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INTERNATIONAL ENERGY AGENCY SOLAR HEATING AND COOLING PROGRAM

MODEL TESTING WORKSHOP

June 25-30, 1989
Fort Collins, Colorado

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ACKNOWLEDGEMENT

The following individuals participated in the workshop. The modeling experts are listed with their models. These experts contributed analyses and observations as well as data to the workshop. They also provided written contributions to the workshop report. Bill Ferguson compiled the data, constructed the graphics, and helped produce the report. All those listed participated in reviewing the draft report material.

Bill Beckman -- United States/TRNSYS and F-CHART
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Pierre Bremer -- Switzerland/Observer
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Bill Duff -- United States/Workshop Leader
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1 INTRODUCTION

1.1 REPORT PURPOSE

This report is intended primarily for those who have expertise in both simplified and detailed solar energy systems modeling. It provides descriptions, discussions, analyses, comparisons, graphics, and data that were originated in a June 1989 workshop of most of the world's principal active solar energy systems models and modeling experts.

1.2 BACKGROUND

As early as 1980 International Energy Agency Solar Heating and Cooling Program Task VI Experts saw unexplained phenomena in their experimental work that existing modeling approaches did not satisfactorily predict. The Task Experts began an ad hoc modeling effort to try to understand the relevant physical mechanisms. As a natural extension of these efforts, several computer codes were developed. These codes have been validated against Task VI experimental results and have proven to be accurate robust performance prediction and component selection and sizing tools. To further verify these codes and to disseminate the associated knowledge gained by the Task VI Experts, a workshop was organized. The narrative for the proposal for this workshop is given in Appendix I.

1.3 APPROACH

A six day workshop was held at Colorado State University to accomplish the following objectives:

- To facilitate the upgrading of nationally accepted solar energy design and performance prediction codes based on the collective efforts of Task VI.
- To verify the Task VI codes by comparing their predictions with those obtained from previously verified national codes.

Leading active solar energy system modeling experts from the United States, Germany, Switzerland, Canada, Sweden, and Spain participated in the workshop. These experts were developers, or co-developers, of the models used in the workshop:

ISFH	Germany
G^3	Switzerland
TRNSYS	United States
WATSUN	Canada
MINSUN	Sweden
F-CHART	United States

Each participant sent a description of his model to the other participants three months prior to the workshop.

A pre-workshop case study was sent to the participants two months before the workshop. Experience with this case study helped guide and motivate the choice of discussion issues and the applications, components, concepts, and climates included in the case studies run during the workshop.

During the workshop domestic hot water and industrial process heat case studies were designed by the experts and the case studies run on their codes. Results were then compared, analyzed, and discussed.

The participants also prepared material for the workshop report. The report was reviewed twice by the participants and once by the Solar Heating and Cooling Program Executive Committee.

2 CASE STUDIES

2.1 DOMESTIC HOT WATER (DHW) SYSTEM BENCH MARK SYSTEM APPROACH

The workshop participants established a bench mark domestic hot water system. The bench mark system was formulated to eliminate as many of the differences among models as was practical. For example, the collector was horizontally mounted so as to use the horizontal radiation data directly and therefore bypass the effects of different radiation processors. A set of associated experiments is used to assess the impact on system performance of changing a comprehensive range of parameters one or two at a time. The approach can be used by other modelers to compare their models to the models tested in the workshop.

2.1.1 Bench Mark System -- Initial Base Case:

Experiment 1

Parameter	Value
Collector Area	6 m^2
Collector Tilt	Horizontal
$F'T_A$	.82
$F'U_L$	3.8 W/m^2-K
Collector Flow	.015 l/s-m^2
Collector Capacitance	0. KJ/m^2-K
Incidence Angle Modifier	1
Collector Fluid	50/50 Ethylene glycol (Duffie-Beckman specs)
Pump Power	0
Controls	ideal
Pipe UA	0. KJ/m^2-K
Pipe Capacitance	0. KJ/m^2-K
Pipe Dimensions	26.75 mm outer diameter 1.5 mm thickness
Pipe Length	1 m/m^2 outside x 2 6 m inside x 2
Heat Exchanger	none
Storage Volume	50 l/m^2
Tank Model	Fully Mixed
Aspect Ratio	3 to 1
Insulation Conductance	0.1 W/m-K
Insulation Thickness	0.1 m on the tanks 0.05 m on the pipes
Draw	175 l 6am to 8am 175 l 5pm to 10pm

Mains Temperature	10 °C
Set Temperature	50 °C
Overheat Protection	100 °C
Tempering Valve	included
Auxiliary Tank Volume	175 l
Weather	Miami TMY

2.1.2 Associated Experiments

Experiments 1a through 3 are variations on Experiment 1.

Experiment 1a: Decrease the collector area of Experiment 1 to 3 m^2.

Experiment 1b: Increase the collector area of Experiment 1 to 9 m^2 .

Experiment 2: Increase the collector capacitance in Experiment 1 to 10 KJ/m^2-K.

Experiment 2a: Increase the collector capacitance in Experiment 2 to 10 KJ/m^2-K. Use copper (C = 385 KJ/kg) pipe with an outer diameter of 26.75 mm and a wall thickness of 1.5 mm. Use 0.05 m of pipe insulation having a thermal conductivity of 0.1 w/m-K.

Experiment 3 -- New Base Case: Change the fully mixed tank model of Experiment 1 to a stratified model.

One model, G^3, has a stratified tank model built into it. Therefore, experiments 4 through 15 are made variations on Experiment 3 rather than Experiment 1.

Experiments 4 through 15 are variations on experiment 3.

Experiment 4: Run the same parameter values as Experiment 3 with collector flow rate changed to .003 l/s-m^2.

Experiment 5: Run the same parameter values as Experiment 3 and 4, but use one tank instead of two. Tank volume is 50 l/m^2 + 175, with the upper 175 liters heated with an electrical element. The top 175 liters is a fully mixed area of the tank kept at the set temperature.

Experiment 6: Experiment 3 is run with a) Seattle and b) Albuquerque TMY weather data.

Experiment 7: Experiment 3 is run with collector tilts of a) 25° and b) 45°

Experiment 8: Run Experiment 3 with a detailed collector model.

$$F'\tau_A = 0.82$$
$$F'U_L = 3.50 + .012*T_{fluid} - .006*T_{ambient}$$

where the temperatures are in degrees Celsius.

Experiment 9: Run Experiment 3 with high and low performance collectors.

	a) High	b) Low
$F'T_A$ =	0.72	0.70
$F'U_L$ =	1.70	7.00

Experiment 10: Run Experiment 3 with one 350 liter draw from 4-6:00 AM.

Experiment 11: a) Run Experiment 3 with a 100 W/K-m² external heat exchanger. b) Rerun it with a 50 W/K-m² external heat exchanger.

Experiment 12: Run Experiment 3 with the incident angle modifier profile given below:

Degrees	0	15	30	45	60
IAM	1.00	0.99	0.98	0.94	0.80

Experiment 13: Run Experiment 3 with the delivery temperature set at 80 °C.

Experiment 14: Run Experiment 3 with infinite storage at a temperature of a) 40° and b) 60° C.

Experiment 15: Run Experiment 1 with the following changes:

Collector Capacitance of 10 KJ/m²-K as in Experiment 2
Pipe UL as in Experiment 2a
Pipe Capacitance as in Experiment 2a
Stratified Tank as in Experiment 3
Collector flow rate as in Experiment 4
Climates: a) Seattle, b) Albuquerque, and c) Miami
Collector Tilt equals latitude
Collector equations as in Experiment 8
Heat Exchanger at 100 W/m²-K
Incidence Angle Modifiers as in Experiment 12

Experiment 16: Use Experiment 15 as the base case. Instead of using daily data, calculate the monthly averages and run your program based on these averages.

2.2 INDUSTRIAL PROCESS HEAT (IPH) SYSTEM WITH SERIAL STORAGE

An evacuated tubular collector, a parabolic trough collector oriented E-W and N-S, four collector areas, three climates, and two storage volumes were specified. The performance of each of the 72 process heat system combinations was calculated by ISFH and F-CHART. The performance of the 32 combinations involving the evacuated collector were also calculated and G^3. Four of the ETC combinations were also run by WATSUN. The parabolic trough runs were not made with these two codes because they have not implemented a tracking collector capability. Though TRNSYS has a tracking collector and industrial process heat capability, industrial process heat case TRNSYS runs were not made because it required all the available workshop time to setup and run TRNSYS for the domestic hot water system cases.

2.2.1 Specifications and Variations

- Load: 1500 kWh/day (from 8 to 20 hours, seven days a week), demand temperature 115 °C, return temperature 85 °C. Supplement with auxiliary and mixing valve after the storage.

- Climate: TMY for Seattle, Albuquerque, and Miami.

- ETC: $F'T_A$ = .66, $F'U_L$ = . 7 W/m^2-K (20 C), 1 W/m^2-K (90 C), E-W mounted, inclined at latitude = - 10°. Capacitance 5 KJ/m-K.

  Incidence Angle Modifiers

angle	15°	30°	45°	60°	
IAM	1	1	1	1	(transverse)
IAM	.99	.98	.94	.80	(axial)

- PTC: $F'T_A$ = .72 (beam only), $F'U_L$ = .26+3.1E-3*DT, One axis tracking. Two cases: 1) E-W mounted and 2) N-S inclined to latitude. Capacitance 2 KJ/m^2-K.

  Incidence Angle Modifiers

angle	7.5°	22.5°	37.5°	52.5°	67.5°
IAM	1.0	.99	.96	.88	.65

- Storage: 1) 50 m^3 and 2) 100 m^3, aspect ratio 3:1, Insulation thickness 0.2 m, stratified, conductance .08 W/m-K. Maximum temperature 135 °C. Surrounding temperature equals ambient temperature.

- Piping: 2*120 m (to collectors), 60 m/200 m^2 for the ETC, and 2*5 m/200 m^2 for the PTC. All losses are to the outside ambient. Flow velocities 2 m/s in the main piping, and 1 m/s in the loops. Insulation thickness .06 m, conductance 0.06 W/m-K.

- Flow rate in collectors: 30 l/m^2 for both collector types. The storage flow is also 30 l/m^2.

- Heat Exchanger: 50 W/K-m^2.

- Collector Area Range: 400-1000 m^2, in steps of 200 m^2.

3. RESULTS

3.1. REPORT GRAPHICS AND DATA

Solar energy incident on the collector aperture, solar energy delivered to the solar storage Q102, and auxiliary energy, including parasitics, QAUX for each month of the year is reported from all model runs. This data is assembled onto a LOTUS 123 spread sheet and then presented in several different ways graphically. The graphs are provided in Appendix III. All figure number references in this report that do not have a section prefix are to figures in that Appendix. A diskette with the LOTUS 123 and ASCII files is also included with this report. The graphical presentation of the data is as follows:

- Line plots of the solar energy incident on the collector aperture versus months and year for all models - one plot for each city and each experiment where the collector tilt is different. (Figures 1, 10, 12, 14, 16, 28, 30, 32, 86 through 94, 108, 117, 126, 135, 140, and 145)

- Line plots of solar energy delivered to the solar storage Q102 and auxiliary energy, including parasitics, QAUX versus months and year for all models - one plot for each experiment. (Figures 2 through 9, 11, 13, 15, 17 through 27, 29, 31, 33, 109 through 116, 118 through 125, 127 through 134, 136 through 139, 141 through 144, and 146 through 149)

- Line plots of the solar energy incident on the collector, energy delivered to storage, and auxiliary energy for real daily data and synthetic daily data derived from monthly data - one plot for each climate and model. (Figures 34 through 36)

- One bar plot per experiment of the sum of the absolute value of each model's monthly predictions of Q102 versus the TRNSYS predictions. (Figures 37 through 57)

- One bar plot per experiment of the sum of the absolute value of each model's monthly predictions of QAUX versus the TRNSYS predictions. (Figures 37 through 57)

- One bar plot per experiment of the sum of the absolute value of each model's monthly predictions of Q102 less that of TRNSYS minus the monthly average predictions of Q102 less that of TRNSYS. (Figures 37 through 57)

- One bar plot per experiment of the sum of the absolute value of each model's monthly predictions of QAUX less that of TRNSYS minus the monthly average predictions of QAUX less that of TRNSYS. (Figures 37 through 57)

- One bar plot per experiment and model of the ratio of annual Q102 to user demand. (Grouped by Experiment - Figures 58 through 62 and Grouped by Model - Figures 96 through 101)

- One line plot per model and city of solar radiation on the collector aperture H100, Q102+QAUX, user demand, Q102 versus months. This plot uses

- One line plot per model and city of solar radiation on the collector aperture H100, Q102+QAUX, user demand, Q102 versus months. This plot uses Experiments 1 (Miami), 6a (Albuquerque) and 6b (Seattle). (Figures 68 through 85)

- One bar plot per experiment and model of the ratio of annual QAUX to user demand. (Grouped by Experiment - Figures 63 through 67 and Grouped by Model - Figures 102 through 107)

- One line plot per model and city of solar radiation on the collector aperture H100, Q102+QAUX, user demand, Q102 versus months. This plot uses Experiments 1 (Miami), 6a (Albuquerque) and 6b (Seattle). (Figures 68 through 85)

- One line plot per model of the ratio of monthly radiation on tilt variations of 25° and 45° in experiments 7a and 7b to that on the horizontal in experiment 1 versus months and year. (Figures 86 through 89)

- One line plot per model of the ratio of monthly radiation on the tilt equal latitude collector surface in experiments 15a, b, and c to that on horizontal in Experiments 1 and 6a, and b (Miami, Seattle, and Albuquerque) versus months and year. (Figures 90 through 94)

3.2 DHW CASE STUDY

As can be seen in Table 1, most of the DHW experiments address one technical issue at a time, relative to the base case. Differences among models

Table 1. Technical Issues Addressed by Each Experiment

Issues	Case																
	1	2	2a	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Collector Area	x																
Collector Cap.		x	x													x	
Pipe Capacitance			x													x	
Tank Stratification				x	x	x										x	
Collector Flow Rate					x	x										x	
Tank Volume						x											
Climate							x									x	
Collector Tilt								x								x	
Col. Temp. Dependance									x							x	
Collector Performance											x						
Draw Timing											x						
Heat Exchanger												x				x	
IAM													x			x	
Delivery Set Temp.														x			
Constant Inlet Temp.															x		
Synthetic Weather Data																	x

were greatest for collector areas, tank stratification, high insolation climates, constant inlet temperature/ infinite storages, and combinations of effects. (Figures 4, 8, 13, 27, and 29) Differences among model results were the least for small collector areas, large collector and pipe capacitance, cloudy climates, detailed collector models, high performance collectors, and higher delivery temperatures. (Figures 3, 5, 11, 18, 19, and 25)

Two model comparison issues were explored: 1) How accurately does a model predict the monthly energy delivered to storage or auxiliary energy used and 2) Once the accuracy bias is removed and the prediction shifted by the amount of the bias, how precisely does a model track actual monthly performance?

Accuracy and precision for each model were calculated by using TRNSYS results as the bench mark. TRNSYS is the best choice for a bench mark. However, TRNSYS is not a perfect bench mark for, as noted below, it is prone to certain types of identifiable errors. Nevertheless, TRNSYS has been extensively validated against other detailed models and to a lesser extent against real data. It was also identified as the validation bench mark in the workshop proposal.

Prediction accuracy for each experiment was measured by summing the absolute values of each model's monthly predictions less the TRNSYS predictions:

Prediction Accuracy = Σ_{months} | model prediction - TRNSYS prediction |.

For energy delivered to storage over all of the DHW experiments the accuracy ranged from

25 to 270 MJ/month	ISFH
20 to 280 MJ/month	G^3
10 to 570 MJ/month	WATSUN
70 to 730 MJ/month	F-CHART
70 to 440 MJ/month	MINSUN

The Task VI models by and large had prediction accuracies in the favorable part of these ranges. Average monthly accuracies of ISFH and G^3 for solar energy delivery to storage and for auxiliary energy are usually within one hundred MJ of TRNSYS. (Figures 37 through 57)

Prediction precision for each experiment was measured by summing the absolute values of the difference between each model's monthly predictions less the TRNSYS predictions and less the average value of the difference between each model's monthly predictions and the TRNSYS predictions:

Prediction Precision = Σ_{months} | model prediction - TRNSYS prediction - average monthly (model prediction - TRNSYS prediction) |.

The precision measure shifts each model's monthly performance curves so that their average performance is the same as that of TRNSYS. For energy delivered to storage over all of the DHW experiments the precision ranged from:

15 to 190 MJ/month	ISFH
10 to 110 MJ/month	G^3
5 to 270 MJ/month	WATSUN
40 to 170 MJ/month	F-CHART
50 to 170 MJ/month	MINSUN

The Task VI models by and large had prediction precisions in the favorable portion of these ranges. Average monthly precisions of ISFH and G^3 for solar energy delivery to storage and for auxiliary energy are usually within fifty MJ of TRNSYS. (Figures 37 through 57)

Anomalies in TRNSYS performance showed up in experiment 5, 10, 15B and possibly 6A. (Figures 9, 11, 21, and 31) Collector capacitance was not incorporated into the TRNSYS runs for experiment 15. It is possible that inappropriate choices of controller "stickiness", time step, or "maximum number of iterations" caused some of the incorrect results. The root causes for the above-mentioned discrepancies have not been determined. Experiments 2, 2A, and 14, involving collector and piping capacitance and constant temperature storage, were not run by TRNSYS because new subroutines would have to have been created. Of the remaining DHW system runs performed, the results obtained through TRNSYS were similar to those obtained by a number of the other programs.

ISFH and G^3 give results that are close to each other in most of the experiments. They also give results that are close to TRNSYS in most of the experiments.

Dumping of energy occurs in the DHW experiments for Albuquerque. F-CHART differs from most of the programs in that when a storage tank over temperature condition occurs it dumps energy from the collector loop, rather than dumping it from the tank. This difference is apparent when the F-CHART energy delivered to storage is compared with that of the other models in runs where substantial energy is dumped. (Figure 13) G^3 also apparently dumps energy from the collector loop as can be seen more clearly in the IPH results.

Overall WATSUN over predicted as compared to ISFH and G^3, though it often produced results close to those of TRNSYS. The differences show up with the radiation processor. (Figure 28) WATSUN seems to over predict radiation by about seven percent. This may be due to the diffuse model used. Over prediction also shows up for low flow rates in stratified tanks. (Figure 8) Over prediction here may be due to the assumption of perfect stratification. TRNSYS, whose performance is closest to WATSUN uses a similar tank model.

3.3. INDUSTRIAL PROCESS HEAT SYSTEM

There were differences in modeling time, both for the input process and calculations. Once set up, ISFH, G^3, and F-CHART all performed the calculations rapidly. ISFH was the first to finish calculations for the initial sixty IPH systems.

The influence of storage volume in the IPH system was investigated using ISFH, G^3, WATSUN, and F-CHART. The trend of the three programs is very similar, except for the larger collector areas for G^3 and F-CHART in Albuquerque and, for F-CHART, in Miami. (Figures 105 through 131) With collector area of 600 m^2 or less the performance is, for all practical purposes, identical for both tanks. Thus, comparisons can be made below 600 m^2 of collector area without considering storage volume.

For the ETC systems in Miami, ISFH and G^3 performance predictions are generally within a few percent of each other, whereas WATSUN values are higher and F-CHART values lower by about fifteen percent. For Seattle conditions F-CHART and ISFH agree well, whereas G^3 is higher by five to ten percent. For Albuquerque conditions G^3 values are ten percent higher than ISFH and F-CHART values are ten percent lower. In all cases F-CHART shows the lowest performance, with ISFH nearly always intermediate between F-CHART and G^3.

ISFH and F-CHART were the only programs to perform the parabolic trough collector calculations. WATSUN and G^3 did not make these runs, since they did not have tracking methods in their program. No TRNSYS IPH runs were made because TRNSYS needed the entire week to make the DHW runs. Thus, only a limited comparison of the different models is possible. (Figures 132 through 146) For larger collector areas, F-Chart shows anomalous behavior partly due to rejection of energy in the collector loop rather than from the tank as was specified in the case study. This can be seen in figures 139 through 141, (Figures 139 through 141, 145, and 146.

3.4 GENERAL

TRNSYS proved a cumbersome program to use in a setting such as this workshop. TRNSYS has the greatest flexibility of any of the models, but the price of this flexibility is a much greater possibility of introducing errors when configuring a system for simulation. Some of the assumptions made in the base case of the DHW system, such as zero pipe capacitance, initially caused either numerical errors, such as "divide by zero", or convergence errors. Consequently, considerable time was spent debugging the DHW simulation deck. Due to the detailed nature of the simulation, each run took approximately 15-20 minutes. A simplified method of inputing simulation deck information could reduce the amount of time needed to eliminate errors in the specification of the deck. Simplifying the input method while retaining the current full flexibility has been found to be a complicated undertaking.

WATSUN gives results similar to TRNSYS in most cases, It is also considerably easier to use. WATSUN has more flexibility than F-CHART, but runs more slowly than F-CHART

There were differences in the radiation processors of the various models. (Figure 28) ISFH shows an under prediction since radiation values for ISFH exclude incidence angle modifiers. Therefore, ISFH values are lower in the radiation plots. Since incidence angles are accounted for later on, there is no error in other computations.

Small differences show up in the F-CHART plots of radiation on the horizontal. (Figure 1) This is due to the fact that the built-in weather data was used rather than the TMY data that was supplied.

The MINSUN program was written for large scale seasonal storage systems. Its use to simulate DHW systems is limited as the daily time step in the system simulation is too large, especially when specifying a daily collector flow that is larger than the tank volume, as was the case for all the DHW experiments. Also, only indoor or buried piping can be specified in MINSUN. Thus, DHW experiment results may be effected, though IPH systems should give reliable results.

ISFH is specifically structured to allow fast multiple runs for many of the parameters. Some of the other programs, such as MINSUN, also have provisions for making multiple runs easily.

F-CHART was developed before the general availabilit of personal computers. Its initial purpose was to provide estimates of solar energy system performance using pencil and paper. As a result it is overly simplified for today's powerful microcomputer environment. In spite of the limitations of the F-CHART method, the F-CHART results compare favorably with the other, more detailed, programs.

One major deficiency in the F-CHART method is the use of a fully mixed storage tank. A fully mixed tank leads to conservative estimates of auxiliary energy requirements.

4 OTHER PRINCIPAL RESULTS

4.1 IMPROVEMENTS MADE IN EACH MODEL AS A RESULT OF THIS WORKSHOP

This section is a compilation of workshop participant contributions.

4.1.1 In preparation for the workshop:

A simple solar collector component capable of handling a non-standard equation for $F'U_L$ was developed for TRNSYS. While this component will not become a part of the standard library of TRNSYS routines, the pre-workshop case pointed out the need for additional flexibility in the standard solar collector model. Additionally, the pre-workshop case suggested a modification in the standard pump component to allow for the transfer of a given fraction of the pump power to the fluid.

A large number of runs were required in preparing the pre-workshop case study. Consequently, a new "file read" option was added to F-CHART so that all runs could be set-up in a single file. The output was directed to an output file for later viewing or printing. Although the pre-workshop study is not the usual way that F-CHART is used, this new "file read" option should prove useful to some users.

During the preparation of the workshop it turned out that the installation instruction (READ.ME file) in MINSUN was not complete even for a computer expert. Also the first test runs caused problems due to the fact that files have to be copied and deleted manually before the program runs without error messages.

While preparing for the workshop it turned out that the second order heat loss term in the MINSUN program was defined according to the old assumption $(DT/I)^2$ instead of $(DT)^2/I$. This has only a minor influence on previous investigations as the second order term seldom has been used. During the workshop no second order heat loss term was used so the program could be used without changes.

The pre-workshop case study specified that only a portion of the power be added to the fluid, T_{co} dead band control, some of the piping inside and some outside the building, and a three parameter F_RU_L model. These features were added to WATSUN.

4.1.2 During the workshop:

WATSUN required cumbersome calculations of wall area for input when tank sizes were changed. In order to allow the program to make these calculations, the input format was changed to include the aspect ratio and a shape factor for the floor. WATSUN had not previously included tracking. Two-axis tracking and vertical axis azimuth tracking were both added during the workshop.

4.1.3 As a result of the workshop:

Only stratified tanks were possible in ISFH. This was changed to include fully mixed tanks.

The G^3-model has been used in Switzerland without any change for almost 2 years. Further improvements in the G^3 Program are foreseen, but in close cooperation with interested users of the in Switzerland and elsewhere.

In collaboration with other modelers TRNSYS plans to exchange methods of modeling specific components with the aim of improving both programs. We would welcome this type of collaboration with other modelers. Additionally, serious consideration will be given to improved methods of specifying information for TRNSYS simulation decks, with the aim of reducing user errors.

TRNSYS and WATSUN are exchanging codes. WATSUN desires to exchange code or compiled modules with others and to receive well monitored data for solar installations (radiation - beam, diffuse on the plane, ambient temperature, load, system description, as described in the format of the TMY data sent by Colorado State University). There is a definite need for exchange of algorithms and the mathematical models used in different programs since some of the programs contain very advanced models of specific components.

WATSUN has incorporated general one axis tracking with the axis in the plane of the collector. The weather processing code was substantially modified to allow these trackers to work well. Equations from a 1983 paper by Braun and Mitchell were used.

A number a new features were also added to the WATSUN economic analysis code.

The main problem while using MINSUN during the workshop was that a collector tilt = 0 always is changed to latitude tilt in the program without notice. (probably to avoid mathematical problems). This caused a lot of extra work as most of the basic cases were designed for horizontal collector to separate the influence of different radiation processors. The problem was discovered first when comparing data after the second day. This problem could be easily solved by using Tilt = 0.1 instead of 0. Therefore no change in the MINSUN code was necessary during the workshop. While analyzing the results it turned out that the system chosen for comparison was very sensitive to the simulation of the pipe losses (large pipe diameter). MINSUN can only simulate collector piping indoors or buried in ground (not outdoors as specified here).

4.2 DISCUSSION OF INCIDENCE ANGLE MODIFIER CALCULATIONS

Incidence angle modifiers for asymmetric collectors are currently calculated by taking the product of the incident angle modifiers in the two coordinate directions. The sparse literature on incidence angle modifiers supports using this approach. However, the product of incidence angle modifiers in the two coordinate directions of a symmetric collector does not yield the obvious result of directly using the incidence angle to calculate the incidence angle modifier. It was suggested that the correct result can be obtained by the use of spherical geometric relations. This issue should be addressed and resolved prior to any future modeling workshop.

4.3 COMMUNICATIONS NETWORK

It was recommended that a communication network be set up among workshop participants. As first step, BITNET addresses were exchanged.

5 SUMMARY AND CONCLUSIONS

The following are the significant findings of this workshop:

- o The Task VI models, ISFH and G^3, consistently had prediction accuracies and precisions that were comparable to the previously validated detailed model TRNSYS
- o Task VI models could be set up and run very rapidly
- o Task VI models provide considerable flexibility in the number of different system that can be run
- o Most of the TRNSYS DHW results were similar to those of a number of other programs.
- o Occasional instabilities in TRNSYS caused prediction errors. The root causes for these instabilities have not been determined.
- o The previously validated detailed model TRNSYS was more flexible in regard to the variety of systems that could be handled
- o TRNSYS could be improved in the areas of user input and debugging
- o The workshop activity resulted in significant improvements to most of the models.

6 RECOMMENDATIONS

6.1 RECOMMENDATION FOR A SECOND WORKSHOP

The participants made recommendations for activities which they felt would strengthen the models of their national programs and further the state-of-the-art of modeling in general. Specifically, a second workshop should be scheduled for the Summer of 1990. Most of the case studies would be designed and run throughout the six months preceding the workshop because of the following issues brought up in this Summer's workshop:

- the detailed models required much lengthier input preparation and debugging
- the group would like to evaluate a more ambitious set of case studies than could be run in one week
- it is sometimes desireable to carry out modifications to improve a model as a case study is conducted

Included in the arrangements would be procedures for exchanging information and designing and running case studies prior to the workshop itself.

The workshop and preparatory activities would be designed to achieve the following goals:

- It seems apparent that there is a connection between daily energy input/output curves and the utilizability approach. This issue would be investigated.
- Very rapid and accurate sizing and optimization capabilities of Task VI mathematical compression approaches for specific systems have been demonstrated.
  - Further studies would be undertaken to establish the statistical and scientific basis for this procedure.
  - Economic/energy optimizations using all the models would be performed.
- Daily energy input/output concepts can improve the performance and/or efficiency of the design tools that do not currently use them. These concepts would be incorporated into these models.
- Many of the workshop models now incorporate tracking as well as non-tracking collectors. Tracking system performance would be compared with that of non-tracking systems.
- Daily energy input/output curves have uses in performance reporting, performance prediction, short term testing activities, and system diagnostics. Such uses would be further defined and delineated.

- Component models and computational refinements, such as tank stratification representations and evacuated collector performance prediction routines, have been developed by the Task and by other researchers. These advances can be incorporated into all of the models.

- Commonalities in model input and output structure would aid information transfer among modeling groups. Commonalities will be established and exploited when practical.

- Data and model exchanges can improve everyone's capabilities. These have been started and will continue.

- Some models incorporate photovoltaic performance modules. Use of these modules will be explored.

7 OTHER DISCUSSIONS AND RESULTS

7.1 PRE-WORKSHOP CASE STUDY

The pre-workshop case study is presented and participant results and observations are given in Appendix II. Though the pre-workshop case study provided good guidance and motivation for subsequent workshop work, the results were not useful for comparisons due to the complexity of the case and variety of interpretations taken by the participants.

7.2 REAL DATA CASE STUDY

A real data case study was prepared for the workshop. However, there was not enough time to conduct this exercise, a two tank variable volume storage with isothermal delivery from the collectors. Many of the models would have to be changed to address that system and, though the system could have been directly implemented on TRNSYS, the additional work that would be needed for everyone would have precluded more important workshop activities. Several of the models would also have required more data than was available.

7.3 CODE CONSISTENCY EXPERIMENT

Compute the elasticity of a given energy quantity by plotting dQ/Q versus dP/P. Use parameters such as F'TA, $F'U_L$, collector capacitance, heat exchanger effectiveness, etc. Use experiment #15. The consistency experiment was not done due to lack of time.

Quantity	P	dP
$F'T_A$	0.82	-0.05
$F'U_L$	3.80 W/m²-K	-.40 W/m²-K
Col. Cap.	10	+2
Pipe Insulation	0.50	-0.025
Pipe Diameter	26.75 mm	+5.00 mm
Storage Insulation	0.10 m	-0.02
Heat Exchanger	100 W/m²-K	-20 W/m²-K

7.4 DAILY ENERGY INPUT/OUTPUT RELATIONSHIPS AND UTILIZABILITY

The relationship between daily energy input/output analyses and utilizability was discussed. The use of daily energy input/output curves come from the practical experience of systems experimentation within the International Energy Agency Solar Heating and Cooling Program Task VI.

For most solar heating systems from DHW to large seasonal storage systems measured daily collector array output and energy delivered to storage is a very nearly linear function of daily insolation on the collector plane. The nearly linear relationship is also valid for monthly values. During the workshop some participants used this relationship to check and compare their calculations.

All of the models show a near linear relationship for their monthly predictions with an intercept near the origin. This may be expected for DHW systems since the operating time and operating temperature differences, and hence heat losses, decrease in parallel with the insolation. This can be seen when the Albuquerque monthly data are used to draw a monthly energy/input output line. The winter months provide low insolation values and the summer months, high values. (Figures 12 and 13) For Miami, though the seasonal variation in solar radiation is much less pronounced, the linear relationship based on monthly values is no less apparent. (Figures 1 and 7)

A change in system type with identical collector array characteristics will shift the monthly relationship. With a change in a constant collection system inlet temperatures from 40°C to 60°C, the linear function's intercept is not so near origin and the slope is less. (Figures 1, 26, and 27) This also corresponds to measured data from district heating systems in IEA Task VI.

It has been shown that the absorbed daily energy in the collector array is almost exactly linearly dependent on the daily insolation. For energy collected, daily energy losses, including capacitance effects, must be subtracted from the absorbed energy. The lower the daily heat losses, the less the spread between the daily energy input/output curves.

In the most simple cases the daily heat losses are independent of the daily irradiation. A district heating system approaches this ideal. This would yield a slope of the daily energy input/output function that is approximately the daily optical efficiency of the collector, with the daily average incidence angle effect taken into account. The offset on the abscissa is approximately the daily heat losses divided by the daily optical efficiency. (Figures 1, 26, and 27)

For a real system the daily heat losses, and to some extent daily optical efficiency, will vary with daily insolation. For a DHW system the heat losses will vary almost linearly with daily insolation. This gives a monthly input/output relationship that goes almost through the origin with a small offset depending on the difference between ambient temperature and the mains water temperature. (Figures 12 and 13 and 1 and 7)

Both these relations work because of the simple energy balance presented above. The input/output method originates from practical experiments whereas the utilizability method comes from theoretical analyses of solar systems and climate analyses. The difficulty is to model the daily energy losses in a simplified way.

The workshop participants would have liked to have more clearly related the two methods. This would be of great value for the understanding of both methods. Due to lack of time this could not be done.

7.5 TOPICS FOR FUTURE WORKSHOPS

The workshop participants have recommended that a second workshop be held next year. Substantial pre-workshop exchanges would be conducted by electronic mail and FAX. A International Energy Agency sponsored sequence of workshops or a modeling task would provide enormous benefits to all participants. A list of topics for examination in future workshops is given Table 2.

Table 2 Topics for Future Workshops

Testing the Modeling of Hardware Components

- Large area collectors
- Optical and thermal properties of advanced flat plate collectors with convection suppression*
- Evacuated collectors with reflectors
- Internal CPC collectors*
- Microflow piping
- Internal heat exchangers*
- Air collectors
- Dual tank variable volume storage*

Testing Software Components

- Radiation processors*

Achieving Greater Commonality Among Codes

- Common front end for all codes
- Common supplied data sets, such as TMY climates and hot water usage profiles.*
- Increased commonality in input, output, graphics, and definitions

Code Refinements

- Refinements to improve robustness*
- Refinements to improve consistency*
- Integration of component models from other participant's codes*
- Integration of other non-active-thermal solar models

Functional Concepts

- Low flow*
- Constant temperature collection*
- Stratification enhancement*
- Control strategies*

Applications

- Industrial process heating*
- Space heating
- Individual family DHW*
- Multifamily and commercial DHW*
- Ventilation air heating
- Swimming pools

Issues

- o Experimental results versus modeling predictions -- validation against real data*
- o The effect of climate on performance*
- o Collector performance characterization*
- o Collection system capacitance*
- o Testing the effectiveness of the codes for design and optimization
- o Optimization of real systems to account for practical considerations such as shading, obstructions, different micro climates, incomplete climate data, etc.
- o Expert system solar energy system designer
- o Analyses and test to determine model limitations*
- o Tests to determine robustness*
- o Tests to determine consistency*
- o Sensitivity analysis*
- o Code consistency analyses*

Exchanges

- o Exchange of component models and ideas*
- o Exchange of models as negotiated between the participants (source codes or executable versions)*
- o Establish a collective of expertise that is durable

Dissemination

- o Microcomputer based solar building energy educational workshops

Further System Modeling

- o Modeler interactions*
- o Programmer interactions
- o Discuss algorithms and methods*
- o User and programmer interactions/needs
- o A flexible modeling environment
- o Expert system front end to prepare input to all models, select appropriate models for the problem, and access data bases of climate and available components

The *ed items are ones that were determined to be especially important.

An electronic workshop might be considered where participants would BITNET or FAX input and results.

8 PARTICIPANT ANALYSES OF WORKSHOP OUTCOMES

This section consists of material contributed by each participant. Only minor editing changes have been made.

8.1 ISFH

Three different collector systems were investigated in the course of the workshop, i. e. two DHW systems (including the pre-workshop case) and an IPH system. The pre-workshop case (DHW system with both FPC and ETC) was distributed early in 1989. With this, a special (rather unrealistic) system design was chosen (low optical efficiencies, high capacitances, etc.) in order to investigate the limitations of the different models. However, due to mailing problems and travel, some participants did not receive the messages in time and there were furthermore some misinterpretations. The results of the pre-workshop case studies were hence only comparable in a very limited way. The participants felt furthermore, that the modeling should start from very simple systems (horizontally mounted collector with both fully mixed solar and hot water tank, no piping nor heat exchanger), and additional features should be investigated only afterwards. Thus a new base case (DHW system, Miami, selective flat plate collectors, two storage tanks , demand 59 MJ/d) was defined.

The F-CHART operator was available only for a limited time, thus some results were missing. MINSUN was developed primarily for systems with very large (seasonal) storage tanks, thus it was not applicable for all investigations. The remaining models were hence G^3, ISFH, TRNSYS, and WATSUN.

TRNSYS is the most widely spread, accepted, and validated of those models. Furthermore, by its inherent structure, it shows the highest flexibility, as new features may be modeled by the operator himself by writing the respective codes. Thus TRNSYS was intended to act as landmark for the other programmes. However, it revealed shortly, that both input procedure and calculation time were too long for such a "Modeling Race", so that only a few calculations could be performed in time. It showed furthermore, that the input structure of TRNSYS is so complex, that with a hurry even the related experts could easily perform some mistakes and that the results had to be corrected repeatedly. Thus the suitability of TRNSYS was somewhat restricted.

Examples are given in figs. 8.1 ... 8.5. The results may be comprised in the following way:

- o the different programmes may be best compared in proceeding from a very simple base case to complex systems by adding successively new features and investigating the respective effects
- o it is impossible to validate this procedure by experiments
- o validation by experiments is only possible in a few cases with particular experiments

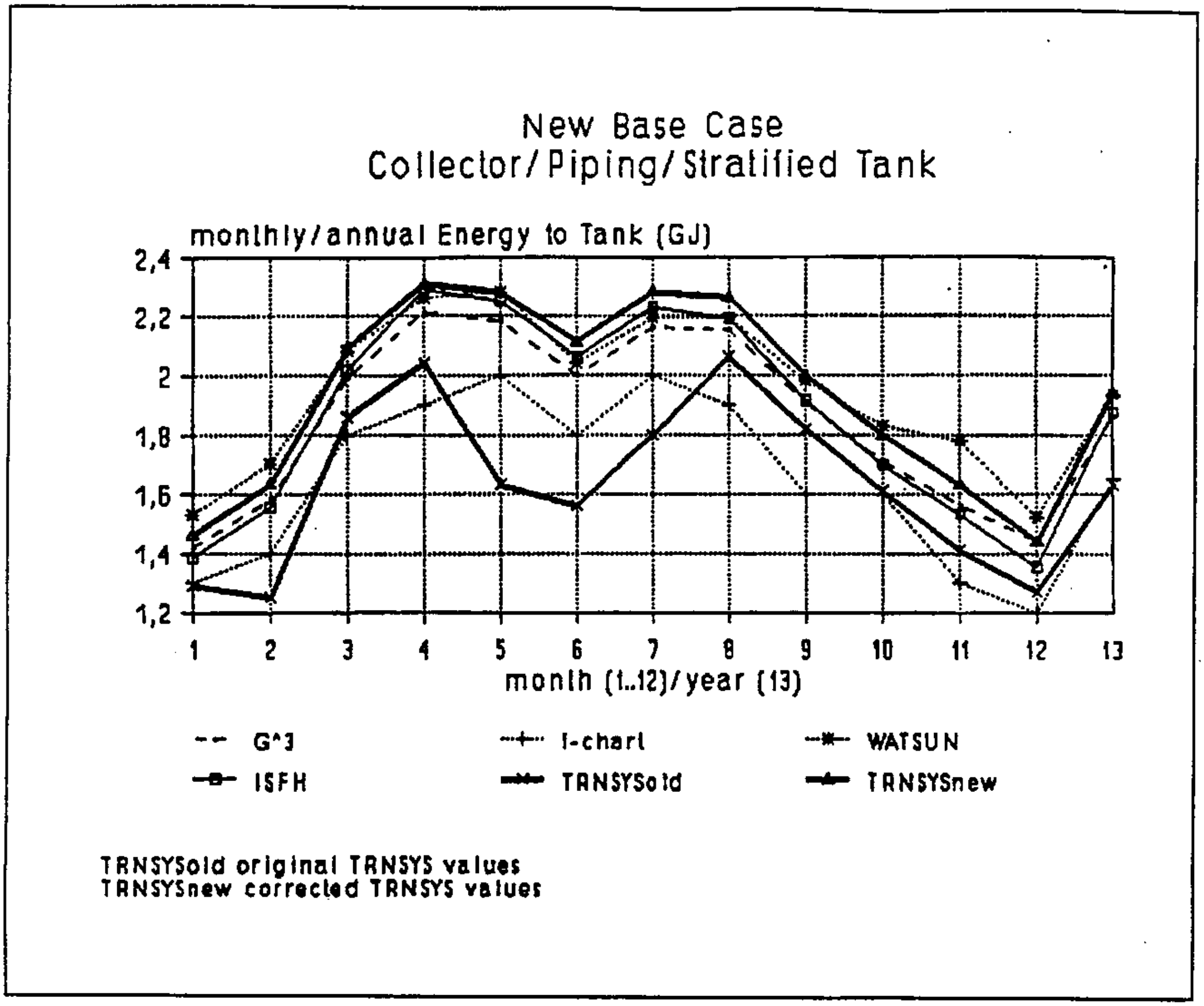


Fig 8.1 New Base Case: Monthly/Annual Output of the Collector System (Miami Weather Data)

- o an accurate, well and widely validated simulation model is best suited as validation tool
- o TRNSYS has to be given a prolonged time to treat the respective problems
- o the results of the European programmes (G^3 and ISFH) agreed excellently, whereas the WATSUN results showed some typical deviations; this effect is especially marked with experiment 15, where all the a. m. features are considered (figs. 9.3 .. 9.5); however, due to the few TRNSYS runs and the restricted significance of the respective results , it was impossible to judge which one was wrong.

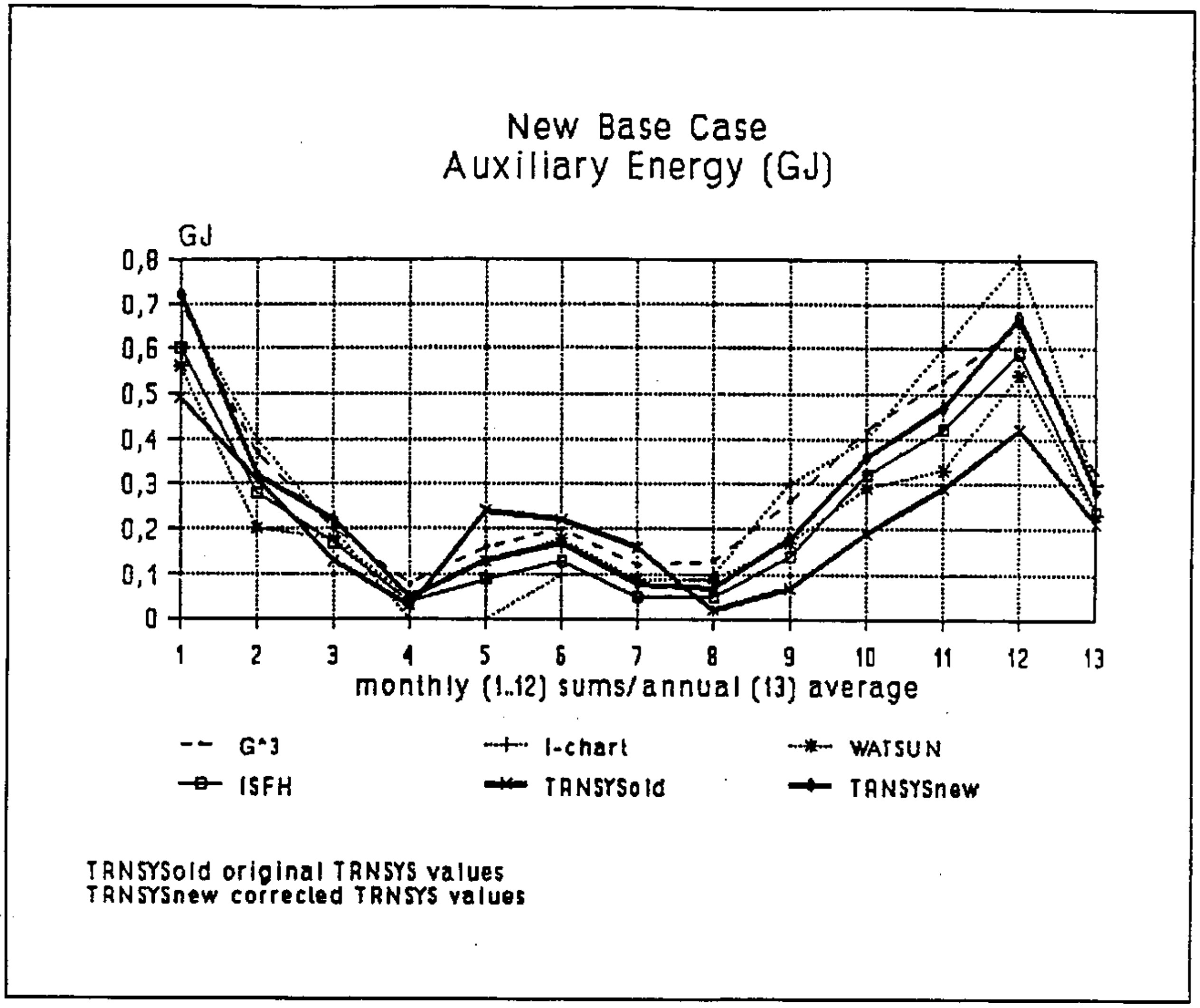


Fig. 8.2 New Base Case: Auxiliary Energy (Miami Weather Data)

Within the discussion of the results it was pointed out, that the (constant) cold water inlet temperature of 10 °C is surely not realistic for Miami; the inlet temperature should rather conform to the mean annual ambient temperature, which is approximately 22 °C. Thus, during operation, the cold water was usually preheated and the effects of an increased piping and/or collector capacitance could only incompletely established.

The next case was an industrial process heat installation with a demand of 1500 kWh/day temperatures 115/85 °C). Both ETC and PTC (these last ones either East-West mounted, altitudinally tracked, or North-South mounted, inclined to latitude, azimuthally tracked) with areas of up to 1000 m² should be combined with a storage tank (either 50 m^3 or 100 m^3) to meet the demand. The piping

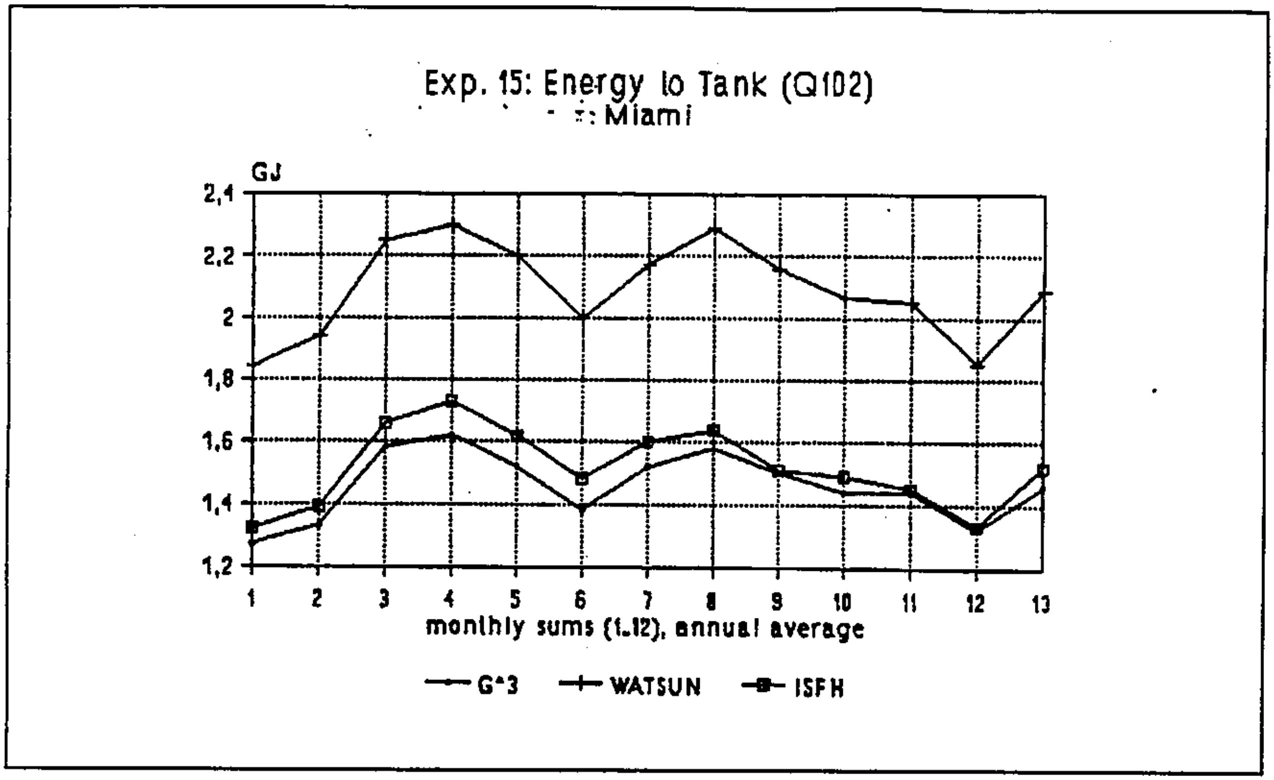


Fig 8.3 Experiment 15: Energy to Tank (Miami)

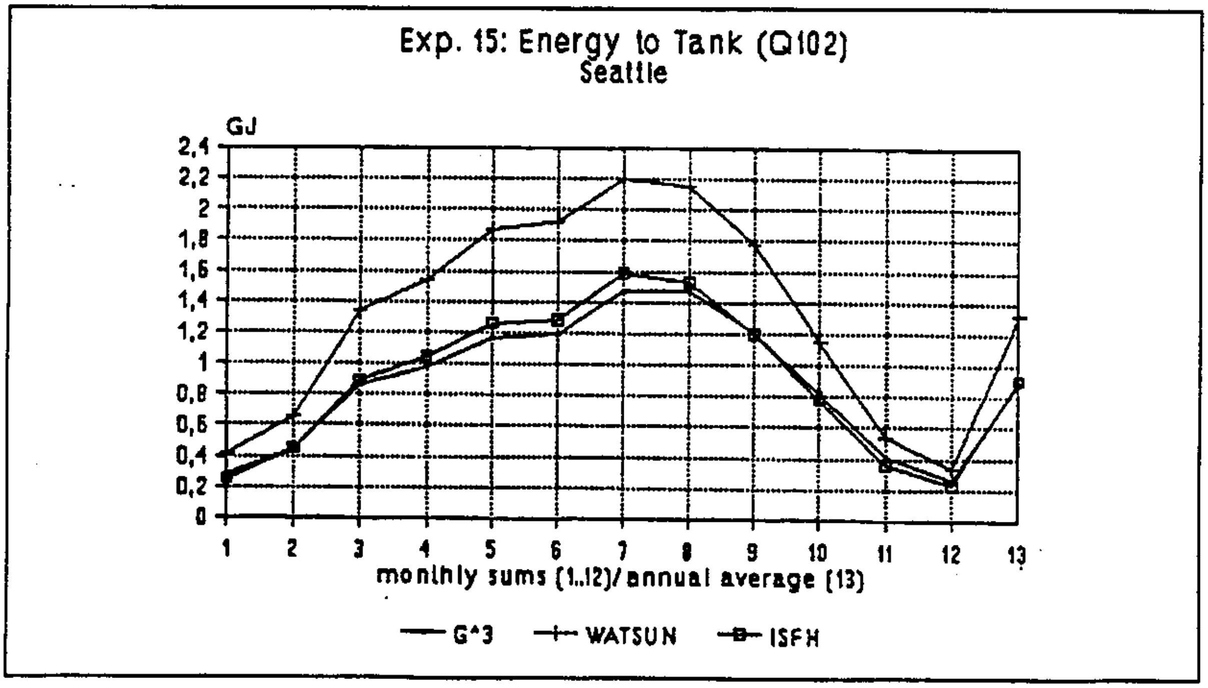


Fig 8.4 Experiment 15: Energy to Tank (Seattle)

consisted of 2*160 m to the field and the interconnecting pipes of the loops.

These investigations revealed substantial differences as to the operation time both for input procedure and calculation. ISFH was by far the quickest method, finishing first in completing 60 different calculations, i. e. the ETC installations with both 50 m^3 and 100 m^3 storage tank, and the two PTC (E/W and N/S mounted) ones with 50 m^3 storage tank (the calculation of the PTC systems with 100 m^3 tank was omitted, as the differences of the two storage tanks revealed to be minute in the ETC case). The other programmes treated only the ETC installations, as the different tracking methods caused some difficulties: G^3 completed 24 cases, F-CHART 12, and WATSUN 4. Thus only a limited comparison of the different models is possible.

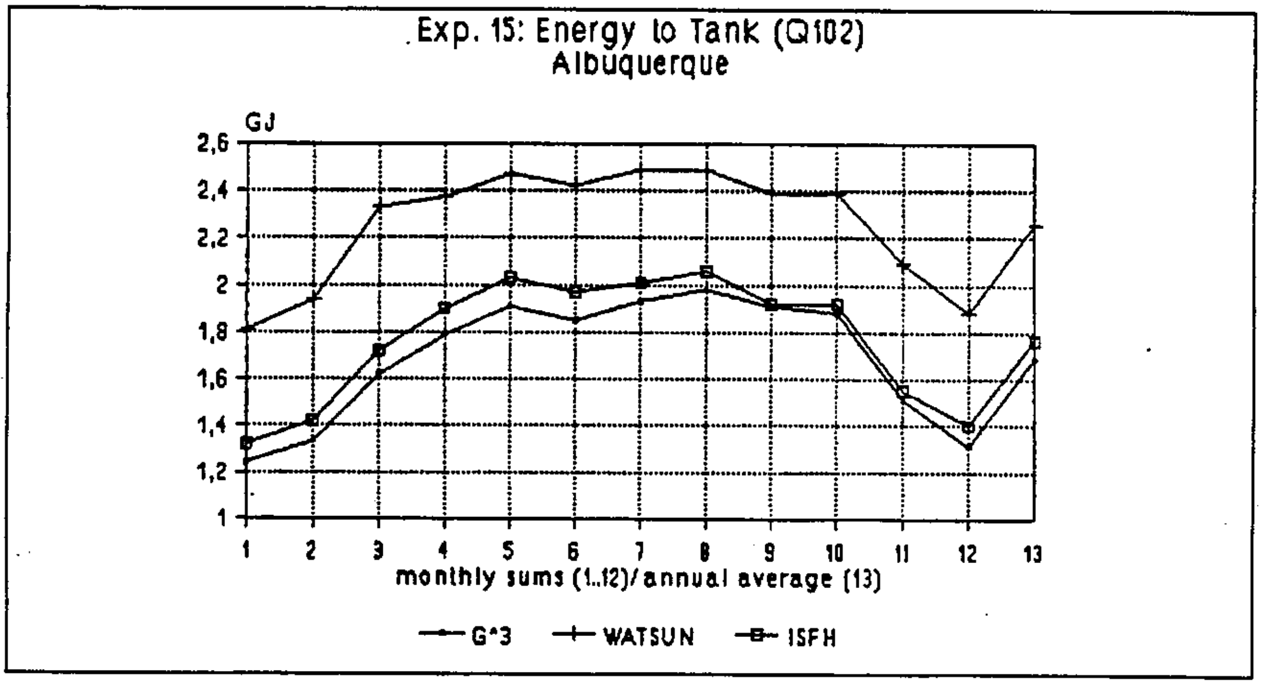


Fig 8.5 Experiment 15: Energy to Tank (Albuquerque)

The influence of the storage volume has been only investigated by ISFH and G^3. The trend of both programmes is very similar. As an example, we show in Table 8.1 the "solar fraction ratio" for Miami

$$SFR = \frac{\text{solar fraction with large tank}}{\text{solar fraction with small tank}}$$

which shows, that with collector area of approximately 700 m^2 the solar fractions are identical with both tanks. However, the differences are small enough, and we constrict our discussion in the following on systems with 50 m^3 tanks.

The solar fraction of the ETC installations is shown in the figs. 8.6 .. 8.8. ISFH and G^3 are rather close together with Miami conditions, whereas the WATSUN values are higher and the F-CHART values lower by approximately 15 %.

Table 9.1 Solar Fraction Ratios of the 100 m^3 and the 50 m^3 System

A_c	200	400	600	800	1000	m^3
ISFH	.920	.968	.988	1.019	1.034	
G^3	n.a.	.980	.980	1.008	1.008	

For Seattle conditions F-CHART and ISFH agree well, whereas G^3 is higher by some 5 ... 10 %. With Albuquerque conditions the G^3 values are by 10 % higher and the F-CHART ones by 10 % lower as the ISFH values. In all cases F-CHART shows the lowest solar fractions and ISFH takes always the intermediate position. The solar fractions and ISFH takes always the intermediate position. The solar fraction of the different collector installations are shown in the figs. 8.9 .. 8.11

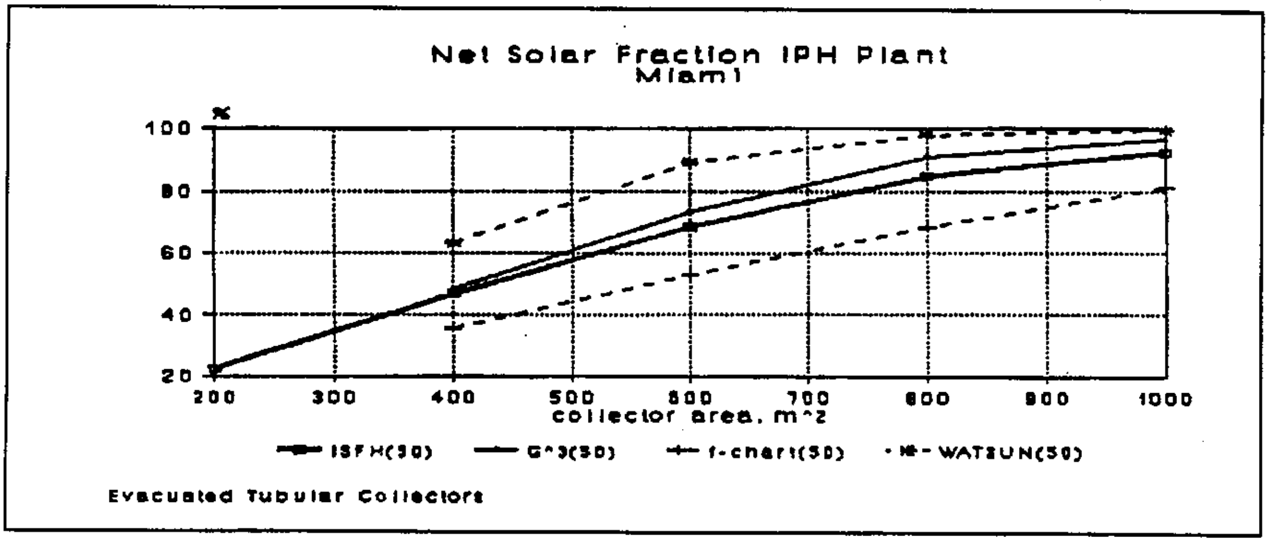


Fig. 8.6 Net Solar Fraction IPH Plant (Miami)

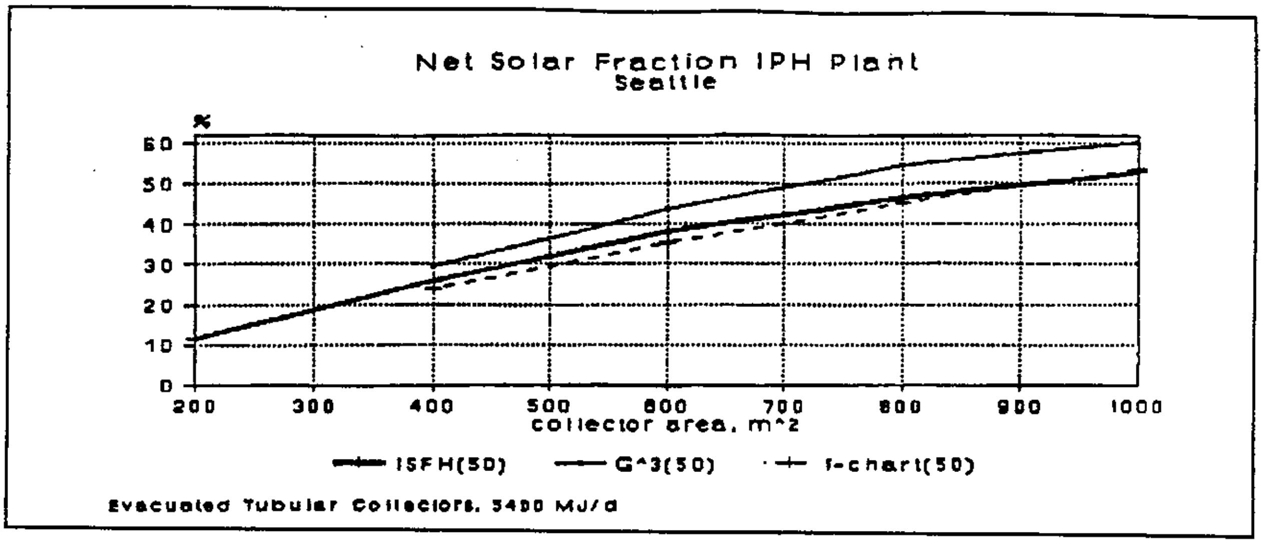


Fig. 8.7 Net Solar Fraction IPH Plant (Seattle)

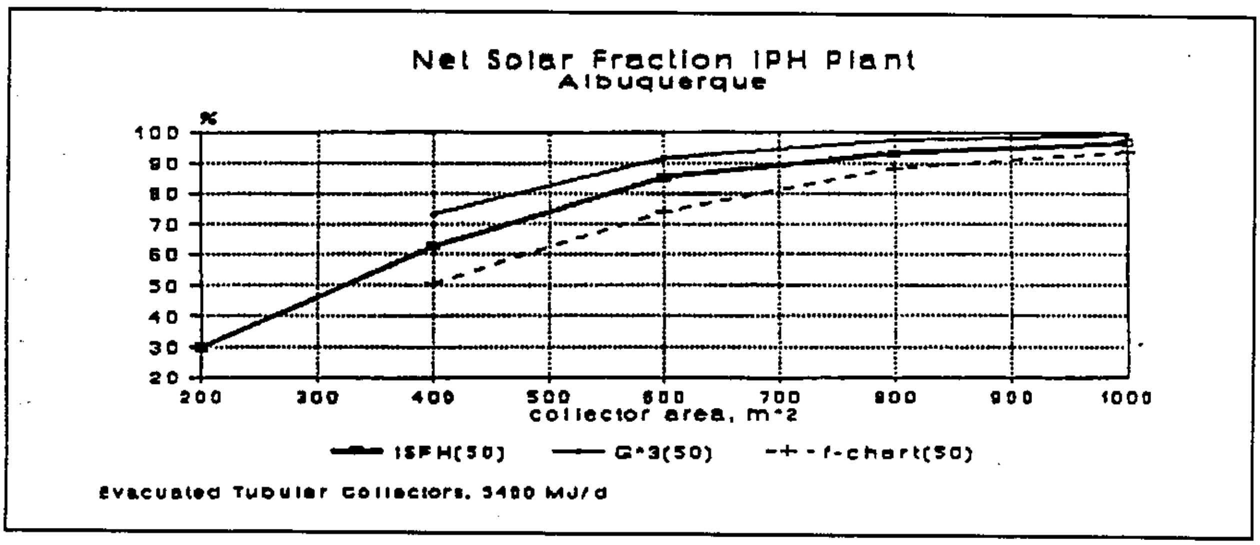


Fig. 8.8 Net Solar Fraction IPH Plant (Albuquerque)

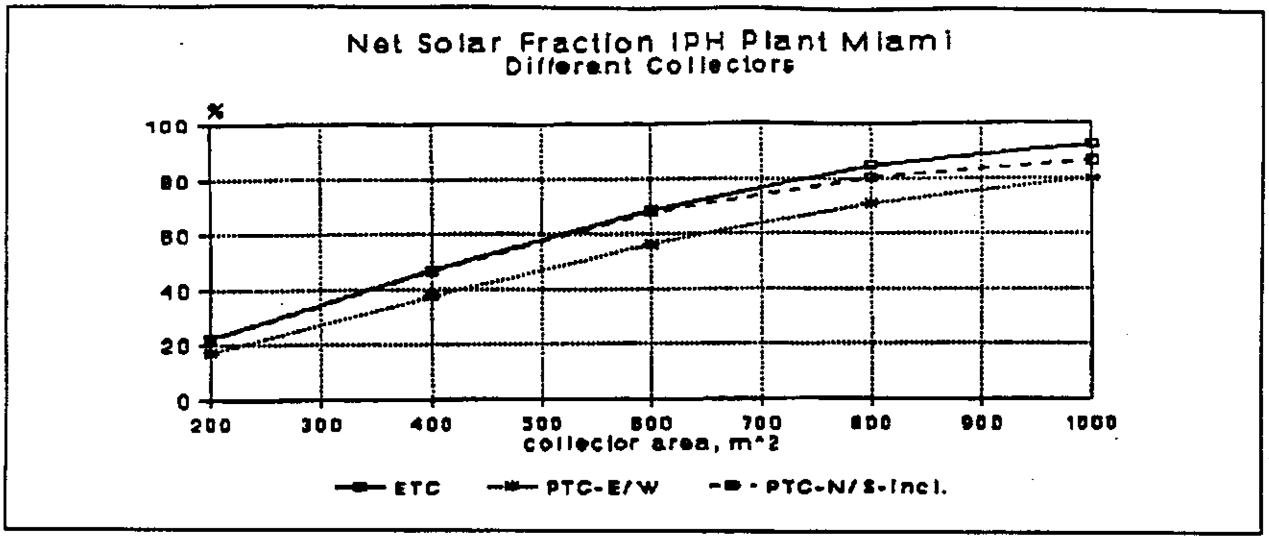


Fig. 8.9 Net Solar Fraction Rates IPH Plant Miami Different Collectors (ISFH Values)

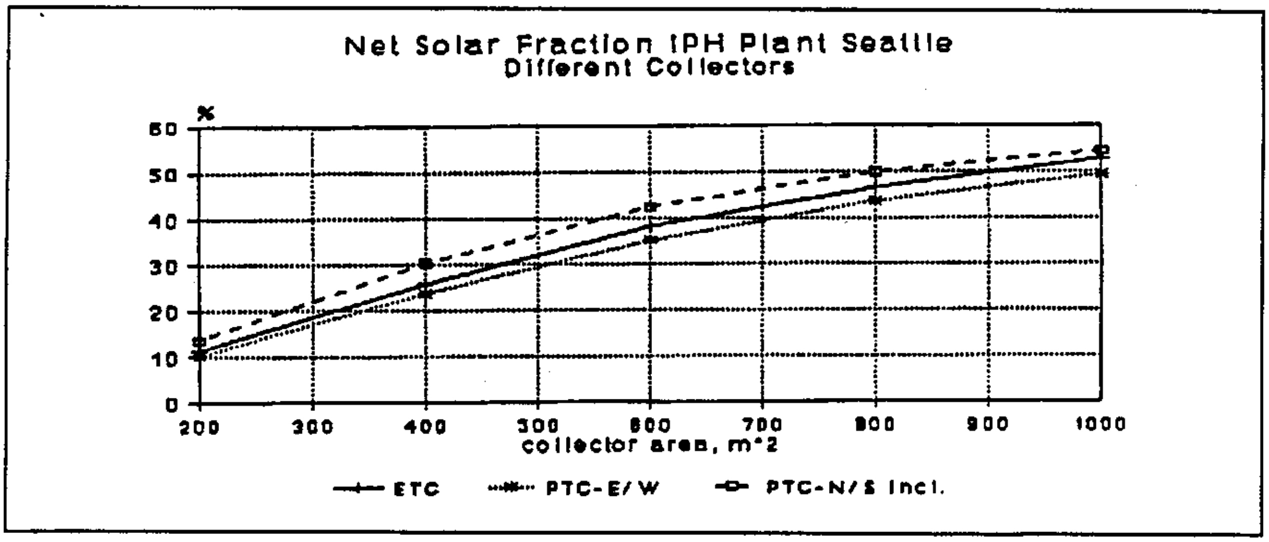


Fig. 8.10 Net Solar Fraction Rates IPH Plant Seattle Different Collectors (ISFH values)

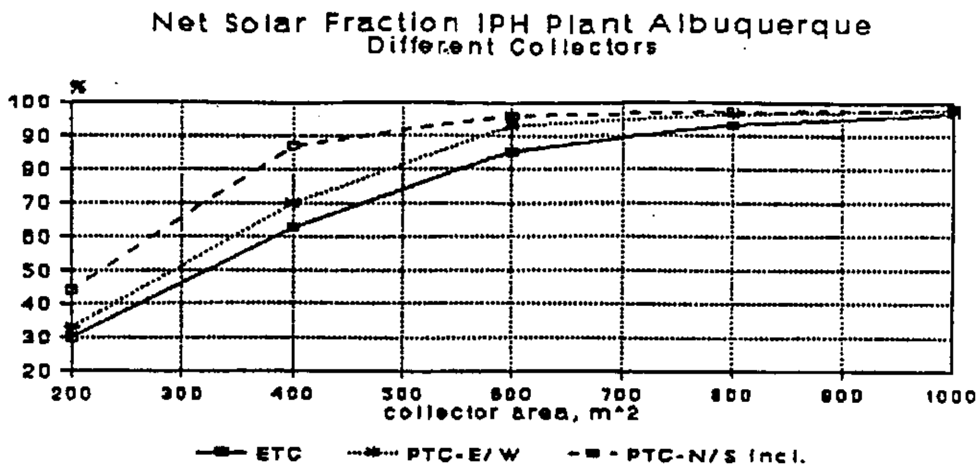


Fig. 8.11 Net Solar Fraction IPH Plant Albuquerque Different Collectors (ISFH values)

As for the concentrating collectors only ISFH values were available, we restrict the discussion to this model. For Miami conditions (high insolation, ambient temperature, and diffuse part) the ETC shows the best results. For Seattle with the far lower ambient temperatures the N/S mounted PTC performs best, and for the clear climate of Albuquerque both PTC show higher solar fraction rates. However, except for the last case, the differences are never substantial.

8.2 G^3

To compare different models is a very difficult exercise. It can explain why the results of the workshop are not very satisfactory. The comparisons between models led to a rough feeling about differences, prediction power, etc... In other words, we got some qualitative information rather than quantitative. In order to improve such comparisons we should be more careful on a few points:

- o Select real cases for comparisons rather than to invent unrealistic cases where improvisation leads to serious mistakes.
- o Methods should be defined not only properly and clearly but also in advance, in such a way that participants can agree with the methods and be prepared before the meeting. For instance, inputs/outputs and units, tables and graphics have to be defined once for all.

8.2.1 Performance of G^3:

Very satisfactory considering the other models and the range of applications. As a result of this workshop, our model appears as one of the fastest models and in very good agreement with the others.

8.2.2 Performance of other participants' models:

Because of lack of time some other models failed to provide us with on line data. We are sure that such models could give good results but is was not demonstrated at the meeting.

As already said only qualitative conclusions can be drawn to for it appears that ISFH and G^3 are very close together, that WATSUN overestimated as compared to ISFH and G^3, and that we miss information so far to judge the performances of TRNSYS and F-CHART models.

8.2.3 Benefits of working closely with other modelers:

Always stimulating and interesting.

8.2.4 Exchange of models among the modelers:

It is well known that a modeler usually uses only his own model. It is difficult to work simultaneously with different models, but sometimes it can help for comparisons or improvements.

8.3 TRNSYS

8.3.1 Performance of TRNSYS:

TRNSYS is a cumbersome program to use in a setting such as this workshop. The great flexibility of TRNSYS allows for a great possibility of introducing errors when configuring a simulation. In addition, some of the assumptions made in the base case of the DHW system (zero pipe capacitance, for example) initially caused either numerical errors (such as "divide by zero") or convergence errors. Considerable time was consequently spent debugging the DHW simulation deck. Each simulation run took approximately 15-20 minutes to perform, due to the detailed nature of the simulation. A simplified method of inputing simulation deck information could reduce the amount of time needed to eliminate errors in the specification of the deck. Simplifying the input method while retaining the full flexibility currently available in the specification of a TRNSYS deck has been found to be complicated.

Due to a lack of time, none of the IPH runs were attempted. Additionally, experiments 2, 2A, and 14 of the DHW set of routines were not run as they would require creating additional new subroutines. The collector capacitance was neglected for experiment 15.

Of the DHW system runs performed, most of the results obtained through TRNSYS were similar to those obtained by a number of other programs. The exceptions are experiment 5, with the single tank, experiment 10 with the modified water draw, and experiment 15b. It was observed that inappropriate choices of controller "stickiness", time step, or "maximum number of iterations" caused incorrect results. The reasons for the above-mentioned discrepancies have not been determined.

8.3.2 Performance of other participant's models:

No comments.

8.3.3 Benefits of working closely with other modelers:

Exchanging ideas among modelers should obviously improve all models. Much of the current workshop was spent making computer runs. We suggest that future workshops place less emphasis on computer runs and greater emphasis on specific modeling concepts and techniques.

8.3.4 Exchange of models among the modelers:

The exchange of techniques, and possibly code, among modelers could be very helpful to TRNSYS. Plans are being made for collaboration between WATSUN and TRNSYS developers to exchange the particularly good models from each program, with the aim of improving both programs. We would welcome this type of collaboration with other modelers.

8.4 WATSUN

8.4.1 Performance of WATSUN:

On the whole, the WATSUN program over-predicted as compared to ISFH and G^3, and in the cases we examined, it produced results close to those of TRNSYS. The differences are in the order of 10% generally, and as high as 25-50% in Experiment 15. We will re-examine these differences as soon as we return to Waterloo.

The differences begin to show with a) radiation processor - WATSUN seems to over predict by about 7%; this may be due to the diffuse model we use, b) experiment 4 with low flow rates in stratified tanks; this may be due to the assumption of perfect stratification. It would be interesting to compare it with TRNSYS which uses a similar tank model, c) experiment 8 with the temperature dependent collector model. I am pleased to say that in most cases, the differences are within 5-10%.

8.4.2 Performance of other participant's models:

The other models, ISFH and G^3, give results that are close to each other. In my opinion, these models are excellent as compared to detailed models. A well written user's manual and documentation of the algorithms and justification of assumptions should be provided. Although these models seem to perform well for the DHW and IPH systems considered, more complex and extreme systems should be tried in order to test the range of applicability of these models. The more detailed models provide flexibility and detail at the cost of more time needed to set up the data file and to execute the programs. It was suggested that an integration across different levels of detail may be important for the development of a powerful modeling environment. To this end, perhaps a more common input, output and graphics specifications would be useful.

8.4.3 Benefits of working closely with other modelers:

The benefits of working with the experienced modelers is obvious. Our group learned a lot about various models and were able to make important changes to the WATSUN code. Such a group should be encouraged to cooperate and conduct research. Perhaps future workshops could be arranged in specific areas, such as model exchange, validation of models against measured data, expert systems development.

8.5 MINSUN

8.5.1 Performance of MINSUN:

By using the tank model in MINSUN it is possible to calculate the performance also for systems with seasonal storage. The MINSUN program can not fully compete with the other models for simulation of DHW systems as the daily time step in the system simulation is too large especially when specifying a collector flow that is higher than the tank volume per day. This was the case for both 0.015 and 0.03 $l/s/m^2$.

Also the high piping losses to the outdoor temperature caused a systematic shift of the MINSUN results which was difficult to correct with a change of input data. (only indoor or buried pipes can be specified in the present version). IPH-systems comes closer to the normal range where MINSUN gives reliable results. The design study was easy to do with the multiple run option in MINSUN.

It turned out that there are significant differences in the radiation processors. MINSUN seem to give values between WATSUN and ISFH for all three locations(Miami, Albuquerque and Seattle) for latitude tilt. It is very easy to make small mistakes while changing input data. Especially when using a model outside the normal range.

A common format for input variables could be very helpful.

8.6 F-CHART

8.6.1 Performance of F-CHART:

The F-CHART method was developed before the general availability of personal computers. Its initial purpose was to provide estimates of solar system performance using pencil and paper. With modern PC's there is no need for new F-CHART type correlations since hourly simulations can be done in less than one minute with careful programming. In spite of the limitations of the F-CHART method, the F-CHART results compare favorably with the other, more detailed, programs. The small differences in input radiation could have been eliminated by writing a short program to preprocess the TMY tapes. Since the typical user would not have done this, it was decided to use the built-in weather data. Actually, the F-CHART monthly weather data is the long-term average data that will best represent long-term performance. The TMY data used by all other programs is close to this long-term average.

One major deficiency in the F-CHART method is the use of a fully mixed storage tank. A fully mixed tank will lead to conservative estimates of auxiliary energy requirements. However, recent analysis and experiments have shown that significant system performance gains are possible with stratified tanks. F-CHART may be too conservative for these new systems.

9 INDIVIDUAL INTERPRETATIONS AND DEFINITIONS

This section consists of material contributed by each participant. Only minor editing changes have been made.

There were some variations from case study specifications, usually due to built in features of some of the models.

9.1 ISFH

In the June version of ISFH only stratified storage were possible. ISFH now includes fully mixed tanks.

Radiation values for ISFH exclude incidence angle modifiers. Therefore, ISFH values are lower in the radiation plots. Since incidence angles are accounted for later on, there is no error in other computations.

Energy dumping in ISFH occurs in a device that is attached to the storage. In other models it occurs prior to delivery to storage. Therefore, ISFH collection values will be higher when there is surplus energy collected. This approach does not introduce errors in the simulation.

9.2 G^3

All definitions were clearly presented in the material sent to the participants.

9.3 TRNSYS

None.

9.4 WATSUN

The WATSUN radiation model has undergone some changes as a result of incorporating collector tracking capabilities. These change could alter results of the workshop cases slightly. It has also become clear that the Klucher model used in WATSUn over predicts in some situations.

Collector thermal capacitance is not modeled in WATSUN and therefore was included by means of pipe capacitance. It was split evenly between inlet piping and outlet piping.

Heat exchanger modeling required that the heat transfer rate be translated into a heat exchanger effectiveness value forinput to WATSUN.

9.5 MINSUN

During the workshop it turned out that the different programs are putting emphasis to different parameters and treat them differently. To make an accurate comparison between the models a lot of details has to be sorted out. One example is the thermal capacitance, time-constant and response time for the collector array. Another is the incidence of angle modifiers.

9.6 F-CHART

F-CHART does not directly output the quantity of energy transferred to the pre-heat tank. This quantity was estimated by subtracting the auxiliary energy needed from the load. The load includes the energy required to heat the supplied water plus the energy lost from the preheat tank.

The F-CHART method is not intended to be used to provide monthly values. Only the annual values are considered accurate.

F-CHART uses monthly weather quantities, not TMY data. In some cases, the monthly values used by F-CHART are slightly different from the monthly averages of TMY data.

APPENDIX I

WORKSHOP PROPOSAL

WORKSHOP PROPOSAL

Objectives

1. To facilitate the upgrading of nationally accepted solar energy design and performance prediction codes based on the collective efforts of Task VI.

2. To verify the FRG code and other Task VI developed codes by comparing their predictions with those obtained from previously verified national codes.

Background

As a result of working closely with performance data from many well instrumented systems, the IEA SHAC Program Tasks VI Experts saw as early as 1980 that there were some unexplained effects. Because existing modeling approaches did not provide satisfactory predictions of these effects, the Task Experts began an ad hoc modeling effort to try to understand the relevant physical mechanisms. The experts succeeded in explaining and modeling most of these effects. Some of these explanations and models impact performance prediction significantly in systems using conventional as well as evacuated collectors.

As a natural extension of these efforts, several computer codes were developed which incorporate these models. One of these was developed by Germany. This code has undergone extensive development during the last four years. One of the main structural characteristics of the code is a daily energy input/output curve characterization of the collection system. While it is simple to use, it is anything but a "simplified" model. Some of its other features are that it is very user friendly, it provides considerable flexibility in system design, it uses readily available monthly weather data, it is very robust in that its predictive precision is little affected by extreme climate types, it runs very quickly on a personal computer, its accuracy may be close to that of conventional detailed simulations such as TRNSYS, and it has some very sophisticated component models, including models of collector performance and storage stratification.

Other codes developed in Task VI, such as the Swiss code, have used different approaches to modeling and have other unique and desireable features These codes will be included in the workshop exercise.

Approach

An intense six day exercise, conducted by and held at Colorado State University during the Summer of 1989, will accomplish the two objectives. Some activities will be conducted prior to the workshop.

Participant wishes and time available will govern the applications, subsystems, and comparisons included in this exercise. Some candidates are industrial process heat, space heating, DHW, long and short term storage and no storage, internal and external heat exchangers and no heat exchangers, normal and low flow rates, and flat plate, evacuated, and tracking concentrating collectors.

The Solar Energy Applications Laboratory microcomputer laboratory will be completely dedicated for the use of the meeting participants. It consists of two XT and four AT personal computers with co-processors, several printers including a laser printer, a Hewlett Packard six pen color plotter, and 1200 and 9600 baud modem connections to DEC Vax computers, a CDC Cyber mainframe, and a CDC Supercomputer. Connections to computers in other locations are available via a network and can also be made by modem and telephone. Additional equipment is available elsewhere in the university and will be provided as needed.

Colorado State University will provide data and software for the exercise, including: complete detailed accurate real data from our solar houses, floppy disk data sets for any TMY location, and a number of compete SOLMET location data sets; most of the popular personal computer active, passive, and load analysis software including TRNSYS (both the PC and Mainframe versions), F-CHART, SOLCOST (the PC version of SERI-RES), TRAKLOAD, etc; personal computer spread sheet, data base, word processing, engineering graphics, experimental design, statistics, optimization, and communications software; and personal computer PASCAL, FORTRAN (two different compilers), BASIC, C, and PROLOG software. Additional support software will be made available provided adequate advance notice is given and workshop funds are sufficient.

Work Plan

1. Colorado State University will schedule a week long working group meeting of modelers in Fort Collins for mid to late summer 1989. Meeting participants will include Task VI modelers Konrad Schreitmüller of Germany and Olivier Guisan of Switzerland. Modelers from other participating countries will be designated by their Executive Committee members by the end of January.

2. Each meeting participant will provide a description of his model to the other participants by mid February.

3. By the end of April 1989 the participants will send their codes and installation instructions to Colorado State University so we may insure that all codes are completely installed and functioning by the beginning of the meeting.

4. By mid April Colorado State University will send out specifications and a data set for an application and climate and a format for presentation of model results. The participants will make model runs with this data set and prepare a presentation on model setup and results for the first day of the meeting.

5. During the evening of the first day of the meeting and on the second day a second round of model runs will be collectively designed. These may

include applications, designs, climates, and other details not included in the first round.

6. During the third day of the meeting the participants will make the required second round runs and prepare to present them on the fourth day.

7. At the beginning of the fifth day the participants will be given the specifications and real climate data for a system at the Solar Energy Applications Laboratory. They will also have the opportunity to examine the actual system. Runs will be made that afternoon and results will be presented on the sixth day.

8. While at the meeting, the participants will prepare the material they presented for publication as a workshop report. Within one month these submissions will be edited for clarity, integrated into a coherent workshop report, and sent to the participants for their review. Within two months after that a final version will be sent to the Executive Committee members for approval.

APPENDIX II

PRE-WORKSHOP CASE STUDY

PRE-WORKSHOP CASE STUDY

Domestic Hot Water System.

DHW System and Preheat Tank:

325 liter solar energy storage tank
175 liter electrically heated DHW tank

Both tanks are cylindrical with three to one aspect ratios and four inches of insulation. The tank insulation has an effective specific conductance of 0.1 W/m-K.

Hot water is delivered according to the following schedule:

250 liters between 6:30AM and 8:00AM
100 liters between 5:00PM and 9:30PM

The hot water temperature setting for the DHW tank is 50°C. A tempering valve is used to adjust the delivery temperature to the user to 50°C if the water in the DHW tank is hotter than this.

Flow is out of the top layer and into the bottom layer for both tanks. The temperature of the main water is 5°C all year.

Collection System:

Six meters of the supply and six meters of the return piping are located within the building which is maintained at an average temperature of 20°C. Two meters of the supply and two meters of the return piping are located outside the building.

The piping has an internal diameter of 1.5 cm and is covered with 2.0 cm of insulation having an effective specific conductance of 0.1 W/m-K.

Run two different counter-flow heat exchangers with heat delivery capabilities of

HXA: 750 W/K -- 99% efficiency at a LMTD of 10°C
HXB: 75 W/K -- 58% efficiency at a LMTD of 10°C

The flow rate of the 50/50 ethylene glycol/water solution on the collector side of the heat exchanger is two liters per minute and of the water on the storage side, one liter per minute.

Assume that 60 percent of the 200 W of power to the pumps is transferred to the fluid.

Run two different collectors of nine square meters aperture mounted facing due south at a 45° slope. The characteristics of each are

Collector A:

$F'U_L = .75 + .004*T_{fluid} - .003*T_{ambient}$
$F'\alpha\tau = .50$
Capacitance = 40 KJ/K-m² based on aperture

Incident Angle Modifiers at	0°	15°	30°	45°	60°
Transverse	1.00	1.05	1.15	1.12	0.85
Axial	1.00	0.99	0.98	0.94	0.80

This evacuated tubular collector with a CPC reflector is oriented with the tubes running North-South.

Collector B:

$F'U_L = 3.50 + .012*T_{fluid} - .006*T_{ambient}$
$F'\alpha\tau = .82$
Capacitance = 30 KJ/K-m² based on aperture

Incident Angle Modifiers at	0°	15°	30°	45°	60°
Transverse	1.00	0.99	0.98	0.94	0.80
Axial	1.00	0.99	0.98	0.94	0.80

This is a flat plate collector with convection suppression.

Controls:

When the collector plate temperature is six degrees Kelvin above the temperature at the bottom of the preheat tank the collector loop is turned on. When the collector loop temperature falls to one degree above the temperature at the bottom of the preheat tank the collector and storage loops are turned off. When the collector loop temperature rises to ten degrees above the temperature at the bottom of the preheat tank the storage loop is turned on. The storage loop is turned off for overheat protection at 90°C.

Climate:

TMY data for Seattle and Albuquerque are to be used to build a climate data input file for running your model. Conversion of this data to the form required by your model is part of the initial case study. We will look at the effect of differences in radiation processors. However, for some of the cases run at the workshop, we may want to standardize on a particular climate data reduction approach to better compare other factors.

Format specifications for the TMY data on the enclosed disks are given below. The data consists of hourly data for one year for the following five variables: direct normal solar radiation, total horizontal radiation, ambient temperature, dew point temperature and wind speed, The variables are in successive fields, and in ASCII format.

When there are hourly periods with no solar radiation, the value of 9999 is given to the first and second variable. Note the temperature and wind speed variables are expressed as a multiple of ten to give one decimal accuracy and to have them recorded as integer variables, for space saving purposes in binary.

TMY WEATHER FILE FORMAT

	VARIABLE	DATA TYPE COMPRESSED ASCII Units	Field Width
1.	Direct Normal Radiation	KJ/m^2	4
2.	Total Horizontal	KJ/m^2	4
3.	Ambient Temperature	C°•10	5
4.	Dew Point Temperature	C°•10	5
5.	Wind Speed	M/SEC•10	4

Radiation Processors:

If your model produces such data, provide a table of estimates of hourly direct, diffuse, and total radiation in MJ/m^2 onto the plane of the collector for Albuquerque on and Seattle on

For the eighteen days, construct three bar graphs of estimates of daily direct, diffuse, and total radiation onto the plane of the collector, one each for Summer, Winter, and Spring. Use 1 cm = 2 MJ/m^2, 1 cm for the width of the bars, ½ cm space between the bars, and 3½ cm space between Albuquerque and Seattle.

Sensitivity Analyses (Use Seattle, collector ColA, and heat exchanger HXB as the base case):

For 1) collector areas of 3, 5, 7, 9, 11, 13, 15, and 17 and 2) solar storage tank volumes of 175, 225, 275, 325, 375, 425, 475, and 525 provide a table of monthly predictions of average daily radiation onto the collector plane (H100), average daily energy collected (Q112), average daily energy delivered to the heat exchanger, average daily solar energy delivered to storage (Q102), and average daily solar energy delivered to the load (Q300). If you keep track of pump energy, indicate what portion of each of the above quantities is contributed by the pump.

Plot the collector area and tank volume sensitivity analyses results for the months of January, April, and July. Use 1 cm = 1 m², 1 cm = 25 liters, and 5 cm = 10 MJ/m². Use symbols like x, , o, etc. for average daily radiation onto the collector plane, average daily energy collected, average daily energy delivered to the heat exchanger, average daily solar energy delivered to storage, and average daily solar energy delivered to the load.

Collector/Heat Exchanger/Climate Combinations:

For each the eight possible combinations (Seattle/Albuquerque, ColA/ColB, HXA/HXB) plot the following figures adhering to the specifications in the Task VI reporting document I sent you: Daily Energy Input/Output Curves (pages 28-30) for Q112, Energy Supply and Delivery Bar Charts (pages 34-37), Average Energy Use Rate (page 37), and Average Monthly System Efficiency and Solar Fraction (pages 37-40).

RESULTS OF THE PRE-WORKSHOP CASE STUDY

Table II-1 provides the parameters and assumptions used by each of the participants in running the pre-workshop case study. Table II-2 provides results for those parts of the case study where all participants performed calculations.

TABLE II-1 Parameters Used by Each Model for the Pre-Workshop Case Study

	FCHART	G^3	ISFH	TRNSYS	WATSUN	MINSUN
HX MODEL	const E = 0.58	HXA K = 750W/K	****	const E = 0.58	const E = 0.58	****
CAPACITANCE	store only	yes	collector + piping	storage+pipes	piping+coll	no (adjust collector parameters)
RADIATION	isotropic 0-H?	Hay, Liu/Jordan	ISFH2 airmass 2*matched	*****	anisotropic Klutcher	Boes diffuse model
COLL FLOW RATE	0.0039 kg/m²/s	****	0.0039	constant ind area	0.0039 kg/m²/s	variable
COLLECTOR LOSS FACTOR	FRUL = 0.815	0.7+0.004*DT	$0.75+0.004*T_{abs}$ $-0.003*T_{amb}$	f(Tfluid+Tamb)	$0.75+0.004*T_{abs}$ $-0.003*T_{amb}$	$U0+U1*(T_{fluid}-T_{amb})$
LOAD DRAW	daily	day+night	hourly	hourly as given	hourly as given	constant 24 hr. load for DHW
IAM	Mc Intyre	b_o ASHRAE	z-orthogonal functions	Mc Intyre-average diffuse	horizontal + vertical factored	b_o or table for ETC
PUMP POWER	neglected	zero	neglected	60% into fluid	60% into fluid	none
PIPE/HX	equiv.coll	internal HXA	2*f/r pipes external HX	included	included	yes
STORAGE MODEL	mixed	stratified	stratified solar and mixed hot water	stratified-4 nodes	plug flow stratified 9 layer	Stratified 4-nodes
CONTROL	ideal	Ideal	+10K / +2K	dead band	Ideal dead band	ideal on-off flow control
METEOROLOGICAL	solmet	TMY daily	TMY daily	TMY hourly	TMY-hourly	TMY-hourly
INDOOR PIPE	neglected	******	yes	yes	included	yes

TABLE II-2 Pre-Workshop Case Study Solar Fractions and Energy Delivered to Storage for Each Model

CASE A1

MONTH	AREA	FCHART	ISFH	G^3	TRNSYS	WATSUN
APRIL	3	0.20	0.252		0.36	0.31
	5	0.35	0.364	0.37	0.49	0.45
	7	0.49	0.451		0.63	0.58
	9	0.61	0.547	0.57	0.74	0.68
	11	0.72	0.605		0.80	0.73
	13	0.82	0.654	0.71	0.82	0.77
	15	0.90	0.676		0.84	0.78
	17	0.98	0.681		0.86	0.78
JANUARY		1.30		1.1	1.15	1.23
APRIL		4.20		3.8	4.07	4.29
JULY		6.60		5.29	5.97	
ANNUAL		42.4		37.2	40.7	

CASE A2

MONTH	AREA	FCHART	ISFH	G^3	TRNSYS	WATSUN
APRIL	3	1.7			1.27	1.39
	5	1.4		1.31	1.00	1.07
	7	1.1			0.73	0.74
	9	0.8		0.92	0.51	0.51
	11	0.6			0.39	0.35
	13	0.4		0.65	0.34	0.25
	15	0.2			0.31	0.21
	17	0.0			0.28	

APPENDIX III

LOTUS 123 SPREADSHEET AND WORKSHOP GRAPHICS

LOTUS 123 SPREADSHEET AND WORKSHOP GRAPHICS

A Lotus 123 spreadsheet was prepared that includes the following performance results from each model and experiment:

- o Radiation onto the Collector Aperture (GJ/month and year) for the base case and for cases where the collector is not horizontal
- o Auxiliary energy, including all purchased energy (GJ/month and year)
- o Solar energy into the solar storage tank (immediately after the collector) (GJ/month and year)

A diskette with Lotus 1-2-3 and ASCII files of this spread sheet file is included with this report.

Information from this spread sheet is presented in graphs in this Appendix. A number of different types of graphs have been constructed.

- o Line plots of the solar energy incident on the collector aperture versus months and year for all models - one plot for each city and each experiment where the collector tilt is different. (Figures 1, 10, 12, 14, 16, 28, 30, 32, 86 through 94, 108, 117, 126, 135, 140, and 145)
- o Line plots of solar energy delivered to the solar storage Q102 and auxiliary energy, including parasitics, QAUX vs months and year for all models - one plot for each experiment. (Figures 2 through 9, 11, 13, 15, 17 through 27, 29, 31, 33, 109 through 116, 118 through 125, 127 through 134, 136 through 139, 141 through 144, and 146 through 149)
- o Line plots of the solar energy incident on the collector, energy delivered to storage, and auxiliary energy for real daily data and synthetic daily data derived from monthly data - one plot for each climate and model. (Figures 34 through 36)
- o One bar plot per experiment of the sum of the absolute value of each model's monthly predictions of Q102 versus the TRNSYS predictions. (Figures 37 through 57)
- o One bar plot per experiment of the sum of the absolute value of each model's monthly predictions of QAUX versus the TRNSYS predictions. (Figures 37 through 57)
- o One bar plot per experiment of the sum of the absolute value of each model's monthly predictions of Q102 less that of TRNSYS minus the monthly average predictions of Q102 less that of TRNSYS. (Figures 37 through 57)
- o One bar plot per experiment of the sum of the absolute value of each model's monthly predictions of QAUX less that of TRNSYS minus the monthly average predictions of QAUX less that of TRNSYS. (Figures 37 through 57)

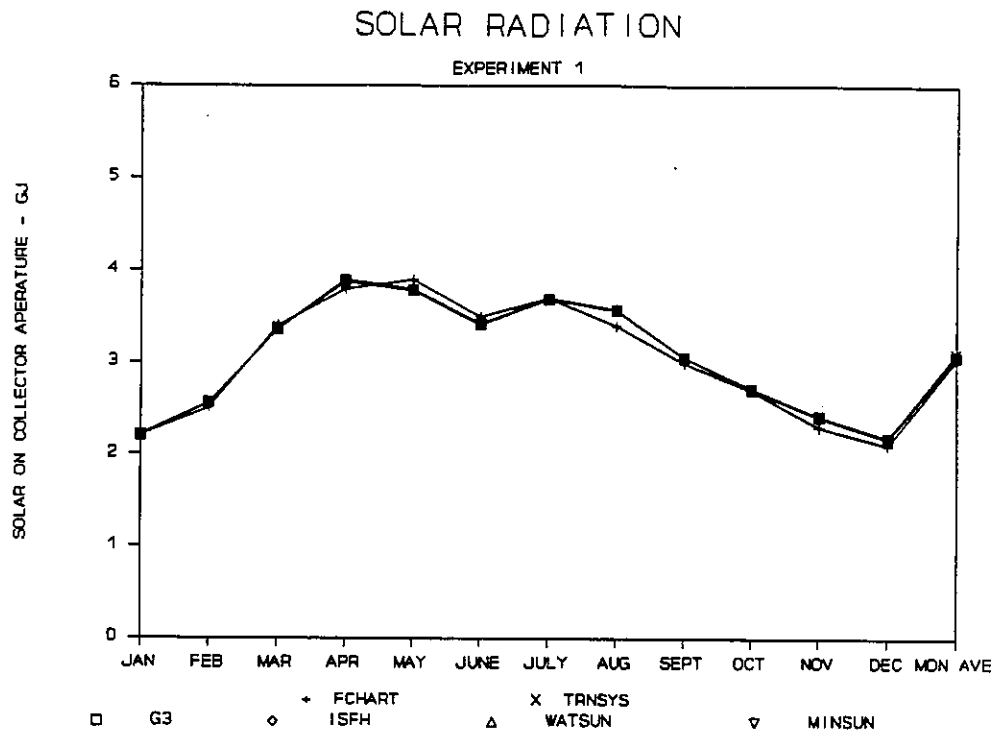
- One bar plot per experiment and model of the ratio of annual Q102 to user demand. (Grouped by Experiment - Figures 58 through 62 and Grouped by Model - Figures 96 through 101)

- One bar plot per experiment and model of the ratio of annual QAUX to user demand. (Grouped by Experiment - Figures 63 through 67 and Grouped by Model - Figures 102 through 107)

- One line plot per model and city of solar radiation on the collector aperture H100, Q102+QAUX, user demand, Q102 vs months. This plot uses Experiments 1 (Miami), 6a (Albuquerque) and 6b (Seattle). (Figures 68 through 85)

- One line plot per model of the ratio of monthly radiation on tilt variations of 25° and 45° in experiments 7a and 7b to that on the horizontal in experiment 1 vs months and year. (Figures 86 through 89)

- One line plot per model of the ratio of monthly radiation on the tilt equal latitude collector surface in experiments 15a, b, and c to that on horizontal in Experiments 1 and 6a, and b (Miami, Seattle, and Albuquerque) vs months and year. (Figures 90 through 94)



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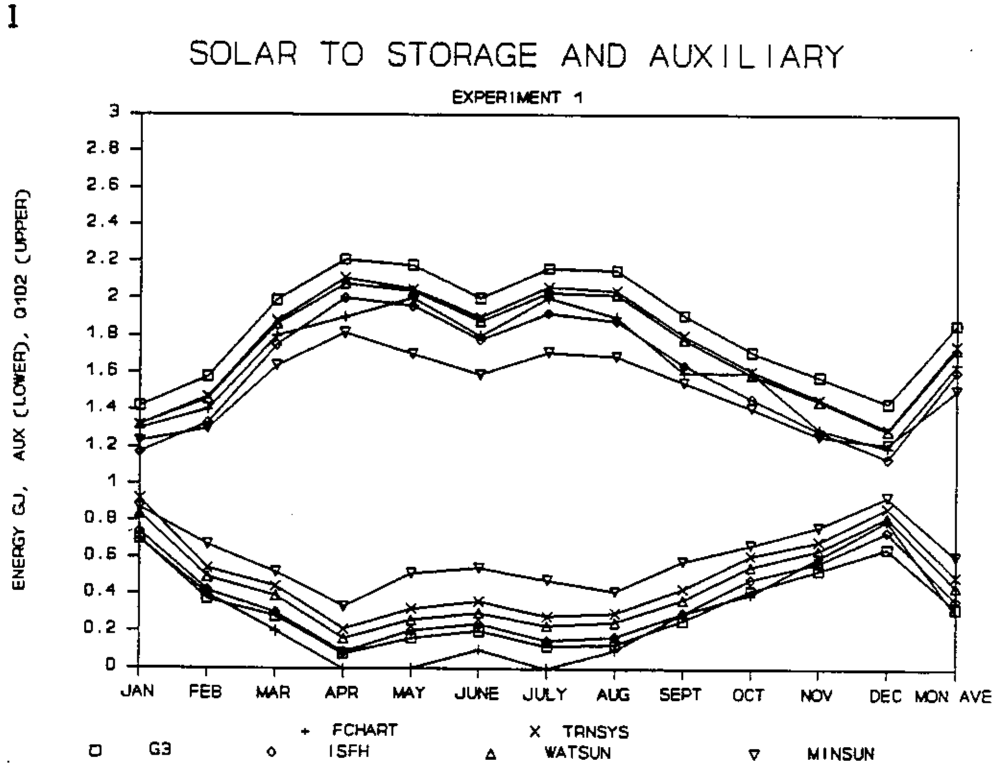

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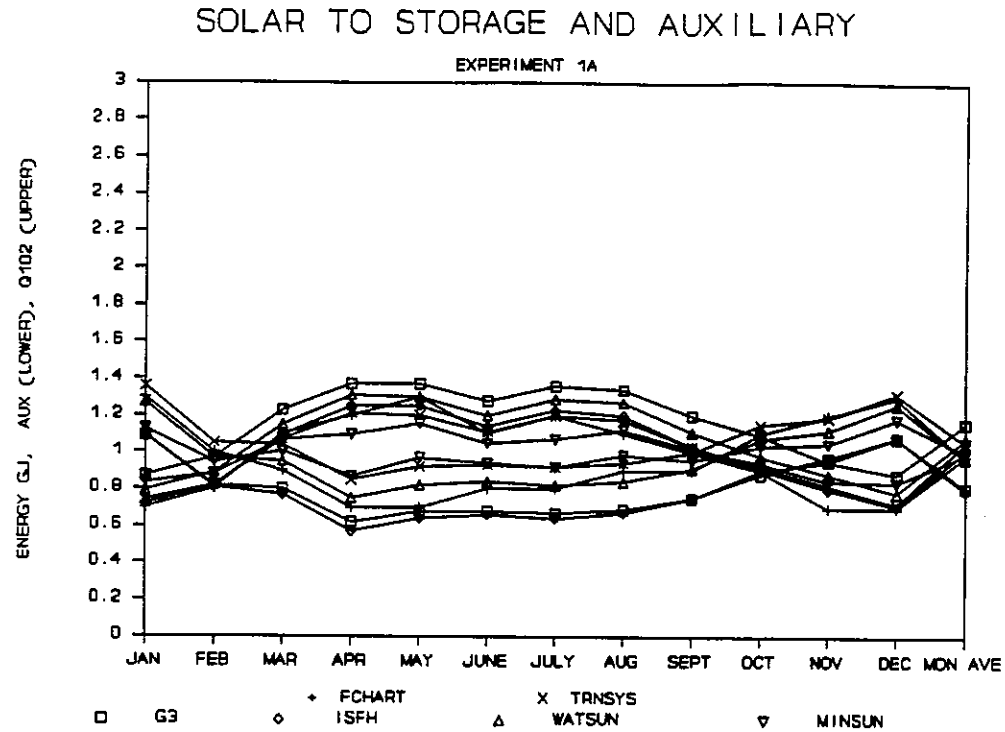
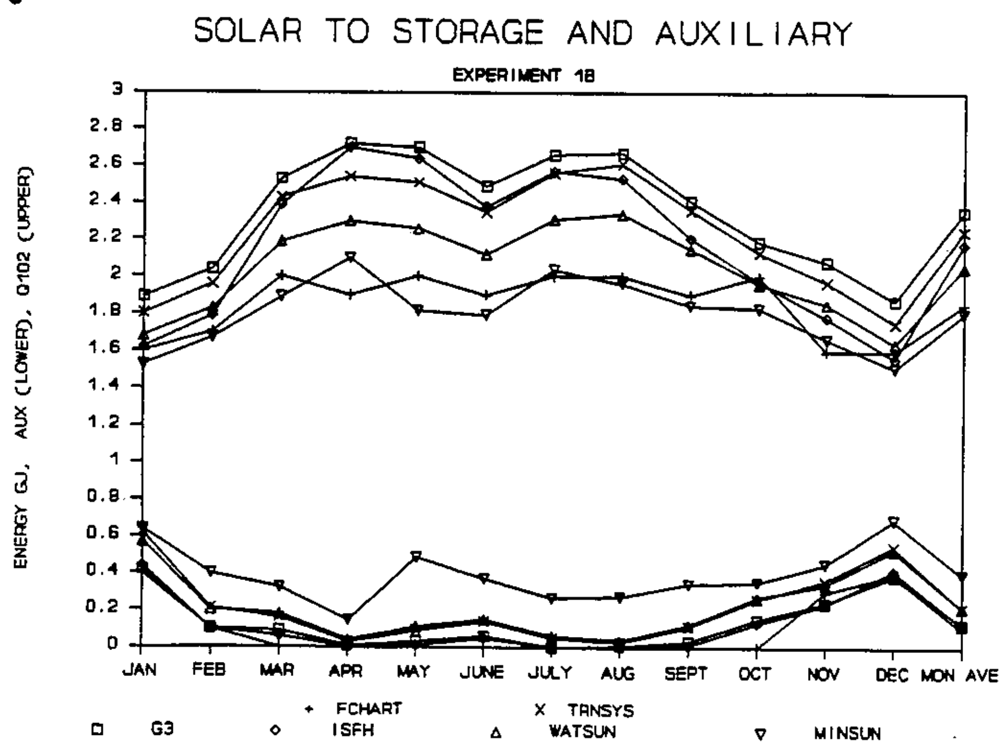


Figure 3



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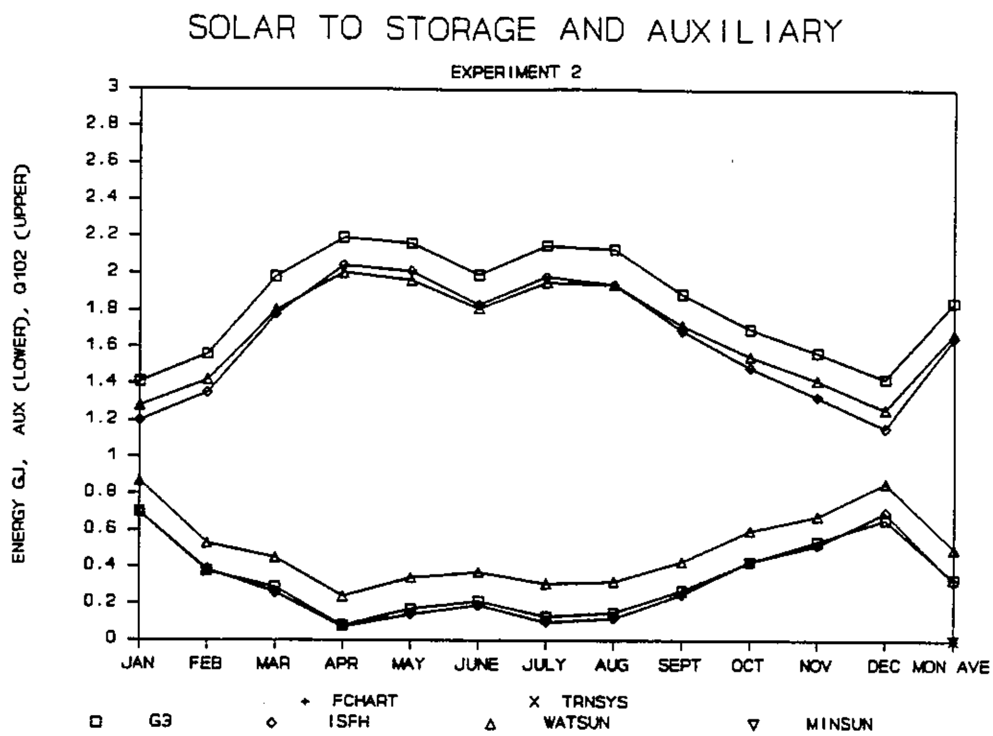

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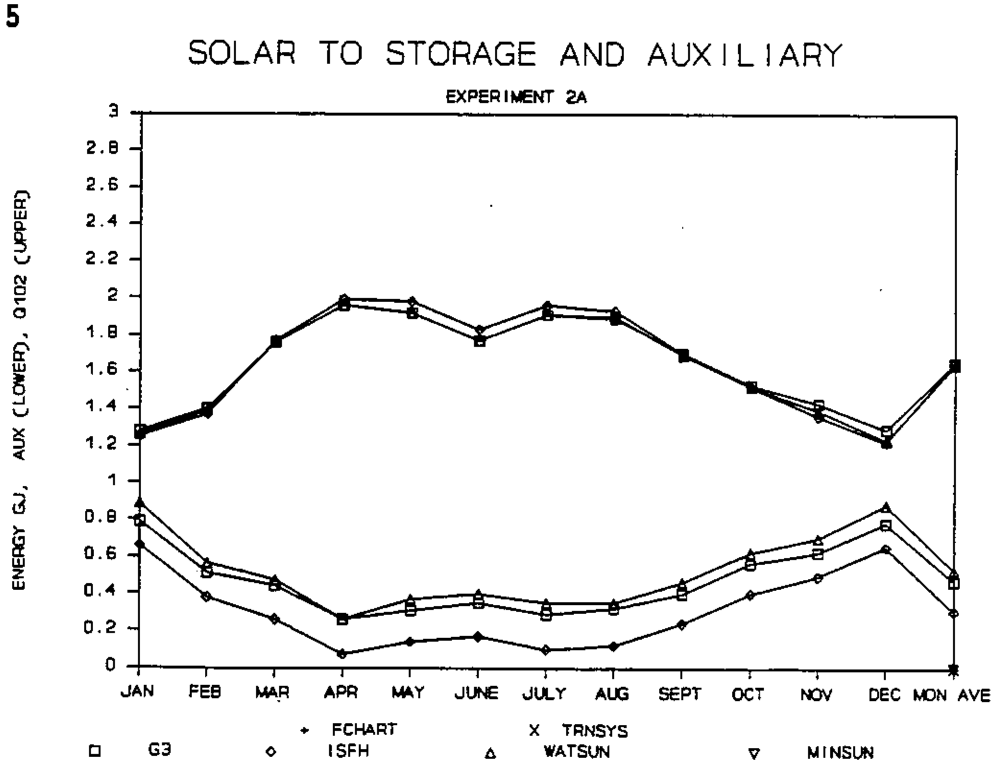

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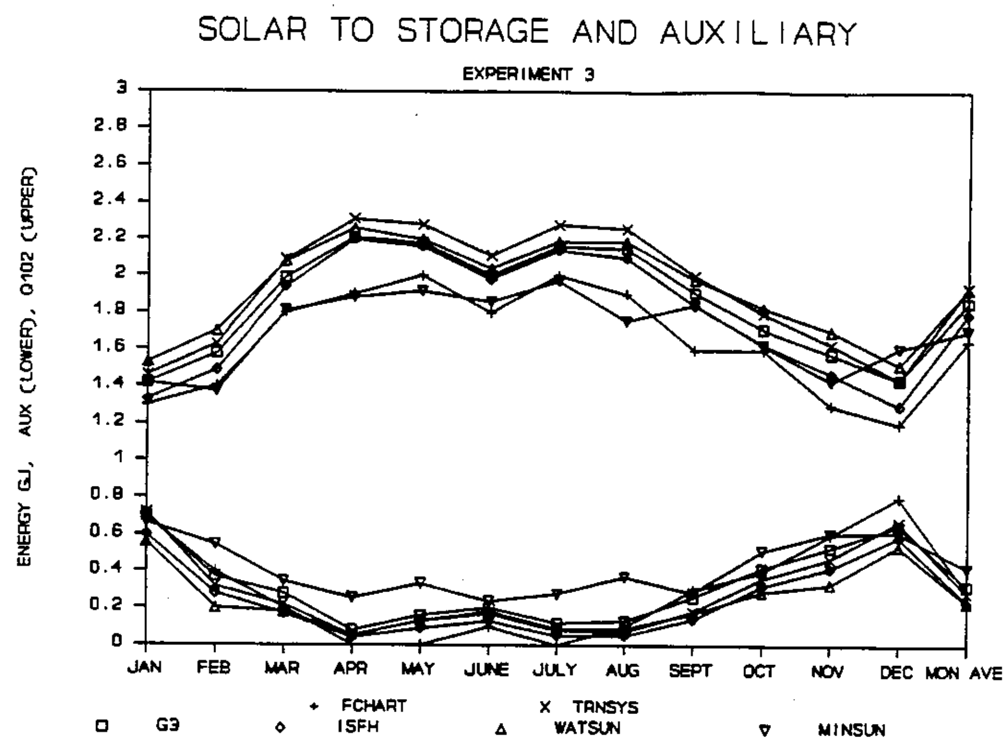

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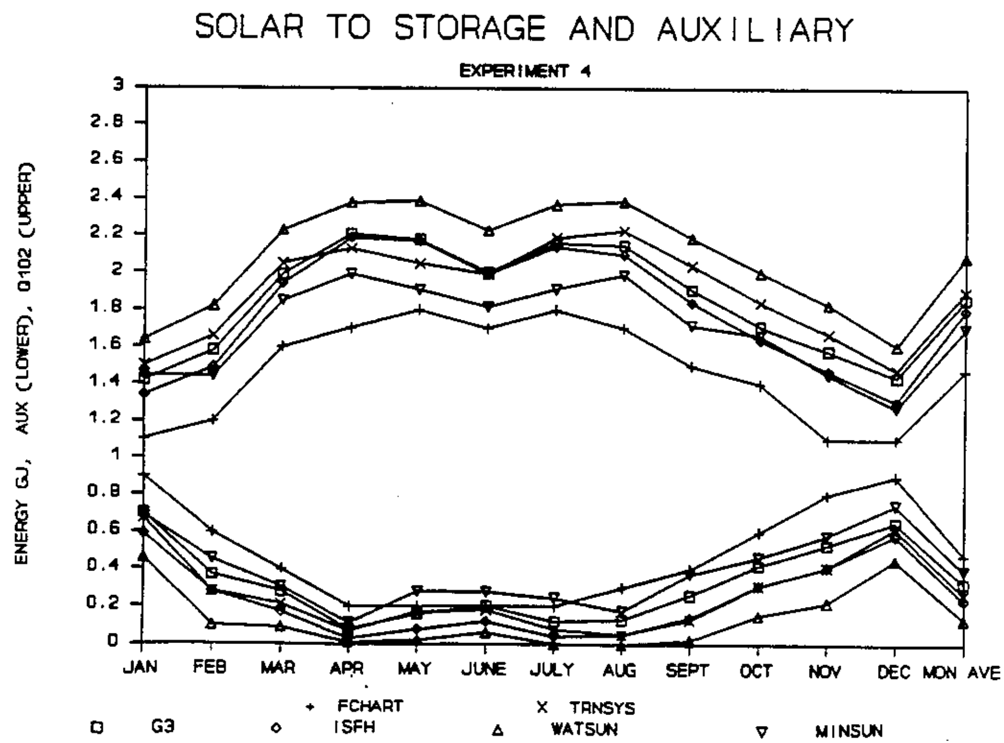

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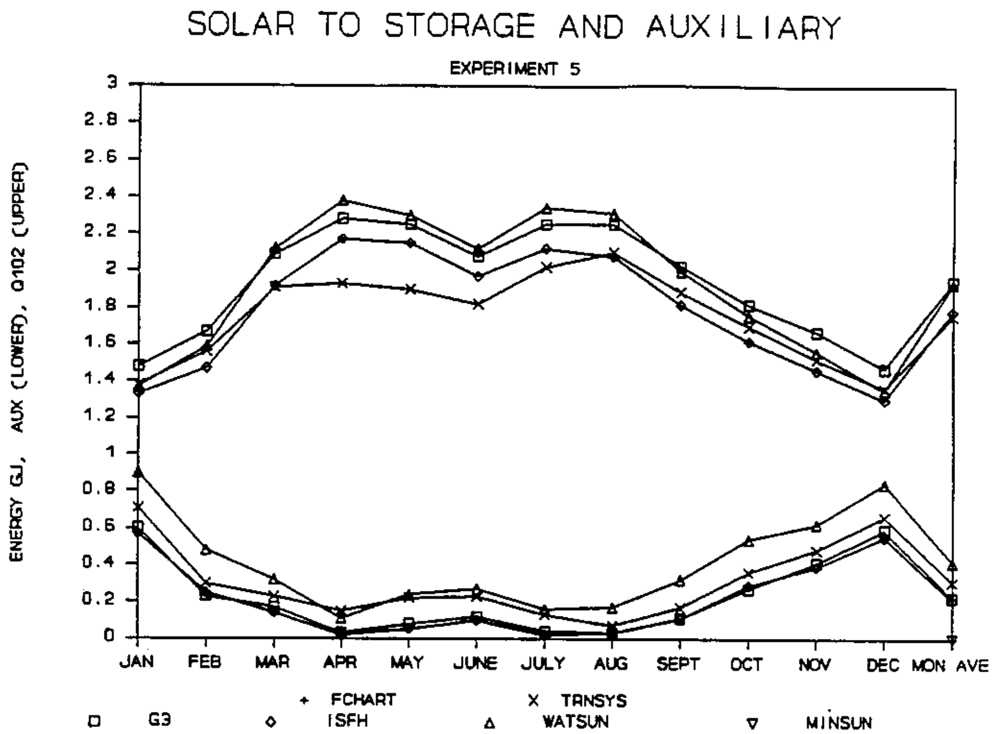
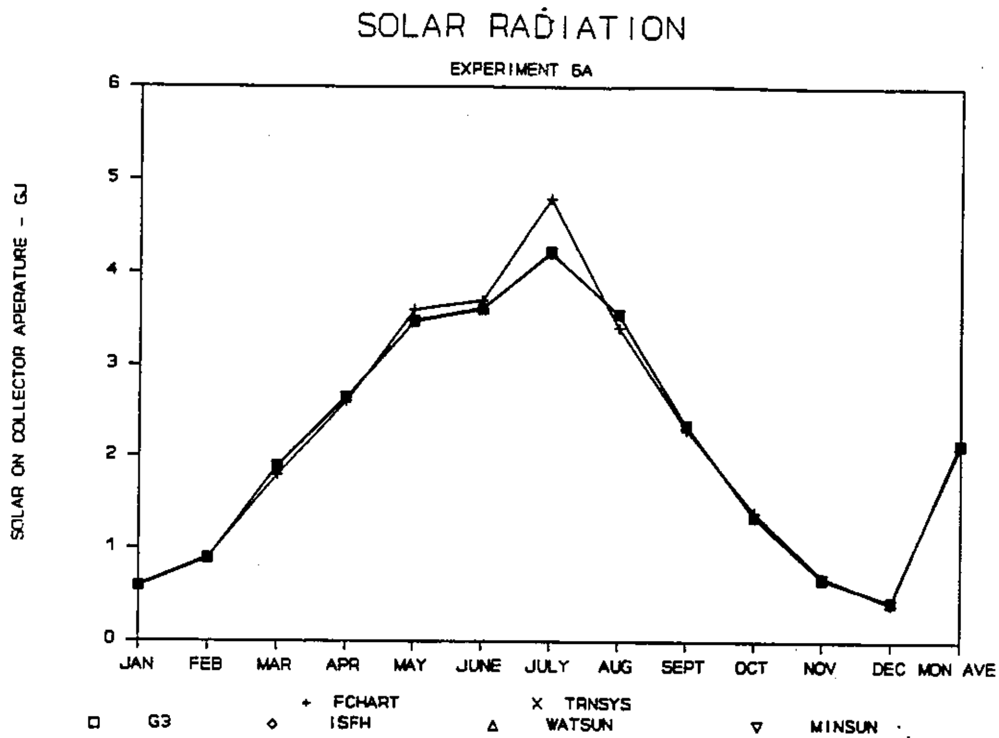

SOLAR TO STORAGE AND AUXILIARY
EXPERIMENT 5
ENERGY GJ, AUX (LOWER), Q102 (UPPER)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
MON AVE
+ FCHART
X TRNSYS
G3
ISFH
WATSUN
MINSUN

Figure 9



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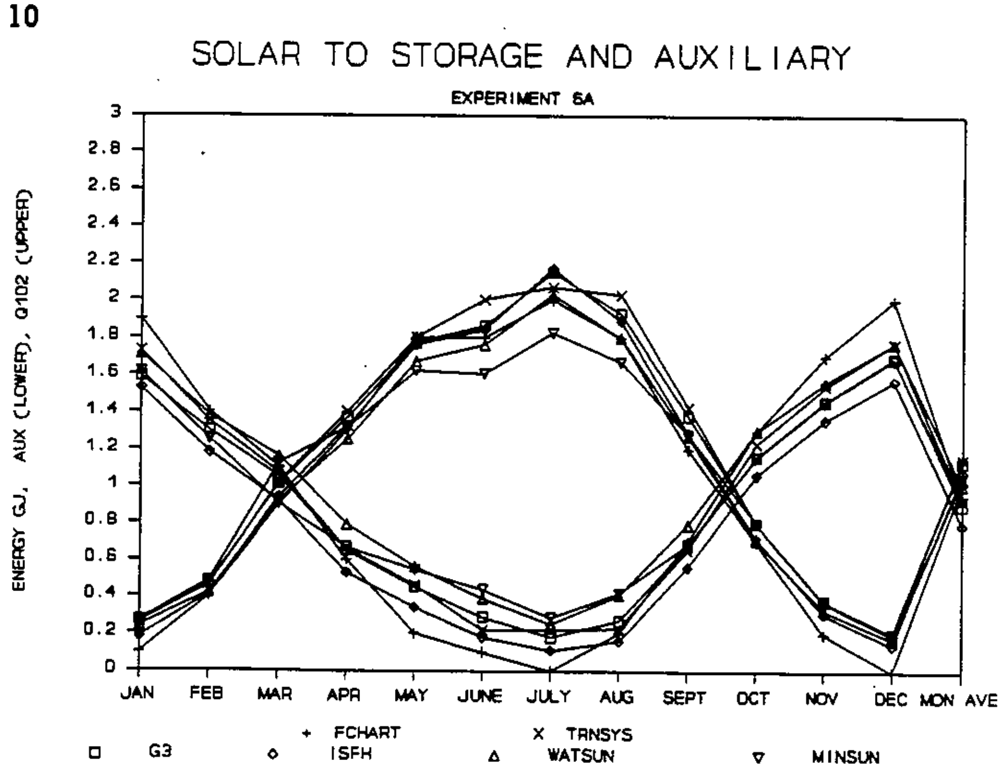

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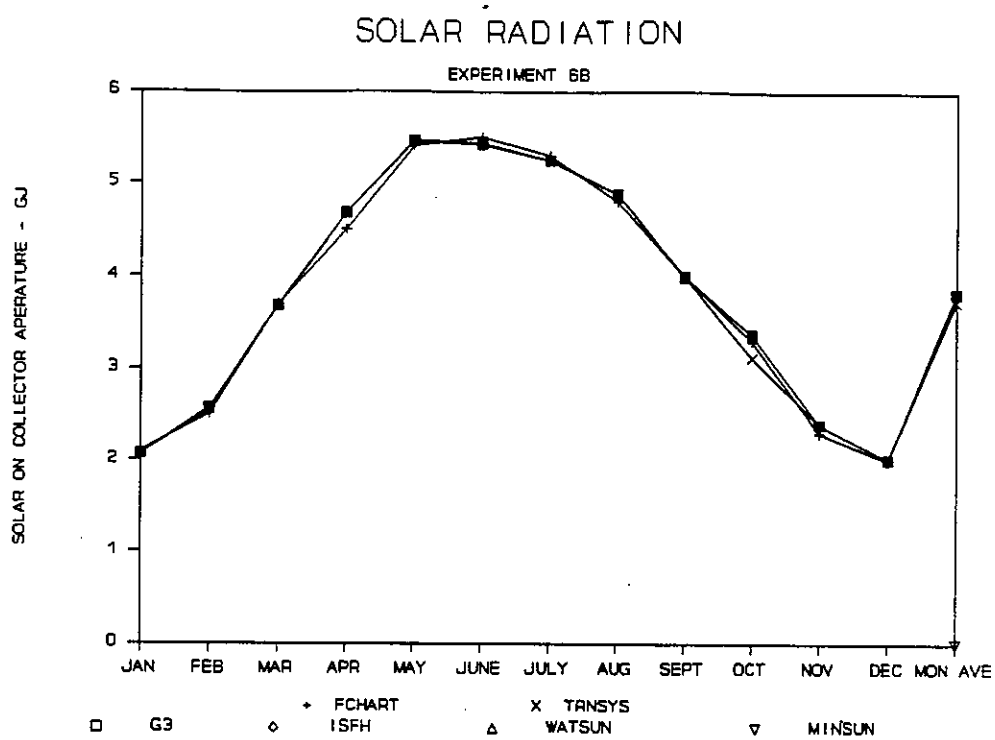

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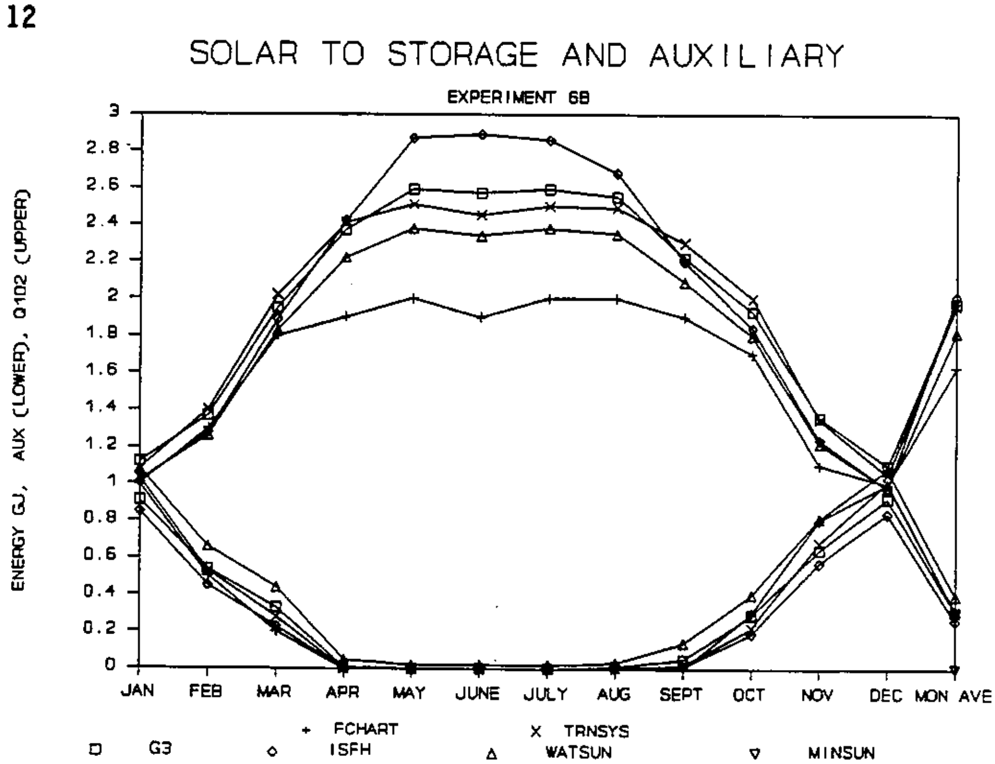

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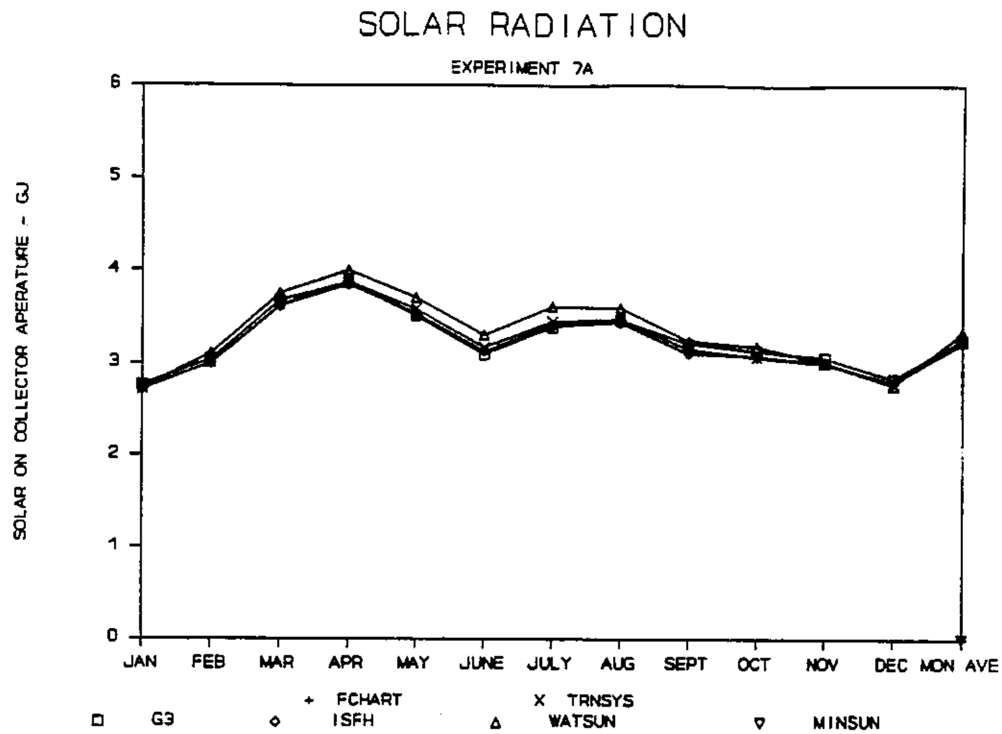

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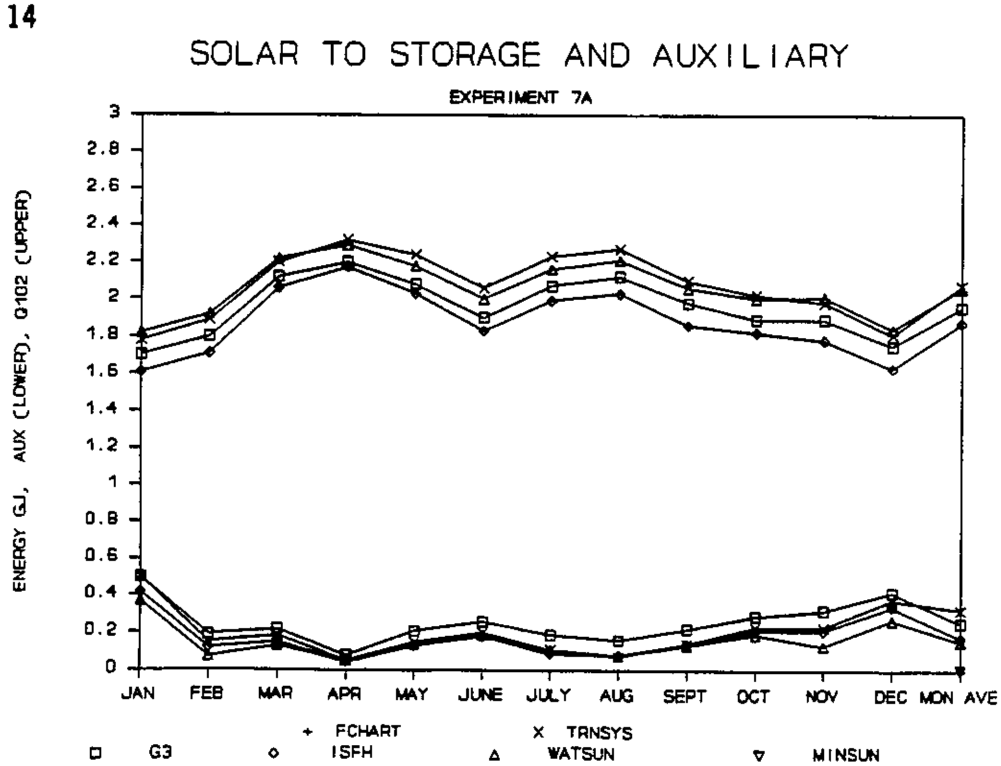

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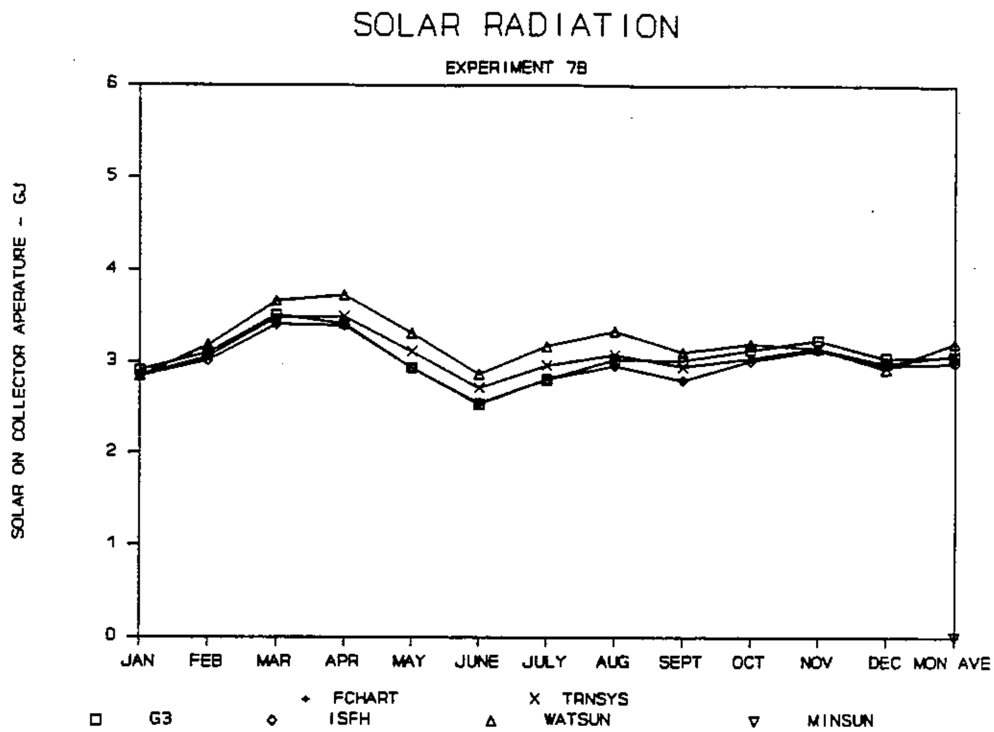

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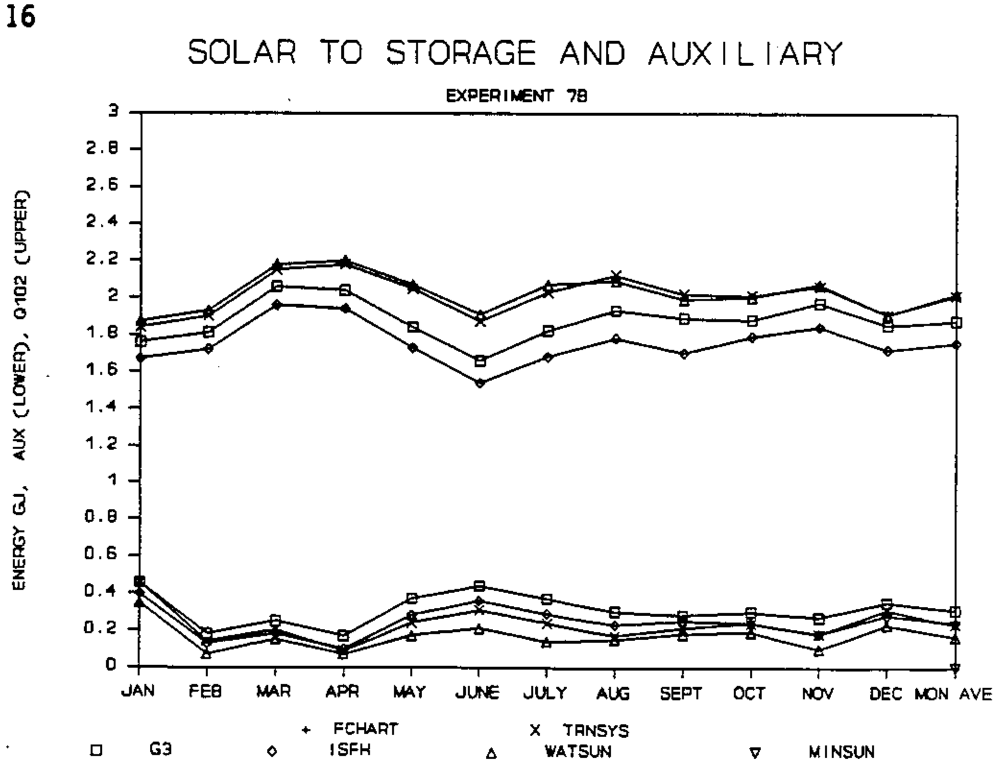

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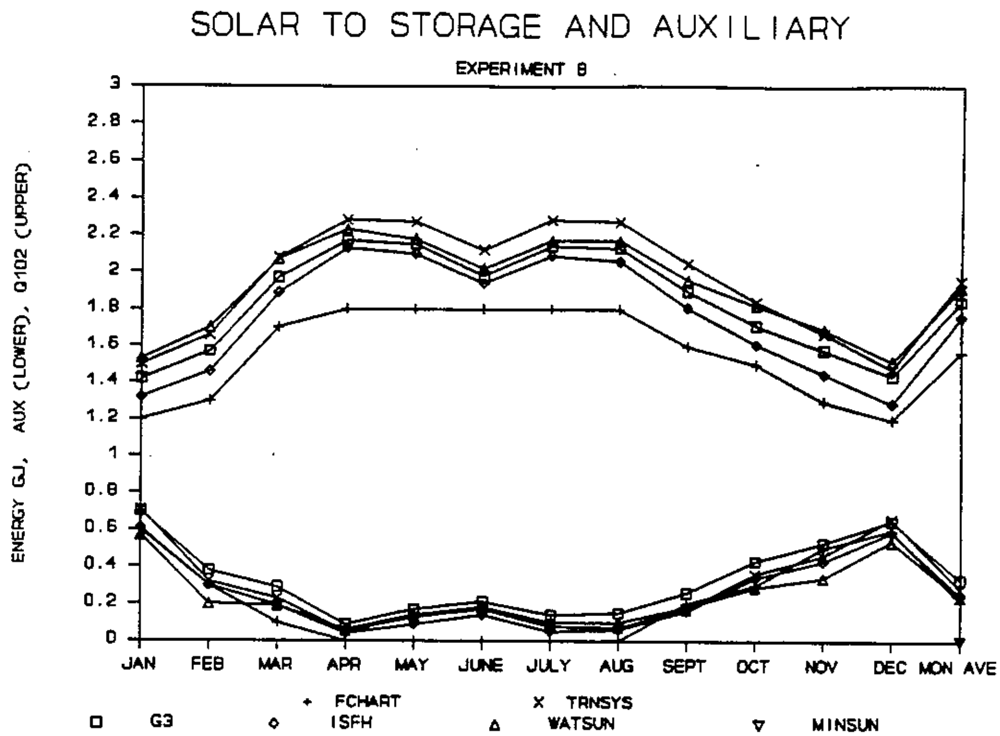

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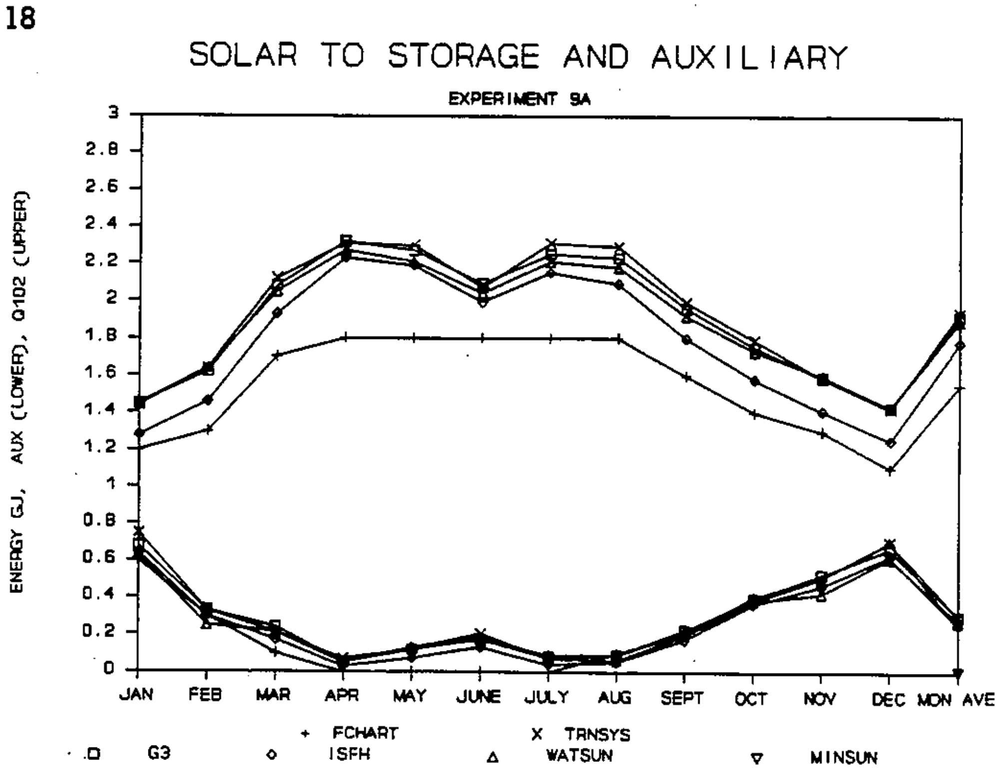

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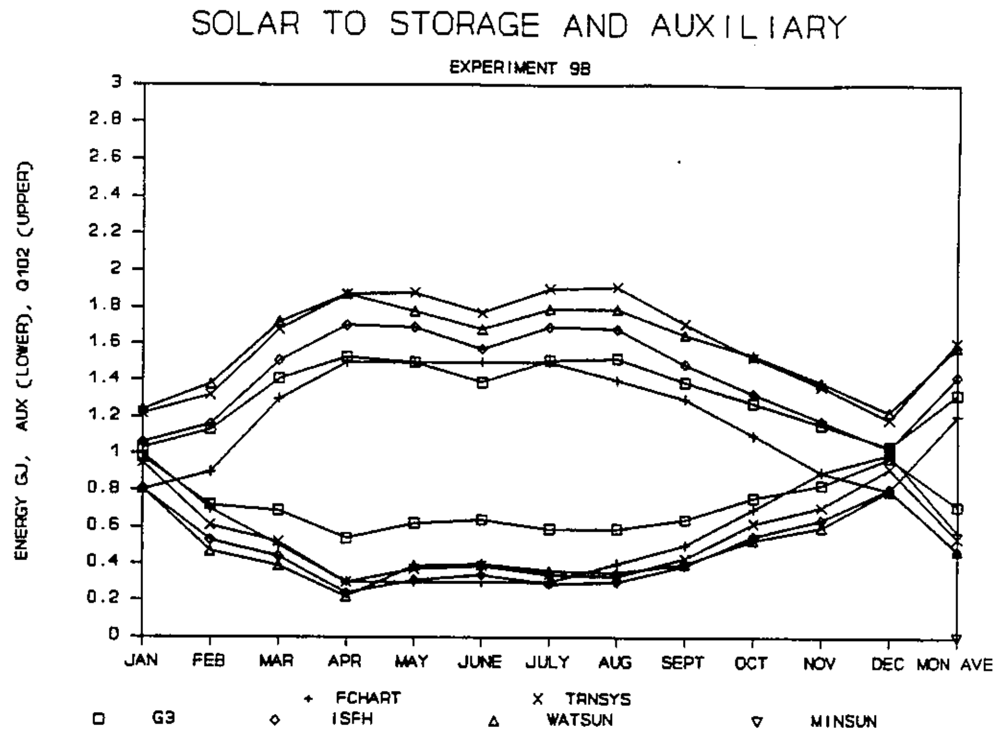

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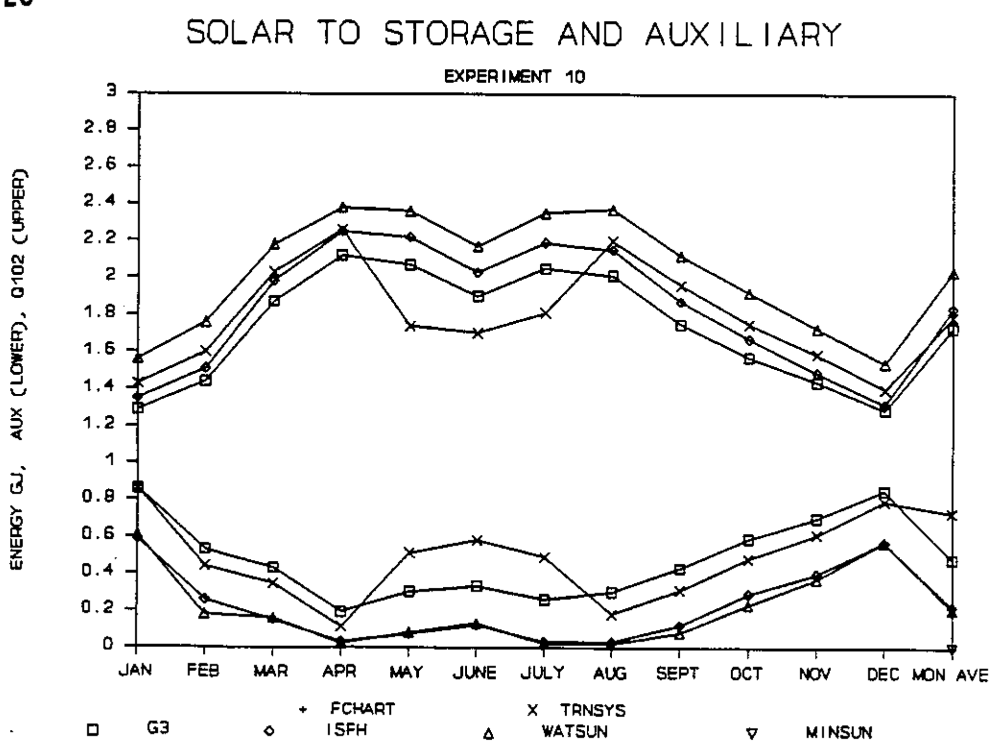

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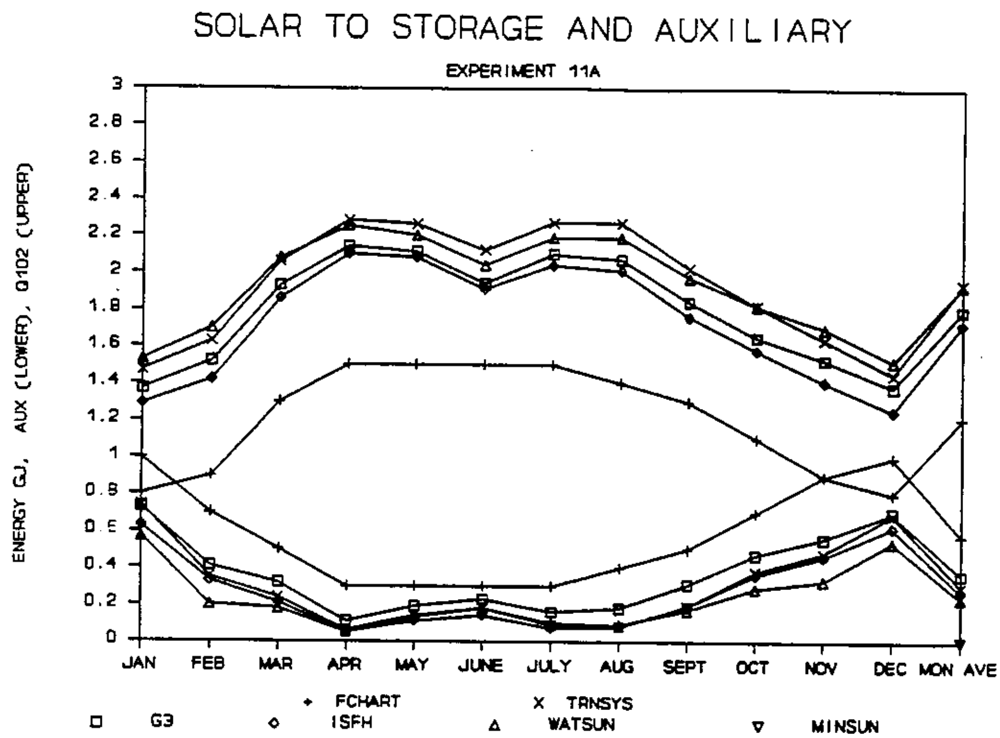

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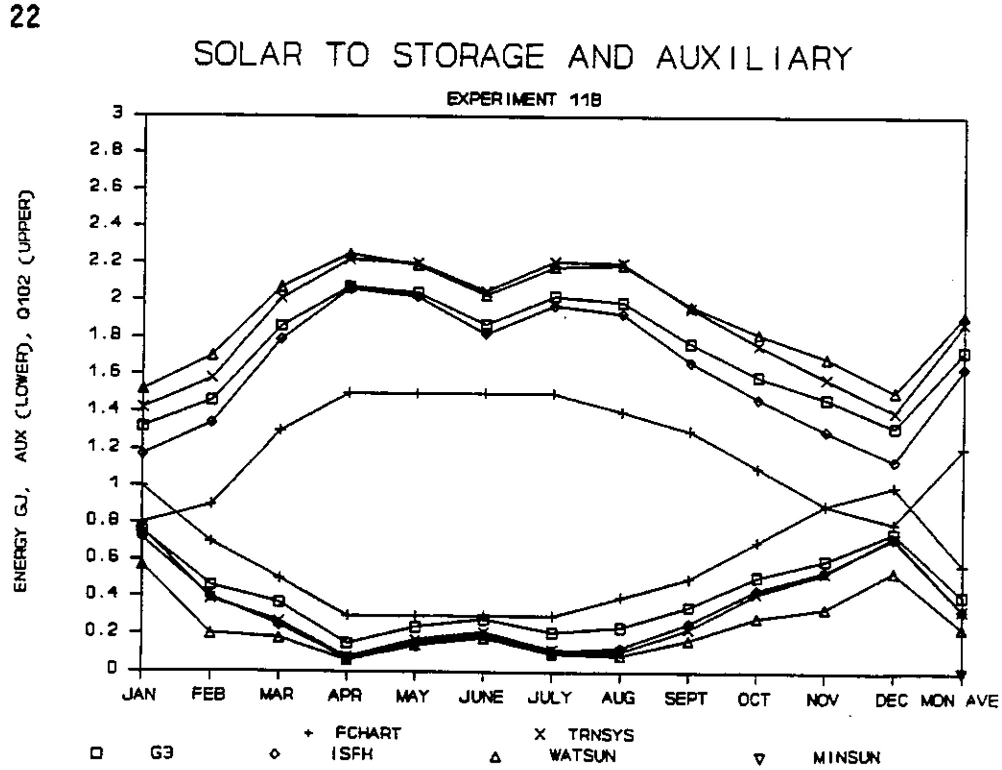

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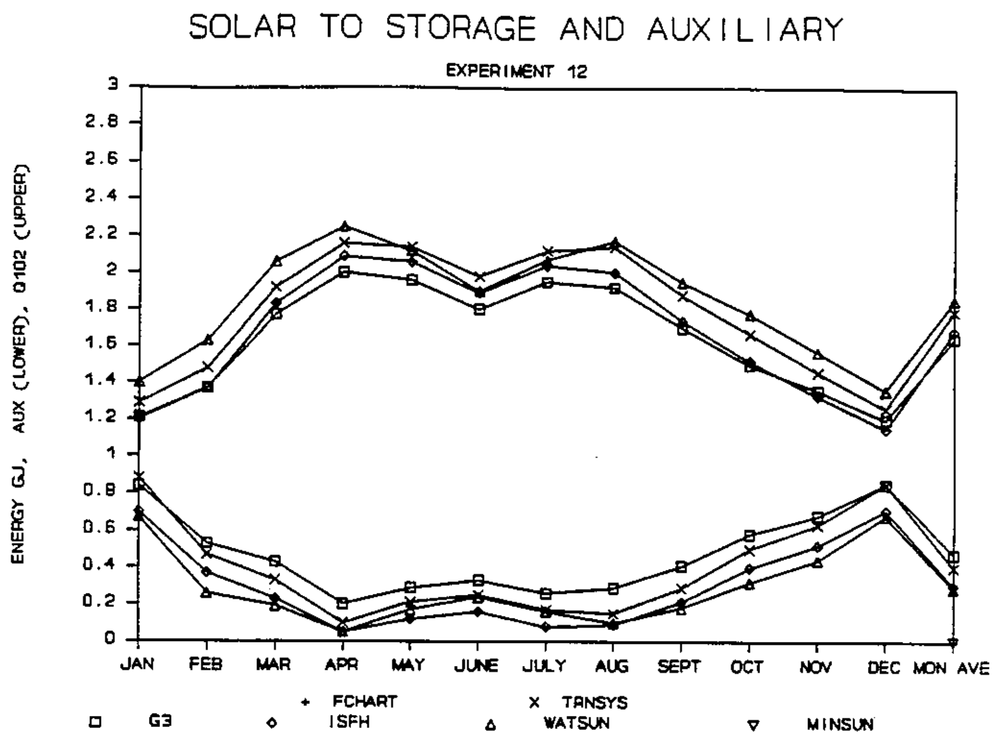

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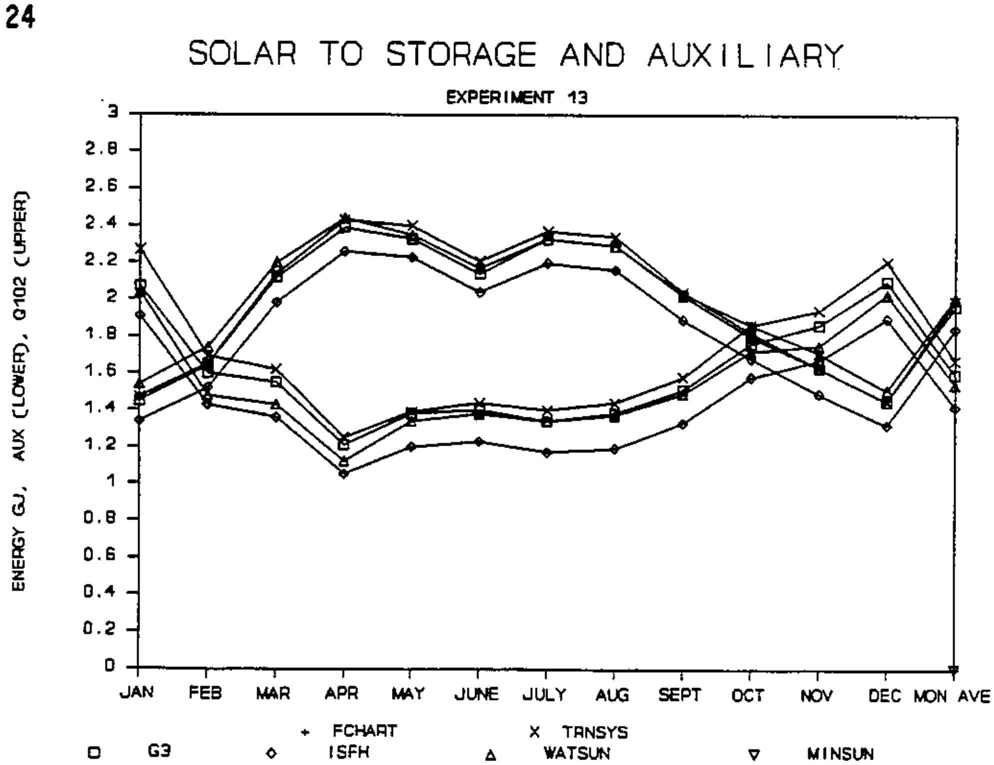

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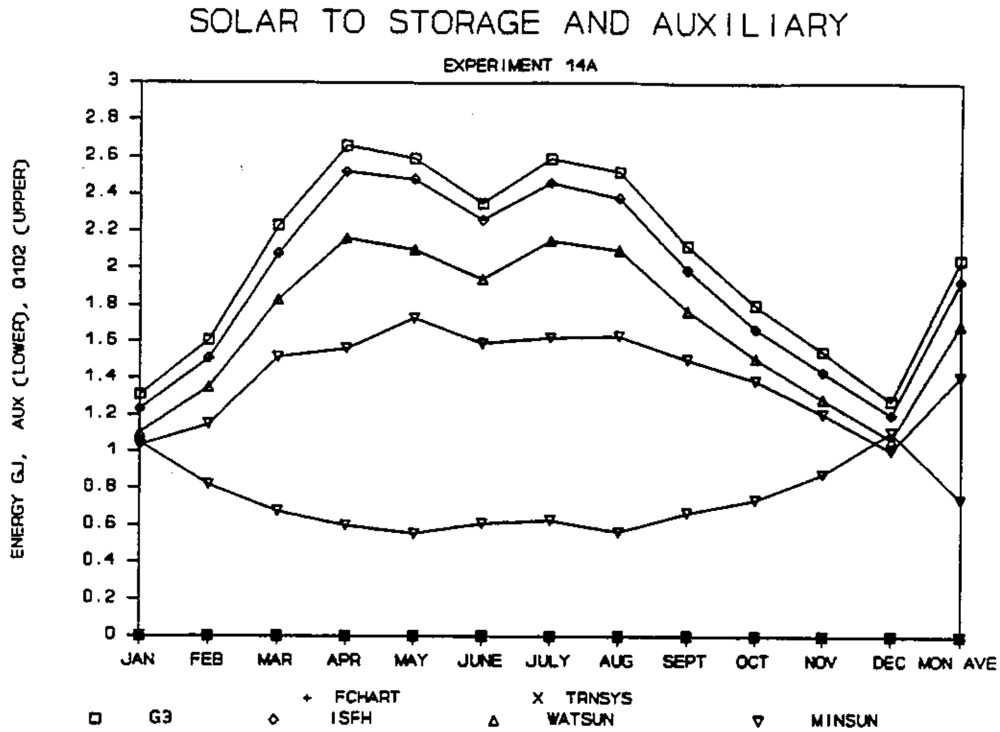

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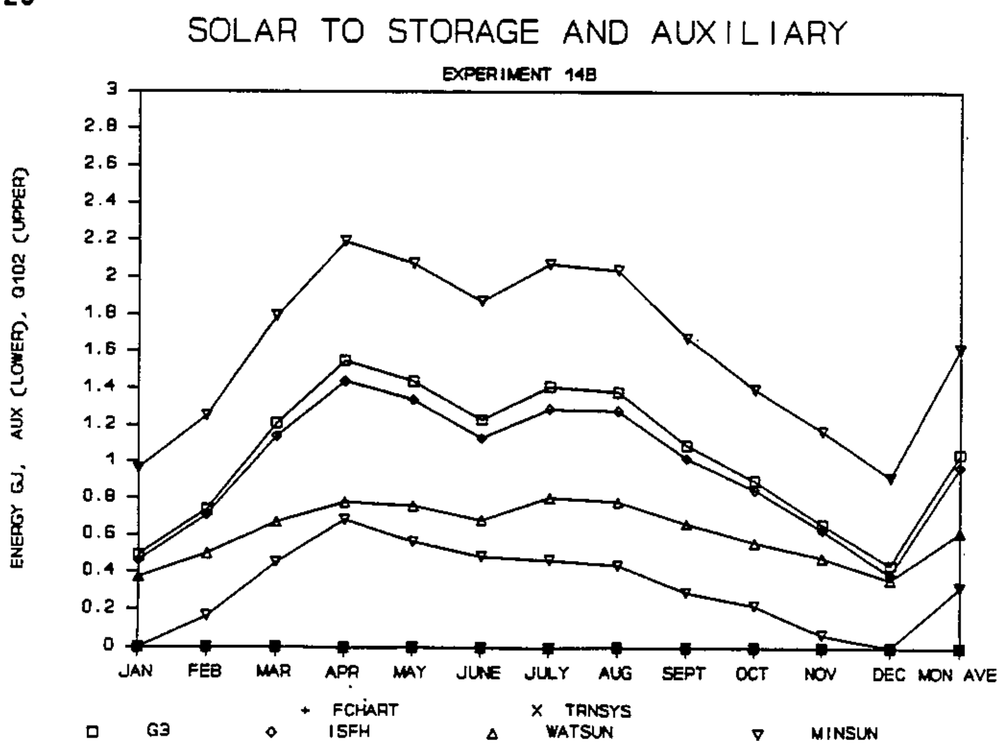

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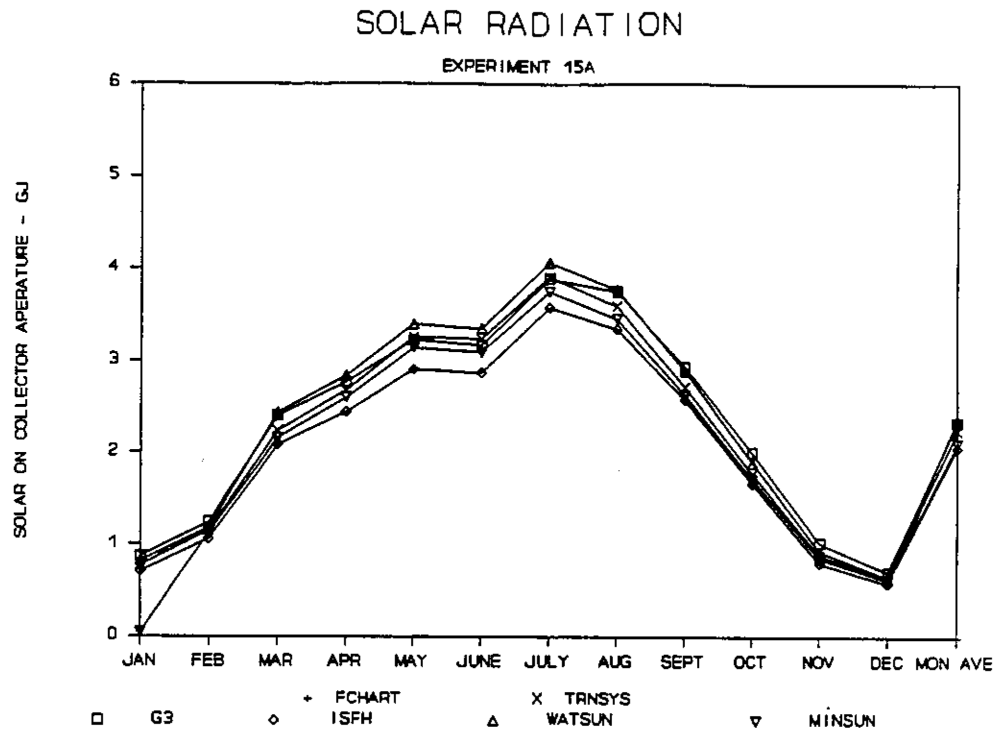

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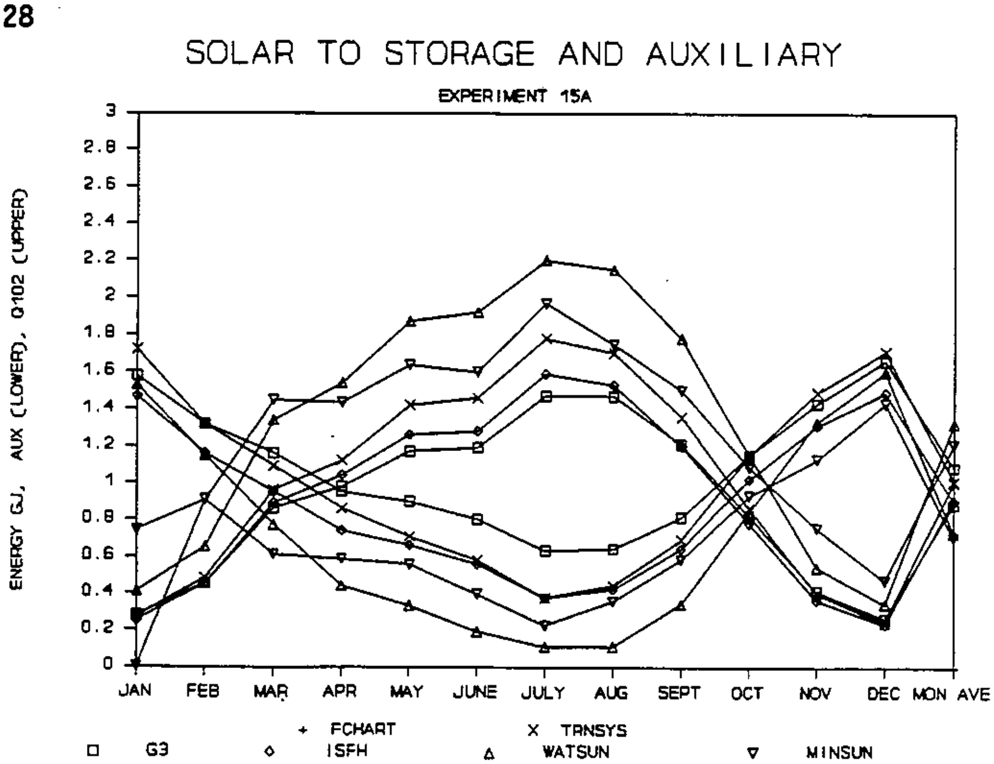

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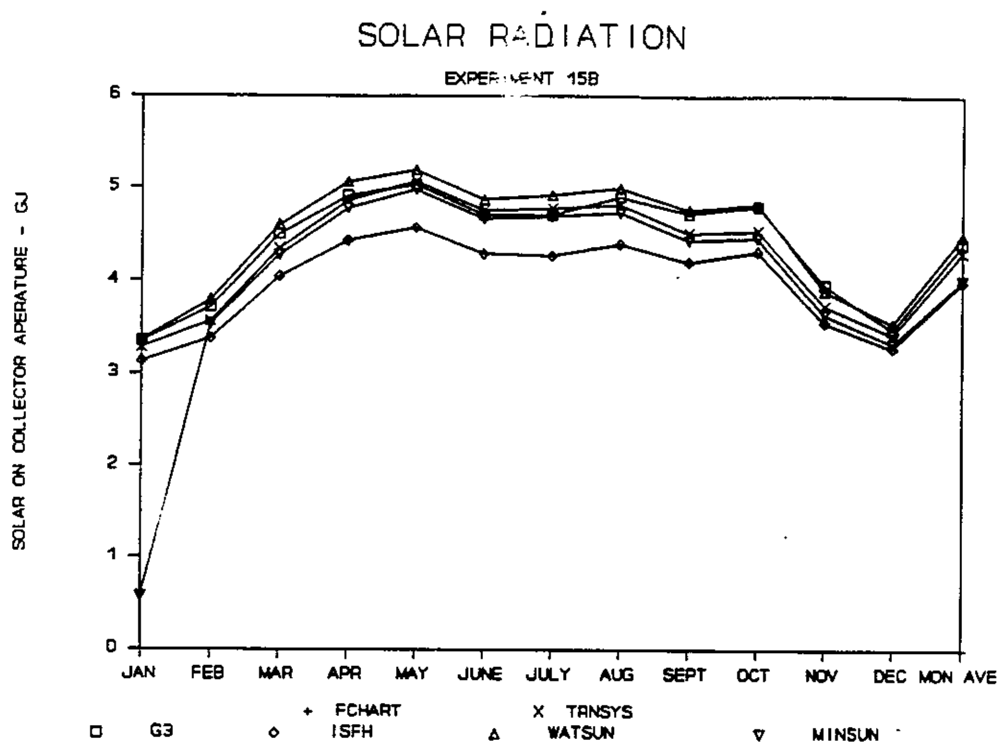

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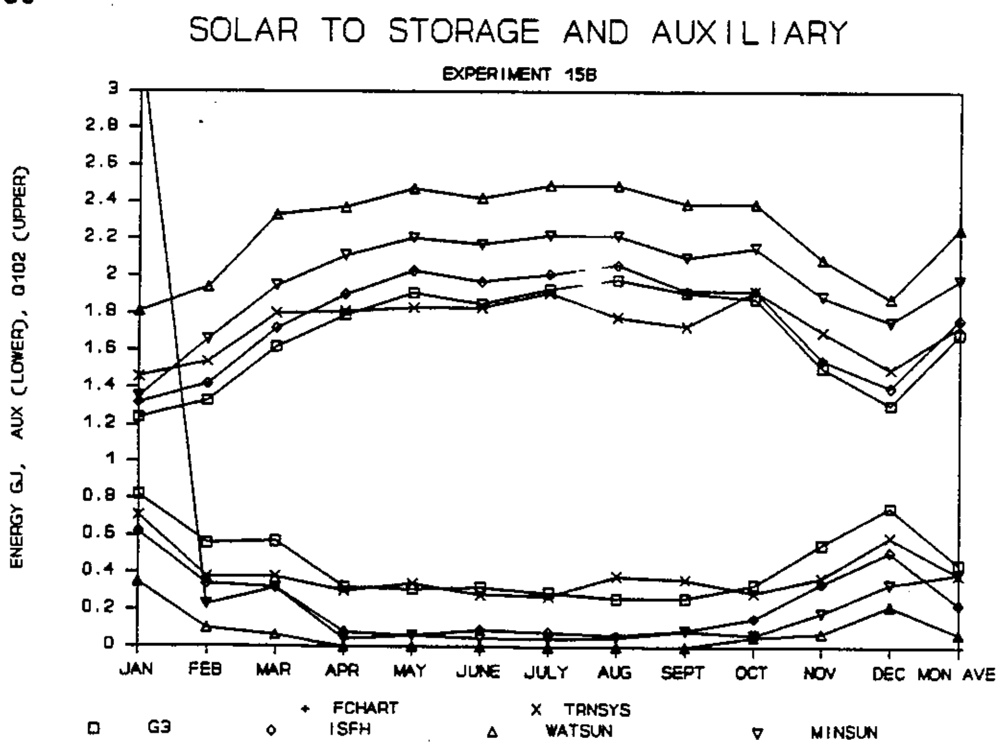

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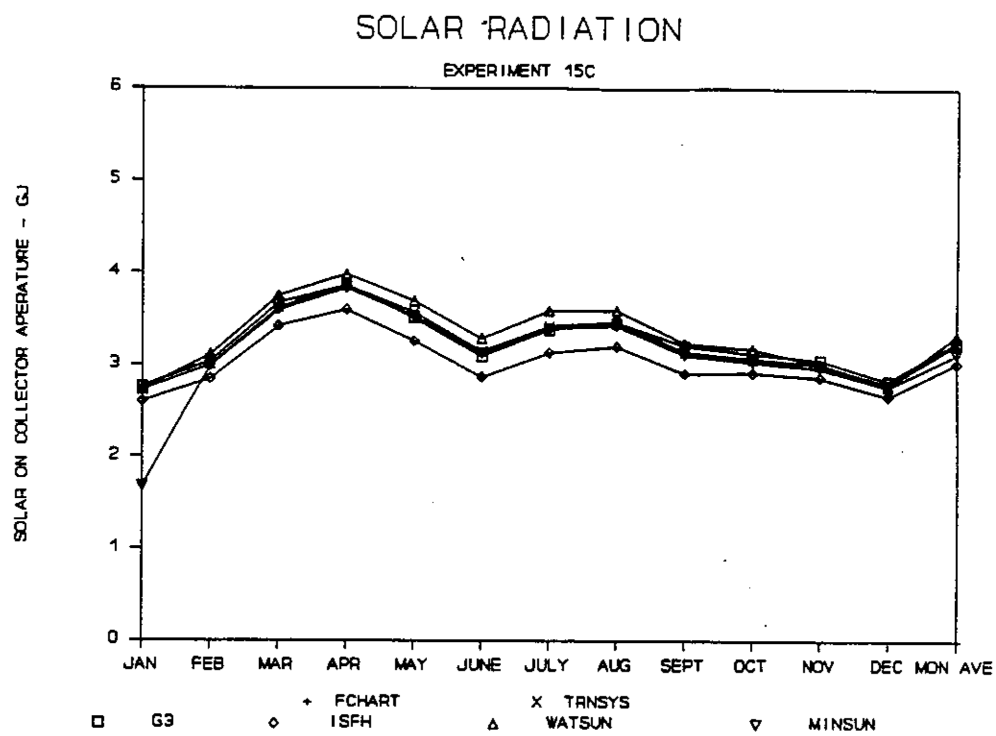


Figure 32

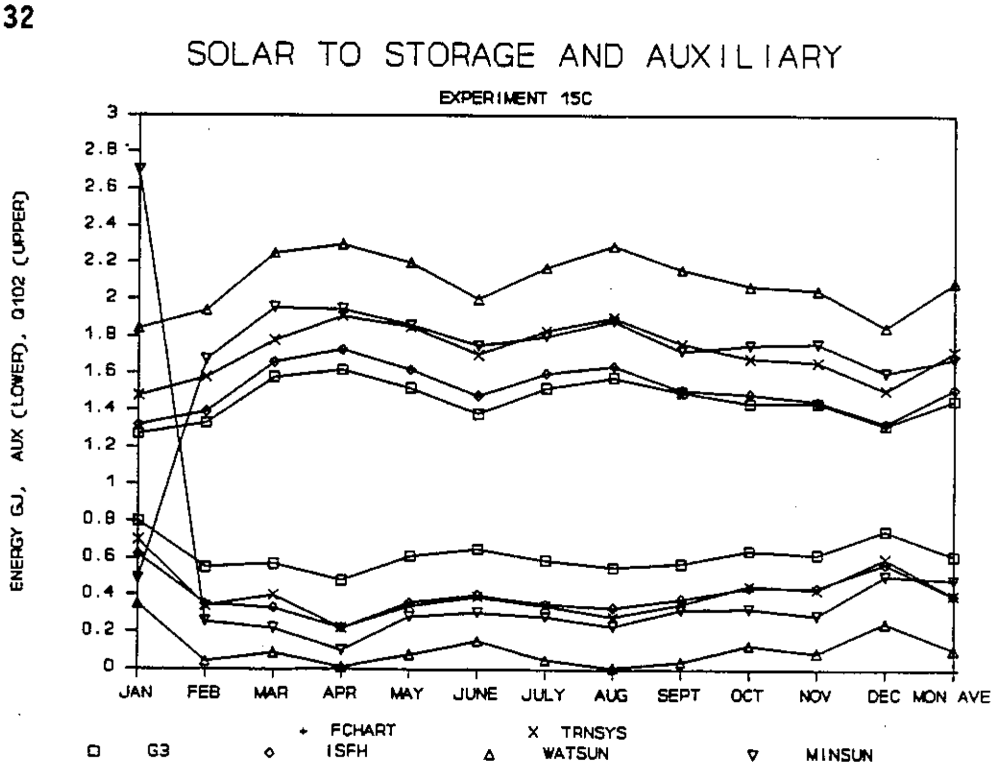


Figure 33

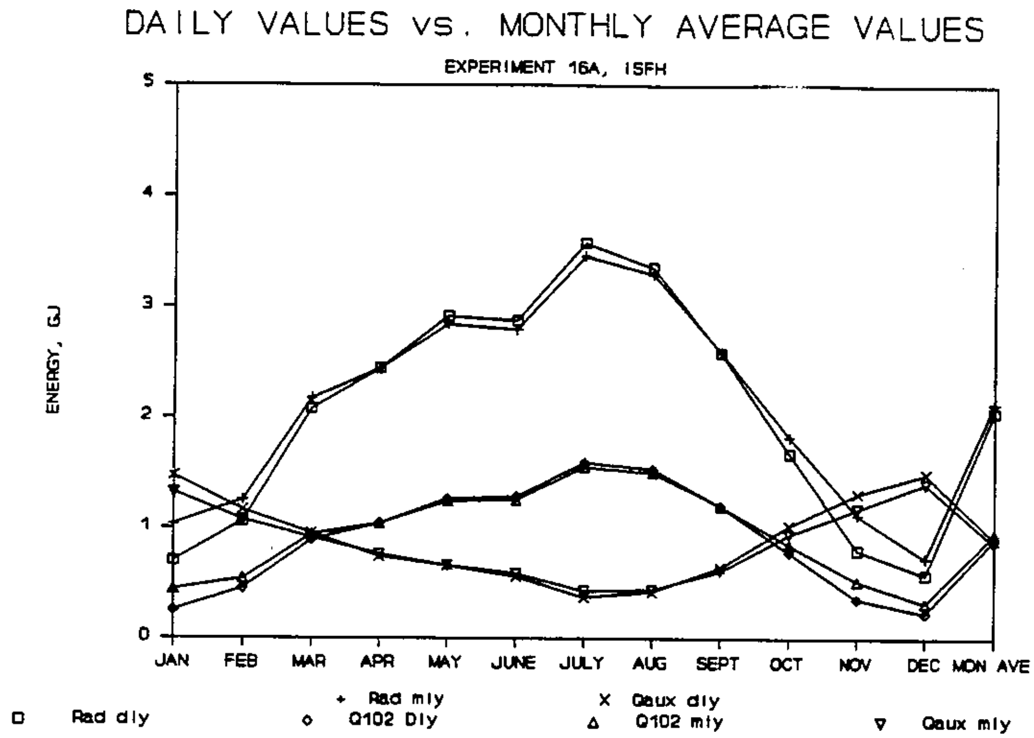


Figure 34

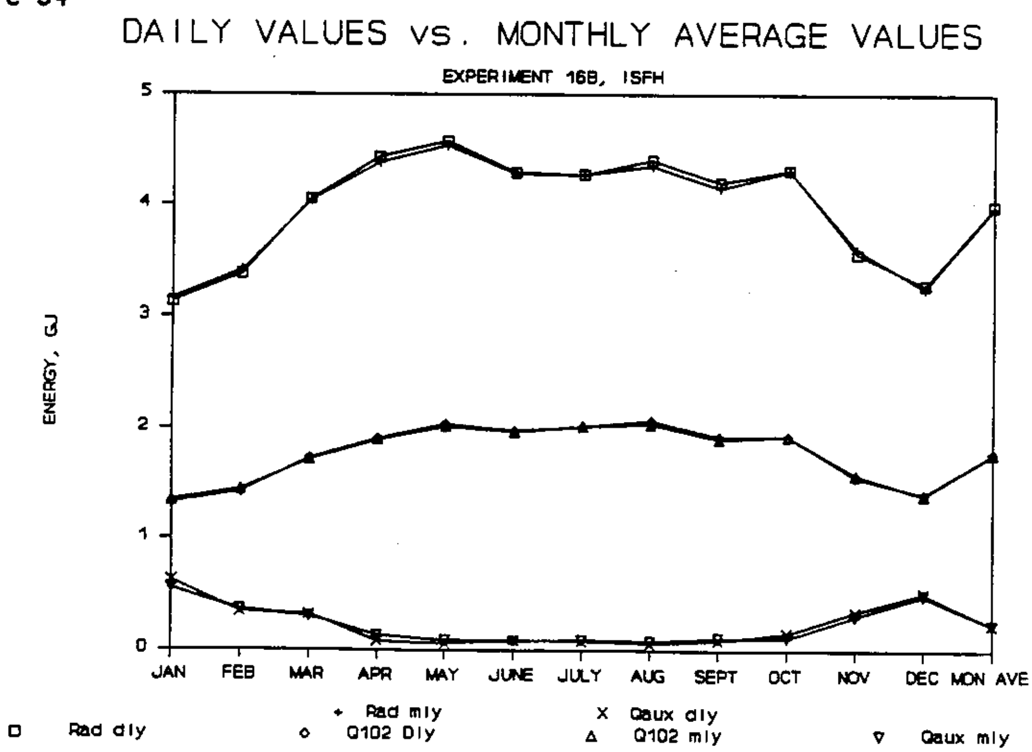
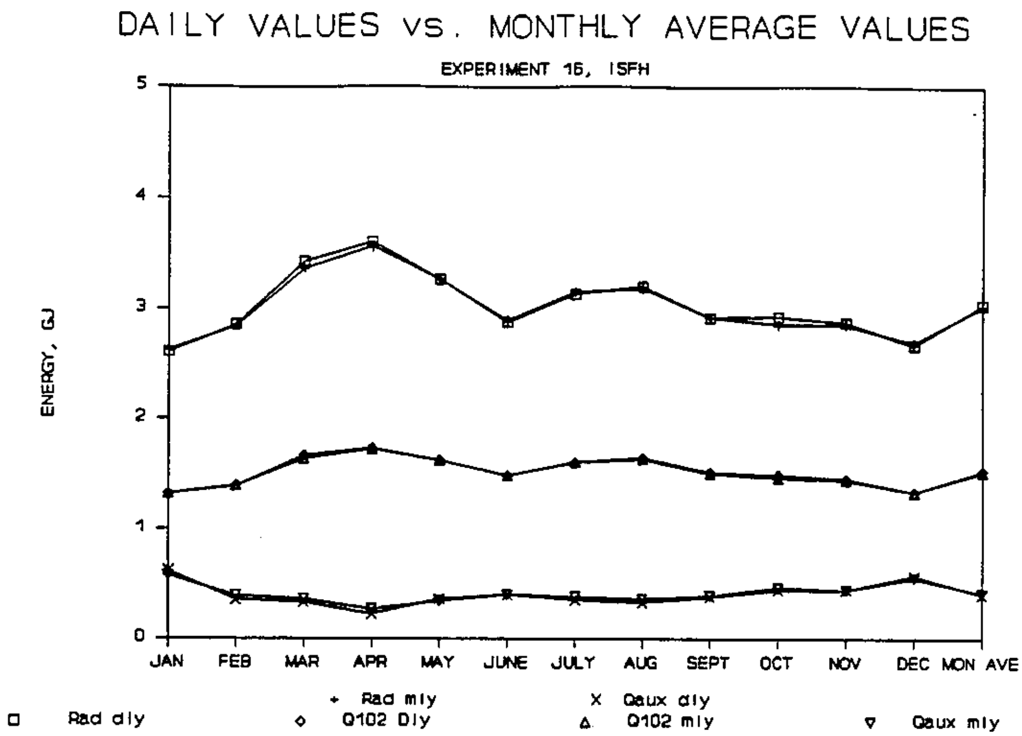


Figure 35



DAILY VALUES vs. MONTHLY AVERAGE VALUES
EXPERIMENT 16, ISFH
ENERGY, GJ
0
1
2
3
4
5
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
MON AVE
Rad mly
Qaux dly
Rad dly
Q102 Dly
Q102 mly
Qaux mly

Figure 36

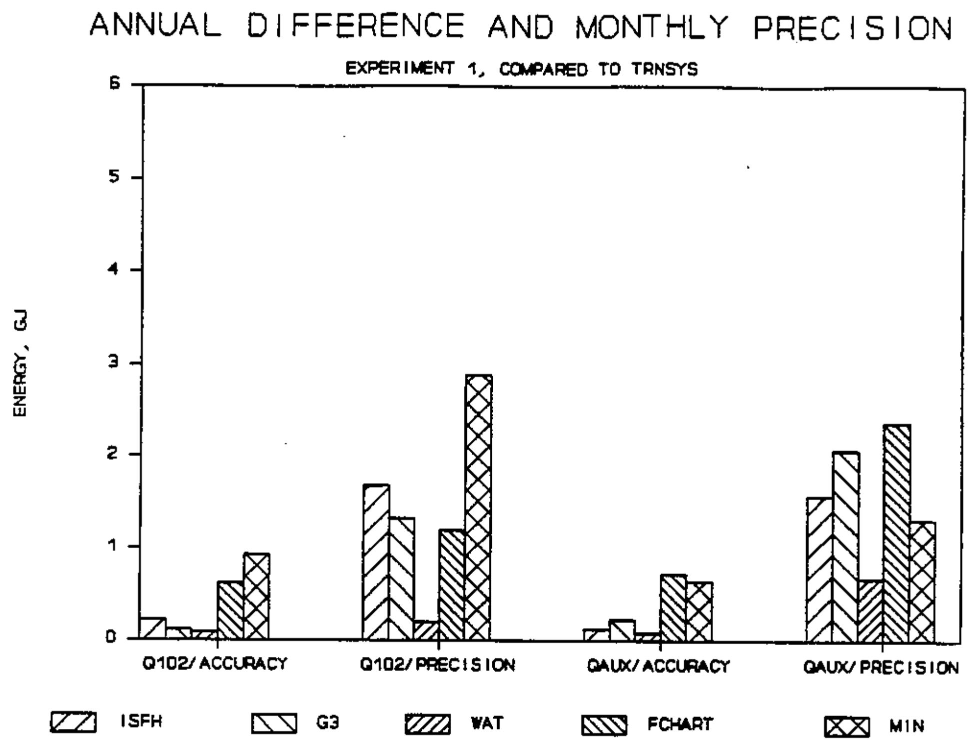


Figure 37

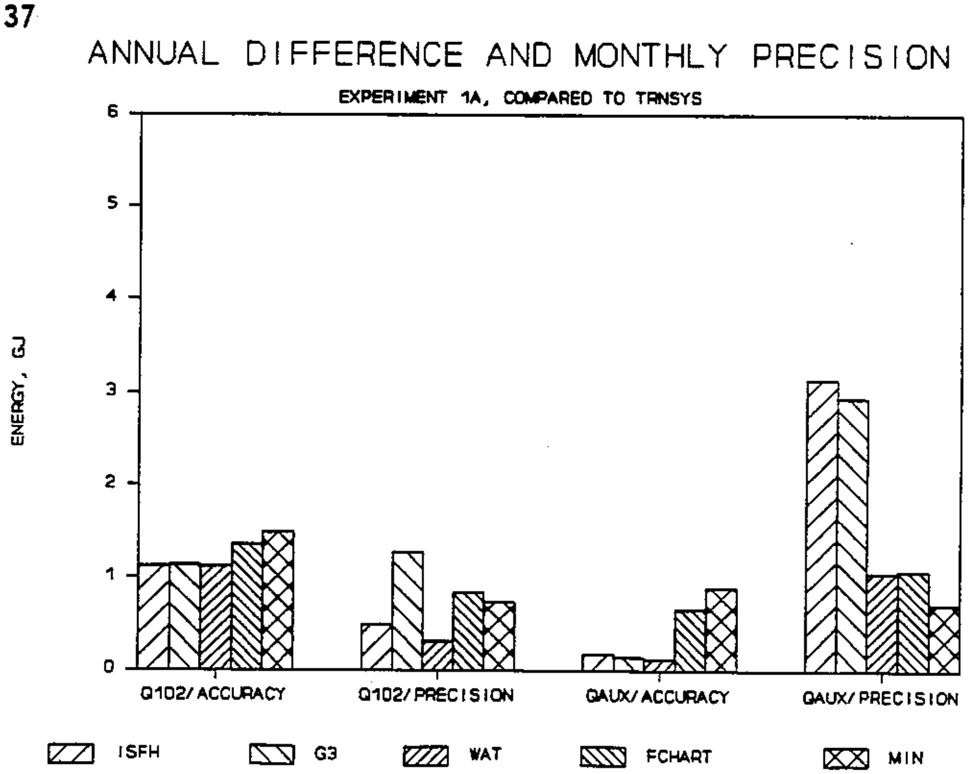


Figure 38

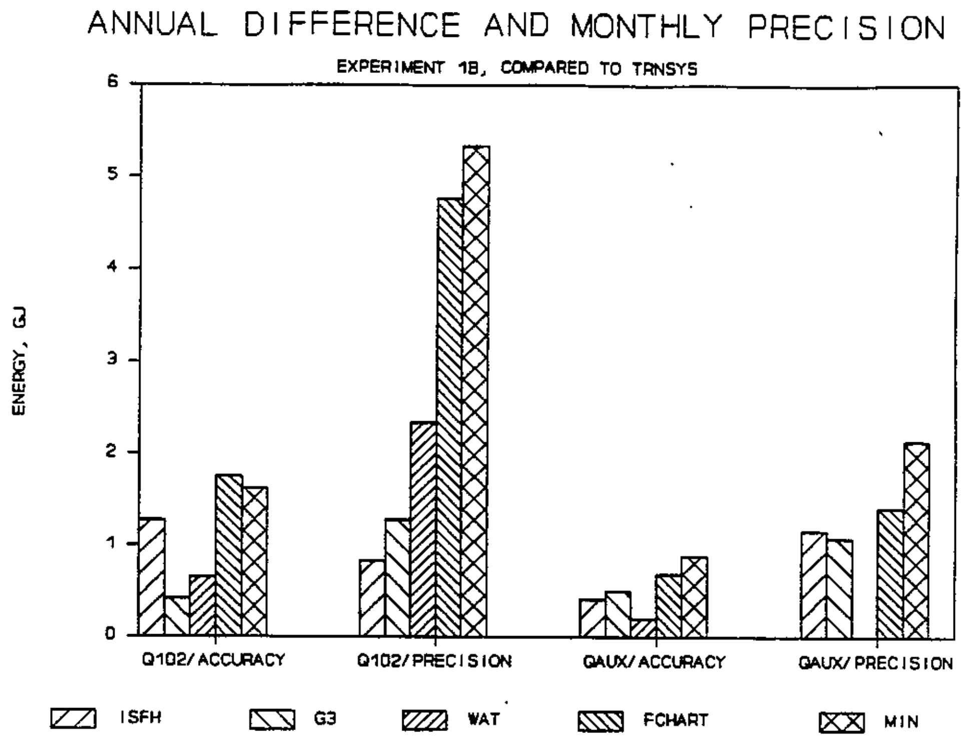


Figure 39

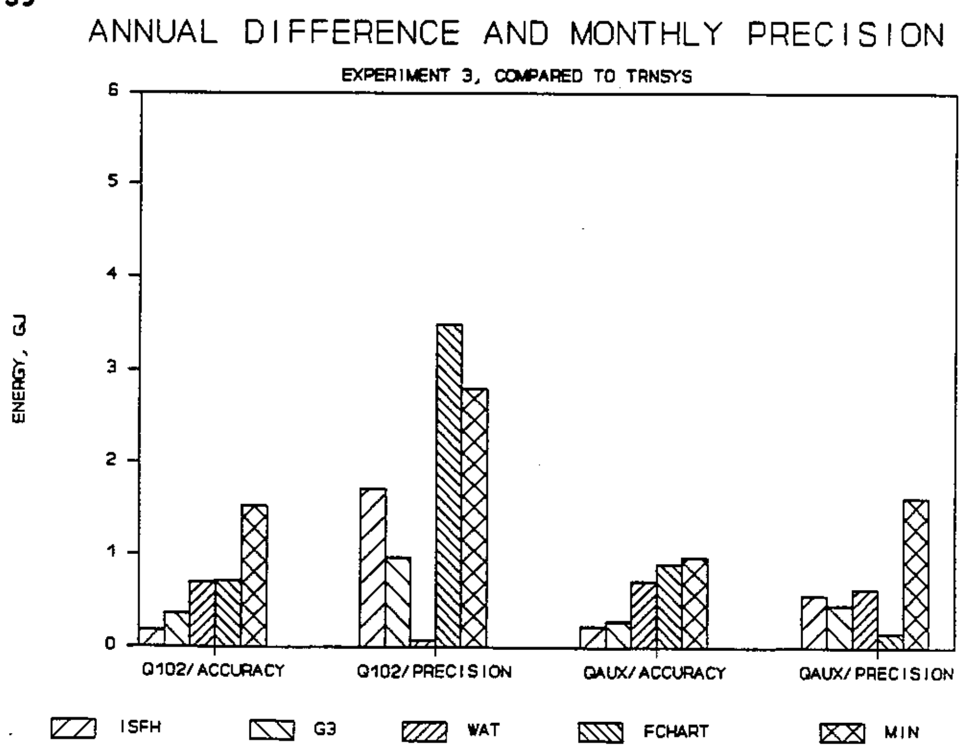


Figure 40

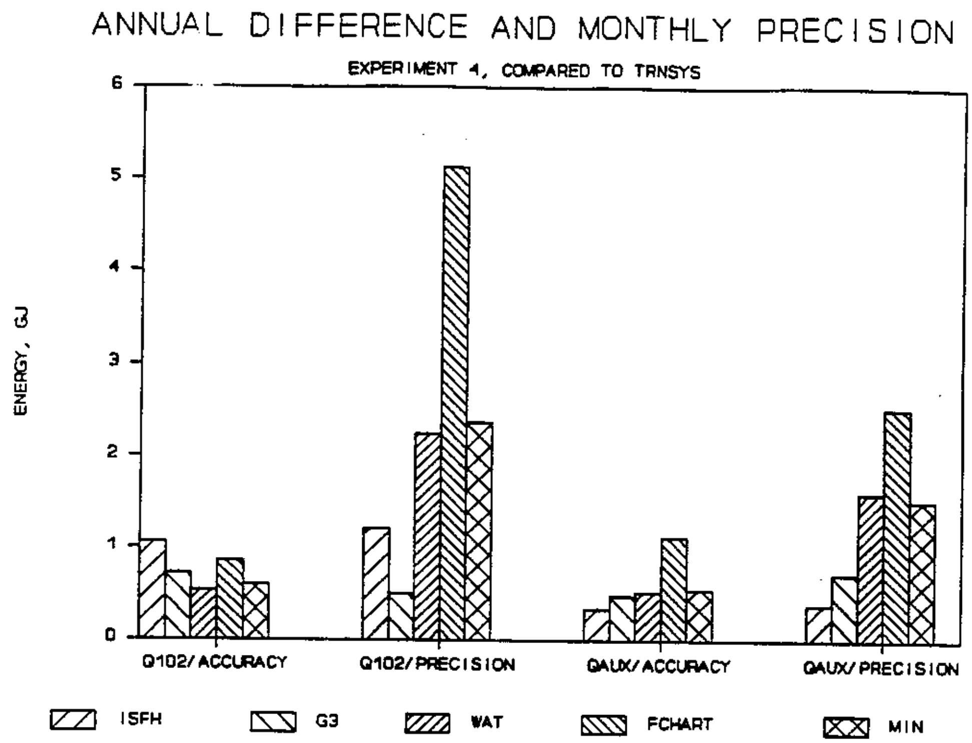


Figure 41

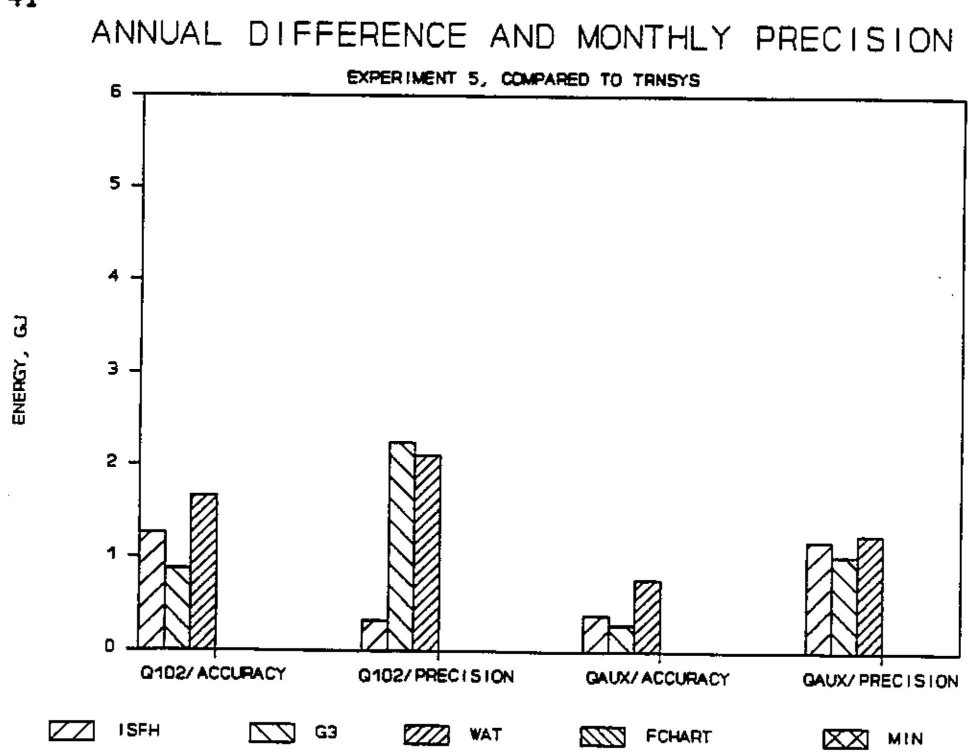


Figure 42

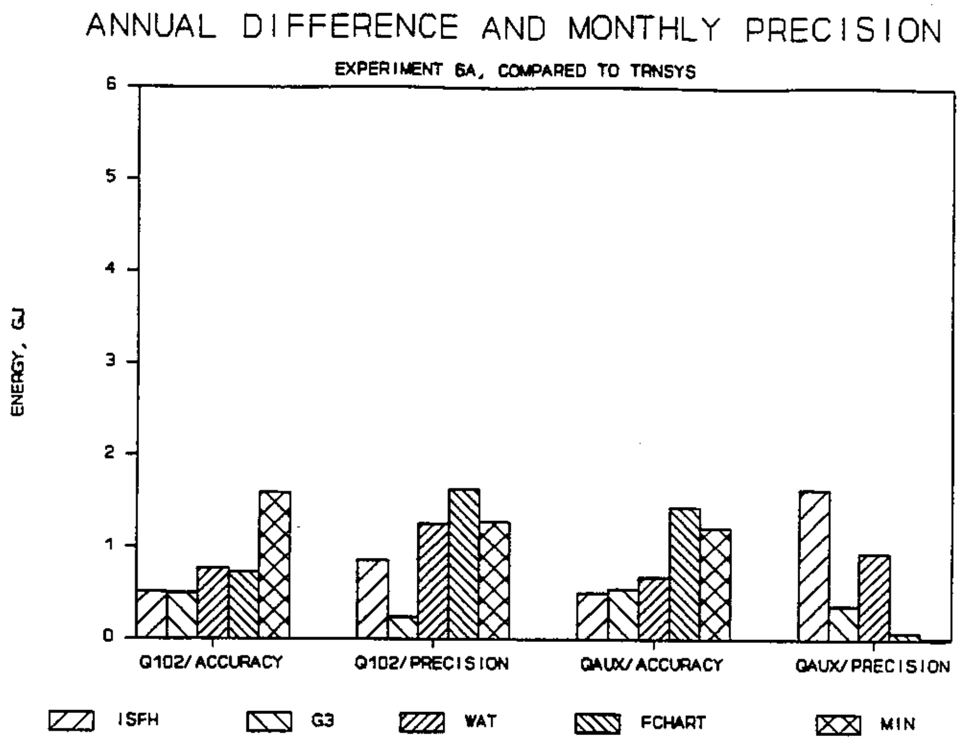


Figure 43

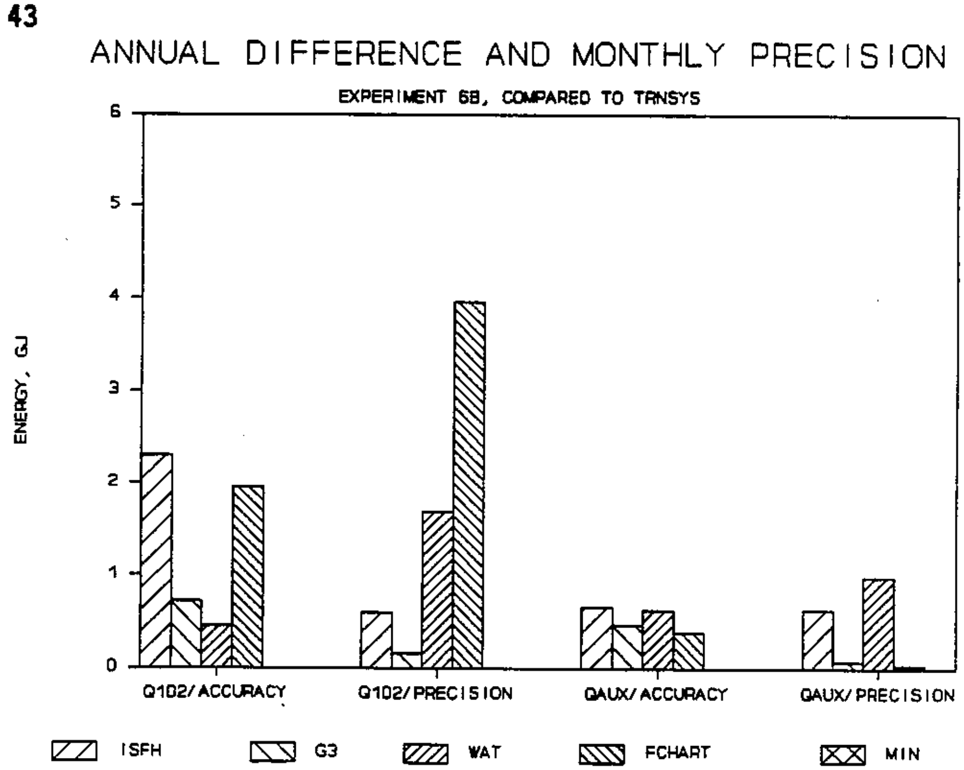


Figure 44

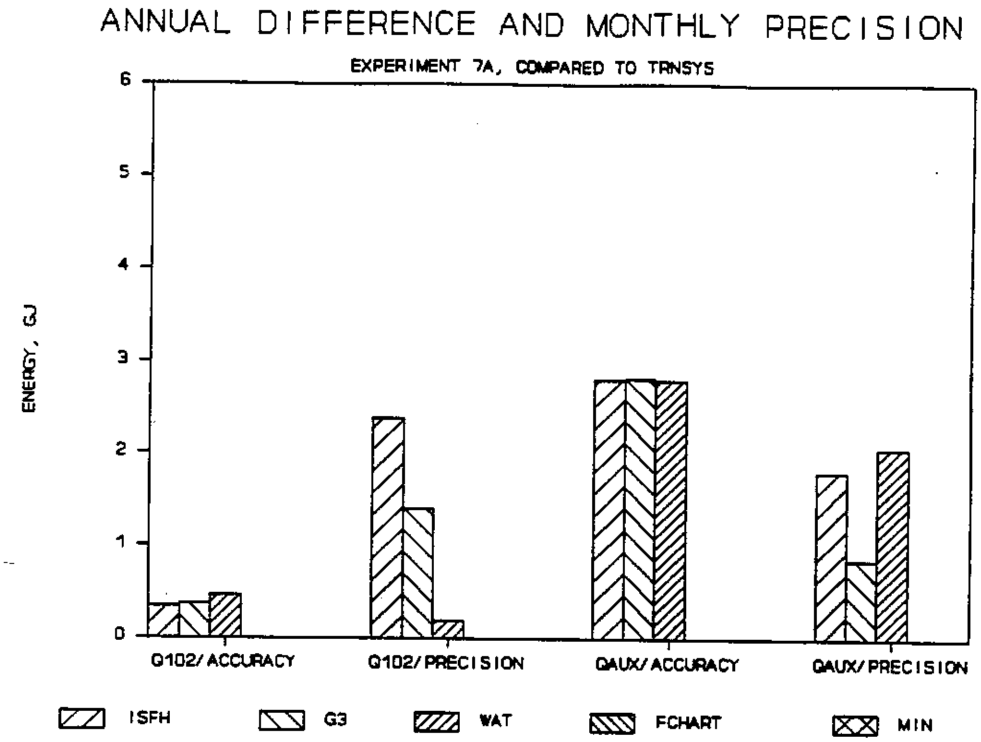


Figure 45

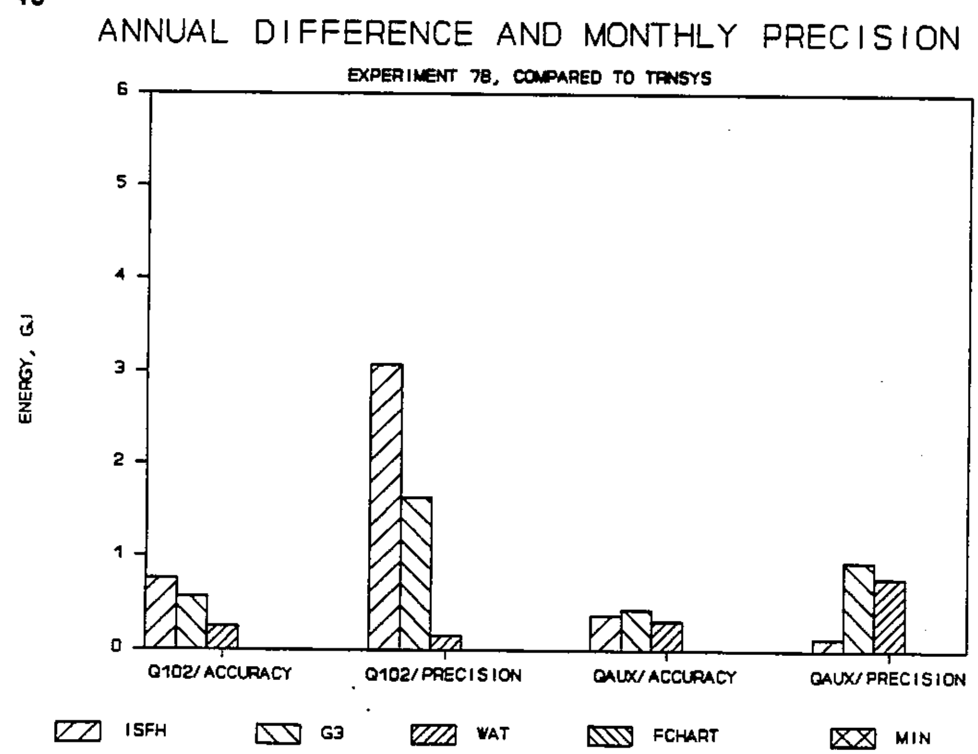


Figure 46

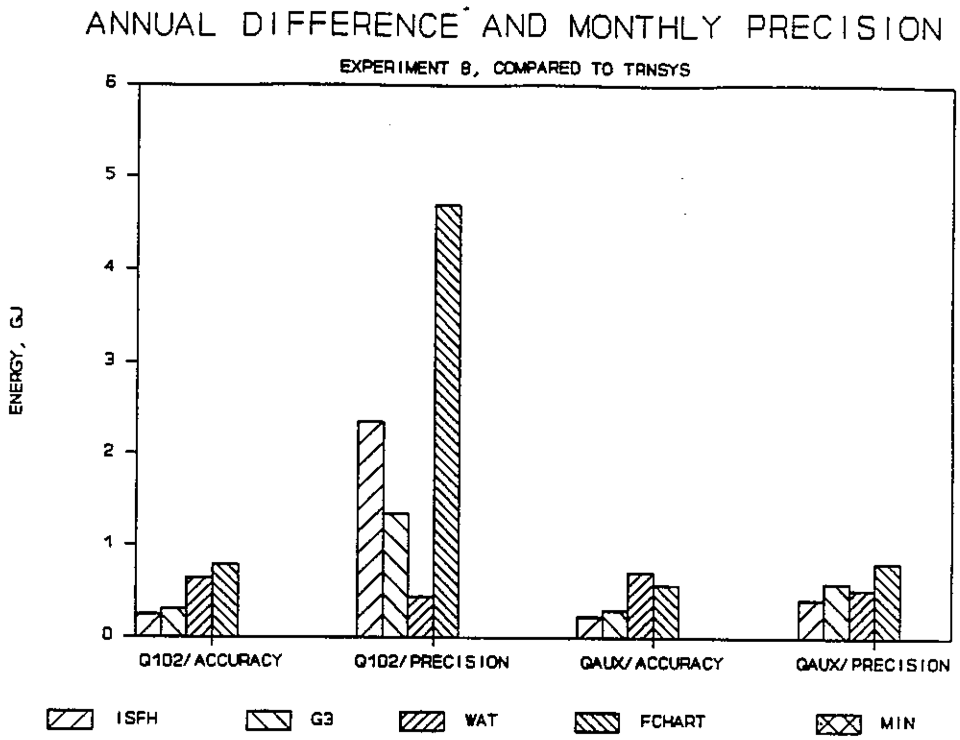


Figure 47

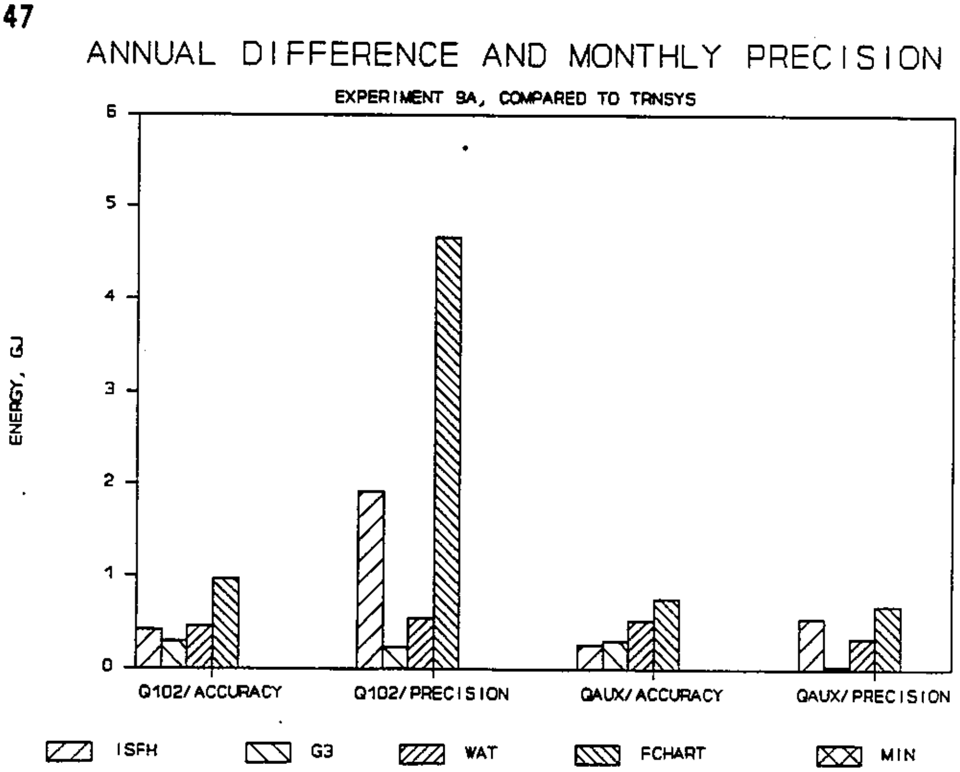


Figure 48

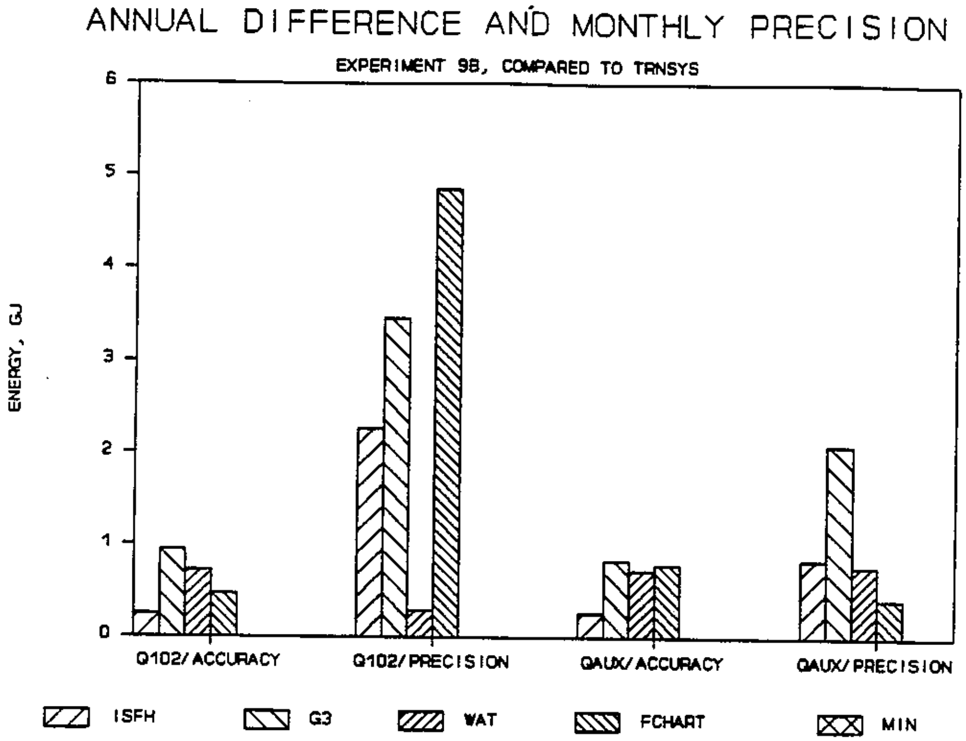


Figure 49

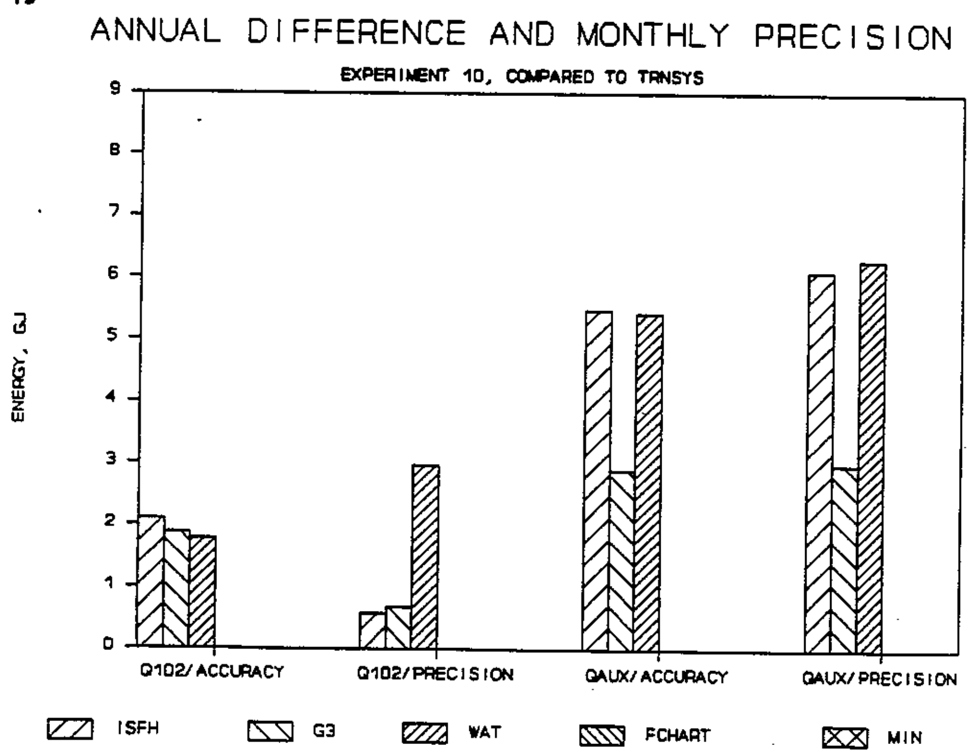


Figure 50

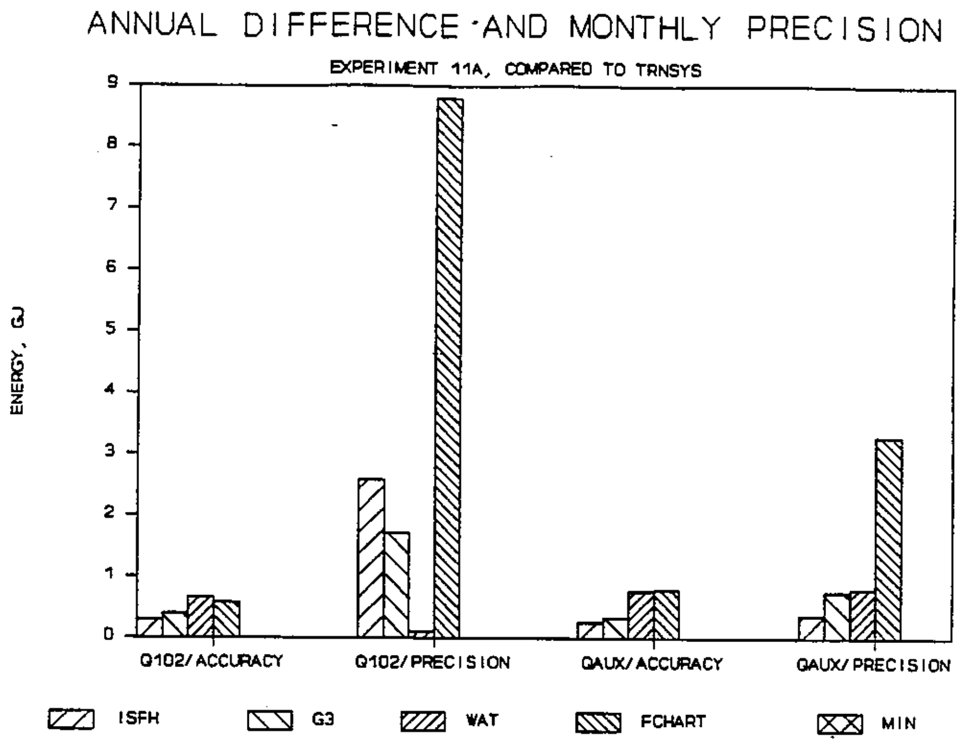


Figure 51

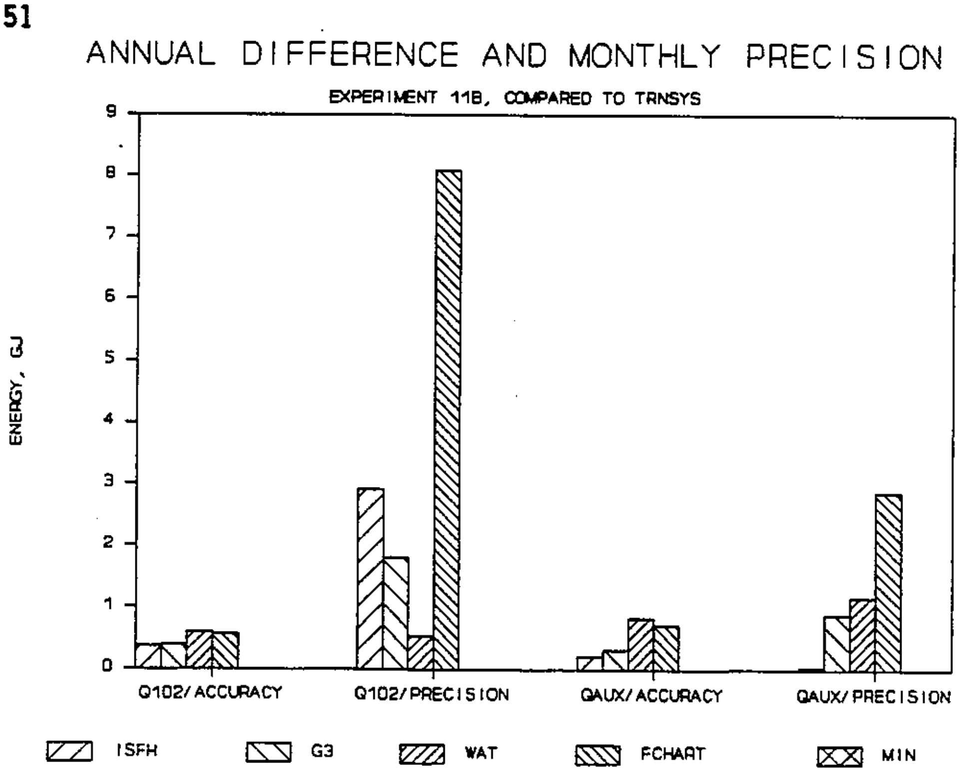


Figure 52

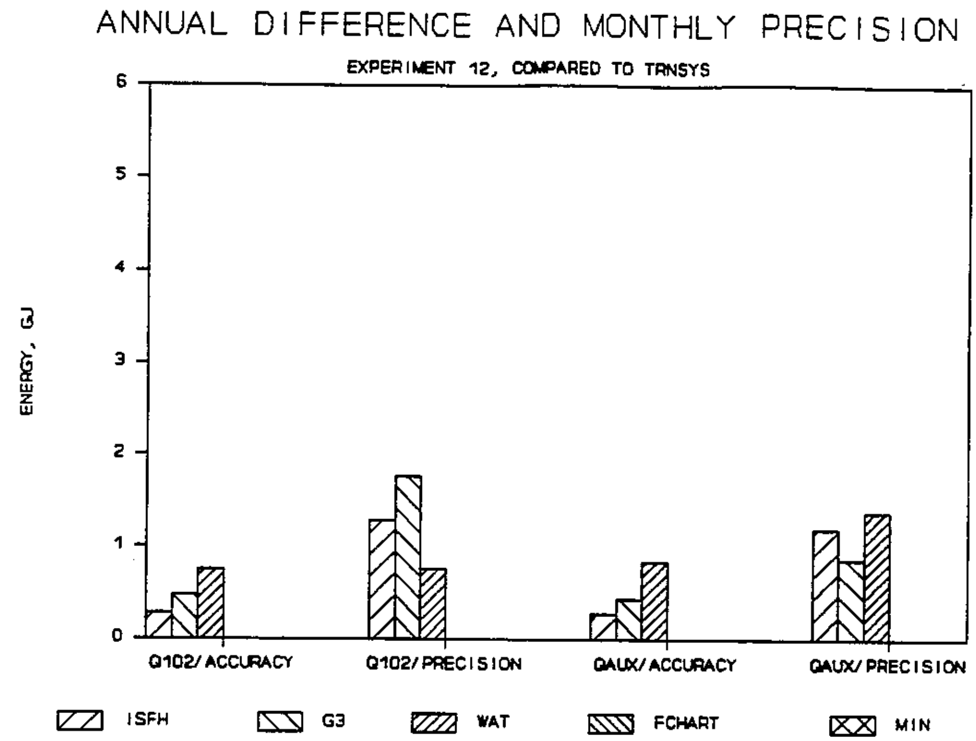


Figure 53

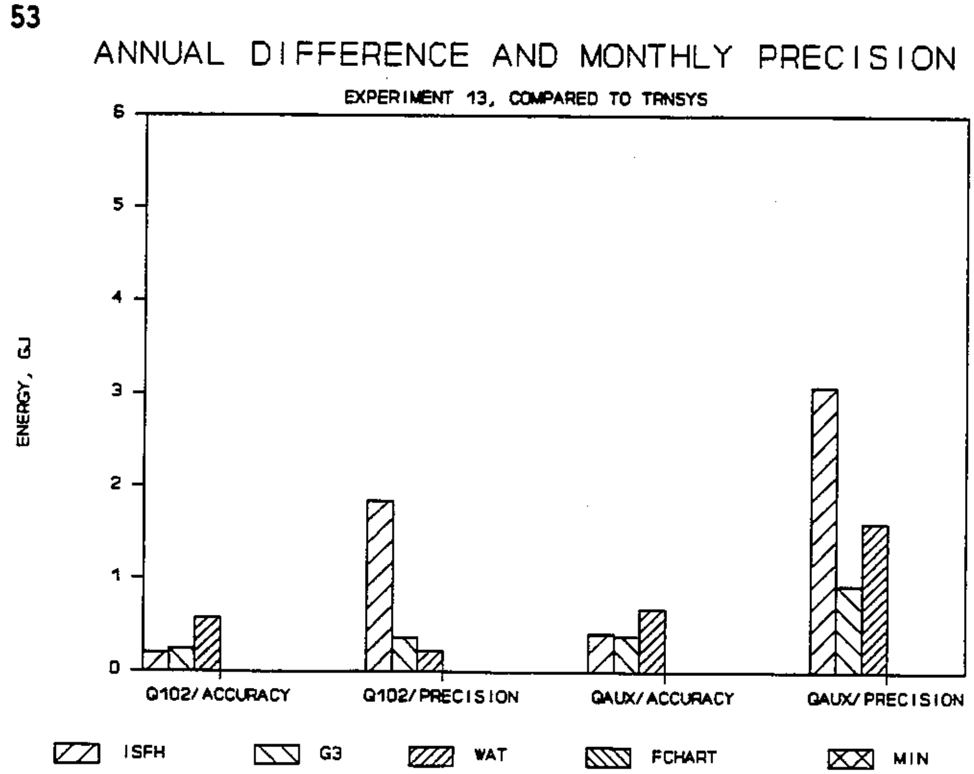


Figure 54

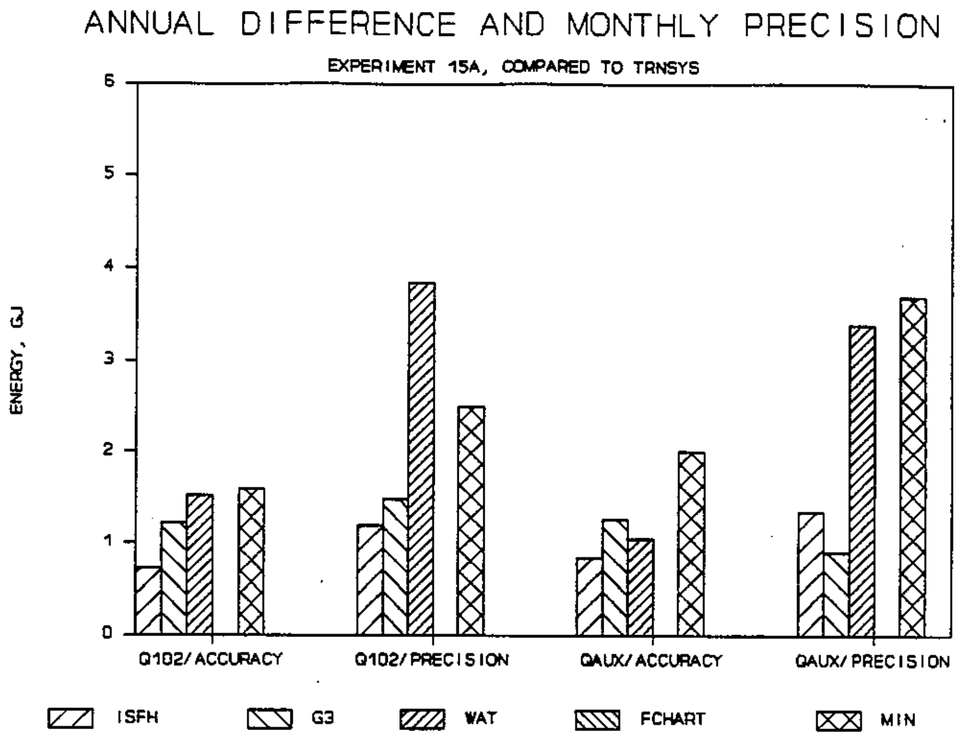


Figure 55

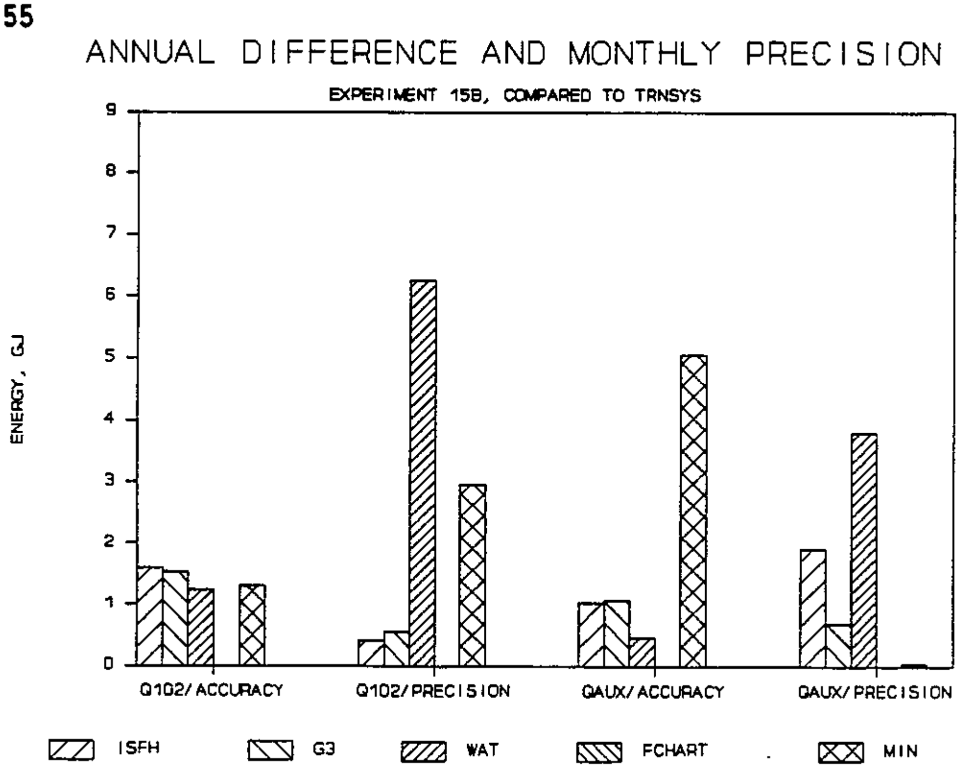
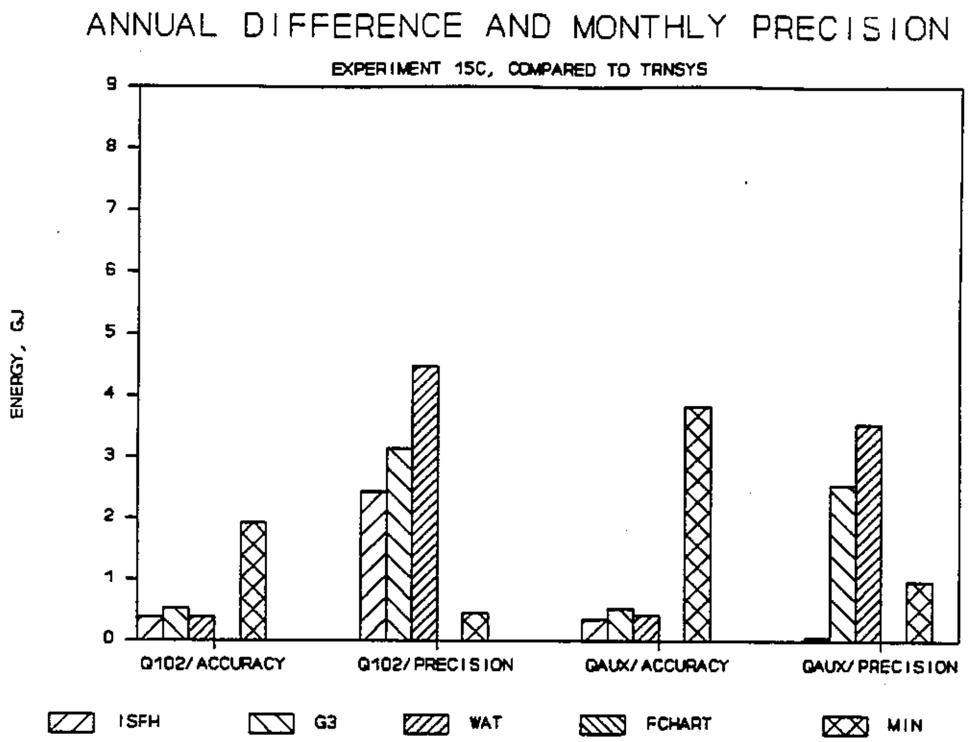


Figure 56



ANNUAL DIFFERENCE AND MONTHLY PRECISION
EXPERIMENT 15C, COMPARED TO TRNSYS
ENERGY, GJ
0
1
2
3
4
5
6
7
8
9
Q102/ACCURACY
Q102/PRECISION
QAUX/ACCURACY
QAUX/PRECISION
ISFH
G3
WAT
FCHART
MIN

Figure 57

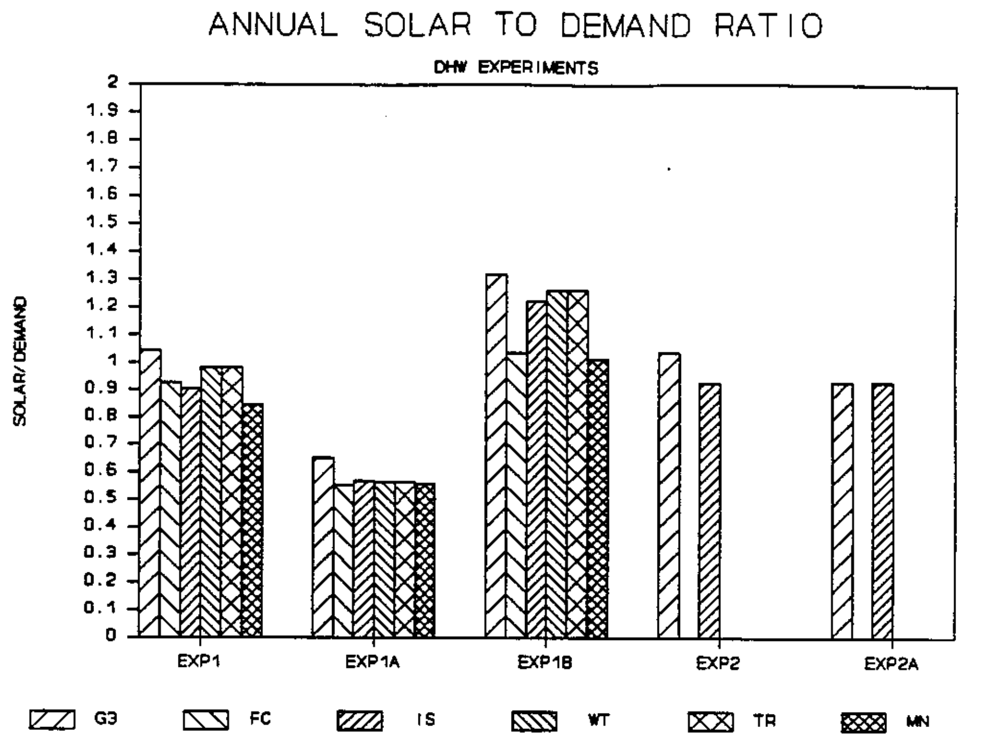


Figure 58

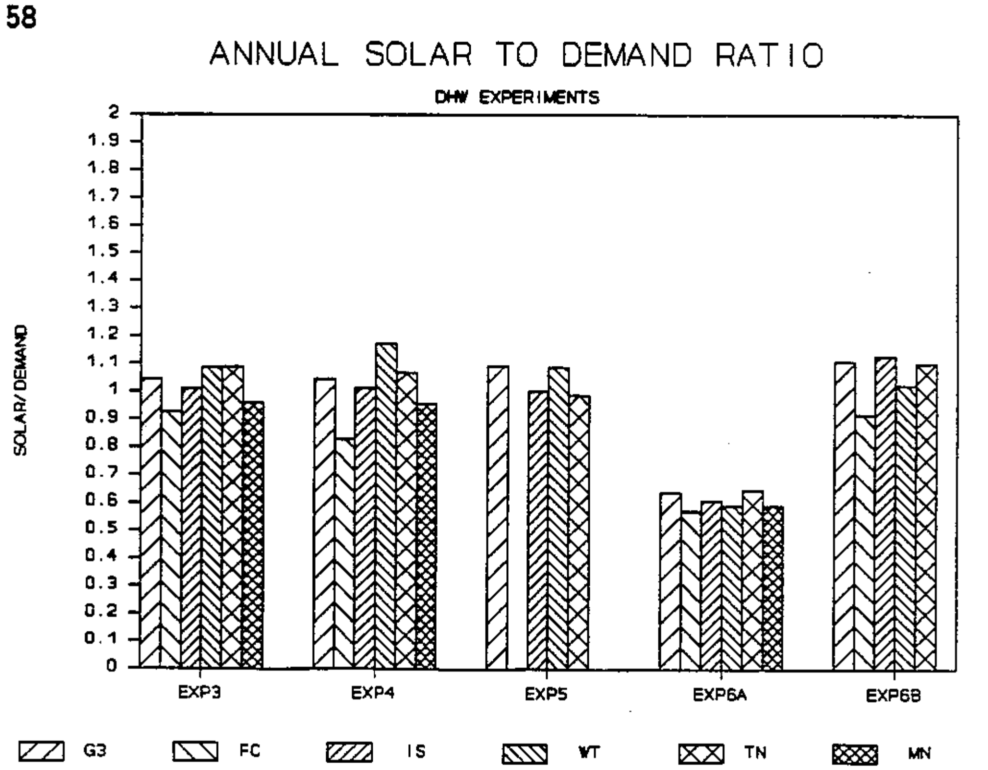


Figure 59

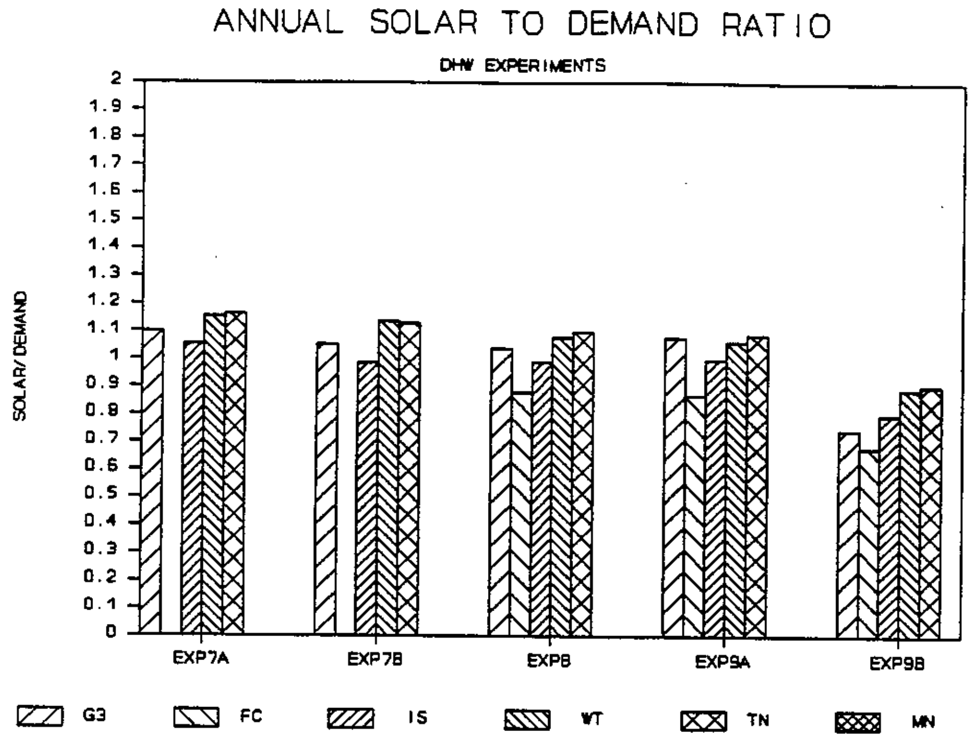


Figure 60

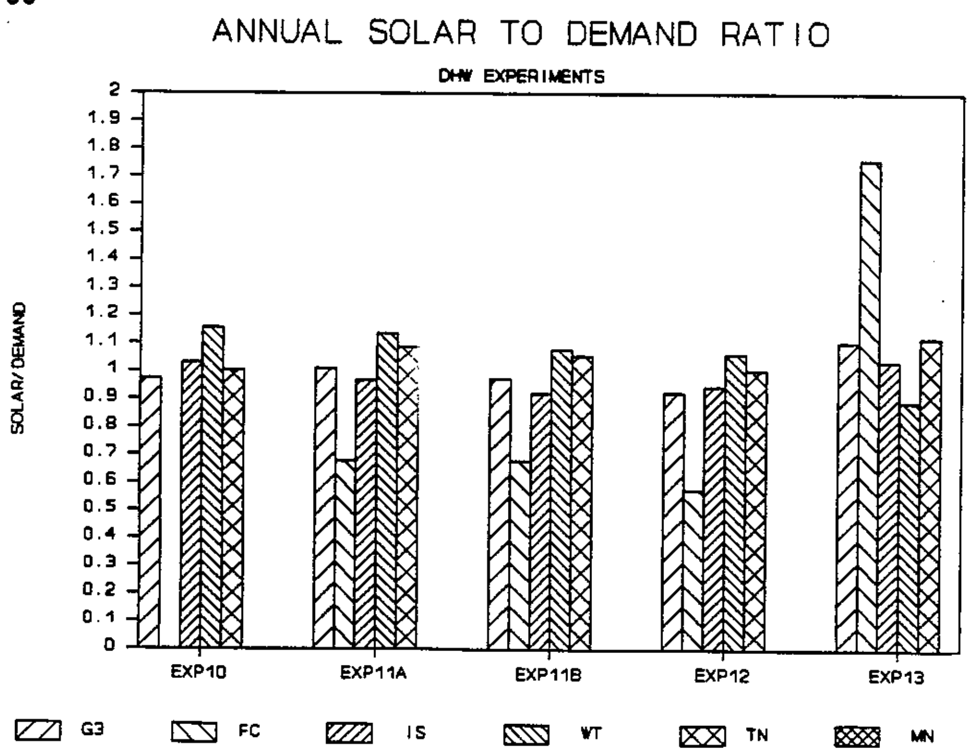


Figure 61

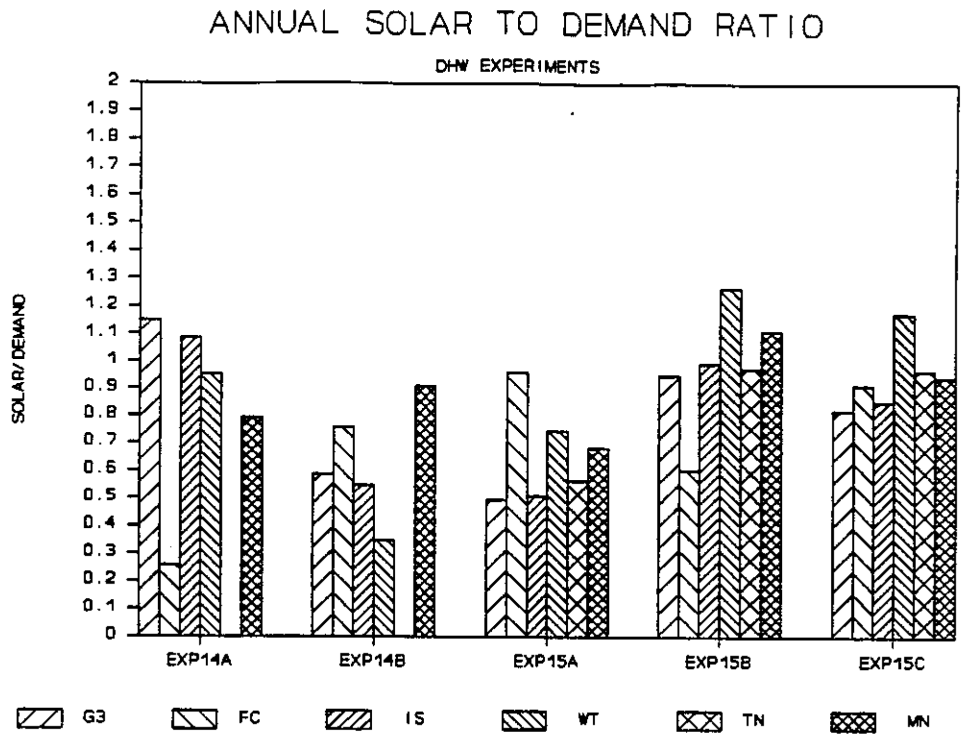


Figure 62

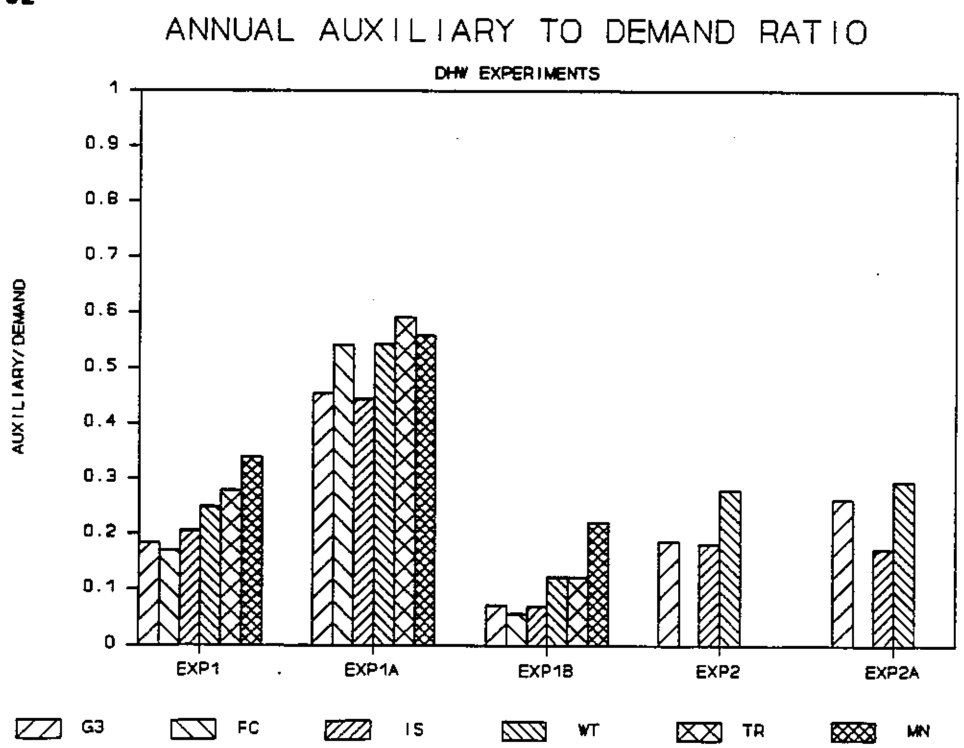


Figure 63

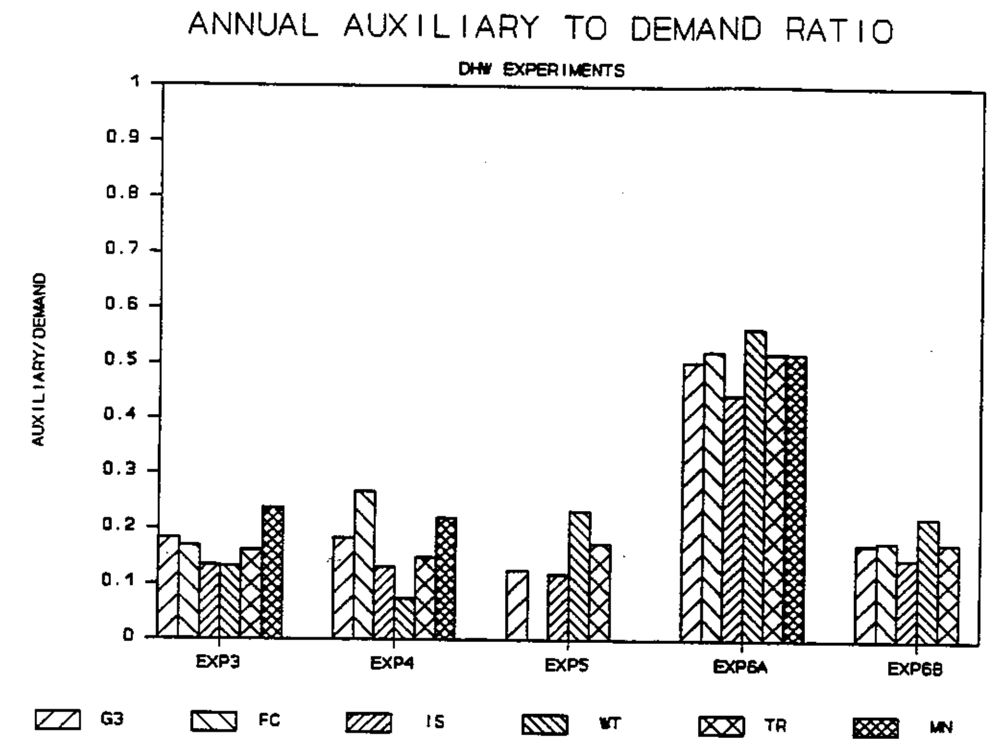


Figure 64

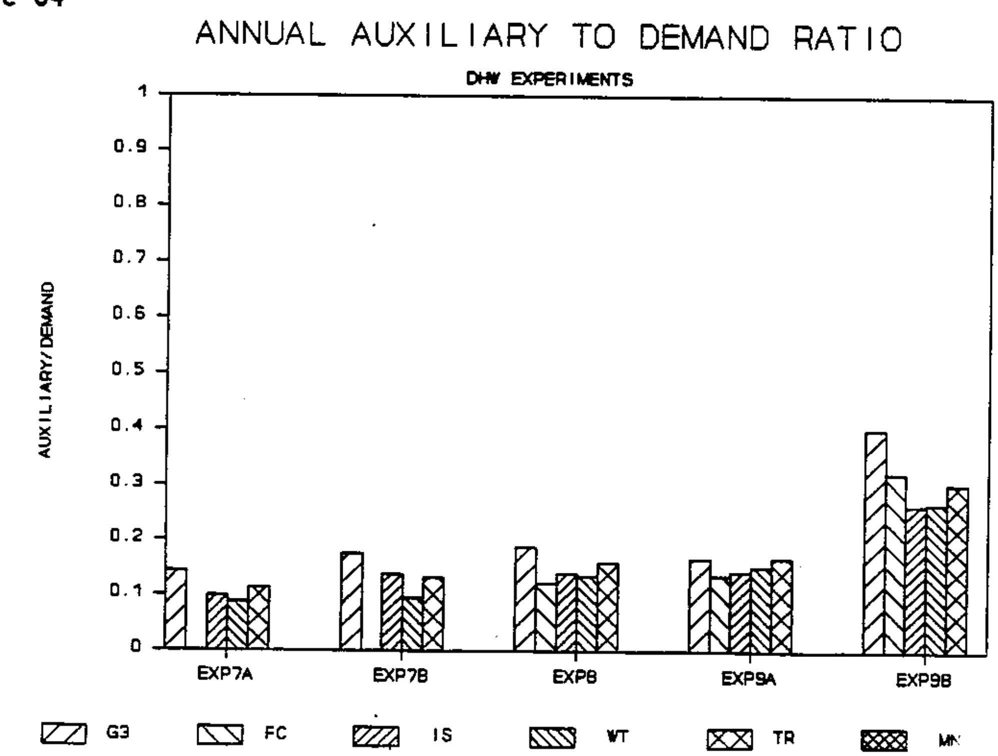


Figure 65

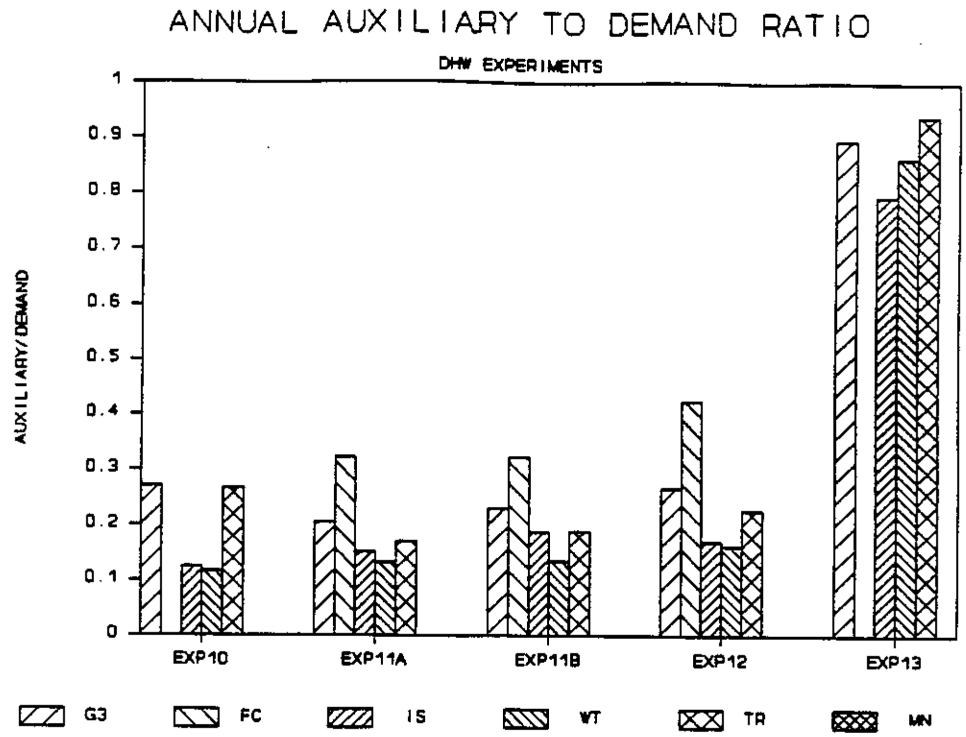


Figure 66

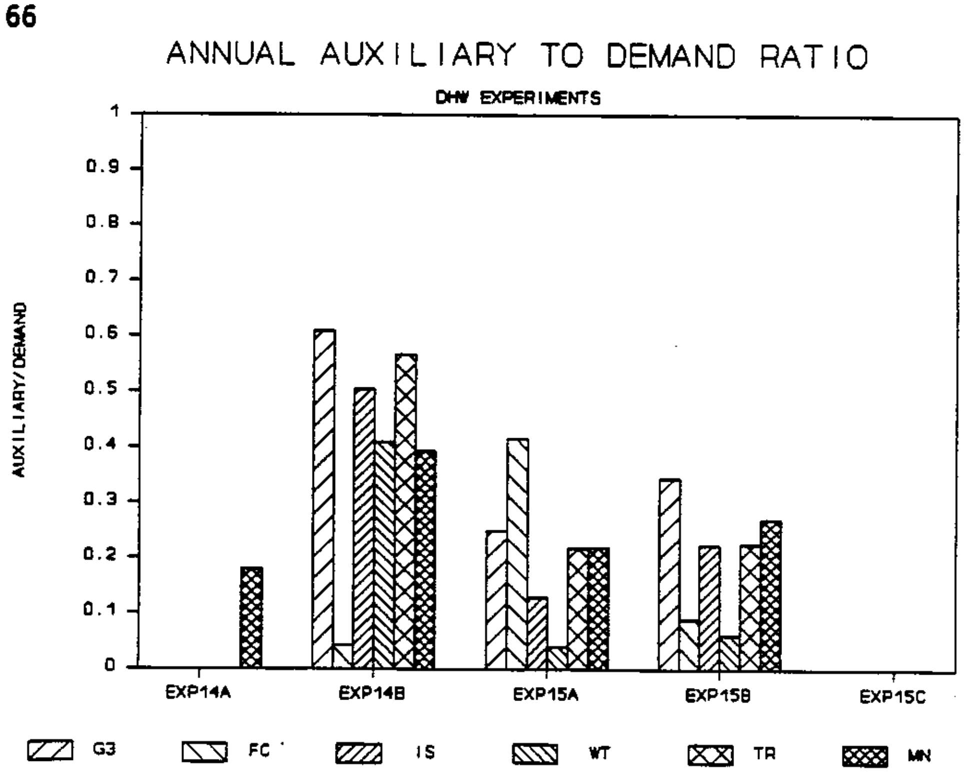


Figure 67

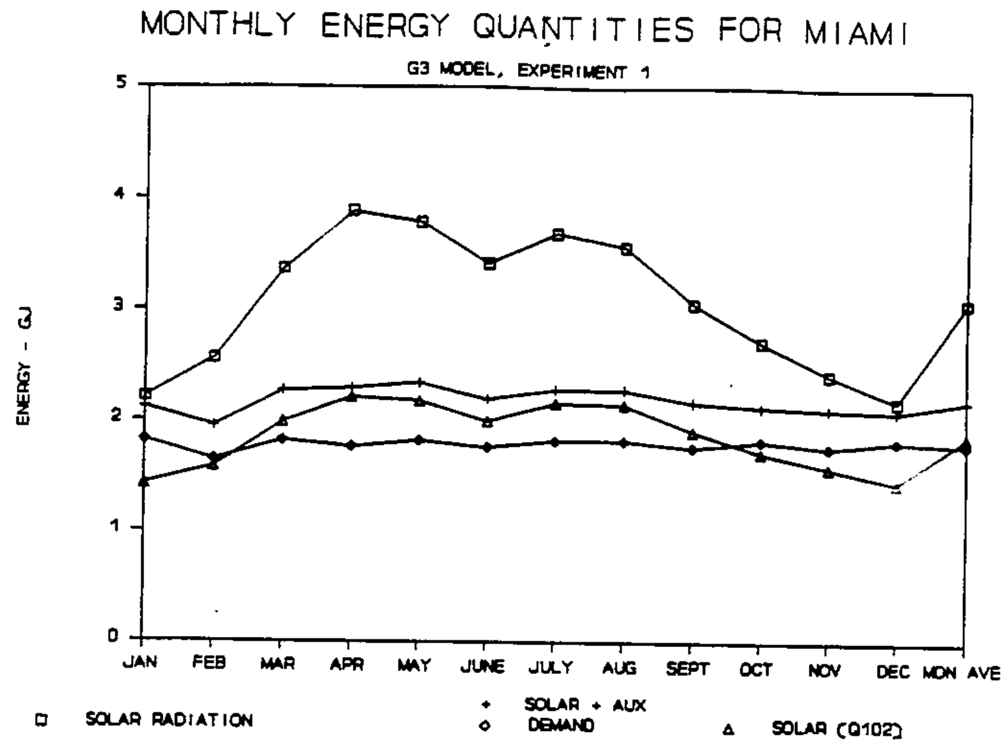


Figure 68

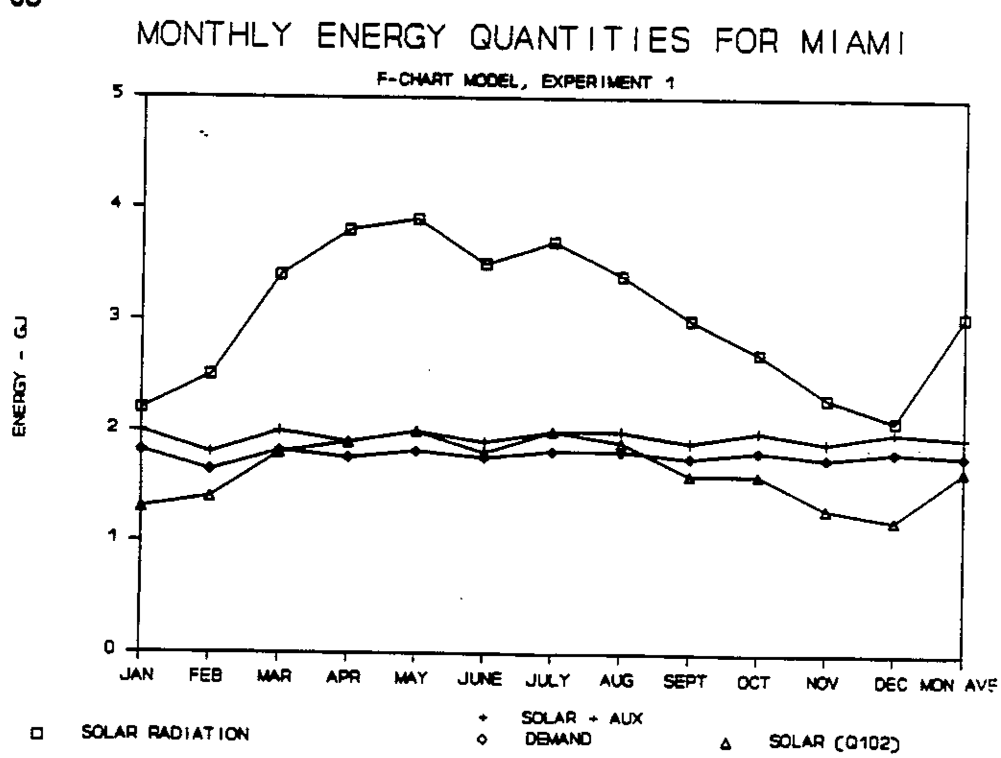


Figure 69

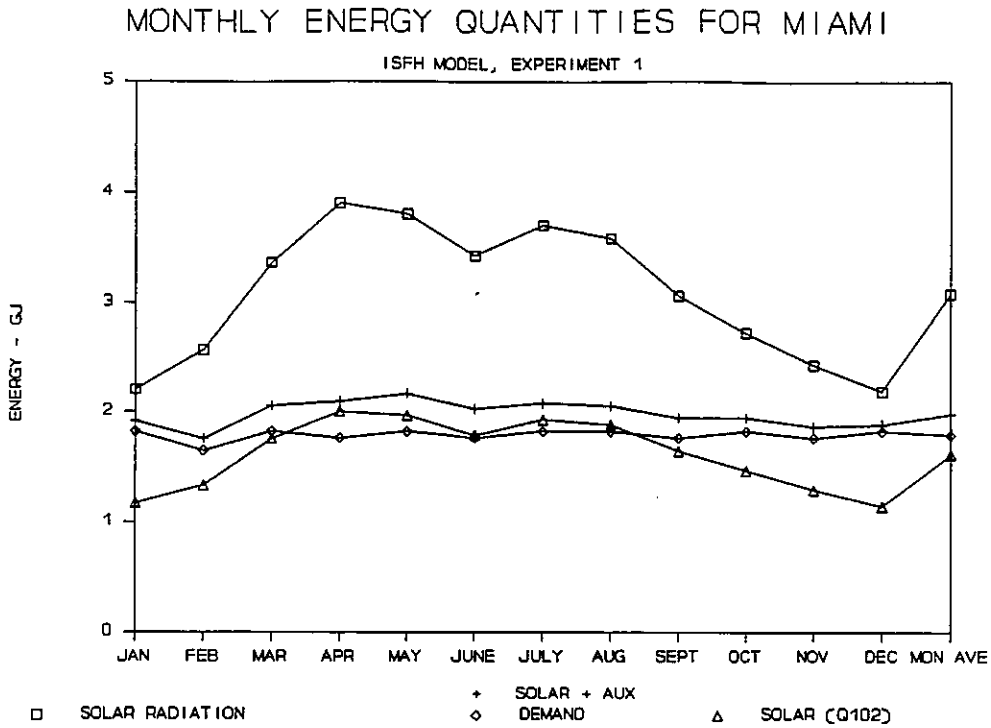


Figure 70

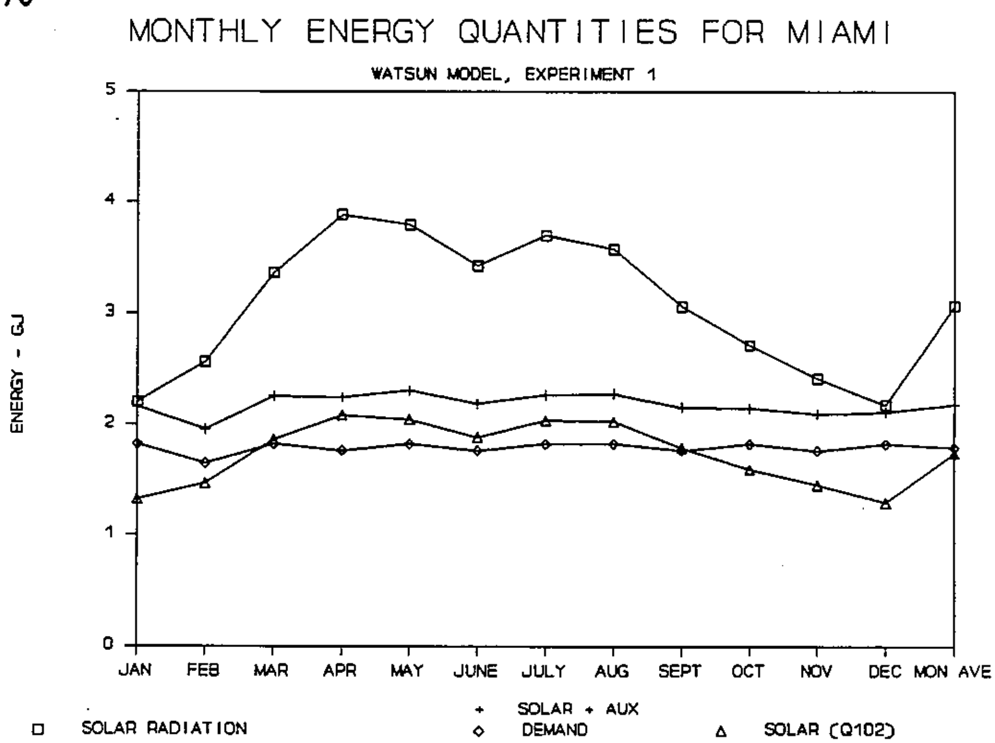


Figure 71

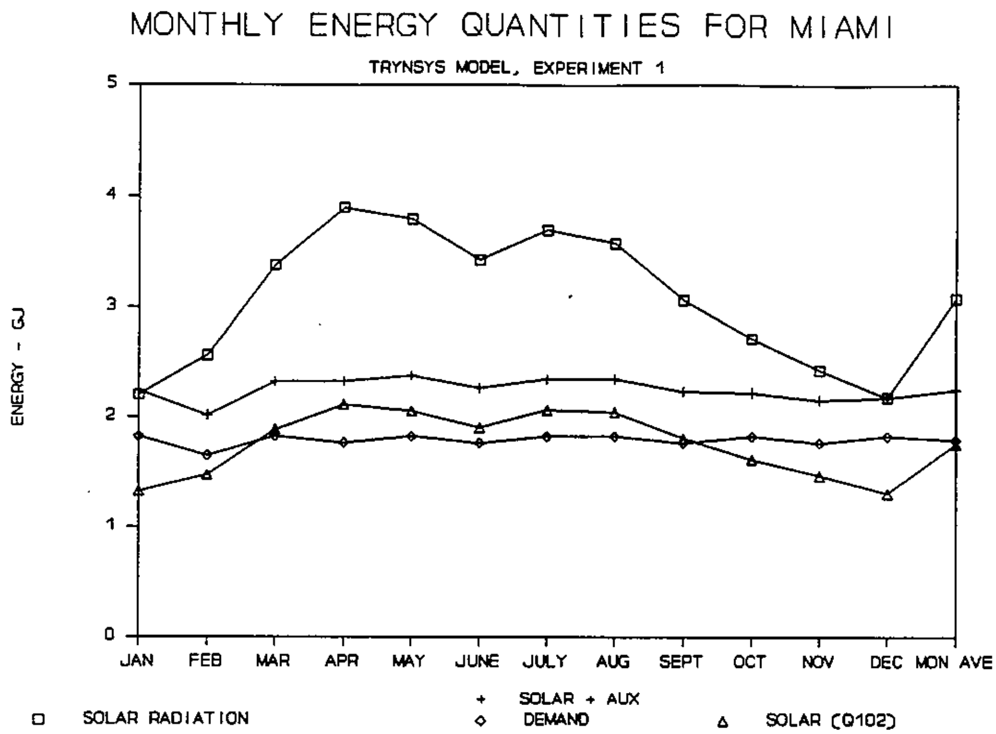


Figure 72

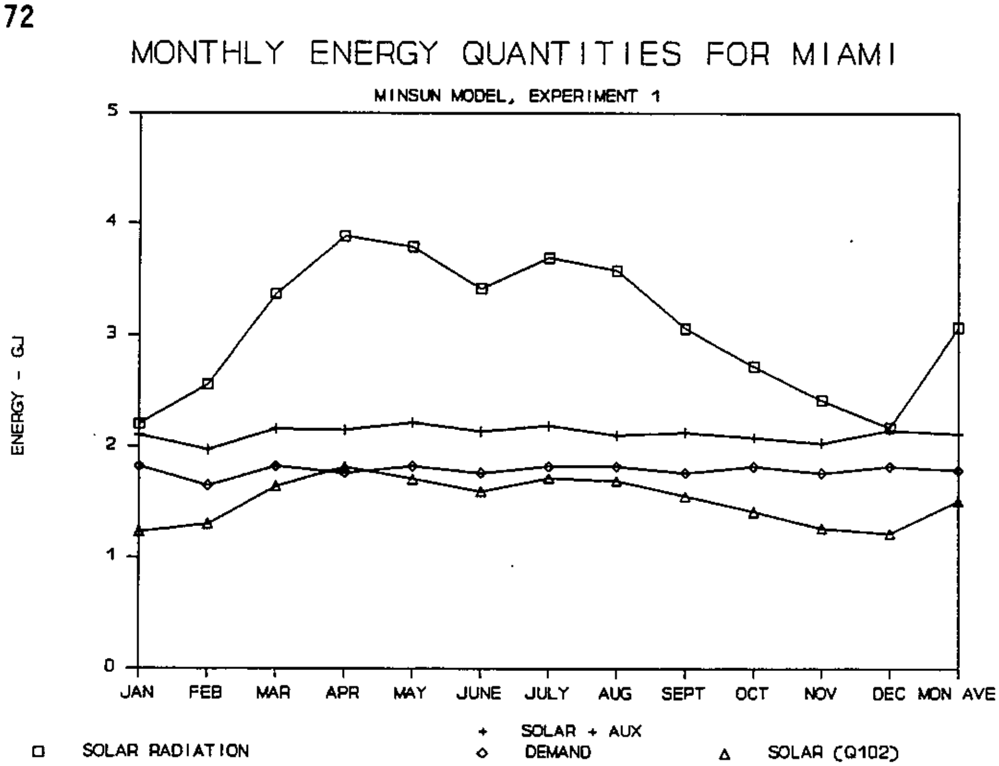


Figure 73

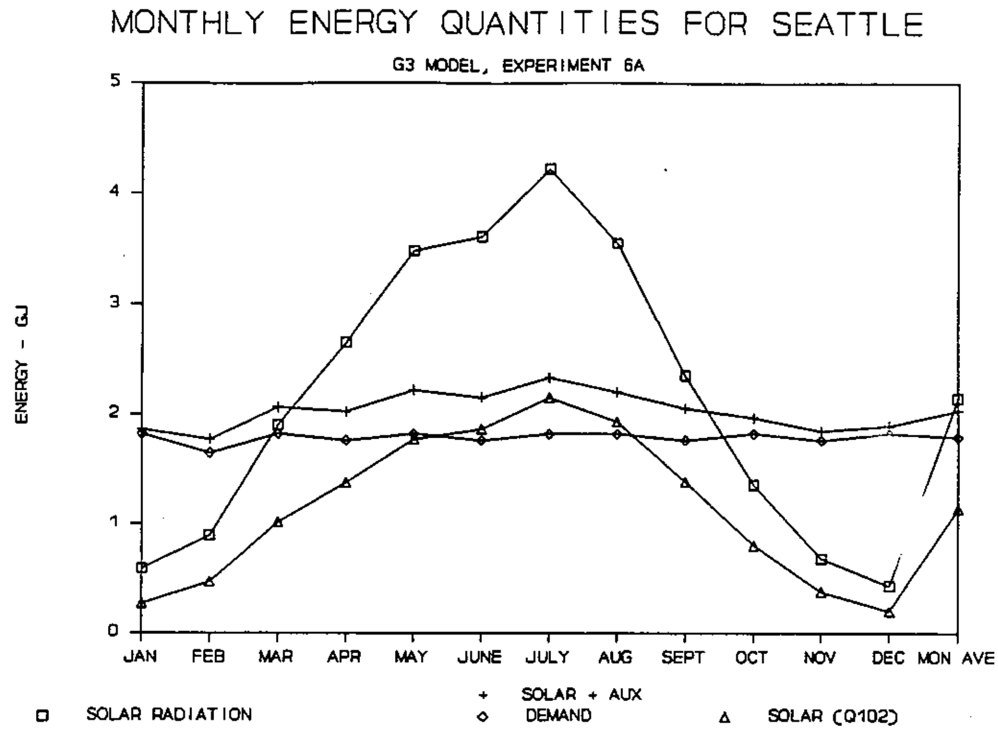


Figure 74

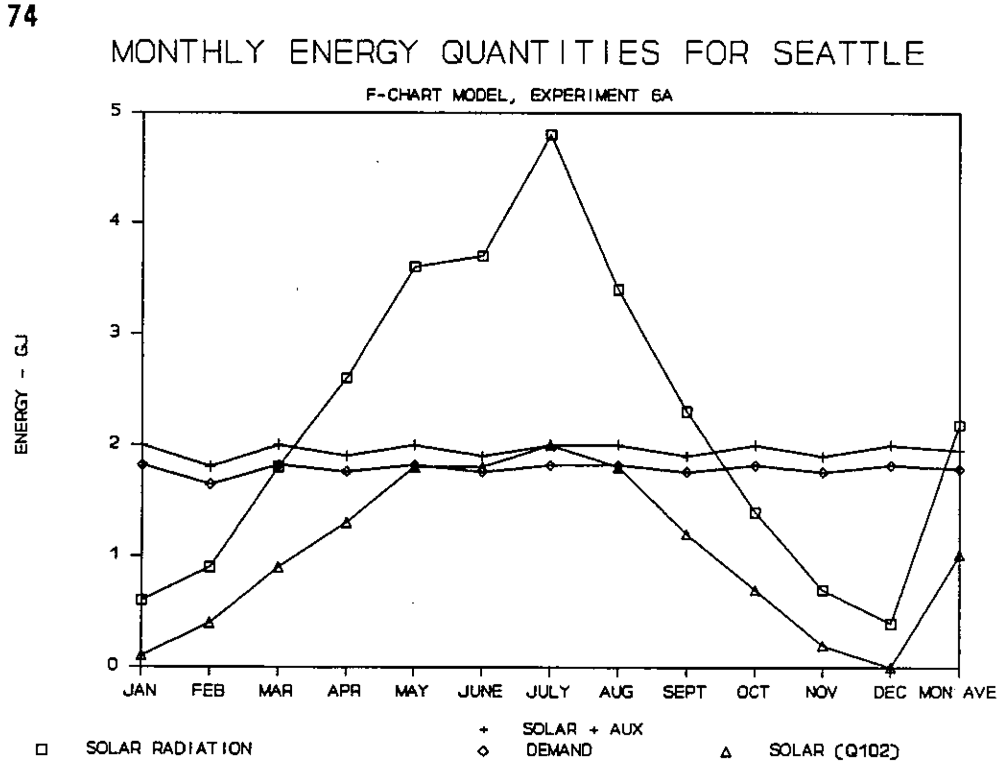


Figure 75

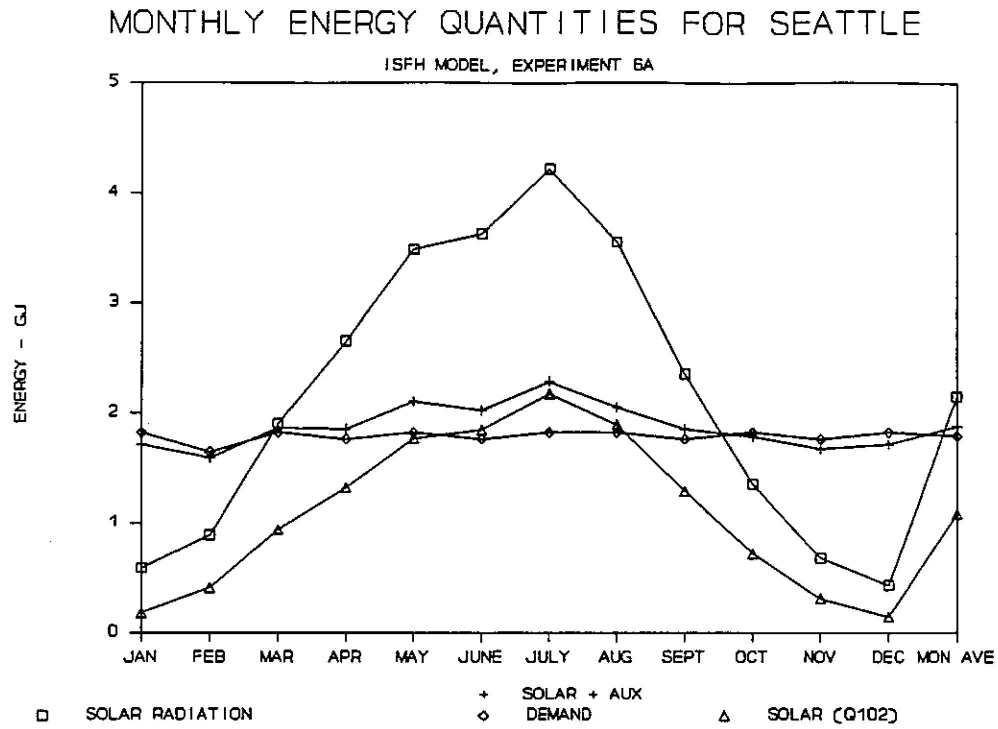


Figure 76

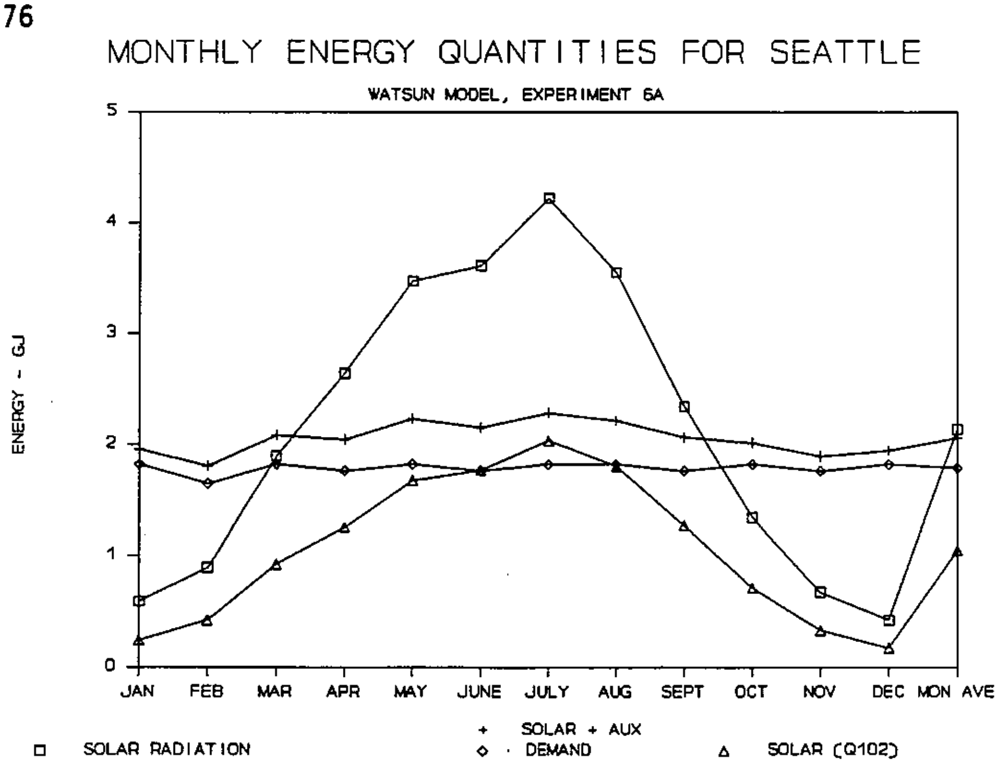


Figure 77

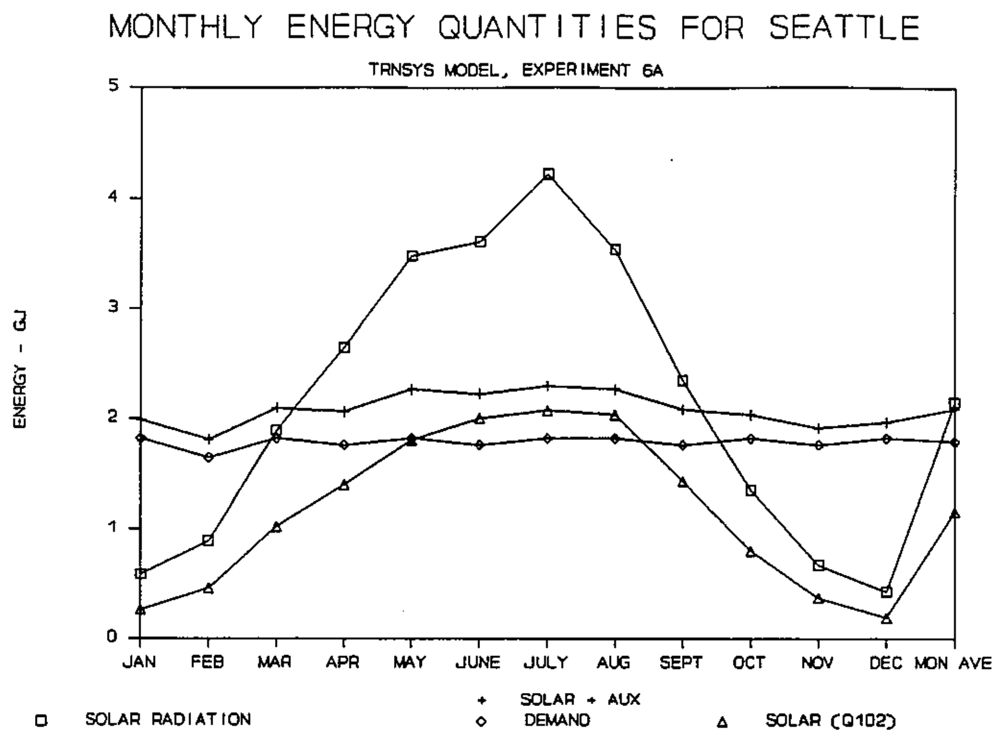


Figure 78

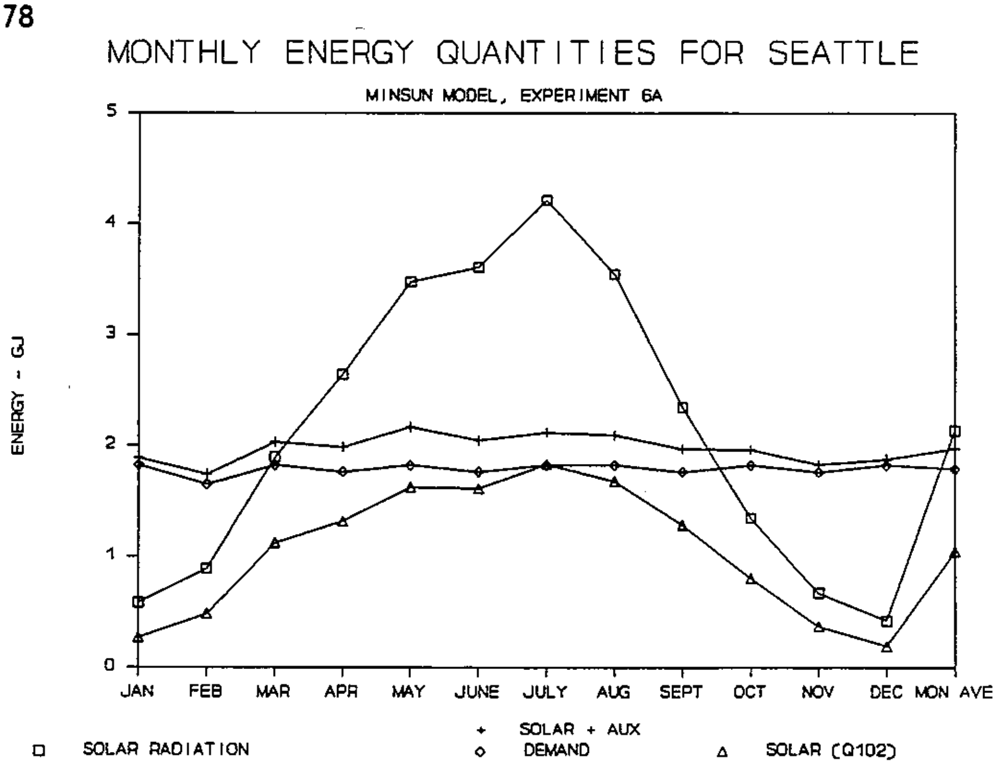


Figure 79

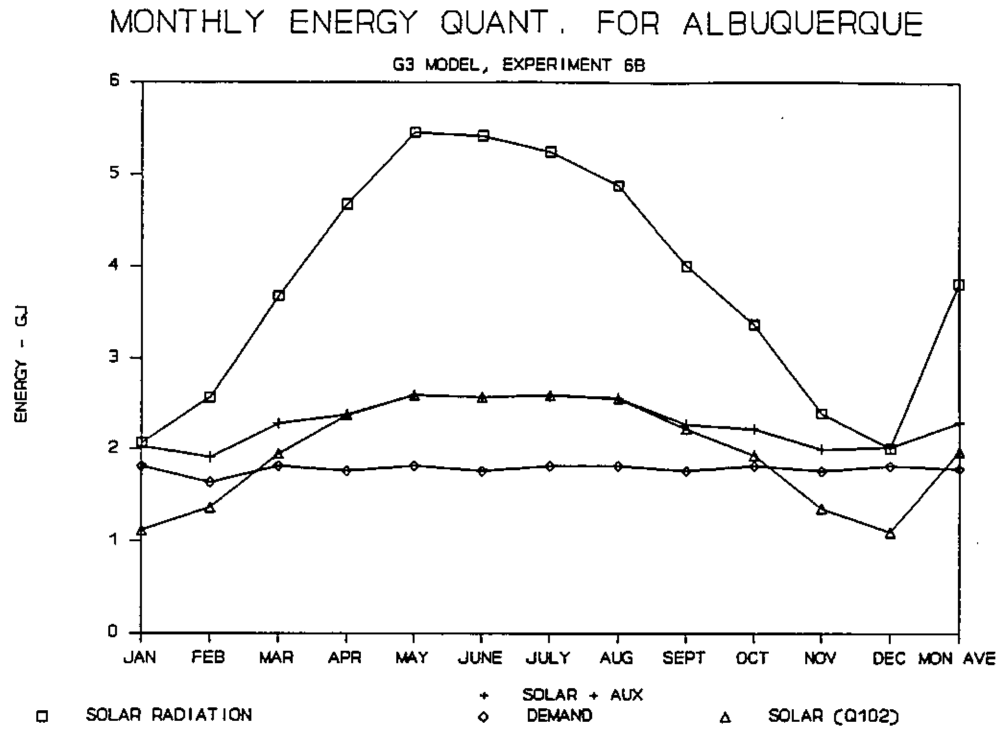


Figure 80

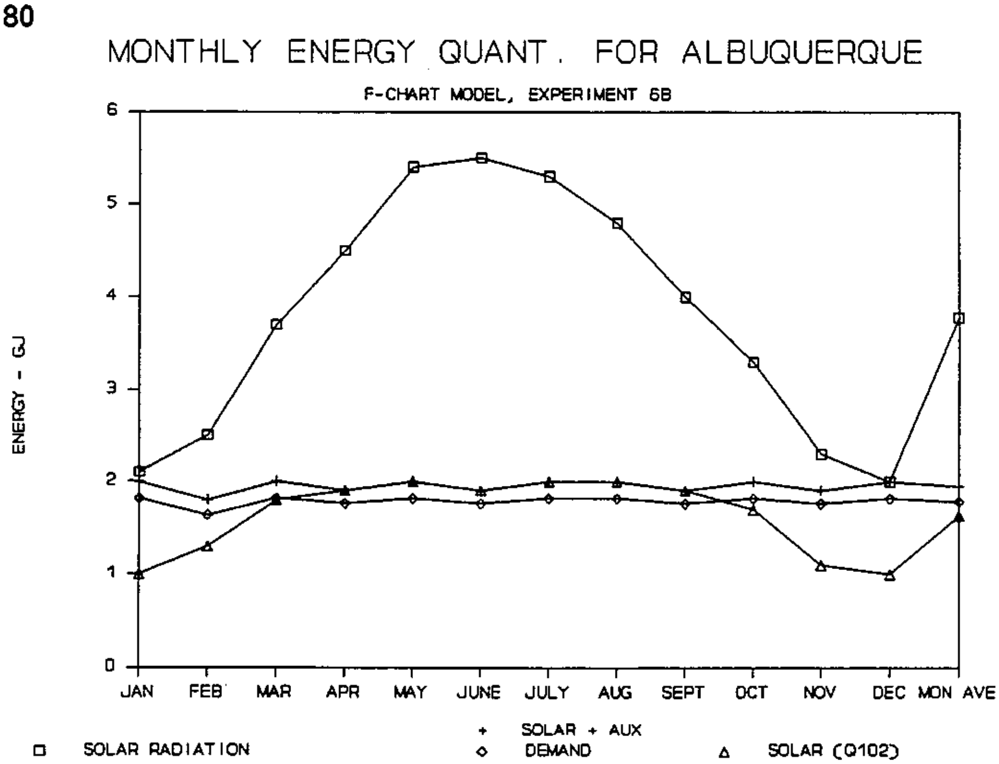


Figure 81

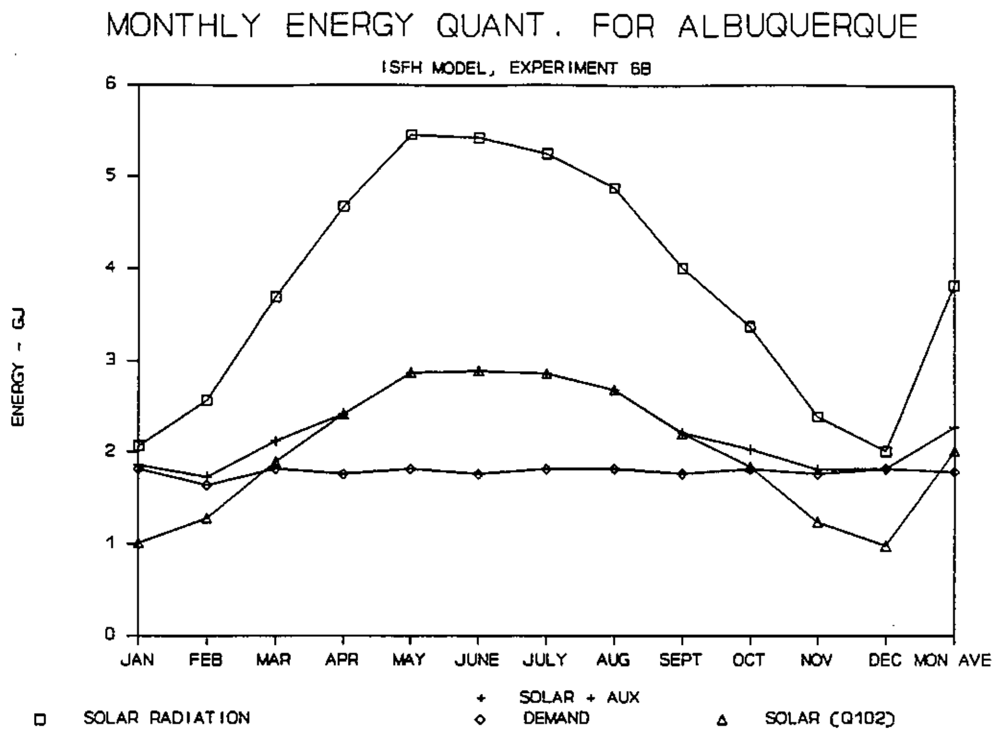


Figure 82

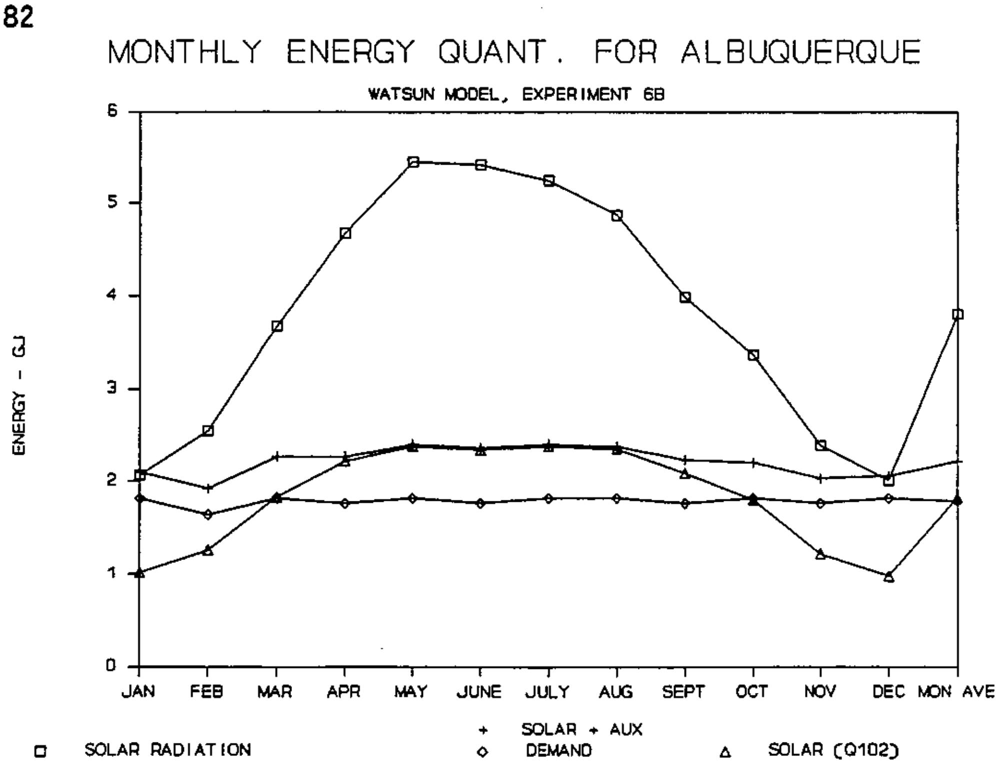


Figure 83

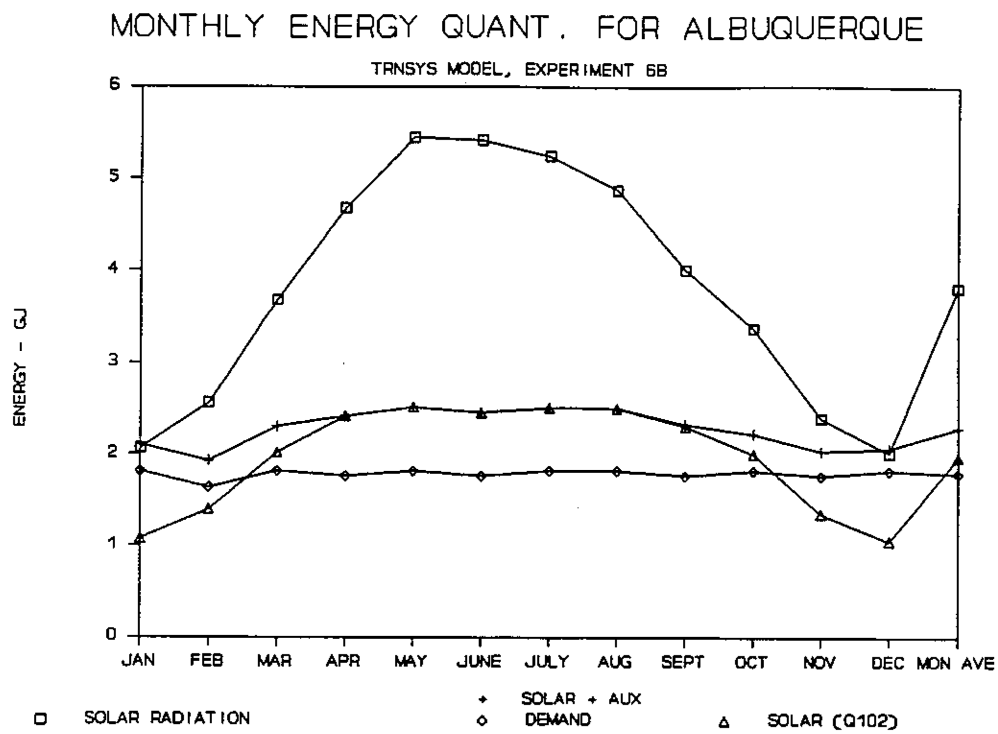


Figure 84

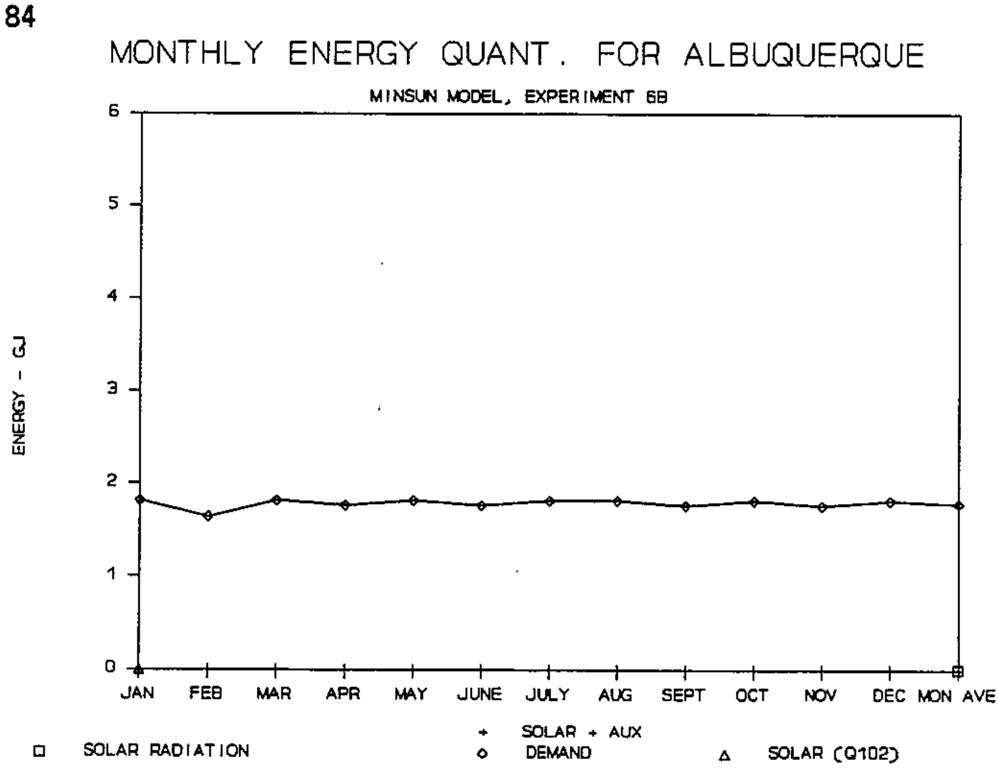


Figure 85

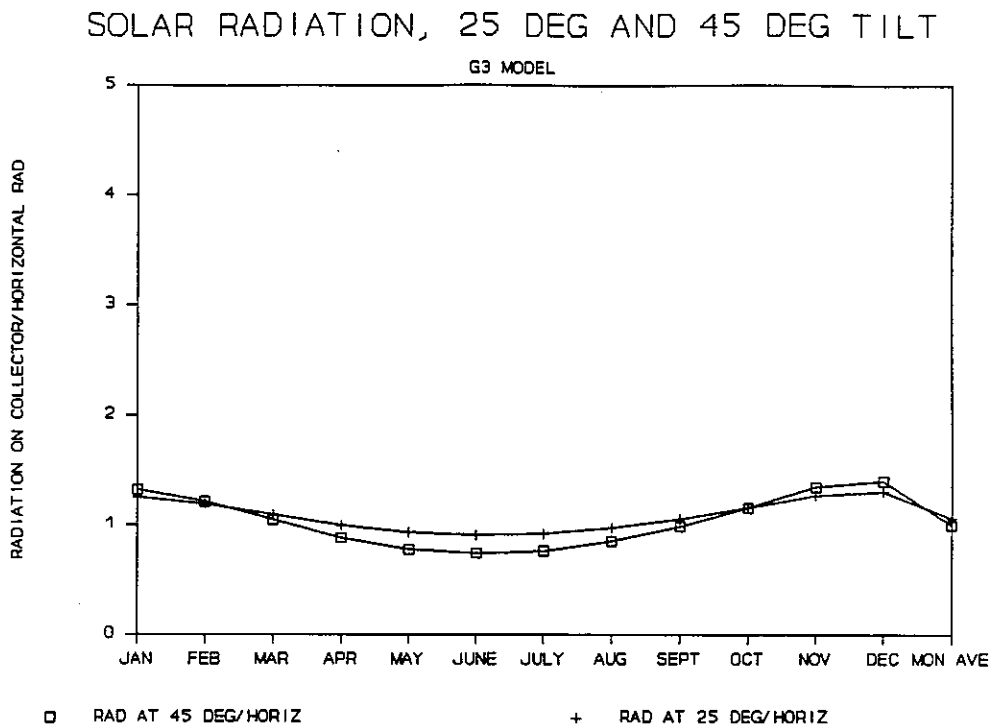


Figure 86

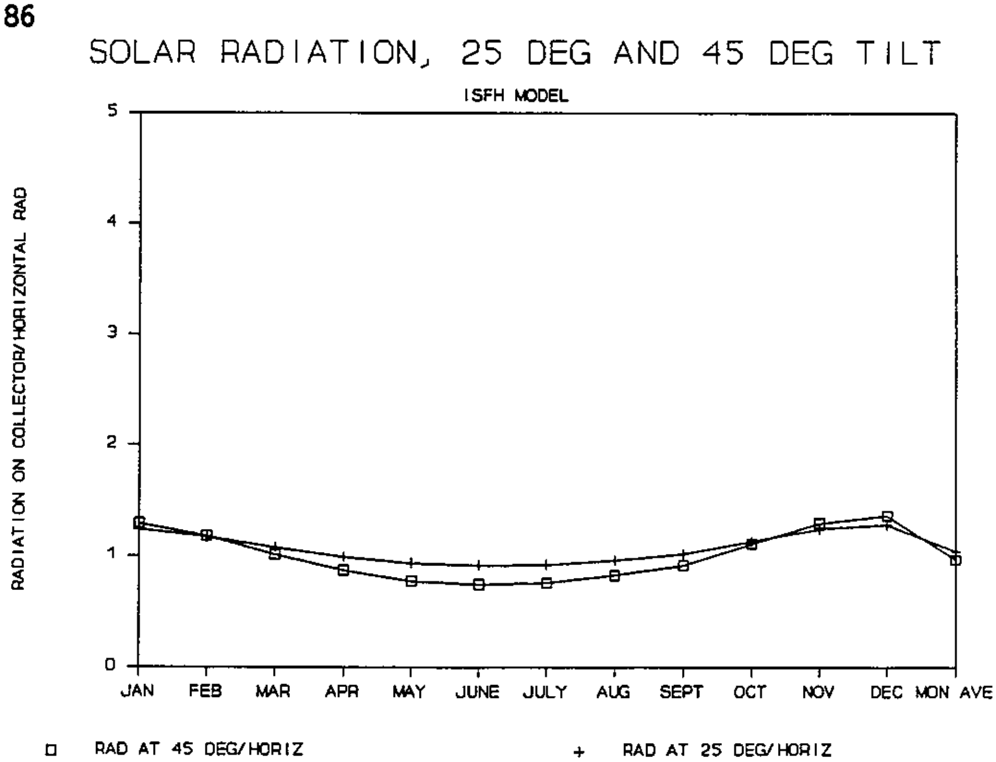


Figure 87

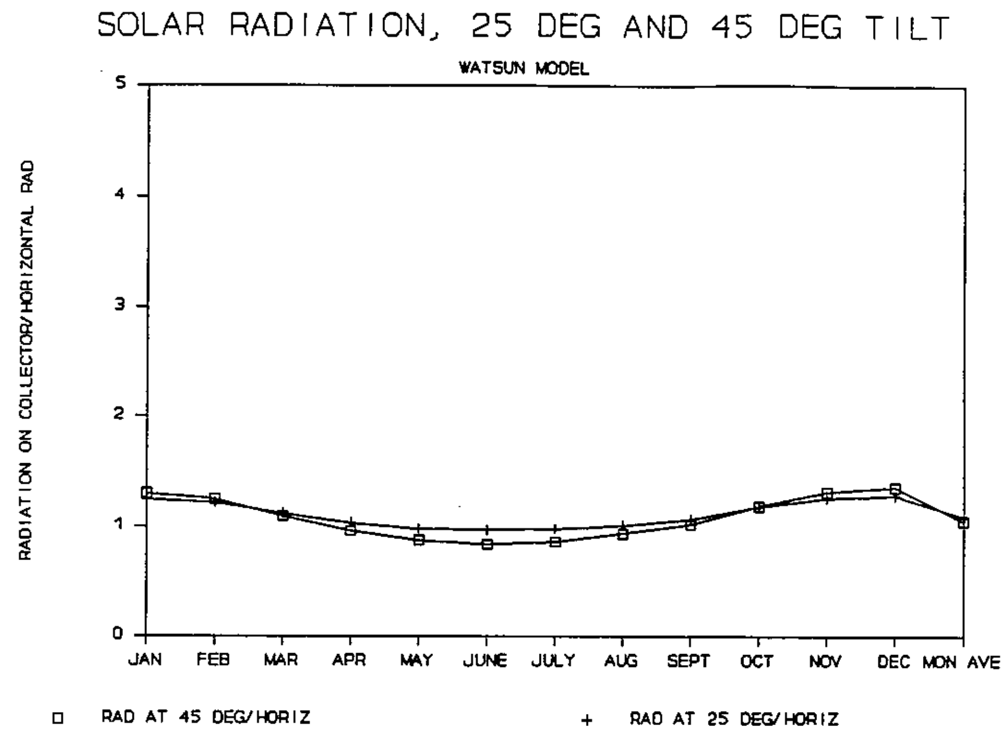


Figure 88

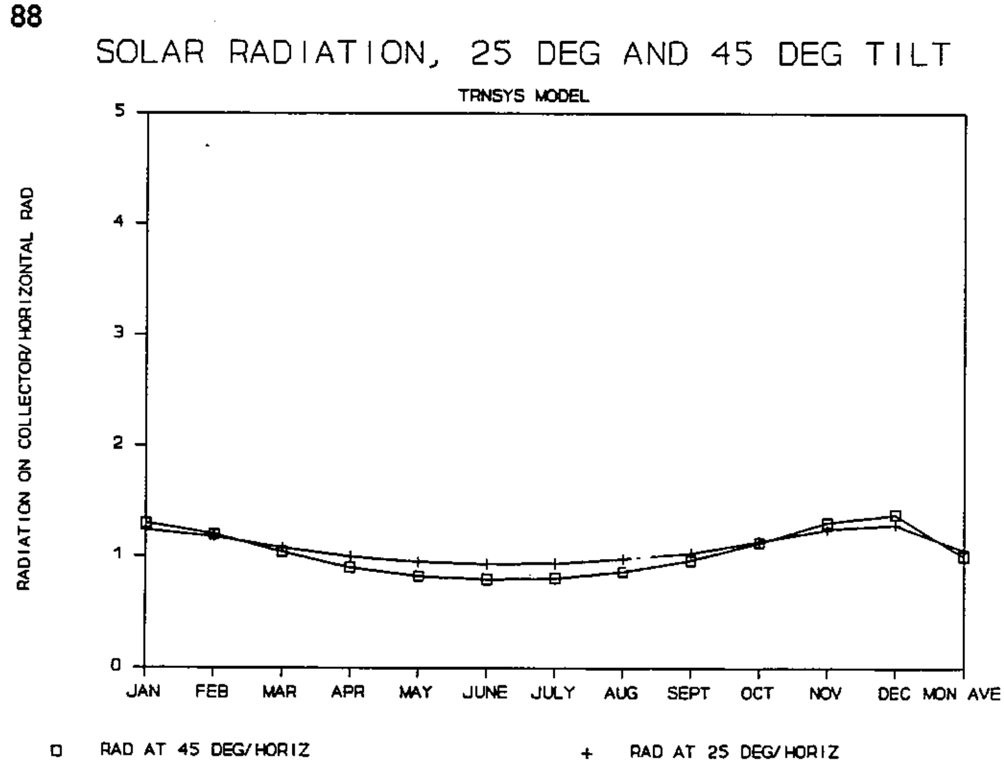


Figure 89

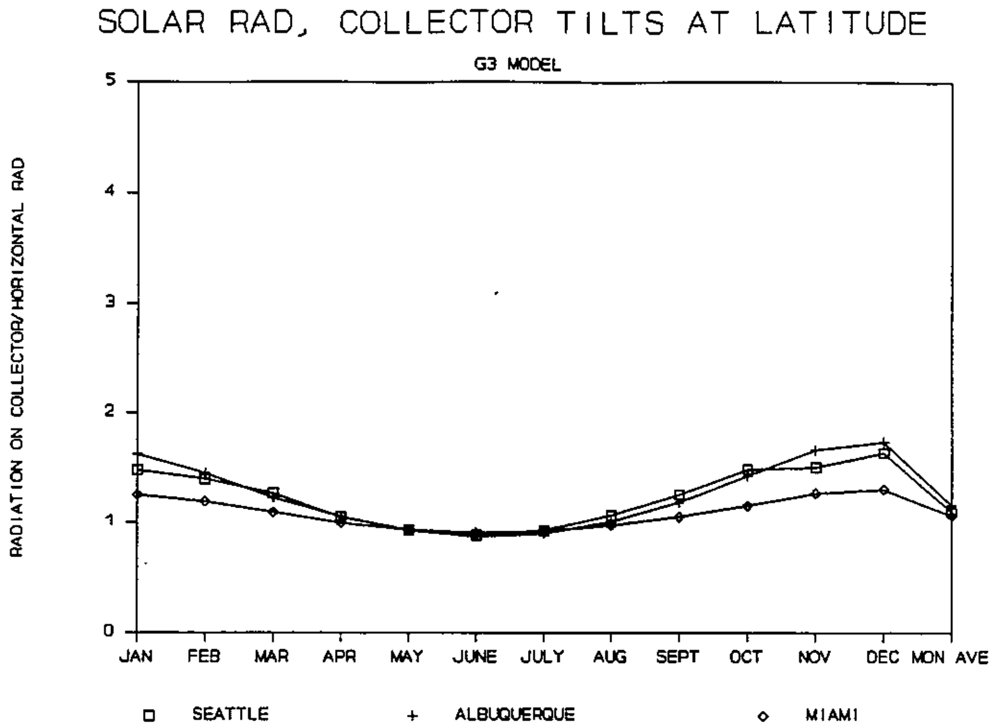


Figure 90

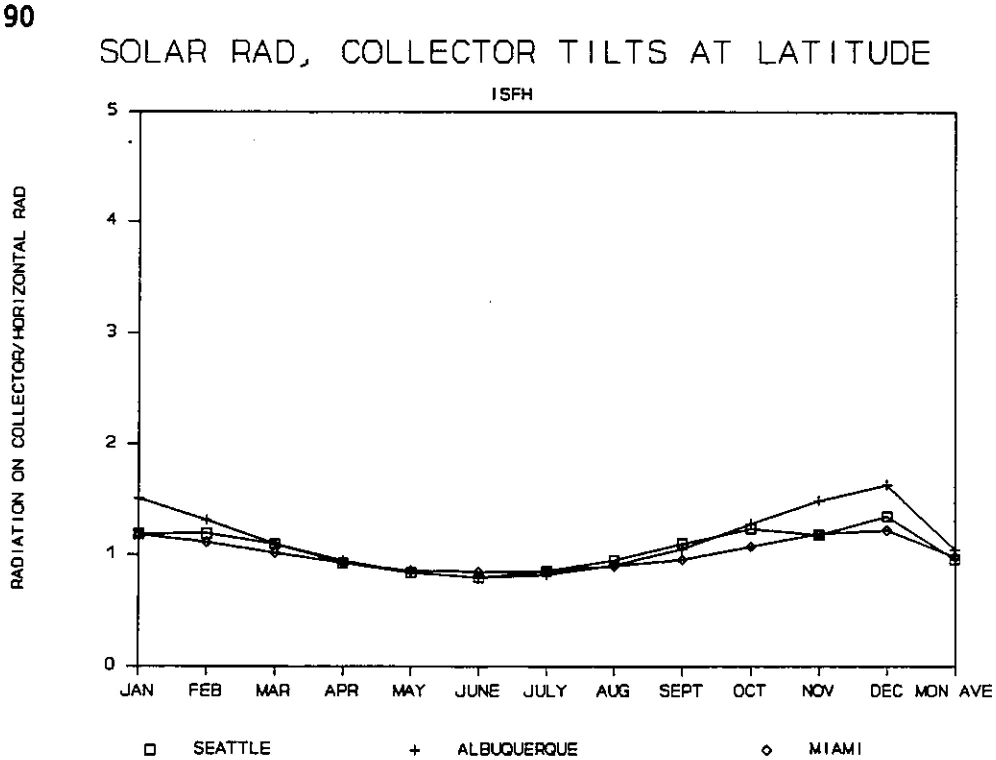


Figure 91

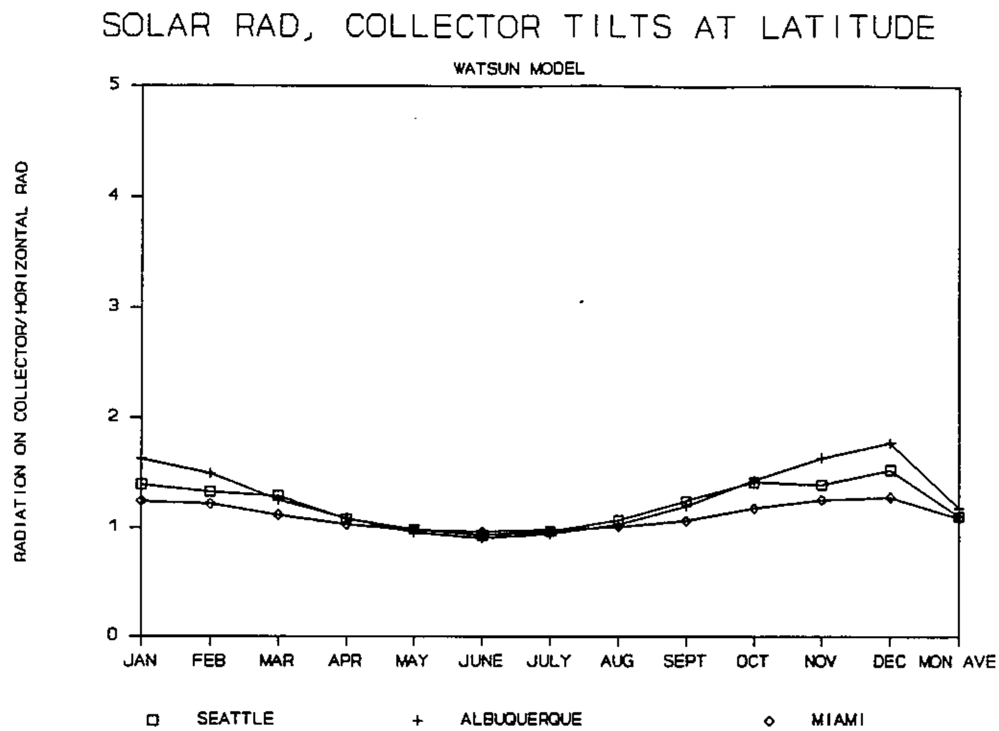


Figure 92

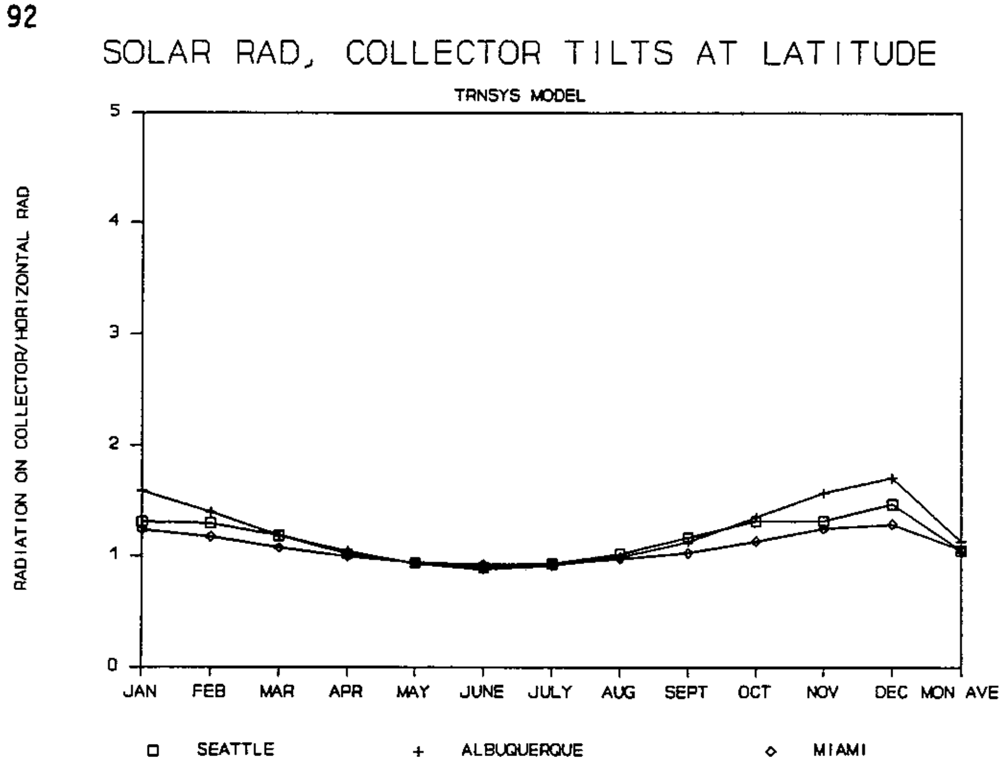


Figure 93

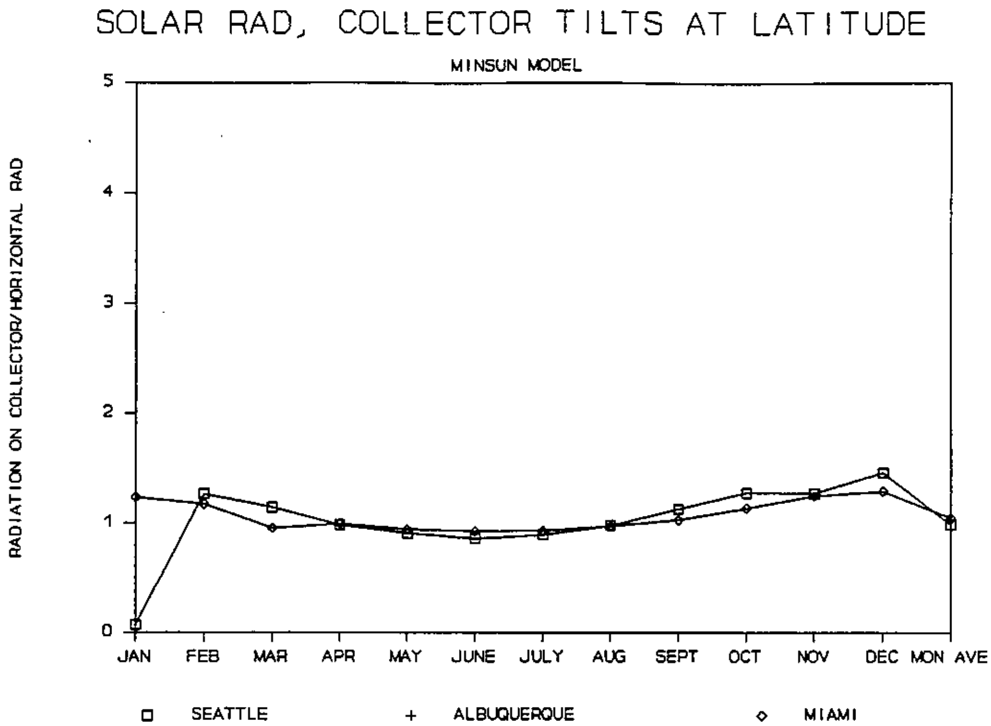
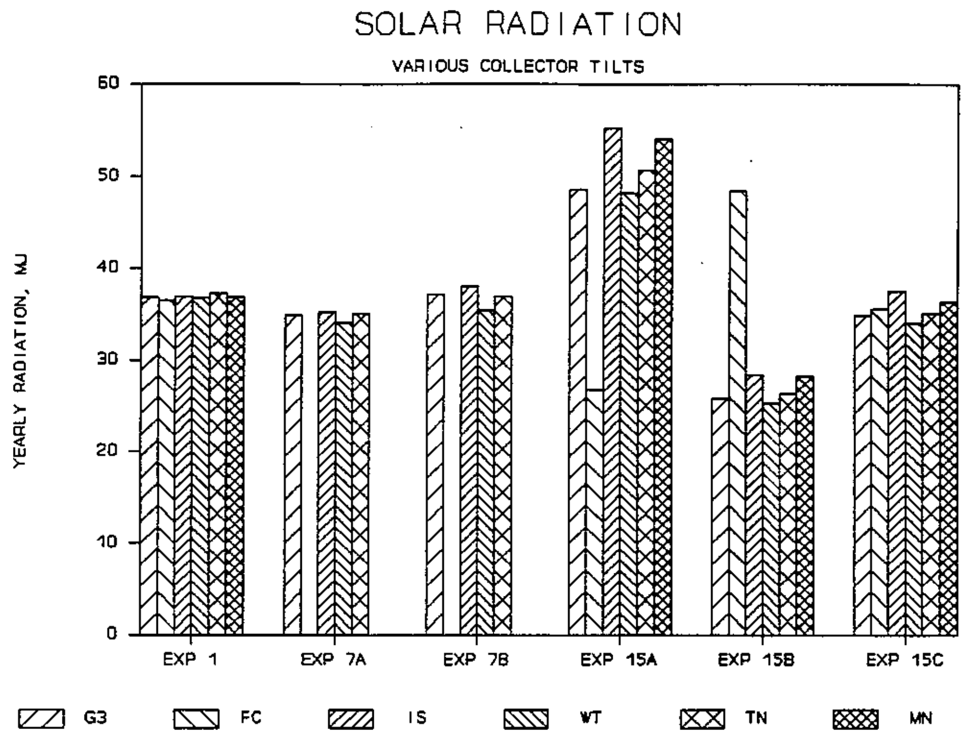

SOLAR RAD, COLLECTOR TILTS AT LATITUDE
MINSUN MODEL
RADIATION ON COLLECTOR/HORIZONTAL RAD
0
1
2
3
4
5
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
MON AVE
SEATTLE
ALBUQUERQUE
MIAMI

Figure 94



SOLAR RADIATION
VARIOUS COLLECTOR TILTS
YEARLY RADIATION, MJ
0
10
20
30
40
50
60
EXP 1
EXP 7A
EXP 7B
EXP 15A
EXP 15B
EXP 15C
G3
FC
IS
WT
TN
MN

Figure 95

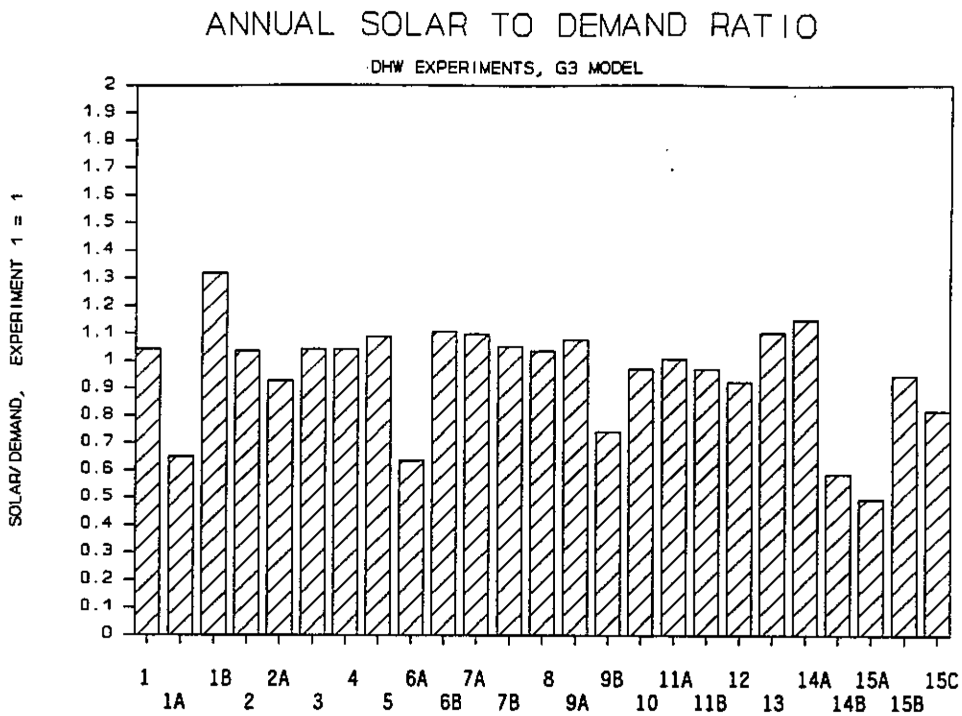


Figure 96

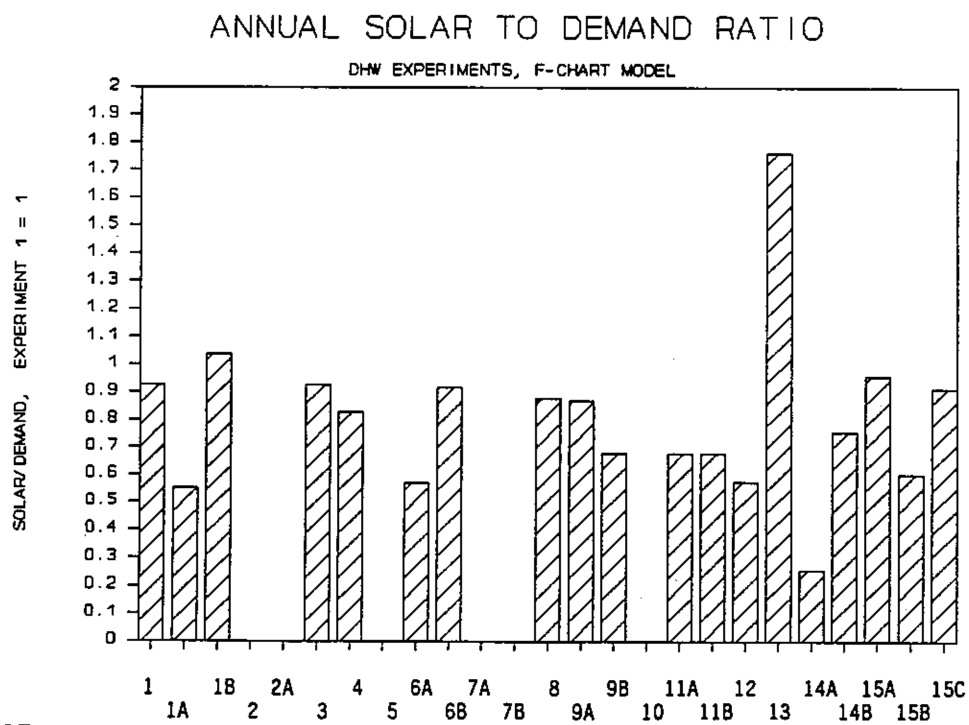


Figure 97

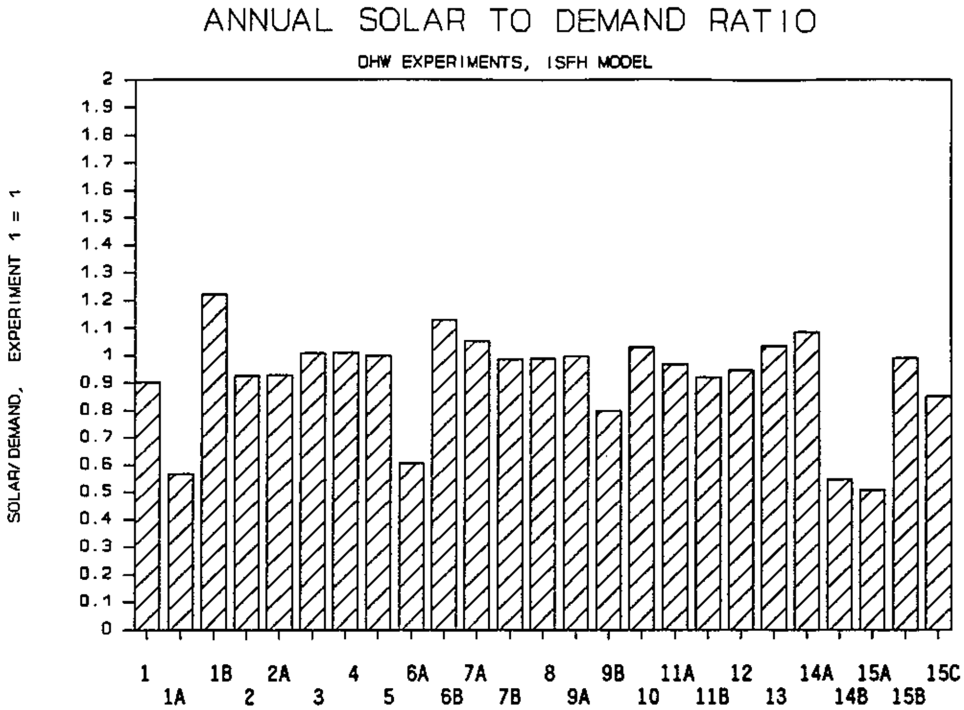


Figure 98

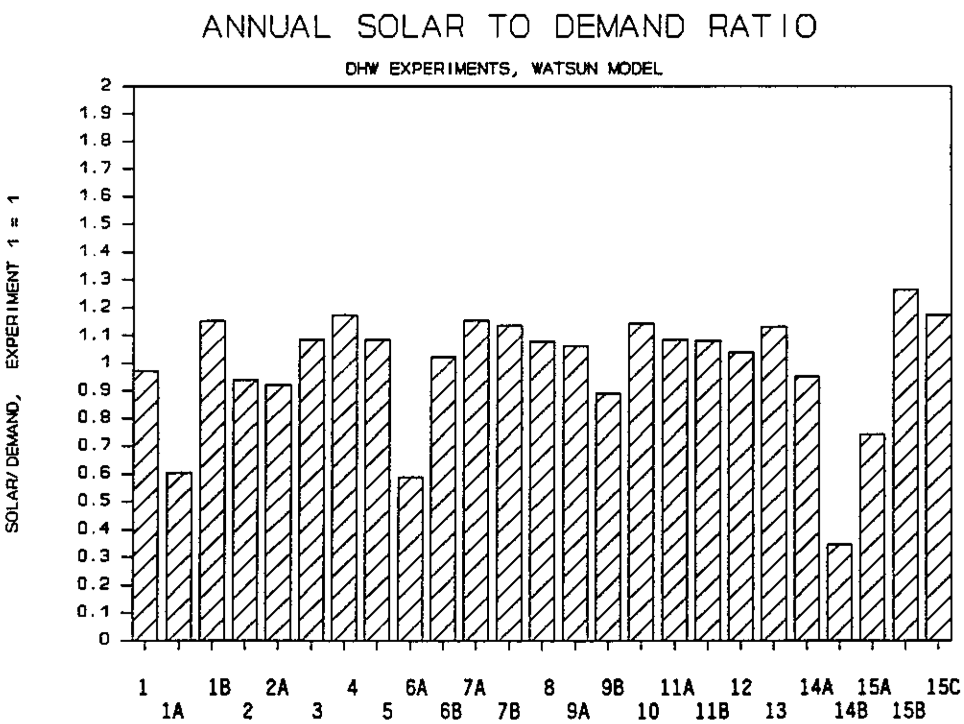


Figure 99

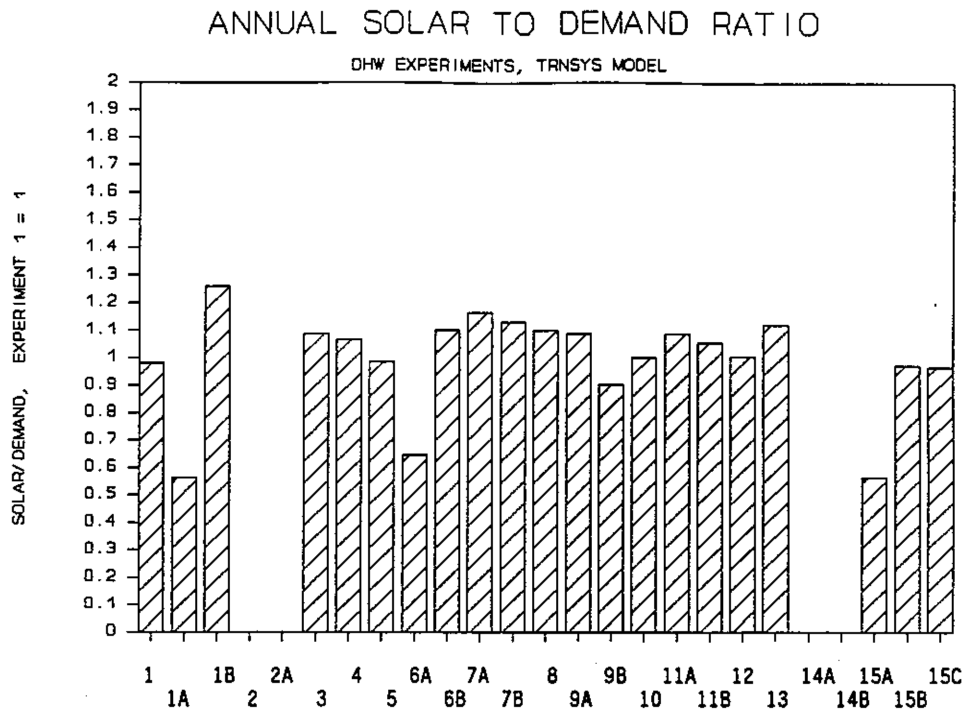


Figure 100

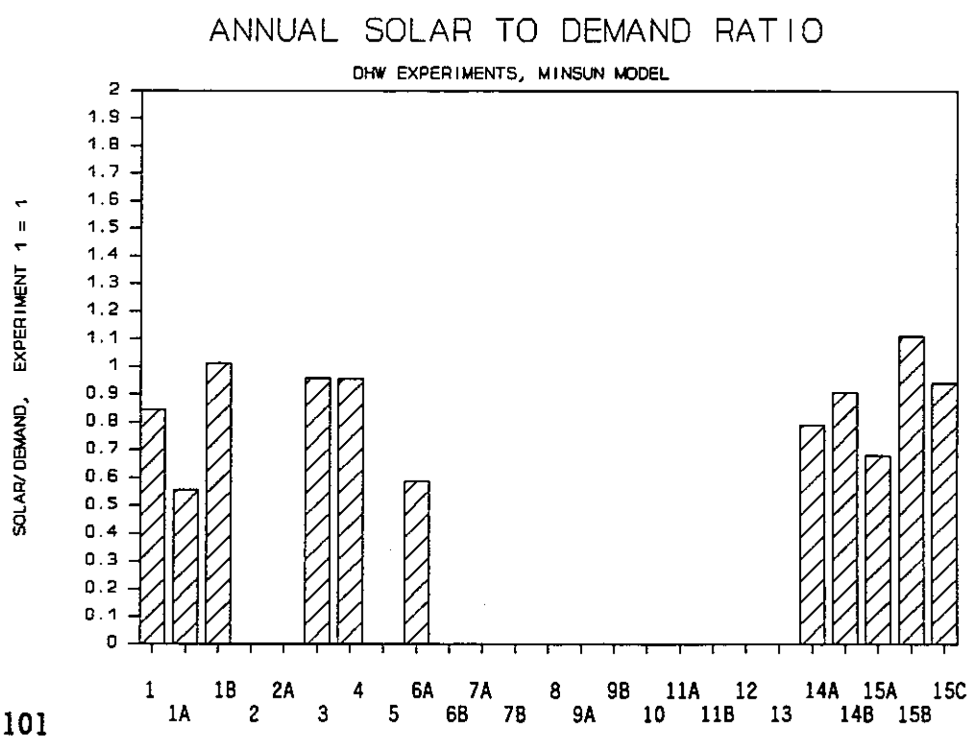


Figure 101

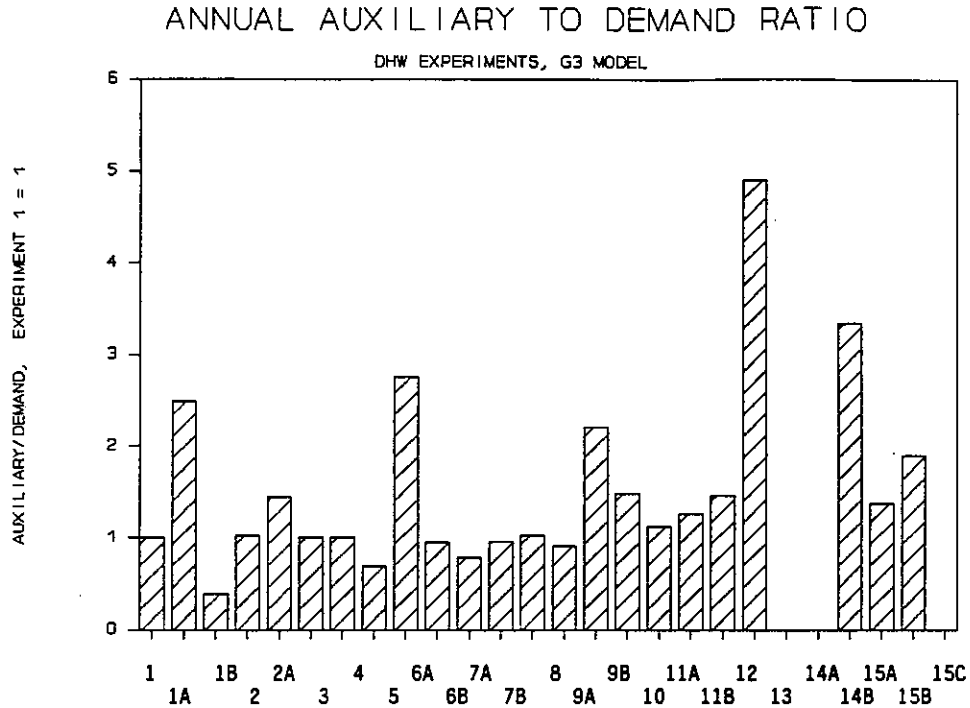
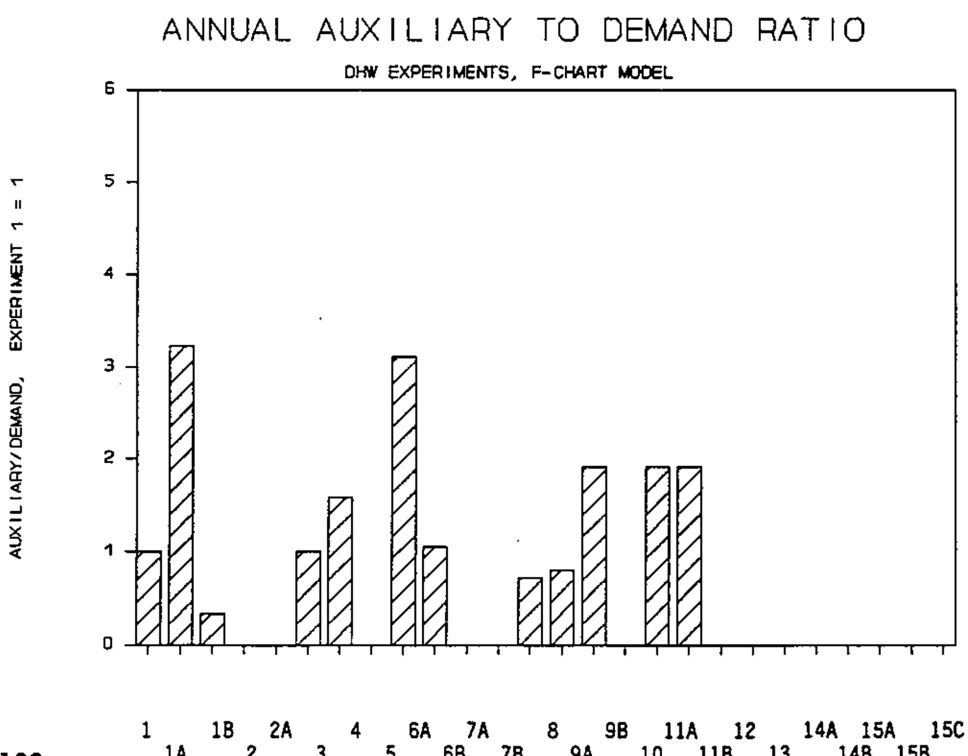


Figure 102



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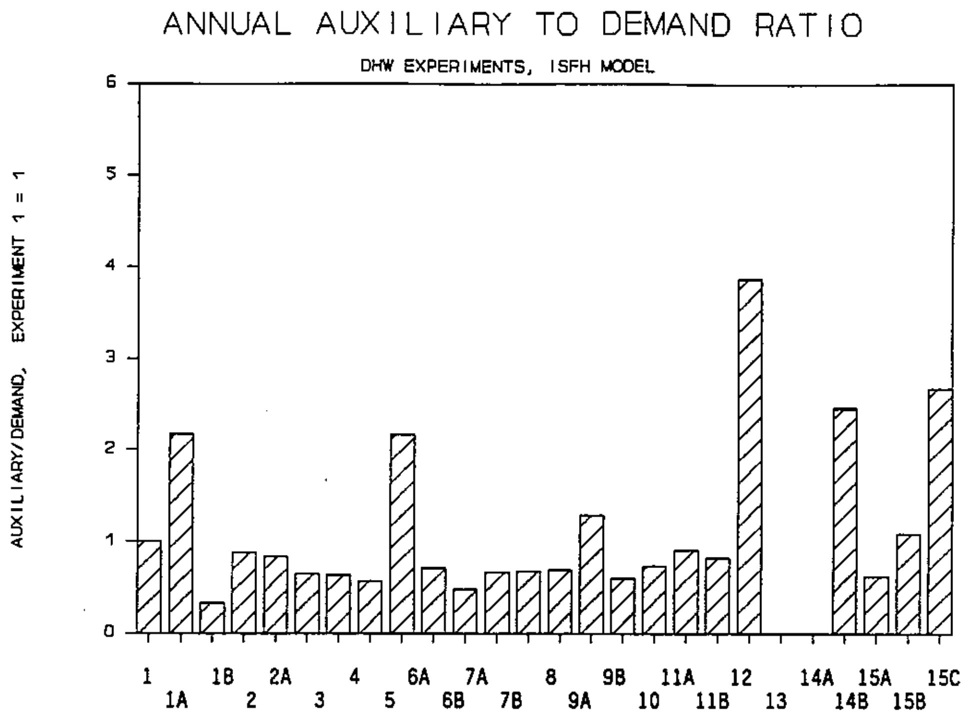

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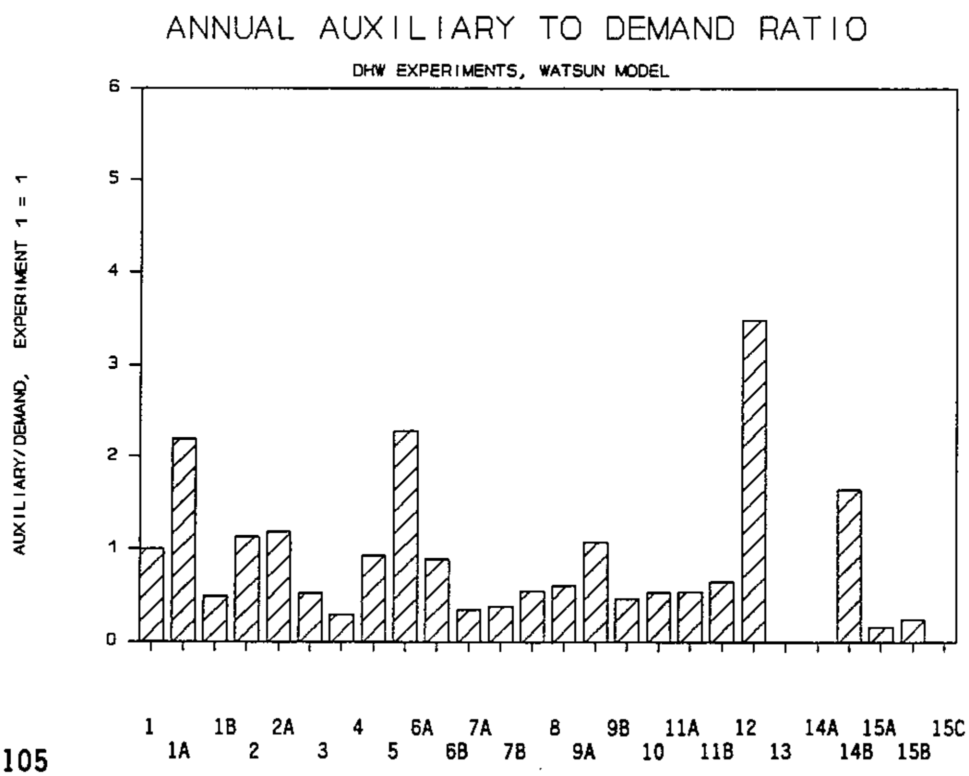

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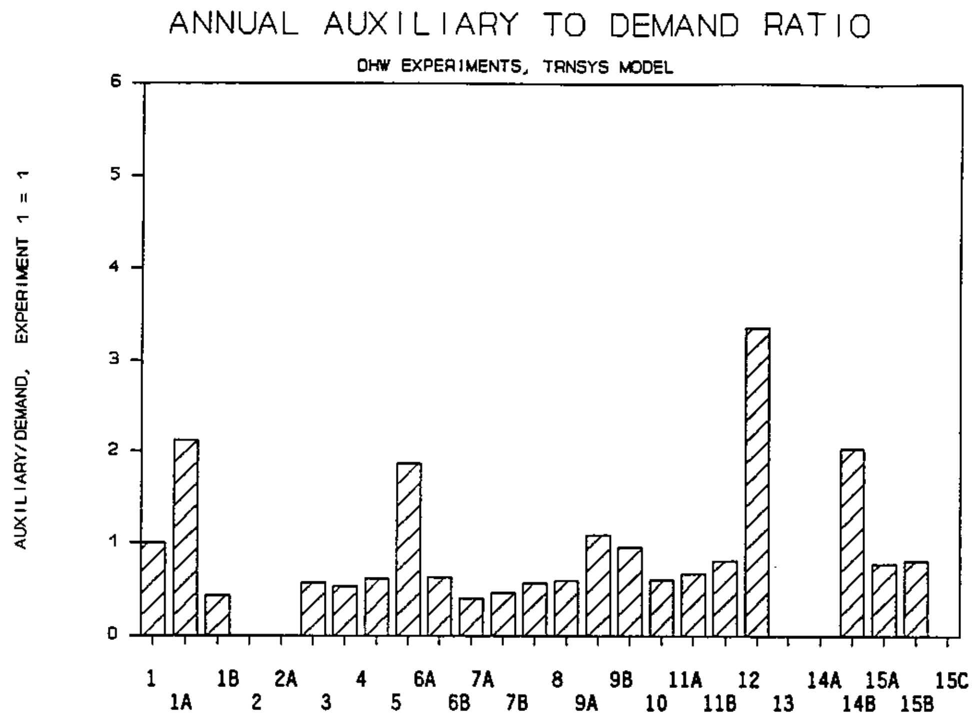

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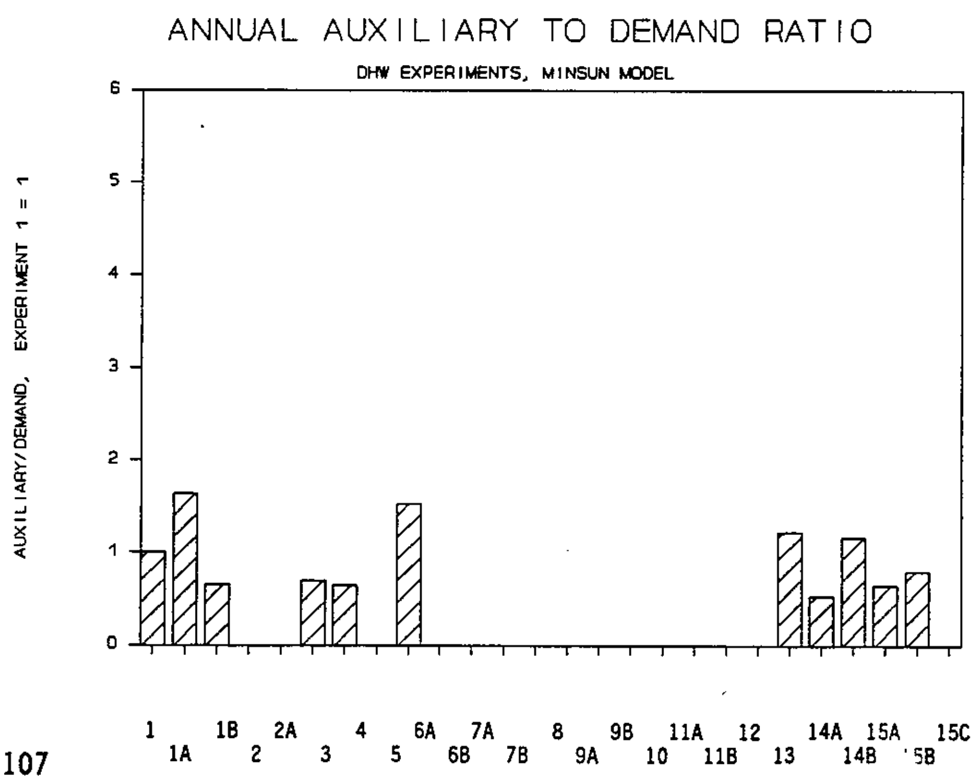

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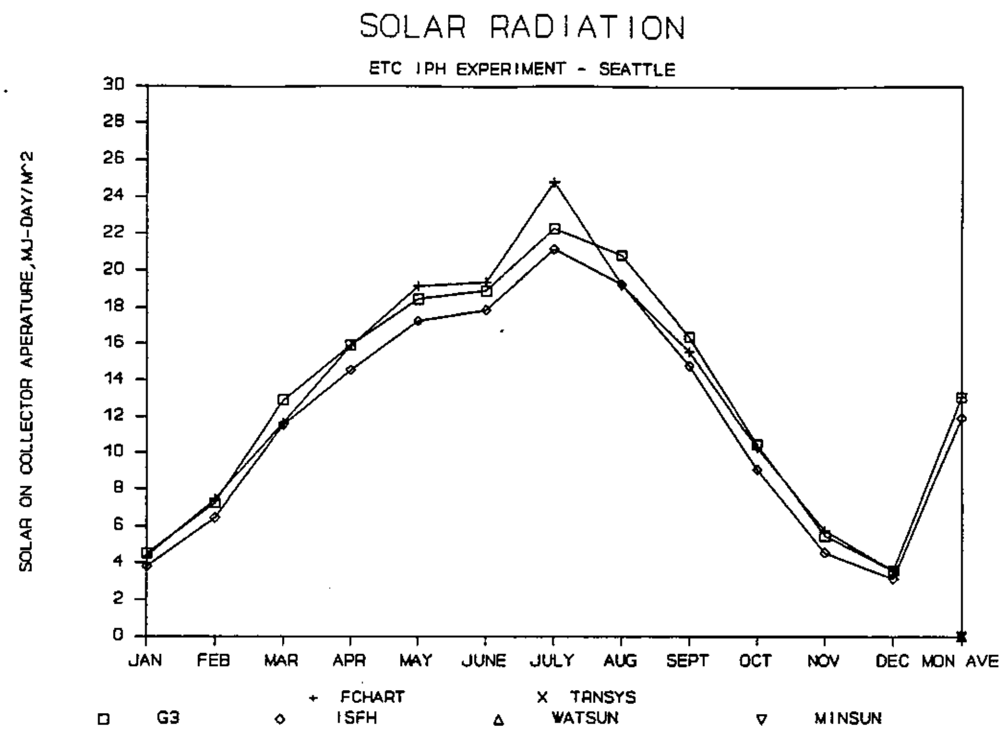

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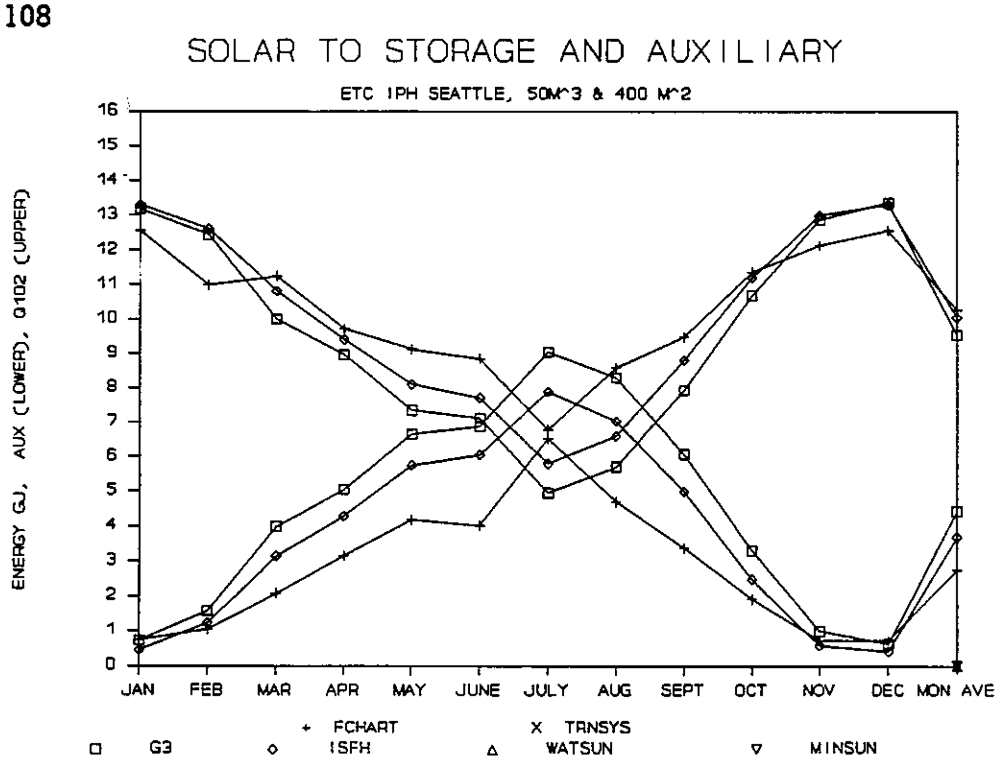

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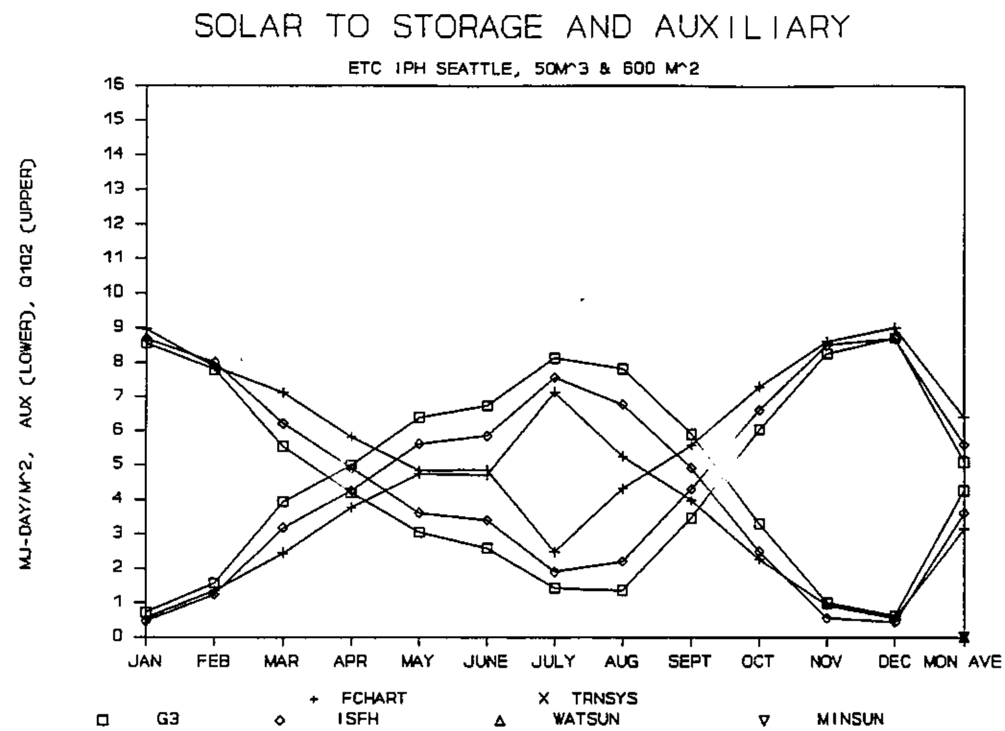

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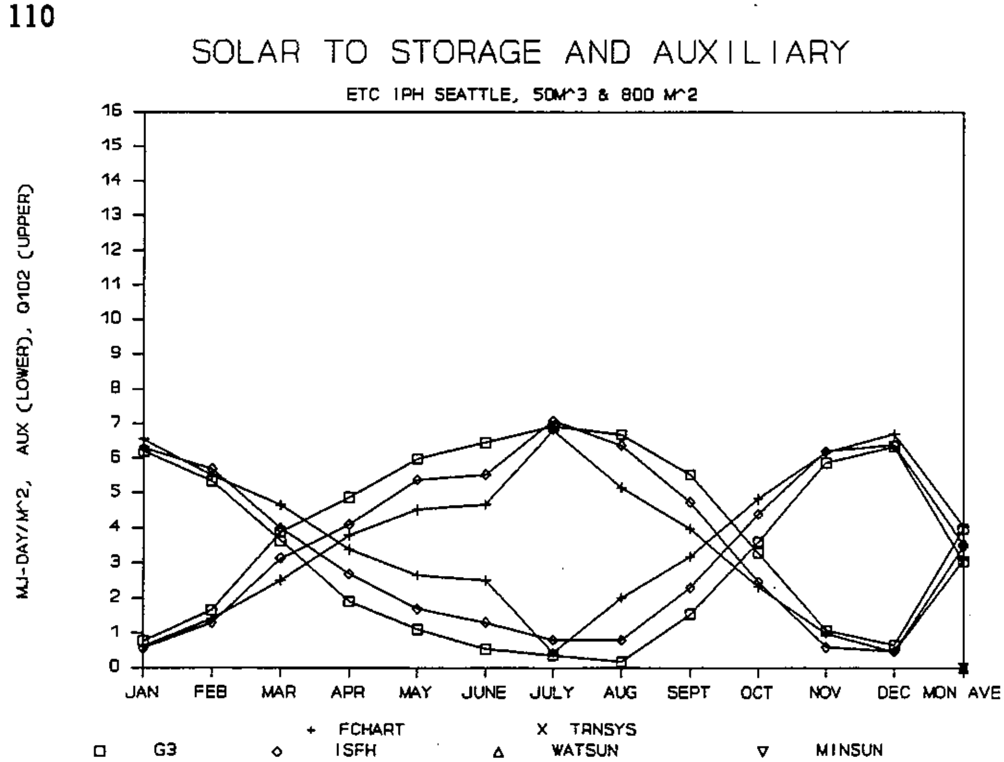

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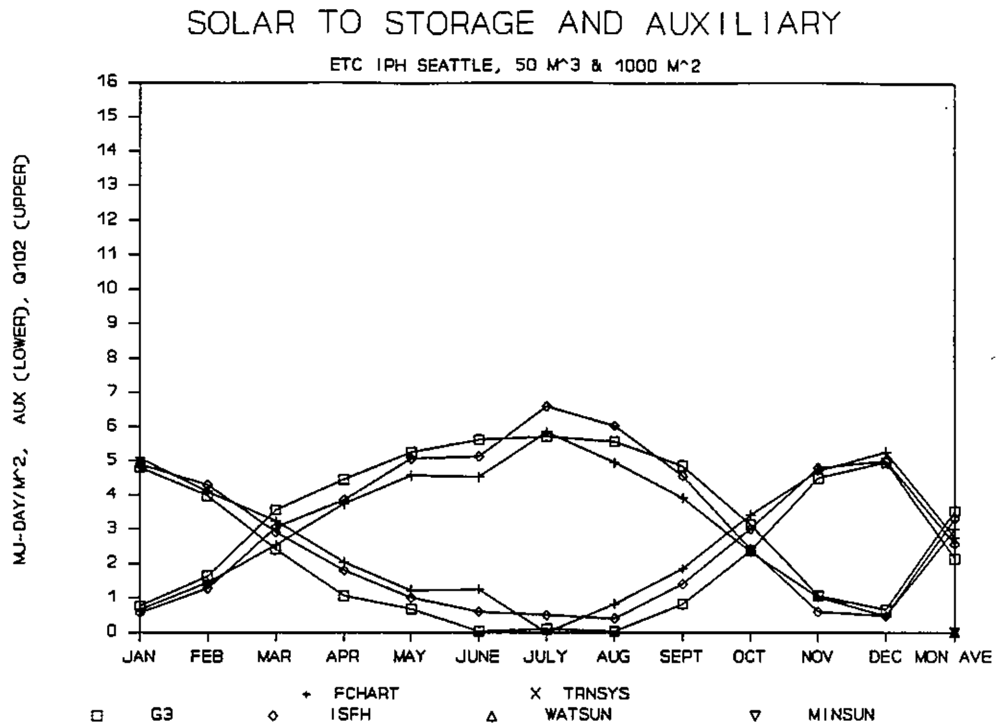

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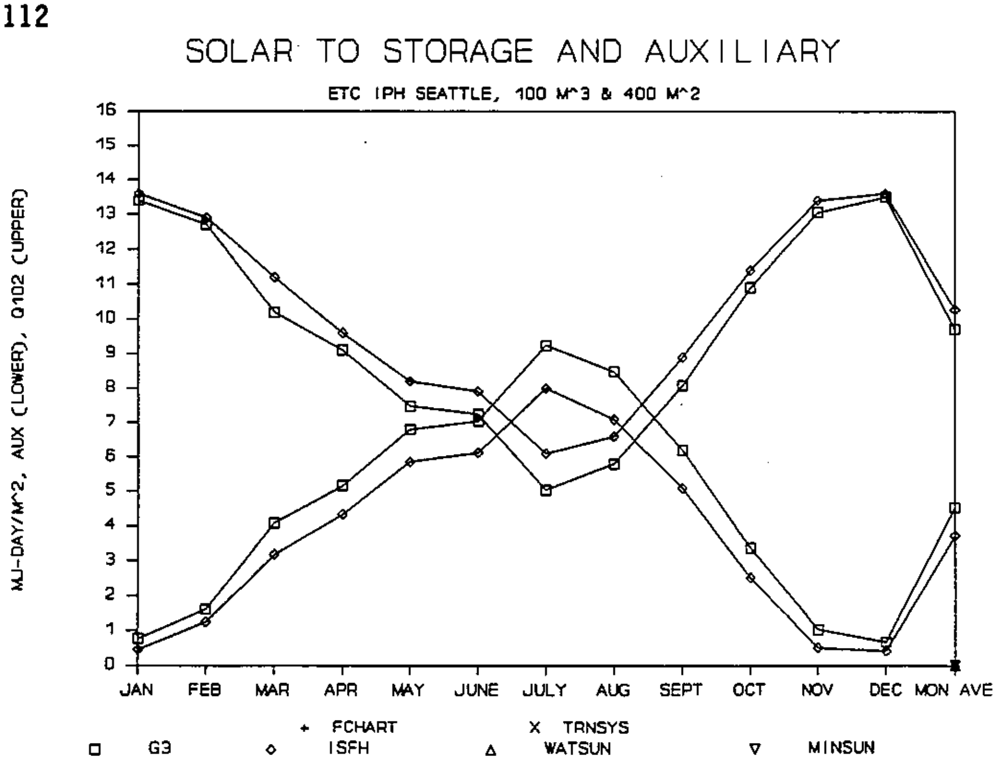

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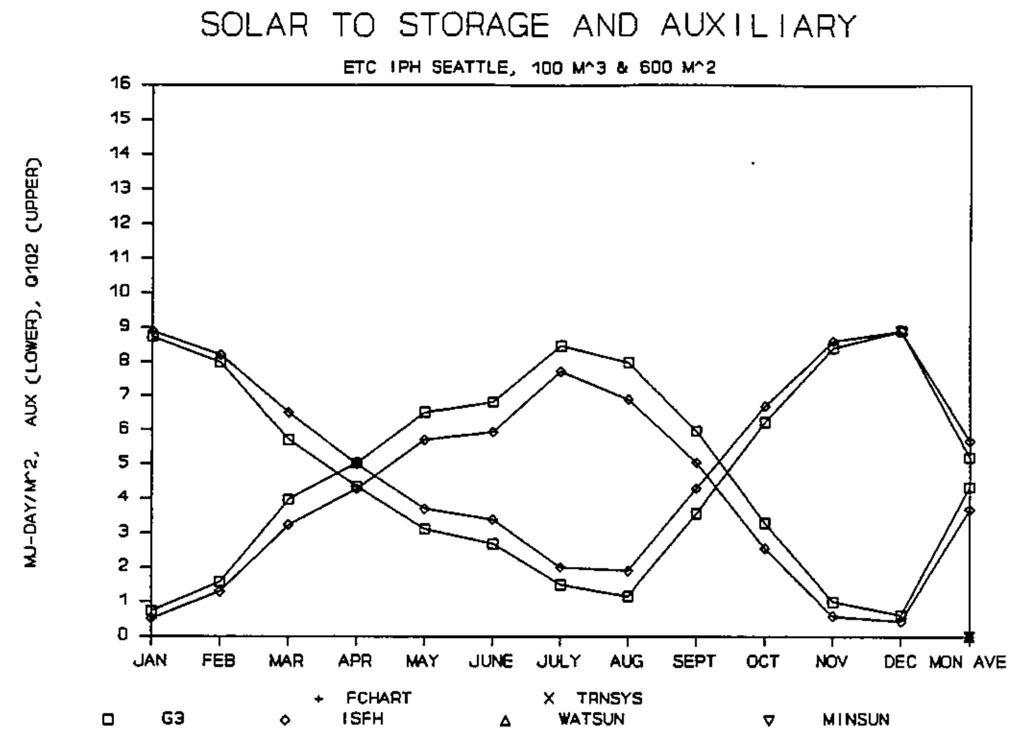

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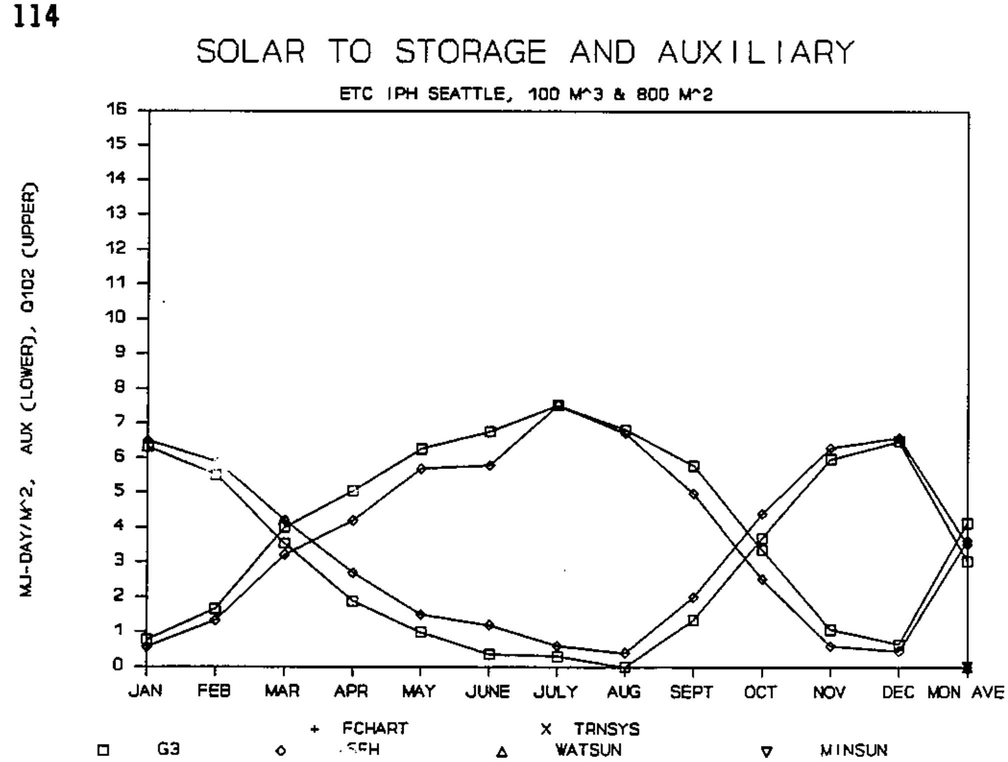

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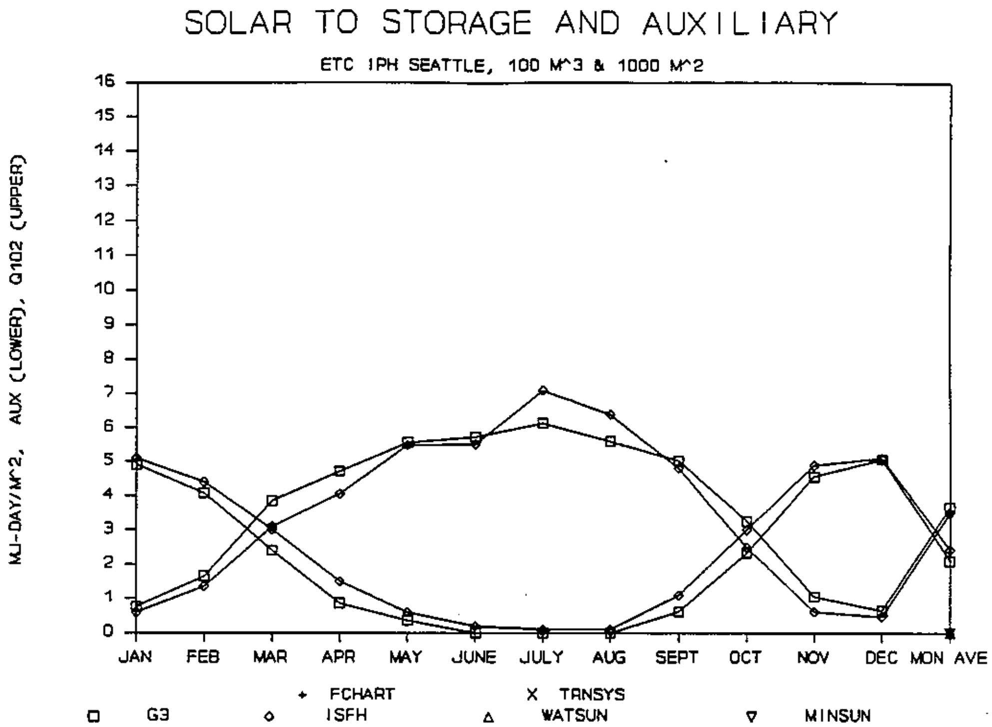

SOLAR TO STORAGE AND AUXILIARY
ETC 1PH SEATTLE, 100 M^3 & 1000 M^2
MJ-DAY/M^2, AUX (LOWER), Q102 (UPPER)
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+ FCHART
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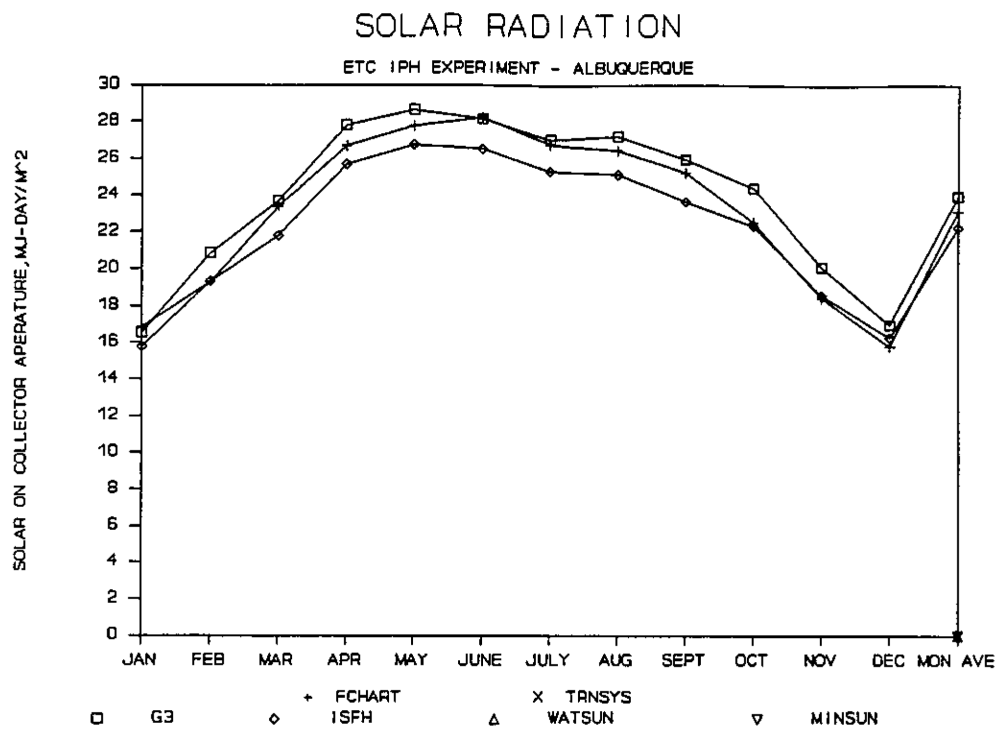
MINSUN

Figure 116



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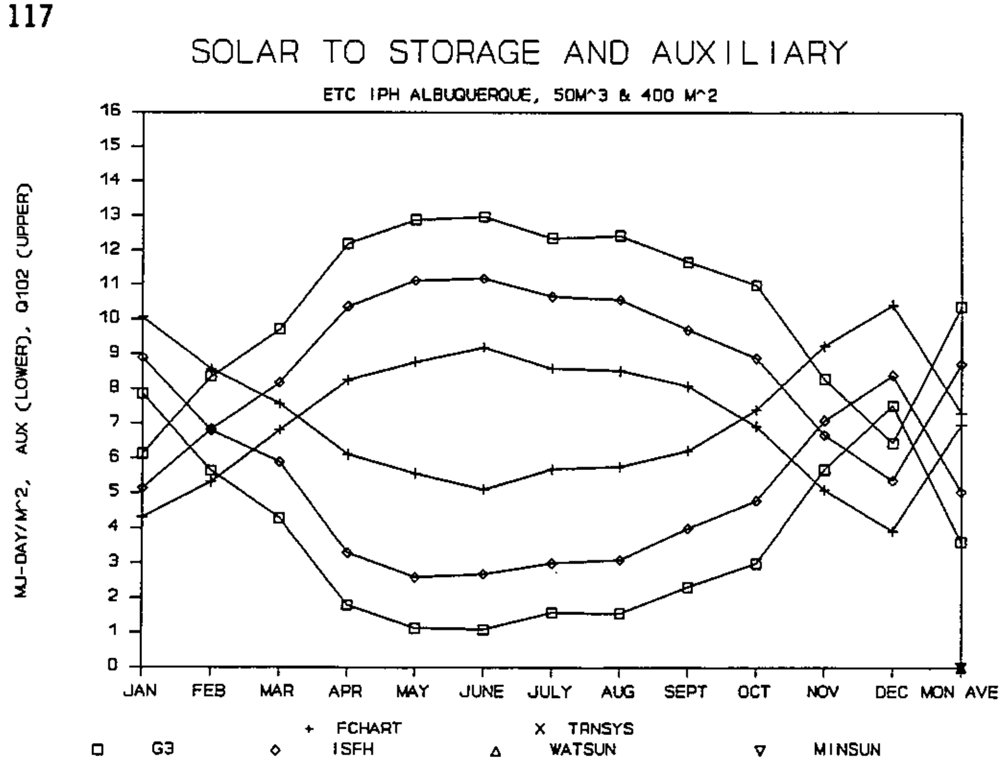

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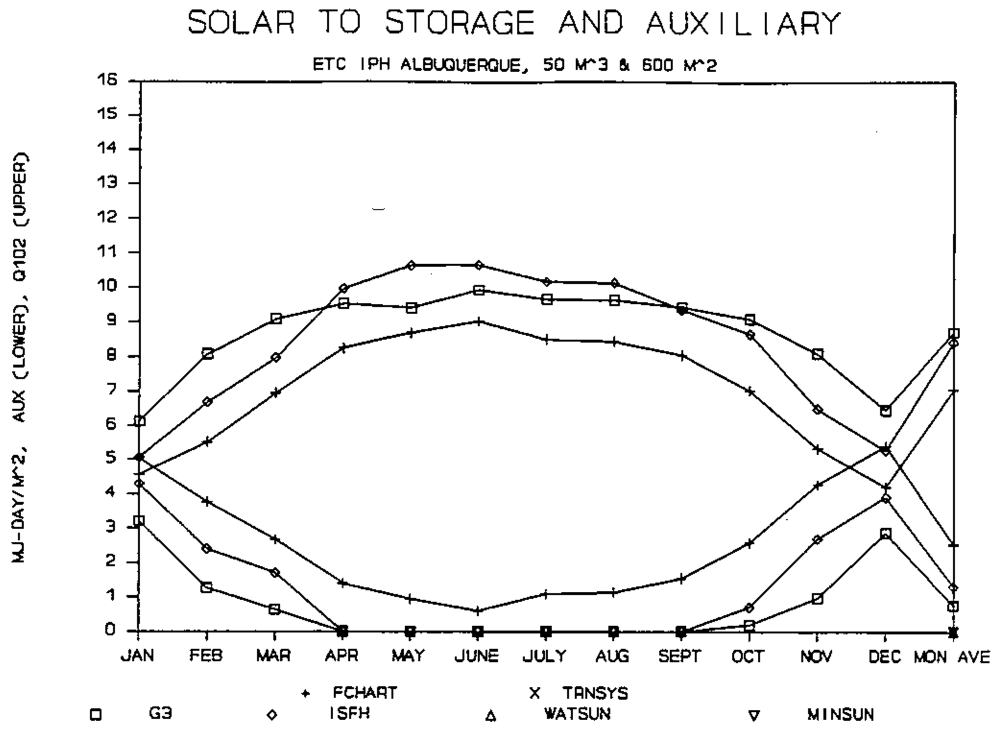

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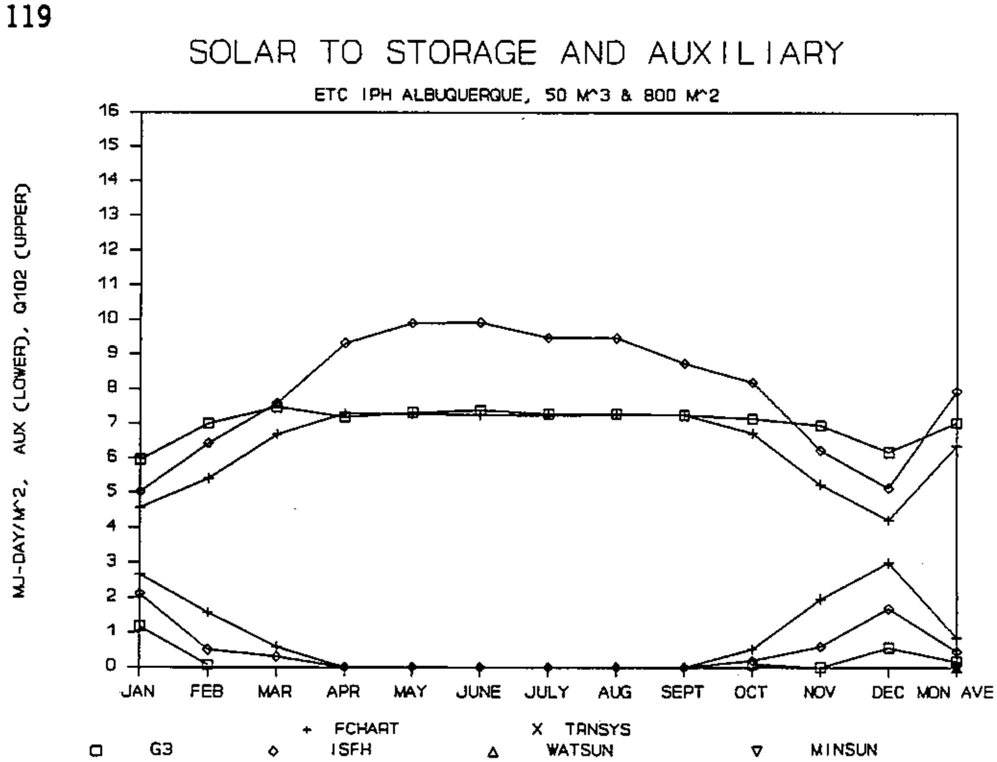

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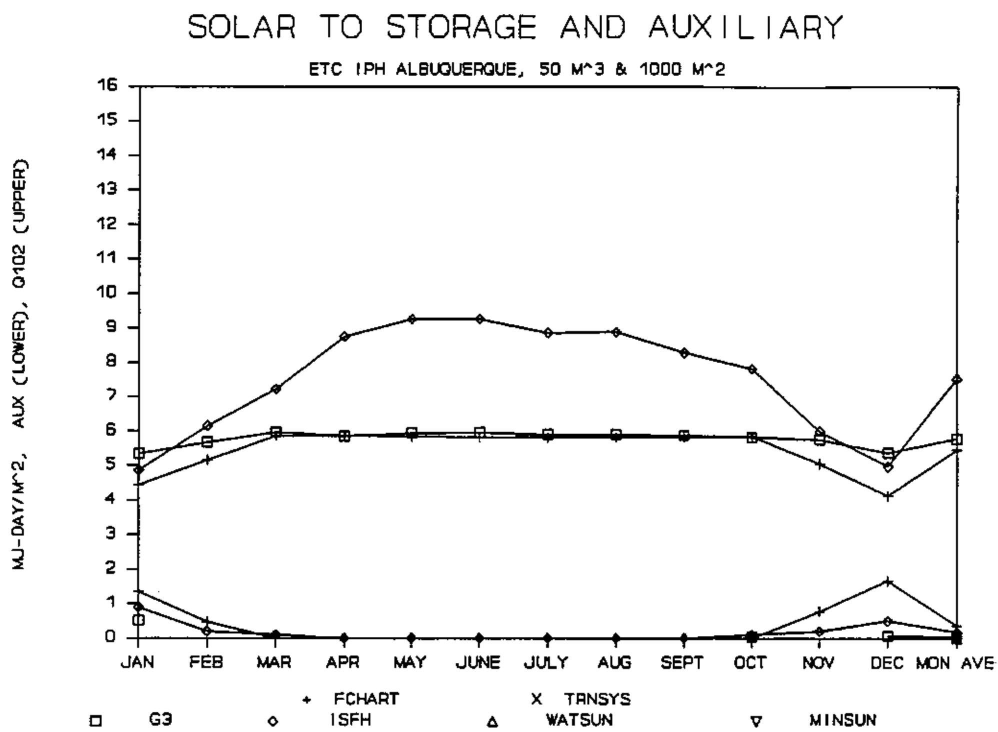

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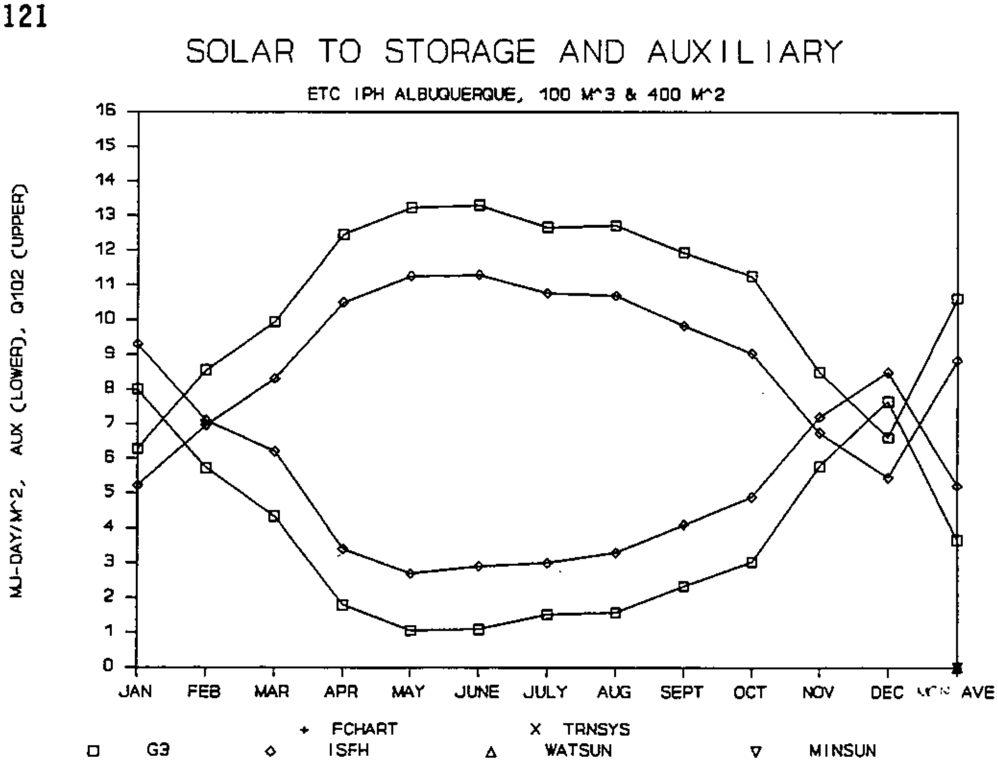

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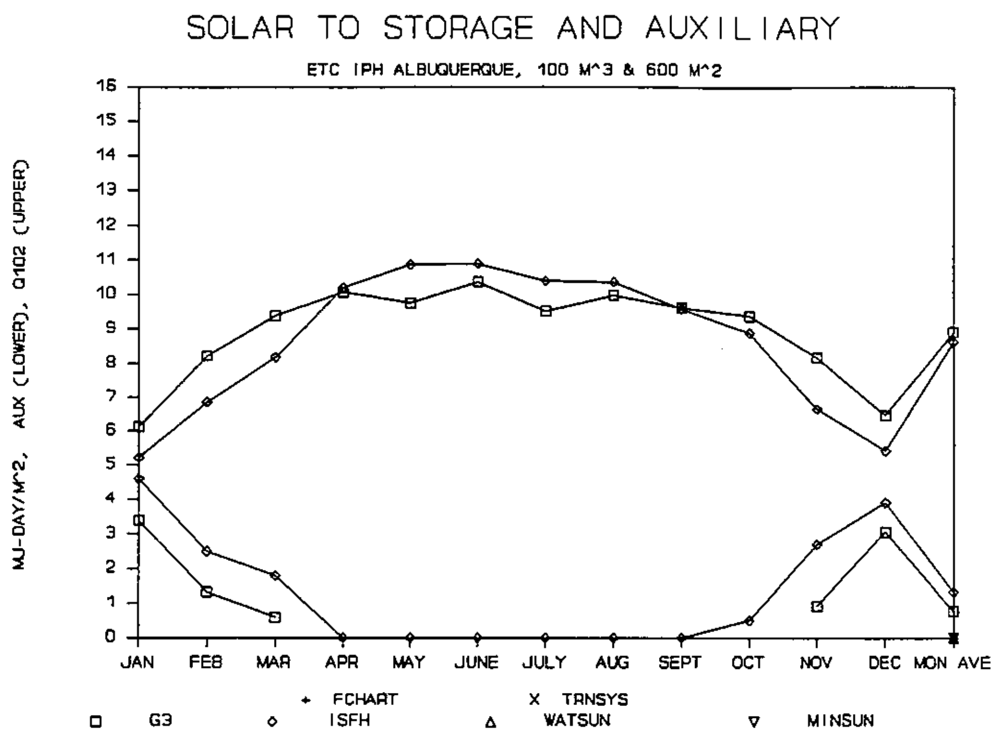

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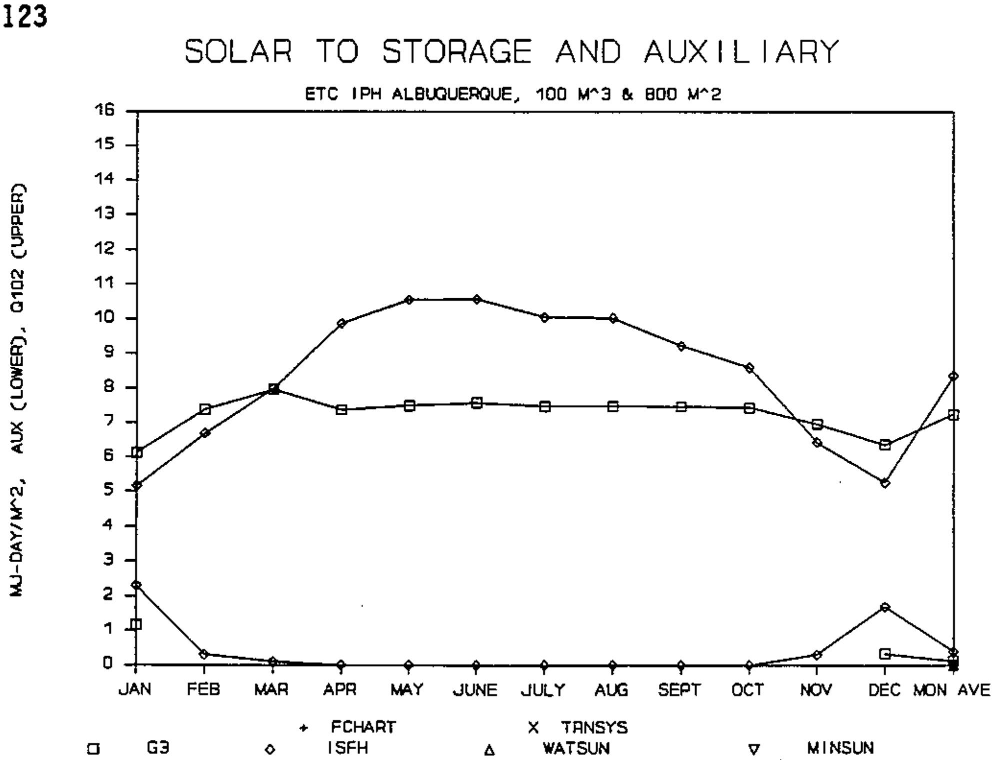

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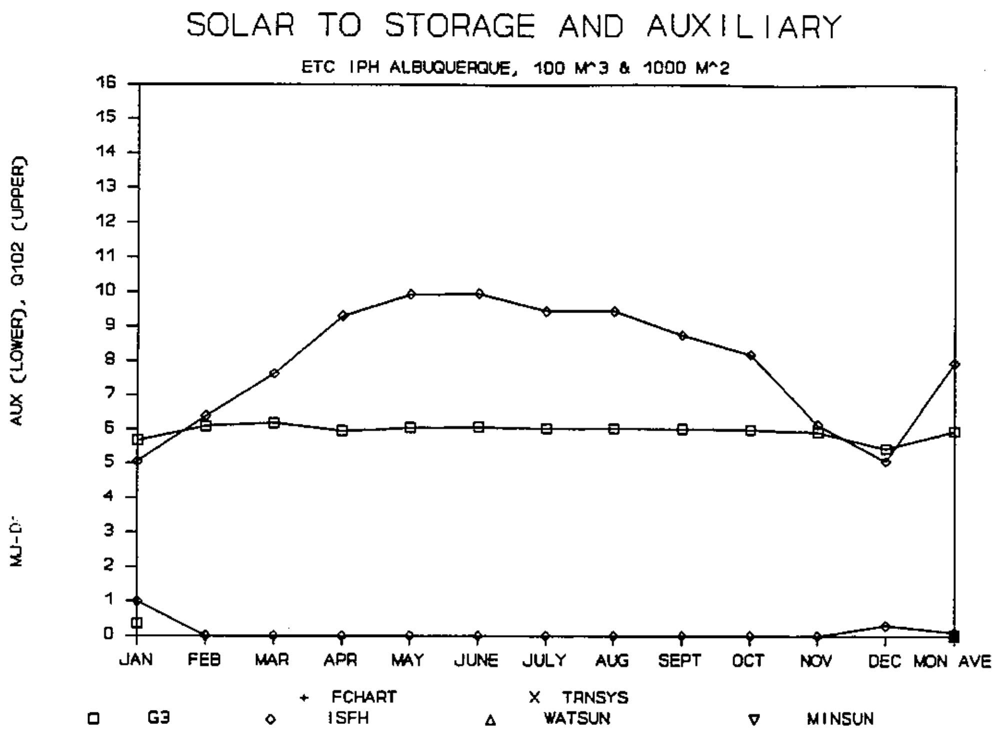
SOLAR TO STORAGE AND AUXILIARY
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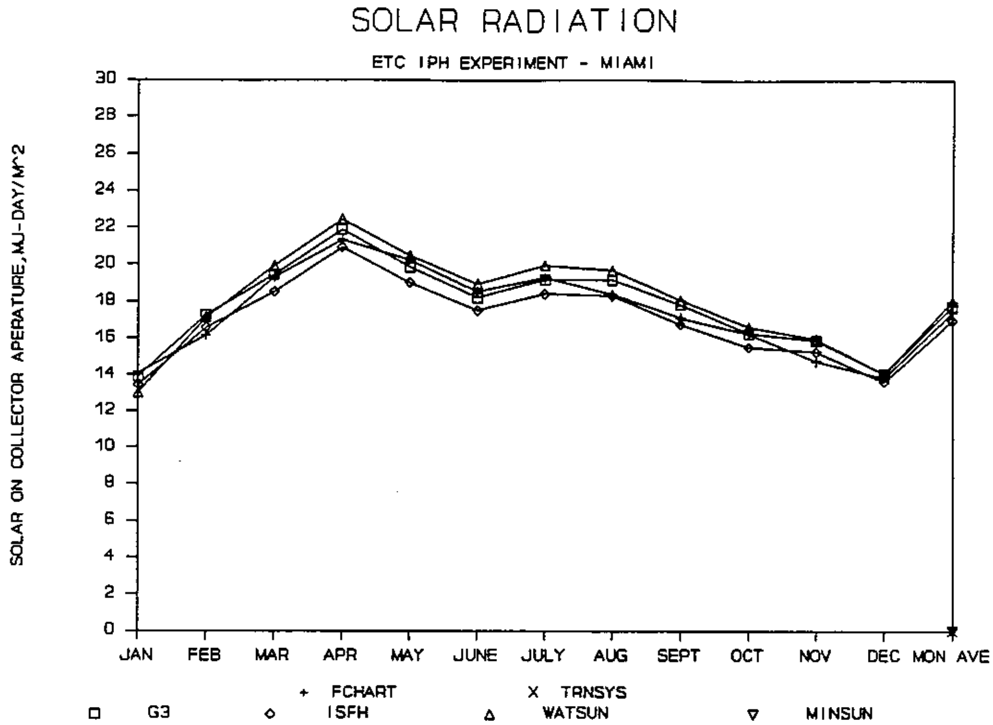
Figure 125



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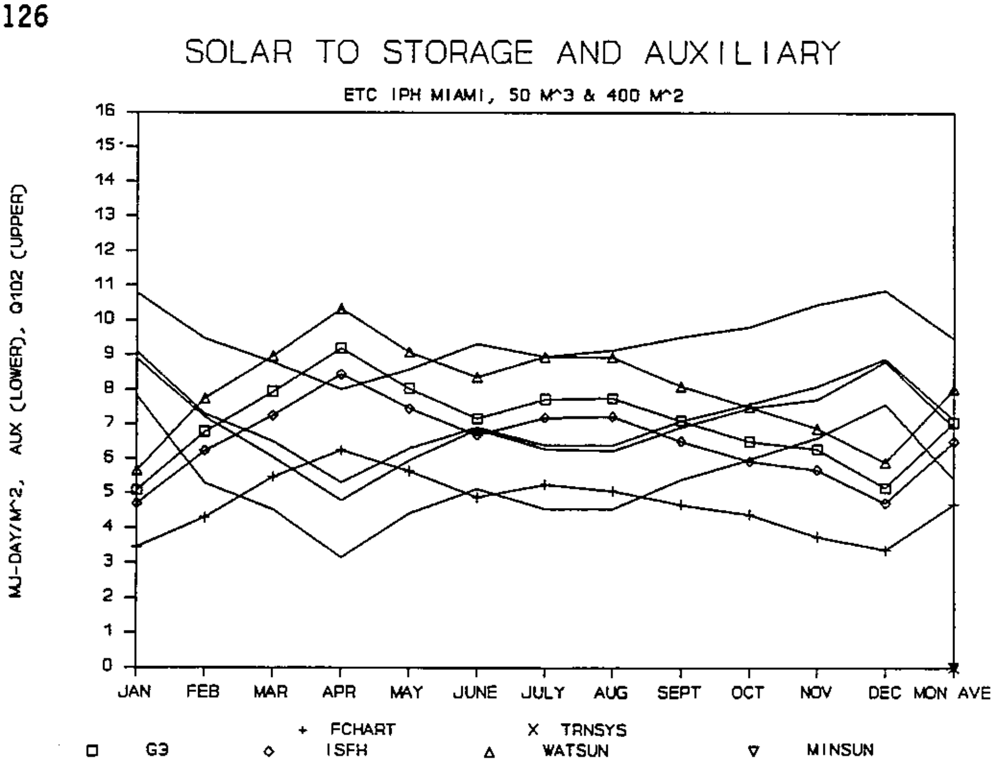

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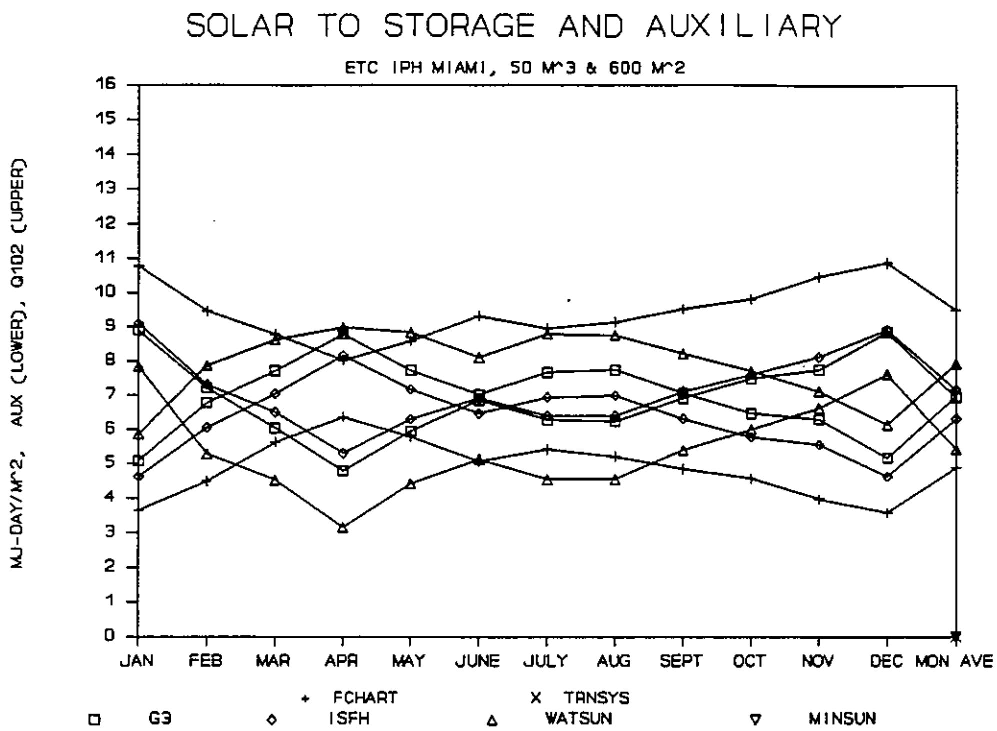

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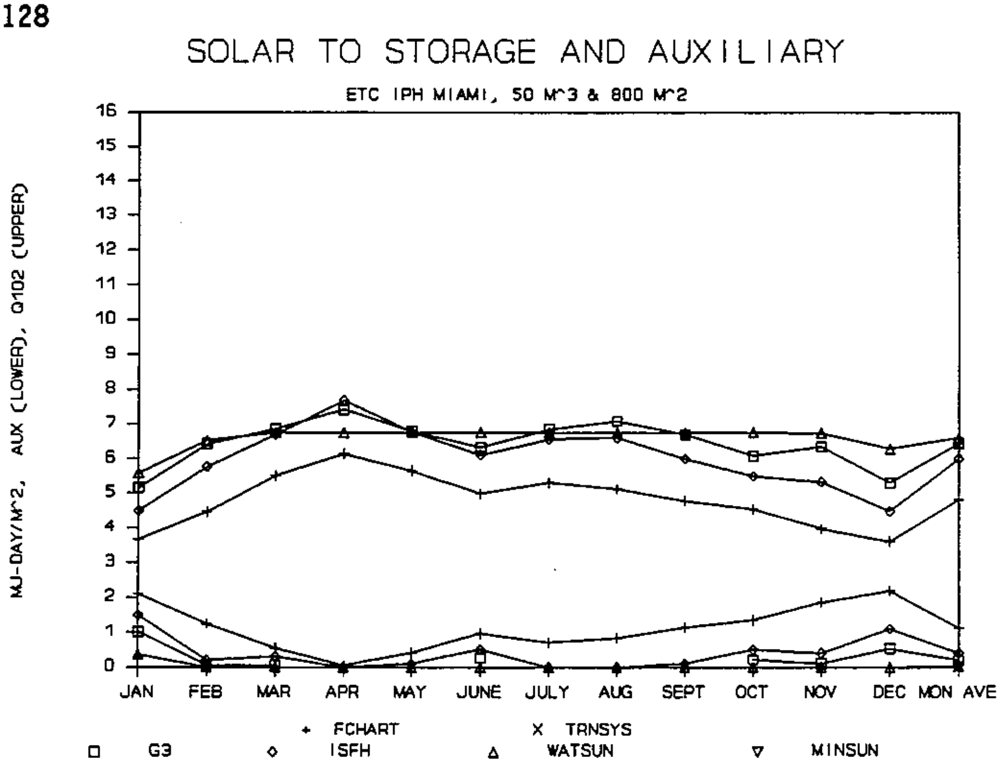

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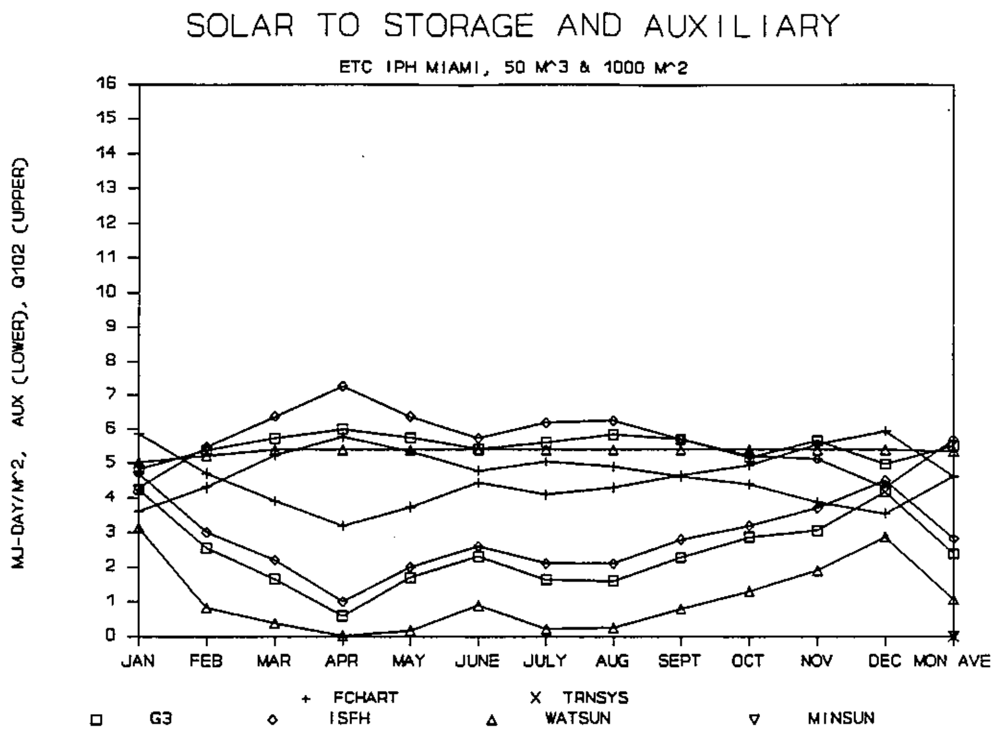

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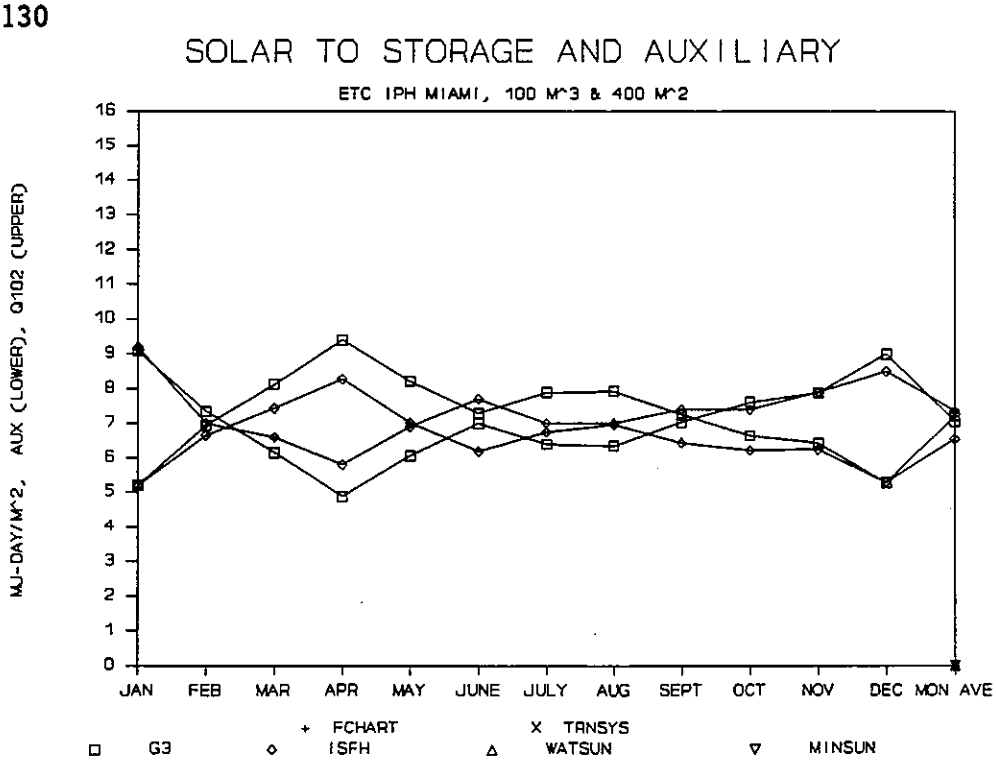

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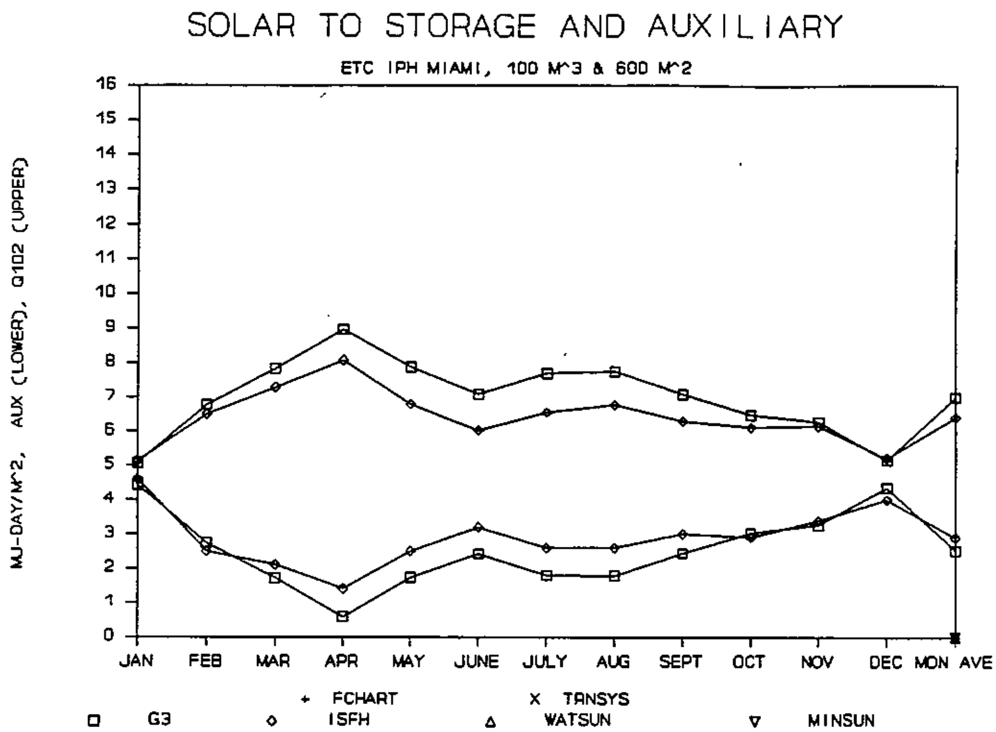

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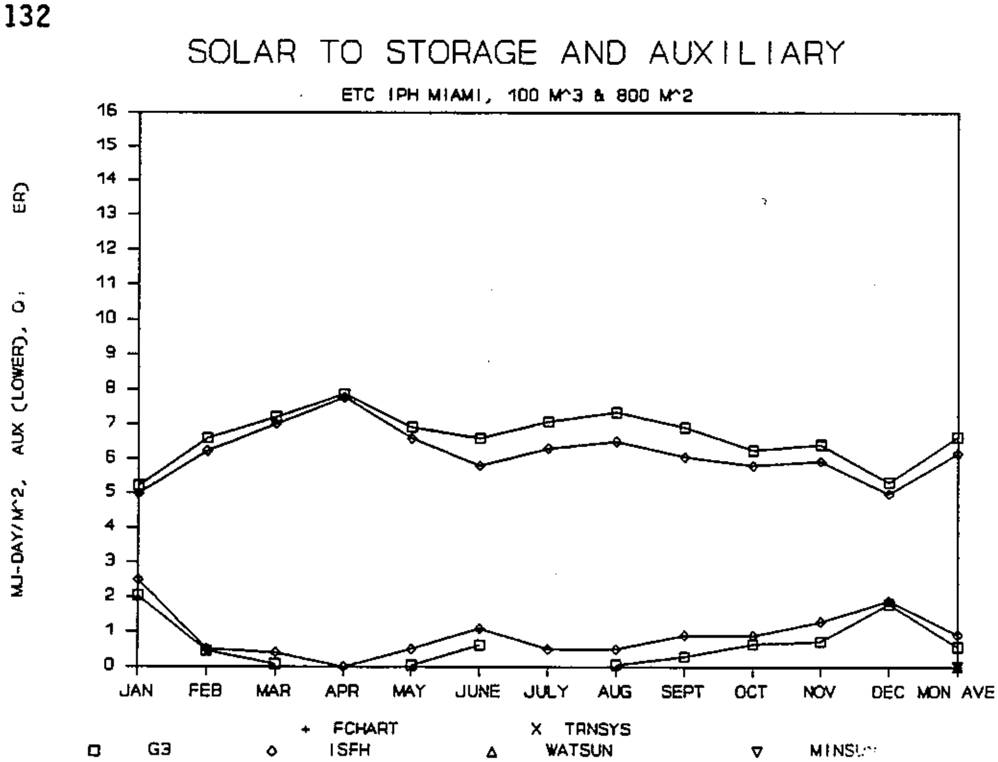

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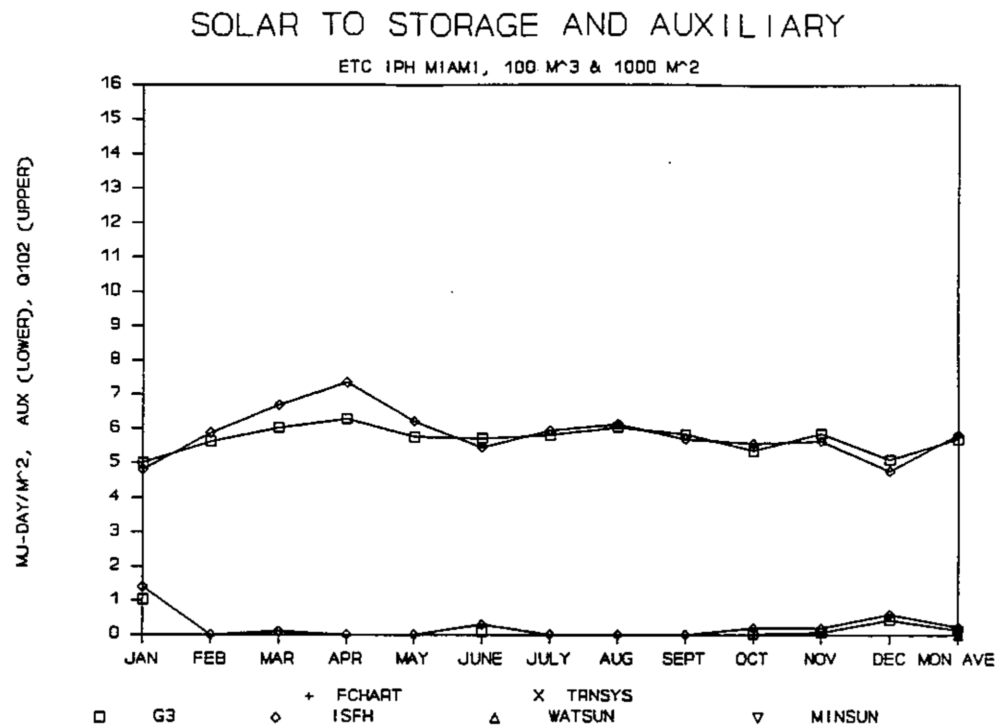
SOLAR TO STORAGE AND AUXILIARY
ETC IPH MIAMI, 100 M^3 & 1000 M^2
MJ-DAY/M^2, AUX (LOWER), Q102 (UPPER)
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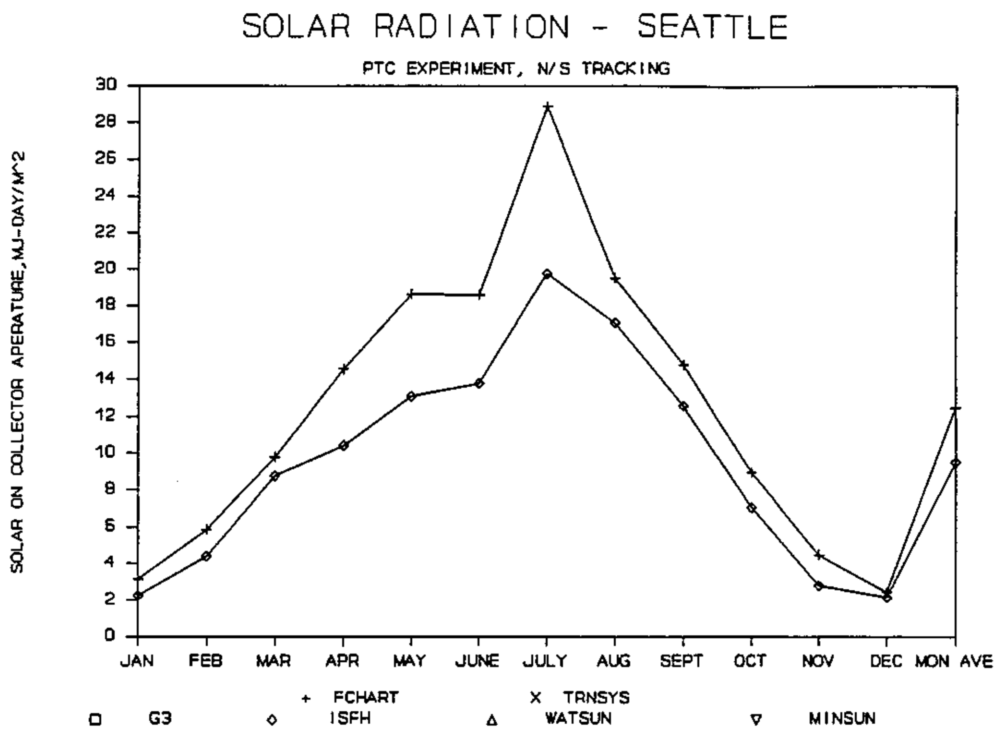
Figure 134



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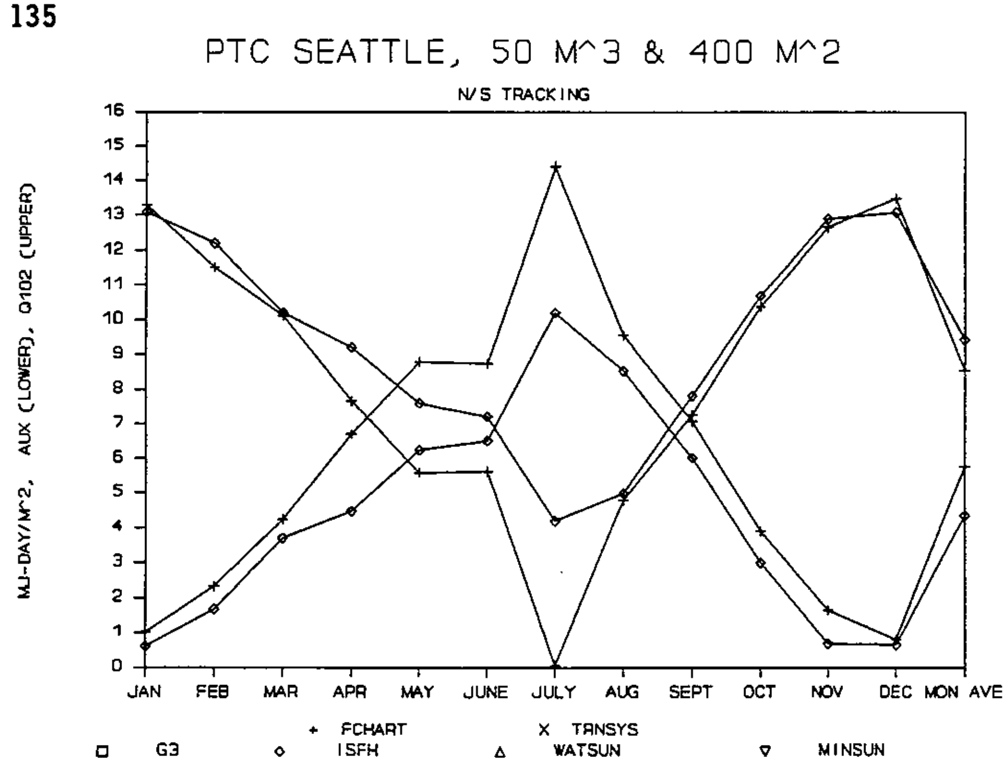

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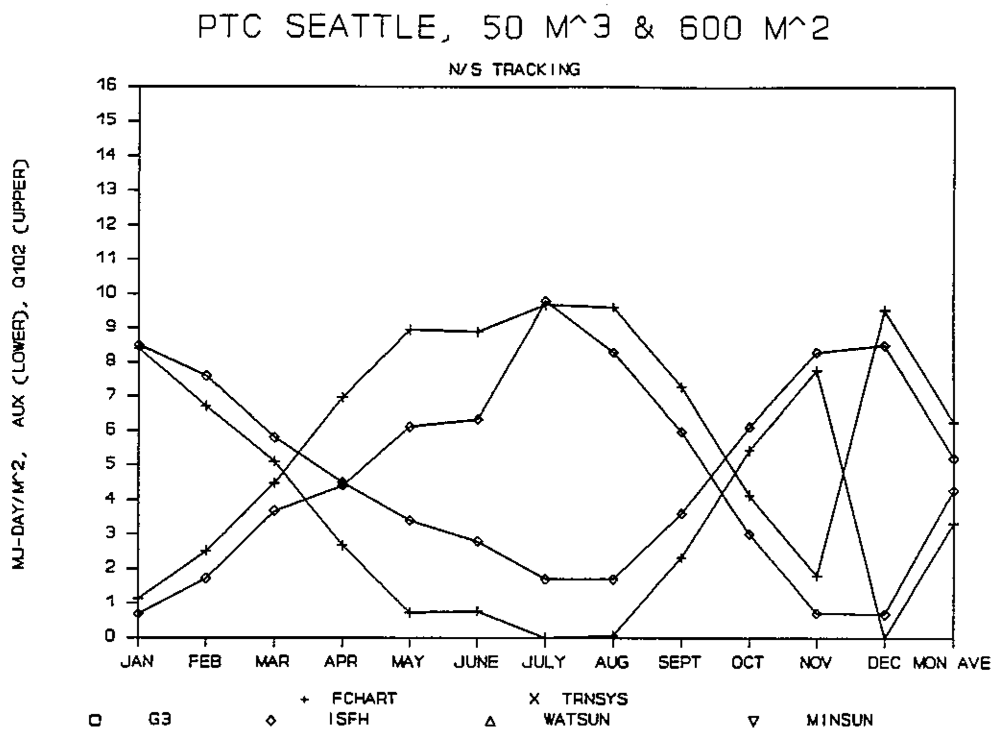

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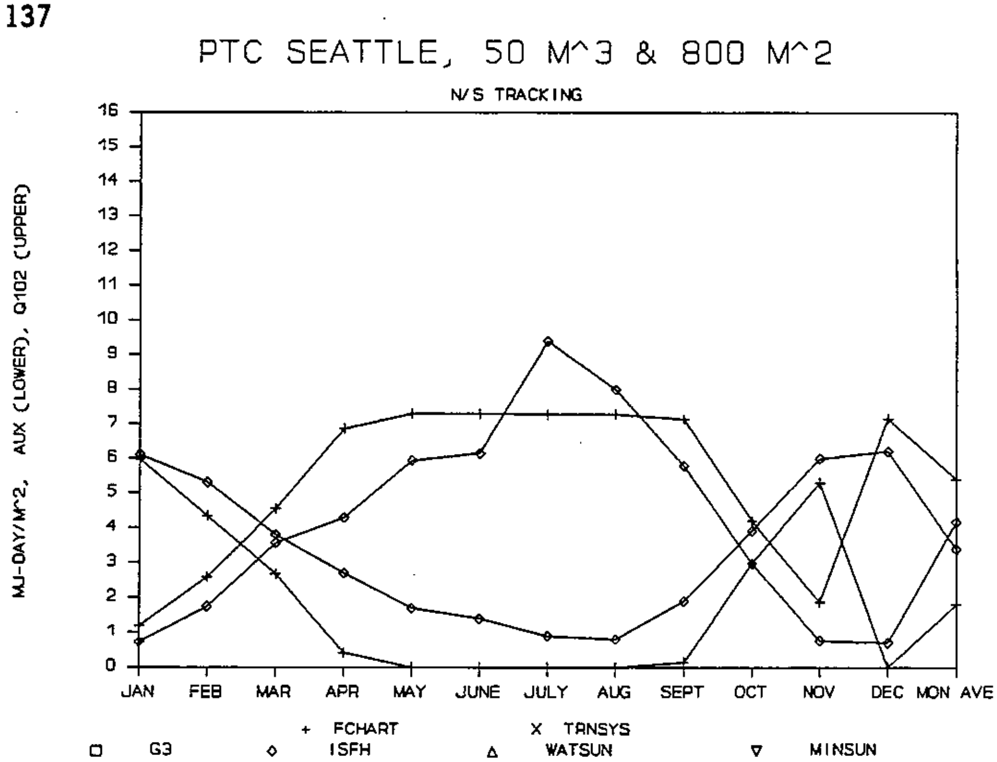

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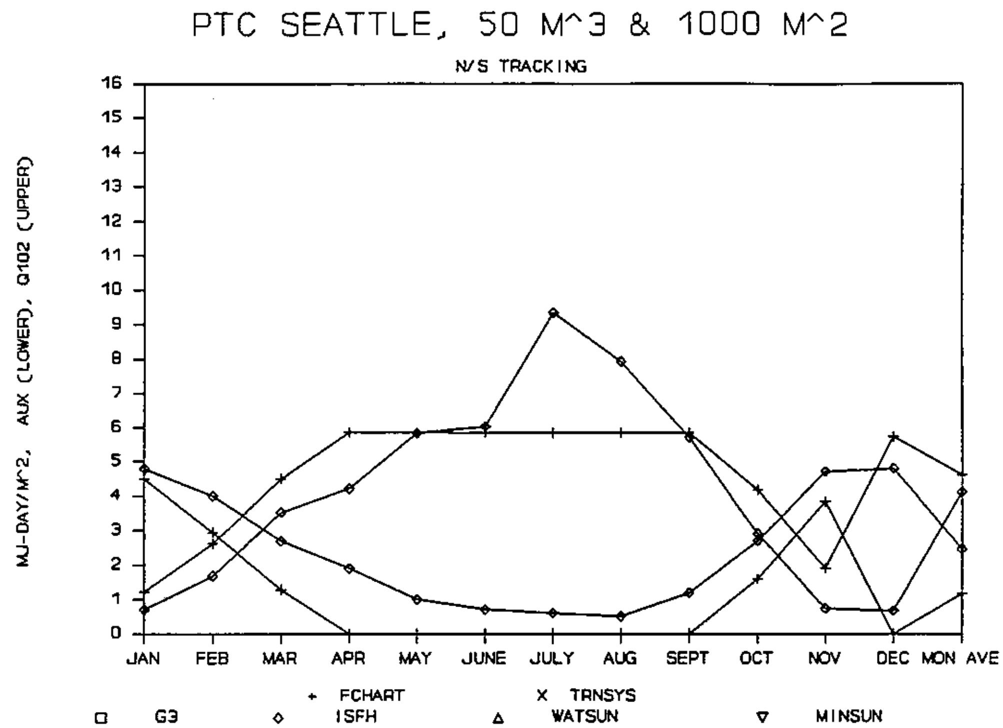
PTC SEATTLE, 50 M^3 & 1000 M^2
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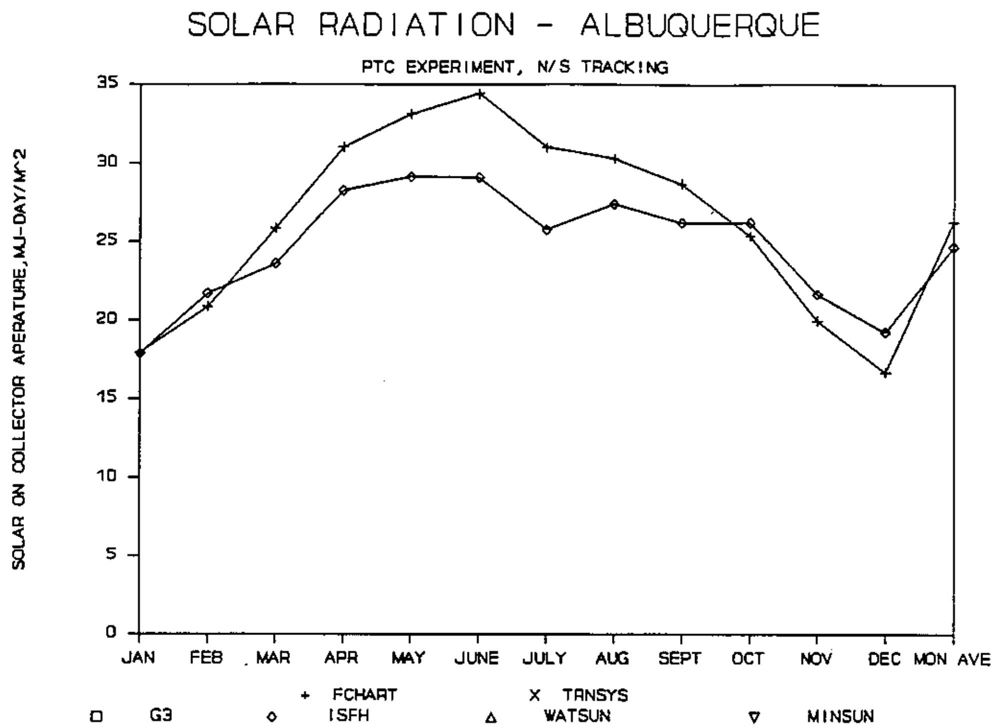
Figure 139



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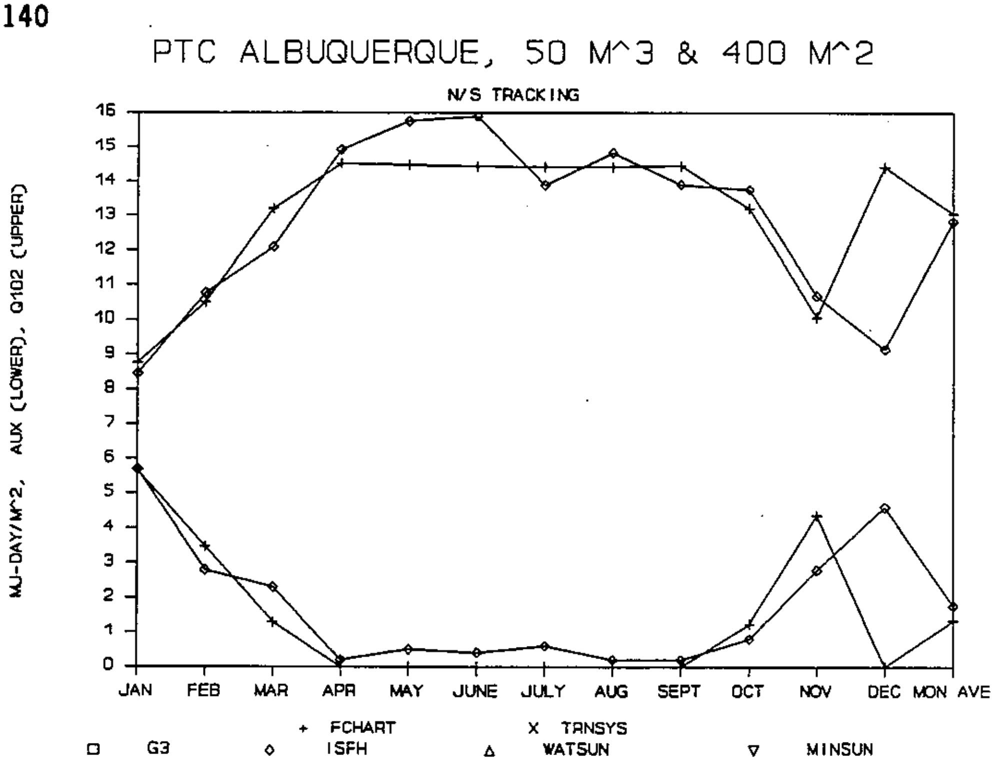

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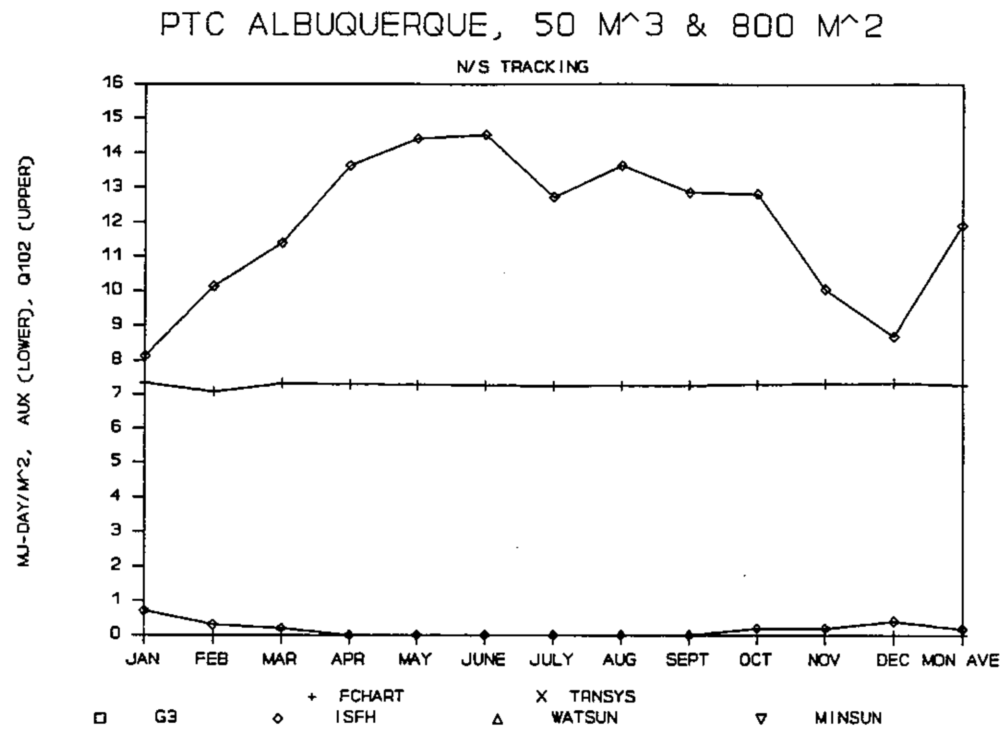

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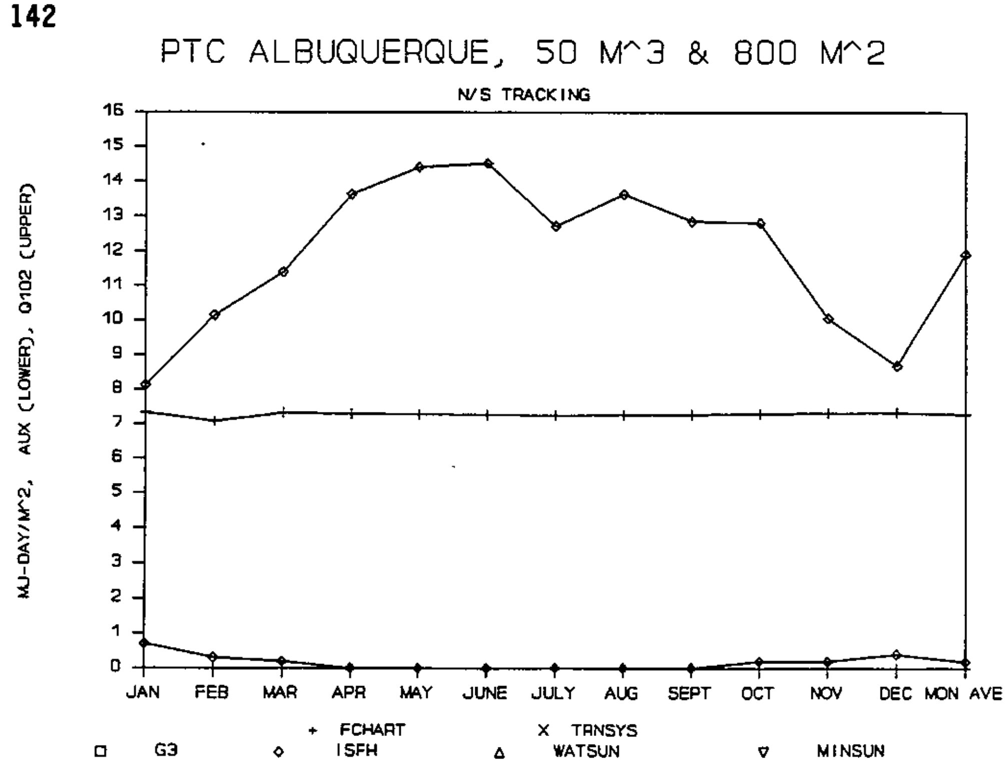

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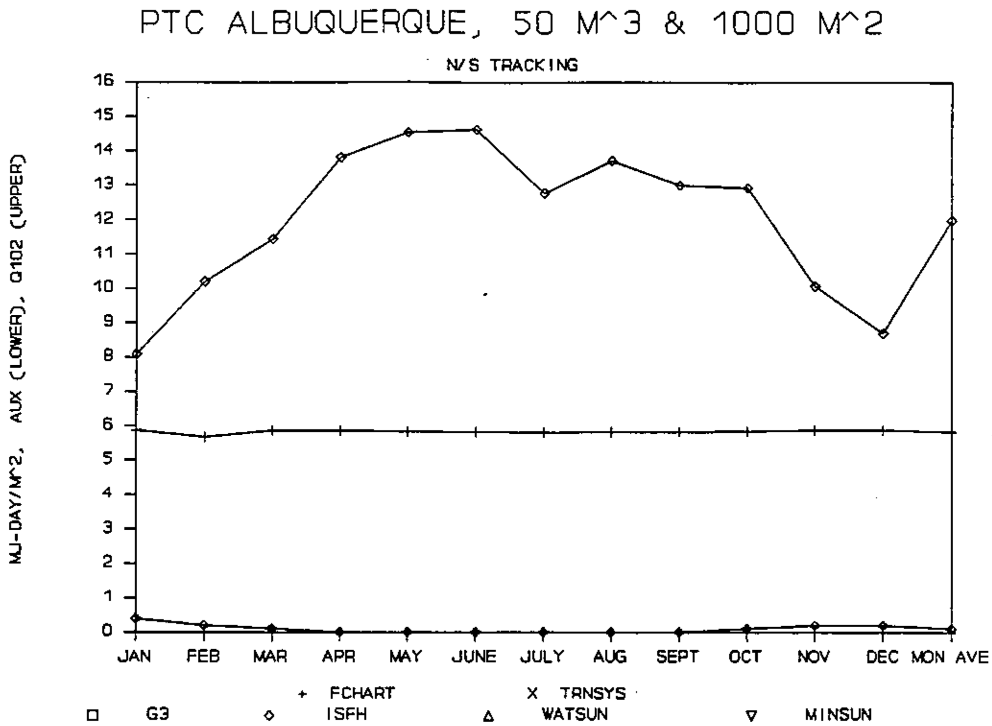
PTC ALBUQUERQUE, 50 M^3 & 1000 M^2
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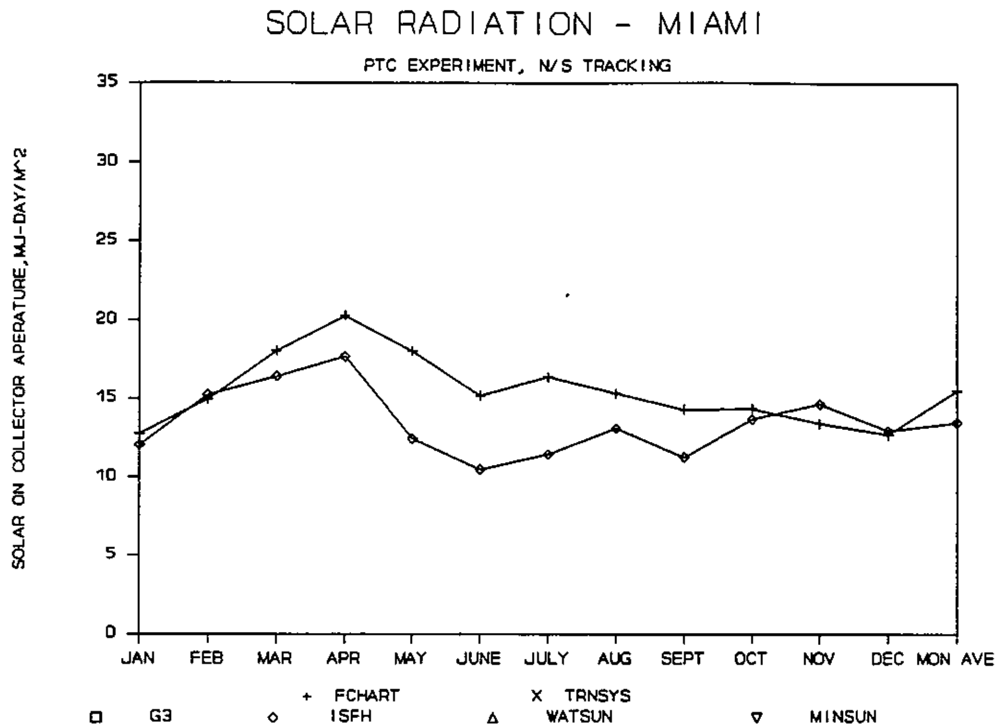
Figure 144



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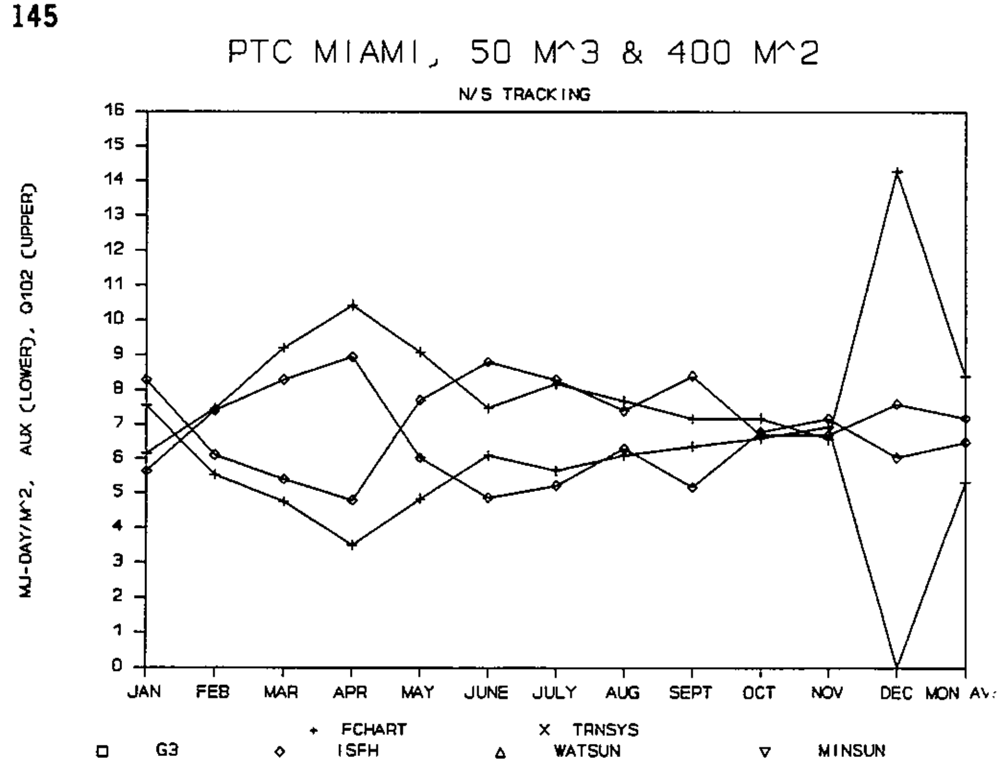

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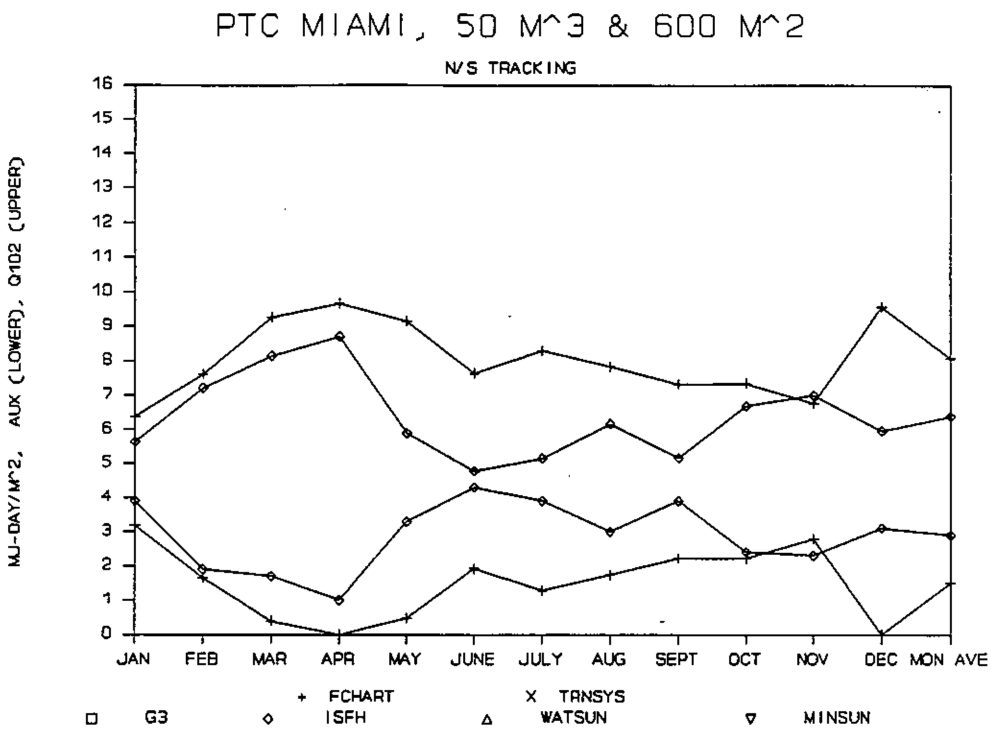

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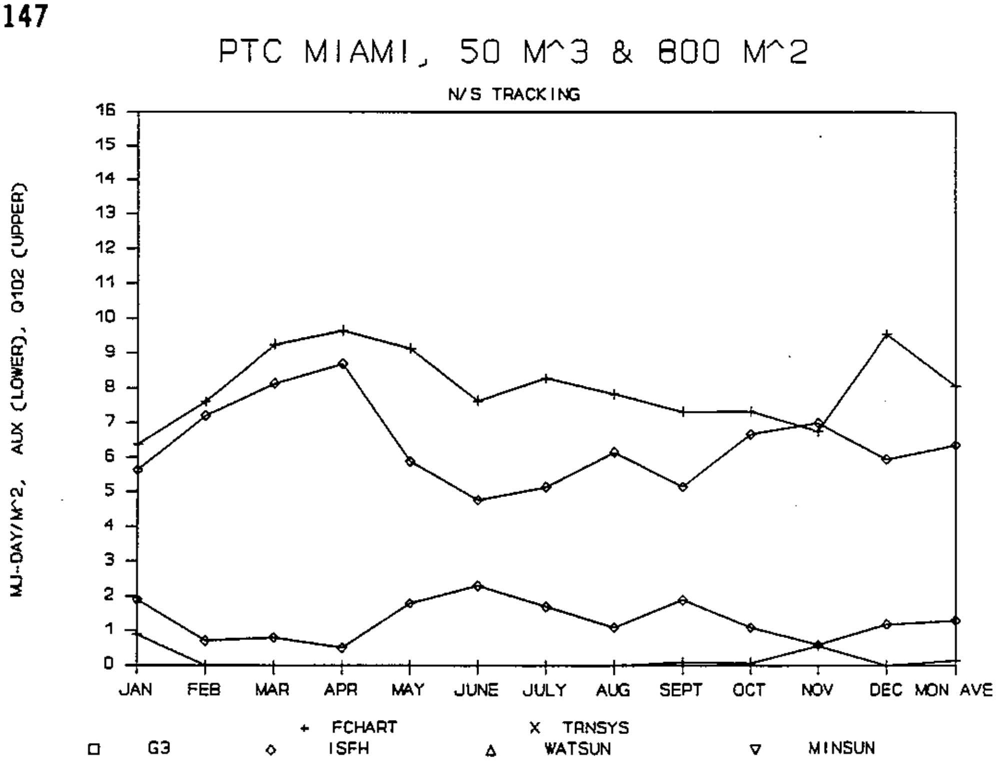

Figure 148

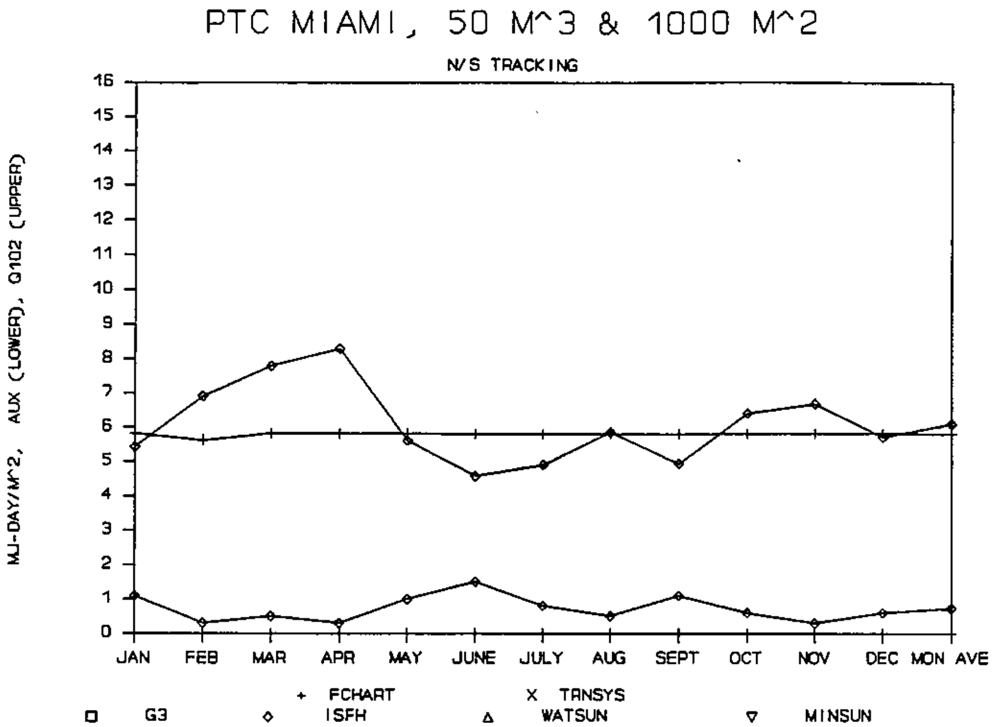
PTC MIAMI, 50 M^3 & 1000 M^2
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Figure 149

APPENDIX IV

DESCRIPTIONS OF THE MODELS USED IN THE WORKSHOP

CONTRIBUTIONS BY WORKSHOP PARTICIPANTS

ISFH

ISFH is a complete system based design/calculation method within the IEA Task VI context. It shall be treated therefore in greater detail. It is based on various component based simulation programmes (/[31], [32], [33]/) and extensive experimental work (/[34], [35], [36], [37]/).

The philosophy of the method is the determination of comprehensive characteristics (components, systems) by means of detailed modeling on a "lower level" and a subsequent statistical analysis, and to use these characteristics in the next level. Hence a detailed component oriented model is used for the determination of the system characeristics, whereas the component characteristics are determined in a similar way by modeling on the subcomponent level. We hold that this procedure is the most economic one in modeling and solves a given task within minimum time.

The structure of the method is shown in Table 7.1. It consists of two parts, with the first determining the system characteristics of a given installation (with variations) and the second one using these to calculate the monthly and annual performance of the installation. Within both parts modifications may be performed in order to extend the range of validity. The method is virtually self-explaining, that means, it is rather fully equipped with "help files" to provide explanations if needed. Some subprogrammes are provided or planned for particular informations (i.e. optimization of the piping, collector characteristics, incident angle modifiers, etc.). The model runs on IBM-XT (or compatibles) and upgraded computers. By various programming techniques the calculation time is rather short, so that a complete optimization may be performed within an hour.

7.2 The Determination of the Holistic Characteristics (IODs)

The following "systems" may be investigated

- insolation onto an arbitrarily oriented, if needed tracked plane (including incidence angle modifiers)
- collector only, with constant inlet temperature and unlimited demand (very fast calculation, but rather academic and only suited for fast comparisons)
- collector with piping, constant inlet temperature and unlimited demand (e.g. large district heating systems or industrial process heat systems without storage)
- collector with piping and storage system (domestic hot water/industrial process heat system with limited demand).

The most important component of the system is the collector itself. It is therefore modeled in a very detailed manner. The following parameters are taken into account:

ISFH

Part "A"

Data Bank	Main Programme	Subprogrammes
Heat Transfer Fluids (6)	Storage Tank (10 Parameters)	
10 Generic Types	Collector (10 Parameters)	Determination of Characteristics (24 Parameters)
	Piping (2*8*7 Parameters)	
	Heat Exchanger (2...3 Parameters)	Characteristics of Internal HX (18 Parameters)
	Consumer Demand (Profile/total Amount)	
	Weather Type (3 Generic Types)	

Part"B"

Data Bank	Main Programme	Subprogrammes
>350 Locations 18 TMY (monthly values) 18 TMY (daily values)	Climatic Data	5 Radiation Processors, User's Data
	Collector System Area & Orientation	
11 Standard Curves	Incidence Angle Modifiers	Refraction Index & number of Panes, User's Data
	Obstructions	
Fixed Mounting & 4 Tracking Modes	Tracking Systems	

Results

Collector Output
Solar to Load
Solar Fraction
Surplus Energy
Auxiliary Energy

Fig. 7.1 Schematics of ISFH-Programme

- optical efficiency: the optical efficiency $\tau\alpha$ with normal (i.e. vertical) incidence is modeled to be independent of the radiation intensity (the apparent dependence of somre collectors is due to the limited absorber-fluid conductivity). The variations of the optical acceptance with inclined radiation are taken into account within part B by means of orthogonal functions and either symmetric or asymmetric acceptance angles
- internal absorber-fluid conductivity: this parameter is especially important with heat-pipe collectors, as it may then be rather limited and the mean absorber temperature consequently exceed substantially the mean fluid temperature; it is assumed to be slightly depending on the flow rate (important with microflow operation)
- thermal losses: as the calculation model covers a wide temperature range the thermal losses cannot be assumed to be constant, but are described by the equation

$$U_c = (U_0 + U_1 * T_{abs} + U_2 * T_{amb})*(1 + v_w*C_w)$$

  thus depending both on the (mean) absorber and the ambient temperature, and the wind velocity. They are assumed to increase linearly with wind velocity, with the proportional factor being a specific constant for each collector type
- thermal capacity: this parameter depends on the collector construction and the type of the heat transfer medium; it is assumed to be constant (the temperature dependence of the fluid capacity is not accounted for); reference temperature is the mean fluid temperature
- reference temperature (losses and controls): the reference temperatures are the mean absorber and the mean fluid temperature; this approach is valid down to very low specific flow rates (i.e. approximately 3 kg/(m^2*h)).

The influence of the internal conductivity and the varying thermal losses on the collector characteristics is depicted schematically in <u>fig. 7.2</u>.

The model uses some uncommon collector parameters (especially the thermal loss parameters and the incidence angle modifiers). In order to avoid user frustration these values are given for a wide range of collector constructions, or may be determined by means of special subprogrammes for a specified construction (collector defined by 24 parameters), or may be typed in according to measured values.

The next most important component is the storage tank. It is described by ten parameters, i.e.

- the total volume
- the effective conductance of the insulation material (which may exceed the calculatory one by a factor of up to six due to thermal bridges, break-throughs, insulation flaws, etc.)

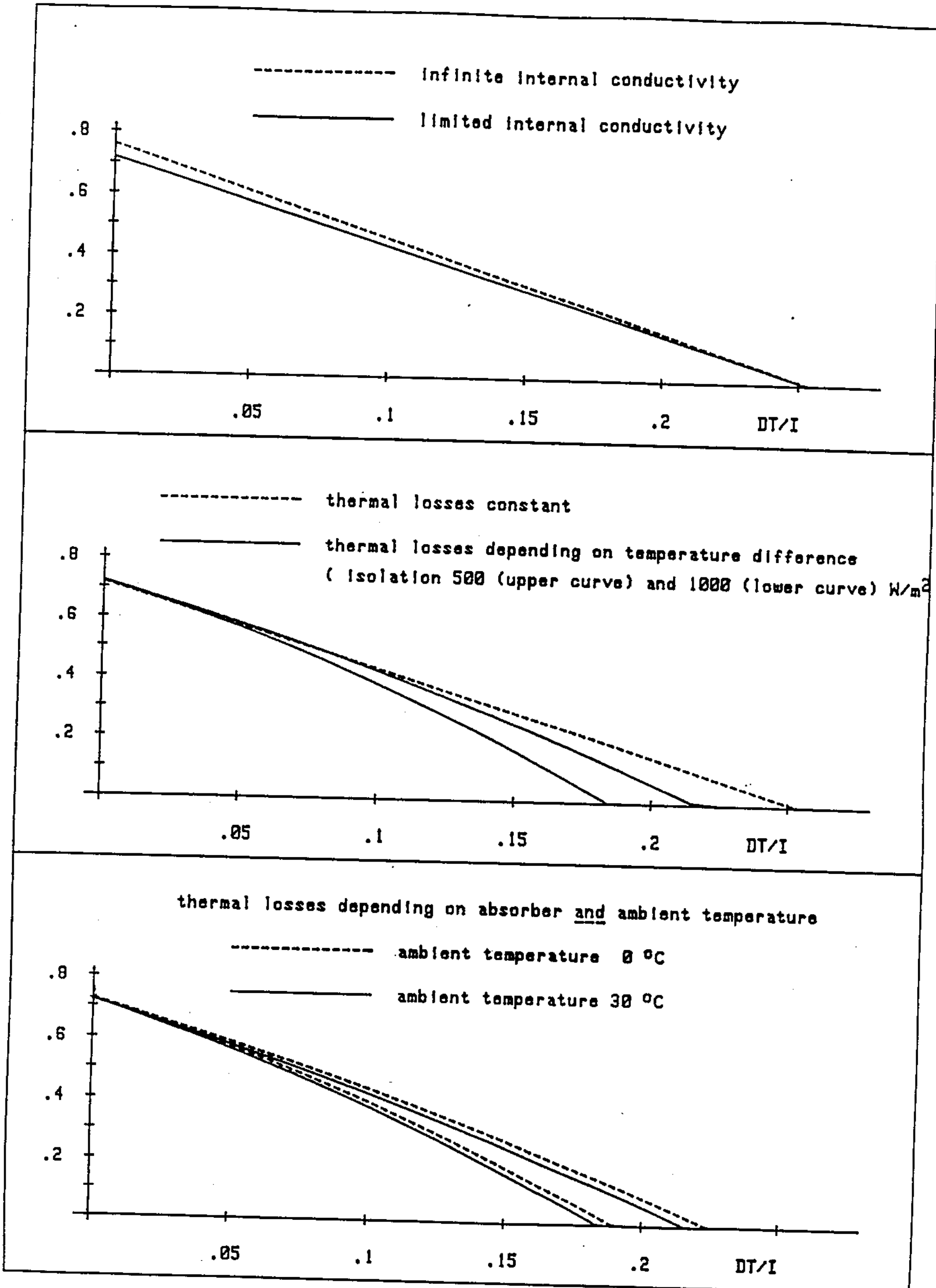


Fig. 7.2. Influence of Internal Conductivity and Varying Thermal Losses

- the insulation thickness
- the number of layers within the tank (a measure for the stratification)
- the number of (upper) heated layers
- the aspect ratio (height/diameter)
- the ambient temperature (either indoor and constant or outdoor and varying)
- the existence of a bypass
- the layer where the return flow from the collector or heat exchanger enters the tank
- the maximum tank temperature.

The thermal losses are distributed on the different storage layers according to their respective surface area, thus are concentrated in the lower and upper part of the tank. The interaction between adjacent layers is due to

- volume flow (collector/heat exchanger flow and demand flow)
- conduction (only due to the storage medium)
- convection.

A "partial" mixing of the collector/heat exchanger return flow with the respective retur layer is assumed if its temperature is below that of this layer (/[38]/); in the other case, the mixing is complete.

Systems either with or without heat exchangers are possible. External heat exchangers are characterized by three parameters, i.e.

- the specific exchanger value (W/K),
- the storage layer of the return flow,
- the capacitance flow ratio (primary to secondary flow).

The characterization of internal heat exchangers is far more complex. It is performed in the following manner

- the heat exchanger is within the lowest (coldest) storage layer
- the heat exchanger coil is described by its geometrical dimensions and its material conductivity
- the internal (collector fluid) and secondary (storage medium) Reynolds and Prandtl numbers are determined according to the material properties of the respective fluids and the relevant temperatures according to (/[39]/) for approximately 80 different operational conditions
- the efficient heat exchanger values are determined and subsequently statistically processed to derive the characteristics of the internal heat exchanger.

Both the forward and return piping may consist of up to eight serially connected parts (e.g. a large collector field with twelve collector loops may consist of two parts: a single forward pipe to the field and twelve parallel pipes within the loops). Each part is characterized by six values, i.e.

- the length of the respective pipe (with several pipes in parallel: average pipe length)
- the inner diameter of the pipe
- the effective conductance of the insulation (W/m*K), taking into account all thermal bridges, leakages, and flaws of the insulation; this value may consequently exceed that of the material itself by a factor of up to four
- the ambient temperature (either indoor and constant or outdoor and varying)
- the number of parallel pipes of the same kind.

The wall thickness of the tubes and thus the capacity of the (empty) tubes is determined according to a German standard for steel tubes (DIN 2449). Other standards for both steel and copper tubes will be shortly implemented.

The consumer is characterized by the following parameters:

- the total daily hot water demand,
- the demand temperature,
- the (cold) water inlet temperature (either from mains or return flow from process), which may show a seasonal swing (e. g. the return temperature of a district heating system, which is higher in winter)
- the demand profile, which may be defined in hourly steps.

The following weather patterns may be chosen:

- "steady" weather conditions (sinusoidal radiation profile)
- "variable" weather conditions (sinusoidal profile with perturbations)
- "real" weather conditions (mixture of "steady", "variable", "morning-oriented", and "afternoon-oriented" days).

For most applications "steady" weather conditions lead to the lowest output (maximum operation time), but the differences are small with well designed systems.

There is a recommendation for the timestep, which provides a "reasonable" accuracy. For very accurate calculations it may be decreased by a factor of two to three.

After the definition of the system the system behavior is determined

- for two different day lengths (9 and 15 hrs.)
- for two different mean ambient temperatures (ambient temperature ± 10 °C)
- for two different collector areas (minimum and maximum),
- and a set of eight (fifteen) subsequent days with varying insolation,

thus for a sample of up to 120 days. The results are either plotted graphically or printed numerically on the screen; a hardcopy is possible (if a printer is available). An example for the I/O-plot is given in fig. 7.3 with the I/O-lines for a DHW-system (A_c = 5 m², V_{st} = 300 l). Note the hysteresis of the daily values due to the different initial conditions (i.e. after a "good" day the mean tank temperature is rather high and hence the collector output somewhat decreased).

When all daily values are determined the statistical processing takes place. Here a comment as to the optimal choice of the independent parameters is necessary. We identified up to nine, partially composed parameters of influence to describe the output of the collector system and the solar fraction, which lead typically to regression coefficients r^2 = 99.5 %. Thus we are quite confident, that this mathematical condensation does not imply major errors. However, for some other parameters of interest (i. e. maximum tank temperature, surplus energy, and else) the regression coefficients are significantly lower (96...98 %), and we look furtheron for better approaches.

All relevant values of the system may be stored for later use. The regression parameters of the first calculation are used within part B for the determination of the system's output.

After these calculations, which need typically a few minutes on a IBM-AT or compatible, modifications may be performed. Thus for instance the following combinations may be investigated:

- (original case): collector only, with constant inlet temperature (unlimited demand)
- (1st modification): ditto, plus piping
- (2nd modification): ditto, plus heat exchanger
- (3rd modification): ditto, plus storage tank and limited demand.

7.3 The Application of the System Characteristics to Design an Active Solar Energy System

The envisaged application area of the ISFH-model covers developing countries, too, for which TMYs are hardly available; thus it uses monthly averages of the daily radiation sum and the mean ambient temperature to generate a "synthetical climate", consisting of some good, average, and bad days (the number of days depends on the weather variability of the respective location). The monthly averages are available within a subprogramme for more than 350 locations all over the world, however, the user may implement his own climate as well. The monthly and daily values of 18 US TMYs are similarly implemented (when the daily values are used the implications connected to the synthetical climate are of course excluded).

The "real" system is then characterized by the following parameters:
- relevant set of system parameters (from part A)
- the daily demand (similarly as in part A)
- collector area and orientation (inclination and azimuth)
- incident angle modifiers (either symmetric or asymmetric)
- acceptance angles (either symmetric or asymmetric)
- the tracking system (either none, or altitudinal tracking with horizontal axis, or azimuthal tracking with inclined or vertical axis, or two-axes-tracking)
- possible obstructions shading the collector
- storage overall loss value, storage ambient and maximum temperature.

The parameters should, if applicable, correspond to or be at least similar to those used within part A. Thus a set of regression coefficients derived for collector areas $A_c = 3...7\ m^2$ may be used for an area of $8\ m^2$, too, but must not used for $40\ m^2$. For these cases with extended parameter variations several calculations within part A have to be performed and the respective sets of regression coefficients chosen.

The calculation includes the following steps
- generation of the synthetical climate
- determination of the daily radiation sums onto the collector plane
- determination of the thermal output and - if applicable - the solar fraction by means of the system characteristics.

The determination of the instantaneous beam and diffuse radiation densities is done in the following way (this applies to monthly means; the processing of daily means is of course far simpler):
- the daily radiation sum on the horizontal plane is calculated for "good", "average",and "bad" days basing on the monthly means
- the daily diffuse to total radiation ratio is determined using a correlation similar to (/[40], [41]/): however, it shows a dependency to the mean monthly solar altitude (i.e., the daily diffuse to total radiation ratios are higher with low solar altitudes (/[42]/); other radiation processors (/[13], [14]) are similarly available
- the instantaneous diffuse to total radiation ratio depends on the respective air mass; the extraterrestrial radiation density is chosen in order to fit both the daily radiation sum and diffuse to total radiation ratio. This approach corresponds to a two-fold extinction model, where one part of the spectrum is absorbed completely and the remainder only partially within the atmosphere.

After the determination of the hourly beam and diffuse radiation densities the radiation sum on the collector (taking into account both the orientation of the collector and possible obstructions, the incident angle modifiers, the acceptance angles, and the way of tracking) is determined. Eventually, either the output of the collector only or that of the collector system together with the solar fraction and the possible surplus energy is calculated by means of the system characteristics and a simplified method (which avoids the determination of the initial storage conditions by means of regression parameters). These calculations need typically one (no storage tank, radiation onto collector already known) to 30 seconds (radiation values unknown, with storage).

The calculations may subsequently be modified changing the location, the orientation of the collector, the collector or storage parameters, the size and shape of incidence angle modifiers, acceptance angles, or obstructions, the user demand, the radiation processor (Liu-Jordan or Pereira-Rabl), the set of system parameters, or similar.

G^3

G^3

G^3-program for PC allows the user to evaluate rapidly, simply and with a good accuracy, the daily, monthly and annual solar gains from active systems. The number of parameters and data are strongly reduced. Different versions, configurations and conditions are possible. It is the result of detailed studies, validated by numerous experiments. It is a good tool for evaluations, sensitivity analyses, comparisons, optimisations and others.

1. Introduction.

The G^3-program is conceived for a fast, simple and accurate evaluation of daily, monthly and annual performances of active solar systems with steady collectors which can be either flat, evacuated or weakly focusing. System parameters and meteorological data can be varied in a flexible way.

The program is based on two main features: a direct computation of the daily output of a solar system (which corresponds to the G^3-model itself) and a day by day simulation for the evaluation of monthly or yearly performances. It also includes a solar radiation generator, based on the usual correlations as well as on many observations and able to convert the provided meteorological data into the required inputs.

All these procedures have been validated with extensive and careful experiments, measurements and detailed simulations.

2. The G^3-Model.

The G^3-model applies to a given day and to the solar collection subsystem which includes the collectors and the solar loop up to the storage (not included), the heat exchanger or the user. We give a brief view of the main characteristics of the G^3-model.

The time evolution of the collection subsystem during the day has to obey the following equation:

$$\dot{Q} = h_a - K \cdot \Delta T - C \cdot \dot{T} \quad [W/m^2].$$

where
- $\dot{Q}$ = solar gains (flux).
- h_a = solar radiation absorbed by absorbers.
- K = heat loss factor (collectors and their plumbing and solar loop) as adapted to operation conditions (K may depend on temperature).
- ΔT = temperature difference between collection subsystem and ambient ($\Delta T = T - T_a$).
- C = thermal capacity (collectors and their plumbing and solar loop).
- T = temperature of the collection subsystem.

During preheating $\dot{Q} = 0$ until the temperature reaches the load temperature ($T = TL$). Then, the system is operating ($\dot{T} = 0$) until the temperature starts to decline: $T < TL$. See Figure 1.

We use the following assumptions for the computation:

- the temperature of the collection subsystem is homogeneous (isothermal). Its temperature at sunrise is ambient.
- $h_a(t)$ is simulated by a sin-profile: $h_a = h_{ao} \cdot \sin\ (\pi \cdot t/L)$

$$H_a = \int_0^L h_a \cdot dt = L \cdot h_{ao} \cdot 2/\pi$$

L corresponds to the day length for the appropriate plane (absorber or collector). The ratio H_a/h_{ao} is called profile index p; it is evaluated for a given plane by use of solar radiation models for clear sky. Sin-profile and index p are thus determined for any type of day. Only the daily sum of the solar radiation and the index p are significant.

It was carefully verified that such assumptions, even if they are not fully realistic, lead to satisfactory results as long as daily values are concerned.

Thanks to these assumptions, the computation is achieved numerically and relatively simply by using reduced variables:

$$\left.\begin{aligned} H_{ar} &= H_a/(K\cdot \Delta TL\cdot p) \\ Q_r &= Q/(K\cdot \Delta TL\cdot p) \\ \tau_r &= C/(K\cdot p\cdot \pi/2) \end{aligned}\right\} \Rightarrow Q_r = Q_r(H_{ar}, \tau_r)$$

where Q and H apply for daily values.

The reduced solar gains Q_r depend only on two variables or parameters: the reduced absorbed solar radiation H_{ar} and the reduced time constant τ_r. The function Q_r represents the daily characteristics of a collection subsystem, the whole dynamics being included. In other words, it is the expression of universal daily Input-Output diagrams. This universal characteristic is illustrated in Figure 2. A useful by-product of the G^3-model is the evaluation of the operation time (OT).

Altogether, the collection subsystem is characterized by K, C and the collector optical efficiency. For the solar radiation, we need its daily sum in the collector plane as well as the profile index computed by using models. For the load, we need its temperature as referred to the ambient one ($\Delta TL = TL - T_a$). These are the only data which are needed, and can be further reduced to two (H_{ar} and τ_r) when using the G^3-model.

It is shown in Figure 3 and 4 how the yearly behaviour, day by day, of two well monitored systems, SOLARCAD and SOLARIN, fits very satisfactorily with the universal Input-Output diagrams as predicted by the G^3-model. SOLARCAD is a system of 1000 m² of evacuated collectors connected to a district heating system in Geneva. At Hallau (SH), also in Switzerland, SOLARIN is a system of 400 m² of evacuated collectors providing process heat and heating for a food factory.

For SOLARCAD, the standard deviation on the solar gains Q, as applied to daily differences, between the G^3-model and the measurements, the G^3-model and a detailed simulation or between the detailed simulation and the measurements, looks comparable and amounts at the most to 0.26 MJ/m²·day or 6% of Q, which corresponds to less than 5 minutes of bright sunshine. The mean bias is significantly lower than the standard deviation.

Then, the G^3-model gives results with an accuracy comparable to the one of a detailed simulation. It is very satisfactory, especially when considering intrinsic errors affecting meteorolgoical data and the parameters of a system, as they need to be known.

3. The G^3-Program.

By using the G^3-Model, applied daily to the collection subsystem, the G^3-program simulates day by day the whole system (storage, back-up, load, overheating and other characteristics) and evaluates monthly and annually performances of the whole system.

Also some restricting conditions of the G_3-model are extended in order to cover current needs. It involves corrections combined with an iterative use of the G^3-model. For instance:

- The collector efficiency takes into account effects such as: non-linear dependency $K = K_1 + K_2 \cdot \Delta T$, the collector efficiency factor F' (as related to the thermal resistance from absorber to fluid).
- If the time constant of the solar loop is larger than the collector one, it may happen (as observed at SOLARCAD) that the solar loop is still warm at the morning start while the collectors are cold. Separate exponential decays and corrections applied to the thermal capacities take such effects into account.
- The collection subsystem is warmer than the load temperature, due to a temperature drop of the heat exchanger and to finite fluid flows. Iterative corrections are applied to the temperature, knowing the exhange factor of the heat exchanger, the solar gains, the operating time and the flows.
- If the storage temperature varies during the day, a mean temperature is determined by iteration.

All these corrections were successfully checked.

Different parts are included in the G^3-program:

- A solar radiation generator provides for every day during the year the global and the diffuse radiation on the horizontal plane as well as the ambient temperature during the day (as opposed to the night). The minimum required data are the monthly values of the global radiation on the horizontal plane and of the temperature.
- The evaluation of the radiation to be absorbed by the absorbers is achieved in a second radiation generator. The main optical effects are taken into account here; they deal with geometries, orientations, transposition, incidence angle modifier and shading. Incidence angle effects can be rather important, especially when flat absorbers are tilted with respect to the collector plane (which is the case, for instance, of the tubular evacuated collectors of the SOLARCAD project).
- The definition of the system has to be complemented: collector area, thermal parameters, back-up, storage, heat exchanger, pumps, load and other characteristics. Simulations, computations and energy balances are performed day by day and once a day for the different systems and configurations chosen.

Different solar systems are foreseen in the G^3-program:

- . domestic hot water (DHW) system with 1 storage, solar in the lower part, back-up in the upper part.
- . DHW system with 2 storages, 1 for solar, 1 for back-up (downstream).
- . DHW system with 1 storage, solar and back-up in the lower part.
- . Solar system without storage (directly coupled to a district heating system, for instance), outside back-up.
- . System for industrial applications with storage and outside back-up.
- . Mixed system for industrial applications with storage, priority to a direct coupling to the load, load difference between the week-end and the rest of the week, outside back-up.

. Output results are provided in the form of tables, histograms and figures, displaying daily, monthly and/or yearly quantities such as radiations, temperatures, solar gains, excess heat, back-up, efficiencies and others.

The G^3-program was validated with well monitored systems. We present here some figures obtained at SOLARCAD: comparing the monthly values of the solar gains (Q) from the G^3-program to the ones from the measurements, leads to a standard deviation (based on 12 values) equivalent to 0.11 $MJ/m^2 \cdot day$, or 2.5% of Q. Using monthly rather than daily values, and using the global radiation alone rather than diffuse and global as inputs to the G^3-program, lead to errors smaller than the standard deviation mentioned above. For the yearly value, the difference (or bias) between the measurements and the G^3-program is smaller than 2%. Such results are quite satisfactory.

The G^3-program was written for PCs. Versions in French and English exist for IBM standard, Hercules and ATT-Olivetti PCs. Only a French documentation has been written so far (see bibliography).

4. Applications.

With the G^3-program, it is possible to check the performances of existing installations (as long as they are well enough known) and to optimize the design of new systems by varying the main parameters such as orientation, climate, collectors, plumbing and other characteristics.

As an example, we define the elasticity ε of a given parameter P by the relative variation of the solar gains (Q) as referred to the relative variation of the considered parameter.

$$\varepsilon (P) = (\Delta Q/Q) / (\Delta P/P)$$

For SOLARCAD and its own characteristics, we find:

. b_o factor, incidence angle modifier for optical transmissions	b_o: $\varepsilon = - 0.05$
. optical efficiency	η_o: $\varepsilon = + 1.56$
. collector losses	K_c: $\varepsilon = - 0.45$
. plumbing losses	K_p: $\varepsilon = - 0.14$
. collector thermal capacity	C_c: $\varepsilon = - 0.08$
. plumbing capacity	C_p: $\varepsilon = - 0.03$

etc.

We can see here, as a first approximation, that the optical efficiency plays an important role; that, by neglecting the b_o factor, the solar gains are overestimated by 5% and that, with a plumbing twice less good (losses or capacity), lower solar gains by 14% or 3%.

5. Conclusion.

Many years of research have led to the G^3-program. The actual version is quite satisfactory, which does not exclude other possible improvements.

This program could be extended, keeping the same basic ideas, to solar systems with a high concentration ratio or also to photovoltaic systems, which is a real and present need.

6. Bibliography.

Many reports and papers have been written by the same authors. Amongst the most important, let us mention the following:

- Characterization of Evacuated Collectors, Arrays, and Collection Subsystems. IEA-SHAC-TV1-3. June 1986.
- SOLARIN Project. IEA - Final Report. October 1986.
- G^3-Model. Journal SSES, N° 6/1987, 36-37.
- SOLARCAD 1000 Project. IEA - Final Report. February 1988.
- Le programme G^3 pour PC. Description, validations et mode d'emploi. Version 1. Mai 1988.

Figure 1. G^3-Model.

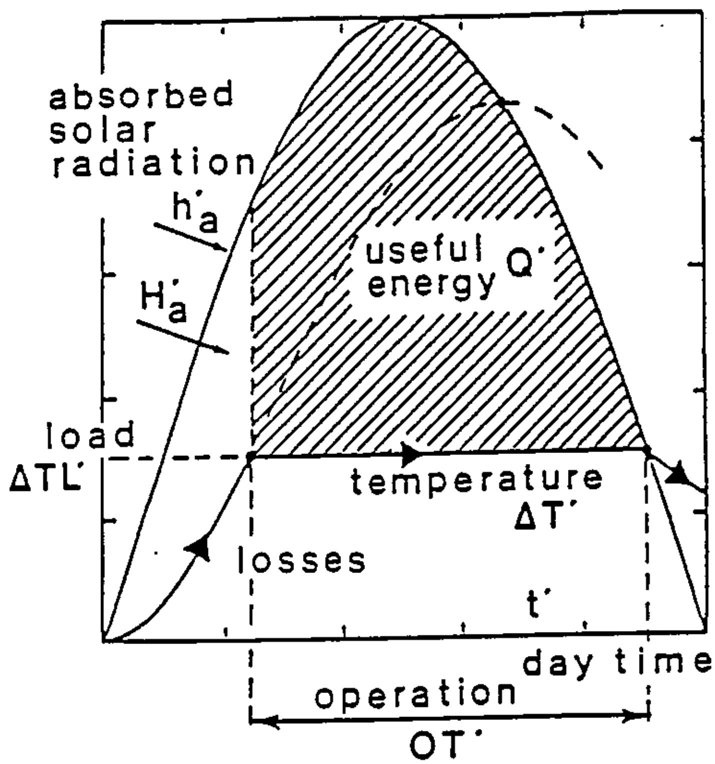
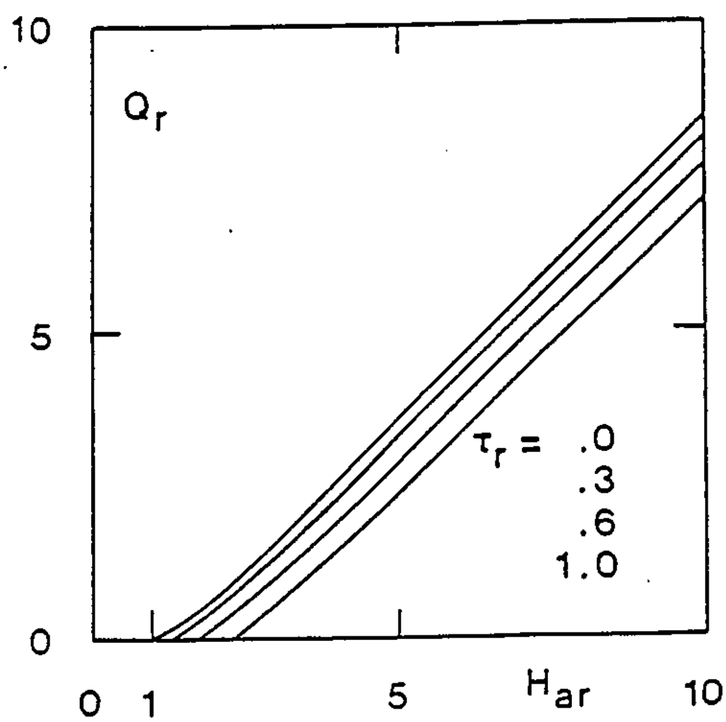
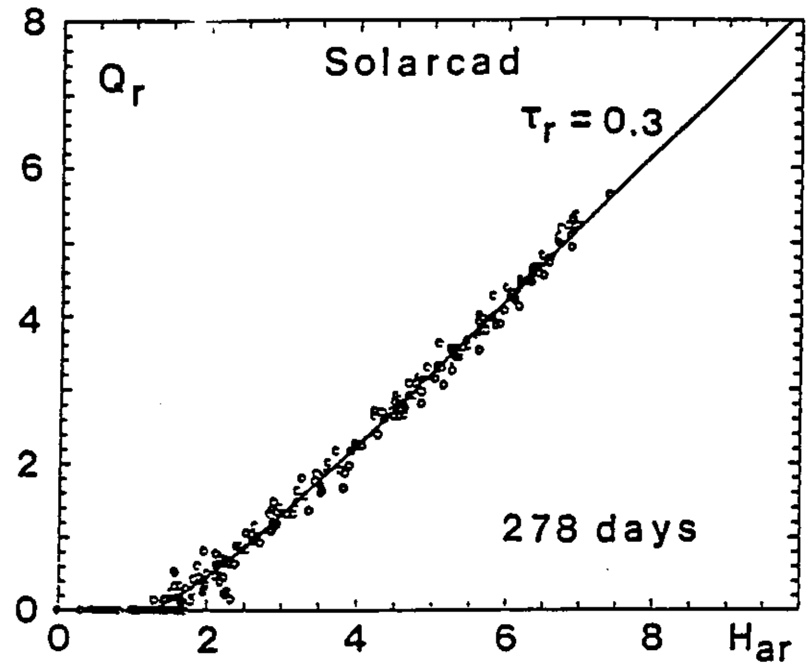


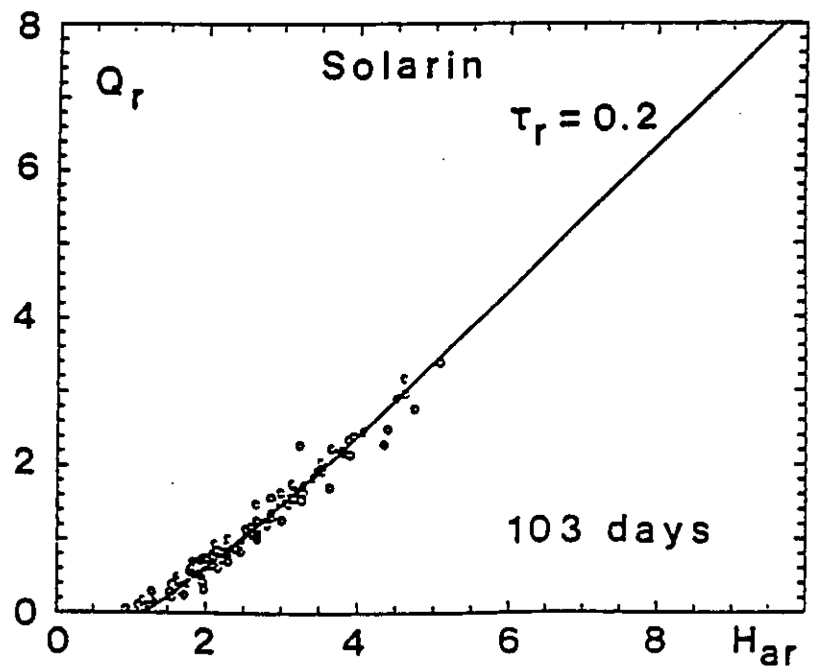
Figure 2. Universal I/O Diagrams (G^3).



Figures 3 and 4.

Universal Diagrams (G^3) and Measurements.





TRNSYS

TRNSYS

TRNSYS is a modular transient system simulation program. It recognizes a system description language in which the user specifies the components that constitute the system and the manner in which they are connected. The TRNSYS library includes many components commonly found in solar and thermal energy systems, as well as component routines to handle input of weather data or other time- dependent forcing functions and output of simulation results. Care has been taken to make it as easy as possible for users to add their own components to the library.

Simulations are picked for a user-specified length of time with a user-specified time step. Typically, annual emulations are performed on an hourly basis using TMY weather data. At each time step, the steps forming the simulation are repeatedly called until the outputs from each component converge to within a user-specified tolerance. TRNSYS 12.2 is available in mainframe and DOS versions. A number of new simulation commands will become available with the release of TRNSYS 13.0. At that time, TRNSYS will also be supported for the Macintosh II.

TRNSYS 12.2

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TRNSYS is a modular system simulation program. It recognizes a system description language in which the user specifies the components that constitute the system and the manner in which they are connected. The TRNSYS library includes many of the components commonly found in thermal energy systems, as well as component routines to handle input of weather data or other time-dependent forcing functions and output of simulation results. Care has been taken to make it as easy as possible for users to add their own components to the library. The present version of TRNSYS is supplied with the following standard component models or options:

Utility Components

Data Reader
Time-Dependent Forcing Function
Algebraic Operator
Radiation Processor
Quantity Integrator
Psychrometrics
Load Profile Sequencer
Collector Array Shading
Convergence Promoter
Weather Data Generator

Solar Collectors

Linear Thermal Efficiency Data
Detailed Performance Map
Single or Bi-Axial Incidence Angle Modifier
Theoretical Flat-Plate
Theoretical CPC

Thermal Storage

Stratified Liquid Storage (finite-difference)
Algebraic Tank (plug flow)
Rockbed

Building Loads and Structures

Energy/(Degree-Hour) House
Detailed Zone (transfer function)
Roof and Attic
Overhang and Wingwall Shading
Window
Thermal Storage Wall
Attached Sunspace
Multi-Zone Building

Hydronics

Pump/Fan
Flow Divertor/Mixing Value/Tee Piece
Pressure Relief Valve
Pipe

Controllers

Differential Controller with Hysterisis
Three-Stage Room Thermostat
Microprocessor Controller

Equipment

On/Off Auxiliary Heater
Absorption Air Conditioner
Dual-Source Heat Pump
Conditioning Equipment
Cooling Coil
Cooling Tower
Chiller

Output

Printer
Plotter
Histogram Plotter
Simulation Summarizer
Economics

Heat Exchangers

Heat Exchanger
Waste Heat Recovery

User-Contributed Components

PV/Thermal Collector
Storage Battery
Regulator/Invertor
Electrical Subsystem

Utility Subroutines

DATA Interpolation
First Order Differential Equations
View Factors
Matrix Inversion
Least Squares Curve Fitting

Combined Subsystems

Liquid Collector-Storage
Air Collector-Storage System
Domestic Hot Water
Thermosiphon Solar Water Heater

Many components may operate in any of several modes, offering differing degrees of model complexity. Also, the capabilities of component routines may overlap. Building loads, for example, may be calculated using the simple "degree-hour" load model or with the more detailed transfer function zone component. Alternatively, TRNSYS can accept hourly loads generated by other load programs.

There are three additional programs that are included in the TRNSYS package. DEBUG is an interactive program useful for testing or performing parametric studies on a single TRNSYS component. PREP can be used in an interactive or batch mode to generate transfer function coefficients for walls, roofs, etc., for use with the detailed transfer function zone model. BID is used to create a multi-zone building description which is read by the multi-zone component during simulations.

The TRNSYS users manual explains the construction of the program and its use. The manual presents the concepts central to the TRNSYS approach to system simulation, as well as general and mathematical descriptions of each component model. Methods for formulating component models and preparing input data for system simulations are given. There are also a variety of example problems of differing levels of complexity provided.

For most simulations, TRNSYS requires records of meteorological data at short and regular time intervals (e.g., hourly). The National Climatic Center in Asheville, NC has a variety of data tapes available, including the SOLMET data. Re-formatted typical meteorological year (TMY) data is also available from the University of Wisconsin Solar Energy Laboratory for each of 26 locations. The Weather Generator component generates a typical year of hourly meteorological data given the monthly average values of radiation, temperature, and humidity. A file of monthly average weather data for 329 North American locations is included with the program.

TRNSYS is written in ANSI standard FORTRAN-77. It is relatively easy to overlay the program or to create smaller programs that only include components of current interest. The program has been run on a wide variety of machines with very little or no modification, and is also available for personal computers (PC).

The source code for TRNSYS is available on magnetic tape for mainframe computers. Specify either EBCDIC or ASCII and 1600 or 6250 BPI when ordering. The PC version is available on 5.25" double-sided double-density diskettes written in IBM-PC compatible format.

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TRNSYS—A TRANSIENT SIMULATION PROGRAM

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A solar energy system is a group of interacting pieces of equipment designed to collect solar radiation, store the collected energy in one form or another, and distribute the energy as needed for some specific purpose. The performance of all solar energy systems is dependent upon weather. In a solar heating/cooling system, for example, both the energy collected and the energy demand are functions of the solar radiation, the ambient temperature, and other meteorological variables. These forcing functions are unique in that they are neither completely random, nor deterministic; they are best described as irregular functions of time, both on a small (e.g. hourly or daily) and large (e.g. seasonally or yearly) time scale.

It is this irregular behavior of the forcing functions which complicates the analyses of solar energy systems. In general, these systems exhibit a nonlinear dependence upon the weather which is further complicated by the time lags introduced from thermal capacitance effects. It is thus not possible to analyze these systems by observing their response to average weather conditions. Because the forcing functions are time variable on both small and large time scales, the analyses of these systems require an examination of their performance at small increments of time over a large time period.

Solar energy systems are characteristically capital-intensive. Thus the economic feasibility of these systems is critically dependent upon their design. The determination of an optimum design requires a comparative analysis of many different designs. If possible at all, comparative experiments are very costly and time-consuming.

In theory, mathematical models can be formulated which, when supplied with sufficient meteorological data, simulate the transient performance of these systems. In practice, however, the formulation of such varied models is complex. Because a system consists of components, a mathematical description of system performance can be developed by combining the mathematical models of all of the system components. This modular approach reduces the complexity involved in the formulation of a system model because each of the components can be mathematically described with little regard for the description of other components. In addition, many components are common to several systems, and thus the mathematical models of these components can often be used in different simulations with little or no modification, provided that they are formulated in a general manner. Once all of the components of a system have been identified and a mathematical model for each has been formulated, the models must be connected together in the desired manner and information must be transferred among them. This information transfer can be schematically represented by an information flow diagram of the system which identifies the input and output variables of each of the component models and indicates their interrelationship.

A transient simulation formulated from component models requires a simultaneous solution of a system of algebraic and differential equations which describe the component models. Solar energy systems in particular often exhibit several recycles in the information flow among component models; thus an iterative scheme (in addition to that which may be used to solve the differential equations of the system) is needed to obtain a simultaneous solution of these equations. This paper describes TRNSYS, a computer program designed specifically to connect

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TABLE 1 (Cont.)

Type	Name	Description
15	Algebraic Operations	Permits algebraic operation using Reverse Polish notation.
16	Solar Radiation Processor	Estimates beam and diffuse radiation on surface of any orientation from total radiation on horizontal surface.
17	Wall	Components that can be used to model buildings, which include the effects of thermal capacity, infiltration, fenestration, etc.
18	Roof	
19	Room and Basement	
20	Heat Pump	Water or air source using manufacturers performance data.
24	Integrator	Integrates any quantity with respect to time (not used to solve differential equations).
25	Printer	Prints desired information in easy-to-read format.
26	Plotter	Plots information on line printer.

Each TRNSYS component is described either by algebraic or differential equations. The collector model (TYPE 1) is an example of component with only algebraic equations while the storage tank (TYPE 4) is a component with algebraic and differential equations.

As an illustration of an algebraic component, we will use the Hottel-Whillier-Bliss equations, as presented by Duffie and Beckman[1], for a flat plate collector.

$$\dot{Q}_u = AF_R[H_T(\tau\alpha)-U_L(T_{in}-T_a)] \quad (1)$$

$$\dot{Q}_u = \dot{m}C_p(T_{out}-T_{in}) \quad (2)$$

$$F_R/F' = (1-e^{-\phi})/\phi \quad (3)$$

$$\phi = AF'U_L/\dot{m}C_p \quad (4)$$

$$U_L = f_1 \text{ (collector design, } T_a, T_{plate}, \text{ wind, tilt)} \quad (5)$$

$$F' = f_2 \text{ (collector design)} \quad (6)$$

$$(\tau\alpha) = f_3 \text{ (collector design, angle of incidence of solar radiation)} \quad (7)$$

For preliminary design purposes, U_L, F' and $(\tau\alpha)$ can often be considered as constants throughout the simulation and therefore can be entered into the program as parameters. The collector component receives "information" such as H_T, $\dot{m}$, T_{in}, and T_a from other components and must calculate T_{out} and $\dot{Q}_u$ to be transmitted to other components. This transfer of information into and out of a subroutine is shown in Fig. 1, which indicates the ordering of INPUTS, OUTPUTS and PARAMETERS. (The TRNSYS Users Manual[2] contains complete documentation for each component in the library.) Note that the mass flow rate, $\dot{m}$, is an OUTPUT but is never changed by the collector subroutine; it is an OUTPUT so that TRNSYS systems can be constructed which resemble the flow of material in real systems.

If more detail is required than is given by this simple collector model with constant parameters, another subroutine could be written to include as much detail as desired. For example, the dependence of U_L on ambient conditions can be included. This would require an additional INPUT corresponding to the wind speed and additional parameters for the number of covers, cover spacing, plate infrared emittance and the back and edge coefficients. TRNSYS has, in effect, four collector models giving the user four choices as to level of detail (more detail is almost always associated with higher computer costs). Instead of having four different subroutines, a single subroutine was written which has four modes of operation. The first parameter of the collector model is the MODE (1,2,3, or 4) which determines the level of component models in a specified manner, solve the simultaneous equations of the system model, and display the results.

COMPONENT MODELING

Solar energy system components are described by individual FORTRAN subroutines. These subroutines, as listed in Table 1, comprise a growing library of equipment models available to the user for system simulation. If a particular component is not available in the library, the user can supply his own. These subroutines may be fairly complex, as in the case for the multi-node storage tank, or they may be very simple, which is the case for a constant flow-rate pump. For some hardware, analytical mathematical modeling is impractical as an analytic model may be very difficult to develop or expensive to use in a lengthy simulation. In addition, a user may want to simulate a system that includes a particular piece of hardware for which he has actual performance data. In these cases, the component model may be empirically defined by transfer functions obtained from curve-fitting theoretical or actual performance characteristics. An example of such an empirical model is the TRNSYS absorption air conditioner subroutine (TYPE 7).

TABLE 1
Current TRNSYS Library

Type	Name	Description
1	Collector	Uses Hottel-Whillier-Bliss equations for collector performance. Mode 1: all collector parameters are assumed constant. Mode 2: loss coefficient is calculated as function of conditions. Mode 3: cover transmission is calculated as founction of angle. Mode 4: combination of Modes 2 and 3.
2	Differential Controller	Outputs 0 or 1 depending upon difference in two input signals.
3	Pump	Fixed flow rate pump (on or off).
4	Liquid Storage Tank	N-section model of liquid thermal storage tank.
5	Heat Exchanger	Counter, parallel or cross-flow heat exchanger.
6	Auxiliary Heater	On-off heater with set temperature and deadband.
7	Space Load and Air Conditioner	Simple house load calculated by energy per unit time per unit temperature difference method, with built in absorption air conditioner and cooling tower.
8	Three Stage Room Thermostat	For use in controlling combined heating and air conditioning systems.
9	Card Reader	Reads data from cards or mass storage (usually weather data).
10	Packed Bed Energy Storage Tank	N-section model of packed bed thermal storage unit.
11	Tee, Flow Mixer, Damper	Flow controllers for air or water.
12	Space Heating Load	Simple energy per unit time per unit temperature difference load, with Mode 1: parallel auxiliary. Mode 2: series auxiliary. Mode 3: no auxiliary. Mode 4: no auxiliary with thermal lag.
13	Relief Valve	"Dumps" energy to maintain temperature below specified maximum.
14	Time Dependent Forcing Functions	Permits time varying data to be introduced into simulation (usually periodic).

detail. Each mode has a different set of INPUTS, PARAMETERS and OUTPUTS.

Communication between each component subroutine and TRNSYS is through the calling argument. For any TYPEn model, the appropriate FORTRAN statement is

```
SUBROUTINE TYPEn (TIME, XIN, OUT, T, DTDT, PAR, INFO)
```

where

TIME = integration time

XIN = an array containing the INPUTS

OUT = an array which the subroutine fills with the appropriate OUTPUTS

T = an array containing the dependent variables of any differential equations

DTDT = an array which the subroutine fills with the time dependent derivatives

PAR = an array containing the PARAMETERS

INFO = an array containing TRNSYS control information

For MODE 1 of the collector model, the array XIN corresponds to T_{in}, $\dot{m}$, T_a and H_T; the array OUT corresponds to T_o, and $\dot{Q}_u$ as calculated from Eq. 1 and 2 and $\dot{m}$, which was an input; the T array and the DTDT array are not used since no differential equations are involved, the PAR array contains MODE, A, F', C_p, α, U_L and τ.

The tank model is an example of a component described by differential equations. A fully mixed tank is described by the following differential equation which relates the rate of temperature rise of the tank to the net energy into the tank from the collector, the load and the surroundings[1].

$$(MC_p)_s \frac{dT_s}{dt} = (\dot{m}C_p)_c \; (T_o-T_s) + (\dot{m}C_p)_L \; (T_L-T_s) + (UA)_s \; (T_a-T_s) \tag{8}$$

TRNSYS handles component differential equations with its own internal integrator. Through the T array, TRNSYS supplies the subroutine with values of the dependent variables. TIME is always the independent variable. The component subroutine calculates values of the time derivatives and puts them in the DTDT array. For the one node tank model, a single differential equation is involved so that T(1) is T_s and DTDT(1) is dT_s/dt.

The internal TRNSYS integrator uses the modified-Euler integration algorithm which predicts new values of the dependent variable using simple Euler and corrects using the trapezoid rule. The advantage of this integration scheme for systems of combined algebraic and differential equations is that the iterations occur at a constant value of time. As the differential equations converge (by successive substitution).

"Black-box" component models are identical to algebraic models although the relationship between independent and dependent variables may be in the form of tables rather than analytical equations.

SYSTEMS AND INFORMATION FLOW DIAGRAMS

Once all of the components of a system are available in the TRNSYS library the next step is to construct a system information flow diagram. An information flow diagram is a schematic representation of the flow of information between each of the system components. In the diagram, each component is represented by a component diagram like Fig. 1. Each piece of information required to completely describe the component is represented as an arrow directed into the box.* Each piece of information calculated by the algebraic or differential equations describing the component can be represented as an arrow directed out of the box.

*A component must receive values for all its INPUTS, but it is not necessary to use all of the OUTPUTS.

It is often helpful to think of the arrows connecting component inputs and outputs as information exchanged via pipes and wires in a real system. A collector outlet flowstream temperature and flowrate connected to the inlet of some other piece of hardware is "information" transmitted through a pipe. A controller on-off output connected to a pump is information transmitted through a wire. The analogy between information flow and pipes and wires is, however, not perfect. In a real system a pipe may carry a flowstream through some component which does not affect one or more variables that characterize the flow. In these cases it is not necessary to route those particular pieces of information through the component.

In order to demonstrate the construction of an information flow diagram, consider a very simple solar water-heating system consisting of a solar collector and an auxiliary energy heater as shown in Fig. 2. Cold water, at a fixed temperature T_{in}, is circulated at a constant rate $\dot{m}$, to the collector. If the outlet temperature from the collector is less than T_{set}, the water is heated from T_0 to T_{set} by the auxiliary heater. The problem is to determine Q_B, the total auxiliary energy required over a specified time period using the collector model of Fig. 1. The system information flow diagram is assembled from the collector component diagram and from the component diagrams described below.

Time dependent solar radiation on the plane of the collector and the ambient temperature are assumed to be available on punched cards. The card reader (TYPE 9) is shown in Fig. 3.

The instantaneous auxiliary energy required, $\dot{Q}_B$, is described by the following equation:

$$Q_B = \begin{cases} \dot{m}c_p[T_{set}-T_0];\ T_r = T_{set}, T_0 \leq T_{set} \\ 0;\ T_r = T_0 \qquad \text{otherwise} \end{cases} \tag{9}$$

The information flow diagram for the heater is shown in Fig. 4.

In order to determine the total auxiliary energy required, Q_B, the instantaneous auxiliary energy must be summed or integrated over the period of operation. For this purpose, it is necessary to include a "quantity integrator" as one of the system components. Note that a quantity integrator component is used only to integrate some calculated OUTPUT quantity over a period of time; it is distinct from the internal integrator used to solve first-order differential equations which are part of the mathematical description of differential components. A quantity integrator is treated as any other system component. The equation describing it is

$$Q_B = \int^{TIME} \dot{Q}_B \, dt \tag{10}$$

The diagram for the quantity integrator is shown in Fig. 5.

One more component is needed to allow the results of the simulation to be made available to the user. For this purpose, TRNSYS has both printer and plotter components. The analogous pieces of equipment in a physical system would perhaps be a multichannel digital display and/or strip chart recorders, which would monitor, record, and display various quantities.

It is necessary to include either a printer or a plotter component (or both) in the system information flow diagram; otherwise no output will occur. In fact, TRNSYS recognizes this and unless it detects either of these component models in the system information flow diagram, it will not execute and the appropriate error message will be displayed.

In the example being considered, the user may wish to print Q_B and T_0 as the integration progresses with time. The Printer is shown in Fig. 6.

The information flow diagram of a system is constructed by joining all of the diagrams of the system components. TRNSYS recognizes the position of each component in the information flow diagram by the user assigning to each component a unique UNIT number. The component UNIT number should not be confused with its TYPE number; the two numbers are unrelated. The UNIT number is nothing more than a reference number which will aid in conveying the information flow diagram of the system to TRNSYS. The user is free to select any unit number he chooses. The only restriction imposed on the UNIT number selection is that no two system component can have the same UNIT number. The information flow diagram of the solar water heating system is shown in Fig. 7 with UNIT and TYPE numbers.

A TRNSYS PROGRAM

In order to convey the information of Fig. 7 to TRNSYS, a simple language has been developed that is based essentially upon seven key-words*. The first card of a TRNSYS deck must be of the form

SIMULATION t_o t_f Δt

where t_o is the time at the start of the simulation

t_f is the time at the end of the simulation

Δt is the timestep to be used by the integrator.

The final card of a deck must be an END card. Between these two cards, there is a set of cards for each component of the general form.

UNIT n TYPE m Comment

PARAMETERS j

p_1, p_2, $\cdots p_j$

INPUTS k

u_1, O_1 u_2, O_2, $\cdots$ u_k, O_k

v_1, v_2, $\cdots$ v_k

DERIVATIVES ℓ

i_1, i_2, $\cdots$ i_ℓ

where

n is a unique unit number

m is a type number from the TRNSYS library

j is the number of parameters for TYPE m

p_1, p_2, $\cdots$ p_j are the j values of the parameters, listed in order indicated in the manual, e.g. as shown for TYPE 1 in Fig. 1.

k is the number of INPUTS for TYPE m

u_1, O_1 u_2, O_2 $\cdots$ u_k, O_k are the UNIT numbers and corresponding OUTPUT numbers for the first, second $\cdots$ and k^{th} INPUT to this UNIT n.

v_1, v_2, $\cdots$ v_k are the initial values of the k INPUT variables. A special notation is used whenever an INPUT is to be a constant. When both u_i and O_i are set to zero, v_i is then the value of the i^{th} input throughout the simulation.

ℓ is the number of derivatives used to describe TYPE m. For an algebraic component this is zero and this and the following cards are not used.

i_1, i_2 $\cdots$ i_ℓ are the ℓ initial values of the dependent variables for TYPE m.

If a particular component does not have INPUTS, PARAMETERS or DERIVATIVES, the corresponding cards are not necessary.

*The seven key-words are SIMULATION, UNIT, TYPE, PARAMETERS, INPUTS, DERIVATIVES and END. Other key-words exist in TRNSYS but their use is optional and will not be discussed here.

In order to illustrate the TRNSYS language, the following deck would be required to simulate the water heater problem for 100 hr. beginning at time zero. The numerical values of some of the PARAMETERS were selected to be representative of current practice. The units in this example are S.I.

```
SIMULATION 0, 100, 1
UNIT 17 TYPE 9 CARD READER
PARAMETERS 2
2, 1
UNIT 14 TYPE 1 MODE 1 COLLECTOR
PARAMETERS 7
1, 2, 0.95, 4,2, 0.9, 15.0, 0.8
INPUTS 4
0,0 0,0 17,1 17,2
15.0 100. 20.0 0.0
UNIT 32 TYPE 6 HEATER
PARAMETERS 4
1.E6, 60, 2, 4.2
INPUTS 2
14,1 14,2
20.0 0.0
UNIT 43 TYPE 24 INTEGRATOR
INPUTS 1
32,3
0.0
UNIT 25 TYPE 25 PRINTER
PARAMETERS 1
1
INPUTS 2
14,1 43,1
TO, QB*
END
```

(Data to be read in by CARD READER must be placed after the END card. It was assumed here that each data card contains two pieces of information, and each card represents one hour.)

*The initial values of INPUTS to the printer are nmeumonics which identify the printed output.

Klein, et al.[3] have presented the detailed results of several heating simulations using TRNSYS.

CONCLUSIONS

TRNSYS is a compiler for a high level computer language designed specifically to connect component models of transient systems and solve the resulting simultaneous algebraic and differential equations describing the system. TRNSYS has the following desirable features:

1. Each component model is formulated as a separate FORTRAN subroutine. The requirements for compatibility of the component subroutine with TRNSYS are minimal. Components which provide the capability to print, plot or integrate various quantities as the simulation progresses are built into TRNSYS and need not be formulated.

2. TRNSYS is general in the sense that it can be used to simulate any transient system for which the system component models are expressible in FORTRAN statements. TRNSYS is particularly applicable to solar energy system simulations because a library of component subroutines modeling the components common in these systems has been established.

3. The input data to TRNSYS is essentially the information flow diagram of t system. This information is communicated to TRNSYS in a very simple manner requiring only en keywords. An error-checking facility is provided to diagnose most data input errors.

4. The computation scheme incorporated into TRNSYS recognizes the existence of information recycles, and it will provide the iterative calculations needed to solve the simultaneous algebraic and differential equations of the system model. An important part of the TRNSYS computation scheme is that only those component subroutines involved in the recycles are recalled for additional iterative calculations. In this manner, TRNSYS requires a minimum of computational effort to achieve a simultaneous solution to the equations describing the system.

5. The user need not concern himself with the order in which the component subroutines are called during the simulation since the computation scheme built into TRNSYS will solve the system equations, within a specified accuracy, regardless of the calculation order. However, since the calculation order may affect computation time, it may be optionally specified by the user.

6. The entire TRNSYS program is written in ASA standard FORTRAN IV. It requires relatively small storage space; it is thus usable on most modern computers.

NOMENCLATURE

A	Collector area
C_p	Heat capacity
F_R	Collector heat removal factor
F'	Collector plate efficiency factor
H_T	Total solar radiation on plane of collector per unit area
M	Mass of water in the storage tank
$\dot{m}$	Mass flow rate
$\dot{Q}_u$	Useful energy output of collector
Q_B	Total auxiliary energy
$\dot{Q}_B$	Auxiliary energy rate
T_a	Ambient temperature
T_{in}	Fluid temperature at collector inlet
T_o	Fluid temperature at collector outlet

T_{set}	Set temperature for auxiliary heater
U_L	Collector loss coefficient
UA	Product of loss coefficient and area
α	Solar absorptance of collector plate
τ	Solar transmittance of collector cover system

SUBSCRIPTS

c	Collector
L	Load
s	Storage

REFERENCES

1 J.A. Duffie and W.A. Beckman, Solar Energy Thermal Processes, Wiley, New York (1974).

2 TRNSYS - A Transient Simulation Program, Report #38, University of Wisconsin, Engineering Experiment Station (Nov. 1975).

3 S.A. Klein, et al., "A Method of Simulation of Solar Processes and its Application." Solar Energy 17, p 29 (1975).

ACKNOWLEDGMENTS

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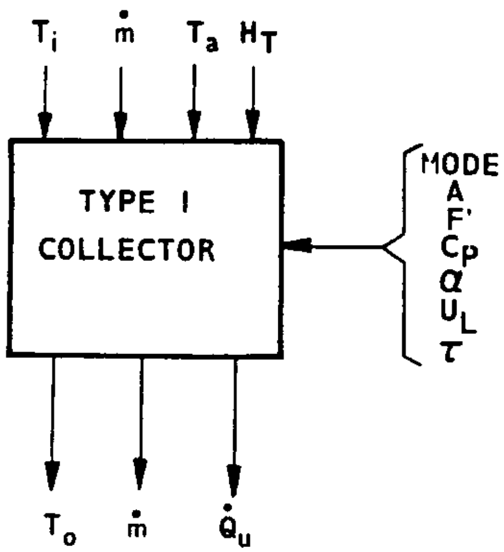

Fig. 1 Component diagram for simple collector

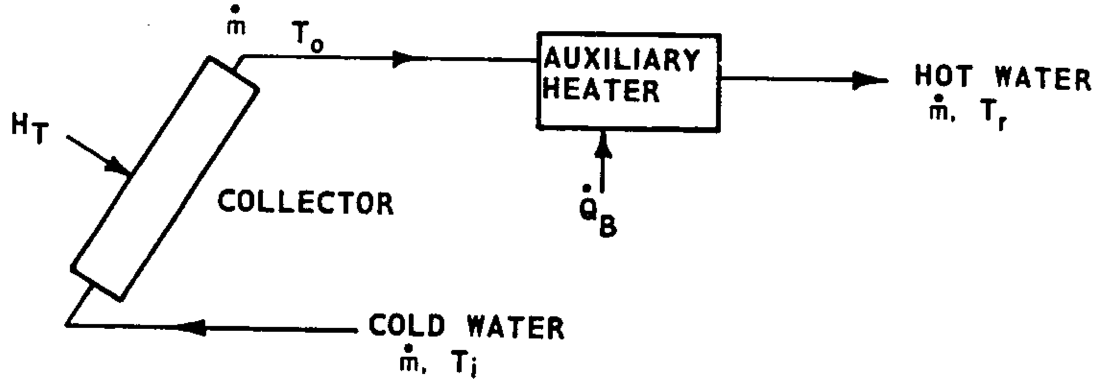

Fig. 2 Simple solar water heating system

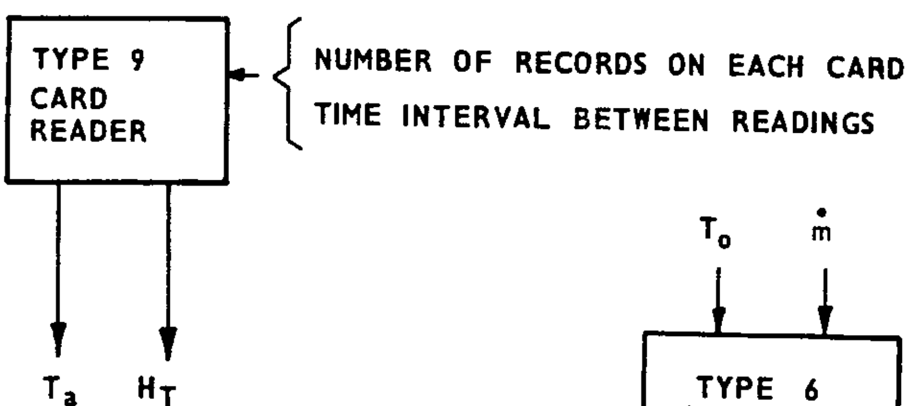

Fig. 3 Component diagram for card reader

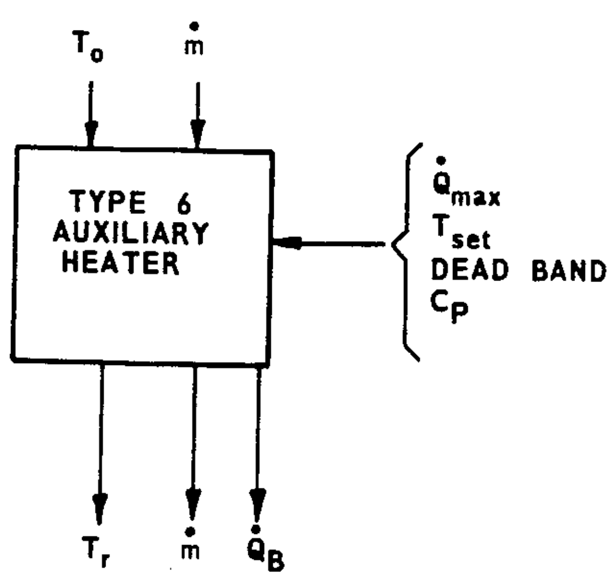

Fig. 4 Component diagram for auxiliary heater

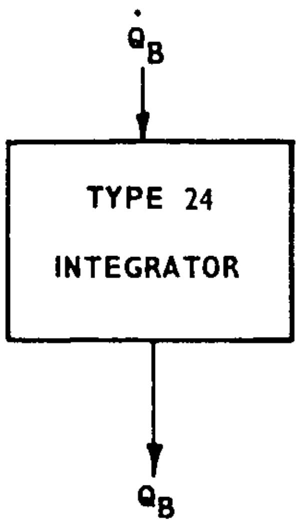

Fig. 5 Component diagram for integrator

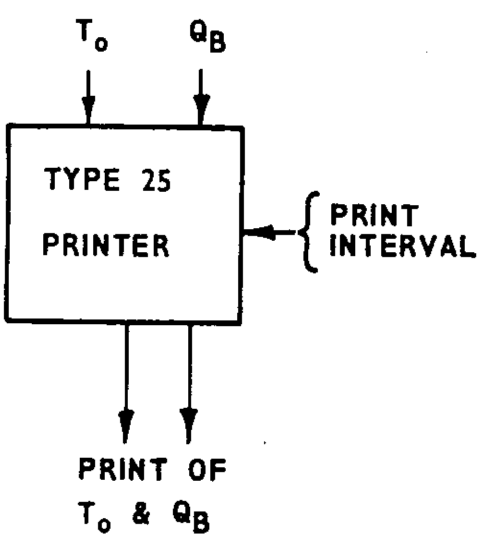

Fig. 6 Component diagram for printer

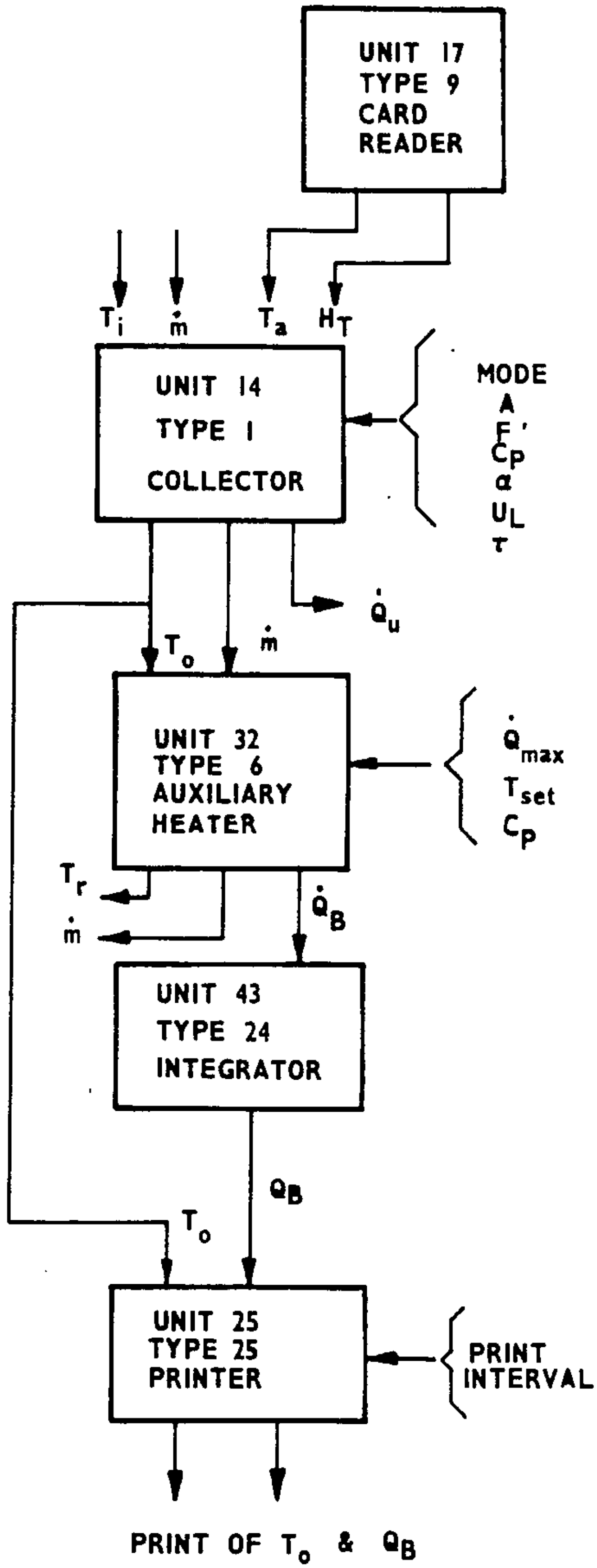

Fig. 7 Information flow diagram for solar water heater

WATSUN

WATSUN

Architecture

WATSUN is divided into two main sections: an interactive routine for managing user entry of the required system data, and a simulation routine e for carrying out the actual modelling. The interactive routine creates (or modifies) a data file which will be read by the simulator.

The simulator also requires a weather data file for the particular site where the modelled system is located. The first step of simulation is the processing of the weather file. This step is kept separate so that if the same collector orientation is to be used repeatedly, the processed weather can be re-used. The next step is the actual simulation. The processed weather and the system data file are used as inputs and the final output listing is produced.

Systems

WATSUN models a large number of active thermal solar systems, and there is also a WATSUN-PV package available for photovoltaic simulations. The active systems can be grouped into three major categories: Domestic Hot Water Heating, Industrial Process Heating, and Swimming Pool.

Weather Data Processing

The most commonly used weather files for WATSUN are known as TMY files (Typical Meteorological Year). These contain the total horizontal radiation, ambient temperature, windspeed, and relative humidity for each hour. The program separates the total radiation into its beam, diffuse, and reflected components and then "tilts" these values according to the orientation of the collector. It then adds them back together.

Collector Model

WATSUN uses a 5 parameter collector model, so that nonlinear systems such as evacuated tube collectors can be modelled adequately. The first two parameters, A and B, make up the collector heat removal factor times effective transmittance absorptance product, $F_R(\tau\alpha)_e$ (where A is the constant component and B is multiplied by the difference between collector inlet temperature and ambient temperature). Similarly parameters C and D make up the collector heat removal factor times collector heat transfer coefficient, $F_R U_L$. The fifth parameter, E, is a threshold value below which no energy will be collected.

The equation for energy collected is:

$$Q_c = A_c[F_R(\tau\alpha)_e A_{KT} H_T - F_R U_L(T_{ci} - T_a) - E]$$

where

Q_c = Energy collected

A_c = Collector area

$F_R(\tau\alpha)_e$ and $F_R U_L$ are defined above

A_{KT} = incidence angle modifier

H_T = total radiation incident on collector surface

T_{ci} = collector inlet temperature

T_a = ambient temperature

E = collector cut-off radiation value

becomes

$$Q_c = A_c[(A-B(T_{ci}-T_a))A_{KT}H_T-(C+D(T_{ci}-T_a))(T_{ci}-T_a)-E]$$

The $F_R(\tau\alpha)_e$ and $F_R U_L$ values are also adjusted for flowrate through the collector.

Control Strategy

The collector is turned on or off according to two different control strategies. The user may specify a differential temperature for control. The collector will then operate whenever the collector stagnation temperature exceeds the ambient temperature by this differential temperature. Alternatively, the user can specify which hours of the day the collector will operate.

Storage Model

WATSUN includes non-storage systems, mixed tank systems, and stratified storage systems. Some systems may not include an auxiliary tank.

The model used by WATSUN for stratification is called the "bumping" model. In this model, water in the tank is in discrete layers, ordered from hottest to coolest from the top of the tank downwards. When a collector draw occurs, the required layers, or pieces of layers, are taken from the bottom of the tank, mixed together, passed through the collector, and then replaced into the tank as a new layer. The new layer is positioned so that the layers are still in order. A similar pattern occurs for load draws, but the layers are taken from the top of the tank, and the new layer coming in is generally mains temperature water.

Losses are calculated as the summation of the losses of each layer, according to its temperature, through the walls of the tank, plus the losses at the top and bottom layers.

The energy supplied by the preheat tank to the load, for each layer removed, is:

$$Q_{SHW(i)} = \rho V c_p (T_{S1S2(t)} - T_{MAIN})$$

where

$Q_{SHW(i)}$ = energy supplied by preheat to load for layer (i)

ρ = density of fluid

V = volume of top element of tank

c_p = specific heat of fluid

T_{S1S2} = temperature of element 9i) in the tank

T_{MAIN} = mains water temperature

The total energy supplied is then the summation of the energy for each element that is required to meet the load volume.

Hot Water Demand Model

The hot water demand for a given hour depends on parameters specified by the user, and also upon the mains temperature, which fluctuates through the year on a sinusoidal pattern, between the minimum and maximum values specified by the user. The equation for hourly load is:

$$QDHW(i) = cQ_d QP(i) Q_m(j)(TDHW(i) - T_{MAIN})$$

where

i = hour

$QDHW(i)$ = load for hour i

c = 4.19 [nJ/R - *C]

R_d = daily load (in litres)

$QP(i)$ = fraction of daily load at hour i

$QM(j)$ = monthly load scale factor at month j

$TDHW(i)$ = load temperature for hour i

T_{main} = mains water temperature

Heat Exchangers

In this system, external, wraparound, or immersed coil heat exchangers can be included at two locations (between collector and preheat tank, and between preheat tank and load). For the wraparound and immersed coil exchangers, an equivalent effectiveness is calculated, and they are then modelled as external. A tank in tank exchanger is available in mixed-tank models, but not in stratified tanks.

Pipe Losses

The direct pipe losses, due to temperature difference from the environment, are calculated each hour. In addition, pipe capacitance losses are calculated. These occur, for example, when the piping cools down overnight.

Other Models

Many of the other systems modelled have similarities to the DHWS system. The swimming pool models, both indoor and outdoor, are of course very different, and are not covered in this write-up. Another system that is substantially different is the batch water heaters which incorporates an integral tank in the collector module.

The industrial process heaters include reclaim loops, either before or after the collectors, but are otherwise quite similar to the domestic hot water systems. WATSUN also includes an economic analysis package.

MINSUN

MINSUN

The original version of the MINSUN simulation program was developed at Studsvik Energy in Sweden for IEA SH&C task VII. Later both Canada and other countries improved the program and made it available in a PC-version. New versions are still under development and will be available from IEA task VII when finished and validated.

MINSUN is developed for design studies on large seasonal storage systems within IEA task VII. Both cost and performance can be studied in detail.The program uses hourly climate data in a detailed simulation model developed from TRNSYS to calculate the daily collector array output and operating time at five different operating temperatures (as specified in the input file). Six different collector models are available (Flat Plate, Salt Pond, ETC, Central Receiver, Parabolic Trough and Shallow Pond).

The daily values are also modified for large array effects as piping, capacitance and shadowing losses. To save simulation time in the following system simulation the program then uses the daily collector array values as solar energy input. Due to the slow temperature change in a seasonal storage this method can be used without loss of accuracy.

The system model contains four different storage models (Tank, Pit/Rock Cavern, Duct Storage and Aquifer Storage). All storage models take into account the thermal inertia and heat resistance of the ground which is very important for optimization of the insulation for a seasonal storage. Stratification in the storage is also modelled in detail.

Minsun also contains models for heatpumps, auxiliary boiler, load simulation (spaceheating and domestic hot water) and distribution system (district heating network).

The MINSUN program has been validated against measured data (ie the Lyckebo plant with a 100000 m^3 rock cavern and 4000 m^2 high efficiency flat plate collectors).

At this workshop the MINSUN program has been tested in a range of systems commonly used all over the world but far away from the original applications. This means that the accuracy can not be expected to be too high in comparison to other models. Especially not on a short term basis.

F-CHART

F-CHART

F-CHART is solar energy system analysis and design program available for both IBM and Macintosh computers. It uses a combination of the F-CHART method and the phi-bar F-CHART method to predict the performance of several kinds of solar energy collectors (flat-plate, evacuated tubes, CPC's and tracking collectors) in various kinds of systems (water storage heating, pebble bed storage heating, building storage heating, domestic water heating, swimming pool heating, industrial process heating, passive direct-gain, and passive collector-storage wall). Monthly weather data for 329 locations is provided, and additional data sets can be added by the user. Parameters can be varied by month, SI or English units can be used, and a life-cycle economics analysis capability is provided.