ORNL/Sub/80-7800/1

MODELS OF SIMULTANEOUS HEAT AND MOISTURE TRANSFER IN SOILS

Prepared by

Robert D. Fischer

August 1982

BATTELLE COLUMBUS LABORATORIES
505 King Avenue
Columbus, Ohio 43201

Date Published: October 1983

Prepared under Subcontract 7800-19X06

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830

Operated by

UNION CARBIDE CORPORATION

for the

UNITED STATES DEPARTMENT OF ENERGY

Contract No. W-7405-eng-26

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MODELS OF SIMULTANEOUS HEAT AND MOISTURE TRANSFER IN SOILS

ABSTRACT

Moisture migration in soils due to thermal effects is a phenomenon of interest to designers of ground-coupled heat-pump systems because of the concern about moisture migration away from buried pipes during cooling operation. Such moisture migration should have deleterious effects on heat transfer capabilities of the soil and, consequently, overall performance of the ground-coupled heat-pump system.

A number of models for simultaneous heat and moisture transfer in soils have been identified; but, these models all have their origins in disciplines other than ground-coupled heat pumps. This report presents an evaluation of these models for application in modeling the performance of ground coupling during cooling operation.

Two models are identified which may hold promise for modeling heat and moisture transfer in soils adjacent to horizontal ground coils of a ground-coupled heat pump during cooling operation. Recommendations are given as to the data and development that may be needed to bring these models to operational status for this particular application.

TABLE OF CONTENTS

Page

INTRODUCTION. 1

MODELS. 2

DISCUSSION. 4

SOIL PROPERTIES 6

CONCLUSIONS AND RECOMMENDATIONS 7

BIBLIOGRAPHY. 8

APPENDIX

Summary of Information on Models for Heat and Moisture Transfer in Soils. A-1

LIST OF TABLES

Table 1. Chronological List of Major Documents on Simultaneous Heat and Moisture Transfer in Soils 3

SUMMARY REPORT

on

MODELS OF SIMULTANEOUS HEAT AND MOISTURE TRANSFER IN SOILS

to

OAK RIDGE NATIONAL LABORATORY
CONSERVATION TECHNOLOGY
OAK RIDGE, TENNESSEE

from

BATTELLE
Columbus Laboratories

by

Robert D. Fischer

August 9, 1982

INTRODUCTION

Moisture migration in soils due to thermal effects is a phenomenon of interest to a number of disciplines. Designers of ground-coupled heat pump systems are concerned about the moisture migration away from buried pipes during cooling operation. Solar engineers are concerned about the effect of moisture migration on heat losses from buried thermal energy storage. Agricultural engineers are concerned about moisture migration in assessment of soil warming, irrigation practices, and plant growth studies; civil engineers are concerned about moisture migration in evaluation of pavement systems; and electrical engineers are concerned about moisture migration away from buried electrical transmission cables. Due to differences in modeling goals and relative isolation of respective literature for each discipline, there has been little adaptation of modeling capability from one discipline to another.

In the program "State-of-the-Art Survey of Existing Knowledge for the Design of Ground-Source Heat Pumps" conducted by Battelle, no models for simultaneous heat and moisture transfer in soils were located in the U.S. and European literature on ground-coupled heat pumps. However, near the end of that program a number of such models were located in literature from the other disciplines. This report presents an evaluation of these models for application in modeling the performance of ground coupling during cooling operation.

MODELS

Table 1 provides a list of major documents on simultaneous heat and moisture transfer in soils in chronological order. It is evident that a large number of educational institutions have been involved in this work over the years. The challenging nature of such analyses is indicated by the fact that most authors used their work as a thesis program for a Ph.D. degree. Most of the work was conducted in the 1970s and was based on theory developed by Philip and de Vries or Taylor and Cary in the late 1950s and early 1960s.

Fourteen computer models have been identified from these documents. Information on the computer program, basis of theory, solution technique, modeling features, validation, and soil properties are provided in the appendix for each model at the page numbers indicated in Table 1. Most of the earlier models were one-dimensional in the depth coordinate, but later models were two-dimensional in the horizontal and depth coordinates as required for application to ground-coupled cooling operation. Two models are one-dimensional in the radial coordinate, which can also be applied to ground-coupled operation with approximations for surface influences. Most models were developed for transient analysis, but three steady-state models were identified. One model was developed for performance evaluation of buried thermal energy storage for solar systems. Five models were developed to optimize the utilization of waste heat from utility power plants for warming the soil to improve crop production. Three models were developed for study of plant growth and optimization of irrigation strategies. Three models were developed to enhance the science of soil physics. One model was developed to study moisture flow and frost action in highway pavement systems. One model was developed to study moisture migration away from buried electrical transmission cables.

TABLE 1. CHRONOLOGICAL LIST OF MAJOR DOCUMENTS ON SIMULTANEOUS HEAT AND MOISTURE TRANSFER IN SOILS

Author	Thesis	Affiliation (at time of work)	Year	Number of Dimensions	Steady State or Transient	Application	Reference Number	Appendix Page Number
Walker	--	Colorado State Univ.	1981	2	Transient	Thermal storage	1	A-1
Ahmed	Ph.D.	Ohio State Univ.-Wooster	1980	2	Transient	Soil warming	6	A-2
Sophocleous	Ph.D.	Univ. of Alberta	1978	1 (depth)	Transient	Soil physics	7	A-3
Jury and Letey	--	Univ. of California-Riverside	1978	2	Transient	Soil physics (compares theories--Philip and de Vries vs. Taylor and Cary)	35	--
Hartley	Ph.D.	Georgia Tech	1977	1 (radial)	Transient	Buried electrical cable	10	A-4
Johnson	M.S.	Ohio State Univ.	1976	2	Steady State	Soil warming	14	A-5
Bondurant	M.S.	Univ. of Arkansas	1975	1 (radial)	Steady State (theory for Transient)	Soil warming (similar to work reported by Havens)	16	A-6
Shapiro	Ph.D.	Ohio State Univ.	1975	2	Steady State (theory for Transient)	Soil warming	19	A-7
Slegel	Ph.D.	Oregon State Univ.	1975	2	Transient	Soil warming and sub-surface irrigation	23	A-8
Schroeder	Ph.D.	Texas A&M	1974	2	Transient	Plant growth and irrigation	25	A-9
Havens, et al	--	Univ. of Arkansas	1974	1 (radial)	Steady state (theory for Transient)	Soil warming	36	--
Jury	Ph.D.	Univ. of Wisconsin	1973	1 (depth)	Transient	Plant growth and surface evaporation	29	A-11
Hauk	Ph.D.	Cornell Univ.	1971	1 (depth)	Transient	Plant growth and irrigation	28	A-12
Cassel	--	Univ. of California-Davis	1969	1 (depth)	Transient	Soil physics	30	A-13
Dempsey	Ph.D.	Univ. of Illinois	1969	1 (depth)	Transient	Highway pavement systems	31	A-14
Gee	Ph.D.	Washington State Univ.	1966	1 (depth)	Transient	Soil physics	18	A-15
Taylor and Cary	--	Utah State Univ. and Univ. of California-Davis	1964	2	Transient	Basic theory (based on irreversible thermo-dynamics)	17	--
de Vries	--	CSIRO (Australia)	1958	2	Transient	Basic theory (uses four moisture-dependent diffusivities--includes effect of gravity)	3	--
Philip and de Vries	--	CSIRO (Australia)	1957	2	Transient	Basic theory (uses four moisture-dependent diffusivities)	2	--

DISCUSSION

From study of the documents on heat and moisture models and listings of the programs, it appears that a number of good programs are available for modeling heat and moisture transfer in soils. There seems to have been considerable duplication of effort in program development; however, the equations are challenging to solve. Most authors rewrote the basic theory in finite difference form for numerical solution. Approaches for converging to a solution with minimum computing time were about as varied as the number of authors.

The theoretical basis of most programs is the Philip and de Vries[2,3] theory developed in 1957 and 1958 in Australia. Comparisons of the two basic theories by Cassel[30] and Jury[35] using measurements from one-dimensional transient experiments showed superior accuracy with the Philip and de Vries theory.

Little detail in close proximity to the pipe is provided by these models because heat and/or moisture flow from the pipe is modeled by specifying the temperature and moisture content at the pipe node.

General comments on various models and modeling features will now be given to substantiate our selection of the Slegel and Schroeder models for analysis of the performance of ground coupling during cooling operation. The Walker model[1] has extensive capabilities, but needs improved accuracy in predicting values of moisture content. This model is the only one using a finite element solution approach which is more sophisticated mathematically and less understandable to engineers than a finite difference approach.

The Ahmed model[6] is soundly developed for a specific experimental apparatus and would require modification.

The Sophocleous one-dimensional model[7] appears to be soundly developed and could be extended to two dimensions with moderate effort.* It may provide superior modeling capability for layered soils and soil regions with the water table located near the surface at a depth influenced by surface effects.

---

* Comfirmed by phone with the author.

The Hartley model[10] is soundly developed in the thesis and appears to be capable of predicting the onset of a "runaway" condition for formation of a dry core about the cable. Surface effects can only be crudely approximated in this model. The thesis contains an excellent discussion of correlations for soil properties, property data, and correlation equations for two soils.

The Johnson model[14] is a simple, validated steady-state model for soil temperatures in a two-dimensional region between two pipes and the surface using constant soil properties.

The Bondurant model[16] is similar to but less elegant than the Hartley model.

The Shapiro thesis and related documents[19-22] provide an excellent discussion of the theory based on volume-averaged soil properties. He describes a means for experimental determination of the moisture diffusivity coefficients required in the Philip and de Vries model.

The Slegel[23] and Schroeder[25] models utilize a finite difference approach for solution of the governing equations. Both models utilize rectangular nodes in the subsurface region between pipes. In addition, the Schroeder model utilizes triangular nodes at surface nodes to accommodate sloping and mounded surface topography as well as a flat surface. Sources and sinks of heat and moisture at piping nodes can be modeled by specifying the temperature and moisture content at piping nodes. Both models can accommodate layered soils and the influence of the water table. Surface temperatures and moisture flows in both models are computed from weather data. The Schroeder model is very large ($\sim$ 4000 statements) and the computing time may be high. It contains sophisticated computational devices to minimize computing time and assure convergence, such as automatic calculation of maximum timestep permitted and automatic increase in nodes in regions of high gradients. The Schroeder model accounts for gravity effects on moisture flow. The relatively large timestep of 24 hours used in examples with the Slegel model indicates that very small timesteps are not needed for stability--probably because an implicit method of iteraction is used for solution of the finite-difference equations.

The Jury[29], Hauk[28], Cassel[30], Dempsey[31], and Gee[18] models are all one-dimensional in the depth coordinate and so are not directly useful in ground-coupling modeling. The Dempsey model is judged to have superior treatment of the effect of weather data on surface temperatures and moisture flows.

SOIL PROPERTIES

Tabular data and correlations of soil properties were provided for selected soils by a few authors as indicated in the appendix. In considering the wide variation in soil types, it is evident that relatively little data are available at present for use in heat and moisture models. In the course of this program, a number of individuals listed below were identified that are believed to be currently active in measurement of soil properties and are familiar with heat and moisture modeling.

B. J. Dempsey
Department of Civil Engineering
University of Illinois
Urbana, IL 61801

M. Sophocleous
Kansas Geological Survey
University of Kansas
Lawrence, KS 66044

H. N. Shapiro
Department of Mechanical Engineering
Engineering Research Institute
Iowa State University
Ames, IA 50010

W. Z. Black, Professor
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332

J. W. Cary
Soil Scientist
Snake River Conservation Research Center
Kimberly, ID 83341

W. A. Jury
Associate Prof. of Soil Physics
Department of Soil and Environmental Sciences
University of California
Riverside, CA 92521

CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations from this program are given below.

(1) Two fairly comprehensive computer programs are available for modeling heat and moisture transfer in soils adjacent to horizontal ground coils of a ground-coupled heat pump during cooling operation. These programs are the Slegel and Schroeder models.

(2) Effort to bring these programs to operational status, prepare appropriate input data, and conduct parametric performance runs appears to be reasonable. Computing time for these runs may be substantial.

(3) Property data on some soils are available, but the quantity of data appears to be inadequate for any geographic performance characterization. Since soil-property measurements require specialized instrumentation, we recommend that the people listed as currently active in this work be given the opportunity to interact in some way with planning and execution of soil-property measurement.

BIBLIOGRAPHY

1. Walker, W. R., et al, "Studies of Heat Transfer and Water Migration in Soils", Colorado State University Report DOE/CS/30130-T1 (April 1981).

2. Philip, J. R., and de Vries, D. A., "Moisture Movement in Porous Materials Under Temperature Gradients", Trans. American Geophysical Union, 38, pp 222-232 (1957).

3. de Vries, D. A., "Simultaneous Transfer of Heat and Moisture in Porous Media", Trans. American Geophysical Union, 39 (5), pp 909-916 (1958).

4. de Vries, D. A., "The Thermal Conductivity of Granular Materials", Annexe 1952-1 Bulletin, Institute International du Froid, pp 115-131 (1952).

5. de Vries, D. A., Thermal Properties of Soils, Chapter in Physics of the Plant Environment, W. R. Van Wijk, Editor, North Holland Publishing Co., Amsterdam, Netherlands (1963).

6. Ahmed, E. A., "Simulation of Simultaneous Heat and Moisture Transfer in Soils Heated by Buried Pipes", Ph.D. Thesis, Ohio State University, (1980).

7. Sophocleous, M. A., "Analysis of Heat and Water Transport in Unsaturated-Saturated Porous Media", Ph.D. Thesis, University of Alberta (1978).

8. Sophocleous, M., "Analysis of Water and Heat Flow in Unsaturated-Saturated Porous Media", Water Resources Research, 15 (5), pp 1195-1206 (October 1979).

9. Richtmyer, R. D., and Morton, K. W., Difference Methods for Initial Value Problems, Interscience, New York (1967).

10. Hartley, J. G., "An Analysis of the Thermal Stability of the Soil Environment of Underground Electrical Cables", Ph.D. Thesis, Georgia Tech (1977) [77-29213].*

11. Hartley, J. G., and Black, W. Z., "Predicting Thermal Stability and Transient Response of Soils Adjacent to Underground Power Cables", IEEE Paper CH1139-5/79/0000-0316 (1979).

12. Hartley, J. G., Transient Simultaneous Heat and Mass Transfer in Moist, Unsaturated Soils, J. of Heat Transfer, ASME Trans., 103 (2), pp 376-382 (May 1981).

13. Luikov, A. V., "Systems of Differential Equations of Heat and Mass Transfer in Capillary-Porous Bodies (Review), Int. J. Heat Mass Transfer, 18, pp 1-14 (1975).

---

* Number in brackets is the University Microfilm accession number.

14. Johnson, S. E., "Soil Temperature and Moisture Content Measurements for a System of Subsurface Heating Pipes", M.S. Thesis, Ohio State University (1976).

15. Kendrick, J. H., and Havens, J. A., "Heat Transfer Models for a Subsurface Water Pipe, Soil-Warming System", J. of Environmental Quality, 2 (2), pp 186-196 (1973).

16. Bondurant, J. L., "Coupled Heat and Moisture Transfer in Soil with Applications to the Design of a Warmwater Subsurface Irrigation System", M.S. Thesis, University of Arkansas (1975).

17. Taylor, S. A., and Cary, J. W., "Linear Equations for the Simultaneous Flow of Matter and Energy in a Continuous Soil System", Soil Soc. of Amer. Proc., 28, pp 167-172 (1964).

18. Gee, G. W., "Water Movement in Soils as Influenced by Temperature Gradients", Ph.D. Thesis, Washington State University (1966) [66-13560].

19. Shapiro, H. N., "Simultaneous Heat and Mass Transfer in Porous Media with Application to Soil Warming with Power Plant Waste Heat", Ph.D. Thesis, Ohio State University (1975) [76-10044].

20. Shapiro, H. N., and Moran, M. J., "Modeling of a Soil Warming System", Proc. of First Int'l Conf. on Mathematical Modeling, St. Louis, MO, pp 1101-1110 (August 1977).

21. Shapiro, H. N., and Moran, M. J., "Simultaneous Heat and Mass Transfer in Soil with Application to Waste Heat Utilization", Proc. of Sixth Int'l Heat Transfer Conf., Toronto, Canada, 3, pp 19-24 (1978).

22. Shapiro, H. N., and Hsi, M. Y., "Experimental Determination of Transport Coefficients for Soil", Iowa State University Report ISU-ERI-AMES-80061 to National Science Foundation (November 1979).

23. Slegel, D. L., "Transient Heat and Mass Transfer in Soils in the Vicinity of Heated Porous Pipes", Ph.D. Thesis, Oregon State University (1975) [74-29733].

24. Slegel, D. L., and Davis, L. R., "Transient Heat and Mass Transfer in Soils in the Vicinity of Heated Proous Pipes", ASME J. of Heat Transfer, 99, pp 541-546 (1977).

25. Schroeder, C. N., "The Development of an Optimized Computer Simulation Model for Heat and Moisture Transfer in Soils", Ph.D. Thesis, Texas A&M (1974) [75-2891].

26. Schroeder, C. N., "Modeling Heat and Moisture Flow in Soils", Simulation, pp 173-179 (November 1978).

27. Philip, J. R., "The Theory of Infiltration", Soil Science, 83, pp 345-357, (1957).

28. Hauk, R. W., "Soil Temperature and Moisture Fields as Predicted by a System of Coupled Equations", Ph.D. Thesis, Cornell University (1971) [72-8852].

29. Jury, W. A., "Simultaneous Transport of Heat and Moisture Through a Medium Sand", Ph.D. Thesis, University of Wisconsin (1973) [73-27109].

30. Cassel, D. K., et al, "Soil-Water Movement in Response to Imposed Temperature Gradients", Soil Science Soc. Proc., 33, pp 493-500 (1969).

31. Dempsey, B. J., "A Heat-Transfer Model for Evaluating Frost Action and Temperature Related Effects in Multilayered Pavement Systems", Ph.D. Thesis, University of Illinois (1969) [70-13289].

32. Dempsey, B. J., "A Mathematical Model for Predicting Coupled Heat and Moisture Movement in Unsaturated Soil", Int'l J. for Numerical and Analytical Methods in Geomechanics, 2, pp 19-34 (1978).

33. Dempsey, B. J., and Thompson, M. R., "A Heat-Transfer Model for Evaluating Frost Action and Temperature-Related Effects in Multilayered Pavement Systems", Highway Research Record, No. 342, pp 39-56 (1970).

34. Janssen, D. J., and Dempsey, B. J., "Soil Water Properties of Subgrade Soils", University of Illinois, Civil Engineering Report UILU-ENG-80-2010 (April 1980).

Related References

35. Jury, W. A., and Letey, J., "Water Vapor Movement in Soil: Reconciliation of Theory and Experiment", Soil Science Soc. of Amer. J., 43 (5) pp 823-827 (1979).

36. Havens, J. A., and Babcock, K. E., "Heat and Moisture Conduction in Unsaturated Soils", University of Arkansas Report PB-242-328 to Office of Water Research and Technology, Department of Interior (June 1974).

APPENDIX

SUMMARY OF INFORMATION ON MODELS FOR HEAT AND MOISTURE TRANSFER IN SOILS

APPENDIX

SUMMARY OF INFORMATION ON MODELS FOR HEAT AND MOISTURE TRANSFER IN SOILS

This appendix summarizes information on 14 heat and moisture models to supplement general information provided in Table 1. Models are discussed in chronological order for convenience in accordance with the order of listing in Table 1. Information topics include the computer program, basis of theory, solution technique, modeling features, validation, and soil properties.

MODEL NO.	1
AUTHOR	Walker, W. K., et al (Colorado State University)
REPORT TITLE	Studies of Heat and Water Migration in Soils
*REFERENCE NO.**	1
DATE	1981
DIMENSIONS	2 (horizontal and depth)
STEADY STATE OR TRANSIENT	Transient
COMPUTER PROGRAM	FORTRAN (about 2070 source statements). Well documented internally and in report
BASIS OF THEORY	Modified Philip and de Vries[2,3]. Excellent discussion of vapor and liquid diffusivities and other soil parameters required in the model.
SOLUTION TECHNIQUE	Temperature and moisture content are computed for a layered 2-D soil region in either cartesian or cylindrical coordinates by a finite element approach. Coupled partial differential equations are converted to nonlinear first order differential equations by the Galerkin method. A predictor-corrector method by Douglas and Dupont is used that is second-order correct in time. New values of moisture

* References are listed in the bibliography section.

potential are computed from values at the present time-step. Then temperatures are computed and results made to converge by iteration. Timestep is adjusted automatically.

MODELING FEATURES

Model is intended for simulation of trans-seasonal performance of subsurface storage of thermal energy in solar systems. Layered soils can be accommodated by program modification, but only homogeneous soils were modeled in the present program. Moisture and heat transfer equations can be decoupled by a simple change to an input parameter. Fluxes of water and heat, water content, and temperature can be specified for any node. Point sources or sinks of water or heat can be specified. Convective heat flux at boundary nodes are modeled by a convective coefficient or a distributed heat flux.

VALIDATION

Predictions of moisture content in a 1-D test apparatus were poor even though temperatures agreed quite well. Lack of agreement was attributed to use of suction potential fitted as a function of moisture content only, whereas theory was developed for suction potential as a function of both moisture content and temperature. Changes to the program are suggested but not given in detail.

SOIL PROPERTIES

Suction potential and hydraulic conductivity are input in tabular form as a function of moisture content and accessed via spline fits. Report gives excellent details on calculation of specific heat and thermal conductivity of soils by the de Vries[4,5] method as a function of water content, temperature, soil mineralogical composition, and bulk density. Calculated values of soil thermal conductivity for clay, clay-loam, sandy-loam, and loamy-sand soils agreed well with experimental values.

MODEL NO. 2

AUTHOR Ahmed, A. E. (Ohio State University)

Ph.D THESIS TITLE Simulation of Simultaneous Heat and Moisture Transfer in Soils Heated by Buried Pipes

REFERENCE NO. 6

DATE 1980

DIMENSIONS 2 (horizontal and depth)

STEADY STATE OR TRANSIENT Transient

COMPUTER PROGRAM	CSMP (about 550 source statements). Well documented internally and in thesis. Can be converted to FORTRAN but uses an integration routine and function generators within CSMP.
BASIS OF THEORY	Philip and de Vries[2,3]
SOLUTION TECHNIQUE	Finite difference approach uses a parabolic approximation for spatial partial derivatives to reduce equations to ordinary time-base differential equations. Simultaneous differential equations for moisture and temperature at each node are solved by fourth order Runge-Kutta integration with a variable timestep, which is adjusted at each timestep to meet stability and convergence criteria.
MODELING FEATURES	Nodal region has square nodes and is bounded by a vertical plane through a pipe on left and a vertical adiabatic boundary midway between pipes on right. Top boundary conditions at 10 cm depth are set up for direct input of measured values of uniform moisture content at a constant temperature. Pipe temperature is a time-dependent input value. Gravity effects are retained with sandy soil but omitted with silty loam soil. Equations are given for all unique nodes, so other, less specific, nodal geometry could be modeled with appropriate changes to the source code.
VALIDATION	Computed results compared well with analytical results for 2-D transient conduction in a constant-property medium. Computed results compared well with measured steady-state and transient data with sand and silty-loam soils.
SOIL PROPERTIES	Algorithms and data are provided for properties of sand and silty-loam soil.

MODEL NO.	3
AUTHOR	Sophocleous, M. A. (University of Alberta, Edmonton, Canada)
Ph.D. THESIS TITLE	Analysis of Water and Heat Flow in Unsaturated-Saturated Porous Media
REFERENCE NO.	7, 8
DATE	1978
DIMENSIONS	1 (depth)

STEADY STATE OR TRANSIENT	Transient
COMPUTER PROGRAM	FORTRAN
BASIS OF THEORY	Modified Philip and de Vries[2,3]. Author extended use of basic equations to nonhomogeneous and saturated conditions by expressing the equations as a function of the suction potential rather than the moisture content.
SOLUTION TECHNIQUE	Temperature and moisture content are computed by a finite difference approach using the Richtmyer and Morton[9] form of the Crank-Nicholson implicit method. Author stated that extension to 2-D should be feasible.
MODELING FEATURES	The model is intended for simulation of water and heat flow in an unsaturated-saturated soil region. Use of suction potential as the independent variable (rather than moisture content) preserves continuity in passing from unsaturated to saturated conditions or from one soil layer to another. Top boundary conditions consist of time-dependent soil temperature and moisture flux at the surface. Model used two soil layers--one for unsaturated and one for saturated soil.
VALIDATION	Test site was extensively monitored with piezometer, psychrometers (all failed), thermisters, thermal conductivity probes, and tensiometers to measure soil properties required in the analysis. Computed values of temperatures and moisture content agreed well with measured values except for discrepancies attributed to nonhomogeneous clay-loam lenses.
SOIL PROPERTIES	Properties for sandy loam and sandy soil were measured and used in the model.

MODEL NO.	4
AUTHOR	Hartley, J. G. (Georgia Tech)
Ph.D. THESIS TITLE	An Analysis of the Thermal Stability of the Soil Environment of Underground Electrical Cables
REFERENCE NO.	10, 11, 12
DATE	1977
DIMENSIONS	1 (radial)

STEADY STATE OR TRANSIENT	Transient
COMPUTER PROGRAM	Not available in thesis
BASIS OF THEORY	Substantially modified Philips and de Vries[2,3] and Luikow[13]
SOLUTION TECHNIQUE	Temperature and moisture content are computed for cylindrical nodes about the cable by an implicit finite difference approach. Equations are expressed in normalized form with dimensionless groups of variables. A bitridiagonal algorithm is used to solve the pair of simultaneous difference equations at each node. An iterative scheme is used to accommodate soil properties at present values of temperature and moisture content. Moisture content is solved first at each timestep followed by temperature based on decoupled mass and energy equations.
MODELING FEATURES	Model is intended for simulation of heat and moisture flows in a radial region about a cable buried below surface influences. Thus, surface evaporation or infiltration, daily temperature variation, presence of a water table, and gravity effects are not modeled. A constant heat flux from the coil was assumed. Progress of a drying front is modeled using special fractional-step finite difference equations. Analysis showed existence of a critical moisture content at the surface of the pipe at which the rate of drying is a minimum. Rate of drying accelerates at moisture contents below the critical value producing a thermal "runaway" condition.
VALIDATION	Computed values of moisture content near the pipe agreed well with measurements, but computed values at some distance from the pipe were significantly higher than measurements. Needle probe temperatures were higher than predicted, but onset of significant drying was accurately predicted.
SOIL PROPERTIES	Soil properties and correlations are given for Plainfield and sandy silt, commonly called "Georgia red clay". An excellent discussion of correlation equations for soil properties is presented.

MODEL NO.	5
AUTHOR	Johnson, S. E. (Ohio State University)
M.S. THESIS TITLE	Soil Temperature and Moisture Content Measurements for a System of Subsurface Heating Pipes

REFERENCE NO.	14
DATE	1976
DIMENSIONS	2 (horizontal and depth)
STEADY STATE OR TRANSIENT	Steady state
COMPUTER PROGRAM	CSMP (about 30 source statements). Could be easily rewritten in FORTRAN.
BASIS OF THEORY	Kendrick and Havens[15]
SOLUTION TECHNIQUE	Line source with superposition.
MODELING FEATURES	Simple model computes soil temperatures in the region between two buried pipes and the surface. Moisture migration and freezing are not modeled.
VALIDATION	Validated by the author for use when a dry core about the pipe is not present. Also validated in two other studies and by Kendrick and Havens.
SOIL PROPERTIES	A silt loam soil was used in laboratory experiments.

MODEL NO.	6
AUTHOR	Bondurant, J. L. (University of Arkansas)
REPORT TITLE	Coupled Heat and Moisture Transfer in Soil with Applications to the Design of a Warm Water Subsurface Irrigation System
REFERENCE NO.	16
DATE	1975
DIMENSIONS	1 (radial)
STATE STATE OR TRANSIENT	Steady state (theory given for transient)
COMPUTER PROGRAM	CSMP (about 650 source statements). Well documented internally. Requires CSMP integration procedure.

BASIS OF THEORY	Taylor and Cary[17] (based on concepts of irreversible thermodynamics)
SOLUTION TECHNIQUE	Temperature and moisture values in unsaturated soil are computed as a function of radius from the pipe by numerical integration of two simultaneous differential equations.
MODELING FEATURES	Model is axisymmetric about pipe. Steady-state equations are solved without the need for a nodal representation of the modeled region. Convergence was unsatisfactory when boundary temperature and moisture content values were set at some distance from pipe. Instead, heat and moisture flows were set at the boundary.
VALIDATION	Computed values for moisture content and temperature compared fairly well with experimental data by Gee[18].
SOIL PROPERTIES	Properties for Palouse silt loam measured by Gee[18] were used in the model. Thesis contains properties for many soils from the literature required in the Taylor and Cary model.

MODEL NO.	7
AUTHOR	Shapiro, H. N. (Ohio State University)
Ph.D. THESIS TITLE	Simultaneous Heat and Mass Transfer in Porous Media with Application to Soil Warming with Power Plant Waste Heat
REFERENCE NO.	19, 20, 21, 22
DATE	1975
DIMENSIONS	2 (horizontal and depth)
STEADY STATE OR TRANSIENT	Steady state (theory given for transient)
COMPUTER PROGRAM	FORTRAN (about 230 source statements). Used an IBM proprietary program NONLIN to solve simultaneous nonlinear equations.
BASIS OF THEORY	Philip and de Vries[2,3]. Excellent discussion of theory and diffusion transport coefficients of the soil. Generalized formulation of volume-averaged equations for heat and moisture flow in soils were reduced to Philip and de Vries theory.

SOLUTION TECHNIQUE	A central finite-difference approach was used to solve for values of temperature and moisture content. Program NONLIN was used to solve the matrix of simultaneous non-linear equations by reducing the residuals to a negligible amount.
MODELING FEATURES	The nodal region with square nodes was bounded on left by vertical plane through the supply pipe and at right by a vertical plane through the return pipe. Supply and return pipes may have different temperatures. At the top and bottom boundary surfaces, values for moisture content and temperature were assumed to be constant. The bottom boundary was located at two times the burial depth of the pipe.
VALIDATION	Temperatures compared well with the Kendrick and Havens[15] constant property model. Example problems with variable properties gave consistent results. Temperature and moisture profiles compared well with 1-D measurements by Gee[18].
SOIL PROPERTIES	An excellent discussion is given of a semi-empirical method for determining transport diffusivity coefficients for the soil. Property values for Palouse silt loam soil were used in the model.

MODEL NO.	8
AUTHOR	Slegel, D. L. (Oregon State University)
Ph.D. THESIS TITLE	Transient Heat and Mass Transfer in Soils in the Vicinity of Heated Porous Pipes
REFERENCE NO.	23, 24
DATE	1975
DIMENSIONS	2 (horizontal and depth)
STEADY STATE OR TRANSIENT	Transient
COMPUTER PROGRAM	FORTRAN (about 630 source statements). Some internal documentation and annotated example input data.
BASIS OF THEORY	Modified Philip and de Vries[2,3]. Equations are developed using gradients of vapor density and water tension, whereas Philip and de Vries equations contain gradients of temperature and water content.

SOLUTION TECHNIQUE	Spatial differential equations were simplified with dimensionless variables and expressed in finite-difference form using a central-difference scheme. Resulting equations were solved by an implicit, backwards-difference approach with iteration until temperature and moisture content arrays converged within a specified error. Trial values used in the iteration scheme were altered by a penalty function to maintain stability. A relatively large timestep of 24 hours can be used.
MODELING FEATURES	Nodal region with rectangular nodes is bounded by a vertical plane of symmetry through the supply pipe on the left and a vertical adiabatic boundary midway between pipes on the right. The number of nodes and spacing in both planes is controlled by simple inputs. Heating and moisture source at the pipe is modeled by specifying the temperature and moisture content of the node representing the pipe. Water table can be explicitly modeled by specifying depth of unsaturated soil. Temperature and moisture values at the top boundary are computed from effects of rain, convection, humidity, and solar radiation. Temperature is fixed at the bottom boundary and the moisture is fixed at saturation for all nodes below the water table. Soil properties required are water suction potential and thermal conductivity as a function of moisture content, soil thermal capacitance for unsaturated and saturated layers, porosity, and tortuosity. Atmospheric parameters of ambient temperature, wind speed, cloud cover, precipitation, and relative humidity are required weather data for each timestep.
VALIDATION	Predicted moisture and temperature values compared well with 2-D data from experiments with subsurface porous pipe buried in sandy soil.
SOIL PROPERTIES	Very little discussion of soil property data is given. Data and correlations for sandy soil are used in the model.

MODEL NO.	9
AUTHOR	Schroeder, C. N. (Texas A&M University)
Ph.D. THESIS TITLE	The Development of an Optimized Computer Simulation Model for Heat and Moisture Transfer in Soils
REFERENCE NO.	25, 26
DATE	1974
DIMENSIONS	2 (horizontal and depth)

STEADY STATE OR TRANSIENT	Transient
COMPUTER PROGRAM	FORTRAN (large source code of about 4000 statements). Well documented internally and in a user's manual.
BASIS OF THEORY	Slightly modified Philip and de Vries[2,3]
SOLUTION TECHNIQUE	A forward, finite-difference approach with exact second derivatives are used. Values of moisture content are computed for each node with iteration until convergence is reached. Then, temperature values are computed with iteration until convergence is reached. Timestep for computing moisture values is three to five times the timestep for computing temperature values. Timesteps for the next time are computed using the previous timestep and moisture and temperature gradients to maintain stability with largest timesteps. A finer nodal mesh size is employed in regions of high gradients to force convergence if needed. An excellent discussion of methods for accelerating convergence is provided.
MODELING FEATURES	A nodal network with rectangular and triangular nodes is self-generated from inputs of surface topography (flat, sloped, mounded), width between pipes, and depth of modeled region. Up to two rectangular sources and sinks in both moisture and/or temperature can be specified. Top surface values are computed from hourly inputs of solar radiation, rain, rain temperature, humidity, and ambient temperature or the top surface temperature can be specified. Infiltration or evapotranspiration of moisture is computed. Effect of wind is accounted for by a surface boundary layer resistance. Effect of gravity on moisture flow is modeled. Surface soil layer and up to five subsurface soil layers can be characterized by inputs of bulk density and porosity for each layer. Soil thermal conductivity is computed from moisture, bulk density, porosity, and temperature by the de Vries method[4,5]. Water suction potential, gradient of potential with moisture content, and hydraulic conductivity are required as a function of moisture content. All input values must be coded into source statements.
VALIDATION	Computed results compared well with vertical 1-D isothermal moisture migration measurements by Philip[27]. Computed results compared well with vertical 1-D measurements by Hauk[28]. Consistent results were obtained on various 2-D sample problems.
SOIL PROPERTIES	Input requirements are adequately discussed but property data or correlations are not presented.

MODEL NO.	10
AUTHOR	Jury, W. A. (University of Wisconsin)
Ph.D. THESIS TITLE	Simultaneous Transport of Heat and Moisture Through a Medium Sand
REFERENCE NO.	29
DATE	1973
DIMENSIONS	1 (depth)
STEADY STATE OR TRANSIENT	Transient
COMPUTER PROGRAM	FORTRAN (about 180 source statements). Adequate documentation is provided.
BASIS OF THEORY	Philip and de Vries[2,3]
SOLUTION TECHNIQUE	Equations are simplified by transformation of variables. Spatial derivations were reformulated to a set of first order differential equations in time by using the six-point polynomial-approximation technique called orthoganal collocation. Resulting equations were solved by a fifth order Runge-Kutta approach.
MODELING FEATURES	The model is intended for simplified simulation of drying of the soil surface, so the modeled region is only 5 cm deep. The model uses exponential correlations for moisture diffusivities and hydraulic conductivity as a function of moisture content. Constant values are required for thermal diffusivity and conductivity of the soil, ambient-air temperature, and solar radiation. Zero moisture flux is assumed at the 5-cm-deep bottom boundary. Information on a more complex model based on the theory in the thesis is available from the author.
VALIDATION	Direct comparison with slab measurements were not possible because not enough data were available on moisture diffusivities at low moisture content. The orthoganal collocation approach for converting spatial derivatives introduced errors at moisture contents below 0.05 percent by volume, which limited accuracy of dry-out predictions.
SOIL PROPERTIES	Good experimental data are provided on Plainfield sand.

MODEL NO.	11
AUTHOR	Hauk, R. E. (Cornell University)
Ph.D. THESIS TITLE	Soil Temperature and Moisture Fields Predicted by a System of Coupled Equations
REFERENCE NO.	28
DATE	1971
DIMENSIONS	1 (depth)
STEADY STATE OR TRANSIENT	Transient
COMPUTER PROGRAM	FORTRAN (about 590 source statements). Well documented.
BASIS OF THEORY	Taylor and Cary[16]
SOLUTION TECHNIQUE	Temperature and moisture values are computed as a function of depth using an implicit finite-difference approach with iteration by a combination of Crank-Nicholson approach at start followed by a three-level Lees approach. The Lees approach uses values from the previous and present timesteps to compute values for the next timestep. A Gausian elimination procedure is used to solve the tridiagonal matrix of equations.
MODELING FEATURES	Model is one-dimensional in depth and is intended for use in modeling soil drying for agricultural purposes. Moisture gradient and constant temperature were fixed at the 100-cm-deep bottom boundary. At the top surface boundary, evaporation and surface temperature are computed as a function of solar radiation, atmospheric radiation, soil-emitted radiation, relative humidity and temperature of the ambient air, and wind. Heat and moisture equations can be decoupled to minimize computing time by changing an input value.
VALIDATION	Consistent data were computed for a number of cases, but no direct comparisons with experimental measurements were provided.
SOIL PROPERTIES	Correlations for moisture content, gradient of water suction potential with moisture content, and hydraulic conductivity as a function of water suction potential, and correlations for thermal conductivity as a function of moisture content are provided for Geary silt loam, Sharpy loam, and Webster silty clay loam soils.

MODEL NO.	12
AUTHOR	Cassel, D. K. et al (University of California-Davis)
REPORT TITLE	Soil-Water Movement in Response to Imposed Temperature Gradients
REFERENCE NO.	30
DATE	1969
DIMENSIONS	1 (depth)
STEADY STATE OR TRANSIENT	Transient
COMPUTER LISTING	Not available in report
BASIS OF THEORY	Philip and de Vries[2,3] and Taylor and Cary[17]
SOLUTION TECHNIQUE	Numerical analysis.
MODELING FEATURES	Model was designed to predict temperatures and moisture contents in a cylindrical test sample using moisture diffusivities and soil properties for a Columbia fine sandy loam soil.
VALIDATION	Experimental moisture flows were obtained by gamma ray attenuation. Prediction accuracy for three theories for test durations of 3 to 7 days were:

	Measured/Predicted Moisture Flow
Philip and de Vries	∿1.0
Taylor and Cary	∿10 to 40
Fick's law	∿5

SOIL PROPERTIES	No soil property data were given in the report, but an excellent discussion was provided on calculation of the moisture diffusivity terms required in the Philip and de Vries method.

MODEL NO.	13
AUTHOR	Dempsey, B. J. (University of Illinois)
Ph.D. THESIS TITLE	A Heat-Transfer Model for Evaluating Frost Action and Temperature Related Effects in Multilayered Pavement Systems
REFERENCE NO.	31, 32, 33, 34
DATE	1969
DIMENSIONS	1 (depth)
STEADY STATE OR TRANSIENT	Transient
COMPUTER PROGRAM	FORTRAN (about 850 source statements). Well documented.
BASIS OF THEORY	Philip and de Vries[2,3]
SOLUTION TECHNIQUE	Implicit finite difference approach with Gauss elimination is used for solution of simultaneous equations. For each node, values of moisture content are computed using values of moisture and temperature from the previous timestep. Then temperature is computed and moisture content is recalculated. Final values are obtained by iteration. With this approach, temperature values lag moisture values by one timestep.
MODELING FEATURES	The model is structured for study of moisture flow in layered highway pavement systems. Surface temperatures are computed from daily meteorological data including ambient temperature extremes, rainfall, snowfall, wind, percent sunshine, and times of sunrise and sunset. The program models annual freeze/thaw cycles.
VALIDATION	Predicted values of moisture content compared well with values measured in laboratory experiments with 1-D isothermal tests with both sand and sandy loam soils.
SOIL PROPERTIES	Property data and correlations are provided for Lakeland fine sand and Illinois sandy loam soils for unfrozen and frozen conditions. Values of water suction potential and hydraulic conductivity as a function of moisture content are given for 24 soil series in Illinois[34].

MODEL NO.	14
AUTHOR	Gee, G. W. (Washington State University)
PhD. THESIS TITLE	Water Movement in Soils as Influenced by Temperature Gradients
REFERENCE NO.	18
DATE	1966
DIMENSIONS	1 (depth)
STEADY STATE OR TRANSIENT	Transient
COMPUTER PROGRAM	Not available in thesis
BASIS OF THEORY	Philip and de Vries[2,3] and Taylor and Cary[17]
SOLUTION TECHNIQUE	Numerical analysis
MODELING FEATURES	Model was designed to predict temperatures and moisture content in a cylindrical test sample. Excellent discussion of isothermal and non-isothermal vapor and liquid diffusivities required in the Philip and de Vries theory is provided.
VALIDATION	Experimental values of moisture content were measured with a neutron beam approach. Comparison results at the end of 24 hours are:

	Measured/Predicted Moisture Flows
Philip and de Vries	∿2.7
Taylor and Cary	∿0.77
Fick's Law	∿7.8

SOIL PROPERTIES	Property data are provided for Palouse silt loam soil.

INTERNAL DISTRIBUTION

1. V. D. Baxter
2. R. S. Carlsmith
3. F. A. Creswick
4. R. C. DeVault
5. J. E. Dobson
6. R. D. Ellison
7-10. P. D. Fairchild
11. S. K. Fischer
12. W. Fulkerson
13. V. O. Haynes
14. P. Intemann
15. S. V. Kaye, Consultant
16. T. R. LaPorte, Consultant
17. R. N. McGill
18. V. C. Mei
19. J. W. Michel
20. R. E. Minturn
21. W. R. Mixon
22. L. I. Moss, Consultant
23. J. C. Moyers
24. E. A. Nephew
25. M. W. Russell, Consultant
26. W. H. Williams, Consultant
27-28. Central Research Library
29. Document Reference Section
30. Laboratory Records - RC
31-32. Laboratory Records Department
33. ORNL Patent Section

EXTERNAL DISTRIBUTION

34. Phil Albertson, Manager, Charles Machine Works, Inc., P.O. Box 66, Perry, OK 73077
35. C. H. Atkinson, Environmental Division, Acres Consulting Serv., Ltd., 5259 Dorchester Road, Niagara Falls, Ontario 12E G61
36. Falk Auer, Battelle Institute, e.V., Frankfurt, West Germany
37. B. Backstrom, Chalmers University of Technology, Jordvarme Gruppen, S-41296, Goteborg, Sweden
38. David A. Ball, Battelle Columbus Laboratories, 505 King Avenue, Columbus, OH 43201
39. Michael K. Bergman, Staff Scientist, American Public Power Assoc., 2301 M Street, N.W., Washington, DC 20037
40. W. Z. Black, Professor, School of Mech. Eng., GA Institute of Technology, Atlanta, GA 30332
41. Andrew L. Blackshaw, Manager, R&D, E-Tech, Inc., 3750 American Drive, Atlanta, GA 30341
42. James E. Bose, School of Technology, Oklahoma State University, Stillwater, OK 74078
43. David Cabot, President, Avondale Solar Corporation, P.O. Box 501, 44 Avondale Road, Westerly, RE 02891
44. James M. Calm, Project Manager, Heat Pump Development, Electric Power Res. Inst., 3412 Hillview Avenue, Palo Alto, CA 94303
45. Barry J. Dempsey, Dept. of Civil Engineering, University of Illinois, Urbana, IL 61801
46. R. J. Denny, Air-Conditioning & Refrigeration Institute, 1815 N. Fort Meyer Drive, Arlington, VA 22209
47. Richard Dougall, Dept. of Mechanical Engineering, University of Pittsburgh, Pittsburg, PA 15261

48. G. D. Duffy, Air Conditioning News, P.O. Box 2600, Troy, MI 48007
49. David G. Dutton, Vice President - Marketing, McElroy Manufacturing, Inc., P.O. Box 15580, Tulsa, OK 74112
50. John A. Edwards, North Carolina State University, Department of Mechanical and Aerospace Engineering, P.O. Box 5246, Raleigh, NC 27607
51. Don Ellis, Genesis Energy Systems, Div. of Hattersly & Sons, Inc., 3989 Mobil Avenue, Fort Wayne, IN 46896
52. Robert D. Fischer, Battelle Columbus Laboratories, 505 King Avenue, Columbus, OH 43201
53. R. J. Fiskum, Energy Conversion Equipment Branch, CE-113.2, Department of Energy, 1000 Independence Avenue S.W., Washington, DC 20585
54. Victor Goldschmidt, Ray W. Herrick Laboratories, Purdue University, W. Lafayette, IN 47907
55. E. Granryd, Dept. of Applied Thermodynamics and Refrigeration, Royal Institute of Technology, S-10044 Stockholm, Sweden
56. Robert M. Gregson, Vice President, Alten Northwest, 1134 Poplar Place, S., Seattle, WA 98144
57. G. C. Groff, Director, Research Division, Carrier Corporation, Carrier Parkway, Syracuse, NY 13201
58. Floyd Hayes, Thermal Systems, The Trane Company, 3600 Pammell Creek Road, LaCrosse, WI 54601
59. David Hodgett, Battelle Columbus Laboratories, 505 King Avenue, Columbus, OH 43201
60. Mark R. Hogan, Manager, Westinghouse Electric Corporation, R&D Center, Purdue Industrial Res. Park, 1291 Cumberland Avenue, West Lafayette, IN 47906
61. Michael Hughes, Friedrich Air Conditioning & Refrigeration, 2007 Beechgrove Pl., Utica, NY 13507
62. Patrick J. Hughes, P.E., W. S. Fleming & Associates, Inc., 5802 Court Street Road, Syracuse, NY 13206
63. G. Hultmark, Secretary, Chalmers Univ. of Technology, Jordvarme Gruppen, S-41296, Goteborg, Sweden
64. Douglas Jardine, Kaman Sciences Corporation, 1500 Garden of the Gods Rd., Colorado Springs, CO 80907
65. William S. Johnson, P.E., University of Tennessee, Energy, Environment and Resources Center, Knoxville, TN 37916
66. W. A. Jury, Assoc. Professor of Soil Physics, Dept. of Soil & Environ. Sci., University of California, Riverside, CA 92521
67. Mark Kalman, E-Tech Incorporated, 3570 American Drive, Atlanta, GA 30341
68. Herbert Kaufman, ARCO Comfort Products Company, 1271 Avenue of the Americas, New York, NY 10020
69. Richard Kurtz, Naval-Base-Housing Engineering, Naval Civil Engineering Lab., Port Hueneme, CA 93043
70. Edward A. Kush, 65 Crystal Rock Ct., Middle Island, NY 11953
71. Arvo Lannus, Residential & Commercial Applications, Electric Power Research Inst., 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94303
72. Terry R. Larson, Marketing Services Manager, PLEXCO, 3240 N. Manniheim Road, Franklin Park, IL 60131
73. Calvin D. MacCracken, Calmac Manufacturing Company, 150 South Van

Brunt Street, Englewood, NJ 07631

74. Philip Metz, Brookhaven National Laboratory, Building 701, Upton, NY 11973
75. P. Munter, Teknologisk Institut, Gregersensvej, DK-2630 Tastrup, Denmark
76. Joseph P. Murphy, Director of Education and Training, Oasis Energy Systems, 4425 N. High Street, Columbus, OH 43214
77. Richard A. O'Neil, Niagara Mohawk Power Corporation, 300 Erie Blvd. West, Syracuse, NY 13202
78. Sven G. Oskarsson, Cantherm, 8089 Trans-Canada Hwy., St. Laurent, Quebec H4S 1S4
79. Jerald Parker, School of Mechanical & Aerospace Eng., Oklahoma State University, 218 Engineer North, Stillwater, OK 74078
80. James R. Partin, GeoSystems, Inc., 3623 N. Park Drive, Stillwater, OK 74074
81. M. Porsvig, Danish Geotechnical Inst., 1 Maglebjergvej, DK-2800 Lyngby, Denmark
82. J. Rizzuto, New York State Energy Research & Development Auth., Agency Building No. 2, Rockefeller Plaza, Albany, NY 12223
83. G. Rosenbald, Chalmers University of Technology, Jordvarme Gruppen, S-41296, Goteborg, Sweden
84. J. D. Ryan, Energy Conversion Equipment Branch, CE-113.2, Department of Energy, 1000 Independence Avenue S.W., Washington, DC 20585
85. F. Schabkar, Graz University of Technology, Kopernikusgasse 24, A-8010 GRAZ, Austria
86. Ralph Schlichtig, P.E., Unconventional Heat and Power Sources, 11212 3rd Avenue, S., Seattle, WA 98168
87. A. H. Schroer, Sales Development Manager, Shell Chemical Company, Polybutylene Department, One Shell Plaza, P.O. Box 2463, Houston, TX 77002
88. Howard N. Shapiro, Dept. of Mech. Eng., Engineering Research Inst., Iowa State University, Ames, IA 50010
89. Graham Siegel, TVA Chattanooga, Research & Development, 1850 Commerce Union Bank Bldg., Chattanooga, TN 37401
90. Gary Skartvedt, American Heliothermal Corporation, Denver, CO 80222
91. Mason Somerville, Professor, Dept. of Mech. Eng., University of Arkansas, Fayetteville, AR 72701
92. Mario A. Sophocleous, Kansas Geological Survey, University of Kansas, Lawrence, KS 66044
93. Don Stephenson, National Research Council, Division of Buildings Res., Montreal Road, Ottawa, Canada KIA 0R6
94. Lee Sumner, Research Engineer, York Division, Borg-Warner Corporation, P.O. Box 1592, York, PA 17405
95. O. J. Svec, Geotechnical Section, Division of Building Research, National Research Council of, Canada, Ottawa, Ontario KIA 0R6
96. M. Keith Swinehart, Vanguard Plastics, Inc., 831 N. Vanguard Street, McPherson, KS 67460
97. Sherwood G. Talbert, Battelle Columbus Laboratories, 505 King Avenue, Columbus, OH 43201
98. Ralph Tilney, Alco Controls, 336 Chasselle, St. Louis, MO 63141
99. Jeffrey W. Wright, Engineering Consultant, Kansas Gas and

Electric Co., Wichita, KS

100. Office of the Assistant Manager for Energy R&D, U.S. Department of Energy, Oak Ridge Operations, Oak Ridge, TN 37830

101-127. Technical Information Center, Department of Energy, P.O. Box 62, Oak Ridge, TN 37830