DESIGN OF FLAT-PLATE SOLAR ENERGY COLLECTORS FOR SPACE COOLING APPLICATIONS UTILIZING COMMERCIALLY AVAILABLE MATERIALS

A Thesis

Presented to

the Faculty of the Department of Mechanical Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Arthur C. Ratzel

May 1976

In Memory of My Father

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Abstract

This thesis presents the results of a recent compilation of available commercial materials suitable for use in flat-plate solar energy collectors. A literature and industrial search of data pertaining to cover plate materials, intermediate temperature insulation, and selective and non-selective absorber materials is provided in chart form. Cost data current through November, 1975, is included as well as estimated performance and durability data and other important mechanical and radiative properties.

A computer simulation has been developed which predicts performance of a general flat-plate collector. All the data discussed above has been coded for use as input to this computer simulation. In this way all combinations of cover assemblies, absorbers, and insulation can be examined. The computer simulation also assigns figures-of-merit to the various designs based on user supplied weighting functions applied to cost, weight, durability, temperature limits, and performance at 120 Btu/hr-ft^2 and 150 Btu/hr-ft^2 heat load removals. In addition, minimum service can be required regarding any of the above quantities. For example, if the calculated absorber temperature exceeds a predetermined maximum value, the design is rejected.

The computer simulation is employed to select optimal single and double cover flat-plate solar collectors which are

suitable in terms of performance and economics for space cooling applications in the summer in Houston, Texas. In addition, general performance predictions for single and double cover collector assemblies are provided for different weather conditions and degrees of absorber surface selectivity ($\alpha_S/\varepsilon_{IR}$ ratios). This information can be employed for estimating collector performance should new selective absorber surfaces be developed in the future.

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NOMENCLATURE

CDL	Coded estimated life of the absorber plate
CF	Criterion function
CF1	Criterion function one
CF2	Criterion function two
D30	Absorber plate temperature constraint at 120 $Btu/hr\text{-}ft^2$
D50	Absorber plate temperature constraint at 150 $Btu/hr\text{-}ft^2$
DT30	Absorber plate temperature at 120 $Btu/hr\text{-}ft^2$ load
DT50	Absorber plate temperature at 150 $Btu/hr\text{-}ft^2$ load
DUR	Coded collector durability
DURA	Coded absorber material durability
EFFIM	Coded effective cover impact resistance
h_{a1}	Convection coefficient between the absorber plate and the inside cover
h_{12}	Convection coefficient between the cover plates
$h_{1s}(h_{2s})$	Convection coefficient between the outside cover and the surroundings
IMPR	Coded cover plate impact resistance
LDUR	Coded collector durability constraint
LIFE	Coded collector durability
LLIFE	Coded collector expected life constraint
LOWGT	Minimum total collector weight per square foot

Nomenclature (Continued)

LOW$	Minimum total collector cost per square foot
q_L (Q_L,QL)	Heat load (flux) removed
q_s (Q_s,QS)	Solar incident flux
T_A (TA)	Ambient temperature
T_{FP} (TFP)	Absorber plate temperature
T_s (TS)	Effective black body sky temperature
T_1 (T1)	Inside cover temperature
T_2 (T2)	Outside cover temperature
TDUR	Maximum coded collector durability
TLIFE	Maximum coded collector expected life
TWGT	Total collector weight constraint per square foot
TWT	Total collector weight per square foot
TZ	Total collector cost constraint per square foot
T$$	Total collector cost per square foot
T30	Maximum absorber temperature at 120 Btu/hr-ft^2 load
T50	Maximum absorber temperature at 120 Btu/hr-ft^2 load
WETH	Coded cover plate weatherability

Greek Symbols

α_s	Solar absorptivity
β	Dimensionless temperature - $(T_{FP}-T_A)/(q_L/\sigma)$
γ	Angle of solar flux incidence with respect to the cover normal
ε_{IR}	Thermal emissivity

Nomenclature (Continued)

Greek Symbols

$\varepsilon_{a_{IR}}$	Thermal emissivity of the absorber plate
$\varepsilon_{1_{IR}}$	Thermal emissivity of the inside cover
$\varepsilon_{2_{IR}}$	Thermal emissivity of the outside cover
ε_{a_s}	Solar absorptivity of the absorber plate
ε_{1_s}	Solar absorptivity of the inside cover
ε_{2_s}	Solar absorptivity of the outside cover
θ	Collector tilt angle
λ	Wavelength
ρ_{IR}	Thermal reflectivity
ρ_s	Solar reflectivity
$\rho_{a_{IR}}$	Thermal reflectivity of the absorber plate
$\rho_{1_{IR}}$	Thermal reflectivity of the inside cover
$\rho_{2_{IR}}$	Thermal reflectivity of the outside cover
ρ_{a_s}	Solar reflectivity of the absorber plate
ρ_{1_s}	Solar reflectivity of the inside cover
ρ_{2_s}	Solar reflectivity of the outside cover
$\sigma(\delta)$	Stefan-Boltzmann constant
τ_{IR}	Thermal transmissivity
$\tau_s(\tau_{vis})$	Solar transmissivity
$\tau_{1_{IR}}$	Thermal transmissivity of inside cover
$\tau_{2_{IR}}$	Thermal transmissivity of outside cover
τ_{1_s}	Solar transmissivity of inside cover
τ_{2_s}	Solar transmissivity of outside cover

Chapter One

INTRODUCTION

Background

A major concern of people throughout the world today is diminishing oil and natural gas reserves and the corresponding increase in cost in procuring and using these existing resources. The demand for oil in the United States alone has grown at such a phenomenal rate that within the last decade the United States has gone from a period of self-sufficiency to one in which nearly 35% of the oil required for daily use is being imported. Adding to this dilemma is the fact that costs for oil have nearly tripled over the same time span, and these costs promise to increase even further as the need for energy grows. Such alarming statistics signal the emergence of new energy sources (e.g., fusion) or perhaps better use of existing available energy options (e.g., geothermal, hydroelectric, wind, fission, and solar).

Of the existing available energy options, solar energy may prove to be the best for emphasis in the coming decades. The solar energy striking the earth, while diffuse in nature, is estimated at 177 trillion kW, which is 500,000 times the electric power capacity of the United States [1-1].* Therefore, the tapping of only a small fraction of this potential energy source would eliminate the anticipated energy dilemma.

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*Bracket numbers ([x-y]) indicate references which may be found at the conclusion of the thesis. The 'x' indicates the chapter in which the reference is used.

At present, the majority of solar work being undertaken can be divided into two areas: 1) heating and cooling, and 2) electric power generation. The technology for the latter area is still in a developmental period. Heating and cooling by solar energy is a different matter, however, since a technology has existed since the early 1900's incorporating flat-plate collectors and concentrating parabolic and cylindrical collectors. To be sure, the technology in this area is still developing (e.g., the evacuated and moderately concentrating stationary collectors as well as various tracking designs). The majority of work, however, still incorporates flat-plate configurations, since they have been proven to be acceptable for heating from both a performance and economic standpoint.

At present, the flat-plate solar collector can provide sufficient energy for between 50% and 90% of the domestic heating, cooling, and hot water requirements of the United States [1-2], though the upper bound is presently considered unacceptable based on economic considerations. Since approximately 30% of the United States energy consumption is directed towards heating and cooling of buildings [1-3], an important energy savings can be accomplished by flat-plate technology. However, two major shortcomings of flat-plate energy collection - cost and performance at elevated temperatures - as well as the availability of previously cheaper fossil fuels have curtailed solar implementation. Development of new flat-plate collector materials or better application of presently available materials may alleviate such problems and thus must be considered critical to making solar energy utilization feasible.

Discussion of the Problem

The typical flat-plate solar collector consists of five components: 1) the cover panel, 2) the absorbing surface, 3) the absorber plate, 4) the side and back insulation, and 5) the collector box. The cover panel usually consists of one or two cover plates which are employed to reduce heat losses (in the form of convective and radiative heat losses) from the absorber surface. The cover panel should allow solar radiation transmission and should also protect the absorbing surface and insulation from weather extremes. The absorbing surface should effectively absorb solar radiation. Since the absorber surface can achieve relatively high temperatures, re-emission of collected energy can be significant. If justified, the absorbing surface can be designed to reduce emission while maintaining high solar absorptivity - the selective surface. The absorbing plate is generally a metal with high thermal conductivity. It serves to efficiently conduct the absorbed heat to the working fluid (usually water or air). The insulation is employed to reduce back and side heat losses from the collector assembly. The collector box serves as a structural housing for the other four collector components. These major collector components may presently be obtained separately or may be purchased as working systems from several manufacturers. Five currently marketed flat-plate collector systems are shown in Table 1-1.

TABLE 1-1

FIVE REPRESENTATIVE FLAT-PLATE SOLAR COLLECTOR ASSEMBLIES

FLAT-PLATE COLLECTOR DESIGNATION	MANUFACTURER	ABSORBER PANEL	ABSORBING SURFACE	COVER ASSEMBLY	INSULATION	SIZE AND WEIGHT	DESIGNED USE	ESTIMATED ABSORBER[2] TEMPERATURE AT 40% EFFICIENCY (°F)	COST DATA[3] ($/ft^2) / ($/Panel)
Baseline Solar Collector	P.P.G. Industries, Inc.	Roll Bond Type 1100 Aluminum Panel or Roll Bond Copper Panel	Duracron Super 600 L/G Flat Black Paint α_s = .95 ϵ_{IR} = .95	Two sheets of 125 mil Tempered Glass	3" Backing of Fiberglass	$34\frac{3}{16}$" x $76\frac{3}{16}$" x $4\frac{5}{16}$" Weight is 6 lb./ft^2 when tubes filled	Space Heating and Hot Water	170-180	Number of Units Type / 1-7 / 8-23 / 24-95 / 96+ Aluminum 11.93/214. 10.70/192.00 9.64/173.00 8.92/160.00 Copper 14.93/268. 13.43/241.00 12.09/217.00 11.20/201.00 All price data is F.O.B. Ford City, Pennsylvania
Torex 14 Solar Collector	Reynolds Aluminum	Integrally Finned Extruded Aluminum Tube	Siliconized Polyester Flat Black Paint α_s = .95 ϵ_{IR} = .95	Two sheets of 4 mil Tedlar	1" Spun Glass plus 0.8 Closed Cell Foam	4' x 8' x $3\frac{5}{8}$" Weight is 67.8 lbs. when tubes filled	Space Heating and Hot Water	175-185	"Torex Model 14": 8.00/256.00 Price data based on single collector orders "Torex Model 14": 6.00/192.00 Based on orders of 10 to 24 panels All price data is F.O.B. Torrance, California
General Electric Solar Collector	General Electric	Roll Bond Type 1100 Aluminum Panel	Selective coating α_s = .949 ϵ_{IR} = .38	Two sheets of 63 mil Lexan UV Inhibited	Upjohn CPR 9545 Foam Fiberglass Batt	95.46" x 38.12" x 4.75" Total Weight 94 lb.	Space Heating, Hot Water, Space Cooling	210-220	General Electric Solar Collector: 9.89/250.00 Based on orders under 200 panels. All price data is F.O.B. Valley Forge, Pennsylvania
Modular Collector	Revere Copper and Brass, Inc.	Copper Panel with tubes attached $5\frac{1}{2}$" - 6" on centers	Flat Black Paint α_s = .95 ϵ_{IR} = .95	One or Two sheets of 125 mil Tempered Glass	Special Revere Copper Laminated Panel and $3\frac{1}{2}$" Fiberglass	2' x 8' size or 36" x 78" x 5" Weight is 6.5 lb/ft^2	Space Heating and Hot Water	160-180 Depending on tube spacing and number of covers	Modular Collector (Double Glass cover): 8.80/237.60 Modular Collector (Single Glass cover): 8.50/229.50 All price data is F.O.B. Rome, New York. Estimated Price per square foot will decrease by 5% for orders greater than 100 panels
Models 100/200	Grumman Aerospace Corp.	Copper tubes bonded to Aluminum sheet	Alcoa Black α_s = .9 ϵ_{IR} = .35	One or Two sheets of glass	3" Backing of Fiberglass	Single cover 3' x 9' x 5.5" No weight data given	Space Heating and Cooling(?)	165-180 Depending on number of covers	Model 50 (Plexiglas cover with aluminum panel designed for hot water production): 10.00/250.00 (approximate price data F.O.B. Elto, Nevada) Model 100/200 to be distributed before 12/76.

1: Technical data provided through phone conversations and sales and performance brochures received.
2: Temperature ranges estimated for a summer insolation of 300 BTU/hr-ft^2 and wind velocity of 7 MPH. The values shown are extrapolated from performance data provided by companies contacted.
3: Price data current through April, 1976, except for information from Reynolds Aluminum. This data was attained from commercial brochure of 8/75.

Growing governmental support and industrial and academic interest has led to extensive flat-plate collector solar heating and cooling demonstration programs utilizing the tabulated on-the-market products. The majority of the collector systems tabulated have been designed for space heating applications and have been proven acceptable from economic and performance standpoints. They have also been generally found to be impractical for space cooling, unless the collector systems have operated at low efficiencies (low heat removals) [1-4]. This is due to the fact that absorber plate temperatures above 190°F are required to provide hot water suitable for absorption refrigeration air-conditioning systems. As can be seen from Table 1-1, most of the systems cannot reach this required temperature limit at insolations around 300 Btu/hr-ft^2 unless the operating efficiency is below 40%. Such low operating efficiencies make the presently available collector assemblies economically unattractive since much more additional collector area above the heating requirement size is required. In addition, collector size constraints based on installation location (e.g., size of roof) often make solar cooling utilizing currently marketed collectors physically impossible.

Consideration of the materials which comprise the collector assemblies shown in Table 1-1 gives rise to understanding why solar cooling is presently cost and performance wise unfeasible. Commercially available patio-door sized temper glass is employed in three of the solar collectors. The fact that the overall solar transmission for a double cover of temper glass is approximately 70% substantially reduces the solar flux which can be absorbed by the absorber surface. (In comparison, two sheets of 4 mil Tedlar P.V.F. have an effective solar transmission of 85%.) Similarly, the use of nonselective black paints (solar absorptivity is the same as the thermal emissivity) allows for reradiation of the thermal energy of the absorber, since the thermal emissivity approaches 100%. Of the five commercially available collector systems shown in Table 1-1, only the General Electric collector can be efficiently applied to air-conditioning uses. This results from the dual effect of good solar transmission (approximately 76% for the two cover system) and low thermal energy emission due to use of a selective coating.

Further, the choice of solar collector materials employed in the collectors of Table 1-1 appears to be based on economics rather than performance constraints. From studying the tabulated assemblies, it appears that the flat-plate collectors were designed with materials which the manufacturers either produced themselves or which were readily available. The P.P.G. collector most clearly points out this fact. The Baseline Solar Collector is composed of two sheets of P.P.G. Herculite glass, a coating of P.P.G. Duracron flat black paint, and a P.P.G. insulation. The absorber plate is purchased from Olin Brass, the leading solar panel manufacturer in the United States. The combination of these materials does not result in a high performance collector, but it will provide sufficient energy for space heating while allowing P.P.G. Industries, Inc. to market its glass, paint and insulation. Similar analogies can be drawn to the General Electric, Revere, and Reynolds Aluminum collectors. As can be seen, choice of materials has been based on what the manufacturer can make the greatest profit on rather than what materials can be matched to create a high performance collector. Economic pressures, then, may be seen to have restrained the development of solar collectors which can provide suitable heat for the air-conditioning process.

In summary, the currently available collector systems will acceptably provide space heating and associated hot water requirements for buildings. Solar cooling, requiring higher temperature levels for absorption air-conditioning operation, can be obtained currently only at great expense using available systems because of poor collector assembly design. The selection of materials utilized in the tabulated collector assemblies is based on the manufacturer's intent to use his own produced materials rather than the best materials available. More careful consideration of cover and absorber material radiative properties can, however, result in flat-plate collectors which can serve space cooling performance requirements.

Objectives and Outline of Study

The objective of the work to be presented is to consider the problem of space cooling and arrive at optimum single and double cover flat-plate assemblies that can meet absorption refrigeration air conditioning heat load requirements while being economically competitive with presently available solar collectors. In addition, durability, weight, and expected collector life constraints will be considered so that the designed collectors will be acceptable for marketing.

In order to accomplish this objective, the following steps are taken:

1. Investigate and compile the current data available on insulation, absorber and cover materials with respect to mechanical, thermal, and radiative properties. In addition, provide estimated cost data on the materials studied.
2. Code the material properties for computer input for later optimization of single and double cover flat-plate collectors.
3. Model single and double cover flat-plate solar collectors. Derive working equations which will allow for calculation of absorber plate and cover plate(s) equilibrium, steady state, temperatures for various heat load removal conditions.
4. Consider the effects of variation of wind velocity, insolation, and absorber solar absorptivity on the equilibrium absorber plate temperatures. Various degrees of selectivity (varying the $\alpha_S/\varepsilon_{IR}$ ratio) will be considered with typical single and double cover plate assemblies.
5. Apply results gained from the performance analyses to select collector assembly performance constraints. Economic, weight, expected life, weathering, and durability constraints should be selected based on observations from the materials study.

6. Create a criterion function to assist in selection of optimal single and double cover flat-plate collectors which can provide suitable temperatures at elevated efficiencies for space cooling.
7. Employ the computer simulation to select optimal single and double cover flat-plate assemblies.

Steps (1) and (2) are presented in Chapter Two. Chapter Three will include the derivation of the energy balance equations (step 3) required for determination of the equilibrium temperatures. In addition, assumptions to be included in the analysis will be provided in this section. Chapter Four will include general performance data as described in step 4. This data will primarily be presented graphically with conclusions and discussion also being provided. The basis of the computer simulation and optimization will be discussed in Chapter Five, and the constraints chosen for analysis will also be discussed. Chapter Six will consider the results of the computer simulation and optimization, and conclusions will be drawn from this information.

Chapter Two

SOLAR COLLECTOR MATERIALS

Introduction

As has been indicated in Chapter One, most present commercially available flat-plate solar collectors cannot meet the high temperature-high heat load removal requirements necessary for space cooling. This is essentially due to poor selection of commercially available materials which comprise cover assemblies, insulations, and absorbing surfaces. Continued use of time proven materials (such as glass, fiberglass, and black paint) has retarded the development of collectors composed of materials with better radiative and durability properties. Economic constraints, rather than performance requirements, have justified the continued use of the aforementioned materials though educational, governmental, and some industrial groups are providing better alternative materials for solar collector design.

The majority of the solar work done by researchers in educational, industrial, and governmental fields is scattered throughout the literature. Compilation of material data in terms of mechanical, thermal, and radiative properties in the literature is limited, and as a result, comparison of different cover, absorber, and insulation materials requires exhaustive research. In addition, economic studies of collector component materials can seldom be found, and as a result, considerations of new absorber and cover materials (which are currently cost prohibitive but which could become economically competitive with widespread usage) are often neglected.

The intention of this chapter is thus to investigate the currently available industrial and technical literature and compile the material data available on commercial absorber materials, cover materials, and insulation materials. This tabulated information includes present and anticipated future production cost data as estimated by the industries involved in the material manufacture and by other informed sources (such as N.A.S.A. Lewis and Honeywell, Inc.). In addition, problems associated with comparison of mechanical, weatherability, and durability data for cover and absorber materials is discussed.

The chapter is divided into four sections. The first three sections deal with the basic components of any flat-plate solar collector: Cover Materials, Absorber Materials, and Insulation Materials. The fourth section discusses the coding of the tabulated data for later use in flat-plate solar collector design optimization.

COVER MATERIALS

In theory, an optimal cover material for a flat-plate solar collector would meet the following constraints.

1. The cover would allow a major fraction of the solar insolation to be transmitted.

2. The cover would limit the transmission of thermal radiative energy from the absorber panel.

3. The cover would be durable in terms of weathering and impact resistance criteria.

4. The cover would be lightweight.

5. The cover would be inexpensive.

6. The cover would have a "long life".

7. The cover would be easily cleaned, repaired, and replaced.

As might be expected, no one cover material currently available can meet the above seven constraints. The cover materials to be discussed, however, are all suitable for flat-plate collector utilization depending upon the emphasis placed on the criteria listed. Tables 2-1, 2-2, and 2-3 summarize the data pertaining to cover material mechanical, radiative, and economic data by which the different materials can be compared. The majority of this data has been gathered from manufacturer technical brochures, with the cost data provided by material distributors and the manufacturers.*

*The manufacturers of components used in flat-plate solar collectors are acknowledged in Appendix One. Addresses for the different distributors and manufacturers are listed.

It should be noted that the majority of the cover materials tabulated have registered trademark names. These materials have become known in the literature by these designations, and thus the discussion of the materials will utilize the most commonly accepted names. The following cover materials have registered trademark names.

Teflon F.E.P.(R)	-	E. I. DuPont de Nemours & Company
Tedlar P.V.F.(R)	-	E. I. DuPont de Nemours & Company
Mylar S(R)	-	E. I. DuPont de Nemours & Compnny
Lexan(R)	-	General Electric Company
Plexiglas(R)	-	Rohm and Haas Company
Lucite A.R.(R)	-	E. I. DuPont de Nemours & Company
Sunadex(R)	-	A.S.G. Industries, Inc.

The trademark designation [(R)] is omitted in the text for the above materials.

Table 2-1 provides the mechanical properties of cover plate materials. The majority of the data has been obtained using ASTM testing procedures. Problems found in comparing the different materials can be noted by studying the various mechanical properties measured. The glasses, for example, are brittle materials for which data on flexural strength, bursting strength, and ultimate elongation would be meaningless. For the materials like Lexan, however, such properties are their major "selling points" and thus their inclusion in technical brochures is emphasized. Further, the data provided on impact strength points out a major problem in comparison of different material properties. As can be seen from Table 2-1, several impact tests are employed. The results of these tests cannot be compared because of the variations in test conditions. For example, the DuPont Pneumatic

Table 2-1

MECHANICAL PROPERTIES OF COVER MATERIALS

Material Name	Density (lbf/ft³)	Tensile Strength (lbf/in²)	Compressive Strength (lbf/in²)	Modulus of Elasticity (lbf/in²)	Flexural Strength (lbf/in²)	Bursting Strength lbf/(in²-mil)	Impact Strength (variable)	Ultimate Elongation (%)
LEXAN (Polycarbonate)	74.85 [1] (D 792)	9,500 (D 638)	12,500 (D 695)	345,000 (D 638)	13,500 (D 790)	Not Available	16 ft-lbf/in (D 256-IZOD)	110 (D 638)
PLEXIGLAS (Acrylic)	74.22 (D 792)	10,000 (D 638)	18,000 (D 695)	450,000 (D 695)	16,000 (D 790)	Not Available	0.4 ft-lbf/in (D 256-IZOD)	4.9 (D 638)
TEFLON F.E.P. (Fluorocarbon)	134.10 (D 1505)	3,000 (D 882-61T)	Not Available	70,000 (D 882-61T)	Not Available	11 (D 774-46)	2 kg-cm/mil [3] (Du Pont Pneumatic Test)	300 (D 882-61T)
TEDLAR P.V.F. (Fluorocarbon)	86.07 (D 1505)	13,000 (D 882A)	Not Available	260,000 (D 882A)	Not Available	70 (D 774)	5.3 kg-cm/mil (Du Pont Pneumatic Test)	115-250 (D 882A)
MYLAR (Polyester)	87.01 (D 1505)	25,000 (D 882A)	Not Available	500,000 (D 882A)	Not Available	66 (D 774-63T)	6.0 kg-cm/mil (Du Pont Pneumatic Test)	120 (D 882A)
SUNLITE (Fiberglass)	87.32 (D 792)	16,000 (D 638)	Not Available	Flexural Modulus 1,000,000 (D 790)	24,500 (D 790)	Not Available	18 ft-lbf/in (D 256-IZOD)	Not Available
FLOAT GLASS (Glass)	155.93 (P.P.G. Specification)	6,500 (Determined as Modulus of Rupture in Bending)	50,000 (P.P.G. Specification)	10,000,000 (P.P.G. Specification)	Not Available	Not Available	Poor	Not Available
TEMPER GLASS (Glass)	155.93 (P.P.G. Specification)	29,500 (Determined as Modulus of Rupture in Bending)	50,000 (P.P.G. Specification)	10,000,000 (P.P.G. Specification)	Not Available	Not Available	Fulfills [2] Requirements of USAS-Z26-1-1966	Not Available
CLEAR LIME SHEET GLASS (Low Iron Oxide Glass)	156.5 (A.S.G. Specification)	1,600[4]	Not Available	10.5 (10^6) PSI (A.S.G. Test Data)	Not Available	Not Available	Poor	Not Available
CLEAR LIME TEMPER GLASS (Low Iron Oxide Glass)	156.5 (A.S.G. Specification)	6,400[4]	Not Available	10.5 (10^6) PSI (A.S.G. Test Data)	Not Available	Not Available	Fulfills Requirements of USAS-Z26-1-1966	Not Available
SUNADEX WHITE CRYSTAL GLASS (.01% Iron Oxide Glass)	154.3 (A.S.G. Specification)	1,600[4]	Not Available	10.5 (10^6) PSI (A.S.G. Test Data)	Not Available	Not Available	Fulfills Requirements of USAS-Z26-1-1966	Not Available

1: All parenthesed numbers refer to ASTM test codes.

2: No more than two 12" × 12" panels may shatter upon impact of 0.5# steel ball dropped 10 ft.

3: Test is now also listed as ASTM-D3099.

4: Design tensile values are for a safety factor of 2.5 and probability of 0.8% failure under one-minute windloading.

test (ASTM D3099) essentially measures the change in velocity of a fired bullet as it passes through a plastic of known thickness. For glass, the test employed determines whether the glass breaks when impacted with a steel ball dropped from a designated height. The manner in which each material is supported, and the size of each material being tested is different. Thus, comparison of the results is an arbitrary process. (It should be noted that of the materials tabulated, only Lexan is warranteed against impact breakage.) Differences in the measurement procedures point out the need for a fixed testing program which compares materials of the same size supported by the same means. (A standard collector panel size could be selected for the purposes of comparing how cover materials would hold up under various loading conditions.) A testing program of this nature would provide more useful information than all of the data coded in Table 2-1 and is thus recommended for future work.

Table 2-2 presents the thermal and radiative properties tabulated for representative cover material thicknesses. As in Table 2-1, data provided on weatherability and chemical resistance were not based on a single standardized testing procedure. The glasses, having been used in varied chemical and weather conditions, are time proven with regard to weatherability and chemical resistance. Materials like the fiberglass covers and plastic film covers have not been utilized in different environments long enough that data on their weatherability and chemical resistance can have much significance. Further, unlike the glasses which

Table 2-2

THERMAL AND RADIATIVE PROPERTIES

Material Name	Index of Refraction (n_D)	τ (Solar)[4] (%)	τ (Solar)[2] (%)	τ (Infrared)[3] (%)	Expansion Coefficient (IN/IN-°F)	Temperature Limits (°F)	Weatherability (comment)	Chemical Resistance (comment)
LEXAN (Polycarbonate)	1.586[1] (D 542)	125 mil 84.1 (±.8)	125 mil 72.6 (±.1)	125 mil[5] 2.0 (EST)	3.75 (10^{-5}) (D 696)	250°-270° Service Temperature	Good: 2 yrs exposure in Florida caused yellowing; 5 years caused 5% loss in τ	Good: Comparable to Acrylic
PLEXIGLAS (Acrylic)	1.49 (D 542)	125 mil 89.6 (±.3)	125 mil 79.6 (±.8)	125 mil[5] 2.0 (EST)	3.9 (10^{-5}) @ 60°F 4.6 (10^{-5}) @ 100°F	180°-200° Service Temperature	Average to Good: Based upon 20 yrs testing in Arizona, Florida, and Pennsylvania	Good to Excellent: Resists most acids and alkais
TEFLON F.E.P. (Fluorocarbon)	1.343 (D 542)	5 mil 92.3 (±.2)	5 mil 89.8 (±.4)	5 mil 25.6 (±.5)	5.9 (10^{-5}) @ 160°F 9.0 (10^{-5}) @ 212°F	400° continuous use 475° short term	Good to Excellent: Based on 15 yrs exposure in Florida environment	Excellent: Chemically Inert
TEDLAR P.V.F. (Fluorocarbon)	1.46 (D 542)	4 mil 92.2 (±.1)	4 mil 88.3 (±.9)	4 mil 20.7 (±.2)	2.8 (10^{-5}) (D 696)	225° continuous use 350° short term	Good to Excellent: 10 yrs exposure in Florida with slight yellowing	Excellent: Chemically Inert
MYLAR (Polyester)	1.64-1.67 (D 542)	5 mil 86.9 (±.3)	5 mil 80.1 (±.1)	5 mil 17.8 (±.5)	0.94 (10^{-5}) (D 696-44)	300° continuous use 400° short term	Poor: Ultraviolet degradation great	Good to Excellent: Comparable to Tedlar
SUNLITE[7] (Fiberglass)	1.54 (D 542)	25 mil (P) 86.5 (±.2) 25 mil (R) 87.5 (±.2)	25 mil (P) 75.4 (±.1) 25 mil (R) 77.1 (±.7)	25 mil (P) 7.6 (±.1) 25 mil (R) 3.3 (±.3)	1.4 (10^{-5}) (D 696	200° continuous use causes 5% loss in τ	Fair to Good: Regular (7 yrs solar life), Premium (20 yrs solar life)	Good: Inert to chemical atmospheres
FLOAT GLASS (Glass)	1.518 (D 542)	125 mil 84.3 (±.1)	125 mil 78.6 (±.2)	125 mil[5] 2.0 (EST)	4.8 (10^{-6}) (D 696)	1350° Softening point; 100° thermal shock[6]	Excellent: Time Proven	Good to Excellent: Time Proven
TEMPER GLASS (Glass)	1.518 (D 542)	125 mil 84.3 (±.1)	125 mil 78.6 (±.2)	125 mil[5] 2.0 (EST)	4.8 (10^{-6}) (D 696)	450°-500° continuous use; 500°-550° short term	Excellent: Time Proven	Good to Excellent: Time Proven
CLEAR LIME SHEET GLASS (Low Iron Oxide Glass)	1.51 (D 542)	Insufficient data provided by ASG	125 mil 87.5 (±.5)	125 mil 2.0 (EST)	5.0 (10^{-6}) (D696)	400°F for continuous operation	Excellent: Time Proven	Good to Excellent: Time Proven
CLEAR LIME TEMPER GLASS (Low Iron Oxide Glass)	1.51 (D 542)	Insufficient data provided by ASG	125 mil 87.5 (±.5)	125 mil 2.0 (EST)	5.0 (10^{-6}) (D 696)	400°F for continuous operation	Excellent: Time Proven	Good to Excellent: Time Proven
SUNADEX WHITE CRYSTAL GLASS (.01% Iron Oxide Glass)	1.50 (D 542)	Insufficient data provided by ASG	125 mil 91.5 (±.2)	125 mil 2.0 (EST)	4.7 (10^{-6}) (D 696)	400°F for continuous operation	Excellent: Time Proven	Good to Excellent: Time Proven

1: All parenthesed numbers refer to ASTM Test Codes.

2: Numerical Integration ($\Sigma\ \tau_{avg} \cdot F_{\lambda_1 T-\lambda_2 T}$) for λ = 0.2μM to λ = 4.0μM.

3: Numerical Integration ($\Sigma\ \tau_{avg} \cdot F_{\lambda_1 T-\lambda_2 T}$) for λ = 3.0μM to λ = 50.0μM.

4: Compiled data based on ASTM Code E 424 Method B.

5: Data not provided; estimate of 2% to be used for 125 mil samples.

6: Degrees differential to rupture 2 × 2 × 1/4 - inch samples. Glass specimens heated and then quenched in water bath @ 70°F.

7: Sunlite Premium data is denoted by (P); Sunlite Regular data is denoted by (R).

have been tested in the support configurations required for solar collector use, tests on materials like Tedlar P.V.F., Teflon F.E.P., and Plexiglas G have been undertaken without consideration of how the materials are to be used. For example, Tedlar P.V.F. was nailed to a board while it was tested in the Florida environment [2-1] and thus did not undergo wind loading conditions. As can be seen, standardized weather and chemical testing programs should be established in order to provide more realistic environmental information on solar collector cover materials.

The most critical factor in solar collector material cover choice is how well the cover will transmit the incident solar flux. An optimal collector cover in this respect would have spectral transmission properties similar to those presented in Figure 2-1. From Figure 2-1. it can be seen that cover transmission properties can be divided into two wavelength bands. For the band from $\lambda \cong 0.3\mu m$ to $\lambda \cong 2.10\mu m$, it is desired that all the incident radiant energy should be transmitted through the cover. At wavelengths greater than $\lambda \cong 2.10\mu m$, it is desired that the cover become opaque (in terms of transmission properties) to trap the emission from the absorber. The two wavelength bands described correspond to the energy bands in which the sun and a black body at a temperature between 100°F and 500°F would emit radiative energy. (The sun has spectral radiative emission properties similar to those of a black body at 10,400°R.) The normalized energy emitted for each black body is shown in Figure 2-2, taken from work presented by Duffie and Beckman [2-2].

FIG. 2-1

OPTIMAL COVER MATERIAL
SPECTRAL RADIATIVE PROPERTIES

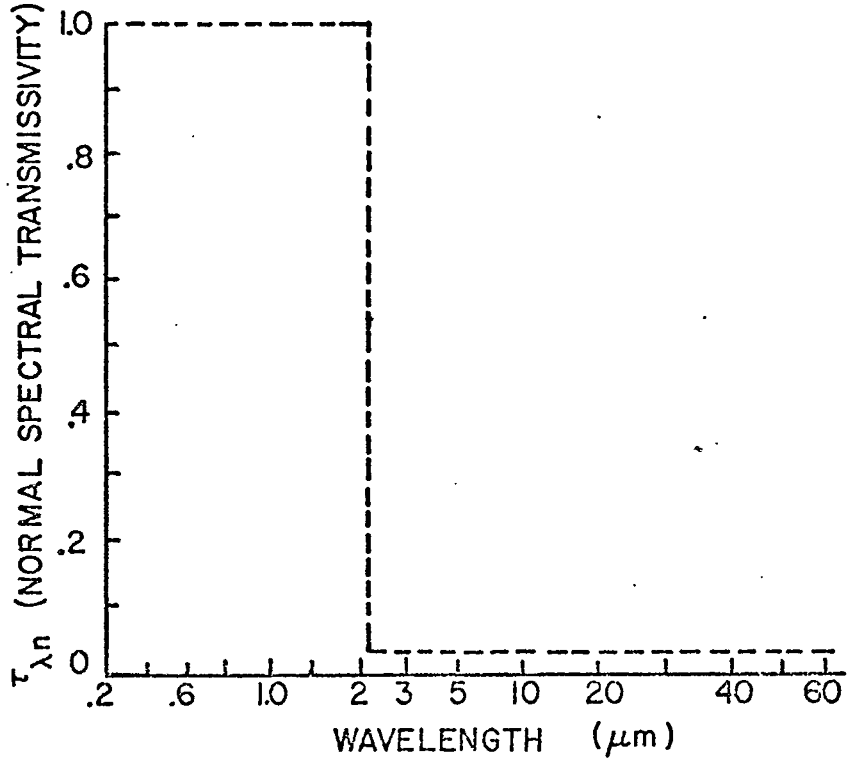
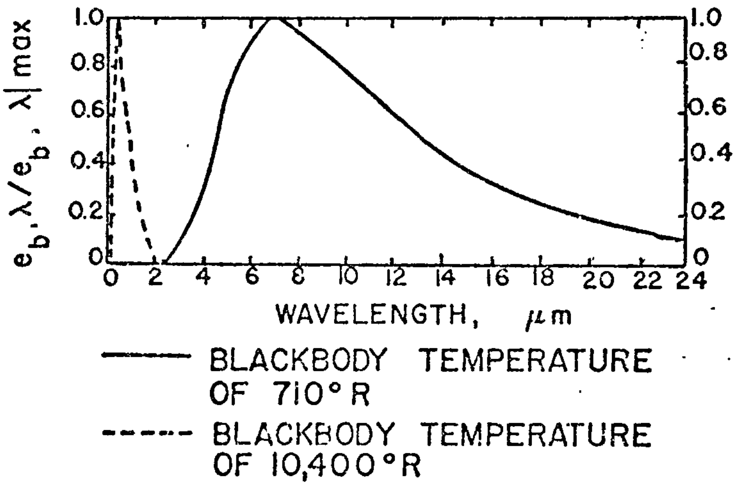


FIG. 2-2

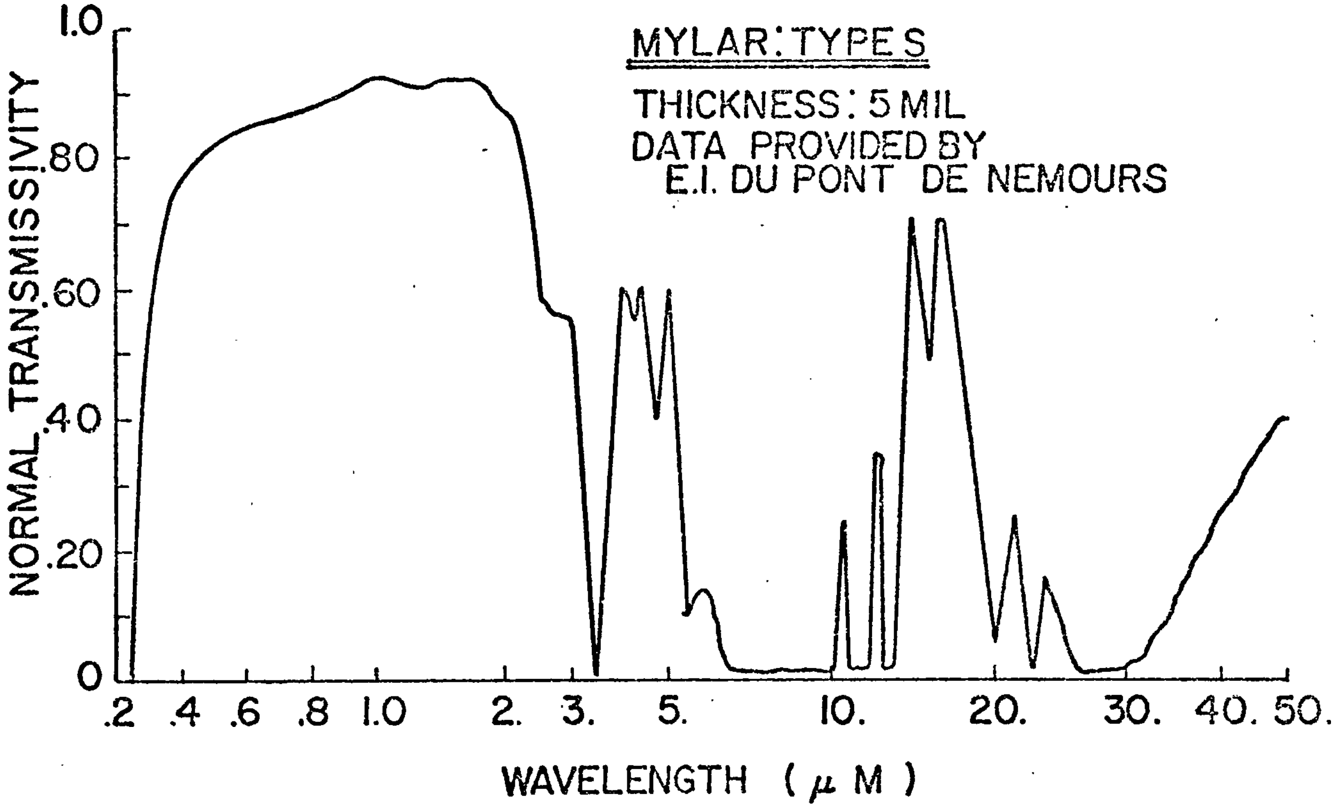
NORMALIZED SPECTRAL DISTRIBUTION
OF BLACKBODY RADIATION



The transmission properties for representative cover materials are shown in Figures 2-3A, B, C, D, and E. As can be seen, none of the materials have perfect solar transmission properties (i.e., $\tau_n = 1.0$ for $\lambda = 0.3\mu m$ to $\lambda = 2.10\mu m$). Nonetheless, materials like Teflon F.E.P., Tedlar P.V.F., Sunadex Glass, and Plexiglas G exhibit good solar transmission properties for solar collector usage. The glasses, polycarbonates, and acrylics are excellent cover materials in terms of poor transmission properties in the thermal band ($\lambda = 3.0\mu m$ to $\lambda = 50.0\mu m$). The plastics, Teflon F.E.P., Tedlar P.V.F., and Mylar S exhibit relatively high transmission of thermal radiative energy. Since design of cover assemblies must consider both transmission bands, however, the plastics cannot be neglected because they have such high solar transmission properties. (Choice of cover type, in fact, has been shown to be tied to the absorber surface radiative properties [2-3])

Numerical values for the thermal and solar transmission properties of representative cover materials are given in Table 2-2. Insufficient data was obtained on the effects of radiation incidence angle on transmission properties, and thus only normal averaged transmission of solar and thermal radiative energy is considered. The average values shown for normal solar transmissivity (τ_s) are calculated two ways. The first approach is the most commonly employed procedure and is based on ASTM Code E 424 Method B [2-4]. The radiative solar energy shown in Figure 2-2 is divided into energy bundles which can be considered to fall

FIG. 2-3A
COVER MATERIAL DATA



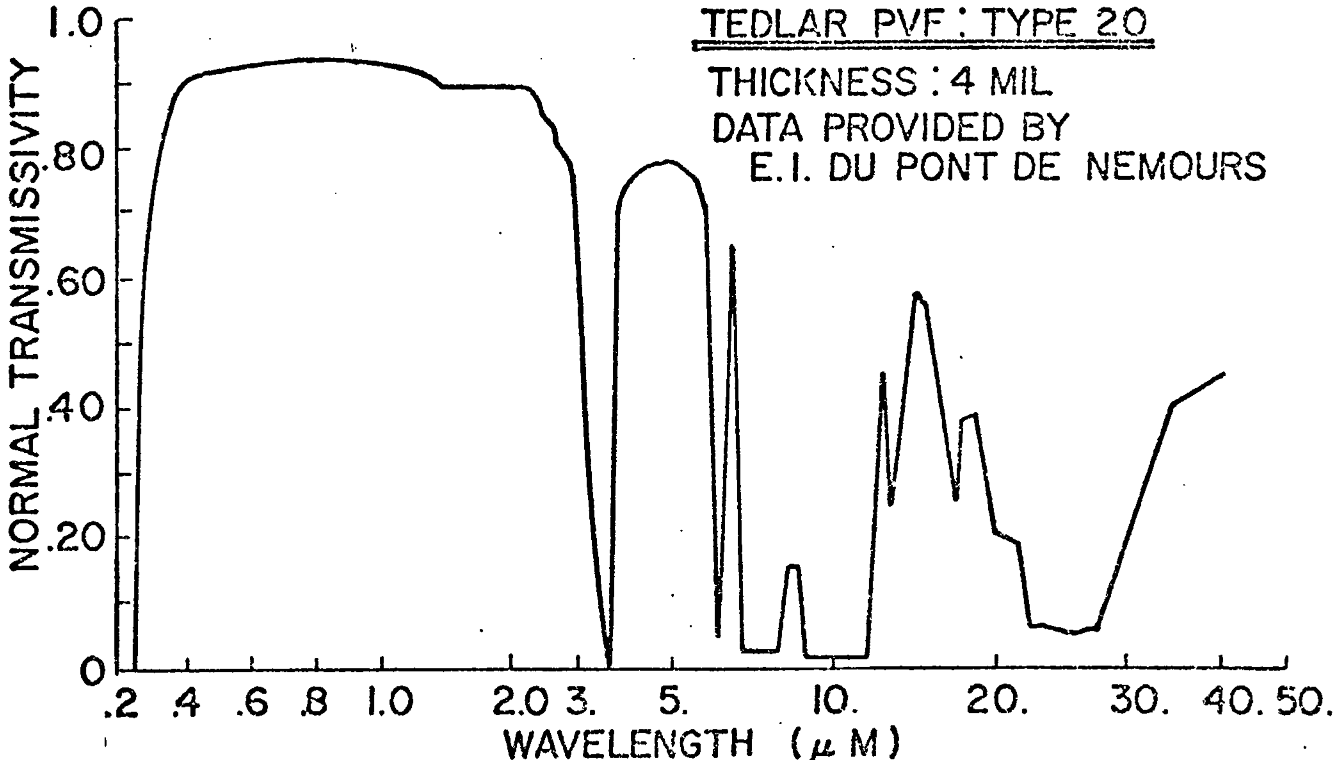
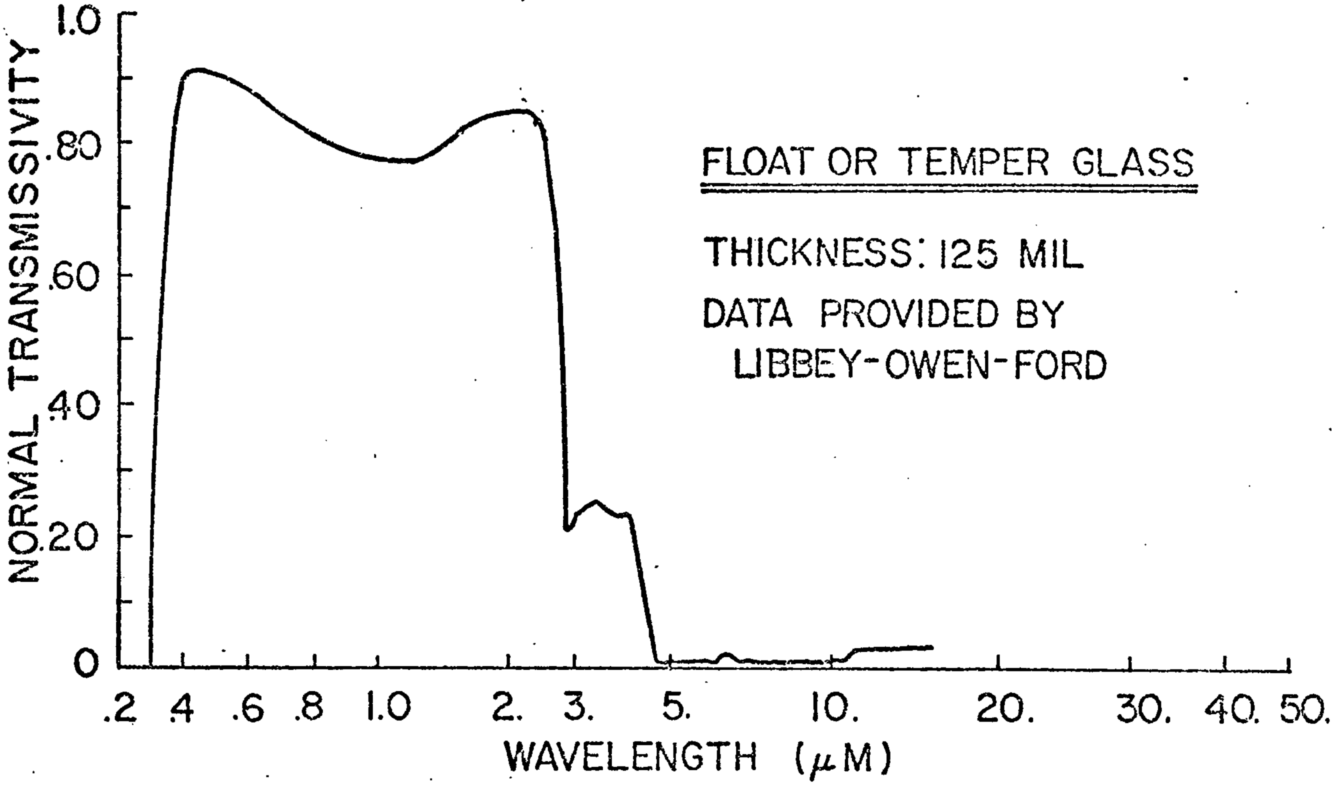


FIG. 2-3B
COVER MATERIAL DATA



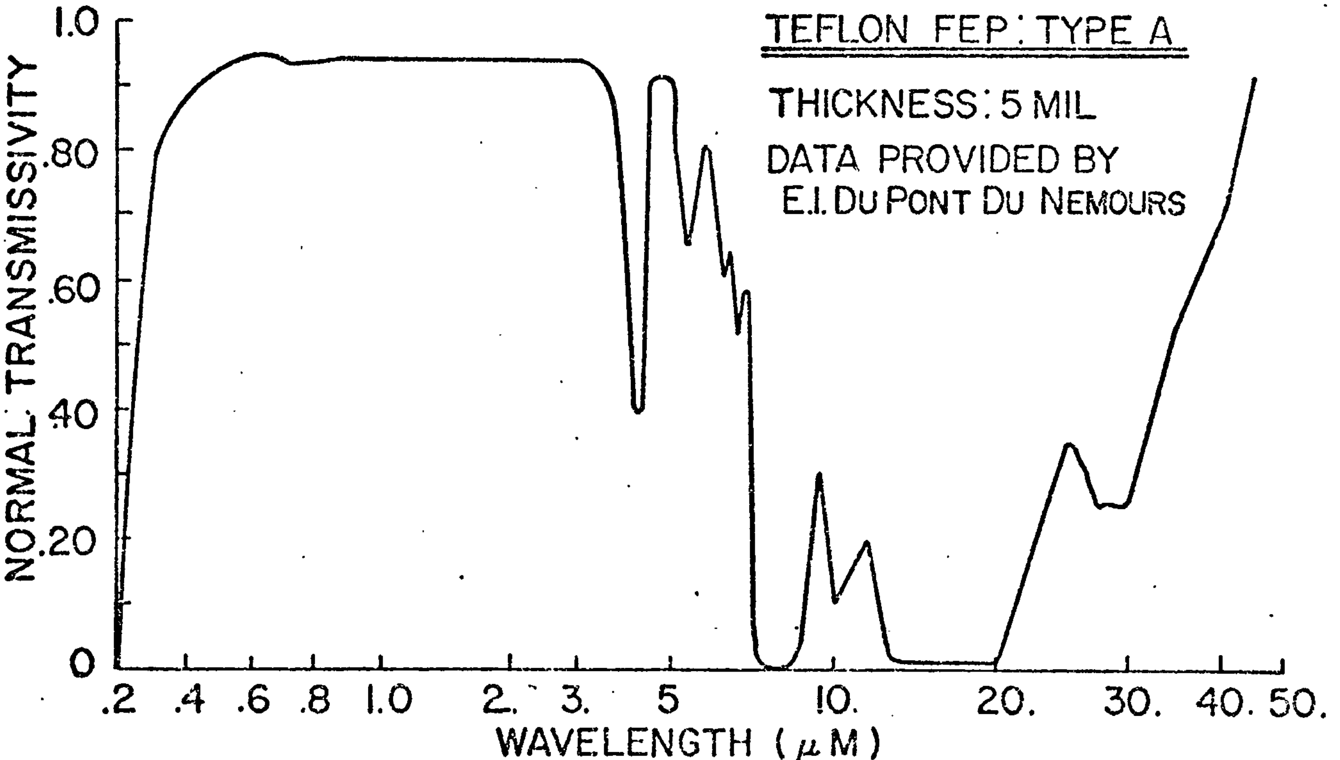
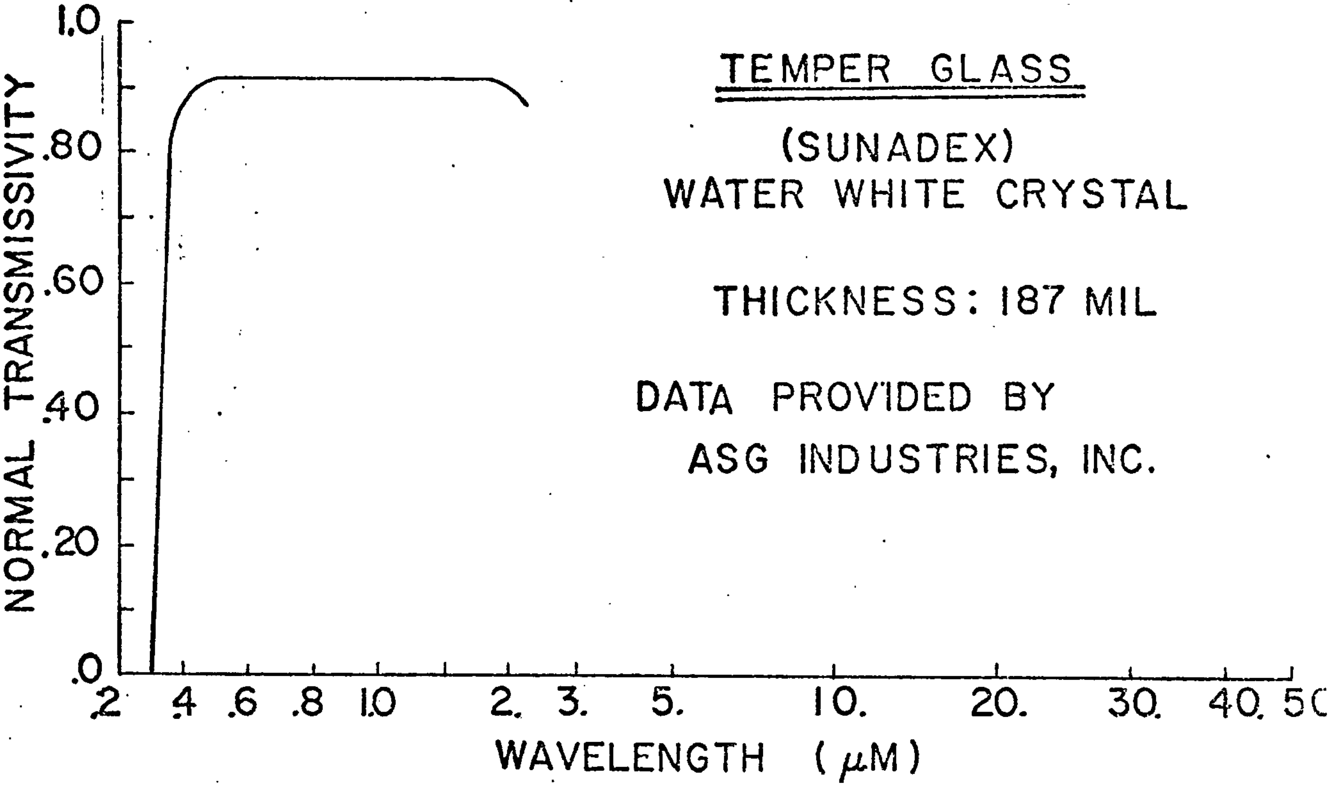


FIG. 2-3C
COVER MATERIAL DATA



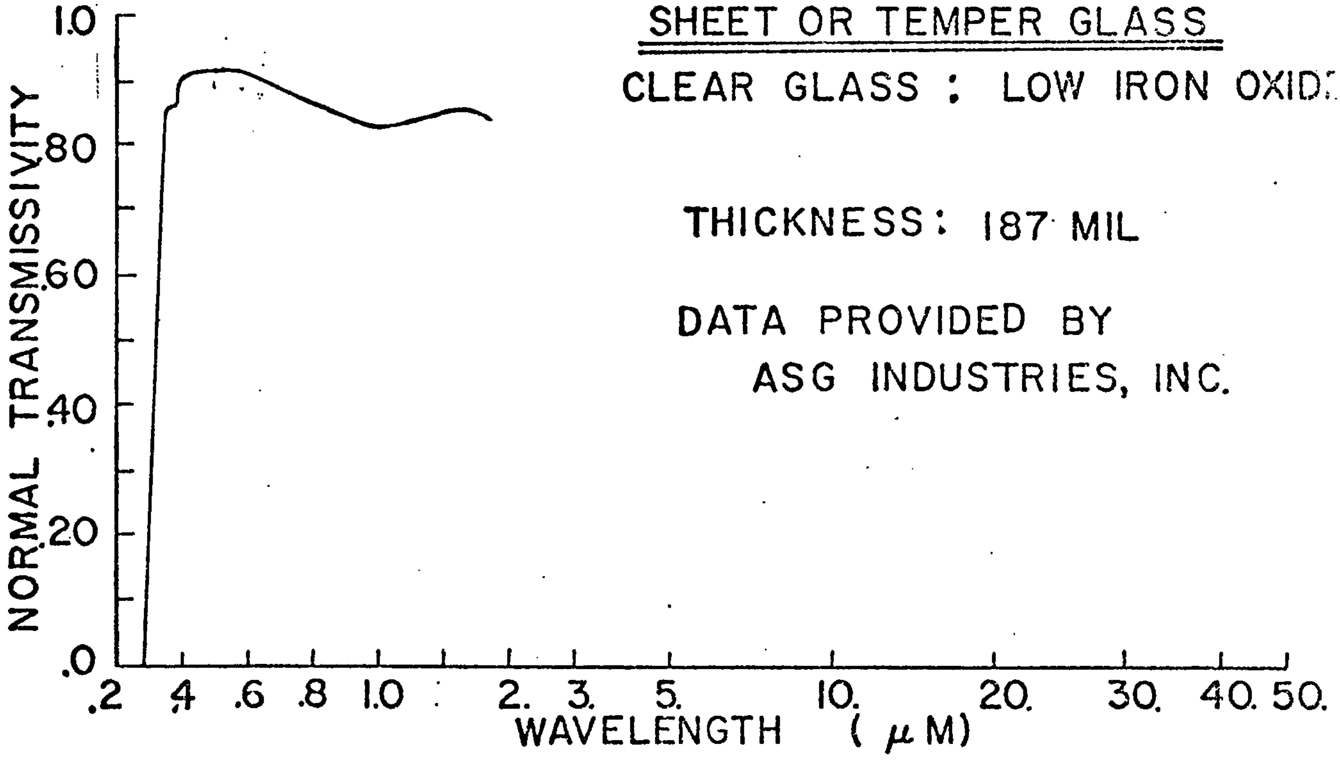
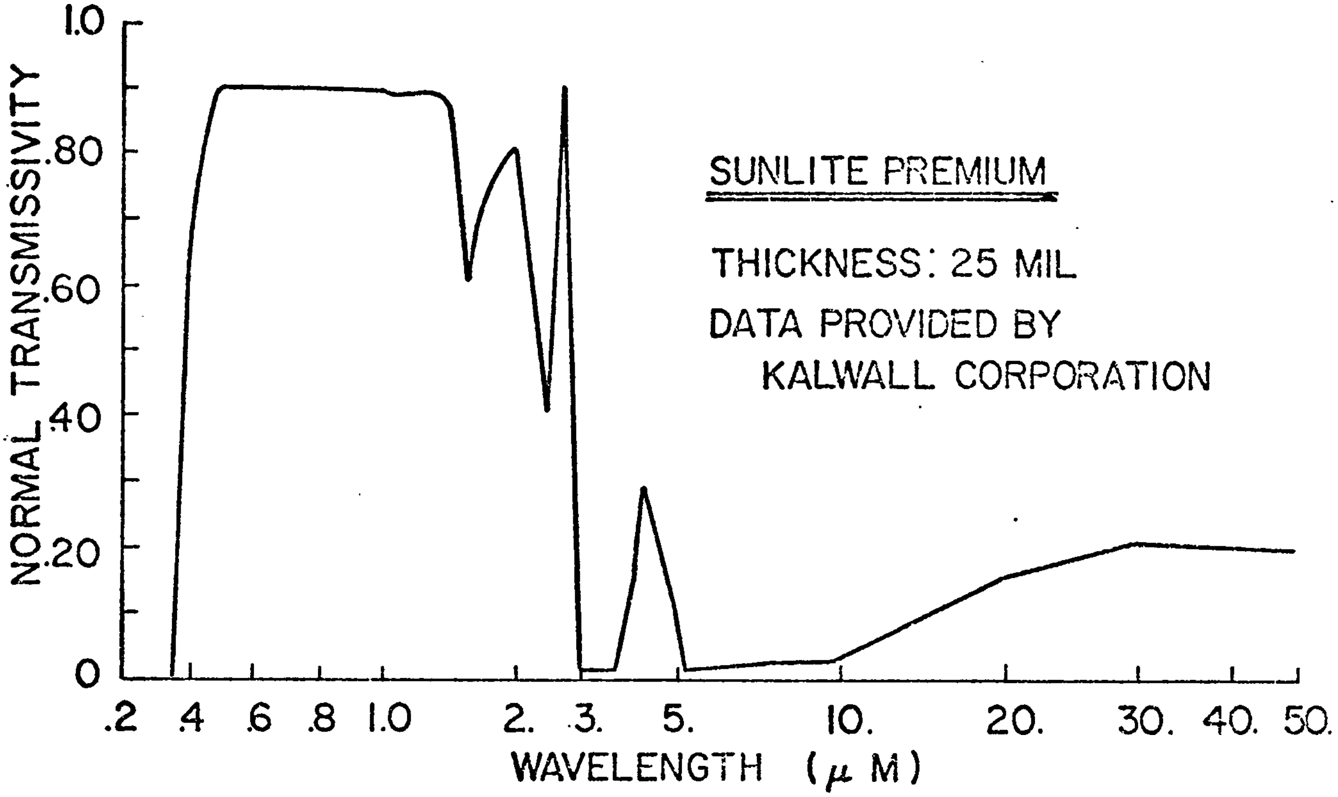


FIG. 2-3D
COVER MATERIAL DATA



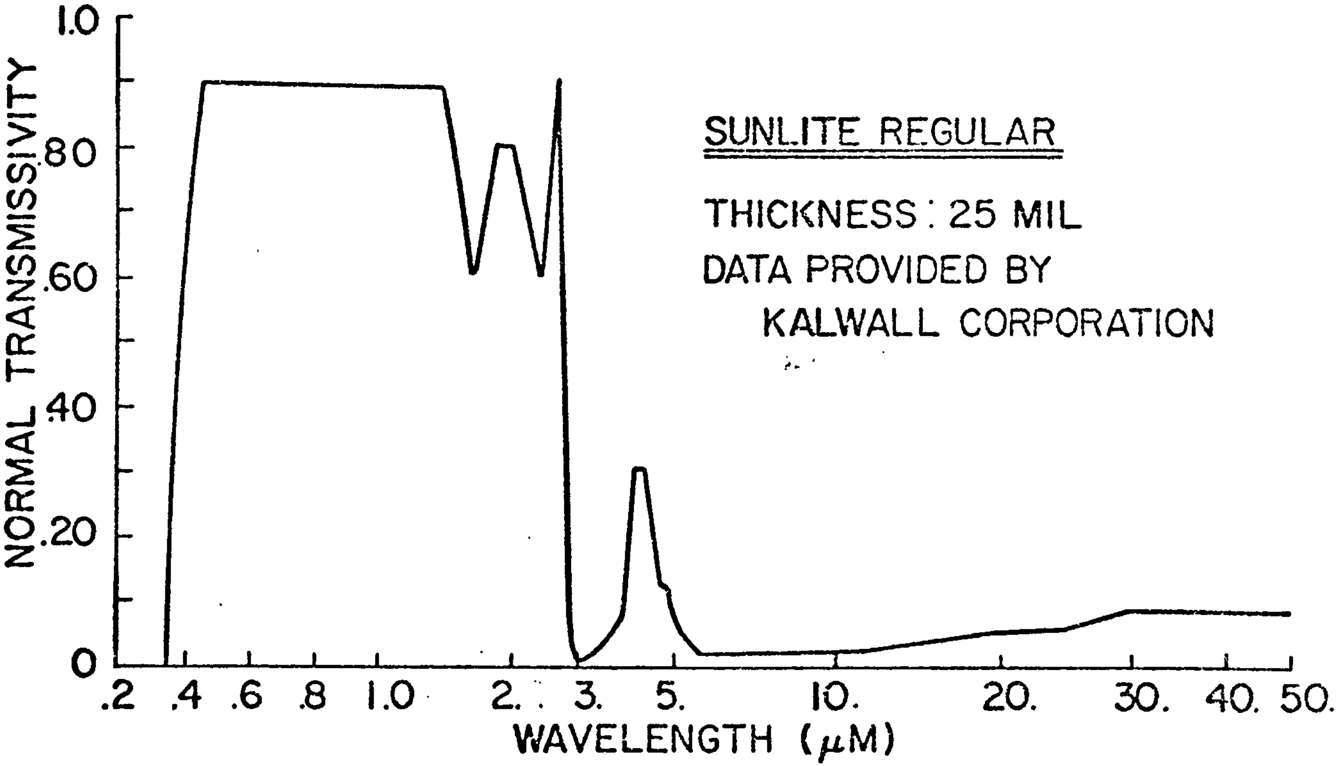
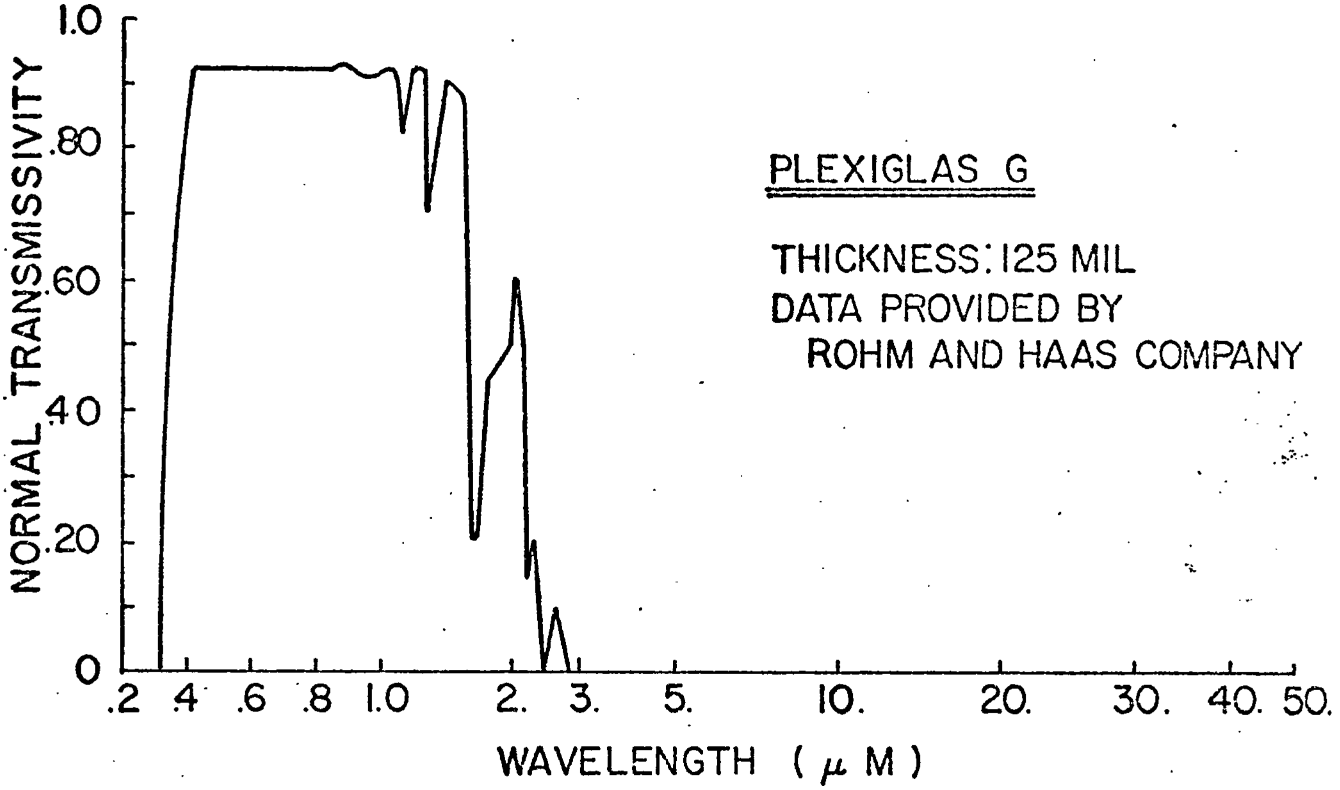
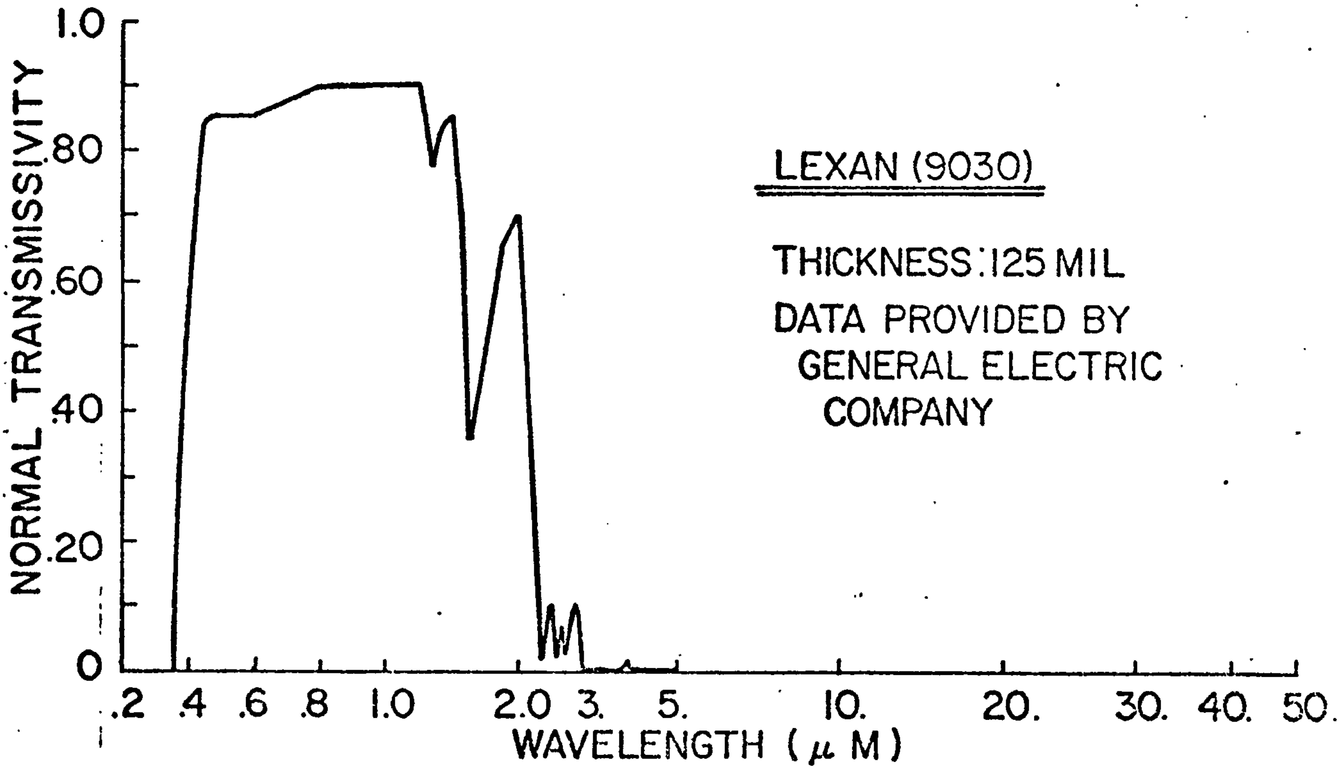


FIG. 2-3E
COVER MATERIAL DATA





within select wavelength bands. Equation (2.1)* can thus be used to find the effective solar transmissivity if spectral transmissivity data for the cover material are available.

$$\tau_{solar} = \tau_s = \sum_{i=1}^{36} a_{\lambda_i} \tau_{\lambda_i} \tag{2.1}$$

where

τ_{λ_i} = the spectral transmissivity at the selected wavelength

a_{λ_i} = the weighted coefficients as shown below.

i	λ_i	a_{λ_i}	i	λ_i	a_{λ_i}	i	λ_i	a_{λ_i}
1	.35	1.27	13	.95	3.29	25	1.55	1.49
2	.40	3.18	14	1.00	4.25	26	1.60	1.36
3	.45	6.79	15	1.05	3.72	27	1.65	1.17
4	.50	8.20	16	1.10	1.70	28	1.70	.89
5	.55	8.03	17	1.15	1.46	29	1.75	.54
6	.60	7.88	18	1.20	2.52	30	1.80	.01
7	.65	7.92	19	1.25	2.21	31	1.85	0
8	.70	7.48	20	1.30	1.78	32	1.90	0
9	.75	5.85	21	1.35	.12	33	1.95	.12
10	.80	5.79	22	1.40	0	24	2.00	.02
11	.85	5.66	23	1.45	.16	35	2.05	.26
12	.90	3.24	24	1.50	1.06	36	2.10	.58

The summation of the weighted coefficients

$$\sum_{i=1}^{36} a_{\lambda_i} = 100 \tag{2.2}$$

shown in equation (2.2) totals 100% which is what would be expected for a cover having the transmission properties of Figure 2-1. For

*Parenthesed numbers, (x.y), indicate equations shown in the text. The 'x' indicates the chapter in which the reference is used.

a black body having a temperature of 10,400°R, the wavelength band analyzed in ASTM test E 424 Method B accounts for 90% of the total energy actually emitted since 6% of emitted energy is at wavelength less than 0.35μm and 4% is at a wavelength greater than 2.1μm.

A second technique for calculating solar transmissivity for cover materials employs a numerical integration [2-5]. Equation (2.3) shown below

$$\tau_n(T) = 1/\sigma T^4 \int_{\lambda=0}^{\lambda=\infty} \tau_{\lambda_n}(\lambda,T)\, e_{\lambda_b}(\lambda,T)\, d\lambda \tag{2.3}$$

where

σ = Stefan-Boltzmann constant

$\tau_{\lambda_n}(\lambda,T)$ = normal spectral transmissivity

$e_{\lambda_b}(\lambda,T)$ = spectral emissive power for a black surface

can be approximated by

$$\tau_n(T) = \sum_{i=1}^{n} \tau_{avg_{\lambda_{i-1}-\lambda_i}} \cdot F_{\lambda_{i-1}T-\lambda_i T} \tag{2.4}$$

where

$\tau_{avg_{\lambda_{i-1}-\lambda_i}}$ = an average value for normal transmissivity between wavelengths λ_i and λ_{i-1}

$F_{\lambda_{i-1}T-\lambda_i T}$ = the fraction of emissive power for a black body at temperature T between wavelengths λ_i and λ_{i-1}

$$= 1/\sigma \left[\int_0^{\lambda_i T} \frac{e_{\lambda_b}(\lambda)}{T^5}\, d\lambda T - \int_0^{\lambda_{i-1} T} \frac{e_{\lambda_b}(\lambda)}{T^5}\, d\lambda T \right]$$

$$= F_{0-\lambda_i T} - F_{0-\lambda_{i-1} T}$$

Values for $F_{0-\lambda_i T}$ are tabulated in [2-5] for products of wavelength and absolute temperature.

Equation (2.4) is used for calculating τ_s by assuming that the sun has radiative emissive properties similar to that of a black body at 10,400°R. Figures 2-3A, B, C, D, and E can be divided into rectangular sections of constant τ_{avg}. The numerical integration is performed between $\lambda = .2\mu m$ and $\lambda = 4.0\mu m$. This wavelength range corresponds to 99% of the total energy which could be emitted by a black body at 10,400°R. The values obtained using equation (2.4) are shown in Table 2-2.

Comparison of the results obtained from the two calculation methods indicates that the second procedure provides lower measurements of solar transmissivity. This is largely due to the fact that most cover materials are poor transmitters of ultraviolet energy between $\lambda = .2\mu m$ and $\lambda = .35\mu m$. Using method two, a black body at 10,400°R would emit nearly 6% of its total energy between $\lambda = .2\mu m$ and $\lambda = .35\mu m$. Thus, if the cover transmits poorly in the ultraviolet range indicated, solar transmissivity readings could be as much as 6% less than what they would be using τ_s as calculated using the ASTM E 424 Method B guidelines. A similar argument could be posed for the range of $\lambda = 2.1\mu m$ to $\lambda = 4.0\mu m$ where nearly 4% of the total energy of a black body at 10,400°R would be emitted. Thus, comparisons between the two procedures could be as much as 10% apart depending upon the spectral transmission properties of the cover plate.

Method two incorporating equation (2.4) is used to calculate normal thermal transmissivity (τ_{IR}). The wavelength range of $\lambda = 3.0\mu m$ to $\lambda = 50\mu m$ was analyzed, and close agreement between the values obtained in this method and a method utilized by Christie [2-6] was found. (The Christie analysis considers the wavelength range of $3\mu m$ to $20\mu m$ and neglects the far-infrared wavelengths.) The data calculated is presented in Table 2-2.

Two other points concerning the α_s and ε_{IR} calculations should be discussed. The first point concerns the manufacturers' supplied data. For both techniques employed in the calculation of average normal transmissivity, values of spectral transmissivity were taken from plots similar to Figures 2-3A through 2-3D. Due to the reduced scale of the supplied graphical data, its readability was poor. Discrepancies in the reading of the figures were accounted for by performing each set of calculations twice. An average of the two calculated transmissivities is provided in Table 2-2 along with a possible error based on the two calculation differences. The second point concerns estimation of τ_{IR} for several cover materials. The data provided by manufacturers and distributors of glass, acrylic, and polycarbonate materials was limited to data over the solar wavelength band. Additional notes indicating that these materials could be considered "opague" to thermal radiative energy were provided, though spectral transmissivity data was not included to substantiate manufacturer claims. Based on manufacturer comments and discussions from the literature, τ_{IR} values have been estimated to be between 0.01 and 0.03 depending upon the material thickness.

The final data provided on cover materials consider material availability and cost. This data are summarized for various thicknesses of cover materials in Table 2-3. As can be seen from this table, solar collector size may need to be selected based on the cover material chosen for use, since standard available sizes vary so.

The cost data provided are based on manufacturer and distributor estimates for moderately large production purchases. The cost data are current through November, 1975. In addition, estimated price increases per year ranging from 10% to 12% were provided by the manufacturers and distributors contacted. It should also be noted that the price data presented for the cover materials include freight to Houston, Texas where needed. All materials except for Tedlar P.V.F. and Sunlite can be obtained in Houston through distributors or manufacturer warehouses.

The cover materials section is concluded by pointing out that several studies are underway for improving the radiative properties of several materials presently marketed and utilized in solar work. Improvements can be made on the cover material transmission properties if the work done on producing antireflection coatings for glass and plastics is successful. Durability and economics are currently the major shortcomings [2-7]. Further development work with MgF_2 coatings [2-8] may improve the float glass solar transmission properties, for example, by as much as 7%. Such coatings, however, will not be considered in this analysis, since durability and weatherability factors presently limit their applicability over extended time periods.

Table 2-3

COVER PLATE MATERIALS: AVAILABILITY AND COST

Material Classification	Manufacturer	Material Type	Material Thickness (mils)	Available Forms Standard Sizes (variable)	Cost Data[1] Qty. (ft^2)	Cost ($\$/ft^2$)	Qty. (ft^2)	Cost ($\$/ft^2$)
POLYCARBONATE	General Electric Company	Lexan Mr-4000	63	(4' x 8') Sheet	400-1000	1.29-D	1000+	1.23-D
			125	(4' x 8') (6' x 8') Sheet	400-1000	2.92-D	1000+	2.47-D
			187	(4' x 8') (6' x 8') Sheet	400-1000	4.21-D	1000+	3.56-D
	Sheffield Polyglaz, Inc.	Polyglaz (Lexan-9030)	63	(4' x 8') Sheet	400-1000	1.12-D	1000-5000	1.05-D
			125	(4' x 8') Sheet	400-1000	2.24-D	1000-5000	1.90-D
			187	(4' x 8') Sheet	400-1000	3.30-D	1000-5000	2.76-D
ACRYLIC	E.I. DuPont De Nemours & Company	Lucite A.R.	63	(4' x 6') Sheet	400-1000	2.15-D	1000+	1.86-D
			125	(4' x 8') (5' x 8') Sheet	400-1000	2.19-D	1000+	1.90-D
			187	(4' x 8') (5' x 8') Sheet	400-1000	2.44-D	1000+	2.11-D
	Rohm and Haas Company	Plexiglas G	63	(4' x 6') (4' x 8') Sheet	1000-3000	1.27-D	3000+	1.14-D
			125	(4' x 8') (6' x 8') Sheet	1000-3000	1.36-D	3000+	1.22-D
			187	(4' x 8') (6' x 8') Sheet	1000-3000	1.61-D	3000+	1.45-D
FLUOROCARBON	E.I. DuPont De Nemours & Company	Tedlar P.V.F. Type 20	4	Roll: 2"-64" width 1250' length	Below 1000 1000-3500	0.25-D 0.19-DP	1000+ 3500+	0.23-D 0.18-DP
		Teflon F.E.P. Type A	5	Roll: 2"-46" width 960' length	1000-3000	0.736-D	3000+	0.693-D
POLYESTER		Mylar Types	5	Roll: 1.5"-50" width 1000' length	1000-4000	0.085-D	4000+	0.071-D
FIBERGLASS	Kalwall Corporation	Sunlite Regular	25	Rolls or Reels (5' width)	1000-8000	0.35-K	8000+	0.325-K
			40		1000-8000	0.38-K	8000+	0.355-K
		Sunlite Premium	25	Roll: 50 Lineal Feet	1000-8000	0.41-K	8000+	0.36-K
			40	Reel: 1200 Lineal Feet	1000-8000	0.48-K	8000+	0.455-K
GLASS	P.P.G. Industries, Inc. and Libbey-Owen-Ford Company	Float Glass	125	(36" x 84") (48" x 84") Sheet	1200+	0.33-D	NO DATA	NO DATA
			187	(36"x 120") (48"x 120") Sheet	1200+	0.485		
		Temper Glass	125	(28" x 76") (34" x 76") Sheet	1600+	0.70-D	2400+	0.64-D
			187	(34" x 76") (46" x 76") Sheet	1600+	0.58-D	NO DATA	NO DATA
GLASS (Low Iron Oxide Content)	ASG Industries, Inc.	Sheet Lime Glass	125	(36" x 84") (48" x 84") Sheet	NO DATA	NO DATA	Truckload[2]	0.33-ASG
			187	(36"x 120") (48" x 84") Sheet			Truckload	0.485-ASG
		Temper Lime Glass	125	(28" x 75") (34" x 76") Sheet	NO DATA	NO DATA	Truckload[2]	0.55-ASG
			187	(34" x 76") (46" x 76") Sheet			Truckload	0.58-ASG
		Sunadex Water White Crystal Temper Glass	125	(34" x 76") Sheet	NO DATA	NO DATA	Truckload[2]	0.83-ASG
			156	(34" x 76") (46" x 76") Sheet			Truckload	0.93-ASG
			187	(34" x 76") (46" x 76") Sheet			Truckload	1.03-ASG
			219	(46" x 96") (46"x 120") Sheet			Truckload	1.17-ASG

1: Cost data based on large scale purchases as shown. Cost to include freight where necessary to transport materials to Houston and are current through November 10, 1975. Cost data from Houston distributors denoted by (D); cost data from Kalwall denoted by (K); cost data from DuPont denoted by (DP); cost estimates by ASG representative denoted by (ASG).

2: Truckload quantities of glass refer to purchases of 38,000 to 40,000 pounds of glass.

ABSORBER MATERIALS

Absorber materials should be designed to meet the following criteria:

1. The absorber material should absorb incident solar radiation.
2. The absorber material should not emit thermal radiation.
3. The absorber material should have good durability and high temperature.
4. The absorber material should have a "long life".
5. The absorber material should survive exposure to high humidity.
6. The absorber material should be easily applied to an absorber panel.
7. The absorber material should be inexpensive.

The absorber coating for a flat-plate collector may be either selective ($\alpha_s/\varepsilon_{IR} > 1$) or nonselective ($\alpha_s/\varepsilon_{IR} = 1$). Collector performance would be about the same with either type coating at low temperatures, but the nonselective coating may offer cost and possibly durability advantages. If the collector application is for heating and cooling, then a selective coating would probably be preferable. Increased collector performance may justify the higher cost required for selective coating usage.

Information on absorber materials with respect to technical and economic data has been compiled in a series of six tables. The absorber materials analyzed fall into three major categories. They are:

1. Selective and nonselective paints.

2. Electroplated surfaces.

3. Dip or chemical conversion surfaces.

These divisions have been selected since cost, durability, and application processes vary so much. General observations on each class of absorber surface are summarized below.

Selective and Nonselective Paints

1. Of the absorber materials investigated, the paints are found to be the least expensive.

2. Durability of absorber paints is generally good with respect to moisture (humidity) attack.

3. Temperature limitations for painted surfaces are low enough that failure of the heat removal system to operate (during installation or in case of pump failure) might lead to absorber surface degradation.

Electroplated Surfaces

1. Of the absorber materials investigated, the electroplated materials are considered to be the most durable with respect to high temperature degradation and moisture attack.

2. Electroplated surfaces are presently the most expensive absorber materials commercially available.

3. Of the absorber materials studied, the electroplated materials cataloged have the best radiative properties for solar energy absorption and limited thermal energy emission.

Dip or Chemical Conversion Surfaces

1. The chemical conversion surfaces have questionable durability properties. Upper temperature limits are low enough that like, paints absorber surface degradation could result in the event of solar collector non-use. In addition, moisture can cause rapid degradation of the surface.

2. Present production costs for chemical conversion surfaces are low enough that economically competitive selective coated flat-

plate collectors may be designed using these absorbing materials.

The individual absorber material technical data are provided in Tables 2-4A, 2-4B, and 2-4C. Cost and application data for the three types of absorbers can be found in Tables 2-5A, 2-5B, and 2-5C.

The technical data presented in Tables 2-4A, B, and C indicate that the application procedure for absorbing surfaces can radically affect the radiative properties at the surface. Based on the wavelength bands in which the sun and a black body at 100°F-500°F emit radiative energy (refer to Figure 2-2), an optimum absorbing surface would have spectral reflectivity properties similar to those found in Figure 2-4. For absorber surface radiative properties, Kirchhoff's law [2-5] can be written

$$\alpha_{\lambda,n}(\lambda,T) + \rho_{\lambda,n}(\lambda,T) + \tau_{\lambda,n}(\lambda,T) = 1.0 \tag{2.6}$$

In addition, the selective surface is treated as an opaque body with respect to radiation so that

$$\alpha_{\lambda,n}(\lambda,T) + \rho_{\lambda,n}(\lambda,T) = 1.0 \tag{2.7}$$

For the solar energy incident on the absorbing surface, it is desired that the spectral reflectivity should be negligible. If such is the case, equation (2.7) reduces to

$$\alpha_{\lambda,n}(\lambda,T) \cong 1.0 \text{ for } \lambda = 0.35\mu\text{m to } \lambda = 2.1\mu\text{m} \tag{2.8}$$

and maximum insolation absorption results. In addition, it is desired to limit the thermal energy which the absorber would emit due to its temperature. Thus, in terms of optimizing properties, it is desireable for the absorbing surface to absorb little

Table 2-4A

ABSORBER MATERIALS: TECHNICAL DATA

MATERIAL	SUBSTRATE	PLATING OR COATING DATA	SOLAR[2] ABSORPTIVITY (%)	THERMAL[1] EMISSIVITY (%)	$\frac{\alpha_s}{\epsilon_{IR}}$	TEMPERATURE LIMITS (^{o}F)	DURABILITY
SELECTIVE AND NONSELECTIVE PAINTS							
BLACK ACRYLIC PAINT	STEEL ALUMINUM	THOROUGHLY CLEAN THE ALUMINUM SURFACE. SPRAY DURACRON SUPER 600 L/G AND BAKE AT 375^{o}F FOR 15 MINUTES.	95	95	1	325^{o} - 375^{o}	HUMIDITY TESTS SHOW NO DEGRADATION. TEMPERATURES ABOVE 325^{o}F CAUSE SURFACE DULLING. SURFACE HARDNESS BETTER ON THERMOSETTING ACRYLIC.
		SIMILAR PROCESS EXCEPT NEXTEL BLACK PAINT USED.	96.7	96.7	1		
SELECTIVE PAINT PbS: PIGMENT SILICON: BINDER	STEEL ALUMINUM	0.1 MICRON THICKNESS SILICON WEIGHT: 0.5 mg/cm^2 PbS WEIGHT: 0.17 mg/cm^2	84	19	4.4	ABOVE 350^{o}	ANTICIPATED DURABILITY EQUAL TO BLACK ACRYLIC WITH BETTER TEMPERATURE LIMITATIONS.
		SILICON WEIGHT; 0.17 mg/cm^2 PbS WEIGHT: 0.55 mg/cm^2	90	37	2.4		
SELECTIVE PAINT METEOR - 7890 $Cu\text{-}CrO_x$: PIGMENT EPD[4]: BINDER	STEEL ALUMINUM	0.21 MIL THICK COATING. 30% PIGMENT VOLUME CONCENTRATION.	95	47 $\epsilon_H = 61$[3]	2.02	NO DATA	FORMAL DURABILITY TESTS NOT PERFORMED. ANTICIPATED TO BE EQUAL TO THAT OF ACRYLIC PAINT.
SELECTIVE PAINT CdTe: PIGMENT EPD[4]: BINDER	STEEL ALUMINUM	0.20 MIL THICK COATING. 30% PIGMENT VOLUME CONCENTRATION.	90	48 $\epsilon_H = 49$[3]	1.9	NO DATA	FORMAL DURABILITY TESTS NOT PERFORMED. ANTICIPATED TO BE EQUAL TO ACRYLIC PAINT.
SELECTIVE PAINT METEOR 7890 $Cu\text{-}CrO_x$: PIGMENT EPDM[5]: BINDER	STEEL ALUMINUM	30% PIGMENT VOLUME CONCENTRATION 0.05 MIL COATING	92	30	3.0	NO DATA. BINDER HAS EXCELLENT TEMPERATURE RESISTANCE	FORMAL DURABILITY TESTS NOT PERFORMED THOUGH EXPECTED TO BE EQUAL OR OR BETTER THAN ACRYLIC PAINT
		0.13 MIL COATING	94	45	2.1		

1. Thermal Emissivity Data is based on the absorber emitting energy as a temperature ranging from 200^{o}F to 500^{o}F and data is numerically attained through analysis of reflectivity data using $\epsilon_{IR} = 1 - \rho_{IR}$. (Hemispheric values shown).
2. Solar absorptivity data is found by integration of reflectivity data over the solar spectrum and application of $\alpha_s = 1 - \rho_s$. (Hemispheric values shown).
3. Total hemispherical thermal emissivity measured calorimetrically at 200^{o}F.
4. EPD is abbreviation for Ethylene - Propylene - Diene Polymer.
5. EPDM is abbreviation for Ethylene - Propylene - Diene - Material.

Table 2-4B

ABSORBER MATERIALS: TECHNICAL DATA

MATERIAL	SUBSTRATE	PLATING OR COATING DATA	SOLAR[3] ABSORPTIVITY (%)	THERMAL[2] EMISSIVITY (%)	$\frac{\alpha_s}{\epsilon_{IR}}$	TEMPERATURE LIMITS (^oF)	DURABILITY[1]
ELECTROPLATED ABSORBER SURFACES							
BLACK CHROME OVER DULL NICKEL	STEEL	PLATING DENSITY: 180 AMPS/ft^2 PLATING TIME: 30 SECONDS	87	6	14.5	ABOVE 700^o	EXCELLENT DURABILITY IN HUMID ENVIRONMENT. FIVE DAYS HUMIDITY TESTING YIELDED 1% LOSS IN α_s and 5% GAIN IN ϵ_{IR}. ESTIMATED LIFE IS 20 YEARS.
	COPPER	PLATING DENSITY: 180 AMPS/ft^2 PLATING TIME: 1 MINUTE.	96	10	9.6		
	ALUMINUM	PLATING DENSITY: 180 AMPS/ft^2 PLATING TIME: 2 MINUTES	96	12	8		
BLACK CHROME	STEEL AND GALVANIZED STEEL	PLATING DENSITY: 300 AMPS/ft^2 PLATING TIME: 2 MINUTES	95	15	6.3	ABOVE 800^o	HUMIDITY TESTS ON GALVANIZED STEEL ABSORBER YIELDED MINOR RUSTING. ON STEEL ABSORBERS MAJOR RUSTING OCCURRED. OXIDATION ON COPPER ABSORBER DEVELOPED.
	COPPER	COPPER CLEANED AND BUFFED PLATING DENSITY: 180 AMPS/ft^2	95 - 90 (ESTIMATE BY OLYMPIC)	20 - 25 (ESTIMATE BY OLYMPIC)	4.75 - 3.6		
BLACK NICKEL OVER NICKEL	STEEL COPPER ALUMINUM	PLATING DENSITY[4] 1: .93 AMPS/ft^2 PLATING TIME 1 : 1 - 2 MINUTES	87.7	6.6	13.3	ABOVE 550^o	DESTROYED BY MOISTURE AS INDICATED BY HUMIDITY TESTS. TWO LAYERS OF NICKEL HAVE QUESTIONABLE TWENTY YEAR LIFE.
		PLATING DENSITY 2: 1.86 AMP/ft^2 PLATING TIME 2: 1 - 2 MINUTES	96	7	13.7		
BLACK NICKEL	STEEL AND GALVANIZED STEEL	PLATING DENSITY: 1.86 AMPS/ft^2 PLATING TIME: 2-4 MINUTES	88.6	12.2	7.3	ABOVE 400^o	HUMIDITY TEST RESULTED IN RUST DEVELOPING ON STEEL ABSORBERS. COPPER ABSORBER OXIDIZES AND NICKEL PLATE BREAKS DOWN UNDER MOISTURE AND ACID.
	COPPER	PROPRIETARY DATA OF SOLAR EQUIPMENT CORPORATION	87	10	8.7		
			91.4	11.6	7.9		

1. Durability data is based on temperature limitations and on humidity tests as conducted by Honeywell, Inc. Principal humidity test employed used a temperature cycle of 90^o to 160^oF at 95% relative humidity over a 24 hour period. Test designation is MIL-STD-810B.

2. Thermal emissivity data is based on the absorber emitting energy at a temperature ranging from 100^o to 300^oF and data is numerically attained through analysis of reflectivity versus wavelength curves assuming that $\epsilon_{IR} = 1 - \rho_{IR}$ (Hemispheric values shown).

3. Solar absorptivity data is found by integration of reflectivity data over the solar spectrum and application of assumption that $\alpha_s = 1 - \rho_s$. (Hemispheric values shown).

4. Data on electroplating two layers of nickel on the substrate metal are shown. Plating data provided yields varied α_s/ϵ_{IR} ratios depending upon lengths of plating time. The two sets of radiative data provide examples of variance in possible results.

Table 2-4C

ABSORBER MATERIALS: TECHNICAL DATA

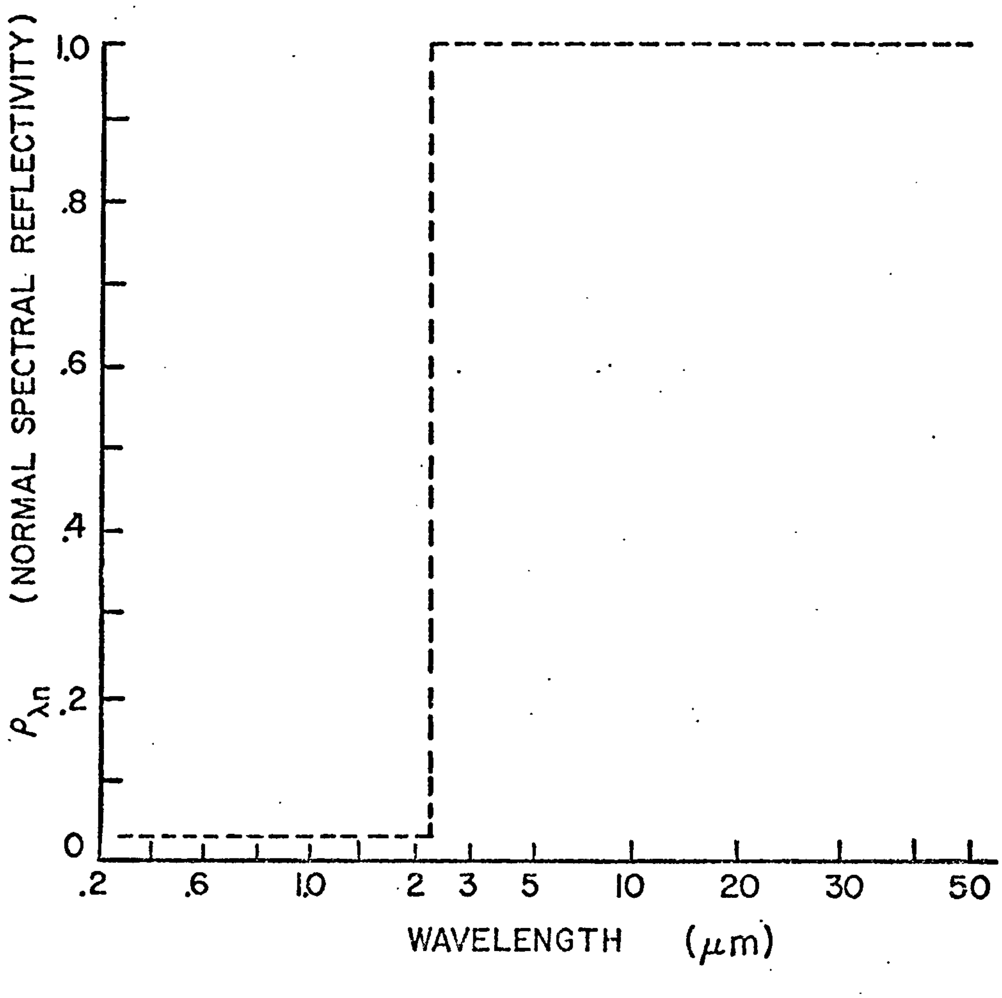
MATERIAL	SUBSTRATE	PLATING OR COATING DATA	SOLAR[3] ABSORPTIVITY (%)	THERMAL[2] EMISSIVITY (%)	$\frac{\alpha_s}{\epsilon_{IR}}$	TEMPERATURE LIMITS (°F)	DURABILITY[1]
DIP OR CHEMICAL CONVERSION ABSORBER SURFACES							
BLACK COPPER (COPPER OXIDE)	COPPER	PROPRIETARY DATA OF ENTHONE INC. (DATA IS GUARANTEED)	90	12	7.5	375° CONTINUOUS USE 400° SHORT TERM	ENTHONE INC. GUARANTEES ABSORBER TO BE 80% EFFECTIVE AFTER FIVE YEARS. DURABILITY QUESTIONABLE IN HUMID ATMOSPHERES AND AT TEMPERATURES ABOVE 300°F.
		BATH TIME: 5 MINUTES BATH TEMPERATURE: 219°F	91	16	5.7		
		BATH TIME: 10 MINUTES BATH TEMPERATURE: 140°F	90	20	4.5		
		BATH TIME: 270 SECONDS BATH TEMPERATURE: 150°F	88	16	5.5		
BLACK COPPER (COPPER OXIDE)	ALUMINUM	BATH TIME: 3 MINUTES BATH TEMPERATURE: 290°F	79	5	15.8	COMPARABLE TO BLACK COPPER ON COPPER	QUESTIONABLE DURABILITY AT TEMPERATURES ABOVE 300°F. HUMID ENVIRONMENTS HAVE ADVERSE EFFECTS ON COATING.
		BATH TIME; 8 MINUTES BATH TEMPERATURES: 290°F	89	17	5.2		
BLACK IRON (IRON OXIDE)	STEEL	BATH TIME: 2 MINUTES BATH TEMPERATURE: 295°F	84	8	10.5	600° - 700° (ESTIMATED BY ENTHONE)	ONE MICRON THICK COATING WITHSTOOD HUMIDITY TEST WITH MINOR RUSTSPOTS OCCURRING. LESS THICK COATINGS MAY BREAK DOWN OR RUST THROUGH IN HUMID ENVIRONMENTS.
		BATH TIME: 9 MINUTES BATH TEMPERATURE: 295°F	89	35	2.5		
		BATH TIME: 15 MINUTES BATH TEMPERATURE: 286°F	85	10	8.5		
		BATH TIME: 3 MINUTES BATH TEMPERATURE: 300°F	90	7	12.9		
IRON OXIDE	STEEL	HEAT CARBON STEEL IN AIR TO 550° - 600°F. QUENCH IN WATER ONCE STEEL ATTAINS DARK BLUE COLOR.	88	12 (ESTIMATED BY HONEYWELL)	7.3	ABOVE 600°	HUMID ENVIRONMENTS MAY BREAK MAY BREAK DOWN COATING AND PROMOTE RUST. DIFFICULT TO ATTAIN UNIFORM PROPERTIES.
ALCOA BLACK	ALUMINUM	CHEMICAL CONVERSION PROCESS KNOWN AS ALCOA PROCESS 655 AND IS PROPRIETARY DATA OF ALCOA.	90	30	3.0	350°	EXTREMELY DURABLE IN CONTROLLED HUMIDITY ENVIRONMENT NEAR 200°F. COATING DESTROYED UNDER WATER IMPINGEMENT.
			90	40	2.2		

1. Durability data is based on temperature limitations and on humidity tests as conducted by Honeywell, Inc. Principal humidity test employed used a temperature cycle of 90° to 160°F at 95% relative humidity over a 24 hour period. Test designation is MIL-STD-810B.

2. Thermal Emissivity data is based on the absorber emitting energy at a temperature ranging from 100°F to 300°F and data is numerically attained through analysis of reflectivity versus wavelength curves assuming that $\epsilon_{IR} = 1 - \rho_{IR}$. (Vales are hemispheric)

3. Solar absorptivity data is found by integration of reflectivity data over the solar spectrum and application of $\alpha_s = 1 - \rho_s$. Humid environment may break down coating and promote rust. (Values are hemispheric).

FIG. 2-4
OPTIMAL ABSORBER MATERIAL
SPECTRAL RADIATIVE PROPERTIES



thermal energy, since

$$\alpha_{\lambda,n}(\lambda,T) = \varepsilon_{\lambda,n}(\lambda,T) \tag{2.9}$$

Thus, the spectral reflectivity should be maximized in the thermal energy wavelength band (λ = 3.0μm to λ = 50μm), and equation (2.7) reduces to

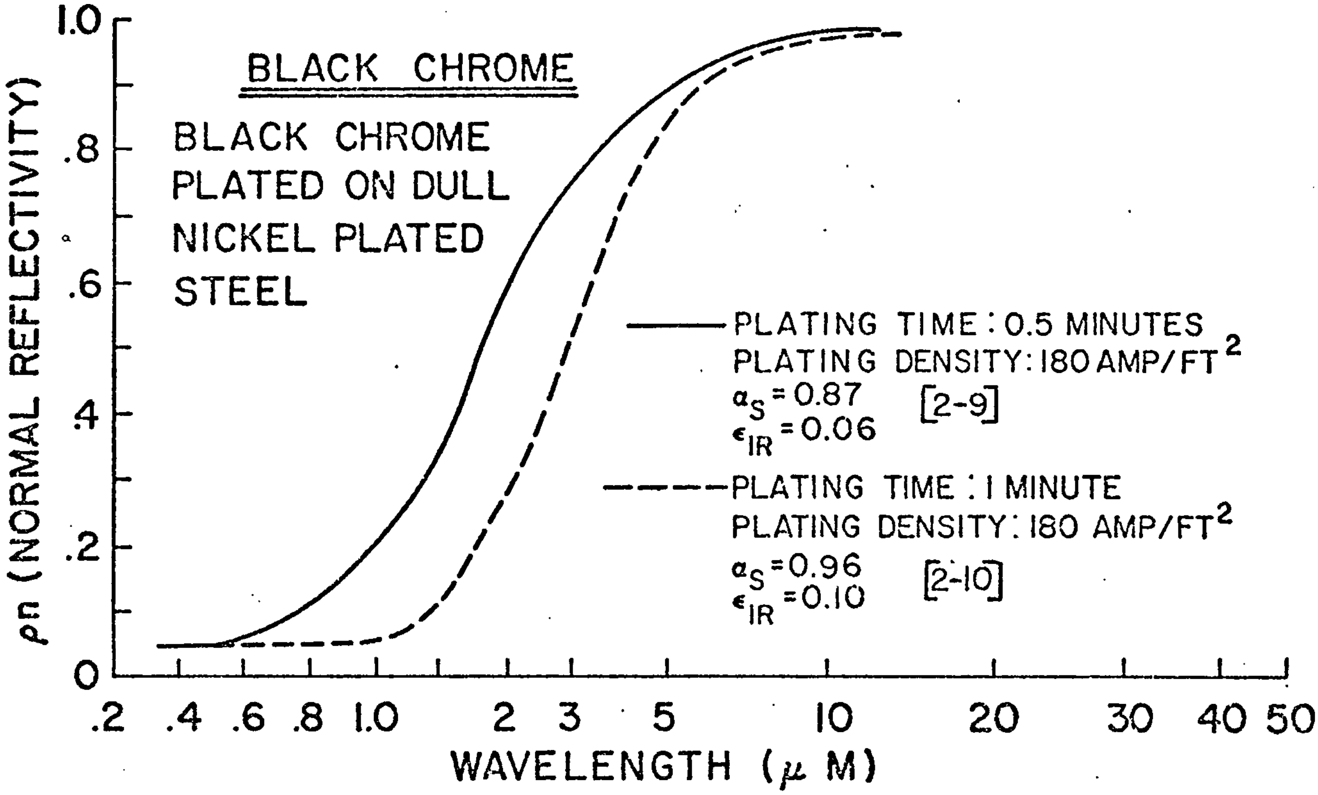
$$\alpha_{\lambda,n}(\lambda,T) \cong 0 \text{ for } \lambda = 3\mu m \text{ to } \lambda = 50\mu m \tag{2.10}$$

Figures 2-5A, B, C, and D are provided for several of the absorber materials tabulated. Application data, where provided, are included in the figures along with the references from which the spectral data was attained.

The average normal solar absorptivity and thermal emissivity data presented in Tables 2-4A, B, and C have been taken from the literature available and from absorber material manufacturers. Methods employed in the calculating of average normal transmissivities could also be employed to obtain the radiative absorption properties. However, several absorber material manufacturers would not provide spectral data on their coatings for this study, and these calculations were not made. Of the spectral data received, use of ASTM E 424 Method B [2-4] for solar spectral reflectivity data yielded values of solar absorptivity which closely matched the data provided by the manufacturers. Use of the provided data was thus found acceptable for analysis purposes.

The cost data presented in Tables 2-5A, B, and C indicate why selective surfaces ($\alpha_s/\varepsilon_{IR}$ ratios greater than one) have not been used more extensively in solar flat-plate collector work.

FIG. 2-5A
ABSORBER MATERIAL DATA



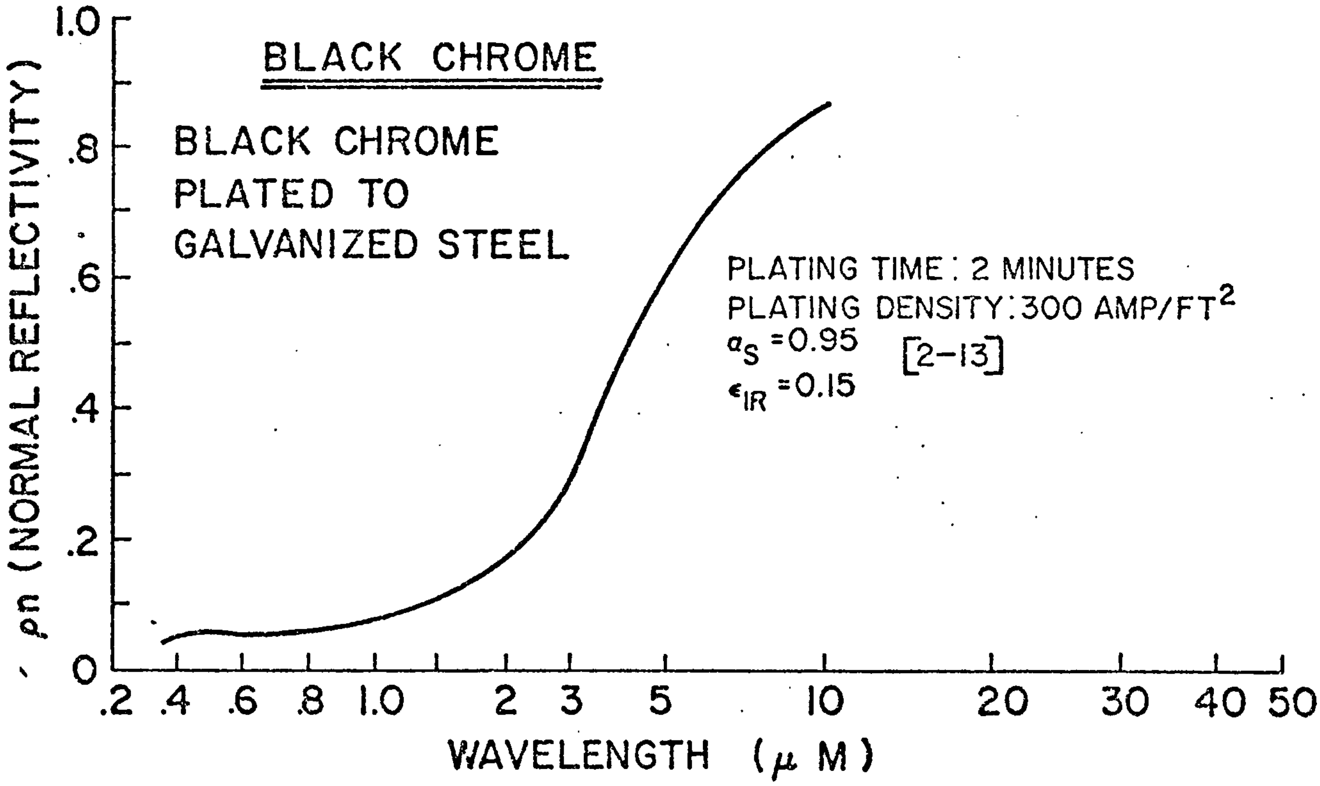
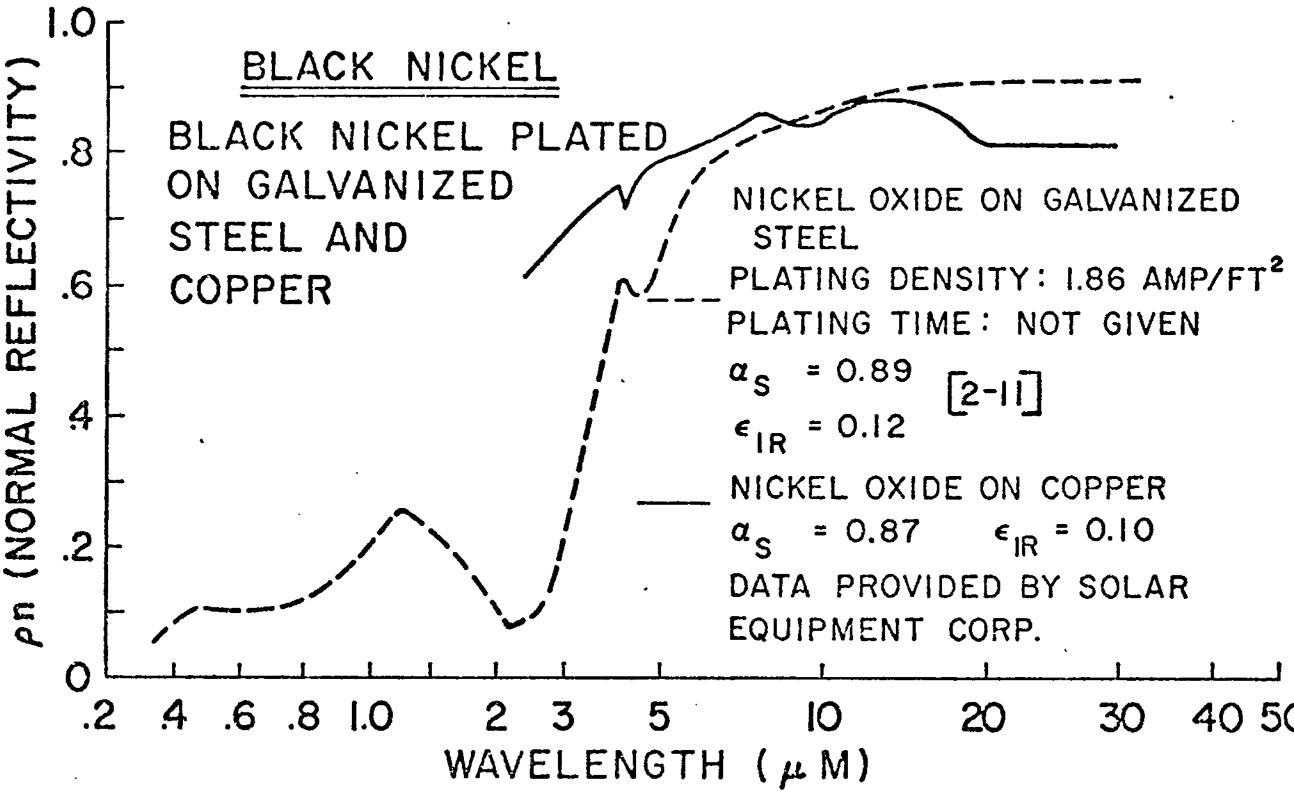


FIG. 2-5B

ABSORBER MATERIAL DATA



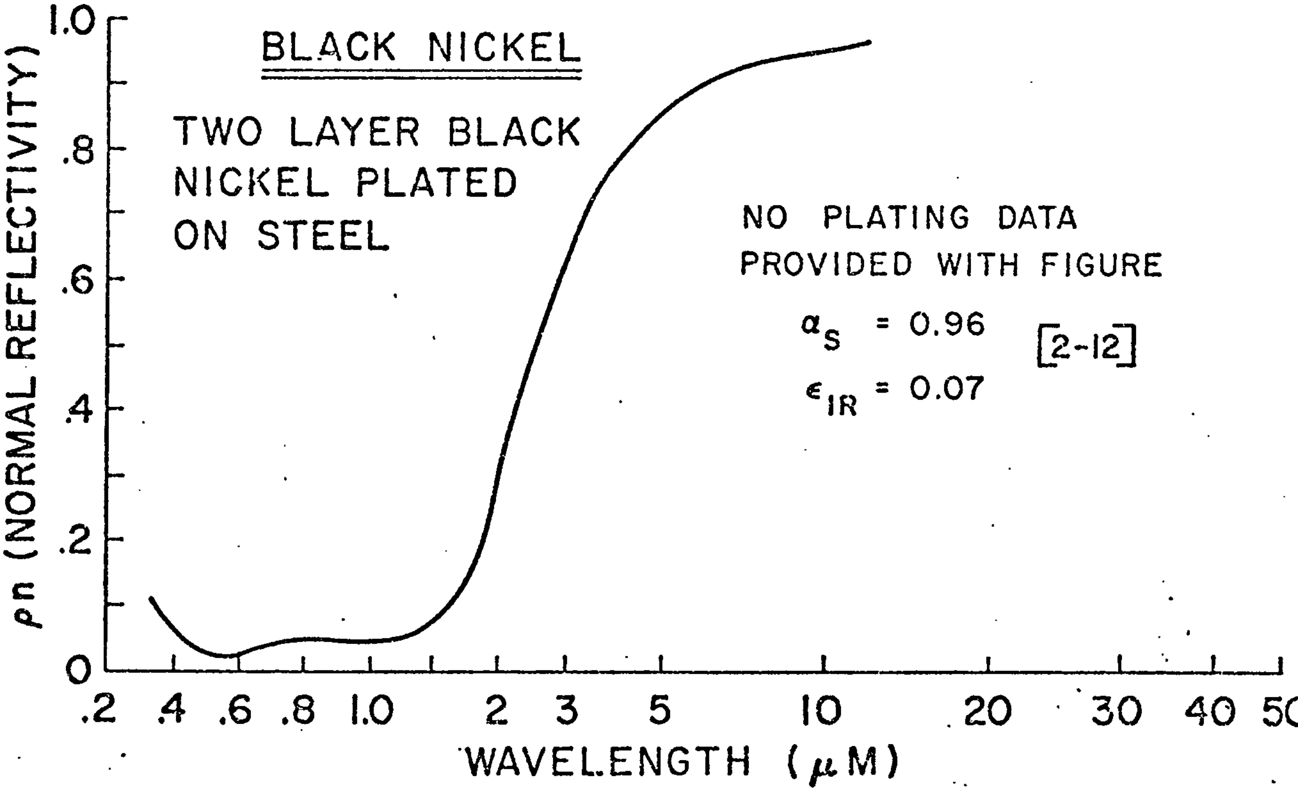
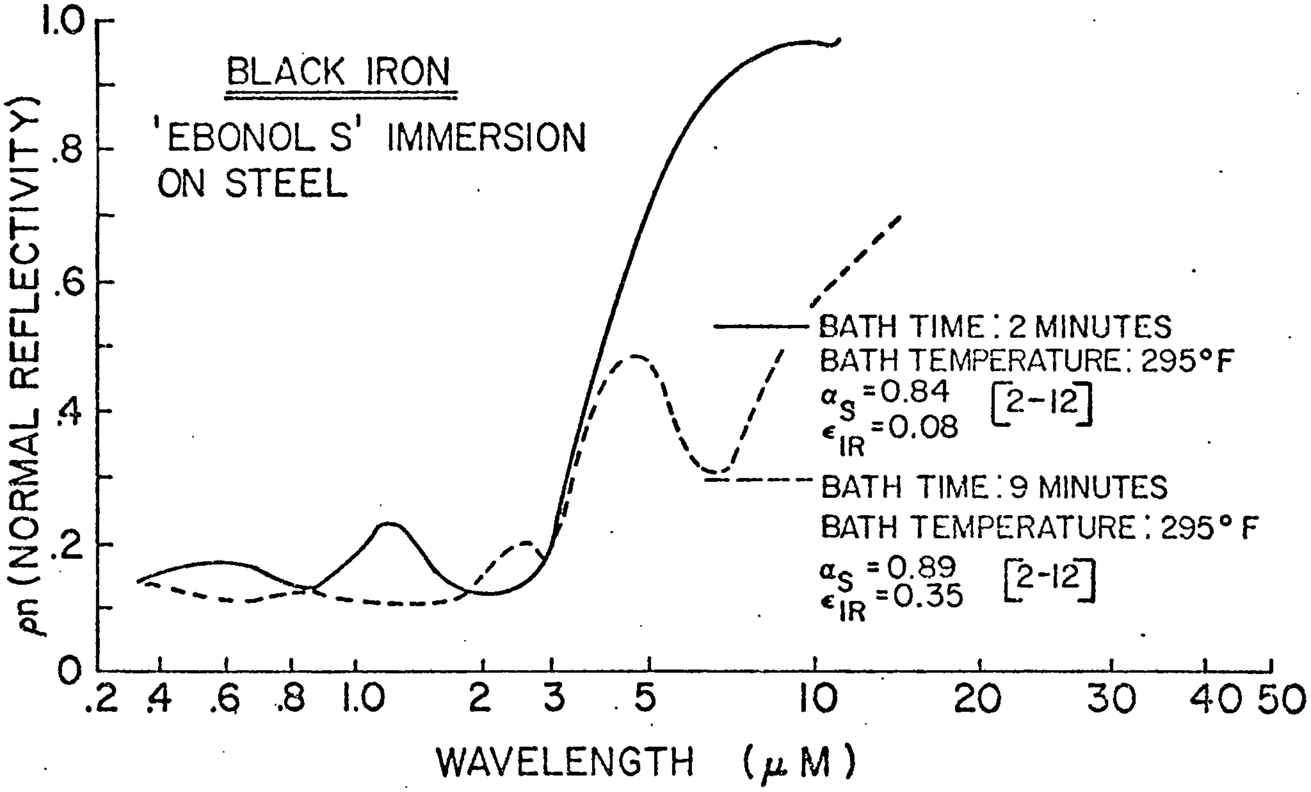


FIG. 2-5C
ABSORBER MATERIAL DATA



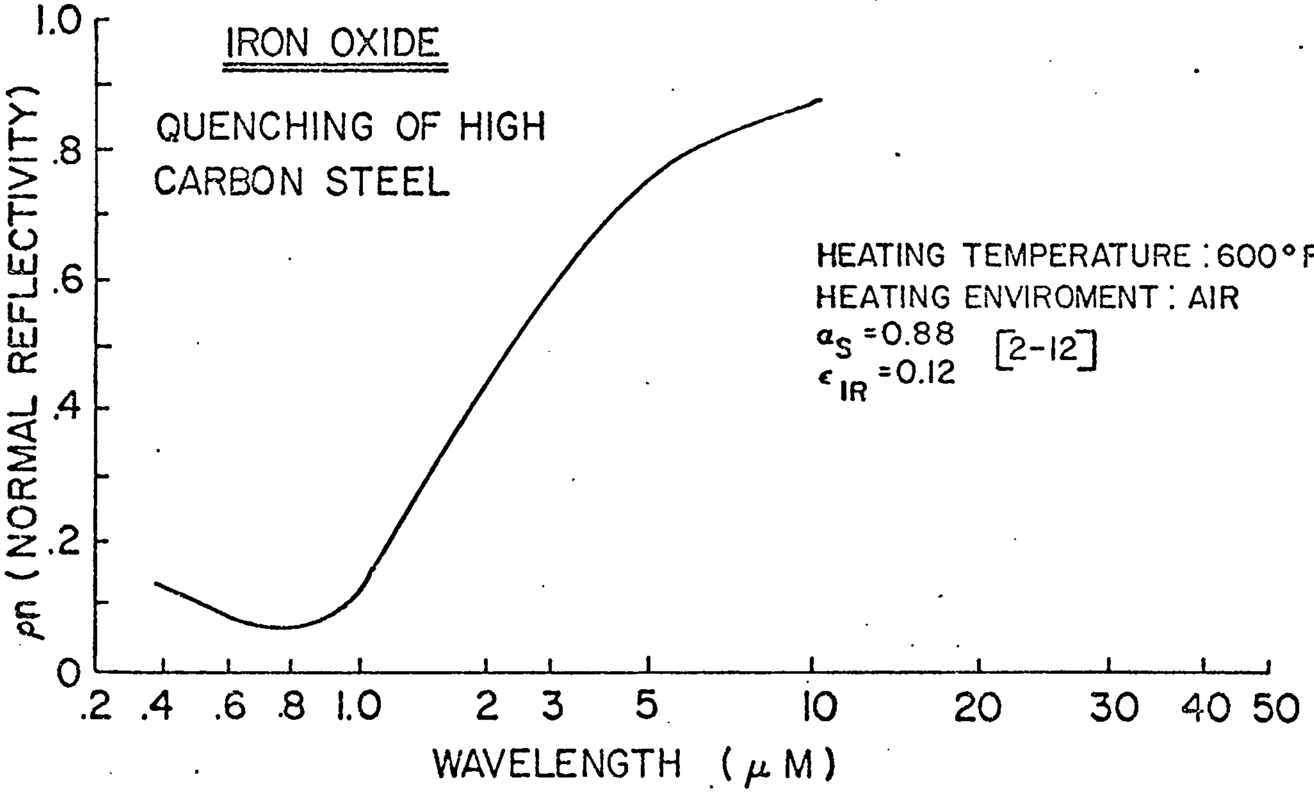
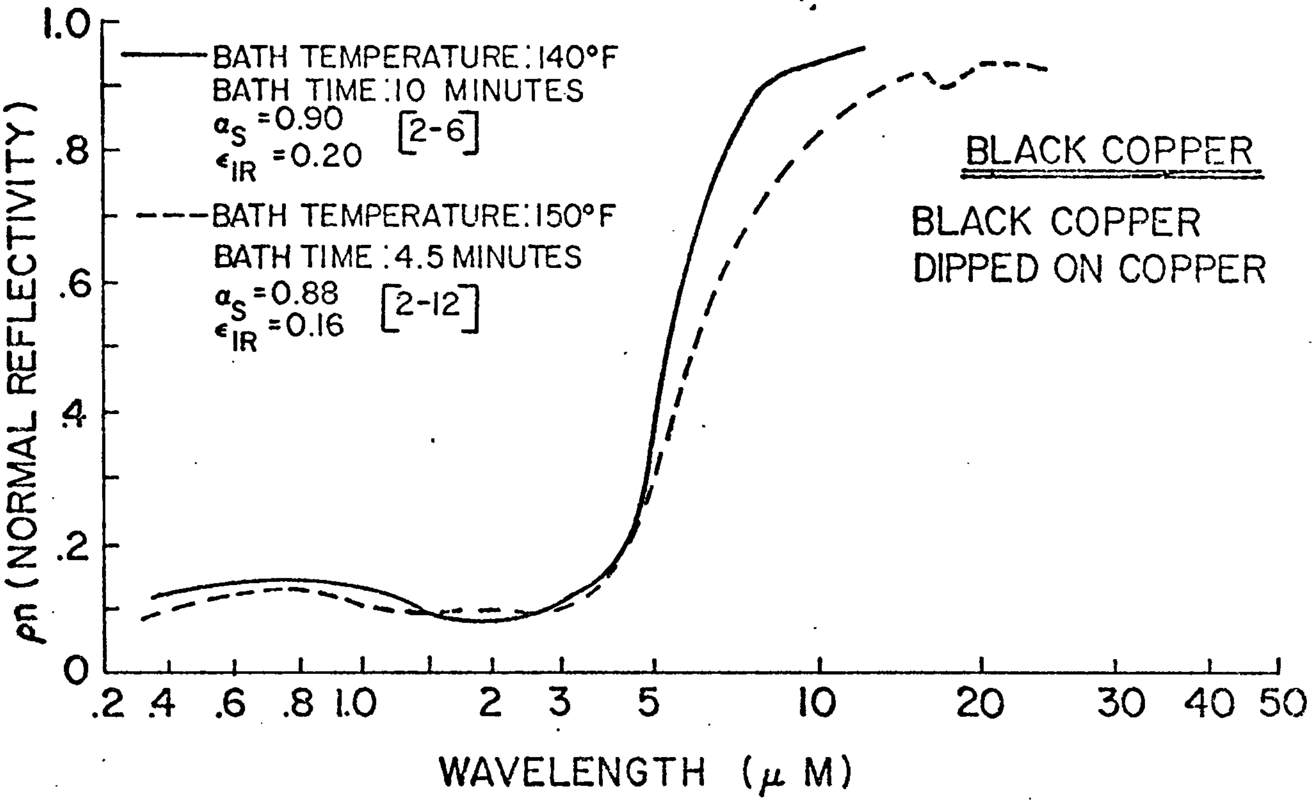
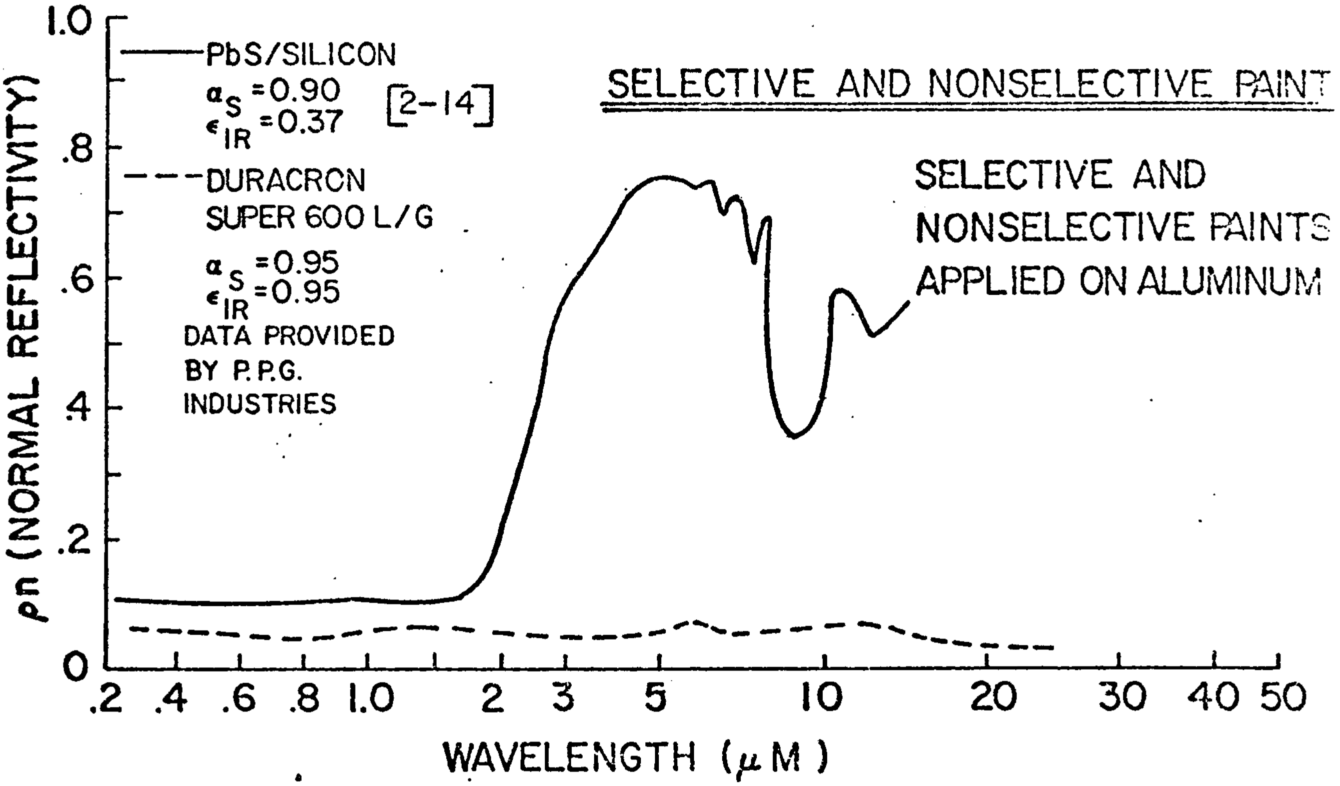


FIG. 2-5D
ABSORBER MATERIAL DATA





With the exception of some of the selective paints and chemical conversion absorbing surfaces, the present cost of utilizing selective surfaces is extremely high. Costs for applying electroplated absorbers are all above one dollar per square foot, which eliminates them from consideration if the current theory that absorber material cost should be limited to less than $0.50 per square foot is used [2-15]. However, the majority of the present cost data represents limited assembly line production for coating panels with absorbing materials. Therefore, estimated future cost data are included in Tables 2-5A, B, and C to point out that significant price reduction for coating absorbing materials may result if the current solar market improves.

As a final note, it should be emphasized that breakthroughs in optimizing the radiative properties of absorber surfaces are providing new absorbing materials for consideration. Work done at Honeywell, Inc., ([2-7], [2-12], [2-13]) and N.A.S.A. Lewis ([2-9], [2-10]) has already significantly improved the radiative properties of black nickel and black chrome. With more careful consideration of bath temperature limits and immersion times, it may be expected that the black copper, copper oxide, iron oxide, and Alcoa black surfaces can be improved so that the solar absorptivities will approach 0.95 [2-13]. In addition, selective paint studies have recently been undertaken by such industries as Honeywell, Inc., and preliminary results as tabulated in the absorber material tables have been favorable. With the low estimated production costs, selective paint absorber radiative

Table 2-5A

ABSORBER MATERIALS: APPLICATION AND COST DATA

MATERIAL	SUBSTRATE	METHOD OF APPLICATION	PRODUCER	PRESENT PRODUCTION COST ($\$/ft^2$)	FUTURE ESTIMATED COST ($\$/ft^2$)
SELECTIVE AND NONSELECTIVE PAINTS					
BLACK ACRYLIC PAINT (AIR DRY)	STEEL ALUMINUM	CLEAN PLATES THOROUGHLY TO REMOVE OXIDATION LAYER. APPLY SUITABLE PRIMER (ZINC CHROMATE: ALUMINUM; IRON OXIDE PRIMER: STEEL). SPRAY ON ACRYLIC AND ALLOW TO DRY IN AIR.	DURACRON PAINT PRODUCER: P.P.G. INDUSTRIES	0.03 - 0.05 (P)	0.03 - 0.05(P)
BLACK ACRYLIC PAINT (THERMOSETTING)	STEEL ALUMINUM	ALUMINUM: CLEAN, DESMUT AND APPLY ALODINE 47-700 PROCESS. SPRAY ACRYLIC AND BAKE FOR 15 - 20 MINUTES AT 375°F. STEEL: DEGREASE, PHOSPHATE AND PRIME (EPOXY PRIMER). SPRAY ACRYLIC AND BAKE FOR EXTENDED TIME AT 375°F UNTIL SURFACE HARDENED.	DURACRON PAINT PRODUCER: P.P.G. INDUSTRIES APPLICATOR: HOWMET CORP.	0.20 -0.25 (P) (HOWMET ESTIMATE)	0.10 - 0.20 (P) (HOWMET ESTIMATE)
SELECTIVE PAINT PbS: PIGMENT SILICON: BINDER	STEEL ALUMINUM	PRECIPITATE PbS CRYSTALS FROM SOLUTIONS. ADD SILICON RESIN TO ATTAIN SOLUTION. SPRAY PAINT ONTO CLEANED PLATE AND DRY FOR ONE HOUR AT 485°F.	EXPERIMENTAL WORK	NOT AVAILABLE	0.03 - 0.10 (H)
SELECTIVE PAINT METEOR - 7890 $Cu\text{-}CrO_x$: PIGMENT EPD[2]: BINDER	STEEL ALUMINUM	MIX PIGMENT WITH BINDER SO THAT PIGMENT HAS 30% VOLUME CONCENTRATION. SPRAY ON CLEANED PLATE AND HEAT TO REMOVE SOLVENTS.	HARSHAW CHEMICAL PRODUCES THE PIGMENT EXXON PRODUCES THE BINDER.	PIGMENT COST 3.00/lb (H) BINDER COST 0.50/lb (H)	0.005 - 0.05 (H)
SELECTIVE PAINT CdTe: PIGMENT EPD[2]: BINDER	STEEL ALUMINUM	FOLLOW SIMILAR PROCEDURE AS IN METEOR - 7890 SELECTIVE PAINT	NO DATA PROVIDED.	PIGMENT COST 30.-100./lb (H) BINDER COST 0.50/lb (H)	0.02 - 0.10 (H)
SELECTIVE PAINT METEOR - 7890 $Cu\text{-}CrO_x$: PIGMENT EPDM[3]: BINDER	STEEL ALUMINUM	FOLLOW SIMILAR PROCEDURE AS IN METEOR - 7890 SELECTIVE PAINT.	HARSHAW CHEMICAL PRODUCES THE PIGMENT EXXON PRODUCES THE BINDER.	PIGMENT COST 3.00/lb (H) BINDER COST NOT GIVEN.	0.005 - 0.05 (H)

1. Cost data considers coating and preparing the panel prior to coating. Transportation and packaging price information are neglected. Cost data is estimated for coating of 10,000 square feet or larger orders. Quotations from the producer are designated by (P). Estimates from Honeywell, Inc. are designated by (H).
2. EPD is abbreviation for Ethylene - Propylene - Diene Polymer.
3. EPDM is abbreviation for Ethylene - Propylene - Diene Material.

Table 2-5B

ABSORBER MATERIALS: APPLICATION AND COST DATA

MATERIAL	SUBSTRATE	METHOD OF APPLICATION	PRODUCER	PRESENT PRODUCTION COST[1] ($/ft²)	FUTURE ESTIMATED COST ($/ft²)
ELECTROPLATED ABSORBER SURFACES					
BLACK CHROME WITH DULL NICKEL	STEEL COPPER	PLATES CLEANED AND THEN PLATED WITH DULL NICKEL (0.0005 INCHES THICK). BLACK CHROME PLATED FOR REQUIRED TIME AT 180 AMPS/ft². PLATE RINSED AND DRIED.	OLYMPIC PLATING INDUSTRIES	1.87 - 10,000ft² 1.65 - 50,000ft² (P) 1.51 - 100,000ft² (COST SAME FOR ANY PLATE TYPE)	0.80 - 1.00 (P) (COST SAME FOR ANY PLATE TYPE) 0.70 - 0.80 (N) (STEEL OR COPPER PLATES)
	ALUMINUM	ALUMINUM ZINCATED AND THEN PLATED WITH COPPER. PROCESS FOR STEEL PLATE FOLLOWED.			
BLACK CHROME	COPPER	COPPER PLATE BUFFED TO REMOVE OXIDATION PRIOR TO PLATING OF BLACK CHROME AT 180 AMPS/ft² FOR REQUIRED TIME.	OLYMPIC PLATING INDUSTRIES	4.00 (P) (ESTIMATE DUE TO BUFFING COSTS)	3.50 (P) (ESTIMATE DUE TO BUFFING COSTS)
	GALVANIZED STEEL	SUBSTRATE PLACED IN DILUTE HYDROCHLORIC - CHROMIC ACID FOR ONE MINUTE TO PRODUCE UNIFORM FILM WHICH IS THEN REMOVED BY CHROMIC ACID. BLACK CHROME IS THEN PLATED FOR REQUIRED TIME AND IS THEN RINSED AND DRIED.	OLYMPIC PLATING INDUSTRIES	NO PRESENT COST DATA SINCE PROCESS NOT COMMERCIALLY NEEDED	BELOW 0.80 (P) BELOW 0.70 (H)
BLACK NICKEL OVER NICKEL	STEEL COPPER	METAL SUBSTRATE CLEANED AND IMMERSED IN ELECTROLYTIC BATH AT 90°F. ELECTROLYSIS CARRIED ON 2 - 4 MINUTES AT REQUIRED CURRENT.	OLYMPIC PLATING INDUSTRIES	1.40 - 10,000ft² 1.24 - 50,000ft² (P) 1.13 - 100,000ft² (COST SAME FOR ANY PLATE TYPE)	0.30 - 0.40 (H) (STEEL OR COPPER)
	ALUMINUM	ALUMINUM ZINCATED AND THEN PLATED WITH COPPER. PROCESS FOR STEEL AND COPPER THEN FOLLOWED.			0.40 - 1.00 (H) (ALUMINUM)
BLACK NICKEL (NICKEL OXIDE)	GALVANIZED STEEL COPPER	METAL SUBSTRATE CLEANED AND IMMERSED IN ELECTROLYTIC BATH AT 90°F. ELECTROLYSIS CARRIED ON 2 -4 MINUTES AT REQUIRED CURRENT DENSITY.	SOLAR EQUIPMENT CORPORATION	0.50 - 0.60 (P) SEE NOTE 2 FOR ADDITIONAL DATA	0.10 - 0.20 (P)

1. Cost data considers plating and preparing the panel prior to plating. Transportation and packaging price information are neglected. Cost data unless indicated otherwise is estimated for plating of 10,000 square feet or larger orders. Quotations from the producer are designated by (P). Estimates from Honeywell, Inc. are designed by (H) and from NASA Lewis are designated by (N).

2. Solar Equipment Corporation sells selectively coated copper sheet and copper coated steel sheet. Price data current through June 1975 and does not include shipping or packaging.

QUANTITY (SQUARE FEET)	COPPER .013" x 24" ($/ft²)	COPPER COATED STEEL .013" x 24" ($/ft²)	ED COPPER .007" x 24" ($/ft²)
10,000+	-	-	0.90
5,000 - 10,000	1.80	0.90	1.08
2,000 - 5,000	2.16	1.08	1.17
1,000 - 2,000	2.34	1.17	1.26
500 - 1,000	2.52	1.26	1.80
UNDER 500	3.20	1.60	(REQUEST)

Table 2-5C

ABSORBER MATERIALS: APPLICATION AND COST DATA

MATERIAL	SUBSTRATE	METHOD OF APPLICATION	PRODUCER	PRESENT[1] PRODUCTION COSTS ($/ft^2)	FUTURE ESTIMATED COST ($/ft^2)
DIP OR CHEMICAL CONVERSION ABSORBER SURFACE					
BLACK COPPER (COPPER OXIDE)	COPPER	CLEAN COPPER SURFACE TO ATTAIN BRIGHT SURFACE. IMMERSE PANEL IN EBONOL-C BATH FOR BETWEEN 3 AND 13 MINUTES. RINSE AND DRY.	ENTHONE INC.	0.25 - 0.50 (P) SEE NOTE 2 FOR ADDITIONAL DATA	0.10 (H)
COPPER OXIDE	ALUMINUM	ALUMINUM COVERED WITH OXIDE LAYER BY ANODIZING. AFTER RINSING, PLATE IS IMMERSED IN SOLUTION CONTAINING COPPER NITRATE AND POTASSIUM PERMANGATE FOR 15 MINUTES. PLATE DRIED AND HEATED AT 850°F UNTIL SURFACE BLACKENS	NO DATA AVAILABLE ON COMMERCIAL PRODUCER	NO DATA AVAILABLE SINCE NO PRODUCTION WORKUPS	0.10 (H)
BLACK IRON (IRON OXIDE)	STEEL	CLEAN STEEL WITH DILUTE HCl BATH. IMMERSE STEEL INTO CAUSTIC EBONOL S SOLUTION AT 295°F FOR PRESCRIBED TIME. RINSE AND DRY.	ENTHONE INC.	0.25 - 0.50 (P) (ESTIMATED BY ENTHONE)	0.05 - 0.15(H)
IRON OXIDE	STEEL	HEAT HIGH CARBON STEEL TO 550° - 600°F IN AIR UNTIL STEEL TURNS DARK BLUE. FOLLOW WITH QUENCHING IN WATER. DRY IN AIR.	INDUSTRIAL PROCESS DATA	NO COST DATA AVAILABLE	NO COST DATA AVAILABLE
ALCOA BLACK	ALUMINUM	ALCOA 655 PROCESS (PROPRIETARY) EMPLOYED. THOROUGHLY CLEAN ALUMINUM AND DESMUT AND USE ALODINING PROCESS. PLACE PANEL IN BATH AND ALLOW CHEMICAL CONVERSION PROCESS TO RESULT. REMOVE, RINSE AND DRY IN AIR.	ALUMINUM COMPANY OF AMERICA	0.30 - 0.50 (P)	0.25 - 0.30(P)

1. Cost data considers coating and preparing the panel prior to coating. Transportation and packaging price information are neglected. Cost data unless otherwise indicated is estimated for coating of 10,000 square feet or larger orders. Quotations from the producer and designated by (P). Estimates from Honeywell, Inc. are designated by (H) and from Nasa Lewis are designated by (N).

2. Sunworks Inc. of Guilford, Connecticut will market entire flat plate collector assemblies and selectively coated absorber plates. (21" x 90" Available Plate) composed of copper sheet with silver solder connected copper tubing. For purchases of 1 - 10 plates, estimated costs are (excluding packaging and shipping) $6.00 per square foot. For 11-100 plates, estimated costs are $5.00 per square foot. For 101 - 1000 plates, estimated costs are $4.50 per square foot.

property improvement may make the use of solar flat-plate technology feasible from an economic and performance standpoint.

INSULATION MATERIALS

The back surface of the collector absorber plate should be thermally insulated to minimize the amount of heat lost to the collector housing. In the construction industry, many insulation materials are available that can be utilized in the collector assembly for reducing these heat losses. These materials may be divided into four major groups: fiberglass, foamglas, mineral wool, and industrial felt.* Technical and economic data is presented for these materials in Tables 2-6A, B, and C. The federal specification numbers are included in these tables for the various materials to provide further reference data. Additional technical data can also be obtained from <u>Thermal Insulation</u> by Malloy. This text is considered to be the best single reference on insulation performance data [2-16].

In addition to reducing the heat loss during normal operation, the insulation should be selected or designed to withstand the high temperature which will occur under conditions of no heat removal (e.g., no flow of the heat transfer fluid). Since optimal

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*The following insulations are registered trademark names.

Fiberglas(R) - Owens-Corning (fiberglass)

Foamglas(R) - Pittsburgh Corning (foamglas)

MT Board(R) - Eagle-Picher (mineral wool)

Thermafiber(R) - United States Gypusm (industrial felt)

The trademark designation ((R)) is omitted in the text for the above materials.

Table 2-6A

MINERAL WOOL: INSULATION DATA[3]

Material	Nominal Density (lb/ft³)	Temperature Limitation (°F)	Mean Temperature Thermal Conductivity (°F)	(BTU-IN)/(HR-FT²-F)[4]	Federal Specification Compliance	Producer	Standard Sizes (variable)	Cost[1] ($/BD-FT)
#10 Insulation	10.0	1200°	200° 350° 500°	0.26 0.32 0.375	HH-I-558 B Form A, Class 4	Forty-Eight Insulations	2' × 4' (Board) THK: 1"-3" (1/2" inc)	0.125-0.14 (DIST)[2] Carload: 30,000 BD FT
ETR Insulation	8.0	1000°	200° 350° 500°	0.27 0.32 0.385	HH-I-558 B Form A, Class 4	Forty-Eight Insulations	2' × 4' (Board) THK: 1"-4" (1/2" inc)	0.105-0.115 (DIST) Carload: 30,000 BD FT
I-T Insulation	6.0	850°	200° 350° 500°	0.27 0.34 0.45	HH-I-558 B Form A, Class 3	Forty-Eight Insulations	2' × 4' (Board) THK: 1"-4" (1/2" inc)	0.095-0.10 (DIST) Carload: 30,000 BD FT
MT-BOARD (MT-10)	10.0	1050°	200° 350° 500°	0.25 0.333 0.445	HH-I-558 B Form A, Class 1,2,3	Eagle-Picher	2' × 4' (Board) THK: 1"-3" (1/2" inc)	0.13-0.14 (DIST) Carload: 36,000 BD FT
MT-BOARD (MT-8)	8.0	1050°	200° 350° 500°	0.255 0.350 0.470	HH-I-558 B Form A, Class 1,2,3	Eagle-Picher	2' × 4' (Board) THK: 1"-4" (1/2" inc)	0.107-0.12 (DIST) Carload: 36,000 BD FT
MT-BOARD (MT-6)	6.0	1050°	200° 350° 500°	0.270 0.373 0.495	HH-I-558 B Form A, Class 1,2,3	Eagle-Picher	2' × 4' (Board) THK: 1"-4" (1/2" inc)	0.085-0.10 (DIST) Carload: 36,000 BD FT

1: Cost data current through October 30, 1975. Costs are based on carload purchases and include freight where necessary to move insulation to Houston.

2: Cost from Houston distributors noted by (DIST).

3: All insulations listed will not cause or aggravate corrosion and will absorb less than 1% moisture. All insulations listed appear as semi-rigid board which are composed of silica base refractory fibers bonded with special binders for service in indicated temperature ranges.

4: Units are consistently employed within the insulation industry. Conductivity measurements consider a test specimen one inch thick and one square foot normal area.

Table 2-6B

INDUSTRIAL FELT: INSULATION DATA[3]

Material	Nominal Density (lb/ft^3)	Temperature Limitation (°F)	Mean Temperature Thermal Conductivity (°F)	(BTU-IN)/(HR-FT^2-F)[5]	Federal Specification Compliance	Producer	Standard[4] Sizes (variable)	Cost[1] ($/BD FT)
THERMAFIBER (SF-234)	8.0	1000°	200° 350° 500°	0.27 0.36 0.48	HH-I-558 B Form A, Class 1,2,3	United States Gypsum	THK: 1"-2" (NJ) Length: 60" THK: 1"-2½" (IND) Length: 48"	0.131 (DIST)[2] 7,000-38,000 BD FT
THERMAFIBER (SF-240)	6.0	1000°	200° 350° 500°	0.27 0.37 0.50	HH-I-558 B Form A, Class 1,2,3	United States Gypsum	THK: 1"-2½" (TEX) Length: 90" THK: 1"-3½" (IND) Length: 48"	0.095-0.113 (DIST) 7,000-38,000 BD FT
THERMAFIBER (SF-250)	4.5	800°	200° 350° 500°	0.29 0.415 0.55	HH-I-558 B Form A, Class 1,2	United States Gypsum	THK: 1"-4" (TEX) Length: 90" THK: 1"-5" (IND) Length: 48"	0.081-0.10 (DIST) 7,000-38,000 BD FT
THERMAFIBER (SF-252)	4.0	800°	200° 350° 500°	0.30 0.435 0.59	HH-I-558 B Form A, Class 1,2	United States Gypsum	THK: 1"-4" (TEX) Length: 90" THK: 1"-5" (IND) Length: 48"	0.07-0.087 (DIST) 7,000-38,000 BD FT
THERMAFIBER (SF-256)	3.5	600°	200° 350° 500°	0.33 0.47 0.62	HH-I-558 B Form A, Class 1,2	United States Gypsum	THK: 1"-4" (TEX) Length: 90" THK: 1"-6" (IND) Length: 48"	0.066-0.084 (DIST) 7,000-38,000 BD FT
THERMAFIBER (SF-260)	3.0	500°	200° 350° 500°	0.35 0.50 0.65	HH-I-558 B Form A, Class 1,2	United States Gypsum	THK: 1"-4" (TEX) Length: 90" THK: 1"-6" (IND) Length: 48"	0.064-0.082 (DIST) 7,000-38,000 BD FT
THERMAFIBER (SF-270)	2.5	400°	200° 350° 500°	0.39 0.56 ----	No Data Provided	United States Gypsum	THK: 1"-4" (TEX) Length: 90" THK: 1"-5" (IND) Length: 48"	0.06-0.078 (DIST) 7,000-38,000 BD FT

1: Cost data current through October 30, 1975. Costs are based on carload purchases and include freight where necessary to move insulation to Houston. Low price quotation for insulation from Texas facility. High price quotation for insulation from Indiana facility.

2: Cost from Houston distributors noted by (DIST).

3: Industrial felt is pre-formed mineral fiber felt which will not cause or sustain corrosion. It absorbs less than 1% moisture by weight and is rated noncombustible.

4: Insulation to be ordered in varying thicknesses and lengths. Standard width of 24" employed.

5: Units are consistently employed within the insulation industry. Conductivity measurements consider a test specimen one inch thick and one square foot normal area.

Table 2-6C

FOAMGLAS AND FIBERGLAS: INSULATION DATA

Material Name	Nominal Density	Temperature Limitation	Mean Temperature Thermal Conductivity		Specification Compliance[1]	Producer	Standard Sizes	Cost[2]
	(lb/ft^3)	(°F)	(°F)	(BTU-IN)/(HR-FT-°F)[6]			(variable)	($/BD FT)
FOAMGLAS[4]	8.5	600°	200° 350° 500°	0.46 0.58 0.74	HH-I-551D (FED) ASTMC 552-73	Pittsburgh Corning	1' × 1.5' (Board) 1½' × 2' (Board) THK: 1½"-4" (½" inc)	0.22-0.24[3] (Corning) Carload: 36,000 BD FT
701 FIBERGLAS[5]	1.6	450°	200° 350°	0.33 0.51	HH-I-558B Form A, Class 1 HH-I-558B, Type 1 Form B, Class 7	Owens-Corning Fiberglas	2' × 4' (Board) THK: 1½"-4" (½" inc)	0.07-0.08 (DIST) Carload: 30,000-35,000 BD FT
703 FIBERGLAS[5]	3.0	450°	200° 350°	0.30 0.41	HH-I-558B Form A, Class 1,2	Owens-Corning Fiberglas	2' × 4' (Board) THK: 1"-2" (½" inc)	0.14-0.15 (DIST) Carload: 30,000-35,000 BD FT
705 FIBERGLAS[5]	6.0	450°	200° 350°	0.27 0.38	HH-I-558B Form A, Class 1,2	Owens-Corning Fiberglas	2' × 4' (Board) THK: 1"-2" (½" inc)	0.25-0.27 (DIST) Carload: 30,000-35,000 BD FT
THERMAL INSULATING WOOL TYPE I[5]	1.25	1000°	200° 350° 500°	0.41 0.65 0.85	HH-I-558B Form B, Type 1, Class 8	Owens-Corning Fiberglas	Rolls Width: 2' or 3' THK: 2",3",4" Length: 76',52',38'	0.04-0.06 (Corning) ½ Carload: 35,000 BD FT
THERMAL INSULATING WOOL TYPE II[5]	2.4	1000°	200° 350° 500°	0.30 0.44 0.60	HH-I-558B Form B, Type 1, Class 7,8	Owens-Corning Fiberglas	2' × 8' 2' × 4' (Board) THK: 1"-3" (½" inc)	0.08-0.09 (Corning) 0.14-0.15 (DIST) Carload: 35,000 BD FT
IS BOARD[5]	4.0	800°	200° 350° 500°	0.30 0.44 0.61	HH-I-558B Form A, Class 3	Owens-Corning Fiberglas	2' × 4', 3' × 4' 4' × 8' (Board) THK: 1"-6" (½" inc)	0.10-0.13 (Corning) 0.18-0.20 (DIST) Carload: 35,000 BD FT

1: All codes are federal specifications unless otherwise noted.

2: Cost data current through October 30, 1975. Costs are based on carload sizes indicated and include freight where necessary to move insulation to Houston.

3: Cost from corning Houston warehouse noted by (Corning). Cost from Houston distributor noted by (DIST).

4: Foamglas is an impermeable, incombustible, rigid insulation composed of completely sealed glass cells with no binder material. Its rigid form may allow for foamglas being implemented as the collector box.

5: Insulations are made of inorganic glass fibers preformed into semi-rigid to rigid rectangular boards (TlW I in blankets). Insulations will not accelerate nor cause corrosion and will absorb less than 1% moisture (by volume).

6: Units are consistently employed within the insulation industry. Conductivity measurements consider a test specimen one inch thick and one square foot normal area.

cover materials and absorber materials are being considered to provide heat for space cooling, the no load condition would probably result in the absorber surface reaching temperatures in excess of 350°F under typical summer weather conditions. Thus, the low temperature urethane and polystyrene insulations can not be considered for use and are therefore omitted from the tables. In fact, all insulation materials provided in Tables 2-6A, B, and C are considered to be intermediate temperature (300°F through 1000°F) insulations.

The angle of the collector assembly dictates that the insulation should not settle or compact near the bottom, which is the case with loose or poured insulations. The settling of the insulation would decrease the efficiency of the collector by increasing the heat loss from the absorber plates. In fact, insulation distributors recommend adhering or at least pinning the insulation boards or blankets to the absorber panel in order to insure that the insulation can optimally reduce back heat losses. It should also be noted that a loose insulation would not be desireable during repair or maintenance operations.

The cost data provided are based on carload purchases from the distributor or directly from the warehouses and factories where the insulations are produced. The prices quoted include freight charges where necessary to move the material to Houston, Texas. (For a rough estimate of freight charges, B&B Distributors of Houston quoted a charge of $1.10 per hundred pounds weight of insulation for carload - 30,000 - 40,000 board feet - quantities). In terms of cost, the industrial felts and fiberglasses listed are the most inexpensive. However, these materials also are the lower density - higher thermal conductivity insulations, and thus greater thicknesses are required in limiting back heat loss than for the mineral wools. As can be seen, thickness, weight, cost, and performance requirements must be considered in the analysis for optimal insulation material selection for flat-plate collector usage.

As a final note, foamglas insulation may provide the dual functions of insulation and housing. Foamglas is an impermeable, incombustible, rigid insulation composed of completely sealed glass cells with no binder material. Because of its physical properties, foamglas can be used to support the absorber panel and one or two cover plates [2-17]. While the cost of foamglas used as an insulation alone may be excessive compared to that of fiberglass, consideration of the savings which result by not having to build or purchase an assembled collector housing may justify using this rigid insulating material.

COMPUTER CODING

The various cover, absorber, and insulation materials presented earlier can be used to design optimal flat-plate solar collectors for heating, cooling, hot water production, or even steam production uses. Analysis of material durability, cost, and performance properties is required for this design process. Thus, the material data tabulated should be more concisely coded than has been previously shown.

As stated in the introductory chapter, the flat-plate solar collector consists of five components. Two of these, the collector housing and the collector panel, have not been previously discussed. This is because both components will be treated as design constants for the analysis (i.e., a fixed housing and collector panel type will be chosen prior to consideration of absorber, cover, and insulation material options). For the analysis, the housing will be considered to be a separate component (i.e., foamglas will be considered as an insulation material only). Sheet metal housings for modular collectors can be assembled to any dimensions specified, and thus a cost per square foot can be applied independent of the design. It has been estimated ([2-18]) that if sheet metal housings are produced in quantities of 100,000 square feet per year, costs of $0.69 per square foot can be used. (This cost estimate is based on June

1974 labor and material costs.) Since the estimated housing cost is constant regardless of the collector assembly makeup, it will not be included in the total cost calculations.

Different absorber panel configurations were analyzed prior to selection of one type of panel for the study. The basic types of panels considered are: (1) the bonded panel, (2) the extruded panel, and (3) the tube and sheet panel., The latter two panel designs are rejected for the following reasons:

Extruded Panels:

Work done with the Reynolds Aluminum extruded panel indicated that the design is not rigid enough to prevent bending of the panel. Buckling of the absorber plate led to poor contact of the plate with the insulation. In addition, the panel came in contact with the cover plate because of the bending. Both aspects impaired the efficiency of the Reynolds Torex-14 solar collector [2-19].

Tube and Sheet Panels:

Since no company manufactured tube and sheet panels for sale (except when entire collector assemblies are purchased), cost of producing such absorber plates was difficult to estimate. Labor costs fluctuated so greatly depending upon what types of sheet and tube combinations were employed, that cost estimates had to be arbitrarily made. In addition, Whillier [2-20] indicated that the contact between tube and sheet is critical for maximum heat transfer to the working fluid. Questions pertaining to the loss of efficiency were found to depend upon the workmanship.

The bonded panel has therefore been selected for use in the flat-plate design analysis. Olin Brass panels are used in the study, since they are commercially available in large quantities. In addition, the copper and aluminum Olin Brass panels have been extensively employed in solar work and have had excellent durability and life cycle records. Olin Brass produces standard sized panels and will also custom build panels depending upon the quantities ordered. Since the materials shown in the previous discussions vary so in available size, the ability to design different sized collector panels cannot be understated. For the analysis, Table 2-7 gives cost and weight data for representative copper and aluminum panels as provided by Olin Brass.

Table 2-7

OLIN BRASS ABSORBER PANELS

Material	Size	Weight		Cost/Quantity (250 Panels)	
		lb./panel	lb./sq. ft	\$/panel	\$/sq. ft
Alloy 122 Copper	22" × 96"	22.29	1.86	62.00	3.58
Alloy 1100 Aluminum	22" × 96"	12.42	0.847	19.36	1.32

Coded data for the cover plate, absorber, and insulation materials is found in Tables 2-8, 2-9, and 2-10 respectively. The majority of the data is self explanatory. Discussion on durability of absorber materials and weatherability and impact resistance for cover materials is required, however, since an arbitrary coding procedure has been used.

In attempting to analyze the data with respect to durability, impact resistance, and weatherability, questions arose as to the

Table 2-8

CODED DATA FOR COVER PLATE MATERIALS

Material Name	Cover Designation	Index of Refraction	τ_{vis}	τ_{IR}	Temperature Limit (°F)	Weather Code[1]	Impact Code[2]	Weight (lb./SQ. FT)	Cost ($/SQ. FT)
4 mil Tedlar P.V.F.	CP-1	1.46	0.922	0.207	225°	4.0	3.3	0.029	0.19
5 mil F.E.P. Teflon	CP-2	1.343	0.923	0.257	400°	4.2	3.6	0.056	0.693
5 mil Mylar-'S'	CP-3	1.64	0.869	0.178	300°	1.0	3.6	0.036	0.085
25 mil Sunlite Reg.	CP-4	1.54	0.875	0.033	140°	2.0	2.0	0.175	0.35
40 mil Sunlite Reg.	CP-5	1.54	0.853	0.008	140°	2.0	2.5	0.294	0.38
25 mil Sunlite Prem.	CP-6	1.54	0.865	0.076	200°	4.0	2.0	0.175	0.41
40 mil Sunlite Prem.	CP-7	1.54	0.843	0.027	200°	4.0	2.5	0.294	0.48
125 mil Plate Glass	CP-8	1.518	0.843	0.02	500°	4.3	1.5	1.62	0.33
125 mil Temper Glass	CP-9	1.518	0.843	0.02	500°	4.8	2.7	1.62	0.64
187 mil Plate Glass	CP-10	1.518	0.795	0.01	500°	4.5	1.8	2.45	0.485
187 mil Temper Glass	CP-11	1.518	0.795	0.01	500°	5.0	3.0	2.45	0.58
63 mil Plexiglas G	CP-12	1.49	0.907	0.03	200°	3.0	2.5	0.375	1.14
125 mil Plexiglas G	CP-13	1.49	0.896	0.02	200°	3.0	3.0	0.75	1.22
187 mil Plexiglas G	CP-14	1.49	0.881	0.01	200°	3.0	4.0	1.10	1.45
63 mil Lucite A.R.	CP-15	1.49	0.907	0.03	200°	3.0	2.6	0.375	1.86
125 mil Lucite A.R.	CP-16	1.49	0.896	0.02	200°	3.2	3.5	0.75	1.90
187 mil Lucite A.R.	CP-17	1.49	0.881	0.01	200°	3.3	4.1	1.10	2.11
63 mil Polyglaz	CP-18	1.586	0.865	0.03	260°	3.0	3.6	0.39	1.05
125 mil Polyglaz	CP-19	1.586	0.841	0.02	260°	3.1	4.2	0.78	1.90
187 mil Polyglaz	CP-20	1.586	0.827	0.01	260°	3.2	4.8	1.17	2.76

Table 2-8 (Continued)

CODED DATA FOR COVER PLATE MATERIALS

Material Name	Cover Designation	Index of Refraction	τ_{vis}	τ_{IR}	Temperature Limit (°F)	Weather Code[1]	Impact Code[2]	Weight (lb./SQ. FT)	Cost ($/SQ. FT)
63 mil Lexan MR-4000	CP-21	1.586	0.865	0.03	260°	3.0	3.8	0.39	1.23
125 mil Lexan MR-4000	CP-22	1.586	0.841	0.02	260°	3.2	4.5	0.78	2.47
187 mil Lexan MR-4000	CP-23	1.586	0.827	0.01	260°	3.3	5.0	1.17	3.56
125 mil Clear Glass	CP-24	1.51	0.875	0.02	400°	4.3	1.5	1.63	0.33
125 mil Clear Temper	CP-25	1.51	0.875	0.02	400°	4.8	2.7	1.63	0.55
187 mil Clear Glass	CP-26	1.51	0.875	0.01	400°	4.5	1.8	2.51	0.485
187 mil Clear Temper	CP-27	1.51	0.855	0.01	400°	5.0	3.0	2.51	0.58
125 mil Sunadex Glass	CP-28	1.50	0.915	0.02	400°	4.8	2.7	1.61	0.83
156 mil Sunadex Glass	CP-29	1.50	0.910	0.02	400°	4.9	2.8	2.03	0.93
187 mil Sunadex Glass	CP-30	1.50	0.905	0.01	400°	5.0	3.0	2.41	1.03
219 mil Sunadex Glass	CP-31	1.50	0.90	0.01	400°	5.0	3.2	2.81	1.17

1: Weather Code

1.0 = No weather resistance. Degrades rapidly under chemical environment.
2.0 = U.V. degradation limits solar lifetime to under seven years.
3.0 = 5 to 7% decrease in τ_{vis} over ten years. Good chemical resistance.
4.0 = Effective weathering life of twenty years. Superior chemical resistance.
5.0 = Effective weathering life of thirty years. No chemical degradation over lifetime.

2: Impact Code

1.0 = No wind load resistance. Impact strength minimal.
2.0 = Effective impact strength of 25 mil sunlite.
3.0 = Effective resistance of 187 mil tempered glass.
4.0 = Effective resistance of 187 mil plexiglas G.
5.0 = Warranteed against impact breakage.

Table 2-9

CODED DATA FOR ABSORBER MATERIALS

Material Name	Absorber Specification	α_s	ϵ_{IR}	Temperature Limit (°F)	Durability Code[1]	Present Cost ($/SQ. FT)	Future Projected Cost ($/SQ. FT)
Black Chrome over Nickel (30 sec. plate)	C-1	0.87	0.06	700.0	4.8	1.87	0.75
Black Chrome over Nickel (1 min. plate)	C-2	0.96	0.10	700.0	5.0	1.87	0.75
Black Nickel over Nickel	C-3	0.96	0.07	550.0	3.2	1.40	0.35
Black Nickel (Solar E)	C-4	0.87	0.10	400.0	2.5	0.55	0.15
Black Copper of Enthone	C-5	0.90	0.12	375.0	3.0	0.375	0.10
Duracron Thermosetting Acrylic Paint	A-1	0.95	0.95	350.0	4.6	0.225	0.15
Duracron Air-Drying Acrylic Paint	A-2	0.95	0.95	350.0	4.2	0.05	0.03
Meteor 7890 Selective Paint (.05 mil)	A-3	0.92	0.30	350.0	4.3	0.05	0.03
Meteor 7890 Selective Paint (.21 mil)	A-4	0.95	0.47	350.0	4.5	0.05	0.03
Black Chrome over Nickel (30 sec. plate)	A-5	0.87	0.06	700.0	4.8	1.87	0.90
Black Chrome over Nickel (1 min. plate)	A-6	0.96	0.10	700.0	5.0	1.87	0.90
Black Nickel over Nickel	A-7	0.96	0.07	550.0	3.2	1.4	0.70
Alcoa Black	A-8	0.90	0.35	350.0	2.8	0.40	0.25

1: Durability Code:

1.0 = No resistance to environment (requires vacuum).
3.0 = Stable coating except under water impingement.
5.0 = Coating maintains integrity under weathering extremes.

Table 2-10

CODED DATA FOR INSULATION MATERIALS

Material Name	Insulation Specification	Thermal Conductivity[1]			Density	Temperature Limit	Cost
		at 200°	at 350°	at 500°	(#/CU-FT)	(°F)	($/BD-FT)
#10 Mineral Wool	INS-1	0.0217	0.0267	0.0313	10.	1200.	0.13
ETR Board	INS-2	0.0225	0.0267	0.0321	8.	1000.	0.11
IT Insulation	INS-3	0.0225	0.0283	0.0375	6.	850.	0.10
MT-10 Mineral Wool	INS-4	0.0208	0.0278	0.0371	10.	1050.	0.13
MT-8 Mineral Wool	INS-5	0.0212	0.0292	0.0392	8.	1050.	0.11
MT-6 Mineral Wool	INS-6	0.0225	0.0311	0.0412	6.	1050.	0.09
SF-234 Felt	INS-7	0.0225	0.030	0.040	8.	1000.	0.131
SF 240 Felt	INS-8	0.0225	0.0308	0.0417	6.	1000.	0.104
SF 250 Felt	INS-9	0.0242	0.0346	0.0458	4.5	800.	0.09
SF-252 Felt	INS-10	0.0250	0.0362	0.0492	4.	800.	0.079
SF-256 Felt	INS-11	0.0275	0.0392	0.0517	3.5	600.	0.075
SF-260 Felt	INS-12	0.0292	0.0417	------	3.	500.	0.073
SF-270 Felt	INS-13	0.0235	0.0467	------	2.5	400.	0.069
Foamglas	INS-14	0.0383	0.0483	0.0617	8.5	600.	0.22
IS Board	INS-15	0.025	0.0367	0.0508	4.	850.	0.13
TIW Type II	INS-16	0.025	0.0367	0.050	2.4	1000.	0.085
TIW Type I	INS-17	0.0342	0.0542	0.0667	1.25	1000.	0.06
705 Fiberglas	INS-18	0.0225	0.0317	------	6.	450.	0.26
703 Fiberglas	INS-19	0.025	0.0342	-------	3.	450.	0.145
701 Fiberglas	INS-20	0.0275	0.0425	-------	1.6	450.	0.075

1: Units on mean thermal conductivity are BTU/HR-FT-F.

accuracy of the data provided by the companies contacted. This was primarily due to the testing procedures employed (as has been discussed earlier). Also, several of the companies measured mechanical properties and weatherability differently, and therefore the data proved difficult to compare. With respect to the properties of durability, weatherability, and impact resistance, then, an arbitrary ranking system was set up, whereby the materials could be compared against one another and assigned figures of merit. For weatherability and impact resistance properties of cover materials, two codes based on scales of one to five are selected. The codes can be found for these two properties in Table 2-8 along with the coded values for the various cover materials. The durability code for absorber materials is also based on a scale of one to five and can be found in Table 2-9.

Radiative properties of normal transmissivity and absorptivity are listed for covers and absorber materials in Tables 2-9 and 2-10 respectively. It was decided to use the transmission data obtained from ASTM E-424 test procedure, since these values are more commonly accepted in industry and literature work. Using Kirchhoff's law, normal reflectivity for absorber materials can be obtained using equation (2.11a,b)

$$1.0 - \alpha_S = \rho_S \tag{2.11a}$$

$$1.0 - \varepsilon_{IR} = \rho_{IR} \tag{2.11b}$$

For cover materials, Kirchhoff's law must include the transmissivity term.

$$\alpha_S + \rho_S + \tau_S = 1.0 \tag{2.12a}$$

$$\varepsilon_{IR} + \rho_{IR} + \tau_{IR} = 1.0 \tag{2.12b}$$

Since only τ_s and τ_{IR} are tabulated, it appears that α_s, ρ_s, ε_{IR}, and ρ_{IR} cannot be solved for. However, using electromagnetic theory for dielectrics [2-5], a one surface reflected fraction of radiation in air can be written using equation (2.13).

$$r = \left(\frac{n_i - 1}{n_i + 1}\right)^2 \tag{2.13}$$

where

n_i = the refractive index of the cover material which the radiation is incident on.

Equation (2.13) assumes normal incidence.

Using a ray tracing technique shown in work by Siegel [2-21], a total (two surface) reflectivity for the incident radiation can be found by using (2.14)

$$\rho_{total} = r[1 + (1 - r)^2\tau^2/(1 - r^2\tau^2)] \tag{2.14}$$

where

τ = transmissivity of the cover material

r = the one surface reflected fraction of incident energy.

Thus, since ρ_{IR} and ρ_s can be calculated using index of refraction data and transmissivity data, equations (2.12a,b) can be used to calculate α_s and ε_{IR} for cover materials.

In summing up this chapter, it must be pointed out that the data coded for later computer use is based on the writers interpretation of the compiled data. The computer simulation to be developed is based on this interpretation, and thus discretion must be exercised in accepting the results obtained. Justification for the coding of durability and weathering data has been given. Other people, however, may order the cover and absorber materials differently. Therefore different conclusions employing the same computer analysis could result.

Chapter Three

DERIVATION OF ENERGY BALANCE EQUATIONS

Introduction

Design of single and double cover flat-plate solar collectors requires consideration of cover plate(s) and absorber panel equilibrium temperatures under different weather and heat removal conditions. As a result, a series of energy balances will be derived for single and double cover collector assemblies for steady state conditions.

Approximate techniques for the evaluation of flat-plate solar collector temperatures have been provided by Austin Whillier [3-1] and by Duffie and Beckman [3-2]. These analyses neglect the radiative properties of cover materials by employing effective cover transmissivities and by assuming that cover absorption of solar and thermal radiative energies can be neglected. Simplified equations for absorber plate temperature analysis are thus attained. The temperatures obtained from such analyses have proven acceptable for sizing of solar flat-plate collectors. However, because of the simplifications employed, cover plate temperature calculations are inaccurate. Since knowledge of these temperatures is required for design purposes, the work done by Whillier and Duffie and Beckman cannot be used in this study. In addition, an intention of the work being undertaken is to consider new cover plate alternatives. The work done by the above three authors treats specific cover configurations of glass and Tedlar P.V.F. Their equations have limited applicability to other materials as a result. Therefore, a more complete general derivation is required.

The derivation to be presented outlines the procedure employed to develop energy balance equations for single and double cover collectors which more accurately depicts the radiative performance of the covers. Assumptions employed in the work are listed. Methods of solving the non-linear equations that are derived are discussed.

THE DERIVATION

The radiative properties of cover plate and absorber materials shown in Chapter Two are averaged over two wavelength bands. The first band, from $\lambda = 0.3\mu m$ to $\lambda = 2.1\mu m$, is the wavelength range over which 90% of the sun's radiant energy is emitted, absorbed, reflected, and transmitted. The second band, from $\lambda = 3.0\mu m$ to $\lambda = 50\mu m$, covers the thermal wavelength range over which a material of 100°F to 500°F temperature would radiate energy. (This band includes 98% of the thermal energy emitted by a black body at a temperature of 300°F.) Properties of materials for both bands are critical to flat-plate collector design, as has been indicated previously. The derivation thus considers radiative energy exchange for the two wavelength bands, using the averaged normal properties summarized in Table 2-2.

The analysis is based on steady state equilibrium conditions. Energy balances are obtained for the cover plate(s) and the absorber panel by including the radiation, convection, and conduction effects. The analysis, however, is excessively complicated unless the design configuration is simplified. As a result, the following simplifying assumptions are considered prior to extensive derivation analysis.

1. As stated earlier, steady state performance is to be considered.

2. The absorber panel surface is to be considered flat for analysis purposes. While the Olin Brass panels being considered have surface curvature due to the tube shapes, this curvature is neglected.

3. The headers cover a small area of the collector panel and can be neglected.

4. The cover plates are considered to be isothermal (i.e., no temperature gradient through the thickness).

5. There is one-dimensional heat flow through the back insulation.

6. The sky can be considered as a black body for the thermal wavelength band at an equivalent sky temperature.

7. The temperature gradients around the tubes can be neglected.

8. Radiative properties for the cover(s) and absorber materials are independent of temperature.

9. Dust and dirt on the solar collector are negligible [3-3].

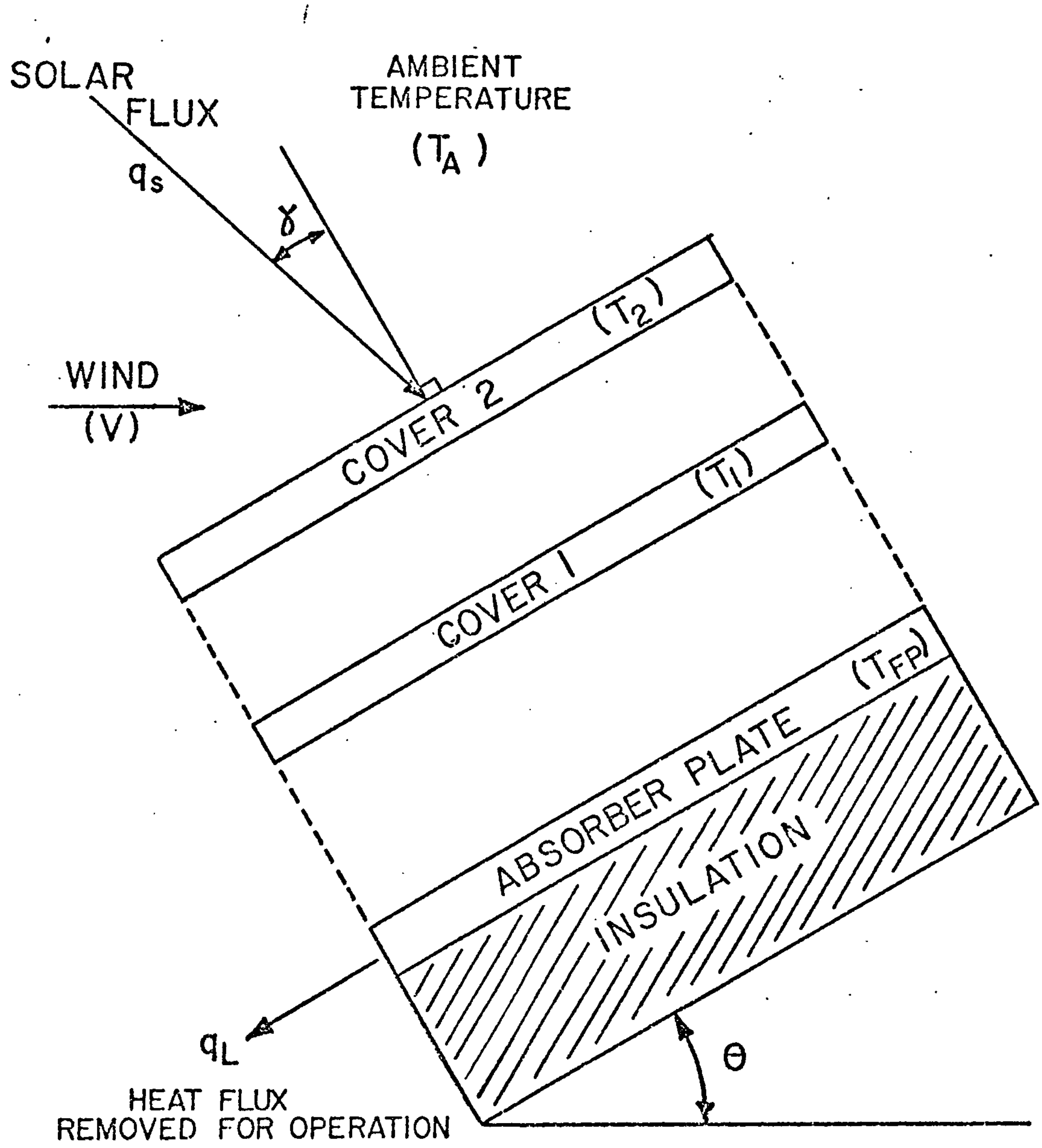
10. Shading of the collector absorber plate is negligible.

11. Direct and diffuse insolation is combined for the analysis. (This is done because the radiative properties being used are for near-normal incidence. The diffuse component can not be accurately considered separately as a result.)

12. The required insulation thickness is designed using a no heat load condition. The cold face insulation temperature (back of the collector assembly) is set at 150°F for this condition.

A typical double cover flat-plate collector is shown in operation in Figure 3-1. The collector is oriented to some angle theta (θ) in order to receive maximum near-normal insolation at solar noon [3-4]. The incident solar flux at some time other than solar noon is shown to be incident to the cover assembly at some angle gamma (γ) with respect to the normal. The ambient temperature and wind velocity can be measured, and an effective black body sky temperature can be calculated using

FIG. 3-1
TYPICAL FLAT-PLATE SOLAR COLLECTOR
IN OPERATION



equation (3.1) developed by Whillier [3-2],

$$T_{sky} = T_{air} - 10.8° \tag{3.1}$$

where the temperatures are in degrees Fahrenheit.

For the configuration shown, three unknown temperatures (T_2, T_1, and T_{FP}) can be solved for if a known heat load (q_L) is being removed. [If a single cover collector were being studied, two unknown temperatures (T_1 and T_{FP}) could be solved for.] This can be accomplished by writing energy balances for each cover and for the absorber plate and solving the two or three (depending on number of covers) independent equations simultaneously.

Single Cover Analysis

The energy balance for a single cover flat-plate collector assembly can be accomplished using a Ray Tracing Technique [3-5] or the Net-Radiation Method [3-6]. For a double cover flat-plate assembly, however, the Ray Tracing Technique proved impractical if thermal radiation transmission through the covers is considered. The Net-Radiation Procedure is thus presented, since this technique can also be readily applied to more than two covers, though the derivation becomes cumbersome.

The Net Radiation Method essentially considers energy fluxes crossing imaginary boundaries. Since under steady state conditions the total energy into a body must equal the total energy out, the different radiation, convection, and conduction effects can be considered using equation (3.2),

$$\sum_{i=1}^{n} q_{i_{in}} = \sum_{j=1}^{m} q_{j_{out}} \tag{3.2}$$

where

$q_{i_{in}}$ = energy flux incident on a surface

$q_{j_{out}}$ = energy flux leaving a surface.

Prior to considering the flat-plate configurations, additional nomenclature should be defined.

$q_{0,J-K_{IR}}$ = the thermal (infrared) radiative energy flux leaving surface J and directed towards surface K.

$q_{0,J-K_s}$ = the solar radiative energy flux leaving surface J and directed towards surface K.

$q_{c_{J-K}}$ = the convective energy flux from surface J to surface K.

q_{cond} = the energy flux conducted through the insulation.

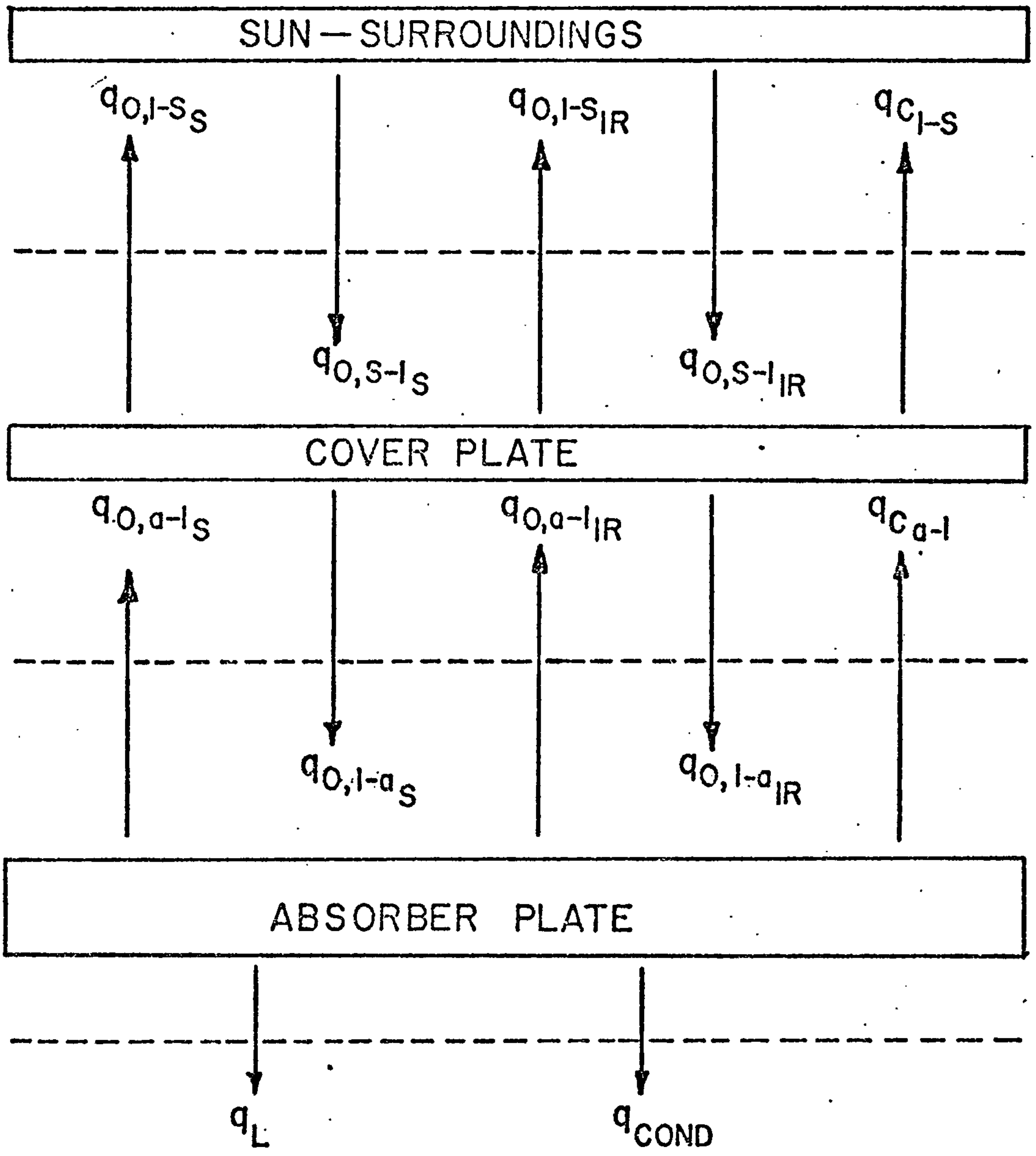
q_L = the heat flux to be removed to provide energy for heating, cooling, or hot water applications.

Figure 3-2 shows the single cover flat-plate collector with the different energy fluxes crossing imaginary boundaries between the sky and the cover plate and between the cover plate and absorber panel. Energy balance equations will be derived for this assembly and will be discussed. The double cover assembly derivation follows the same procedures as to be outlined. The algebraic manipulation, being much more tedious, will be neglected.

Energy balances can be written for (1) the cover plate and (2) the absorber panel using equation (3.2). They are shown respectively in equations (3.3) and (3.4).

FIG. 3-2

ENERGY FLUX EXCHANGE FOR A SINGLE COVER FLAT-PLATE COLLECTOR



$$q_{0,1-s_{IR}} + q_{0,1-s_s} + q_{0,1-a_{IR}} + q_{0,1-a_s} + q_{c_{1-s}} = q_{c_{a-1}} + q_{0,a-1_{IR}} + q_{0,a-1_s} + q_{0,s-1_s} + q_{0,s-1_{IR}} \tag{3.3}$$

$$q_{0,a-1_s} + q_{0,a-1_{IR}} + q_{c_{a-1}} + q_{cond} + q_L = q_{0,1-a_s} + q_{0,1-a_{IR}} \tag{3.4}$$

An additional simplification can be made to the absorber plate energy equation (3.4). Based on experimental verification, the heat conducted through the insulation is found to be equal to approximately one-tenth the upward heat loss [3-1].

Therefore,

$$q_{cond} = .1{*}q_{up} \tag{3.5}$$

where

$$q_{up} = \text{upward heat loss}$$
$$= q_{c_{a-1}} + q_{0,a-1_{IR}} - q_{0,1-a_{IR}}$$

Thus,

$$q_{cond} = .1{*}(q_{c_{a-1}} + q_{0,a-1_{IR}} - q_{0,1-a_{IR}}) \tag{3.6}$$

The absorber plate energy balance thus reduces to equation (3.7),

$$q_L + q_{0,a-1_s} + 1.1q_{0,a-1_{IR}} + 1.1q_{c_{a-1}} = 1.1q_{0,1-a_{IR}} + q_{0,1-a_s} \tag{3.7}$$

or rearranging

$$q_L + (q_{0,a-1_s} - q_{0,1-a_s}) + 1.1{*}(q_{0,a-1_{IR}} - q_{0,1-a_{IR}} + q_{c_{a-1}}) = 0 \tag{3.8}$$

Equations (3.3) and (3.8) may be reduced from their present forms to equations consisting of known and unknown temperatures, incident solar flux, heat transfer coefficients, geometric constraints, and radiative properties of the cover plate and absorber panel. This is accomplished using the following known relationships,

$$q_{c_{a-1}} = h_{a1}(T_{FP} - T_1) \tag{3.9a}$$

$$q_{c_{1-s}} = h_{1s}(T_1 - T_A) \tag{3.9b}$$

$$q_{0,s-1_{IR}} = \sigma T_s^4 \tag{3.9c}$$

$$q_{0,s-1_s} = q_s \cos\gamma \tag{3.9d}$$

$$q_{0,1-s_{IR}} = \varepsilon_{1_{IR}} \sigma T_1^4 + \rho_{1_{IR}} \sigma T_s^4 + \tau_{1_{IR}} q_{0,a-1_{IR}} \tag{3.9e}$$

$$q_{0,1-s_s} = \rho_{1_s} q_s \cos\gamma + \tau_{1_s} q_{0,a-1_s} \tag{3.9f}$$

$$q_{0,1-a_{iR}} = \varepsilon_{1_{IR}} \sigma T_1^4 + \tau_{1_{IR}} \sigma T_s^4 + \rho_{1_{IR}} q_{0,a-1_{IR}} \tag{3.9g}$$

$$q_{0,1-a_s} = \tau_{1_s} q_s \cos\gamma + \rho_{1_s} q_{0,a-1_s} \tag{3.9h}$$

$$q_{0,a-1_{IR}} = \varepsilon_{a_{IR}} \sigma T_{FP}^4 + \rho_{a_{IR}} q_{0,1-a_{IR}} \tag{3.9i}$$

$$q_{0,a-1_s} = \rho_{a_s} q_{0,1-a_s} \tag{3.9j}$$

Following considerable algebraic substitution and manipulation, equations (3.10) and (3.11) are obtained.

Energy Balance for the Cover Plate:

$$a_{11}T_1^4 + b_{11}T_1 + a_{12}T_{FP}^4 + b_{12}T_{FP} - C_1 = 0 \tag{3.10}$$

Energy Balance for the Absorber Panel:

$$a_{21}T_1^4 + b_{21}T_1 + a_{22}T_{FP}^4 + b_{22}T_{FP} - C_2 = 0 \tag{3.11}$$

where

$$a_{11} = \varepsilon_{1_{IR}} \sigma [1.0 + \rho_{a_{IR}} \tau_{1_{IR}} + \varepsilon_{a_{IR}} - (1 - \tau_{1_{IR}}) \rho_{a_{IR}}] / (1 - \rho_{a_{IR}} \rho_{1_{IR}})$$

$$a_{12} = -(\varepsilon_{a_{IR}}\varepsilon_{1_{IR}}\sigma/(1-\rho_{a_{IR}}\rho_{1_{IR}}))$$

$$a_{21} = -(1.1\varepsilon_{1_{IR}}\varepsilon_{a_{IR}}\sigma/(1-\rho_{a_{IR}}\rho_{1_{IR}})$$

$$a_{22} = 1.1\varepsilon_{a_{IR}}\sigma(\tau_{1_{IR}}+\varepsilon_{1_{IR}})/(1-\rho_{a_{IR}}\rho_{1_{IR}})$$

$$b_{11} = h_{a1}+h_{1s}$$

$$b_{12} = -h_{a1}$$

$$b_{21} = -1.1h_{a1}$$

$$b_{22} = 1.1h_{a1}$$

$$C_1 = h_{1s}T_A+\varepsilon_{1_{IR}}\sigma[1+\tau_{1_{IR}}\rho_{a_{IR}}/(1-\rho_{a_{IR}}\rho_{1_{IR}})]T_s^4$$

$$+\varepsilon_{1_s}[1+\tau_{1_s}\rho_{a_s}/(1-\rho_{a_s}\rho_{1_s})]\ q_s\cos\gamma$$

$$C_2 = \tau_{1_s}\varepsilon_{a_s}q_s\cos\ /(1-\rho_{a_s}\rho_{1_s})-q_L+1.1\tau_{1_{IR}}\varepsilon_{a_{IR}}\sigma\ T_s^4/\ (1-\rho_{a_{IR}}\rho_{1_{IR}})$$

As can be seen, equations (3.10) and (3.11) have been written in terms of radiation components ($a_{xy}T_x^4$) and convection components ($b_{xy}T_x$). The insolation, radiation, and convection effects related to the ambient temperature are combined in a C_x term. The two equations appear to consist of constants multiplied by unknown temperatures.

Calculations for the convection coefficients h_{a1} and h_{1s} must be discussed since they are not constants like the radiative properties provided for the cover(s) and absorber material. Both forced and natural convection are considered in the analysis. For forced convection, analytical derivations for air passing over the cover plate [3-7] require that the flow is parallel to the plate. Such may not occur since the plate is oriented at an angle theta to the horizontal. Further, depending upon the wind velocity and temperature of the air, the flow may be laminar or turbulent making the choice of analytical tools difficult. Thus, a simplification proposed by Whillier [3-1] is incorporated in the work. For forced convection

$$h = 1.0 + .3V \tag{3.12}$$

where

V = velocity of wind in miles per hour.

The free convection coefficient is more easily obtained since extensive experimental modelling of this phenomena has been reported in the literature. For free convection, in air between two plates

$$Nu = f(Gr, \theta) \tag{3.13}$$

where

Nu = the Nusselt number

$= hL/k$ (3.14)

Gr = the Grashof number

$= gL^3\beta\Delta T/\nu^2$ (3.15)

θ = the tilt angle measured with respect to horizontal

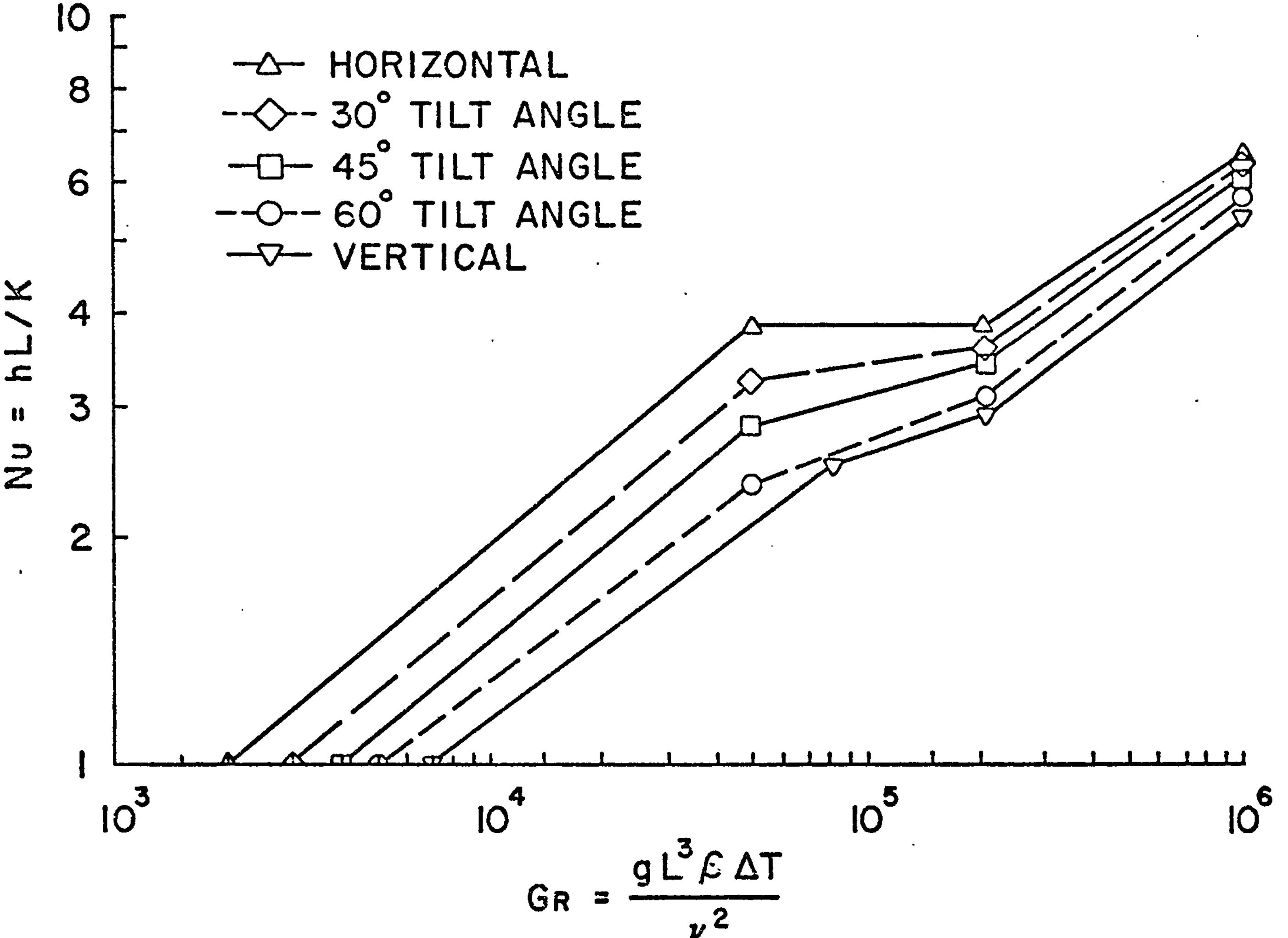
g = the gravitational acceleration constant

k = the conduction coefficient for the air space

L = the normal distance between the two plates

FIG. 3-3

EXPERIMENTAL FREE CONVECTION DATA AS A FUNCTION OF TILT ANGLE



ΔT = the temperature difference between the two plates

β = volumetric coefficient of expansion of air

ν = kinematic viscosity

For the analysis, the experimental results reported by DeGraaf and Van der Held [3-8] are employed. The relationships between the Nusselt number and the Grashof number are provided in Figure 3-3 for representative tilt angles.

With the radiative, convective and conduction parameters determined, equations (3.10) and (3.11) can now be solved for the cover and absorber temperatures.

Double Cover Analysis

The Net Energy method is also used to write the energy balances for a two cover solar collector assembly. Figure 3-4 diagrams the energy fluxes crossing the imaginary boundaries surrounding the cover plates and absorber panel. Based on this representation, equations (3.16), (3.17) and (3.18) are written.

Absorber Plate Energy Balance:

$$q_{c_{a-1}} + q_{cond} + q_L + q_{0,a-1_{IR}} + q_{0,a-1_s} = q_{0,1-a_s} + q_{0,1-a_{IR}} \quad (3.16)$$

Inside Cover Plate Energy Balance:

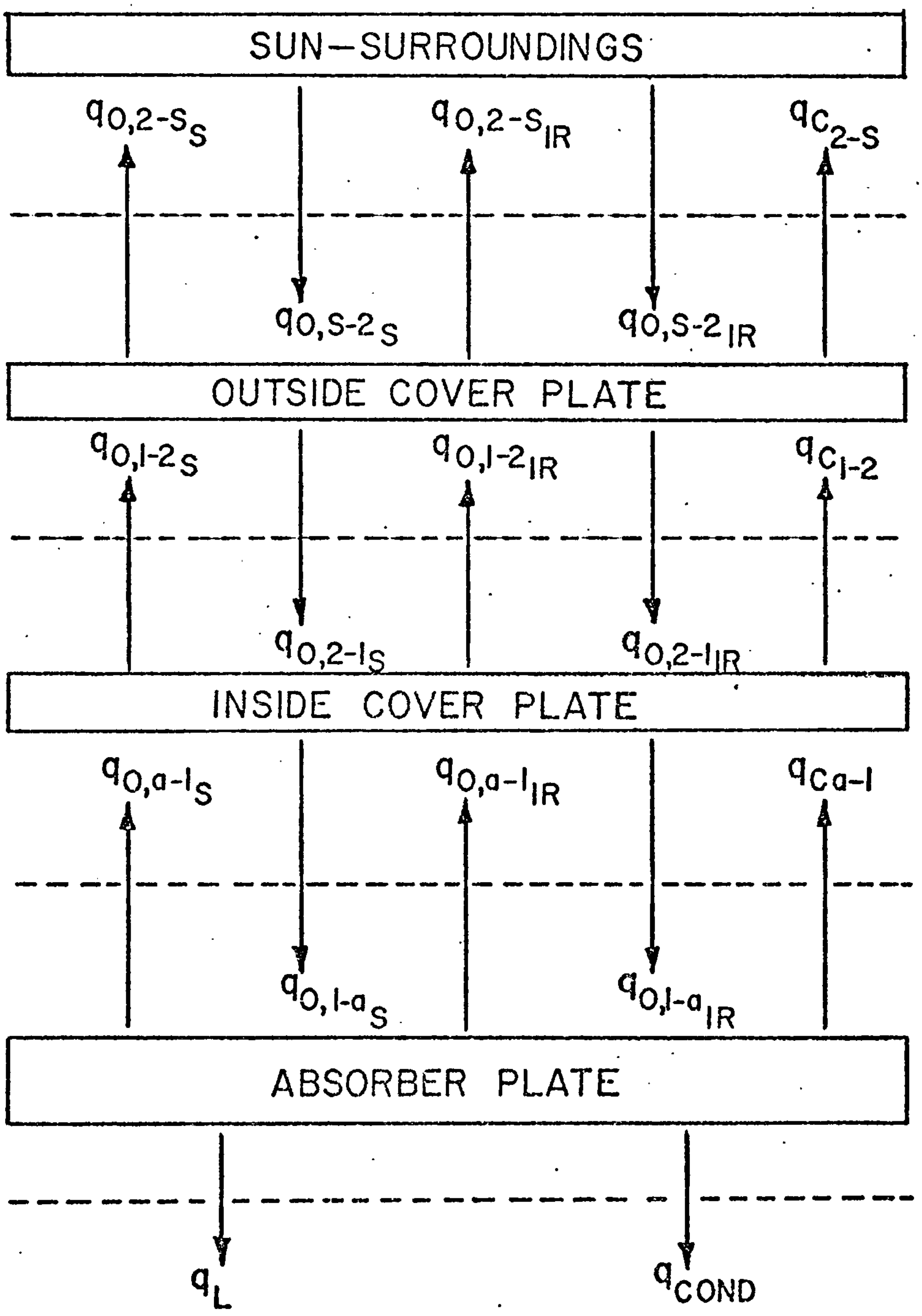
$$\begin{aligned} q_{0,a-1_{IR}} + q_{0,a-1_s} + q_{c_{a-1}} + q_{0,2-1_s} + q_{0,2-1_{IR}} &= q_{0,1-a_{IR}} \\ + q_{0,1-a_s} + q_{0,1-2_s} + q_{0,1-2_{IR}} &+ q_{c_{1-2}} \end{aligned} \quad (3.17)$$

Outside Cover Plate Energy Balance:

$$\begin{aligned} q_{0,1-2_{IR}} + q_{0,1-2_s} + q_{0,s-2_s} + q_{0,s-2_{IR}} + q_{c_{1-2}} &= q_{0,2-1_{IR}} \\ + q_{0,2-1_s} + q_{0,2-s_s} + q_{0,2-s_{IR}} &+ q_{c_{2-s}} \end{aligned} \quad (3.18)$$

FIG. 3-4

ENERGY FLUX EXCHANGE FOR A DOUBLE COVER FLAT PLATE COLLECTOR



These equations have been reduced to three equations involving three unknown temperatures by incorporating equation (3.5) for the conduction term and equations (3.19) listed below.

$$q_{0,s-2_s} = q_s\cos\gamma \tag{3.19a}$$

$$q_{0,s-2_{IR}} = \sigma T_s^4 \tag{3.19b}$$

$$q_{0,2-s_s} = \rho_{2_s} q_s\cos\gamma + \tau_{2_s} q_{0,1-2_s} \tag{3.19c}$$

$$q_{0,2-s_{IR}} = \varepsilon_{2_{IR}}\sigma T_2^4 + \rho_{2_{IR}}\sigma T_s^4 + \tau_{2_{IR}} q_{0,1-2_{IR}} \tag{3.19d}$$

$$q_{0,2-1_s} = \rho_{2_s} q_{0,1-2_s} + \tau_{2_s} q_s\cos\gamma \tag{3.19e}$$

$$q_{0,2-1_{IR}} = \varepsilon_{2_{IR}}\sigma T_2^4 + \rho_{2_{IR}} q_{0,1-2_{IR}} + \tau_{2_{IR}}\sigma T_s^4 \tag{3.19f}$$

$$q_{0,1-2_s} = \rho_{1_s} q_{0,2-1_s} + \tau_{1_s} q_{0,a-1_s} \tag{3.19g}$$

$$q_{0,1-2_{IR}} = \varepsilon_{1_{IR}}\sigma T_1^4 + \rho_{1_{IR}} q_{0,2-1_{IR}} + \tau_{1_{IR}} q_{0,a-1_{IR}} \tag{3.19h}$$

$$q_{0,1-a_s} = \rho_{1_s} q_{0,a-1_s} + \tau_{1_s} q_{0,2-1_s} \tag{3.19i}$$

$$q_{0,1-a_{IR}} = \varepsilon_{1_{IR}}\sigma T_1^4 + \rho_{1_{IR}} q_{0,a-1_{IR}} + \tau_{1_{IR}} q_{0,2-1_{IR}} \tag{3.19j}$$

$$q_{0,a-1_s} = \rho_{a_s} q_{0,1-a_s} \tag{3.19k}$$

$$q_{0,a-1_{IR}} = \varepsilon_{a_{IR}}\sigma T_{FP}^4 + \rho_{a_{IR}} q_{0,1-a_{IR}} \tag{3.19l}$$

$$q_{c_{a-1}} = h_{a1}(T_{FP}-T_1) \tag{3.19m}$$

$$q_{c_{1-2}} = h_{12}(T_1-T_2) \tag{3.19n}$$

$$q_{c_{2-s}} = h_{2s}(T_2-T_A) \tag{3.19o}$$

Eliminating the algebraic substitutions in the interest of space, equations (3.16), (3.17), and (3.18) reduce to the following.

$$a_{11}T_{FP}^4 + b_{11}T_{FP} + a_{12}T_1^4 + b_{12}T_1 + a_{13}T_2^4 + b_{13}T_2 - C_1 = 0 \quad (3.19)$$

$$a_{21}T_{FP}^4 + b_{21}T_{FP} + a_{22}T_1^4 + b_{22}T_1 + a_{23}T_2^4 + b_{23}T_2 - C_2 = 0 \quad (3.20)$$

$$a_{31}T_{FP}^4 + b_{31}T_{FP} + a_{32}T_1^4 + b_{32}T_1 + a_{33}T_2^4 + b_{33}T_2 - C_3 = 0 \quad (3.21)$$

where

$$a_{11} = (A-D)\varepsilon_{a_{IR}}\sigma/C$$

$$a_{12} = \varepsilon_{1_{IR}}\sigma[(A-D)\rho_{a_{IR}}/C-E\tau_{1_{IR}}\rho_{2_{IR}}-1]$$

$$a_{13} = -E\tau_{1_{IR}}\varepsilon_{2_{IR}}\sigma$$

$$a_{21} = [(A-D)-(1-\rho_{2_{IR}})\tau_{1_{IR}}]\varepsilon_{a_{IR}}\sigma/C$$

$$a_{22} = \varepsilon_{1_{IR}}\sigma[[(A-D)\rho_{a_{IR}}/C-E\tau_{1_{IR}}\rho_{2_{IR}}-1]$$
$$-[(1-\rho_{2_{IR}})(\rho_{a_{IR}}\tau_{1_{IR}}[A+\tau_{1_{IR}}\rho_{2_{IR}}]+C)/AC]]$$

$$a_{23} = \varepsilon_{2_{IR}}\sigma(V+E\tau_{1_{IR}})$$

$$a_{31} = \varepsilon_{a_{IR}}\varepsilon_{2_{IR}}\tau_{1_{IR}}\sigma/C$$

$$a_{32} = \varepsilon_{2_{IR}}\varepsilon_{1_{IR}}\sigma[C+\tau_{1_{IR}}\rho_{a_{IR}}(A+\tau_{1_{IR}}\rho_{2_{IR}})]/(AC)$$

$$a_{33} = \varepsilon_{2_{IR}}\sigma[V-(AC+\tau_{2_{IR}}[\rho_{1_{IR}}C+\tau_{1_{IR}}^2\rho_{a_{IR}}]]/(AC)$$

$$b_{11} = h_{a1}$$

$$b_{12} = -h_{a1}$$

$$b_{13} = 0.0$$

$$b_{21} = h_{a1}$$

$$b_{22} = -(h_{12}+h_{a1})$$

$$b_{23} = h_{12}$$

$$b_{31} = 0.0$$

$$b_{32} = h_{12}$$

$$b_{33} = -(h_{12}+h_{2s})$$

$$c_1 = [E_s\tau_{1_s}\tau_{2_s}q_s\cos\gamma-q_L]/1.1+E\tau_{1_{IR}}\tau_{2_{IR}}\sigma T_s^4$$

$$c_2 = \tau_{2_s}q_s\cos\gamma[V_s+E_s\tau_{1_s}]+\tau_{2_{IR}}\sigma T_s^4[V+E\tau_{1_{IR}}]$$

$$c_3 = -[q_s\cos\gamma(P_s+V_s\tau_{2_s})+\sigma T_s^4(P+V\tau_{2_{IR}})+h_{2s}T_A]$$

and

$$A = 1-\rho_{2_{IR}}\rho_{1_{IR}}$$

$$A_s = 1-\rho_{2_s}\rho_{1_s}$$

$$B = 1-\rho_{1_{IR}}\rho_{a_{IR}}$$

$$B_s = 1-\rho_{1_s}\rho_{a_s}$$

$$C = AB-\rho_{a_{IR}}\rho_{2_{IR}}\tau_{1_{IR}}^2$$

$$C_s = A_sB_s-\rho_{a_s}\rho_{2_s}\tau_{1_s}^2$$

$$D = \tau_{1_{IR}}^2\rho_{2_{IR}}+A\rho_{1_{IR}}$$

$$D_s = \tau_{1_s}^2 \rho_{2_s} + A_s \rho_{1_s}$$

$$E = [(D-A)\rho_{a_{IR}} + C]/(AC)$$

$$E_s = [(D_s - A_s)\rho_{a_s} + C_s]/(A_s C_s)$$

$$P = [AC(1-\rho_{2_{IR}}) - \tau_{2_{IR}}^2 (C\rho_{1_{IR}} + \tau_{1_{IR}}^2 \rho_{a_{IR}})]/(AC)$$

$$P_s = [A_s C_s (1-\rho_{2_s}) - \tau_{2_s}^2 (C\rho_{1_s} + \tau_{1_s}^2 \rho_{a_s})]/(A_s C_s)$$

$$V = [(1-\rho_{2_{IR}})\tau_{1_{IR}}^2 \rho_{a_{IR}} - (1-\rho_{1_{IR}})C]/(AC)$$

$$V_s = [(1-\rho_{2_s})\tau_{1_s}^2 \rho_{a_s} - (1-\rho_{1_s})C_s]/(A_s C_s)$$

SOLUTION TECHNIQUES

The sets of equations obtained from the energy balance analysis are non-linear algebraic equations. As a result, the unknown temperatures cannot be directly solved for by linear matrix reduction. Instead, iteration techniques must be used, based on assuming values for the unknown temperatures and correcting these initial temperature guesses to obtain the actual equilibrium temperatures. Two solution techniques are chosen for use in the computer analysis. For the one cover collector assembly, a simple Newton-Raphson iteration technique [3-9] is used. For the two cover assembly, the Newton-Raphson iteration technique is found to be too time consuming, and thus a linearization of the three equations is employed.

The Newton-Raphson iteration technique used for the single cover plate collector requires rearranging equations (3.10) and (3.11) into the following forms,

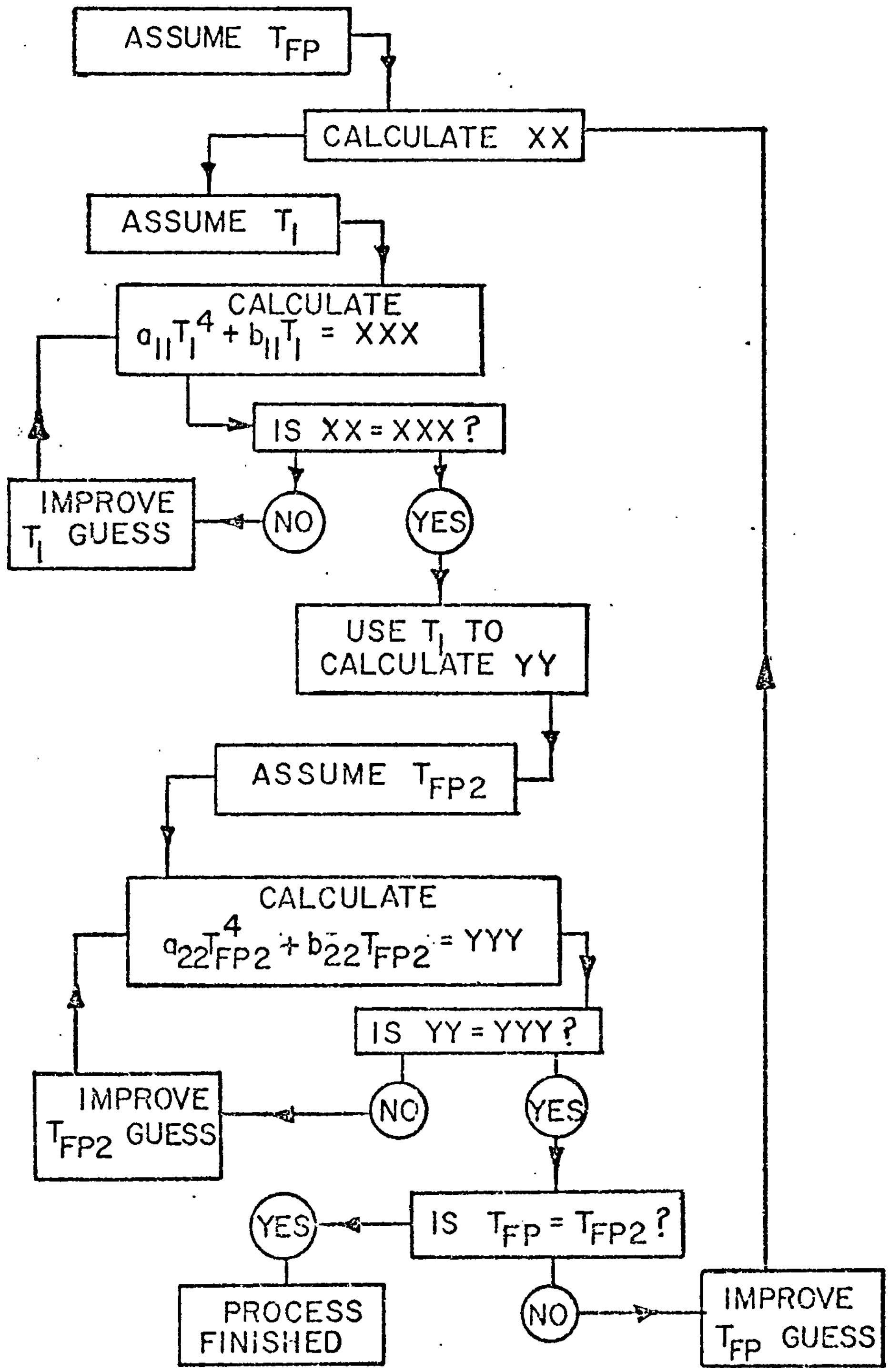
$$a_{11}T_1^4 + b_{11}T_1 = xx \tag{3.10'}$$

$$a_{22}T_{FP}^4 + b_{22}T_{FP} = yy \tag{3.11'}$$

where xx consists of the absorber plate temperature terms and the ambient temperature and insolation terms and yy consists of the cover plate temperature terms and other known terms. With the equations in these forms, the iterative scheme illustrated in Figure 3-5 is utilized to obtain the required temperatures.

FIG. 3-5

EVALUATION OF UNKNOWN TEMPERATURES FOR A SINGLE COVER SOLAR COLLECTOR



For the two cover collector assembly, the three equations, (3.19), (3.20), and (3.21), are linearized using a procedure known as the Newton-Raphson method [3-10]. In this method, approximations for the temperatures shown in (3.22) are employed.

$$T_j = h_j + T_{j0} \tag{3.22}$$

where

h_j is a correction factor

T_{j0} is an assumed temperature

T_j is the corrected temperature.

The corrected temperatures (T_j's) are used to compute new h_j's and the process is continued until the h_j's become smaller than a specified value. The h_j's are found from the following set of linear equations:

$$\begin{aligned} f_{11}h_1 + f_{12}h_2 + f_{13}h_3 + f_1 &= 0 \\ f_{21}h_1 + f_{22}h_2 + f_{23}h_3 + f_2 &= 0 \\ f_{31}h_1 + f_{32}h_2 + f_{33}h_3 + f_3 &= 0 \end{aligned} \tag{3.23}$$

The coefficients f_1, f_2 and f_3 are given by

$$f_i = \sum_{j=1}^{n} (a_{ij}T_{j0}^4 + b_{ij}T_{j0}) - C_j \tag{3.24}$$

and the f_{ij} are given by

$$f_{ij} = b_{ij} + 4a_{ij}T_{j0}^3. \tag{3.25}$$

The linear equations (3.23) presented can be solved using a Gauss-Jordan reduction scheme with the maximum pivot criterion [3-9]. The above linearization has been selected because it can be performed on a computer and because convergence is so rapid.

The method is also noteworthy in that it can be employed for n equations and n unknowns, whereas the Newton-Raphson iteration technique is limited to two or three equations.

Chapter Four

FLAT-PLATE COLLECTOR PERFORMANCE PREDICTIONS

Introduction

The performances of the most extensively employed flat-plate solar collectors (one or two glass covers with a flat black paint absorber) are well tabulated in the literature today. Experimental work has substantiated the most often referenced performance analysis of Hottel and Woertz [4-1] indicating that equilibrium absorber temperatures for nonselective surfaces are not high enough for solar cooling except at low operating heat removals and 'perfect' weather conditions. As a result, implementation of flat-plate technology for space cooling has been generally considered unfeasible.

With the advent of new cover materials and selective surface alternatives, solar cooling using flat-plate collectors may now be possible from a performance standpoint. (Collector economics must still be considered.) As a result, additional performance predictions should be undertaken to provide estimations on absorber equilibrium temperatures for various operating conditions. Such data could give rise to additional flat-plate collector utilization in high heat requirement work such as space cooling and steam production.

General flat-plate performance work will thus be undertaken employing representative cover materials under several different insolations, absorber solar absorptivities, and wind conditions. A single heat removal of 120 Btu/hr-ft² will be analyzed. Absorber plate equilibrium temperatures will be obtained for various degrees of selectivity (i.e., for various $\alpha_S/\varepsilon_{IR}$ ratios), and results will be presented graphically. The work will analyze single cover and double cover flat-plate assemblies, and comparison of results obtained from collectors comprised of both types of cover assemblies will also be provided.

Of the thirty-one cover plate options, four representative materials will be analyzed because of the large range of their transmission properties. These covers are listed in Table 4-1 along with other pertinent data.

Table 4-1

REPRESENTATIVE COVER PLATE MATERIALS

Material	Thickness	τ_{solar}	τ_{IR}
Teflon F.E.P.	5 mil	0.923	0.257
Plexiglas G	63 mil	0.907	0.03
Mylar S	4 mil	0.869	0.178
Temper Glass	125 mil	0.843	0.02

As can be seen, two of the materials, Teflon F.E.P. and Mylar S, allow for considerable infrared transmission of emitted absorber energy. They also have higher solar transmissivities than do their counterpart materials, Plexiglas G and Temper Glass.

Comparisons of the absorber plate temperatures for various $\alpha_s/\varepsilon_{IR}$ ratios will thus provide guidelines to establish the conditions under which each type of material should be used. Note also that of the materials tabulated in Table 2-8, Teflon F.E.P. and Temper Glass have two of the highest and lowest solar transmissivities shown. These materials are being analyzed to provide upper and lower bounds on absorber plate performance.

Single Cover Flat-Plate Collectors

Three parameters - insolation, absorber plate solar absorptivity, and wind velocity - are varied to provide a basis for selection of single cover flat-plate assemblies. Their effects on absorber equilibrium temperature can be seen through review of Figures 4-1, 4-2, 4-3, and 4-4.

Solar insolation variation, as shown in Figure 4-1, most critically affects the absorber equilibrium temperature for a given heat removal. Based upon an absorber temperature constraint of 190°F for absorption air conditioning requirements, it can be seen that for an insolation below 240 Btu/hr-ft^2 and a heat removal of 120 Btu/hr-ft^2, there appear to be no combinations of cover plate and selective surface that will provide suitable heat for space cooling. For an upper unrealistic insolation of 400 Btu/hr-ft^2, it is also seen that nonselective absorber materials may be used. A more typical design insolation of 300 Btu/hr-ft^2 indicates that selective absorbing surfaces of $\alpha_s/\varepsilon_{IR} = 1.5$ (with $\alpha_s = 0.90$) or better are required if the flat-

FIG. 4-1

EFFECTS OF SOLAR FLUX VARIATON ON THE ABSORBER EQUILIBRIUM TEMPERATURE FOR A SINGLE COVER ASSEMBLY

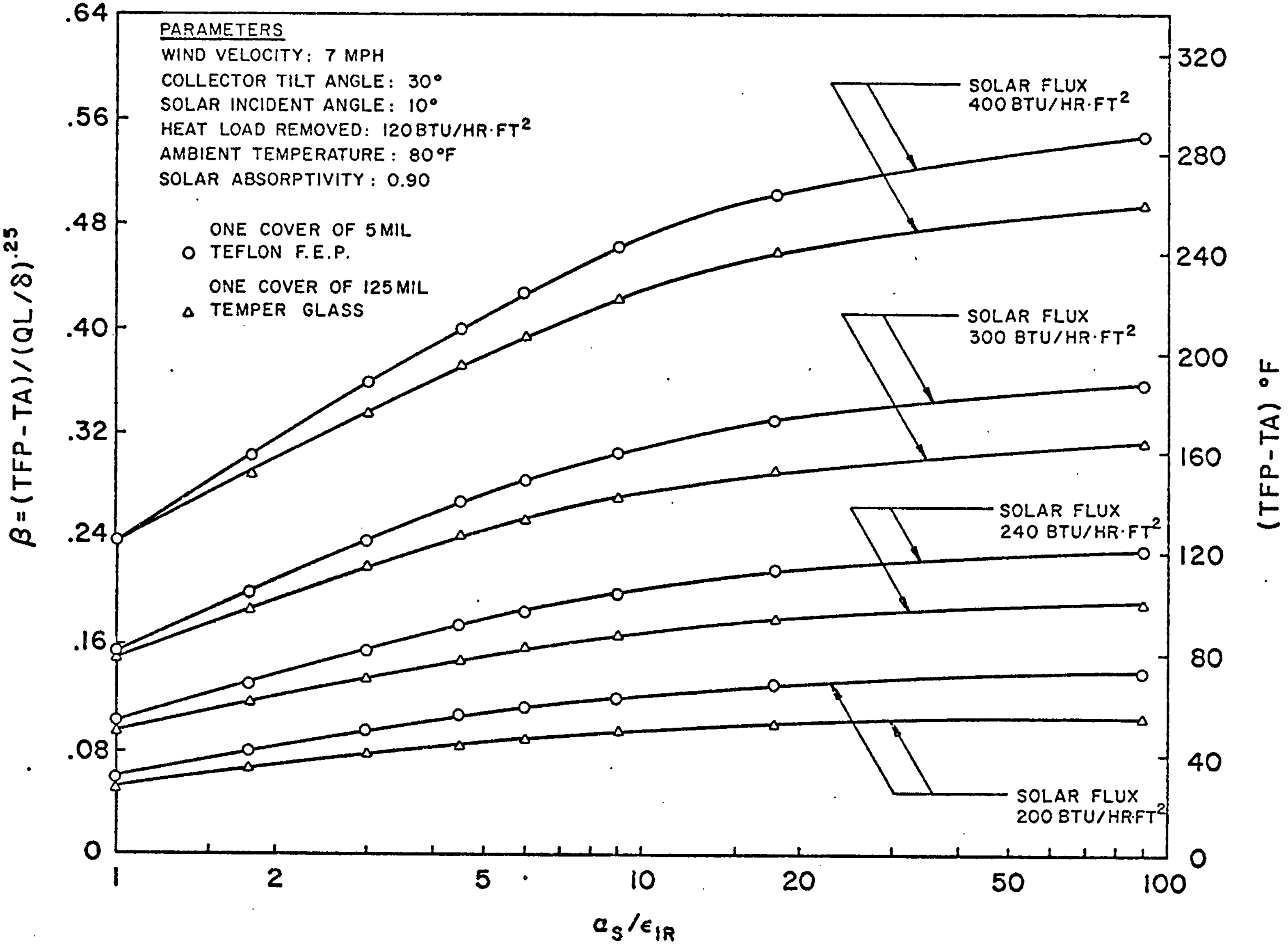


plate collector is to provide 120 Btu/hr-ft^2 heat at 190°F for space cooling.

Figure 4-2 shows the effects of absorber material solar absorptivity variation at an insolation of 300 Btu/hr-ft^2. The twenty percent drop in α_s from 100% to 80% necessitates use of a selective surface with an $\alpha_s/\varepsilon_{IR}$ ratio of at least 6.0 for a Temper Glass cover and 3.5 for either Plexiglas G or Teflon F.E.P. From Figure 4-2, also, the choice of materials like Plexiglas G or Teflon F.E.P. for a cover can be made depending upon the $\alpha_s/\varepsilon_{IR}$ ratio used. For a selective surface having an $\alpha_s/\varepsilon_{IR}$ (α_s = 1.0) ratio of 4.6 or greater, Teflon F.E.P. is a more effective cover because of its superior solar transmissivity. The low thermal transmissivity of Plexiglas G makes up for the solar transmission difference below an $\alpha_s/\varepsilon_{IR}$ ratio of 4.6, since it does not transmit the thermal radiation of the absorber plate.

Wind variation effects are revealed in Figures 4-3 and 4-4. Figure 4-3 indicates that a substantial absorber plate temperature drop (of as much as 30°F for a 5 mil Teflon F.E.P. cover and an absorber surface of α_s = 0.90 and ε_{IR} = 0.01) can occur because the wind velocity over the cover is 14 mph instead of 0 mph at an insolation of 300 Btu/hr-ft^2. Figure 4-4 considers this trend more closely by comparing absorber temperatures under three wind conditions and three insolations. For Teflon F.E.P., it is shown that high wind velocities will prevent absorber temperatures from reaching 190°F at 120 Btu/hr-ft^2 heat removal regardless of the degree of selectivity at insolations around 240 Btu/hr-ft^2.

FIG. 4-2
EFFECTS OF FLAT PLATE SOLAR ABSORPTIVITY VARIATION ON THE ABSORBER EQUILIBRIUM TEMPERATURE FOR A SINGLE COVER ASSEMBLY

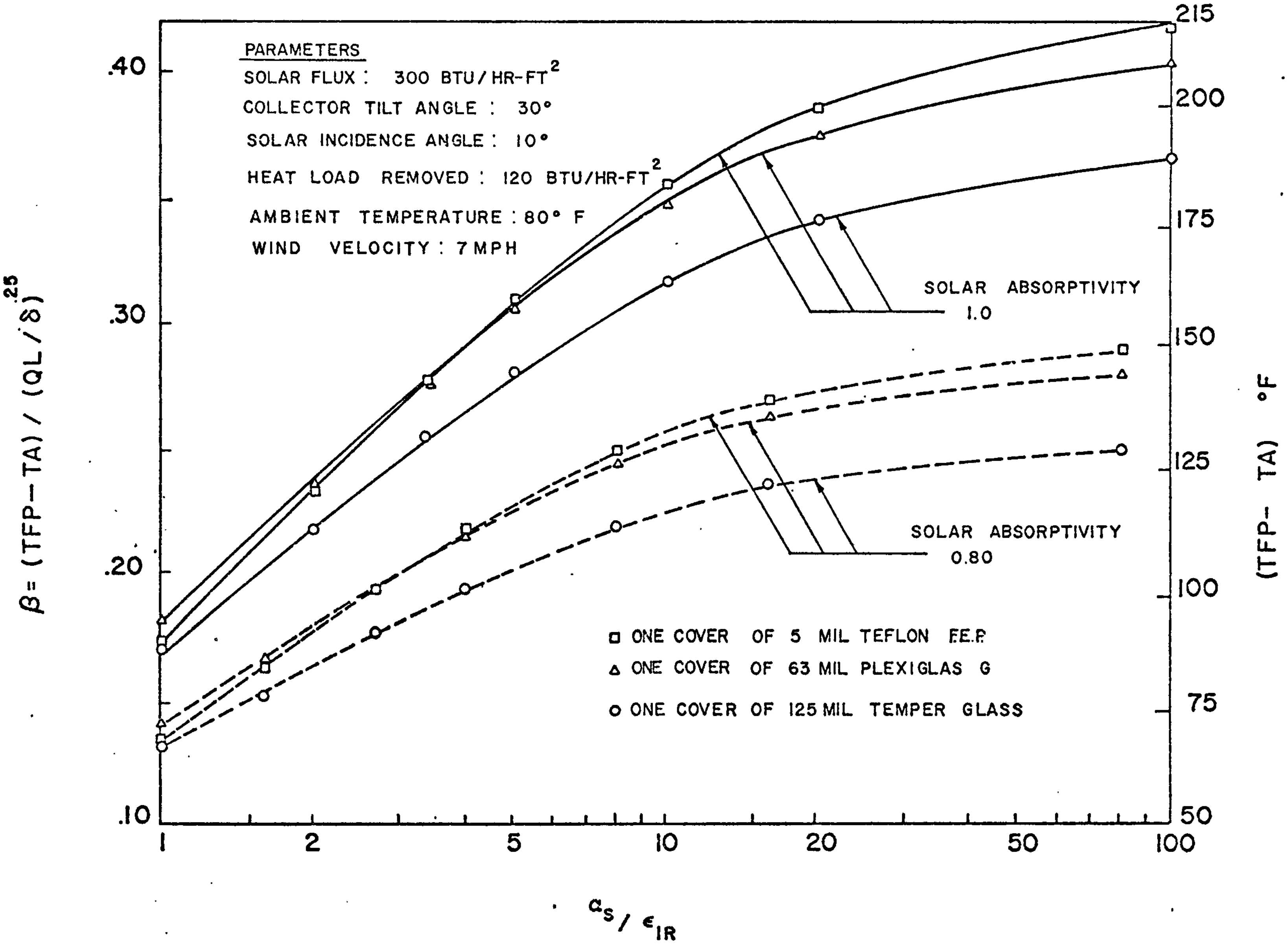


FIG. 4-3
EFFECTS OF WIND VELOCITY ON THE ABSORBER EQUILIBRIUM TEMPERATURE FOR A SINGLE COVER ASSEMBLY

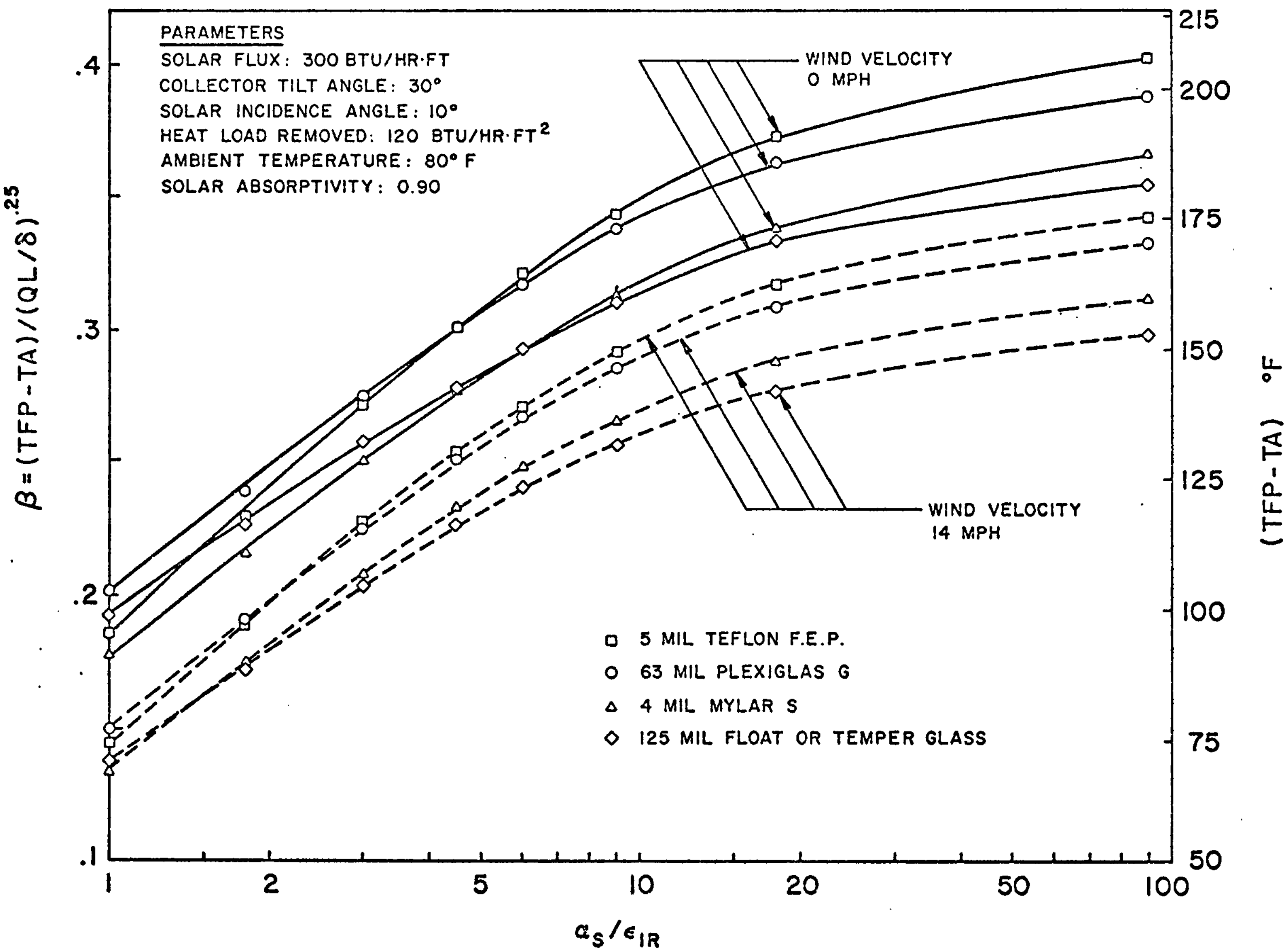
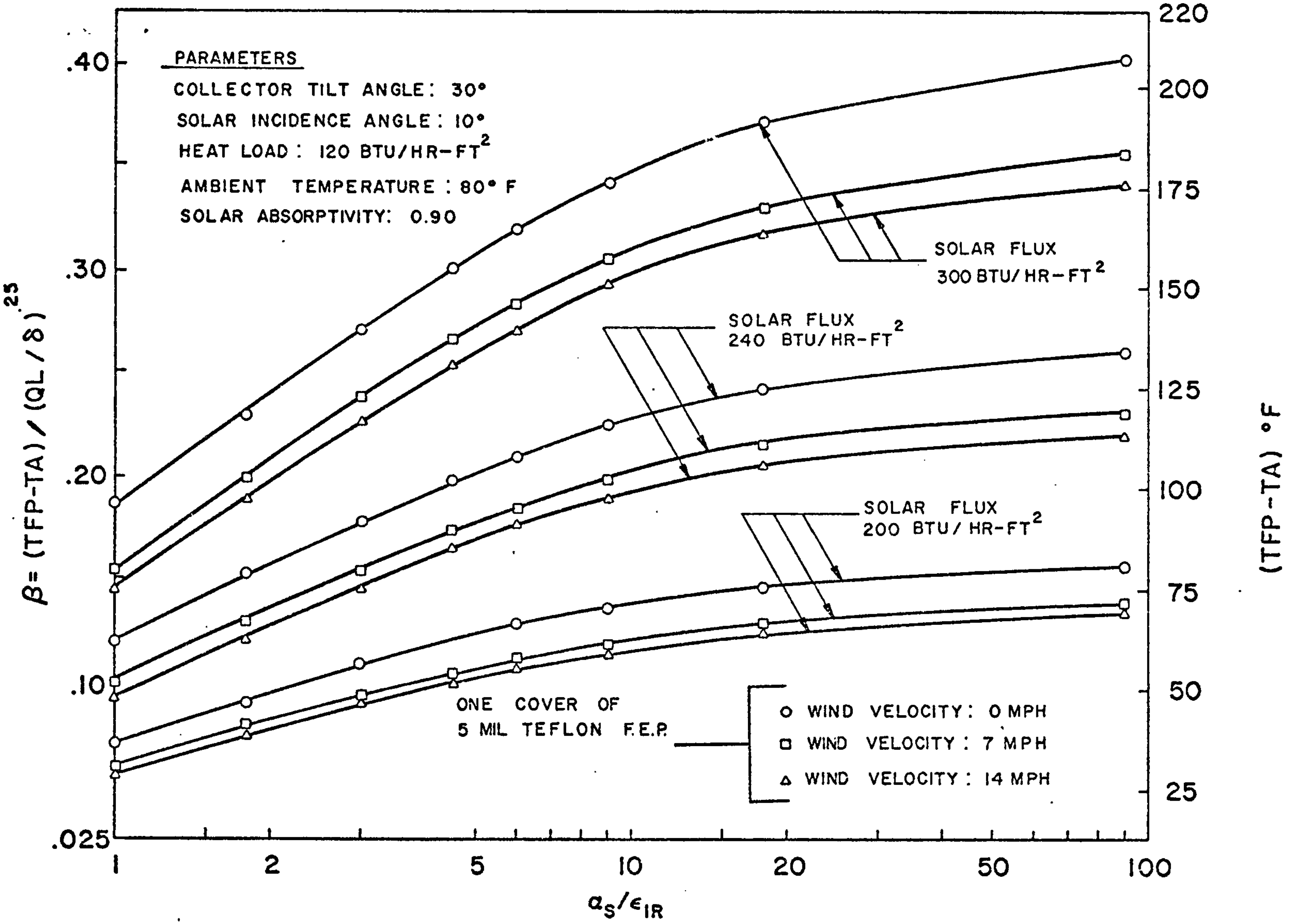


FIG. 4-4

EFFECTS OF WIND VELOCITY ON THE ABSORBER EQUILIBRIUM TEMPERATURE FOR A SINGLE COVER ASSEMBLY



(Under no wind conditions, a flat-plate assembly using Teflon F.E.P. could fulfill solar cooling requirements with an absorbing surface of $\alpha_s = 0.90$ and $\varepsilon_{IR} = 0.06$). Such results indicate that for single cover flat-plate assemblies, under-design is necessary to insure that wind variations will not prevent the collector from attaining suitable temperatures at elevated loads. As in Figure 4-2, Figure 4-3 also provides data for cover plate material trade-offs between materials like glass and Mylar S and materials like Teflon F.E.P. and Plexiglas G.

The trends presented may be summarized by stating that absorption air conditioning requirements may be fulfilled at 120 Btu/hr-ft^2 loads using single cover flat-plate collectors if insolations greater than 240 Btu/hr-ft^2 occur. In addition, selective absorbing materials with solar absorptivities above 0.90 should be incorporated in single cover collector design. Finally, since wind effects are so critical to single cover collector performance, average or above average wind velocities should be considered in the design of single cover flat-plate collectors.

Double Cover Flat-Plate Collectors

As in the case of the single cover collector analysis, insolation, absorber solar absorptivity, and wind velocity variations are analyzed. The double cover assembly options studied include combinations of Temper Glass and Teflon F.E.P., and combinations of Plexiglas G and Teflon F.E.P. In addition, two covers of Plexiglas G, Teflon F.E.P., and Temper Glass are considered. The data pertaining to this analysis is presented in Figures 4-5 through 4-10.

Effects of insolation variation are shown in Figures 4-5 and 4-6 for four double cover assemblies. As in the single cover analysis, the elevated temperatures required for solar cooling necessitate insolations of at least 240 Btu/hr-ft^2 (refer to Figure 4-5) with high solar absorption and low thermal emission. Unlike the single cover collector results, double cover assemblies at conditions prescribed in Figures 4-5 and 4-6 may attain temperatures near 190°F at 120 Btu/hr-ft^2 heat removal and 300 Btu/hr-ft^2 insolation with nonselective absorber surfaces. However, choice of a selective absorbing surface for 300 Btu/hr-ft^2 insolation still appears more reasonable, since the non-selective surface equilibrium temperature of 190°F allows for no fluctuation of the conditions shown. Figure 4-6 provides comparison data for the different possible arrangements of Temper Glass and Teflon F.E.P. cover materials. Because the Temper Glass has negligible infrared transmission properties, it should be employed as the inside cover panel unless the selective surface being considered has a low thermal emissivity. The trend revealed through Figure 4-6 indicates that the inner cover of the double cover assembly should be selected based on its low thermal transmissivity if optimal absorber performance is required.

FIG. 4-5
EFFECTS OF SOLAR FLUX VARIATION ON THE ABSORBER EQUILIBRIUM TEMPERATURE FOR A TWO COVER ASSEMBLY

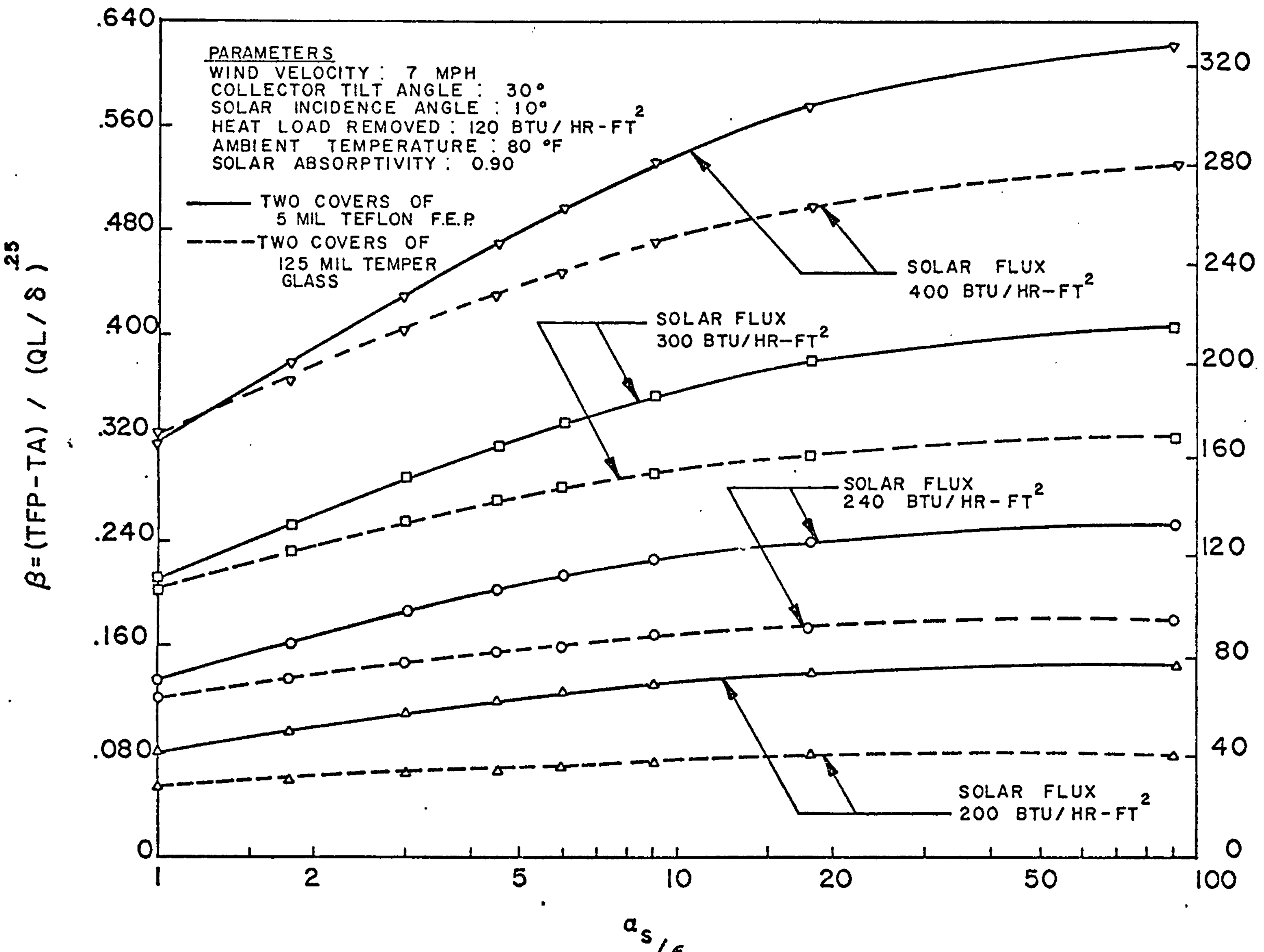
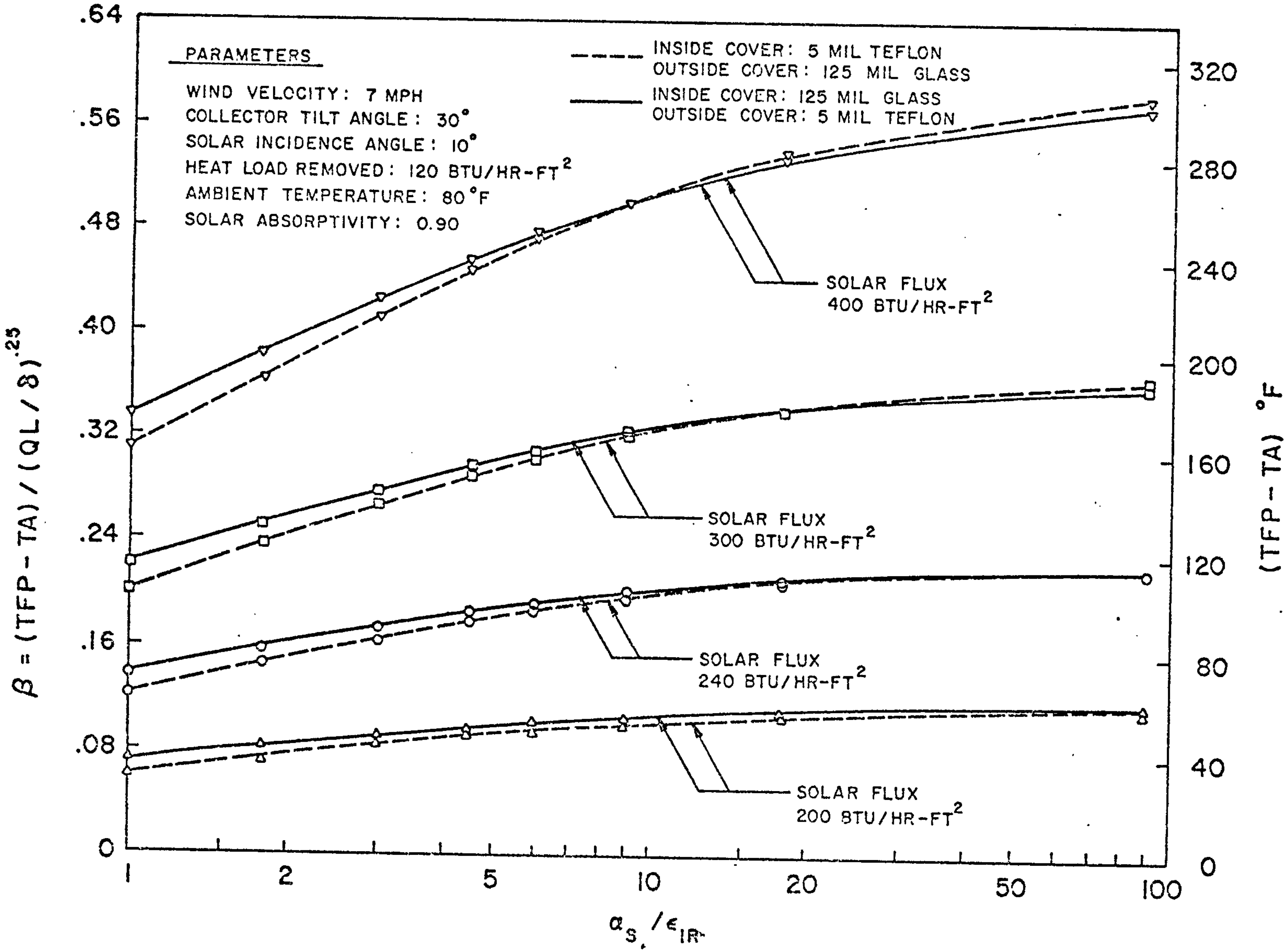


FIG. 4-6

EFFECTS OF SOLAR FLUX VARIATION ON THE ABSORBER EQUILIBRIUM TEMPERATURE FOR A TWO COVER ASSEMBLY



Variation of absorber plate solar absorptivity for a fixed insolation of 300 Btu/hr-ft^2 (shown in Figures 4-7 and 4-8), emphasizes the importance which must be placed on using materials with high values of α_s. A ten percent decrease in solar absorptivity from $\alpha_s = 1.0$ to $\alpha_s = 0.90$ for a two cover collector of Teflon F.E.P. (refer to Figure 4-7) results in an absorber plate temperature drop of 30°F, at an $\alpha_s/\varepsilon_{IR}$ ratio of 10. While such temperature drops are not so great at lower $\alpha_s/\varepsilon_{IR}$ ratios, they are none-the-less significant. Cover plate material selection is shown to be critical from results presented in Figures 4-7 and 4-8. The choice of two covers of materials like Plexiglas G or two covers like Teflon F.E.P. should be based on what type of absorbing surface is being used. While the effective solar transmissivity of two covers of Plexiglas G is lower than that of two covers of Teflon F.E.P., the fact that Plexiglas G has a low thermal transmissivity makes the Plexiglas G assembly a better alternative for $\alpha_s/\varepsilon_{IR}$ ratios below 7. Further, a collector comprised of two panels of glass with an absorber material having an $\alpha_s/\varepsilon_{IR} = 3.0$ or higher (with $\alpha_s = 1.0$) is shown in Figure 4-7 to perform not as well as the collector with two covers of Plexiglas G or Teflon F.E.P., even if the absorber material used for these covers has an $\alpha_s = 0.90$. This results because the effective solar transmission for two covers of Temper Glass is so low (approximately 70%). Figure 4-8 provides additional data substantiating use of collector materials with low infrared transmission properties for inner cover plates.

FIG. 4-7

EFFECTS OF FLAT PLATE SOLAR ABSORPTIVITY VARIATION ON THE ABSORBER EQUILIBRIUM TEMPERATURE FOR A TWO COVER ASSEMBLY

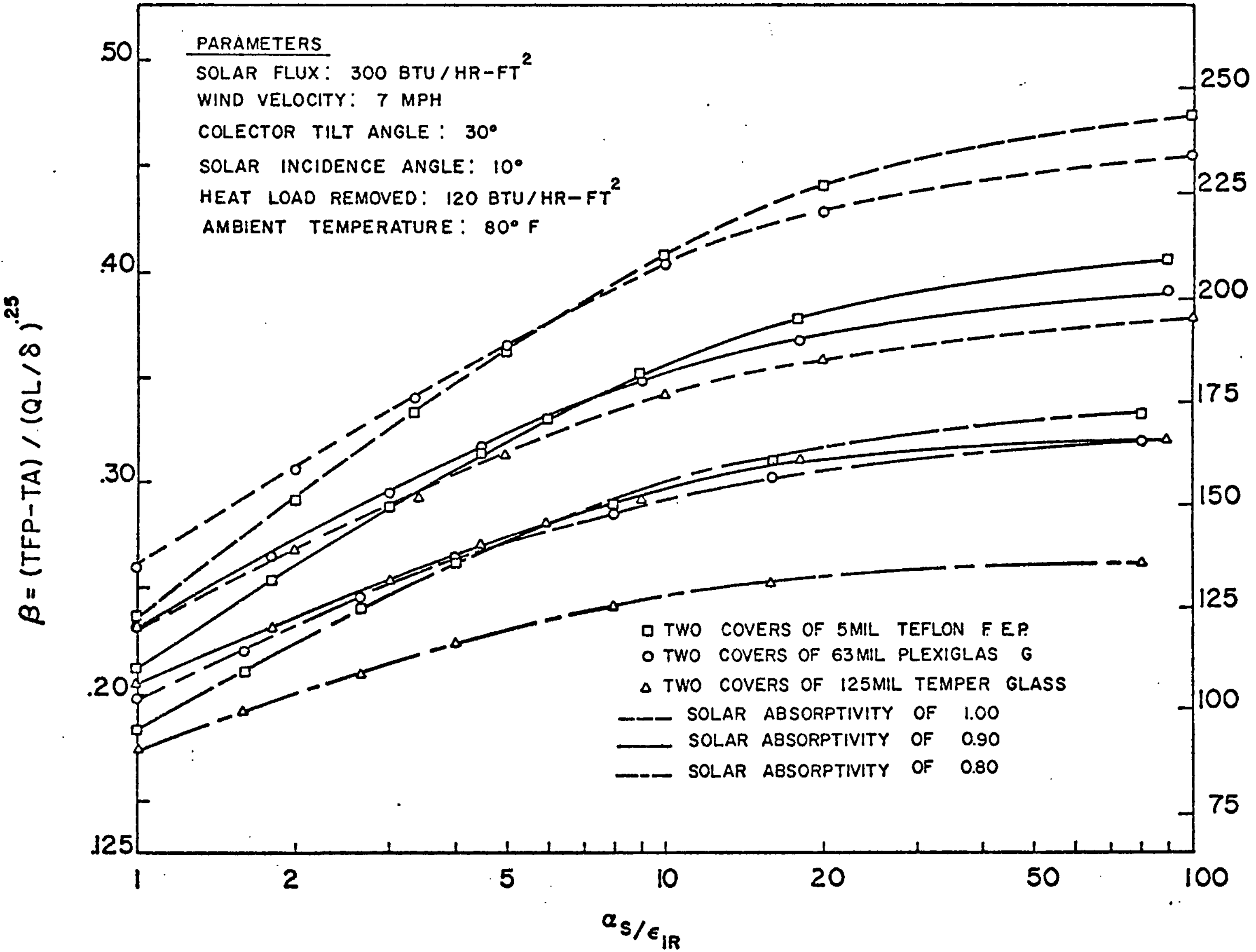
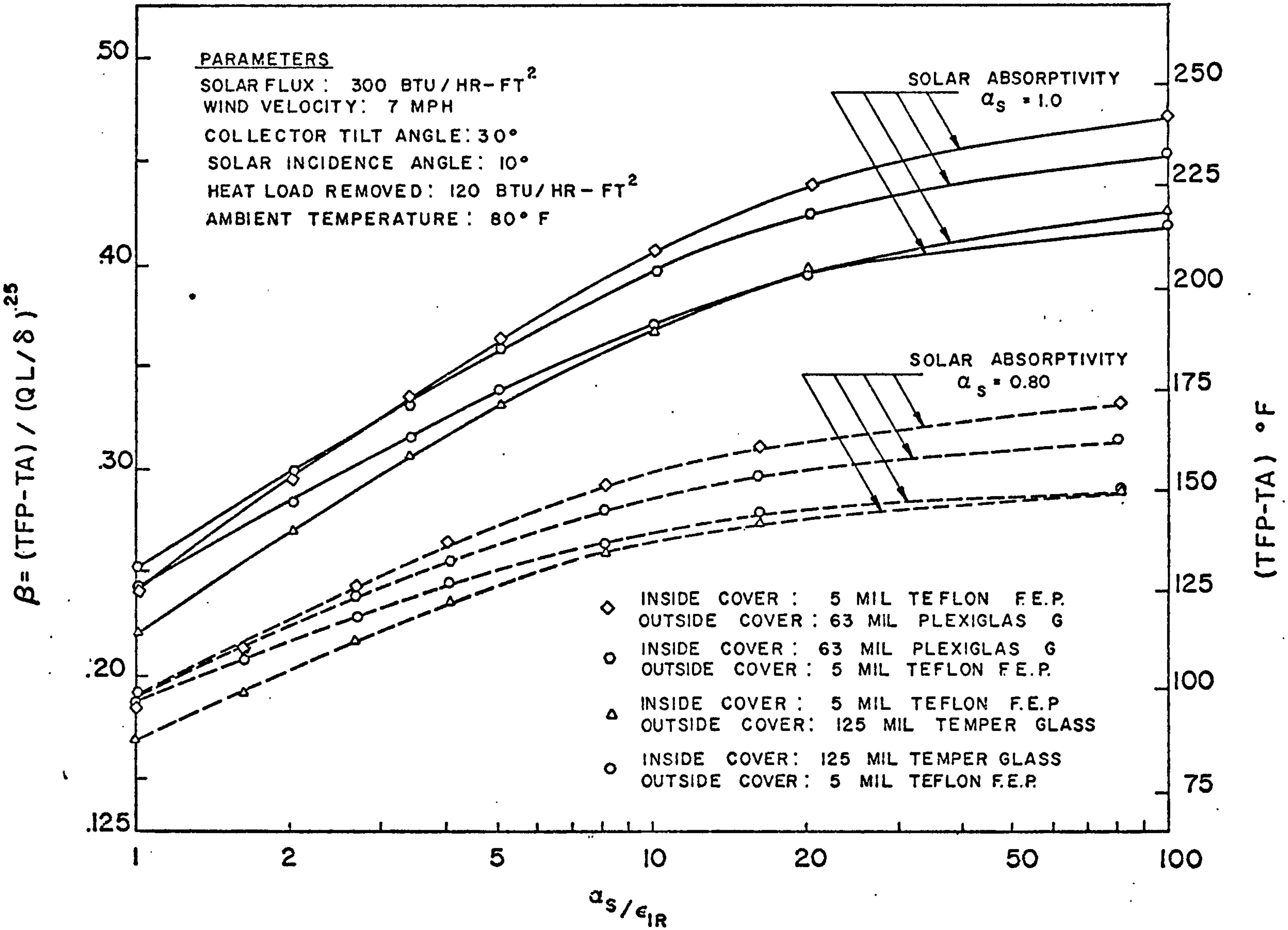


FIG. 4-8
EFFECTS OF FLAT PLATE SOLAR ABSORPTIVITY VARIATION ON THE ABSORBER EQUILIBRIUM TEMPERATURES FOR A TWO COVER ASSEMBLY



Fluctuations in wind velocity as shown in Figures 4-9 and 4-10 are found to be less critical for double cover assemblies than they were for single cover assemblies. The absorber plate temperature for a double cover of Teflon F.E.P., for example, will decrease by approximately twenty degrees Fahrenheit for a change in wind velocity from 0 mph to 14 mph for $\alpha_S = 0.90$ and $\varepsilon_{IR} = 0.01$ at an insolation of 300 Btu/hr-ft^2, while a 30°F decrease in absorber temperature occurs for the same conditions if a single cover of Teflon F.E.P. is used. The additional cover plate serves to increase absorber performance by its ability to suppress the forced convection effect using the air space between the twc covers.

The conclusions drawn from Figures 4-5 through 4-10 are expectedly similar to those formulated for single cover collectors. Space cooling utilizing heat energy obtained from double cover flat-plate collectors appears feasible. The major limitation to application of flat-plate technology for cooling appears to be the insolation available. With careful selection of cover materials and selective surfaces, this drawback can be overcome at the 120 Btu/hr-ft^2 load analyzed, so long as the insolation remains above 240 Btu/hr-ft^2.

Comparison of Single and Double Cover Collectors

Performance analyses on single and double cover flat-plate assemblies have indicated that space cooling applications for flat-plate technology are feasible. While economic and durability

FIG. 4-9

EFFECTS OF OUTSIDE WIND VELOCITY ON THE ABSORBER EQUILIBRIUM TEMPERATURE FOR A TWO COVER ASSEMBLY

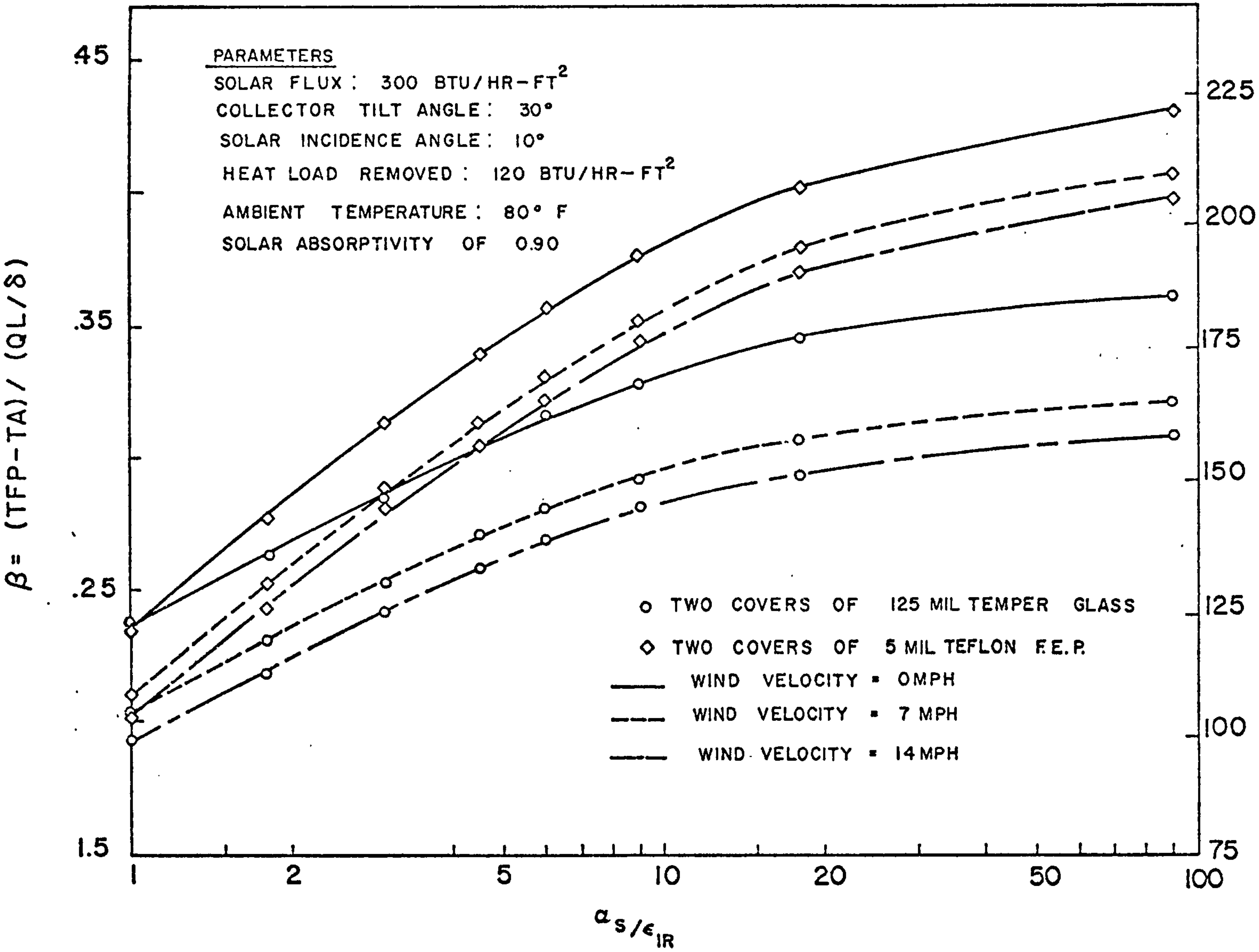
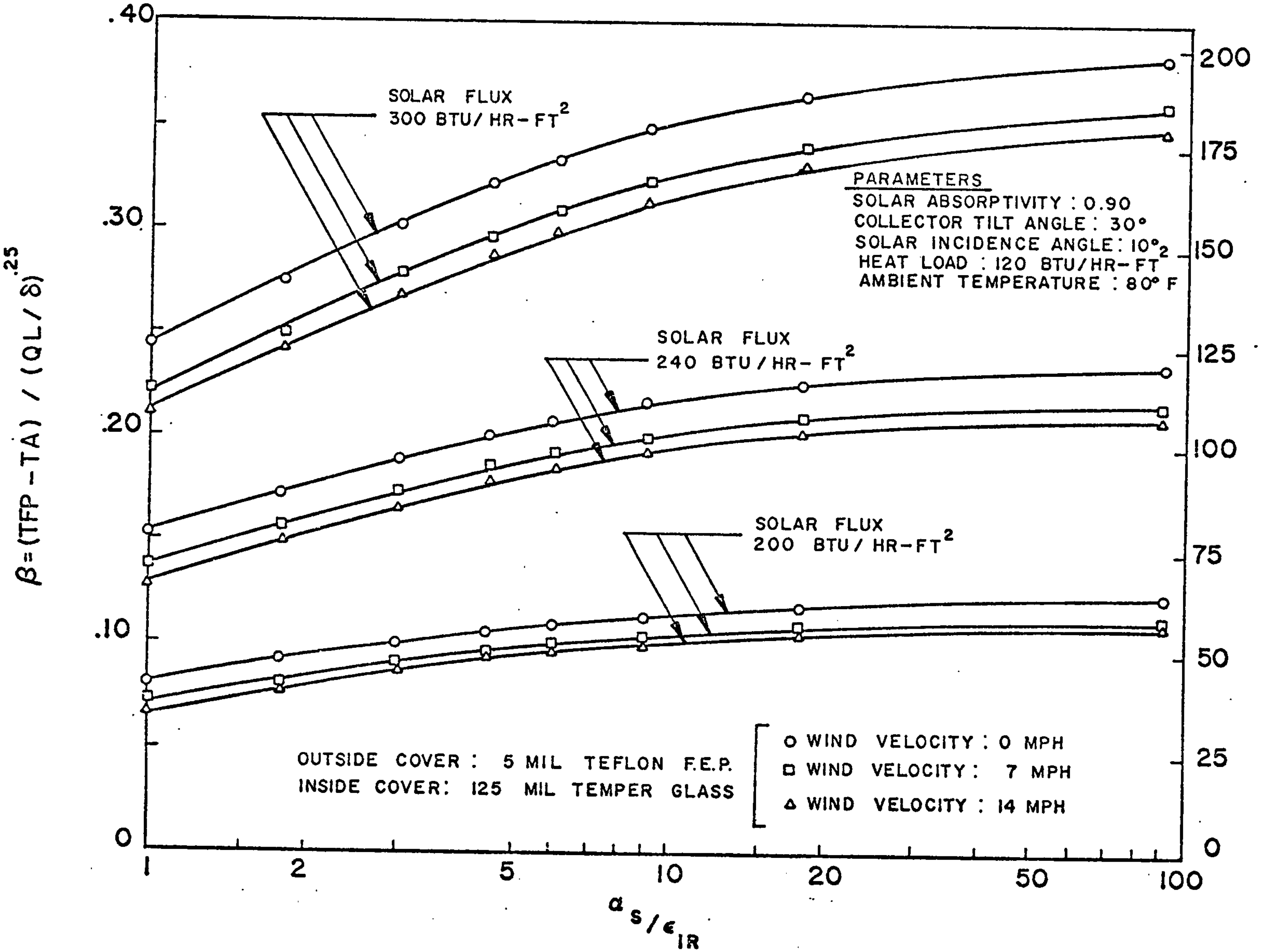


FIG. 4-10
EFFECTS OF OUTSIDE WIND VELOCITY ON THE ABSORBER EQUILIBRIUM TEMPERATURE FOR A TWO COVER ASSEMBLY



constraints may affect the choice between one or two covers, performance comparisons must also be considered. Such comparisons can be made based on conclusions drawn from Figure 4-11 and Figure 4-12. Figure 4-11 compares single and double cover collector assemblies of Teflon F.E.P. and glass at 300 Btu/hr-ft^2 insolation, and Figure 4-12 compares single and double cover assemblies of Teflon F.E.P. for two wind velocities and two insolations.

It is shown from Figure 4-11 that collectors with two covers attain higher absorber plate equilibrium temperatures than do single cover collectors under the same conditions. In fact, from Figure 4-11, it can be seen that under the conditions of 300 Btu/hr-ft^2 insolation and 7 mph wind velocity, the two single cover collectors attain the lowest absorber temperatures if the $\alpha_s/\varepsilon_{IR}$ ratio (with $\alpha_s = 0.90$) is below 5.0. This indicates that for higher performance requirements (above 120 Btu/hr-ft^2 loads or above 190°F absorber temperatures) double cover collector assemblies may emerge as the only design option if flat-plate technology is to be incorporated. Further justification of this concept can be found in analyzing Figure 4-12. Wind velocity variations are shown to have less effect on double cover assemblies of Teflon F.E.P. than on single Teflon F.E.P. cover collectors.

As has been shown, the incorporation of selective absorbing surfaces and high solar transmitting covers makes space cooling using flat-plate technology possible. The performance of double

FIG. 4-11
COMBINATIONS OF GLASS AND TEFLON AS
SINGLE AND DOUBLE COVER PLATE ASSEMBLIES

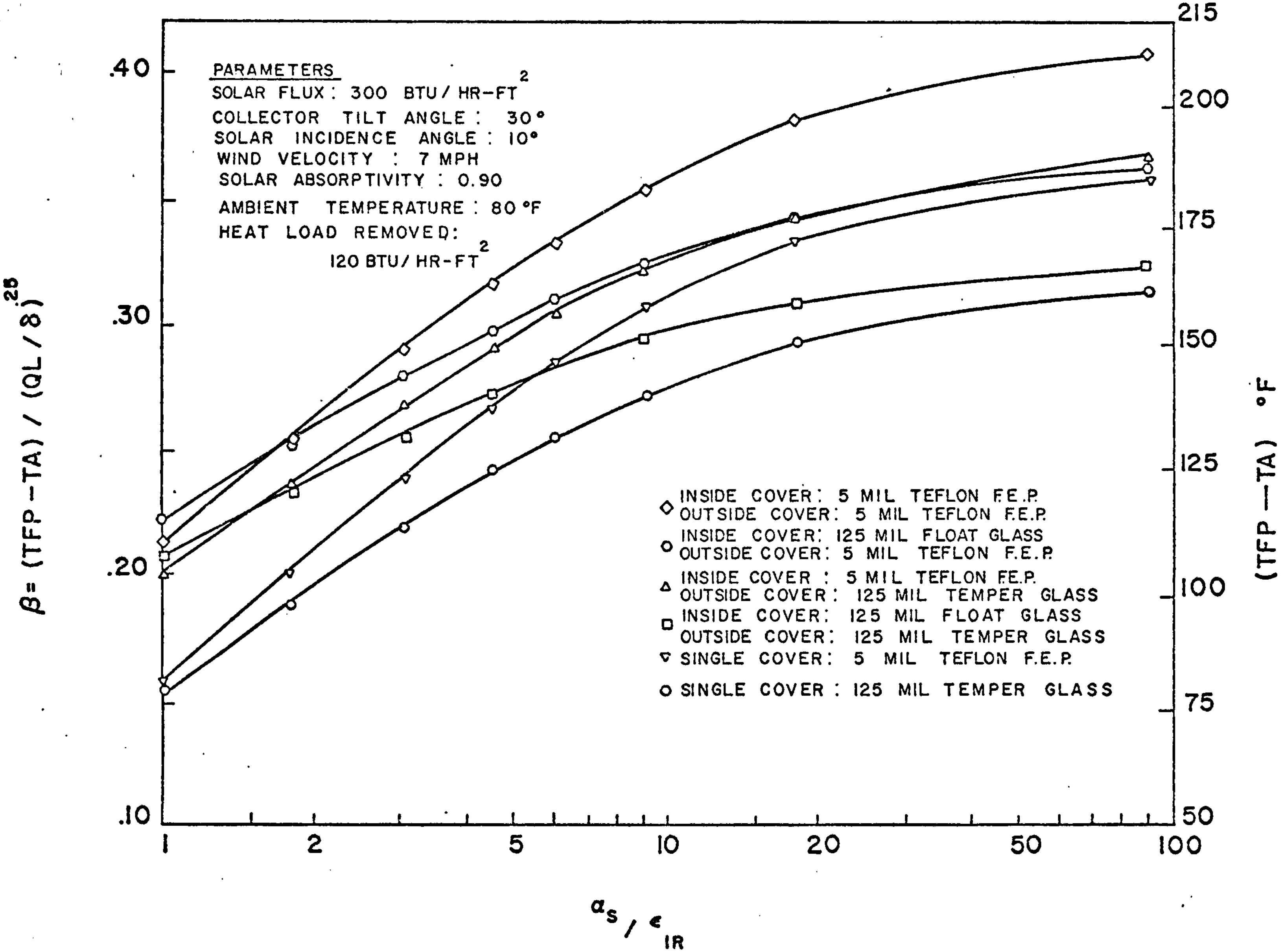
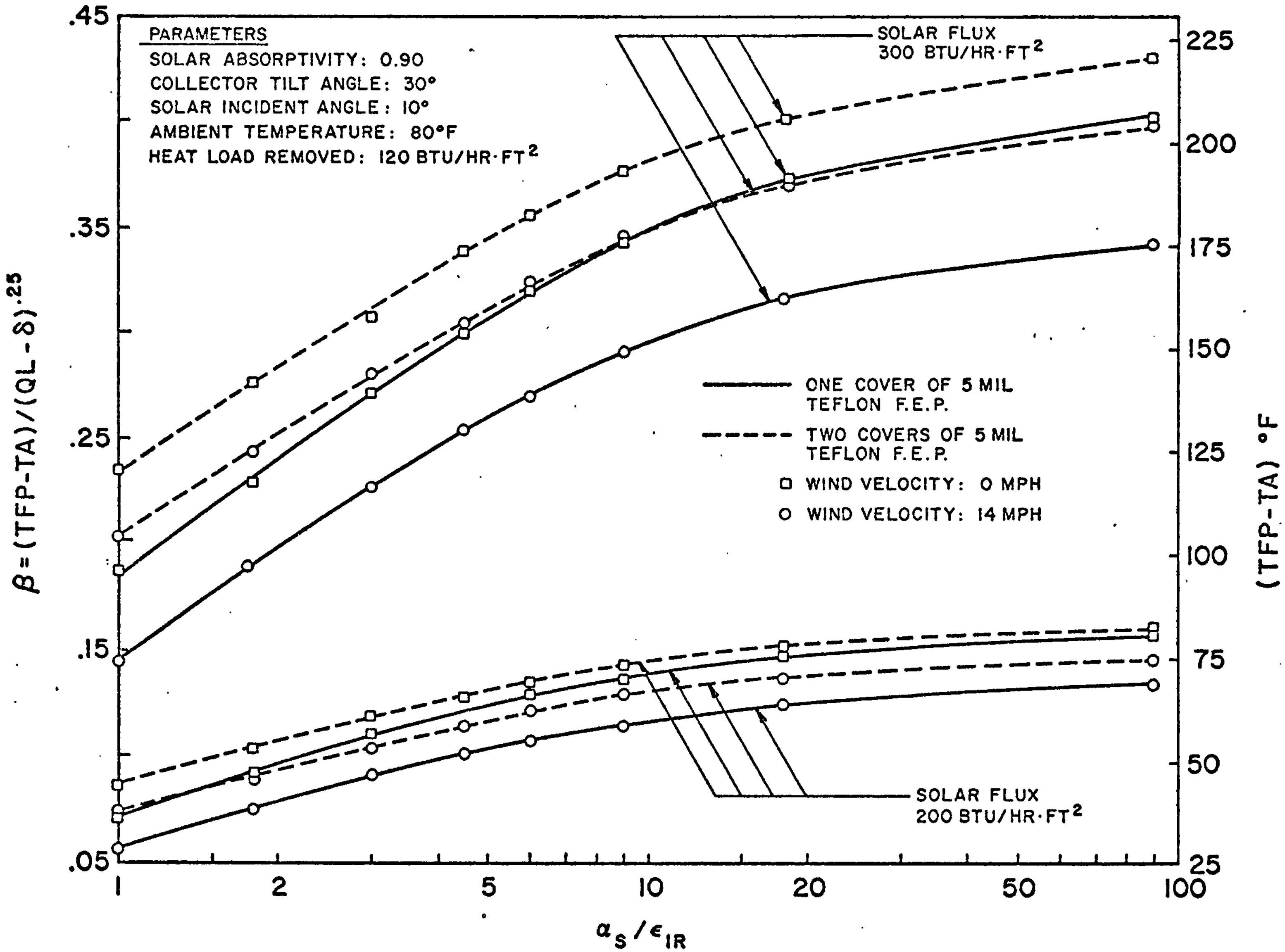


FIG. 4-12
COMPARISON OF SINGLE AND DOUBLE COVER ASSEMBLIES OF TEFLON F.E.P.



cover collectors is superior to that of single cover collectors if all other conditions are held constant. Both single and double cover flat-plate collectors, however, can provide sufficient heat for solar cooling.

Chapter Five

THE COMPUTER SIMULATION

Introduction

The selection of optimal flat-plate solar collectors will be accomplished through a computer analysis employing the collector material coded in Chapter Two. From conclusions obtained in the flat-plate collector performance chapter, the feasibility of attaining suitable absorber equilibrium temperatures at elevated heat removals for absorption refrigeration air conditioning has been established. Questions concerning collector cost, weight, durability, and expected life cycles must also be considered in the total design analysis, however, since performance considerations alone will not provide acceptable marketable products. Only the most durable high performance flat-plate assemblies must be chosen, and of these, only the most inexpensive will probably prove acceptable for consumer use.

The computer simulation will select flat-plate collectors that meet the consumer demands through a two step procedure. The first step will be a constraint analysis, which will be employed to eliminate solar collector designs that cannot meet performance, durability, and economic restrictions imposed. The second step will be an optimization analysis, which will select only the best of the acceptable flat-plate solar collector designs. Since different importance may be placed on economics, performance, and durability, the optimization will be accomplished through use of a criterion function analysis. This type of optimization procedure allows the designer to emphasize that part of the design (e.g., cost or durability) which he considers most critical to consumer acceptance.

Chapter Five will be divided into two sections: the constraint analysis and the criterion function. The first section will discuss the problems associated with flat-plate collector design. Constraints employed in the selection of acceptable assemblies will be chosen based on these problems. The second section will give background for use of the criterion function and will define the components which make up this optimization tool.

FLAT-PLATE SOLAR COLLECTOR CONSTRAINTS

The design of acceptable flat-plate solar collectors should be based on three criteria: cost, durability, and performance. While these criteria may be treated separately, the overall design must consider their integrated effect. First, the cost of the solar energy collecting assembly is critical. Unless the cost of solar implementation is competitive with that of conventional energy sources, acceptance of the new energy source will be limited. Second, the durability of the flat-plate collector system is important. The large initial capital expenditure required in a solar installation requires a long pay-back period - usually ten to fifteen years. Therefore, small incremental additional costs associated with increased collector life expectancy are justified up to a point. Third, the requirement of good performance in the form of high collector temperatures and high efficiency is necessary. In summary, a good solar collector, like a component of any good system, is the result of a complete engineering analysis which balances performance against cost. The omission of any of the three criteria - cost, performance, or durability - renders solar energy utilization unfeasible when compared with present time-proven energy alternatives.

In order to satisfy cost, durability and performance requirements, constraints must be chosen which can be used to design flat-plate collector assemblies. Though the flat-plate configuration is simple in design, numerous limitations based upon operation under no load and heat load removal conditions must be considered. For the purpose of discussion, these restrictions are divided into four sections: weather and geometry constraints, material constraints, performance constraints, and overall assembly constraints.

Weather and Geometry Constraints

The flat-plate solar collector assemblies to be designed are expected to function in typical Houston weather conditions. For operation at required performance levels, hourly weather fluctuations are not considered due to limited computer memory and insufficient weather data. However, for the sake of analysis, average Houston summer conditions have been obtained from the U. S. Weather Service. This information is shown in Table 5-1 and provides all necessary data except for average hourly insolation. The incident solar flux values to be used must include both the direct and diffuse elements of insolation, since they were not treated separately in the heat balance derivations. The solar flux information employed comes from consideration of data provided by the Southwest Research Institute [5-1] and by the U. S. Weather Service in San Antonio, Texas [5-2] and may be up to fifteen percent in error due to location, weather and pollution differences between Houston and San Antonio [5-3]. Therefore, in considering average incident solar fluxes for

Table 5-1

AVERAGE SUMMER WEATHER DATA FOR HOUSTON, TEXAS*

Information	May	June	July	August	September
Average Daily Temperature High (°F)	86	91	94	94	90
Average Daily Temperature Low (°F)	66	71	73	72	68
Highest Temperature Achieved (°F)	93	99	101	101	97
Lowest Temperature Achieved (°F)	46	52	62	62	51
Average Daily Wind Velocity (mph)	7.5	7.0	6.3	5.1	6.8
Highest Wind Velocity (mph)	36	45	46	32	35
Lowest Wind Velocity (mph)	0	0	0	0	0
Average Number of Overcast Days	13	10	10	11	14
Average Monthly Rainfall (inches)	5.01	4.52	4.21	4.35	4.65

*Information provided by the United States Weather Service.

Houston, conservative estimates of insolation are employed to allow for over design of acceptable solar collector systems. Average insolation data and other weather information is provided in Table 5-2.

Table 5-2

AVERAGE SUMMER CONDITIONS FOR

HOUSTON, TEXAS

Ambient Temperature:	80°F
Black Body Sky Temperature:	70°F
Wind Velocity:	7 m.p.h.
Incident Solar Flux:	280 Btu/hr-ft^2
Incident Solar Flux Angle:	10° Off Normal

In addition, since the durability of the collector assembly is critical, extreme summer conditions should be accounted for. The solar collector design is based upon a no heat removal condition such as would occur during collector installation or pump breakdown and associated system failure. The collector equilibrium temperatures are maximized at this point. If above average weather conditions occur, this may cause components of the flat-plate collector to deteriorate because of temperature extremes. Thus, for the protection of the assembly, the design of the collector is based on no heat removal-extreme summer condition criteria.

Two extreme summer weather conditions are provided in Table 5-3. The difference between the two data sets is the solar insolation and the corresponding ambient temperature. While the more extreme conditions insure that the collector will be protected in the event of no heat removal from the absorber panel, the cost may also be significantly higher as only the most durable components can be employed. Since the no heat removal case is to occur seldom, application of the lesser summer constraints may allow for less expensive assemblies which can provide suitable heat for solar air conditioning. Both sets of extreme summer weather conditions will be studied to see how significant the no load-extreme summer condition is on assembly cost.

Table 5-3

EXTREME SUMMER CONDITIONS FOR

HOUSTON, TEXAS

<u>More Restrictive Conditions</u>

Ambient Temperature:	95°F
Black Body Sky Temperature:	84°F
Wind Velocity:	0 m.p.h.
Incident Solar Flux:	350 Btu/hr-ft^2
Incident Solar Flux Angle:	0° (Normal)

<u>Less Restrictive Conditions</u>

Ambient Temperature:	80°F
Black Body Sky Temperature:	70°F
Wind Velocity:	0 m.p.h.
Incident Solar Flux:	300 Btu/hr-ft^2
Incident Solar Flux Angle:	0° (Normal)

A final point which should be considered concerns the geometric orientation of the flat-plate assembly. The intent of the collector tilt is to allow maximum near-normal solar flux incidence. Based upon actual flat-plate assemblies in operation in Houston, a thirty degree tilt angle has been selected. While this angle is not optimal for solar cooling, the flat-plate orientation of thirty degrees will serve efficiently for both summer cooling and winter heating. Also, an average angle of solar flux incidence should be included since hourly incident fluxes are not treated in the analysis. An average incidence angle of direct insolation during the period of four hours before and after solar noon when most solar energy absorption occurs can not be chosen without consideration of the diffuse solar component. This occurs because the total solar incident flux includes the direct and diffuse terms together in the heat balance derivations. A second point which complicates the choice of the solar flux incidence angle is that the material data being studied is based on normal incidence angles. Beyond a twenty degree off-normal angle, the transmission and reflection data is inaccurate and cannot be employed in the heat balance analyses. Therefore, for the work presented, a near-normal incidence angle of ten degrees will be employed for average summer conditions. For the extreme summer condition, normal incidence will be assumed in order to provide maximum solar fluxes for the analysis of a no heat removal condition.

Material Constraints

The most critical part of the flat-plate solar collector is the cover assembly. The cover must not only be lightweight and inexpensive, but must also protect the often not so durable absorbing surface. Further, it should transmit solar energy while retarding most re-radiation of thermal energy. The cover also must be able to withstand temperature fluctuations and temperature extremes resulting from no wind and no heat removal situations. As such, the cover assembly is emphasized in the constraint analysis, since its function is so important.

In general, single and double cover panels must be designed to withstand average weathering and impact loading situations such that the integrity of the collector assembly is maintained. As was indicated earlier in the materials section, consideration of weatherability and impact strength must be accomplished arbitrarily, since the materials are so different in physical appearance and chemical makeup. Nonetheless, by considering average and above average values of weathering and impact resistance, the assembly should prove acceptable to most environments. Therefore, in considering single cover assemblies, impact resistances of 2.5 and 2.75 were studied with weathering values of 2.5 and 2.75 for a range of four cover equilibrium temperatures (150, 175, 200 and 225°F). This data can be found in Table 5-4 comparing temperature, impact resistance, and weatherability with cost per square foot and in Table 5-5 comparing the same parameters with weight per square foot.

By reviewing the data provided, it becomes apparent that the equilibrium temperature of the cover and the cover impact

Table 5-4

ACCEPTABLE SINGLE COVER PLATE ASSEMBLIES BASED ON COST

TLIM	WETH-IMPR	COST IN DOLLARS PER SQUARE FOOT											
(°F)	(Coded)	3.00	2.75	2.50	2.25	2.00	1.75	1.50	1.25	1.00	0.75	0.50	0.25
225	2.75-2.75	12	11	11	10	10	10	9	9	5	4	1	1
	2.75-2.5	15	14	14	13	13	12	12	12	8	6	1	1
	2.5-2.75	12	11	11	10	10	10	9	9	5	4	1	1
	2.5-2.5	15	14	14	13	13	12	12	12	8	6	1	1
200	2.75-2.75	16	15	15	14	13	11	11	10	5	4	1	1
	2.75-2.5	22	21	21	20	19	16	16	15	9	7	2	1
	2.5-2.75	16	15	15	14	13	11	11	10	5	4	1	1
	2.5-2.5	22	21	21	20	19	16	16	15	9	7	2	1
175	2.75-2.75	16	15	15	14	13	11	11	10	5	4	1	1
	2.75-2.5	22	21	21	20	19	16	16	15	9	7	2	1
	2.5-2.75	16	15	15	14	13	11	11	10	5	4	1	1
	2.5-2.5	22	21	21	20	19	16	16	15	9	7	2	1
150	2.75-2.75	16	15	15	14	13	11	11	10	5	4	1	1
	2.75-2.5	22	21	21	20	19	16	16	15	9	7	2	1
	2.5-2.75	16	15	15	14	13	11	11	10	5	4	1	1
	2.5-2.5	22	21	21	20	19	16	16	15	9	7	2	1

Constraint Code

TLIM: Minimum Cover Temperature
WETH: Minimum Cover Weatherability
IMPR: Minimum Cover Impact Resistance

Other Constraints

Maximum Weight Per Square Foot: 3 lb.
Minimum Visible Transmissivity: 0.70
Maximum Infrared Transmissivity: 0.30

Table 5-5

ACCEPTABLE SINGLE COVER PLATE ASSEMBLIES
BASED ON WEIGHT

TLIM	WETH-IMPR	WEIGHT IN POUNDS PER SQUARE FOOT								
(°F)	(Coded)	3.0	2.5	2.0	1.5	1.0	0.5	0.25	0.15	0.05
225	2.75-2.75	12	10	7	7	6	4	2	2	1
	2.75-2.5	15	12	9	7	6	4	2	2	1
	2.5-2.75	12	10	7	7	6	4	2	2	1
	2.5-2.5	15	12	9	7	6	4	2	2	1
200	2.75-2.75	16	14	11	11	8	4	2	2	1
	2.75-2.5	22	19	16	14	11	7	2	2	1
	2.5-2.75	16	14	11	11	8	4	2	2	1
	2.5-2.5	22	19	16	14	11	7	2	2	1
175	2.75-2.75	16	14	11	11	8	4	2	2	1
	2.75-2.5	22	19	16	14	11	7	2	2	1
	2.5-2.75	16	14	11	11	8	4	2	2	1
	2.5-2.5	22	19	16	14	11	7	2	2	1
150	2.75-2.75	16	14	11	11	8	4	2	2	1
	2.75-2.5	22	19	16	14	11	7	2	2	1
	2.5-2.75	16	14	11	11	8	4	2	2	1
	2.5-2.5	22	19	16	14	11	7	2	2	1

<u>Constraint Code</u>

TLIM: Minimum Cover Temperature
WETH: Minimum Cover Weatherability
IMPR: Minimum Cover Impact Resistance

<u>Other Constraints</u>

Maximum Cost Per Square Foot: 3.00
Minimum Visible Transmissivity: 0.70
Maximum Infrared Transmissivity: 0.30

resistance strongly influence the number of acceptable cover candidates. Further, the choice of 2.5 or 2.75 for weatherability is shown to be unimportant. Since the impact resistance parameter is more critical, the lesser value of 2.5 will be employed, also, to allow for more cover assemblies in the analysis. Because the assembly cost is critical, a maximum cost of two dollars per square foot will be specified. Further, the maximum weight parameter of 3 pounds per square foot will be acceptable for preliminary analysis. The cover temperature must also be preliminarily specified. This temperature is dependent upon the no load-extreme Houston summer conditions described earlier. Based upon data obtained from early performance computer analysis, this limiting equilibrium temperature is set at 175°F. All single cover constraint data is shown in Table 5-6.

The problems associated with single cover constraint assignment balloon as multiple cover plates are considered. The pairing of thirty-one cover materials results in 961 possible cover assemblies. The task of analyzing each of these systems with five copper and eight aluminum absorbing surfaces is staggering. In fact, the computer employed cannot accept such massive data storage. Therefore, cover constraint analysis is essential to limiting the number of applicable two-cover combinations.

From the work done on single cover plates, it was decided to assign a minimum outside cover weatherability constraint of 2.5. The inside cover, while not subjected to wind loading and chemical environments, still experiences ultraviolet degradation

Table 5-6

MINIMUM SINGLE AND DOUBLE

COVER PLATE PERFORMANCE CONSTRAINTS

Single Cover Plate Constraints

Minimum Visible Transmissivity:	0.70
Maximum Infrared Transmissivity:	0.30
Minimum Coded Weatherability:	2.5
Minimum Coded Impact Resistance:	2.5
Minimum Temperature (°F):	175.0
Maximum Cost ($/ft^2):	2.00
Maximum Weight (lb./ft^2):	3.00

Double Cover Plate Constraints:

Minimum Visible Transmissivity:	0.65
Maximum Infrared Transmissivity:	0.30
Minimum Coded Weatherability (Outer Cover):	2.5
Minimum Coded Weatherability (Inner Cover):	2.0
Minimum Coded Impact Resistance (Outer Cover):	2.75
Minimum Coded Effective Impact Resistance:	2.5
Minimum Temperature (Outer Cover) (°F):	175.0
Minimum Temperature (Inner Cover) (°F):	225.0
Maximum Total Cost ($/ft^2):	2.50
Maximum Total Weight (lb./ft^2):	4.00

and may face typical weathering problems should the outside cover be damaged. Therefore, a minimum weatherability constraint of 2.0 for the inner cover will be required.

An additional impact resistance constraint should be defined at this point. This constraint, the effective impact resistance for a two cover system, is based upon the fact that a major purpose of the cover assembly is to protect the absorbing surface. Since the outside cover is to provide the majority of the protection, 'EFFIM', the effective impact resistance, will be defined as follows:

$$\mathrm{EFFIM} = (2.0 \times \mathrm{IMPR}_{\substack{\text{outside}\\ \text{cover}}} + \mathrm{IMPR}_{\substack{\text{inside}\\ \text{cover}}})/3.0 \qquad (5.1)$$

In considering impact resistance, then, the two parameters of 'IMPR' and 'EFFIM' should be studied. In an attempt to limit the two cover assembly totals, average and above average impact codes of 2.5 and 2.75 were studied at various inside and outside cover temperature levels and are presented in Table 5-7, shown for various costs, and in Table 5-8 shown for various total weights.

As can be seen by Tables 5-7 and 5-8, the number of candidate systems has been substantially reduced by the application of constraints listed, though the totals are still over computer limitations. Since a major desire is to develop a collector cover which is impact resistant, an outer cover constraint of 2.75 is selected while the effective cover impact strength constraint is chosen to be comparable to that of the single cover, i.e., 2.5. In addition, temperature constraints of 225°F and 175°F were

Table 5-7

ACCEPTABLE DOUBLE COVER PLATE ASSEMBLIES BASED ON COST

TLIM1-TLIM2	IMPR-EFFIM	TOTAL COST FOR COVER ASSEMBLY IN DOLLARS PER SQUARE FOOT															
(°F)	(Coded)	4.00	3.75	3.50	3.25	3.00	2.75	2.50	2.25	2.00	1.75	1.50	1.25	1.00	0.75	0.50	0.25
200-150	2.5-2.5	525	498	479	451	404	370	331	266	224	172	104	65	25	10	1	0
	2.5-2.75	443	416	398	370	324	295	258	204	165	118	68	45	16	8	1	0
	2.75-2.5	395	372	356	332	294	267	239	191	156	120	71	45	21	8	1	0
	2.75-2.75	369	246	330	306	268	242	214	166	132	96	54	35	13	6	1	0
225-175	2.5-2.5	365	249	335	316	288	267	246	209	179	139	86	54	20	8	1	0
	2.5-2.75	312	296	282	263	235	216	196	164	136	99	59	39	14	6	1	0
	2.75-2.5	277	263	251	235	213	196	179	150	125	95	57	37	17	6	1	0
	2.75-2.75	259	245	233	217	195	178	161	132	107	77	45	29	11	4	1	0
250-200	2.5-2.5	342	326	313	294	266	246	226	190	163	123	71	43	13	5	0	0
	2.5-2.75	289	273	260	241	213	195	176	145	120	83	44	28	77	3	0	0
	2.75-2.5	260	246	235	219	197	181	165	137	114	84	47	30	13	5	0	0
	2.75-2.75	242	228	217	201	179	163	147	119	96	66	35	22	7	3	0	0
275-225	2.5-2.5	168	164	161	153	143	137	134	127	118	98	62	37	13	5	0	0
	2.5-2.75	142	138	135	127	117	111	108	101	92	73	41	26	7	3	0	0
	2.75-2.5	141	137	134	126	116	110	107	100	91	75	45	29	13	5	0	0
	2.75-2.75	127	123	120	112	102	96	93	86	77	61	33	21	7	3	0	0

<u>Constraint Code</u>

TLIM1: Minimum Inside Cover Temperature
TLIM2: Minimum Outside Cover Temperature
IMPR: Minimum Outside Cover Impact Resistance
EFFIM: Minimum Effective Cover Impact Resistance

<u>Other Cover Constraints</u>

Minimum Outside Cover Weatherability: 2.5
Minimum Inside Cover Weatherability: 2.0
Maximum Weight Per Square Foot: 5.0 lb.
Minimum Visible Transmissivity: 0.65
Minimum Infrared Transmissivity: 0.30

Table 5-8

ACCEPTABLE DOUBLE COVER PLATE ASSEMBLIES BASED ON WEIGHT

TLIM1-TLIM2	IMPR-EFFIM	TOTAL WEIGHT IN POUNDS PER SQUARE FOOT												
(°F)	(Coded)	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.25	0.15	0.05
200-150	2.5-2.5	525	510	473	429	372	287	214	155	73	26	6	4	0
	2.5-2.75	443	432	403	362	318	245	185	142	63	26	6	4	0
	2.75-2.5	395	380	355	314	269	202	152	116	52	20	6	4	0
	2.75-2.75	369	358	341	300	257	193	149	115	51	20	6	4	0
225-175	2.5-2.5	365	350	313	279	233	169	111	72	40	18	4	4	0
	2.5-2.75	312	301	272	241	208	153	102	72	40	18	4	4	0
	2.75-2.5	277	262	237	206	172	120	77	54	28	12	4	4	0
	2.75-2.75	259	248	231	200	168	116	75	54	28	12	4	4	0
250-200	2.5-2.5	342	327	290	256	210	148	93	57	29	11	2	2	0
	2.5-2.75	289	278	249	218	185	132	84	57	29	11	2	2	0
	2.75-2.5	260	245	220	189	155	105	65	42	20	8	2	2	0
	2.75-2.75	242	231	214	183	151	101	63	42	20	8	2	2	0
275-225	2.5-2.5	168	153	116	102	80	50	22	7	6	4	2	2	0
	2.5-2.75	142	131	102	91	78	48	20	7	6	4	2	2	0
	2.75-2.5	141	126	101	90	77	47	19	7	6	4	2	2	0
	2.75-2.75	127	116	99	88	75	45	17	7	6	4	2	2	0

Constraint Code

TLIM1: Minimum Inside Cover Temperature
TLIM2: Minimum Outside Cover Temperature
IMPR: Minimum Outside Cover Impact Resistance
EFFIM: Minimum Effective Cover Impact Resistance

Other Cover Constraints

Minimum Outside Cover Weatherability:	2.0
Minimum Inside Cover Weatherability:	2.0
Maximum Cost Per Square Foot:	$4.00
Minimum Visible Transmissivity:	0.65
Maximum Infrared Tramsmissivity:	0.30

previously obtained from no load-extreme summer condition preliminary performance data. Since economics is so critical, however, the candidate totals can best be limited through consideration of cost. Based upon the above chosen temperature, weather, and impact constraints, total costs of \$2.75, \$2.50, \$2.25, and \$2.00 per square foot were considered versus total weight. From this data shown below, a maximum cost per square foot of \$2.50 and a maximum weight of 4.0 pounds per square foot are chosen as constraints. All double cover constraint data is summarized in Table 5-9.

Table 5-9

DOUBLE COVER CANDIDATE TOTALS BASED ON TOTAL COST AND WEIGHT CONSTRAINTS

COST	TOTAL WEIGHT IN POUNDS PER SQUARE FOOT						
$/ft^2$	5.0	4.5	4.0	3.5	3.0	2.5	2.0
2.75	196	181	156	142	122	83	45
2.50	179	164	139	130	110	73	39
2.25	150	135	110	103	96	64	32
2.00	125	113	88	83	79	51	26

By consideration of the cover assemblies prior to actually matching absorbers with covers, a reduction in single cover candidates from thirty-one to nineteen resulted. In the two cover case, only 139 systems appear feasible for further design con-

consideration out of the original 961 candidates, if the outside cover plate temperature minimum is 175°F and the inside cover temperature limitation is 225°F.

While the preliminary cover constraint analysis serves to limit applicable systems, each combination of cover, absorber, and insulation material must be studied together. The intent of the compilation of materials was to provide different materials for construction of solar collectors. In order to decide which components may be matched, performance at elevated heat removals is critical. Possibly more important, however, may be insuring that the materials will not fail under elevated temperatures or weather extremes. By employing the extreme summer weather data under no heat load conditions, maximum equilibrium temperatures for the cover(s), absorbing surface, and insulation may be reached. The ability of all three components to survive the elevated temperatures virtually assures that the combination of materials is compatible.

The no load-severe summer weather constraint may seem to be one of over design. However, since durability and long expected lives are required for the collector assembly, the no load removal constraint is not so unusual. Further, the integrity of the products offered to the consumer is essential to furthering public interest. While the cost of the resulting assemblies may be slightly higher, product guarantees may influence consumer implementation.

Three other material constraints must be included. In the interest of minimizing the size and weight of the flat-plate collector, maximum limitations on insulation thickness and weight are chosen. These two constraints are five inches and three pounds per square foot. Finally, while the cover assembly is designed to protect the absorbing surface, the durability of the absorber material should also be considered. With suitable sealing of the collector and with the addition of desicants within the assembly, moisture problems should be limited. As such a minimum absorber durability constraint of 2.0 will be considered acceptable.

Performance Constraints

The primary intent of the work undertaken has been to attain equilibrium absorber temperatures suitable for absorption air conditioning. Pursuant to this purpose, technical data from Arkla Industries, Inc., was obtained on Solaire, a lithium-bromide absorption air conditioning system presently marketed in three ton and twenty ton cooling load sizes. These two air conditioning units can provide cooling capacity for single family dwellings and for multi-unit apartments, and moderate sized shopping and office buildings. With conventional energy costs rising, such commercial and residential air conditioning markets can be captured by solar cooling if required performance constraints can be met.

The Solaire models considered employ hot water as the heat source and require that the inlet water temperature should be at minimum 190°F and at maximum 245°F. Since temperatures below 190°F will not provide enough heat to allow efficient operation of the refrigeration process, the Solaire system has a natural gas fired water heater to provide supplemental energy. Pertinent data on the lithium-bromide absorption units is provided below.

Table 5-10

SPECIFICATIONS FOR ARKLA SOLAIRE

AIR CONDITIONING UNITS

OPERATION DATA	Model 501-WF	Model WF-300
Hot Water Input (Btu/hr)	55,000	435,000
Delivered Capacity (Btu/hr)	36,000	300,000
Hot Water Inlet Temperature (°F)	210	225
Hot Water Flow (gpm)	11	60
Maximum Permissible Flow (gpm)	22	90
Pressure Drop (feet of water)	4.6	9.5
Heat Rejection (Btu/hr)	91,000	735,000

For analysis purposes, two heat loads are selected that will be large enough that collector size can be limited. These loads are 120 Btu/hr-ft^2 and 150 Btu/hr-ft^2. For the average incident flux of 280 Btu/hr-ft^2 being considered, the loads correspond to efficiencies of 42.9% and 53.6% respectively (efficiency is defined as the ratio of the heat load per square foot per hour removed to the incident solar flux). Further, minimum temperature levels are assigned for each operating load to provide hot water for solar air conditioning. For single cover flat-plate assemblies, the absorber plate temperature must be 190°F or higher. For double cover flat-plate assemblies, a slighter higher performance constraint of 195°F is considered in order to limit the total number of acceptable systems. The use of flat-plate collectors to provide low process heat may also be studied by considering the imposed constraints of 190°F or 195°F at 150 Btu/hr-ft^2 heat removal. At a lower efficiency of about 40% (115 Btu/hr-ft^2 heat removal), absorber equilibrium temperatures between 220°F and 250°F would be expected. These temperatures are suitable for steam production at atmospheric pressure and thus industrial use of flat-plate collectors could be considered.

The two heat loads are analyzed in order to see if the cost of the collector system is reduced significantly by operating at the reduced efficiency. At 150 Btu/hr-ft^2 heat removal, only the most expensive selective absorbing surfaces may be applicable since their solar absorptivities are so high and thermal emissivities are so low. If the reduction in operating efficiency allows for the use of selective paints and other "dipped process" absorber materials, then a significant absorber price drop of as must as one dollar per square foot could occur. This cost decrease might justify the collector area increase required to make up for the 30 Btu/hr-ft^2 less heat removed.

Overall Assembly Constraints

The ultimate aim of the constraint analysis is to select solar collector assemblies that not only meet durability and performance criteria but which also are marketable. For a collector assembly to be marketable, total weight and cost must be emphasized. Excessive weight may result in additional cost in the installation of solar equipment since the roof which usually supports the flat-plate assemblies may need structural modification. Also, excessive initial flat-plate assembly cost lengthens the time required for the consumer to obtain a return on his investment. If this payback period exceeds ten to fifteen years the initial investment can not be justified. Therefore, overall assembly constraints are assigned to keep the flat-plate collector lightweight and inexpensive.

Four types of flat-plate collectors are to be considered. They are: single cover with aluminum absorber (SCA), single cover with copper absorber (SCC), double cover with aluminum absorbers (DCA), and double cover with copper absorbers (DCC). The differences among the weight constraints for the four types of assemblies result from differences in weight per square foot between copper and aluminum panels (see Table 2-7) and between choice of one or two covers. The weight per square foot difference between single and double covers has been set at one pound. The difference between copper and aluminum panels is approximately one pound per square foot. By selection of a maximum weight for the lightest assembly, single cover with aluminum absorber, the maximum weight constraints for the other assemblies can be assigned based on absorber panel and additional cover weight differences. The maximum weight for the single cover with aluminum absorber is set at five pounds per square foot, and all other weight constraints can be found in Table 5-11.

Although it is desired to limit the cost per square foot of all four types of collectors, care must be taken to insure that moderately priced high performance systems are not eliminated. The high performance collectors, in fact, might be utilized for industrial low temperature process heat, instead of solar cooling, and therefore different economic considerations would be needed. Further, while the maximum cost constraints may seem high, it should be noted that the constraint analysis is performed not to pick the optimal collector assembly but rather to limit the number of acceptable candidates. As in the overall weight constraint selections, a maximum cost per square foot for the single cover with aluminum absorber assembly is chosen and additional costs for the use of a second cover and/or a copper absorber plate are included. This overall cost data is summarized in Table 5-11.

Table 5-11

OVERALL ASSEMBLY CONSTRAINTS

ASSEMBLY TYPE	Maximum Weight (lb/ft^2)	Maximum Cost ($\$/ft^2$)
Single Cover with Aluminum Absorber Plate (SCA)	5.0	4.50
Single Cover with Copper Absorber Plate (SCC)	6.0	6.75
Double Cover with Aluminum Absorber Plate (DCA)	6.0	5.00
Double Cover with Copper Absorber Plate (DCC)	7.0	7.25

THE CRITERION FUNCTION

Upon completion of the constraint analysis, a series of acceptable candidate systems remain which will fulfill the minimum performance, cost, durability, and weight constraints. Since the acceptable candidate list may be excessive due to unrestrictive constraints, the problem then becomes deciding which assemblies are best suited for use. In order to make such a decision, the designer should consider the relative importance of the major judging criteria - cost, weight, performance, durability, and expected life.

To assist in this process, an overall effectiveness for each acceptable solar collector assembly should be considered [5-4]. This effectiveness is made up of the sum of the individual judging criteria effects and the product of their interactions. While the intent is to maximize the total effectiveness, all the constitutent criteria can never be maximized simutaneously, except under rare coincidences (for example, though a Tedlar cover with a black nickel absorbing surface may be the least expensive and best performing assembly, it will not be as durable as an acceptable assembly of Lexan cover and black chrome absorber). As a result, the various desireable (and undesireable) features and qualities must be blended together by "tradeoffs" in order to reach a maximum overall effectiveness.

The overall effectiveness of a given collector design is measured using a criterion function (also known as an objective function). The intent is to maximize the value of this function.

$$CF = \sum_{i=1}^{n} a_i X_i \text{ (dimensionless)} \tag{5.2}$$

where

a_i = weighting coefficients, measuring respective importance

X_i = criterion variable, as a system function or a parameter.

This CF is the sum of n individual constituent effects, X_i, each weighted or proportioned by the coefficients, a_i, so as to balance the respective X_i importances in the final result. In other words, in choosing candidate designs and their components, the designer must combine them in such a way as to obtain the highest effectiveness out of the whole system.

In attempting to select optimal flat-plate solar collector designs, two general criterion functions are established based upon six design constraints. The constraints are: (1) collector cost, (2) collector weight, (3) absorber plate temperature at 120 Btu/hr-ft^2 heat load, (4) absorber plate temperature at 150 Btu/hr-ft^2 heat load, (5) collector durability, and (6) expected collector life. The functions for each criterion (shown in Figures 5-1 and 5-2) are created with the intention of comparing acceptable systems against one another. In addition, the values of the functions are normalized so that various weight coefficients may be assigned to each functional value depending upon the designers' needs.

FIG. 5-1

SIX COMPONENTS OF CRITERION FUNCTION ONE

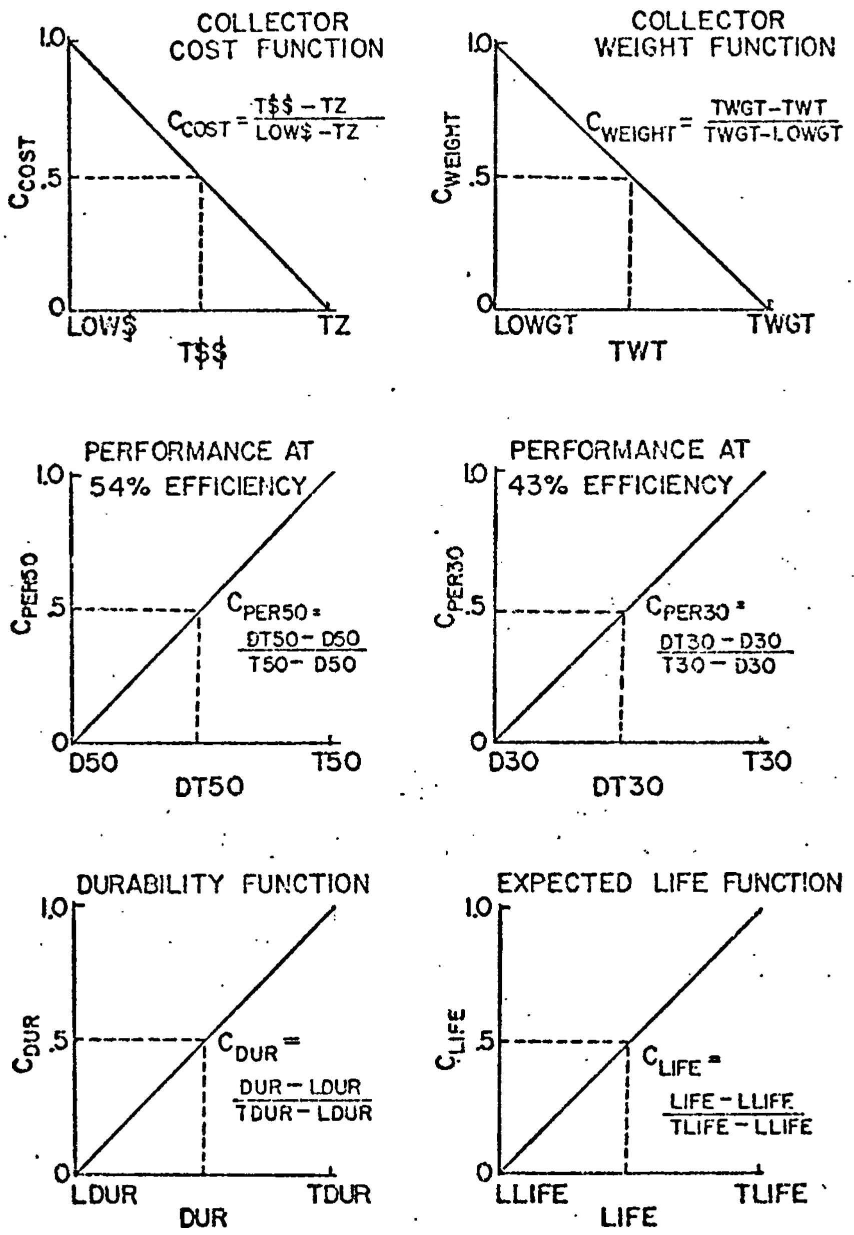
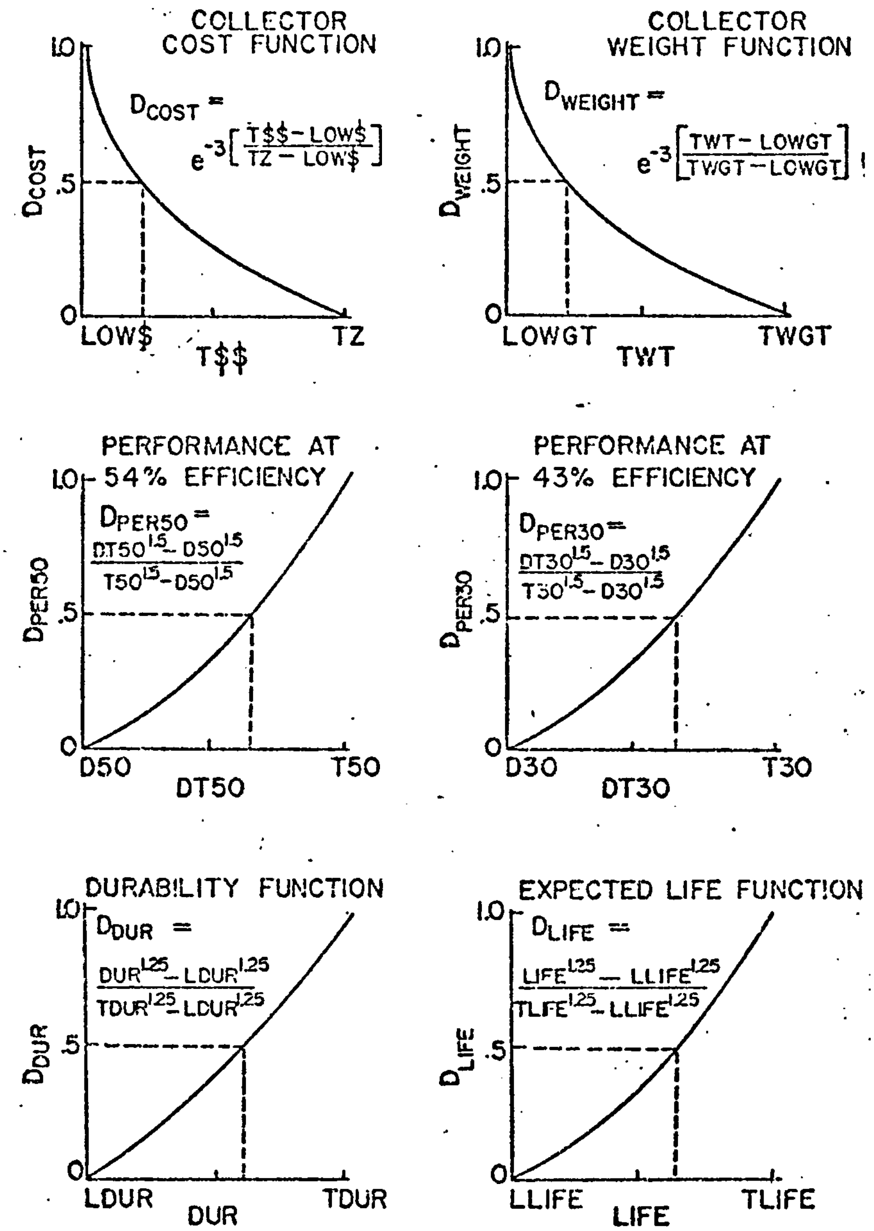


FIG. 5-2

SIX COMPONENTS OF CRITERION FUNCTION TWO



Two functional relations for each of the design criteria have been selected. One is a linear relation between the best and worst conditions attainable among the solar collectors which fulfill the minimum constraints assigned. The second relation is a power function, which has been arbitrarily selected to emphasize high performance in each design constraint. For example, the collector cost function found in Figure 5-2 is an exponential relation. A collector assembly which has an average cost (halfway between the maximum cost constraint and the minimum cost attained) would have a cost function value of 0.223 for the power function relation and 0.50 for the linear relation. It may be seen from this that the criterion function composed of the power function criteria is actually doubly weighted, since these functions emphasize high criteria performance prior to use of weighting factors selected by the designer.

The four functional relationships for cost, weight, and absorber performances at 120 Btu/hr-ft^2 and 150 Btu/hr-ft^2 are based on calculated values of total cost, total weight, and absorber equilibrium temperatures as calculated through the constraint analysis. The durability and expected life functions are more difficult to analyze, since both are functions of the components which comprise the solar collectors. Functional relationships for the two are based upon the following.

LIFE = f(cover assembly weatherability, collector plate type, and absorber surface)

DUR = f(cover assembly impact resistance, durability of the absorber surface).

The collector durability function considers the ability of the solar collector to survive within the environment. The major design consideration must be to maintain the absorber surface (especially if expensive selective surfaces are used), because the absorbing material is critical to attaining high equilibrium temperatures. Collector durability is thus defined as

$$DUR = 2.0*EFFIM + DURA \tag{5.3}$$

where

EFFIM = the coded effective impact resistance of a two cover assembly or the coded impact resistance for a single cover. (The code is provided in Table 2-8).

DURA = the coded durability of the absorber material. (The code is provided in Table 2-9).

The upper limit of the durability function is 'TDUR' and is calculated for maximum values of 'EFFIM' and 'DURA' obtained from the acceptable assemblies. 'LDUR' is calculated using the minimum constraints for absorber durability and cover plate resistance.

The expected life function considers the ability of the solar collector to operate for an extended time period. Weather effects on the cover are critical, since the cover serves to protect the assembly while also allowing maximum insolation transmission. (Cover yellowing and cover ultraviolet degradation can severely limit the assembly life and must be designed against.) Further, the collector panel expected life is critical. While copper absorbers may have twenty year expected lives, corrosion problems may limit aluminum and steel collector panel lifetimes to under ten years unless inhibitors are used in the heat absorbing fluid [5-5]. Absorber durability must be considered also, since loss of the surface for solar energy absorption will prevent the solar collector from operating effectively. 'LIFE' will be defined as follows.

$$LIFE = WETH + (DURA + (EFFIM*DURA)/25.0)/2.0 + 4.0*CDL \qquad (5.4)$$

where

WETH = effective weatherability of the cover assembly. (The code is provided in Table 2-8.)

$$WETH_{\substack{two \\ covers}} = (3.0*WETH_{\substack{outside \\ cover}} + WETH_{\substack{inside \\ cover}})/4.0 \qquad (5.5A)$$

$$WETH_{\substack{one \\ cover}} = WETH_{\substack{outside \\ cover}} \qquad (5.5B)$$

DURA = coded absorber durability.

EFFIM = coded cover assembly effective impact resistance.

CDL = coded expected life for the collector plate.

CDL = 1.5 for steel absorber panels.

CDL = 2.25 for aluminum absorber panels.

CDL = 3.00 for copper absorber panels.

As in the case of the 'DUR' minimum and maximum values, 'TLIFE' represents the 'LIFE' function consisting of maximum values of 'DURA', 'EFFIM', 'CDL', and 'WETH' parameters while 'LLIFE' is determined from the prescribed constraints.

To analyze the various acceptable assemblies, weighting coefficients are assigned to each of the six criteria so that they total 100%. Two criterion functions for each assembly may then be calculated. They are

$$CF1 = CR_{DUR}*C_{DUR} + CR_{LIF}*C_{LIFE} + CR_{C}*C_{COST} + CR_{WT}*C_{WEIGHT} + CR_{50}*C_{PER50} + CR_{30}*C_{PER30} \tag{5.6A}$$

and

$$CF2 = CR_{DUR}*D_{DUR} + CR_{LIF}*D_{LIFE} + CR_{C}*D_{COST} + CR_{WT}*D_{WEIGHT} + CR_{50}*D_{PER50} + CR_{30}*D_{PER30} \tag{5.6B}$$

where CR_{DUR}, CR_{LIF}, CR_{C}, CR_{WT}, CR_{50}, and CR_{30} are the weighting coefficients.

The computer program is arranged so that the designer may choose to emphasize one or all of the six criteria by his choice of weighting factors. Collector cost and collector performance at 120 Btu/hr-ft^2 and 150 Btu/hr-ft^2 heat removal will be emphasized in the optimization analysis, since these three design criteria are most critical to consumer acceptance of flat-plate technology being employed for space cooling.

Chapter Six

COMPUTER SIMULATION RESULTS

Introduction

The results developed from the computer simulation may be used to select optimal single and double cover flat-plate solar collectors. From the constraints selected in Chapter Five, two different extreme summer weather conditions are studied for the no heat removal case. Only two heat loads (120 Btu/hr-ft^2 and 150 Btu/hr-ft^2) have been selected for performance constraints in order to limit the number of candidate assemblies. Nonetheless, with single and double cover options and with copper or aluminum absorber plate choices, a series of sixteen cases must be considered (eight single cover collector assembly types and eight double cover collector assembly types). Due to the large collection of data, Appendix II is provided to summarize the work undertaken. In addition, only particular cases (e.g., one no load weather constraint with a specified performance criteria) are analyzed. Choice of the cases selected, however, can be justified through preliminary study of the data tabulated in Appendix II and are discussed in this chapter.

The criterion function optimization results are also presented for selected weighted coefficient inputs. (Refer to Chapter Five for the weighted coefficient description.) Performance at the design load removal and total collector assembly cost are emphasized in this work. The effects of total weight, collector durability, and estimated collector life are also considered, though these parameters are treated as constants in the optimization procedure. Elevated temperature collector performance (i.e., absorber plate equilibrium temperature at a specified load of 120 Btu/hr-ft^2 or 150 Btu/hr-ft^2) is studied for possible flat-plate collector usage in process heat or steam generation applications. Cost is emphasized to determine whether single or double cover flat-plate collectors can economically provide heat for absorption-refrigeration air conditioning.

This chapter is divided into three sections. The first two sections discuss acceptable single and double collector assemblies respectively. From the data, generalizations on the component makeup for solar flat-plate collectors are provided. Optimal collector designs are tabulated and compared using the criterion function. Performance plots for some of the better collector assemblies are also included. The third section compares the single and double cover collectors from performance and cost standpoints. Recommendations on selection of collector assembly types (whether to use single or double cover assemblies) are provided to conclude the work presented.

Prior to single cover collector results analysis, the coding system employed should be explained. There are sixteen different collector assembly types analyzed in the results. In order to simplify the description of each collector type (i.e., under what conditions each collector can be applied for use) a four symbol code has been chosen and is shown below

$$XXYZ \tag{6.1}$$

where

XX = cover number
SC = single cover
DC = double cover

Y = absorber plate type
A = aluminum
C = copper

Z = weather and performance constraints applied in analysis

1 = more restrictive no load weather condition and 150 Btu/hr-ft^2 load

2 = less restrictive no load weather condition and 150 Btu/hr-ft^2 load

3 = more restrictive no load weather condition and 120 Btu/hr-ft^2 load

4 = less restrictive no load weather condition and 120 Btu/hr-ft^2 load

As an example, the 'SCA3' collector designation would be a single cover with aluminum absorber collector assembly which has an absorber temperature of 190°F or better for a heat removal of 120 Btu/hr-ft^2. In addition, the 'SCA3' assembly can withstand the more restrictive no load weather condition found in Table 5-3.

Table II-1 in Appendix II provides the collector assembly designation data.

SINGLE COVER FLAT-PLATE COLLECTOR ANALYSIS

Employing the constraints tabulated in Chapter Five, combinations of thirty-one cover materials, eight aluminum and five copper absorber materials were analyzed by the computer. Four different performance and no load weather constraints were considered. In addition, maximum total costs of $4.50 and $6.75 and maximum total weights of 5.0 and 6.0 pounds per square foot for aluminum and copper assemblies respectively were specified. Table 6-1 below indicates the number of acceptable aluminum and copper collector systems from the analyses for each set of constraints. Information on the coded materials and properties for

Table 6-1

ACCEPTABLE SINGLE COVER COLLECTOR ASSEMBLIES

Aluminum Collectors		Copper Collectors	
Designation	Collector Total	Designation	Collector Total
SCA1	13	SCC1	12
SCA2	18	SCC2	18
SCA 3	24	SCC3	23
SCA 4	44	SCC4	66

each of these assemblies are tabulated in Tables II-2 through II-9 in Appendix II. Each of the systems listed in Tables II-2 through II-9 has been designed for space cooling applications.

As can be seen by Table 6-1, the constraints chosen have severely limited the number of acceptable assemblies. This is particularly true when the more restrictive no load weather constraints are applied. For this weather constraint, absorber temperatures in excess of 400°F are reached. Since the majority of the absorber coatings coded in Table 2-9 have temperature limitations below 400°F, only the electroplated materials can be considered for analysis. In addition, the requirement to obtain an absorber plate temperature of 190°F for 150 Btu/hr-ft^2 load requires limited thermal energy emission and maximum solar radiation absorption by the absorber material.

Questions pertaining to varying cost and performance requirements are answered by studying Figures 6-1A through 6-4A (the A designates aluminum absorber panels while the C represents copper absorber panels) for aluminum absorber collectors and 6-1C through 6-4C for copper collector assemblies. Figures 6-1A 6-3A, 6-1C, and 6-3C examine the effects of varying the absorber plate equilibrium temperature at the two designated loads. Figures 6-2A, 6-4A, 6-2C, and 6-4C study the effects of lowering the maximum total cost requirement. As would be expected, the acceptable candidate totals decrease with more restrictive constraints.

FIG. 6-1A

EFFECT OF CHANGING THE MINIMUM ABSORBER PLATE TEMPERATURE CONSTRAINT AT 150 BTU/(HR-FT^2) HEAT REMOVAL

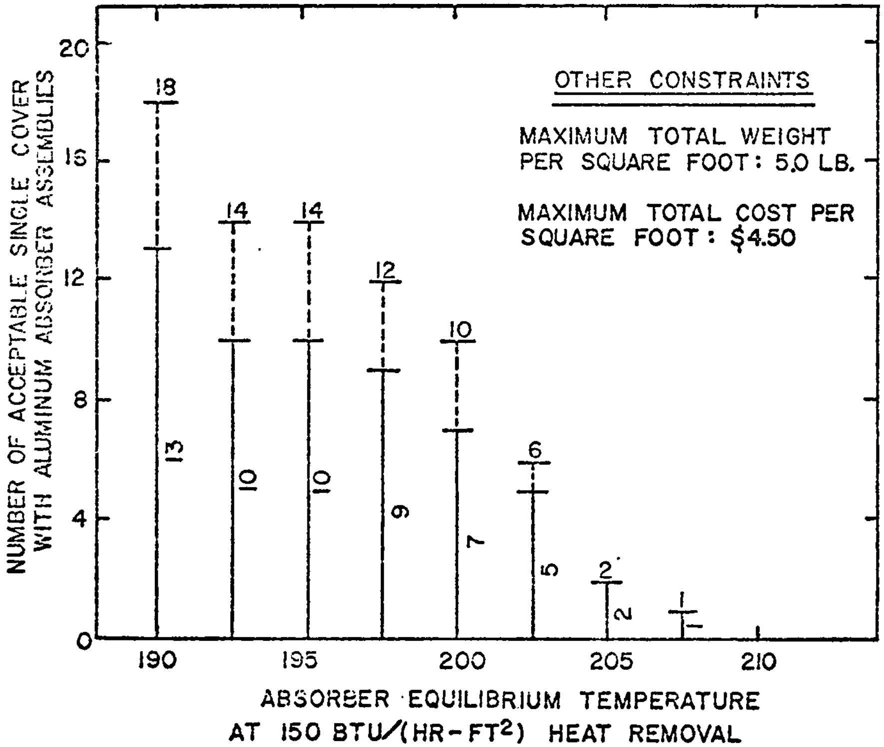
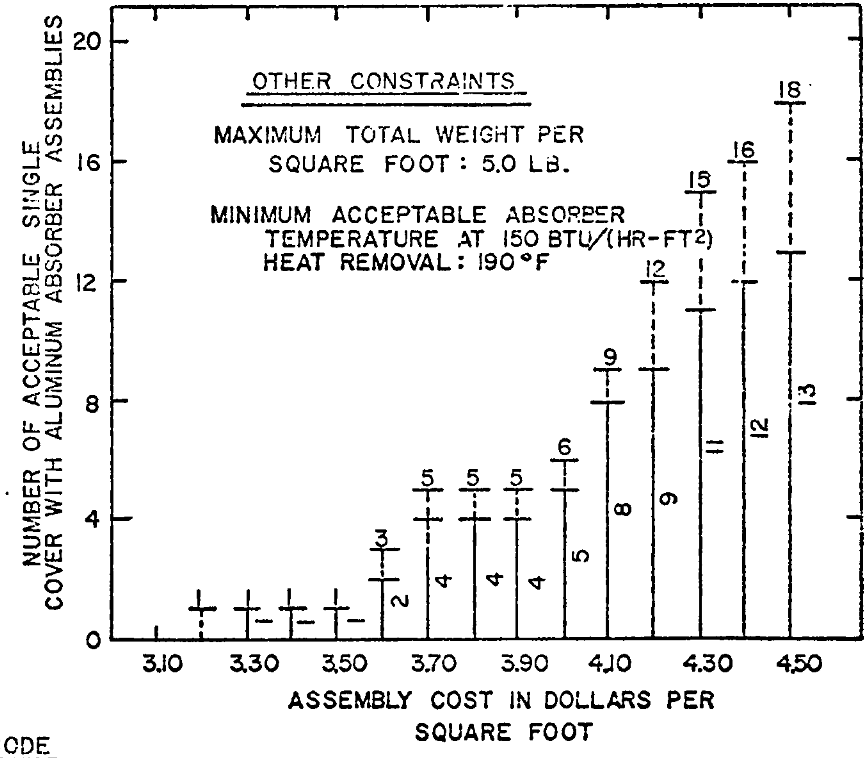


FIG. 6-2A

EFFECT OF CHANGING THE MAXIMUM ALLOWABLE FLAT-PLATE ASSEMBLY COST



ASSEMBLY CODE

—— SCA1 COLLECTORS

- - - - SCA2 COLLECTORS

FIG. 6-3A

EFFECT OF CHANGING THE MINIMUM ABSORBER PLATE TEMPERATURE CONSTRAINT AT 150 BTU/(HR-FT^2) HEAT REMOVAL

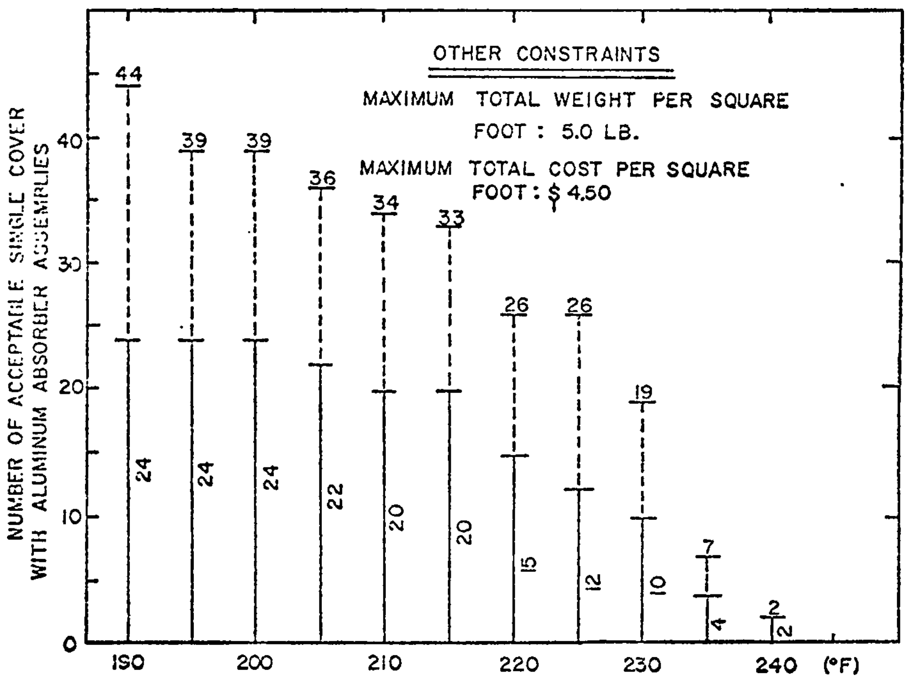
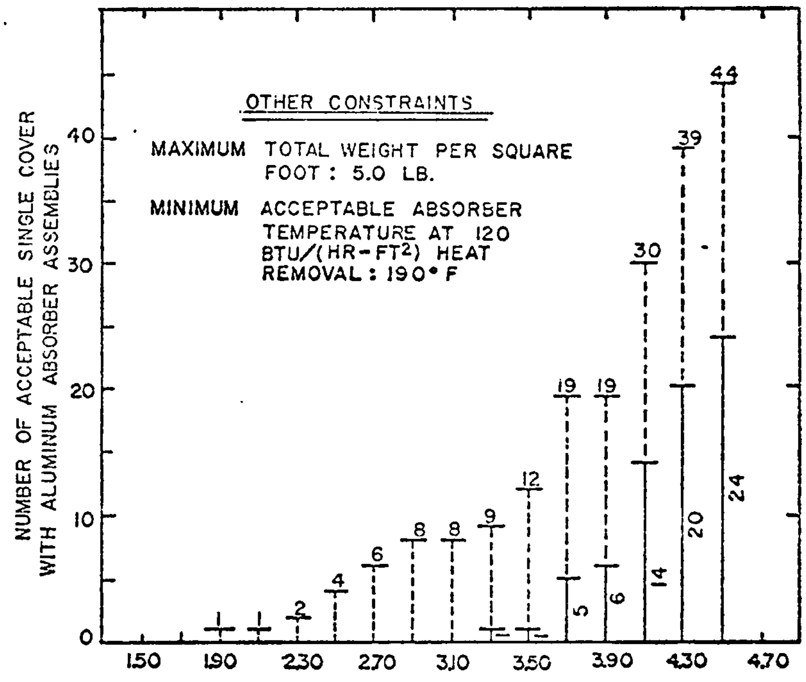


FIG. 6-4A

EFFECT OF CHANGING THE MAXIMUM ALLOWABLE FLAT-PLATE ASSEMBLY COST



ASSEMBLY CODE

—— SCA3 COLLECTORS

- - - - SCA4 COLLECTORS

FIG. 6-1C

EFFECT OF CHANGING THE MINIMUM ABSORBER PLATE TEMPERATURE CONSTRAINT AT 150 BTU/(HR-FT^2) HEAT REMOVAL

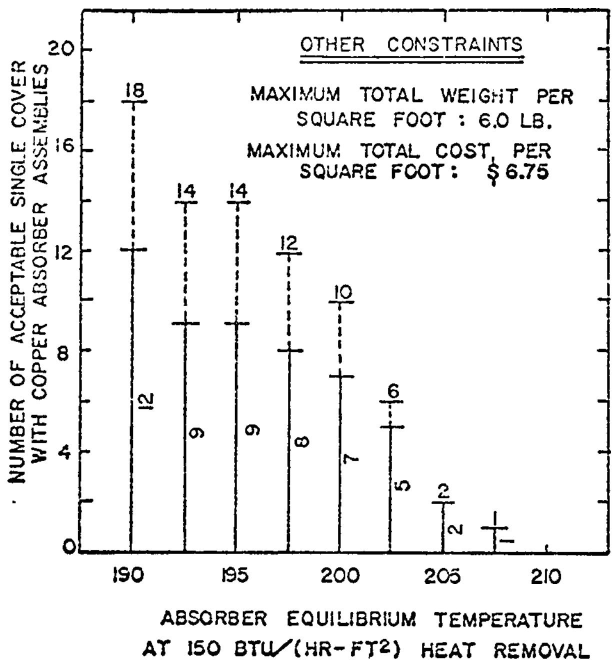
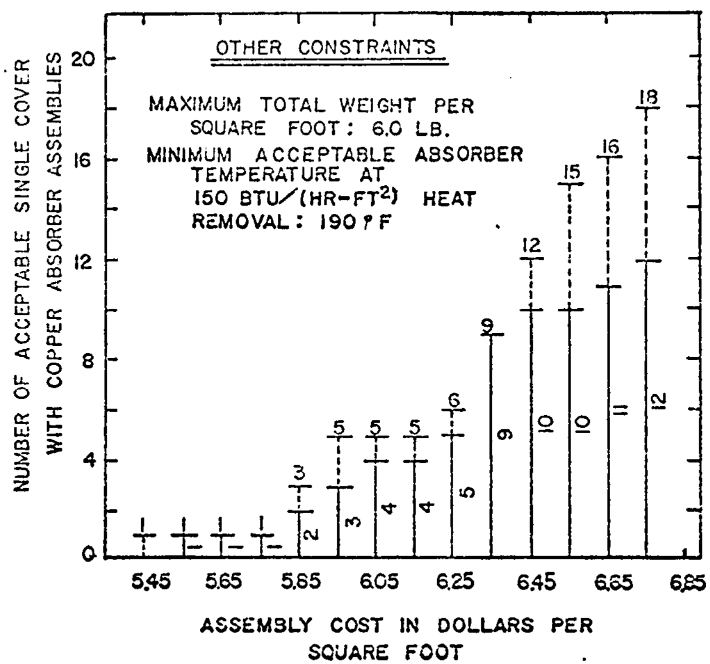


FIG. 6-2C

EFFECT OF CHANGING THE MAXIMUM ALLOWABLE FLAT-PLATE ASSEMBLY COST



ASSEMBLY CODE

——— SCC1 COLLECTORS

- - - - - SCC2 COLLECTORS

FIG. 6-3C

EFFECT OF CHANGING THE MINIMUM ABSORBER PLATE TEMPERATURE CONSTRAINT AT 120 BTU/(HR-FT^2) HEAT REMOVAL

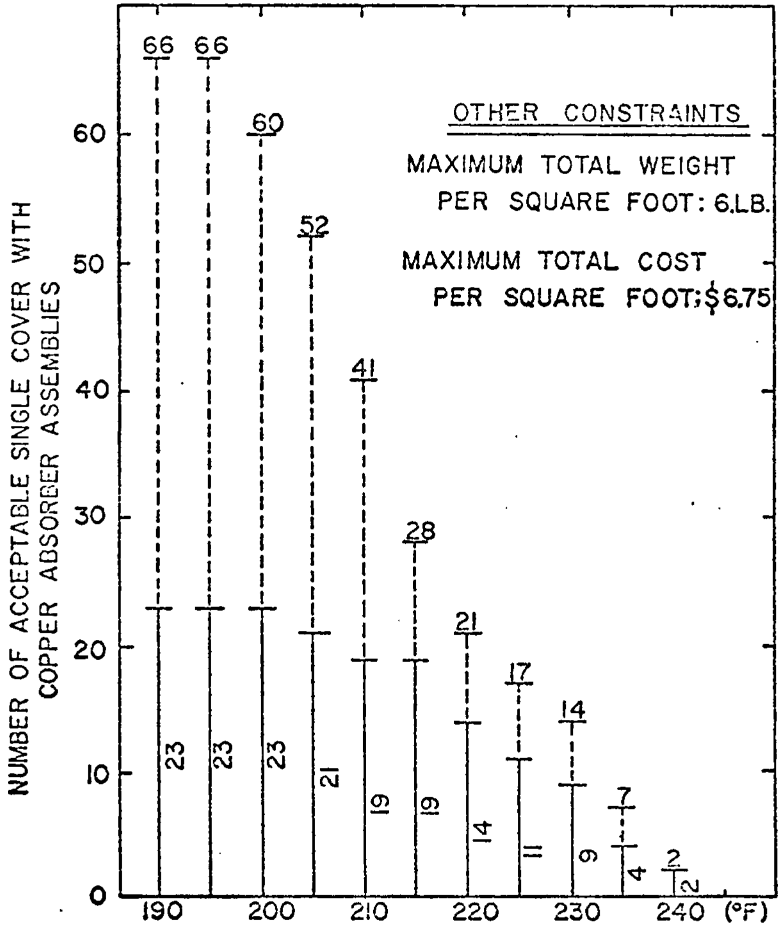
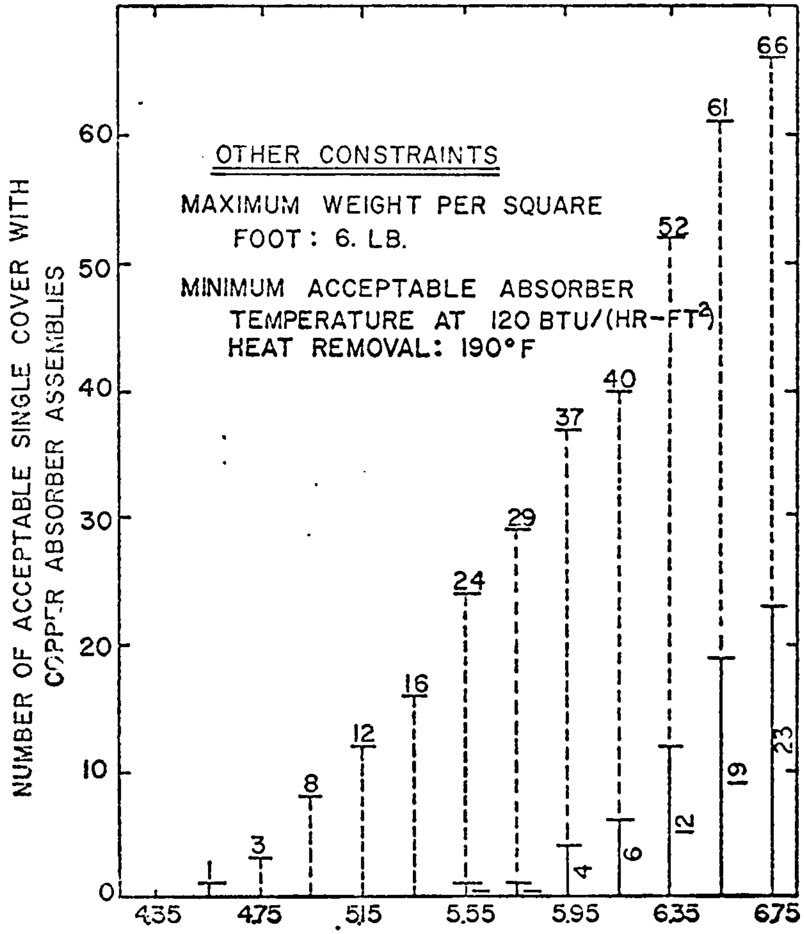


FIG. 6-4C

EFFECT OF CHANGING THE MAXIMUM ALLOWABLE FLAT-PLATE ASSEMBLY COST



ASSEMBLY CODE

——— SCC3 COLLECTORS

- - - - - SCC4 COLLECTORS

Based on the figures shown and on the data tabulated on the assemblies found in Appendix II, the following generalizations may be applied:

1. The performance constraint that the absorber plate maintain a temperature above 190°F for 150 Btu/hr-ft^2 heat removal requires high solar absorption-low thermal emission absorbing materials. Of the absorbers considered, only the electroplated surfaces (black nickel and black chrome) could meet the performance constraints required.

2. The performance constraint that the absorber plate maintain a temperature of 190°F for 120 Btu/hr-ft^2 heat removal allows consideration of less selective materials than the electroplated surfaces. Nevertheless, the nonselective flat-black paints fail to provide absorber temperatures suitable for space cooling due to their high emission of thermal radiation.

3. Designs incorporating the more restrictive no load weather conditions severely limit the collector options for further analysis. Since the no load condition should be avoided the majority of the time through operation, the less restrictive conditions should be incorporated in the design of single cover assemblies. An emergency recycle system incorporating a second pump could also be included in the collector piping if no load constraints are too critical to neglect.

4. Comparison of data presented in Figures 6-2A and C and Figures 6-4A and C point out that the specification of the lesser performance constraint allows consideration of less expensive collectors assemblies which can still meet space cooling requirements. For copper absorber flat-plate collectors, the removal of 30 less Btu's per square foot per hour from the absorber can reduce the minimum acceptable collector cost by $1.07 per square foot. For the aluminum assembly, a $1.45 per square foot minimum cost difference between collectors that can fulfill the two performance constraints results. From an economic standpoint, the lesser performance constraints should certainly be applied in designing aluminum solar collectors. For copper assemblies, the choice of performance constraints is less clear, since a performance reduction of 20% (30 Btu/150 Btu) results in a collector price reduction of about 20% ($1.07/$5.45).

5. For applications where higher equilibrium temperatures are required (as in process heat applications) the best single cover flat-plate collectors (from performance standpoints) can not provide temperatures above 245°F at 120 Btu/hr-ft^2

loads and 210°F at 150 Btu/hr-ft^2 loads. These collectors being made up of electroplated absorbing surfaces of black nickel, are also some of the more expensive assemblies tabulated.

Analysis of the summarized tables in Appendix II provides information on the component materials. Conclusions on material choice are presented below:

1. The insulations employed to reduce heat loss to the back of the collector to under 10% of the upward loss are the lesser density materials. Fiberglas and industrial felt are most often employed because of their low cost. For the more restrictive no load summer weather constraints, some usage of mineral wool may be required since insulation hot face temperatures in excess of 400°F are reached and the fiberglas and industrial felts have low temperature limits (refer to Table 2-10).

2. Three cover materials are found to be best from performance standpoints. They are Tedlar P.V.F, Teflon F.E.P., and Sunadex Temper Glass. When combined with absorbers which emit over 30% of their thermal energy, the Sunadex provides slightly higher absorber temperatures. For the electroplated materials, the plastics, having slightly better solar transmission properties (refer to Table 2-8) are superior.

3. As previously stated, the performance requirements specified necessitate the use of a selective surface. For best performance, $\alpha_s > 0.90$ is required.

4. The most commonly utilized cover, temper float glass, is limited to use with a high solar radiation absorbing absorber material. This is expected from the work done in Chapter Four.

From prior discussion, the optimization analysis will consider applicable assemblies which can withstand the less restrictive no load summer weather constraints. Since the intention of this work is to select high performance-low cost collector assemblies, the criterion function analysis considered various combinations of collector cost and performance to arrive at optimal flat-plate assemblies. For the four cases considered

(SCA2, SCA4, SCC2, SCC4 acceptable assemblies) data on optimal collectors (in terms of cost and performance) is provided in Tables 6-2A and 6-2C. For each case, three optimal collector assemblies are provided in terms of cost and performance.

The optimal single cover with copper and aluminum absorber assemblies have been selected based on both criterion functions shown in Chapter Five. The second criterion function consisting of power functions for the six judging criteria (refer to Figure 5-2) yielded the same trends as the criterion function comprised of six linear criteria. Since the criterion analysis based on power functions is the more arbitrarily chosen optimization function, the linear criterion function will be used to graphically show the effects of varying the weighting coefficients for performance and cost. This data can be seen in Figures 6-5A through 6-8A.

To choose the best system for a particular set of performance and cost weights, the designer should select the system from the graph which has the highest criterion function value. From Figure 6-5A, for example, while SCA2-8 has the best performance characteristics (when 100% weight is applied to performance, SCA2-8 has the highest criterion function value), SCA2-7 is a more economical alternative. Thus, if a designer chooses to emphasize performance but also wants to consider the economics, he would select assembly SCA2-7 (refer to Figure 6-5A) because the criterion function for this assembly is superior so long as a weighted cost coefficient of 35% or higher is selected. Also,

TABLE 6-2A

OPTIMAL SINGLE COVER WITH ALUMINUM ABSORBER ASSEMBLIES

Designation	Absorber Coating	Cover Panel	Cost of System in Dollars per Square Foot	Absorber Equilibrium Temperature (°F) at Specified Load	
				120 $^{Btu}/_{Hr\text{-}Ft^2}$	150 $^{Btu}/_{Hr\text{-}Ft^2}$
SCA2-1	Black Chrome over Nickel (1 minute)	4 mil Tedlar P.V.F.	3.64	233.9	201.4
SCA2-7	Black Nickel over Nickel	4 mil Tedlar P.V.F.	3.19	241.4	207.1
SCA2-8	Black Nickel over Nickel	5 mil Teflon F.E.P.	3.69	242.5	208.4
SCA2-14	Black Nickel over Nickel	125 mil Clear Temper Glass	3.55	230.5	195.2
SCA2-15	Black Nickel over Nickel	187 mil Clear Temper Glass	3.58	225.6	190.0
SCA2-16	Black Nickel over Nickel	156 mil Sunadex	3.93	239.0	204.3
SCA4-1	Meteor 7890 Selective Paint (.05 mil)	4 mil Tedlar P.V.F.	1.74	192.7	166.6
SCA4-2	Meteor 7890 Selective Paint (.05 mil)	5 mil Teflon F.E.P.	2.24	192.9	167.1
SCA4-7	Meteor 7890 Selective Paint (.05 mil)	125 mil Sunadex	2.34	194.1	167.3
SCA4-30	Black Nickel over Nickel	4 mil Tedlar P.V.F.	3.19	241.4	207.1
SCA4-31	Black Nickel over Nickel	5 mil Teflon F.E.P.	3.69	242.5	208.4
SCA4-42	Black Nickel over Nickel	156 mil Sunadex	3.93	239.0	204.3

TABLE 6-2C

OPTIMAL SINGLE COVER WITH COPPER ABSORBER ASSEMBLIES

Designation	Absorber Coating	Cover Panel	Cost of System in Dollars per Square Foot	Absorber Equilibrium Temperature (°F) at Specified Load	
				120 Btu/Hr-Ft^2	150 Btu/Hr-Ft^2
SCC2-1	Black Chrome over Nickel (1. minute)	4 mil Tedlar P.V.F.	5.90	233.9	201.4
SCC2-7	Black Nickel over Nickel	4 mil Tedlar P.V.F.	5.45	241.4	207.1
SCC2-8	Black Nickel over Nickel	5 mil Teflon F.E.P.	5.95	242.5	208.4
SCC2-14	Black Nickel over Nickel	125 mil Clear Temper Glass	5.81	230.5	195.2
SCC2-15	Black Nickel over Nickel	187 mil Clear Temper Glass	5.84	225.6	190.0
SCC2-16	Black Nickel over Nickel	156 mil Sunadex	6.19	239.0	204.3
SCC4-19	Black Nickel over Nickel	4 mil Tedlar P.V.F.	5.45	241.4	207.1
SCC4-20	Black Nickel over Nickel	5 mil Teflon F.E.P.	5.95	242.5	208.4
SCC4-31	Black Nickel over Nickel	156 mil Sunadex	6.19	239.0	204.3
SCC4-34	Black Nickel (Solar E)	4 mil Tedlar P.V.F.	4.58	210.8	176.6
SCC4-49	Black Copper of Enthone	4 mil Tedlar P.V.F.	4.38	214.7	182.0
SCC4-51	Black Copper of Enthone	40 mil Sun-Lite Premium	4.70	198.9	164.6

FIG. 6-5

OPTIMAL SINGLE COVER WITH ALUMINUM ABSORBER ASSEMBLIES BASED ON COST AND PERFORMANCE AT 150 BTU/(HR-FT^2) HEAT REMOVAL

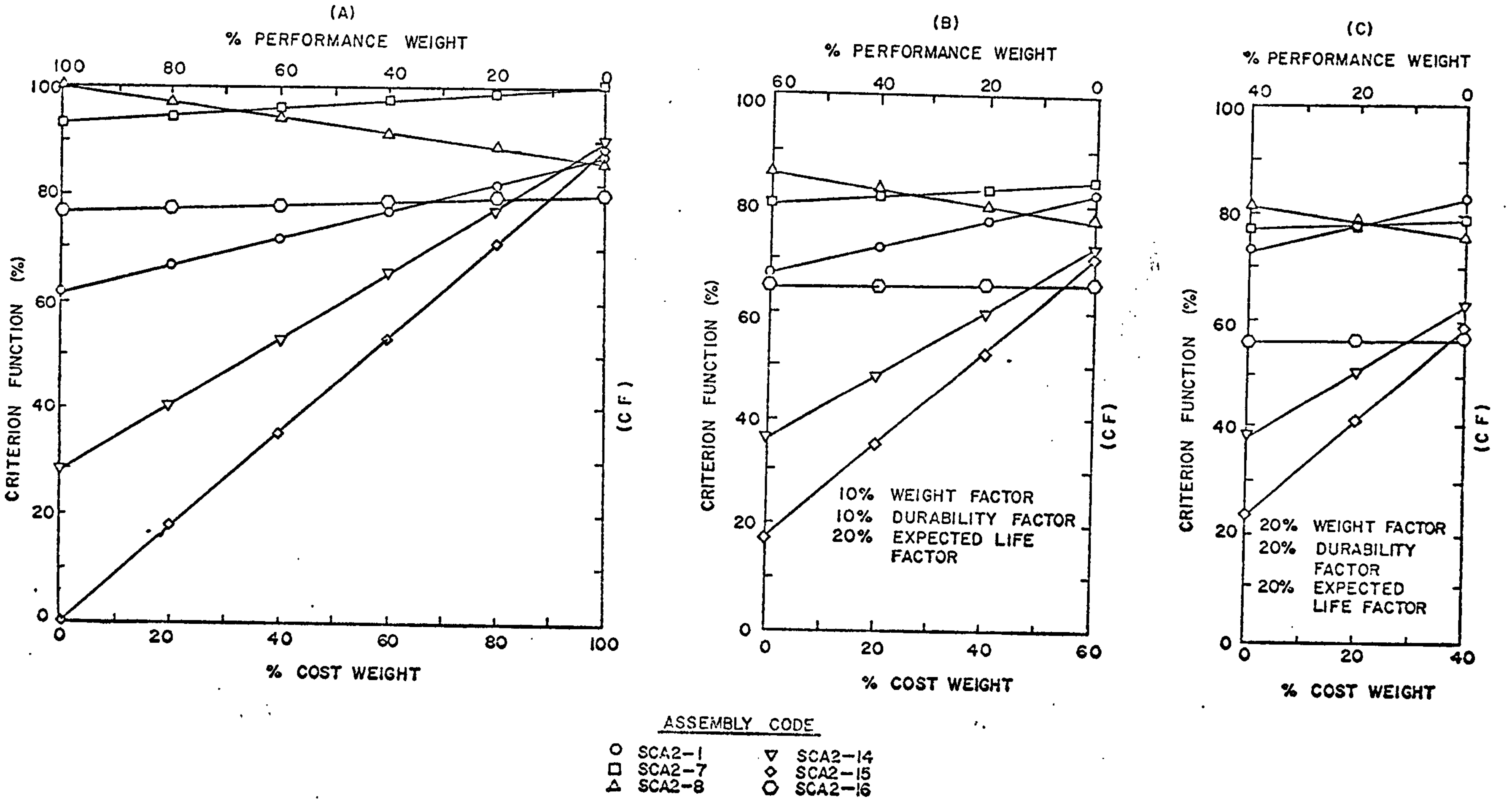


FIG. 6-6

OPTIMAL SINGLE COVER WITH ALUMINUM ABSORBER ASSEMBLIES BASED ON COST AND PERFORMANCE AT 120 BTU/(HR-FT^2) HEAT REMOVAL

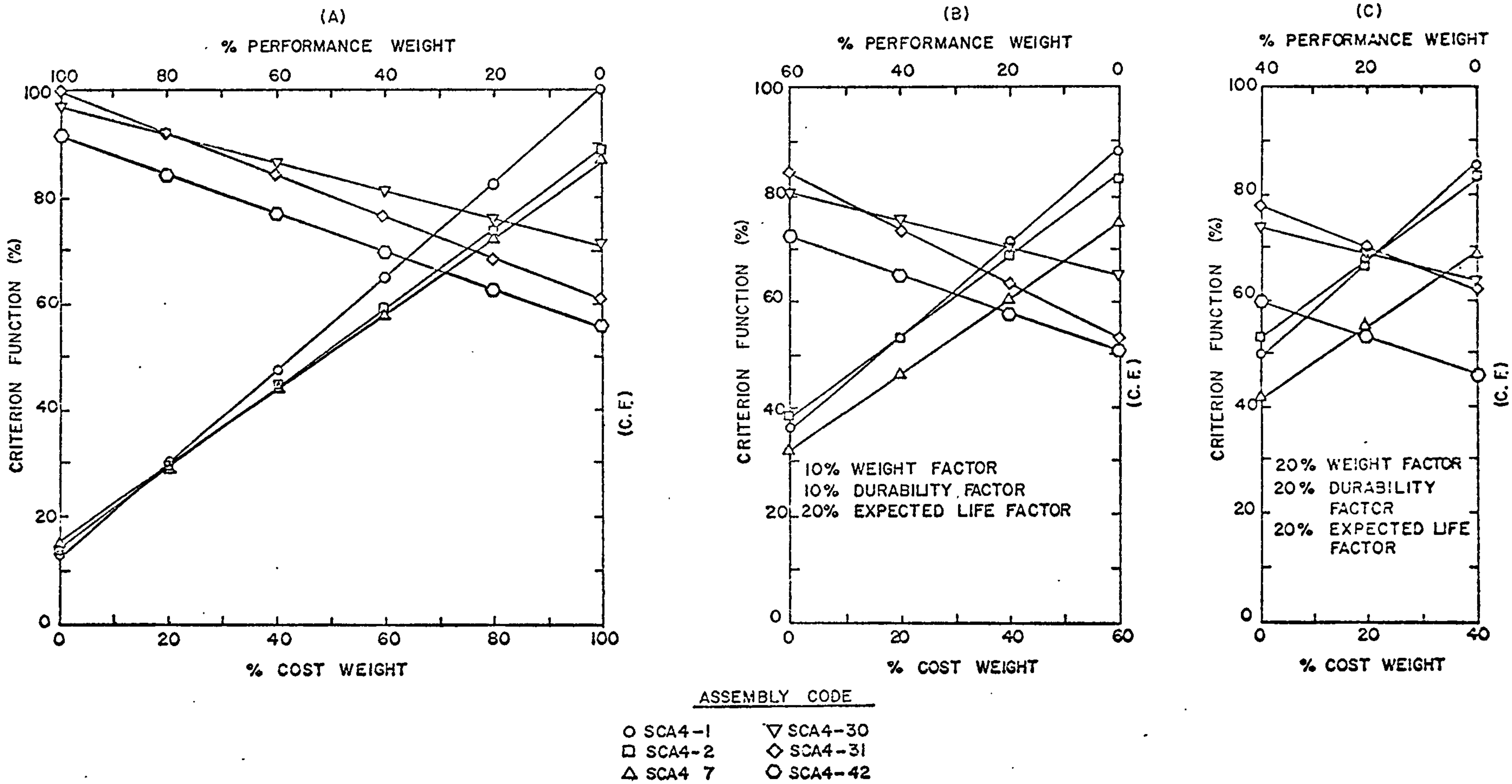


FIG. 6-7

OPTIMAL SINGLE COVER WITH COPPER ABSORBER ASSEMBLIES BASED ON COST AND PERFORMANCE AT 150 BTU/(HR-FT^2) HEAT REMOVAL

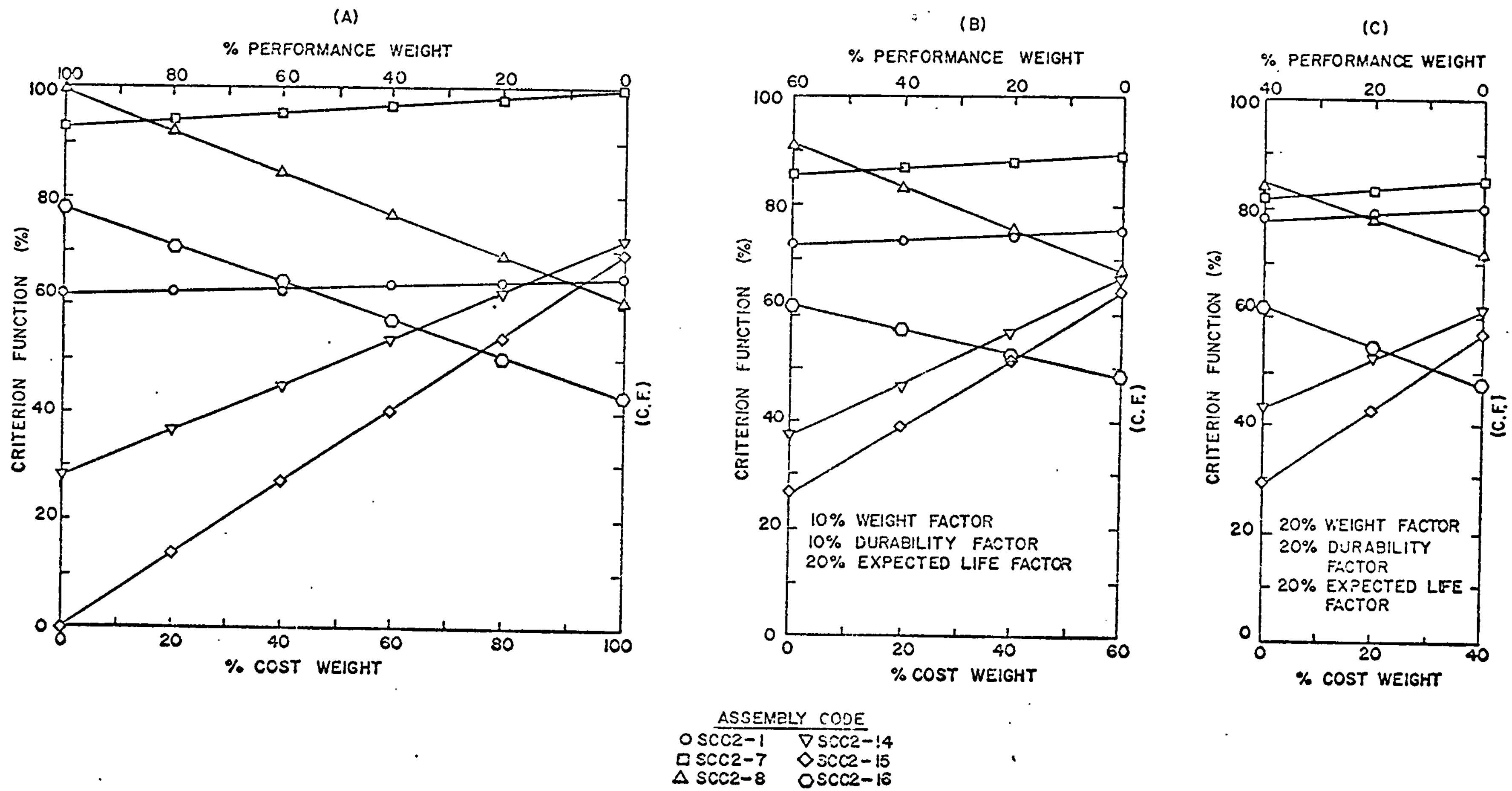
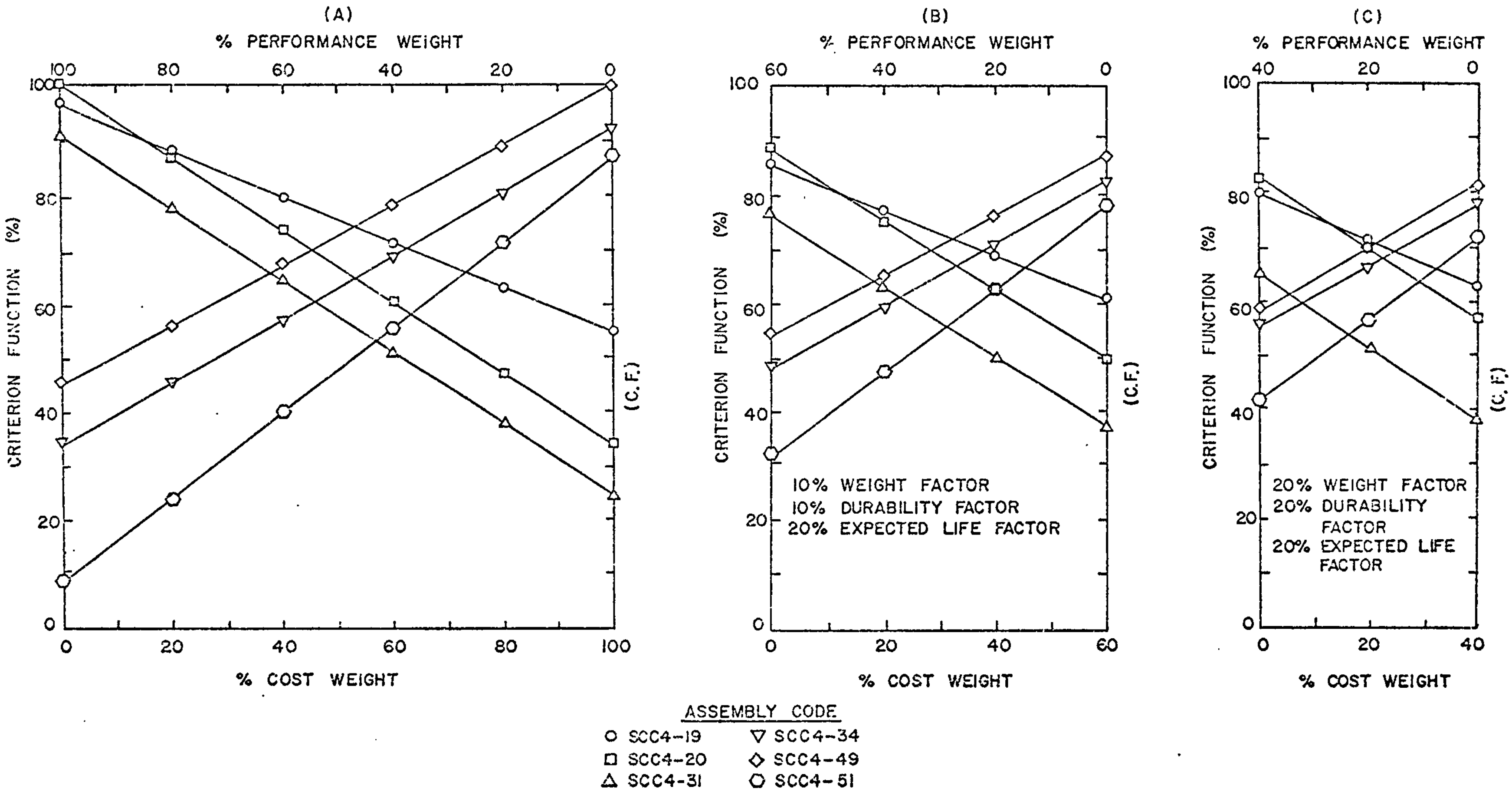


FIG. 6-8

OPTIMAL SINGLE COVER WITH COPPER ABSORBER ASSEMBLIES BASED ON COST AND PERFORMANCE AT 120 BTU/(HR-FT^2) HEAT REMOVAL



since three other criteria - weight, durability, and expected life - may need to be considered, constant weighted coefficients for these functions are applied and shown in Figures 6-5B and C through 6-8B and C. These figures show the effects of varying the percentages of cost and performance weights while holding the other three criteria at fixed weight percentages.

Based on the criterion function analysis, optimal cover plate and absorber material combinations have been tabulated in Tables 6-2A and 6-2C. Comparison of these combinations can also be shown through efficiency versus absorber temperature plots. Figures 6-9 and 6-10 provide such information. The two figures also indicate the temperature cut off level for absorption refrigeration air conditioning utilization.

As a final comment, it should be noted that while the collector assemblies selected for graphical analysis are best in terms of cost and performance, the other collectors listed in Tables II-2 through II-9 are also acceptable for space cooling applications. Several acrylic materials are shown in the tables to be good cover materials. Other absorber materials such as black chrome may even be more acceptable for use than black nickel should absorber durability problems develop.

FIG. 6-9

PERFORMANCE CHARACTERISTICS OF OPTIMAL SINGLE COVER FLAT-PLATE SOLAR COLLECTORS

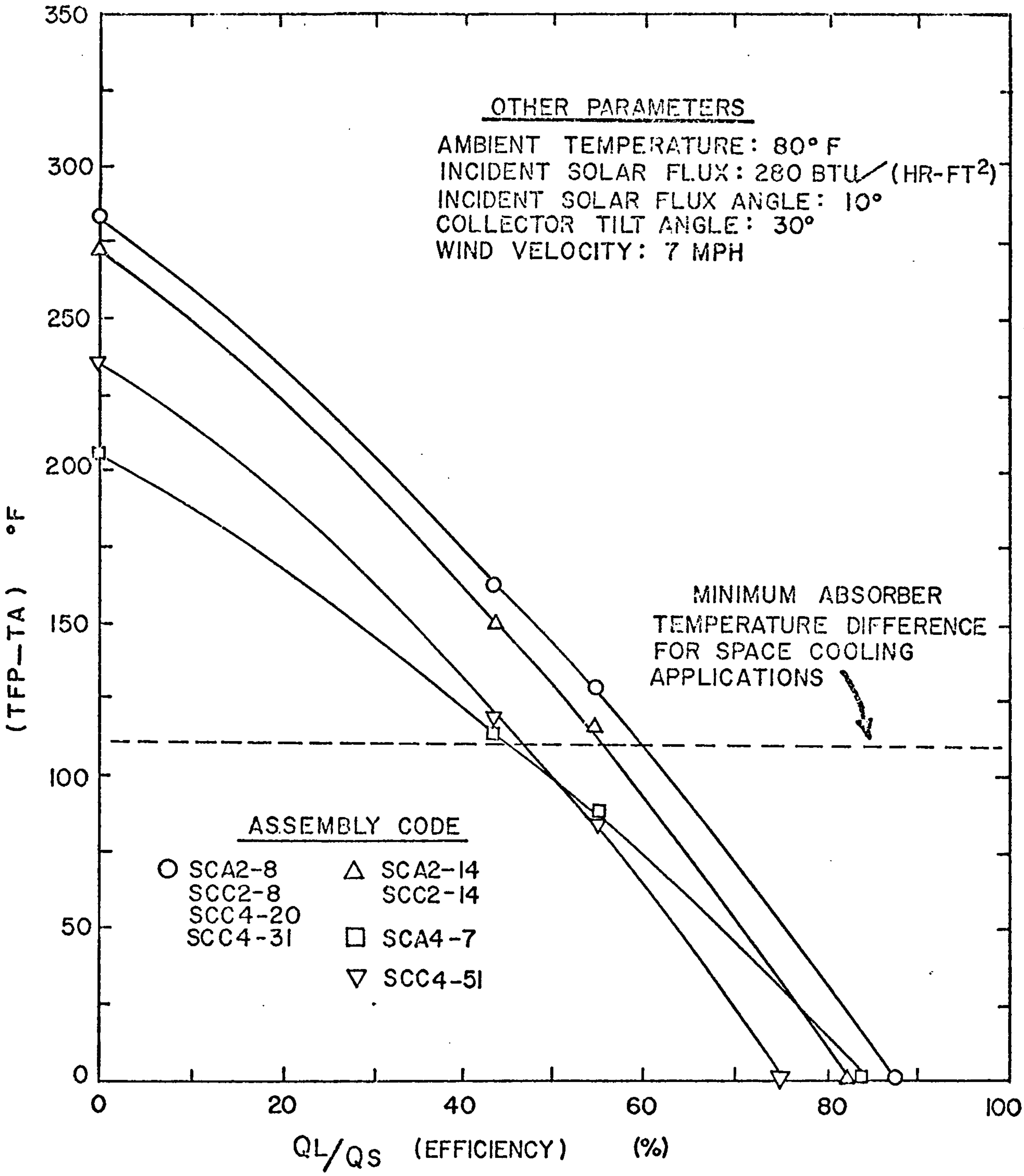
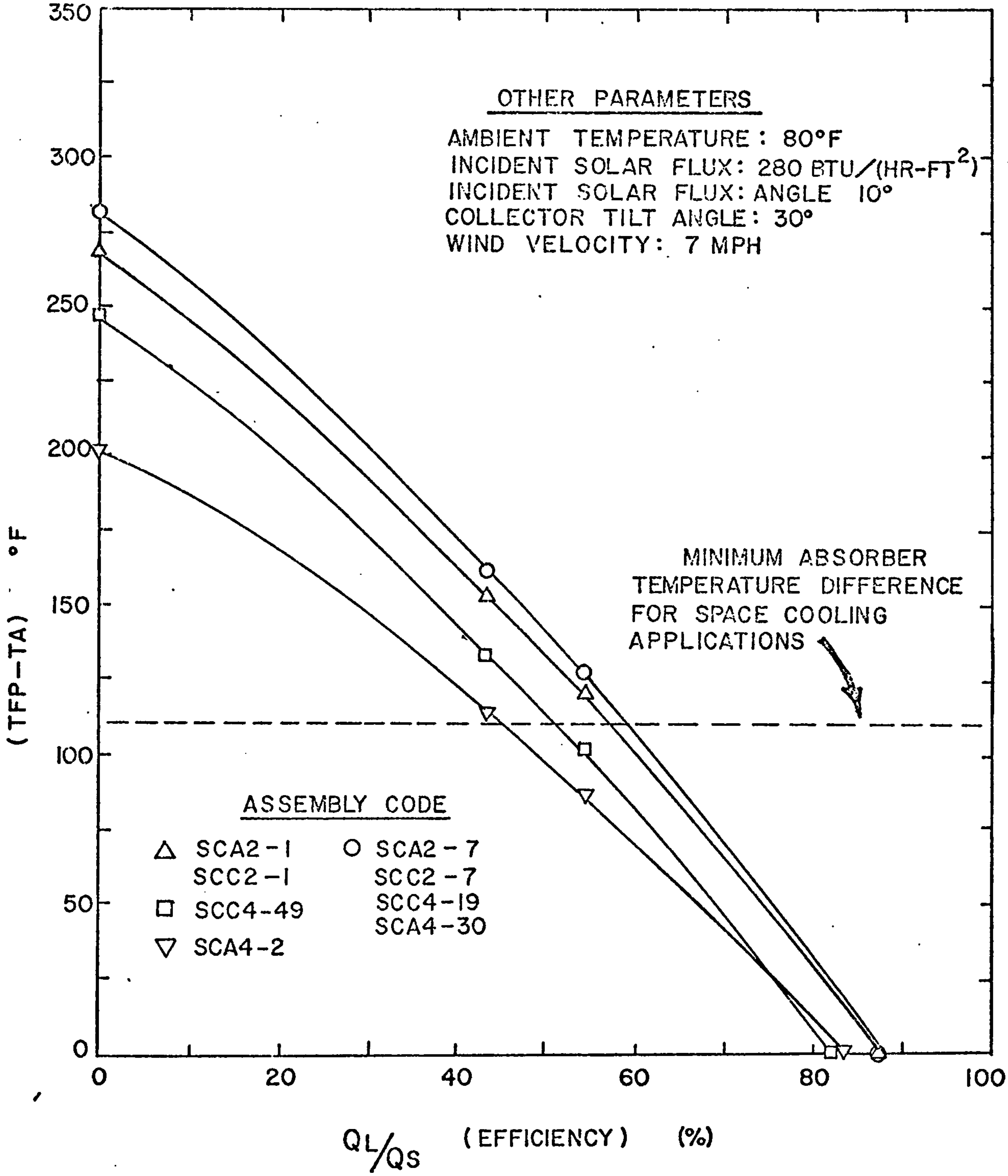


FIG. 6-10

PERFORMANCE CHARACTERISTICS OF OPTIMAL SINGLE COVER FLAT-PLATE SOLAR COLLECTORS



DOUBLE COVER FLAT-PLATE COLLECTOR ANALYSIS

Analyses similar to those described for the single cover collectors were performed for double cover collectors. The same no load weather constraints were considered, though different performance constraints were used. (The equilibrium temperature constraint for the two specified loads (120 Btu/hr-ft^2 and 150 Btu/hr-ft^2) was increased five degrees to 195°F.) Using these constraints and other constraints discussed in Chapter Five, eight analyses based on varying absorber materials, weather constraints, and performance constraints were performed to identify acceptable flat-plate collector assemblies. From Chapter Five, the double cover constraints limited the number of cover plate combinations to 139 assemblies. Combined with the five copper and eight aluminum absorber materials, acceptable flat-plate collector combinations total 1807 (695 with copper absorber and 1112 with aluminum absorbers). The constraint choices, however, sufficiently reduce these totals to those presented in Table 6-3. Appendix II summarizes data for each set of acceptable collector assemblies in Tables II-9 through II-17.

Variation in the acceptable collector candidate totals by changing cost and performance constraints is shown for the eight cases in Figures 6-11A and C through 6-14A and C. Combining this information with the summary tables of Appendix II, several facts may be pointed out. They are as follows:

FIG. 6-11A

EFFECT OF CHANGING THE MAXIMUM ALLOWABLE FLAT-PLATE ASSEMBLY COST

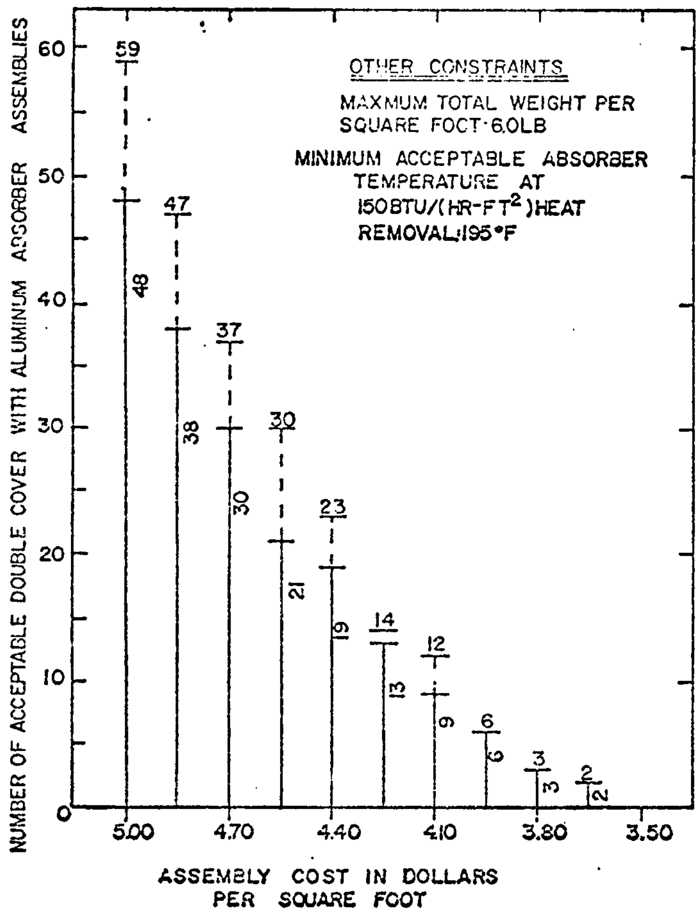
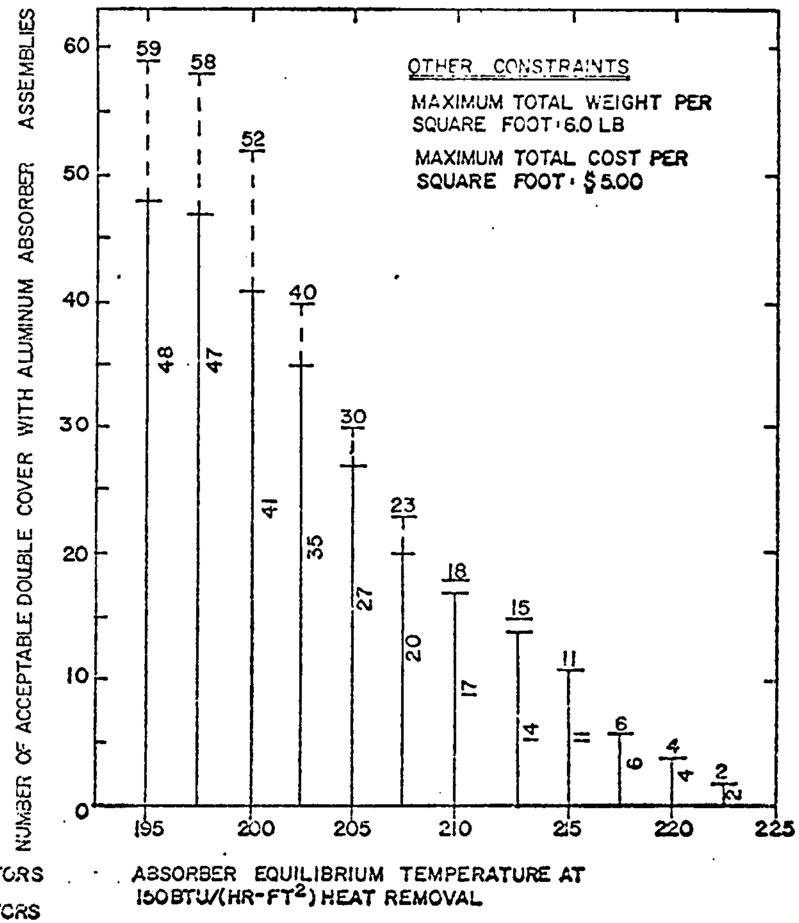


FIG. 6-12A

EFFECT OF CHANGING THE MINIMUM ABSORBER PLATE TEMPERATURE CONSTRAINT AT 150BTU/(HR-FT^2) HEAT REMOVAL



ASSEMBLY CODE

——— DCA 1 COLLECTORS

–––+––– DCA 2 COLLECTORS

FIG. 6-13A

EFFECT OF CHANGING THE MAXIMUM ALLOWABLE FLAT-PLATE ASSEMBLY COST

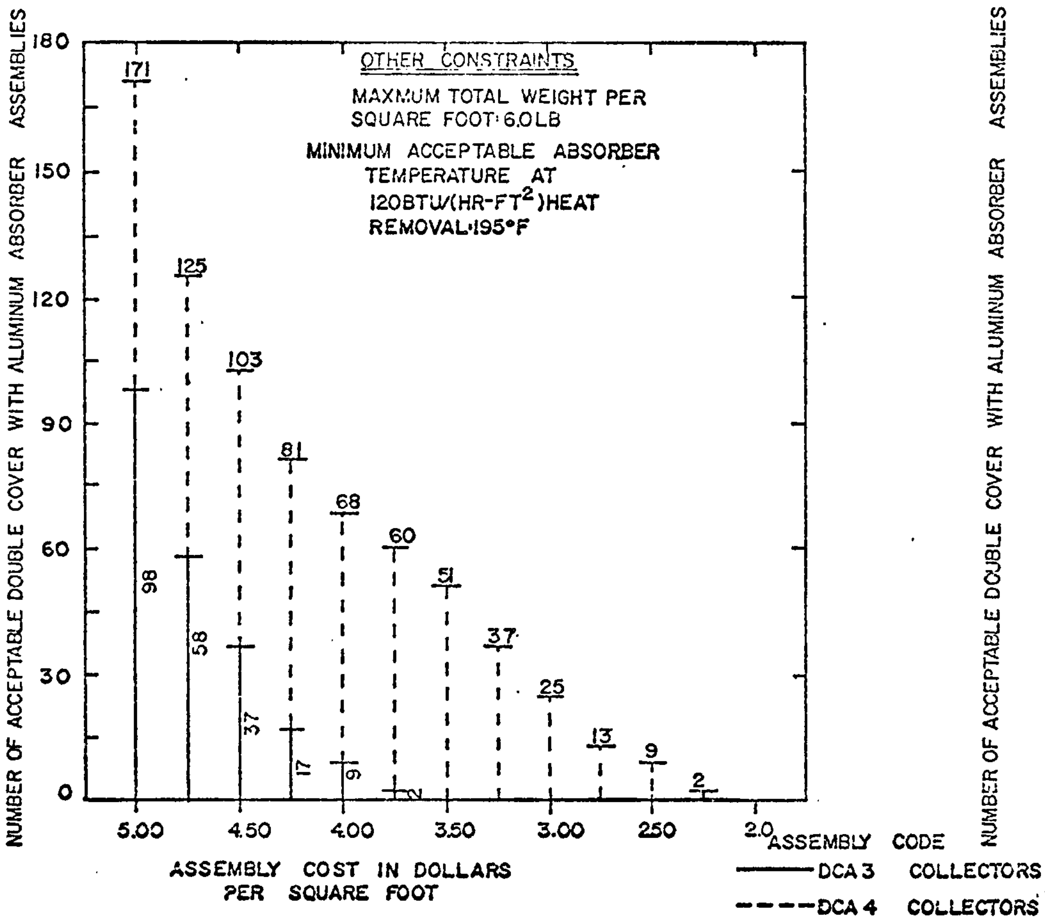


FIG. 6-14A

EFFECT OF CHANGING THE MINIMUM ABSORBER PLATE TEMPERATURE CONSTRAINT AT 120 BTU/(HR-FT^2) HEAT REMOVAL

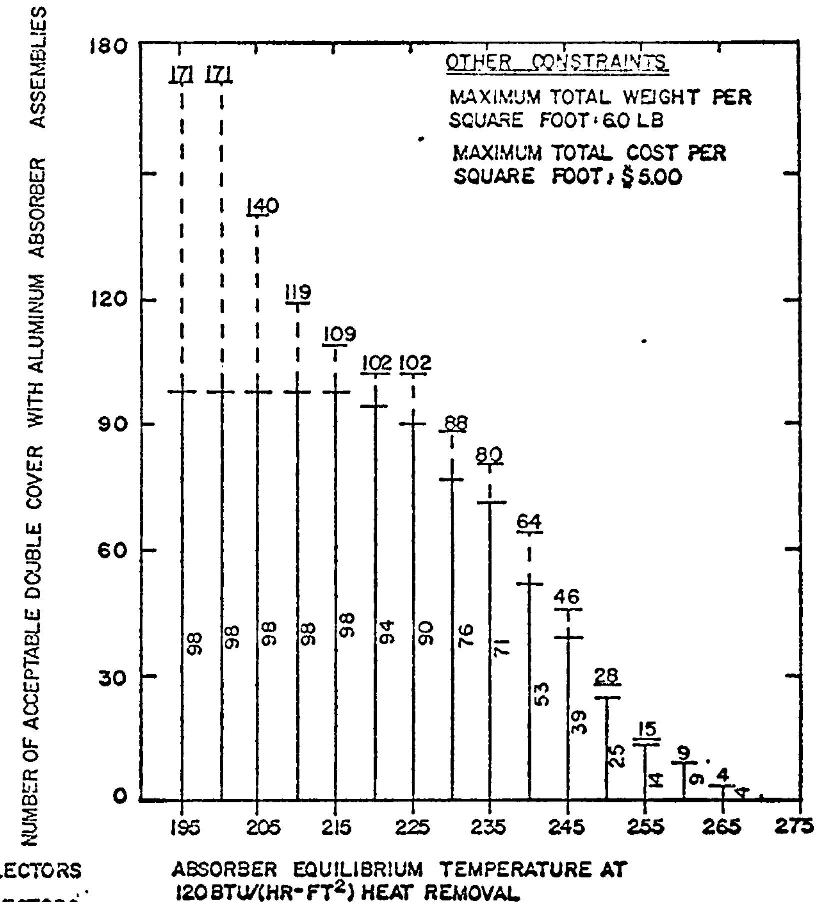


FIG. 6-11C

EFFECT OF CHANGING THE MAXIMUM ALLOWABLE FLAT-PLATE ASSEMBLY COST

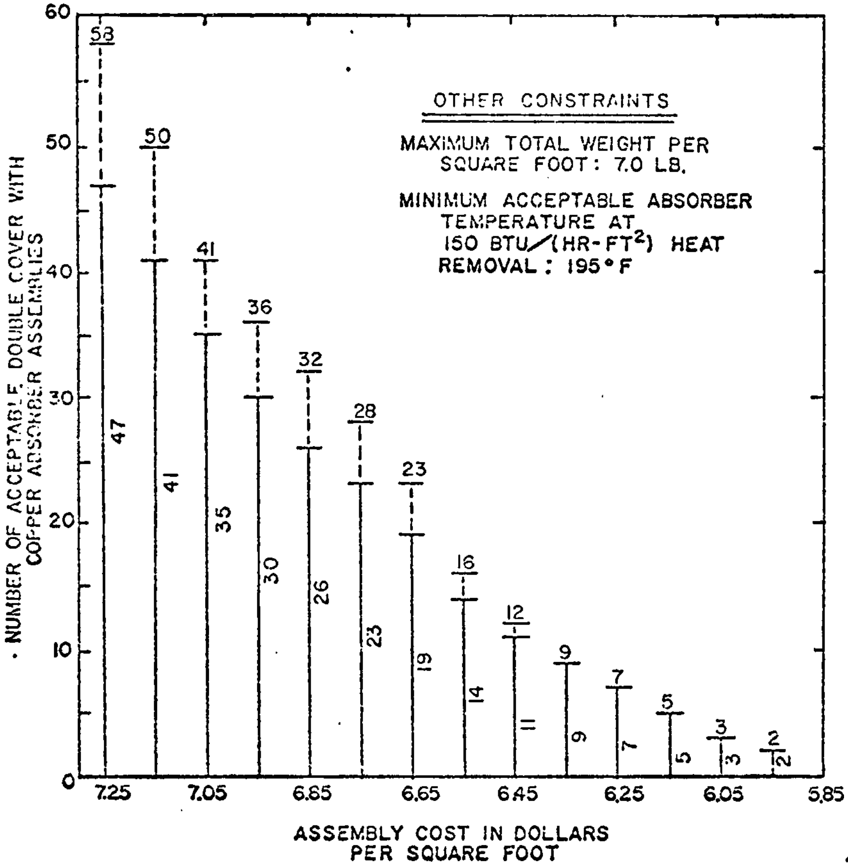
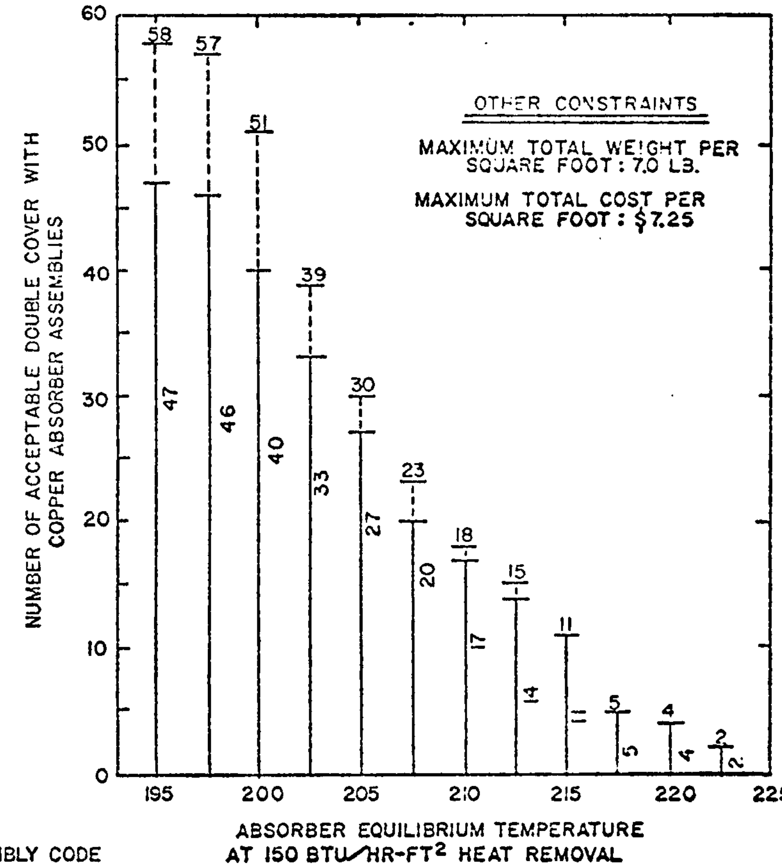


FIG. 6-12 C

EFFECT OF CHANGING THE MINIMUM ABSORBER PLATE TEMPERATURE CONSTRAINT AT 150 BTU/(HR-FT^2) HEAT REMOVAL



ASSEMBLY CODE

—— DCC1 COLLECTORS

- - - - DCC2 COLLECTORS

FIG. 6-13C

EFFECT OF CHANGING THE MAXIMUM ALLOWABLE FLAT-PLATE ASSEMBLY COST

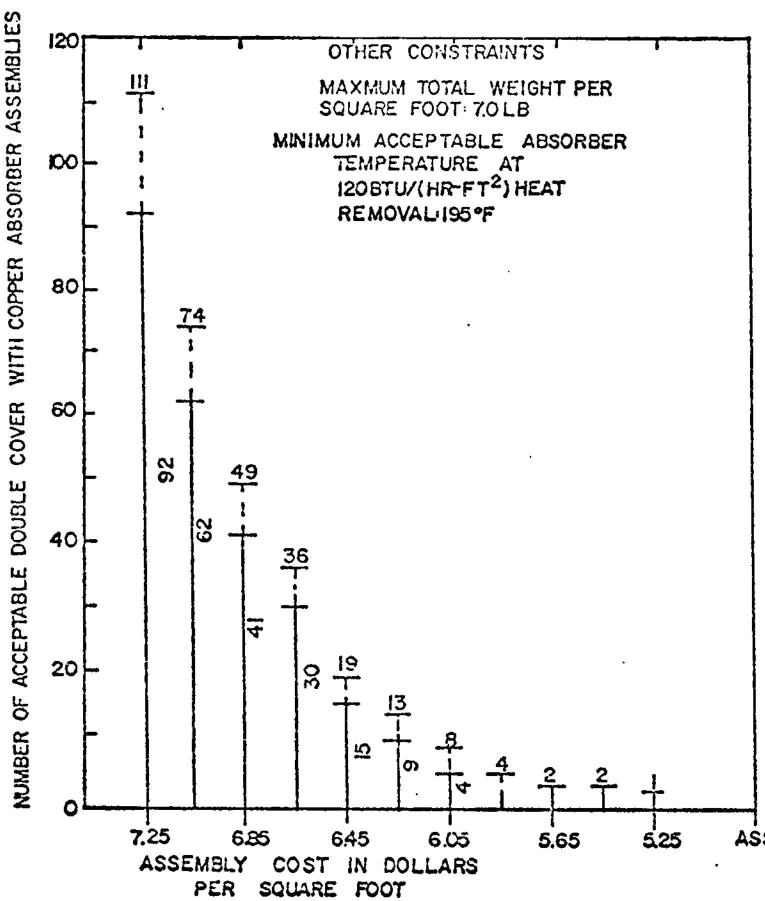


FIG. 6-14C

EFFECT OF CHANGING THE MINIMUM ABSORBER PLATE TEMPERATURE CONSTRAINT AT 120 BTU/(HR-FT^2) HEAT REMOVAL

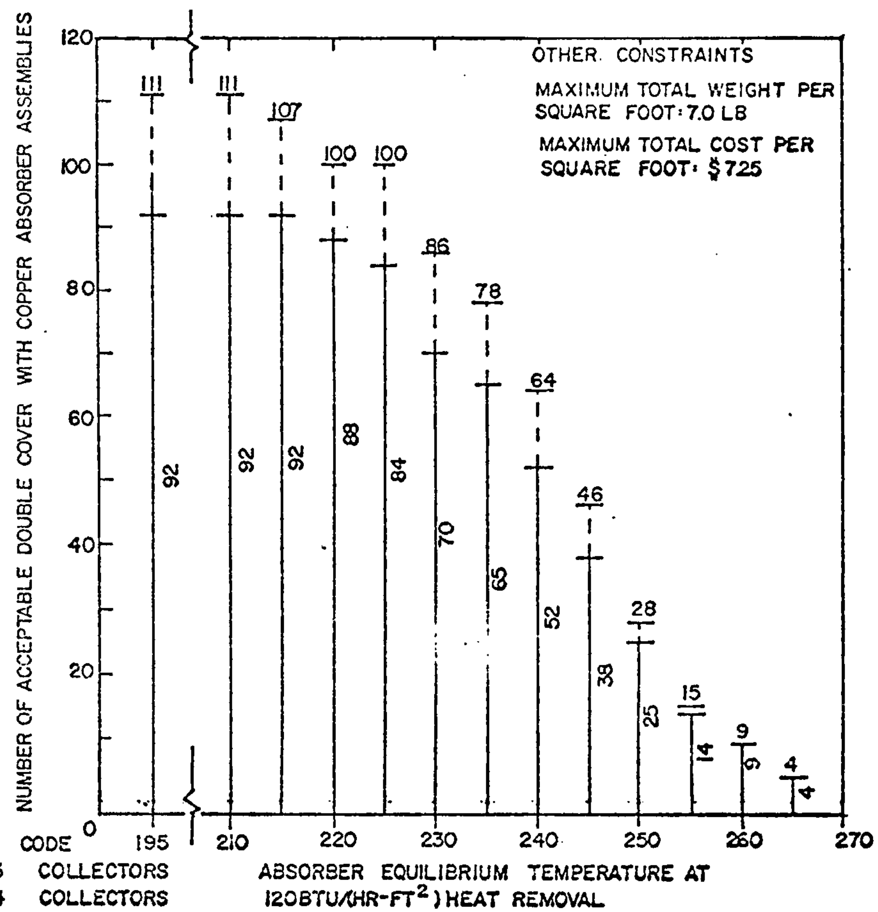


Table 6-3

ACCEPTABLE DOUBLE COVER COLLECTOR ASSEMBLIES

Aluminum Collectors		Copper Collectors	
Designation	Collector Total	Designation	Collector Total
DCA1	48	DCC1	47
DCA2	59	DCC2	58
DCA3	98	DCC3	92
DCA4	171	DCC4	111

1. The solar collector assemblies which attain the highest equilibrium temperatures all utilize electroplated absorber materials. The excessive cost of these absorber coatings limit the number of double cover assemblies which can be used. Since high solar transmission properties and low cost are required, the three most commonly used cover materials are the two plastics, Teflon F.E.P. and Tedlar P.V.F., and the clear lime glasses (iron oxide contents of 0.05 to 0.06%).

2. The most inexpensive acceptable collector assemblies are comprised of selective paint absorbers for aluminum panels and black nickel electroplated surfaces by Solar E for copper. (It should be noted that the Solar E absorber is a single step electroplating process. It is less durable and less effective from performance standpoints than black nickel over nickel, which is a two step electroplated surface.) For these collector assemblies, use of plastic films (Tedlar P.V.F. an Teflon F.E.P.) is required to provide maximum solar transmission, since the absorption characteristics of the absorber materials are marginal. (i.e., the absorbers named emit large fractions of their thermal radiative energy or absorb less than 90% of the solar incident energy).

3. The selection of performance constraints (i.e., whether to remove 120 Btu/hr-ft^2 or 150 Btu/hr-ft^2 and require absorber equilibrium temperatures above 195°F) limits the economic study. As can be seen from Figures 6-11A and C and Figures

6-13A and C, cost savings per square foot of nearly \$0.75 for copper collectors and \$1.30 for aluminum assemblies may be realized by lowering the load constraint to 120 Btu/hr-ft^2. As indicated in the single cover collector section, economics dictates use of the lesser heat removal for double cover aluminum assemblies. Choice of load constraints for copper absorber assemblies is not so obvious, and other constraints such as durability and weatherability may also need to be considered in the selection process.

4. The more restrictive no load weather conditions also restrict the absorber materials which can be utilized in flat-plate technology. No load absorber temperatures in excess of 400°F result using the more restrictive conditions even for non-selective absorbing materials. Since only the electroplated absorber coatings have temperature limitations above this level, the lowest total assembly costs are substantially higher than for collectors where the less restrictive no weather constraints are employed. This is best seen in Figures 6-13A and C where for the same load removed, the different weather conditions are used to limit the candidate totals. Substantial savings in collector cost per square foot can be realized from these figures.

Based on the general trends presented, 'DCA4' and 'DCC4' were selected for further optimization studies. These two cases consider collectors which can withstand the less restrictive no load weather constraints and still provide 195°F absorber temperatures at 120 Btu/hr-ft^2 heat removal. They were chosen for analyzes because both high performance collectors and low cost collectors can be chosen from the candidate lists in Tables II-13 and II-17. The high performance collectors listed in these tables are composed of the same materials required for high performance collectors chosen using the other constraint conditions. (This can be seen by analyzing Figures 6-12A and C and 6-14A and C.) However, the number of low cost system candidates is limited if high performance requirements or more restrictive weather constraints are employed. The relaxing of the constraints to that of 'DCC4' and 'DCC4' assures consideration of the less expensive absorber materials.

Using the two criterion functions, twelve candidates for each absorber panel type have been chosen. They are listed in Tables 6-4A and 6-4C. Six of the twelve assemblies for copper and aluminum panels are chosen based on economics, and six are selected because of their superior performance capabilities. While the high performance collectors are significantly more expensive than the low cost assemblies (by over \$1.00 for copper assemblies and nearly \$2.00 for aluminum assemblies), these collectors may be utilized in industrial process heat applications. Further, these assemblies can be utilized for solar air conditioning at greater heat loads (refer to Tables 6-4A and C) than 120 Btu/hr-ft^2.

Representative double cover aluminum and copper absorber assemblies are compared in Figures 6-15 and 6-16 for differently weighted coefficients for cost and performance. The data obtained using the linear criterion function is again shown, though similar relationships between the different collector designs could be pointed out using the criterion function composed of power functions. The choice of an optimal collector type, if collector weight, expected life, or durability is critical, can be made through consideration of Figures 6-15B and 6-16B and 6-15C and 6-16C depending upon the importances of these judging criteria.

Figures 6-17 and 6-18 are provided to present the performance characteristics of several of the optimal double cover

TABLE 6-4A

OPTIMAL DOUBLE COVER ALUMINUM ABSORBER ASSEMBLIES

Designation	Absorber	Cover Panels: Inside	Cover Panels: Outside	Cost of System in Dollars per Square Foot	Absorber Equilibrium Temperature (°F) for Two Loads: $120^{Btu}/hr\text{-}ft^2$	Absorber Equilibrium Temperature (°F) for Two Loads: $150^{Btu}/hr\text{-}ft^2$
DCA4-1	Meteor 7890 Selective Paint (.05 mil)	5 mil Teflon F.E.P.	4 mil Tedlar P.V.F.	2.46	208.7	179.0
DCA4-3	Meteor 7890 Selective Paint (.05 mil)	125 mil Temper Glass	4 mil Tedlar P.V.F.	2.44	205.8	172.9
DCA4-9	Meteor 7890 Selective Paint (.05 mil)	125 mil Clear Glass	4 mil Tedlar P.V.F.	2.13	209.0	176.3
DCA4-10	Meteor 7890 Selective Paint (.05 mil)	125 mil Clear Temper Glass	4 mil Tedlar P.V.F.	2.35	209.0	176.3
DCA4-11	Meteor 7890 Selective Paint (.05 mil)	187 mil Clear Glass	4 mil Tedlar P.V.F.	2.28	207.5	174.5
DCA4-12	Meteor 7890 Selective Paint (.05 mil)	187 mil Clear Temper Glass	4 mil Tedlar P.V.F.	2.38	207.5	174.5
DCA4-99	Black Nickel over Nickel	5 mil Teflon F.E.P.	4 mil Tedlar P.V.F.	3.96	266.3	222.5
DCA4-110	Black Nickel over Nickel	125 mil Sunadex	4 mil Tedlar P.V.F.	4.10	262.2	217.4
DCA4-111	Black Nickel over Nickel	156 mil Sunadex	4 mil Tedlar P.V.F.	4.20	261.2	216.4
DCA4-114	Black Nickel over Nickel	5 mil Teflon F.E.P.	5 mil Teflon F.E.P.	4.46	265.4	222.0
DCA4-158	Black Nickel over Nickel	5 mil Teflon F.E.P.	187 mil Sunadex	4.84	265.9	221.3
DCA4-159	Black Nickel over Nickel	5 mil Teflon F.E.P.	219 mil Sunadex	4.98	264.4	219.7

TABLE 6-4C

OPTIMAL DOUBLE COVER COPPER ABSORBER ASSEMBLIES

Designation	Absorber	Cover Panels Inside	Cover Panels Outside	Cost of System in Dollars per Square Foot	Absorber Equilibrium Temperature (°F) for Two Loads: 120 Btu/hr-ft^2	Absorber Equilibrium Temperature (°F) for Two Loads: 150 Btu/hr-ft^2
DCC4-49	Black Nickel over Nickel	125 mil Float Glass	4 mil Tedlar P.V.F.	5.87	247.2	203.0
DCC4-55	Black Nickel over Nickel	125 mil Clear Glass	4 mil Tedlar P.V.F.	5.85	253.9	209.0
DCC4-108	Black Nickel (Solar F)	187 mil Float Glass	4 mil Tedlar P.V.F.	5.16	212.8	166.4
DCC4-109	Black Nickel (Solar E)	187 mil Temper Glass	4 mil Tedlar P.V.F.	5.25	212.8	166.4
DCC4-110	Black Nickel (Solar E)	187 mil Float Glass	5 mil Teflon F.E.P.	5.66	211.6	165.5
DCC4-111	Black Nickel (Solar E)	187 mil Temper Glass	5 mil Teflon F.E.P.	5.76	211.6	165.5
DCC4-48	Black Nickel over Nickel	5 mil Teflon F.E.P.	4 mil Tedlar P.V.F.	6.22	266.3	222.5
DCC4-59	Black Nickel over Nickel	125 mil Sunadex	4 mil Tedlar P.V.F.	6.35	262.2	217.4
DCC4-60	Black Nickel over Nickel	156 mil Sunadex	4 mil Tedlar P.V.F.	6.45	261.2	216.4
DCC4-63	Black Nickel over Nickel	5 mil Teflon F.E.P.	5 mil Teflon F.E.P.	6.72	265.4	222.0
DCC4-106	Black Nickel over Nickel	5 mil Teflon F.E.P.	187 mil Sunadex	7.10	265.9	221.3
DCC4-107	Black Nickel over Nickel	5 mil Teflon F.E.P.	219 mil Sunadex	7.24	264.4	219.7

FIG. 6-15
OPTIMAL DOUBLE COVER WITH ALUMINUM ABSORBER ASSEMBLIES BASED ON COST AND PERFORMANCE AT 120 BTU/(HR-FT^2) HEAT REMOVAL

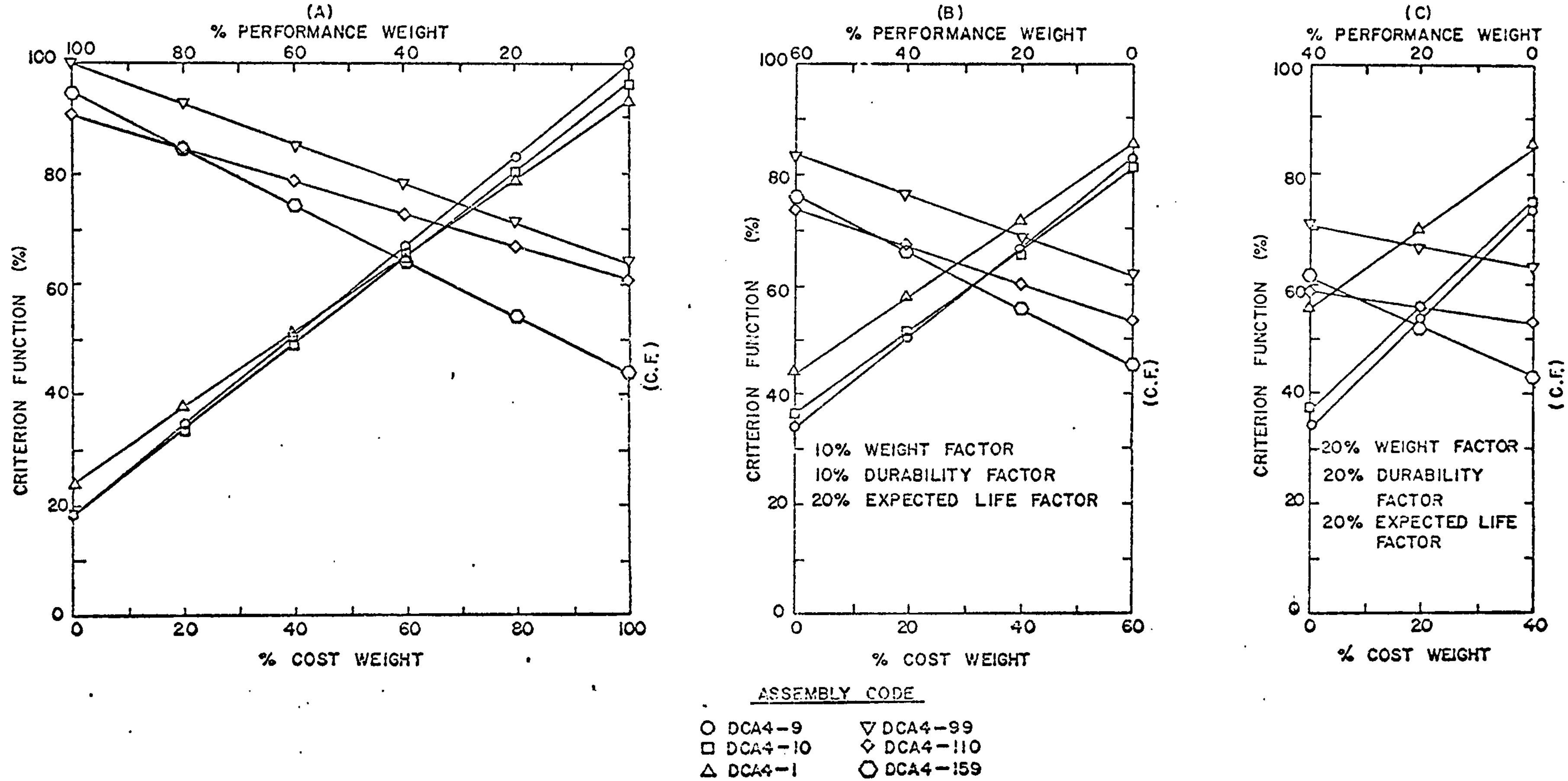
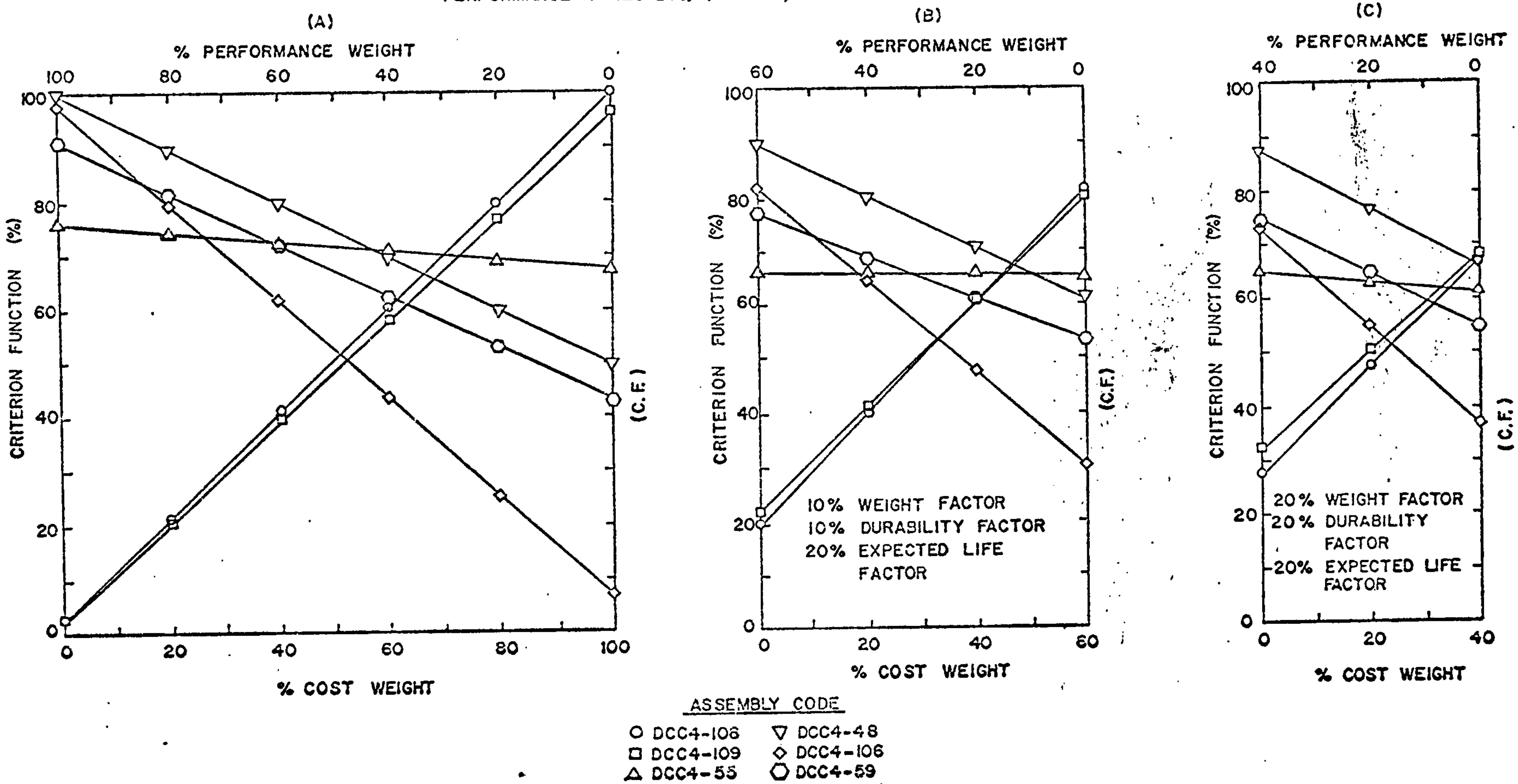


FIG. 6-16

OPTIMAL DOUBLE COVER WITH COPPER ABSORBER ASSEMBLIES BASED ON COST AND PERFORMANCE AT 120 BTU/(HR-FT^2) HEAT REMOVAL



flat-plate collectors. Different facts can be pointed out by these curves. Consideration of the no load condition (Q_L/Q_s = 0.0) for the DCA4-10 and DCC4-49 assemblies (refer to Figure 6-17) points out the effect which the absorber thermal emissivity has on the absorber equilibrium temperature. While both collector assemblies absorb approximately the same quantity of solar energy (This is seen by comparing their efficiencies at the T_{FP} = T_A condition.), the copper assembly, DCC4-49, emits much less thermal radiative energy (for the copper absorber, ε_{IR} = 0.07, for the aluminum absorber, ε_{IR} = 0.47). Thus, higher equilibrium temperatures for the copper assembly are possible. In addition, since several collectors have superior absorber equilibrium temperatures at the designated heat removal of 120 Btu/hr-ft^2, Figures 6-17 and 6-18 indicate that higher heat removals are possible while still fulfilling space cooling requirements.

In concluding this section, observations on the use of Tedlar P.V.F. in double cover assemblies can be developed based on the computer analyses. Work reported by Whillier [6-1] indicated that this plastic film should be used for inside cover plates and that temper glass should be used for outside cover plates. This conclusion resulted from the fact that Tedlar P.V.F. has questionable weatherability and durability properties. From a performance standpoint, however, it has been shown in Chapter Four that higher absorber equilibrium temperatures can be obtained if glass is used as the inside cover, owing to its low thermal transmissivity. From the constraints analysis, this is again

FIG 6-17

PERFORMANCE CHARACTERISTICS OF OPTIMAL DOUBLE COVER FLAT-PLATE SOLAR COLLECTORS

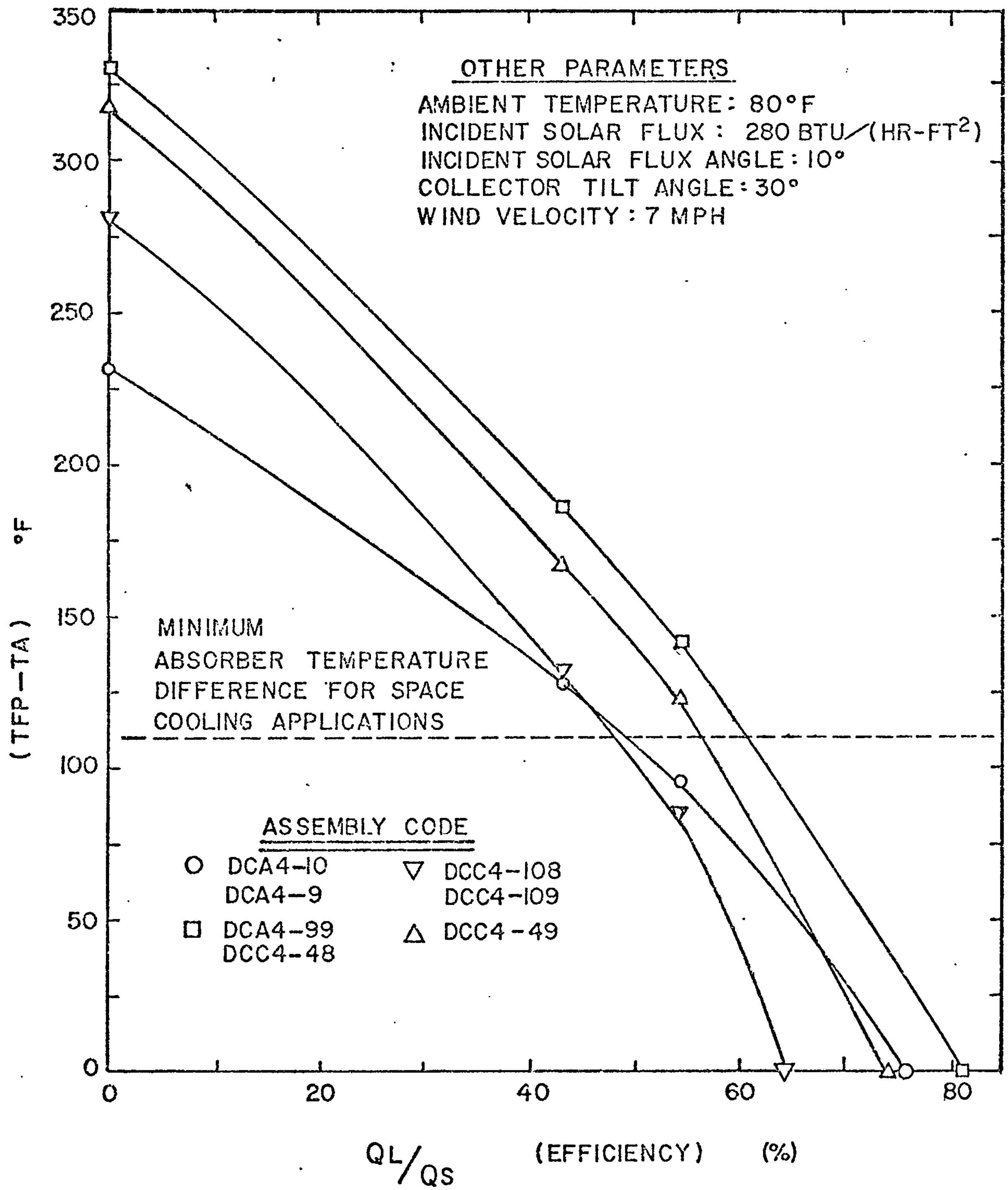
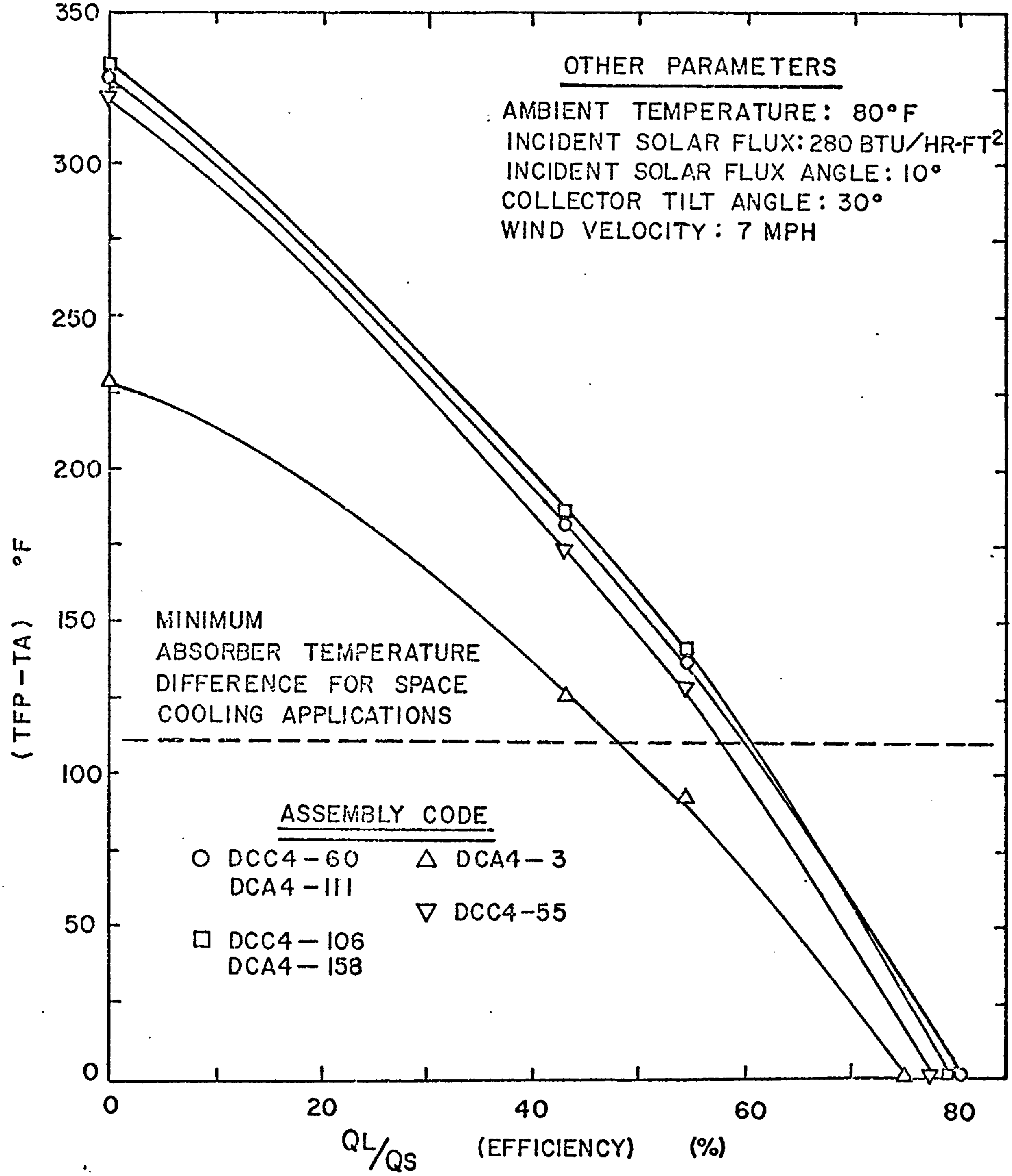


FIG. 6-18
PERFORMANCE CHARACTERISTICS OF OPTIMAL
DOUBLE COVER FLAT-PLATE SOLAR COLLECTORS



the result since Tedlar P.V.F. has temperature limitations that prevent its use as an inside cover for the no load-extreme summer weather conditions. Thus use of Tedlar P.V.F. may be limited, especially if excessive durability and weatherability constraints are applied, because this material should be used only as an outside cover material for a two cover assembly.

COMPARISON OF SINGLE AND DOUBLE COVER COLLECTOR ASSEMBLIES

The results of the computer simulation indicate that there are cover and absorber material combinations suitable for space cooling. Twenty-four optimal assemblies have been tabulated. Questions concerning choice of optimal single or double cover assemblies can be answered by employing the criterion function plots provided, so long as designer imposed weighting coefficients for cost, performance, durability, expected life, and weight are specified. A design problem not yet considered is the choice between single or double cover optimal flat-plate collectors. Since optimal designs for each case can provide for solar cooling, additional consideration of the relative importance placed on cost, performance, and durability must be undertaken. The choice is perhaps as arbitrary as the one which would have to be made for absorber panel types (aluminum or copper).

Cost considerations alone favor the single cover collector assemblies. Tables 6-2A and C and 6-4A and C indicate that savings between DCC4-108 and SCC4-49 of \$0.78 per square foot can be realized. Both of these collectors have comparable performance characteristics so that use of the more expensive models cannot be justified through increasing the heat removal.
For aluminum absorbers, similar trends are noted. Savings of nearly \$0.40 per square foot can be realized by using the SCA4-1

assembly instead of DCA4-9. The only difference between these two collector types, in fact, is in the use of a sheet of clear lime glass for an inner cover. Such savings are even more substantial if labor costs are considered. Based on a crude approximation that the retail cost for solar collectors at most should equal three times the material costs [6-2], savings of as much as $1.20 and $2.34 per square foot for aluminum and copper collectors respectively could be realized using one cover plate. This trend would be expected since cost of assembling two cover flat-plate solar collectors would be greater due to increased labor time.

Durability considerations favor the use of double cover flat-plate collector assemblies. The cover materials most often utilized in the single cover design are the plastics, Teflon F.E.P. and Tedlar P.V.F. From Chapter Two, questions pertaining to extended life cycles for these materials are brought up. In addition, while the plastics are lightweight, failure due to fatiguing from cyclic wind loading has been reported in the literature [6-3]. For the double cover assemblies, glass and plastic cover material combinations are shown in Tables 6-4A and C. For the most inexpensive double cover collectors listed, non-tempered glass is used for the inner cover. While this material has poor impact resistance properties, it has good temperature limitation properties and good chemical resistance in the event of outside cover rupture. The overall superior durability of a two cover assembly cannot be neglected, particularly if expensive-not-so-durable selective surfaces are used.

The performance characteristics of double cover flat-plate solar collectors have previously been shown in Chapter Four to be superior to those of single cover flat-plate collectors. If space cooling is required, it has been shown that single cover collectors can be utilized at less expense than can double cover collectors. However, for higher temperature requirements such as might be needed for low pressure industrial steam production, temperature differences of nearly 25°F (266°F for double cover collectors; 242°F for single cover collectors) can be found for a heat load removal of 120 Btu/hr-ft^2. At 150 Btu/hr-ft^2 heat removal, differences of approximately 14°F can be estimated for the best performing single and double cover flat-plate assemblies. Thus, application of the double cover flat-plate collector for process heat production at elevated heat removal rates may be justified while single cover collectors appear questionable with respect to this application.

The choice of one or two cover plates for collector design must be based on all three criteria, however. Since durability and performance properties are so critical to collector life expectancy, the inclination is to utilize double cover plate collectors. The destruction of the single plastic cover necessitates immediate replacement in order to protect the absorber and insulation. The additional labor and materials costs are great enough to justify the initial greater expense. It must also be stated, however, that if economic limitations must be emphasized, all of the collectors of Tables 6-2A and C have been designed to survive average weathering and durability problems.

In concluding this section, two other points should be noted. The first point addresses the selection of copper or aluminum collector panels. Analyses have been performed and presented for both copper and aluminum collector systems because there are presently two major opinions on how emphasis should be placed on absorber panel cost and durability. As was shown in Chapter Five, the Olin Brass aluminum collector is significantly less expensive (by $2.26 per square foot) than the same copper assembly. While, this price difference is excessive, support for use of the more expensive collector panel can be found if the corrosion problems of aluminum are not impeded. Olin Brass recommends use of corrosion inhibitors in the aluminum panel flow passages [6-4]. Such use not only prevents the aluminum panels from being used to also provide hot water for domestic applications, but also increases the cost of the total collector system. In addition, excessive corrosion problems could result in leaks in the panel flow network. Damage to both the insulation and absorber surface could result. (It must be pointed out that Olin Brass estimates that use of inhibitors will allow the absorber to function from between ten to twenty years depending upon the occasional flushing of the system and replacement of the inhibitor [6-4].) Thus, the selection of aluminum or copper absorber solar collectors is left to the designer's discretion.

The final point considers the question of collector economics (i.e., are the optimal collectors listed economically competitive with present marketed collectors?). From Table 1-1, present costs of the collectors can be found. For the General Electric and P.P.G. collectors, the materials utilized have all been tabulated and thus estimated material costs can be made. These costs, and the actual selling prices are provided in Table 6-5.

Table 6-5

COST DATA ON REPRESENTATIVE COMMERCIAL COLLECTORS .

Collector	Absorber Panel	Estimated Material Cost ($/ft^2)	Estimated Selling Price* ($/ft^2)
P.P.G. Baseline Solar Collector	Aluminum	2.90	8.92
	Copper	5.16	11.20
General Electric Collector	Aluminum	3.92	9.98

*Based on price data provided in Table 1-1.

Based on this table, it may be estimated that competitive price limitations are $6.00 per square foot for copper (higher than $5.16 listed in Table 6-5 because the collector tabulated cannot provide solar cooling at the specified heat removal rate) and around $3.00 per square foot for aluminum absorber assemblies. Comparison of these constraints with the optimal collectors tabulated in Tables 6-2A, 6-2C, 6-4A, and 6-4C indicates that competitive systems have indeed been designed which can provide space cooling. If different, less expensive copper or aluminum panels are utilized, or if the lower estimated production costs on absorbing materials are ever reached, then the economics will make solar energy utilization for space cooling attractive to the consumer.

Chapter Seven

CONCLUDING REMARKS

The work presented has indicated that space cooling incorporating flat-plate technology to provide heat for absorption refrigeration air conditioning is feasible from economic, performance, and durability considerations. The compilation of materials comprising flat-plate solar collectors has allowed for a more extensive comparison of solar collector materials than has previously been found in the literature. Cost data, while current only through 1975, has been compiled to provide a basis for moderately large production cost comparisons. The mechanical, thermal, and radiative properties tabulated provide other means by which the collector materials can be compared. As such, the material data provided represents the single most important contribution which this thesis offers for future solar work.

Utilizing a computer simulation which determines steady state equilibrium temperatures for the cover(s) and absorber surfaces, two sets of results have been presented. The first set of data obtained considers general performance characteristics for representative cover materials and different degrees of absorber material selectivity (i.e., different $\alpha_s/\varepsilon_{IR}$ ratios). Data with respect to different wind velocities, insolations, and absorber solar absorption properties has been presented graphically. This data may be employed to predict flat-plate collector performance for different absorber materials and should prove useful as new selective surfaces are developed for solar utilization.

The second collection of data considers performance and additional flat-plate collector constraints with respect to durability and economics. For estimated Houston summer conditions, sixteen computer analyses have been presented. From these simulations, optimal flat-plate solar collector systems for space cooling have been chosen. These optimal collectors are summarized in Tables 6-2A, 6-2C, 6-4A, and 6-4C.

Of the assemblies tabulated, one half of these collectors are especially suited for providing high temperature heat for absorption refrigeration air conditioning. These systems have been shown to be economically competitive with presently available commercial collector systems. The other assemblies are the more expensive high performance flat-plate collectors which may be utilized for industrial process heat or steam production.

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Appendix I

The data which has been gathered on existing solar equipment and on solar collector component materials could not have been obtained without the assistance of the industries, governmental agencies, and universities involved in solar work. The author therefore wishes to express his appreciation to these organizations through the following acknowledgement of groups which provided technical and economic information.

1. A-1 Plastics (Distributor)
   5822 S.W. Freeway
   Houston, Texas 77027

2. Aluminum Company of America
   Alcoa Technical Center
   Alcoa Center, Pennsylvania 15069

3. Arkla Industries, Inc.
   Arkla Plaza - 400 E. Capitol
   Little Rock, Arkansas 72203

4. ASG Industries, Inc.
   P. O. Box 929
   Kingsport, Tennessee 37662

5. B&B Insulations, Inc. (Distributor)
   8011 Blankenship, P. O. Box 2531
   Houston, Texas 77001

6. Binswanger Glass Company (Distributor)
   207 N. Main
   Houston, Texas

7. Cadillac Plastics (Distributor)
   P. O. Box 03000
   Detroit, Michigan 48203

8. E. I. DuPont De Nemours & Co.
   Film Department or Plastics Department
   Wilmington, Delaware 19898

9. Eagle-Picher Industries, Inc.
   Fibers Department - P. O. Box 779
   Cincinnati, Ohio 45201

10. Enthone, Inc.
    P. O. Box 1900
    New Haven, Connecticut 06508

11. Forty-Eight Insulations, Inc.
    P. O. Box 1148
    Aurora, Illinois 60507

12. General Electric - Sheet Plastics Section
    1 Plastics Avenue
    Pittsfield, Massachusetts 01201

13. General Electric - Solarquip Products
    P. O. Box 13601
    Philadelphia, Pennsylvania 19101

14. Grumman Aerospace Corporation
    Energy Programs
    Bethpage, New York 11714

15. Harshaw Chemical Company
    1945 E. 97th Street
    Cleveland, Ohio 44106

16. Honeywell, Inc.
    2600 Ridgeway Parkway
    Minneapolis, Minnesota 55413

17. Howmet Corporation
    No Address Provided
    Phone (214) 226-7671

18. Kalwall Corporation
    1111 Candia Road - P. O. Box 237
    Manchester, New Hampshire 03105

19. Libbey-Owen-Ford Company
    2300 W. Loop South - Suite 515
    Houston, Texas 77027

20. N.A.S.A. Lewis Research Center
    Mail Stop - Building 51-1
    21000 Brook Park
    Cleveland, Ohio 44135

21. Olin Brass - Roll Bond Products
    East Alton, Illinois 62024

22. Olympic Plating Industries, Inc.
    208 - 15th Street
    Canton, Ohio 44707

23. Owens-Corning Fiberglas Corporation
    Power and Process Division
    Fiberglas Tower
    Toledo, Ohio 43659

24. P.P.G. Industries, Inc.
    One Gateway Center
    Pittsburgh, Pennsylvania 15222

25. Pittsburgh Corning Corporation
    800 Presque Isle Drive
    Pittsburgh, Pennsylvania 15239

26. Revere Copper and Brass, Inc.
    P. O. Box 191
    Rome, New York 13440

27. Reynolds Aluminum - Reynolds Metal Co.
    P. O. Box 27003
    Richmond, Virginia 23261

28. Rohm and Haas Company
    Adair Center, Suite 405
    6300 Hillcroft Street
    Houston, Texas 77036

29. Sabine Industries, Inc. (Distributor)
    4400 East Park
    Houston, Texas

30. San Jacinto Glass (Distributor)
    8003 Channelside
    Houston, Texas

31. Sheffield Poly-Glaz, Inc.
    Sheffield, Massachusetts 01257

32. Solar Equipment Corporation
    P. O. Box 327
    Edison, New Jersey 08817

33. Stonaber, Inc. (Distributor)
    2508 Fairway Park Drive
    Houston, Texas 77018

34. Suntek Incorporated
    33 Edinboro Street
    Boston, Massachusetts 02111

35. Sunworks, Inc.
    669 Boston Post Road
    Guilford, Connecticut 06437

36. Transilwrap Company
    1118 Quaker Street
    Dallas, Texas 75207

37. United States Gypsum Company
    101 South Wacker Drive
    Chicago, Illinois 60606

Appendix II

The results of the computer analysis employed to select single and double cover flat-plate solar collectors which can attain suitable temperatures for use in absorption air conditioning are provided in Tables II-2 through II-17. The solar collector assemblies listed fulfill various performance and weather conditions as discussed in the flat-plate collector constraints section. Table II-1 summarizes the conditions met by sixteen sets of acceptable flat-plate solar collectors. The sixteen acceptable collector tables provided include cost, weight, durability, weatherability, and performance data on the assemblies. The coded components which make up the collector assembly are listed. In order to use this information, a nomenclature explaining the computer printout abbreviations is included below.

Nomenclature

ABS: Coded absorber material designation. In order to know whether the absorber material is for the copper or aluminum absorber panel, the 'MAT' column must be checked.

CODE FOR ALUMINUM ABSORBER MATERIAL OPTIONS

1 *** Duracron Thermosetting Acrylic Paint (baked and cured on aluminum)
2 *** Duracron Air-Drying Acrylic Paint (sprayed on aluminum)
3 *** Meteor 7890 Selective Paint (sprayed and cured on aluminum: 0.05 mil)
4 *** Meteor 7890 Selective Paint (sprayed and cured on aluminum: 0.21 mil)
5 *** Black Chrome over Dull Nickel (electroplated on aluminum: 30 seconds)

6 *** Black Chrome over Dull Nickel (electroplated on aluminum: 1 minute)
7 *** Black Nickel over Nickel (electroplated on aluminum)
8 *** Alcoa Black (Alcoa 655 process applied to aluminum by immersion)

CODE FOR COPPER ABSORBER MATERIAL OPTIONS

1 *** Black Chrome over Dull Nickel (electroplated on copper: 30 seconds)
2 *** Black Chrome over Dull Nickel (electroplated on copper: 1 minute)
3 *** Black Nickel over Nickel (electroplated on copper)
4 *** Black Nickel (electroplated on copper by Solar Equipment Corp.)
5 *** Black Copper (copper oxide on copper by immersion process of Enthone)

ASSY: Acceptable flat-plate collector assembly. 'ASSY' is numbered consecutively without consideration of which collector performs most effectively.

DTL1: Absorber equilibrium temperature difference with the ambient temperature (TFP-TA) at a heat removal of 120 Btu/hr-ft^2 under average weather conditions.

DTL2: Absorber equilibrium temperature difference with the ambient temperature (TFP-TA) at a heat removal of 150 Btu/hr-ft^2 under average weather conditions.

DURA: Coded estimated durability of the absorber material.
1.0 = no resistance to environment (requires vacuum)
3.0 = stable coating except under water impingement
5.0 = coating maintains integrity under weathering extremes.

EFFIM: Coded impact resistance of cover assembly. For a single cover, 'EFFIM' is the cover impact resistance. For a double cover, 'EFFIM' is the effective impact resistance (as defined in Chapter 4).
1.0 = no wind load resistance. Impact strength minimal.
2.0 = effective impact strength of 25 mil Sunlite.
3.0 = effective resistance of 187 mil Tempered glass.
4.0 = effective resistance of 187 mil Plexiglas G.
5.0 = warranteed material. Effective strength of 187 mil Lexan MR-4000.

ICP: Coded inside cover panel for the two cover plate assembly.

CODE FOR COVER PLATE MATERIALS

1 *** 4 mil Tedlar P.V.F.
2 *** 5 mil Teflon F.E.P.
3 *** 5 mil Mylar Type S
4 *** 25 mil Sunlite Regular
5 *** 40 mil Sunlite Regular
6 *** 25 mil Sunlite Premium
7 *** 40 mil Sunlite Premium
8 *** 125 mil Float Glass
9 *** 125 mil Tempered Glass
10 *** 187 mil Float Glass
11 *** 187 mil Tempered Glass
12 *** 63 mil Plexiglas G
13 *** 125 mil Plexiglas G
14 *** 187 mil Plexiglas G
15 *** 63 mil Lucite AR
16 *** 125 mil Lucite AR
17 *** 187 mil Lucite AR
18 *** 63 mil Polyglaz (polycarbonate)
19 *** 125 mil Polyglaz (polycarbonate)
20 *** 187 mil Polyglaz (polycarbonate)
21 *** 63 mil Lexan MR-4000
22 *** 125 mil Lexan MR-4000
23 *** 187 mil Lexan MR-4000
24 *** 125 mil Clear Lime Sheet Glass
25 *** 125 mil Clear Lime Temper Glass
26 *** 187 mil Clear Lime Sheet Glass
27 *** 187 mil Clear Lime Temper Glass
28 *** 125 mil Sunadex Glass (0.01% iron oxide)
29 *** 156 mil Sunadex Glass (0.01% iron oxide)
30 *** 187 mil Sunadex Glass (0.01% iron oxide)
31 *** 219 mil Sunadex Glass (0.01% iron oxide)

INS: Coded insulation used to cut down back heat losses.

CODE FOR INSULATION MATERIAL OPTIONS

1 *** Mineral Wool (10#): 10# density
2 *** Mineral Wool (ETR Board): 8# density
3 *** Mineral Wool (IT Insulation): 6# density
4 *** Mineral Wool (MT-10): 10# density
5 *** Mineral Wool (MT-8): 8# density

6 *** Mineral Wool (MT-6): 6# density
7 *** Industrial Felt (SF-234): 8# density
8 *** Industrial Felt (SF-240): 6# density
9 *** Industrial Felt (SF-250): 4.5# density
10 *** Industrial Felt (SF-252): 4# density
11 *** Industrial Felt (SF 256): 3.5# density
12 *** Industrial Felt (SF-260): 3# density
13 *** Industrial Felt (SF- 270): 2.5# density
14 *** Foamglas: 8.5# density
15 *** Fiberglas (IS Board): 4# density
16 *** Fiberglas (TIW Type II): 2.4# density
17 *** Fiberglas (TIW Type I): 1.25# density
18 *** Fiberglas (705 Series): 6# density
19 *** Fiberglas (703 Series): 3# density
20 *** Fiberglas (701 Series): 1.6# density

MAT: Code for the absorber panel used.
1.0 = steel absorber plate
2.0 = copper absorber plate
3.0 = aluminum absorber plate

OCP: Coded outside cover panel for the two cover plate assembly; coded single cover plate for the one cover plate assembly. Refer to 'ICP' for coded cover plate materials.

TIN: Insulation thickness in inches. Designed for under no load-extreme summer conditions.

TWTC: Total weight of the collector assembly in pounds per square foot.

T$$: Total cost of the collector assembly in dollars per square foot.

WETH: Coded weatherability of cover assembly. For a two cover system, 'WETH' is the effective cover weathering parameter as defined by

$$WETH = (WETH_{\substack{inside\\cover}} + 3.0*WETH_{\substack{outside\\cover}})/4.0$$

1.0 = no weather resistance. Degrades rapidly under chemical environment.
2.0 = U.V. degradation limits lifetime (solar) to under seven years.
3.0 = 5 to 7% decrease in transmission over 10 years. Good chemical resistance.
4.0 = effective weathering life of 20 years. Superior chemical resistance.
5.0 = effective weathering life of 30 years. No chemical degradation.

TABLE II-1

CODED COLLECTOR ASSEMBLY DESIGNATION DATA

Collector Assembly Designation	Number of Covers	Absorber Plate Material	Extreme-No Load Weather Constraints Analyzed	Performance Constraints Analyzed (Minimum Temperature Required)
SCA1 (Table II-2)	1	Aluminum	More Restrictive	190° F at 150 $^{Btu}/_{hr\text{-}ft^2}$ Load
SCA2 (Table II-3)	1	Aluminum	Less Restrictive	190° F at 150 $^{Btu}/_{hr\text{-}ft^2}$ Load
SCA3 (Table II-4)	1	Aluminum	More Restrictive	190° F at 120 $^{Btu}/_{hr\text{-}ft^2}$ Load
SCA4 (Table II-5)	1	Aluminum	Less Restrictive	190° F at 120 $^{Btu}/_{hr\text{-}ft^2}$ Load
SCC1 (Table II-6)	1	Copper	More Restrictive	190° F at 150 $^{Btu}/_{hr\text{-}ft^2}$ Load
SCC2 (Table II-7)	1	Copper	Less Restrictive	190° F at 150 $^{Btu}/_{hr\text{-}ft^2}$ Load
SCC3 (Table II-8)	1	Copper	More Restrictive	190° F at 120 $^{Btu}/_{hr\text{-}ft^2}$ Load
SCC4 (Table II-9)	1	Copper	Less Restrictive	190° F at 120 $^{Btu}/_{hr\text{-}ft^2}$ Load
DCA1 (Table II-10)	2	Aluminum	More Restrictive	195° F at 150 $^{Btu}/_{hr\text{-}ft^2}$ Load
DCA2 (Table II-11)	2	Aluminum	Less Restrictive	195° F at 150 $^{Btu}/_{hr\text{-}ft^2}$ Load
DCA3 (Table II-12)	2	Aluminum	More Restrictive	195° F at 120 $^{Btu}/_{hr\text{-}ft^2}$ Load
DCA4 (Table II-13)	2	Aluminum	Less Restrictive	195° F at 120 $^{Btu}/_{hr\text{-}ft^2}$ Load
DCC1 (Table II-14)	2	Copper	More Restrictive	195° F at 150 $^{Btu}/_{hr\text{-}ft^2}$ Load
DCC2 (Table II-15)	2	Copper	Less Restrictive	195° F at 150 $^{Btu}/_{hr\text{-}ft^2}$ Load
DCC3 (Table II-16)	2	Copper	More Restrictive	195° F at 120 $^{Btu}/_{hr\text{-}ft^2}$ Load
DCC4 (Table II-17)	2	Copper	Less Restrictive	195° F at 120 $^{Btu}/_{hr\text{-}ft^2}$ Load

Table II-2

SCA1 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	3.0	2.37	3.65	347.0	153.9	121.4	5.00	3.30	4.00	3.0	1	***	6	6
2	3.0	2.40	4.15	347.9	154.9	122.5	5.00	3.60	4.20	3.0	2	***	6	6
3	3.5	3.64	4.02	341.7	144.1	110.4	5.00	2.70	4.80	3.0	25	***	6	10
4	3.5	3.62	4.30	349.5	153.2	120.3	5.00	2.70	4.80	3.0	28	***	6	10
5	3.5	4.04	4.40	348.6	152.1	119.1	5.00	2.80	4.90	3.0	29	***	6	10
6	3.5	4.42	4.50	347.9	151.1	117.9	5.00	3.00	5.00	3.0	30	***	6	10
7	4.0	2.04	3.21	367.1	161.4	127.1	3.20	3.30	4.00	3.0	1	***	7	11
8	4.0	2.07	3.71	368.5	162.5	128.4	3.20	3.60	4.20	3.0	2	***	7	11
9	3.5	2.99	4.08	356.1	147.2	111.7	3.20	3.60	3.00	3.0	18	***	7	6
10	3.5	2.99	4.26	356.1	147.2	111.7	3.20	3.80	3.00	3.0	21	***	7	6
11	3.5	4.23	3.58	359.5	150.5	115.2	3.20	2.70	4.80	3.0	25	***	7	6
12	4.0	4.04	3.95	367.1	159.0	124.3	3.20	2.80	4.90	3.0	29	***	7	11
13	4.0	4.42	4.05	366.3	157.8	123.1	3.20	3.00	5.00	3.0	30	***	7	11

Table II-3

SCA2 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	3.5	1.90	3.64	312.7	153.9	121.4	5.00	3.30	4.00	3.0	1	***	6	11
2	3.5	1.92	4.15	313.6	154.9	122.5	5.00	3.60	4.20	3.0	2	***	6	11
3	4.5	2.94	4.01	307.6	144.1	110.4	5.00	2.70	4.80	3.0	25	***	6	17
4	4.5	2.92	4.29	314.7	153.2	120.3	5.00	2.70	4.80	3.0	28	***	6	17
5	4.5	3.34	4.39	313.9	152.1	119.1	5.00	2.80	4.90	3.0	29	***	6	17
6	4.5	3.72	4.49	313.3	151.1	117.9	5.00	3.00	5.00	3.0	30	***	6	17
7	3.5	2.04	3.19	329.5	161.4	127.1	3.20	3.30	4.00	3.0	1	***	7	10
8	3.5	2.07	3.69	330.9	162.5	128.4	3.20	3.60	4.20	3.0	2	***	7	10
9	3.5	2.39	4.14	328.6	158.3	123.6	3.20	2.50	3.00	3.0	12	***	7	10
10	3.5	2.76	4.22	326.7	155.7	120.8	3.20	3.00	3.00	3.0	13	***	7	10
11	3.5	3.11	4.45	324.1	152.2	117.0	3.20	4.00	3.00	3.0	14	***	7	10
12	3.5	2.40	4.05	319.4	147.2	111.7	3.20	3.60	3.00	3.0	18	***	7	10
13	3.5	2.40	4.23	319.4	147.2	111.7	3.20	3.60	3.00	3.0	21	***	7	10
14	3.5	3.64	3.55	322.5	150.5	115.2	3.20	2.70	4.80	3.0	25	***	7	10
15	3.5	4.52	3.58	318.9	145.6	110.0	3.20	3.00	5.00	3.0	27	***	7	10
16	3.5	4.04	3.93	329.2	159.0	124.3	3.20	2.80	4.90	3.0	29	***	7	10
17	3.5	4.42	4.03	328.5	157.8	123.1	3.20	3.00	5.00	3.0	30	***	7	10
18	3.5	4.62	4.17	327.5	156.7	121.8	3.20	3.20	5.00	3.0	31	***	7	10

Table II-4

SCA3 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TMTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	3.5	2.62	3.69	349.3	139.2	102.7	4.80	3.30	4.00	3.0	1	•••	5	6
2	3.5	2.65	4.20	350.6	140.0	103.5	4.80	3.60	4.20	3.0	2	•••	5	6
3	3.5	2.89	3.96	335.6	121.4	63.2	4.80	2.50	4.00	3.0	7	•••	5	6
4	3.5	4.22	4.14	335.9	121.5	83.4	4.80	2.70	4.80	3.0	9	•••	5	6
5	3.5	4.23	4.05	342.1	129.0	91.4	4.80	2.70	4.80	3.0	25	•••	5	6
6	3.5	4.21	4.33	349.7	138.0	101.2	4.80	2.70	4.80	3.0	28	•••	5	6
7	3.5	4.63	4.43	348.8	136.9	100.0	4.80	2.60	4.90	3.0	29	•••	5	6
8	3.0	2.37	3.65	347.0	153.9	121.4	5.00	3.30	4.00	3.0	1	•••	6	6
9	3.5	2.40	4.15	347.9	154.9	122.5	5.00	3.60	4.20	3.0	2	•••	6	6
10	3.5	3.63	4.11	335.4	136.6	102.4	5.00	2.70	4.80	3.0	9	•••	6	10
11	5.0	3.62	4.07	326.3	125.3	90.2	5.00	3.00	5.00	3.0	11	•••	6	17
12	3.5	3.64	4.02	341.7	144.1	110.4	5.00	2.70	4.80	3.0	25	•••	6	10
13	3.5	4.52	4.05	338.2	139.6	105.5	5.00	3.00	5.00	3.0	27	•••	6	10
14	3.5	3.62	4.30	349.5	153.2	120.3	5.00	2.70	4.80	3.0	28	•••	6	10
15	3.5	4.04	4.40	348.6	152.1	119.1	5.00	2.80	4.90	3.0	29	•••	6	10
16	3.5	4.42	4.50	347.9	151.1	117.9	5.00	3.00	5.00	3.0	30	•••	6	10
17	4.0	2.04	3.21	367.1	161.4	127.1	3.20	3.30	4.00	3.0	1	•••	7	11
18	4.0	2.07	3.71	368.5	162.5	128.4	3.20	3.60	4.20	3.0	2	•••	7	11
19	3.5	4.22	3.67	352.7	142.6	106.7	3.20	2.70	4.80	3.0	9	•••	7	6
20	3.5	2.99	4.08	356.1	147.2	111.7	3.20	3.60	3.00	3.0	18	•••	7	6
21	3.5	2.99	4.26	356.1	147.2	111.7	3.20	3.80	3.00	3.0	21	•••	7	6
22	3.5	4.23	3.58	359.5	150.5	115.2	3.20	2.70	4.80	3.0	25	•••	7	6
23	4.0	4.04	3.95	367.1	159.0	124.3	3.20	2.60	4.90	3.0	29	•••	7	11
24	4.0	4.42	4.05	366.3	157.8	123.1	3.20	3.00	5.00	3.0	30	•••	7	11

Table II-5

SCA4 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	3.0	1.19	1.74	238.3	112.7	86.6	4.30	3.30	4.00	3.0	1	***	3	17
2	3.0	1.21	2.24	237.7	112.9	87.1	4.30	3.60	4.20	3.0	2	***	3	17
3	2.5	1.55	2.70	244.3	112.7	85.9	4.30	2.50	3.00	3.0	12	***	3	20
4	2.5	2.43	2.79	243.6	111.1	84.1	4.30	3.00	3.00	3.0	13	***	3	10
5	2.5	1.55	3.42	244.3	112.7	85.9	4.30	2.60	3.00	3.0	15	***	3	20
6	2.5	2.43	3.47	243.6	111.1	84.1	4.30	3.50	3.20	3.0	16	***	3	10
7	2.5	2.79	2.39	245.6	114.1	87.3	4.30	2.70	4.80	3.0	28	***	3	20
8	2.5	3.21	2.49	245.1	113.3	86.5	4.30	2.80	4.90	3.0	29	***	3	20
9	2.5	4.09	2.60	245.0	112.6	85.7	4.30	3.00	5.00	3.0	30	***	3	10
10	2.5	4.49	2.74	244.5	111.8	84.9	4.30	3.20	5.00	3.0	31	***	3	10
11	3.5	2.04	3.66	312.6	139.2	102.7	4.80	3.30	4.00	3.0	1	***	5	10
12	3.5	2.07	4.16	313.9	140.0	103.5	4.80	3.60	4.20	3.0	2	***	5	10
13	5.0	1.66	3.97	300.0	121.4	83.2	4.80	2.50	4.00	3.0	7	***	5	17
14	5.0	2.99	4.13	300.4	121.5	83.4	4.80	2.70	4.80	3.0	9	***	5	17
15	5.0	3.00	4.04	305.9	129.0	91.4	4.80	2.70	4.80	3.0	25	***	5	17
16	5.0	3.88	4.07	302.7	124.4	86.5	4.80	3.00	5.00	3.0	27	***	5	17
17	3.5	3.62	4.30	312.8	138.0	101.2	4.80	2.70	4.80	3.0	28	***	5	10
18	3.5	4.04	4.40	312.0	136.9	100.0	4.80	2.80	4.90	3.0	29	***	5	10
19	3.5	4.42	4.50	311.3	135.8	98.8	4.80	3.00	5.00	3.0	30	***	5	10
20	3.5	1.90	3.64	312.7	153.9	121.4	5.00	3.30	4.00	3.0	1	***	6	11
21	3.5	1.92	4.15	313.6	154.9	122.5	5.00	3.60	4.20	3.0	2	***	6	11
22	4.5	1.61	3.94	301.4	136.3	102.1	5.00	2.50	4.00	3.0	7	***	6	17
23	4.5	2.93	4.10	301.9	136.6	102.4	5.00	2.70	4.80	3.0	9	***	6	17
24	3.0	4.90	4.04	293.5	125.3	90.2	5.00	3.00	5.00	3.0	11	***	6	6
25	4.5	2.94	4.01	307.6	144.1	110.4	5.00	2.70	4.80	3.0	25	***	6	17
26	4.5	3.82	4.04	304.4	139.6	105.5	5.00	3.00	5.00	3.0	27	***	6	17
27	4.5	2.92	4.29	314.7	153.2	120.3	5.00	2.70	4.80	3.0	28	***	6	17
28	4.5	3.34	4.39	313.9	152.1	119.1	5.00	2.80	4.90	3.0	29	***	6	17
29	4.5	3.72	4.49	313.3	151.1	117.9	5.00	3.00	5.00	3.0	30	***	6	17
30	3.5	2.04	3.19	329.5	161.4	127.1	3.20	3.30	4.00	3.0	1	***	7	10
31	3.5	2.07	3.69	330.9	162.5	128.4	3.20	3.60	4.20	3.0	2	***	7	10
32	3.5	2.31	3.48	315.8	142.3	106.4	3.20	2.50	4.00	3.0	7	***	7	10
33	3.5	3.63	3.64	316.2	142.6	106.7	3.20	2.70	4.80	3.0	9	***	7	10
34	5.0	3.82	3.60	307.1	130.6	93.8	3.20	3.00	5.00	3.0	11	***	7	17
35	3.5	2.39	4.14	328.6	156.3	123.6	3.20	2.50	3.00	3.0	12	***	7	10
36	3.5	2.76	4.22	326.7	155.7	120.8	3.20	3.00	3.00	3.0	13	***	7	10
37	3.5	3.11	4.45	324.1	152.2	117.0	3.20	4.00	3.00	3.0	14	***	7	10
38	3.5	2.40	4.05	319.4	147.2	111.7	3.20	3.60	3.00	3.0	18	***	7	10
39	3.5	2.40	4.23	319.4	147.2	111.7	3.20	3.60	3.00	3.0	21	***	7	10
40	3.5	3.64	3.55	322.5	150.5	115.2	3.20	2.70	4.80	3.0	25	***	7	10
41	3.5	4.52	3.58	318.9	145.6	110.0	3.20	3.00	5.00	3.0	27	***	7	10
42	3.5	4.04	3.93	329.2	159.0	124.3	3.20	2.80	4.90	3.0	29	***	7	10
43	3.5	4.42	4.03	328.5	157.8	123.1	3.20	3.00	5.00	3.0	30	***	7	10
44	3.5	4.82	4.17	327.5	156.7	121.8	3.20	3.20	5.00	3.0	31	***	7	10

Table II-6

SCC1 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	3.0	3.39	5.91	347.0	153.9	121.4	5.00	3.30	4.00	2.0	1	***	2	6
2	3.0	3.42	6.41	347.9	154.9	122.5	5.00	3.60	4.20	2.0	2	***	2	6
3	3.5	4.66	6.28	341.7	144.1	110.4	5.00	2.70	4.80	2.0	25	***	2	10
4	3.5	4.64	6.56	349.5	153.2	120.3	5.00	2.70	4.60	2.0	28	***	2	10
5	3.5	5.06	6.66	348.6	152.1	119.1	5.00	2.80	4.90	2.0	29	***	2	10
6	4.0	3.06	5.47	367.1	161.4	127.1	3.20	3.30	4.00	2.0	1	***	3	11
7	4.0	3.08	5.97	368.5	162.5	126.4	3.20	3.60	4.20	2.0	2	***	3	11
8	3.5	4.00	6.34	356.1	147.2	111.7	3.20	3.60	3.00	2.0	18	***	3	6
9	3.5	4.00	6.52	356.1	147.2	111.7	3.20	3.80	3.00	2.0	21	***	3	6
10	3.5	5.24	5.84	359.5	150.5	115.2	3.20	2.70	4.80	2.0	25	***	3	6
11	4.0	5.06	6.21	367.1	159.0	124.3	3.20	2.80	4.90	2.0	29	***	3	11
12	4.0	5.44	6.31	366.3	157.8	123.1	3.20	3.00	5.00	2.0	30	***	3	11

Table II-7

SCC2 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	3.5	2.91	5.90	312.7	153.9	121.4	5.00	3.30	4.00	2.0	1	***	2	11
2	3.5	2.94	6.40	313.6	154.9	122.5	5.00	3.60	4.20	2.0	2	***	2	11
3	4.5	3.96	6.27	307.6	144.1	110.4	5.00	2.70	4.80	2.0	25	***	2	17
4	4.5	3.94	6.55	314.7	153.2	120.3	5.00	2.70	4.80	2.0	28	***	2	17
5	4.5	4.36	6.65	313.9	152.1	119.1	5.00	2.80	4.90	2.0	29	***	2	17
6	4.5	4.74	6.75	313.3	151.1	117.9	5.00	3.00	5.00	2.0	30	***	2	17
7	3.5	3.06	5.45	329.5	161.4	127.1	3.20	3.30	4.00	2.0	1	***	3	10
8	3.5	3.08	5.95	330.9	162.5	128.4	3.20	3.60	4.20	2.0	2	***	3	10
9	3.5	3.40	6.40	328.6	158.3	123.6	3.20	2.50	3.00	2.0	12	***	3	10
10	3.5	3.78	6.46	326.7	155.7	120.8	3.20	3.00	3.00	2.0	13	***	3	10
11	3.5	4.13	6.71	324.1	152.2	117.0	3.20	4.00	3.00	2.0	14	***	3	10
12	3.5	3.42	6.31	319.4	147.2	111.7	3.20	3.60	3.00	2.0	18	***	3	10
13	3.5	3.42	6.49	319.4	147.2	111.7	3.20	3.80	3.00	2.0	21	***	3	10
14	3.5	4.66	5.81	322.5	150.5	115.2	3.20	2.70	4.80	2.0	25	***	3	10
15	3.5	5.54	5.84	318.9	145.6	110.0	3.20	3.00	5.00	2.0	27	***	3	10
16	3.5	5.06	6.19	329.2	159.0	124.3	3.20	2.80	4.90	2.0	29	***	3	10
17	3.5	5.44	6.29	328.5	157.8	123.1	3.20	3.00	5.00	2.0	30	***	3	10
18	3.5	5.84	6.43	327.5	156.7	121.8	3.20	3.20	5.00	2.0	31	***	3	10

Table II-8

SCC3 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	T$$	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	3.5	3.64	5.95	349.3	139.2	102.7	4.80	3.30	4.00	2.0	1	***	1	6
2	3.5	3.67	6.46	350.6	140.0	103.5	4.80	3.60	4.20	2.0	2	***	1	6
3	3.5	3.90	6.24	335.6	121.4	83.2	4.80	2.50	4.00	2.0	7	***	1	6
4	3.5	5.23	6.40	335.9	121.5	83.4	4.80	2.70	4.80	2.0	9	***	1	6
5	3.5	5.24	6.31	342.1	129.0	91.4	4.80	2.70	4.80	2.0	25	***	1	6
6	3.5	5.22	6.59	349.7	138.0	101.2	4.80	2.70	4.80	2.0	28	***	1	6
7	3.5	5.64	6.69	348.8	136.9	100.0	4.80	2.80	4.90	2.0	29	***	1	6
8	3.0	3.39	5.91	347.0	153.9	121.4	5.00	3.30	4.00	2.0	1	***	2	6
9	3.0	3.42	6.41	347.9	154.9	122.5	5.00	3.60	4.20	2.0	2	***	2	6
10	3.5	4.65	6.37	335.4	136.6	102.4	5.00	2.70	4.80	2.0	9	***	2	10
11	5.0	4.83	6.33	326.3	125.3	90.2	5.00	3.00	5.00	2.0	11	***	2	17
12	3.5	4.66	6.28	341.7	144.1	110.4	5.00	2.70	4.80	2.0	25	***	2	10
13	3.5	5.54	6.31	338.2	139.6	105.5	5.00	3.00	5.00	2.0	27	***	2	10
14	3.5	4.64	6.56	349.5	153.2	120.3	5.00	2.70	4.80	2.0	28	***	2	10
15	3.5	5.06	6.66	348.6	152.1	119.1	5.00	2.80	4.90	2.0	29	***	2	10
16	4.0	3.06	5.47	367.1	161.4	127.1	3.20	3.30	4.00	2.0	1	***	3	11
17	4.0	3.08	5.97	368.5	162.5	128.4	3.20	3.60	4.20	2.0	2	***	3	11
18	3.5	5.23	5.93	352.7	142.6	106.7	3.20	2.70	4.80	2.0	9	***	3	6
19	3.5	4.00	6.34	356.1	147.2	111.7	3.20	3.60	3.00	2.0	18	***	3	6
20	3.5	4.00	6.52	356.1	147.2	111.7	3.20	3.80	3.00	2.0	21	***	3	6
21	3.5	5.24	5.84	359.5	150.5	115.2	3.20	2.70	4.80	2.0	25	***	3	6
22	4.0	5.06	6.21	367.1	159.0	124.3	3.20	2.80	4.90	2.0	29	***	3	11
23	4.0	5.44	6.31	366.3	157.8	123.1	3.20	3.00	5.00	2.0	30	***	3	11

Table II-9

SCC4 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	APS	INS
1	3.5	3.06	5.92	312.6	139.2	102.7	4.80	3.30	4.00	2.0	1	***	1	10
2	3.5	3.08	6.42	313.9	140.0	103.5	4.80	3.60	4.20	2.0	2	***	1	10
3	5.0	2.67	6.23	300.0	121.4	83.2	4.80	2.50	4.00	2.0	7	***	1	17
4	5.0	4.00	6.39	300.4	121.5	83.4	4.80	2.70	4.90	2.0	9	***	1	17
5	5.0	4.01	6.30	305.9	129.0	91.4	4.80	2.70	4.80	2.0	25	***	1	17
6	5.0	4.89	6.33	302.7	124.4	86.5	4.80	3.00	5.00	2.0	27	***	1	17
7	3.5	4.64	6.56	312.8	138.0	101.2	4.80	2.70	4.80	2.0	28	***	1	10
8	3.5	5.06	6.66	312.0	136.9	100.0	4.80	2.80	4.90	2.0	29	***	1	10
9	3.5	2.91	5.90	312.7	153.9	121.4	5.00	3.30	4.00	2.0	1	***	2	11
10	3.5	2.94	6.40	313.6	154.9	122.5	5.00	3.60	4.20	2.0	2	***	2	11
11	4.5	2.62	6.20	301.4	136.3	102.1	5.00	2.50	4.00	2.0	7	***	2	17
12	4.5	3.95	6.36	301.9	136.6	102.4	5.00	2.70	4.90	2.0	9	***	2	17
13	3.0	5.81	6.30	293.5	125.3	90.2	5.00	3.00	5.00	2.0	11	***	2	6
14	4.5	3.96	6.27	307.6	144.1	110.4	5.00	2.70	4.80	2.0	25	***	2	17
15	4.5	4.84	6.30	304.4	139.6	105.5	5.00	3.00	5.00	2.0	27	***	2	17
16	4.5	3.94	6.55	314.7	153.2	120.3	5.00	2.70	4.80	2.0	28	***	2	17
17	4.5	4.36	6.65	313.9	152.1	119.1	5.00	2.80	4.90	2.0	29	***	2	17
18	4.5	4.74	6.75	313.3	151.1	117.9	5.00	3.00	5.00	2.0	30	***	2	17
19	3.5	3.06	5.45	329.5	161.4	127.1	3.20	3.30	4.00	2.0	1	***	3	10
20	3.5	3.08	5.95	330.9	162.5	128.4	3.20	3.60	4.20	2.0	2	***	3	10
21	3.5	3.32	5.74	315.8	142.3	106.4	3.20	2.50	4.00	2.0	7	***	3	10
22	3.5	4.65	5.90	316.2	142.6	106.7	3.20	2.70	4.80	2.0	9	***	3	10
23	5.0	4.83	5.86	307.1	130.6	97.8	3.20	3.00	5.00	2.0	11	***	3	17
24	3.5	3.40	6.40	329.6	158.3	123.6	3.20	2.50	3.00	2.0	12	***	3	10
25	3.5	3.78	6.48	326.7	155.7	120.8	3.20	3.00	3.00	2.0	13	***	3	10
26	3.5	4.13	6.71	324.1	152.2	117.0	3.20	4.00	3.00	2.0	14	***	3	10
27	3.5	3.42	6.31	319.4	147.2	111.7	3.20	3.60	3.00	2.0	18	***	3	10
28	3.5	3.42	6.49	319.4	147.2	111.7	3.20	3.80	3.00	2.0	21	***	3	10
29	3.5	4.66	5.81	322.5	150.5	115.2	3.20	2.70	4.80	2.0	25	***	3	10
30	3.5	5.54	5.94	319.9	145.6	110.0	3.20	3.00	5.00	2.0	27	***	3	10
31	3.5	5.06	6.19	329.2	159.0	124.3	3.20	2.80	4.90	2.0	29	***	3	10
32	3.5	5.44	6.29	328.5	157.8	123.1	3.20	3.00	5.00	2.0	30	***	3	10
33	3.5	5.84	6.43	327.5	156.7	121.8	3.20	3.20	5.00	2.0	31	***	3	10
34	3.5	2.36	4.58	291.6	130.8	96.6	2.50	3.30	4.00	2.0	1	***	4	20
35	3.5	2.38	5.09	292.3	131.4	97.3	2.50	3.60	4.20	2.0	2	***	4	20
36	3.5	2.70	5.53	292.2	128.5	93.8	2.50	2.50	3.00	2.0	12	***	4	20
37	3.5	3.63	5.61	290.8	126.3	91.4	2.50	3.00	3.00	2.0	13	***	4	11
38	4.5	3.43	5.85	288.7	123.2	88.0	2.50	4.00	3.00	2.0	14	***	4	17
39	3.5	2.70	6.25	292.2	128.5	93.8	2.50	2.60	3.00	2.0	15	***	4	20
40	3.5	3.63	6.29	290.8	126.3	91.4	2.50	3.50	3.20	2.0	16	***	4	11
41	3.5	3.27	5.44	284.8	119.1	83.6	2.50	3.60	3.00	2.0	18	***	4	11
42	3.5	3.27	5.62	284.8	119.1	83.6	2.50	3.80	3.00	2.0	21	***	4	11
43	4.5	3.96	4.95	287.4	121.8	86.5	2.50	2.70	4.80	2.0	25	***	4	17
44	4.5	4.94	4.98	284.6	117.6	81.9	2.50	3.00	5.00	2.0	27	***	4	17
45	3.5	3.94	5.22	293.5	130.2	95.6	2.50	2.70	4.80	2.0	28	***	4	20
46	3.5	4.36	5.32	292.8	129.1	94.4	2.50	2.80	4.90	2.0	29	***	4	20
47	3.5	4.74	5.42	292.3	128.2	93.4	2.50	3.00	5.00	2.0	30	***	4	20
48	3.5	5.69	5.56	291.5	127.1	92.7	2.50	3.20	5.00	2.0	31	***	4	11
49	3.0	2.89	4.38	289.6	134.7	102.0	3.00	3.30	4.00	2.0	1	***	5	10
50	3.0	2.92	4.98	290.2	135.3	102.8	3.00	3.60	4.20	2.0	2	***	5	10
51	3.5	2.62	4.70	280.7	118.9	84.6	3.00	2.50	4.00	2.0	7	***	5	20
52	3.5	3.95	4.86	281.1	119.1	84.6	3.00	2.70	4.80	2.0	9	***	5	20
53	3.5	2.70	5.36	290.9	132.6	99.5	3.00	2.50	3.00	2.0	12	***	5	20
54	3.5	3.08	5.44	289.5	130.5	97.1	3.00	3.00	3.00	2.0	13	***	5	20
55	3.5	3.43	5.67	287.6	127.4	93.8	3.00	4.00	3.00	2.0	14	***	5	20
56	3.5	2.70	6.08	290.9	132.6	99.5	3.00	2.60	3.00	2.0	15	***	5	20
57	3.5	3.08	6.12	289.5	130.5	97.1	3.00	3.50	3.20	2.0	16	***	5	20
58	3.5	2.72	5.27	283.5	123.2	89.2	3.00	3.60	3.00	2.0	18	***	5	20
59	3.5	3.11	6.12	280.1	118.2	83.7	3.00	4.20	3.10	2.0	19	***	5	20
60	3.5	2.72	5.45	287.5	123.2	89.2	3.00	3.80	3.00	2.0	21	***	5	20
61	3.5	3.96	4.77	286.1	125.9	92.7	3.00	2.70	4.80	2.0	25	***	5	20
62	3.5	4.84	4.80	287.4	121.8	87.7	3.00	3.00	5.00	2.0	27	***	5	20
63	3.5	3.94	5.05	292.3	134.3	101.2	3.00	2.70	4.80	2.0	28	***	5	20
64	3.5	4.36	5.15	291.6	133.3	100.1	3.00	2.80	4.90	2.0	29	***	5	20
65	3.5	4.74	5.25	291.1	132.3	99.1	3.00	3.00	5.00	2.0	30	***	5	20
66	3.5	5.14	5.39	295.3	131.3	[illegible]	3.00	3.20	5.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table II-10

DCA1 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	T$$	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	5.0	2.60	4.47	392.9	161.2	115.1	4.80	3.40	4.05	3.0	1	2	5	10
2	4.5	2.43	4.43	390.3	178.6	137.1	5.00	3.40	4.05	3.0	1	2	6	10
3	4.5	3.99	4.07	380.6	162.2	119.6	5.00	2.70	4.07	3.0	1	8	6	10
4	4.5	3.99	4.38	380.6	162.2	119.6	5.00	3.10	4.20	3.0	1	9	6	10
5	4.5	4.00	4.07	385.5	167.9	125.4	5.00	2.70	4.07	3.0	1	24	6	10
6	4.5	4.00	4.29	385.5	167.9	125.4	5.00	3.10	4.20	3.0	1	25	6	10
7	4.5	4.88	4.22	382.9	164.4	122.1	5.00	2.30	4.12	3.0	1	26	6	10
8	4.5	4.88	4.32	382.9	164.4	122.1	5.00	3.20	4.25	3.0	1	27	6	10
9	4.5	3.98	4.57	391.4	175.7	132.7	5.00	3.10	4.20	3.0	1	28	6	10
10	4.5	4.40	4.67	390.7	174.8	131.7	5.00	3.13	4.22	3.0	1	29	6	10
11	4.5	4.78	4.77	390.4	174.0	130.8	5.00	3.20	4.25	3.0	1	30	6	10
12	4.5	5.18	4.91	389.6	173.1	130.0	5.00	3.27	4.25	3.0	1	31	6	10
13	4.5	2.46	4.93	387.2	177.7	136.5	5.00	3.60	4.20	3.0	2	2	6	10
14	4.5	4.02	4.57	377.5	161.2	118.9	5.00	2.90	4.22	3.0	2	8	6	10
15	4.5	4.02	4.38	377.5	161.2	118.9	5.00	3.30	4.35	3.0	2	9	6	10
16	4.5	4.03	4.57	382.3	166.9	124.7	5.00	2.90	4.22	3.0	2	24	6	10
17	4.5	4.03	4.79	382.3	166.9	124.7	5.00	3.30	4.35	3.0	2	25	6	10
18	4.5	4.91	4.72	379.8	163.4	121.4	5.00	3.00	4.27	3.0	2	26	6	10
19	4.5	4.91	4.92	379.8	163.4	121.4	5.00	3.40	4.40	3.0	2	27	6	10
20	5.0	2.39	3.98	410.8	186.3	142.5	3.20	3.40	4.05	3.0	1	2	7	11
21	5.0	4.16	3.63	397.6	167.2	123.0	3.20	2.70	4.07	3.0	1	8	7	10
22	5.0	4.16	3.94	397.6	167.2	123.0	3.20	3.10	4.20	3.0	1	9	7	10
23	5.0	4.17	3.63	402.9	173.9	129.0	3.20	2.70	4.07	3.0	1	24	7	10
24	5.0	4.17	3.85	402.9	173.9	129.0	3.20	3.10	4.20	3.0	1	25	7	10
25	5.0	5.05	3.79	400.0	170.0	125.6	3.20	2.80	4.12	3.0	1	26	7	10
26	5.0	5.05	3.88	400.0	170.0	125.6	3.20	3.20	4.25	3.0	1	27	7	10
27	5.0	3.94	4.11	409.4	182.2	137.4	3.20	3.10	4.20	3.0	1	28	7	11
28	5.0	4.36	4.21	408.6	181.2	136.4	3.20	3.13	4.22	3.0	1	29	7	11
29	4.5	2.46	4.46	407.5	185.4	142.0	3.20	3.60	4.20	3.0	2	2	7	10
30	5.0	4.19	4.14	394.3	166.2	122.3	3.20	2.90	4.22	3.0	2	8	7	10
31	5.0	4.19	4.45	394.3	166.2	122.3	3.20	3.30	4.35	3.0	2	9	7	10
32	5.0	5.08	4.29	396.7	169.0	124.9	3.20	3.00	4.27	3.0	2	26	7	10
33	5.0	5.08	4.39	396.7	169.0	124.9	3.20	3.40	4.40	3.0	2	27	7	10
34	4.0	4.51	4.60	406.0	181.1	136.7	3.20	3.30	4.35	3.0	2	28	7	6
35	5.0	4.39	4.72	405.3	180.2	135.6	3.20	3.33	4.37	3.0	2	29	7	11
36	5.0	4.77	4.82	404.8	179.3	134.6	3.20	3.40	4.40	3.0	2	30	7	11
37	5.0	5.17	4.96	404.0	178.3	133.6	3.20	3.47	4.40	3.0	2	31	7	11
38	4.5	5.47	4.67	407.8	165.0	119.1	3.20	2.50	3.32	3.0	13	8	7	6
39	4.5	5.47	4.98	407.8	165.0	119.1	3.20	2.90	3.45	3.0	13	9	7	6
40	5.0	4.89	4.66	412.9	170.5	125.1	3.20	2.50	3.32	3.0	13	24	7	10
41	5.0	4.89	4.88	412.9	170.5	125.1	3.20	2.90	3.45	3.0	13	25	7	10
42	5.0	5.24	4.89	410.3	166.4	120.6	3.20	3.17	3.32	3.0	14	24	7	10
43	5.0	2.96	4.86	411.7	172.7	127.6	3.20	3.60	3.30	3.0	18	2	7	10
44	5.0	4.51	4.99	410.4	168.6	121.9	3.20	3.30	3.45	3.0	18	28	7	10
45	5.0	5.00	4.39	411.5	170.2	125.2	3.20	3.20	4.80	3.0	27	2	7	10
46	5.0	4.60	4.74	424.1	187.2	142.6	3.20	3.07	4.72	3.0	29	2	7	10
47	5.0	4.98	4.34	423.9	185.9	141.3	3.20	3.20	4.80	3.0	30	2	7	10
48	5.0	5.38	4.98	422.6	184.4	139.7	3.20	3.33	4.80	3.0	31	2	7	10

Table II-11

DCA2 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	4.5	2.43	4.43	352.6	161.2	115.1	4.80	3.40	4.05	3.0	1	2	5	10
2	4.5	2.24	4.41	353.0	178.6	137.1	5.00	3.40	4.05	3.0	1	2	6	11
3	4.5	3.99	4.07	343.8	162.2	119.6	5.00	2.70	4.07	3.0	1	8	6	10
4	4.5	3.99	4.38	343.8	162.2	119.6	5.00	3.10	4.20	3.0	1	9	6	10
5	4.5	2.76	4.79	344.8	164.1	121.1	5.00	3.40	3.75	3.0	1	18	6	10
6	4.5	2.76	4.97	344.8	164.1	121.1	5.00	3.47	3.75	3.0	1	21	6	10
7	4.5	4.00	4.07	348.1	167.9	125.4	5.00	2.70	4.07	3.0	1	24	6	10
8	4.5	4.00	4.29	348.1	167.9	125.4	5.00	3.10	4.20	3.0	1	25	6	10
9	4.5	4.88	4.22	345.9	164.4	122.1	5.00	2.80	4.12	3.0	1	26	6	10
10	4.5	4.88	4.32	345.9	164.4	122.1	5.00	3.20	4.25	3.0	1	27	6	10
11	4.5	3.80	4.55	353.3	175.7	132.7	5.00	3.10	4.20	3.0	1	28	6	11
12	4.5	4.40	4.67	352.7	174.8	131.7	5.00	3.13	4.22	3.0	1	29	6	10
13	4.5	4.78	4.77	352.4	174.0	130.8	5.00	3.20	4.25	3.0	1	30	6	10
14	4.5	5.18	4.91	351.8	173.1	130.0	5.00	3.27	4.25	3.0	1	31	6	10
15	4.5	2.27	4.91	350.1	177.7	136.5	5.00	3.60	4.20	3.0	2	2	6	11
16	4.5	4.02	4.57	340.9	161.2	118.9	5.00	2.90	4.22	3.0	2	8	6	10
17	4.5	4.02	4.88	340.9	161.2	118.9	5.00	3.30	4.35	3.0	2	9	6	10
18	4.5	4.03	4.57	345.1	166.9	124.7	5.00	2.90	4.22	3.0	2	24	6	10
19	4.5	4.03	4.79	345.1	166.9	124.7	5.00	3.30	4.35	3.0	2	25	6	10
20	4.5	4.91	4.72	342.9	163.4	121.4	5.00	3.00	4.27	3.0	2	26	6	10
21	4.5	4.91	4.82	342.9	163.4	121.4	5.00	3.40	4.40	3.0	2	27	6	10
22	4.5	4.91	4.82	354.3	164.1	121.0	5.00	3.20	4.80	3.0	27	2	6	10
23	4.5	2.43	3.96	369.8	186.3	142.5	3.20	3.40	4.05	3.0	1	2	7	10
24	5.0	3.95	3.61	357.6	167.2	123.0	3.20	2.70	4.07	3.0	1	8	7	11
25	5.0	3.95	3.92	357.6	167.2	123.0	3.20	3.10	4.20	3.0	1	9	7	11
26	4.5	2.76	4.32	358.8	169.9	124.6	3.20	3.40	3.75	3.0	1	18	7	10
27	4.5	2.76	4.50	358.8	169.9	124.6	3.20	3.47	3.75	3.0	1	21	7	10
28	4.5	4.00	3.60	362.2	173.9	129.0	3.20	2.70	4.07	3.0	1	24	7	10
29	4.5	4.00	3.82	362.2	173.9	129.0	3.20	3.10	4.20	3.0	1	25	7	10
30	5.0	4.84	3.77	359.7	170.0	125.6	3.20	2.80	4.12	3.0	1	26	7	11
31	5.0	4.84	3.86	359.7	170.0	125.6	3.20	3.20	4.25	3.0	1	27	7	11
32	4.5	3.98	4.10	367.9	182.2	137.4	3.20	3.10	4.20	3.0	1	28	7	10
33	4.5	4.40	4.20	367.2	181.2	136.4	3.20	3.13	4.22	3.0	1	29	7	10
34	4.5	4.78	4.30	366.8	180.3	135.4	3.20	3.20	4.25	3.0	1	30	7	10
35	4.5	5.18	4.44	366.1	179.3	134.3	3.20	3.27	4.25	3.0	1	31	7	10
36	4.5	2.46	4.46	366.8	185.4	142.0	3.20	3.60	4.20	3.0	2	2	7	10
37	4.5	4.02	4.10	354.5	166.2	122.3	3.20	2.90	4.22	3.0	2	8	7	10
38	4.5	4.02	4.41	354.5	166.2	122.3	3.20	3.30	4.35	3.0	2	9	7	10
39	4.5	2.79	4.82	355.7	168.8	123.8	3.20	3.60	3.90	3.0	2	18	7	10
40	4.5	2.79	5.00	355.7	168.8	123.8	3.20	3.67	3.90	3.0	2	21	7	10
41	4.5	4.03	4.10	359.1	172.9	128.3	3.20	2.90	4.22	3.0	2	24	7	10
42	4.5	4.03	4.32	359.1	172.9	128.3	3.20	3.30	4.35	3.0	2	25	7	10
43	4.5	4.91	4.25	356.6	169.0	124.9	3.20	3.00	4.27	3.0	2	26	7	10
44	4.5	4.91	4.35	356.6	169.0	124.9	3.20	3.40	4.40	3.0	2	27	7	10
45	4.5	4.01	4.60	364.8	181.1	136.7	3.20	3.30	4.35	3.0	2	28	7	10
46	4.5	4.43	4.70	364.1	180.2	135.6	3.20	3.33	4.37	3.0	2	29	7	10
47	4.5	4.81	4.83	363.7	179.3	134.6	3.20	3.40	4.40	3.0	2	30	7	10
48	4.5	5.21	4.94	363.0	178.3	133.6	3.20	3.47	4.40	3.0	2	31	7	10
49	5.0	4.68	4.66	366.9	165.0	119.1	3.20	2.50	3.32	3.0	13	8	7	10
50	5.0	4.28	4.97	366.9	165.0	119.1	3.20	2.90	3.45	3.0	13	9	7	10
51	5.0	4.89	4.66	371.4	170.5	125.1	3.20	2.50	3.32	3.0	13	24	7	10
52	5.0	4.89	4.88	371.4	170.5	125.1	3.20	2.90	3.45	3.0	13	25	7	10
53	5.0	5.77	4.82	369.0	167.3	121.7	3.20	2.60	3.37	3.0	13	26	7	10
54	5.0	5.77	4.91	369.0	167.3	121.7	3.20	3.00	3.50	3.0	13	27	7	10
55	5.0	5.24	4.89	369.1	166.4	120.6	3.20	3.17	3.32	3.0	14	24	7	10
56	5.0	2.96	4.86	370.7	172.7	127.6	3.20	3.60	3.30	3.0	18	2	7	10
57	5.0	5.08	4.39	370.5	170.2	125.2	3.20	3.20	4.80	3.0	27	2	7	10
58	5.0	4.98	4.64	381.8	185.9	141.3	3.20	3.20	4.80	3.0	30	2	7	10
59	5.0	5.39	4.98	380.7	184.4	139.7	3.20	3.33	4.80	3.0	31	2	7	10

Table II-12

DCA3 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	5.0	2.60	4.47	392.9	161.2	115.1	4.80	3.40	4.05	3.0	1	2	5	10
2	5.0	4.16	4.10	381.0	144.7	97.6	4.80	2.70	4.07	3.0	1	8	5	10
3	5.0	4.16	4.41	381.0	144.7	97.6	4.80	3.10	4.20	3.0	1	9	5	10
4	4.5	5.57	4.27	374.8	137.6	89.3	4.80	2.80	4.12	3.0	1	10	5	6
5	4.5	5.57	4.36	374.8	137.6	89.3	4.80	3.20	4.25	3.0	1	11	5	6
6	5.0	4.17	4.10	385.4	149.7	102.9	4.80	2.70	4.07	3.0	1	24	5	10
7	5.0	4.17	4.32	385.4	149.7	102.9	4.80	3.10	4.20	3.0	1	25	5	10
8	5.0	5.05	4.26	383.0	146.6	99.8	4.80	2.80	4.12	3.0	1	26	5	10
9	5.0	5.05	4.35	383.0	146.6	99.8	4.80	3.20	4.25	3.0	1	27	5	10
10	5.0	4.15	4.60	390.6	156.9	109.1	4.80	3.10	4.20	3.0	1	28	5	10
11	5.0	4.57	4.70	390.0	156.0	108.4	4.80	3.13	4.22	3.0	1	29	5	10
12	5.0	4.95	4.80	389.6	155.2	107.7	4.80	3.20	4.25	3.0	1	30	5	10
13	5.0	5.35	4.94	389.0	154.4	107.0	4.80	3.27	4.25	3.0	1	31	5	10
14	5.0	4.19	4.61	377.5	143.3	96.6	4.80	2.90	4.22	3.0	2	8	5	10
15	5.0	4.19	4.92	377.5	143.3	96.6	4.80	3.30	4.35	3.0	2	9	5	10
16	4.5	5.60	4.77	371.3	136.4	88.4	4.80	3.00	4.27	3.0	2	10	5	6
17	4.5	5.60	4.87	371.3	136.4	88.4	4.80	3.40	4.40	3.0	2	11	5	6
18	5.0	4.20	4.61	381.8	148.3	101.9	4.80	2.90	4.22	3.0	2	24	5	10
19	5.0	4.20	4.83	381.8	148.3	101.9	4.80	3.30	4.35	3.0	2	25	5	10
20	5.0	5.08	4.76	379.5	145.3	98.9	4.80	3.00	4.27	3.0	2	26	5	10
21	5.0	5.08	4.86	379.5	145.3	98.9	4.80	3.40	4.40	3.0	2	27	5	10
22	4.5	5.66	4.27	394.5	146.3	98.2	4.80	3.20	4.80	3.0	27	2	5	6
23	4.5	2.43	4.43	390.3	178.6	137.1	5.00	3.40	4.05	3.0	1	2	6	10
24	4.5	3.99	4.07	380.6	162.2	119.6	5.00	2.70	4.07	3.0	1	8	6	10
25	4.5	3.99	4.38	380.6	162.2	119.6	5.00	3.10	4.20	3.0	1	9	6	10
26	4.5	4.00	4.07	385.5	167.9	125.4	5.00	2.70	4.07	3.0	1	24	6	10
27	4.5	4.00	4.29	385.5	167.9	125.4	5.00	3.10	4.20	3.0	1	25	6	10
28	4.5	4.88	4.22	382.9	164.4	122.1	5.00	2.80	4.12	3.0	1	26	6	10
29	4.5	4.88	4.32	382.9	164.4	122.1	5.00	3.20	4.25	3.0	1	27	6	10
30	4.5	3.98	4.57	391.4	175.7	132.7	5.00	3.10	4.20	3.0	1	28	6	10
31	4.5	4.40	4.67	390.7	174.8	131.7	5.00	3.13	4.22	3.0	1	29	6	10
32	4.5	4.78	4.77	390.4	174.0	130.8	5.00	3.20	4.25	3.0	1	30	6	10
33	4.5	5.18	4.91	389.6	173.1	130.0	5.00	3.27	4.25	3.0	1	31	6	10
34	4.5	2.46	4.93	387.2	177.7	136.5	5.00	3.60	4.20	3.0	2	2	6	10
35	4.5	4.02	4.57	377.5	161.2	118.9	5.00	2.90	4.22	3.0	2	8	6	10
36	4.5	4.02	4.88	377.5	161.2	118.9	5.00	3.30	4.35	3.0	2	9	6	10
37	5.0	4.81	4.74	370.7	153.5	110.2	5.00	3.00	4.27	3.0	2	10	6	11
38	5.0	4.81	4.84	370.7	153.5	110.2	5.00	3.40	4.40	3.0	2	11	6	11
39	4.5	4.03	4.57	382.3	166.9	124.7	5.00	2.90	4.22	3.0	2	24	6	10
40	4.5	4.03	4.79	382.3	166.9	124.7	5.00	3.30	4.35	3.0	2	25	6	10
41	4.5	4.91	4.72	379.8	163.4	121.4	5.00	3.00	4.27	3.0	2	26	6	10
42	4.5	4.91	4.82	379.8	163.4	121.4	5.00	3.40	4.40	3.0	2	27	6	10
43	5.0	5.02	4.86	377.6	146.4	101.3	5.00	3.20	4.80	3.0	11	2	6	10
44	5.0	4.52	4.96	382.3	151.2	105.8	5.00	2.90	3.32	3.0	18	8	6	10
45	5.0	4.53	4.96	386.9	156.3	111.6	5.00	2.90	3.32	3.0	18	24	6	10
46	5.0	2.39	3.98	410.8	186.3	142.5	3.20	3.40	4.05	3.0	1	2	7	11
47	5.0	4.16	3.63	397.6	167.2	123.0	3.20	2.70	4.07	3.0	1	8	7	10
48	5.0	4.16	3.94	397.6	167.2	123.0	3.20	3.10	4.20	3.0	1	9	7	10
49	5.0	4.99	3.79	390.1	158.9	113.8	3.20	2.80	4.12	3.0	1	10	7	10

Table II-12 (Continued)

DCA3 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
50	5.0	4.99	3.88	390.1	158.9	113.8	3.20	3.20	4.25	3.0	1	11	7	10
51	5.0	4.17	3.63	402.9	173.9	129.0	3.20	2.70	4.07	3.0	1	24	7	10
52	5.0	4.17	3.85	402.9	173.9	129.0	3.20	3.10	4.20	3.0	1	25	7	10
53	5.0	5.05	3.79	400.0	170.0	125.6	3.20	2.80	4.12	3.0	1	26	7	10
54	5.0	5.05	3.89	400.0	170.0	125.6	3.20	3.20	4.25	3.0	1	27	7	10
55	5.0	3.94	4.11	409.4	182.2	137.4	3.20	3.10	4.20	3.0	1	28	7	11
56	5.0	4.36	4.21	408.6	181.2	136.4	3.20	3.13	4.22	3.0	1	29	7	11
57	4.5	2.46	4.46	407.5	185.4	142.0	3.20	3.60	4.20	3.0	2	2	7	10
58	5.0	4.19	4.14	394.3	166.2	122.3	3.20	2.90	4.22	3.0	2	8	7	10
59	5.0	4.19	4.45	394.3	166.2	122.3	3.20	3.30	4.35	3.0	2	9	7	10
60	5.0	5.02	4.29	386.8	157.9	113.1	3.20	3.00	4.27	3.0	2	10	7	10
61	5.0	5.02	4.39	386.8	157.9	113.1	3.20	3.40	4.40	3.0	2	11	7	10
62	5.0	5.08	4.29	396.7	169.0	124.9	3.20	3.00	4.27	3.0	2	26	7	10
63	5.0	5.08	4.39	396.7	169.0	124.9	3.20	3.40	4.40	3.0	2	27	7	10
64	4.0	4.51	4.60	406.0	181.1	136.7	3.20	3.30	4.35	3.0	2	28	7	6
65	5.0	4.39	4.72	405.3	180.2	135.6	3.20	3.33	4.37	3.0	2	29	7	11
66	5.0	4.77	4.82	404.8	179.3	134.6	3.20	3.40	4.40	3.0	2	30	7	11
67	5.0	5.17	4.96	404.0	178.3	133.6	3.20	3.47	4.40	3.0	2	31	7	11
68	4.5	5.60	4.40	396.2	151.6	104.7	3.20	3.20	4.80	3.0	11	2	7	6
69	4.5	5.47	4.67	407.8	165.0	119.1	3.20	2.50	3.32	3.0	13	8	7	6
70	4.5	5.47	4.98	407.8	165.0	119.1	3.20	2.90	3.45	3.0	13	9	7	6
71	5.5	5.88	4.86	400.5	156.9	110.0	3.20	2.60	3.37	3.0	13	10	7	10
72	5.5	5.88	4.95	400.5	156.9	110.0	3.20	3.00	3.50	3.0	13	11	7	10
73	5.0	4.89	4.66	412.9	170.5	125.1	3.20	2.50	3.32	3.0	13	24	7	10
74	5.0	4.89	4.88	412.9	170.5	125.1	3.20	2.90	3.45	3.0	13	25	7	10
75	5.5	5.40	4.93	405.2	161.0	114.6	3.20	3.17	3.32	3.0	14	8	7	10
76	5.0	5.24	4.89	410.3	166.4	120.6	3.20	3.17	3.32	3.0	14	24	7	10
77	5.0	2.96	4.86	411.7	172.7	127.6	3.20	3.60	3.30	3.0	18	2	7	10
78	4.5	5.11	4.50	399.2	155.6	108.7	3.20	2.90	3.32	3.0	18	8	7	6
79	4.5	5.11	4.81	399.2	155.6	108.7	3.20	3.30	3.45	3.0	18	9	7	6
80	5.5	5.52	4.69	392.1	147.6	99.4	3.20	3.00	3.37	3.0	18	10	7	10
81	5.5	5.52	4.78	392.1	147.6	99.4	3.20	3.40	3.50	3.0	18	11	7	10
82	5.0	4.53	4.49	404.2	161.0	114.7	3.20	2.90	3.32	3.0	18	24	7	10
83	5.0	4.53	4.71	404.2	161.0	114.7	3.20	3.30	3.45	3.0	18	25	7	10
84	4.5	6.00	4.66	401.5	157.9	111.2	3.20	3.00	3.37	3.0	18	26	7	6
85	4.5	6.00	4.75	401.5	157.9	111.2	3.20	3.40	3.50	3.0	18	27	7	6
86	5.0	4.51	4.99	410.4	168.6	121.9	3.20	3.30	3.45	3.0	18	28	7	10
87	4.5	5.11	4.68	399.2	155.6	108.7	3.20	3.03	3.32	3.0	21	8	7	6
88	4.5	5.11	4.99	399.2	155.6	108.7	3.20	3.43	3.45	3.0	21	9	7	6
89	5.5	5.52	4.87	392.1	147.6	99.4	3.20	3.13	3.37	3.0	21	10	7	10
90	5.5	5.52	4.96	392.1	147.6	99.4	3.20	3.53	3.50	3.0	21	11	7	10
91	5.0	4.53	4.67	404.2	161.0	114.7	3.20	3.03	3.32	3.0	21	24	7	10
92	5.0	4.53	4.89	404.2	161.0	114.7	3.20	3.43	3.45	3.0	21	25	7	10
93	4.5	6.00	4.84	401.5	157.9	111.2	3.20	3.13	3.37	3.0	21	26	7	6
94	4.5	6.00	4.93	401.5	157.9	111.2	3.20	3.53	3.50	3.0	21	27	7	6
95	5.0	5.08	4.39	411.5	170.2	125.2	3.20	3.20	4.80	3.0	27	2	7	10
96	5.0	4.60	4.74	424.1	187.2	142.6	3.20	3.07	4.72	3.0	29	2	7	10
97	5.0	4.98	4.84	423.9	185.9	141.3	3.20	3.20	4.80	3.0	30	2	7	10
98	5.0	5.38	4.98	422.6	184.4	139.7	3.20	3.33	4.80	3.0	31	2	7	10

Table II-13

DCA4 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	3.5	1.30	2.46	255.5	128.7	99.0	4.50	3.40	4.05	3.0	1	2	4	17
2	3.0	3.49	2.13	262.2	125.8	92.7	4.50	2.70	4.07	3.0	1	8	4	10
3	3.0	3.49	2.44	262.2	125.8	92.7	4.50	3.10	4.20	3.0	1	9	4	10
4	3.0	4.32	2.28	259.7	121.5	87.6	4.50	2.80	4.12	3.0	1	10	4	10
5	3.0	4.32	2.38	259.7	121.5	87.6	4.50	3.20	4.25	3.0	1	11	4	10
6	2.5	2.51	2.83	261.8	125.7	92.6	4.50	3.40	3.75	3.0	1	18	4	6
7	3.0	2.65	3.70	261.0	123.9	90.4	4.50	3.60	3.77	3.0	1	19	4	10
8	2.5	2.51	3.01	261.8	125.7	92.6	4.50	3.47	3.75	3.0	1	21	4	6
9	3.0	3.50	2.13	264.4	129.0	96.3	4.50	2.70	4.07	3.0	1	24	4	10
10	3.0	3.50	2.35	264.4	129.0	96.3	4.50	3.10	4.20	3.0	1	25	4	10
11	3.0	4.39	2.28	263.9	127.5	94.5	4.50	2.80	4.12	3.0	1	26	4	10
12	3.0	4.38	2.38	263.9	127.5	94.5	4.50	3.20	4.25	3.0	1	27	4	10
13	3.0	2.88	2.61	267.2	132.8	100.6	4.50	3.10	4.20	3.0	1	28	4	20
14	3.0	3.30	2.71	266.9	132.4	100.1	4.50	3.13	4.22	3.0	1	29	4	20
15	2.5	4.53	2.81	267.3	132.4	100.0	4.50	3.20	4.25	3.0	1	30	4	6
16	2.5	4.93	2.95	267.0	131.9	99.5	4.50	3.27	4.25	3.0	1	31	4	6
17	2.5	1.79	2.95	252.9	127.8	98.4	4.50	3.60	4.20	3.0	2	2	4	10
18	3.0	3.52	2.63	259.7	124.9	92.1	4.50	2.90	4.22	3.0	2	8	4	10
19	3.0	3.52	2.94	259.7	124.9	92.1	4.50	3.30	4.35	3.0	2	9	4	10
20	3.0	4.35	2.78	257.2	120.6	87.0	4.50	3.00	4.27	3.0	2	10	4	10
21	3.0	4.35	2.88	257.2	120.6	87.0	4.50	3.40	4.40	3.0	2	11	4	10
22	2.5	2.54	3.34	259.3	124.8	92.0	4.50	3.60	3.90	3.0	2	18	4	6
23	2.5	2.54	3.52	259.3	124.8	92.0	4.50	3.67	3.90	3.0	2	21	4	6
24	2.5	3.78	2.62	262.0	128.1	95.7	4.50	2.90	4.22	3.0	2	24	4	6
25	2.5	3.78	2.84	262.0	128.1	95.7	4.50	3.30	4.35	3.0	2	25	4	6
26	3.0	4.41	2.78	261.4	126.7	93.9	4.50	3.00	4.27	3.0	2	26	4	10
27	3.0	4.41	2.88	261.4	126.7	93.9	4.50	3.40	4.40	3.0	2	27	4	10
28	3.0	2.91	3.12	264.7	132.0	100.1	4.50	3.30	4.35	3.0	2	28	4	20
29	3.0	3.33	3.22	264.4	131.5	99.6	4.50	3.33	4.37	3.0	2	29	4	20
30	3.0	3.71	3.32	264.8	131.5	99.4	4.50	3.40	4.40	3.0	2	30	4	20
31	3.0	4.11	3.46	264.5	131.1	98.9	4.50	3.47	4.40	3.0	2	31	4	20
32	2.5	2.93	3.51	265.3	128.5	97.4	4.50	3.20	3.30	3.0	13	2	4	6
33	4.5	4.51	3.34	269.9	121.0	85.5	4.50	2.60	3.37	3.0	13	10	4	17
34	4.5	4.51	3.44	268.9	121.0	85.5	4.50	3.00	3.50	3.0	13	11	4	17
35	2.5	3.25	3.74	264.2	125.9	94.4	4.50	3.87	3.30	3.0	14	2	4	6
36	3.5	4.03	3.41	270.0	122.3	87.3	4.50	3.17	3.32	3.0	14	8	4	20
37	3.5	4.03	3.72	275.0	122.3	87.3	4.50	3.57	3.45	3.0	14	9	4	20
38	3.5	2.83	4.13	269.3	122.1	87.1	4.50	3.87	3.00	3.0	14	18	4	20
39	4.5	4.51	4.02	268.9	121.0	85.5	4.50	2.93	3.52	3.0	16	10	4	17
40	4.5	4.51	4.12	268.9	121.0	85.5	4.50	3.33	3.65	3.0	16	11	4	17
41	3.5	4.03	4.07	270.0	122.3	87.3	4.50	3.23	3.55	3.0	17	8	4	20
42	2.5	2.54	3.34	260.2	121.9	89.9	4.50	3.60	3.30	3.0	18	2	4	6
43	3.5	3.33	3.01	268.2	121.4	86.3	4.50	2.90	3.32	3.0	18	24	4	20
44	3.5	3.33	3.23	268.2	121.4	86.3	4.50	3.30	3.45	3.0	18	25	4	20
45	2.5	2.54	3.52	260.2	121.9	89.9	4.50	3.73	3.30	3.0	21	2	4	6
46	3.5	3.33	3.19	268.2	121.4	86.3	4.50	3.03	3.32	3.0	21	24	4	20
47	3.5	3.33	3.41	268.2	121.4	86.3	4.50	3.43	3.45	3.0	21	25	4	20
48	3.0	4.41	2.88	260.8	120.7	88.5	4.50	3.20	4.80	3.0	27	2	4	10
49	2.5	4.18	3.22	267.0	131.2	100.4	4.50	3.07	4.72	3.0	29	2	4	6
50	2.5	4.56	3.32	267.2	130.5	99.6	4.50	3.20	4.80	3.0	30	2	4	6
51	2.5	4.96	3.46	266.5	129.6	98.5	4.50	3.33	4.80	3.0	31	2	4	6
52	4.5	2.43	4.43	352.6	161.2	115.1	4.80	3.40	4.05	3.0	1	2	5	10
53	5.0	4.99	4.26	336.3	137.6	89.3	4.80	2.80	4.12	3.0	1	10	5	10
54	5.0	4.99	4.35	336.3	137.6	89.3	4.80	3.20	4.25	3.0	1	11	5	10
55	4.5	2.76	4.79	342.2	146.0	98.8	4.80	3.40	3.75	3.0	1	18	5	10
56	4.5	2.76	4.97	342.2	146.0	98.8	4.80	3.47	3.75	3.0	1	21	5	10
57	5.0	3.96	4.08	345.2	149.7	102.9	4.80	2.70	4.07	3.0	1	24	5	11

Table II-13 (Continued)

DCA4 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	T$$	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
58	5.0	3.96	4.30	345.2	149.7	102.9	4.80	3.10	4.20	3.0	1	25	5	11
59	4.5	3.98	4.57	349.8	156.9	109.1	4.80	3.10	4.20	3.0	1	28	5	10
60	4.5	4.40	4.67	349.3	156.0	108.4	4.80	3.13	4.22	3.0	1	29	5	10
61	4.5	4.78	4.77	349.0	155.2	107.7	4.80	3.20	4.25	3.0	1	30	5	10
62	4.5	5.18	4.91	348.5	154.4	107.0	4.80	3.27	4.25	3.0	1	31	5	10
63	4.5	2.46	4.93	349.5	160.0	114.2	4.80	3.60	4.20	3.0	2	2	5	10
64	5.0	5.02	4.76	333.0	136.5	88.4	4.80	3.00	4.27	3.0	2	10	5	10
65	5.0	5.02	4.86	333.0	136.5	88.4	4.80	3.40	4.40	3.0	2	11	5	10
66	4.5	4.03	4.57	342.0	148.3	101.9	4.80	2.90	4.22	3.0	2	24	5	10
67	4.5	4.03	4.79	342.0	148.3	101.9	4.80	3.30	4.35	3.0	2	25	5	10
68	5.0	4.87	4.74	340.0	145.3	98.9	4.80	3.00	4.27	3.0	2	26	5	11
69	5.0	4.87	4.84	340.0	145.3	98.9	4.80	3.40	4.40	3.0	2	27	5	11
70	5.0	4.53	4.96	347.6	138.3	88.9	4.80	2.90	3.32	3.0	18	24	5	10
71	5.0	5.08	4.86	354.2	146.3	98.2	4.80	3.20	4.80	3.0	27	2	5	10
72	4.5	2.24	4.41	353.0	178.6	137.1	5.00	3.40	4.05	3.0	1	2	6	11
73	4.5	3.99	4.07	343.8	162.2	119.6	5.00	2.70	4.07	3.0	1	8	6	10
74	4.5	3.99	4.38	343.8	162.2	119.6	5.00	3.10	4.20	3.0	1	9	6	10
75	4.5	4.82	4.22	337.8	154.5	110.9	5.00	2.80	4.12	3.0	1	10	6	10
76	4.5	4.82	4.32	337.9	154.5	110.9	5.00	3.20	4.25	3.0	1	11	6	10
77	4.5	2.76	4.79	344.8	164.1	121.1	5.00	3.40	3.75	3.0	1	18	6	10
78	4.5	2.76	4.97	344.8	164.1	121.1	5.00	3.47	3.75	3.0	1	21	6	10
79	4.5	4.00	4.07	348.1	167.9	125.4	5.00	2.70	4.07	3.0	1	24	6	10
80	4.5	4.00	4.29	348.1	167.9	125.4	5.00	3.10	4.20	3.0	1	25	6	10
81	4.5	4.88	4.22	345.9	164.4	122.1	5.00	2.80	4.12	3.0	1	26	6	10
82	4.5	4.88	4.32	345.9	164.4	122.1	5.00	3.20	4.25	3.0	1	27	6	10
83	4.5	3.80	4.55	353.3	175.7	132.7	5.00	3.10	4.20	3.0	1	28	6	11
84	4.5	4.40	4.67	352.7	174.8	131.7	5.00	3.13	4.22	3.0	1	29	6	10
85	4.5	4.78	4.77	352.4	174.0	130.8	5.00	3.20	4.25	3.0	1	30	6	10
86	4.5	5.18	4.91	351.8	173.1	130.0	5.00	3.27	4.25	3.0	1	31	6	10
87	4.5	2.27	4.91	350.1	177.7	136.5	5.00	3.60	4.20	3.0	2	2	6	11
88	4.5	4.02	4.57	340.9	161.2	118.9	5.00	2.90	4.22	3.0	2	8	6	10
89	4.5	4.02	4.38	340.9	161.2	118.9	5.00	3.30	4.35	3.0	2	9	6	10
90	4.5	4.85	4.72	334.8	153.5	110.2	5.00	3.00	4.27	3.0	2	10	6	10
91	4.5	4.85	4.82	334.8	153.5	110.2	5.00	3.40	4.40	3.0	2	11	6	10
92	4.5	4.03	4.57	345.1	166.9	124.7	5.00	2.90	4.22	3.0	2	24	6	10
93	4.5	4.03	4.79	345.1	166.9	124.7	5.00	3.30	4.35	3.0	2	25	6	10
94	4.5	4.91	4.72	342.9	163.4	121.4	5.00	3.00	4.27	3.0	2	26	6	10
95	4.5	4.91	4.82	342.9	163.4	121.4	5.00	3.40	4.40	3.0	2	27	6	10
96	4.5	4.85	4.62	341.5	146.4	101.3	5.00	3.20	4.80	3.0	11	2	6	10
97	4.5	4.57	4.93	349.7	156.3	111.6	5.00	2.90	3.32	3.0	18	24	6	10
98	4.5	4.91	4.82	354.3	164.1	121.0	5.00	3.20	4.80	3.0	27	2	6	10
99	4.5	2.43	3.96	369.8	186.3	142.5	3.20	3.40	4.05	3.0	1	2	7	10
100	5.0	3.95	3.61	357.6	167.2	123.0	3.20	2.70	4.07	3.0	1	8	7	11
101	5.0	3.95	3.92	357.6	167.2	123.0	3.20	3.10	4.20	3.0	1	9	7	11
102	5.0	4.99	3.79	351.0	158.9	113.8	3.20	2.80	4.12	3.0	1	10	7	10
103	5.0	4.99	3.86	351.0	158.9	113.8	3.20	3.20	4.25	3.0	1	11	7	10
104	4.5	2.76	4.32	358.8	169.9	124.6	3.20	3.40	3.75	3.0	1	18	7	10
105	4.5	2.76	4.50	358.8	169.9	124.6	3.20	3.47	3.75	3.0	1	21	7	10
106	4.5	4.00	3.69	362.2	173.9	129.0	3.20	2.70	4.07	3.0	1	24	7	10
107	4.5	4.00	3.82	362.2	173.9	129.0	3.20	3.10	4.20	3.0	1	25	7	10
108	5.0	4.84	3.77	359.7	170.0	125.6	3.20	2.80	4.12	3.0	1	26	7	11
109	5.0	4.84	3.86	359.7	170.0	125.6	3.20	3.20	4.25	3.0	1	27	7	11
110	4.5	3.98	4.10	367.9	192.2	137.4	3.20	3.10	4.20	3.0	1	28	7	10
111	4.5	4.40	4.20	367.2	181.2	136.4	3.20	3.13	4.22	3.0	1	29	7	10
112	4.5	4.78	4.30	366.8	180.3	135.4	3.20	3.20	4.25	3.0	1	30	7	10
113	4.5	5.18	4.44	366.1	179.3	134.3	3.20	3.27	4.25	3.0	1	31	7	10
114	4.5	2.46	4.46	366.8	185.4	142.0	3.20	3.60	4.20	3.0	2	2	7	10

Table II-13 (Continued)

DCA4 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	T$$	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
115	4.5	4.02	4.10	354.5	166.2	122.3	3.20	2.90	4.22	3.0	2	8	7	10
116	4.5	4.02	4.41	354.5	166.2	122.3	3.20	3.30	4.35	3.0	2	9	7	10
117	4.5	2.79	4.82	355.7	168.8	123.8	3.20	3.60	3.90	3.0	2	18	7	10
118	4.5	2.79	5.00	355.7	168.8	123.8	3.20	3.67	3.90	3.0	2	21	7	10
119	4.5	4.03	4.10	359.1	172.9	128.3	3.20	2.90	4.22	3.0	2	24	7	10
120	4.5	4.03	4.32	359.1	172.9	128.3	3.20	3.30	4.35	3.0	2	25	7	10
121	4.5	4.91	4.25	356.6	169.0	124.9	3.20	3.00	4.27	3.0	2	26	7	10
122	4.5	4.91	4.35	356.6	169.0	124.9	3.20	3.40	4.40	3.0	2	27	7	10
123	4.5	[illegible]	4.60	364.8	181.1	136.7	3.20	3.30	4.35	3.0	2	28	7	10
124	4.5	4.43	4.70	364.1	180.2	135.6	3.20	3.33	4.37	3.0	2	29	7	10
125	4.5	4.81	4.90	363.7	179.3	134.6	3.20	3.40	4.40	3.0	2	30	7	10
126	4.5	5.21	4.94	367.0	178.3	133.6	3.20	3.47	4.40	3.0	2	31	7	10
127	5.0	5.02	4.39	356.7	151.6	104.7	3.20	3.20	4.80	3.0	11	2	7	10
128	5.0	5.35	4.74	346.9	136.7	87.5	3.20	3.20	4.50	3.0	11	18	7	10
129	5.0	5.35	4.92	346.8	136.7	87.5	3.20	3.27	4.50	3.0	11	21	7	10
130	5.0	4.98	4.66	366.9	165.0	119.1	3.20	2.50	3.32	3.0	13	8	7	10
131	5.0	4.98	4.97	366.9	165.0	119.1	3.20	2.90	3.45	3.0	13	9	7	10
132	5.0	4.89	4.66	371.4	170.5	125.1	3.20	2.50	3.32	3.0	13	24	7	10
133	5.0	4.89	4.98	371.4	170.5	125.1	3.20	2.90	3.45	3.0	13	25	7	10
134	5.0	5.77	4.82	369.0	167.3	121.7	3.20	2.60	3.37	3.0	13	26	7	10
135	5.0	5.77	4.91	369.0	167.3	121.7	3.20	3.00	3.50	3.0	13	27	7	10
136	5.0	5.23	4.89	364.6	161.0	114.6	3.20	3.17	3.32	3.0	14	8	7	10
137	5.0	5.24	4.89	369.1	166.4	120.6	3.20	3.17	3.32	3.0	14	24	7	10
138	5.0	2.96	4.26	370.7	172.7	127.6	3.20	3.60	3.30	3.0	18	2	7	10
139	5.0	4.52	4.49	359.1	155.6	108.7	3.20	2.90	3.32	3.0	18	8	7	10
140	5.0	4.52	4.80	359.1	155.6	108.7	3.20	3.30	3.45	3.0	18	9	7	10
141	4.5	5.94	4.66	352.9	147.6	99.4	3.20	3.00	3.37	3.0	18	10	7	6
142	4.5	5.94	4.75	352.9	147.6	99.4	3.20	3.40	3.50	3.0	18	11	7	6
143	5.0	4.53	4.49	363.6	161.0	114.7	3.20	2.90	3.32	3.0	18	24	7	10
144	5.0	4.53	4.71	363.6	161.0	114.7	3.20	3.30	3.45	3.0	18	25	7	10
145	5.0	5.41	4.65	361.1	157.9	111.2	3.20	3.00	3.37	3.0	18	26	7	10
146	5.0	5.41	4.74	361.1	157.9	111.2	3.20	3.40	3.50	3.0	18	27	7	10
147	5.0	4.52	4.67	359.1	155.6	108.7	3.20	3.03	3.32	3.0	21	8	7	10
148	5.0	4.52	4.98	359.1	155.6	108.7	3.20	3.43	3.45	3.0	21	9	7	10
149	4.5	5.94	4.84	352.9	147.6	99.4	3.20	3.13	3.37	3.0	21	10	7	6
150	4.5	5.94	4.93	352.9	147.6	99.4	3.20	3.53	3.50	3.0	21	11	7	6
151	5.0	4.53	4.67	363.6	161.0	114.7	3.20	3.03	3.32	3.0	21	24	7	10
152	5.0	4.53	4.89	363.6	161.0	114.7	3.20	3.43	3.45	3.0	21	25	7	10
153	5.0	5.41	4.83	361.1	157.9	111.2	3.20	3.13	3.37	3.0	21	26	7	10
154	5.0	5.41	4.92	361.1	157.9	111.2	3.20	3.53	3.50	3.0	21	27	7	10
155	5.0	5.08	4.39	370.5	170.2	125.2	3.20	3.20	4.80	3.0	27	2	7	10
156	5.0	5.41	4.74	360.0	154.7	107.7	3.20	3.20	4.50	3.0	27	18	7	10
157	5.0	5.41	4.92	360.0	154.7	107.7	3.20	3.27	4.50	3.0	27	21	7	10
158	5.0	4.98	4.84	381.8	185.9	141.3	3.20	3.20	4.80	3.0	30	2	7	10
159	5.0	5.38	4.98	380.7	184.4	139.7	3.20	3.33	4.80	3.0	31	2	7	10
160	3.0	1.93	2.84	266.1	128.2	95.1	2.80	3.40	4.05	3.0	1	2	8	10
161	3.5	1.73	3.22	269.8	123.1	86.7	2.80	3.40	3.75	3.0	1	18	8	20
162	3.5	1.73	3.40	269.8	123.1	86.7	2.80	3.47	3.75	3.0	1	21	8	20
163	3.5	2.21	3.33	263.4	127.2	94.4	2.80	3.60	4.20	3.0	2	2	8	6
164	3.5	2.99	3.01	267.7	122.2	86.0	2.80	2.90	4.22	3.0	2	8	8	20
165	3.5	2.99	3.32	267.7	122.2	86.0	2.80	3.30	4.35	3.0	2	9	8	20
166	3.5	1.76	3.73	267.3	122.1	86.0	2.80	3.60	3.90	3.0	2	18	8	20
167	3.5	1.76	3.91	267.3	122.1	86.0	2.80	3.67	3.90	3.0	2	21	8	20
168	3.5	3.00	3.01	269.9	125.4	89.7	2.80	2.90	4.22	3.0	2	24	8	20
169	3.5	3.00	3.23	269.9	125.4	89.7	2.80	3.30	4.35	3.0	2	25	8	20
170	3.5	3.88	3.16	269.3	123.9	87.8	2.80	3.00	4.27	3.0	2	26	8	20
171	3.5	3.88	3.26	269.3	123.9	87.8	2.80	3.40	4.40	3.0	2	27	8	20

Table II-14

DCCl Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	5.0	3.61	6.73	392.9	161.2	115.1	4.80	3.40	4.05	2.0	1	2	1	10
2	4.5	3.44	6.69	390.3	176.6	137.1	5.00	3.40	4.05	2.0	1	2	2	10
3	4.5	5.01	6.22	380.6	162.2	119.6	5.00	2.70	4.07	2.0	1	8	2	10
4	4.5	5.01	6.63	360.6	162.2	119.6	5.00	3.10	4.20	2.0	1	9	2	10
5	4.5	5.02	6.32	385.5	167.9	125.4	5.00	2.70	4.07	2.0	1	24	2	10
6	4.5	5.02	6.54	385.5	167.9	125.4	5.00	3.10	4.20	2.0	1	25	2	10
7	4.5	5.90	6.48	382.9	164.4	122.1	5.00	2.60	4.12	2.0	1	26	2	10
8	4.5	5.90	6.57	382.9	164.4	122.1	5.00	3.20	4.25	2.0	1	27	2	10
9	4.5	5.07	6.82	391.4	175.7	132.7	5.00	3.10	4.20	2.0	1	28	2	10
10	4.5	5.42	6.92	390.7	174.8	131.7	5.00	3.13	4.22	2.0	1	29	2	10
11	4.5	5.80	7.02	390.4	174.0	130.8	5.00	3.20	4.25	2.0	1	30	2	10
12	4.5	6.20	7.16	389.6	173.1	130.0	5.00	3.27	4.25	2.0	1	31	2	10
13	4.5	3.47	7.19	387.2	177.7	136.5	5.00	3.60	4.20	2.0	2	2	2	10
14	4.5	5.04	6.83	377.5	161.2	118.9	5.00	2.90	4.22	2.0	2	8	2	10
15	4.5	5.04	7.14	377.5	161.2	118.9	5.00	3.30	4.35	2.0	2	9	2	10
16	4.5	5.05	6.83	382.3	166.9	124.7	5.00	2.90	4.22	2.0	2	24	2	10
17	4.5	5.05	7.05	382.3	166.9	124.7	5.00	3.30	4.35	2.0	2	25	2	10
18	4.5	5.93	6.98	379.8	163.4	121.4	5.00	3.00	4.27	2.0	2	26	2	10
19	4.5	5.93	7.08	379.8	163.4	121.4	5.00	3.40	4.40	2.0	2	27	2	10
20	5.0	3.40	6.24	410.8	186.3	142.5	3.20	3.40	4.05	2.0	1	2	3	11
21	5.0	5.18	5.89	397.6	167.2	123.0	3.20	2.70	4.07	2.0	1	8	3	10
22	5.0	5.18	6.20	397.6	167.2	123.0	3.20	3.10	4.20	2.0	1	9	3	10
23	5.0	5.19	5.89	402.9	173.9	129.0	3.20	2.70	4.07	2.0	1	24	3	10
24	5.0	5.19	6.11	402.9	173.9	129.0	3.20	3.10	4.20	2.0	1	25	3	10
25	5.0	6.07	6.05	400.0	170.0	125.6	3.20	2.80	4.12	2.0	1	26	3	10
26	5.0	6.07	6.14	400.0	170.0	125.6	3.20	3.20	4.25	2.0	1	27	3	10
27	5.0	4.96	6.37	409.4	182.2	137.4	3.20	3.10	4.20	2.0	1	28	3	11
28	5.0	5.38	6.47	408.6	181.2	136.4	3.20	3.13	4.22	2.0	1	29	3	11
29	4.5	3.47	6.72	407.5	185.4	142.0	3.20	3.60	4.20	2.0	2	2	3	10
30	5.0	5.20	6.40	394.3	166.2	122.3	3.20	2.90	4.22	2.0	2	8	3	10
31	5.0	5.20	6.71	394.3	166.2	122.3	3.20	3.30	4.35	2.0	2	9	3	10
32	5.0	6.09	6.55	396.7	169.0	124.9	3.20	3.00	4.27	2.0	2	26	3	10
33	5.0	6.09	6.65	396.7	169.0	124.9	3.20	3.40	4.40	2.0	2	27	3	10
34	4.0	5.53	6.86	406.0	191.1	136.7	3.20	3.30	4.35	2.0	2	28	3	6
35	5.0	5.40	6.98	405.3	180.2	135.6	3.20	3.33	4.37	2.0	2	29	3	11
36	5.0	5.78	7.08	404.8	179.3	134.6	3.20	3.40	4.40	2.0	2	30	3	11
37	5.0	6.18	7.22	404.0	178.3	133.6	3.20	3.47	4.40	2.0	2	31	3	11
38	4.5	6.48	6.93	407.8	165.0	119.1	3.20	2.50	3.32	2.0	13	8	3	6
39	4.5	6.48	7.24	407.8	165.0	119.1	3.20	2.90	3.45	2.0	13	9	3	6
40	5.0	5.91	6.92	412.9	170.5	125.1	3.20	2.50	3.32	2.0	13	24	3	10
41	5.0	5.91	7.14	412.9	170.5	125.1	3.20	2.90	3.45	2.0	13	25	3	10
42	5.0	6.26	7.15	410.3	166.4	120.6	3.20	3.17	3.32	2.0	14	24	3	10
43	5.0	3.97	7.12	411.7	172.7	127.6	3.20	3.60	3.30	2.0	18	2	3	10
44	5.0	6.09	6.65	411.5	170.2	125.2	3.20	3.20	4.80	2.0	27	2	3	10
45	5.0	5.61	7.00	424.1	187.2	142.6	3.20	3.07	4.72	2.0	29	2	3	10
46	5.0	5.99	7.10	423.9	185.9	141.3	3.20	3.20	4.80	2.0	30	2	3	10
47	5.0	6.39	7.24	422.6	184.4	139.7	3.20	3.33	4.80	2.0	31	2	3	10

Table II-15

DCC2 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIN	WETH	MAT	OCP	ICP	ABS	INS
1	4.5	3.44	6.69	352.6	161.2	115.1	4.80	3.40	4.05	2.0	1	2	1	10
2	4.5	3.26	6.67	353.0	178.6	137.1	5.00	3.40	4.05	2.0	1	2	2	11
3	4.5	5.01	6.32	343.8	162.2	119.6	5.00	2.70	4.07	2.0	1	8	2	10
4	4.5	5.01	6.63	343.8	162.2	119.6	5.00	3.10	4.20	2.0	1	9	2	10
5	4.5	3.78	7.04	344.8	164.1	121.1	5.00	3.40	3.75	2.0	1	18	2	10
6	4.5	3.75	7.22	344.8	164.1	121.1	5.00	3.47	3.75	2.0	1	21	2	10
7	4.5	5.02	6.32	348.1	167.9	125.4	5.00	2.70	4.07	2.0	1	24	2	10
8	4.5	5.02	6.54	348.1	167.9	125.4	5.00	3.10	4.20	2.0	1	25	2	10
9	4.5	5.90	6.48	345.9	164.4	122.1	5.00	2.80	4.12	2.0	1	26	2	10
10	4.5	5.90	6.57	345.9	164.4	122.1	5.00	3.20	4.25	2.0	1	27	2	10
11	4.5	4.81	6.81	353.3	175.7	132.7	5.00	3.10	4.20	2.0	1	28	2	11
12	4.5	5.42	6.92	352.7	174.8	131.7	5.00	3.13	4.22	2.0	1	29	2	10
13	4.5	5.60	7.02	352.4	174.0	130.6	5.00	3.20	4.25	2.0	1	30	2	10
14	4.5	6.20	7.16	351.8	173.1	130.0	5.00	3.27	4.25	2.0	1	31	2	10
15	4.5	3.28	7.17	350.1	177.7	136.5	5.00	3.60	4.20	2.0	2	2	2	11
16	4.5	5.04	6.33	340.9	161.2	118.9	5.00	2.90	4.22	2.0	2	8	2	10
17	4.5	5.04	7.14	340.9	161.2	118.9	5.00	3.30	4.35	2.0	2	9	2	10
18	4.5	5.05	6.83	345.1	166.9	124.7	5.00	2.90	4.22	2.0	2	24	2	10
19	4.5	5.05	7.05	345.1	166.9	124.7	5.00	3.30	4.35	2.0	2	25	2	10
20	4.5	5.93	6.98	342.9	163.4	121.4	5.00	3.00	4.27	2.0	2	26	2	10
21	4.5	5.93	7.08	342.9	163.4	121.4	5.00	3.40	4.40	2.0	2	27	2	10
22	4.5	5.93	7.08	354.3	164.1	121.0	5.00	3.20	4.80	2.0	27	2	2	10
23	4.5	3.44	6.22	369.8	186.3	142.5	3.20	3.40	4.05	2.0	1	2	3	10
24	5.0	4.97	5.87	357.6	167.2	123.0	3.20	2.70	4.07	2.0	1	8	3	11
25	5.0	4.97	6.18	357.6	167.2	123.0	3.20	3.10	4.20	2.0	1	9	3	11
26	4.5	3.78	6.57	358.8	169.9	124.6	3.20	3.40	3.75	2.0	1	18	3	10
27	4.5	3.78	6.75	358.8	169.9	124.6	3.20	3.47	3.75	2.0	1	21	3	10
28	4.5	5.02	5.85	362.2	173.9	129.0	3.20	2.70	4.07	2.0	1	24	3	10
29	4.5	5.02	6.07	362.2	173.9	129.0	3.20	3.10	4.20	2.0	1	25	3	10
30	5.0	5.86	6.03	359.7	170.0	125.6	3.20	2.80	4.12	2.0	1	26	3	11
31	5.0	5.86	6.12	359.7	170.0	125.6	3.20	3.20	4.25	2.0	1	27	3	11
32	4.5	5.00	6.35	367.9	182.2	137.4	3.20	3.10	4.20	2.0	1	28	3	10
33	4.5	5.42	6.45	367.2	181.2	136.4	3.20	3.13	4.22	2.0	1	29	3	10
34	4.5	5.60	6.55	366.8	180.3	135.4	3.20	3.20	4.25	2.0	1	30	3	10
35	4.5	6.20	6.69	366.1	179.3	134.3	3.20	3.27	4.25	2.0	1	31	3	10
36	4.5	3.47	6.72	366.8	185.4	142.0	3.20	3.60	4.20	2.0	2	2	3	10
37	4.5	5.04	6.36	354.5	166.2	122.3	3.20	2.90	4.22	2.0	2	8	3	10
38	4.5	5.04	6.67	354.5	166.2	122.3	3.20	3.30	4.35	2.0	2	9	3	10
39	4.5	3.81	7.08	355.7	168.8	123.8	3.20	3.60	3.90	2.0	2	18	3	10
40	4.5	5.05	6.36	359.1	172.9	128.3	3.20	2.90	4.22	2.0	2	24	3	10
41	4.5	5.05	6.56	359.1	172.9	128.3	3.20	3.30	4.35	2.0	2	25	3	10
42	4.5	5.93	6.51	356.6	169.0	124.9	3.20	3.00	4.27	2.0	2	26	3	10
43	4.5	5.93	6.61	356.6	169.0	124.9	3.20	3.40	4.40	2.0	2	27	3	10
44	4.5	5.03	6.86	364.8	181.1	136.7	3.20	3.30	4.35	2.0	2	28	3	10
45	4.5	5.45	6.96	364.1	180.2	135.6	3.20	3.33	4.37	2.0	2	29	3	10
46	4.5	5.83	7.06	363.7	179.3	134.6	3.20	3.40	4.40	2.0	2	30	3	10
47	4.5	6.23	7.20	363.0	178.3	133.6	3.20	3.47	4.40	2.0	2	31	3	10
48	5.0	5.90	6.92	366.9	165.0	119.1	3.20	2.50	3.32	2.0	13	8	3	10
49	5.0	5.90	7.23	366.9	165.0	119.1	3.20	2.90	3.45	2.0	13	9	3	10
50	5.0	5.91	6.92	371.4	170.5	125.1	3.20	2.50	3.32	2.0	13	24	3	10
51	5.0	5.91	7.14	371.4	170.5	125.1	3.20	2.90	3.45	2.0	13	25	3	10
52	5.0	6.79	7.08	369.0	167.3	121.7	3.20	2.60	3.37	2.0	13	26	3	10
53	5.0	6.79	7.17	369.0	167.3	121.7	3.20	3.00	3.50	2.0	13	27	3	10
54	5.0	6.26	7.15	369.1	166.4	120.6	3.20	3.17	3.32	2.0	14	24	3	10
55	5.0	3.97	7.12	370.7	172.7	127.6	3.20	3.60	3.30	2.0	18	2	3	10
56	5.0	6.09	6.65	370.5	170.2	125.2	3.20	3.20	4.80	2.0	27	2	3	10
57	5.0	5.99	7.10	381.8	185.9	141.3	3.20	3.20	4.80	2.0	30	2	3	10
58	5.0	6.39	7.24	380.7	184.4	139.7	3.20	3.33	4.80	2.0	31	2	3	10

Table II-16

DCC3 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	5.0	3.61	6.73	392.9	161.2	115.1	4.80	3.40	4.05	2.0	1	2	1	10
2	5.0	5.18	6.36	381.0	144.7	97.6	4.80	2.70	4.07	2.0	1	8	1	10
3	5.0	5.18	6.67	381.0	144.7	97.6	4.80	3.10	4.20	2.0	1	9	1	10
4	4.5	6.59	6.53	374.8	137.6	89.3	4.80	2.80	4.12	2.0	1	10	1	6
5	4.5	6.59	6.62	374.8	137.6	89.3	4.80	3.20	4.25	2.0	1	11	1	6
6	5.0	5.19	6.36	385.4	149.7	102.9	4.80	2.70	4.07	2.0	1	24	1	10
7	5.0	5.19	6.58	385.4	149.7	102.9	4.80	3.10	4.20	2.0	1	25	1	10
8	5.0	6.07	6.52	383.0	146.6	99.8	4.80	2.80	4.12	2.0	1	26	1	10
9	5.0	6.07	6.61	383.0	146.6	99.8	4.80	3.20	4.25	2.0	1	27	1	10
10	5.0	5.17	6.86	390.6	156.9	109.1	4.80	3.10	4.20	2.0	1	28	1	10
11	5.0	5.59	6.96	390.0	156.0	108.4	4.80	3.13	4.22	2.0	1	29	1	10
12	5.0	5.97	7.06	389.6	155.2	107.7	4.80	3.20	4.25	2.0	1	30	1	10
13	5.0	6.37	7.20	389.0	154.4	107.0	4.80	3.27	4.25	2.0	1	31	1	10
14	5.0	5.20	6.87	377.5	143.3	96.6	4.80	2.90	4.22	2.0	2	8	1	10
15	5.0	5.20	7.18	377.5	143.3	96.6	4.80	3.30	4.35	2.0	2	9	1	10
16	4.5	6.62	7.03	371.3	136.4	88.4	4.80	3.00	4.27	2.0	2	10	1	6
17	4.5	6.62	7.13	371.3	136.4	88.4	4.80	3.40	4.40	2.0	2	11	1	6
18	5.0	5.21	6.87	381.8	148.3	101.9	4.80	2.90	4.22	2.0	2	24	1	10
19	5.0	5.21	7.09	381.8	148.3	101.9	4.80	3.30	4.35	2.0	2	25	1	10
20	5.0	6.09	7.02	379.5	145.3	98.9	4.80	3.00	4.27	2.0	2	26	1	10
21	5.0	6.09	7.12	379.5	145.3	98.9	4.80	3.40	4.40	2.0	2	27	1	10
22	4.5	6.68	7.13	394.5	146.3	98.2	4.80	3.20	4.80	2.0	27	2	1	6
23	4.5	3.44	6.69	390.3	178.6	137.1	5.00	3.40	4.05	2.0	1	2	2	10
24	4.5	5.01	6.32	380.6	162.2	119.6	5.00	2.70	4.07	2.0	1	8	2	10
25	4.5	5.01	6.63	380.6	162.2	119.6	5.00	3.10	4.20	2.0	1	9	2	10
26	4.5	5.02	6.32	385.5	167.9	125.4	5.00	2.70	4.07	2.0	1	24	2	10
27	4.5	5.02	6.54	385.5	167.9	125.4	5.00	3.10	4.20	2.0	1	25	2	10
28	4.5	5.90	6.48	382.9	164.4	122.1	5.00	2.80	4.12	2.0	1	26	2	10
29	4.5	5.90	6.57	382.9	164.4	122.1	5.00	3.20	4.25	2.0	1	27	2	10
30	4.5	5.00	6.82	391.4	175.7	132.7	5.00	3.10	4.20	2.0	1	28	2	10
31	4.5	5.42	6.92	390.7	174.8	131.7	5.00	3.13	4.22	2.0	1	29	2	10
32	4.5	5.80	7.02	390.4	174.0	130.8	5.00	3.20	4.25	2.0	1	30	2	10
33	4.5	6.20	7.16	389.6	173.1	130.0	5.00	3.27	4.25	2.0	1	31	2	10
34	4.5	3.47	7.19	387.2	177.7	136.5	5.00	3.60	4.20	2.0	2	2	2	10
35	4.5	5.04	6.83	377.5	161.2	118.9	5.00	2.90	4.22	2.0	2	8	2	10
36	4.5	5.04	7.14	377.5	161.2	118.9	5.00	3.30	4.35	2.0	2	9	2	11
37	5.0	5.82	7.00	370.7	153.5	110.2	5.00	3.00	4.27	2.0	2	10	2	11
38	5.0	5.82	7.10	370.7	153.5	110.2	5.00	3.40	4.40	2.0	2	11	2	11
39	4.5	5.05	6.83	382.3	166.9	124.7	5.00	2.90	4.22	2.0	2	24	2	10
40	4.5	5.05	7.05	382.3	166.9	124.7	5.00	3.30	4.35	2.0	2	25	2	10
41	4.5	5.93	6.98	379.8	163.4	121.4	5.00	3.00	4.27	2.0	2	26	2	10
42	4.5	5.93	7.08	379.8	163.4	121.4	5.00	3.40	4.40	2.0	2	27	2	10
43	5.0	6.03	7.12	377.6	146.4	101.3	5.00	3.20	4.80	2.0	11	2	2	10
44	5.0	5.54	7.22	382.3	151.2	105.8	5.00	2.90	3.32	2.0	18	8	2	10
45	5.0	5.55	7.22	386.9	156.3	111.6	5.00	2.90	3.32	2.0	18	24	2	10
46	5.0	3.40	6.24	410.8	186.3	142.5	3.20	3.40	4.05	2.0	1	2	3	11

Table II-16 (Continued)

DCC3 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
47	5.0	5.18	5.89	397.6	167.2	123.0	3.20	2.70	4.07	2.0	1	8	3	10
48	5.0	5.18	6.20	397.6	167.2	123.0	3.20	3.10	4.20	2.0	1	9	3	10
49	5.0	6.01	6.05	370.1	158.9	113.8	3.20	2.80	4.12	2.0	1	10	3	10
50	5.0	6.01	6.14	390.1	158.9	113.8	3.20	3.20	4.25	2.0	1	11	3	10
51	5.0	5.19	5.69	402.9	173.9	129.0	3.20	2.70	4.07	2.0	1	24	3	10
52	5.0	5.19	6.11	402.9	173.9	129.0	3.20	3.10	4.20	2.0	1	25	3	10
53	5.0	6.07	6.05	400.0	170.0	125.6	3.20	2.80	4.12	2.0	1	26	3	10
54	5.0	6.07	6.14	400.0	170.0	125.6	3.20	3.20	4.25	2.0	1	27	3	10
55	5.0	4.96	6.37	409.4	182.2	137.4	3.20	3.10	4.20	2.0	1	28	3	11
56	5.0	5.38	6.47	408.6	181.2	136.4	3.20	3.13	4.22	2.0	1	29	3	11
57	4.5	3.47	6.72	407.5	185.4	142.0	3.20	3.60	4.20	2.0	2	2	3	10
58	5.0	5.20	6.40	394.3	166.2	122.3	3.20	2.90	4.22	2.0	2	8	3	10
59	5.0	5.20	6.71	394.3	166.2	122.3	3.20	3.30	4.35	2.0	2	9	3	10
60	5.0	6.03	6.55	386.8	157.9	113.1	3.20	3.00	4.27	2.0	2	10	3	10
61	5.0	6.03	6.65	386.8	157.9	113.1	3.20	3.40	4.40	2.0	2	11	3	10
62	5.0	6.09	6.55	396.7	169.0	124.9	3.20	3.00	4.27	2.0	2	26	3	10
63	5.0	6.09	6.65	396.7	169.0	124.9	3.20	3.40	4.40	2.0	2	27	3	10
64	4.0	5.53	6.86	406.0	181.1	136.7	3.20	3.30	4.35	2.0	2	28	3	6
65	5.0	5.40	6.98	405.3	180.2	135.6	3.20	3.33	4.37	2.0	2	29	3	11
66	5.0	5.78	7.08	404.8	179.3	134.6	3.20	3.40	4.40	2.0	2	30	3	11
67	5.0	6.18	7.22	404.0	176.3	133.6	3.20	3.47	4.40	2.0	2	31	3	11
68	4.5	6.62	6.66	396.2	151.6	104.7	3.20	3.20	4.80	2.0	11	2	3	6
69	4.5	6.48	6.93	407.8	165.0	119.1	3.20	2.50	3.32	2.0	13	8	3	6
70	4.5	6.48	7.24	407.8	165.0	119.1	3.20	2.90	3.45	2.0	13	9	3	6
71	5.5	6.89	7.12	400.5	156.9	110.0	3.20	2.60	3.37	2.0	13	10	3	10
72	5.5	6.89	7.21	400.5	156.9	110.0	3.20	3.00	3.50	2.0	13	11	3	10
73	5.0	5.91	6.92	412.9	170.5	125.1	3.20	2.50	3.32	2.0	13	24	3	10
74	5.0	5.91	7.14	412.9	170.5	125.1	3.20	2.90	3.45	2.0	13	25	3	10
75	5.5	6.41	7.19	405.2	161.0	114.6	3.20	3.17	3.32	2.0	14	8	3	10
76	5.0	6.26	7.15	410.3	166.4	120.6	3.20	3.17	3.32	2.0	14	24	3	10
77	5.0	3.97	7.12	411.7	172.7	127.6	3.20	3.60	3.30	2.0	18	2	3	10
78	4.5	6.12	6.76	399.2	155.6	108.7	3.20	2.90	3.32	2.0	18	8	3	6
79	4.5	6.12	7.07	399.2	155.6	108.7	3.20	3.30	3.45	2.0	18	9	3	6
80	5.5	6.53	6.95	392.1	147.6	99.4	3.20	3.00	3.37	2.0	18	10	3	10
81	5.5	6.53	7.04	392.1	147.6	99.4	3.20	3.40	3.50	2.0	18	11	3	10
82	5.0	5.55	6.75	404.2	161.0	114.7	3.20	2.90	3.32	2.0	18	24	3	10
83	5.0	5.55	6.97	404.2	161.0	114.7	3.20	3.30	3.45	2.0	18	25	3	10
84	4.5	6.12	6.94	399.2	155.6	108.7	3.20	3.03	3.32	2.0	21	8	3	6
85	5.5	6.53	7.13	392.1	147.6	99.4	3.20	3.13	3.37	2.0	21	10	3	10
86	5.5	6.53	7.22	392.1	147.6	99.4	3.20	3.53	3.50	2.0	21	11	3	10
87	5.0	5.55	6.93	404.2	161.0	114.7	3.20	3.03	3.32	2.0	21	24	3	10
88	5.0	5.55	7.15	404.2	161.0	114.7	3.20	3.43	3.45	2.0	21	25	3	10
89	5.0	6.09	6.65	411.5	170.2	125.2	3.20	3.20	4.80	2.0	27	2	3	10
90	5.0	5.61	7.00	424.1	187.2	142.6	3.20	3.07	4.72	2.0	29	2	3	10
91	5.0	5.99	7.10	423.9	185.9	141.3	3.20	3.20	4.80	2.0	30	2	3	10
92	5.0	6.39	7.24	422.6	184.4	139.7	3.20	3.33	4.80	2.0	31	2	3	10

Table II-17

DCC4 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
1	4.5	3.44	6.69	352.6	161.2	115.1	4.80	3.40	4.05	2.0	1	2	1	10
2	5.0	6.01	6.52	336.3	137.6	89.3	4.80	2.80	4.12	2.0	1	10	1	10
3	5.0	6.01	6.61	336.3	137.6	89.3	4.80	3.20	4.25	2.0	1	11	1	10
4	4.5	3.78	7.04	342.2	146.0	98.8	4.80	3.40	3.75	2.0	1	18	1	10
5	4.5	3.78	7.22	342.2	146.0	98.8	4.80	3.47	3.75	2.0	1	21	1	10
6	5.0	4.98	6.34	345.2	149.7	102.9	4.80	2.70	4.07	2.0	1	24	1	11
7	5.0	4.98	6.56	345.2	149.7	102.9	4.80	3.10	4.20	2.0	1	25	1	11
8	4.5	5.00	6.82	349.8	156.9	109.1	4.60	3.10	4.20	2.0	1	28	1	10
9	4.5	5.42	6.92	349.3	156.0	108.4	4.80	3.13	4.22	2.0	1	29	1	10
10	4.5	5.80	7.02	349.0	155.2	107.7	4.80	3.20	4.25	2.0	1	30	1	10
11	4.5	6.20	7.16	348.5	154.4	107.0	4.80	3.27	4.25	2.0	1	31	1	10
12	4.5	3.47	7.19	349.5	160.0	114.2	4.80	3.60	4.20	2.0	2	2	1	10
13	5.0	6.03	7.02	333.0	136.5	88.4	4.80	3.00	4.27	2.0	2	10	1	10
14	5.0	6.03	7.12	333.0	136.5	88.4	4.80	3.40	4.40	2.0	2	11	1	10
15	4.5	5.05	6.83	342.0	148.3	101.9	4.80	2.90	4.22	2.0	2	24	1	10
16	4.5	5.05	7.05	342.0	148.3	101.9	4.80	3.30	4.35	2.0	2	25	1	10
17	5.0	5.88	7.00	340.0	145.3	98.9	4.80	3.00	4.27	2.0	2	26	1	11
18	5.0	5.88	7.10	340.0	145.3	98.9	4.80	3.40	4.40	2.0	2	27	1	11
19	5.0	5.55	7.22	347.6	138.3	88.9	4.80	2.90	3.32	2.0	18	24	1	10
20	5.0	6.09	7.12	354.2	146.3	98.2	4.80	3.20	4.80	2.0	27	2	1	10
21	4.5	3.26	6.67	353.0	178.6	137.1	5.00	3.40	4.05	2.0	1	2	2	11
22	4.5	5.01	6.32	343.8	162.2	119.6	5.00	2.70	4.07	2.0	1	8	2	10
23	4.5	5.01	6.63	343.8	162.2	119.6	5.00	3.10	4.20	2.0	1	9	2	10
24	4.5	5.84	6.48	337.8	154.5	110.9	5.00	2.80	4.12	2.0	1	10	2	10
25	4.5	5.84	6.57	337.8	154.5	110.9	5.00	3.20	4.25	2.0	1	11	2	10
26	4.5	3.78	7.04	344.8	164.1	121.1	5.00	3.40	3.75	2.0	1	18	2	10
27	4.5	3.78	7.22	344.8	164.1	121.1	5.00	3.47	3.75	2.0	1	21	2	10
28	4.5	5.02	6.32	348.1	167.9	125.4	5.00	2.70	4.07	2.0	1	24	2	10
29	4.5	5.02	6.54	348.1	167.9	125.4	5.00	3.10	4.20	2.0	1	25	2	10
30	4.5	5.90	6.48	345.9	164.4	122.1	5.00	2.80	4.12	2.0	1	26	2	10
31	4.5	5.90	6.57	345.9	164.4	122.1	5.00	3.20	4.25	2.0	1	27	2	10
32	4.5	4.81	6.81	353.3	175.7	132.7	5.00	3.10	4.20	2.0	1	28	2	11
33	4.5	5.42	6.92	352.7	174.8	131.7	5.00	3.13	4.22	2.0	1	29	2	10
34	4.5	5.80	7.02	352.4	174.0	130.8	5.00	3.20	4.25	2.0	1	30	2	10
35	4.5	6.20	7.16	351.8	173.1	130.0	5.00	3.27	4.25	2.0	1	31	2	10
36	4.5	3.28	7.17	350.1	177.7	136.5	5.00	3.60	4.20	2.0	2	2	2	11
37	4.5	5.04	6.83	340.9	161.2	118.9	5.00	2.90	4.22	2.0	2	8	2	10
38	4.5	5.04	7.14	340.9	161.2	118.9	5.00	3.30	4.35	2.0	2	9	2	10
39	4.5	5.87	6.96	334.8	153.5	110.2	5.00	3.00	4.27	2.0	2	10	2	10
40	4.5	5.87	7.08	334.8	153.5	110.2	5.00	3.40	4.40	2.0	2	11	2	10
41	4.5	5.05	6.83	345.1	166.9	124.7	5.00	2.90	4.22	2.0	2	24	2	10
42	4.5	5.05	7.05	345.1	166.9	124.7	5.00	3.30	4.35	2.0	2	25	2	10
43	4.5	5.93	6.98	342.9	163.4	121.4	5.00	3.00	4.27	2.0	2	26	2	10
44	4.5	5.93	7.08	342.9	163.4	121.4	5.00	3.40	4.40	2.0	2	27	2	10
45	4.5	5.87	7.08	341.5	146.4	101,3	5.00	3.20	4.80	2.0	11	2	2	10
46	4.5	5.38	7.18	349.7	156.3	111.6	5.00	2.90	3.32	2.0	18	24	2	10
47	4.5	5.93	7.08	354.3	164.1	121.0	5.00	3.20	4.80	2.0	27	2	2	10
48	4.5	3.44	6.22	369.8	186.3	142.5	3.20	3.40	4.05	2.0	1	2	3	10
49	5.0	4.97	5.87	357.6	167.2	123.0	3.20	2.70	4.07	2.0	1	8	3	11
50	5.0	4.97	6.18	357.6	167.2	123.0	3.20	3.10	4.20	2.0	1	9	3	11
51	5.0	6.01	6.05	351.0	158.9	113.8	3.20	2.80	4.12	2.0	1	10	3	10
52	5.0	6.01	6.14	351.0	158.9	113.8	3.20	3.20	4.25	2.0	1	11	3	10
53	4.5	3.78	6.57	358.8	169.9	124.6	3.20	3.40	3.75	2.0	1	18	3	10
54	4.5	3.78	6.75	358.8	169.9	124.6	3.20	3.47	3.75	2.0	1	21	3	10
55	4.5	5.02	5.85	362.2	173.9	129.0	3.20	2.70	4.07	2.0	1	24	3	10
56	4.5	5.02	6.07	362.2	173.9	129.0	3.20	3.10	4.20	2.0	1	25	3	10

Table II-17 (Continued)

DCC4 Collector Assemblies

SUMMARY DATA ON ACCEPTABLE OPTIONS

ASSY	TIN	TWTC	TSS	DTNL	DTL1	DTL2	DURA	EFIM	WETH	MAT	OCP	ICP	ABS	INS
57	5.0	5.86	6.03	359.7	170.0	125.6	3.20	2.80	4.12	2.0	1	26	3	11
58	5.0	5.86	6.12	359.7	170.0	125.6	3.20	3.20	4.25	2.0	1	27	3	11
59	4.5	5.00	6.35	367.9	182.2	137.4	3.20	3.10	4.20	2.0	1	28	3	10
60	4.5	5.42	6.45	367.2	181.2	136.4	3.20	3.13	4.22	2.0	1	29	3	10
61	4.5	5.80	6.55	366.8	180.3	135.4	3.20	3.20	4.25	2.0	1	30	3	10
62	4.5	6.20	6.69	366.1	179.3	134.3	3.20	3.27	4.25	2.0	1	31	3	10
63	4.5	3.47	6.72	366.8	185.4	142.0	3.20	3.60	4.20	2.0	2	2	3	10
64	4.5	5.04	6.36	354.5	166.2	122.3	3.20	2.90	4.22	2.0	2	8	3	10
65	4.5	5.04	6.67	354.5	166.2	122.3	3.20	3.30	4.35	2.0	2	9	3	10
66	4.5	3.81	7.08	355.7	168.8	123.8	3.20	3.60	3.90	2.0	2	18	3	10
67	4.5	5.05	6.36	359.1	172.9	128.3	3.20	2.90	4.22	2.0	2	24	3	10
68	4.5	5.05	6.58	359.1	172.9	128.3	3.20	3.30	4.35	2.0	2	25	3	10
69	4.5	5.93	6.51	356.6	169.0	124.9	3.20	3.00	4.27	2.0	2	26	3	10
70	4.5	5.93	6.61	356.6	169.0	124.9	3.20	3.40	4.40	2.0	2	27	3	10
71	4.5	5.03	6.86	364.8	181.1	136.7	3.20	3.30	4.35	2.0	2	28	3	10
72	4.5	5.45	6.96	364.1	180.2	135.6	3.20	3.33	4.37	2.0	2	29	3	10
73	4.5	5.83	7.06	363.7	179.3	134.6	3.20	3.40	4.40	2.0	2	30	3	10
74	4.5	6.23	7.20	363.0	178.3	133.6	3.20	3.47	4.40	2.0	2	31	3	10
75	5.0	6.03	6.65	356.7	151.6	104.7	3.20	3.20	4.80	2.0	11	2	3	10
76	5.0	6.37	7.00	346.8	136.7	87.5	3.20	3.20	4.50	2.0	11	18	3	10
77	5.0	6.37	7.18	346.8	136.7	87.5	3.20	3.27	4.50	2.0	11	21	3	10
78	5.0	5.90	6.92	366.9	165.0	119.1	3.20	2.50	3.32	2.0	13	8	3	10
79	5.0	5.90	7.23	366.9	165.0	119.1	3.20	2.90	3.45	2.0	13	9	3	10
80	5.0	5.91	6.92	371.4	170.5	125.1	3.20	2.50	3.32	2.0	13	24	3	10
81	5.0	5.91	7.14	371.4	170.5	125.1	3.20	2.90	3.45	2.0	13	25	3	10
82	5.0	6.79	7.08	369.0	167.3	121.7	3.20	2.60	3.37	2.0	13	26	3	10
83	5.0	6.79	7.17	369.0	167.3	121.7	3.20	3.00	3.50	2.0	13	27	3	10
84	5.0	6.25	7.15	364.6	161.0	114.6	3.20	3.17	3.32	2.0	14	8	3	10
85	5.0	6.26	7.15	369.1	166.4	120.6	3.20	3.17	3.32	2.0	14	24	3	10
86	5.0	3.97	7.12	370.7	172.7	127.6	3.20	3.60	3.30	2.0	18	2	3	10
87	5.0	5.54	6.75	359.1	155.6	108.7	3.20	2.90	3.32	2.0	18	8	3	10
88	5.0	5.54	7.06	359.1	155.6	108.7	3.20	3.30	3.45	2.0	18	9	3	10
89	4.5	6.95	6.92	352.9	147.6	99.4	3.20	3.00	3.37	2.0	18	10	3	6
90	4.5	6.95	7.01	352.9	147.6	99.4	3.20	3.40	3.50	2.0	18	11	3	6
91	5.0	5.55	6.75	363.6	161.0	114.7	3.20	2.90	3.32	2.0	18	24	3	10
92	5.0	5.55	6.97	363.6	161.0	114.7	3.20	3.30	3.45	2.0	18	25	3	10
93	5.0	6.43	6.91	361.1	157.9	111.2	3.20	3.00	3.37	2.0	18	26	3	10
94	5.0	6.43	7.00	361.1	157.9	111.2	3.20	3.40	3.50	2.0	18	27	3	10
95	5.0	5.54	6.93	359.1	155.6	108.7	3.20	3.03	3.32	2.0	21	8	3	10
96	5.0	5.54	7.24	359.1	155.6	108.7	3.20	3.43	3.45	2.0	21	9	3	10
97	4.5	6.95	7.10	352.9	147.6	99.4	3.20	3.13	3.37	2.0	21	10	3	6
98	4.5	6.95	7.19	352.9	147.6	99.4	3.20	3.53	3.50	2.0	21	11	3	6
99	5.0	5.55	6.93	363.6	161.0	114.7	3.20	3.03	3.32	2.0	21	24	3	10
100	5.0	5.55	7.15	363.6	161.0	114.7	3.20	3.43	3.45	2.0	21	25	3	10
101	5.0	6.43	7.09	361.1	157.9	111.2	3.20	3.13	3.37	2.0	21	26	3	10
102	5.0	6.43	7.18	361.1	157.9	111.2	3.20	3.53	3.50	2.0	21	27	3	10
103	5.0	6.09	6.65	370.5	170.2	125.2	3.20	3.20	4.80	2.0	27	2	3	10
104	5.0	6.43	7.00	360.0	154.7	107.7	3.20	3.20	4.50	2.0	27	18	3	10
105	5.0	6.43	7.18	360.0	154.7	107.7	3.20	3.27	4.50	2.0	27	21	3	10
106	5.0	5.99	7.10	381.8	185.9	141.3	3.20	3.20	4.80	2.0	30	2	3	10
107	5.0	6.39	7.24	380.7	184.4	139.7	3.20	3.33	4.80	2.0	31	2	3	10
108	4.5	5.84	5.16	319.8	132.8	86.4	2.50	2.80	4.12	2.0	1	10	4	10
109	4.5	5.84	5.25	319.8	132.8	86.4	2.50	3.20	4.25	2.0	1	11	4	10
110	4.5	5.87	5.66	316.7	131.6	85.5	2.50	3.00	4.27	2.0	2	10	4	10
111	4.5	5.87	5.76	316.7	131.6	85.5	2.50	3.40	4.40	2.0	2	11	4	10

Appendix III

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