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MODELING OF SOLAR HEATING AND AIR CONDITIONING

Progress Report, October 31, 1974—December 31, 1975

J. A. Duffie
W. A. Beckman

December 31, 1975

Work Performed Under Contract No. E(11-1)-2588

University of Wisconsin
Engineering Experiment Station
Madison, Wisconsin

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

from the

SOLAR ENERGY LABORATORY
UNIVERSITY OF WISCONSIN-MADISON

MODELING OF SOLAR HEATING AND AIR CONDITIONING

Contract E(11-1)-2588

31 December 1975

University of Wisconsin-Madison
Engineering Experiment Station
1500 Johnson Drive
Madison, Wisconsin 53706

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I. OBJECTIVES

The objectives of this study are as follows:

The principal objective of the research is to develop the means to identify and optimize practical systems for heating and cooling of buildings with solar energy in the United States. This will be done through simulation methods.

Secondary objectives are to: extend and refine TRNSYS; develop the means of supporting TRNSYS users in other laboratories; use TRNSYS (and other simulation programs) to develop design procedures for solar heating and cooling processes; design, and evaluate an experimental solar heating system on a Wisconsin farm residence.

II. SUMMARY

In the past several years this laboratory has concentrated its research effort on digital computer modeling of solar energy thermal processes. A modular solar energy system simulation program called TRNSYS has evolved to meet the need for a general, easy to use means of performance evaluation in research and design, and in the classroom. Due to a very strong demand for the program outside this University, TRNSYS has received a great deal of our attention during this reporting period. Recent improvements and expansions, extensive documentation and support effort, and widespread utilization of the program have made TRNSYS almost the "industry standard" solar simulation program.

This report discusses some of the new features and component models available in the program. These include the capability to model air systems and heat pump systems. System studies involving Rankine engines, open cycle cooling, and solar drying are underway with TRNSYS compatible component models, though these are not yet available to the public.

An important outgrowth of the computer simulation work is the recent development of a design procedure for solar heating systems. Simulations have been used to develop a relationship between solar system and load parameters, the weather, and the fraction of the load carried by solar. This permits a straightforward estimation of system performance without the aid of a computer.

Much progress on the design of the Arlington solar house has been made, though administrative problems have forced delays in the house construction. The house will provide data on a unique air heating system using off-peak electric auxiliary and will be used to further validate our simulation technique.

III. PROGRESS ON OBJECTIVES

The development of the basic TRNSYS program for simulation of solar processes is in a generally satisfactory state. We use it routinely in the laboratory and classroom to simulate many different kinds of processes, and we are aware that other holders of the program are also using it. In the following paragraphs we note further progress on TRNSYS itself, on component programs, and on system studies. Also, we note the development of simplified design procedures for solar heating systems, and progress on design of a unique heating system for the Arlington farm building.

A. TRNSYS*

The basic objective of this research has been to develop a general and easy to use program for simulating a variety of solar energy thermal systems. The result of this study has been TRNSYS, a FORTRAN computer program for transient systems simulation. TRNSYS is described in a paper published in Solar Energy (1)†, in a forthcoming paper in ASHRAE Transactions (2), and in the TRNSYS Manual (3).

The TRNSYS program listing, manual and tape (or card deck at extra cost) have been provided to approximately 125 outside organizations, and several more requests are received each week. (Until December 31, 1975, a charge of $100.00 had been made for these materials to cover out of pocket costs. The charge has been increased to $200.00 as of January 1, 1976, reflecting increases in the sizes of the program and in our direct expenses in providing user services.)

Holders are kept informed by letter of changes so that all users are kept up to date with the latest version being distributed. As an alternative method of updating old versions, a current holder of TRNSYS can return his old tape and receive a new tape copy for $50.00.

Several modifications to the basic TRNSYS program have been made since the last report to NSF/RANN.

1. TRNSYS diagnostics have been further improved to make debugging easier.

2. A MAP option has been added which prints the component hook-up in the reverse order from the normal input and print-out order, facilitating the identification of interconnection errors.

3. The TRNSYS component subroutine library has been expanded as described in the next section.

*Inquiries regarding TRNSYS should be addressed to the TRNSYS Coordinator, 1303 Engineering Research Bldg., University of Wisconsin, 1500 Johnson Dr., Madison, WI 53706.

†References are listed in section VIII.

B. TRNSYS Component Models

During the period covered by this report TRNSYS has been changed, refined and expanded. In addition to liquid based heating systems and cooling systems based on LiBr-H_2O absorption cooling, standard TRNSYS library components now allow simulation of air-based systems and heat pump systems. Table I shows the current list of component subroutines in the TRNSYS library. A short description of the major new components follows Table I.

TABLE I

TRNSYS Components as of 31 December 1975

TYPE 1	-	Flat-Plate Solar Collector
TYPE 2	-	On/Off Differential Controller With Hysteresis
TYPE 3	-	Pump
TYPE 4	-	Stratified Fluid Storage Tank
TYPE 5	-	Heat Exchanger
TYPE 6	-	On/Off Auxiliary Heater
TYPE 7	-	Space Cooling Load and Air Conditioner
TYPE 8	-	Three Stage Room Thermostat
TYPE 9	-	Card Reader
TYPE 10	-	Rock Bed Thermal Storage
TYPE 11	-	Tee Piece, Flow Diverter and Flow Mixer
TYPE 12	-	Energy/(Degree-Hour) Space Heating Load
TYPE 13	-	Pressure Relief Valve
TYPE 14	-	Time Dependent Forcing-Function
TYPE 15	-	Algebraic Operator
TYPE 16	-	Solar Radiation Processor
TYPE 17	-	Wall
TYPE 18	-	Roof
TYPE 19	-	Room and Basement
TYPE 20	-	Heat Pump
TYPE 24	-	Integrator
TYPE 25	-	Printer
TYPE 26	-	Plotter

1. The collector model has been revised to give the user the choice of several options: Fixing U_L and $\tau\alpha$; fixing $\tau\alpha$ and computing U_L as a function of conditions; fixing U_L and computing $\tau\alpha$ as a function of angle of incidence; or computing both U_L and $\tau\alpha$.

2. A revised liquid storage tank model is now used which treats stratification in a slightly different way than the previous model. This is based on experiments of S.A. Klein, et al. (4) in Australia.

3. A detailed transient load model supplements the degree-day heating model that already existed in the TRNSYS library. Thermal capacitance models commonly used in heat transfer studies were developed for walls, roofs, ceilings and rooms in the early simulation work done for Colorado State University's Solar House I (5). These models have been expanded and are now available in the form of three components which can be combined to model building heating loads. The TYPE 17 wall model has several typical wall construction modes provided or the user may provide a wall of his own construction by specifying conductances and capacitances as suggested by the ASHRAE handbooks. The TYPE 18 roof and attic model represents a pitched or a flat roof with or without a collector or can be modified by the user to fit his own needs. Roof and wall models provide heat flows to a TYPE 19 room. The room model incorporates thermal capacitance, infiltration and internal heat generation.

The load calculations using TYPES 17, 18 and 19 require the solution of differential equations. An effort is currently being made to develop a response-factor load model, such as suggested in the ASHRAE Handbook of Fundamentals, that is compatible with TRNSYS. This new method would have two main advantages:

a. It would employ algebraic equations which are less expensive to solve than the differential equations. This cost factor becomes important for long term simulations where computing costs become quite large.

b. Currently a user must have a basic understanding of heat transfer analysis if the building does not fall into one of the limited number of categories currently available. This may restrict the number of users. It would be far easier for a simulator to identify the wall or roof of his choice from the types listed by ASHRAE and specify response factor coefficents from the tables as input parameters. This would expand use to anyone with access to and working knowledge of the ASHRAE handbook.

In addition, an evaluation of various load models is under way to determine under what conditions which load models are appropriate (i.e., long-term simulations of adequate accuracy at least cost.)

4. The thermal behavior of practical pebble bed storage units is adequately represented by a simple model used in a new TRNSYS component. This new component allows all systems to be modeled as inexpensively as water systems. The model was derived from the conventional packed bed equations by assuming that the corrected number of Transfer units (NTU_c), the parameter describing the operation of the bed as a heat exchanger, is infinite. This assumption was justified using simulation techniques. The performance of a typical solar air system was shown to be insensitive to NTU_c larger than the practical minimum. The full development of the simple gravel bed model has been documented in the form of a technical paper to be published in 1976 (6).

5. A TRNSYS heat pump model was described in our last report. This model consisted of an analytical solution of the highly interdependent thermodynamic processes in each of the components of the vapor-compression cycle. The model was used to create 'performance maps' (families of predicted performance curves) for several real heat pumps. By appropriate choice of various design parameters these predicted characteristics could be made to agree with manufacturer's published performance data.

The performance maps generated by the model were then used to simulate two different solar assisted air-to-air and water-to-water heat pump systems. The "in-line" system consisted of a solar collector and water storage system which served as heat pump source in the heating mode but could meet the load directly by bypassing the heat pump when storage temperature exceeded a minimum setting. The "parallel" system consisted of a "conventional" solar heating system operating in parallel with an air-to-air heat pump using only ambient air as its source. These two systems were simulated in both heating and cooling modes in Albuquerque for several different collector, load and heat pump sizes. The resulting thermal performance predictions were combined with cost assumptions and it was shown that the "parallel" system was somewhat more cost effective. A more complete account of this study is given in (7,8).

More recently, research emphasis was shifted to the development of a more convenient heat pump model to be used in TRNSYS simulations. This model was developed with two important goals in mind. One was that it should be able to use manufacturer's performance data to define the operation of any desired heat pump. The second was that the model should be universal, capable of simulating air-air, water-air, or a heat pump having switchable evaporators in the heating mode, i.e., capable of using either storage tank fluid or outside air as the heat source. This model, now part of the TRNSYS library, includes the capability of bypassing the vapor compression cycle to heat the building directly with storage tank fluid. Electrical resistance auxiliary heaters are built into the model.

6. In addition to these major changes, a number of other components have been added to TRNSYS primarily to permit modeling of air systems. These include a flow diverter, a flow mixer, and a tee piece.

C. System Studies

1. We have modeled a Rankine cycle engine coupled to a vapor compression air conditioner for residential cooling. This model has been used with TRNSYS in a preliminary study of various engine designs and long term performance of solar cooling systems. A design study was undertaken to determine for a given set of design restrictions the optimal set of Rankine engine components. These components include; boiler feed pump, boiler, shut-off valve, expander, condenser, and working fluid. On the basis of engine design, a control strategy was investigated for various load conditions.

The system study considered a flat plate collector and thermal storage tank, Rankine engine, vapor compression air conditioner, cooling tower, and residential cooling load. Performance was based on meteorological data for Albuquerque. Effects of engine size and collector area were investigated to determine percent cooling load and excess energy generated by solar means. The results of the engine design and system performance study have been presented in a thesis by Beekman (9).

Continuing research is in progress to eliminate many of the restrictive assumptions made for the Rankine engine design model. Further simulation studies are being made of the Rankine engine and solar system for uses other than strictly residential cooling. (Mechanical energy that is used to operate the vapor compression air condtioner for summer cooling could also be used for electrical power generation or other uses.)

2. Open cycle cooling systems employ combinations of heat exchangers, humidifiers, dehumidifiers, and an energy supply to produce cooling for air conditioning. Since these systems have not reached a highly developed stage, we are studying the processes as combinations of their basic components. To this end, TRNSYS component subroutines have been written as described below. To date all the components apply to a system using a solid desiccant and air-to-air heat exchangers.

a. A dehumidifier-desiccant wheel subroutine has been written, assuming that the air flow rates and cycle times for each of the heat and mass exchanger are equal, and no mass carryover is included. A set of data for the absorbent material is required which the user can supply. Presently the data set is for silica gel operating at standard atmospheric pressure.

b. An evaporative cooler subroutine employs the simplified relation

$$\frac{t_{out} - t_{in}}{t_{wet\ bulb} - t_{in}} = 1 - \exp(-NTU)$$

This is thought to be adequate for use in cycle studies where the small inaccuracy introduced by it is not critical. The evaporative cooler is assumed to operate at standard atmospheric pressure.

c. A heat exchanger-regenerator subroutine has been written assuming that air flow rates and cycle times for each side of the heat exchanger are equal; however, carryover effects are considered. The mathematical model parallels the model presented in Compact Heat Exchangers by Kays and London. A set of data describing the various physical properties and operational characteristics of the heat exchanger matrix is required. Presently, the data is for an infinite parallel passage matrix constructed of polypropolene sheets.

Using these components in a TRNSYS simulation, we will examine the interrelation between system and component behavior including fan power consumption. This is the beginning of a planned major effort in examination of open-cycle solar cooling.

3. A simulation study of solar drying by indirect means (i.e., supply of solar-heated air from a collector and storage unit) has been started. The first problem addressed is drying of deep beds of grain. The approach is to add mass transfer considerations to the pebble bed storage models, to simulate the "load", i.e., the material being dried.

D. Design Procedure for Solar Heating Systems

One approach to the problem of finding the minimum cost solar space and water heating system is to use computer simulations directly as a design tool. This application was one incentive for the development of TRNSYS. The use of computer simulations to aid in the design of every solar heating application is, in general, unsatisfactory, particularly for those architects and heating engineers concerned with the design of small buildings who do not have access to computing facilities. Consequently, the widespread utilization of solar heating will require a simplified design procedure for use by the heating industry, particularly for standard types of systems where costs of simulations cannot be justified.

The ϕ-curve method described by Hottel and Whillier (10) and Liu and Jordan (11) represents the only general design procedure for solar heating systems up to this time. With the ϕ-curves, the monthly thermal performance of a solar collector can be estimated. The difficulty with the ϕ-curves is that they attempt to evaluate solar collector performance without regard to the performance of the other components in a solar heating system, such as the storage tank or the heating load. As a result, the ϕ-curves involve several restrictive assumptions which reduce their utility.

Our approach to the development of a general design procedure has been to use many simulations to develop a relationship among the characteristics of the building loads, and the fraction of loads carried by solar energy. An inexpensive, special purpose simulation program capable of estimating the long-term thermal performance of solar heating systems was developed for a "standard" liquid-based heating and hot water system. The amount of meteorological data required by the simulation in order to estimate long-term system performance was studied using eight years of hour-by-hour data for Madison; a "design year" has been specified which adequately represents the eight years studied. The thermal performance results of many simulations have been correlated and presented in a graphical form. The result is a simple graphical method requiring monthly average meteorological data which can be used to estimate long-term thermal performance as a function of major solar system variables, and thus to design economical solar heating systems. The design procedure for liquid-based systems (i.e., systems using liquids, either water or antifreeze solution, as the energy storage and transfer mediums) is described in detail in (12) and (13). The design procedure for solar air heating systems is near completion. An abstract of (12), a paper presented at the Los Angeles ISES meeting, is enclosed in Appendix 1.

E. The Arlington House

Funding is provided in the current contract for design, instrumentation and evaluation of a solar heating system on a farm residence at Arlington, Wisconsin. Funds for construction of the house and purchase and installation of the heating system have been obtained from the Wisconsin Electric Utilities Research Foundation, and from the State of Wisconsin; in addition, equipment for the heating system is being supplied at no cost by Johnson Controls, Inc. and for the collectors at nominal cost by Owens-Illinois.

The system has been designed, using TRNSYS as the tool. The unique features are:

a. The auxiliary energy supply will be off-peak electrical energy, stored in the form of thermal energy.

b. An advanced, low-loss coefficient collector will be used, i.e. the evacuated tubular collectors developed by Owens-Illinois.

Several system configurations have been studied, based on the O-I collectors and on conventional 2-cover, non-selective flat plate air heaters. The system configuration uses a single pebble bed storage unit to store both auxiliary and solar energy. The performance penalty associated with a single storage unit is small with the O-I collectors (but substantial with conventional collectors). This study is described in detail in a thesis by Hughes (14).

Instrumentation and controls for the house have been designed, and major items purchased. The planned measurements will permit adequate determination of the energy balances on the solar heating system and component performance.

IV. PROBLEMS ENCOUNTERED

1. The most serious delays have been in the construction of the Arlington house. For a variety of reasons, bids came in higher than had been expected (for the house without a heating system); redesign and rebidding under Wisconsin's administration regulations will mean that data will not be obtained until the winter of 1976-77. We now hope to begin construction in March 1976.

2. We see no fundamental problems that will not yield to effort as far as modeling and simulation are concerned, and present and future efforts are aimed at improving several component models for which present capabilities are not satisfactory. Two examples are cited. 1) Our present absorption air conditioner models do not adequately take into account the kinds of transient performance characteristics noted in CSU House I, and are being reexamined. 2) The Rankine engine model is representative of an engine "between" a reciprocating and a rotary expander, and is being modified to make it more realistic.

3. We have had a problem in obtaining adequate meteorological data. Most of our work during this report period has been based on data for Madison, Wisconsin; Boston, Massachusetts; Charleston, South Carolina; Albuquerque, New Mexico; and Boulder, Colorado.

4. Providing a service to an increasing number of TRNSYS holders is requiring a significant level of effort, and we are working on methods to improve this service.

V. PLANS FOR THE COMING PERIOD

Plans for the coming period are to continue work on the following: TRNSYS components; control concepts and strategies; design methods; simulation studies of particular systems; design and construction of the Arlington experiment; and TRNSYS service. Plans are substantially as outlined in the proposal on which the current contract is based.

VI. RESEARCH UTILIZATION

A. TRNSYS Service

At present, over 125 copies of TRNSYS have been purchased by persons and organizations interested in solar system simulations. These users are from a broad cross section of major industries, small consulting companies, architectural firms, government laboratories and agencies, and the academic community. Feedback from the large user base has resulted in several innovations that have given the program greater error checking and diagnostic capability, great flexibility to simulate more unconventional systems, and little or no computer dependency. Users are provided with a version of the program on magnetic tape or punched cards, a copy of the manual and a listing of the program. A limited amount of free consultation by phone and mail is also provided to users having special problems or questions regarding the program's use.

On November 13, 1975, a TRNSYS user's meeting was held at the Solar Energy Laboratory. In response to our invitation to TRNSYS users, approximately 30 people from approximately 25 organizations outside the University of Wisconsin attended the meeting. We discussed current developments in component and system modeling at the laboratory, problems with numerical stability and control strategy, the purposes of simulations, use of meteorological data, and methods of reducing costs of simulations. In the afternoon, several TRNSYS users gave short presentations on their work with TRNSYS, and an open discussion of user problems and experience ensued.

The response from the people at the meeting and from TRNSYS users in general is very positive. There have been many requests to repeat the TRNSYS users meeting in the near future and for the University to provide additional information exchange services to TRNSYS holders. There have been many inquiries about the availability of additional models (like evacuated tube and focusing collectors, open cycle cooling components, and Rankine engines). Some users have suggested working with us on the development of TRNSYS compatible component models (such as photovoltaics) that could be made available to all users. In summary, interest in TRNSYS is substantial. It is constantly being used, tested, refined and expanded. A great deal of effort is being made to maintain the Users Manual as an updated document of maximum utility.

B. Professional and Technical Papers and Meetings

A major mechanism by which the results of this research are disseminated to users is through technical meetings. Since the beginning of this grant and contract, the following papers have been presented or published. Abstracts of the papers are included in Appendix 1.

1. Beckman, W.A. and J.A. Duffie, "Solar Heating and Cooling of Buildings," published in Proc. 20th Annual Meeting of Inst. Environmental Sciences, Apri 1974.

2. Butz, L.W., W.A. Beckman and J.A. Duffie, "Simulation of a Solar Heating and Cooling System," Solar Energy, 16, 129, 1974.

3. Gutierrez, G., F. Hincapie, J.A. Duffie and W.A. Beckman, "Simulation of Forced Circulation Water Heaters; Effects of Auxiliary Energy Supply, Load Type and Storage Capacity," Solar Energy, 15, 287, 1974.

4. Klein, S.A., W.A. Beckman and J.A. Duffie, "Transient Considerations of Flat-Plate Solar Collectors," Trans. ASME, J. Engr. Power, 96, Series A, 1974.

5. Abdel-Khalik, S.A., "Heat Removal Factor for a Flat-Plate Solar Collector With a Serpentine Tube," presented at 1975 ISES meeting, Los Angeles.

6. Freeman, T.L., W.A. Beckman, J.W. Mitchell and J.A. Duffie, "Computer Modeling of Heat Pumps and the Simulation of Solar-Heat Pump Systems," presented at ASME meeting, Houston, 1975.

7. Klein, S.A., W.A. Beckman, J.A. Duffie, "A Design Procedure for Solar Heating Systems," accepted for publication in the Solar Energy Journal, 1975.

8. Klein, S.A., T.L. Freeman, P.I. Cooper, D.M. Beekman, W.A. Beckman and J.A. Duffie, "A Method of Simulation of Solar Processes and Its Application," Solar Energy, 17, 29, 1975.

9. Klein, S.A., "Calculation of Flat-Plate Collector Loss Coefficients," Solar Energy, 17, 79, 1975.

10. Oonk, R.L., W.A. Beckman and J.A. Duffie, "Modeling of the CSU Heating/Cooling System," Solar Energy, 17, 21, 1975.

11. Report #38, TRNSYS - A Transient Simulation Program, prepared by the Solar Energy Laboratory, 1975.

12. Cooper, P.I., S.A. Klein and C.W.S. Dixon, "Experimental and Simulated Performance of a Closed Loop Solar Water Heating System," presented at the 1975 ISES meeting, Los Angeles.

13. Oonk, R.L., W.A. Beckman and J.A. Duffie, "Comparison of Simulated and Measured Performance of the CSU Solar House I Heating System," presented at the 1975 ISES meeting, Los Angeles.

14. Beckman, W.A., J.A. Duffie and S.A. Klein, "Simulation of Solar Heating Systems," to be published as Chapter 9 in the ASHRAE book, Applications of Solar Energy for Heating and Cooling of a Building, 1976.

15. Klein, S.A., W.A. Beckman and J.A. Duffie, "TRNSYS-A Transient Simulation Program," to be published in ASHRAE Transactions, 1976.

16. Klein, S.A., P.J. Hughes and D.J. Close, "Packed Bed Thermal Storage Models for Solar Air Heating and Cooling Systems," submitted to ASME Journal of Heat Transfer, 1976.

17. Duffie, J.A. and W.A. Beckman, "Solar Heating and Cooling," Science, 191, 4223, January 16, 1976.

Also, members of the laboratory staff have been active in organizing and conducting technical meetings; J.A. Duffie was general technical program chairman for the 1975 ISES meeting in Los Angeles. W.A. Beckman was a session chairman for the session on Flat Plate Collector Fundamentals, and is a member of the Division Committee of the Solar Energy Division of ASME.

C. Education

We continue to hold to the idea that University research and education are inseparable, and our research provides the major educational tool for our graduate students. In addition to working with graduate students, we teach a course in Solar Energy Technology to seniors and graduate students in engineering.

In January 1975, we repeated for the third time our short course entitled, "Solar Energy Thermal Processes." Again the enrollment limit of 50 was reached. Appendix 2 includes a list of attendees and a copy of the announcement. This short course is to be repeated again January 19-23, 1976.

J.A. Duffie, with G.O.G. Löf of Colorado State University, has provided three, two-day seminars for American Institute of Chemical Engineers, and J.A. Duffie and W.A. Beckman provided a two day seminar for federal agency personnel, under the sponsorship of the National Bureau of Standards.

The principals in this program (including J.W. Mitchell) have given many lectures to public, technical and industrial groups. W.A. Beckman and J.A. Duffie have written a general paper on Solar Heating and Cooling which will be published in Science in January 1976, and will serve to outline the principles, problems and opportunities in this field for a broad spectrum scientific audience. In November 1974 the book Solar Energy Thermal Processes by Duffie and Beckman was published by Wiley.

The educational activities (except for those described in the first paragraph) are not supported directly by ERDA. However, they would not be possible without the research program supported by ERDA.

VII. PERSONNEL

A. The professorial staff responsible for this project is:

W.A. Beckman, Professor of Mechanical Engineering
J.A. Duffie, Professor of Chemical Engineering
J.W. Mitchell, Professor of Mechanical Engineering

B. Visiting staff during the reporting period:

Dr. S. Abdel-Khalik, Post-doctoral Fellow (9/74-2/75)
Dr. D.J. Close, Visiting Associate Professor, from James Cook University of Northern Queensland (8/75-1/76)

C. Profession staff:

T.L. Freeman, TRNSYS Engineer (7/75-to date)
N.A. Duffie, TRNSYS Engineer (9/74-4/75)

D. Research Assistants (graduate students) and research topics:

D.L. Beekman, (M.S., Mech. Engr., 1975) Solar-Rankine engine air conditioning system: now with Trane Company.

L.W. Butz, (M.S., Mech. Engr., 1973) Simulation of a heated and cooled house: now with Trane Company.

M. Eberlein, (M.S., Mech. Engr., 1976) High performance air heaters: now with Ametek.

D. Research Assistants (continued)

T.L. Freeman, (M.S., Mech. Engr., 1975) Solar heat pump systems: now TRNSYS Engineer, Solar Energy Laboratory.

H. Grunes, (M.S., Mech. Engr., 1976) Manifold design for evacuated tube collectors.

Hanson, M. (M.S., Ch.E., 1976) Grain drying with solar energy.

P.J. Hughes, (M.S., Mech. Engr., 1975) Off-peak electric auxiliary solar system: now with Solar Energy Laboratory.

V. Karman, (M.S., Mech. Engr., 1976) Solar augmented heat pump studies.

S.A. Klein, (M.S., Ch.E., 1973; Ph.D., Ch.E., 1976) A wide range of studies on simulations, primary author of TRNSYS.

D. Morrison, (M.S., Mech. Engr., 1976) Heat of fusion storage study.

J. Nelson, (M.S., Mech. Engr., 1976) Open cycle cooling.

J. Olson, (M.S. Mech. Engr., 1976) Solar-Rankine cycle study.

R. Oonk, (M.S., Mech. Engr., 1975) Simulation of CSU House I: now with Solaron Company.

M. Pawelski, (M.S., Mech. Engr., 1976) Load calculation studies.

J. Roberts, (M.S., Mech. Engr., 1976) Cold side storage.

E. Special Project Students

J. Dekker (B.S., Chem. Engr., 1975) Use of design charts in regional feasibility study.

VIII. REFERENCES

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3. Report #38, TRNSYS - A Transient Simulation Program, prepared by the Solar Energy Laboratory, 1975.

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9. Beekman, D.M., M.S. Thesis, 1975, University of Wisconsin-Madison, "The Modeling of a Rankine Cycle Engine for Use in a Residential Solar Energy Cooling System."

10. Hottel, H.C., and Whillier, A., Transactions of the Conference on the Use of Solar Energy, 2, Part I, 74, University of Arizona Press, 1958. "Evaluation of Flat-Plate Collector Performance."

11. Liu, B.Y.H. and R.C. Jordan, Solar Energy, 7, 53 (1963). "The Long-Term Average Performance of Flat-Plate Solar Energy Collectors."

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13. Beckman, W.A., J.A. Duffie and S.A. Klein, "Simulation of Solar Heating Systems," to be published as Chapter 9 in the ASHRAE book, Applications of Solar Energy for Heating and Cooling of a Building, 1976.

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(1)

SOLAR HEATING AND COOLING OF BUILDINGS

W.A. Beckman and J.A. Duffie

ABSTRACT

This review paper notes many of the various building heating and cooling systems that have been proposed, analyzed and/or tested since 1937. It is noted that solar heating systems have been widely studied and used for some time, but combined systems for heating and cooling have not yet received the same attention.

A major portion of the paper discusses a simulation method for solar cooling and/or heating. The simulations can be used to evaluate systems, predict their thermal performance, and evaluate the effects of design changes; the results of a particular simulation are used to illustrate a method of economic analysis.

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(2)

SIMULATION OF A SOLAR HEATING AND COOLING SYSTEM

L.W. Butz, W.A. Beckman and J.A. Duffie

Abstract—This paper presents thermal and economic analyses of a solar heated and air conditioned house in the Albuquerque climate. The system includes the following components: water heating collector, a water storage unit, a service hot water facility, a lithium bromide-water air conditioner (with cooling tower), an auxiliary energy source, and associated controls. The analysis of the thermal performance indicates the dependence of output on collector area (considered as the primary design variable) and shows, for example, the manner in which annual system efficiency decreases as collector area increases. Based on the computed thermal performance, cost estimates are made which show variations in annual cost as functions of collector area and costs of collector and fuel.

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(3)

SIMULATION OF FORCED CIRCULATION WATER HEATERS; EFFECTS OF AUXILIARY ENERGY SUPPLY, LOAD TYPE AND STORAGE CAPACITY*

G. GUTIERREZ† F. HINCAPIE,‡ J. A. DUFFIE§ and W. A. BECKMAN§

(*Received* 29 *March* 1973, *in revised form* 19 *July* 1973)

Abstract—A hybrid computer was used to simulate forced circulation solar water heater systems using stratified storage. A single month of hourly meteorological data was used to examine the effects of three types of auxiliary heating systems and three different sized tanks. Various time distributions and magnitudes of the load were studied. Results are shown in terms of the ratio of auxiliary energy requirements to total load and indicate best methods for adding auxiliary energy to maximize solar energy gain.

(4)

S. A. KLEIN
Graduate Student.
J. A. DUFFIE
Professor and Director.
W. A. BECKMAN
Professor. Mem. ASME
Solar Energy Laboratory,
The University of Wisconsin,
Madison, Wis.

Transient Considerations of Flat-Plate Solar Collectors[1]

The effects of thermal capacitance in the modeling of the performance of a flat plate solar collector have often been neglected because of the computation involved. But because the solar collector is inherently exposed to continuously variable weather conditions, capacitance effects may be significant. To investigate these effects, three different models of flat-plate collectors have been investigated. The first, a quasi-steady-state model, simulates the performance of a collector of zero capacitance. The second model accounts for capacitance effects by assuming that a single value of thermal capacitance can be determined for the collector as a unit. The third model divides the collector into many isothermal segments, or nodes. For all three models the heat transfer coefficients are calculated as a function of operating conditions. The results show that, when hourly meteorological data are used, the zero-capacitance model is adequate.

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(5)

HEAT REMOVAL FACTOR FOR A FLAT-PLATE SOLAR COLLECTOR WITH A SERPENTINE TUBE

S.I. Abdel-Khalik

Abstract

The performance of a flat-plate solar collector is investigated. The collector is of the sheet-and-tube design and the tube is bonded to the absorbing plate in a serpentine fashion. Equations describing the variation of the fluid temperature in the different segments of the serpentine are derived. These equations are then used to determine the heat removal factor, F_R, for the collector.

It is shown that for the general case of an N-bend serpentine, the heat removal factor depends on three non-dimensional groups containing the different operational and design variables of the collector. A generalized chart for estimating F_R fir collectors with serpentines of arbitrary geometry and number of bends is presented.

(6)

Computer Modeling of Heat Pumps and the Simulation of Solar-Heat Pump Systems

T. L. FREEMAN W. A. BECKMAN J. W. MITCHELL J. A. DUFFIE

ABSTRACT

A generalized digital computer model of a residential size heat pump is described. The modeling strategy is to "design" or "size" the four major components in the vapor compression cycle to yield any desired design condition performance. Once the system has been defined, the program is able to compute a "performance map" of heat added and heat rejected at all possible combinations of inlet flowstream conditions.

The model is applied to the thermal performance simulation of several different solar-heat pump heating and cooling systems using the modular simulation program, TRNSYS. Performance of "in-line" heat pump boosted solar systems which use solar energy storage as the heat source are compared to "parallel" systems where the heat pump acts only as an auxiliary and ambient air provides the source. Finally, a simplified economic analysis is undertaken in which it is determined that the parallel system is the more cost effective configuration.

(7)

A DESIGN PROCEDURE FOR SOLAR HEATING SYSTEMS

S.A. Klein, W.A. Beckman, and J.A. Duffie

University of Wisconsin
Madison, Wisconsin

ABSTRACT

This paper is concerned with the design of solar space and water heating systems for residences. A simulation model capable of estimating the long-term thermal performance of solar heating systems is described. The amount of meteorological data required by the simulation in order to estimate long-term performance is investigated. The information gained from many simulations is used to develop a general design procedure for solar heating systems. The result is a simple graphical method requiring monthly average meteorological data which architects and heating engineers can use to design economical solar heating systems. A method of estimating the monthly average radiation on tilted surfaces is given in the Appendix.

(8)

A METHOD OF SIMULATION OF SOLAR PROCESSES AND ITS APPLICATION*

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Solar Energy Laboratory, University of Wisconsin, Madison, Wisconsin, U.S.A.

(*Received* 20 *August* 1974)

Abstract—TRNSYS, a program for simulating the dynamic thermal behavior of transient systems, is a general program for solving sets of differential and algebraic equations which describe solar energy systems. It is based on a modular approach which enables the user to readily simulate a wide variety of systems. The program consists of component models (for collectors, controls, storage tanks, heat exchangers, furnaces, building loads, integrators, recorders, etc.) and an executive routine.

The designer selects both his components and the design parameters describing the components and specifies, in a simple fashion, the way in which the components are interconnected. The whole process is analogous to specifying an experimental system. The designer also selects the information he wants from the simulation, again in a manner analogous to a physical experiment, and includes the appropriate instrument components in his simulation.

The use of the program is illustrated by a comparison of methods of operating a solar heating system.

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(9)

CALCULATION OF FLAT-PLATE COLLECTOR LOSS COEFFICIENT

S.A. Klein

(No Abstract)

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(10)

MODELING OF THE CSU HEATING/COOLING SYSTEM*

R. L. OONK, W. A. BECKMAN and J. A. DUFFIE
University of Wisconsin, Madison, Wisconsin, U.S.A.

(*Received* 20 *August* 1974)

Abstract—This paper resents a thermal simulation of the Colorado State University solar house. A computer model of the solar energy system was developed and computer runs were made using one year of meteorological data to determine the important design features. The system consists of a flat plate solar collector, main storage tank, service hot water storage tank, auxiliary heater, absorption air conditioner with cooling tower and heat exchangers between the collector and storage, storage and service hot water tank and storage and residence. This system very closely models the CSU house in operating mode one.

The results are in the form of monthly integrated values for the pertinent energy quantities. In addition, results are presented which show the effect on the system performance of the collector tilt, collector area and number of covers.

(11)
REPORT #38
TRNSYS - A TRANSIENT SIMULATION PROGRAM

(No Abstract)

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(12)

EXPERIMENTAL AND SIMULATED PERFORMANCE OF A CLOSED LOOP SOLAR WATER HEATING SYSTEM

By P.I. Cooper, S.A. Klein & C.W.S. Dixon
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A prerequisite to the overall economic design of solar processes is a satisfactory mathematical model of the system thermal behaviour. Mathematical analyses of most of the usual components in a solar energy system have been available for some time, but in general only simple system configurations have been considered.

A closed loop solar water heating system was designed, constructed and carefully instrumented to provide meaningful experimental data on the system performance. It consisted of a bank of series-connected, single-glazed, flat-plate collectors coupled to a fluid thermal storage tank. Pumped circulation was controlled by a simple but effective controller which approximates the performance characteristics of a differential controller. The load on the tank was an ambient air cooled heat exchanger, chosen to approximate a solar space heating system in which the energy dissipated is dependent on ambient conditions.

A flow diagram of the experimental system is shown in Fig.1. In conjunction with the experimental system, a mathematical model was constructed using TRNSYS [1], a program for simulating the dynamic thermal behaviour of transient systems. It was necessary to experimentally determine various component characteristics of the system for use in the simulation model, such as the gain and loss coefficients of the collectors and the effectiveness of the heat exchanger. It was envisaged that series connecting the collectors would greatly aid in determining their operational characteristics.

Initial experimentation indicated that the stratified storage tank model of Close [2] was possibly not sufficient for comparison of experimental and simulated performance on an instantaneous basis. Examination of the measured storage tank temperatures suggested that a more representative 'black-box' model of the tank could be devised and used in TRNSYS. This model was found to more closely approximate the short-term performance of the storage tank, though it is suspected that a simple, unstratified model will be sufficient for long-term performance predictions.

The most critical parameters required to simulate the system performance are the thermal characteristics of the flat-plate collectors. These are the local efficiency η_o at the inlet when the inlet fluid temperature is equal to the effective temperature of the surrounds and the overall thermal loss coefficient. Spectral measurements were available from laboratory tests which quantified the optical parameters of the collector type and internal measurements under controlled conditions had indicated the magnitude of the overall loss coefficient. These values provided a guide as to the accuracy of experimentally determining the characteristics from external measurements taken while the system was in operation.

Basically, two methods were used to determine the collector characteristics. The first involved plotting the efficiency of each collector for different values of $^{\Delta T}/_{G}$ (where ΔT is the potential for losses and G is the average radiation rate over a period of time). Analysis indicated that for an assumed linear system, the ordinate intercept of efficiency would be η_o while the slope would be U. Though this method gave satisfactory values of the parameters for the simulation, they were not directly comparable with the values expected from internal measurements. This is due mainly to non-linearity in the behaviour of the collectors. The second method consisted of plotting the instantaneous inlet and outlet water temperatures of each collector against the progressive collector area of the bank. Two such curves for different radiation levels but approximately the same wind velocity and ambient temperature allow η_o to be inferred. The heat loss coefficient U_o is then found as a function of conditions from heat balances at different times, on the assumption that η_o is unaffected by conditions. Values found initially in this manner agreed well with those expected, but subsequent attempts at reproducing them indicated that this method can be subject to a large degree of error.

Comparison of simulated and measured values on an instantaneous basis when the solar radiation is not varying rapidly indicated that the mathematical model was able to closely follow the experimental performance of the system. The agreement was not as close on days of rapidly varying insolation, because of inadequacies in the collector model and the difficulty of accurately measuring and deriving the system performance under these conditions.

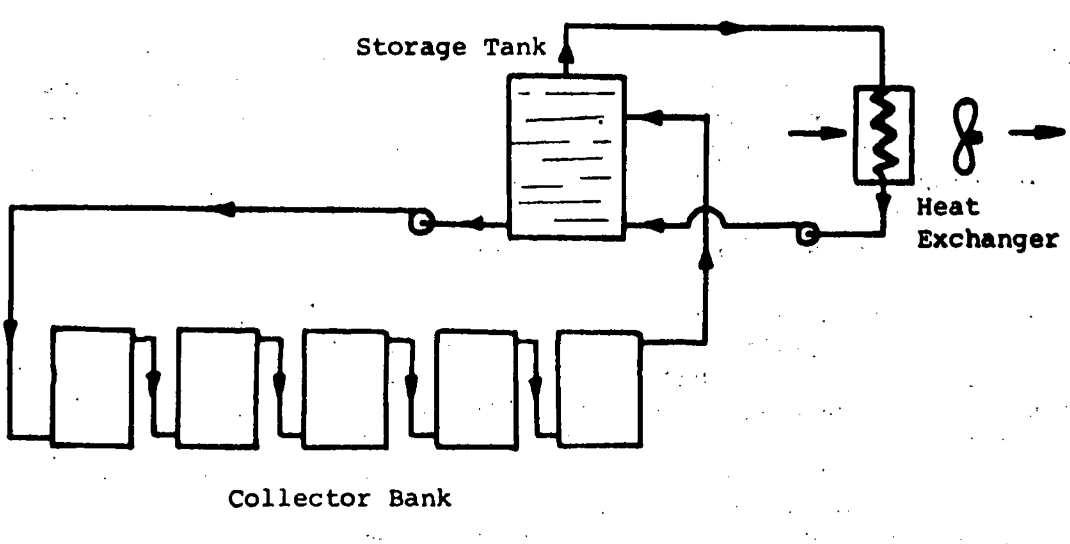

FIG. 1

REFERENCES

[1] KLEIN, S.A., COOPER, P.I., BECKMAN, W.A. & DUFFIE, J.A. - "TRNSYS, A Transient Simulation Program", Engineering Experiment Station, University of Wisconsin, Report No.38 (1974).

[2] CLOSE, D.J. - "A Design Approach for Solar Processes", Solar Energy, Vol.11, No.2 (1967).

FOOTNOTE : The authors are, respectively, Senior Research Scientist, CSIRO D.M.E.; Research Assistant, Solar Energy Laboratory, University of Wisconsin; and Student, Dept. of Mech. Engng, University of Melbourne, Victoria, Australia.

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(13)

COMPARISON OF SIMULATED AND MEASURED PERFORMANCE OF THE CSU SOLAR HOUSE I HEATING SYSTEM

R.L. Oonk, W.A. Beckman and J.A. Duffie
University of Wisconsin
Madison, Wisconsin

The solar energy system installed in the Colorado State University house consists of a flat plate solar collector, main storage tank, domestic hot water storage tank, auxiliary heater, absorption air conditioner with cooling tower, and heat exchangers between the collector and the storage, storage and domestic hot water tank, and storage and residence. The results of a simulation study which were part of the process of design of this system are reported in a recently published paper (Oonk, et al., "Modeling of the CSU Heating/Cooling System", Solar Energy, 17, 21 (1975)).

It is now of interest to compare the measured performance of the system with predicted performance (based on observed weather) over extended time periods. Hourly weather data measured at the house were used to drive TRNSYS, a general solar process simulation program (Klein, et al., "A Method of Simulation of Solar Processes and Its Applications," Solar Energy, 17, 29 (1975)). The resulting predicted thermal performance of the simulated system has been compared to the corresponding measured thermal performance.

Comparisons were made over a 235 hour period from November 22 to December 2, 1974. The behavior of the system over this time period was somewhat unique, since there was no auxiliary energy or domestic hot water consumed. Due to this unique behavior it was possible to determine several space heating load parameters necessary to drive the model. Load parameters such as internal generation and infiltration rate were selected so that the predicted heating load equaled the measured load. The resulting predicted integrated thermal performance (based in part on the experimentally determined load characteristics) was compared to the measured integrated thermal performance for the ten day period, as summarized in Table 1.

Table 1
Energy Quantities, November 22 to December 2, 1974

	Predicted	Measured
Collector useful energy gain (10^6kJ)	1.792	1.749
Auxiliary energy (10^6kJ)	0.063	0
Space heating load (10^6kJ)	2.036*	2.013*
Tank internal energy change (10^6kJ)	-0.320	-0.202

*Forced to agree by adjusting the infiltration and internal generation rates.

In addition to integrated performance over ten days, the dynamics of the system performance can be compared with predicted dynamics. Figure 1 shows calculated and measured useful gain from the collector for the ten day period. The measured performance was higher early in the period, but the reverse situation existed for the last three days. Measured storage tank temperatures matched predicted temperatures quite well during most of the period, but were higher during the last three days.

A second comparison was made over a 69 hour period from January 27, 1975 to January 30, 1975. In these comparisons the infiltration and generation rates determined from the earlier comparison were used to calculate the space heating load. Thus it is possible to check the validity of the heating load model, since the model should predict the same heating load that was measured. The results of this comparison is summarized in Table 2.

Table 2
Energy Quantities for January 27 to January 30

	Predicted	Measured
Collector useful energy gain (10^6kJ)	0.779	0.620
Auxiliary energy	0.207	0.522
Space heating load	0.996	0.971
Domestic hot water load	0.067	0.079
Tank internal energy change	-0.099	0.054

Refinements in experimental measurements and longer time periods of operation are being studied and will be discussed in the final paper. In general, the simulations are considered to satisfactorily represent both the dynamics and long term integrated performance.

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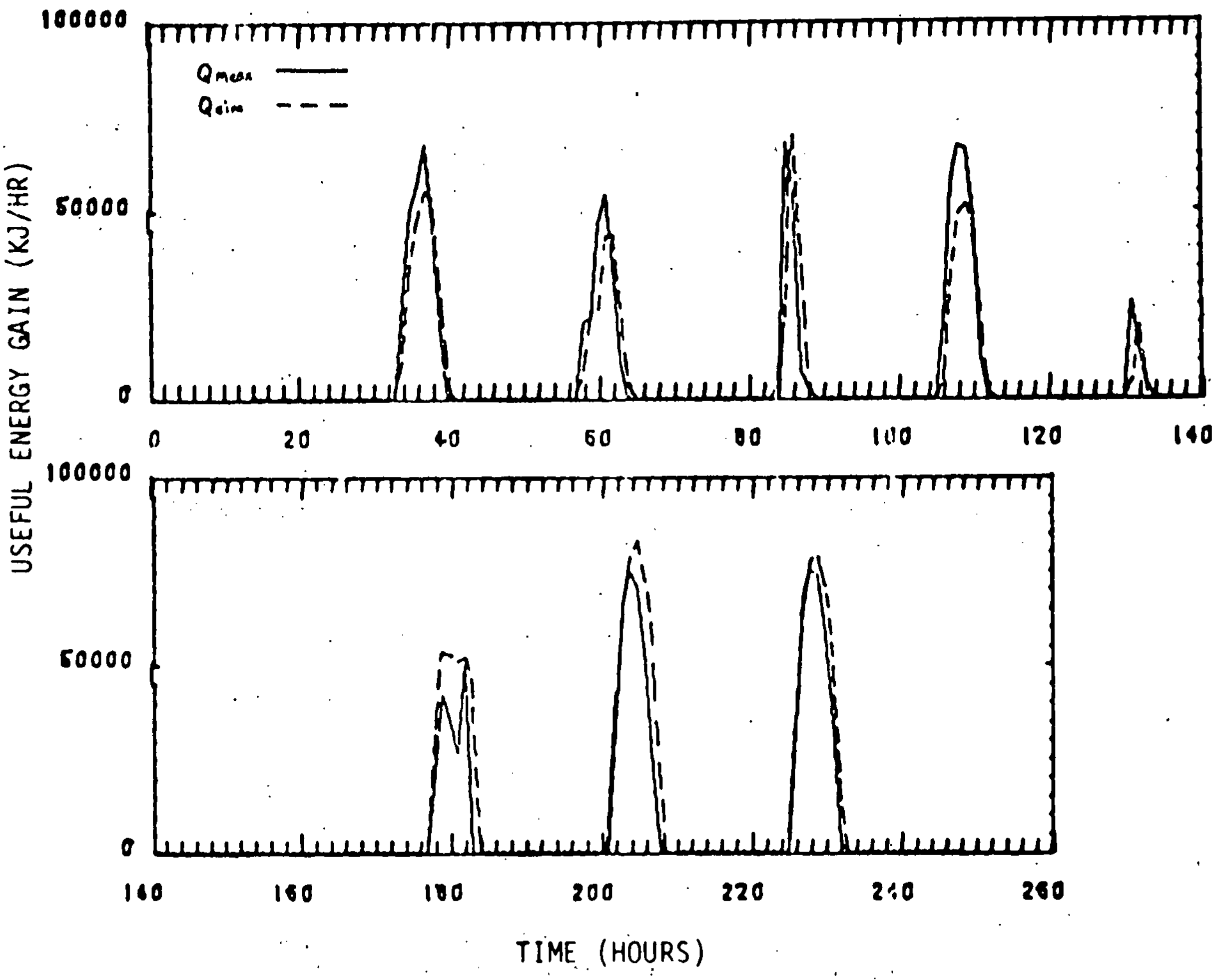
FIGURE 1



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(14)

SIMULATION OF SOLAR HEATING SYSTEMS
CHAPTER 9

W.A. Beckman, J.A. Duffie and S.A. Klein

(No Abstract)

(15)

TRNSYS - A TRANSIENT SIMULATION PROGRAM

ABSTRACT

A solar energy system can be regarded as a collection of interconnected components, which normally operate in transient modes. To facilitate the simulation of such systems, a computer program called TRNSYS has been developed to interconnect components in any desired manner and solve the simultaneous algebraic and differential equation describing the system. With this program, the essential problem of transient system simulation reduces to one of formulating mathematical models for each of the components in the system. General mathematical models of many components common in solar energy systems have been developed. Because these component models can be interconnected in any specified manner, simulations of many different systems are possible with little or no programming effort.

The formulations of models for typical components are described. The interconnection of component models in TRNSYS to obtain system performance is illustrated by example.

KEY WORDS: Load-Calculation, Modeling, Solar, Systems-Building, Thermal-Response

(16)

PACKED BED THERMAL STORAGE MODELS FOR SOLAR AIR HEATING AND COOLING SYSTEMS

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S.A. Klein, Research Assistant
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Solar Energy Laboratory
University of Wisconsin-Madison

ABSTRACT

Using simulation techniques, this paper investigates the sensitivity of the thermal performance of solar air heating systems to NTU_c, a parameter which describes the heat transfer characteristics of a packed bed store. It is found that the long term performance of most practical system designs is insensitive to NTU_c. A simple gravel bed model which assumes NTU_c is infinitely large is described. The model is shown to provide an adequate representation of the performance of gravel beds of reasonable design, with much less computational effort than that required for the solution of conventional packed bed relations. Furthermore, it is concluded that considerable freedom may be allowed in the choice of gravel bed geometry without incurring a performance penalty.

†Presently Senior Lecturer, Department of Engineering, James Cook University, Townsville, Queensland, Australia.

(17)

Solar Heating and Cooling

Solar energy for buildings is developing rapidly in the United States.

John A. Duffie and William A. Beckman

Thermal energy for buildings, supplied at temperatures near or below 100°C, constitutes an important segment of the U.S. energy economy and accounts for about one-quarter of the nation's energy use. Energy at these temperatures can readily be delivered from flat-plate solar energy collectors, and the solar energy incident on most buildings is more than adequate to meet these energy needs. Flat-plate collectors are manufactured and sold on a small but growing scale in the United States; they have been in use for more than a decade in heating water for buildings in Australia, Israel, and Japan. We expect that solar heating and cooling for buildings, with energy collected by flat-plate collectors, will be the first large-scale application of solar energy.

The basic problem with solar heating and cooling has been that the energy could not, except in special cases, be delivered at costs competitive with costs of energy from other sources. This situation is rapidly changing, and interest in solar energy is increasing almost daily as fuel costs rise. In areas where new natural gas connections are no longer available, where oil is not distributed, and where electrical resistance heating is the only alternative among conventional sources, solar heating is economically attractive.

In addition to technical and economic considerations, several social factors will influence the course and pace of developments. Two examples are worth examining. First, architectural constraints are imposed by the need for collectors to be oriented within rather narrow limits. This will make it difficult to fit solar heating systems to many existing buildings; thus new residential construction will be the easiest starting place for conversion to solar heating. Solar cooling may first be installed in existing low-rise, flat-roof buildings such as schools and shopping centers, where cooling is usually more important than heating. Second, tax policy is important. Today the installation of solar heating or cooling systems brings an increase in property valuation in most states, and a corresponding modest increase in real estate taxes. Government encouragement to invest in solar energy systems in the form of tax write-offs or other inducements (as are provided for investments by other energy producers) could very rapidly change the competitive position of solar energy in relation to conventional energy sources.

In all buildings, intelligent practices for energy conservation are worth following. The basic advantages of reducing energy needs by good thermal design apply whether buildings are supplied with solar or conventional energy. If solar energy costs the same as an alternative energy source, the value of energy conservation techniques, such as extra glazing on windows and doors or added insulation, is the same whether solar energy or the alternative is being used.

APPENDIX 2

Announcement and list of attendees at the January 1975 "Solar Energy Thermal Processes" short course.

SOLAR ENERGY THERMAL PROCESSES

January 6-10, 1975

(REPEAT of Engineering Short Course held in January and May 1974)

OBJECTIVES OF THE COURSE

The major objective of this course is to provide engineers with a working knowledge of thermal processes for solar energy utilization. The course is structured to cover: solar radiation, its measurement, and data and their uses; the design and performance of solar energy collectors, energy storage units and other system components; solar process system analysis methods; applications of solar energy to thermal energy needs of buildings; power generation processes; and costs of solar processes. Each topic builds on those previously covered, to provide continuity in the development of the subject from basic principles to applications.

The course is designed for engineers who are or may be responsible for design and evaluation of solar energy systems and assumes some background in heat transfer and thermodynamics. The course will consist of a series of lectures, combined with tutorial sessions in which problems will be worked with the aid of the staff.

The book, *Solar Energy Thermal Processes* (Wiley-Interscience, New York, 1974) will be used as a text, and a copy will be provided to each participant.

At the end of the course, the participants will have had experience in prediction of the thermal performance of solar energy systems and a method of making economic assessments of solar energy. The course will reflect current research on solar energy processes.

This course MAY be applicable for credit toward the University of Wisconsin's Professional Development Degree in Engineering. Details of this degree program are available upon request.

....a program at MADISON

SOLAR ENERGY THERMAL PROCESSES

January 6-10, 1975

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For Enrollment / CALL: 262-1299

GENERAL INFORMATION

ENROLLMENT: Register in advance by mail or phone. Early registrations are confirmed by mail. Be sure you have a confirmed enrollment. FEE covers session cost, notebook and handout materials, break refreshments, one scheduled dinner and lunches. Lodging and other meals NOT included.

LOCATION: Madison programs (unless noted otherwise in this bulletin) are held in The WISCONSIN CENTER.... northeast corner of campus at Langdon and Lake streets. Check program details.

PARKING: There is metered public parking in Lake St. Ramp (between State St. & University Ave.) and at street level in Helen White Hall (Park St. opposite Wisconsin Union).... both a block from The WISCONSIN CENTER. Posted AREAS are restricted to permit holders. Some permits may be available (nominal fee) for nearby parking. Registrants will receive information.

LODGING OVERNIGHT: A campus map and Madison area hotel/motel information will be sent to all registrants. Make advance reservations directly with the place you select.

REFUND: If program is cancelled for any reason, your Fee will be refunded. If YOU cancel, notify us at least a day before an INSTITUTE or REFRESHER program and at least a week before a SHORT COURSE start date to receive your refund.

• PROCEEDINGS ARE NOT PUBLISHED •

A Certificate of Participation is presented to each registrant

SOLAR ENERGY THERMAL PROCESSES

January 6-10, 1975

In Cooperation with the College of Engineering, UW-Madison

MONDAY, JANUARY 6

AM
8:00 Registration
The Wisconsin Center
Corner of Langdon and Lake streets
Madison, Wisconsin
Introduction to the Course
Review of Heat Transfer Topics Important in Solar Energy

PM
Solar Radiation I
Solar Flat-Plate Collectors I
6:00 Get-Acquainted Social Hour and Dinner (Cash Bar)—The Wisconsin Center

TUESDAY, JANUARY 7

AM
Solar Radiation II
Tutorial Session on Solar Radiation Calculations

PM
Solar Flat-Plate Collectors II
Tutorial Session on Flat-Plate Collector Design and Performance

WEDNESDAY, JANUARY 8

AM
Solar Focusing Collectors
Energy Storage I

PM
Energy Storage II
Tutorial Session on Collector Storage System Performance

THURSDAY, JANUARY 9

AM
Review of Solar Space Heating Experience
Modeling of Solar Heating and Cooling Systems

PM
Economics of Heating and Cooling Systems
Tutorial Session on Heating and Cooling System Performance

FRIDAY, JANUARY 10

AM
Review of Solar Energy Activities
Solar Power Systems
Lunch—Presentation of Certificates

PM
Open Tutorial on Topics of Interest to Registrants

SHORT COURSE FORMAT

Each day the short course will consist of three sessions. The morning session will be from 8:00 to 11:00 a.m., and will be in two parts separated by a coffee break. Each of the parts will be a lecture on a major topic, or a tutorial, problem-working session at which the staff will assist registrants in working out design and performance problems.

The early afternoon session, from 1:00 to 2:00 p.m., will be reserved for individual consultations and work at the Engineering Computing Laboratory. The afternoon sessions will be from 2:00 to 5:00 p.m. and will be in the same format as the morning session. Topics for the morning and afternoon sessions are indicated in the outline. Luncheon will be daily at noon in The Wisconsin Center Cafeteria.

INSTRUCTORS FOR THE COURSE

John A. Duffie, Professor of Chemical Engineering, Associate Dean of the Graduate School of University of Wisconsin—Madison, and Director of the Solar Energy Laboratory. Dr. Duffie is immediate Past President of the International Solar Energy Society and has been active in solar energy research for 20 years.

William A. Beckman, Professor of Mechanical Engineering at University of Wisconsin—Madison. Dr. Beckman is chairman of the Solar Energy Division of the American Society of Mechanical Engineers, a specialist in numerical modeling of thermal systems, and has worked and published extensively in solar energy and related fields.

TEXT

Professors Duffie and Beckman are authors of the book, *Solar Energy Thermal Processes* (Wiley-Interscience, October, 1974) which will be furnished to each enrollee. Text will be sent *in advance* to all enrollees whose paid registration is received at least 4 weeks before course starts.

UNIVERSITY OF WISCONSIN-EXTENSION

JOHN P. KLUS, Chairman
Department of Engineering

WILLIAM W. WUERGER, Director
Engineering Institute & Short Courses

SOLAR ENERGY THERMAL PROCESSES

JANUARY 6-10, 1975

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Madison, Wisconsin

JOHN A. DUFFIE
Professor of Chemical Engineering
University of Wisconsin
Madison, Wisconsin

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SOLAR DATA TAPES

Prepared by the University of Wisconsin Solar Energy Laboratory

DESCRIPTION

The solar data tapes contain hourly solar radiation and meteorological data, assembled from Weather Bureau tapes and other sources, for several cities in the United States. Solar radiation, wind speed, and dry bulb temperature data are available for all cities. Additional data on visibility, humidity, wind direction and cloud cover is available for many of the cities.

TAPE FORMAT

The tapes are written either in 7-track BCD mode with even parity and 800 bpi density or 9-track EBCDIC mode with odd parity and 800 bpi or 1600 bpi density. A tape is divided into files, each containing a year of hourly data for one city. Table II sequentially lists the contents of each file on the tape.

A complete file contains 8760 hourly records followed by an end of file mark. Each hourly record is an 80 character card image and these are blocked 240 records per block. Data must therefore be read from the tape in 240 hour blocks, and there are 37 blocks in every file. (The last block is only half filled with data since every year has 365 daily records. February 29 has been deleted from leap years.) Table I describes the general card image format. Note that not all of the data listed is available for every city. Where data is not available, the field is filled with 9's so that free format reading can always be used. The data available for each city is indicated in Table II.

TABLE I. HOURLY RECORD FORMAT

Column	Abbrev.	Description	Units
2-6	STN	Weather Bureau station number	-
8-9	YR	Year (19--)	-
11-12	MO	Month (1-12)	-
14-15	DY	Day (1-31)	-
17-18	HR	Hour (0-23)	-
20-23	SOL	Total solar radiation on a horizontal surface Δ	W/m^2
25-26	WD	Wind direction	degrees/10*
28-29	WS	Wind speed	m/s
31-35†	DBT	Dry bulb temperature	°C
37-41†	WBT	Wet bulb temperature	°C
43-47†	DPT	Dew point temperature	°C
49-51	RH	Relative humidity	percent
53-54	CC	Cloud cover	tenths
56-60	VIS	Visibility	kilometers

Δ total radiation over the past hour

* 0 is wind from the north, 9 is from east, 18 is from south, etc...

† 5 character field with decimal point second from the right

TABLE II. SOLAR DATA TAPE FILE STRUCTURE

File	City	Period	Additional Data†
1	Madison, WI	DESIGN YEAR	WD, HUM, VIS, WBT, DPT
2	Madison, WI	1/1/48-12/31/48	WD, HUM, VIS, WBT, DPT
3	Madison, WI	1/1/49-12/31/49	WD, HUM, VIS, WBT, DPT
4	Madison, WI	1/1/50-12/31/50	WD, HUM, VIS, WBT, DPT
5	Madison, WI	1/1/51-12/31/51	WD, HUM, VIS, WBT, DPT
6	Madison, WI	1/1/52-12/31/52	WD, HUM, VIS, WBT, DPT
7	Madison, WI	1/1/53-12/31/53	WD, HUM, VIS, WBT, DPT
8	Madison, WI	1/1/54-12/31/54	WD, HUM, VIS, WBT, DPT
9	Madison, WI	1/1/55-12/31/55	WD, HUM, VIS, WBT, DPT
10	Madison,WI	7/1/61-6/30/62	WD, HUM, VIS, WBT, DPT
11	Boulder, CO	1/1/56-12/31/56	WBT
12	Miami, FL	1/1/55-12/31/55	WD, HUM, CC, VIS
13	Charleston, NC	1/1/55-12/31/55	WD, HUM, CC, VIS
14	Blue Hill, MA	1/1/58-12/31/58	WD, HUM, CC, VIS
15	Albuquerque, NM	1/1/59-12/31/59	WD, HUM, CC, VIS
16	Albuquerque, NM	7/1/62-6/30/63	WD, HUM, VIS, WBT, DPT
17	Phoenix, AZ	1/1/56-12/31/56	WD, HUM, CC, VIS
18	Santa Maria, CA	1/1/55-12/31/55	WD, HUM, CC, VIS
19	Seattle, WA	1/1/60-12/31/60	WD, HUM, CC, VIS
20	Fresno, CA	7/1/57-6/30/58	WD, HUM, VIS, WBT, DPT
21	Medford, OR	7/1/61-6/30/62	WD, HUM, VIS, WBT, DPT
22	El Paso, TX	7/1/54-6/30/55	WD, HUM, VIS, WBT, DPT
23	Dodge City, KA	7/1/55-6/30/56	WD, HUM, VIS, WBT, DPT
24	Bismark, ND	7/1/54-6/30/55	WD, HUM, VIS, WBT, DPT
25	New York, NY	7/1/57-6/30/58	WD, HUM, VIS, WBT, DPT

† All files contain the station no., year, month, day, hour, solar radiation, wind speed, and dry bulb temperature.

Acknowledgements & Disclaimers

The data in files 1 through 9 were assembled by the University of Wisconsin Solar Laboratory. The radiation measurements came from Solar Lab records of data taken both by the University of Wisconsin and the U.S. Weather Bureau in Madison. These data were integrated with "surface observations" for Madison over the same period obtained from the National Oceanographic and Atmospheric Administration (NOAA). This data had numerous small gaps which were filled in with actual readings from the Madison weather bureau archives wherever possible and interpolated values when no data was available. The design year was constructed by selecting the months from the eight consecutive years whose total radiation and degree days most closely matched the monthly averages of the eight year period.

The data in files 11-15 and 17 were obtained from Professor Richard Tybout of Ohio State University and the data in files 10, 16, and 18-25 were obtained from James Hedstrom of Los Alamos Scientific Laboratory. The UW Solar Lab altered only the format and units of these data to make them compatible with our own. We do not intend to characterize these data as "design years" or even as being representative of the location in question. Furthermore, it has been found that US weather bureau data, especially radiation measurements, are often 5 to 10% in error and occassionally as high as 20% in error.

THE UNIVERSITY OF WISCONSIN
INTERACTIVE SOLAR HEATING DESIGN PROGRAM, FCHART

The Solar Energy Laboratory of the University of Wisconsin has developed a quick design method for solar heating systems*, based on standard system configurations, using either liquid or air as the heat transfer medium. This method treats collector area as the main design variable, but includes means for taking into account secondary design variables such as storage unit capacity. We refer to this method as the f-chart method. The f-charts are the result of correlating hundreds of detailed simulations of solar heating systems. For standard system configurations, the f-charts eliminate the need for detailed simulations using hourly meteorological data.

The meteorological data required to use the f-chart method are: the long term monthly average of daily total solar radiation on a horizontal surface, the long term monthly average ambient temperature, and the long term monthly average heating degree days (65°F base).

The solar energy system data needed for the f-chart method includes: the $F_R U_L$ and $F_R(\tau\alpha)$ products for the collector (which are the slope and intercept of collector efficiency versus $(T_{in}-T_{ambient})$/(incident radiation) curves); the effectiveness of heat exchangers between collector and tank (for liquid-based systems); the storage capacity per unit area of collector; and the orientation of the collector.

The building heating load is incorporated either by specifying the monthly load (calculated by any standard technique), or by specifying the building overall loss coefficient (energy-per-degree-day concept), which is the design heating load divided by the design temperature difference. In addition, a service hot water load can be added to the heating load.

Given these numbers, the fraction of monthly total loads, and the fraction of the annual loads to be carried by solar energy can readily be determined for any collector area.

The f-chart method has proven useful for design and for economic studies. Its utility has led us to develop an interactive program which will give the thermal and economic performance. The appropriate meteorological data are stored in the program for approximately 100 stations in North America; it is necessary to select from the list of stations the one that is most representative of the location of interest.

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*Klein, S.A., Beckman, W.A., and Duffie, J.A., "A Design Procedure for Solar Heating Systems," Solar Energy, 18, 113 (1976).

Klein, S.A., Beckman, W.A., and Duffie, J.A., "A Design Procedure for Solar Air Heating Systems", Paper for ISES Meeting, Winnipeg, Aug. 1976.

There are two options in the use of the program. First, the collector area can be specified (along with the other design data noted above), and the annual (and monthly if desired) performance is returned. In addition, if cost data are supplied an economic assessment can also be returned. The attached program output illustrates the required input data and computed thermal and economic performance for Madison, Wisconsin, for an average residential structure.

The second option is to ask the program to find the economic optimum collector area. The program uses a numerical technique to optimize the collector area and returns the same information as the first option but for the optimum area.

The economic optimum collector area is found by calculating the present value of future costs of the solar system and of the conventional system (including, if desired, the effects of escalating fuel prices, property and income taxes, tax rebates, interest, depreciation, insurance, and maintenance). The optimum collector area is that which minimizes the sum of the present value of future costs plus the initial cost of the solar system above the cost of a conventional heating system.

The equations for the f-charts are simple, and the economic analysis is straightforward. Under these circumstances, it had been our intention to provide (through publication in the technical literature) the basis of the program but not the program itself. However, there has been sufficient interest in it that we have now decided to make the program itself available. We will do so at a charge of $100.00 for a card deck (2000 cards) or a punched paper tape, a program listing, data for over 100 stations, and the paper describing the basis of the program.

The program is written in standard FORTRAN II for use in interactive mode. It can be used in a batch mode but this is not very convenient. There is no documentation other than the listing (and the technical paper). However, the program is self explanatory in the interactive mode. On the University of Wisconsin UNIVAC 1110 system, a point design costs substantially less than one dollar.

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UNIVERSITY OF WISCONSIN
SOLAR ENERGY LABORATORY
FCHART VERSION 1.2

THIS PROGRAM UTILIZES THE DESIGN CHARTS DEVELOPED AT THIS LABORATORY
TO SIZE COLLECTORS FOR SOLAR SPACE AND DOMESTIC WATER HEATING SYSTEMS
OF CONVENTIONAL DESIGN. TO USE, ANSWER THE QUESTIONS.

YOU MAY USE EITHER SI OR ENGLISH UNITS.
DO YOU WISH TO USE SI UNITS?
YES
WOULD YOU LIKE A LISTING OF LOCATIONS FOR WHICH CALCULATIONS CAN BE
MADE?
NO
YOU MAY MODEL THE SPACE HEATING LOAD USING THE DEGREE-DAY CONCEPT
OR YOU MAY TYPE IN A SPACE HEATING LOAD FOR EACH MONTH.
DO YOU WISH TO USE THE DEGREE-DAY CONCEPT?
YES
YOU MAY EITHER HAVE THE GROUND REFLECTANCE SET TO 0.2 FOR ALL MONTHS
OR YOU MAY TYPE IN A VALUE FOR EACH MONTH
DO YOU WISH TO HAVE THE GROUND REFLECTANCE SET TO 0.2 FOR ALL MONTHS?
YES
WOULD YOU LIKE THE PROGRAM TO PERFORM AN ECONOMIC ANALYSIS?
YES
IS THIS AN INCOME PRODUCING BUILDING (NOT A RESIDENCE)?
YES
DO YOU NEED INSTRUCTIONS TO CHANGE OTHER PARAMETERS?
YES
THE FOLLOWING LIST CONTAINS THE SYSTEM PARAMETERS AND THEIR PRESENT VAL
UES. TO CHANGE ANY PARAMETER VALUE, TYPE IN THE  CODE NUMBER AND NEW
VALUE OF THE PARAMETER. WHEN CHANGING DIMENSIONAL QUANTITIES BE SURE
TO USE THE PROPER UNITS.
IF YOU WISH TO LIST THE VALUES OF THE PARAMETERS, TYPE IN "LIST"
WHEN YOU HAVE FINISHED MAKING CHANGES, TYPE IN "RUN".
IF YOU WISH TO CHANGE MONTHLY VALUES OF LOAD OR GROUND REFLECTANCE,
TYPE IN "CHANGE".
IF YOU WISH TO STOP, TYPE IN "STOP".
TO LIST THE VALUE OF ONE PARAMETER TYPE IN "LIST" AND THE CODE NUMBER.
```

CODE	VARIABLE DESCRIPTION	VALUE	UNITS
1	AIR SYSTEM=1,LIQUID SYSTEM=2..................	2.00	
2	COLLECTOR AREA................................	50.00	M2
3	FRPRIME-TAU-ALPHA PRODUCT(NORMAL INCIDENCE)..	.70	
4	FRPRIME-UL PRODUCT............................	17.00	KJ/HR-C-M2
5	NUMBER OF TRANSPARENT COVERS..................	2.00	
6	COLLECTOR SLOPE...............................	43.00	DEGREES
7	AZIMUTH ANGLE (E.G. SOUTH=0, WEST=90).........	.00	DEGREES
8	STORAGE CAPACITY..............................	315.00	KJ/C-M2
9	EFFECTIVE BUILDING UA.........................	1000.00	KJ/HR-C
10	CONSTANT DAILY BLDG HEAT GENERATION...........	.00	KJ/DAY
11	HOT WATER USAGE...............................	300.00	L/DAY
12	WATER SET TEMPERATURE.........................	60.00	C
13	WATER MAIN TEMPERATURE........................	11.00	C
14	CITY CALL NUMBER..............................	62.00	
15	THERMAL PRINT OUT BY MONTH=1, BY YEAR=2......	1.00	
16	ECONOMIC ANALYSIS ? YES=1, NO=2...............	1.00	
17	USE OPTMZD. COLLECTOR AREA=1, SPECFD. AREA=2.	1.00	
18	PERIOD OF THE ECONOMIC ANALYSIS..............	20.00	YEARS
19	COLLECTOR AREA DEPENDENT SYSTEM COSTS........	100.00	$/M2 COLL.
20	CONSTANT SOLAR COSTS.........................	1000.00	$
21	DOWN PAYMENT(% OF ORIGINAL INVESTMENT).......	10.00	%
22	ANNUAL INTEREST RATE ON MORTGAGE.............	8.00	%
23	TERM OF MORTGAGE.............................	20.00	YEARS
24	ANNUAL NOMINAL(MARKET) DISCOUNT RATE.........	8.00	%
25	EXPENSES(INSUR.,MAINT.) OF SYSTEM IN 1ST YEAR	25.00	$
26	ANNUAL % INCREASE IN ABOVE EXPENSES..........	6.00	%
27	PRESENT COST OF AUXILIARY FUEL (CF)..........	6.00	$/GJ
28	CF RISE: LINEAR=1,%/YR=2,SEQ. OF VALUES=3....	2.00	
29	IF 1, WHAT IS THE SLOPE OF CF INCREASE?......	.00	$/GJ-YR
30	IF 2, WHAT IS THE ANNUAL RATE OF CF RISE.....	10.00	%
31	ECONOMIC PRINT OUT BY YEAR=1, CUMULATIVE=2...	1.00	
32	EFFECTIVE FEDERAL-STATE INCOME TAX RATE......	25.00	%
33	TRUE PROP. TAX RATE PER $ OF ORGINAL INVEST..	2.00	%
34	INCOME PRODUCING BUILDING? YES=1,NO=2........	2.00	

TYPE IN CODE NUMBER AND NEW VALUE

MADISON WI 43.08

****ECONOMIC ANALYSIS****

OPTIMIZED COLLECTOR AREA = 47. M2

INITIAL COST OF SOLAR SYSTEM($)= 5652.

YR	MORT PAYMT	INTRST PAID	DEPRC DEDUCT	PRP.TX PAID	INC.TX SAVED	FUEL EXPNSE	MISC EXPNSE	TOTAL COST	SOLAR SAVNGS
1	518.	407.	0.	113.	130.	352.	25.	878.	-114.
2	518.	398.	0.	113.	128.	387.	26.	917.	-77.
3	518.	388.	0.	113.	125.	426.	28.	960.	-35.
4	518.	378.	0.	113.	123.	468.	30.	1006.	10.
5	518.	367.	0.	113.	120.	515.	32.	1058.	61.
6	518.	355.	0.	113.	117.	567.	33.	1114.	116.
7	518.	342.	0.	113.	114.	623.	35.	1176.	177.
8	518.	328.	0.	113.	110.	686.	38.	1244.	245.
9	518.	312.	0.	113.	106.	754.	40.	1319.	319.
10	518.	296.	0.	113.	102.	829.	42.	1401.	401.
11	518.	278.	0.	113.	98.	912.	45.	1491.	491.
12	518.	259.	0.	113.	93.	1004.	47.	1589.	590.
13	518.	238.	0.	113.	88.	1104.	50.	1698.	700.
14	518.	216.	0.	113.	82.	1214.	53.	1817.	821.
15	518.	192.	0.	113.	76.	1336.	57.	1947.	954.
16	518.	165.	0.	113.	70.	1470.	60.	2091.	1100.
17	518.	137.	0.	113.	63.	1616.	64.	2249.	1262.
18	518.	107.	0.	113.	55.	1778.	67.	2422.	1440.
19	518.	74.	0.	113.	47.	1956.	71.	2612.	1636.
20	518.	38.	0.	113.	38.	2152.	76.	2820.	1852.

PRESENT WORTH OF YEARLY TOTAL COSTS WITH SOLAR($)= 13916.

PRESENT WORTH OF YEARLY TOTAL COSTS W/O SOLAR($) = 16935.

****THERMAL ANALYSIS****

TIME	PERCENT SOLAR	INCIDENT SOLAR (GJ)	HEATING LOAD (GJ)	WATER LOAD (GJ)	DEGREE DAYS (C-DAY)	AMBIENT TEMP (C)
JAN	30.8	17.81	19.64	1.91	818.	-8.
FEB	39.6	18.88	16.99	1.72	708.	-6.
MAR	60.3	25.93	14.84	1.91	618.	-0.
APR	77.7	23.83	8.24	1.85	343.	7.
MAY	99.2	25.83	4.13	1.91	172.	13.
JUN	100.0	27.38	1.36	1.85	57.	19.
JUL	100.0	29.27	.33	1.91	14.	21.
AUG	100.0	27.92	.53	1.91	22.	20.
SEP	100.0	27.18	2.32	1.85	97.	15.
OCT	88.0	24.29	6.32	1.91	263.	10.
NOV	37.7	15.42	12.40	1.85	517.	1.
DEC	30.7	16.65	17.73	1.91	739.	-5.
YR	53.9	280.38	104.84	22.48	4368.	

TYPE IN CODE NUMBER AND NEW VALUE

STOP

GOOD-BYE

JOHN A. DUFFIE
Professor
Chemical Engineering Department
College of Engineering
The University of Wisconsin
Madison, Wisconsin 53706

Birth Date: March 31, 1925 U.S. Citizen

Married, 3 children

Education:

Rensselaer Polytechnic Institute	B. Ch.E.	1945
Rensselaer Polytechnic Institute	M. Ch.E.	1948
University of Wisconsin	Ph.D. (ChE)	1951

Professional Experience:

1946-49	Instructor in Chemical Engineering, Rensselaer Polytechnic Institute
1949-51	Research Assistant and Research Fellow (Proctor & Gamble), Chemical Engr., University of Wisconsin
1951	Research Engineer, Electrochemicals Department of Du Pont Company, Niagara Falls, New York
1952-53	Scientific Liaison Office, U.S. Navy Office of Naval Research, Chicago, Ill.
1954-to date	College of Engineering, University of Wisconsin Project Associate, 1954-57 Assistant Professor of Engineering, 1957-58 Associate Professor of Engineering, 1958-62 Professor, 1962-to date Director, Solar Energy Laboratory, 1956-to date Assistant Director, Engr. Exp. Station, 1957-65 Director, University-Industry Research Program, 1965-72 Associate Dean, Graduate School, 1965-present
1964	Fulbright Research Scholar and Guggenheim Fellow at the Mechanical Engineering Dept., University of Queensland, Australia, and at the Mech. Engr. Div. of Commonwealth Scientific & Industrial Research Organization, Australia

Member of: American Institute of Chemical Engineers
International Solar Energy Society, Past President
American Society for Engineering Education
American Association for the Advancement of Science
NSF/NASA Solar Energy Panel (1972)

Books:

Daniels, F. and Duffie, J.A. (Eds. and contributing authors), Solar Energy Research, University of Wisconsin Press, Madison (1955).

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54. Beckman, W.A. and J.A. Duffie, "Calculation of Flat Plate Collector Performance, paper presented at ERDA Workshop on Solar Energy in Cold Climates, University of Detroit, (1976).

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Books:

1. Duffie, J.A., and Beckman, W.A., Solar Energy Thermal Processes, published by John Wiley and Sons, October 1974.

Publications:

1. "A Photographic Study of Boiling in an Accelerating System," Journal of Heat Transfer, American Society of Mechanical Engineers, Series C, vol. 87, pp. 374-380, 1965 (with Herman Merte, Jr.).

2. "Design Considerations for a High Solar Flux Photovoltaic Power System," Solar Energy Journal, vol. 10, no. 3, pp. 132-136, July-September 1966 (with Schoffer, Hartman and Löf).

3. "An Experimental High Solar Flux Photovoltaic Power System," Proceedings of the 20th Annual Power Sources Conference, October 1966 (with Schoffer).

4. "Optimization of Contact Grid Spacing for High Solar Flux Photovoltaic Cells," ASME Journal of Engineering for Power, Series A, vol. 89, pp. 415-518, July 1967.

5. "Evaluation of a Distributed Model of a Photovoltaic Cell," Proceedings of the 6th Annual Photovoltaic Specialists Conference, April 1967 (with Schoffer).

6. "Radiation and Convection Heat Transfer in a Porous Bed," ASME Journal of Engineering for Power, Series A, vol. 90, pp. 51-54, January 1968.

7. "Temperature Uncertainties in Systems with Combined Radiation and Conduction Heat Transfer," Proceedings of the 1968 ASME Aerospace Conference, March 1968.

8. "Theoretical Performance of an Ammonia-Sodium Thiocyanate Intermittent Absorption Refrigeration Cycle," Solar Energy Journal, vol. 12, pp. 137-146, 1968 (with S.L. Sargent).

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10. "Transpiration Cooling of Radiatively Heated Porous Beds," ASME Paper 69-WA/Sol-6, 1969 (with Y.H. Hamid).

11. "Determination of the Thermal Conductivity of Protective Coatings on Long Cylinders of Finite Diameters, Part II," Journal of Paint Technology, 42, pp. 189-192, 1970 (with J.W. Mitchell).

12. "Transient Response of Fin-Tube Space Radiations," ASME Journal of Heat Transfer, Series C, vol. 92, pp. 196-198, 1970 (with Palmquist and Moriarty).

13. "Solution of Heat Transfer Problems on a Digital Computer," Solar Energy Journal, vol. 13, pp. 293-300, 1971.

14. "Performance of Air-Cooled, Radiatively-Heated Screen Matrices," ASME Journal of Engineering for Power, Series A, vol. 93, no. 2, pp. 221-224, 1971 (with Y.H. Hamid).

15. "An Exponential Model for Real Gas Spectral Transmissivity," Environmental and Geophysical Heat Transfer, ASME HTD-vol. 4, 1971 (with S.L. Sargent).

16. "Optimum Thermal Design of Radiative-Conductive Systems," ASME Journal of Engineering for Industry, Series B, vol. 94, no. 2, pp. 373-380, 1972 (with R.W. Palmquist).

17. "HEAT - a Heat Transfer Computer Program Written in FORTRAN V Language," The University of Wisconsin Engineering Experiment Station Report #37, 1972.

18. "A Numerical Model of Thermal Radiation in a Dusty Atmosphere," Journal of the Atmospheric Sciences, vol. 30, pp. 88-94, January 1973 (with S.L. Sargent).

19. "Thermal Model for Prediction of a Desert Iquana's Daily and Seasonal Behavior," ASME Journal of Heat Transfer, Series C, vol. 95, no. 2, pp. 257-262, 1973 (with J.W. Mitchell and W.P. Porter).

20. "Behavioral Implications of Mechanistic Ecology," Oecologia 13, 1-54 (1973), (with W.P. Porter, J.W. Mitchell and C.B. DeWitt).

21. "Simulation of Forced Circulation Water Heaters; Effect of Auxiliary Energy Supply, Load Type and Storage Capacity," Solar Energy, 15, pp. 287-298, (1974).

22. "Conduction and Radiation in Artificial Fur," published in Perspectives of Biophysical Ecology, D.M. Gates and R.B. Schmerl, eds., Springer-Verlag, New York, 549 (1975), (with D. Skuldt, J.W. Mitchell and W.P. Porter).

23. "Convective Heat Transfer from a Desert Surface," Trans. ASME, Series C, 97, 1, 104 (1975), (with S.A. Klein and J.W. Mitchell).

24. "Transient Considerations of Flat-Plate Solar Collectors," Trans. ASME, J. Engr Power, 96, Series A (1974), (with S.A. Klein and J.A. Duffie).

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27. "Microclimate Modeling of the Desert," presented at 1974 Int'l. Seminar on Heat and Mass Transfer in the Environment of Vegetation, published in Heat and Mass Transfer in Biospheric, Part 1, Trans. Proc. in Plant Environment, D.A. Devries and N.H. Afgan, eds., Scripta Book Co., Washington, D.C., 275 (with J.W. Mitchell, R.T. Bailey and W.P. Porter).

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29. "Modeling of the CSU Heating/Cooling System," Solar Energy, 17, 21 (1975), (with R.L. Oonk and J.A. Duffie).

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31. "Comparison of Simulated and Measured Performance of the CSU Solar House I Heating System," presented at the 1975 ISES meeting, Los Angeles (with R.L. Oonk and J.A. Duffie).

32. "Simulation of Solar Heating Systems," to be published as Chapter 9 in ASHRAE Temperature Engineering Applications to Solar Energy (1975), (with J.A. Duffie and S.A. Klein).

33. "Solar Heating and Cooling," Science, 191, (January 16, 1976), (with J.A. Duffie).

34. "Computer Modeling of Heat Pumps and the Simulation of Solar-Heat Pump Systems," ASME, 75-WA/Sol 3, (1976), (with T.F. Freeman, J.W. Mitchell and J.A. Duffie).

35. "TRNSYS - A Transient Simulation Program," to be published in ASHRAE Transactions, (1976) (with S.A. Klein and J.A. Duffie).

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38. "A Parametric Study of Critical Fuel Costs for Solar Heating in North America," to be presented at the ISES American Section Meeting, Winnipeg, Canada, (1976) (with J.A. Duffie and M.J. Brandemuehl).

39. "Simulation Study of Several Solar Heating Systems With Off Peak Auxiliary," to be presented at the ISES American Section Meeting, Winnipeg, Canada, (1976) (with P.J. Hughes and J.A. Duffie).

40. "A Design Procedure for Solar Air Heating Systems," to be presented at the ISES American Section Meeting, Winnipeg, Canada, (1976) (with S.A. Klein and J.A. Duffie).

41. "A Review of Solar Cooling," to be presented at the ISES American Section Meeting, Winnipeg, Canada, (1976) (with J.A. Duffie).

42. "Estimation of Optimum Solar System Performance in Northern Climates," paper presented at ERDA Workshop on Solar Energy in Cold Climates," University of Detroit, (1976).

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1956-62	Research Assistant, Stanford University
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1955-56	Ames Research Center, Moffett Field, California
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Industrial Press Achievement Award, 1956
NASA-ASEE Faculty Fellowship, Summer 1964, 1967
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Publications

1. "The Transient Response of Gas-Turbine Plant Heat Exchangers-Regenerators, Intercoolers, Precoolers, and Ducting," Trans. ASME, Series A, 81: 433-448, (A. L. London, F. R. Biancardi, J. W. Mitchell), 1959.

2. "Heat-Transfer and Flow-Friction Characteristics of Crossed Rod Matrices," Trans. ASME, Series C, 82: 192-213, (A. L. London, J. W. Mitchell, W. A. Sutherland), 1960.

3. "A Method of Estimating Cross-Flow Heat Exchanger Transients," ASHRAE Transactions, 71: 225-231, (G. E. Myers, J. W. Mitchell, R. Nagaoka), 1965.

4. "Heat Transfer from a Shrouded Rotating Disk to a Single Fuild Stream," Trans. ASME, Series C, 87: 485-492, (J. W. Mitchell and D. E. Metzger), 1965.

5. "Heat Transfer from a Shrouded Disk with Film Cooling," Journal of Heat Transfer, Trans. ASME, Series C, 88: 140-146, (D.E. Metzger and J.W. Mitchell), 1966.

6. "Thermocouple Corrections from Irreversibility Theory," American Journal of Physics, 34: 549-555, (R.A. Gaggioli and J.W. Mitchell), 1966.

7. "Perivascular Cooling of Blood Flow in Arteries and Veins," Proceedings of 19th Annual Conference on Engineering in Medicine and Biology, (R.S. Muka, J.W. Mitchell and G.E. Myers), November 1966.

8. "The Transient Response of Cross-Flow Heat Exchangers, Evaporators, and Condensers," Trans. ASME, Series C, 89: 75-80, (G.E. Myers, J.W. Mitchell, R.F. Norman), 1967.

9. "Measurement of Drilling Temperature by the Garter Spring Thermocouple Method," Microtecnic, 6, (M.F. DeVries, S.M. Wu, J.W. Mitchell), 1967.

10. "An Analytical Model of Counter-Current Heat Exchange Phenomena," Biophysical Journal, 8: 897-911, (J.W. Mitchell, G.E. Myers), 1968.

11. "A Technique for the Evaluation of the Thermal Conductivity of Coating Materials," Proceedings of the 8th Conference on Thermal Conductivity, 887-894, (with W.A. Beckman), 1969.

12. "An Expression for Internal Flow Heat Transfer for Polynomial Wall Temperature Distributions," Technical Brief, Trans. ASME, Series C, 91: 175-177, 1969.

13. "Homework Experiments in a Heat Transfer Course," Journal of Engineering Education, 60: 925-926, (J.W. Mitchell), 1970.

14. "Determination of the Thermal Properties of a Siltstone Rock," Twelfth Symposium on Rock Mechanics, University of Missouri, Rolla, Mo., (C. C. Hanninen, L. D. Clark, and J.W. Mitchell), 1970.

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17. "An Experimental and Analytical Investigation of an Internal Cooling Technique," J. of Appl. Physiol., 28: 695-699, (J.W. Mitchell, G.E. Myers, W. Hutchinson, M. Javid), 1970.

18. "Thermal Response of Human Legs During Cooling," J. of Applied Physiol., 29: 859-865, (J.W. Mitchell, T.L. Galvez, J. Hengle, G.E. Myers, K.L. Siebecker), 1970.

19. "Systems Studies of DDT Transports," Science, 170: 503-508, (H.L. Harrison, O.L. Loucks, J.W. Mitchell, D.F. Parkhurst, C.R. Tracy, D.G. Watts, V.J. Yanneconne, Jr.), 1970.

20. "Base Heat Transfer in Two-Dimensional Subsonic Fully Separated Flows," Trans. ASME, Series C, 93: 342-347, 1971.

21. "Cooling Boot for Refrigeration Anesthesia," Anesthesia and Analgesia, 50: 569-570, (T.L. Galvez, J.W. Mitchell, G.E. Myers, K.L. Siebecker), 1971.

22. "The Rabbit Ear as a Temperature Sensor," Life Sciences, 10: 895-899, (M.J. Kluger, R.R. Gonzalez, J.W. Mitchell, J.D. Hardy), 1971.

23. "Peripheral Modifications to the Central Drive for Sweating," J. of Appl. Physiol., 31: 828-833, (E.R. Nadel, J.W. Mitchell, B. Saltin, J.A.J. Stolwijk), 1971.

24. "Theoretical and Experimental Studies of Energy Exchange from Jack Rabbit Ears and Cylindrically Shaped Appendages," Biophysical Journal, 11: 1030-1047, (P. Wathen, J.W. Mitchell, W.P. Porter), 1971.

25. "Thermal Sensitivity Coefficients of Different Skin Areas," Proceedings of Int'l. Union of Physiol. Sci., IX, XXV International Conference, Munich, (J.W. Mitchell, E.R. Nadel, J.A.J. Stolwijk), 1971.

26. "Control of Local and Total Sweating During Exercise Transients," Int. J. Biometeor, 15: 201-206, (E.R. Nadel, J.W. Mitchell, J.A.J. Stolwijk), 1971.

27. "Modification of the Central Sweating Drive at the Periphery," Int. J. Biometeor, 15: 268-272, (J.A.J. Stolwijk, E.R. Nadel, J.W. Mitchell, B. Saltin), 1971.

28. "Local and Total Sweating During Exercise Transients," Proceedings of Int'l. Union of Physiol. Sci., IX, XXV International Conference, Munich, (E.R. Nadel, J.W. Mitchell, J.A.J. Stolwijk), 1971.

29. "Respiratory Weight Losses During Exercise," Journal of Applied-Physiology, 32: 474-476, (J.W. Mitchell, E.R. Nadel, J.A.J. Stolwijk), 1972.

30. "Model Simulation of Blood Flow and Oxygen Uptake During Exercise," Biophysical Journal, 12: 1452-1466, (J.W. Mitchell, J.A.J. Stolwijk, E.R. Nadel), 1972.

31. "Thermal Model for Prediction of a Desert Iguana's Daily and Seasonal Behavior," Trans. ASME, Series C, 95: 257-262, (W.A. Beckman, J.W. Mitchell, W.P. Porter), 1973.

32. "Differential Thermal Sensitivity in the Human Skin," Pflugers Arch, 340: 71-76, (E.R. Nadel, J.W. Mitchell, J.A.J. Stolwijk), 1973.

33. "Behavioral Implications of Mechanistic Ecology," Oecclogia, 13: 1-54, (W.P. Porter, J.W. Mitchell, W.A. Beckman, C.B. DeWitt), 1973.

34. "Blood Flow and Oxygen Uptake During Exercise," Trans. ASME, Series G, 95 (3): 274-278; (also in Regulation and Control in Physiological Systems, A.S. Iberall & H.C. Guyton, pp. 383-387), (J.W. Mitchell, J.A.J. Stolwijk, E.R. Nadel), 1973.

35. "Heat Transfer from Animal Appendage Shapes - Cylinders, Arcs, and Cones," Trans. ASME, Series C, 96: 536-540, (P.M. Wathen, J.W. Mitchell, W.P. Porter), 1974.

36. "An Experimental Method for Determining Convective Heat Transfer from a Desert Surface," Trans. ASME, Series C, 97: 104-109, (R.T. Bailey, J.W. Mitchell, W.A. Beckman), 1975.

37. "Central and Peripheral Components of the Metabolic Response to Cold in the Hairless Gerbil," J. of Appl. Physiol., 37: 712-71' (M.F. Roberts, W.P. Porter, J.W. Mitchell), 1974.

38. "Microclimatic Modeling of the Desert" in "Heat and Mass Transfer in the Biosphere, Part I, Transfer Processes in the Plant Environment," D.A. deVries and N.H. Afgan, ed., Scripta Book Co., Washington, D.C., (J.W. Mitchell, W.A. Beckman, R.T. Bailey, and W.P. Porter), 275-286, 1975.

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41. The Wisconsin Regional Energy Model," Proceeding of the SIMS Research Application Conference on Energy, Alta, Colorado, (W.K. Foell, J.W. Mitchell, J. L. Pappas), 1975.

42. Lecture Notes in Economics and Mathematical Systems, M. Beckman and H.P. Kungi, eds., Springer-Verlag, Berlin, 1975.

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44. "Heat Transfer from Spheres in the Natural Turbulent Outdoor Environment," ASME Paper 75-WA/HT-57, (G. Kowalski J.W. Mitchell), November 1975. To be published in J. of Heat Transfer.

45. "Heat Transfer from Spheres and Other Animal Forms," Biophysical J. 16: 561-569, (J.W. Mitchell), 1976

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1. "Simple Deaminations. Preparation and Some Properties of N-Alkyl-N, N-disulfonimides," Organic Chemistry, 39, p. 3525-3532, (1974)(with P.J. DeChristopher, J.P. Adamek, G.D. Lyon, and R.J. Baumgarten).

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5. "TRNSYS - A Transient Simulation Program," to be published in ASHRAE Transactions (with W.A. Beckman and J.A. Duffie).

6. "Simulation of Solar Heating Systems," to be published as Chap. 9 in the ASHRAE book, Applications of Solar Energy for Heating and Cooling a Building (1976)(with W.A. Beckman and J.A. Duffie).

7. "A Design Procedure for Solar Heating Systems," accepted for publication in Solar Energy Journal (1975)(with W.A. Beckman and J.A. Duffie).

8. "Experimental and Simulated Performance of a Closed Loop Solar Water Heating System," presented at the I.S.E.S. Meeting (1975) and to be submitted to Solar Energy Journal (1975)(with P.I. Cooper and C.W.S. Dixon).

9. "Packed Bed Thermal Storage Models for Solar Air Heating and Cooling Systems," to be submitted to ASME Journal of Heat Transfer (1975) (with P.J. Hughes and D.J. Close).

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4. "Simulation Study of Solar-Heat Pump Systems," to be presented at the ISES Meeting, Winnipeg, Canada, August 15-20, 1976 (with V.D Karman and J.W. Mitchell).

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15. Supplementary Notes

16. Abstracts

The overall objective of this work is to develop simulation techniques useful in the thermal evaluation of particular solar heating and cooling systems and apply these results to economic evaluations. During this reporting period major emphasis have been on: extension of the general solar process simulation program TRNSYS, by addition of new components to the TRNSYS library; application of TRNSYS to several heating/cooling systems; and development of simplified design procedures for standard types of solar heating systems.

TRNSYS has been shipped to approximately 125 outside agencies for their use in simulating solar processes.

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