Progress Report: 10/79
Contract EY-76-S-02-2588
Modification No. A003

MASTER

REPORT TO THE

UNITED STATES DEPARTMENT OF ENERGY
CONSERVATION AND SOLAR APPLICATIONS
SOLAR HEATING AND COOLING SYSTEMS
DEVELOPMENT BRANCH

ON

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SIMULATION AND DESIGN OF SOLAR THERMAL PROCESSES

CONTRACT: EY-76-S-02-2588.A003

by the

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PROGRESS REPORT TO
U.S. DEPARTMENT OF ENERGY

on

SIMULATION OF SOLAR HEATING AND COOLING SYSTEMS

Supported by

#EY-76-S-02-2588

Solar Energy Laboratory
University of Wisconsin-Madison

This report is for work supported during the contract period Jan. 1, 1979 through Dec. 31, 1979 and includes projections for the last two months of the period. It is arranged according to task areas as outlined in the contract. The narrative is brief, and more detail is given on most of the items in the form of publications which are appended to and are part of this report.

INTRODUCTION

The research described was first supported by the National Science Foundation, then the Energy Research and Development Administration and now the Department of Energy. It is a continuing effort on development of methods of predicting the performance of solar thermal processes and designing those processes. The general approach has been to develop appropriate mathematical formulations for the various components used in solar thermal processes, program these component models in TRNSYS compatible form, and add them to the TRNSYS library. The component models are also used in system simulation studies as a means of checking the models and also developing information about new kinds of systems and system configurations.

In addition to the simulation studies, and closely related to them, are studies on the development of "quick" design methods for standard system configurations which avoid the necessity of doing detailed hour by hour simulations. The first major method from this program is the FCHART method; later developments have included the ϕ , f-chart method and a generalized method for estimating $\bar{\phi}$, the monthly average radiation availability for solar processes.

The major outputs of this research can be thought of as two programs. The first is TRNSYS, which is now being distributed in Version 10.1. This is a general purpose transient system simulation program that is widely used in the U.S. and abroad for system explorations studies, design of large systems, assessment of the impacts of component characteristics on system performance and other purposes. The second program is FCHART, an interactive design program for standard system configurations for heating by air and liquid systems and for domestic water heating. The version currently being distributed is 3.0; it too is widely distributed and used in U.S. and abroad.

The benefits accruing to the National Solar Energy Program from this research and development activity include the following:

Knowledge of how to simulate, design, and evaluate solar processes has continued to advance. This knowledge is made available to the public through publications, presentations, presentation of short courses and other related means.

The TRNSYS and FCHART programs have been carefully and extensively documented and made widely available. They are backed up by responsive user services and user's meetings.

Engineering graduates, skilled in solar process systems analysis and design and the general fundamentals of solar thermal processes, have gone from our laboratory to responsible posts in industry and government, largely in the solar energy field.

In addition to the direct benefits of research, indirect benefits also accrue from this work, although not paid for by the contract. This includes the development of courses which include current research, a range of public service activities in the form of lectures, services on committees and boards etc.

In the sections below, the progress made in the past year on the tasks outlined in the contract are presented. Following the technical summary is a listing of the personnel who have been involved in the research. In the past year six students have received MS degrees in engineering from the program.

RESEARCH PROGRESS

The following discussion is based on the tasks outlined in the contract. The comments here are brief; for details, see the appended papers on many of the topics.

In addition to papers presented and published, reference is made to the TRNSYS manual for version 10.1, which contains detailed information on the current version, and the FCHART version 3.0 manual which discusses in detail the basis and use of the FCHART program. A list of innovations in TRNSYS 10 is included as Appendix A-1. Copies of these two manuals are available from the Engineering Experiment Station of the University of Wisconsin.

Task A: Further System Analysis Studies and Development of the TRNSYS Simulation Program

The objective of this task area has been a further development of

component models for TRNSYS and the use of these component models in system simulation studies.

A.1 New components developed or under development for TRNSYS include the following:

- A radiation data processor for movable surfaces and suitable for use with concentrating collectors is in TRNSYS version 10.1. This "component" interpolates radiation data, calculates quantities related to the position of the sun and estimates insolation on up to six surfaces of either fixed or variable orientation.
- A model of a CPC collector, primarily for use in industrial process heat (IPH) applications, has been included in TRNSYS 10.1.
- An advanced absorption cooler, taking into account start up and cooled shut down transients, has been developed and appropriate time constants measured for an Arkla three ton lithium bromide-water machine at Colorado State University. This transient absorption cooler model is now in TRNSYS 10.1. The model is briefly described in Appendix B-1 and in more detail in (1).
- A new model of a cooling coil has been added to TRNSYS; this is the result of modeling of water chiller absorption coolers and the subsequent need for a component account for heat exchange between chilled water and air conditioned spaces. This is also described in detail in (1).

Work is proceeding on several other projects which will result in TRNSYS components in the coming months. These include the following:

- A model of a photovoltaic converter based on work at Arizona State University, will be available.
- Models of components in chemical heat pumps adequate to simulate these systems are now being checked out and used in simulation and studies of various configurations of chemical heat pumps.
- Formulation of models of linear parabolic concentrators is now underway.

A.2 The above components are all related to active systems. In addition, the following passive components have been added to TRNSYS and are in version 10.1.

- Overhang and wingwall shading can be modeled by a new Type 34 component. The development and formulation of this model is described in (2). (Appendix B-2 describes a further evaluation of this method to obtain monthly average shading by finite overhangs, was presented at the 1978 ISES passive workshop and is to be published in the Solar Energy Journal.)
- A collector-storage wall is now modeled in TRNSYS Type 36. The model is based on a multinode thermal circuit which takes into account temperature gradients in the lateral direction through the wall, heat

transferred to air circulating between wall and glazing, and other phenomena associated with the absorption of energy and the dissipation of energy from storage walls. Details are in (2).

-Window (direct gain component) with variable insulation can be modeled by Type 35.

The standard TRNSYS program is thus now capable of simulating a variety of direct gain and collector-storage wall passive systems. Simulations using this capability have been used in the design procedure studies which will be noted under Task Area C.

A preliminary economics subroutine for inclusion in TRNSYS has been developed. This subroutine requires parameters which (for mode 1), are P_1 and P_2 (combinations of approximately 20 economic parameters such as interest rates, inflation rates in terms of analysis, etc., and costs of equipment see (3)). It is analogous to the simulation summarizers in that at the end of a simulation it uses amount of auxiliary energy required (of interest in IPH applications) and calculates life cycle costs of interest to non-business users annualized life cycle costs. We are now looking at the problem of computation of return on investment. A mode 2 will be added which will use as parameters all of the economic data needed to calculate P_1 and P_2 ; these will be calculated internally. It is expected that this economics subroutine will be included in the next version of TRNSYS.

Extensive studies have been done of the performance of solar water heating systems. The basic conclusion from these studies is that if systems are well designed and well installed, system configuration makes relatively little difference in long term performance. There are not large differences between systems with or without tempering valves, systems with internal or external heat exchangers, etc. The differences between one and two tanks are largely a matter of heat losses from the tank. A preliminary paper on this work was presented at the Atlanta ISES meeting; a more detailed paper, which is being submitted for consideration for publication in Solar Energy, is attached as Appendix B-3.

Models have been developed for multi-zone buildings, using variable air volume systems. This work is described in a thesis by Ottenstein (4); further work on this area is needed before these models will be ready for inclusion in TRNSYS.

Task B: TRNSYS and FCHART User Services

We have continued to provide user services for TRNSYS and FCHART. J.C. Mitchell and Warren Buckles, with assistance from other members of the laboratory staff, provided program support in 1979. Major activities included the following.

-Version 10.1 of TRNSYS with its associated documentation was produced and released during the contract period. This was a major undertaking with many revisions in the program and several new component models. The TRNSYS manual reflects the program enhancements with approximately 200 new pages, including five new example simulations covering passive, industrial process heating, and space cooling systems. Appendix A-1 summarizes the additional features of version 10.1 over version 9.

-A two day TRNSYS users meeting was held on August 23 and 24. The first day was a TRNSYS "short course" to introduce new users to the program structure and simulation capabilities. The second day included discussions of new (version 10.1) program features and more advanced simulation considerations. A copy of the user's meeting agenda is included as Appendix A-2.

-We have continued to respond to many telephone calls and letters from users of TRNSYS and FCHART. Our log indicates that approximately 50 to 75 phone calls per month have been answered with technical information and program explanation. The majority of the inquiries regard TRNSYS but include FCHART discussions and meteorological data investigations. (FCHART services are also provided by SERI.)

A major current activity is the preparation of FCHART version 4. This program will have many capabilities beyond the current version, including analyses useful for the design of certain air conditioning, industrial process heating, passive, long-term energy storage, and phase-change energy storage systems. The new version of FCHART is scheduled for release in early 1980 and incorporates much of the work described under Tasks A and C.

Task C: The Development of Design Procedures

The utility of the FCHART method for designing standard types of space heating and water heating systems has lead to the development of additional simplified design tools for additional kinds of systems. This includes the following.

-A method has been developed for designing parallel solar energy-heat pump systems. This is briefly described in Appendix B-4 and in detail in (5). Work is well along on the development of a method to handle series - heat pump systems. This may be ready and may be included in FCHART 4.

-An extensive restudy of the FCHART method for analysis of service hot water systems has been completed, and the details are described in Appendix B-3. As noted above, we find relatively little differences among the various systems configurations as long as the effectiveness of collector heat exchangers is maintained at adequate levels (above about 0.5) and losses from piping and tanks are kept at low levels. Comparisons of FCHART prediction of performance with a full year's experimental data on several systems at the National Bureau of Standards indicates that FCHART does very well at predicting the performance of domestic water heating systems. (See Table 11 in Appendix B-3 and Appendix A-3.) Two cautions must be observed, however. First, in accordance with our notice to FCHART holders of August 1978, losses from auxiliary tanks should be included as part of the loads when using FCHART to estimate the fraction of those loads to be carried by solar. Second, it is necessary to include losses from pipes and ducts. (These losses should be minimized through minimizing lengths of runs and using adequate insulation.) The calculations of the effects are readily done, but as they depend on collector area it is not possible to include them in the FCHART version 3 optimization program. The methods for these calculations are in the FCHART users manual.

A project on long term energy storage is being completed in December. The generalized ϕ methods can be directly applied to estimation of performance of systems of this type with storage capacities ranging all the way down to the capacities at which FCHART can be used. Thus estimation of the performance of systems with very large energy storage capacity are relatively quick and easy, and simulations are no longer required. This will be detailed in (6).

A method is being studied for design of collector-storage wall and direct gain passive systems that will allow for estimation of performance of systems with a wide variety of characteristics. This method is based on the observations for collector-storage wall systems (a) that on a monthly average basis temperature gradients in storage walls are very nearly linear, and (b) that flow rate of air through the gap between wall and glazing has relatively little effect on the total solar energy transferred into the building. Using these observations a simple linear network can be used to describe inputs through collector-storage walls. This concept is briefly described in Appendix B-5; the average shading factors described in B-2 are used in these calculations as are the monthly mean $(\tau\alpha)$ described in Appendix B-6. (The method for determining the amount of auxiliary energy required is developing along different lines than those described in B-5).

Task D: Validation of Models and Computer Codes

Two major comparisons have been made of experiments and computer results. The comparisons of FCHART predictions with NBS measurements is shown in Appendix A-3 and is discussed in Appendix B-3. Agreement is satisfactory.

Detailed study has been made of operating data from the Arlington House and comparisons made with the results of TRNSYS simulations. The operating data for a two-week period have been "cleaned up" in the sense of removing spurious numbers caused by problems in the data logger. Detailed TRNSYS simulations were done for the same period, using the measured weather data to drive the simulations. (This is probably the most complex simulation yet done in our laboratory.) It was necessary to determine several constants in the simulation from measurements; when this was done agreement between simulated and measured energy balances was excellent. Collected energy agreed within 3%, and auxiliary energy agreed almost exactly with experiment. An additional 10 day period was also measured and simulated; the results were again in very good agreement, with collected energy within 3% and auxiliary required was within 12% (at a solar fraction of about 0.5). Also, the dynamics of the experimental process, as measured by collector outlet temperature and room temperature, were duplicated very well by the simulations. (These activities will be reported at the SS/EA meeting in San Diego in January 1980.)

In addition, we have continued to participate in intercomparison under SS/EA programs for passive heating and industrial process heating, and have continued to make many comparisons of results from detailed simulations and design procedures such as f-chart, ϕ charts, and ϕ , f-chart.

PERSONNEL

The principal investigators have continued to work in the program with part of their stipends paid from the contract and part from the University of Wisconsin:

Prof. W.A. Beckman has worked about 1/4 time on the program during the academic years and over 1/2 time in the summer of 1979.

Prof. J.A. Duffie has spent about 1/2 time on the program through the period of the contract.

Prof. S.A. Klein has spent about 1/4 time on the program through the academic years and full time during the summer of 1979.

Prof. J.W. Mitchell has worked about 1/4 time on the program during the academic year and full time during the summer of 1979.

The TRNSYS-FCHART Engineers on the program have been W. Buckles and J.C. Mitchell.

The following Research Assistants (graduate students in Mechanical or Chemical Engineering) have been or are working on the program:

J.V. Anderson (MS-ME June 1979), Parallel heat pump systems. Now at SERI.

J.C. Blinn (MS-ChE Jan. 1979), Transient absorption cooler operation. Now at Kodak.

M.J. Brandemuehl, Economic analyses; heat and mass transfer analysis methods. Now working on PhD on desiccant cooling project.

J.E. Braun (MS-ME expected Dec. 1979), Long term energy storage. Will stay on as TRNSYS engineer.

M. Daugherty (MS-ME expected Dec. 1979), Arlington house operations and comparisons with TRNSYS.

D. Erbs (MS student, ME), Diffuse radiation models.

J.J. Jurinak (MS-ME Jan. 1979), Phase change storage; systems studies of desiccant cooling. Now PhD student on desiccant cooling project.

M. McLinden (MS & PhD student, ChE), Chemical heat pump systems.

W. Monsen (MS student, ME), Passive heating design methods.

D. Olegard (MS student, ME), Industrial process heating.

J. Ottenstein (MS-ME 1979), Large building systems. Now at Johnson Controls Company.

K. Pearson (MS student, ME), ϕ design of solar water heaters.

W. Ryan (MS-ME 1979), CPC models for TRNSYS.

M. Seigel (MS student, ME), Modeling and design of photovoltaic processes.

C. Svard (MS student, ME), Design method for series heat-pump systems.

J. Theilacker (MS student, ME), Methods for calculating $\bar{\phi}$.

D.M. Utzinger (MS Engr, Aug. 1979), Passive heating models for TRNSYS.

In addition the following were associated with the program but did not receive stipends from contract funds.

D. Campos V. (PhD student in ChE), Absorption cooling models.

C. Gleason (Senior in ChE), Economic model for TRNSYS.

L. Piessens (MS student in ME), Control component for TRNSYS.

Prof. Z. Chen, visitor from Hunan University, Peoples Republic of China, is studying our methods and developments and is headquartered at the laboratory.

In addition, Ms. S.A. Quamme, the secretary in the laboratory has spent full time working in this program and related activities. We also have been assisted by student helpers in preparation and shipping of program materials and documents.

REFERENCES

1. Blinn, J.C. MS Thesis, Chem. Engr., U. of Wisconsin-Madison (1979)
"Simulation of Solar Absorption Air Conditioning"
2. Utzinger, D.M. MS Thesis, Engr. U of Wisconsin-Madison (1979)
"Analyses of Building Components Related to Direct Heating of Buildings"
3. Brandemuehl, M.J. and Beckman, W.A., Solar Energy 23, 1 (1979)
Economic Evaluation and Optimization of Solar Heating Systems"
4. Ottenstein, J. MS Thesis, Mech. Engr., U of Wisconsin-Madison (1979)
"Application of Solar Energy to Multizone Buildings"
5. Anderson, J.V., MS Thesis, Mech. Engr., U of Wisconsin-Madison (1979)
"Procedure for Predicting the Performance of Air-to-Air Heat Pumps in
Stand-Alone and Parallel Solar-Heat Pump Systems"
6. Braun, J.E., MS Thesis, Mech. Engr., U of Wisconsin-Madison (1979)
"Seasonal Storage of Energy in Solar Heating"

Additional papers not cited in the report but presented or published during
the contract period include:

7. Klein, S.A., Mitchell, J.W., Duffie, J.A., and Beckman, W.A., Energy, 4,
483 (1979) "Computers in the Design of Solar Energy Systems"
8. Jurinak, J.J., and Abdel-Khalik, S.I., Solar Energy 22, 355 (1979)
"Sizing Phase-Change Energy Storage Units for Air-Based Solar Heating
Systems"
9. Ryan, W.A., Klein, S.A., and Beckman, W.A., paper presented at Atlanta
ISES meeting, 1979. "Prediction of Long-Term Performance of Closed-Loop
Concentrating Solar Collector Systems"
10. Brandemuehl, M.J., and Beckman, W.A., paper to be published in Solar
Energy. "Transmission of Diffuse Radiation Through CPC and Flat-Plate
Collector Glazings"

APPENDICES:

- A-1 TRNSYS Version 10.1 Changes
- A-2 TRNSYS Users Meeting Agenda
- A-3 Comparisons of NBS Experiments with FCHART

- B-1 Blinn, J.C., Mitchell, J.W., and Duffie, J.A., paper presented at Atlanta ISES Meeting. "Modeling of Transient Performance of Residential Solar Air Conditioning Systems"
- B-2 Utzinger, D.M., and Klein, S.A., paper to be published in Solar Energy. "A Method of Estimating Monthly Average Solar Radiation on Shaded Receivers" *removed*
- B-3 Buckles, W.E., and Klein, S.A., paper submitted to Solar Energy. "Analysis of Solar Domestic Hot Water Heaters" *removed*
- B-4 Anderson, J.V., Mitchell, J.W., and Beckman, W.A., paper presented at Atlanta ISES Meeting. "A Design Method for Parallel Solar-Heat Pump Systems"
- B-5 Monsen, W.A., Klein, S.A., Beckman, W.A., and Utzinger, D.M., paper presented at 4th Passive Heating Conference. "The Resistance Network Design Method for Passive Solar Systems"
- B-6 Klein, S.A., paper to be published in Solar Energy. "Calculation of the Monthly-Average Transmittance-Absorption Product" *removed*

TRNSYS VERSION 10.1

Main Program

1. New program structure and time clock. The new program organization makes it easier to fit TRNSYS onto small computers.
2. No limit on number of inputs per component.
3. Automatic trace during problem timesteps. Components called more than a specified number of times in a timestep are automatically traced.
4. Constants Card. This feature allows users to name constants in their TRNSYS input decks and to use these constant names whenever numbers are required on TRNSYS control cards. This is helpful when doing parametric or sensitivity studies.
5. Storage Allocation Algorithm. This helps users who write their own component models to save values from timestep to timestep.
6. Function TALF. Calculates transmittance-absorptance product for collector, window, thermal storage wall, and other models.
7. Month clock. Allows for monthly prints, plots, etc.

New Components

1. Revised Radiation Processor. New algorithms treat radiation data as integrated rather than instantaneous values, calculate solar zenith and azimuth angles, and output radiation for tracked as well as fixed surfaces.
2. Compound Parabolic Concentrating (CPC) collector model. Trough-like concentrating reflector with flat plate absorber.
3. Absorption Air Conditioner. Model with start-up and shut-down transients replaces older steady-state model.
4. Cooling Coil. Interface between load model and any cooling component; determines latent loads.
5. Humidity ratio and wet bulb. Simple psychrometrics component.
6. Thermal Storage Wall. Finite difference model includes air circulation to room or to the outside. Air flow may be forced by fan or result of density differences (thermocirculation).
7. Shading Component. Models effect of overhang and/or wingwalls on vertical collector.
8. Window with variable insulation. Suitable for modeling direct gain system with insulating curtain drawn at night.

Modifications to Existing Components

1. TYPE 19 Room and Basement - ventilation flowstream, room humidity and latent loads added. Also, it is now possible to have more than one TYPE 19 component in a simulation.
2. TYPE 8 Thermostat - hysteresis and time-dependent or condition-dependent set back options added.
3. TYPE 17 Wall or Flat Roof - the flat roof can be at any tilt.
4. TYPE 28 Simulation Summary - non-integrated input channels and energy balance checking added.
5. TYPE 1 Collector - incidence angle modifier added to performance data mode (Mode 5).
6. TYPE 12 Energy/(Degree-Hour) Load - constant sensible load multiplier added to account for latent cooling loads.
7. TYPE 22 Air Collector-Storage Subsystem - summer mode in which the rock bed is bypassed has been added.
8. TYPE 23 Domestic Hot Water Subsystem - maximum tank temperature parameter and option to remove heat exchanger are now included.
9. TYPES 24-27 Output Components - print and reset intervals can now be specified in number of months as well as number of hours.

TRNSYS USER'S MEETING
AUGUST 23-24, 1979

THURSDAY, AUGUST 23

- 8:30 AM Welcome and Introduction [John C. Mitchell & Sandy Klein]
 A. Purpose of Simulations
 B. What is TRNSYS?
 C. When to use TRNSYS and when not to
- 9:00 TRNSYS Program Structure [Bill Beckman]
 A. Program Organization
 B. Executive Routines
 1) Proc-keyword recognition, system interconnections, etc.
 2) Main-simulation control, differential equation solution
 3) Exec-TYPE calls, algebraic equation solution
 C. Meteorological Data Input
 D. Output of Simulation Results and Debugging Aids
- 10:30 COFFEE BREAK
- 11:00 Component Summary [Sandy Klein]
 Overview of Hardware Component Models
- 12:00 LUNCH BREAK
- 1:00 PM Preparation of Input (with examples) [Warren Buckles]
 A. Information Flow Diagrams
 B. Simulation Control Cards
 C. Listing Control Cards
 D. Component Control Cards
 E. Meteorological Data
 F. Output Routines
 G. Critical Interpretation of Results
- 2:00 COFFEE BREAK
- 3:00 User Formulation of Components [John C. Mitchell]
 A. Concepts
 B. Parameters, Inputs, Outputs, Derivatives
 C. Use of INFO Array and Utility Routines

FRIDAY, AUGUST 24

- 9:00 New Components and Features for Version 10.1 [W. Buckles, J.C. Mitchell,
 A. Constants card Mike Utzinger]
 B. Function TALF
 C. Radiation Processor
 D. Air Conditioner, Cooling Coil, and Load Model Modifications
 E. CPC Collector
 F. Passive Components
- 10:30 COFFEE BREAK

- 11:00 Control Strategies [Sandy Klein]
A. Energy Rate & Temperature Level Control
B. Problems with Combining Control Strategies
C. Hysteresis & Sticky Controllers
D. Building Complex Controllers out of Simple Controller Models
- 11:30 Timesteps, Error Tolerances, & Convergence [John C. Mitchell]
A. Convergence Criteria for Differential Equations
B. Convergence Criteria for Algebraic Equations
C. Accuracy vs. Cost Considerations in Choosing Timestep and Tolerances.
- 12:00 LUNCH BREAK
- 1:00 PM Output Routines and Simulation Tricks [John C. Mitchell]
A. Output Components (Types 24-28)
B. Complicated Time-Dependent Functions
C. Time of Day Rates
D. Conditional Histogram Plots
- 2:00 Closing Remarks [Jack Duffie]

SOLAR WATER HEATING
NBS EXPERIMENTS COMPARED WITH FCHART

<u>System</u>	<u>Test</u>	<u>FCHART*</u>
1-Tank Ext. Heat Ex.	0.36	0.37
2-Tank Ext. Heat Ex.	0.37	0.40
1-Tank Int. Heat Ex.	0.45	0.43
2-Tank Int. Heat Ex.	0.33	0.30

*Modified to account for preheat tank losses as per Solar
Lab Notice to FCHART holders of August 1978.