000	Includes distillate and rain water piping to collection reservoirs
Electrical installation	1,270	Includes the installation of a power line from the storage building to the still
D .C . air blower system	450	
Brine drain	1,400	Concrete culvert to carry piping and return brine to the sea
Duplicate distillate cisterns	1,000	On site collection cisterns, 3,800 US gals. each
Piping to the Storage Area reservoir	1,300	3" PVC pipe to the fresh water system
Low level cistern	3,500	One quarter of the large reservoir will store distillate
Contingencies	2,750	15% of the total amount
Investment in Plant auxiliaries	19,110	Investment cost per sq. ft. of solar still = 19,110/15 x 1,285 = $ 0.99 US/ft^2

Total investment in solar still plant = $ 3.13 US/ft^2

TABLE NO. 7

PRELIMINARY ESTIMATES - June, 1968

Annual Operating Charges for Solar Distillation Plant
(based on 1 solar still bay)

ITEM	U.S. $	Useful Life / Sum of Single Payment Present Worth Factors	Capital Recovery Factor for 20 year life @ 8% = 0.10185
Amortization of Solar Stills	280		
Amortization of Auxiliaries	129		
Amortization of Pumps	16	........5 years..................... 1.4590	
Amortization of Blower System	5	Blowers - 5 years (all system)..... 1.4590	
Amortization of still components	88	Transparent cover - 5 years......... 1.4590	
	21	Floating layer - 4 years............ 1.9680	
	214	Clamping system - 2 years........... 4.5057	
Electrical	4	1 battery/year	
	10	Electrical power consumption	
Labour	81	1 attendant full time at $3 per day	
Maintenance	80	2% of capital investment of 60,360	
Insurance, administration	80		
Estimated annual costs	1008		

Estimated distillate production from solar still, taken from Chapter 2, = 33,000 U.S. gallons per bay.

Estimated cost per 1,000 gal. = 1008/33 = $30.50 per 1,000 gal.

The collection efficiency of rainfall should be at least 90%, hence for the catchment area of 1,530 sq. ft., the following rainfall collection should be realized:

Rainfall in./year	Collected Rain Water U.S. gals.	Cost of Fresh Water from Combined Water Plant U.S. $/1,000 U.S. gals.
20	17,250	20.00
25	21,500	18.50
30	25,900	17.10
35	30,100	16.00
40	34,500	14.90
45	38,800	14.05
50	43,100	13.20

It should be realized that the distillate production may be affected during periods of greater rainfall intensity.

TABLE NO. 8

PRELIMINARY ESTIMATES - June 1968

THE CAPACITY OF THE WATER STORAGE CISTERNS ON PETIT ST. VINCENT

LOCATION	SIZE US gals.	COST US $	REMARKS
Pavilion	17,200	2,700	
High Level Cistern	51,600	3,300	
Low Level Cistern	240,000	14,000 *	Being constructed - four compartments
Windward Beach	12,600 *		
Cisterns	8,500 *	2,900 *	These three cisterns have not been built and the sizes are variable and might be altered slightly
	10,000 *		
Guest Cottages - No. 1	9,600	880	
No. 2	9,600	880	
No. 3	10,800	880	

Total Cistern Capacity 369,900 U.S. Gallons
Total Cistern Cost 25,540 U.S. Dollars

* Estimates

N.B. For each cistern an additional cost of $75 has been charged for miscellaneous piping, sight glass, downspouts, etc.

This includes anticipated construction projects till the end of 1968.

TABLE NO. 9

PRELIMINARY ESTIMATES - June, 1968

PIPING SYSTEM FOR RAINWATER (WALLABA) COLLECTION AND DISTRIBUTION

SECTION OF PIPE	Approx. length ft.	Trench Charge $US/ft.	Trench Cost $ US	Pipe Size ins.	Pipe Cost per 100 ft. $ US	Pipe Cost $ US
Guest Houses to Treatment Plant	550	0.15	83	1-1/2	20.73	114
Pavilion to Treatment Plant	50	0.12	6	2	27.93	14
Guest houses to Beach Cottages	1,260	0.15 and 0.10	153	1-1/2	20.73	262
Manager's House etc. to Cistern	140	0.15	21	1-1/2	20.73	29
Pavilion to Low Level Cistern	280	0.15	42	1-1/2	20.73	58
	2,280		305		-	477

10% Extras, Miscellaneous	48
* 50% Valves, fittings, etc.	260
Estimated Labour charge for installation	286
Total Piping Cost	1,071
Excavation charge	102
	1,173
Administrative charge 20%	234
Total charges	1,407

The excavation trench will also hold the fresh water and electrical connections.

1/2 cost of trench charged to the fresh water system
1/6 to electrical
1/3 to wallaba water

* This is an estimate based on actually calculated costs on other piping systems.

TABLE NO. 10

PRELIMINARY ESTIMATES - June, 1968

Cost of Building Guttering Systems

In all cases the guttering system used is identical and costs of the order of $1.65 US per foot of length. The cost of regular guttering has been deducted from this price and a total cost of $1.52 US per foot has been used in most cases.

Building Type	Number of Buildings	Perimeter per roof ft.	Installed Cost US $ per roof	Total Cost US $
Pavilion	1			
Guest Cottages	6	152	230	1,380
Beach Cottages	6	197	300	1,800
Staff Day Quarters	1	123	186	186
Ice House	1	228	347	347
Power House *	1	60	8	8
Staff Houses *	2	140	18	36
Manager's House *	1	64	35	35
New Beach Cottages	2	186	283	566
		Total Cost of Gutters		4,358

* Use of Conventional Gutters.
In Manager's House, different type.

Capital Investment Charges for Rain Water Collection System

	US $
Cisterns - includes all cisterns except the high level and 3/4 of the low level tanks	11,720
Pumps for Water Conveyance, installed and sheltered (spare)	1,000
Piping for Wallaba Water and Installation	1,407
Treatment Cistern and Auxiliary Equipment	500
Guttering System	4,358
Miscellaneous - 10% of above	1,990
Administration - 20% of all items except piping and guttering	3,010
Total investment	23,985

TABLE NO. 11

PRELIMINARY ESTIMATES - June, 1968

Annual Charges for the Operation of the Rainfall Collection System

Maintenance)	Cleaning of gutters etc. labour	$ 525 U.S.	
and Supplies)	Paint - gutters	60	
	Paint - roofs	193	
	Roof painting - labour	14	
	Tank cleaning - labour	35	
	Screens for cistern filters	50	
	Spare parts, miscellaneous, etc	300	Capital Recovery Factor for 20 year life @ 8% = 0.10185.
Power Costs		40	
Amortization of Fixed Assets over 20 years		2,440	Sum of Single Payment- Present Worth factors = 1.4590.
Amortization of Pumps over 5 years		148	
Treatment of Rain Water-	Chemicals	50	
	Supervision Labour, operation of system, etc.	600 *	
	Administration, Contingencies etc.	500	
	Approximate Annual Costs	4,955	

* Initially the cost should be greater, but will diminish with time.

It should be borne in mind that in a few years the stain from the wallaba shingles should be less and this will reduce to some extent the annual charges. The principal charges will be relatively unaffected however, as the investment has already been undertaken. The power, chemical, extra labour costs are not necessarily excessive.

Examining daily rainfall records for the neighbouring regions, about 2% of the rainfall occurs in intensities of less than 5 parts of an inch and must be discounted. Allowing another 3% miscellaneous losses and an average wallaba roof collection efficiency of 85%, and assuming that of the collected water 20% is lost to leakage, spoilage, treatment wastage, etc., the following table estimates the unit cost of this water:

TABLE NO. 11 Continued

Annual Rainfall ins./annum	Potential Rainfall Collection US gals./annum	Actual Collection. of Rain Water US gals./annum	Approx. Cost per 1,000 US gals. assuming reasonably fixed Annual Charges $ US
20	408,000	252,000	19.70
25	510,000	326,000	15.20
30	612,000	391,000	12.70
35	714,000	457,000	10.85
40	816,000	522,000	9.50
45	918,000	588,000	8.42
50	1,020,000	652,000	7.60

These figures should be modified by the addition of the rain water collected from the galvanized steel roofs of the low level storage cistern and the storage building, a total area of 7,500 sq. ft. The collection efficiency is ninety per cent, and an overall loss factor of ten per cent has been allowed in this case. The additional investment charges are very small and this will not affect the annual operating charges. This water requires no treatment, except filtration and chlorination.

20	94,000	75,000	15.20
25	117,000	94,000	11.80
30	140,000	112,000	9.87
35	164,000	131,000	8.43
40	187,000	150,000	7.38
45	211,000	169,000	6.55
50	234,000	187,500	5.92

TABLE NO. 12

PRELIMINARY ESTIMATES - June, 1968

Cost of Fresh Water Piping System on PSV

Pipe Size ins.	Distance ft.	Cost of Trench US $	Cost of Pipe US $	Cost of Fittings	Connecting Points
3	882	133	512	130	High level cistern to pumphouse
3	227	34	132	80	Pumphouse to pavilion
1-1/2	550	83	114	50	Pavilion to 3 guest houses
2-1/2	946	114	420	64	Pavilion to dockhouse
1	280	28	36	50	Dockhouse to jetty
2	840	185	235	85	Dockhouse to Cross Hill houses
1-1/2	400	60	83	25	- do - Manager's house
2	1,260	133	352	150	Guest houses to beach cottages and beach main line
1	200	20	26	50	Beach cottage feeders
2	840	126	235	85	- do - to staff houses to Power station
3	160	25	93	171	Low level cistern to power station
2	840	126	235	85	To new guest cottages on NE hill
	7,425	1,067	2,473	1,130	(Includes 10% for extras)

In order to get an effective		247	10% extras for piping, for handling etc.
charge for the excavation, the		1,130	extras for valves, fittings etc.
following deductions must be		3,850	
made:		770	20% for administration, supervision
20% for Administration	200	4,620	Total piping charge
	1,267	800	Estimated labour installation cost
Less wallaba cost	102	5,420	Piping cost, labour and materials
Less electricals	200		
Charge to fresh water	965	965	
		6,385	Investment in Water System Piping

TABLE No. 13

P R E L I M I N A R Y   E S T I M A T E S - June, 1968

ANNUAL COSTS FOR THE FRESH WATER RETICULATION SYSTEM

Investment in Equipment	US $
Piping and Installation charges	6,385
Cisterns - high level storage and 1/2 low level storage	10,300
Reticulation Pumps	850
Installation of Pumps, Electrical connection, power house space, etc.	750
Total Investment	18,285

Annual Operating Charges - based on annual demand of 1,600,000 US gals.

Electric power costs	100
Amortization of piping system + cisterns - 20 year life	1,855
Amortization of pumps etc. - 5 year life	127
Maintenance: Cistern cleaning	50
Repairs to piping	100
Materials	200
Operating labour (2/3 attendant)	500
Annual Charges	2,932

Estimated charge to water per 1,000 US gals. = 2,932/1600 = $1.83 US per 1,000 US gals.

This charge can be allocated between the two principal water supply sources, the solar stills and the rain water collection system in proportion to the amount each supplies to the system.

Capital recovery factor for 20 year life @ 8 % = 0.10185.

Sum of Single Payment - Present Worth factors
for pumps -- 5 year life @ 8 % = 1.459

TABLE NO. 14

COMPARISON OF THE CHARACTERISTICS OF THE WATER SUPPLY SYSTEMS ON PETIT ST. VINCENT

Characteristic	Solar Distillation Plant	Rainfall Collection System
Technical Considerations Present Situation	Considerable effort is underway for the improvement of the components of the stills, bearing in mind the semi-experimental nature of the installation. The chief difficulties are the design of the clamping system and the precipitation of salts on the floating wicks. Studies are continuing on most details of the stills to improve the output and the efficiency. This should also reduce the amount of operating labour necessary. Improvements in techniques and components have already been rewarded through increased productivities.	A serious problem exists in the precipitation of the wallaba stain from the rain water. This problem has yet to be satisfactorily resolved although it is expected that a solution will be forthcoming shortly. The operating procedures of the flocculation treatment plant have not yet been finalized. These will more adequately determine the amount of wastage during the treatment process which affects the overall yield of usable effluent.
Future Prospects	New developments in solar distillation technology along with continuing improvement of the existing plant, point to increased fresh water outputs in the future. Plans are underway to determine the technical and economic feasibility of insulating the basins of a number of bays. Also the use of off-peak electrical power to preheat the sea water feed is being contemplated. This would extend the operation of the stills into nocturnal production, which constitutes a study in itself. The earlier work of Tleimat in this field has been noted.[66]	There does not appear much that can be done to increase the yields. This technology is well established and the collection systems have been substantially equipped. On the contrary, the future should see increased effort and expenditure to ensure that the water does not become contaminated as the collection system must store water from the wet summer season to the dry winter season, the period of maximum demand.

TABLE NO. 14 Continued

Characteristic	Solar Distillation Plant	Rainfall Collection System
Dependability of System	The variation of solar radiation intensity has been given in Tables Nos. E-1 and B-2. The fluctuations do not appear too great and a reasonably predictable output, as outlined in Chapter II, can be relied upon. In addition, the solar stills in P.S.V. have certainly proven to be an effective, highly efficient rainfall catchment producing an effluent of good quality.	The cyclical variation of rainfall intensity is not well documented for the Grenadines. All of the available information is listed in Table No. B-1. From these records, a severe reduction in precipitation resulting in drought does not seem to be common, save for the comments on climatology outlined in Appendix B.
Water Quality	There can be no doubt that good quality water can be easily produced from the solar stills. Contamination may arise from the rain water collected from the transparent canopy and from later transfer and storage stages.	There is a constant danger from contamination which must be scrupulously checked if a high quality water is desired. This is particularly true of the operation of storage reservoirs in tropical regions.
Acceptability	During the period of time of operation of these stills, there have been no complaints regarding the quality of the distilled water. Generally, desalinated water is looked upon favourably by the tourist.	The use of rain water seems quite acceptable, once the discolouration problem has been satisfactorily rectified. In some circles the tourist trade does not find rain water acceptable as a sole source of fresh water supply.
Costs	These have been outlined and discussed in Chapter 3.	These have been outlined and discussed in Chapter 4.

In both cases, the reticulation system costs, as outlined in Chapter 4, must be added in proportion to the amount of fresh water produced.

The results are in basic agreement with the findings of Howe in his work in the South Pacific where he states:

> "It should be emphasized that rainfall catchment on roof areas should be cheaper than the combination of solar distillation with rainfall collection on the top of the solar still, wherever roof areas are of sufficient magnitude. Only when the cost of the cistern capacity is extremely large can the solar still be justified in competition with a catchment system on an existing roof."(33, p. 180)

APPENDIX A

HISTORICAL REVIEW OF SOLAR DISTILLATION

It is written in La Sainte Bible: "Ce qui fut, cela sera; ce qui s'est fait, se refera; et il n'y a rien de nouveau sous le soleil."(1,p.848)

Solar distillation is really no exception. Its principle was known to the ancients. Although there may be others, the first mention of solar distillation known to the author was reported by Mouchot(2,p.13) who stated that the Arabs "se servaient de vases de verre pour opérer certaines distillations au soleil." He then elaborated on their method as follows: "Au dire des alchimistes, les Arabes pour opérer certaines distillations au soleil, se servaient de miroirs concaves, polis, fabriqués à Damas."(2,p.87) In l'Histoire Naturelle, published in 1551, Adam Loncier depicted by means of an illustration a similar procedure for distilling, amongst other items, the essential oils of flowers.(2,p.87)

The next report on solar distillation comes in the excellent historical review of desalination by Nebbia and Menozzi[3]. They quote the work of Della Porta,[4] published in 1589, whose apparatus is illustrated in Plate No. A-1, page A-2.

Obviously, the distillation capabilities of solar energy were well understood although no specific reference to water desalination was made. It must be noted, however, that Della Porta published several other books on desalination experiments.(3,p.141) haec in latas fidelias aquae plenas immittus, vt citiùs vapores in aquam crassescant. Optimè omnia iam parata, obuerte ad intensissimũ solarium radiorum æstum: nam extemplo in vapores soluuntur, & guttatim in subiecta vasa stillabunt. Vesperi post Solis occasum remoue, ac nouis herbis reple. Herba poligonus, siue *lingua passerina* vulgò vocata, concisa, extillataq; maximè oculorum inflammationibus præstat, alijsq; morbis. Ex hiperico elicitur aqua omne spasmum profligatura, si dolens membra ea abluerit: & alia, quæ longum esset recensere. Modus distillandi pictura prostat.

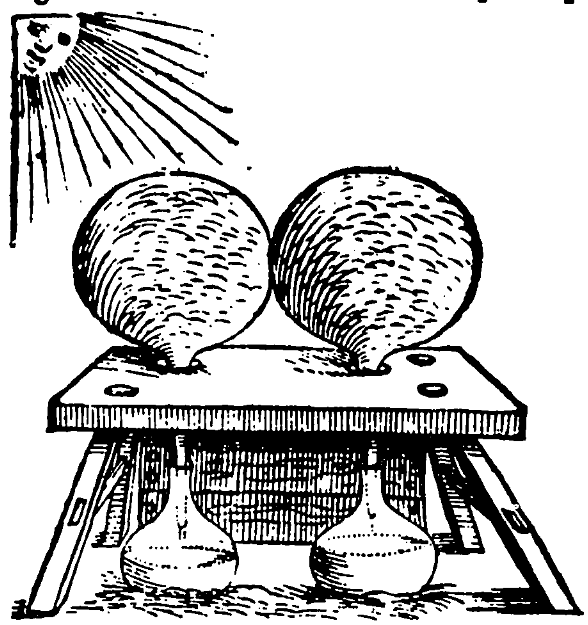


PLATE A-1: SOLAR DISTILLATION APPARATUS OF DELLA PORTA

Translation of the Latin kindly supplied by the Department of Education, Macdonald College of McGill University.

ABOUT DISTILLING

....insert these into wide earthen pots full of water, so that the vapours may thicken more quickly into water. Turn all this apparatus, when it has been very carefully prepared, to the most intense heat of the sun's rays : for immediately they dissolve into vapours, and will fall drop by drop into the vases which have been placed underneath. In the evening, after sunset, remove them and fill with new herbs. Knot-grass, also commonly called "sparrow's tongue", when it has been cut up and distilled is very good for inflammation of the eyes and other afflictions. From the ground-pine is produced a liquid which will end all convulsions if the sick man washes his limbs with it : and there are other examples too numerous to mention. The picture demonstrates the method of distilling.

The first specific reference to the possibilities of solar distillation were made by an Italian, Nicolò Ghezzi, who wrote a short treatise in 1742 where he proposed the following which has been freely translated from the original Italian script:(3,p.162)

> "Perhaps placing a cast iron vase containing sea water in such a manner that the sun's rays will strike it (and during mild days and seasons, not an insignificant amount of vapour will be formed) and if the spout of the vase is shaded from the sun, it will result in a more copious and more extended flow of fresh water."

The next reference to solar distillation was given by Harding[5] who reported on a 51,200 sq. ft. still erected near Las Salinas, Chile. This unit was of the greenhouse or roof type solar still. No mention is made of what inspired the builder, a Mr. Wilson, regarding this design. It is known that the productivity of the still in summer was upwards of one pound of fresh water produced per square foot of evaporating surface per day.(5,p.287) It is an interesting reflection on the simplicity of the process that productivities reported from solar stills recently built are of the same order of magnitude.

For a while after this, no reports of solar stills appear to have been published. In the decade following World War 1, interest was renewed in solar distillation. Many publications have followed with reports on the process in general, often accompanied by descriptions of small stills of the roof type, V-covered, tilted-wick, inclined tray, suspended envelope, tubular, or air inflated design.

These are listed below:

6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18,
19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30,

31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41,

42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52,

53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63,

64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74,

75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85

In order to increase the productivity, several workers have tried forced circulation systems to condense the water vapour externally from the still. Others tried to recapture the latent heat of evaporation through multiple effect systems or humidification systems. The following is a list of publications dealing with these efforts:

74, 75, 76, 86, 87, 88, 89, 90, 91, 92, 93,

94, 95, 96, 97, 98, 99, 100

Several large solar distillation schemes have been proposed while others have considered combination plants which generated power as well as desalting saline water.[31, 101, 102, 103, 104, 105, 106]

Alternative uses besides desalination were also found for solar stills, such as regenerating solutions, and obtaining fresh water from the ground.[63, 107, 108, 109]

There are a number of plans and specifications for the building of solar stills which have been published.[110, 111, 112, 113, 114, 115]

Quite a few patents have also been issued in this field. With a few exceptions, they generally deal with small solar stills, etc.

116, 117, 118, 119, 120, 121, 122, 123, 124,

125, 126, 127, 128, 129, 130, 131, 132, 133,

134, 135, 136, 137, 138, 139, 140

It goes without saying that small stills of under several hundred square feet in area, as have been described, are most useful for individual family units in isolated areas. Stills of this type have been extensively tested, particularly at the University of California, Berkeley, as reported in 1961 by McLeod, et al.[52] They give results of productivity of a small solar still for seven years, 1952-1959 which is, to the author's knowledge, the longest recorded output of a solar still.[(52,p.6)] The Las Salinas still in Chile was reputed to have run for 40 years but records do not appear to have been published.[31]

Work on larger solar stills was initiated through the efforts of the Office of Saline Water, U.S. Department of the Interior, reported mainly by Löf and the Battelle Memorial Institute. This work was carried out chiefly at the Solar Research Station, Daytona Beach, Florida.[8, 9, 45, 46, 141, 142, 143, 144, 145, 146, 147]

These stills were glass covered units, and one was 2,500 square feet in area. Although primarily designed as deep basin evaporators with a depth of sea water up to 12 inches, there was continuous experimentation in solar still operation, which was excellently reported in the final publication in this series.[147]

Concurrently, several other designs of stills were tested, including the air inflated plastic and tilted wick stills. The former were tested for the Church World Service[147] who were instrumental, in 1964, in the installation of the first large plastic solar still on Symi, a small Greek island in the Dodecanese.[148, 149] Subsequently, several other stills were built on small Greek islands.[19, 150, 151] Recent communication from the Church World Service has indicated that continued interest in solar distillation has resulted in the installation, lately, of a new type of solar distillation unit on Symi and Perdika (Greece).[152, 153] The initial results are encouraging and these developments merit close attention.

Other significant activities have resulted in solar still installations in Spain[154, 155, 156, 157] and Australia[158, 159, 160, 161, 162]. In both countries, glass covered stills have been favoured. The Australians have built the largest still, 38,000 square feet of evaporator area, to date at Coober Peby, South Australia.[158]

The important work of Howe, Tleimat, et al, in this field must be mentioned.[33, 34, 35, 79, 151] In particular, their collaborative efforts with the South Pacific Commission in the testing and installation of solar stills on small islands in the Pacific Ocean have been most informative and useful in resolving problems affecting fresh water provision to small communities. These installations are not quite so large as the others, having been designed mainly for family use. One unit on Fiji was nearly 300 square feet in area.[151] The work of this group in stressing the importance of rainfall collection and storage in combination with solar stills clearly parallels the present study.

Finally, the recent work of Edlin on a new type of solar distillation unit has yet to be published and discussed in the technical literature. Nonetheless, this might hold promise for more efficient solar distillation plants in the future.[163] Prototypes of this model are being installed in Symi and Perdika, Greece. The technical performance has yet to be confirmed. Also, the economics of the operation are not known.

The above analysis is indicative of the very nature of solar distillation technology. It is by no means stagnant. In this respect, this report must not be regarded as the final word in this field. Improvements are continuously being made which hopefully will reduce the costs and increase the productivity of solar stills. With this in mind, further advances in technology should make the future use of solar distillation even more feasible.

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APPENDIX B

Physical Geography and Climatology of the Grenadines and Environment

Prior to an analysis of the existing water works, an assessment of the physical environment will elucidate some of the reasons for the utilization of this particular technology in this area.

Physical Geography

In order to appreciate the conditions under which this study is being undertaken, it is necessary to examine the geographical characteristics of the region.

The Grenadines form a series of numerous, small islands located in the far eastern Caribbean, stretching between Grenada and St. Vincent. Their general geographical location lies between latitudes 12° N and 14° N and longitudes 60° W and 62° W. Politically they are dependencies of these two territories, about one third of the group belonging to Grenada, including Carriacou, which is the largest and most populous. Petit St. Vincent (PSV) is the most southerly of the islands administered by St. Vincent. The general area is well illustrated in Map No. 1. Petit St. Vincent was accidentally granted to the jurisdiction of St. Vincent in 1791 when latitude was used as the basis for partitioning the Grenadines.[1, p.22] Its proximity to the other islands attached to Grenada, in particular Petit Martinique, presents some significant administrative difficulties regarding questions of customs, immigration and communications.

The total land area of the Grenadines is only 35 square miles, while the local population probably does not exceed 20,000. The most recent study of the region has been undertaken by Kingsbury[1]. His excellent work continuously stresses the lack of water in the region and the effect this has had on commercial activities. The average rainfall for the Grenadines is between 35 and 55 inches per year, with the heaviest precipitation generally in the period June to September. Water shortages are not uncommon, and in periods of drought, water must often be hauled to the islands, especially those lying between Carriacou and Canouan. Severe droughts have afflicted the islands for centuries, as attested by articles quoted by Kingsbury. Even as late as 1959, a serious drought in Carriacou necessitated the expedition of emergency food supplies from Grenada to avoid starvation.(1, p.27)

The vegetation on Petit St. Vincent consists mainly of short, scrawny trees, principally manchineel and sea grape, which are often stunted and bent over due to the strong, prevailing trade winds. The island is quite hilly, particularly in the northeastern section. The solar stills are located at the western edge of one of the few relatively flat sections stretching across the centre of the island.

Until the initiation of this hotel development project, the island had been uninhabited. It has, in the past, provided the neighbouring islanders with firewood.

It is interesting to note that the neighbouring islanders also used to come to Petit St. Vincent to obtain supplies of fresh water following heavy showers. According to local tradition, shallow wells were dug in low lying areas in the centre of the island, where presumably a lens of fresh water overlies the sea water following a heavy rainfall. These wells apparently turned brackish after a few days use. Several shallow wells have also been dug in recent years. However, they have all proved unsuitable for human consumption.

The climatology of Petit St. Vincent is not documented, save for the readings included in this report. As a result, it has been necessary to gather whatever information happened to be available from the neighbouring populated Grenadine Islands, and even from as far away as Barbados, a distance of some 125 miles.

In general, however, the climatic conditions on these low relief islands in the south-eastern Caribbean vary little from one to another. They lie in the trade wind belt which moderates the temperatures so there is not much seasonal change. The solar radiation does vary throughout the year, but not markedly. The rainfall intensity changes from year to year as well as during the year. There are two seasons, one dry and one wet. This cycle is crucial in the Grenadines, however. Kingsbury[1, p. 5-6] has described general conditions as follows:

> "Further, there are no permanent streams, no lakes, and few other natural storage facilities, and the common, short, heavy downpours run off rapidly down the sharp slopes to the sea.
>
> So unreliable is this rainfall and so unsuccessful are the inhabitants and their land in retaining what is received that all of these islands face a perpetual water shortage."

This brief outline serves as background material to illustrate the reasons for the choice on Petit St. Vincent of a dual solar distillation-rainfall catchment water works system.

Rainfall Estimates

In order to evaluate the performance of the rainfall collection system, both from the solar still covers and the building roofs, it was necessary to measure the rainfall. Rain gauges were first installed on P.S.V. in mid-December, 1967, and measurements have been recorded continuously ever since. In order to assess the rainfall for the community (P.S.V.) and examine its cyclical variation, records for stations in the neighbouring Grenadine islands and Barbados were gathered and monthly and annual means were calculated. All these data are listed in Table No. B-1. The locations of each of these islands, apart from Barbados, are shown on Map No. 1. Bequia, the most northerly and closest to St. Vincent, has by far the highest average rainfall. There is a significant variation in rainfall -- apparently fluctuating from 35 to 55 inches per year for the islands south of Bequia.

The records for 5 stations were averaged, along with a composite reading for Carriacou, for the period 1935-1943. It is interesting to note that, on the average, this period was 15% wetter than the 1963-67 readings for the same locations. For completeness, results for the heavier rainfall islands of Bequia and Mustique have also been listed. Finally, the measured rainfall from P.S.V. has been compared directly with values from adjacent islands for the same time period and the results are listed in Table No. E-4.

Relating these results to the regional average given in Table No. B-1, an estimate of the anticipated annual rainfall for P.S.V. can be made for a preliminary cost assessment of the rainfall collection systems.

It is evident that a definite dry season exists from January to May, with the greatest precipitation falling from July to November. This constitutes the principal reason for the selection of a desalination system to supplement rainfall collection on P.S.V. The period of the greatest demand for fresh water from the tourist trade comes during the interval from December to March, which falls precisely during the time of minimum supply from rainfall. Hence, storage must be resorted to, with all its inherent difficulties and expenditure. Therefore, a reliable and suitable desalination system, such as a solar distillation plant, can satisfy, in part, the regular daily fresh water requirement during this period of maximum demand. In dealing with such a fickle industry as tourism, insurance of an adequate and satisfactory water supply constitutes sound investment practice.

Solar Radiation

The most readily available and reliable solar radiation records of the area are those measured at the Brace Experiment Station, Barbados, a distance of some 125 miles north east of P.S.V. These are listed in Table No. B-2. Unfortunately no dependable measurements are currently being taken so it has been necessary to compare the measured values of solar radiation intensity on P.S.V. with this data of 1963-64. The mean daily diffuse radiation for 1964 has also been given and the percentage of diffuse radiation calculated for this year.

The climatological records measured on P.S.V. including the solar radiation intensities have been tabulated in Appendix E.

APPENDIX B

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TABLE No. B-1

RAINFALL RECORDS FOR CERTAIN LOCALITIES IN EASTERN CARIBBEAN

(All Amounts indicated in Inches per Month)

Island	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total	Year Recorded	Reference No.
Canouan (Grenadines)	2.27	1.38	1.04	1.43	2.12	4.43	5.53	5.49	4.35	5.16	5.28	3.67	42.15	1954 - 1962 1963 - 1967	2 3
Union Island (Grenadines)	2.10	1.61	1.14	1.73	2.97	4.73	5.63	5.57	4.70	5.93	6.17	3.98	46.26	1954 - 1962 1963 - 1967	2 3
Limlair (Carriacou)	2.29	1.06	0.77	1.95	2.32	5.44	5.28	5.17	6.90	5.03	5.54	3.84	45.59	1963 - 1967	4
Dumfries (Carriacou)	2.75	1.30	1.54	2.67	2.95	5.32	5.22	5.03	5.96	5.12	4.01	4.76	46.63	1963 - 1967	4
Carriacou	3.26	1.80	1.70	1.86	2.74	4.72	7.11	4.08	6.33	6.78	7.66	5.39	53.43	1935 - 1943	5
Waterford (Barbados)	2.50	1.23	1.06	1.75	1.32	4.44	7.50	3.78	6.44	6.17	3.60	4.18	43.97	1961 - 1965	6
Average	2.52	1.39	1.20	1.89	2.40	4.84	6.04	4.85	5.78	5.69	5.37	4.30	46.33		
Mustique (Grenadines)	3.10	1.92	2.10	3.38	2.10	4.77	5.22	5.69	6.44	8.14	8.29	3.36	54.51	1954 - 1956	2
Bequia (Grenadines)	3.45	2.39	2.03	2.43	2.56	6.17	6.31	6.60	6.53	7.26	5.91	4.27	55.91	1954 - 1962 1963 - 1967	2 3

TABLE No. B-2

SOLAR RADIATION RECORDS - BARBADOS

Mean Daily Total Solar Radiation on Horizontal - Langleys per Day

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1963	394	471	450	498	492	478	480	465	368	439	404	423	447
1964	453	475	513	509	511	449	451	478	411	442	429	432	463
Standard Deviation 1964	18	18	23	26	21	34	32	26	35	27	24	22	26

Mean Daily Diffuse Solar Radiation on Horizontal - Langleys per Day

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1964	122	159	169	212	193	204	210	187	199	160	124	114	171
Diffuse Percentage of 1964 Total Reading	27	34	33	42	38	45	47	39	48	36	29	26	37

Jan. 1963 - Dec. 1964 — Total Solar Radiation measured by 50 Junction Eppley pyrheliometer located at the Brace Experiment Station, St.James, Barbados, W.I. Elevation - on the coast; Latitude - 13° 11' 22"; Longitude - 59° 38' 32".

Jan. 1964 - Dec. 1964 — Diffuse Solar Radiation measured by Silicon Cell Shielded by a Shadow Band (sited at same location).

APPENDIX C

DESCRIPTION OF THE SOLAR DISTILLATION PLANT

Introduction: The solar distillation plant currently in use on Petit St. Vincent is described in this section. When completed, fifteen solar still bays, nominally 10 feet wide by 150 feet long, will be in operation. The entire system includes a sea water intake, pumps, reservoir, distillate and rain water collection cisterns, circulation pumps, piping to the reticulation system and a large fresh water storage reservoir.

This section deals primarily with the solar still units themselves. It must be stressed that they are continually undergoing modification and improvement as with any other type of equipment. Hence, certain aspects of the description might be superceded in the future by these alterations.

Description of Terrain: The site chosen for the solar distillation plant comprises a relatively flat area at the south-eastern edge of a 250 foot hill as shown in MAP No. 2. In general, the location is free from major obstructions which might shade the stills during the period of greatest solar radiation, i.e. from 0800 hours to 1600 hours. However, a certain amount of shading may occur around the time of the summer solstice, when the sun lies north of the island, but this would not be critical. On the other hand, the steeply rising slope does present a danger due to the occurrence of tropical rainstorms in the region. An excessively heavy rainfall might cause an undue spate of water to rush down the hillside, carrying with it stones, debris and the like, which might possibly damage the solar stills. This phenomenon has yet to be observed during the period of still operation. However, provision has been made against this possibility by the erection of a low retaining wall along the side of the hill adjacent to the solar still installation. The proximity of the hill might also partially account for the apparent dampness of the soil in the area. Part of the rain water falling on the hillside soaks into the ground and slowly works its way down into the water table underlying the stills. As these are almost at sea level, the water table is high and this could present difficulties at a later date. This must be taken into account in the design of the stills. Substantial capillary action would keep the soil moist, drawing off heat from the underside of the solar stills. Tests undertaken as part of these studies, using seven ground moisture probes set out over the site have shown that the soil drains slowly. These investigations are continuing and should give more conclusive results during the period of maximum precipitation.

Preparation of the Foundations: Initially, it was necessary to clear the area of trees, bushes, roots and the like. Not too much leveling was required. The stills themselves rest directly on the ground. They are graded three-quarters of a degree to the south. Each still is laid down consecutively, that is, the edge support of the first bay forms the side wall of the next bay. As it was impossible to grade the land exactly to three-quarters of a degree, the entire area was surveyed to two-inch contours. The top edge of each rail was then designed to be at the same elevation above sea level. This means that the side rails, described later, are all at the same elevation for any given section. This is necessary to ensure that the distillate can run off satisfactorily out of the stills. In addition, if continuous flow operation is instituted, the gentle slope will allow a smooth, cascading flow of sea water within the stills. Measurements along the 150 foot length of the stills indicate a difference in elevation of approximately twenty-nine inches.

The soil was first treated with a weed-killer which should be effective in discouraging future growth of organic matter. Below Still No. 1, in order to achieve an insulating effect, a five-inch layer of dried finger coral was laid down. This was covered by a polyethylene film, followed by five or six inches of dry beach sand. This plastic film is quite advantageous in that it eliminates any possibility of moisture rising through the sub-soil to dampen the underside of the evaporators. The effectiveness, however, of the five-inch coral layer has not been proven and this is somewhat difficult to ascertain. In any case, the marginal economic benefits would appear to be dubious. There is, nevertheless, one disadvantage associated with the use of a sub-soil impermeable film, which acts effectively as a damp-proof course. If any leakage of sea water brine from the solar still occurs, it will cause the liquid to be trapped in the enclosed six inch layer of sand. It has been customary to use sea sand for the final six inch layer immediately below the still basins. This sand, which is thoroughly impregnated with salt, completely eliminates the growth of grass, weeds and other matter. Below Stills Nos. II, III, IV, and V, the coral layer and polyethylene film have not been laid down. Instead, ten inches of beach sand have been used. However, the use of a film has been advocated for some of the subsequent bays currently being built.

Preparation of the Basin: The procedure involved, in preparing the basin for a solar still, has been outlined in Reference No. 1 where it was used in the preparation of a Brace Research Institute still in Barbados. The area between the peripheral concrete curbs was excavated to a depth of four inches and filled with building sand. The area was sprayed with several applications of weed killer and eventually a quantity of sea water was sprayed over the area to further discourage the growth of grass, etc. Once the sand had been rendered sterile, earth mounds were formed every five feet to act as water impounding dams. The area between the foot-walls and the dams was levelled as follows:

> "Two boards were cut and laid across the gutters in such a way that the board bottoms were at the required depth of the still which was 1 to 1-1/2 inches below the top of the lower mound. By running the boards in the direction of the foot-walls, the surface was levelled to insure a level perpendicular to these boards. A third board was cut, resting on the initial two, perpendicular and run between the walls. Thus, a satisfactory level was assured."[1]

For the P.S.V. stills, a similar procedure was followed, excepting that the depth of water in the section was 2 inches. By suitably cutting the base of these levelling boards, the ponds were evenly formed and levelled. This preparation is critical for the satisfactory operation of the solar stills. Failure to insure satisfactory levels and depths might lead to the formation of dry spots or areas where scale and algae accumulate. In this particular case, the basins and the edges of the sand impounding dams are also lined with pitch pine boards. This is not really necessary, and involves additional expenditure. The individual pond widths vary from four to seven feet. The effective evaporating area per bay is 1285 square feet.

Description of Evaporator Basin: The basin liner, a 30 mil thick black butyl rubber sheet, is laid directly over the prepared sand surfaces. In addition, the 11 foot 2 inch wide sheet is also lapped over the edge of the concrete foot-walls so as to cover the distillate gutters. This is indicated in Fig. No. C - 2. The edge of the sheet is glued directly to the concrete rails. The distillate is thus collected in a trough with an impervious liner. The end walls of the stills are cast in concrete and rounded to follow the arc of the transparent cover. On the higher level, openings are left for the sea water feed, an observation port, and the air inlet from the blowers which inflate the transparent canopy. The butyl rubber lining is carried right up over these end walls and held in place by the cover clamping system.

The sea water feed flows into the stills through a perforated plastic pipe set along the inlet end to ensure even distribution. The blower inlet is made using a 3 inch polyvinyl chloride pipe. At the lower end of the still, pipe of the same size is used as an overflow drain to carry away the concentrated brine. The ends of the distillate gutters are fitted with plastic pipe, 1-1/2 inches in diameter, which lead the fresh water to a measuring tank. Covered openings have been installed in each end wall to permit access and observation of the still interior.

Description of the Curb Walls: There will eventually be 15 solar still bays, each measuring approximately 10 feet by 150 feet. They are laid down side by side with an eight foot offset at each end. They are aligned longitudinally on a North-South axis. The curb walls for Stills Nos. I to V have been cast in the shape illustrated in Fig. No. C - 1. Each rail is 150 feet long and serves as a peripheral support for the solar still basins and the distillate troughs. As a result of continuing investigations, modifications have been undertaken in all rails built after March 1968, which ensure that rain water is collected all along the length of the still as illustrated in Fig. No. C - 2. It was quite essential that these alterations be undertaken as the initial design did not allow for rain water to be removed continually from the cover of the solar still. As a result, during heavy downpours, there was a congregation of rain water at the lower end of the stills, resting on the inflated 4 mil Tedlar cover. If the fans could not maintain sufficient inflation pressure, the abnormal load of water collapsed the Tedlar canopy. This condition has arisen often when the batteries feeding the blowers were not sufficiently charged. When the cover collapsed in one location, it was followed by a general collapse of inflation along the length of the bay as rain water rushed along to fill in the voids. Not only did this inhibit production during these periods, but in addition, after inflation pressure had been re-established, some sea water adhered to the underside of the Tedlar cover, which contaminated the fresh water distillate during the subsequent period of production. As a result, it is absolutely necessary that inflation be maintained continuously. By undertaking certain modifications to the cover clamping support design and construction, this problem should now be eliminated on these initial bays.

The foot-walls are cast using a 1:3:5 concrete mixture of cement-sand-stones. There is no reinforcing steel in the sections. The grooves are cast around concrete forms fashioned to the particular shape indicated in Fig. No. C - 2. Generally, the top of the concrete rails is sealed with a fine cement-sand grout, and waterproofing compound.

Floating Mat on Brine Surface: The stills are provided with a floating radiation absorbing layer, made of a loose, non-woven black fabric. In this case, the material is made of poly-acrylonitrile fibres, which are resistant to degradation by sunlight and the concentrated brine. The fibres are coloured black. The material is known as Orlon, a trade name registered with the United States Patent Office. During the prolonged exposure to the extreme conditions within the stills, the non-woven mats of poly-acrylonitrile are reputed not to degrade or mat and the fibres apparently do not embrittle, weaken or hydrolyse[2]. A sample removed after 11 months operation conclusively attested to the satisfactory quality of this material. Unfortunately, due to poor operation of the still during the first trial period of operation, the fibres picked up a considerable quantity of brine salts which matted on the upperside of the layer.

Chemical analysis of the deposit indicated the following composition:

Calcium Carbonate - 72%

Magnesium Carbonate - 14%

Insoluble Brownish Silt - 5%

Remainder could have been Cl^-, $SO_4^=$ and moisture.

The sample was not heated to remove the occluded water for fear of destroying the fibres.[3]

It is evident that either the basin temperature or the salt concentration or both have exceeded their upper desirable limits. On this question Spiegler[4] states: (Chap.10, Scale Formation and Prevention, by York and Schorle) "Normal sea water (concentration factor of 1) has a total alkalinity of about 120 mg/litre, and hence at a concentration factor of 2, the total alkalinity would be 240 mg/litre. Note that at a concentration factor of 2, with no loss of alkalinity, the pH of the solution should be less than 7.0 if temperatures above 140°F. are to be employed. Since normal sea water ranges in pH from 7.5 to 8.1, it may be seen that cold sea water is essentially saturated with $CaCO_3$."

Hence, if this scaling of the Orlon felt, with its detrimental effects continues, it may be necessary either to change the sea water more frequently or else to acidify the feed to reduce the pH to below 6.5.

The wet fibres of the floating Orlon mat project out from the brine surface providing an increased surface area for evaporation. Under normal operating conditions, the salts and other matter in the saline water should remain beneath the floating wick, reducing reflection from scale deposits to a minimum. Although the initial experience with the Orlon mat of Solar Still No. I was not too encouraging, it must be stressed that during the 11 months of operation the sea water feed was not screened or filtered nor was the operation of the still closely controlled.

On occasion, the sea water was not changed as frequently as it should have been. Brine concentrations built up to higher levels than desirable. Since a period of positive testing and control was instituted, and the water works department set up, regular, daily measurements of the reject brine have indicated a variation of specific gravity from 1.03 to 1.04, a sea water concentration of just over one and one half times normal.

Tests undertaken in Florida with uninsulated basin-type solar stills showed that the use of a floating mat increased the productivity by ten to twenty per cent. It was not felt that this was sufficient to justify the added cost of the wick.[5,p.6] Preliminary results drawn from comparing productivities of stills on P.S.V. with and without floating wicks indicate increased outputs of the same order of magnitude when the wicks are used.

<u>Description of the Transparent Cover</u>: The basin of the solar stills is covered by a transparent canopy, clamped to the edges of the curb walls. There is no framework to support the cover. Instead, air, under a slight pressure, is blown into the stills, inflating the cover to form a curvature of low arc-to-chord ratio as indicated in Fig. No. C-1. This type of still has been developed and used successfully in the United States,[5] Greece,[6] and elsewhere.

The transparent film used in this case is a 4 mil polyvinyl fluoride film manufactured by the E.I. du Pont de Nemours Company. The trade name, Tedlar, is registered with the United States Patent Office. As most films are hydrophobic, it is necessary to treat the side of the film, on which water vapour condensation will occur, in order to produce a wettable surface. This renders the film hydrophylic. Filmwise, condensation takes place in lieu of dropwise condensation. The treatment process is known as "mettabraiding" and the material is sometimes referred to as "mettabraided" Tedlar. The vapour condensing on the canopy flows off to the peripheral collection gutters as indicated in Fig. No. C-2.

Preparation of the Transparent Cover Wettable Surface: In order to render the polyvinyl fluoride film hydrophylic, it is necessary to roughen the surface to the extent of at least 50 to 200 irregularities or undulations per inch.[2] This can be accomplished by sandpapering, sandblasting with wet sand, or by embossing undulations into the film surface with a calender. The sandpapering method has been tried on an experimental still in Barbados with not too much success.[7] Analysis of a sample of this film indicated that it

> "lacked good wettability, was highly crystalline showing excessive mechanical working, had a high permeability to air and particularly to water vapour, and lacked that somewhat intangible roughness that makes a good glazing." [8]

For satisfactory results, Edlin claims that indentations in the film should be of the order of 0.5 to 0.75 mil deep. He also claims that if 1,000 to 4,000 irregularities per inch are made on the inner surface of the transparent canopy, long-wave re-radiation by the still is reflected by the cover without significantly reducing the transmission of incident solar radiation.[2]

The Desirability of a Wettable Surface: In order that a process such as "mettabraiding" be considered economical, the additional cost of treating the surface must be more than offset by a corresponding increase in the quantity of water produced,the value of which will write off the cost of the added investment. Edlin states that a still having a transparent cover with a wettable inner surface will produce 10 to 25 per cent more distillate than a similar still covered by a non-wettable canopy, subject to dropwise condensation.[2]

If an average still produces 0.10 U.S. gallons per square foot per day and operates for 360 days per year, it will produce 36 U.S. gallons per square foot per annum and an additional 3.6 to 9 U.S. gallons per square foot per annum if the film has been treated. The treatment cost amounts to approximately $0.10 U.S. per square foot.[9] If the Tedlar lasts 10 years, as Edlin claims,[8] the water produced through this increased investment will cost approximately $1.00 to $3.00 U.S. per 1,000 gallons. For small installations, this is a reasonable rate of unit water cost. As a result, it appears as though the production of a wettable surface is economically justifiable. All the bays of the P.S.V. solar stills are fitted with wettable Tedlar covers.

Cover Configuration: Solar stills of the type having a flexible, transparent, air-supported canopy are characterized by a low arc-to-chord ratio of between 1.01 and 1.20. The particular configuration of these stills is indicated in Fig. No. C-1. The arc length, in this case, is the exterior periphery of the inflated film and the chord is the minimum distance between the two edge supports. The P.S.V. stills have an arc-to-chord ratio of 1.01. Although they do not conform to the pattern set out by Edlin,[2] it is interesting to note the values he quotes for comparitive purposes. For an incident solar radiation intensity on the horizontal of 2,000 Btu per square foot per day, he lists the following results:

Still Width (feet)	Optimum Arc-to-Chord Ratio	Production of Fresh Water USGPD/sq. ft.
3	1.110	0.163
6	1.045	0.160
9	1.020	0.150
12	1.015	0.140
15	1.012	0.135

For a 12 foot wide still, he shows the variation of arc-to-chord ratios with productivity as follows:

Ratio	Productivity USGPD/sq. ft.
1.017	0.13 - too high a crown
1.015	0.14 - optimum
1.013	0.11 - too low a crown

These productivities are greater than those which have been measured on the P.S.V. stills. For these units, the optimum ratio is 1.027, according to this data. Edlin maintains that a ratio below 1.01 causes refluxing of the distillate while a ratio in excess of 1.2 forms an undesirable air foil which can damage the film.[2] At both extremes, the efficiency is apparently reduced.

<u>Description of Canopy Clamping System</u>: It is essential that a rigid well-designed clamping system be used to attach the transparent cover to the concrete curb walls and to seal the edges of the still. The clamp components are plywood strips, electrical conduit and nickel plated expansion bolts. While several types of clamps have been tried, Fig. No. C-2 illustrates the one currently in use, which is still being improved. Basically, it is assembled as follows:

(1) Standard lengths of plastic electrical conduit are spliced with short sections of conduit and glued together to form continuous lengths.

(2) The concrete anchor bolts are driven into the rails as indicated in Fig. No. C-2.

(3) Pieces of exterior quality plywood are prepared according to the following specifications:

(a) 3/4" plywood - two 6 inch wide strips running along the length of the concrete rail, on each side of the Tedlar canopy.

(b) 3/4" plywood - one 6 inch strip running along the length of each end wall.

Strip (a) is drilled three inches from each side, every eighteen inches along the length, to accept the three inch threaded expansion bolts. A length of conduit is fixed to the edge of the concrete curb wall as illustrated in Fig. No. C-2. The butyl rubber sheet is lapped over the conduit and glued with adhesive to the concrete rail to a width of about six inches. Holes are cut out in the liner so that it passes over the protruding anchor bolts. Strips (a) are each fitted with a similar conduit strip, screwed into the underface on one side, and overlapping the strip edge by 1/8 inch. This conduit and the edge of the plywood strip are covered by two inch wide, butyl rubber adhesive tape.

One edge of the transparent cover film is lapped around a third length of conduit.

The sections are set up as indicated with strip (a) forcing down the canopy film against the air inflation pressure. To open up a section of the still, the nuts retaining strip (a) must be removed, and the strip lifted off. Special strips (b) are drilled to fit over previously attached concrete anchor bolts in the end walls of the still. The strips (b) have conduit screwed into the underside edge as above. The edge of the Tedlar film is wrapped around another conduit and the joint is sealed as before.

<u>Air Blower System</u>: The transparent canopies of the solar stills are inflated by air under a pressure of 0.25 in. water gauge, supplied by 135 cfm, centrifugal fans powered by twelve volt, direct current motors.

Theoretically, the fans should be delivering very little air as the cover edges should be well sealed, the only air loss being the permeability of the transparent canopy. It has been estimated that under extreme conditions, this amounts to about one pound per hour of water vapour and approximately one half pound per hour of air, or about 30 cubic feet per hour per still. In practice, unfortunately, the leakage losses from the edges are not entirely eliminated. Naturally as water vapour is lost as well as air, these losses cut down the productivity.

The blowers are battery operated and consume 72 watts each. The batteries were originally charged by a six foot diameter, wind powered electric generating set, mounted on a twenty seven and one half foot tower. At present, alternating current electric power is available. It is converted by a silicon rectifier into direct current power to operate the blowers.

The windcharger began charging the batteries at a windspeed of 7 mph and was governed at maximum output at a windspeed of 23 miles per hour. Under these conditions it produced about 210 watts.

The problem in the use of the original system was that the blowers consumed more power than the generator was able to supply when the windspeed was low for any period of time. As a result, low inflation pressure was maintained and any significant rain storms resulted in the collapse of the canopy. The operation of the stills had been plagued by continual problems of inflation pressure for the preceding few months. Unfortunately, the continual flexing of the Tedlar sheet due to deflation limits its useful life and poses other problems as outlined earlier.

In order to ensure continuous operation, a special advance relay is connected to two blowers in such a manner that if one fan motor blows out, or is otherwise rendered inoperative, it will automatically switch over to the other unit. Thus a constant inflation pressure should be guaranteed.

Finally, it has been recommended that a similar type of relay be used to connect a fan driven by an AC motor which could operate, if desired, when AC power is available. As a result of this action, two services of electric power, both AC and DC, would be available to operate this most critical part of the still.

The current system operates quite effectively and adequate inflation pressures have been maintained for the past few months since the use of the windcharger was discontinued.

<u>Operation of the Solar Stills</u>: A solar still is essentially a very simple piece of equipment. Fresh, clean sea water is fed into the still either on a batch basis or in a continuous flow. Recently, in Australia, a continuous saline water feed rate of 0.1 pound per hour per square foot of still has been

used.[10] This is about twice the maximum daily distillation output. Essentially, a windmill pumps saline water to a constant head tank which discharges a reasonably consistent flow into the stills. If no preheating is used, it can be estimated that this produces a heat loss of the order of two per cent.

In the batch system, fresh, clean sea water is delivered to the still early every other morning in an amount at least double the anticipated distillate production for the run. In this manner, scaling is reduced to a minimum.

In the P.S.V. plant, sea water is pumped from a shallow depth offshore into a 2,500 U.S. gallon storage tank. The quantity of saline water in each bay is approximately 1,500 U.S. gallons. About 1,200 U.S. gallons of fresh sea water is added to each bay every two days. The feed should be screened and possibly filtered before entering the storage tank or the stills. A buildup of sand and debris was noted in several of the stills, especially those which have been operated the longest with nonfiltered sea water.

When the feed is admitted to a bay, waste brine flows out of the overflow pipe at the opposite end of the still. This results in the filling of over eighty per cent of the basin ponds with fresh sea water to a depth of two inches. During the daytime, when the temperatures within the still are well above ambient, a small flow of reject brine is automatically discharged from the still. It is felt that the heating of the basin water causes expansion which is aided by capillary action within the floating wick resting on the impounding dams. Thus a small quantity of water is moved from pond to pond and discharges from the lower end. This small discharge is by no means detrimental and the loss of heat is less than one per cent. No measurement is taken of the quantity of brine discharge during filling. A drain leads the concentrated brine back to the sea. The fresh water produced by the stills is collected in a distillate measuring tank. Then it flows to a 3,800 U.S. gallon collection cistern. It is then pumped directly from these cisterns to the storage reservoirs of the reticulation system. There is currently a capacity of 8,300 U.S. gallons of distillate and rain water storage on the plant site, including a 4,500 gallon section of the reservoir building. When the second collection cistern is built, there will be 7,600 U.S. gallons of storage capacity at the plant site. This is approximately 6 to 12 days distillate production storage for the 6 stills currently operating, i.e. as of June 1968. The distillate salinity is checked continuously, especially following periods of cover deflation. Eventually a continuously operating electrical conductivity probe connected to a solenoid valve will be installed. All distillate with a measured salinity of over 500 ppm will be rejected automatically.

Each bay is also equipped with a rain water collection tank at the discharge end. The collected rain water is led to the same storage tanks as the distillate. It has been recommended, however, that the rain water be filtered prior to being mixed with the distillate in order to maintain product quality.

On this latter point, bacteriological tests have been undertaken to determine the quality of the solar still and storage reservoir waters for drinking purposes. While the results are incomplete, in some cases quantities of Bact.coli and Bact.aerogenes were found. These tests have been repeated and have indicated that few pathogenic bacteria are found in the solar still effluent, but that the bacterial count, in some cases, is very high. At times, samples taken of the water from the storage reservoirs did indicate the presence of fecal matter.[11] It therefore seems desirable to chlorinate the water before it enters the reticulation system.

Plates Nos. C-1 to C-4 illustrate the stills and some aspects of their construction and operation.

APPENDIX C

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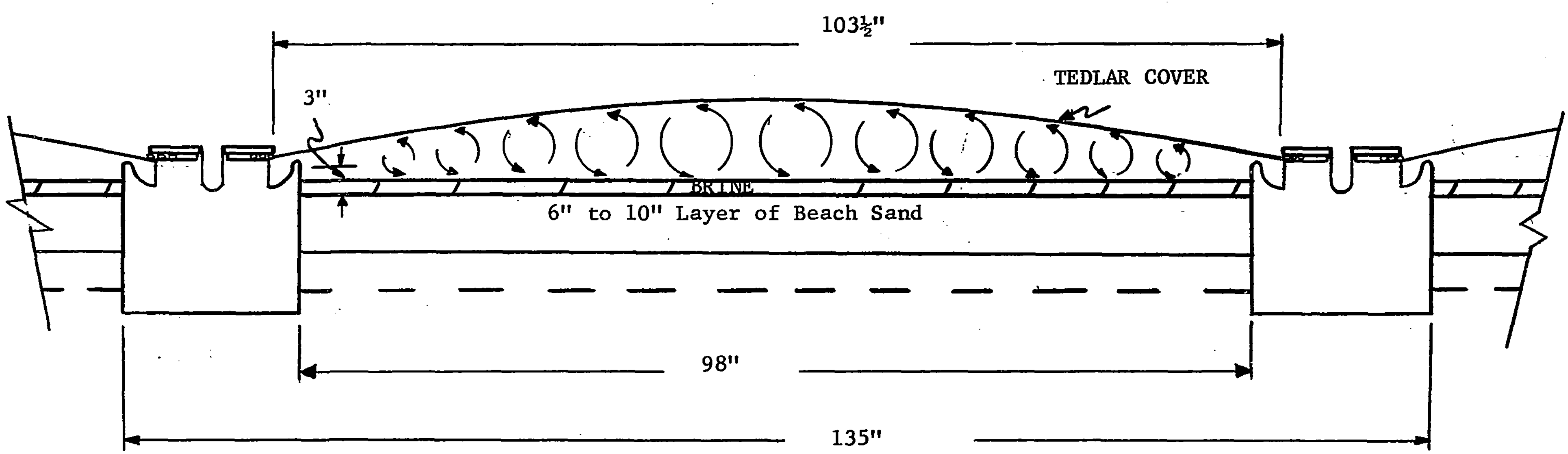
11. Best, C. Private Communication on tests carried out at Public Health Laboratory, Enmore, Bridgetown, Barbados, File 60/08, Brace Research Institute, McGill University, 30 December, 1967, 16 May, 1968 and 1 June, 1968.

Figure No. C-1

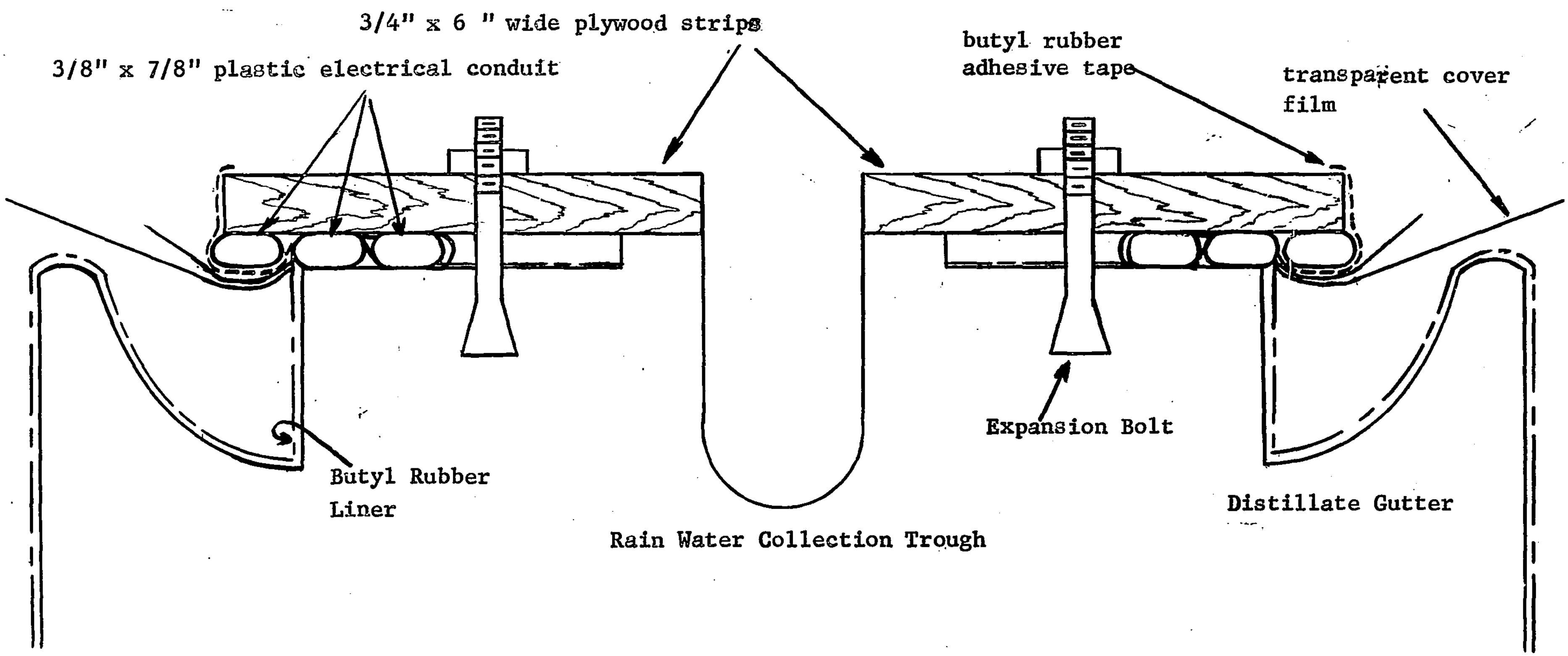
SECTION VIEW OF SOLAR STILL BAY



Scale: 3/4" = 1'

SECTION OF TRANSPARENT COVER CLAMPING SYSTEM

FIGURE NO C - 2



Scale: 1" = 2".

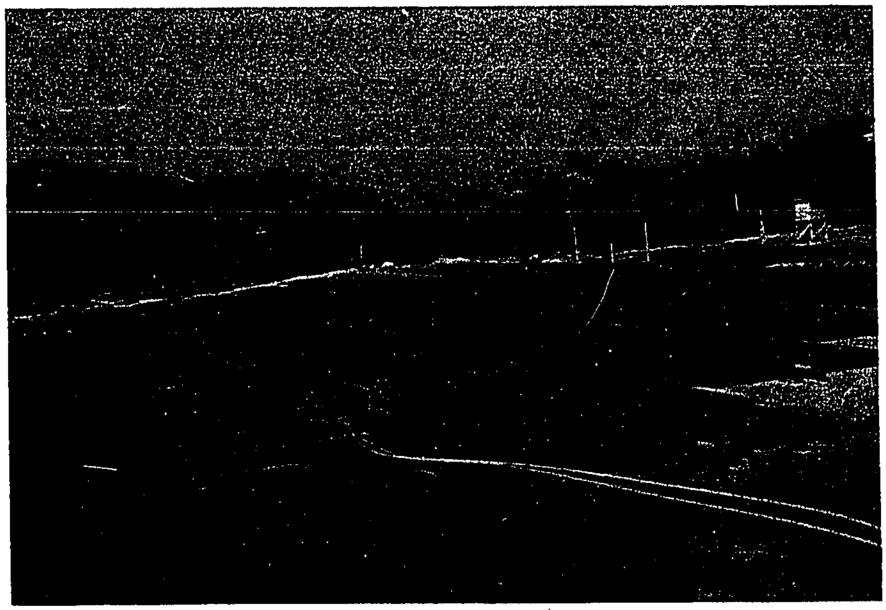


Plate No. C-1 shows several bays deflated on the right hand and the prepared basin evaporators on the left.

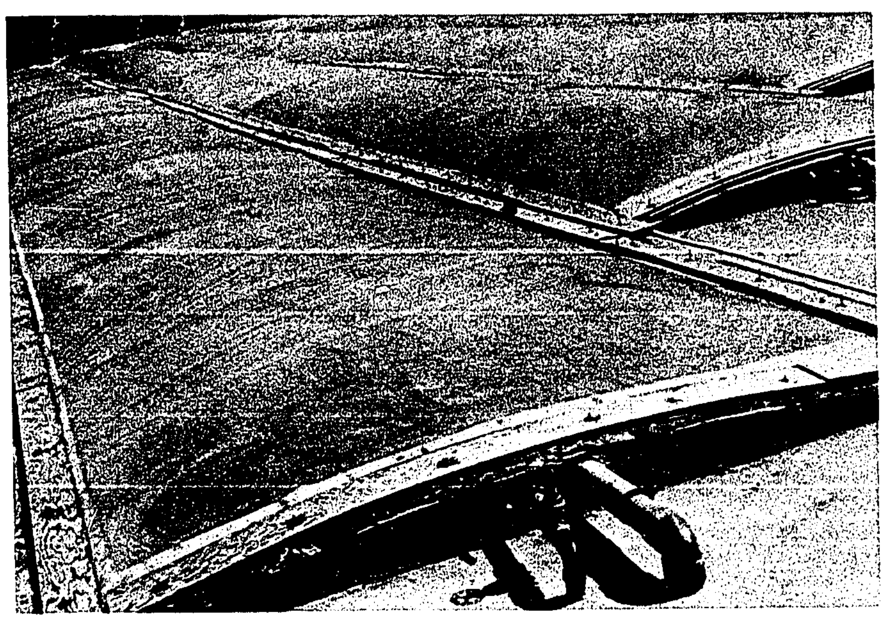


Plate No. C-2 shows a number of bays, inflated and in operation.

Plate No. C-3 indicates the construction of a concrete rail of a solar still bay.

Plate No. C-4 - View taken inside a bay, showing the scale encrusted floating mat. Sediment lies below on the basin liner.

APPENDIX D

DESCRIPTION OF THE INSTRUMENTATION USED ON PETIT ST. VINCENT

Climatological Instrumentation: In order to predict and evaluate the performance of both the solar distillation units and the rainfall collection system, it was necessary to gather climatological data. As no information of this type had ever been collected on Petit St. Vincent, a small climatological station was set up in December, 1967 to record data pertinent to these investigations. The locations of these instruments are shown in Fig. No. D - 1. Generally, the instruments have been installed according to the instructions and practice of the Meteorological Service of the Department of Transport, Canada. However, this can by no means be classified even as a sub-station, as the instrumentation in use is more suitable for the provision of data for engineering evaluation than for meteorological purposes. It should be noted that the ground on which the instruments have been installed is reasonably flat and generally covered with short grass. A description of the climatological instruments has been given in Table No. D - 1.

Measurement of Solar Still Parameters: The following variables are measured in order to assess the heat and mass transfer characteristics of the solar stills.

Temperatures:

(1) Transparent Canopy - A composite reading of the cover temperature is taken at several locations along the length of a bay.

(2) Evaporator Basin - A composite reading taken as above.

(3) Ambient Air - The ambient air above the stills is measured during tests.

(4) Distillate - Periodic readings of the distillate temperature are taken.

(5) Ground - Temperatures of the ground beneath and surrounding the solar stills are taken occasionally.

These temperatures are measured using a Thermistemp Telethermometer manufactured by the Yellow Springs Instrument Co., Ohio, USA.

Temperature values are readable to $\pm$ 0.4 per cent of the scale range, which is 59° F. to 212° F. Three types of interchangeable probes are used.

(A) ordinary fluid or ground probes

(B) special surface probes

(C) special gas or vapour probes

In addition, the measurements are continually being checked by mercury-in-glass thermometers, and special expansion-coil surface thermometers. The calibration is verified periodically using a decade resistance box, with resistors of $\pm$ 0.5 per cent accuracy. On completion of a series of tests in May, 1968, the instrument and all the probes were thoroughly checked and found to be reading correctly.

Mass Transfer Measurements:

Distillate Production: The amount of distillate produced is measured in the tanks at the base of each solar still bay. This is a volumetric measurement in which the level in each tank is read in the mornings at 0800 hours. These tanks are then emptied into the collection cisterns. Any residual amount of water in the tank is noted and deducted from the following day's production.

Sea Water Feed: The volume of sea water fed to each still bay is recorded through changes in the level of the sea water reservoir.

Brine Discharge: No facilities exist for the measurement of this flow, although it has been metered approximately on a few occasions.

Rain Water: Rainfall incident on the stills passes directly through special rain water tanks into the collection cistern, where a change in levels is used to record the amount collected.

Additional Measurements:

Salinity: A close check on the salinity of the solar still distillate is made with a Bouyoucous Moisture Meter, fitted with a conductivity probe. The meter was calibrated so that the readings can be related directly to ppm of sodium chloride.[1] The specific gravity of the sea water feed and the reject brine are measured with a hydrometer.

Relative Humidity: During periods of test, the ambient air relative humidity is recorded continuously on a humidigraph, manufactured by the Bristol Instrument Co. Instantaneous readings are taken at regular intervals with a sling psychrometer.

Ground Moisture: In order to verify the rate of moisture diminution from the soil beneath the solar stills, the relative change of moisture content is measured in gypsum blocks, using the Bouyoucous Moisture Meter. A series of blocks have been placed at different levels over the site of the solar distillation plant. This provides the water works department with a continual check on the condition of the ground below the stills.

Frequency of Readings: Measurements of the still temperatures are taken at four hour intervals during the day. These are reduced to one hour intervals during periods of test. The distillate production is measured daily. During tests, however, the output is recorded hourly.

Summary: It should be stressed that all the equipment used is relatively simple, inexpensive and unsophisticated. In any small village or isolated community, it would be difficult to service or operate more complex instrumentation.

References:

1. Private Communication, Sugar Technology Research Unit, Edgehill, Barbados 11 December, 1967, on the calibration of the moisture meter., Brace Research Institute, McGill University, File 60/08

TABLE NO. D - 1

SUMMARY OF CLIMATOLOGICAL INSTRUMENTATION ON PETIT ST. VINCENT

ITEM	INSTRUMENT	SUPPLIER	FREQUENCY OF READINGS HOURS	HEIGHT ABOVE GROUND
1. Solar radiation intensity on a horizontal surface	Silicon cell sensor coupled with a D.C. watt/hour meter continuous integrator and an instantaneous intensity indicator.	D.T.I. Co., Tucson, Arizona, U.S.A.	0800 (1200) (1600)	5' 6" to base
2. Windspeed	Munro Cup Anemometer - continuously totalizing miles of wind run.	Munro Ltd., England	0800 (1200) (1600)	4 ft. to counter level
3. Rainfall	Australian, plastic funnel type, graduated scale - two gauges placed 23 ft. apart. Rainfall taken as average. Six other gauges of this type have been placed at other key locations on the island for measuring rainfall in areas near large roof catchments.	Marquis, Australia	0800 1600	6 ft. from funnel to ground
4. All other readings are taken from sensors located in a Stevenson Screen - the base of which is 5 ft. above ground level.				
a) Ambient Air Temperature	Mercury-in-glass Thermometer	Taylor Instruments, Montreal, Canada	0800 (1200) (1600)	
b) Air Temperature Minimum-Maximum	Min-Max Thermometer	" "	0800	
c) Relative Humidity	Sling Psychrometer	Casella Co. London, England.	0800 (1200) (1600)	

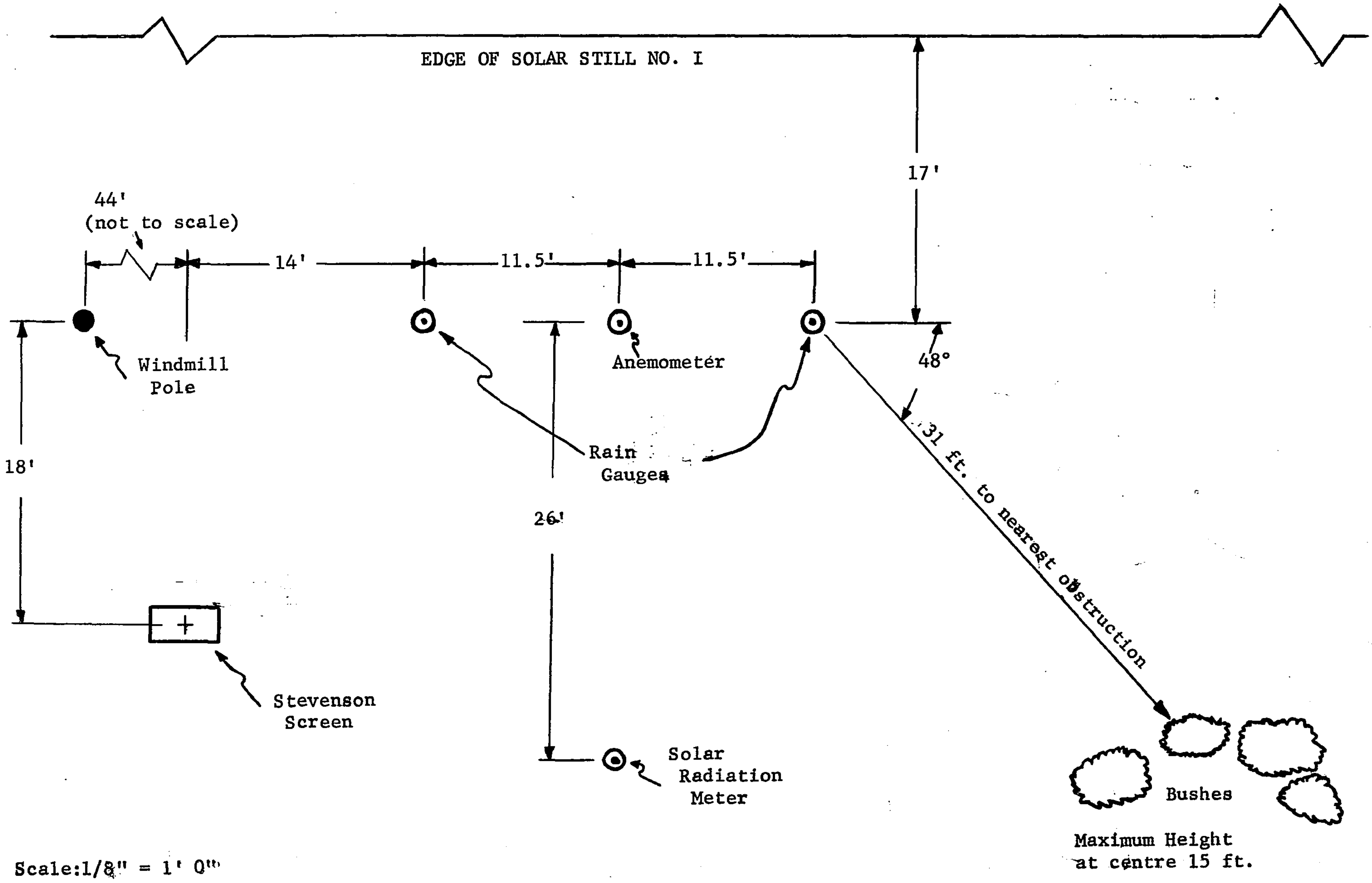
Note: All readings are taken at 0800 hours and other readings are often taken at the hours enclosed in parentheses.

All the instruments are located at the solar distillation plant site as illustrated in Fig. No. D - 1.

The location of these instruments is approximately latitude, 12°32' 10" N and longitude 61°23' 16" W.

Figure No. D-1

LAYOUT OF CLIMATOLOGICAL INSTRUMENTS INSTALLED AT THE SOLAR DISTILLATION PLANT



APPENDIX E

EXPERIMENTAL MEASUREMENTS AND RESULTS

This section lists the measurements and experimental results taken on Petit St. Vincent during the course of these investigations. No discussion has been included as all comments on these data have been made in the relevant chapters of the thesis.

The following information has been presented in this appendix:

a) the climatological measurements of solar radiation, windspeed, ambient air temperatures and precipitation are given in Tables E-1 to E-4.

b) the experimental readings and calculated results for one of the test evaluations of a solar still bay have been enumerated in Table E-5. The variation of basin temperatures during this test has been illustrated in Figure No. E-1.

c) the average productivities for the solar distillation units are indicated in Table No. E-6.

TABLE No. E-1

TOTAL SOLAR RADIATION INTENSITY ON HORIZONTAL SURFACE FOR PETIT ST.VINCENT, ST.VINCENT, WEST INDIES

(Figures enclosed in brackets are adjusted or estimated)

DAY	Dec./67	Jan./68	Feb.	Mar.	Apr.	May	June
1		394 R	471	597	(643)		
2		(454)	490	574	(514)	510 R	
3		(454)	(522)	547	632	662	
4		457	(527)	578	648	696	490
5		513	547	(443) R	512	606	622
6		536	300 R	(558)	606	484 R	545
7		449	(409)	589	632	498 R	192 R
8		324 R	(537)	628	558 R	602	
9		(473) R	401	490	528	664	
10		(413)	351 R	435 R	598	669	573
11		473	480 R	529		658	298 R
12		494	(577) R	631 R		651	386 R
13		390	(495) R	453 R		531	214 R
14		480	499	640		630	524
15		512	495	661		675	
16		454	528	640	690	581	
17	426	506	550	(585)	627	635	618
18	465	498	525	(589)	395 R	572	513
19	422	525	542	405 R	620	634 R	598 R
20	481	-	(595)	606	602	474 R	545 R
21	362 R	-	(558)	(615)	644	608	637
22	469	-	599	(619)	615	523	
23	507	-	591	653	620	610 R	
24	492	356 R	597	644 R	585	595	579
25	449	492	591	621	615	650	464 R
26	(385)	488	614	553 R	657	597	590
27	385 R	471	413	345 R		679	637
28	463 R	541	610	665	R	644	
29	431 R	490	597	614	685		
30	471	435		651			
31	424 R	432		642			
Mean	442	463	518	574	602	605	501
Standard Deviation	41	52	94	82	70	63	79

R - indicates day on which more than 0.05 inches of rain fell.
All readings indicated are in langleys.

TABLE No. E-2

VARIATION OF THE WINDSPEED

OVER THE SOLAR STILLS ON PETIT ST. VINCENT

(All readings are in miles per hour)

DAY	Hours	Dec/67	Jan/68	Feb.	Mar.	Apr.	May	June
1	0800-1600		9.3	8.1	7.7	9.2		
	0800-0800		9.6	7.7	6.2	8.3		
2	0800-1600		10.6	8.4	6.9	7.5	6.0	
	0800-0800		10.5	9.9	7.0	6.8	6.3	
3	0800-1600		8.8	11.7	8.2	7.2	8.0	
	0800-0800		9.3		7.2	8.1	7.9	
4	0800-1600		10.5		6.3	8.6		5.8
	0800-0800		9.4		4.2	8.3	9.0	6.8
5	0800-1600		8.6	10.6	9.3	8.3		7.3
	0800-0800		8.9	10.7	7.9	8.3	9.3	6.0
6	0800-1600		10.3	11.3	7.9	8.8	9.2	1.0
	0800-0800		10.2	11.2	7.7	9.6	9.2	4.7
7	0800-1600		8.3	11.0	7.2	11.2	7.6	7.0
	0800-0800		8.7	9.8	5.8	9.4	7.9	6.4
8	0800-1600		8.8	9.7	7.0	9.3		4.3
	0800-0800		9.4	8.1	6.8	10.2	7.8	
9	0800-1600		10.3	7.4	9.1	10.3		
	0800-0800		11.8	6.7	10.2	10.8	7.9	
10	0800-1600		13.2	7.1	6.7	9.7	6.8	3.6
	0800-0800		8.6	6.0	6.7	10.2	6.8	2.9
11	0800-1600		9.9		6.6	8.5		3.7
	0800-0800		8.8	7.3	7.9		7.9	5.6
12	0800-1600		8.5	8.5	10.8			8.5
	0800-0800		8.1	7.3	10.3		7.6	8.5
13	0800-1600		9.5	7.5	5.1		6.8	6.3
	0800-0800		8.2	7.7	7.8		6.8	9.4
14	0800-1600		9.4	7.2	9.8		5.9	10.0
	0800-0800		9.1	8.4	9.4		6.8	10.0
15	0800-1600		8.5	9.5	9.4		7.0	
	0800-0800		8.4	9.1	8.4			
16	0800-1600		8.7	9.9	6.0	4.5		
	0800-0800		8.1	9.1	5.9	5.0		

Table E-2 continued on following page.....

TABLE No. E-2 cont. Variation of the Windspeed, P.S.V.

(All readings in miles per hour)

DAY	Hours	Dec/67	Jan/68	Feb.	Mar.	Apr.	May	June
17	0800-1600		7.0	8.5	6.2	6.0		6.3
	0800-0800	7.7	7.5	8.7	6.2	5.3		7.2
18	0800-1600		7.5	10.4	8.3	3.9		7.6
	0800-0800	9.9	5.9	9.0	8.4	2.8	7.4	9.1
19	0800-1600		5.3	8.2	7.4	2.9	8.6	9.9
	0800-0800	9.4	4.1	8.4	6.8	1.9	8.8	10.7
20	0800-1600			8.6	6.5	4.1	7.5	
	0800-0800	7.8		7.1	5.3	3.8	5.6	9.4
21	0800-1600			4.1	3.7	6.2	5.6	7.9
	0800-0800	7.6		5.5	4.2	5.8	6.1	7.8
22	0800-1600	6.5		8.4	6.2	5.5	5.5	
	0800-0800	9.0		10.5	7.1	4.2	5.5	
23	0800-1600	8.6		9.4		4.9	5.1	
	0800-0800	6.8		7.8	7.7	4.0	6.5	
24	0800-1600		10.7	8.8	7.8	4.0	7.5	8.9
	0800-0800	7.4	10.8	7.1	9.1	3.7	6.9	9.5
25	0800-1600	9.4	10.5	5.9	7.5	6.5		8.1
	0800-0800		10.1	6.2	8.2	7.2	5.8	8.0
26	0800-1600		10.3	7.2	9.1	8.2	6.8	9.0
	0800-0800		8.8	6.4	8.0	8.8	6.1	11.3
27	0800-1600	8.8	7.9	5.4	9.0		11.2	13.4
	0800-0800	9.3	6.6	8.5	8.9		8.7	12.8
28	0800-1600	9.8	6.2	8.6	7.3		9.2	9.9
	0800-0800	9.5	4.7	8.9	7.0		7.8	
29	0800-1600	7.7	4.9	8.4	9.0	6.4	7.3	
	0800-0800	8.1	5.9	7.9	8.3	6.6		
30	0800-1600	10.4	7.5		8.6	4.9	4.2	
	0800-0800	9.2	7.5		8.2		4.8	
31	0800-1600	10.3	7.0		9.3		6.4	
	0800-0800	8.8	6.8		9.2			
Mean Daytime Windspeed		8.9	8.8	8.5	7.7	6.9	7.3	7.0
Mean Daily Windspeed		8.5	8.4	8.2	7.5	6.8	7.3	7.5

TABLE No. E-3

VARIATION IN AMBIENT AIR TEMPERATURES
FOR PETIT ST.VINCENT, ST.VINCENT, WEST INDIES

(All readings are in degrees F.)

DAY	Dec./67		Jan./68		February		March		April		May		June	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
1					80	76	81	73	81	77				
2					81	75	81	74	82	77	82	76		
3					81	73	81	74	83	76	84	79		
4							80	76	83	77	84	79	82	77
5			82	72	81	75	81	75	83	78	84	77	83	75
6			84	76	82	75	81	75	82	76	84	78	83	76
7					81	74	81	76	82	75	84	72	80	75
8			81	74	80	76	82	76	81	77				
9			78	73	81	76	82	76	82	73				
10			81	73	81	74			81	77			83	77
11					83	76	82	75	81	77			82	76
12					80	76	80	74					82	75
13					81	75	79	73					81	75
14			84	78	81	72	81	75					83	79
15			80	78	81	73	80	76						
16			83	78	81	75	79	75	83	76				
17			82	75	81	74	81	75	84	78			83	79
18					81	76	81	76	83	79			83	79
19					80	76	81	76	84	74			83	76
20					82	77	82	76	83	76			83	79
21					81	76	82	77	82	76			83	78
22	79	75			81	76	85	77	83	77				
23					82	76	82	77	83	77				
24			83	74	81	75	82	77	83	78				
25			81	74	82	76	82	75	84	78	83	78		
26			82	76	81	75	82	77	83	79	83	78	84	75
27			80	76	82	76	82	73	83	76	83	79	83	80
28			81	76	81	77	79	75			84	79		
29			80	74	83	77	81	76	83	76	84	79		
30			80	74			81	77	84	78	82	76		
31			81	76			81	77			82	76		
Mean	79	75	81	75	81	75	81	76	83	77	83	77	83	77

TABLE NO. E-4

RAINFALL MEASUREMENTS ON PETIT ST. VINCENT AND NEIGHBOURING ISLANDS FOR 1968

All figures are in inches of rainfall

	Jan.	Feb.	March	April	May	June
Petit St. Vincent	0.51	0.54	3.60	2.32	1.99	3.75
Union Island		1.36	3.67			
Carriacou						
Belair Park	0.82	0.69	3.11	2.08		
Dumfries Estate		0.94	4.29	2.32		
Limlair Agricultural Station		0.51	2.96	1.70		

It is interesting to note that the rainfall measured on PSV for the first five months of the year is 95% of the average, for the region, as indicated in Table No. B-1, for the same corresponding time period.

N.B. It must be remembered that the type of raingauge in use differs at most localities.

The readings for PSV have been taken from the rain gauges installed at the solar distillation plant site.

TABLE No. E-5 (a)

EXPERIMENTAL RESULTS OF SOLAR STILL EVALUATION, PETIT ST.VINCENT, ST.VINCENT, May 24, 1968

Time Hours	Solar Radiation Distribution I_H	I_D	I_d	τ_D	$\tau_D I_D$	$r_D I_D$	$\alpha_D I_D$	$\tau_d I_d$	$r_d I_d$	$\alpha_d I_d$	Measured Parameters Average Windspeed over Stills	Average Relative Humidity	Distillate Production per sq.ft. of A_H	Air Temp. over Stills	Average Basin Temp. See Fig. E-1
UNITS	Btu	Btu	Btu		Btu	Btu	Btu	Btu	Btu	Btu	mph	%	lbs water	°F	°F
0600-0700	15.7	0.0	15.7	0.775	0.0	0.0	0.0	13.2	1.6	0.9	6.6	81	- -	82.5	91.9
0700-0800	86.6	52.8	33.8	0.805	42.5	5.7	4.6	28.2	3.5	2.1	8.0	82	- -	84.0	95.0
0800-0900	118.1	80.3	37.8	0.89	72.3	5.0	3.0	31.7	3.9	2.2	8.1	78	0.0080	85.0	99.4
0900-1000	299.1	236.2	62.9	0.915	216.2	11.2	8.8	52.8	6.5	3.6	8.1	78	0.0397	85.0	107.7
1000-1100	322.7	206.6	116.1	0.92	190.2	8.3	8.1	97.4	12.0	6.7	8.7	78	0.0477	88.0	116.0
1100-1200	369.9	284.8	85.1	0.92	262.2	11.4	11.2	71.5	8.8	4.8	7.4	77	0.0955	90.0	124.4
1200-1300	283.3	226.7	56.6	0.92	208.3	9.1	9.3	47.6	5.8	3.2	8.9	76	0.0795	90.0	130.2
1300-1400	251.8	183.9	67.9	0.92	169.2	7.4	7.3	57.0	8.0	2.9	6.4	75	0.0795	89.0	134.2
1400-1500	251.8	183.9	67.9	0.915	168.2	8.7	7.0	57.0	8.0	2.9	6.6	75	0.0795	89.0	137.1
1500-1600	141.7	109.1	32.6	0.89	97.8	6.8	4.5	27.2	3.4	2.0	5.6	76	0.0636	89.5	137.0
1600-1700	55.1	32.8	22.3	0.805	26.4	3.5	2.9	19.2	2.3	0.8	5.2	80	0.0477	87.0	132.0
1700-1800	31.5	15.1	16.4	0.775	11.7	2.0	1.4	12.2	1.7	2.5	5.8	80	0.0542	84.0	124.2
1800-1900											6.8	80	0.0255	82.0	117.0
1900-2200											6.7	87	0.0636	81.5	109.3
2200-0600											7.3	87	0.0700	80.0	98.2
TOTAL	2227.3	1612.2	615.1		1465.0	79.1	68.1	515.0	65.5	34.6	Average 7.1		0.7540		

Basis: One square foot of solar still area, Test done on Solar Still No. V.

TABLE No. E-5 (b)

				Overall Heat Balance on Solar Still												
No:				1	2	3	4	5	6	7	8	9	10	11	12	13
Time Hours	Sky Temp.	Estimated Cover Temp.	h_c	$q_{r,ca}$	$q_{c,ca}$	$\frac{A_C}{A_H}(1+2)$	$r_d I_d + r_D I_D$	R_O	q_b	$\frac{A_G}{A_H}(q_b)$	$q_{r,1t}$	$\frac{A_R}{A_H}(q_{r,1t})$	3+4 +5+7 +9	I_H -10	$\frac{dT_b}{dt}$	C_{wg} Calculated
UNITS	°F	°F	Btu/°F	Btu	Btu	Btu	Btu	Btu	Btu	Btu	Btu	Btu	Btu	Btu	°F	Btu/°F
0600-0700	58	83.0	3.0	16.5	1.5	18.3	1.6	0.7	2.1	3.8	0.9	0.9	25.3	-9.6	3.0	-3.2
0700-0800	60	84.5	3.4	16.5	1.7	18.5	9.2	3.5	2.2	4.0	1.1	1.0	36.2	50.4	3.2	15.8
0800-0900	61.5	90	3.5	19.5	17.5	37.5	8.9	5.2	3.3	5.9	1.3	1.2	58.7	59.4	4.4	13.5
0900-1000	64	(93)	3.5	20.0	28.0	48.7	17.7	13.5	4.8	8.6	1.9	1.8	90.3	208.8	6.9	30.3
1000-1100	65	95	3.6	21.5	25.2	47.4	20.3	14.4	4.1	7.4	2.3	2.2	91.7	231.0	9.7	23.9
1100-1200	65	(105)	3.2	28.5	48.0	77.6	20.2	16.7	7.7	13.9	2.8	2.7	131.1	238.8	7.2	33.0
1200-1300	65	108	3.7	31.0	66.7	98.2	14.9	12.8	9.0	16.2	3.1	2.9	145.0	138.3	4.4	31.1
1300-1400	65	116	2.9	37.0	78.3	117.2	15.4	11.4	10.1	18.2	3.5	3.3	165.5	86.3	3.6	24.0
1400-1500	64	120	3.0	41.5	92.8	136.5	16.7	11.3	10.8	19.4	3.4	3.2	187.1	64.7	2.2	29.4
1500-1600	64	122	2.7	43.0	87.8	132.3	10.2	6.3	10.6	19.0	3.4	3.2	171.0	-29.3	-2.4	12.2
1600-1700	62.5	119	2.6	41.5	83.2	126.5	5.8	2.2	10.0	18.0	3.5	3.3	155.8	-100.5	-7.5	13.4
1700-1800	61	106	2.8	31.5	61.6	94.5	3.7	1.2	8.9	16.0	3.0	2.8	118.2	-86.7	-8.2	10.6
1800-1900	60	(98)	3.1	26.0	49.7	77.0			7.8	13.3	2.6	2.5	92.8	-92.8	-6.1	15.1
1900-2200*	58.5	(94)	3.0	24.5	37.5	63.0			6.3	11.7	2.2	2.1	230.4	-230.4	-9.4	24.6
2200-0600*	57	(87)	3.3	20.5	23.1	44.2			4.4	7.9	1.7	1.6	429.6	-429.6	-12.8	33.3
TOTAL				611.5	939.3	1572.8	144.6	99.2	145.4	262.0	53.0	50.1	2128.7	98.6		Average 24.6

* Heat transfer rates in this row are in Btu per hour

TABLE No. E-5 (c)

Heat Balance on Solar Still Basin									
No.	14	15	16	17	18	19	20	21	22
Time Hours	$q_{c,bc}$	$q_{r,bc}$	$q_{r,lt}$	$\frac{A_B}{A_H}$ (14+15 +16)	q_e	$\frac{A_B}{A_H}(q_e)$	17+19 +5+7	$\tau_D I_D + \tau_d I_d$ - 20	C_{wg} calcu-lated
UNITS	Btu	Btu	Btu	Btu	Btu	Btu	Btu	Btu	Btu
0600-0700	2.4	4.4	0.9	7.3	8.3	7.9	19.7	-6.5	-2.2
0700-0800	3.0	5.6	1.1	9.2	11.5	10.9	27.6	43.1	13.5
0800-0900	2.7	5.9	1.3	9.4	9.4	8.9	29.4	74.6	17.0
0900-1000	4.6	8.5	1.9	14.2	25.2	24.0	60.3	208.7	30.2
1000-1100	3.0	7.7	2.3	12.3	50.0	47.4	81.5	206.1	21.2
1100-1200	7.9	13.5	2.8	22.9	100.0	94.7	148.2	185.5	25.8
1200-1300	9.5	14.3	3.1	25.5	84.0	79.5	134.0	121.9	27.7
1300-1400	7.5	11.3	3.5	21.1	83.0	78.6	129.3	96.9	26.9
1400-1500	7.0	9.0	3.4	18.4	84.0	79.5	128.6	96.6	44.0
1500-1600	6.5	8.5	3.4	17.4	67.0	63.4	106.1	18.9	-7.9
1600-1700	4.6	6.6	3.5	13.9	46.0	43.6	77.7	-32.1	4.3
1700-1800	7.4	13.0	3.0	22.2	56.0	53.1	92.5	-68.6	8.4
1800-1900	7.0	12.5	2.6	20.9	46.0	43.6	77.8	-77.8	12.8
1900-2200	5.3	10.0	2.2	16.6	27.0	25.6	161.7	-161.7	17.2
2200-0600	3.0	7.0	1.7	10.9	11.5	10.9	237.6	-237.6	18.6
TOTAL	113.0	206.8	53.0	351.7	843.4	799.1	1512.0	465.0	Average 16.5

TABLE NO. E - 6

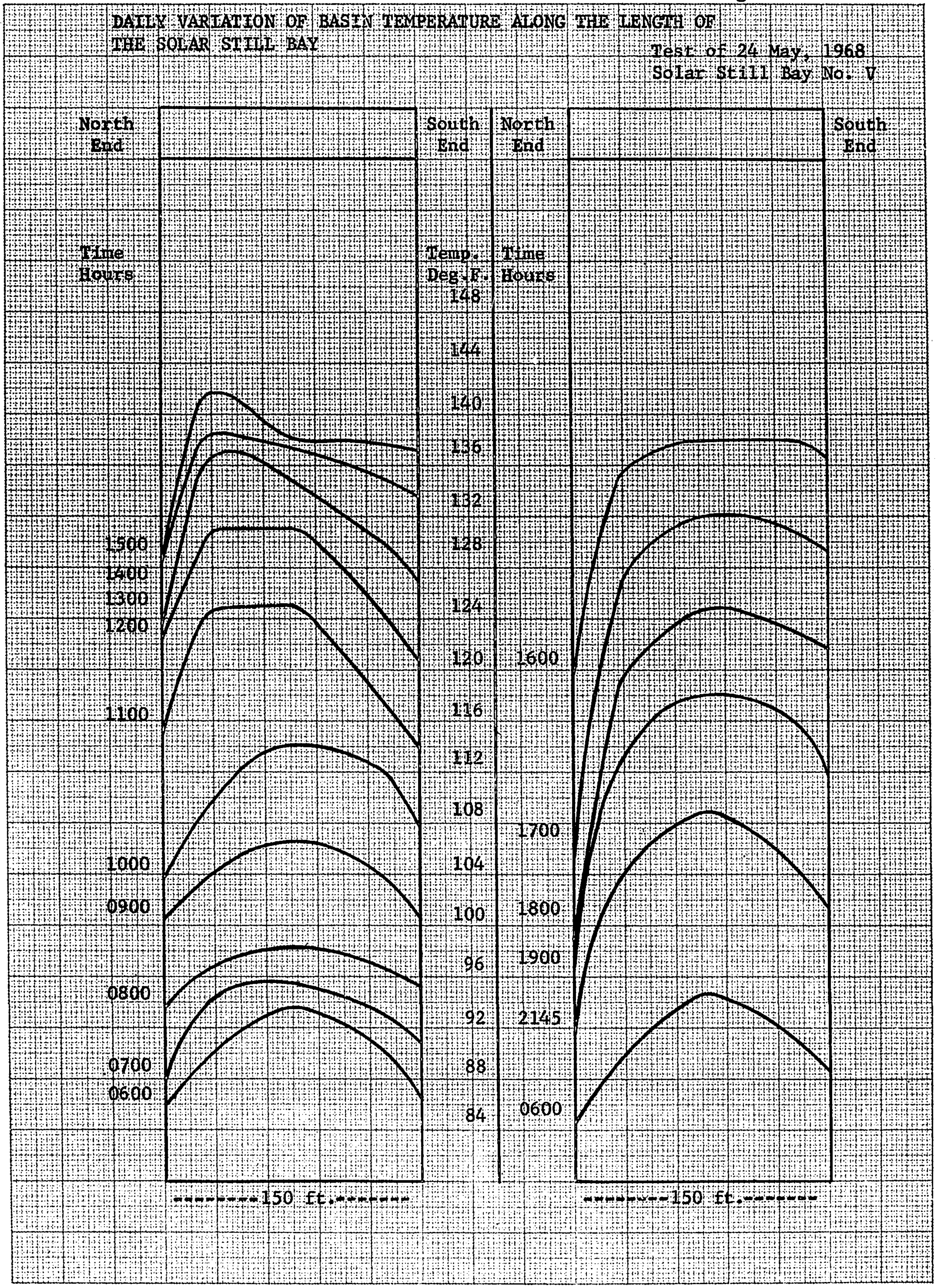
AVERAGE PRODUCTIVITIES OF SOLAR DISTILLATION UNITS

PETIT ST. VINCENT, ST. VINCENT, WEST INDIES

Day	Jan/68	Feb.	Mar.	Apr.	May
1		.052			
2		.052		.076	
3				.100	
4				.097	
5	.078	.066		.085	
6					
7		.039	.086	.108	
8		.062	.091		.084
9				.085	.098
10				.087	
11	.057				.089
12	.062				
13	.050				.055
14					.085
15	.067				
16					.077
17			.076	.092	
18			.085		.082
19		.059		.092	
20			.089		
21			.085		.084
22		.073	.085	.088	
23		.069	.099	.096	
24				.085	
25		.075	.094	.093	
26		.080		.104	.078
27	.053	.040			
28		.077	.099		
29			.091		
30			.093		
31			.096		

All figures are in U.S. gallons per square foot of effective evaporating area, D_W/A_H.

Figure No. E - 1


DAILY VARIATION OF BASIN TEMPERATURE ALONG THE LENGTH OF THE SOLAR STILL BAY
Test of 24 May, 1968
Solar Still Bay No. V
North End
South End
North End
South End
Time Hours
Temp. Deg.F.
Time Hours
148
144
140
136
132
128
124
120
116
112
108
104
100
96
92
88
84
1500
1400
1300
1200
1100
1000
0900
0800
0700
0600
1600
1700
1800
1900
2145
0600
--------150 ft.-------
--------150 ft.-------

APPENDIX F

THE COLLECTION OF RAINFALL

Supply-Demand Relationships: A solar distillation unit of the conventional horizontal evaporator tray type is really no more than a rainfall catchment area which produces additional fresh water during periods of sunny weather. It is very important not to lose sight of this dual role of a solar still for it is essential in justifying its economic viability. In rural communities, the roofs of buildings are commonly used as collection surfaces, the output of fresh water being a direct function of the annual rainfall. Due to the mild climate in some arid regions, dwellings are generally small, as Howe has noted in the South Pacific.[1,p.175] Consequently, to increase yields, it is usually necessary to set up large catchment areas, either through grading, paving or by sealing or packing the soil, often on hill-sides. If the mean annual rainfall is low, it is necessary to utilize large catchment areas to support a small community. It has been reported that the town of Coober Pedy in South Australia has a rainfall catchment area of 120 acres feeding a 500,000 imperial gallon storage reservoir, the former exceeding the total area of the island of Petit St. Vincent. The annual rainfall at the Australian location is only five inches per year and long periods occur without any rain whatsoever. Their storage tank has provided water for residents in a constant, but fairly limited, supply. When this fails, however, water must be hauled in by road at great expense from the nearest water source, a hundred miles away.[2]

Technically, the collection of rain water can be estimated simply as follows:

$$T_{RA} = \eta \times A \times R \ (0.624) \ \ldots\ldots\ldots\ldots \text{F-1}$$

where T_{RA} = rain water collected from a surface in U.S. gallons/annum.

η = rainfall collection efficiency.

A = catchment or roof area -- square feet.

R_I = total rainfall in inches per year.

The amount collected T_{RA} is assumed to be complete. It must be remembered that losses do occur due to spoilage and especially due to evaporation. Wherever possible the tank should be covered or the water surface protected by a monomolecular layer to reduce evaporation. Many workers have studied this aspect of evaporation reduction from reservoirs but a detailed assessment of the latest developments falls outside the scope of the current investigation.

Regarding the consumption of fresh water in a community, the demand can be determined as follows:

$$C_W = 365\ N\ D_N \quad \text{..................................F-2}$$

where C_W = annual demand for fresh water in U.S. gallons/annum

365 = number of days per annum

N = number of individuals or water users under consideration.

D_N = the daily per capita demand for water USGPD/person.

Equations F-1 and F-2 can be combined to study an actual case for a peasant family collecting rain water from the roof of their dwelling. The following assumptions will be made:

A) Sufficient storage capacity is available to collect all the rain water incident on the roof.

B) The area of roof collection is approximately 400 square feet. In many West Indian islands a figure closer to 200 square feet would be more accurate.

C) The average annual rainfall collection efficiency is 80 per cent.

D) The household numbers five persons.

E) Most important of all, the peasant is in a financial position to undertake this collection.

Substituting these figures in equations F-1 and F-2, the annual water supply becomes:

$$T_{RA} = 200\ R_I \quad \ldots\ldots \quad \text{F-3}$$

and the consumption of water becomes:

$$C_W = 1825\ D_N \quad \ldots\ldots \quad \text{F-4}$$

If we further assume that the supply is totally absorbed by the demand, spread equally over the entire year, then:

$$T_{RA} = C_W \quad \text{and}$$

$$R_I = 9.13\ D_N \quad \ldots\ldots \quad \text{F-5}$$

For a series of values of average annual rainfall, the corresponding maximum per capita fresh water availability is shown on Fig. No. F-1. The variation of water demand has been discussed in Appendix I. If a minimum requirement of 2 USGPD/person is set, it is evident that collection from the household dwelling roof cannot satisfy the demand in regions with an annual rainfall below 18 inches per year. It can also be seen that, even in areas of high annual rainfall, the maximum per capita supply is less than 7 USGPD. All this, of course, is hypothetical. However, the figures have been chosen carefully and should not be too much out of line.

From this simple analysis the following conclusions can be drawn:

A) The rural dweller cannot meet all his water requirements through rainfall collection from his roof.

B) To expand his water consumption, a community effort appears necessary, through the establishment of larger, commonly owned and operated rainfall catchments or by using some other means.

C) It does seem to indicate that in any impoverished arid area, there is little the individual can do himself to alter his situation. Collectively, there appear to be greater prospects for success.

Estimates of Rainfall Collection: Returning to equations F-1 and F-2, it is also possible, in the generalized case, to set up a relationship linking rainfall, catchment area, collection efficiency, water demand and the number of individuals served. This is set down in Fig. No. F-2. The following assumptions have been made:

A) The maximum possible rainfall is collected.

B) The per capita demand for water expands to absorb the supply equally over the year.

This graph is designed to give quick reference figures for the capabilities of certain rainfall catchments to meet a specific demand. For example, consideration of the solar stills on P.S.V. as a catchment area gives the following approximate results:

(a) collection area - 23,300 square feet

(b) collection efficiency - 80 per cent

(c) average annual rainfall - 35 inches

(d) water collected per square foot of still - 17.5 USG/year

(e) water collected per year (total) - 410,000 U.S. gallons

(f) This is equivalent to a water supply of:

No. of Persons served/day	Demand/person x day (U.S. gallons)
22	50
45	25
225	5
560	2

If the water collected from the rainfall catchment is added to the yearly production of distillate from the solar still, the overall average water supply potential of the stills can be estimated.

<u>Rainfall Collection Efficiency</u>: A term for collection efficiency has been introduced as it is impossible, in practice, to collect the total amount of rainfall falling on a surface. Telkes[3,p.1113] pointed out that brief showers hardly wet a dry concrete surface and more than one quarter of an inch of rainfall was needed before the rain water actually began to flow. She estimated that only 25 to 30 per cent of the rain water can be collected.

Glass and hydrophobic plastic surfaces, of course, shed water far more quickly than a concrete roof or catchment surface with a corresponding reduction in evaporation losses.

Howe[1,p.178] has also investigated these problems and has listed three principal reasons why the collection of 100 per cent of the rainfall was not possible.

(1) "an appreciable quantity of rain would be absorbed in wetting the surface of the roof and the entire collection system before any run off could reach the cistern.

(2) some of the rainfall would tend to splash from the surface or form fog droplets and thus escape from the system.

(3) in conveying the drainage water to the cistern, severe downpours may exceed the capacity of the gutter and collector system."

He then assumes in his report that 80 per cent of the rainfall below 2.5 inches of rain per day could be collected.[1,p.178] Another observer also assumed a collection efficiency of approximately 80 per cent with rainfalls of about one inch.[4]

Specific tests have been undertaken on P.S.V. to determine the collection efficiency more precisely. Preliminary results corroborate these figures. However, driving rain is propelled almost horizontally in these regions. The material and shape of the roof, its orientation with respect to the prevailing wind and the windspeed all have an influence on the total rainfall collected. A reasonable number of collection efficiency trials were carried out on various catchment surfaces in different parts of the island. As no significantly large rainfalls occurred during the periods of test, the following resumê can be given of these preliminary evaluations, which are continuing. These appear reasonably valid for short duration rainfalls below 0.30 inch in intensity.

(1) The collection efficiency of rainfall incident on the solar stills is of the order of 90 to 100 per cent.

(2) The collection efficiency of wallaba shingled roofs is about 85 per cent, more water being lost in this case owing to the absorption of water by the shingles.

(3) During periods of driving rain there is often no direct correlation between rainfall and water collected.

(4) Very little water appears to be collected during drizzles or showers of less than 0.05 (i.e. 5 parts) of an inch.

Rainfall Cisterns: A complete rainfall collection system requires:

(a) a catchment area, suitably fitted to collect the rainwater e.g. with guttering, in the case of a building roof.

(b) pipes leading from the collection area which should preferably pass through a sand and gravel filter in order to remove leaves, bird droppings, dust, dead insects, etc.[5]

(c) finally, a rain water storage cistern.

All three facets of the system should be kept thoroughly clean in order to avoid contamination of the water. All openings to the cistern should be covered with a wire gauze filter in order to prevent contaminants from entering. They would otherwise discolour the water on decomposition and make it unwholesome. The gauze filter also prevents mosquitoes from breeding within the cistern.

Cisterns may be built of concrete, metal, wood, etc. Their construction has been well documented in the literature.[5,6,7,8,9,10,11] There are many factors to control in the proper operation of cisterns, as outlined in a United Nations Manual on water supply.[(4,p.161-163)]

A) Certain woods, paints, leaves, etc. impart colour or taste or odour to water.

B) Galvanized roofs, as used in the tropics, form the best collection surfaces.

C) Sand filters must be placed at the <u>entrance</u> to the cisterns to remove impurities.

D) Bacteria may increase in the cisterns due to the decomposition of organic matter, held in suspension or solution in the water stored for a long period of time or by passage through filters which have not been properly maintained.

E) Cisterns must be built so that waste surface waters cannot enter into them.

F) Water must not be allowed to stand in gutters or cisterns where mosquitoes or the "aedes aegypti" (yellow fever carrier) can breed.

There are certainly problems involved in rain water collection where the storage period is three to four months. Telkes[(3,p. 1113)] commenting on this, mentions "Towards the end of the (dry) season, the water is replete with algae and higher forms of aquatic life and consequently may be unsanitary." Another opinion from a knowledgeable source stated, "From a public health point of view, a cistern is <u>not</u> considered a safe water supply, unless the water is chlorinated to maintain a constant chlorine residual of 0.5 ppm."

They also felt that no algal growth would occur provided that the cistern is completely covered, protected from organic matter and properly ventilated. Fish or screened inlets should control the mosquito problem.[12]

It is interesting that in Australia, Morse[13] mentions using open, surface cisterns in connection with rainfall catchment systems, apparently without the above listed difficulties. Howe, on the other hand, comments that South Pacific islanders use their house roofs as catchment areas.(1,p.175) Storage tanks vary from steel oil drums to carefully constructed reinforced concrete structures. Each dwelling has its own supply system. There is no piped distribution of water. As rainfall might not occur for several months, larger cistern capacities are required.

As part of these investigations the author undertook a survey of the Carriacou water system.[14] This island can be located on Map No. 1. The findings as specified in this report parallel Howe's comments in many respects. In addition, however, the government authorities have several large cisterns of their own, which collect rain water from the roofs of large public buildings. This water is in turn sold to the population for about $1.20 U.S./1,000 U.S. gallons.

Cistern size is a function of the unevenness of rainfall distribution. In some areas, especially with Mediterranean type climates, for four months or more, no rainfall occurs whatsoever. In order to have water on hand to meet the greater demand during the dry season, the storage capacity must be large, and hence more expensive, as illustrated earlier in the Coober Peby case. A solar distillation unit can function specifically as a damper to these wide fluctuations as the periods of no rainfall generally are the times of greatest still production. Howe(1,p.180) has commented that for certain cases in the South Pacific, it appeared possible to build the solar still, i.e. beneath the rainfall catchment, with the savings resulting from the reduced cistern capacity. In P.S.V. large reservoir tanks have been built in order to ensure a supply during the January to May low rainfall period, which is, of course, the height of the tourist season in the Caribbean. An examination of the rainfall records in Appendix B illustrates this cycle.

The estimation of the most reliable rainfall figure, upon which to base the catchment area required to satisfy a given demand, remains a perplexing problem for both the individual householder and the small community. Clearly the mean or average rainfall for a particular locality appears the logical choice. However, in certain instances it may be necessary to calculate the standard deviation from the mean in order to determine whether the size of the catchment and associated cistern will indeed be sufficient to provide the minimum amount of water required. Such an analysis might prove that it would be cheaper for a community to import water during one or two lean or drought years than for them to build outsized installations only capable of functioning at a fraction of their operating capacity for the bulk of the year. The entire question of the design of rainfall catchment areas is dependent on the

(a) annual variation in rainfall intensity

(b) annual variation in water demand

Hence each community must study its own requirements in the light of its particular climatic regime and population structure.

APPENDIX F

LIST OF REFERENCES

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4. Wagner, E.G. and J.N. Lanoix. Water Supply for Rural Areas and Small Communities. World Health Organization, Geneva, 1959, p. 163.

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6. U.S. Department of Health, Education and Welfare, Manual of Individual Water Supply Systems, Public Health Service Publication, No. 24 (Revised 1962) U.S. Government Printing Office, Washington, pp. 1-121.

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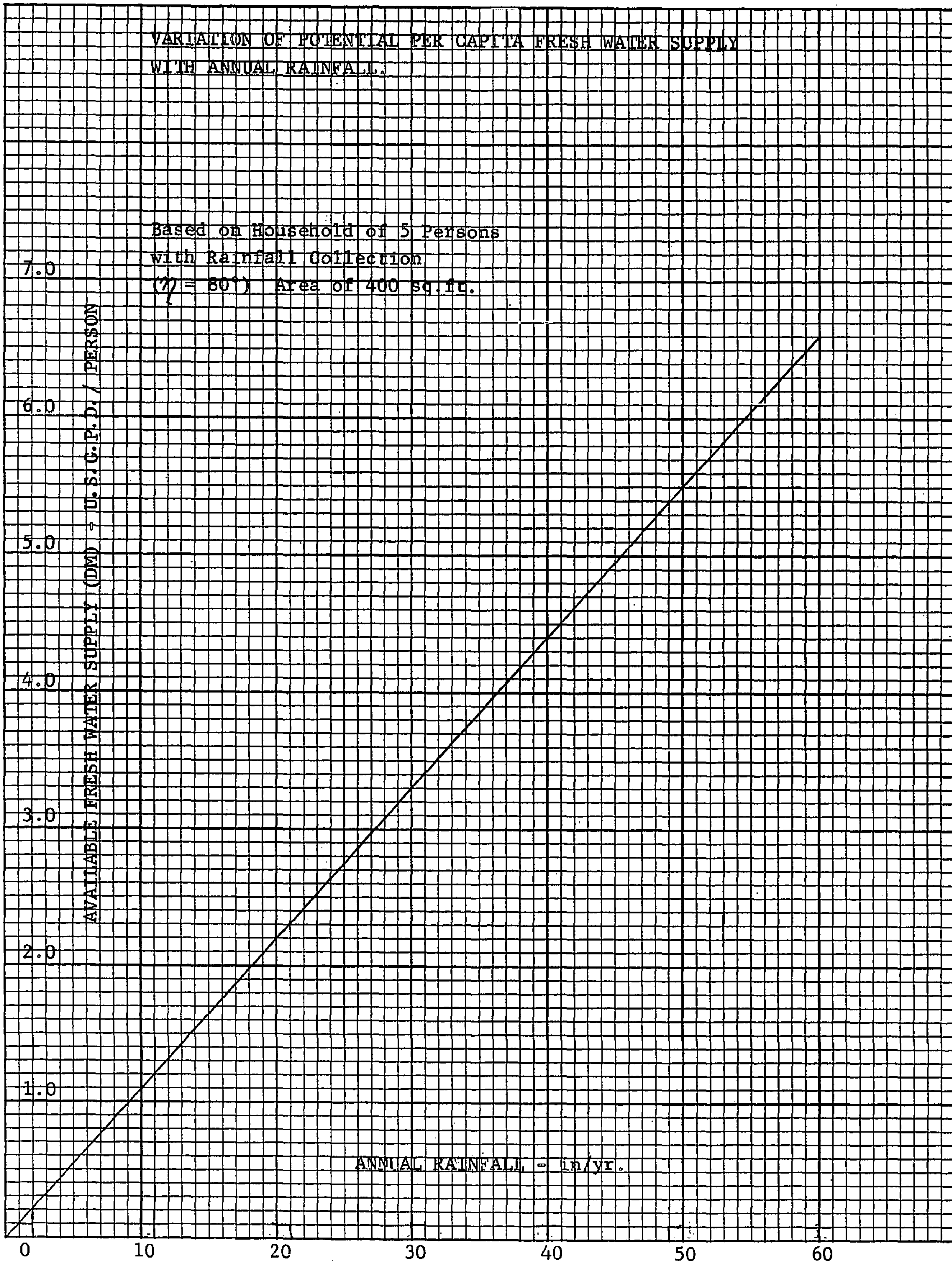
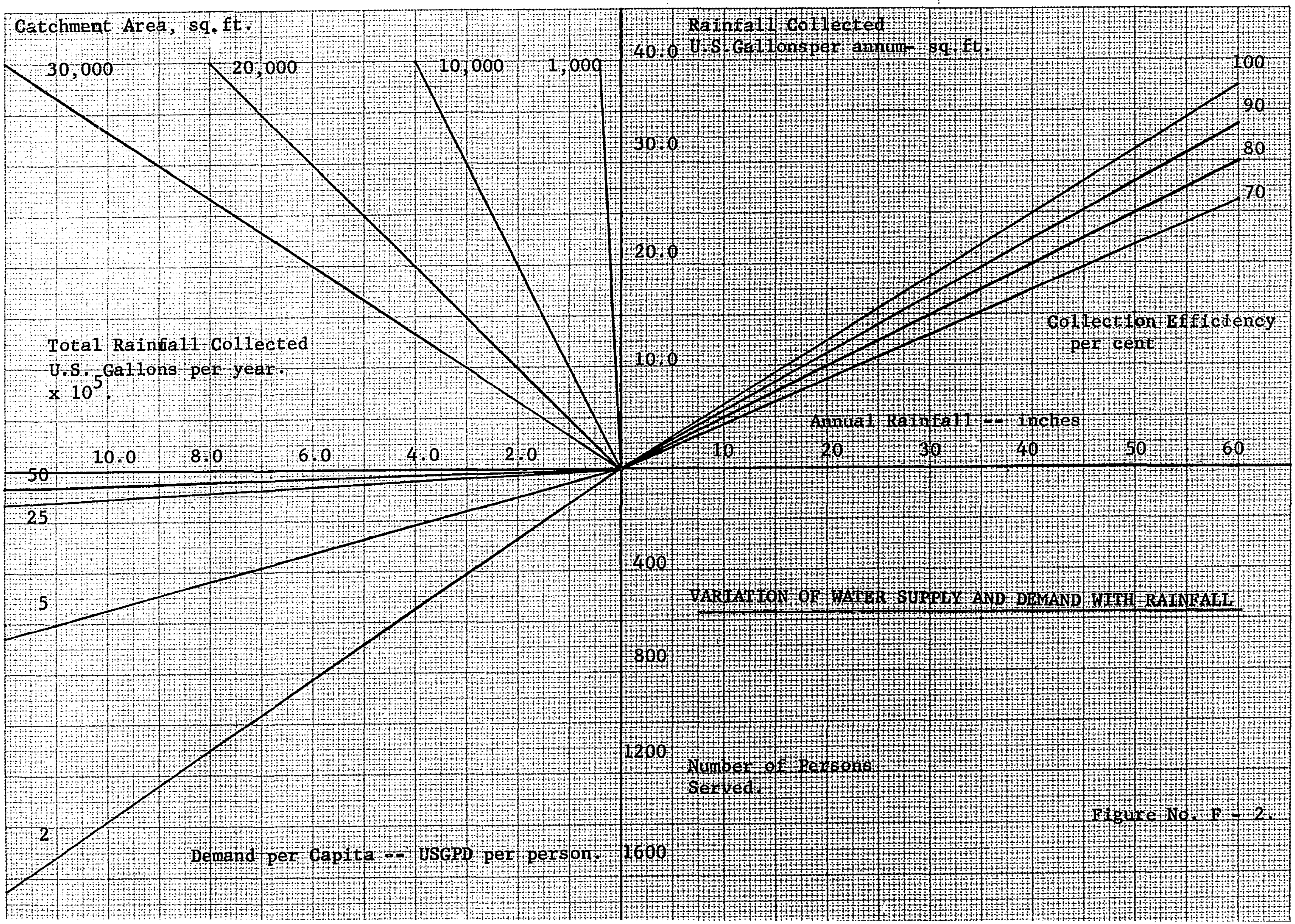
12. Francois, P. Director, Bureau of Environmental Sanitation, Charlotte Amalie, St. Thomas, Virgin Islands, Private communication on the operation of fresh water cisterns, 3 April 1967.

13. Morse, R.N. and W.R.W. Read. "The Development of a Solar Still for Australian Conditions." Mechanical and Chemical Engineering Transactions of the Institution of Engineers, Australia, Volume 3, No. 1, May 1967, pp. 71-80.

14. Lawand, T.A. Note on the Fresh Water Availability in the Island of Carriacou. Survey, 23 December 1967. Brace Research Institute, McGill University, File 60/08.

Figure No. F-1


VARIATION OF POTENTIAL PER CAPITA FRESH WATER SUPPLY
WITH ANNUAL RAINFALL.
Based on Household of 5 Persons
with Rainfall Collection
(η = 80%) Area of 400 sq.ft.
AVAILABLE FRESH WATER SUPPLY (DM) - U.S.G.P.D. / PERSON
7.0
6.0
5.0
4.0
3.0
2.0
1.0
ANNUAL RAINFALL - in/yr.
0
10
20
30
40
50
60



VARIATION OF WATER SUPPLY AND DEMAND WITH RAINFALL

Figure No. F - 2.

APPENDIX G

Rainfall Collection System on Petit St. Vincent

All the roofs of the principal buildings on the island are adapted for the collection of rainfall through the use of a substantial guttering system, as illustrated in Plate No. G-1. The location and size of the catchment areas are listed in Table No. G-1. In all cases, the horizontal projection of the roof is taken as the collection area. On most of the buildings the roof is covered by an asphalt felting which expands when heated by the sun's rays and contracts during the night. As a result, wallaba (eperua falcata) wood shingles have been used to cover the felting. This constitutes a functional solution to the problem, as well as presenting a more aesthetically satisfactory appearance.

Unfortunately, during rainfalls a brownish substance is leached from the shingles discolouring the effluent. Preliminary laboratory scale tests have indicated that this material can be removed by flocculation with aluminum sulphate and a coagulant, and subsequent settling action. The author recently undertook some tests which indicate the following:-

a) there may be some difficulty in achieving in practice the clarification of the wallaba rain water realized in the laboratory.

b) for some time a yellow tainted effluent from the treatment plant might be produced.

The rain water can be treated in batches of 5000 U.S. gallons.

It does appear that, after a few years, the wood will stop bleeding and this problem should be terminated, or at least reduced.

For the moment, however, on this particular island, a separation must be made between the wallaba water and the clean rain water produced by the solar still catchment area, galvanized roofs, etc. The clean rain water requires only filtration and chlorination before it is used.

A series of cisterns have also been built which collect the rain water at different localities on the island. The rain water is then pumped, or flows by gravity, through a piping system known as the'wallaba water system' to the treatment plant. Once an acceptable product is realized, the processed rain water is sent to the low-level reservoir cistern, where pumps circulate the water combined with the solar still distillate, through the reticulation system. Any unused water is forced up into the high-level cistern, illustrated in Plate No. G-2, which pressurizes the fresh water system on the island.

The piping systems on the island are indicated on Map No. 2

TABLE NO. G-1

P R E L I M I N A R Y E S T I M A T E S - June, 1968.

LIST OF CATCHMENT AREAS USED FOR RAINFALL COLLECTION ON PETIT ST. VINCENT

LOCATION	AREA SQ. FT.	ROOF COVERING	TOTAL AREA SQ. FT.	CONSTRUCTED	PROJECTED CONSTRUCTION TO END OF 1968
Pavilion	5,024	Wallaba Shingles	5,024	Yes	
Beach Cottages	1,505 ea.	- do -	9,030	6 built	
New Beach Cottages	1,900 ea.	- do -	3,800	Nil	3 projected - 1 no rainfall collection
Honeymoon Cottages	1,134 ea.	- do -	6,810	3 built	8 more projected - 5 no collection
Ice House	1,536	- do -	1,536	Yes	
Staff Day Quarters	888	- do -	888	Yes	
Staff Buildings	1,248	- do -	2,498	2 built	1 more possible
Manager's House	1,504	- do -	1,504	Yes	
Storage Building	2,624	Galvanized Sheet	2,624	Yes	
Low Level Cistern	4,900	- do -	4,900	Under construction	
High Level Cistern	1,260	Asphalt	1,260	Yes	
Power Station	1,530	Shingles and Felting	1,530	Yes	
Reservoir at Solar Stills	292	Asphalt Felting	292	Yes	
Solar Stills	1,500/bay	Plastic, Concrete, Plywood	23,300 *	Yes	

Total Catchment - Wallaba Shingles -	32,620 sq. ft.
Total Catchment - Not requiring rainwater treatment	30,824 sq. ft.
Other Catchment areas	1,552 sq. ft.
TOTAL RAINFALL CATCHMENT AREA:	64,996 sq. ft.

N.B. Most of the building size and cost figures have been supplied by the Project Architect, A. Hasselquist. The piping costs have been worked out with him using cost figures supplied by H. Richardson.

* All fifteen bays are scheduled to be completed by Sept. 1968.

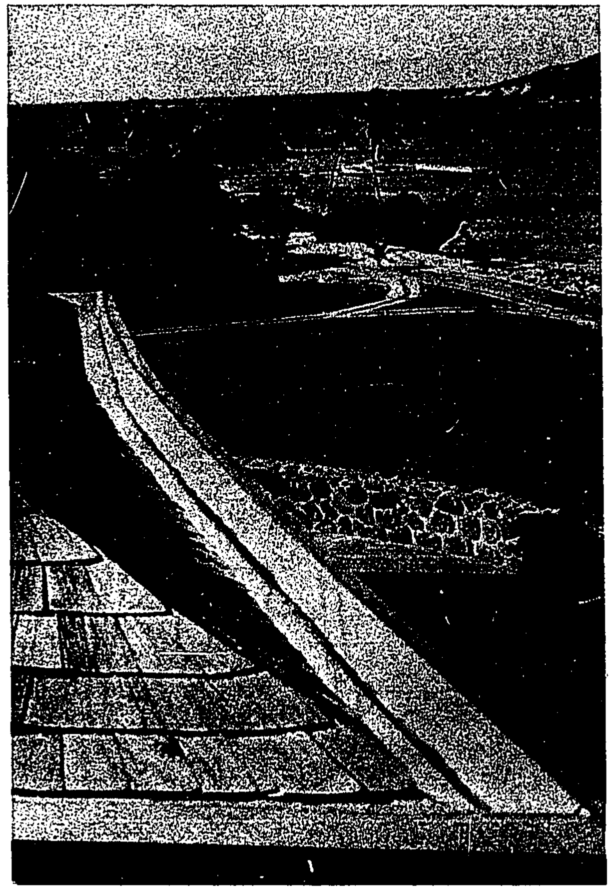


Plate No.: G-1 illustrates guttering system in use on building roofs. Cistern lies below deck flooring.

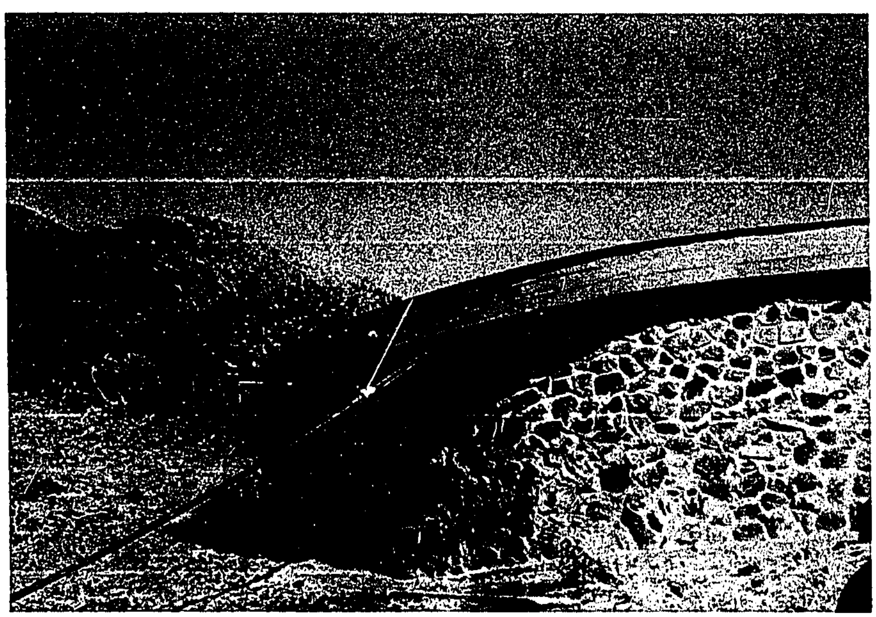


Plate No.: G-2 shows the high level cistern, a circular masonry structure.

APPENDIX H

FRESH WATER AVAILABILITY ON NEIGHBOURING ISLANDS

Present Situation: In determining the feasibility of solar distillation on Petit St. Vincent, it is necessary to assess whether the importation of fresh water from the neighbouring islands presents a competitive alternative. Under extreme conditions resulting from catastrophe, where the local sources of fresh water on the island, i.e. the solar distillation plant and the rainfall collection facilities are destroyed or otherwise rendered inoperative, this method must be reverted to in order to sustain life. The whole question of water importation must be based upon technical and economic considerations relating to:

A) the availability of suitable fresh water on the neighbouring islands.

B) the technical possibilities of transporting the water to the island;

C) the general economic feasibility of the various alternatives.

A suitable source of fresh water would be one which could supply the required demand at any time of the year, it being understood that the water is clean, pure and free from objectionable odour and taste. According to the U.S. Department of Public Health , the salinity content must not exceed 500 p.p.m.[1].

Studies have been conducted on the availability of fresh water within a 50 mile range of Petit St. Vincent. This comprises most of the territories of Grenada and St. Vincent. As the island is a dependency of the latter, it is logical to seek a source within its territorial confines to eliminate customs formalities. A recently published report[2] on the St. Vincent water supply enumerates the following findings. The accuracy of these data is not known and hence they should be used only as a guide, and not viewed in absolute terms.

A) Notwithstanding the plentiful availability of water on the island of St. Vincent, a water shortage, i.e. estimated as unfulfilled demand, amounting to 500,000 IGPY occurred there in 1963[2, p. 1].

B) The availability in that same year of fresh water in the St. Vincent Grenadines from government rainfall catchments was:

Island	Average Annual Rainfall	Collected Rainfall IG/head, day
Bequia	52.8"	2-1/2
Canouan	37.2"	1-1/2
Union	44.6"	2

The availability then of fresh water in these regions is only sufficient for a bare subsistance supply[2, p. 2, 3, 17].

C) Assuming the water were available in St. Vincent, the loading charge at the wharf onto barges would be 15 cents U.S. per 1,000 U.S. gallons and the total delivered charge to the Grenadines is estimated to be $4.40 U.S./1,000 gal.[2, p. 21].

More recent contact with St. Vincent has indicated that, in the interval since 1963, not much change has occurred in the water supply system there. Hence it can be assumed that under the existing water supply system, fresh water would probably not be available there. In any case, no community would wish to rely upon a distant source for its water supply unless it were given firm assurances that adequate quantities of water of the quality already specified, were available at all times on an annual basis.

Looking for supplies closer at hand, an investigation of the possibilities of securing fresh water in Carriacou was carried out[3]. On that island, most of the fresh water used by the local population comes from rain water catchments. There are many privately owned cisterns collecting rain water from roofs. The government owns five large cisterns and sells water to the public for approximately $1.20 U.S./1,000 U.S. gallons. There is by no means an overabundant supply except for a short period during the height of the rainy season. There are two bore-hole wells which are reputed to produce up to 34,000 IGPD. However, this water is not very popular with the local population. Tests taken by the author show the salinities to be between 900 and 1500 p.p.m., classifying these sources as definitely brackish. This is, of course, a matter of taste and habit - in the Senegal, some communities are accustomed to drinking 3,500 p.p.m. water[4]. These West Indian communities, however, generally refuse to accept water which is above 500 p.p.m. as a matter of taste and custom. It is interesting to note here that local fishermen working on the solar stills were able to detect slight increases in salinity while the author required the use of a salinity meter to adequately discern the differences.

Hence, although there appears to be an adequate supply of bore-hole water, it does not seem to have the qualities required. In this respect, it is not considered satisfactory for drinking purposes on Carriacou. In addition, some of the samples taken indicated a need for filtration, which would entail added expenditure.

In summary, therefore, it appears to be unlikely that any large quantities of cistern water would be available from Carriacou. The bore-hole water does not seem to be suitable except perhaps as a last resort for diluting with rain water or distilled water. This, indeed, may eventually become necessary if development continues in Petit St. Vincent.

Technical Problems: It is interesting to note that the Dunlop Rubber Company has published an excellent report on the transportation of fresh water in large neoprene-lined rubber containers called dracones[5]. In addition, they have included a complete and detailed study of the costs involved in transporting 40,000 to 250,000 U.S. gallons up to 100 miles. Depending on the frequency of dracone utilization, the costs of water delivered vary from $2 to $4 U.S./1,000 U.S. gallons. This concurs with the figures quoted by Delyannis on the water cost delivered by dracones in Greece of $2.50 to $3.00 U.S./1,000 U.S. gal.[6]. There are a number of difficulties inherent in this method of fresh water supply, when applied to this particular case. As they are equally applicable to many small communities, they have been enumerated as follows:

1) The demand for water on Petit St. Vincent should be of the order of 4,000 to 5,000 U.S.G.P.D., with the hotel in operation. This can be compared with the average daily demand in the other Grenadine islands.

Bequia	-	3,750 IGPD;
Canouan	-	800 IGPD;
Union	-	2,250 IGPD.

(2, p. 2, 3)

2) There are other factors affecting the use of these dracones in the Grenadines. The coastal waters of this area are strewn with reefs which could render manoeuvring difficult. Obviously, if the dangers of dracone destruction are greater, this will result in a higher water cost due to increased insurance rates, and possible replacement costs, etc. Referring to MAP No. 3, it can be seen that for P.S.V. in particular, the existence of reefs fringing the island almost eliminates this method of transporting fresh water.

3) It is not the intention at this time to discredit this method of fresh water provision. In fact, this may prove to be the eventual method employed to service these communities. However, solar distillation fills the need for intermediate technology which is applicable now, so that the progress of the community will not be retarded until the

time when, either through further radical scientific achievement or a substantial improvement of the central government resources, a more suitable water supply method supplants it.

On P.S.V. there is a 51,300 U.S. gallon high level storage tank. If we assume that this were filled with fresh water from a dracone, the cost of water delivered would be of the order of $1.65 U.S./1,000 U.S.G., plus handling at St. Vincent and Petit St. Vincent, and the initial cost of the water in St. Vincent, making a total cost of well over $2 U.S./1,000 U.S. gallons. However, this cost would be only valid if the system were in operation for about 70 percent of the time. As a full tank on P.S.V. would be sufficient for over 10 days supply, this amounts to a utilization of only 10 to 20 percent. Hence, for a scheme to succeed, it would be necessary to:

a) set out a joint supply system for several islands, including the construction of reservoirs, wharfing facilities to receive the fresh water, services, etc.;

b) purchase the necessary equipment, e.g. dracones, tugs.

For many small communities, the question of water storage versus water immediately consumed represents a difficult economic decision which might sometimes, due to the lack of capital, etc., cause a feasible long term project to be set aside in favour of a more expensive short term scheme.

The report specifies that the required installed horsepower of the tug hauling the dracone must be of the order of 225 to 250 B.H.P., which is far in excess of the normal fishing boat in the area which chugs along with engines of under 20 H.P. Hence, there would have to be a substantial capital investment in plant and organization which would handle the logistics of the operation. In this particular part of the world, this can only come from the public sector, which itself is hampered by the lack of capital and personnel with managerial skill.

Therefore, although the delivered water cost does not appear to be unattractive, if one accepts the figures quoted in this report, it does not represent a satisfactory solution for the individual community. There are innumerable instances in the emerging areas of the world where joint co-operation would render certain projects viable and logical. However, these rarely come to fruition, principally because the communities themselves are too destitute to handle the matter and the central authorities are either unaware of the possibilities or plagued by administrative responsibilities and the lack of organizational experience to set many such projects into orbit.

Consequently, the community must 'go it alone' and fend for itself as best it can. In this case, P.S.V. Limited made the correct choice by setting up its own independent water supply, which, after all, is its 'raison d'être'. This most critical service is, therefore, completely under the jurisdiction and control of the community. This constitutes one of the principal advantages of the use of solar distillation in a region with favourable climatic conditions.

APPENDIX H

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APPENDIX I

THE DETERMINATION OF WATER SUPPLY POLICY FOR A SMALL COMMUNITY IN AN ARID REGION

Economic Considerations: In assessing water supply systems, it is very important that the small community do so in the light of its particular economic situation and not necessarily by those norms which have been determined from the requirements of another area, generally more developed industrially, technically and socially. In these advanced nations, the mechanism of the functioning of the economy is more fully understood and the competitiveness of local commercial enterprises far more acute. The cost of alternative methods of water provision is also known so that the goals of 30 to 50 cents U.S. per 1,000 U.S. gallons can be set up as guide lines for the local communities.[1]

How then should the community approach a water supply scheme and assess what unit water cost allowance will be acceptable, if the standards of the foreign, industrialized nations are not deemed suitable? This can be examined from an economic standpoint as follows:

Suppose a community invests X dollars in land, supplies and materials and provides its own labour for the construction of a solar still, whose annual output is P units of 1,000 gallons of fresh water. In addition to this, R units of 1,000 gallons of rain water are also collected. The annual operating costs of the entire water works, including depreciation and interest on X reduced to an equivalent annual cost basis, allowance for the investment in land, equipment, storage tanks, pumps, energy costs, distribution costs, overheads, etc. amount to A dollars.

It follows then that the cost per 1,000 gallons will be $A/(R+P)$. For a small still, of say 20,000 square feet, the distillate production and an adequate collection of rainfall are indicated in Table No. I-1.

If the total costs come to $2 per square foot of basin area, then the plant investment is $40,000. The annual charges are assumed to amount to 10 to 20 per cent of the capital expenditures per year. The variation of unit water costs is also shown in Table No. I-1. It must be remembered that it is possible to build stills whose unit cost will be less than $ 2 per sq.ft.

These unit costs are somewhat expensive and would immediately be branded as unacceptable in economically developed regions. Although these figures are very approximate and preliminary, they do serve to demonstrate the fact that rather high unit water costs can be faced by a community in an isolated area, primarily due to the small scale of the operation. How then should they view this project? The decision would appear to be more logical if it were based on the beneficial economic returns on the capital investment. It is often difficult to adequately attribute which portion of economic returns can be related to a specific investment, such as water supply.

On Petit St. Vincent, the contention of the owners has been that the provision of fresh water has meant the possibility of economic activity on the island. The investment in a water supply system has:-

A) increased the real estate value of the island itself.

B) made possible the investment of over three-quarters of a million U.S. dollars in this hotel project which is anticipated to be a viable, profit-making operation.

C) injected a sum of over $200,000 U.S. into wages, materials and supplies directly into the local economy. Although the effective marginal propensity to consume (MPC) in these islands is not known, a certain portion is definitely spent within the area and expanded according to a multiplier.

TABLE NO. I - 1

Variation of Fresh Water Production of a Solar Still With Rainfall Intensity

Rainfall Intensity	Rain Water Collected	Solar Still Production		Combined Fresh Water Production	Cost of Fresh Water		
	R		P	P + R	$ U.S. per 1000 U.S. Gal.*		
Inches / year	1000 U.S. Gal. / year	U.S. Gal. / sq.ft.,day	1000 U.S. Gal. / year	1000 U.S. Gal. / year	10%	15%	20%**
10	100	0.11	730	830	4.80	7.20	9.60
20	200	0.10	730	930	4.30	6.45	8.60
30	300	0.09	660	960	4.20	6.25	8.30
40	400	0.08	580	980	4.08	6.10	8.15
50	500	0.08	580	1080	3.70	5.55	7.40
60	600	0.07	510	1110	3.60	5.40	7.20

* Based on a solar distillation plant of 20,000 sq. ft.; capital investment charges $2 U.S./sq.ft.

** Annual Charges as a per cent of the capital investment.

The multiplier effect is equal to $\frac{1}{1-MPC}$ which applies in this case as the local resources have no opportunity costs. Leakage, of course, is not known and depends in essence on the geographical limits of the region being studied. However, the effect of the multiplier is only apropos if the second round expenditures are not all leakage items.

The whole question of the relationship between the multiplier effect and its erosion by leakage of funds to areas of full employment where multiple expansion cannot occur, has been investigated by Haver.[2] He has studied carefully the effects of the portion of project funds spent locally which are expected to induce secondary expansion benefits. It is this modified multiple effect which can determine the real benefits to the region of an investment project.

A solar still represents a typical single shot investment with a tapering off of the regional income as the multiplier effect diminishes. However, owing to the fact that the unit can be maintained using local labour and materials, there is a small but continual injection of funds within the area which exerts an influence on the regional income. A conventional fossil fuel operated desalination plant on the other hand, requires that most of the capital and even operating expenses be obtained from outside the confines of the community, causing a continual drain on the meagre resources available.

Hirshleifer et al[3] have investigated the problem of the economic justification of investment in additional water supplies in quite some detail. In water-resource developments, they feel that some contention arises through the distinction between "financial feasibility" and "economic feasibility" of a project.

They define these terms as follows:[(3,p.123)]

1. A financially feasible project is one which generates revenues sufficient to cover all costs, including interest on funds borrowed, to finance the project.

2. An economically feasible project is one where the economic evaluation of the "benefits", to whomever they accrue, exceeds the economic evaluation of the "costs", to whomever they accrue.

Financial feasibility, as defined above, is ostensibly what every private investor examines in deciding whether to undertake a project. Hirschleifer quotes the following from The Report of the President's Water Resources Policy Commission, Vol. 1, A Water Policy for the American People (Washington, D.C., Government Printing Office, 1950), page 59.

> "Financial feasibility has been urged by some as the determining factor in evaluation, that is, they believe that all water resources projects should be self-liquidating. This view implies that Federal agencies should seek out sound business opportunities wherever they may be found in the water resources field.
>
> The basic fallacy in such reasoning is that it seeks to transfer to public investments the limitations common to private investments. The Federal Government seeks to conserve and develop the Nation's natural resources for the general welfare and not for profit. Hence, financial feasibility is not the same as economic feasibility. Financial costs and returns should be considered in analysis, but financial feasibility alone should not determine the desirability of a program or project. For this reason the Commission is recommending that Congress eliminate the requirement that irrigation projects show financial feasibility."[3, p. 124]

Continuing, Hirschleifer points out that if water is sold freely on the market, consumers will take just so much as to bring their marginal value in use down to the market price.[3,p.125]

On this matter, he continues[3,p.126], "A more direct estimate of the aggregate value in use might be based upon a total monetary comparison of the consumers' well-being before the project and after, over and above the amount paid out to the water-supplying agency."

The benefits of a water works project can be divided into primary benefits[3,p.126], or the net value of the increase in production of outputs associated with the project and secondary benefits, which can be related to technological spillovers, i.e. costs or benefits imposed upon or received by others as a consequence of private actions but not normally taken into consideration in private decisions. The authors feel[3,p.126] that spillovers involving real increases or decreases in productivity outside the project must be taken into account to determine the true effect on the communities' total earning capacity (i.e. their contribution to the gross national product). They also include sections dealing with the effects on employment and intangibles. Considering a small isolated community, and assuming that all the benefits and costs associated with a water supply project are known, how can the merits of the system be determined?

For a project to be justified, the ratio of benefits to costs must exceed unity. This is axiomatic and is precisely the type of study the small community must establish in deciding on the desirability of instituting a desalination system or expanding their water supply. Unfortunately there are few people, if any at all, within the community who are capable of undertaking such an assessment. This remains one of the prime problems and unsolved challenges, if these small isolated hamlets in the emergent areas of the world are ever to be assisted. They generally do not count enough socially, financially or politically for anyone to take an interest in them, whether it be their own governments, international agencies or other philanthropic foundations. However, it is studies of a macroeconomic nature which will determine the feasibilities of these schemes in the long run.

If the community must choose between several methods of constructing their water supply plant, it has been argued[3,p.137-138] that it is the difference between the benefits and the costs which must be maximized. There has been much discussion on this point, but considering alternatives which are similarly priced, this concept should hold and is reasonable.

Actually, any project where the benefits-to-costs ratio exceeds unity could be adopted because this implies a net surplus benefit over cost. The major practical difficulties lie in evaluating the absolute values of these benefits and costs.

Finally, a recent study by the author[4] has indicated that beneficial economic consequences from increased investment in water supply plant appear to have been manifested in many instances in small communities. There can be no hard and fast rules governing the logic for water supply policy for these areas. Each community on its own must assess its particular situation and formulate decisions which will generate a maximum of economic activity for the benefit of its residents.

In their recent study, Stober and Falk[5] have defined the benefit-cost ratio for a local community as the sum of the costs (numerator) of the best alternatives of water supply, if the individual industrial and residential consumers supplied their own water needs, to the cost (denominator) to individual users purchasing water from the community project. Naturally, this ratio must exceed unity for project feasibility.

P.S.V. is a special case of an isolated community:

(a) There is only one consumer - a commercial one, at that.

(b) The fate of the enterprise depends on the water supply. In this case the benefit-cost ratio can be examined as the cost of an alternative method of procuring fresh water to the cost of employing the solar still - rainfall catchment system.

In a small, isolated community, this would mean the cost of individual fresh water provision compared to the cost of a community project. There are some other factors which can be examined as well:

A) Often federal government aid in the form of grants or subsidies is available.

"The local community includes only costs and benefits accruing to the locality, while evaluation of a federal project appropriately considers costs and benefits for the entire nation. Thus a local project may have a favourable ratio from the viewpoint of the local community but the costs to the nation may exceed national benefits".(5,p.328)

B) The annual benefit to the community is the present value of the annual cost savings realized by not undertaking private water supply alternatives.

C) The average annual cost to the community is the net cash outlay for the purchase of water from the water supply project, which just covers the costs entailed.

D) Generally, the cost of capital to the community is less than the comparable cost of capital to the individual resident or water user. Hence, it can be implied that community projects should be less expensive. The same can be said of the income tax structure, although generally, in these remote areas, the effects of personal and corporate income tax are not too significant.

E) It is felt that the benefit-cost ratio will be greater than unity if there are constant returns to scale and both the water supply project and its alternative are discounted at the same rate of interest.(5,p.335)

F) Finally, while increasing returns to scale work to the advantage of the larger community project, diseconomies of scale lower the benefit-cost ratio.(5,p.335)

Alternative Methods of Fresh Water Provision: In the small isolated community in the developing country, the alternative sources of water provision might not be so clearly represented or understood. In fact they might not exist at all, save for the importation of water which makes the communities' existence dependent on another territory. This situation can become somewhat exaggerated especially when political disputes arise between nations.

For example, in 1964, the government of Cuba decided to discontinue supplying water to the United States of America naval base at Guantanamo Bay, Cuba. To relieve the water shortage, the U.S. government was forced to dismantle a multistage flash desalination plant at San Diego, California and reassemble it at Guantanamo Bay.[6]

Again in June, 1967, the Government of China, cut off the water supply to the British crown colony at Hong Kong.[7] Only the later resumption of normalized relations brought relief to the critical water shortages which occurred. Nonetheless, the utter dependency of the territory on its neighbour for its water supply and even its existence was clearly demonstrated.

Another example of international water exchange occurred in the Persian Gulf area. Prior to 1953 water used to be imported by barge from Iraq to Kuwait. Due, however, to the poor quality of the water, the irregularity of the supply and the high cost of transportation,[8] alternative methods were investigated. A survey, referring to Kuwait stated, "........

it is built on a site which has no water. The Kuwaiti has therefore become a sailor, boat builder and trader and has always fetched his fresh water by boat from the Shatt-al-Arab, fifty miles away. Suggestions that he should use his new-found oil wealth to carry it by canal or pipeline have not so far found favour: he dislikes them because the siting of the pipeline would make him beholden to Iraq. Instead, therefore, he has spent some millions of pounds upon installing plants that distil sea water."[9]

The country has embarked on an ambitious programme of desalination which up to 1964 saw an investment of nearly $17 million U.S. with a total of six million gallons per day of installed plant capacity.(8,p.178) These are a few examples of international water problems. There are others as well.

Clearly then, in matters of water provision, the dependency of one country on a source of supply located in another country does not appear to constitute a logical solution. Axiomatically, one might project this further, when dealing with individual communities within the same political region. If the community must import water from some distant source not under its own jurisdiction and control, then it is subject to the vagaries of the district governing this resource. Unless protected by central government legislation dealing with water provision, the importing group is faced with some of the following problems:

A) There may possibly be increased taxation on the water service, at some future time.

B) There might be restrictions on the quantity of water that it is permitted to import. This might seriously affect the future growth plans of the area. An example of this is the constant squabbling over water rights between the states of California and Arizona.

C) Any political disturbance within the country - such as the secession of the other region from the nation, e.g. as illustrated by the separation of Biafra from Nigeria, renders any long distance hauling of water across newly formed "frontiers" hazardous and unsure.

D) The question of logistics really constitutes one of the prime arguments against the importation of water. Dependence upon an erratic source and system of supply, does tend to make the economic prospects of the community somewhat limited in scope. It will certainly be a hindrance to its proper growth and development. An undependable water supply will definitely limit the increase in tourism or the attraction of outside investment which are sometimes some of the few avenues of economic growth open to these areas. This is very important in the light of data published on world receipts from international tourism which show that travel expenditures have been increasing at an average rate of 12 per cent per annum.[10]

The attraction of outside investors to develop some of the local natural resources certainly is a contributing factor to increasing the standard of living in a country. It is not without pitfalls, however. Johnson[11] goes into the advantages and disadvantages of foreign investment in developing countries. Economic activity is nonetheless stimulated by this investment bringing some measure of change to societies which have often remained unscathed by the advancements of modern technology.

If, therefore, the community can realize, through the investment in a water supply system, a return to capital which outweighs the opportunity cost of their initial investment, then the scheme is economically sound for their particular situation, regardless of the unit cost of the water produced. This would be a logical means for the solution of the water supply system. The accrued benefits might be in:

A) the improved sanitation and health of the community;

B) the possibility of earning additional income through the processing, even on a domestic level, of surplus agricultural produce, meats, fish, poultry, etc. It must be stressed that the measurement of benefits and often of costs is extremely difficult.

Independence in these matters does therefore appear to be a desirable, if sometimes expensive, solution to an isolated community's water supply problem. Depending on its size, the community must generally settle on a supply system whose unit cost of water will be high, primarily because of a low annual fresh water production capacity. Water demands amongst native villagers in emergent areas of the world are certainly not high. Some examples are given below:

Variation of Water Consumption Per Capita

	Water Consumption per Capita Day	Reference Number
South Pacific	5 litres (1.3 USGPD)	(12,p.175)
Algeria	3 to 5 litres (0.8 - 1.3 USGPD)	(13)
Spain	11 to 13 litres (2.9 - 3.4 USGPD)	(14)
U.S. Navy Advanced Water Supply Requirements	10 USGPD (bivouacs)	(15)
USA (domestic, rural arid areas)	2 USGPD (hauled in) 30 USGPD (piped in)	(16)
U.S. Virgin Islands	2 USGPD	(17)
Grenadine Islands, W.I.		
Bequia	3 USGPD	
Canouan	1.8 USGPD	(18)
Union	2.4 USGPD	

Ward[19] has also listed a detailed table of water requirements for humans and agricultural animals.

Considering a consumption of even 10 litres per capita day (2 to 3 USGPD/person) in a district of 550 persons, and allowing some water for general use and loss (200 USGPD), a small water supply system might be only 2,000 USGPD, mainly for drinking and cooking purposes. If this were supplemented by rain water for household functions and brackish water for sanitary purposes, the community standards would be reasonable, especially if the water works produced high quality water for human consumption which would have a positive effect on the level of health in the area, with its resultant increased economic benefits. Nor are these effects insignificant.

In a study conducted in Venezuela in 1944, Wagner and Wannoni drew the following conclusions, which have been quoted by Wagner and Lanoix[20,p.32].

"The total annual cost in sickness and death from water-borne diseases and the actual money outlay to buy water from vendors or the outlay of time to carry contaminated water from streams to other sources is Bs. 202,991,814 ($60,600,000). Compared to this, it would cost only Bs. 21,939,750 ($6,600,000) per year to provide a safe, adequate, public water-supply to two million people; and such a programme would eliminate at least 75 per cent of the sickness and death due to water-borne diseases as well as eliminate completely the enormous sums paid to obtain water from other sources. This is a saving - and a national economy - of Bs. 148,554,410 ($44,610,000).

"By employing Bs. 21,939,750 ($6,600,000) per year in the amortization and operation of water-supply systems, the nation can save Bs. 170,494,160 ($51,000,000) annually. In other words, solely from the economical point of view and disregarding completely the human aspect, there is a return of Bs. 8.00 for every one invested. At the same time, the amount of water supplied per head is increased from 10 to 74 litres."

<u>Alternative Desalination Plants</u>: Let us assume that the small village of 500 persons runs a water works, which could be some form of desalination plant, if saline water were the only source available. As outlined in Appendix F, in an arid region with less than eighteen inches rainfall per year, the minimum water demand cannot even be satisfied utilizing rainfall collection from roofs alone. Even where the annual precipitation is greater, the total quantity of water collected does not amount to very much.

In the range of small vapour compression desalination plants of this capacity, the capital cost of the unit alone will vary as follows.[21]

Plant Size	Installed Cost
USGPD	$ per USGPD
500	14
1,000	9
2,000	7

Thus for a 2,000 USGPD unit the capital cost installed is about $14,000 U.S. To this must be added the charges for the land, site preparation, saline water inlet and brine discharge connections, fuel tanks, some form of storage reservoir, pumping, piping and a shelter for the equipment and administrative purposes. This will amount to at least $8,000 U.S. as illustrated by a recent study on this matter which lists the breakdown of disbursements on operating similar type equipment.[22] In addition to the capital expenditures, the annual amounts for fuel, lubricating oil and chemicals will reach roughly 10 to 15 per cent of the installed cost. Other annual expenses are maintenance, interest on capital investment and depreciation. This does not include charges listed for auxiliaries above. These are estimated as approximately $0.70 to $2.00 per 1000 U.S. gallons depending on the size of the plant involved.

Several factors must be borne in mind in operating this type of equipment:

A) Adequately skilled personnel must be available for its maintenance and repair, in order that a reasonably high level of output can be maintained.

B) Most of the disbursements require foreign exchange which is generally unavailable to this type of community.

C) This is a capital-intensive process. Capital is a very scarce, if almost non-existent, resource in these communities.

D) The unit must be constantly provided with fuel and lubricating oil. Administration is needed to ensure their continual provision and a supply must be maintained in storage. The supply vehicle might not come in on schedule and often in these areas it is late, or just fails to appear. The sun, relatively speaking, is extremely reliable - it always rises!

E) Mismanagement of the unit, which is a complex piece of machinery, can lead to severe scaling problems, rectification of which might be beyond the capacity of the residents.

F) The units are often noisy and emit odours from the diesel exhaust, and storage tanks.

Mechanically operated or fossil fuel plants have some decided advantages, however.

(1) If properly handled, they are reasonably dependable.

(2) Water can be provided on demand.

(3) They require little surface area; they are compact.

The isolated small community must allocate its scarce resources very carefully. The seasonal fluctuations of the agricultural or fishing employment cycles, means that there are long periods of time where much of the community is idle. Hence, generally the most abundant resource is labour. As there are usually long periods of unemployment or under-employment, this labour has little opportunity cost and hence, if it is used to construct projects sponsored by the community, the cost of this labour can be considered as nil. The social cost, or shadow price, is the cost to the community or the amount of resources which had to be given up to undertake the project. In this case it would be nil. The accounting cost, on the other hand, might be positive, as society has incurred an obligation. It is always important to examine the economic balance, for there has been an output from labour. An asset has been created. Hence, the ideal water works system for this region would appear to be one which is a labour-intensive process which will make use of this surplus resource. In addition, a unit which has a low expenditure in foreign exchange items and a low annual operating cost would certainly stand far more chance of realization. One of the few, if not the only type of unit, to satisfy these requirements is the combination solar distillation - rain water catchment plant under study. While by no means claiming that solar distillation can necessarily solve most small communities' water supply problems, it has nevertheless the following advantages, where favourable climatic conditions exist.

<u>Advantages and Disadvantages of Solar Distillation Plants</u>: The arguments for and against solar distillation plants have been set out in direct comparison with a conventional fossil fuel desalination plant.

A) Although the initial capital investment in a solar still is high, a breakdown of the costs indicate that a sizeable fraction is for labour (25 to 50 per cent).[23,24,25] Also as many of the components are fabricated in situ, this really is a labour-intensive operation.

B) The labour used to construct, operate and repair the units need not have any special skills. A concrete example of this was the erection of the stills in Petit St. Vincent where a labour force from the adjacent islands has assembled and built the stills.

C) If the transparent canopy is air-inflated, an adequate system of air blower operation must be maintained. In these cases, and for rigid transparent cover units, solar stills can run independently and without attention for long periods of time. The sea water must be changed periodically and provision must be made for the discharge of the distillate and reject brine.

D) A solar still operates quietly, making no noise whatsoever.

E) The operation produces no obnoxious odours nor does it contribute adversely to air pollution.

F) In the short term, the stills can provide an isolated community with an attraction which will draw the attention of the traveller and visitor to the region. This is particularly evident on P.S.V. This would certainly aid the stimulation of trade and local commerce, especially when considering the importance of tourism as an international industry.

G) In some of the more prosperous communities, the plant might be built with government aid or a loan, and the labour will be paid for its efforts. Owing to the relatively high marginal propensity to consume in these regions, the multiplier effect should be very high. Contrasted to this is the outright purchase of a foreign-made plant where the investment stimulates little local economic activity.

H) The stills incorporate mostly locally available construction materials, e.g. cement, stone, sand, asphalt for linings and often glass. Suitable plastics are rarely available, however. As a result, the foreign exchange portion of the investment is generally quite low. In order to assist developing countries to purchase those materials, mainly the transparent cover, which are not locally produced, the U.S. Agency for International Development has recently published a pamphlet[26] on solar distillation indicating amongst other items, methods by which the United States government can facilitate these expenditures through the use of foreign currency balances held in neighbouring countries. This can provide a positive boon to solar still construction.

I) By combining rainfall collection and solar distillation, less cistern capacity is necessary in areas marked by definite wet and dry seasons, where only rainfall is traditionally collected. In fact, Howe has predicted[(12,p.180)] that the savings in cistern capacity can often provide the materials necessary to build the solar still.

J) As no fuel, oil or chemicals are needed in the stills' operation, the plant can be run completely under the communities' control. There is no dependence for the water works operation on the arrival of these commodities from some external source.

K) Considering the labour cost as nil, the annual operating charges of a solar still in these ranges of production are generally less than those using more sophisticated equipment. This is principally due to higher fuel costs in the remote areas of developing countries.[27, (21,p.24)] This is decidedly an advantage in emergent areas of the world where projects are often initiated and constructed but then lapse into oblivion for the lack of operating capital.

L) A high annual operating cost, as often found with conventional desalination equipment of this capacity[(21,p.37)], infers that a reasonable amount of services is necessary for the purchasing of fuel, spare parts, authorizing payments, banking, etc. Developing countries suffer from a lack of personnel with sufficient organizational skills to manage these expenditures. Also, the administrative process in these regions is exceedingly slow and tedious. On the other hand, due to its inherent simplicity, the solar still is free from the majority of these bureaucratic procedures which frequently cause long delays in the operation of conventional equipment.

M) As the solar still is built principally of local materials and labour, its repair can be handled locally as well. Conventional desalination equipment will have to be imported. Hence, spare parts must also be imported, or possibly fashioned in a local workshop. Delays due to the lack of availability of parts, lengthy shipping and delivery times and frequent frustrations in processing the components through local customs are not at all uncommon. Anyone who has lived and worked in an emergent country can attest to the large numbers of machines which are idle mainly due to the reasons specified above.

N) The output of a solar distillation unit can be increased quite readily by building additional modules or bays. This is particularly useful when predicted water production from a plant has failed to materialize due to climatic or design insufficiencies. The extra output can probably be obtained at a marginal cost which is less than the output cost of the main plant.

On the other hand, there are certain disadvantages to solar distillation.

(1) Owing to the diffuse nature of the solar radiation, a reasonably large flat area is needed to supply a village with fresh water. The land must be available, inexpensive and have little opportunity cost.

(2) The solar distillation plant is relatively vulnerable to the ravages of severe storms or a rock-throwing disturbance.

(3) If labour costs are not considered to be nil, then the first cost or capital investment of the plant is generally higher than alternative methods.

(4) The unit will only produce if it is raining or the sun is shining. Nocturnal production of solar stills requires additional investment in plant and energy.

<u>Summary</u>

This section serves only to outline some of the problems encountered by small communities in determining the best method of handling their water supply problems. No hard-and-fast rules can be stipulated as each case will differ in complexity and eventual solution.

APPENDIX I

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