PNL--4422 Vol. 1

DE82 022512

**USER MANUAL FOR GEOCITY: A COMPUTER
MODEL FOR COST ANALYSIS OF GEOTHERMAL
DISTRICT-HEATING-AND-COOLING SYSTEMS**

VOLUME I - MAIN TEXT

H. D. Huber
L. L. Fassbender
C. H. Bloomster

MASTER

September 1982

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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.

**Pacific Northwest Laboratory
Richland, Washington 99352**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Key

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.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

PROLOGUE

The GEOCITY code was originally developed at the Pacific Northwest Laboratory (PNL) in 1977 and 1978 for the U.S. Department of Energy. The original version calculated the cost of residential space heating and sanitary water heating or process heating using geothermal energy. Since that time GEOCITY has been used extensively at PNL and elsewhere. Since its original documentation, GEOCITY has undergone numerous modifications to improve and extend its analytical capabilities and report writing clarity. This user manual, which includes the latest modifications, updates and expands the original GEOCITY documentation. The nature of the major modifications and additions to the original GEOCITY code are as follows:

- Capability to simulate residential space cooling and sanitary water heating or process cooling using lithium bromide/water absorption chillers located at each building.
- Capability to simulate combined residential space heating, space cooling, and sanitary water heating.
- Capability to automatically update and escalate capital, O&M, electrical pumping, and supplemental heating costs.
- Updating of many capital cost models for the fluid transmission system and the distribution system.
- Addition of a drilling model to calculate well drilling costs as another option to directly inputting drilling costs.
- Addition of submersible downhole pumps in the production wells.
- Addition of accelerated depreciation schedules.
- Upgrading of the output capability that has greatly increased the readability and usability of the code results.
- Inclusion of a line printer plotting routine to generate plots of some of the capital cost models for the distribution system.

For ease of handling, the current GEOCITY User Manual is divided into two volumes. Volume I contains the main text, including the introduction, program

description, input data instructions, and description of the output. Volume II contains all the appendices, including cost equations and models for the reservoir and fluid transmission system and the distribution system, descriptions of predefined residential district types for the distribution system, key equations for the cooling degree hour methodology, and a listing of the sample case output. Both volumes include the complete table of contents and lists of figures and tables. In addition, both volumes include the indices for the input parameters and subroutines defined in the user manual. The authors hope this organization will facilitate working with the user manual.

ABSTRACT

Pacific Northwest Laboratory has developed a computer model called GEOCITY. The purpose of this model is to calculate the costs of residential space heating, space cooling, and sanitary water heating or process heating (cooling) using geothermal energy from a hydrothermal reservoir. The model can calculate geothermal heating and cooling costs for residential developments, a multi-district city, or a point demand such as an industrial factory or commercial building.

GEOCITY simulates the complete geothermal heating and cooling system, which consists of two principal parts: the reservoir and fluid transmission system and the distribution system. The reservoir and fluid transmission submodel calculates the life-cycle cost of thermal energy supplied to the distribution system by simulating the technical design and cash flows for the exploration, development, and operation of the reservoir and fluid transmission system. This includes the reservoir wellfield layout, the fluid transmission system for gathering and delivering the geothermal fluid to the distribution system, and the fluid injection system for disposing of the used geothermal fluid.

The distribution system submodel calculates the life-cycle cost of heat (chill) delivered by the distribution system to the end-users by simulating the technical design and cash flows for the construction and operation of the distribution system. Geothermal space heating is assumed to be provided by circulating hot water through radiators, convectors, fan-coil units, or other in-house heating systems. Geothermal process heating is provided by directly using the hot water or by circulating it through a process heat exchanger. Geothermal space or process cooling is simulated by circulating hot water through lithium bromide/water absorption chillers located at each building. Retrofit costs for both heating and cooling applications can be input by the user. The life-cycle cost of thermal energy from the reservoir and fluid transmission system to the distribution system and the life-cycle cost of heat (chill) to the end-users are calculated using discounted cash flow analysis.

GEOCITY is a powerful analytical tool for cost analysis of geothermal heating and cooling systems. The model combines the technical characteristics of

the reservoir and fluid transmission system and the distribution system with financial and tax conditions for the entities operating the two systems into one techno-economic model. Examples of technical characteristics include the geothermal resource conditions and its distance from the distribution system, the climate, demographic factors, thermal energy requirements, and different piping system designs and materials. Examples of financial and tax conditions include the well drilling costs, the capital costs of the piping system, pumps, heat exchanger, and retrofit equipment, capital replacement rates, O&M costs, the debt-equity ratios, rates of return on debt and equity, tax rates, investment tax credits, and depreciation schedules. This provides the flexibility to individually or collectively evaluate the impact of different economic and technical parameters, assumptions, and uncertainties on the cost of providing geothermal heating and cooling.

CONTENTS

PROLOGUE	i
ABSTRACT	iii
LIST OF FIGURES	ix
LIST OF TABLES	xi
1.0 INTRODUCTION	1.1
2.0 DESCRIPTION OF PROGRAM	2.1
2.1 OVERVIEW OF A TYPICAL GEOTHERMAL DISTRICT HEATING AND COOLING INSTALLATION	2.1
2.2 GENERAL PROGRAM DESIGN	2.5
2.3 MAIN PROGRAM	2.13
2.4 DATA INPUT SUBMODEL	2.16
2.5 EXECUTIVE ROUTINE FOR RESERVOIR AND FLUID TRANSMISSION SYSTEM SUBMODEL AND DISTRIBUTION SYSTEM SUBMODEL	2.17
2.6 RESERVOIR AND FLUID TRANSMISSION SYSTEM SUBMODEL	2.23
2.7 DISTRIBUTION SYSTEM SUBMODEL	2.34
2.7.1 Heat Exchanger at Interface to Distribution System	2.34
2.7.2 Overview of Distribution System	2.43
2.7.3 Thermal Energy and Fluid Requirements of Distribution System	2.45
2.7.3.1 Thermal Energy and Fluid Requirements for Residential Space Heating and Sanitary Water Heating	2.46
2.7.3.2 Thermal Energy and Fluid Requirements for Residential Space Cooling and Sanitary Water Heating	2.51
2.7.3.3 Thermal Energy and Fluid Requirements for Combined Residential Space Heating, Space Cooling, and Sanitary Water Heating	2.59

2.7.3.4	Thermal Energy and Fluid Requirements for Process Heating or Cooling	2.60
2.7.4	Technical Design and Economic Costs of Distribution System	2.62
2.8	DISCOUNTED CASH FLOW SUBMODEL FOR RESERVOIR AND FLUID TRANSMISSION SYSTEM	2.70
2.9	DISCOUNTED CASH FLOW SUBMODEL FOR DISTRIBUTION SYSTEM	2.76
2.10	STEAM TABLE FUNCTIONS	2.81
3.0	PREPARATION OF INPUT DATA	3.1
3.1	NAMelist INPUT RULES	3.1
3.2	INPUT INSTRUCTIONS AND SAMPLE CASE INPUT	3.3
3.3	RESERVOIR AND FLUID TRANSMISSION SYSTEM INPUT DATA	3.15
3.3.1	Reservoir Characteristics and Well Properties	3.19
3.3.2	Fluid Pumping System	3.21
3.3.3	Fluid Mixer	3.25
3.3.4	Fluid Transmission Piping System	3.26
3.3.5	Fluid Injection Piping System	3.28
3.4	DISTRIBUTION SYSTEM INPUT DATA	3.29
3.4.1	Operational Mode	3.30
3.4.2	Climatic Parameters for Heating Mode	3.33
3.4.3	Climatic Parameters for Cooling Mode	3.38
3.4.4	Distribution Heat Exchanger	3.45
3.4.5	Absorption Chillers	3.47
3.4.6	Districts	3.49
3.4.6.1	District Geometry	3.50
3.4.6.2	District Type Characteristics	3.53
3.4.7	Distribution System Piping Design	3.57

3.4.8	Point Demand	3.61
3.4.9	Branching Pipe Mains Network for Multi-Residential Districts	3.63
3.5	FINANCIAL INPUT DATA	3.68
3.5.1	Reservoir and Fluid Transmission System Financial Data	3.69
3.5.2	Reservoir Well Drilling Costs	3.71
3.5.3	Distribution System Financial Data	3.74
3.5.4	Distribution System Trenching Costs	3.76
3.5.5	General Economic Parameters	3.78
3.5.5.1	Base Year of Capital and O&M Costs and Depreciation Options	3.78
3.5.5.2	Inflation and Escalation	3.81
3.5.5.3	Cost of Supplemental Heat, Pumping Efficiency, and Pumping Electrical Costs	3.83
3.5.6	Pre-Development, Development, and Operational Time Schedules and Costs for Reservoir and Fluid Transmission System	3.84
3.6	OUTPUT SELECTION OPTIONS	3.91
4.0	DESCRIPTION OF OUTPUT	4.1
5.0	ACKNOWLEDGMENTS	5.1
6.0	REFERENCES	6.1
APPENDIX A	- Pre-Development, Development, and Operational Cost Equations for Reservoir and Fluid Transmission System	A.1
APPENDIX B	- Capital and Operating Cost Models for Distribution System	B.1
APPENDIX C	- Description of Predefined Residential District Types for Default Use in GEOCITY	C.1
APPENDIX D	- Capital Cost Models for Reservoir and Fluid Transmission System	D.1

APPENDIX E - Key Equations for Cooling Degree Hour Methodology . . .	E.1
APPENDIX F - Trouble-Shooting Guide	F.1
APPENDIX G - Listing of Sample Case Output	G.1
APPENDIX H - Index to Input Parameters and Subroutines	H.1

FIGURES

1. Overview of Technical and Economic Simulation for Geothermal District Heating and Cooling System	1.2
2. Overview of Generic Classes of Input Data to GEOCITY	1.5
3. Schematic of Major Elements of Geothermal District Heating and Cooling System	2.2
4. Structure of GEOCITY Computer Model	2.7
5. Flow Diagrams for GEOCITY with Submodels and Sub-routines Shown in the Order of Computational Flow	2.9
6. Sequence of Subroutines Called by the Executive Routine DGHEAT to Simulate the Reservoir and Fluid Transmission System and the Distribution System	2.19
7. Subroutines Called by Subroutines TRANS and INJECT to Simulate the Elements of the Reservoir and Fluid Transmission System	2.25
8. Well Layout Design and Routing of Fluid Transmission Pipes	2.30
9. Conceptual System Design in GEOCITY to Provide Residential Space Cooling and Sanitary Water Heating	2.52
10. Layout for a District with 22 Buildings	2.65
11. Steam Table Subregions as a Function of Temperature and Pressure	2.84
12. Layout of Residential Districts in Small Western City for Sample Input Case	3.9
13. Conceptual Configuration of Reservoir and Fluid Transmission System	3.22
14. Nomenclature for the Temperatures in the Distribution System Heat Exchanger	3.46
15. Examples of Main Configurations Servicing Multi-Residential Districts	3.64
16. Physical Layout of Buried Pipe Trenches Used in the Trenching Cost Model	3.77

17.	Default Time Sequences of Pre-Development, Development, and Operational Activities for Reservoir and Fluid Transmission System	3.90
18.	Production Wellfield Nodes and Exiting Temperature Degradation on a Nodal Basis during Cooling Mode	4.8
19.	Layout for District 7 with 54 Buildings in Sample Case	4.12
B.1	District Heating (Cooling) System Two-Pipe Network	B.2
C.1	Plan of Suburban Residential House	C.2
C.2	Plan for High-Density Single Family Home	C.3
C.3	Plan for Garden Apartment Unit	C.4
C.4	Plan for Townhouse Unit	C.5
C.5	Plan for High-Rise Apartment Unit	C.6

TABLES

1.	ASME Steam Table Single-Valued Functions	2.82
2.	ASME Steam Table Multiple-Valued Functions	2.83
3.	Sample Case Input for Geothermal District Heating and Cooling for a Small Western City in the U.S.	3.5
4.	Reservoir and Fluid Transmission System Input Parameters in NAMELIST Group \$RESVOR for Sample Case	3.7
5.	Summary of District Input Data for Sample Case	3.10
6.	Branching Main Matrix DNET for Sample Case	3.14
7.	Distribution System Input Parameters for Sample Case in NAMELIST Group \$DISTRB	3.16
8.	District Type Characteristics of the Default District Types in GEOCITY	3.54
9.	Matrix Examples for Branching Mains Network	3.67
10A	Activities and Input Costs for Pre-Development, Develop- ment, and Operation of Reservoir and Fluid Transmission System	3.86
10B	Activities, Input Times, and Success Ratios for Pre- Development, Development, and Operation of Reservoir and Fluid Transmission System	3.87
11	Subgrouping of Activities Occurring Parallel in Time for Reservoir and Fluid Transmission System	3.88
12A	Subgrouping of Activities for Reservoir and Fluid Transmission System by Decision Points	3.92
12B	Description of Decision Points	3.92
13	Summary of Computer Output from GEOCITY	4.2
B.1	Distribution System Capital Cost Coefficients	B.8
B.2	Operating Cost Models	B.10
B.3	Calcium Silicate Insulation Cost Equations	B.11
B.4	Valves, FRP Fittings, and Carbon Steel Fittings	B.12

B.5	Steel Casing Fitting	B.13
B.6	PVC Casing Fitting	B.14
B.7	Meter	B.15
B.8	Cost Factors	B.16
C.1	Design Basis for Suburban Residential House	C.2
C.2	Design Basis for High-Density, Single-Family House	C.3
C.3	Design Basis for Garden Apartment Unit	C.4
C.4	Design Basis for Townhouse Unit	C.5
C.5	Design Basis for High-Rise Apartment Unit	C.6
D.1	Categorization of Reservoir and Fluid Transmission System Components into Cost Accounts	D.2
D.2	Reservoir and Fluid Transmission System Capital Cost Coefficients	D.3
D.3	Fluid Transmission System Pipe Schedules	D.5

USER MANUAL FOR GEOCITY

1.0 INTRODUCTION

This user manual describes a computer simulation model called GEOCITY. The purpose of this model is to calculate the costs of residential space heating, space cooling, and sanitary water heating or process heating (cooling) using geothermal energy. The model is a powerful analytical tool for cost analysis of geothermal heating and cooling. It can calculate geothermal heating and cooling costs for residential developments, a multi-district city, or a point demand such as an industrial factory or commercial building. The model was developed in support of the program for Systems and Economic Analysis of Geothermal Energy at the Pacific Northwest Laboratory (PNL) under the sponsorship of the U.S. Department of Energy.

GEOCITY combines a simulation of the technical design, development, and steady-state operation of geothermal heating and cooling systems with an estimation of their capital and operating costs and a detailed cash flow simulation. This combination provides a valuable technical and economic planning tool. It is designed to aid in determining economic feasibility, preliminary design, systematic analysis of design options, sensitivity studies of economic and technical parameters, and integrated system operation. The model can be used for both conceptual analyses and also detailed analyses for specific sites.

The objective of this user manual is to provide users of the GEOCITY code with a basic understanding of the code operation and its capabilities. This manual presents a general description of the computer code, the details of the submodels and subroutines used to simulate the geothermal heating and cooling system, a detailed description of the input instructions and input data for using the code, the input for a sample problem, and a description and listing of the corresponding computer output.

The block diagram in Figure 1 shows an overview of the technical and economic simulation used to calculate the cost of geothermal heating and cooling systems. As Figure 1 delineates, GEOCITY is composed of two principal parts:

FIGURE 1. Overview of Technical and Economic Simulation for Geothermal District Heating and Cooling System

the geothermal reservoir and fluid transmission submodel and the distribution system submodel. The reservoir and fluid transmission submodel simulates the design, development, and operation of a geothermal reservoir, the transmission of geothermal fluid to a distribution system, and the injection of the used geothermal fluid. This submodel also calculates the capital and operating costs of the reservoir and the fluid transmission and injection system.

The distribution system submodel simulates the design, development, and operation of the district heating and cooling distribution system. The distribution submodel can simulate many designs for hot water heating and cooling systems. These designs include an optional heat exchanger at the inlet to the distribution system, various material and configuration options for pipes,

insulation, and conduits, and lithium bromide/water absorption chillers at each building for geothermal space cooling. The distribution system submodel also calculates the capital and operating costs of the distribution system. An iterative process between the two submodels is used to converge on the geothermal fluid requirements by the distribution system, taking into account fluid and thermal losses in the piping system from the reservoir to the end-users.

GEOCITY combines the computed capital and operating costs of the reservoir and fluid transmission system with its financial and tax input data to simulate detailed cash flows for the exploration, development, and operation of the reservoir and fluid transmission system. Cash flows are simulated annually from the beginning of exploration through the system operational lifetime. Well drilling costs may be calculated internally by the well drilling model or input by the user. Discounted cash flow analysis is used to calculate the life-cycle cost of thermal energy from the reservoir and fluid transmission system to the distribution system.

GEOCITY then combines the computed capital and operating costs of the distribution system with its financial and tax input data to simulate detailed cash flows for the construction and operation of the distribution system. Cash flows are simulated annually from the beginning of construction through the system operational lifetime. The purchase of thermal energy from the reservoir and fluid transmission system is one of the annual operating costs to the distribution system in the cash flow simulation. Discounted cash flow analysis is used to calculate the life-cycle cost of heat (chill) delivered by the distribution system to the end-user. The cost is expressed in dollars per million British thermal units (\$/MBtu) of delivered heat (chill) and in dollars per household per year of delivered heat (chill) to the end-user.

Retrofit costs for space heating can also be input by the user to include the cost of radiators, convectors, fan-coil units, or other in-house heating systems in the economic analysis. Retrofit costs for process heating can be input to include the cost of a process heat exchanger at the end-user's location. Geothermal space or process cooling is currently simulated in the model by the use of lithium bromide/water absorption chillers located at each building. Retrofit costs for space or process cooling can also be input to include

the installed cost of the absorption chillers, fan-coil units, and other auxiliary equipment. In the future, dual-temperature heat pumps will also be simulated at each building as another option for designing geothermal space or process heating and cooling systems.

GEOCITY uses discounted cash flow analysis to calculate the unit cost of thermal energy to the distribution system and the unit cost of heat (chill) to the end-user. The calculations are based on the principle that the present worth of the revenues must equal the present worth of the expenses, including investment return, over the economic life of the reservoir and fluid transmission system and distribution system. The model can simulate nearly any financial and tax structure through varying the rates of return on debt and equity, the debt-equity ratios, tax rates, and depreciation schedules. Both private enterprise and municipal utility systems can be simulated. The companies operating the reservoir and fluid transmission system and the distribution system may have the same or differing financial structures and costs of capital.

The model provides the flexibility to individually or collectively evaluate the impact of many technical and economic parameters on the cost of delivered heat (chill) to the end-user. This includes the technical characteristics of the reservoir and fluid transmission system (such as geothermal resource characteristics, well drilling costs, and the distance of the reservoir to the distribution system), the technical characteristics of the distribution system (including climate, demographic factors, thermal energy demands, and different piping system designs and materials), and financial and tax conditions. An overview of the generic classes of input data is presented in Figure 2.

The model has the flexibility to update capital and operating cost estimates of the reservoir, fluid transmission system, and distribution system. Currently, the default value is January 1980 dollars. This updating feature is extremely important to prevent obsolescence of the cost estimates generated by using the code in future years. Of course, radical changes in geothermal technology or construction in future years (e.g., changes affecting well drilling, downhole pumps, heat exchangers, piping systems, or absorption chillers) would require modifications to the subroutines in the code that calculate the costs of these elements.

FIGURE 2. Overview of Generic Classes of Input Data to GEOCITY

The model can also include the effects of inflation and price escalation in calculating the capital and operating costs over the simulated lifetime of the reservoir and fluid transmission system and distribution system. The user can operate the code to perform either current dollar analysis with inflation and price escalation or constant dollar analysis without inflation and price escalation.

The user can specify various levels of output from the model that provide a wide range of technical and economic information on geothermal heating and cooling systems. This includes not only detailed cash flows and cost estimates, but also technical information on the reservoir wellfield layout, fluid transmission and injection piping description, heat exchanger and distribution piping description, flow rates, thermal losses, pressure drops, pumping energy consumption, and the system load factor.

To facilitate finding specific information, this user manual is organized into four major sections and eight appendices. Section 1.0 introduces the user to the background and purpose of the code and scope of the manual. Section 2.0 provides a general description of the GEOCITY code, including the details of the submodels and of the subroutines that carry out the computations arising from the submodels. Section 3.0 describes in detail the preparation of the input data and a sample input problem. Section 4.0 describes the computer output corresponding to the sample input problem. The reader who wants to rapidly learn to use the code can simply read Section 2.1 (Overview), Section 2.2 (General Program Design), Section 3.0 (Preparation of Input Data), and Section 4.0 (Description of Output).

Appendices A through G describe the following items: A) cost equations for the pre-development, development, and operation of the reservoir and fluid transmission system; B) capital and operating cost models stored in the code for the distribution system; C) predefined residential district types stored in the code for the distribution system; D) capital cost models stored in the code for the reservoir and fluid transmission system; E) key equations for the cooling degree hour methodology; F) a trouble-shooting guide in case the code fails to execute properly; and G) a listing of the sample computer output corresponding to the sample data input. The manual concludes with an index to the input

parameters and an index to the subroutines to aid the code user in locating the descriptions of the input parameters and subroutines in this manual.

2.0 DESCRIPTION OF PROGRAM

2.1 OVERVIEW OF A TYPICAL GEOTHERMAL DISTRICT HEATING AND COOLING INSTALLATION

The U.S. Geological Survey has identified many known hydrothermal resources covering a wide range of resource temperatures.⁽¹⁾ These resources have the potential to supply geothermal energy for a wide range of space and process heating or cooling applications.⁽²⁾ The conceptual design in Figure 3 shows the layout of a typical geothermal installation simulated in GEOCITY for extracting and utilizing this thermal energy for district heating and/or cooling.

As Figure 3 delineates, the installation consists of two principal parts: the reservoir and fluid transmission system and the distribution system. The reservoir and fluid transmission system produces the geothermal fluid, transmits the fluid to the inlet of the distribution system, and disposes (or injects) the used fluid. The distribution system delivers either the geothermal fluid or circulating hot water from an optional heat exchanger at the distribution inlet to the end-users for space or process heating and/or cooling.

The major components comprising the reservoir and fluid transmission system in GEOCITY are the production wellfield, the fluid pumping system, an optional fluid mixing tank, the fluid transmission piping system, an optional fluid injection piping system, and an optional injection wellfield. During operation, the geothermal fluid is pumped from the production wells using submersible downhole pumps into a surface transmission piping system. An optional fluid mixer at the outlet of the production wellfield is provided to blend cold water from an external source with the hotter geothermal fluid to lower its temperature (if necessary for safety reasons) prior to transmission to the distribution system. The original or blended geothermal fluid is then pumped through a surface transmission pipeline to the distribution system to extract thermal energy for space or process heating and cooling. The used fluid is either disposed of into a sewer system or pumped through another surface pipeline into an injection piping system. The injection wells can be either located in the production wellfield or in a separate injection wellfield.

FIGURE 3. Schematic of Major Elements of Geothermal District Heating and Cooling System

The major components comprising the distribution system are an optional heat exchanger with tube-side and shell-side pumps and a buried piping system with pumps for delivering the thermal energy to the end-users. During operation, the geothermal fluid is either pumped directly into the distribution system or circulated through the optional heat exchanger to extract its thermal energy. The geothermal fluid or circulating hot water inside the distribution system is then pumped to either a residential development, a multi-district city consisting of multiple residential developments, or a single point demand such as an industrial factory or commercial building.

GEOCITY currently simulates hot water distribution systems. Geothermal space heating is assumed to be provided by circulating hot water through radiators, convectors, fan-coil units, or other in-house heating systems. Geothermal process heating is provided by directly using the hot water or by circulating it through a process heat exchanger. Geothermal space or process cooling is simulated by circulating hot water through lithium bromide/water absorption chillers located at each building. A network of buried, insulated pipes delivers the hot water to the buildings. As shown in Figure 3, the distribution piping system consists of a main, lateral, street pipes, and street-to-house pipes with an optional set of parallel return pipes. One main pipe and one optional return main transmit the hot water to a point demand. Either single or two-pipe distribution systems are available. In single-pipe, once-through distribution systems, fluid disposal is through a conventional sewer system. In two-pipe systems, the fluid is recirculated, conserving the fluid and residual heat.

The preceeding description of the geothermal installation is now followed by an overview of the simulation used in GEOCITY to calculate the cost of geothermal heating and cooling. The technical design, integrated system operation, capital costs, and operating costs of the geothermal system are simulated in the code by an executive routine (DGHEAT), the reservoir and fluid transmission submodel, and the distribution submodel. These submodels are described in Sections 2.5 through 2.7.

The executive routine DGHEAT and the reservoir and fluid transmission submodel employ the characteristics of the geothermal resource, system design

parameters, and computed peak flow requirements of the distribution system to design the reservoir and fluid transmission system and calculate its capital and operating costs. The executive routine uses an iterative procedure between the reservoir and fluid transmission submodel and the distribution submodel to determine the peak and average flow requirements of the distribution system based upon the thermal content of the degraded fluid after transmission to the distribution system. This iterative procedure designs the wellfields, pumps, pipelines, and optional heat exchanger, taking into account fluid and thermal losses in the pipelines.

The reservoir and fluid transmission submodel does not attempt to simulate subterranean fluid or thermal flow within the reservoir. Instead, the salient reservoir characteristics are represented by input parameters that define the flowing wellhead temperature, flow capacity of the well, average well life, well spacing, downhole pump depth, and well depth. Steady-state flow rates and temperatures are assumed for each of the wells over the well lifetime.

The executive routine DGHEAT and the distribution submodel design the hot water distribution system and calculate its capital and operating costs. Climatic parameters and input energy demand characteristics are used in residential space heating and cooling applications to determine peak and average thermal energy demands, peak and average flow rates, the system load factor, and supplemental heating requirements (if any). The computed peak flow rates in each section of pipe are then used in conjunction with material and design options for pipe, insulation, and casing to design the main, lateral, street, and street-to-house piping system. The pipe sizes and insulation thicknesses are automatically optimized to a lowest total cost based upon the mix of capital cost, thermal losses, and required pumping energy.

The input data for the distribution system defines energy demand characteristics for a single point demand (e.g., a large commercial building or factory), residential districts, or a multi-district city. Each district is a contiguous area consisting of buildings of similar heat (chill) demand and uniform density. Five residential district types, representing typical residential areas, and one point demand are defined in the distribution submodel; variations of the district types or other district types (including commercial districts) can be

added to the input data as required. Retrofit costs for a typical building in each district type can be defined in the input data for both heating and cooling applications.

After the executive routine DGHEAT completes the iterative simulation between the reservoir and fluid transmission submodel and the distribution submodel, the capital and operating costs of the two systems are combined with financial and tax input parameters in discounted cash flow submodels for the two systems. These submodels simulate the annual cash flows for all capital and operating costs over the lifetimes of the reservoir and fluid transmission system and the distribution system. Discounted cash flow analysis is used to calculate the life-cycle cost of thermal energy sold to the distribution system by the reservoir and fluid transmission system, and the unit cost of heat (chill) sold to the end-users by the distribution system. These costs (expressed in \$/million Btu and \$/household/yr) are the prices that must be charged to recover all costs of production, including capital investment, operating expenses, taxes, and a specified rate of return on investment.

2.2 GENERAL PROGRAM DESIGN

GEOCITY is designed in modular fashion with 84 technical and economic subroutines. In addition to the standard FORTRAN library functions, 63 subroutines comprising the 1967 ASME Steam Tables^(3,4) are used to calculate thermodynamic and physical properties of pure water, including pressure, temperature, enthalpy, specific volume, density, viscosity and fluid quality. GEOCITY and the steam tables contain approximately 14,000 and 4000 FORTRAN statements respectively.

GEOCITY and the ASME Steam Tables are programmed in ASCII FORTRAN using double precision and are operational on the UNIVAC 1100/44 computer with EXEC level 36 operating system. The overall program requires 30 minutes to compile (without optimization) on the ASCII FORTRAN level 8R1 compiler on the UNIVAC 1100/44 computer. The entire program requires approximately 150,000 decimal words of computer memory for execution. The sample case described in Section 3.2 required 30 seconds of CPU time for execution on the UNIVAC 1100/44 computer.

The source code for GEOCITY and the ASME Steam Tables, the sample data input described in Section 3.2, and the sample computer output in Appendix G are available from the Argonne Code Center on one reel of magnetic tape. The program can be converted to other UNIVAC computer facilities with a minimal set of basic control cards required to compile, load, and execute a FORTRAN source program from tape. Numerous comment cards are provided in the source code to facilitate understanding of the logic in the code. It is recommended that the user initialize computer memory to 0 with an appropriate control card before executing the GEOCITY code.

The block diagram in Figure 4 shows the computational flow through the major submodels of GEOCITY. Figure 5 shows the detailed, logical layout of the subroutines in each major submodel and serves as the basis for the operational description of the major sequence of calculations in GEOCITY.

The major submodels and their associated subroutines in GEOCITY are described in Sections 2.3 through 2.9 in the order of their execution in the computer code. The user may want to refer to Figures 4 and 5 in reading the descriptions of the submodels and their subroutines. The submodels are as follows:

- Main Program
- Data Input Submodel
- Executive Routine for Reservoir and Fluid Transmission System Submodel and Distribution System Submodel
- Reservoir and Fluid Transmission System Submodel
- Distribution System Submodel
- Discounted Cash Flow Submodel for Reservoir and Fluid Transmission System
- Discounted Cash Flow Submodel for Distribution System

The ASME Steam Table functions are called from many subroutines in GEOCITY, but are not shown in Figure 5 for the sake of brevity. These functions are summarized in Section 2.10, following the descriptions of the submodels and their subroutines.

Two small financial subroutines, UPDATE and ESCALT, are also called from many subroutines in the code, but are not shown in Figure 5. Subroutine UPDATE updates the capital and operating costs calculated in the code to base year

FIGURE 4. Structure of GEOCITY Computer Model

FIGURE 5. Flow Diagrams for GEOCITY with Submodels and Subroutines shown in the Order of Computational Flow

FIGURE 5. (continued)

dollars as described in Section 3.5.5.1. The default update is to January 1980 dollars.

Subroutine ESCALT escalates the computed capital and operating costs at a compound rate in each year over the simulated lifetime of the geothermal district heating and cooling system. Input parameters define price escalation rates that reflect a combination of inflation, supply/demand, and other price effects for four generic categories in the reservoir and fluid transmission system and the distribution system: capital equipment, O&M expenses, electrical expenses for pumps, and purchased thermal energy. The parameters are described in Section 3.5.5.2.

2.3 MAIN PROGRAM

The main program controls the sequence of processing by the major submodels to simulate the technical design and calculate the economic costs of the geothermal district heating and cooling system. As previously noted, Figure 3 shows the major submodels called directly or indirectly by the main program. As the first step to set up the initialization, the main program calls the BLOCK DATA subroutine ADATA to initialize the default values for the technical and economic input parameters. This is followed by a series of calls to subroutines from the ASME Steam Tables to initialize constants required by the steam table functions (see Figure 5).

The main program then calls the data input submodel simulated by subroutine LOAD and its associated subroutines. The data input submodel allows the code user to override the default values for the input parameters and to input new values using the NAMELIST feature. The main program next calls the executive routine DGHEAT to initiate and control the iterations between the reservoir and fluid transmission system and the distribution system submodels. This iterative process designs the reservoir and fluid transmission system and the distribution system and calculates their capital and operating costs.

Using these cost estimates, the main program calls the discounted cash flow submodel for the reservoir and fluid transmission system (simulated by subroutine RESVOR and its associated subroutines) to calculate the life-cycle, levelized unit cost of thermal energy from the reservoir and fluid transmission

system, deflated to base year dollars. Subroutine SLEVEL is called to break down the cost of thermal energy from the reservoir and fluid transmission system into three basic components: 1) capital costs, 2) O&M costs, and 3) pumping electricity costs.

The main program next calls the discounted cash flow submodel for the distribution system (simulated by subroutine DISTRB and its associated subroutines) to calculate the life-cycle, levelized unit cost of heat (chill) from the distribution system (to the end-user), deflated to base year dollars. Subroutine DLEVEL is called to break down the cost of heat (chill) from the distribution system into four basic components: 1) capital costs, 2) O&M costs, 3) purchased supplemental heating costs, and 4) pumping electricity costs.

Finally, the main program calls subroutine SPRINT to print a financial summary of the simulation. Subroutine LOAD is then called again to read in the input data for the next simulation case, and execution is terminated if there are no more cases.

The subroutines called by the main program are described below in the order of their execution in the code.

ADATA The BLOCK DATA subroutine that initializes the default values for the input parameters when the code is loaded into computer memory.

CCSR1, CCSR2, Subroutines from the ASME Steam Tables that initialize steam
CCSR3, CCBLL, table constants required in calculations by the steam table
and **COMALL** functions.

LOAD Subroutine LOAD and its associated subroutines described in Section 2.4 comprise the data input submodel. This subroutine reads the input data using the NAMELIST feature to override the default values initialized in BLOCK DATA. Subroutine LOAD also calls supporting subroutines to echo back a record of the input data and generate printer plots of key capital cost equations stored in the code for the distribution system.

DGHEAT The executive routine DGHEAT initiates and controls the iterative process between the reservoir and fluid transmission system and

the distribution system submodels. This iterative process performs the basic design and calculates the capital and operating costs of the reservoir and fluid transmission system and the distribution system. The executive routine DGHEAT is described in Section 2.5; the submodels for the reservoir and fluid transmission system and the distribution system are described in Sections 2.6 and 2.7 respectively.

- RESVOR Subroutine RESVOR and its associated subroutines described in Section 2.8 comprise the discounted cash flow submodel for the reservoir and fluid transmission system. This submodel generates the annual cash flow associated with the pre-development, development, and operation of the reservoir and fluid transmission system and uses discounted cash flow analysis to calculate the unit cost of thermal energy from the reservoir and fluid transmission system.
- SLEVEL Subroutine SLEVEL breaks down the unit cost of thermal energy from the reservoir and fluid transmission system in base year dollars into three basic components: 1) capital costs, 2) O&M costs, and 3) pumping electricity costs.
- DISTRB Subroutine DISTRB and its associated subroutines described in Section 2.9 comprise the discounted cash flow submodel for the distribution system. This submodel generates the annual cash flow associated with the design, construction, and operation of the distribution system and uses discounted cash flow analysis to calculate the unit cost of heat (chill) from the distribution system.
- DLEVEL The second half of subroutine SLEVEL, defined by the entry point DLEVEL, breaks down the unit cost of heat (chill) from the distribution system in base year dollars into four basic components: 1) capital costs, 2) O&M costs, 3) purchased supplemental heating costs, and 4) pumping electricity costs.
- SPRINT Subroutine SPRINT prints a summary of the key financial results at the end of the simulation run.

2.4 DATA INPUT SUBMODEL

The data input submodel is comprised of subroutine LOAD and nine supporting subroutines. This submodel performs the following five activities in the code:

- 1) initializes the default values for several of the input parameters
- 2) reads in new values for the input parameters using the NAMELIST feature
- 3) performs scale conversions for several of the input parameters for internal usage in the code
- 4) prints a record of the input data at the beginning of the simulation run
- 5) generates optional printer plots of several of the key capital cost equations stored in the code for the distribution piping system

The input data and its default values for the reservoir and fluid transmission system and the distribution system are described in Section 3.0. The subroutines called by subroutine LOAD to read, convert, and print the input data are described below in the order of their execution in the code.

ECHO	Prints out a comprehensive record of the input data at the beginning of the simulation run.
PHOTOD	Calls subroutine TOLP to generate printer plots of key capital cost equations stored in the code for estimating the capital costs of various components of the distribution piping system, including pipes, insulation, and casing, over a wide range of pipe diameters. The capital cost equations, which are described in Appendix B, constitute an internal data base stored in the code. The coefficients in the capital cost equations for the distribution system are defined in subroutines DATA, SIZE, DIST, and PHOTOD of the code. Future changes to these coefficients, if needed, can be made through these four subroutines.
SWITCH(0)	Stores the first 35 values of the DINPUT array, DINPUT(N), N=1,...,35, defining input financial and tax data for the reservoir and fluid transmission system (see Section 3.5.1) into an internal work array, D(N), N=1,...,35. SWITCH(1) stores the second set of 35 values of the DINPUT array, DINPUT(N),

N=36,...,70, defining input financial and tax data for the distribution system (see Section 3.5.3) into the same work array, D(N), N=1,...,35. The common work array has similar definitions for the reservoir and fluid transmission system and the distribution system, although the individual elements transferred from the first and second set of 35 values in the DINPUT array can have different numerical values.

DATE Subroutine DATE is a system routine on the UNIVAC computer that returns the current date in the form 'MM/DD/YY'
where: MM = the current month of the year
DD = the current day of the month
YY = the current year.

DEGC Returns centigrade temperature expressed as a positive number when Fahrenheit temperature is input as a negative number. Centigrade temperature input as a positive number is returned unchanged. The input parameter that can use this option is the wellhead temperature, PWTEMP.

FEET Returns meters expressed as a positive number when feet are input as a negative number. Meters input as a positive number are returned unchanged. The input parameter that can use this option is the well depth, STRATA(2,1).

INCHES Returns centimeters expressed as a positive number when inches are input as a negative number. Centimeters input as a positive number are returned unchanged. The input parameter that can use this option is the well diameter, DIA.

PAGE Controls the number of lines printed per page, prints an input title at the top of the page, and numbers pages. This routine is called from various subroutines throughout the code.

2.5 EXECUTIVE ROUTINE FOR RESERVOIR AND FLUID TRANSMISSION SYSTEM SUBMODEL AND DISTRIBUTION SYSTEM SUBMODEL

The executive routine DGHEAT is a key subroutine in the GEOCITY code. It initiates and controls the iterations between the subroutines comprising the

components of the reservoir and fluid transmission system submodel and the distribution system submodel. This iterative procedure simulates the design and calculates the capital and operating costs of these two systems. The major subroutines called by subroutine DGHEAT in simulating the two systems are shown in Figure 6 in the order in which they are called.

The executive routine DGHEAT is summarized below by a walk-through of its operational logic, followed by a brief description of the major subroutines in Figure 6 called by subroutine DGHEAT. Since these subroutines simulate the reservoir and fluid transmission system and the distribution system, a more detailed description is given in the descriptions of the submodels for these two systems in Section 2.6 and 2.7 respectively. The computational steps performed by subroutine DGHEAT are as follows:

1. Several conversion factors used in computing the heat demand required for sanitary water heating are calculated by subroutine CONVRT. The computation of the conversion factors is described in Section 2.7.3.1.
2. Subroutine DGHEAT sets the flowing wellhead temperature and pressure of the geothermal fluid. The wellhead temperature is defined in the input data as the parameter PWTEMP. The wellhead pressure is set by multiplying the saturation pressure corresponding to the input wellhead temperature by the pumping pressurization factor PRFACT. This factor is initially set to 2 in the BLOCK DATA subroutine to prevent flashing and two-phase flow (i.e., permit only compressed liquid flow) in the first iteration through the reservoir and fluid transmission system submodel. It is then minimized during subsequent iterations; however, the final minimized pressurization at the wellhead is still sufficient to prevent two-phase flow in the wellfield piping. The wellhead pressurization is provided by either downhole pumps in the production wells or surface pumps at the production wellheads, depending upon the pumping configuration selected by the user, as explained in Section 3.3.2.
3. In the combined heating and cooling mode (only), the peak fluid requirements of the distribution system are calculated separately in subroutine COMODE for: 1) space heating and sanitary water heating and 2) space cooling and sanitary water heating. In the combined mode, GEOCITY assumes

FIGURE 6. Sequence of Subroutines Called by the Executive Routine DGHEAT to Simulate the Reservoir and Fluid Transmission System and the Distribution System

that the sanitary water heating requirements over the year are split evenly into the heating and cooling modes. Subroutine COMODE labels the mode (heating or cooling) with the larger peak fluid requirement of the distribution system as the major mode. The other mode is labeled the minor mode.

Subroutine COMODE also calculates the average and peak thermal energy requirements, the average and peak fluid requirements, and the load factors separately for the major and minor modes. It then combines the thermal energy requirements and load factors for the two modes to obtain the thermal energy requirements and load factor for the combined mode, as described in Section 2.7.3.3. Descriptions of subsequent calculations using the major and minor modes in the combined heating and cooling mode are deferred until after the description of Step 11 below. The walk-through of subroutine DGHEAT continues with the operational logic for simulating either residential space heating and sanitary water heating or residential space cooling and sanitary water heating or process heating (cooling) in steps 4 through 11 below.

4. The peak fluid requirement of the distribution system is calculated in subroutine CALQNA based upon the degraded conditions (temperature and enthalpy) of the fluid delivered by the reservoir and fluid transmission system to the distribution system or its optional heat exchanger. The fluid conditions at the wellhead or at the outlet from the optional fluid mixing tank (Figure 3) are used as the initial guess of the fluid conditions entering the distribution system or its optional heat exchanger. This procedure is used simply to obtain an initial estimate of the peak fluid requirement for subsequent refinement. The equations for calculating the peak fluid requirement of the distribution system are described in Section 2.7.3.
5. Based upon the peak fluid requirement, the design (size) and cost of the reservoir and fluid transmission system are calculated by subroutine TRANS and its supporting routines. These subroutines calculate the number of required production wells, production wellfield layout, the pipe lengths,

diameters, and schedules, the insulation thickness, thermal losses, pressure drops, pumping requirements, and capital and operating costs of the reservoir and fluid transmission system. Subroutine TRANS and its supporting routines are described in Section 2.6.

6. The peak fluid flow requirement calculated for the distribution system, based upon the degraded fluid conditions entering the distribution system or its optional heat exchanger, in the current iteration is compared in subroutine CONVRG with the peak fluid flow requirement calculated in the previous iteration. The convergence criterion requires that the new peak fluid flow requirement differ by less than 2% from that calculated in the previous iteration. If the peak fluid flow requirement has not yet converged, subroutine DGHEAT returns to steps 4 and 5 to recalculate the peak fluid flow requirement of the distribution system and the number of wells, transmission piping system, fluid degradation (thermal losses and pressure drops), and capital and operating costs of the reservoir and fluid transmission system. The recomputed peak fluid flow requirement of the distribution system, which is based upon the recomputed fluid degradation during fluid transmission from the reservoir to the distribution system, is then retested for convergence in step 6.

After satisfying the convergence criterion, subroutine DGHEAT executes steps 4, 5, and 6 one more time to satisfy the input option (see parameter LL6 in Section 3.6) of printing the final iteration only or printing the entire iteration history of steps 4, 5, and 6. Subroutine DGHEAT then proceeds to step 7. Failure to converge within 20 iterations for steps 4, 5, and 6 stops the execution of the code and prints an error message.

7. If the optional heat exchanger is not used at the inlet to the distribution system, subroutine DGHEAT proceeds to step 9. Otherwise, the design characteristics of the heat exchanger, including its heat transfer coefficients, heat transfer area, number of tubes, tube-side and shell-side pressure drops, and capital and operating costs, are calculated by subroutine SUBHEX and its supporting routines. These subroutines are described in Section 2.7.1.

8. The capital cost and electrical operating cost of pumps at the tube-side and shell-side inlets to the heat exchanger are calculated by subroutine PUMP.
9. Subroutine DGHEAT checks the fluid injection option and calls subroutine INJECT, an entry point in subroutine TRANS, if the injection option is used. The used geothermal fluid is injected from either the distribution system or its optional heat exchanger. Subroutine INJECT and its supporting routines calculate the number of required injection wells, injection wellfield layout, the injection pipe lengths, diameters, and schedules, the pumping requirements, and the capital and operating costs of the injection system. If fluid injection is not specified, the used fluid is assumed to be disposed into a sewer system or river and no disposal costs are calculated.
10. The technical design of the distribution system and its capital and operating costs are calculated by subroutine DIST and its supporting routines. This includes the detailed design and costs of the entire supply and return piping network in the distribution system (Figure 3): street-to-building, street, lateral, and main piping sections. Subroutine DIST and its supporting routines are described in Section 2.7.4.
11. The output for the distribution system is printed by subroutines DIST and DWRIT2.

In the combined heating and cooling mode (only), the reservoir and fluid transmission system and the distribution system are simulated in two principal steps. In terms of Figure 6, the enclosed block of eight subroutines from CALQNA through DWRIT2 are executed twice. In the first step, the major mode (heating or cooling, whichever has the larger peak flow requirement, as determined by subroutine COMODE) is simulated in the enclosed block of eight subroutines. This simulation is used to design and size the reservoir and fluid transmission system and the distribution system based on the thermal energy requirements, peak fluid requirements, thermal losses, pressure drops, and pumping requirements of the major mode. Specifically, this simulation designs and sizes the production wellfield, fluid transmission system, (optional) heat

exchanger, (optional) injection system and injection wellfield, and the distribution system. All capital costs (except distribution retrofit costs associated with the minor mode) and that portion of operating costs associated with the major mode (based on its load factor) are calculated in the simulation of the major mode.

In the second step, the minor mode is simulated in the enclosed block of eight subroutines in Figure 6. This step uses the system design and sizes determined in the simulation of the major mode to calculate the thermal losses, pressure drops, incremental pumping requirements, incremental capital costs (i.e., distribution retrofit costs associated with the minor mode), and incremental operating costs for the minor mode (based on its load factor). In these calculations, the thermal energy requirements and peak fluid requirements for the minor mode are used.

During the second step, the results from the major and minor modes are added to obtain the total thermal energy requirements, load factor, capital costs, and operating costs for the combined heating and cooling mode. A discussion of the rationale for adding the thermal energy requirements and load factors of the major and minor modes is given in Section 2.7.3.3.

After calling the subroutines shown in Figure 6, subroutine DGHEAT returns control to subroutine LOAD and subsequently to the main program in GEOCITY. The main program then calls the discounted cash flow submodels (Figure 4). These submodels combine the total capital costs, operating costs, system load factor, and thermal energy requirements from the reservoir and fluid transmission system and the distribution system with their respective financial and tax input data. Detailed cash flows are simulated over the lifetime of the project and discounted cash flow analysis is used to calculate the life-cycle cost of heating and/or cooling to the end-user.

2.6 RESERVOIR AND FLUID TRANSMISSION SYSTEM SUBMODEL (Technical Design and Costs)

The reservoir and fluid transmission system submodel simulates the design and calculates the capital and operating costs of the reservoir and fluid transmission system previously shown in Figure 3. The major elements comprising

this system are the production wellfield, fluid pumping system, (optional) fluid mixing tank, fluid transmission piping system, (optional) fluid injection piping system, and (optional) injection wellfield. The functional operation of these component elements was previously described in Section 2.1.

The reservoir and fluid transmission system submodel is decomposed into the subroutines that simulate its component elements in Figure 7. As previously described in Section 2.5, the executive routine DGHEAT calls subroutine TRANS to simulate the technical design and calculate the capital and operating costs of the production wellfield, fluid pumping system, (optional) fluid mixing tank, and fluid transmission piping system from the production wells to the inlet of the distribution system. Subroutine TRANS calls 16 supporting subroutines shown in Figure 7 to simulate these four component elements. The quantities calculated in the simulation include:

- Number of wells in the production wellfield.
- Production wellfield layout.
- Downhole and surface pumping requirements.
- Thermodynamic and flow conditions from the optional fluid mixing tank located at the outlet of the production wellfield.
- Optimum pipe diameters, schedules, insulation, and casing for the gathering pipes in the production wellfield and the final transmission pipeline to the distribution system.
- Fluid thermal-hydraulic conditions during transmission from the production wells to the distribution system.
- Capital and operating costs for the pumps and piping system.

Descriptions of the technical parameters used to design the reservoir and fluid transmission system are given in Section 3.3, together with a discussion of their functional usage in the simulation. As noted in Section 3.3, GEOCITY does not have a thermal-hydraulics model to simulate subterranean fluid and thermal flow in the reservoir. Instead, relevant reservoir characteristics and

^aINCLUDES LOGIC FOR DOWNHOLE PUMPS IN SUBROUTINE TRANS

^bINCLUDES CAPITAL AND OPERATING COST MODELS IN SUBROUTINE TRANS

^cINCLUDES CAPITAL AND OPERATING COST MODELS IN SUBROUTINE INJECT

ALL ABOVE SUBROUTINES DESCRIBED IN TEXT

FIGURE 7. Subroutines Called by Subroutines TRANS and INJECT to Simulate the Elements of the Reservoir and Fluid Transmission System

well properties are represented by input parameters that define such steady-state conditions as the flowing production wellhead temperature, the flow capacities of the production and injection wells, average production well life, downhole pump depth, well spacing, well depth, number of excess production wells desired, and number of dry wells drilled.

The major sequence of calculations performed by subroutine TRANS and its supporting subroutines is now summarized. Subroutine TRANS calls subroutine DESIGN to calculate the number of wells in the production wellfield based on the peak flow requirements of the distribution system and several input parameters, which include: the flow capacity of the wells, the fraction of excess wells desired, and the fraction of dry wells drilled. Production and injection wells are located at the vertices of triangular lattices defining the wellfield geometry, as explained below in the description of subroutine DESIGN.

Subroutine TRANS calls subroutines TBPUMP, TBCOST, and PUMP to calculate pumping requirements by downhole and surface pumps to maintain the geothermal fluid in a compressed liquid state during transmission from the production wells to the distribution system. The pumping system configuration is described in Section 3.3.2. Subroutine TRANS also calculates an enthalpy balance across the optional fluid mixing tank to determine the flow rate and temperature of the blended mixture of hot geothermal fluid and cold water (from an external cold water source) pumped from the mixing tank to the distribution system.

The piping system is sized based upon the peak flow rate required from the reservoir by the distribution system. Pipe diameters are optimized for each section of pipe in subroutines TRANS and PIPE to a lowest cost based upon the mix of installed capital costs of pipes and pumps and the annual pumping cost. Pipe schedules, insulation thickness and cost, and casing size and cost are determined in subroutines SCHEDL and INSUL as described below.

Thermal losses and pressure drops are calculated in subroutines SPFLOW and AGELOS for each section of pipe in the transmission piping network from the production wells to the distribution system. Thermal losses during fluid transmission are calculated based upon standard equations of heat transfer by convection and conduction from fluid flowing in an insulated, cylindrical pipe. Pressure drops in the piping network are calculated based upon the Darcy-Weisbach equation.

Capital and operating costs for the wellhead equipment, pumps, and piping network (pipe, insulation, casing and sitework) are calculated in subroutines EQCOST, TRANS, INSUL, TBCOST, and PUMP based upon the capital and operating cost models described in Appendix D. The output results summarizing the material requirements, thermodynamic and flow conditions, and costs of the four elements of the reservoir and fluid transmission system described above are printed by subroutines TRANS and TPRINT.

Two options described in Section 3.3.5 are available in the code for disposing of the used geothermal fluid from the distribution system or from its optional heat exchanger (Figure 3). The first option disposes of the used fluid in a sewer system or river without any disposal costs. The second option assumes that the used fluid is pumped through an injection piping system into an injection wellfield. Injection costs are calculated for the second option, which is described below.

As previously noted in Section 2.5, the executive routine DGHEAT calls subroutine INJECT to simulate the technical design and calculate the capital and operating costs of the injection pumping system, injection piping system, and injection wellfield. Subroutine INJECT, an entry point in the second half of subroutine TRANS, calls six supporting subroutines shown in Figure 7 to simulate these three component elements. The quantities calculated in the simulation include:

- Surface pumping requirements based on one large conceptual pump located at the distribution system (see description of subroutine IBCOST below).
- Optimum pipe diameters and schedules for the injection pipeline from the distribution system to the injection wellfield and for the pipes in the injection wellfield. No insulation or casing is used in the injection piping.
- Number of wells in the injection wellfield.
- Injection wellfield layout.
- Capital and operating costs for the injection pump and injection piping system.

The injection system is currently modeled more simplistically in the code than the transmission (i.e., production) system. In contrast to the transmission system, which calculates fluid degradation in each section of pipe, the injection system currently does not calculate fluid degradation between the distribution system and the injection wellfield. Instead, the pipes in each section of injection piping are sized based upon the peak flow rate for injection, holding constant the temperature, pressure, viscosity, and density of the used fluid in effect at the outlet of the injection pump, which is located at the distribution system or its optional heat exchanger (Figure 3).

The number of wells in the injection wellfield is calculated based upon the peak flow rate for injection from the optional heat exchanger or distribution system and the flow capacity of the injection wells. The latter parameter is input as a ratio relative to the capacity of the production wells.

Capital and operating costs for the injection pump and injection piping network (pipe and site work) are calculated in subroutines INJECT and IBCOST based upon the capital and operating cost models described in Appendix D. The output results summarizing the material requirements, the flow rate, temperature, and pressure of the used fluid to be injected, and the costs of the injection system are printed by subroutines INJECT and TPRINT.

The preceding discussion completes the overall description of the reservoir and fluid transmission system submodel for the heating or cooling mode. In the combined heating and cooling mode, this submodel is simulated in two principal steps. In the first step, the major mode (heating or cooling, whichever has the larger peak flow requirement) is simulated in subroutines TRANS, INJECT, and their supporting routines. This simulation is used to design and size the reservoir and fluid transmission system based upon the peak flow requirements, thermal losses, pressure drops and pumping requirements of the major mode. The simulation of the major mode determines all capital costs of the reservoir and fluid transmission system and that portion of operating costs associated with the major mode (based on its load factor).

In the second step, the minor mode is simulated in subroutines TRANS, INJECT, and their supporting routines. This step uses the system design and sizes determined in the major mode to calculate the thermal losses, pressure

drops, incremental pumping requirements, and incremental operating costs for the minor mode (based on its load factor). In these calculations, the peak flow requirements of the minor mode are used. During the second step, subroutines TRANS and INJECT combine the incremental operating costs of the minor mode with those of the major mode to obtain the total operating costs.

Descriptions of the subroutines called by either subroutine TRANS or INJECT are given below. The descriptions indicate whether one or both call each subroutine.

TROUT Subroutine TROUT is called by subroutine TRANS to print a summary of the key input parameters for the reservoir and fluid transmission system.

DESIGN Subroutine DESIGN is called by both subroutines TRANS and INJECT to calculate the number of production and injection wells, respectively. The injection wells can be either located in a separate area of the production wellfield or in a separate injection wellfield. Since the geometric layout of the two wellfields is similar in the code, the description below will focus on the production wellfield.

The wells are located at the vertices of equilateral triangles (nodes in a triangular lattice) as shown in Figure 8, with pipe runs parallel to the horizontal X-axis. The piping system includes a manifold pipeline for gathering the fluid from all horizontal rows of wells. Subroutine DESIGN calculates an effective average acreage (WACRE) per producing well based upon the input well spacing (WELSPC) in acres and the fraction (FRCNPW) of nonproducing (dry) wells according to the following equation:

$$WACRE = WELSPC * (1. + FRCNPW)$$

The area (WACRE) encompassed by each producing well (shaded area in Figure 8) is equal to the area of two equilateral triangles. Subroutine DESIGN calculates the pipe length (meters) between the producing wells based on the equation for the area of an equilateral triangle as follows:

FIGURE 8. Well Layout Design and Routing of Fluid Transmission Pipes

$$\text{Pipe length (m)} = (0.3048 \text{ m/ft})(5280 \text{ ft/mile})^*$$

$$\sqrt{\frac{\text{WACRE (acres)}}{(0.86603)(640 \text{ acres/sq mile})}}$$

EQCOST

Subroutine EQCOST is called by subroutine TRANS to calculate the cost of valves, instrumentation, and solids separators at the wellheads in the production wellfield. The cost models are defined in Appendix D.

TSTRT

Subroutine TSTRT is called by subroutine TRANS to initialize all production wellhead nodes (Figure 8) with the same input steady-state temperature. The simulation of variable wellhead temperatures would require code modifications.

TBPUMP

Subroutine TBPUMP is called by subroutine TRANS to calculate the number of required surface pumps and their boosted discharge pressures on the final transmission pipeline to the distribution

system. The surface pumps are needed to restore frictional pressure drops and maintain the fluid in a compressed liquid state at all times. The number of surface pumps along the final transmission pipeline is sufficient to avoid unnecessary high pump discharge pressures and, therefore, high pipe schedules; however, it is subject to the constraint that the pumps be located at least one mile apart.

- TBCOST** Subroutine TBCOST is called by subroutine TRANS. It calculates the installed capital cost and electrical usage of the surface booster pumps (determined by subroutine TBPUMP) along the final transmission pipeline to the distribution system.
- PUMP** Subroutine PUMP is called with its argument ITYPE set to 4 by subroutine TRANS. In this mode, it calculates the installed capital cost and the electrical usage of the downhole pumps in the production wells.
- IBCOST** Subroutine IBCOST is called by subroutine INJECT to calculate the installed capital cost and electrical usage of one large conceptual injection pump located at the distribution system (Figure 3.). The pump head is set to 200 psi in subroutine TRANS. Gravity flow is assumed down the injection wells.
- PIPE** Subroutine PIPE has two other entry points, PIPE1 and PIPE2. This subroutine is called by both subroutines TRANS and INJECT. It calculates the optimum pipe diameters for all transmission and injection piping. The calculation is based on the peak flow rate, fluid density and viscosity, and economic trade-offs between the components comprising the total cost function of the fluid transmission system: installed capital costs of pipes and pumps and annual pumping cost to restore frictional pressure drops. The total cost function for each section of pipe in the fluid transmission system is minimized with respect to the internal pipe diameter D by setting its derivative with respect to D equal to zero. An iterative solution for the optimum pipe diameter

in each section of pipe is obtained from the resulting equation based upon the Newton-Raphson algorithm.

SCHEDL

Subroutine SCHEDL is called by both subroutines TRANS and INJECT. It selects the pipe schedule for each section of pipe by selecting the smallest schedule (from a range of 10 to 160) that can withstand the maximum fluid pressure in each section of pipe. The maximum pressure that each schedule can accommodate is given in Appendix D. The pipe schedule and diameter are both used in calculating the installed cost of piping, as shown in Appendix D.

INSUL

Subroutine INSUL is called by subroutine TRANS. It sizes the pipe insulation for each section of transmission piping as a function of the fluid temperature, nominal outer pipe diameter, insulation thickness availability and cost, using two types of insulation. Calcium silicate is used for the inner layers of insulation, and (if required) polyurethane is used for the outer layers. Subroutine INSUL calculates both the cost of the insulation and the protective casing. No insulation or casing is used for the injection piping system in GEOCITY.

SPFLOW

Subroutine SPFLOW is called by subroutine TRANS to calculate the fluid degradation (thermal losses and pressure drops) during single-phase flow in the transmission piping. Fluid degradation is calculated in one step size, equal to the length of the pipe section. Calculations with smaller step size increments, such as 50 ft, showed no significant differences in the computed fluid degradation. However, smaller step size increments can be used by changing the parameter NSTEP in the BLOCK DATA subroutine if desired. The thermal losses are calculated using equations for convective and conductive thermal transfer between fluid flowing inside an insulated, cylindrical pipe and the ambient air. The pressure drops are calculated using the Darcy-Weisbach equation for turbulent flow in a new, cylindrical pipe. The fluid pressure is continuously maintained at or above saturation (i.e., in

a compressed liquid state) to prevent two-phase flow in the piping. Currently, GEOCITY does not model fluid degradation in the injection piping system.

- AGELOS Subroutine AGELOS is called by subroutine TRANS. It multiplies the pressure drop computed in subroutine SPFLOW for new transmission pipe by an age factor defined in the input data (see parameter AGFACT in Section 3.4.7). This increases the pressure drop to account for the increase in relative roughness due to deterioration of the pipes with age.
- FLPROP Subroutine FLPROP is called by subroutine TRANS. It identifies the fluid state in the transmission pipeline as compressed liquid, saturated liquid, two-phase mixture, saturated vapor or superheated steam. Actually, only the compressed liquid state should ever be encountered in the GEOCITY code. This subroutine is called for each section of pipe. The fluid state is identified based upon the pressure and enthalpy by querying subroutine XPHH and the ASME Steam Table functions. After identification of the fluid state in a particular pipe section, subroutine FLPROP calls the appropriate ASME Steam Table function to compute the specific volume, density, viscosity, temperature, or enthalpy of the fluid as requested by subroutine TRANS.
- XPHH Subroutine XPHH is called by subroutine FLPROP to calculate the fluid quality by weight fraction as a function of pressure and enthalpy. It returns 0 for saturated liquid and compressed liquid, 1 for saturated vapor and superheated steam, and values in between for two-phase mixtures of steam and water at saturation.
- TPHASE Subroutine TPHASE is called by subroutine TRANS. It tests whether or not the fluid quality in the pipeline has become unacceptable due to two-phase flow, in which case the code stops execution with an error message.
- TPRINT Subroutine TPRINT is called by subroutines TRANS and INJECT to print the fluid transmission and injection system costs.

MOUT Subroutine MOUT is called by subroutine TPRINT to print nodal arrays (temperature, pressure, density, viscosity, etc.) calculated in the reservoir and fluid transmission system submodel as matrices or vectors with accompanying titles. To reduce the quantity of printout, this feature is currently not being used.

2.7 DISTRIBUTION SYSTEM SUBMODEL (Technical Design and Costs)

2.7.1 Heat Exchanger at Inlet to Distribution System

An option for a heat exchanger is provided at the end of the transmission pipeline from the geothermal reservoir prior to the inlet of the distribution system. The heat exchanger can be used to protect the expensive, buried distribution piping system from scaling and corrosion by the chemical constituents in the geothermal fluid. Heat is transferred from the geothermal fluid to circulating clean water for use in the distribution system. The geothermal fluid is pumped through the tube-side and the circulating clean water is pumped through the shell-side of the heat exchanger.

The design characteristics and size of the heat exchanger are determined in subroutine SUBHEX and its associated subroutines. Subroutine SUBHEX is called from the executive routine DGHEAT before designing the distribution system. The input parameters and temperature profiles of the heat exchanger are described in Section 3.4.4. As previously mentioned in Section 2.5, the pumps at the tube-side and shell-side inlets to the heat exchanger are simulated in subroutine PUMP, also called by the executive routine DGHEAT.

The capital and operating costs of the heat exchanger are calculated in subroutine SUBHEX and included in the costs of the distribution system. The equations for these costs are given in Appendix B. The description of subroutine SUBHEX and its associated subroutines is given below.

SUBHEX Calculates the basic design characteristics and size of a liquid-to-liquid heat exchanger based upon a counterflow, single-pass, shell-and-tube unit constructed of carbon steel with an equilateral-triangular-tube configuration.

The input conditions to subroutine SUBHEX are:

- a) Tube-side and shell-side flow rates (lb/hr)
- b) Tube-side fluid temperatures at the heat exchanger inlet and outlet ($^{\circ}\text{F}$)
- c) Shell-side fluid temperatures ($^{\circ}\text{F}$) and enthalpies (Btu/lb) at the heat exchanger inlet and outlet
- d) Inside and outside fouling factors ($\text{hr}\cdot\text{ft}^2\cdot^{\circ}\text{F}/\text{Btu}$)
- e) Inside and outside tube diameters (ft)
- f) Tube-side fluid velocity (ft/hr).

The basic characteristics calculated for the heat exchanger are:

- a) Inside and outside heat transfer coefficients ($\text{Btu}/\text{hr}\cdot\text{ft}^2\cdot^{\circ}\text{F}$)
- b) Overall heat transfer coefficient ($\text{Btu}/\text{hr}\cdot\text{ft}^2\cdot^{\circ}\text{F}$)
- c) Number of heat exchanger tubes
- d) Total flow area (ft^2) and equivalent flow diameter (ft) for the shell-side
- e) Heat exchanger area (ft^2)
- f) Heat exchanger length (ft).

The characteristics of the heat exchanger are calculated in the steps described below, first for the tube-side and then for the shell-side.

- 1) The average of the inlet and outlet temperatures is calculated for the tube-side fluid and for the shell-side fluid for use in computation of physical properties.
- 2) The thermal conductivity, density, and viscosity of the tube-side fluid are calculated at the average tube-side fluid temperature (Step 1) using function FLUID.
- 3) The Reynolds number of the tube-side fluid is calculated in function REYNO. The Prandtl number is calculated in subroutine SUBHEX based on the specific heat c_p , viscosity μ , and thermal conductivity k of the tube-side fluid:

$$\text{Pr} = \frac{c_p \mu}{k}$$

- 4) The inside (tube-side) heat transfer coefficient is determined in function HTCOEF.
- 5) The number of tubes required for the tube-side fluid is calculated in function TUBES.
- 6) The total flow area and equivalent flow diameter for the shell-side are determined in subroutine QAREA.
- 7) The specific heat, thermal conductivity, density, and viscosity of the shell-side fluid are calculated at the average shell-side fluid temperature (Step 1) using function FLUID.
- 8) The velocity of the fluid in the tubes is set in the input data. The velocity of the fluid in the heat exchanger shell is calculated in function VELOCITY.
- 9) The Reynolds number of the shell-side fluid is calculated in function REYNO. The Prandtl number is calculated in subroutine SUBHEX based on the specific heat, viscosity, and thermal conductivity of the shell-side fluid.
- 10) The outside (shell-side) heat transfer coefficient is determined in subroutine HTCOEF.
- 11) The inside and outside heat transfer coefficients are combined with the thermal conductivity of the tube wall and the fouling factors to determine the overall heat transfer coefficient in function OHTCOE.
- 12) Knowing the amount of overall heat transfer desired, the heat transfer area and heat transfer length are calculated in functions HTAREA and HTLNHG, respectively.
- 13) The capital and operating costs of the heat exchanger are calculated based on equations described in Appendix B.
- 14) The design characteristics, capital costs, and operating costs of the heat exchanger are printed.
- 15) The pressure drops in the tube-side and shell-side of the heat exchanger are calculated in subroutine HXDROP.

The subroutines called by subroutine SUBHEX to calculate the basic characteristics of the heat exchanger are described below. Function FLUID, which is the first routine called by subroutine SUBHEX, is also called from some of the other subroutines (Figure 5) to calculate physical properties of pure water.

FLUID

Correlates physical properties of 10 different fluids to temperature at saturation. In GEOCITY, function FLUID is called only to calculate physical properties of pure water.

Each physical property for a particular fluid is expressed as a polynomial function of temperature in the elementary form:

$$\text{Property value} = K_0 + K_1T + K_2T^2 + K_3T^3 \text{ for } T_x < T < T_y$$

These expressions were correlated to available data in the temperature range T_x to T_y . The data were acquired through a search of numerous reference texts and publications.^(5,6,7)

Within the specified temperature range, there is good agreement between the actual and predicted values. A warning message is printed if the input temperature requires extrapolating the polynomials beyond the temperature range T_x to T_y specified in function FLUID for a given equation.

The polynomial functions are used to predict the following physical properties as a function of temperature at saturation: specific heat, thermal conductivity, density, viscosity, heat of vaporization, and surface tension. Critical pressure, critical temperature, and molecular weight are included as constants. When a physical property is desired, the following statement is made:

$$\text{Property Value} = \text{FLUID}(I, J, T)$$

where T = temperature at which the property is required ($^{\circ}\text{F}$)

$I = 1, 13$ - Property Index

1 - specific heat (liquid)(Btu/lb- $^{\circ}\text{F}$)

- 2 - thermal conductivity (liquid)(Btu/hr-ft-°F)
- 3 - density (liquid)(lb/ft³)
- 4 - viscosity (liquid)(lb_m/ft-hr)
- 5 - specific heat (gas)(Btu/lb-°F)
- 6 - thermal conductivity (gas)(Btu/hr-ft-°F)
- 7 - density (gas)(lb/ft³)
- 8 - viscosity (gas)(lb_m/ft-hr)
- 9 - heat of vaporization (Btu/lb)
- 10 - critical pressure (psia)
- 11 - critical temperature (°F)
- 12 - surface tension (lb_f/ft)
- 13 - molecular weight (lb/lb mole)

J =1- Fluid Index

- 1 - water (only fluid used in GEOCITY)

REYNO

Calculates the Reynolds number based upon the fluid density ρ , viscosity μ , velocity V , and flow diameter D :

$$Re = \rho \frac{DV}{\mu}$$

HTCOEF

Calculates inside and outside heat transfer coefficients based on the Dittus-Boelter equation for fully developed turbulent flow in smooth tubes. Subroutine HTCOEF is called by subroutine SUBHEX to calculate the inside heat transfer coefficients for the tube-side fluid and the outside heat transfer coefficients for the shell-side fluid in the heat exchanger. The Dittus-Boelter equation is summarized below:

$$h_{\text{conv}} = 0.023 Re_d^{0.8} Pr^x \frac{K}{d}$$

where:

h_{conv} = convective heat transfer coefficient
(Btu/hr-ft²-°F)

d = tube diameter (ft)

K = thermal conductivity (Btu/hr-ft-°F)

Pr = Prandtl number

Re_d = Reynolds number based on tube diameter

x = 0.4 when fluid is being heated,

0.3 when fluid is being cooled.

TUBES

Determines the number N of tubes required in the heat exchanger based on the tube-side fluid mass flow rate Q , velocity V , density ρ , and flow diameter D . Fractional values of N are increased to the next largest integer. The basic relationship is:

$$N = \frac{(Q/\rho)}{V \star \frac{\pi D^2}{4}}$$

where:

(Q/ρ) is the total required volumetric flow rate of tube-side fluid,

$\frac{\pi D^2}{4}$ is the cross-sectional flow area per tube,

$V \star \frac{\pi D^2}{4}$ is the volumetric flow rate per tube.

QAREA

Calculates the total cross-sectional flow area A and equivalent flow diameter D_e for the shell-side fluid in the heat exchanger. An equilateral triangular pitch is assumed for the tube configuration, as shown below.

- S - TUBE SPACING, ft
- D_o - TUBE OUTER DIAMETER, ft
- P - WETTED PERIMETER, ft
- A_{unit} - UNIT FLOW AREA, ft

The tube spacing S is assumed to be 1.75 times the tube outer diameter D_o . Based on the area for an equilateral triangle, the unit flow area for the shell-side fluid is calculated by the following equation:

$$A_{\text{unit}} = \frac{SR}{2} - \frac{3}{6} * \frac{\pi D^2}{4}$$

where:

$$R = S * \sin 60^\circ,$$

$$\frac{SR}{2} = \text{area of the equilateral triangle,}$$

$$\frac{3}{6} * \frac{\pi D^2}{4} = \text{area of the 3 pie shapes in the 3 tubes that are not included in the flow area for the shell-side fluid.}$$

The total cross-sectional flow area A is calculated as the number of tubes times the unit flow area A_{unit} . The equivalent flow diameter D_e for the shell-side is calculated as:

$$D_e = \frac{4 * A_{\text{unit}}}{\text{wetted perimeter}}$$

The wetted perimeter P is calculated as:

$$P = 3(S - D_o) + \frac{3\pi D_o}{6}$$

VELOCITY

Calculates the fluid velocity V as a function of the mass flow rate Q , fluid density ρ , and total cross-sectional flow area A as follows:

$$V = \frac{(Q/\rho)}{A}$$

where:

(Q/ρ) is the volumetric flow rate.

OHTCOE

Combines the inside and outside heat transfer coefficients with the thermal resistance of the heat exchanger tube walls and the

fouling factors. This yields an overall heat transfer coefficient on the basis of the following equation:

$$U = \frac{1}{\frac{A_o}{A_i} * \frac{1}{h_i} + \frac{A_o \ln(r_o/r_i)}{2\pi KL} + \frac{1}{h_o} + f_i + f_o}$$

where:

- U = overall heat transfer coefficient (Btu/hr-ft²-°F)
- A_o = outside tube surface area (ft²)
- A_i = inside tube surface area (ft²)
- h_i = inside heat transfer coefficient (Btu/hr-ft²-°F)
- h_o = outside heat transfer coefficient (Btu/hr-ft²-°F)
- r_i = inside tube radius (ft)
- r_o = outside tube radius (ft)
- K = thermal conductivity of the tube wall (Btu/hr-ft-°F)
- L = tube length (ft)
- f_i = inside fouling factor (hr-ft²-°F/Btu)
- f_o = outside fouling factor (hr-ft²-°F/Btu)

The fouling factors reduce the overall heat transfer coefficient to allow for the accumulation of corrosion deposits on the heat transfer surfaces.

HTAREA

Calculates the heat transfer area A for the heat exchanger. The calculation is based on the shell-side fluid flow rate Q, enthalpies of the shell-side fluid at the inlet and outlet H₁ and H₂, overall heat transfer coefficient U, and the logarithmic mean temperature difference LMTD in the following equation:

$$A = \frac{Q * (H_1 - H_2)}{U * (LMTD)}$$

The logarithmic mean temperature difference between the tube-side fluid and shell-side fluid is based on the temperature differences at the two ends of the heat exchanger.

$$LMTD = \frac{\Delta T_{in} - \Delta T_{out}}{\ln (\Delta T_{in} / \Delta T_{out})}$$

where:

ΔT_{in} = temperature difference ($^{\circ}F$) between the tube-side fluid and shell-side fluid at the shell-side fluid inlet to the heat exchanger.

ΔT_{out} = temperature difference ($^{\circ}F$) between the tube-side fluid and shell-side fluid at the shell-side fluid outlet from the heat exchanger.

HTLNHG Calculates the tube length L in the heat exchanger. The calculation is based on the heat transfer area A , tube outer diameter D_o , and number of tubes in the heat exchanger N .

$$L = \frac{A}{\pi D_o N}$$

HXDROP Calculates the pressure drops in the tube-side and shell-side of the heat exchanger, including entrance and exit effects.

Tube or Shell-Side Pressure Losses

$$\Delta P = f \frac{L}{D} \rho \frac{V^2}{2 g_c} \frac{1}{144} \quad (\text{Darcy-Weisbach equation})$$

where:

ΔP = pressure drop (psi)

f = friction factor, approximated as $0.16 \cdot Re^{-.16}$

Re = Reynolds number, computed as $\rho V d / \mu$

ρ = fluid density (lb_m/ft^3)

μ = fluid viscosity ($lb_m/ft\text{-}sec$)

V = average fluid velocity (ft/sec)

d = tube internal diameter or shell equivalent diameter (ft)

L = tube length (ft)

g_c = gravitational constant (32.174 ft/sec^2)

Entrance Loss

$$\Delta P_{in} = \frac{K_c v^2}{(2g_c)(144)}$$

where:

ΔP_{in} = pressure drop at entrance (psi)

K_c = coefficient, computed as $0.5 * CSAREA/EAREA + 0.5$

$CSAREA$ = cross-sectional flow area of tube or shell-side (ft^2)

$EAREA$ = entrance area to heat exchanger (ft^2)

Exit Loss

$$\Delta P_{out} = \frac{v^2}{2g_c 144} \left(1 - \frac{CSAREA}{EAREA} \right)^2 \quad (\text{Borda-Carnot Eq.})$$

where:

ΔP_{out} = pressure drop at exit (psi)

$\Delta P_{total} = \Delta P + \Delta P_{in} + \Delta P_{out}$

2.7.2 Overview of Distribution System

The distribution system submodel simulates the design and calculates the capital and operating costs of the district heating and cooling distribution system. The distribution system can serve a single point demand (e.g., a large commercial building or factory), residential districts, or a multi-district city. The input data to the distribution system submodel is described in Section 3.4. It consists of the climatic conditions, characteristics of the served districts, design options for the distribution piping, insulation, and casing, and special options and adjustment factors for the distribution system. The description of the distribution system submodel is given below in its most general form for a multi-district city.

The city is defined by its distance from the reservoir wellfield, climatic conditions, and the number and type of districts within the city. The distance from the reservoir wellfield to the city is used in designing the fluid transmission line to the city and calculating the fluid temperature and enthalpy

entering the distribution system. The climatic parameters are used in determining the peak and average heating and cooling energy demands, the load factor, and supplemental heating requirements (if any) for the city.

The city is described by disaggregating it into districts. Districts are the basic elements of the distribution system submodel. Each district is a contiguous area consisting of buildings of relatively similar heat (chill) demand and uniform density. Most of the details needed for design of the distribution piping system are derived from the definitions of the districts. Fluid requirements are computed, and the piping networks are designed for each district. Material requirements, capital costs, operating costs, and maintenance costs are also calculated for each district and totaled for the city.

Districts are defined by two types of input parameters: district geometry and district type characteristics. District geometry parameters define the size and location of the districts, and the district type characteristics define the energy demand density. A comprehensive list of these parameters is given in Section 3.4.6. The primary parameters used to define each district are the district type, the density of buildings, the peak space heat demand, peak space chill demand and sanitary water demand per building, the area of the district, and two parameters (length and width) describing a rectangular grid used to approximate the shape of the district.

Five district types, representing typical residential areas, are identified and defined in Sections 3.4.6 and 3.4.6.2. Most residential areas in the United States can be described by one of these district types. A sixth district type is used to represent a single point demand, i.e., a district consisting of one point of heat (chill) demand such as a single commercial building or factory. Variations of the predefined district types or additional district types can also be defined through the district type parameters in the NAMELIST input data.

The distribution system submodel is composed of component subroutines (Figure 5) CALQNA, DIST, and its associated subroutines: GRAPH, SIZE, HEAT, PROP, AND DWRT.

As previously noted in Section 2.5, the fluid requirements of the distribution system are established in iterative calculations between subroutine CALQNA

(which computes the distribution system demand) and the reservoir and fluid transmission system submodel. Subroutine CALQNA calculates the peak and average fluid requirements to meet the heating and cooling demands of the city based on: the area, building density, space heat demand, space chill demand, and sanitary water demand per building for all districts in the city, thermal losses in the fluid, and the climatic data. The total fluid requirements for the city are the sum of the fluid requirements computed for each district in the city.

Subroutine DIST then calls the associated subroutines shown in Figure 5 to determine the design and cost of the distribution system. Subroutine GRAPH is called to design the piping layout for each district in the city based on the area, building density, and a rectangular grid used to approximate the shape (length and width) of the district. Heat and chill demand data and climatic data are used to determine the fluid requirements of each building. Proceeding down the piping network, the fluid requirements are used in subroutine SIZE as a basis for selecting the economic pipe size and insulation thickness and calculating pressure drops for each segment of the piping network. Thermal losses are determined for each segment of the piping network by subroutines HEAT and PROP.

Material requirements for the distribution system are calculated in subroutines DIST and SIZE. Capital, operating, and maintenance costs for the piping network, pumps, meters, and control equipment are derived in subroutine DIST based on the distribution system design options defined in Section 3.4 and the capital and operating cost models described in Appendix B. The output results summarizing the material requirements, thermodynamic and flow conditions, and costs of the distribution system are printed by subroutines DIST, DWRIT, and DWRIT2 (an entry point in subroutine DWRIT).

2.7.3 Thermal Energy and Fluid Requirements of Distribution System

As a prelude to the technical design of the distribution system, the thermal energy and fluid requirements of the total distribution system are first calculated in subroutine CALQNA of the distribution system submodel. The peak flow requirement of the distribution system is used to determine the number of production wells and the size of the fluid transmission piping system from the

reservoir wells to the distribution system. The peak flow requirements in each section of distribution piping (street-to-house, street, lateral, and main) are then subsequently calculated in subroutine DIST during the detailed, technical design of the distribution system.

Subroutine CALQNA calculates the peak and average heat and chill demands during the year (MBtu/hr), the peak and average fluid requirements during the year (lb/hr), and the system load factor. The degree-day method is used for evaluating heat demand for space heating; the degree-hour method is used for evaluating chill demand for space cooling.

2.7.3.1 Thermal Energy and Fluid Requirements for Residential Space Heating and Sanitary Water Heating

The first set of equations formulated in subroutine CALQNA is used to calculate thermal energy and fluid requirements for space heating and sanitary water heating. Descriptions of these equations are given below; all parameters designated as input parameters below are defined in Section 3.4.

The following equation is used to calculate the annual average heat demand AD (MBtu/hr) for space heating and sanitary water heating:

$$AD = \sum_{I=1}^{NDTR} DENSE(J) * AREA(I) * \left[\frac{PHQ(J) * DDGDAY(1)}{365.25 * (65. - TDES(1))} + HW(J) * CHOTW2 \right]$$

where:

NDTR = number of districts in the city (input)

DENSE(J) = density of buildings in district type J, bldg/sq mile (input)

J = district type of district number I (input)

AREA(I) = area of district number I, sq mile (input)

PHQ(J) = peak space heat demand per building in district type J, MBtu/hr-bldg (described in Section 3.4.2)

DDGDAY(1) = number of design heating degree-days per year at the simulated site, °F-days/yr (described in Section 3.4.2.)

TDES(1) = outdoor design temperature for heating, °F (described in Section 3.4.2)

HW(J) = daily sanitary water demand per building in district type J, gal/day (input)

CHOTW2 = conversion factor of 3.631E-5 used to compute the average heat demand (MBtu/hr) needed to supply the daily sanitary hot water demand (gal/bldg-day).

The indoor design temperature for space heating is currently fixed at 65°F in the code. The code assumes 365.25 days per year to take leap years into account over long project lifetimes.

The conversion factor CHOTW2 of 3.631E-5 is based on heating water for sanitary usage from 50°F to 140°F^(a) using a small heat exchanger at the hot water tank. The derivation of this conversion factor is as follows:

$$\begin{aligned} \text{Heat Demand for Sanitary Water Heating (MBtu/bldg-hr)} = \\ \left[\text{Daily Sanitary Water Demand (gal/bldg-day)} * .1337 \right. \\ \left. (\text{ft}^3/\text{gal}) * 61.37 (\text{lb}/\text{ft}^3) * 1 \text{ Btu}/(^{\circ}\text{F}-\text{lb}) * (140-50)^{\circ}\text{F} * \right. \\ \left. 1.E-6 \text{ MBtu/Btu} \right] / 24 (\text{hr}/\text{day}) \end{aligned}$$

This yields the equation:

$$\begin{aligned} \text{Heat Demand for Sanitary Water Heating (MBtu/bldg-hr)} = \\ \text{Daily Sanitary Water Demand (gal/bldg-day)} * \end{aligned}$$

$$3.0769E-5 \left(\frac{\text{MBtu/hr}}{\text{gal/day}} \right)$$

Assuming an 18% heat loss (set in the code) from the hot water storage heater, the equation becomes:

$$\begin{aligned} \text{Heat Demand for Sanitary Water Heating (MBtu/bldg-hr)} = \\ \text{Daily Sanitary Water Demand (gal/bldg-day)} * \\ 3.0769E-5 * 1.18, \text{ i.e., Daily Sanitary Water Demand} \end{aligned}$$

(a) This discussion pertains to the default values of cold and hot water temperatures for sanitary water heating in the city. The cold and hot water temperatures and conversion factors used in calculations for sanitary water heating in the city are generalized in the code to handle the values specified by the user in the NAMELIST input data. See Section 3.4.2 for definition of the cold water temperature (TWATC) and hot water temperature (TWATH) in the input data.

$$(\text{gal/bldg-day}) * 3.631\text{E-}5 \left(\frac{\text{MBtu/hr}}{\text{gal/day}} \right)$$

The following equation is used to calculate the annual peak heat demand PD (MBtu/hr) for space heating and sanitary water heating:

$$PD = \sum_{I=1}^{NDTR} DENSE(J) * AREA(I) * DIVF(J) * [PHQ(J) + HW(J) * CHOTW4]$$

where:

DIVF(J) = diversity factor for district type J, fraction (input)

CHOTW4 = conversion factor of 105.496E-6 used to calculate the peak heat demand (MBtu/bldg-hr) needed to supply the daily sanitary hot water demand (gal/bldg-day).

All other parameters were previously described in the equation for the annual average heat demand for space heating and sanitary water heating. The conversion factor CHOTW4 of 105.496E-6 is based on calculating the peak heat demand needed for peak sanitary hot water usage in which the sanitary water is heated from 50°F to 140°F. The derivation of this conversion factor is as follows:

$$\begin{aligned} \text{Peak Heat Demand for Sanitary Water Heating (MBtu/bldg-hr)} = \\ \text{Daily Sanitary Water Demand (gal/bldg-day)} * 738.47\text{E-}6 \\ \left(\frac{\text{MBtu/day}}{\text{gal/day}} \right) * (1/7), \text{ where the assumption is that the peak} \\ \text{sanitary water demand in 1 hr represents about 1/7th} \\ \text{of the average daily demand for sanitary water in 24 hrs.} \end{aligned}$$

The system load factor PF is calculated as follows:

$$PF = \frac{\text{Annual Average Heat Demand (AD)}}{\text{Annual Peak Heat Demand (PD)}}$$

Subroutine CALQNA considers the optional heat exchanger at the inlet to the distribution system in calculating the peak flow rate required to meet the peak space and sanitary water heating demands of the distribution system. Two peak flow rates are calculated.

First, the required peak flow rate QDIS (lb/hr) inside the distribution system is calculated as follows:

$$QDIS = \sum_{I=1}^{NDTR} DENSE(J) * AREA(I) * DIVF(J) * \left[\frac{PHQ(J) + HW(J) * CHOTW4}{DEL T * SH * HNLOST} \right] * 1.E6$$

where:

DEL T = temperature drop of the hot water between the inlet to the distribution system and the outlet from the building heating system ($^{\circ}F$)

HNLOST = fraction of heat not lost due to thermal losses in the distribution piping system (set in the code to 0.95). Thus, DEL T * HNLOST represents the hot water temperature drop usable for space heating and sanitary water heating.

SH = specific heat of water, which is assumed to be 1 Btu/(lb- $^{\circ}F$)

DIVF(J) = diversity factor for district type J, fraction (input). The diversity factor is used to reduce the magnitude of the peak flow rate by recognizing that the peak demand for space heating and sanitary water heating does not occur simultaneously for all buildings in a district (see Section 3.4.6.2).

Without a heat exchanger, the fluid temperature drop inside the distribution system is calculated as the computed fluid temperature at the inlet to the distribution system minus the fluid temperature at the outlet of the building heating system. With a heat exchanger at the inlet to the distribution system, the fluid temperature drop inside the distribution system is calculated as the circulating water temperature out of the heat exchanger (described in Section 3.4.4) minus the circulating water temperature out of the building heating system.

The above equation for the peak flow rate QDIS inside the distribution system is derived from the following heat transfer equation:

$$\begin{aligned} &\text{Required Heat at Peak Demand (Btu/hr)} = \\ &\text{Temperature Drop (}^{\circ}F\text{)} * \text{Specific Heat (1 Btu/lb-}^{\circ}F\text{)} * \text{HNLOST} * \\ &\text{QDIS (lb/hr)} \end{aligned}$$

The peak flow rate QDIS is used to size the distribution main pipe at the inlet of the distribution system. The parameter HNLOST (set in the code) is used to approximate average thermal losses between the inlet to the distribution system and the individual buildings. The peak flow rates for all sections of pipe (street-to-house, street, lateral, and main) inside the distribution system are calculated in subroutine DIST as described below.

The required peak flow rate QTRANS (lb/hr) from the reservoir wellfield is calculated next. The peak flow rate QTRANS is used in calculating the required number of production wells and sizing the transmission piping from the reservoir wellfield to the distribution system. Without a heat exchanger, the peak flow rate QDIS inside the distribution system and the peak flow rate QTRANS from the reservoir wellfield are the same. With a heat exchanger, the peak flow rate QTRANS (lb/hr) from the reservoir wellfield is calculated by heat balance across the heat exchanger as follows:

$$\begin{aligned} QTRANS &= [QDIS \text{ (lb/hr)} * \text{Temperature Rise of the Circulating} \\ &\quad \text{Water Across the Heat Exchanger (}^{\circ}\text{F)} \\ &\quad * \text{Specific Heat } \left(\frac{1 \text{ Btu}}{1 \text{ lb-}^{\circ}\text{F}} \right)] / [\text{Temperature Drop of the} \\ &\quad \text{Geothermal Fluid Across the Heat Exchanger (}^{\circ}\text{F)} * \\ &\quad \text{Specific Heat } \left(\frac{1 \text{ Btu}}{1 \text{ lb-}^{\circ}\text{F}} \right)] \end{aligned}$$

The calculation of the temperature changes across the heat exchanger is discussed in Section 3.4.4. The specific heat of water is assumed to be 1 in the above equation.

Both peak flow rates QDIS and QTRANS are increased to factor into account the fraction WLEAK of fluid lost due to leakage in the piping systems:

$$\begin{aligned} QDIS &= QDIS * (1. + WLEAK) \\ QTRANS &= QTRANS * (1.+WLEAK) \end{aligned}$$

The parameter WLEAK is defined by the user in the input data (Section 3.4.7.)

2.7.3.2 Thermal Energy and Fluid Requirements for Residential Space Cooling and Sanitary Water Heating

Space or process cooling is simulated in GEOCITY using a lithium bromide/water absorption chiller and small mixing tank located at each residence. The conceptual design of the system configuration used to provide residential space cooling and sanitary water heating is shown in Figure 9.^(a)

During operation, hot water from the distribution system piping is split into two flow streams at each residence. One of the flow streams is circulated through a small heat exchanger located at the sanitary hot water tank to provide sanitary water heating for the residence.^(b) The other flow stream enters a small mixing tank connected to the absorption chiller located at the residence. This stream is mixed with some lower-temperature used water that is recirculated from the absorption chiller into the mixing tank. The blended hot-water mixture is then circulated through the absorption chiller to operate the lithium bromide absorption process for providing chilled water to the building cooling system.

GEOCITY currently assumes that the absorption chiller operates with a design hot water inlet temperature of 195°F into the chiller (recommended by a major chiller manufacturer and set by the parameter THSMIX in subroutine CALQNA). This design feature requires that the temperature of the hot water from the distribution system piping be greater than 195°F so that the blended temperature from the mixing tank into the chiller is 195°F. If the

-
- (a) Logic to simulate space cooling using a central chiller located at the inlet to the distribution system is in the code but appropriate capital and operating cost models have not been integrated into the code. This central chilled water distribution system would pump chilled water through the distribution system piping to individual residences for space cooling. Such a system would not provide sanitary water heating in the combined heating and cooling mode with the current one or two-pipe system in GEOCITY (i.e., supply piping only or supply and return piping that transport either hot water or chilled water but not both simultaneously).
 - (b) Another approach not modeled in GEOCITY would be to cascade some of the used hot water from the absorption chiller to the sanitary water heating system. This approach could be used in lieu of splitting the incoming hot water stream from the distribution system into two flow streams.

FLOW STREAMS (lb/hr)

- 1 - TO MIXING TANK
- 2 - TO SANITARY WATER HEATING SYSTEM
- 3 - TO MIXING TANK FROM CHILLER
- 4 - TO CHILLER FROM MIXING TANK
- 5 - TO BUILDING FROM CHILLER
- 6 - EXCESS FLOW FROM CHILLER
- 7 - MERGED FLOW FROM BUILDING

**TEMPERATURES (°F) IN DISTRICT NUMBER 1
CLASSIFIED AS DISTRICT TYPE J**

- TDIS - INLET TO DISTRIBUTION SYSTEM
- THSMIX - INLET TO CHILLER
- CTWAT - INLET TO BUILDING
- TREJC(J) - OUTLET FROM BUILDING COOLING SYSTEM
- TREJ(J) - OUTLET FROM BUILDING HEATING SYSTEM
- TRET(I) - MERGED RETURN FROM BUILDING
- TTRET - MERGED RETURN TO HEAT EXCHANGER
- CXDELT - HOT WATER TEMPERATURE DROP IN CHILLER

FIGURE 9. Conceptual System Design in GEOCITY to Provide Residential Space Cooling and Sanitary Water Heating

hot water temperature is less than 195°F, the code will stop execution and print a message notifying the user.

The temperature drop of the hot water stream in the chiller, the chilled water outlet temperature, and the coefficient of performance for the chiller are set by the input parameters CXDELTA, CTWAT, and CCOP, respectively, as described in Section 3.4.5. The default values of CXDELTA, CTWAT, and CCOP are 9.1°F, 45°F, and 0.72, respectively, based on the design conditions used by a major chiller manufacturer. Recirculation of some used hot water from the chiller into the mixing tank, at a temperature of THSMIX-CXDELTA (i.e., default value of 195-9.1 = 185.9°F), makes the chiller sensitive to higher geothermal resource temperatures (>195°F) by reducing the chiller's hot water flow requirements from the distribution system.

GEOCITY simulates only the steady-state operation of the mixing tank and chiller. The initial supply of return water from the chiller to the mixer is assumed to be provided during start-up operations. During steady-state operation, GEOCITY calculates the amount of water it needs to recirculate from the chiller into the mixing tank so that the temperature of the blended water out of the mixing tank is 195°F. Excess used water from the absorption chiller, that is not recirculated to the mixing tank, is merged with the used water from the sanitary water heating system. This merged stream is either disposed of into a conventional sewer system or returned to an optional heat exchanger at the inlet to the distribution system. The equations used by the code to calculate the peak flow requirements of all streams shown in Figure 9 are presented later in this section.

We believe that commercially available absorption chillers with a nominal rating of three tons of design cooling capacity (36,000 Btu/hr of chill) are large enough to provide geothermal space cooling for typical residences (households) in U.S. climates. The input parameters used to define the performance characteristics (e.g., inlet and outlet temperatures, coefficient of performance, etc.) of these chillers are defined in Section 3.4.5. The installed capital costs of the chiller, mixing tank, and other components of the building cooling system (e.g., fan-coil units, pumps, controls, cooling tower, ducts, and other auxiliary equipment) are input by the user as retrofit costs for

cooling, which are defined in Section 3.4.6.2. The annual operating costs of the chiller are calculated by the code as 6% of the installed capital cost.

The equations formulated in subroutine CALQNA to calculate thermal energy and fluid requirements for space cooling and sanitary water heating based upon the above system configuration are given below. All parameters designated as input parameters below are defined in Section 3.4.

The following equation is used to calculate the annual average heat demand AD (MBtu/hr) for space cooling and sanitary water heating:

$$AD = \sum_{I=1}^{NDTR} DENSE(J) * AREA(I) + \left[\frac{AVECD(J)}{CCOP} + HW(J) * CHOTW2 \right]$$

where:

NDTR = number of districts in the city (input)

DENSE(J) = density of buildings in district type J, bldg/sq mile (input).

J = district type of district number I (input)

AREA(I) = area of district number I, sq mile (input)

AVECD(J) = average cooling demand per building in district type J, MBtu/hr-bldg of chill (described in Appendix E)

CCOP = coefficient of performance for the absorption chiller, fraction (input). This parameter relates the Btu/hr of chill to equivalent Btu/hr of heat, since the Btu/hr of chill out of the chiller = Btu/hr of heat into the chiller * CCOP.

HW(J) = daily sanitary water demand per building in district type J, gal/day (input)

CHOTW2 = conversion factor of 3.631E-5 used to calculate the average heat demand (MBtu/hr) needed to supply the daily sanitary water demand (gal/bldg-day). The derivation of this factor was previously described in Section 2.7.3.1.

The following equation is used to calculate the annual peak heat demand PD (MBtu/hr) for space cooling and sanitary water heating:

$$PD = \sum_{I=1}^{NDTR} DENSE(J) * AREA(I) * DIVF(J) * \left[\frac{CQ(J)}{CCOP} + HW(J) * CHOTW4 \right]$$

where:

DIVF(J) = diversity factor for district type J, fraction (input).

CQ(J) = peak cooling demand per building in district type J between the indoor design temperature TINDES(2) and the outdoor design temperature TDES(2), MBtu/hr-bldg of chill. The parameter CQ(J) is either input or calculated by the code, as described in Appendix E.

CHOTW4 = conversion factor of 105.496E-6 used to calculate the peak heat demand (MBtu/hr) needed to supply the daily sanitary water demand (gal/bldg-day). The derivation of this factor was previously described in Section 2.7.3.1.

All other parameters were previously described in the equation for the annual average heat demand for space cooling and sanitary water heating. The system load factor PF is calculated as follows:

$$PF = \frac{\text{annual average heat demand (AD)}}{\text{annual peak heat demand (PD)}}$$

The peak flow rate QDIS (lb/hr) required inside the distribution system to provide thermal energy for peak space cooling and sanitary water heating is derived below. This flow rate is computed as the sum of the peak flow rates for space cooling and sanitary water heating. Definitions of parameters in the equations below that were previously defined in this section are not repeated. Mathematically, the equation can be expressed as follows:

$$QDIS = \sum_{I=1}^{NDTR} DENSE(J) * AREA(I) * DIVF(J) * [Q_1(I) + Q_2(I)] * (1.+WLEAK)$$

where:

$Q_1(I)$ = peak flow rate of hot water into the mixing tank (Figure 9) to provide thermal energy for peak space cooling of each building in district number I, lb/hr.

$Q_2(I)$ = peak flow rate of hot water into a small heat exchanger at the sanitary hot water tank to provide thermal energy for peak sanitary water heating of each building in district number I, lb/hr.

WLEAK = fraction of fluid lost due to leakage in the piping system (input)

The peak flow rate $[Q_1(I)]$ of hot water required by the mixing tank and chiller configuration to meet the peak space chill demand of each building in district number I is derived in several steps below. First, the peak flow rate $[Q_5(I)]$ of chilled water required from the absorption chiller by the building cooling system (Figure 9) can be expressed from heat transfer principles as follows:

$$Q_5(I) = \frac{CQ(J) * 1.E6}{[TREJC(J) - CTWAT] * SH}$$

where:

$Q_5(I)$ = peak flow rate of chilled water from the absorption chiller to each building in district number I, lb/hr

$CQ(J)$ = peak chill demand per building in district type J, MBtu/hr-bldg (previously described in this section)

$TREJC(J)$ = temperature of the return chilled water from the building cooling system, °F (input)

$CTWAT$ = temperature of the chilled water out of the absorption chiller, °F (input)

SH = specific heat of the water, which is assumed to be 1 Btu/(lb-°F).

Next, the peak flow rate $[Q_4(I)]$ of hot water from the mixing tank into the absorption chiller can be expressed as follows:

Btu of heat into chiller * CCOP = Btu of chill from chiller, i.e.,

$$Q_4(I) = \frac{Q_5(I) * [TREJC(J) - CTWAT] * SH}{CXDELT * SH * CCOP}$$

where:

$Q_4(I)$ = peak flow rate of hot water into the chiller, lb/hr

$Q_5(I)$ = peak flow rate of chilled water from the chiller, lb/hr

CXDELTA = temperature drop of the hot water in the chiller, °F (input)

CCOP = coefficient of performance for the chiller, fraction (input)

Finally, the peak flow rate $[Q_1(I)]$ of hot water into the mixing tank can be derived by performing a heat balance across the mixing tank as follows:

Btu/hr of heat leaving in stream 4 = Btu/hr of heat entering in stream 1 +
Btu/hr of heat entering in stream 3, i.e.,

$$Q_4(I) * E_4(I) = Q_1(I) * E_1(I) + Q_3(I) * E_3(I),$$

or substituting $Q_3(I) = Q_4(I) - Q_1(I)$,

$$Q_1(I) = \frac{Q_4(I) * [E_4(I) - E_3(I)]}{[E_1(I) - E_3(I)]}$$

where:

$Q_1(I)$ = flow rate of hot water into mixing tank from distribution system, lb/hr

$Q_4(I)$ = flow rate of blended water out of mixing tank into chiller, lb/hr

$E_4(I)$ = enthalpy of blended water out of mixing tank, Btu/lb. The temperature of the blended water from the mixing tank is set in subroutine CALQNA (THSMIX = 195°F)

$E_3(I)$ = enthalpy of recirculating hot water into mixing tank from chiller, Btu/lb. The temperature of this water is defined as THSMIX-CXDELTA. Recall that CXDELTA is the temperature drop of the hot water in the chiller, °F (input).

$E_1(I)$ = enthalpy of hot water into mixing tank from distribution system, lb/h

The peak flow rate $[Q_2(I)]$ of hot water required to provide peak sanitary water heating for each building in district number I is determined as follows:

$$Q_2(I) = \frac{HW(J) * CHOTW4 * 1.E6}{[TDIS - TREJ(J)] * HNLOST * SH}$$

where:

$Q_2(I)$ = peak flow rate of hot water to provide sanitary water heating for each building in district number I, lb/hr

TDIS = temperature of the hot water entering the distribution system, °F (computed).

TREJ(J) = temperature of return water from the building heating system in district type J, °F (input)

HNLOST = fraction of heat not lost due to thermal losses in the distribution piping system (set in the code to 0.95). Thus $[TDIS - TREJ(J)] * HNLOST$ represents the hot water temperature drop usable for sanitary water heating.

The return temperature in stream 7 of Figure 9 is computed as the mass-weighted average of the return temperature in stream 6 (the excess flow not required by the mixing tank) and the return temperature in stream 2. The used water in stream 7 is recirculated into the optional heat exchanger or injected into the injection wellfield. Specifically, the return temperature of stream 7 from each building in district number I is computed as follows:

$$TRET(I) = \frac{Q_6(I) * (THSMIX - CXDELT) + Q_2(I) * TREJ(J)}{Q_2(I) + Q_6(I)}$$

The return temperature from all the districts for recirculation into the heat exchanger or injection into the injection wellfield is computed as follows:

$$TTRET = \frac{\sum_{I=1}^{NDTR} DENSE(J) * AREA(I) * DIVF(J) * TRET(I) * [Q_2(I) + Q_6(I)]}{QTOTAL}$$

where:

QTOTAL is the total return flow in stream 7 from all districts, i.e.,

$$QTOTAL = \sum_{I=1}^{NDTR} [Q_2(I) + Q_6(I)]$$

All parameters in the above three equations have been previously defined in this section.

The required peak flow rate QTRANS (lb/hr) from the reservoir wellfield is determined from the peak flow rate QDIS inside the distribution system in an analogous manner as described for residential space heating and sanitary water heating in Section 2.7.3.1.

2.7.3.3 Thermal Energy and Fluid Requirements for Combined Residential Space Heating, Space Cooling, and Sanitary Water Heating

Equations defining the average and peak thermal energy requirements during the year for space heating and sanitary water heating or space cooling and sanitary water heating were described in the previous two sections. In the combined heating and cooling mode, GEOCITY assumes that sanitary water heating requirements over the year are split evenly into the heating and cooling modes. In mathematical terms, the sanitary hot water demand HW(J) is divided by two in the equations used to compute the annual average heat demands for the heating and cooling modes described in the previous two sections. With this assumption, the annual average heat demand for the combined heating and cooling mode is then the sum of the annual average heat demands computed separately for heating and for cooling.

GEOCITY assumes that the peak sanitary hot water demand is the same in both the heating and cooling modes. With this assumption, the annual peak heat demands for the heating and the cooling modes are computed as previously defined. Moreover, the peak flow rates inside the distribution system for the heating and the cooling modes are also computed as previously defined.

In simulating combined heating and cooling, we labeled the mode with the larger peak hot water flow rate inside the distribution system as the major mode. This mode is simulated first in the code to design and size the entire

geothermal system. The majority of capital and operating costs are computed during the simulation of the major mode. The other mode is labeled the minor mode. It is simulated second to determine incremental capital and operating costs using the system design and sizes determined by the major mode.

The load factors for the major and minor modes are computed in the combined heating and cooling mode as follows:

$$PF_{maj} = \left[\text{average flow rate during the year inside the distribution system for the major mode (lb/hr)} \right] / \left[\text{peak flow rate during the year inside the distribution system for the major mode (lb/hr)} \right]$$

$$PF_{min} = \left[\text{average flow rate during the year inside the distribution system for the minor mode (lb/hr)} \right] / \left[\text{peak flow rate during the year inside the distribution system for the major mode (lb/hr)} \right]$$

Since sanitary water heating requirements are split evenly into the two modes, the combined system load factor is the sum of the load factors computed for the major and minor modes.

The average flow rates inside the distribution system for the major and minor modes are computed in an analogous manner to the peak flow rates with two differences:

1. The average heat demands (not the peak heat demands) are used in the numerators of the equations described in the previous two sections for computing the peak flow rates inside the distribution system.
2. The sanitary water heating requirements in the equations for the average heat demands are split evenly into the heating and cooling modes.

2.7.3.4 Thermal Energy and Fluid Requirements for Process Heating or Cooling

Process heating or cooling is simulated in the code as a single point demand using district number 1 with its district type set to 6. The input parameters to simulate a single point demand are described in Section 3.4.8. The peak thermal energy requirement PD for process heating or cooling is defined in the code directly from the input parameters as follows:

Process Heating: $PD = HQ(6)$

$$\text{Process Cooling: } PD = \frac{CQ(6)}{CCOP}$$

where:

PD = annual peak heat demand for process heating or cooling, MBtu/hr

HQ(6) = peak process heat demand, MBtu/hr of heat (input)

CQ(6) = peak process chill demand, MBtu/hr of chill (input)

CCOP = coefficient of performance for the absorption chiller, fraction (input). This parameter relates the Btu/hr of chill to equivalent Btu/hr of heat, with the Btu/hr of chill out of the chiller = Btu/hr of heat into the chiller * CCOP.

The average thermal energy requirement AD for process heating or cooling is computed from the peak heat or chill demand and the annual load factor. Contrary to residential heating or cooling, the load factor for process heating or cooling is not computed from climatic data, but instead is defined in the input data. The annual average thermal energy requirement AD for process heating or cooling is computed as follows:

$$\text{Process Heating: } AD = HQ(6) * PF$$

$$\text{Process Cooling: } AD = \frac{CQ(6)}{CCOP} * PF$$

where:

AD = annual average heat demand for process heating or cooling, MBtu/hr

PF = annual load factor, fraction (input)

Notice that GEOCITY does not allow sanitary water heating in simulating process heating or cooling, i.e., the default value of the daily sanitary hot water demand HW(6) is 0 (see Section 3.4.6.2).

The distribution piping for process heating or cooling consists of a main pipe and optional return main connecting with the single-point demand. The peak flow rate QDIS of hot water in the main pipe is computed using the equations defined for QDIS in Sections 2.7.3.1 and 2.7.3.2, and the input parameters defined in Section 3.4.8. In simulating process heating, the equation

defined in Section 2.7.3.1 for computing the peak flow rate of hot water inside the distribution system reduces to the following equation:

$$QDIS = \frac{HQ(6) * 1.E6 * (1.+WLEAK)}{DEL T * SH}$$

where:

QDIS = peak flow rate of hot water in the distribution main pipe to the single point demand, lb/hr

DEL T = temperature drop of the hot water between the inlet to the distribution main pipe and the outlet from the point demand heating system i.e., $[TREJ(6)]$, °F

SH = specific heat of the water, which is assumed to be 1 Btu/(lb-°F).

WLEAK = fraction of fluid lost due to leakage in the piping system (input)

Notice that thermal losses in the distribution main pipe to the single point demand are assumed to be negligible. Thus, the fraction of heat not lost due to thermal losses in the main pipe (i.e., the parameter HNLOST in Section 2.7.3.1) is set to 1 in the code for a single point demand.

The peak flow rate of hot water QDIS in the distribution main pipe for process cooling is computed in an analogous manner using the equation defined for QDIS in Section 2.7.3.2, and the input parameters defined in Section 3.4.8.

2.7.4 Technical Design and Costs of Distribution System

After subroutine CALQNA calculates the thermal energy and fluid requirements of the total distribution system, the executive routine DGHEAT calls subroutine DIST (Figure 6) to simulate the technical design and calculate the capital and operating costs of the distribution system. In particular, this includes the detailed design and costs of the entire supply and return piping network in the distribution system: street-to-building, street, lateral, and main piping sections.

Subroutine DIST calls five principal supporting routines in performing its simulation of the distribution system: GRAPH, SIZE, HEAT, PROP, and DWRIT.

Subroutine DIST and its supporting routines are described in this section in the most general framework for a multi-district city. Descriptions are given in the context of either the heating or cooling mode.

In the combined heating and cooling mode, subroutine DIST and its supporting routines are executed twice. As previously described in Section 2.5, the distribution system is simulated in two principal steps in the combined heating and cooling mode. In the first step, the major mode (heating or cooling, whichever has the larger peak flow requirement) is simulated in subroutine DIST and its supporting routines. This simulation is used to design and size the distribution system based on the thermal energy requirements, peak fluid requirements, thermal losses, pressure drops, and pumping requirements of the major mode. All capital costs (except retrofit costs associated with the minor mode) and that portion of operating costs associated with the major mode (based on its load factor) are calculated in the simulation of the major mode.

In the second step, the minor mode is simulated in subroutine DIST and its supporting routines. This step uses the system design and pipe sizes determined in the major mode to calculate the thermal losses, pressure drops, incremental pumping requirements, incremental capital costs (i.e., retrofit costs associated with the minor mode), and incremental operating costs for the minor mode (based on its load factor). In these calculations, the thermal energy requirements and peak fluid requirements of the minor mode are used. During the second step, subroutine DIST adds the results from the major and minor modes to obtain the total thermal energy requirements, load factor, capital costs, and operating costs for the distribution system in the combined heating and cooling mode.

The rationale for adding the average heat demands and load factors of the major and minor modes to obtain the average heat demand and load factor of the combined heating and cooling mode was previously described in Section 2.7.3.3. Descriptions of subroutine DIST and its supporting routines are given below.

DIST Subroutine DIST simulates the design and calculates the material requirements and costs of the distribution system separately for each district in the city. Totals are then computed over all districts in the city. The procedure is described in steps 1-14 below.

- 1) The network of pipes (from buildings to streets, down streets connecting buildings, across the lateral connecting with the midpoint of the streets, and up the main connecting with the midpoint of the lateral) is designed for each district using subroutine GRAPH. An example layout of a piping network is illustrated in Figure 10. The piping network is laid out symmetrically about the main and lateral pipes as described in the description of subroutine GRAPH.
- 2) The required peak fluid flow rate per building is calculated based on the peak space heating (cooling) demand and peak sanitary hot water demand specified in the input data for this district type and the specified temperature drop of the fluid. Based on the peak fluid flow rate, the pipe size and insulation thickness are optimized and the pressure drop is calculated for pipe sections in the supply pipes beginning from the building to the street, down streets, across the lateral, and up the main using subroutine SIZE. Due to the symmetry in the piping network, only a few pipe sections need to be considered to size the whole network for the district. The size of the return pipes is set equal to the size of the supply pipes.
- 3) The thermal losses in the sections of the supply pipes starting with the main, across the lateral, up the street, and from the street to the building are calculated using subroutine HEAT.
- 4) The thermal losses in the sections of the return pipes starting from building to street, down the street, across the lateral, and up the main are calculated using subroutine HEAT.
- 5) The output illustrated on page G.27 is printed. This summarizes the flow rate, thermal loss, supply and return temperatures, pressure drop, nominal outer pipe diameter, and insulation thickness in the sections of pipe from building to street, down a street, across the lateral, and up the

FIGURE 10. Layout for a District with 22 Buildings
(the piping network is symmetrical about
the main and the lateral)

main. Because of the symmetry of the piping network, it is necessary to print only the pipe sections from one building to the street, pipe sections connecting pairs of buildings down a half-street (either above or below the lateral), and pipe sections connecting streets across a half-lateral (either to the right or left of the main).

- 6) The total pressure drop and thermal loss in the piping network are calculated for the district. Based on the total pressure drop, the required pumping capacity and capital cost of the pumps are calculated.
- 7) The material requirements and capital costs of the piping network are calculated based on the material and configuration options specified for pipes, insulation, and casing and the capital cost models described in Appendix B. The length of pipe, number of fittings, valves, and expansion loops, and the capital costs of pipes, fittings, valves, insulation, casing, expansion loops, and trenches are tabulated for up to 23 nominal outer pipe diameters that can be used throughout the piping network. These costs are then summed over all pipe sizes and combined with the costs of meters, pumps, and retrofitting of buildings to obtain total capital costs for the district piping system.
- 8) The output illustrated on page G.28 is printed. This summarizes the material requirements and capital costs calculated in step 7 for up to 23 nominal outer pipe diameters, and also summarizes the total capital costs for the district piping system.
- 9) The annual heat demand (MBtu/yr) is calculated for the district based on the average heat (chill) demand, climate, density, area, and daily sanitary hot water demand. The peak heat demand (MBtu/hr) is calculated for the district based on the peak heat (chill) demand, peak sanitary hot water demand, density, area, and diversity factor. The peak

sanitary hot water demand is assumed to be 1/7 of the daily sanitary hot water demand, occurring at the same time as the hourly peak heat demand. The diversity factor defined in Section 3.4.6.2 is used to reduce the size of the lateral and main supplying a district by considering that the peak loads for all buildings in a district will not occur simultaneously. The annual heat demands and the peak heat demands are also summed over all districts in the city.

- 10) The return temperature from each district is weighted by the mass flow rate for each district to calculate an average return temperature from the city's distribution system.
- 11) The peak supplemental heating requirements (MBtu/hr) are calculated for each district based on the peak heat demand, climate, density, and area of the district. Supplemental cooling requirements are not calculated in GEOCITY.
- 12) The output illustrated on page G.63 is printed. This summarizes the flow rate, thermal loss, supply and return temperatures, pressure drop, nominal outer pipe diameter, and insulation thickness for the mains to the districts.
- 13) The output illustrated on page G.64 is printed. This summarizes the total material requirements and capital costs for the entire city distribution system for up to 23 nominal outer pipe diameters. The total capital costs summed over all pipe sizes and the total operating expenses are also printed for the entire city distribution system.
- 14) The annual supplemental heating requirements (MBtu/yr) are calculated for the city based on the annual heat demand calculated in step 9 for the city and its climate. The cost of providing the annual supplemental heating requirements is also calculated. No supplemental chill is provided in the case of cooling.

GRAPH

Designs the layout of the piping network for the distribution system in each district based upon the area, building density, length, and width, which the user can approximate from a map of the district. Subroutine GRAPH calculates the number of buildings in a given district (area * density) and places them on a rectangular grid such that the ratio of rows to columns is equal to the ratio of width to length of the district. The rectangular grid defaults to a square with length and width equal to 1 mile if these two parameters are not defined in the NAMELIST input data.

An example layout designed by subroutine GRAPH for a district with 22 buildings and with ratio of length to width equal to 2 is shown in Figure 10. Pairs of buildings in columns are assigned by subroutine GRAPH to streets. A lateral pipe, located at the midpoint of the streets, connects all of the street pipes. A main pipe connects with the midpoint of the lateral. If a street cannot be completely filled out with buildings, the remaining buildings are placed on 2 short streets, one at each end of the lateral, so that the resulting network is still symmetrical both about the lateral and the main.

SIZE

Optimizes the pipe diameter and insulation thickness and calculates the pressure drop for each section of pipe in the distribution piping network. Since all pipes from buildings to streets are identical in a given district, and since the piping network is symmetrical about the main and lateral pipes, only a few pipe sections need to be considered to size the whole network in a given district. The optimal pipe diameter for each pipe section is determined by searching a discrete number of different commercial pipe sizes to find the size that will minimize the sum of the annualized capital cost of pipe, insulation, casing, valves, fittings, expansion loops, trenches, and pumps and the annual costs of thermal loss and pumping power. The optimal insulation thickness is determined by minimizing the sum of the annualized

capital cost of insulating the pipes, valves, fittings, and expansion loops, the annualized costs of casing and trenching, and the annual value of lost thermal energy.

The material and configuration options for pipes, insulation, and casings used in subroutine SIZE are defined in the input data described in Section 3.4.7. These design options include: single-pipe systems and various two-pipe systems; use of steel or fiberglass-reinforced-plastic pipes; use of calcium silicate, polyurethane foam, or fiberglass insulation; and use of steel, plastic (PVC), or field-constructed concrete casings. Material requirements including pipe, insulation, casing, valves, fittings, expansion loops, and trenches, are accumulated by size for each section in the distribution piping network. The capital cost models used in subroutine SIZE are based on the design options specified in the input data and are described in Appendix B.

HEAT

Calculates the radial thermal losses (joules/sec-meter) through a composite series of walls (pipe, insulation, annular air space and ground) due to convection and conduction from fluid flowing in a buried cylindrical pipe. Subroutine HEAT is called by both subroutines SIZE and DIST.

DWRIT (entry point DWRIT2)

Prints the output entitled "Definition of Distribution Districts" with results in both English and metric units and the output entitled "District Populations" illustrated on page G.24 to G.26. This output consists principally of the input data defining the districts and district types in the distribution system described in Section 3.4.6. Subroutine DWRIT (entry point DWRIT2) also prints the output entitled "Distribution System Description" with results in both English and metric units. This output summarizes the calculated heat demands, fluid temperatures, fluid flow rates, and costs by district for the distribution system. The output is illustrated on page G.65.

PROP

Calculates the convective heat-transfer coefficient for fluid flowing in a cylindrical pipe based on the Dittus-Boelter equation as follows:

$$h_{\text{conv}} = \frac{.0225 * K * \text{Re}^{0.8} * \text{Pr}^{0.4}}{D}$$

where:

h_{conv} = convective heat-transfer coefficient (joules/sec - meter²-°K)

K = thermal conductivity of the fluid (joules/sec - meter-°K)

Re = Reynolds number

Pr = Prandtl number

D = inside pipe diameter (meters)

Subroutine PROP is called by subroutine HEAT to calculate the portion of radial thermal losses due to convection from fluid flowing in a cylindrical pipe.

2.8 DISCOUNTED CASH FLOW SUBMODEL FOR RESERVOIR AND FLUID TRANSMISSION

After the iterations to design and cost the reservoir and fluid transmission system and distribution system are completed in the executive routine DGHEAT, the main program in GEOCITY calls the discounted cash flow submodel for the reservoir and fluid transmission system (Figure 4). This submodel is simulated by subroutine RESVOR and its associated subroutines; it determines the annual cash flow associated with the pre-development (exploration), development, and operation of the reservoir and fluid transmission system from the beginning of exploration through its operational life. The discounted cash flow submodel provides for escalation of the annual capital costs and interim capital replacements, O&M expenses, and electricity expenses for the reservoir and fluid transmission system using the price escalation rates defined for these generic categories in Section 3.5.5.2.

The exploration process simulated in subroutine RESVOR identifies and evaluates potential reservoir sites by a series of discrete steps, each of

which can occur either sequentially in time or with some specified time overlap. Each step has an activity description, time period, associated cost, and success ratio (finding rate). The major steps are: 1) identification of target reservoir sites, 2) preliminary reconnaissance, 3) detailed reconnaissance, 4) identification of drillable sites, 5) exploratory drilling, 6) development of the reservoir and fluid transmission system, and 7) operation of that system. The steps are described in detail in Section 3.5.6.

Exploration costs are stored in the code based upon exploring reservoir sites capable of supplying 250 MWth of energy at peak demand over the reservoir system lifetime. However, in its calculations, subroutine RESVOR prorates the exploration costs based upon the peak thermal energy demands of the distribution system that is currently being simulated. Thus, smaller (larger) distribution systems permit exploration of smaller (larger) reservoir sites and accordingly smaller (larger) exploration costs than those stored in the code for the default size of 250 MWth. Both capitalized and expensed costs are determined for each of the steps in the reservoir exploration process. Capitalized costs are amortized on a straight-line basis over the operational life of the reservoir. The equations for calculating the exploration costs are described in Appendix A.

Developmental and operational costs are based upon the number of producing, nonproducing, and injection wells and the fluid transmission and injection systems established in the iteration between the reservoir and fluid transmission system submodel and the distribution system submodel. The developmental costs include: drilling costs, based upon the required number of wells and the unit drilling costs per producing, nonproducing, and injection well (either input or calculated by the drilling model); the capital cost of the fluid transmission system calculated in subroutine TRANS; and the capital cost of the fluid injection system calculated in subroutine INJECT. The cost of drilling producing and injection wells is subdivided into both tangible and intangible drilling costs because tax regulations may treat these costs differently.

Operational costs for the reservoir and fluid transmission system include: replacement well drilling (subdivided into tangible and intangible costs), nonproducing well drilling associated with replacement wells, well abandonment,

well maintenance, overhead and management, well redrilling due to scale build-up, replacement of downhole pumps, pumping electricity costs, and maintenance of the fluid transmission and injection systems. Both developmental and operational costs of the reservoir and fluid transmission system are based on the size of the reservoir and fluid transmission system calculated to meet the peak thermal energy demands of the distribution system that is currently being simulated. The equations for calculating the developmental and operational costs are described in Appendix A.

Using discounted cash flow analysis, the unit cost of thermal energy from the reservoir and fluid transmission system is calculated by equating the present worth of the revenues and expenses from the beginning of exploration through the operational life of the reservoir and fluid transmission system. Descriptions follow of the subroutines associated with subroutine RESVOR and the discounted cash flow submodel for the reservoir and fluid transmission system.

CLEAR	Clears consecutive locations in memory for initializing arrays in various subroutines to zero.
TARGTS	Calculates the number of prospective reservoir sites to explore in each of the successive discrete steps comprising the reservoir exploration process, based upon the success ratios (finding rates) input for each step. The successive reduction in the number of reservoir sites to explore at each step culminates in a single successful site at the last step, completing the exploration process.
DATAACK	Calculates and prints the annual operating costs and the annual cash flow statement for the reservoir and fluid transmission system from exploration through its operating lifetime. The annual operating costs printed include the following: O&M costs, pumping electricity costs, general management, replacement well drilling, and the sum of these four costs. The annual cash flow statement lists the year, the distribution system load factor (fraction of annual time the distribution system is operating at

full capacity), and the annual cash flows for the following items: identification of target reservoir sites, remaining reservoir pre-development (exploration) activities beginning with preliminary reconnaissance, development and operation of the reservoir and fluid transmission system, property taxes and insurance, interim capital replacements for the fluid transmission and injection systems, the sum of these costs, and investment tax credits.

FACTRS

Calculates the present worth discount factor based upon the cost of capital from both debt (bond) and equity (stock) financing, using the effective bond interest rate after taxes. All expenses and revenues are assumed to be incurred at midyear. If year-end discounting is desired, the variable TIMD appearing in subroutine FACTRS should be reset from 0.5 to 1.0 in the BLOCK DATA subroutine. Subroutine FACTRS is called by the discounted cash flow submodels for both the reservoir and fluid transmission system and the distribution system, as shown in Figure 5.

PWRCO

Subroutine PWRCO repeatedly calls subroutine DEPREC to calculate the depreciation allowances for the following capitalized items: tangible drilling costs for the producing wells and their interim capital replacements (i.e., tangible drilling costs for the replacement wells), capital costs of the fluid transmission system and its interim capital replacements, tangible drilling costs for the injection wells, and capital costs of the fluid injection system and its interim capital replacements. Subroutine PWRCO also amortizes the capitalized portion of the pre-development (exploration) costs of the reservoir on a straight-line basis over the operational lifetime of the reservoir. The depreciation allowances are printed by subroutine OUTPUT in the statement of annual deductible expenses.

DEPREC

Calculates the annual depreciation of the capital assets of the reservoir and fluid transmission system, including interim capital replacements. The input parameter LL2 selects one of two

available options: the straight-line method (LL2 = 1) or double-declining balance with switch over to straight-line (LL2 = 3). The default option is LL2 = 3.

COSTEQ Calculates the unit cost of thermal energy from the reservoir and
and fluid transmission system by setting the present worth of the
Entry Point revenues equal to the present worth of the expenses from the
COSTQA beginning of exploration through the operating life of the
 reservoir and fluid transmission system.

Unit cost of energy (dollars/MBtu) = (present worth of the expenses - present worth of tax credits) / [(present worth of energy supplied) * (1 - state gross revenue tax rate) * (1 - combined federal and state income tax rate)]

The present worth of thermal energy supplied to the distribution system takes into account the annual load factor of the distribution system.

The first half of subroutine COSTEQ calculates the unit cost of thermal energy on a constant dollar basis (no inflation or price escalation); the second half, defined by the entry point COSTQA, calculates the unit cost of thermal energy on a current dollar basis (with inflation and price escalation).

PAYOUT Calculates the annual income statement and annual payout of investments for the reservoir and fluid transmission system. This includes the total energy sales (gross revenues), state and federal income taxes, revenue taxes, royalty payments, and the changes in capitalization: outstanding bonds, bonds repaid, unrecovered equity, equity recovered, bond interest, and earnings on unrecovered equity.

OUTPUT Prints the statements of annual deductible expenses, annual income, and annual payout of investments for the reservoir and fluid transmission system from the beginning of exploration through the operating lifetime. The statement of annual deductible expenses lists the items: year, present worth factor for

that year, operating expenses, bond interest, well depreciation, the reservoir and fluid transmission system depreciation, total deductible operating expenses, and state income taxes. The statement of annual income lists the items: year, trillion Btu of energy supplied, energy sales, revenue taxes, royalty payments, total tax deductible expenses, taxable income (federal), and federal income tax. The statement of payout of investments lists the items: year, net cash flow, outstanding bonds, equity capital not recovered, bond interest, earnings on unrecovered equity, bonds repaid, and recovery of equity.

SUMARY
and
Entry Point
ASUMRY

The first half of subroutine SUMARY calculates and prints the breakdown of the life-cycle, levelized unit cost of thermal energy from the reservoir and fluid transmission system (on a constant dollar basis) in dollars/MBtu and equivalent annual costs in millions of dollars. These costs are itemized by components as follows: identification and exploration, development, operating costs, revenue taxes, state income taxes, royalty payments, federal income taxes and bond interest. In another set of calculations, the taxes, royalty payments, and bond interest are reallocated to the direct cost components (identification and exploration, development, and operating costs) for the reservoir and fluid transmission system. The rate of return on investment is included in the distributed energy cost for each component. The deductible nature of the bond interest causes this expense to be partially included in the rate of return (the part that is included in the present worth factor) and the remainder to be accounted for separately.

The second half of subroutine SUMARY, defined by the entry point ASUMRY, calculates the annual unit cost of thermal energy from the reservoir and fluid transmission system in current dollars using four different bases: 1) full-cost-recovery basis, 2) out-of-pocket cost basis, 3) operating cost basis, and 4) electrical pumping cost basis. In addition, the equivalent life-cycle,

levelized cost of thermal energy for the full-cost-recovery basis is also calculated in deflated base year dollars (January PRINDX dollars), as defined in Section 3.5.5.1. The calculations use the after-tax discount rate computed in subroutine FACTRS and the general inflation rate defined in Section 3.5.5.2.

2.9 DISCOUNTED CASH FLOW SUBMODEL FOR DISTRIBUTION SYSTEM

As previously shown in Figure 4, the main program in GEOCITY completes the calculations of the cost of space (process) heating, space (process) cooling, and sanitary water heating to the end-user by calling the discounted cash flow submodel for the distribution system. This submodel is simulated by a small executive routine DISTRB and its associated subroutines. It combines the thermal energy cost from the reservoir and fluid transmission system with the capital and operating costs of the distribution system to generate the cash flow associated with the design, construction, and operation of the distribution system throughout its useful life. Note that the annual revenue of the reservoir and fluid transmission system is an annual operating cost to the distribution system. The discounted cash flow submodel provides for the escalation of the annual capital costs and interim capital replacements, O&M expenses, electricity expenses, and purchased supplemental energy for the distribution system using the price escalation rates defined for these four generic categories in Section 3.5.5.2.

The required revenue and unit cost of heat (chill) from the distribution system are determined by using discounted cash flow analysis, and equating the present worth of the revenues and expenses over the operational life of the distribution system. Descriptions of the subroutines called by the small executive routine DISTRB to simulate the discounted cash flow submodel for the distribution system follow.

HCONST	Calculates the following costs appearing in the annual cash flow statement for the distribution system: capital costs, operating costs, interim capital replacements, property taxes and insurance, the sum of all these costs plus the thermal energy cost from the reservoir and fluid transmission system, and investment
--------	--

tax credits. The total capital cost of the distribution system over the construction period (NYC years, defined in Section 3.5.3) is calculated in subroutine DIST according to the component capital cost models in Appendix B. This cost includes the following items: pipe, insulation, casing, fittings, expansion loops, trenches, valves, meters, pumps, metering and control equipment, buildings and land use, building retrofit for heating and cooling (optional), heat exchanger (optional), and engineering and administration. Subroutine HCONST apportions the capital cost by year over the number of years (NYC) input for distribution system construction. The apportionment is based on the following function:

$$C(t) = \frac{100}{[1 + e^{k(a-t)}]}$$

where:

$C(t)$ = is the cumulative percent expenditure at time t .

k = is a constant, 0.0847.

a = is the 50% expenditure point in time, currently set to the 60% point in the construction schedule.

t = is the time in years from beginning of construction.

Annual operating costs are calculated in subroutines DIST and HCONST according to the operating cost models in Appendix B. This includes the following items: personnel costs for operating the distribution system and for administrative functions, routine repair and maintenance of the distribution system, electricity costs for distribution pumps, meter readers, supplemental heating costs (for heating mode), operating costs of the heat exchanger (optional), and operating costs of the absorption chillers (for cooling mode).

Interim capital replacements are calculated annually in subroutine HCONST as a fraction of construction period capital costs.

Interim capital replacements (\$) = [input fraction DINPUT(53), with default value 0.0035] * (construction period capital cost)

Property taxes and insurance are calculated annually as a fraction of total capital costs (construction period capital costs plus all interim capital replacements) up to the year of interest in the calculation.

Property tax (\$) = [input fraction DINPUT(52), with default value 0.0250] * (total capital cost up to the year of interest in the calculation)

Property insurance (\$) = [input fraction DINPUT(54), with default value 0.0012] * (total capital cost up to the year of interest in the calculation)

Investment tax credits in the first year of operation are calculated as a fraction of total construction period capital costs and interim capital replacements during the first year of operation.

Investment tax credit (\$) = [0.01 * input percentage PIVTCP, with default value 0] * (total construction period capital costs and interim capital replacements in the first year of operation).

Investment tax credits in subsequent years of operation are calculated as a fraction of the interim capital replacements.

Investment tax credit (\$) = [0.01 * input percentage PIVTCP, with default value 0] * (interim capital replacements in the year of interest)

Subroutine HCONST (together with subroutine DIST) also calculates the annual net production of usable heat or chill (after allowance for thermal losses in the distribution system piping) in units of Btu/yr and MBtu/yr.

DATAK Prints the following annual operating costs for the distribution system: O&M costs, pumping electricity costs, purchased supplemental heat (discussed in Section 3.5.5.3), and the sum of these three costs.

DPREC Calculates the annual depreciation of the distribution system capital assets, including interim capital replacements. The input parameter LL2 selects one of two available options: the straight-line method (LL2 = 1) or double-declining balance with switch over to straight-line (LL2 = 3). The default option is LL2 = 3.

COSTEG
(and
entry point)
COSTEA Calculates the unit cost of heat (chill) from the distribution system to the end-user by setting the present worth of the revenues equal to the present worth of the expenses over the operational life of the distribution system.

Unit cost of heat (chill) (dollars/MBtu) = $(\text{present worth of expenses} - \text{present worth of tax credits}) / [(\text{present worth of heat (chill) production}) * (1 - \text{state gross revenue tax rate}) * (1 - \text{combined federal and state income tax rate})]$.

The present worth of heat (chill) production takes into account the annual load factor for the distribution system.

The first half of subroutine COSTEG calculates the unit cost of heat (chill) on a constant dollar basis (no inflation or price escalation); the second half, defined by the entry point COSTEA, calculates the unit cost of heat (chill) on a current dollar basis (with inflation and price escalation).

PAYOT Calculates the annual tax deductible expenses, annual income statement, and annual payout of investments for the reservoir and fluid transmission system. This includes the total heat (chill) sales (gross revenues), total tax deductible expenses, taxable income (federal), state and federal income taxes, revenue taxes, and the changes in capitalization: outstanding bonds, bonds

repaid, unrecovered equity, equity recovered, bond interest, and earnings on unrecovered equity.

OUTPLT

Prints the statements of annual cash flow, annual tax deductible expenses, annual income, and annual payout of investments from the beginning of distribution system construction through its economic life. The statement of annual cash flow lists these items: year, distribution system load factor, capital costs, energy costs from the reservoir and fluid transmission system, distribution operating costs, interim capital replacements, property taxes and insurance, the sum of these costs and investment tax credits. The statement of annual tax deductible expenses lists these items: year, present worth factor for that year, operating expenses, bond interest, depreciation, total deductible operating expenses, and state income taxes. The statement of annual income lists these items: year, trillion Btu of heat (chill) sold, heat (chill) sales, revenue taxes, total tax deductible expenses, taxable income (federal), and federal income tax. The statement of payout of investments lists these items: year, net cash flow, outstanding bonds, equity capital not recovered, bond interest, earnings on unrecovered equity, bonds repaid, and recovery of equity.

CPOWER and entry point APOWER

The first half of subroutine CPOWER calculates and prints the breakdown of the life-cycle, levelized unit cost of heat (chill) from the distribution system (on a constant dollar basis) in dollars/MBtu and equivalent annual costs in millions of dollars. These costs are itemized by components as follows: distribution system capital costs, interim capital replacements, energy supply from the reservoir and fluid transmission system, operating expenses, property taxes and insurance, revenue taxes, state income taxes, federal income taxes, and bond interest. The difference between the unit cost of energy at the distribution system and the unit cost of energy from the reservoir and fluid transmission system calculated in subroutine COSTEQ is caused by

thermal losses in the distribution system piping. In another set of calculations, the taxes and bond interest are reallocated to the direct cost components (capital costs, interim capital replacements, energy supply, operating expenses, and property taxes and insurance) for the distribution system.

The second half of subroutine CPOWER, defined by the entry point APOWER, calculates the annual unit cost of heat (chill) in current dollars using four different bases: 1) full-cost-recovery basis, 2) out-of-pocket cost basis, 3) energy supply and operating cost basis, and 4) energy supply cost basis. In addition, the equivalent life-cycle, levelized cost of heat (chill) for the full-cost-recovery basis is also calculated in deflated base dollars (January PRINDX dollars), as defined in Section 3.5.5.1. The calculations use the after-tax discount rate computed in subroutine FACTRS and the general inflation rate defined in Section 3.5.5.2.

2.10 STEAM TABLE FUNCTIONS

Tables 1 and 2 give the 1967 ASME Steam Table functions used to calculate thermodynamic and physical properties of pure water and steam, their arguments, and the temperature-pressure subregions in which they are applicable. The subregions are illustrated relative to the saturation line on the temperature-pressure diagram in Figure 11. Subregion 6 is the area just above and below the saturation line. When calculations of properties are needed near the critical point in subregion 5, the accuracy of the functions used should be checked against the individual requirements, since the properties vary rapidly in this area. Definitions for the symbols used in Tables 1 and 2 follow.

- p - Pressure, psia
- t - Temperature, °F
- h - Specific Enthalpy, Btu/lb
- s - Specific Entropy, Btu/lb-°F
- v - Specific Volume, ft³/lb
- x - Quality by weight fraction, %/100

TABLE 1. ASME Steam Table Single-Valued Functions

State Unknown
(either wet (two-phase) or
superheated)

Saturation Line and Wet Steam

<u>FORTRAN Code Name</u>	<u>Function</u>	<u>Subregion</u>
HPS	$h = f(p, s)$	2,3,4
SPH	$s = f(p, h)$	2,3
VPH	$v = f(p, h)$	2,3
VPS	$v = f(p, s)$	2,3,4
TPH	$t = f(p, h)$	2,3,4
TPS	$t = f(p, s)$	2,3,4
THS	$t = f(h, s)$	2,3,4,6
PHS	$p = f(h, s)$	2,3,4,6
XPH	$x = f(p, h)$	
XPS	$x = f(p, s)$	

<u>FORTRAN Code Name</u>	<u>Function</u>	<u>Subregion</u>
HPSW	$h = f(p, s)$	6
SPHW	$s = f(p, h)$	6
VPHW	$v = f(p, h)$	6
VPSW	$v = f(p, s)$	6
TSL/TSATP	$t = f(p)$	Sat. Line
PHSW	$p = f(h, s)$	6
PSL/PSATT	$p = f(t)$	Sat. Line

Superheated Steam

Compressed Liquid

HPSD	$h = f(p, s)$	2,3,4
HPTD	$h = f(p, t)$	2,3,4
SPHD	$s = f(p, h)$	2,3,4
SPTD	$s = f(p, t)$	2,3,4
VPHD	$v = f(p, h)$	2,3,4
VPSD	$v = f(p, s)$	2,3,4
VPTD	$v = f(p, t)$	2,3,4
TSUPH/TPHD	$t = f(p, h)$	2
TSUPS/TPSD	$t = f(p, s)$	2,3,4
THSD	$t = f(h, s)$	2,3,4
PHSD	$p = f(h, s)$	2,3,4
VISV	$\mu = f(p, t)$	2,3,4
CONDV	$k = f(p, t)$	2,3,4
PRSTM	$Pr = f(p, t)$	2,3,4

HPTL	$h = f(p, t)$	1,3,4
SPTL	$s = f(p, t)$	1,3,4
VPTL/VCL	$v = f(p, t)$	1,3,4
TPHL	$t = f(p, h)$	1,4
TPSL	$t = f(p, s)$	1,4
VISL	$\mu = f(p, t)$	1,2,3,4
CONDL	$k = f(p, t)$	1
PRLIQ	$Pr = f(p, t)$	1

Saturated Vapor

Saturated Liquid

HGP	$h = f(p)$	Sat. Line
HGT	$h = f(t)$	Sat. Line
SGP	$s = f(p)$	Sat. Line
SGT	$s = f(t)$	Sat. Line
VGP	$v = f(p)$	Sat. Line
VGT	$v = f(t)$	Sat. Line
PSV	$p = f(s)$	Sat. Line

TSLH	$t = f(h)$	Sat. Line
HFP	$h = f(p)$	Sat. Line
HFP/HSL	$h = f(t)$	Sat. Line
SFP	$s = f(p)$	Sat. Line
SFT/SSL	$s = f(t)$	Sat. Line
VFP	$v = f(p)$	Sat. Line
VFT/VSL	$v = f(t)$	Sat. Line

Some subroutines have been given two names separated by a slash (/) mark. When calling these subroutines, the names can be used interchangeably.

TABLE 2. ASME Steam Table Multiple-Valued Functions

<u>FORTTRAN Code Name</u>	<u>Function</u>	<u>State</u>
HSSISS	$h, t, v, x = f(p, s)$	Wet or Superheated Steam
HPSISS	$h, t, v, x = f(p, s)$	Superheated Steam
HSS	$h, s, v = f(p, t)$	Superheated Steam
HSV	$h, t, s, v = f(p)$	Saturated Vapor
HCL	$h, s = f(p, t)$	Compressed Liquid
HSSICL	$h, t = f(p, s)$	Compressed Liquid
SSSISS	$s, t, v, x = f(p, h)$	Wet or Superheated Steam
SPSISS	$s, t, v, x = f(p, h)$	Superheated Steam
SSICL	$s, t = f(p, h)$	Compressed Liquid
CRFLO	$f_c, {}^0S = f(p, h)$	Wet or Superheated Steam
CRVEL	$V_c, \gamma = f(p, h)$	Wet or Superheated Steam
<u>Isentropic Drop Subroutines</u>		
ZSDT	$h_1, s_1, x_1, v_1, t_2, x_2, v_2, h_2$ $= f(p_1, p_2, t_1)$	Wet or Superheated Steam
ZSDH	$t_1, s_1, x_1, v_1, t_2, x_2, v_2, h_2$ $= f(p_1, p_2, h_1)$	Wet or Superheated Steam
ZSRT	$h_1, s_1, t_2, h_2 = f(p_1, p_2, t_1)$	Compressed Liquid
ZSRH	$t_1, s_1, t_2, h_2 = f(p_1, p_2, h_1)$	Compressed Liquid

FIGURE 11. Steam Table Subregions as a Function of Temperature and Pressure

- μ - Viscosity, lb/ft-sec
- k - Thermal conductivity, Btu/hr-ft- $^{\circ}$ F
- Pr - Prandtl number
- V_c - Critical velocity, ft/sec
- F_c - Critical flow, lb/hr-in 2
- γ - Isentropic exponent ($pv^{\gamma} = \text{Constant}$)
- $^{\circ}s$ - Degrees superheat

Many of the functions are interdependent. Consequently, if the use of a function is desired, the majority of the steam table functions must be loaded into computer memory.

GEOCITY initially calls the following subroutines in the steam tables to initialize steam table constants appearing in labeled common of the steam tables: CCSR1, CCSR2, CCSR3, CCBLL, and COMALL.

3.0 PREPARATION OF INPUT DATA

3.1 NAMelist INPUT RULES

The first card required in the input data for GEOCITY specifies a Hollerith title of 80 characters or less for identifying the simulation print-out. The remaining data cards permit the user to override default values initialized for the input parameters in the BLOCK DATA subroutine. These cards are input using the NAMelist statement, which permits input of numerical values for parameters and arrays preceded by the identifying parameter or array names. No format specification is used. This section gives a brief description of the NAMelist rules for the UNIVAC computer, which are applicable to most other machines with minor variations. The reader may wish to consult the FORTRAN manual available at his/her installation for a more detailed discussion. A sample case illustrating the NAMelist input is given in the next section. The reader may find it helpful to refer to the sample input during the following discussion. The definitions of the NAMelist input parameters and their default values in GEOCITY are given following the sample input.

The NAMelist input to GEOCITY is composed of two sets of data: 1) the reservoir and fluid transmission system data, and 2) the distribution system data. The reservoir and fluid transmission system data begin in column 2 of the second data card (the first card is the title card mentioned above) with the NAMelist group name \$RESVOR. The distribution system data begin in column 2 of the data card following the reservoir and fluid transmission system data with \$DISTRB. Each NAMelist group name is separated by one or more spaces from its succeeding list of parameters, array names, and their numerical values.

Input parameters and arrays may be defined in three ways.

- parameter = constant
- array name = constant,...,constant,
- array name (integer constant subscript) = constant,...,constant,

Commas separate each definition from succeeding definitions. Constants can be preceded by a repetition number and an asterisk, as for example, array name = 3 * 1.0. This sets the first three locations in the array to the values 1.0. In defining arrays, the number of constants, including repetitions, given for

an array name should not exceed the number of elements in the array. The number of elements in the GEOCITY arrays are given accompanying the definition of the input parameters and their default values following the sample input case. When data are input using the definition "array name (integer constant subscript) = constant,...,constant," the array elements are defined consecutively beginning with the location given by the integer constant subscript. The number of constants need not equal, but may not exceed, the remaining number of elements in the array.

Integer or real constants are converted to the type of the parameter or array in the code. All input parameters to GEOCITY beginning with the letters I through N, except the parameters IO and KINS, are integer. The parameters IO and KINS are declared real (floating point) parameters in GEOCITY. The parameter DFLAG is a logical parameter in GEOCITY. All other input parameters are real.

The parameters, array names, and their numerical values following the NAMELIST group name \$RESVOR or \$DISTRB are read until the characters \$END are encountered to complete the definition of the input data for the reservoir and fluid transmission system or distribution system, respectively. Parameters may be in any order. Blanks may be used freely to improve readability, except between \$ and RESVOR or \$ and DISTRB, or within array names and parameter names, or within numerical values.

A minimum of three data cards is needed to define the input data for a simulation case. The first column of each card is ignored and should not contain any data. All cards except the last for a NAMELIST group must end with a constant (optionally followed by a comma). The last card for each NAMELIST group must end with the characters \$END.

Consecutive simulation cases can be set up in the input data. Each new simulation case requires the following cards: 1) a title card, 2) a \$RESVOR card and, when necessary, continuation cards defining the NAMELIST input parameters to be changed from the preceding simulation case for the reservoir and fluid transmission system, and 3) a \$DISTRB card and, when necessary, continuation cards defining the NAMELIST input parameters to be changed from the preceding simulation case for the distribution system. The last card for each

NAMelist group must end with the characters \$END. The input data for a simulation case may consist of any subset of the NAMelist input parameters. In setting up consecutive simulation cases in the input data, only the input parameters with values differing from the preceding simulation case require redefinition. The values of parameters and arrays not included in the input data for a particular simulation case remain unchanged from:

- The default values in BLOCK DATA for the first simulation case.
- The values from the preceding simulation case for cases after the first case.

If no values are to be changed from the default values in BLOCK DATA IN the first simulation case, the input data consists of: 1) a title card, 2) a card with \$RESVOR \$END beginning in column two, and 3) a card with \$DISTRB \$END beginning in column two.

3.2 INPUT INSTRUCTIONS AND SAMPLE CASE INPUT

The data input to GEOCITY consists of the following three types of cards:

- A title card of 80 characters or less to identify the simulation printout.
- Data cards defining values for the reservoir and fluid transmission system input parameters, beginning in column two with \$RESVOR, according to NAMelist input rules.
- Data cards defining values for the distribution system input parameters, beginning in column two with \$DISTRB, according to NAMelist input rules.

The following steps are suggested for preparing the data input:

- Step 1. Review the NAMelist input rules summarized in the preceding section.
- Step 2. Prepare a title card of 80 characters or less.
- Step 3. Prepare cards defining the technical and economic input parameters for the reservoir and fluid transmission system following the NAMelist input rules.
- Step 4. Prepare cards defining the technical and economic input parameters for the distribution system following the NAMelist input rules.

All input parameters and their default values are defined in Sections 3.3, 3.4, 3.5, and 3.6. Those input parameters not included in the data cards for a given case are set equal to the default values.

To illustrate the data input, the GEOCITY model was used to calculate the cost of residential space heating, space cooling, and sanitary water heating for a small city in the western United States using a geothermal district heating and cooling system. The concept was previously depicted in Figure 3 of Section 2.1. The reader may wish to refer to Figure 3 in following the description of the sample case input shown in Table 3.

The parameters set to override the default values for the reservoir and fluid transmission system and the distribution system are defined in the NAMELIST groups \$RESVOR and \$DISTRB, respectively. The parameters are listed within each NAMELIST group in Table 3 in the chronological order of their description in this User Manual. The sections that describe the parameters are also shown in Table 3. All input parameters not shown were set equal to their default values. The geothermal installation simulated in the sample case will now be described.

Geothermal fluid was withdrawn from a production wellfield drilled to a depth of 2,000 meters (6,562 ft) in a hydrothermal reservoir located in the western United States. Each well encompassed 25 acres and the average production well life was 10 years before replacement wells had to be drilled. Well drilling costs (calculated by the drilling model) were \$831,000 per well in January 1980 dollars.

Downhole pumps located below the drawdown level at 152.4 meters (500 ft) could pump up to 400,000 lb/hr of geothermal fluid to the wellhead at 120°C (248°F). The service life of the downhole pumps was nine months before replacement was needed. At the surface, the fluid was gathered by a network of insulated pipes and pumped 10 miles through an insulated, surface pipeline to a small city with a population of about 29,000.

At the boundary of the city, the geothermal fluid was pumped through a heat exchanger to extract the necessary thermal energy. The spent fluid was then pumped 16,094 meters (10 miles) to an injection wellfield. Circulating

TABLE 3. Sample Case Input for Geothermal District Heating and Cooling for a Small Western City in the U.S.A.

		Section
1	GEO THERMAL DISTRICT HEATING AND COOLING FOR SMALL WESTERN CITY IN USA	
2	\$RESVOR	
3	PWTEMP=120., FLORAT=400000., WELSPC=25., AVGWL=10., STRATA(2,1)=2000.,	3.3.1
4	DHPDEF=152.40, PMLIFE=0.75,	3.3.2
5	PLMANF=1.,	3.3.4
6	PLINJP=16094.,	3.3.5
7	DINPUT(4)=.42, DINPUT(5)=.10, DINPUT(6)=.13, DA=15., PIVTCR=10.,	3.5.1
8	IDRILL=1,	3.5.2
9	PIFELR=7.,	3.5.5.2
10	IPILOT=1,	3.6
11	\$END	
12	\$DISTRH	
13	MODE=2,	
14	ADGDAY(1)=5267., DDGDAY(1)=5267., TMIN=-15., TDES(1)=-15.,	3.4.1
15	MCOOL=2, TDES(2)=95., HDES(2)=.008, ACDGHR=5426.,	3.4.2
16	NDTR=18, DRES=10.,	3.4.3
17	IDTR=4,3,3,3,3,3,4,3,2,3,2,2,5,2,2,5,4,1,	3.4.6.1
18	AREA=.078,.29,.08,.06,.20,.04,.146,.15,.26,.68,.14,.16,.023,.14,	
19	.45,.034,.049,.19,	
20	WIDTH=.12,.62,.18,.27,.51,.15,.27,.42,.23,.53,.40,.39,.21,.48,.28,	
21	.24,.09,.16,	
22	XLNGTH=.62,.70,.60,.32,.58,.40,.48,.53,1.69,2.02,.58,.61,.26,.57,	
23	2.35,.30,.42,1.71,	
24	DDTP=.41,1.59,1.48,.43,.56,.38,.45,.50,.42,1.27,.43,.43,.56,.40,	
25	.40,.21,.51,.87,	
26	HQ=.053,.044,.034,.48,.034,3*0.,	3.4.6.2
27	CQ=.017,.015,.013,.189,.013,3*0.,	
28	HW=60,.60,.60,.1250,.60,3*0.,	
29	DENSE=1568.,2093.,3837.,376.,7898.,3*0.,	
30	NRESO=3*1,21,1,3*0,	
31	POPHSE=2.66,2.66,2.66,55.86,2.66,3*0.,	
32	CRTF=3*500.,10500.,500.,3*0.,	
33	CRTFC=2*5000.,3700.,77700.,3700.,3*0.,	
34	PO=1., TA=0., AGFACT=1.,1.,1.,	3.4.7
35	DNET=1/*1,2,2*0, 15*0,2*2,3*0, 14*1,2,5*0, 3*2,17*0, 3*0,10*1,2,6*0,	3.4.9
36	8*0,5*2,7*0, 3*0,3*1,2*2,12*0, 5*0,2,14*0, 3*0,2*2,15*0, 220*0,	
37	DINPUT(39)=1., DINPUT(40)=.10, DINPUT(41)=0., DINPUT(42)=0.,	3.5.3
38	DINPUT(50)=0., DINPUT(52)=0.,	
39	CSBTU=0., COPUMP=.03,	3.5.5.3
40	\$END	
41	#FIN	

hot water inside the city distribution system was heated to approximately 110°C (232°F) at the heat exchanger. The heated water was then pumped through a network of buried, insulated pipes for residential space heating, space cooling, and sanitary water heating in the city over a 30 year time period. The used water was recirculated from the individual residences to the heat exchanger at the boundary of the city to conserve its residual heat.

Residential space heating was provided by fan-coil units. Residential space cooling was provided by lithium bromide/water absorption chillers and other auxiliary equipment (such as fan-coil units) located at each residence. A small heat exchanger located at the sanitary hot water tank of each residence was used to provide sanitary water heating.

A reservoir developer with 42% debt and 58% equity financing was assumed to construct and operate the reservoir and fluid transmission system. The bond interest rate and the after-tax return on equity were assumed to be 10% and 13%, respectively. The firm was allowed a 15% annual depletion allowance for the reservoir and an annual investment tax credit of 10% for capital and replacement.

The general inflation rate over the project lifetime was assumed to be 6% per annum. Annual escalation rates for capital and O&M costs were assumed to be the same as the general inflation rate. Electricity purchased for pumping the fluid was assumed to escalate at 7% per annum.

The definitions of the parameters set to override the default values for the reservoir and fluid transmission system are given in Table 4. All costs are in January 1980 dollars. The descriptions of all parameters for the reservoir and fluid transmission system and their default values are given in Sections 3.3, 3.5, and 3.6.

To simulate the distribution system, the city in the sample case was divided into 18 residential districts as follows:

- 1 single-family, low-density district
- 5 single-family, medium-density districts
- 7 single-family, high-density districts
- 3 multiple-family apartment districts (21 units per apartment)
- 2 trailer courts

TABLE 4. Reservoir and Fluid Transmission System Input Parameters in NAMELIST AND \$RESVOR for Sample Case

<u>Parameter</u>	<u>Section</u>	<u>Description</u>	<u>Value</u>
PWTEMP	3.3.1	Average wellhead temperature of each production well	120°C
FLORAT	3.3.1	Maximum flow rate of each production well	400,000 lb/hr
WELSPC	3.3.1	Reservoir well spacing	25 acres
AVGWL	3.3.1	Average production well life	10 years
STRATA(2,1)	3.3.1	Well depth	2000 meters
DHPDEP	3.3.2	Depth of downhole pump in each production well	152.4 meters
PMLIFE	3.3.2	Operational life of the downhole pumps before replacement is needed	9 months
PLMANF	3.3.4	Distance from the manifold pipe nodes (J=1 in Figure 18 of Section 4.0) to the first column of well nodes (J=2) in the endfield geometry	1 meter
PLINJP	3.3.5	Distance from the heat exchanger at the distribution system to the injection wellfield	16,094 meters
DINPUT(4)	3.5.1	Fraction of investment in bonds by owner of reservoir and fluid transmission system	0.42
DINPUT(5)	3.5.1	Bond interest rate (fraction)	0.10
DINPUT(6)	3.5.1	Earning rate on equity after taxes (fraction)	0.13
DA	3.5.1	Percentage depletion allowance for the reservoir	15%
PIVTCR	3.5.1	Percent investment tax credit for the reservoir and fluid transmission system	10%
IDRILL	3.5.2	Option to calculate well drilling costs using the drilling model in the code	1 (yes)
PIFELR	3.5.5.2	Annual escalation rate for the cost of purchased electricity for the pumps	7% per yr
IPL0T	3.6	Print switch to display printer plots of capital costs calculated by the code for pipes, insulation, and casing of the distribution piping system	1 (yes)

Figure 12 shows the layout of the 18 residential districts in the city. The GEOCITY code requires that all districts have rectangular shapes, so the actual city zoning map was modified to conform with this requirement. The width, length, and area of each of the 18 districts were determined from the zoning map and input to the code. The geometric description and characteristics of each district are shown in Table 5.

The housing densities used in the simulation were based on the city's zoning ordinances. The simulation consisted of 8,460 single-family dwellings, 103 apartment buildings containing a total of 2,155 apartment units, and 450 mobile homes. This represents a total population of about 29,000, assuming 2.66 people per household according to the 1970 census.

The climate affects district heating and cooling costs calculated by GEOCITY through several factors -- the minimum and maximum extreme temperatures and the annual heating degree days and annual cooling degree hours, respectively. The minimum and maximum temperatures establish the peak-load heating and cooling requirements and determine the size and cost of the pipes and pumps. Lower extreme temperatures in district heating and higher extreme temperatures in district cooling require more flow and larger pipes and pumps. Larger pipes and pumps increase the capital cost of the system. For economic reasons, district heating and cooling systems are usually designed to meet less than the peak demands for heating and cooling. The peak heating requirements are then met with supplemental heat. However, GEOCITY does not meet peak cooling requirements with supplemental chill.

The maximum dry-bulb temperature at the simulated site was 110°F. The outdoor design dry-bulb temperature used to design and size the district cooling system at the simulated site was 95°F [TDES(2) = 95°F]. This is the ASHRAE design dry-bulb temperature at the 2.5% level,⁽⁷⁾ which represents a temperature that is equalled or exceeded by 2.5% of the 2,928 hours during the four summer months (June through September). Thus, 73.2 hours (0.6 hours per day) will be at or above the outdoor design temperature during the four summer months. Recall that no supplemental cooling is provided in GEOCITY for the hours above the outdoor design dry-bulb temperature. The outdoor design wet-bulb temperature at the simulated site was 67°F. The absolute humidity

FIGURE 12. Layout of Residential Districts in Small Western City for Sample Input Case

TABLE 5. Summary of District Input Data for Sample Case

District Geometric Parameters

<u>District Number</u>	<u>District Type</u>	<u>Area (sq mi)</u>	<u>Width (mi)</u>	<u>Length (mi)</u>	<u>Main Length Serving the District (mi)</u>
1	4	.078	.12	.62	.41
2	3	.29	.62	.70	1.59
3	3	.08	.18	.60	1.48
4	3	.06	.27	.32	.43
5	3	.20	.51	.58	.56
6	3	.04	.15	.40	.38
7	4	.146	.27	.48	.45
8	3	.15	.42	.53	.50
9	2	.26	.23	1.69	.42
10	3	.68	.53	2.02	1.27
11	2	.14	.40	.58	.43
12	2	.16	.39	.61	.43
13	5	.023	.21	.26	.56
14	2	.14	.48	.57	.40
15	2	.45	.28	2.35	.40
16	5	.034	.24	.30	.21
17	4	.049	.09	.42	.51
18	1	.19	.16	1.71	.87

District Type Parameters

<u>District Type</u>	<u>Density (Bldg/sq mi)</u>	<u>Peak Heat Demand/Bldg (MBtu/hr)</u>	<u>Peak Chill Demand/Bldg (MBtu/hr)</u>	<u>Sanitary Hot Water Demand (gal/day)</u>	<u>Households per bldg</u>	<u>Diversity Factor</u>	<u>Heating Reject Temp (°F)</u>	<u>Cooling Reject Temp (°F)</u>	<u>Heating Retrofit Cost (\$/Bldg)</u>	<u>Cooling Retrofit Cost (\$/Bldg)</u>
1 Single-Family low-density	1568	.053	.017	60.	1	0	100	55	500	5000
2 Single-Family medium density	2093	.044	.015	60.	1	0	100	55	500	5000
3 Single-Family high-density	3837	.034	.013	60.	1	0	100	55	500	3700
4 Multiple-family apts. (21 units/apt)	376	.48	.189	1260.	21	0	100	55	10500	77700
5 Trailer courts	7898	.034	.013	60.	1	0	100	55	500	3700

(obtained from a psychrometric chart) based on the outdoor design dry-bulb and wet-bulb temperatures was 0.008 lb H₂O/lb air [HDES(2) = 0.008].

The minimum temperature used for district heating at the simulated site was the minimum winter ambient temperature of -15°F [TDES(1) = TMIN = -15°F]. For economic reasons, district heating systems (without cooling) would usually be designed to meet less than the peak heat demand. The peak heat demand would then be met with supplemental heat (see discussion in Section 3.4.2). However, in the combined heating and cooling simulation for this site, examination of an initial GEOCITY simulation run revealed that district cooling was the major mode (mode with larger peak flow requirements). Thus, the system design and size was established based on the peak cooling requirements of the city using a design outdoor dry-bulb temperature of 95°F [TDES(2) = 95°F]. The capacity of the resulting system was large enough to meet the entire peak heating requirements of the city at the minimum winter ambient temperature of -15°F [TDES(1) = TMIN = -15°F]. Thus, the system was able to supply 100% of the peak heating requirements and the design heating degree days were input equal to the annual heating degree days obtained from degree day tables for the simulated site [DDGDAY(1) = ADGDAY(1) = 5267°F-days]. In this case, no supplemental heat was required for district heating at the simulated site.

The annual cooling degree hours input for the simulated site were calculated based on hourly temperature observations between the indoor design temperature for cooling [TINDES(2) = 78°F] and the summer outdoor design dry-bulb temperature [TDES(2) = 95°F]. For the simulated site, the temperature intervals and number of hours in each interval used to calculate the annual cooling degree hours were as follows:

K	Temperature Intervals (°F)	Midpoint of Temperature Interval TAOD(K)	Hours/Year in Temperature Interval HROD(K)
1	(75,80)	77.5	375
2	(80,85)	82.5	303
3	(85,90)	87.5	221
4	(90,95)	92.5	125

The equation for calculating the annual cooling degree hours is described in Appendix E. For the simulated site, the equation is:

$$ACDGHR = \sum_{K=1}^4 [TAOD(K) - 78] * HROD(K)$$

The actual hours in the temperature interval (75,80) that require cooling, i.e., the hours in the interval (78,80), were prorated according to the methodology described in Appendix E.

The peak heat demands $[HQ(N)]$ for space heating of typical buildings in each residential district type in Table 5 are based on ASHRAE design recommendations, an indoor design temperature of 65°F for heating, and a minimum outdoor design temperature of -5°F (Appendix C). These values were increased by the code to reflect the lower minimum outdoor design temperature of -15°F used for the simulated site (see discussion of parameter $HQ(N)$ in Section 3.4.2). The daily sanitary water heating requirements shown in Table 5 are also based on ASHRAE design recommendations (Appendix C).

The peak chill demands $[CQ(N)]$ for space cooling of typical buildings in each residential district type in Table 5 were calculated from the methodology in Appendix E. The calculations were based on the values used for the indoor design temperature for cooling $[TINDES(2) = 78°F]$, the summer outdoor design dry-bulb temperature $[TDES(2) = 95°F]$, and the absolute humidity at the outdoor design dry-bulb and wet bulb temperatures $[HDES(2) = 0.008 \text{ lb } H_2O/\text{lb air}]$.

The cost of the district heating and cooling system must include the installed capital costs of building retrofit. We assumed a heating retrofit cost of \$500 per household in the simulation. We assumed a cooling retrofit cost of \$5,000 per household for single-family, low-density and medium-density districts. For single-family, high-density districts, apartments, and trailers we assumed a cooling retrofit cost of \$3,700 per household. These costs included the installed capital costs of the chiller, mixer, and auxiliary equipment at each household. In a more detailed analysis, a comprehensive survey

of existing heating and cooling systems could be undertaken to determine retrofit costs more accurately.

The network of buried, branching pipe mains used to transport the hot water from the heat exchanger at the boundary of the city to the 18 districts is shown in Figure 12. The layout of the pipe mains is a somewhat arbitrary choice. As shown in Figure 12, we used a total of 9 pipe mains in the simulation. The layout of the pipe mains serving the districts was determined from the city's zoning map. The matrix DNET (district number, main number), which defines the network of branching pipe mains serving 18 districts, is shown in Table 6.

The code lays out lateral pipes, street pipes, and street-to-house pipes inside each district as shown in Figure 3 of Section 2.1 and Figure 10 of Section 2.7. The distribution piping system inside the city was designed as a two-pipe system, in which the used water from individual residences is returned to the heat exchanger at the boundary of the city through the return piping. The design features of the distribution piping system used in the simulation are:

1. A two-pipe system, only supply pipes insulated, with supply and return pipes in a common casing, using schedule 40 carbon steel pipe (default pipe option and default pipe material option)
2. Calcium silicate insulation (default insulation option)
3. Prefabricated steel casing with no annular air spacing between the insulation and casing (default casing option with annular air spacing $TA = 0$)
4. Casing buried 0.5 meter deep in a dirt and rock mixture (default trenching conditions described in Section 3.5.4)

Since no supplemental heat was required in the sample simulation, the cost of supplemental heat was set to 0 [$CSBTU = 0$]. The electrical cost for operating the pumps in the reservoir and fluid transmission system and the distribution system was input as 3 cents per kilowatt-hour [$COPUMP = 0.03$].

A municipal utility was assumed to construct and operate the distribution system in the sample case. Financing for the project was assumed to be provided by the sale of municipal bonds at an interest rate of 10 percent.

TABLE 6. Branching Main Matrix DNET for Sample Case
Matrix DNET (District Number, Main Number) Defining
the Districts Served by the Mains

		Main Number															
		1	2	3	4	5	6	7	8	9	.	.	.	.	20		
District Number Served by the Main	1	1	0	1	2	0	0	0	0	0	All 0's						
	2	1	0	1	2	0	0	0	0	0							
	3	1	0	1	2	0	0	0	0	0							
	4	1	0	1	0	1	0	1	0	2							
	5	1	0	1	0	1	0	1	0	2							
	6	1	0	1	0	1	0	1	2	0							
	7	1	0	1	0	1	0	2	0	0							
	8	1	0	1	0	1	0	2	0	0							
	9	1	0	1	0	1	2	0	0	0							
	10	1	0	1	0	1	2	0	0	0							
	11	1	0	1	0	1	2	0	0	0							
	12	1	0	1	0	1	2	0	0	0							
	13	1	0	1	0	1	2	0	0	0							
	14	1	0	1	0	2	0	0	0	0							
	15	1	0	2	0	0	0	0	0	0							
	16	1	2	0	0	0	0	0	0	0							
	17	1	2	0	0	0	0	0	0	0							
	18	2	0	0	0	0	0	0	0	0							
	19	0	0	0	0	0	0	0	0	0							
	20	0	0	0	0	0	0	0	0	0							

Definition of Matrix Entries DNET (District M, Main MM)

- 0 - Main MM does not transport flow to district M in any way.
- 1 - Main MM transports flow to district M but does not connect directly to district M.
- 2 - Main MM connects directly to district M.

The definitions of the parameters set to override the default values for the distribution system are given in Table 7. All costs are in January 1980 dollars. The description of all parameters for the distribution system and their default values are given in Sections 3.4, 3.5, and 3.6.

The output corresponding to the sample case input is listed in Appendix G and described in Section 4.0. The output shows the input data, printer plots of key capital cost equations for the distribution system, the final techno-economic iteration between the reservoir and fluid transmission system and the distribution system, full economic output (cash flows) for the two systems, and the financial summary of the simulation results for combined residential space heating, space cooling, and sanitary water heating.

3.3 RESERVOIR AND FLUID TRANSMISSION SYSTEM INPUT DATA

This section describes the technical input parameters used by GEOCITY to design the reservoir wellfield layout and size the fluid transmission system for a geothermal district heating and cooling installation. The major components comprising the reservoir and fluid transmission system in GEOCITY are the production wellfield, fluid pumping system, (optional) fluid mixer, fluid transmission piping system, (optional) fluid injection piping system, and (optional) injection wellfield.

The technical parameters used in defining the various components of the reservoir and fluid transmission system are described in the following subsections:

<u>Subsection</u>	<u>Components of Reservoir and Fluid Transmission System</u>
3.3.1	Reservoir Characteristics and Well Properties
3.3.2	Fluid Pumping System
3.3.3	Fluid Mixer
3.3.4	Fluid Transmission Piping System
3.3.5	Fluid Injection Piping System

The default values initialized for the input parameters are defined in each subsection. New values for these parameters to override the default values can be input through the NAMELIST group \$RESVOR.

TABLE 7. Distribution System Input Parameters for Sample Case in
NAMELIST Group \$DISTRB

<u>Parameter</u>	<u>Section</u>	<u>Description</u>	<u>Value</u>
MODE	3.4.1	Operational mode--combined residential space heating, space cooling, and sanitary water heating	2
ADGDAY(1)	3.4.2	Annual heating degree-days based on temperature difference between the indoor design temperature for heating (65°F) and the minimum ambient temperature (TMIN) at the simulated site	5267°F-days
DDGDAY(1)	3.4.2	Design heating degree-days based on temperature difference between the indoor design temperature (65°F) and the winter outdoor design temperature at the simulated site (TDES(1))	5267°F-days
TMIN	3.4.2	Winter outdoor minimum temperature at the simulated site	-15°F
TDES(1)	3.4.2	Winter outdoor design temperature at the simulated site	-15°F
MCOOL	3.4.3	Option to directly input the peak chill demand (CQ(N)) for each building in district type N and the annual cooling degree hours (ACDGHR) at the simulated site	2
TDES(2)	3.4.2	Summer outdoor design dry-bulb temperature at the simulated site	95°F
HDES(2)	3.4.3	Absolute humidity at the summer outdoor design dry-bulb and wet-bulb temperatures at the simulated site	.008 lb H ₂ O/lb air
ACDGHR	3.4.3	Annual cooling degree hours between the indoor design temperature for cooling (78°F) and the summer outdoor design dry-bulb temperature (TDES(2)) at the simulated site	5426°F-hours

TABLE 7. (continued)

<u>Parameter</u>	<u>Section</u>	<u>Description</u>	<u>Value</u>
NDTR	3.4.6.1	Number of districts at the simulated site	18
DRES	3.4.6.1	Length of surface transmission pipeline from outlet of production well-field to heat exchanger at inlet of distribution system	10 miles
IDTR(M)	3.4.6.1	District type N of district number M	Table 5
AREA(M)	3.4.6.1	Area of district number M	Table 5
WIDTH(M)	3.4.6.1	Width of district number M	Table 5
XLNGTH(N)	3.4.6.1	Length of district number M	Table 5
DDTR(M)	3.4.6.1	Length of main serving district number M	Table 5
HQ(N)	3.4.6.2	Peak space heat demand per building in district type N (MBtu/hr-bldg of chill)	Table 5
CQ(N)	3.4.6.2	Peak space chill demand per building in district type N (MBtu/hr-bldg of chill)	Table 5
HW(N)	3.4.6.2	Daily sanitary hot water demand per building in district type N	Table 5
DENSE(N)	3.4.5.2	Density of buildings in district type N	Table 5
NRESN(N)	3.4.6.2	Number of households per building in district type N	Table 5
POPHSE(N)	3.4.6.2	Number of people per building in district type N (used only for printout purposes)	Table 5
CRTF(N)	3.4.6.2	Heating cost per building in district type N	Table 5

TABLE 7. (continued)

<u>Parameter</u>	<u>Section</u>	<u>Description</u>	<u>Value</u>
CRTFC(N)	3.4.6.2	Cooling retrofit cost per building in district type N	Table 5
PO	3.4.7	Pipe option (see Section 3.4.7)	1
TA	3.4.7	Casing annular air space	0 meters
AGFACT(I) I=1,3	3.4.7	Age factor to multiply friction losses in pipes due to age	1.,1.,1.
DNET	3.4.9	Branching pipe mains matrix	Table 6
DINPUT(39)	3.5.3	Fraction of distribution system financed by bonds (municipal utility in sample case)	1.0
DINPUT(40)	3.5.3	Bond interest rate (fraction)	0.10
DINPUT(41)	3.5.3	Earned rate on equity after taxes (fraction)	0.
DINPUT(42)	3.5.3	Federal income tax rate (fraction)	0.
DINPUT(50)	3.5.3	State income tax rate (fraction)	0.
DINPUT(52)	3.5.3	Property tax rate (fraction)	0.
CSBTU	3.5.5.3	Cost of supplemental heat (no supplemental heat used in sample case)	\$0/MBtu
COPUMP	3.5.5.3	Electrical pumping cost	\$.03/kWh

3.3.1 Reservoir Characteristics and Well Properties

GEOCITY does not have a geohydrologic model to simulate subterranean fluid and thermal flow in the reservoir. Instead, the relevant reservoir characteristics and well properties are captured by eight input parameters: flowing production wellhead temperature, the flow capacities of the production and injection wells, average production well life, number of excess production wells desired, number of dry wells drilled, well spacing, and well depth. Two other input parameters, the fraction of the well that is cased and the type of rock hardness in which the well is drilled, are used by the code only if the well drilling model in Section 3.5.2 is employed.

During operation over the production well lifetime, the wellhead temperature and the flow rate of the production wells may diminish due to the overall degradation of the hydrothermal reservoir. In practice, small temperature degradations would probably be met by increasing the flow rate from the production wellfield. Large temperature degradations would either require supplemental energy sources or else force some of the end-users in the distribution system to shut down. GEOCITY is predicated upon steady-state conditions in the reservoir, and assumes that the thermal energy recoverable from the reservoir is sufficient for the project lifetime and that the production wellhead temperature and flow rate are constant over the project lifetime. Indeed, the exploration costs described in Section 3.5.6 are concerned with finding a suitable geothermal reservoir with sufficient thermal energy to supply the distribution system requirements over the project lifetime.

The total number of production wells drilled is determined in the code by the peak system flow required from the reservoir by the distribution system, the flow capacity of the production well, the number of excess production wells desired, and the number of dry wells drilled. The total number of injection wells required is determined in the code by the peak system flow for injection and the flow capacity of the injection wells.

Both production and injection wells are located at the vertices of triangular lattices defining the wellfield geometry, as previously illustrated in Figure 8. Well spacing is dependent upon the quality of the reservoir. The distance between wells (meters) is calculated from the input well spacing

(acres) as previously described in Section 2.6.1. Well flow rate and depth are used by the code to size the downhole pumps and calculate their pumping energy. Well diameter, well depth, fraction of the well that is cased, and rock hardness are used by the drilling model (mentioned in Section 3.5.2) if it is employed to calculate the well drilling cost.

The production well life represents the number of years that the production well can produce before it has depleted the underlying reservoir and a new production well must be drilled. Replacement well drilling costs for production wells are calculated in the code based on the cost of drilling production wells and the production well life (Appendix A). Redrilling costs for the production wells (without relocation) due to scale buildup in the wells is calculated separately in the code (Appendix A). Fluid transmission piping costs associated with drilling new production wells are included in the annual interim capital replacement rate for the transmission system (Section 3.5.1).

The input parameters used to define the reservoir characteristics are defined below. The parameters are input through the NAMELIST group \$RESVOR.

AVGWL	Average production well life (years). The default is 10 years.
CASFRC	Fraction of each well that is cased. The default is 1.
DIA	Average diameter (centimeters if positive, inches if negative) of each well. The default is 22.225 centimeters (8.75 inches).
FLORAT	Maximum flow rate (lb/hr) of each production well. The default is 400,000 lb/hr/well.
FRCNPW	Fraction excess production wells to provide spare wells. The default is 0.2.
FRCNPW	Fraction nonproducing (dry) wells. The default is 0.2.
PWTEMP	Average wellhead temperature of each production well. (Positive input values are treated as Centigrade and negative input values as Fahrenheit.) The default is 100°C.
WELSPC	Reservoir well spacing (acres). The default is 20 acres. This applies to both the production and injection wellfields.

NUMTYP Number of different generic types of rock hardness comprising the strata encountered in drilling the entire depth of each production and injection well. The default value is 1, indicating one hardness for the entire depth of the well.

STRATA(M,N) Stratigraphic data array defining the type of rock hardness to
M=1,2 drilled (M=1) and the depth (M=2, positive if meters, negative if
N=1,10 feet) of each type of strata (N) encountered in drilling the production and injection wells. The possible values of STRATA (1,N) are:

 1 = soil, 2 = soft, 3 = medium, 4 = hard, and 5 = very hard.
The default values are as follows:

 STRATA(1,1) = 3, indicating that the rock type to be drilled is medium for the entire depth of the well.

 STRATA(2,1) = 2000., total well depth in meters.

3.3.2 Fluid Pumping System

The fluid pumping system, at the reservoir wells and in the transmission piping network, supplies and maintains geothermal fluid pressure above saturation at all times (i.e., in a compressed-liquid state). Two pumping system configurations can be selected by the user. The first system consists of a combination of downhole and surface pumps--downhole pumps in the production wells and a series of surface pumps along the final transmission pipeline from the production wellfield to the distribution system. This pumping system is the default option in the code.

The second configuration consists entirely of surface pumps at the production wellheads, manifold pipe nodes, and along the final transmission pipeline from the production wellfield to the distribution system. This configuration should only be selected if the natural artesian pressure of the hydrothermal reservoir is sufficient to produce the desired pressure and flow rate at the production wellhead. The layout of the default pumping system configuration is illustrated in Figure 13.

FIGURE 13. Conceptual Configuration of Reservoir and Fluid Transmission System

Both pumping systems simulate a series of surface pumps along the final transmission pipeline from the production wellfield to the distribution system, as well as surface pumps at the tube and shell-side inlets to the optional heat exchanger at the inlet to the distribution system. The number of surface pumps required along the final transmission pipeline is calculated by the code to avoid unnecessarily high discharge pressures that would require larger pipe schedules, subject to the constraint that the pumps be located at least one mile apart. The pipe schedules are calculated by the code as a function of the discharge pressures (Appendix D). The discharge pressures of the downhole and surface pumps are initially estimated by the code and then minimized during the iterations between the reservoir and fluid transmission system and the distribution system. However, the minimized discharge pressures are still sufficient to maintain compressed-liquid flow throughout the fluid transmission system.

Injection pumping is simulated simplistically in the code with one large conceptual surface pump located at the distribution system (with pump head set to 200 psi in subroutine TRANS). Gravity flow is assumed down the injection wells.

Two input parameters in this section deal specifically with the downhole pumps. The first parameter allows the user to set the depth of the downhole pumps. The depth should be set below the pumping drawdown. The depth should be set below the pumping drawdown level anticipated in the production wells. Downhole pumping energy is calculated by the code based on a total head equal to the sum of the vertical lift (depth) of the downhole pumps, frictional losses in the wells, and frictional losses in the surface piping connecting the matrix of wells. Although vertical lift will, in practice, increase as more drawdown occurs in the wells over long periods of continuous pumping during the production well lifetime and as interference increases from other wells in the reservoir (especially if injection does not occur into the production reservoir), GEOCITY operates with a steady-state drawdown level (downhole pump depth set by the user).

The second parameter related to downhole pumps defines their service life and has economic implications in the code. If the service lifetime is less

than one year, the pump replacement is calculated by the code as an expensed item. If the lifetime is one year or more, the pump replacement is calculated by the code as an interim capital replacement. This parameter does not apply to the replacement of surface pumps. Their replacement should be regarded as part of the interim capital replacement rates input for the transmission and injection systems (parameters DINPUT(18) and DINPUT(20) in Section 3.5.1.).

The equation used by the code to calculate electricity requirements of the downhole and surface pumps is given in Appendix D. The combined motor and pump efficiency required to calculate the electricity requirements is input by the user as the parameter ETA, which is defined in Section 3.5.5.3. This parameter applies to both the transmission and distribution system pumps.

The pump head required to overcome friction losses is conservatively calculated by the code based upon peak system flow rates. Friction losses in the wells and piping network are calculated by the code based upon turbulent flow, using the Darcy-Weisbach equation.

The pump capital costs are calculated in the code based on pump operating conditions (flow rates and pump heads) and cost data obtained from pump manufacturers. Downhole pump cost data is based on downhole pumps constructed of carbon steel that can operate effectively up to 180°C. Surface pump cost data is based on centrifugal pumps constructed of carbon steel.

The input parameters used to select the pumping system configuration and the depth and service life of the downhole pumps are defined below. The parameters are input through the NAMELIST group \$RESVOR.

IPUMP Configuration of the fluid pumping system.

1 - Surface pump at each production wellhead and at each piping manifold node, together with a series of surface pumps on the final transmission pipeline from the production wellfield to the distribution system.

2 - Downhole pump in each production well, together with a series of surface pumps on the final transmission pipeline from the production wellfield to the distribution system.

The default value of IPUMP is 2.

DHPDEP Depth of the downhole pumps in meters. The default is 152.4 meters (500 ft).

PMLIFE Operational life (years) of the downhole pumps before replacement is needed. The default is 0.75 years (9 months).

3.3.3 Fluid Mixer

GEOCITY provides the flexibility to include a fluid mixing tank at the inlet to the final transmission pipeline leading from the reservoir wellfield to the distribution system. The mixing tank blends cold water from an available external source, such as a river or lake, with the hot geothermal fluid to lower its temperature. This option is provided in case state or local safety regulations require the geothermal fluid temperature to be lowered prior to transmission in a surface pipeline to the distribution system. The conceptual system configuration is illustrated in Figure 13.

Capital and operating costs associated with the mixing tank and use of the external cold water source are assumed to be negligible. The input parameters required to include the fluid mixing tank are defined below and are input through the NAMELIST group \$RESVOR.

MIXOP Option for a fluid mixing tank at the inlet to the final transmission pipeline from the reservoir wellfield to the distribution system.
 0 = no fluid mixing tank (default)
 1 = fluid mixing tank

TCOLD Inlet temperature of the external cold water into the fluid mixing tank. Input values must be in Fahrenheit. The default is 59°F (15°C).

TMIX Outlet temperature of the blended water from the fluid mixing tank into the final transmission pipeline leading to the distribution system. Input values must be in Fahrenheit. The outlet temperature from the mixing tank must be less than the wellhead temperature (PWTEMP). The default value of TMIX is 302°F (150°C).

3.3.4 Fluid Transmission Piping System

The major components of the fluid transmission piping system in GEOCITY are the piping, insulation, casing, site work, and wellhead equipment. The elements in each of these categories and the cost models are described in Appendix D. The transmission piping network consists of a connected series of above-ground, insulated, carbon steel pipes gathering geothermal fluid from the production wells and one transmission pipeline transporting the fluid from the production wellfield to the distribution system. The insulation is covered by an aluminum jacketing for protection. The assumed configuration of the transmission piping network is illustrated in Figure 13.

The pipe lengths between adjacent wells in the horizontal rows of production wells are based upon the well spacing, which is dependent upon the quality of the reservoir. The well spacing, which is input by the user, was previously defined in Section 3.3.1. The first input parameter in this section (PLMANF) allows the user to define the lengths of the manifold pipe nodes from the well nodes. The diagonal manifold line in Figure 13 merges confluent flow from successive rows of production wells and transports the merged flow to the outlet of the production wellfield. The length of the final surface transmission pipeline from the production wellfield to the distribution system is defined by the input parameter DRES described in Section 3.4.6.1.

Pipe diameters are sized on the peak flow rate required by the distribution system. The code optimizes the pipe diameter for each section of pipe to a lowest cost, based upon the mix of installed capital costs of pipes and pumps and annual pumping cost. To sum these contributions on an equal basis, the installed capital costs are transformed into continuing costs determined by an annual fixed charge rate. The latter is calculated in the code based on annual charges, including the weighted cost of capital (discount annual charges such as the weighted cost of capital (discount rate), interim capital replacement rate, maintenance rate, taxes, and insurance. The calculated fixed charge rate is printed in the output results from the code.

The pipe optimization procedure leads to a continuous distribution of internal pipe diameters. Discretely sized outer pipe diameters are calculated

in the code. The pipe schedule for each section of pipe is determined based upon the fluid pressure, according to the rules in Appendix D. Insulation thickness for each section of pipe is determined from an empirical expression which summarizes vendor-supplied recommendations for insulation thickness requirements (Appendix D). Two different types of insulation are used to satisfy the computed insulation requirements. Calcium silicate is used for the inner layers of insulation up to two inches, and (if required) polyurethane is used for the outer layers.

Thermal losses and pressure drops are calculated for each section of pipe in the entire transmission piping network. The other two input parameters in this section (TAIR(N), N=1,2) define the average ambient air temperature during the heating and cooling seasons for use in calculating thermal losses from the fluid inside the surface transmission piping to the surrounding air. Thermal losses are calculated based upon standard equations for heat transfer by convection and conduction from fluid flowing in an insulated, cylindrical pipe.

Another parameter (AGFACT(I), I = 1 to 3), defined in Section 3.4.7 for the distribution piping system, also affects the pressure drop calculations for the transmission piping network. This parameter increases the pressure drop calculated for new pipe using the Darcy-Weisbach equation to take into account the increase in relative roughness and deterioration of pipes with age.

The three input parameters included in this section for the fluid transmission piping system are defined below. The parameters are input through the NAMELIST group \$RESVOR.

PLMANF	Distance (meters) from the manifold pipe nodes (J=1 in Figure 18) to the first column of well nodes (J=2 in Figure 18) in the matrix of production or injection wells. The default value of PLMANF is 0, in which case subroutine TRANS sets this distance identical to the distance between well nodes. To override the default value, set PLMANF to the desired distance in meters in the input data.
TAIR(N) N=1,2	Average ambient air temperature ($^{\circ}$ F) at the simulated site during the heating season [TAIR(1)] and cooling season [TAIR(2)], respectively. The default values are as follows:

$$TAIR(1) = 30^{\circ}F$$

$$TAIR(2) = 70^{\circ}F$$

3.3.5 Fluid Injection Piping System

Two options are available to the code user for disposal of the used geothermal fluid at the distribution system. The first option assumes that the used fluid is disposed of into a sewer system or river. No disposal costs are calculated in GEOCITY for the first option. The second option assumes that the used fluid at the distribution system is transported through an injection piping system into an injection wellfield. Injection costs are calculated for the second option. The remainder of this section focuses on the second option.

The major components of the fluid injection piping system are the piping, site work, and wellhead equipment. The elements in each of these categories and the cost models are the same as for the fluid transmission piping system described in Section 3.3.4. The injection piping network consists of above-ground, carbon steel pipes without insulation or casing. An injection pipeline from the distribution system to the injection wellfield and a network of pipes in the injection wellfield transport the used fluid from the distribution system to the injection wells. The assumed configuration of the injection piping network is illustrated in Figure 13.

The length of the injection pipeline from the distribution system to the injection wellfield is set by the user in the input data. The layout of the piping in the injection wellfield is the same as in the production wellfield described in Section 3.3.4. The flow capacity of the injection wells is defined in the input data as a ratio relative to the maximum flow rate of the production wells.

The pipe diameters in the injection piping network are sized on the peak flow rate for injection from the distribution system. The pipe diameter for each section of pipe is optimized as in the transmission piping system described in Section 3.3.4. The pipe schedule is determined based upon the fluid pressure, according to the rules listed in Appendix D. However, thermal losses and pressure drops are not printed for the injection piping network in the output results.

The parameters required to define the fluid injection piping system are defined below. The parameters are input through the NAMELIST group \$RESVOR.

- INJP Option to inject the used geothermal fluid from the distribution system, or from the heat exchanger at the inlet to the distribution system if a heat exchanger is employed.
- 0 = no injection
 1 = injection into an injection wellfield
- The default value is injection into an injection wellfield. If injection is not selected, the used geothermal fluid is assumed to be disposed of into a sewer or river.
- PLINJP Distance (meters) from the distribution system to the injection wellfield. A pipeline of this length is used to transport the used fluid from the distribution system or its optional heat exchanger to the inlet of the injection piping network in the injection wellfield. The default distance is 1000 meters.
- PRDRAT Ratio of injection well to production well flow rate. The default ratio is 2.

3.4 DISTRIBUTION SYSTEM INPUT DATA

This section describes the technical input parameters used by GEOCITY to design and size the distribution system. The distribution system is very flexible and can simulate many designs for district heating and cooling systems, ranging from a single point demand or a single residential district to multi-residential districts comprising an entire city. The design features include an optional heat exchanger at the inlet to the distribution system and various material and configuration options for piping, insulation, and casing.

The technical parameters for the distribution system are logically grouped into major categories that are listed below, along with the subsection describing the parameters in each category.

<u>Subsection</u>	<u>Category of Technical Parameters for Distribution System</u>
3.4.1	Operational Mode
3.4.2	Climatic Parameters for Heating Mode
3.4.3	Climatic Parameters for Cooling Mode
3.4.4	(Optional) Distribution Heat Exchanger
3.4.5	Absorption Chillers
3.4.6	Districts
3.4.6.1	District Geometry
3.4.6.2	District Type Characteristics
3.4.7	Distribution System Piping Design
3.4.8	Point Demand
3.4.9	Branching Pipe Mains Network for Multi-Residential Districts

The default values initialized for the input parameters are also defined in each subsection. New values for the parameters in this section to override the default values can be input through the NAMELIST group \$DISTRB.

3.4.1 Operational Mode

GEOCITY can be operated in four separate modes to simulate geothermal heating and/or cooling of either residential districts or a single point demand:

1. Residential Space Heating and Sanitary Water Heating
2. Residential Space Cooling and Sanitary Water Heating
3. Combined Residential Space Heating, Space Cooling, and Sanitary Water Heating
4. Process Heating or Cooling of a Single Point Demand

A residential district is defined as a contiguous area consisting of multiple buildings of uniform density and relatively similar heat (chill) demand. A point demand is defined as an entire district consisting of one point of heat or chill demand, such as a single commercial building or factory, instead of many individual buildings.

Five residential district types, representing typical residential areas in cities of the United States, and one point demand type are defined in the code:

1. Suburban
2. High-Density Single-Family
3. Garden Apartments
4. Townhouses or Rowhouses
5. High-Rise Apartments
6. Single Point Demand

Most residential areas in the United States can be described by these district types. Variation of the district types or additional district types (including commercial districts) can also be defined through the input data. The residential part of an entire city can be simulated by disaggregating it into multiple residential district types as described in Section 3.4.6. Operation of the code with one or multiple residential district types is described in Sections 3.4.6 and 3.4.9. Operation with a single point demand is described in Section 3.4.8.

The operational mode for simulating geothermal heating, cooling, or combined heating and cooling is set through the input parameter MODE defined below. The remaining categories of technical parameters in the distribution system that are used in simulating the four separate modes of operating the code are also listed below.

1. Residential Space Heating and Sanitary Water Heating (MODE=0)

This mode simulates residential space heating based on annual heating degree days,⁽⁸⁾ with or without sanitary water heating. The input parameter MODE must be set to 0 (its default value). The remaining categories of technical parameters in the distribution system that are used in simulating this mode are described in the following sections.

<u>Section</u>	<u>Category of Parameters</u>
3.4.2	Climatic Parameters for Heating Mode
3.4.4	(Optional) Distribution Heat Exchanger
3.4.6	Districts
3.4.6.1	District Geometry
3.4.6.2	District Type Characteristics
3.4.7	Distribution System Piping Design
3.4.9	Branching Pipe Mains Network for Multi-Residential Districts

2. Residential Space Cooling and Sanitary Water Heating (MODE=1)

This mode simulates residential space cooling based on annual cooling degree hours,⁽⁹⁾ with or without sanitary water heating. The input parameter MODE must be set to 1. The remaining categories of technical parameters in the distribution system that are used in simulating this mode are described in the following sections:

<u>Section</u>	<u>Category of Parameters</u>
3.4.3	Climatic Parameters for Cooling Mode
3.4.4	(Optional) Distribution Heat Exchanger
3.4.5	Absorption Chillers
3.4.6	Districts
3.4.6.1	District Geometry
3.4.6.2	District Type Characteristics
3.4.7	Distribution System Piping Design
3.4.9	Branching Pipe Mains Network for Multi-Residential Districts

3. Combined Residential Space Heating, Space Cooling, and Sanitary Water Heating (MODE=2)

This mode simulates combined residential space heating and space cooling based on annual heating degree days and annual cooling degree hours, respectively, with or without sanitary water heating. The input parameter MODE must be set to 2. This is the operational mode illustrated by the sample case input described in Section 3.2. The remaining categories of technical parameters in the distribution system that are used in simulating this mode are described in the following sections:

<u>Section</u>	<u>Category of Parameters</u>
3.4.2	Climatic Parameters for Heating Mode
3.4.3	Climatic Parameters for Cooling Mode
3.4.4	(Optional) Distribution Heat Exchanger
3.4.5	Absorption Chillers
3.4.6	Districts
3.4.6.1	District Geometry
3.4.6.2	District Type Characteristics

<u>Section</u>	<u>Category of Parameters</u>
3.4.7	Distribution System Piping Design
3.4.9	Branching Pipe Mains Network for Multi-Residential Districts

4. Process Heating or Cooling of a Single Point Demand (MODE=0 or 1)

This mode can be used to simulate either process heating or process cooling, without sanitary water heating. No climatic data is used. Only the peak heating or cooling energy requirements and the annual load factor are input to determine the annual thermal energy requirements for the point demand, as described in Section 3.4.8. The input parameter MODE must be set to 0 to 1 for heating or cooling, respectively. The remaining categories of technical parameters in the distribution system that are used in simulating process heating or cooling of a single point demand are described in the following sections:

<u>Section</u>	<u>Category of Parameters</u>
3.4.4	(Optional) Distribution Heat Exchanger
3.4.5	Absorption Chillers (cooling only)
3.4.7	Distribution System Piping Design
3.4.8	Point Demand

3.4.2 Climatic Parameters for Heating Mode

GEOCITY calculates annual residential heating energy requirements based on the annual heating degree days at the simulated geographic site. The degree day concept assumes that if the mean outdoor temperature for a particular day is equal to the indoor design temperature (65°F in GEOCITY), or above, the number of degree days is zero, and no artificial heating is required. If the daily mean drops below this base, however, heating energy requirements to maintain an inside temperature of 65°F vary directly with the number of degree days (65 degrees minus the daily mean temperature). The daily mean temperature is computed as the average of the daily maximum and the daily maximum temperatures.

The number of design heating degree days used in GEOCITY to size the reservoir fluid transmission system and the distribution system is usually set below

the annual heating degree days based on temperature data. Thus, the fraction of the peak heating demand that is met by geothermal energy is trimmed to improve the system load factor. The default value for the design heating degree days used to size the system is 92% of the annual heating degree days based on temperature data. GEOCITY provides for supplemental heating to meet the remainder of the demand.

The key climatic parameters input to GEOCITY for defining the residential heating demand characteristics are the annual heating degree days, design heating degree days, indoor design temperature, winter outdoor design temperature, and building peak heat demands at the indoor and outdoor design temperatures for the different district types used to represent the simulated site. Several of these input parameters are interdependent. The annual heating degree days depend on the value selected for the indoor design temperature. They are obtained from weather tables that are traditionally based on an indoor design (reference) temperature of 65°F. Currently, the value of the indoor design temperature is fixed in the code at its default value of 65°F.

The peak heat demand of a building (MBtu/hr) is defined as the amount of heat required to maintain the building (i.e., offset its hourly heat loss) at the indoor design temperature when the outside temperature is at the winter outdoor design temperature. Clearly, the peak heat demand required by a typical building in each simulated district type depends on the values selected for the indoor design temperature and the winter outdoor design temperature. Increasing (decreasing) the winter outdoor design temperature from its default value of -5°F will cause GEOCITY to automatically decrease (increase) the peak heat demand of a typical building in each simulated district type.

The input parameters for calculating the heating energy requirements for residential heating and sanitary hot water heating are defined in detail below.

ADGDAY(1) Annual heating degree days based on temperature data between the indoor design temperature (65°F) and the minimum ambient temperature (TMIN) for the simulated geographic site. The default value is 6500°F-days.

DDGDAY(1)

Design heating degree days based on temperature data between the indoor and outdoor design temperatures for the simulated geographic site. Design heating degree days are used in GEOCITY to size the reservoir and fluid transmission system and the distribution system. The default value is 6000⁰F-days (92% of ADGDAY(1)). The user should realize that DDGDAY(1) is dependent on both the indoor design temperature TINDES(1) and the outdoor design temperature TDES(1). Note that DDGDAY(1) will equal ADGDAY(1) if TDES(1) equals TMIN and TINDES(1)=65. In the normal sequence of defining the input parameters, the user would first select TDES(1) and then determine the corresponding value of DDGDAY(1).

Two methods for estimating the value of DDGDAY(1), given TDES(1) and TINDES(1), are discussed here. ADGDAY(1) for a geographic site is calculated by summing the difference between TINDES(1) and the mean daily temperature, summing over all days of the year when this difference is positive. The mean daily temperature is simply the average of the maximum and minimum daily temperatures. A value for DDGDAY(1) can be estimated by limiting the value for any minimum daily temperature to values $\geq$ TDES(1) when employing the method described above.

A second method for estimating DDGDAY(1) is based on the relationship between heating degree days and heating degree hours. Heating degree hours are calculated in a manner similar to that for heating degree days, except the difference is between TINDES(1) and the mean hourly temperature, and the sum is over all the hours when the difference is positive. The advantage of using heating degree hours is the availability of this type of data from the U.S. Department of Commerce. The disadvantage is that heating degree hours divided by 24 does not equal heating degree days. The two parameters do not directly correspond because it is possible for heating degree hours to occur during a day for which there are no heating degree days. This problem can be

mediated by adjusting the number of design heating degree hours between TINDES(1) and TDES(1) by the ratio of annual heating degree days to annual heating degree hours. The equation describing this relation is given below.

$$DDGDAY(1) \cong DDGHR(1) * \frac{ADGDAY(1)}{ADGHR(1)}$$

Supplemental heating is provided for those days represented by the difference between ADGDAY(1) and DDGDAY(1).

The annual supplemental heating requirements (MBtu/yr), used in calculating the annual cost of supplemental heating, are calculated by the code as follows:

$$\begin{aligned} \text{Annual Supplemental Heating Requirements (MBtu/yr)} = \\ \text{Annual Heat Demand Totalled Over All Districts (MBtu/yr)} * \\ \left[\frac{ADGDAY(1) - DDGDAY(1)}{ADGDAY(1)} \right] \end{aligned}$$

HQ(N)
N=1,8

Peak heat demand (MBtu/hr-bldg) for a typical building in district type N based on an indoor design temperature TINDES(1) of 65°F and a winter outdoor design temperature TDES(1) of -5°F. The default values of HQ(N) were calculated by designing typical residential units for each district type and calculating the heat loss according to ASHRAE procedures, assuming -5°F outside temperature, 65°F inside temperature, and a 15 mph wind. The physical layout of the residential units in each of the district types is described in Appendix C. The default values of HQ(N) are as follows:

<u>N</u>	<u>District Type</u>	<u>Building Peak Heat Demand (MBtu/hr-bldg)</u>
1	Suburban	0.053
2	High-Density	0.034
3	Single Family Garden Apartments	1.380
4	Townhouses or Rowhouses	0.900
5	High-Rise Apartments	1.728
6	Point Demand	1.0

District types 7 and 8 are available for definition by the user. The default values of HQ(7) and HQ(8) were arbitrarily set to zero, since these two districts do not have a default description.

If the winter outdoor temperature TDES(1) is input at some value other than its default value of -5°F, GEOCITY automatically prorates the peak heat demands HQ(N) for residential (but not point demand) districts.

Subroutine LOAD calculates a new peak heat demand for each building type according to the following equation:

$$HQ(\text{new}) = HQ(\text{input}) * \frac{65. - TDES(\text{input})}{65. - TDES(\text{default})}$$

For example, if HQ(input) = 1 MBtu/hr-bldg and TDES(input) = 0°F, then HQ(new) is prorated in subroutine LOAD as follows:

$$HQ(\text{new}) = 1. * \frac{65. - 0.}{65. - (-5.)} = 0.9286 \text{ MBtu/hr-bldg}$$

The user should carefully note that this equation prorates input values of HQ(N) for residential districts as well as the default values of HQ(N). Thus, if the outdoor design temperature corresponding to HQ(N) is identical to the input value of TDES(1), but TDES(1) is different from its default value of -5°F, this equation will still prorate the input value for HQ(N).

TINDES(1)

Indoor design temperature (°F) for heating each building type. The default value is 65°F. This parameter currently is fixed in the code. The user must be careful that the indoor reference temperature used in determining the peak heating energy requirements HQ(N) and the annual heating degree days ADGDAY(1) is the same as the indoor design temperature TINDES(1) in the code (fixed at 65°F).

TDES(1)

Winter design outdoor dry-bulb temperature (°F) used for calculating the peak heat demands HQ(N) for each building in district type N. The default value is -5°F. The user should review the description of HQ(N) above to assess the impact of changing

TDES(1) from its default value upon the values of the peak heat demand HQ(N) for each building in district type N.

TMIN Minimum winter outdoor temperature for heating. The default value is -15°F . This value is currently used by the code only to calculate and print out peak supplemental heating requirements (MBtu/hr) but is not used in any cost calculations.

TWATC Cold water temperature in the sanitary hot water tank. This water is heated by the circulating water from the distribution system through a small heat exchanger at the hot water tank. The default value is 50°F .

TWATH Hot water temperature from the sanitary hot water tank after heating. The default value is 140°F .

3.4.3 Climatic Parameters for Cooling Mode

GEOCITY calculates annual residential cooling energy requirements using annual cooling degree hours based on hourly temperature data at the simulated geographic site. The input parameter MCOOL provides the flexibility for the user to either input the following two climatic cooling parameters or let the code calculate them.

- CQ(N), the peak cooling energy requirement for each building in district type N corresponding to the input values for the indoor design temperature, the ambient summer outdoor design temperature, and outdoor absolute humidity. This parameter includes all residences in the building and is expressed in MBtu/hr-bldg of chill.
- ACDGHR, the annual cooling degree hours based on hourly cooling degree data at the simulated geographic site. The reference temperature of the hourly data must be the same as the indoor design temperature input into the code. This parameter is expressed in $^{\circ}\text{F}$ -hours/year.

Specifically, the parameter MCOOL is defined to provide flexibility as follows:

MCOOL = 0 The two parameters CQ(N) and ACDGHR are calculated internally (subroutine COOLHR) according to equations 1 and 2 in Appendix E. This is the default value of MCOOL.

- 1 The parameter CQ(N) is calculated internally (subroutine COOLHR) but parameter ACDGHR is input by the user.
- 2 Both parameters CQ(N) and ACDGHR are input by the user.

The parameters that must be input for each value of MCOOL in order for GEOCITY to calculate the cooling energy requirements are listed below^(a).

MCOOL =	0(default)	1	2
User must input param- eters on right	TINDES(2) Used by TDES(2) code to HDES(2) calculate CQ(N) NTMINT Used by TWIDTH code to TAOD(K) calculate HROD(K) ACDGHR	TINDES(2) Used by TDES(2) code to HDES(2) calculate CQ(N) ACDGHR	TINDES(2) TDES(2) CQ(N) ACDGHR

The definitions of these parameters are summarized below.

TINDES(2) Indoor design temperature (^oF) for cooling each building type. The default value is 78^oF. The indoor design temperature must be the same as the indoor reference temperature upon which the peak cooling energy requirements CQ(N) for each building in district type N and the annual cooling degree hours ACDGHR are based. This equality occurs automatically in equations 1 and 2 of Appendix E when the calculation of CQ(N) and ACDGHR is left to the code (e.g., with MCOOL set to its default value of 0). However, if the user directly inputs CQ(N) or ACDGHR, the user must check that the indoor design temperature TINDES(2) is identical to the indoor reference temperature upon which CQ(N) and ACDGHR are based.

(a) When simulating a single point demand district (i.e., district number one defined as district type (6), the value of MCOOL is ignored. The user must input the peak heat demand HQ(6) or peak chill demand CQ(6) together with the load factor PF as described in Section 3.4.8.

- TDES(2) Summer design outdoor dry-bulb temperature ($^{\circ}\text{F}$) used to calculate peak cooling demands in MBtu/hr of chill for each building type. The default value of TDES(2) is 99°F .
- It is recommended that the peak cooling load of each building type be calculated at a design outdoor temperature TDES(2) below the actual peak summer temperature to improve the system load factor. For example, the user may opt to select the ASHRAE design dry-bulb temperature read at the 2.5% level⁽¹⁰⁾ as the outdoor design temperature TDES(2). This value represents a temperature that is equaled or exceeded by 2.5% of the 2,928 hours during the four summer months (June through September). Thus, 73.2 hours (0.6 hours per day) would be at or above the outdoor design temperature during the four summer months.^(a)
- HDES(2) Absolute humidity (lb H_2O /lb air) at the summer design outdoor dry-bulb and wet-bulb temperatures.⁽¹¹⁾ The default value is 0.0125 lb H_2O /lb air, which corresponds to a dry-bulb/wet-bulb reading of $99^{\circ}\text{F}/74^{\circ}\text{F}$ on a psychrometric chart. The absolute humidity is used to calculate the peak chill demand for each building type (Equation 1 of Appendix E).
- CQ(N)
N=1,8 Peak cooling demand in MBtu/hr-bldg of chill for each building in district type N. This parameter is input only if MCOOL is set to 2. It is automatically calculated in subroutine COOLHR when MCOOL is set to 0 or 1 (Equation 1 in Appendix E).
- If MCOOL is set to 2, the user has the flexibility to directly input the values of CQ(N) or use the default values. However, the user must be careful that the peak chill demands CQ(N) are based on the values of the indoor design temperature TINDES(2) and the outdoor design temperature TDES(2) input into the code. In contrast to the peak heat demand HQ(N), described in Section 3.4.2, no adjustment (prorating) is currently applied to the peak chill demand CQ(N) in the code.

(a) No supplemental cooling is provided in GEOCITY for the hours above the outdoor design temperature.

The default values of CQ(N) are based on equation 1 in Appendix E with the indoor reference temperature TINDES(2) set to 78°F, the outdoor design dry-bulb temperature TDES(2) set to 99°F, the absolute humidity HDES(2) set to 0.0125 lb H₂O/lb air, and the number of residences (households) per building type set to their default values defined in Section 3.4.6.2. The default values of CQ(N) are as follows:

<u>N</u>	<u>District Type</u>	<u>Building Peak Chill Demand (MBtu/hr bldg)</u>
1	Suburban	0.021
2	High-Density Single Family	0.016
3	Garden Apts	0.664
4	Townhouses or Rowhouses	0.392
5	High-Rise Apts	1.020
6	Point Demand	1.0

District types 7 and 8 are available for definition by the user. The default values of CQ(7) and CQ(8) were arbitrarily set to zero, since these two districts do not have default descriptions. For simulating a point demand (district type 6), the value of MCOOL is ignored and the user must input CQ(6).

NTMINT

Number of outdoor dry-bulb ambient temperature intervals used in hourly calculations of cooling energy requirements. The default value is 10. If more than 10 intervals are required, the dimensions of TAOD(10) and HROD(10) must be increased in the code.

TWIDTH

The width of the temperature intervals grouping annual hourly temperature data at a simulated geographic site. The default value is 5°F. This parameter is used when MCOOL is set to 0 to calculate annual cooling degree hours (Equation 2 of Appendix E).

The temperature intervals are determined from the values input for the midpoint TAOD(K) of each temperature interval and the interval width TWIDTH by subroutine COOLHR as follows:

$$(TAOD(K) - TWIDTH/2., TAOD(K) + TWIDTH/2.)$$

The user has the flexibility to input any temperature interval width for which data of annual hourly temperature groupings (temperature histograms) are available. The default value of 5°F represents the width of the temperature intervals in the hourly temperature groupings provided by the National Oceanic and Atmospheric Administration (NOAA).^(a) It is assumed that the temperature intervals in the NOAA data actually run from half a degree below the printed temperature interval to half a degree above, to make the temperature scale continuous, (i.e., 70-74 actually represents the 5°F temperature interval 69.5-74.5.)

TAOD(K),
K=1,NTMINT

Midpoints (°F) of the outdoor dry-bulb temperature intervals (numbering NTMINT in all) grouping annual hourly temperature data spanning the range from the indoor design temperature to the peak outdoor summer temperature. The temperature midpoints are defined in increasing order as K increases; the first temperature interval must either include the indoor design temperature or lie below it.^(b) If this rule is violated, the code will print an error message and stop execution.

The default values of the temperature midpoints, and the corresponding temperature intervals which subroutine COOLHR constructs from the default midpoints and default value of the interval width TWIDTH, are based on the NOAA data as follows:

(a) NOAA Environmental Data Service, National Climatic Center, Asheville, NC.

(b) If any temperature interval lies below the indoor design temperature TINDES(2), subroutine COOLHR in GEOCITY automatically sets the cooling degree hours for that interval to 0. If a temperature interval includes the indoor design temperature, subroutine COOLHR assumes a uniform temperature distribution in the interval and automatically prorates the hours in the interval to include only that portion of the hours that requires cooling (i.e., the reduced temperature interval between the indoor design temperature and the upper boundary of the interval).

<u>K</u>	<u>Temperature Midpoints TAOD(K)</u>	<u>Corresponding Temperature Intervals (F)</u>	<u>NOAA Rounded Temperature Intervals (F)</u>
1	77.	(74.5,79.5)	(75,79)
2	82.	(79.5,84.5)	(80,84)
3	87.	(84.5,89.5)	(85,89)
4	92.	(89.5,94.5)	(90,94)
5	97.	(94.5,99.5)	(95,99)
6	102.	(99.5,104.5)	(100,104)
7	107.	(104.5,109.5)	(105,109)
8	112.	(109.5,114.5)	(110,114)
9	117.	(114.5,119.5)	(115,119)
10	122.	(119.5,124.5)	(120,124)

Note that for the default temperature intervals, the default value for the indoor design temperature TINDES(2) of 78°F lies within the first temperature interval.

HROD(K) Number of hourly temperature observations per year at the simulated geographic site in the temperature interval represented by the midpoint temperature TAOD(K) and interval width TWIDTH, i.e., in the temperature interval:

(TAOD(K) - TWIDTH/2., TAOD(K) + TWIDTH/2.).

The default values for HROD(K) are as follows:

<u>K</u>	<u>Temperature Midpoints TAOD(K)</u>	<u>NOAA Temperature Intervals (F)</u>	<u>Hours/Year in that Temperature Interval HROD(K)</u>
1	77.	(75,79)	982.
2	82.	(80,84)	788.
3	87.	(85,89)	596.
4	92.	(90,94)	440.
5	97.	(95,99)	246.
6	102.	(100,104)	0.
7	107.	(105,109)	0.
8	112.	(110,114)	0.
9	117.	(115,119)	0.
10	122.	(120,124)	0.

If any of the NTMINT temperature intervals have no hourly temperature observations, the user must set the corresponding values of HROD(K) to 0. Otherwise, the code will pick up the above default number of hours for those intervals.

Note that the hours per year $H_{ROD}(K)$ in temperature intervals above the outdoor design temperature $T_{DES}(2)$, with default value of $99^{\circ}F$, should be set to 0 in the input data. This follows from the rationale that the geothermal district cooling system is being designed to provide cooling only between the indoor design temperature $T_{INDES}(2)$ and the summer outdoor design temperature $T_{DES}(2)$. No supplemental cooling is provided in GEOCITY for those hours in which the temperatures are above the outdoor design temperature $T_{DES}(2)$.

ACDGHR

Annual cooling degree hours per year ($^{\circ}F$ -hrs/yr) based on hourly temperature data between the indoor design temperature $T_{INDES}(2)$ and the summer outdoor design temperature $T_{DES}(2)$ at the simulated geographic site. This parameter is input only if M_{COOL} is set to 1 or 2. The default value is $19,571^{\circ}F$ -hrs/yr.

The user must be sure that the indoor reference temperature of the data is the same as the indoor design temperature $T_{INDES}(2)$. This occurs automatically when M_{COOL} is set to 0, since sub-routine $COOLHR$ uses the input parameter $T_{INDES}(2)$ to calculate the annual cooling degree hours according to equation 2 in Appendix E.

If M_{COOL} is set to 1 or 2, the user has the flexibility to input the value of $ACDGHR$ or use the default value. The default value of $ACDGHR$ is based on an indoor design temperature $T_{INDES}(2)$ of $78^{\circ}F$, an outdoor summer design temperature $T_{DES}(2)$ of $99^{\circ}F$, and the default hourly temperature observations (default values of $T_{AOD}(K)$ and $H_{ROD}(K)$). It is calculated according to equation 2 in Appendix E.

When inputting the value of $ACDGHR$, the user should be aware that multiplying data that is originally in terms of cooling degree days by 24 hours/day will not yield results comparable to actual cooling degree hour data unless the degree day data is based on hourly observations.

3.4.4 Distribution Heat Exchanger

An option for a liquid-to-liquid heat exchanger at the inlet to the distribution system is provided in both heating and cooling modes. The heat exchanger may be used to protect the expensive, buried distribution system from scaling and corrosion due to the chemical composition of the geothermal fluid. Heat is transferred from the geothermal fluid to circulating clean water for use in the distribution system. The heat exchanger is modeled as a counter-flow, single-pass, shell-and-tube unit constructed of carbon steel with an equilateral triangular tube configuration.^(a) The geothermal fluid is pumped through the tube side and the circulating clean water is pumped through the shell side of the heat exchanger.

The nomenclature used in defining the temperature distribution in the heat exchanger is illustrated in Figure 14. The temperature difference between the geothermal fluid entering the heat exchanger and the circulating distribution water exiting the heat exchanger is defined as the inlet approach (APPGIN) to the heat exchanger. The temperature difference between the exiting geothermal fluid and the circulating distribution water entering the heat exchanger is defined as the outlet approach (APPGOT) to the heat exchanger.

Referring to the nomenclature in Figure 14, the temperature drop of the geothermal fluid in the heat exchanger is calculated by the code as follows:

$$\text{Geothermal Fluid Temperature Drop (}^{\circ}\text{F)} = \text{TGIN} - (\text{TDIN} + \text{APPGOT})$$

The temperature rise of the circulating distribution water in the heat exchanger is calculated by the code as follows:

$$\text{Distribution Water Temperature Rise (}^{\circ}\text{F)} = (\text{TGIN} - \text{APPGIN}) - \text{TDIN}$$

The heat-transfer coefficients and required heat-transfer area of the heat exchanger are calculated by the code. The capital and operating costs of the heat exchanger and the pumps on the tube side and shell side are also calculated by the code and included in the costs of the distribution system.

(a) Plate-type heat exchangers may also be possible with this type of application. This type of heat exchanger may allow smaller approach temperatures and be more cost-effective than the shell-and-tube heat exchanger. Plate-type heat exchangers are currently not modeled in the code.

TEMPERATURE NOMENCLATURES

- TGIN = Entering geothermal fluid temperature ($^{\circ}\text{F}$) from reservoir and fluid transmission system (calculated by code)
- APPGIN = Inlet approach ($^{\circ}\text{F}$) to heat exchanger
- TGIN-APPGIN = Heated temperature ($^{\circ}\text{F}$) to distribution system
- TDIN = Temperature ($^{\circ}\text{F}$) from distribution system (calculated by code)
- APPGOT = Outlet approach ($^{\circ}\text{F}$) to heat exchanger
- TDIN+APPGOT = Reduced geothermal fluid temperature ($^{\circ}\text{F}$) to fluid injection system

FIGURE 14. Nomenclature for the Temperatures in the Distribution System Heat Exchanger

The input parameters for defining the distribution system heat exchanger are defined below:

HTEXOP	Option for a centralized heat exchanger at the end of the transmission pipeline from the reservoir wellfield (i.e., at the inlet to the distribution system). 0. = No heat exchanger 1. = Heat exchanger (default value).
DIAL, DIAOL	Inner and outer tube diameters (ft) of the heat exchanger. The default values are: DIAL = 0.1 ft DIAOL = 0.1104 ft
FOULFI, FOULFO	Inside and outside fouling factors for the heat exchanger. These factors reduce the overall heat-transfer coefficient in subroutine OHTCOE to allow for the accumulation of corrosion deposits on the inside (tube-side) and outside (shell-side) heat-transfer surfaces. The default values are: FOULFI = $0.001 \text{ hr-ft}^2\text{-}^\circ\text{F/Btu}$ FOULFO = $0.001 \text{ hr-ft}^2\text{-}^\circ\text{F/Btu}$
APPGIN	Inlet approach temperature ($^\circ\text{F}$) to distribution heat exchanger as illustrated in Figure 14. The default is 15°F .
APPGOT	Outlet approach temperature ($^\circ\text{F}$) from distribution heat exchanger as illustrated in Figure 14. The default is 15°F .
WVELL	Velocity (ft/hr) of the geothermal fluid in the heat exchanger tubes. The default is 28,800 ft/hr (i.e., 8 ft/sec). The velocity of the circulating distribution water in the shell side of the heat exchanger is calculated by the code.

3.4.5 Absorption Chillers

The conceptual design combining a mixing tank and lithium bromide/water absorption chiller at each residence to simulate space (or process) cooling and sanitary water heating is shown in Figure 9 of Section 2.7.3.2. The rationale for this combined configuration and a system flow schematic were previously

described. Recall that GEOCITY assumes that commercially available absorption chillers with a nominal rating of three tons of design cooling capacity (36,000 Btu/hr of chill) are large enough to provide geothermal space cooling for typical residences (households) in U.S. climates. Multi-residence buildings, such as apartments, are assumed to have a separate chiller for each residence in the building.

The performance characteristics of the chiller are defined by the parameters described below. The default values for these parameters are based on design conditions recommended by a major chiller manufacturer for optimum operation of its chillers. The user should be careful not to specify unreasonable design values. Any changes contemplated in the design values to simulate different types of chillers should be consistent with the design conditions recommended by the manufacturers of those chillers. Such changes should also be accompanied by a review and possible change in the default value of the retrofit cost parameter for the chiller that is described below.

Several district type parameters needed to complete the definition of the space cooling and sanitary water heating system for residences in district type J are described in Section 3.4.6.2 and are now previewed here. Specifically, the chilled water temperature returning from the outlet of the building cooling system into the chiller is defined by the input parameter TREJC(J). The hot water temperature returning from the outlet of the sanitary water heating system is defined by the input parameter TREJ(J). The installed capital cost of the three-ton chiller, mixing tank, and other components of the building cooling system is defined by the input retrofit cost parameter CRTFC(J). The annual operating cost of the chiller is calculated by the code (subroutine DIST) as 6% of the installed capital cost.

THSMIX Design hot water temperature ($^{\circ}\text{F}$) of the blended mixture out of the mixing tank into the chiller (Figure 9). The default is 195°F , which is currently fixed in subroutine CALQNA of the code. The default value requires that the hot water temperature from the distribution system into the mixing tank (and therefore the geothermal resource temperature) be greater than 195°F . Otherwise, the code will stop execution and print an error message to the user.

CXDELT	Design hot water temperature drop ($^{\circ}\text{F}$) in the chiller. The default is 9.1°F .
CTWAT	Design chilled water outlet temperature ($^{\circ}\text{F}$) from the chiller into the building cooling system. The default is 45°F .
TREJC(J)	Design chilled water outlet temperature ($^{\circ}\text{F}$) from the building cooling system in district type J into the chiller. The default is 55°F . This parameter is also described in Section 3.4.6.2.
CCOP	Coefficient of performance (fraction) for the chiller. This parameter relates Btu of heat into the chiller to Btu of chill out of the chiller, i.e., $\text{Btu of heat into chiller} * \text{CCOP} = \text{Btu of chill out of chiller}$. The default is 0.72.
TREJ(J)	Design hot water outlet temperature ($^{\circ}\text{F}$) from the sanitary hot water heating system of the buildings in district type J. This parameter is also described in Section 3.4.6.2. The default is 100°F .
CHLIFE	Operational life (years) of the chillers before replacement is needed. The default is 10 years. The input value must be one year or more, since the replacement of the chillers is treated as an interim capital replacement for the distribution system.

3.4.6 Districts

Districts are the basic elements of the distribution system submodel. Recall that a residential district is defined as a contiguous, rectangular area consisting of multiple buildings of relatively similar heat or chill demand and uniform density. A point demand is defined as a district consisting of one point of heat or chill demand, such as a single commercial building or factory. Many of the details needed for designing the distribution piping system are derived from the definitions of the districts. Fluid requirements are computed and the piping networks are designed for each district.

Districts are defined by two types of input parameters: district geometry parameters and district type parameters. The geometry parameters define the

area, shape, and relative location of the rectangular districts. The geometry parameters are described in Section 3.4.6.1.

District type parameters define the characteristics of the districts. Five residential district types, representing typical residential areas in cities of the United States, and one point demand type are defined in the code:

- 1) Suburban
- 2) High-Density Single-Family
- 3) Garden Apartments
- 4) Townhouses or Rowhouses
- 5) High-Rise Apartments
- 6) Single Point Demand

Each of the district types has district type parameters assigned to it that define the peak heat (chill) demand, the daily sanitary hot water demand, the density of buildings, reject temperatures for heating and cooling, number of residences (households) per building, and number of people per building. The code is extremely flexible with regard to district types. Variation of the district type parameters defining the district types or additional district types (including commercial districts) can be defined through the input data. The district type parameters are defined in Section 3.4.6.2.

Most residential areas in the United States can be defined by use of the default district types. Zoning maps of cities can be used to describe the residential part of an entire city by disaggregating it into residential district types. Figure 9 in Section 3.2 shows the physical layout of 18 different residential districts used to simulate a small western city in the United States. Note that simulation of additional residential district types, other than the five default residential district types, is illustrated in Figure 9.

3.4.6.1 District Geometry

The initial step in describing the district geometry is to define the number of districts at the simulated site. Current code dimensions permit up to 20 residential districts to be simulated. Each district is then assigned an integer from 1 to 8 which defines its type and appends the district type parameters to the district as described in Section 3.4.6.2.

Three parameters are used to define the area, length, and width of the rectangular shape of each district. The relative distance between adjoining districts is defined by the length of the main pipes required to connect the centers of the adjoining districts. Other parameters allow for definition of the elevation of the districts above the inlet to the distribution system and the degree of crookedness of its streets.

The district geometry parameters are defined below. The majority of these parameters are arrays in which the Mth element is part of the definition of the Mth district.

NDTR	Number of districts at the simulated site. The default is 1.
IDTYPE	<p>The generic type of districts at the simulated site. This parameter is used only for printout purposes.</p> <p>1 = single point demand 2 = residential districts</p> <p>The default is 2.</p>
DRES	Length (miles) of the surface transmission pipeline from the outlet of the production wellfield to the inlet of the distribution system or its optional heat exchanger. The default is 10 miles.
IDTR(M) M=1,20	<p>Type of district, an integer from 1 to 8, defined as follows:</p> <p>1 = Suburban 2 = High-Density Single-Family 3 = Garden Apartments 4 = Townhouses or Rowhouses 5 = High-Rise Apartments 6 = Single Point Demand</p> <p>This parameter appends the peak heat demand, peak chill demand, and daily sanitary hot water demands of typical building units, density of buildings, diversity factor, reject temperatures for heating and cooling, number of residences (households) per building, number of people per building, retrofit cost for heating, and retrofit cost for cooling (i.e., the district type characteristics described in Section 3.4.6.2) to the description of district M. Variation of the district type parameters defining</p>

these district types or additional district types 7 and 8 can be defined through the input data.

Only IDTR(1) is assigned a default value, which is currently set to 1, designating suburban for district number 1. A single point demand is selected by setting IDTR(1) to 6. District type 6 is reserved in the code for simulating a single point demand and should not be redefined as a residential district through the input data. District types 1 through 5 and 7 and 8 are available for use as residential district types. Use of more than 8 different district types would require increasing the dimensions of some of the arrays in the code.

AREA(M) M=1,20	Area of district M (square miles). The default value of AREA(1) only is 1 square mile.
WIDTH(M) M=1,20	Width of district M (miles). The default value of WIDTH(1) only is 1 mile.
XLNGTH(M) M=1,20	Length of district M (miles). The default value of XLNGTH(1) only is 1 mile. The width and length parameters are used to determine the approximate shape of the district. Thus, when the graph for the district is created in subroutine GRAPH, the ratio of rows to columns in the rectangular grid used to approximate the shape of the district is the same as the ratio of width to length. The user can approximate the width and length of a district from a map of the district.
DDTR(M) M=1,20	Length of the main pipe serving district M (miles). The default value of DDTR(1) only is 1 mile. Lengths are measured from either the end of the transmission line (inlet to the distribution system) or the last junction in the main to the center of district M. Illustrations are given in Section 3.4.9 and Figure 15.
ELDIFF(M) M=1,20	Elevation of district M above the end of the transmission pipeline (inlet to the distribution system) in feet. This parameter alters the sizing of the pumps and the calculation of pumping requirements for district M. The default is 0 for all 20 districts.

CSF(M) Crooked street factor. This factor serves to increase (multiply)
M=1,20 the lengths of the lateral, street, and house pipes, but not the
main pipe, in the piping network for the district. The default
is 1 for all 20 districts.

3.4.6.2 District Type Characteristics

District type parameters are used to define the characteristics of each district: the peak heat demand, peak chill demand, and daily sanitary hot water demand of typical building units, density of buildings, diversity factor, reject temperatures for heating and cooling, number of residences (households) per building, number of people per building, retrofit cost for heating, and retrofit cost for cooling per building. Up to eight different district types can be defined through the input data. The description of the six default district types in the code and the default values of their characteristics are given in Table 8.

District type parameters are arrays in which the Nth element is part of the description of the characteristics of the Nth district type. When the user specifies that the district type IDTR(M) for district M is equal to N as described in Section 3.4.6.1, the Nth element of each district type array below is associated with district M.

HQ(N) Peak heat demand (MBtu/hr-bldg) for a typical building in
N=1,8 district type N, based on the indoor design temperature TINDES(1)
for heating and the winter outdoor design temperature TDES(1).
HQ(N) is described in Section 3.4.2 because of its dependency on
these two design temperatures. The user should carefully read
the description of this relationship in Section 3.4.2.

CQ(N) Peak chill demand (MBtu/hr-bldg) for a typical building in
N=1,8 district type N, based on the indoor design temperature TINDES(2)
for cooling and the summer outdoor design temperature TDES(2).
CQ(N) is described in Section 3.4.3 because of its dependency on
these two design temperatures. The user should carefully read
the description of this relationship in Section 3.4.3.

TABLE 8. District Type Characteristics of the Default Types in GEOCITY

District Type N	HQ(N) Bldg Peak Heat Demand(a) (MBtu/hr-bldg)	CQ(N) Bldg Peak Chill Demand(b) (MBtu/hr-bldg)	HW(N) Bldg Daily Sanitary Hot Water Demand(c) (gal/day)	DENSE(N) Density (bldg/sq mi)	DIVF(N) Diversity Factor (fraction)	TREJ(N) Heating Reject Temperature (°F)	TREJC(N) Cooling Reject Temperature (°F)	NRES(D) Number of Residences (resid./bldg)	POPHSE(N) Number of People (people/bldg)	Floor Area (sq ft/ residence)
1 = Suburban	0.053	0.021	60.6	2560	.72	100	55	1	3.2	1620
2 = High-Density Single Family	0.034	0.016	55	4480	.72	100	55	1	4	1000
3 = Garden Apts.	1.380	0.664	3030	293	.72	100	55	60	162	990
4 = Townhouses or Row- Houses	0.900	0.392	1515	373	.72	100	55	30	81	1012
5 = High-Rise Apts	1.728	1.020	5400	385	.72	100	55	108	324	780
6 = Single Point Demand	1.0	1.0	0	1	1.	100	55	1	1	N/A

(a) Default peak heat demand is based on indoor design temperature $T_{INDES}(1) = 65^{\circ}\text{F}$, winter outdoor design temperature $T_{DES}(1) = -50^{\circ}\text{F}$, and a 15 mph wind.

(b) Default peak chill demand is based on indoor design temperature $T_{INDES}(2) = 78^{\circ}\text{F}$, summer outdoor design temperature $T_{DES}(2) = 99^{\circ}\text{F}$.

(c) Sanitary hot water demand is ignored for a single point demand.

HW(N) N=1,8	Daily sanitary hot water demand (gal/day-bldg) for a typical building in district type N. The peak sanitary hot water demand in one hour is assumed to be 1/7 that of the average daily demand in 24 hours. If no sanitary hot water heating is desired for the buildings in district type N, the corresponding value of HW(N) for that district type must be input as 0. No sanitary hot water heating is simulated for a single point demand (district type 6).
DENSE(N) N=1,8	Density of the buildings (buildings/square mile) in district type N.
DIVF(N) N=1,8	Diversity factor (fraction) for district type N. The diversity factor is used to reduce the size of laterals and mains supplying a district by considering that the peak load for all buildings in a district does not occur simultaneously. This factor is set to 1 for a single point demand (district type 6).
TREJ(N) N=1,8	Temperature ($^{\circ}\text{F}$) of the return water at the outlet of the building heating system and the building sanitary water heating system in district type N.
TREJC(N) N=1,8	Temperature ($^{\circ}\text{F}$) of the return chilled water at the outlet of the building cooling system in district type N.
NRESD(N) N=1,8	Number of residences (households) in a typical building of district type N. This parameter is required to print out the cost of heating and/or cooling in dollars/household year. It is also used in the cooling mode when the cooling parameter MCOOL (Section 3.4.3) is set to 0 or 1. Specifically, the parameter NRESD(N), $N=1, \dots, 8$, is used in equation 1 of Appendix E (sub-routine COOLHR) in calculating the peak chill demand CQ(N) for each building in district type N when MCOOL is set to 0 or 1. If MCOOL is set to 2, the user must include the number of residences in the determination of CQ(N).
POPHSE(N) N=1,8	Number of residents in a typical building of district type N. This parameter is used only for printout purposes.

CRTF(N)
N-1,8

Cost (dollars/building) to retrofit building heating systems to handle geothermal heating in district type N. The cost includes the installed capital cost of such equipment as radiators, convectors, fan-coil units, pumps, controls, ducts, and the small heat exchanger at the sanitary hot water tank to provide sanitary water heating. The costs must be input in January, PRINDX base year dollars (Section 3.5.5.2), with default value of January 1980 dollars. Note that this cost must include all residences (households) in a typical building in district type N. The default values of CRTF(N), N=1,...,8, are 0.

CRTFC(N)

Cost (dollars/building) to retrofit building cooling systems to handle geothermal cooling in district type N. The cost includes the installed capital cost of lithium bromide/water absorption chillers, each with a nominal rating of 3 tons of design cooling capacity (36,000 Btu/hr of chill), an associated fluid mixing tank, and other auxiliary equipment (such as fan-coil units, pumps, controls, cooling towers, and ducts). We believe that commercially available absorption chillers with a nominal rating of 3 tons of design cooling capacity are large enough to provide geothermal space cooling for typical residences (households) in U.S. climates.

Normally, the total retrofit cost per building should be input by the user based on one installed chiller with 3 tons of cooling capacity for each residence (household) in the building, totaled over all residences in the building. The number of residences in a typical building in district type N was previously defined as the parameter NRES(D(N)), N=1,...,8. The costs must be input in January, PRINDX base year dollars (Section 3.5.5.1), with default value of January 1980 dollars.

We assumed an installed cost of \$5,000 in January 1980 dollars for the absorption chiller for the suburban district type (with a nominal rating of 3 tons of design cooling capacity), fluid mixing tank, and other auxiliary equipment. For high-density single-family districts, garden apartments, townhouses, and high-rise

apartments, we assumed a chiller cost of \$3,700 per household (2 tons of cooling capacity). The default values for CRTFC(N), N=1,...,8 are as follows:

<u>N</u>	<u>District Type</u>	<u>NRESD(N)</u>	<u>CRTFC(N)</u>
1	Suburban	1	\$ 5,000
2	High-Density Single-Family	1	3,700
3	Garden Apts	60	222,000
4	Townhouses or Rowhouses	30	111,000
5	High-Rise Apts	108	399,600
6	Single Point Demand	1	0

3.4.7 Distribution System Piping Design

The layout of a typical, buried piping network in a residential district was illustrated previously in Figure 10 of Section 2.7. Recall that the piping network consists of a main, a lateral, street pipes, and street-to-house pipes laid out on a rectangular grid system in which a building is associated with each grid point in the rectangular shaped district. The piping network for a single point demand consists only of a supply main and a return main. The pipe, insulation, and casing diameters are optimized in the code based on the annualized costs of capital, pumping power, and thermal losses.

Many material and configuration options for the pipes, insulation, and casings can be simulated. The design options include:

- Single-pipe systems
- Several two-pipe system designs
- Use of steel or fiberglass reinforced plastic (FRP) pipes
- Use of calcium silicate, fiberglass, or polyurethane foam insulation
- Use of steel, plastic (PVC), or field-erected concrete casings

If a two-pipe system is used, the piping network has both supply and return pipes in parallel for the main, lateral, street pipes, and street-to-house pipes. If a single-pipe system is used, the return water from the building heating and cooling systems is disposed of through the sewer system.

The input parameters for selecting the material and configuration options of the distribution piping system are defined below.

P0 Pipe option to design the configuration of the conduit bundle (pipe, insulation, and casing) for the distribution system. The pipe options^(a) are:

1. Two pipes, only supply insulated, with supply and return in common casing.
2. Two pipes, supply and return in common insulation and casing.
3. Two pipes, supply and return insulated separately in a common casing.
4. Two pipes, supply and return insulated separately in separate casings.
5. Two pipes, supply pipe insulated only and in separate casing from the return pipe.
6. Single pipe, supply insulated in casing. The return water from the building heating and cooling system is disposed of through the sewer system.

The default is 1.

(a) The code overrides the input values for the pipe option P0 if the optimized internal pipe diameters are greater than 12 inches and the casing option C0 = 1 or 2 as follows:

- 1) P0 = 1 is reset to P0 = 5 if the internal pipe diameter is greater than 12 inches.
- 2) P0 = 2 or 3 is reset to P0 = 4 if the internal pipe diameter is greater than 12 inches.
- 3) P0 = 4 through 6 are left unchanged.

This automatic change applies only for the conditions stipulated above. The original input value for P0 still applies whenever the internal pipe diameters are less than 12 inches. The reason for automatically switching from common casings to separate casings is an economic one. For internal pipe diameters greater than 12 inches, separate casings are less expensive than common casings according to the capital cost models described in Appendix B.

PMO	<p>Pipe material options:</p> <ol style="list-style-type: none"> 1. Carbon steel, schedule 40 2. Fiberglass-reinforced-plastic (FRP), schedule 40. FRP pipe is currently limited in subroutine SIZE to pipe diameters less than or equal to 12 in. (Table B-4). <p>The default is 1.</p>
IO	<p>Insulation options (IO is declared a floating-point variable in the GEOCITY code):</p> <ol style="list-style-type: none"> 1. Calcium silicate 2. Polyurethane foam 3. Fiberglass <p>The default is 1.</p>
CO	<p>Casing options:</p> <ol style="list-style-type: none"> 1. Prefabricated steel, class A casing 2. Prefabricated plastic (PVC) casing. PVC casing is currently limited in subroutine SIZE to casing diameters less than or equal to 24 in. (Table B-6). 3. Field erected poured concrete casing <p>The default is 1.</p>
TA	<p>Annular air space (meters). The annular air space is between the insulation and the casing to allow air circulation to dry out the insulation. The default is .0254 meters (1 inch).</p>
DPTH	<p>Burial depth (meters) of casing, measured from 2 in. of fill on top of the casing to the surface of the ground (Figure 16 in Section 3.5.4). The default is 0.5 meters (19.69 inches).</p>
CP	<p>Thermal conductivity of the pipe (joules/sec-m-⁰C). The default is 3.56 joules/sec-m-⁰C (24.7 Btu/hr-ft²-⁰F/in.) for carbon steel pipe. This parameter must be changed if the pipe material option PMO is changed from its default value of carbon steel pipe.</p>
CG	<p>Thermal conductivity of the ground (joules/sec-m-⁰C). The default is 0.36 joules/sec-m-⁰C (2.5 Btu/hr-ft²-⁰F/in.).</p>

KINS Thermal conductivity of the insulation around the buried distribution piping (joules/sec-m-⁰C). The variable KINS is declared a floating-point variable in GEOCITY. The default values defined in subroutine DIST are:

1. Calcium silicate: .0418 joules/sec-m-⁰C (.29 Btu/hr-ft²-⁰F/in.)
2. Polyurethane foam: .0187 joules/sec-m-⁰C (.13 Btu/hr-ft²-⁰F/in.)

This parameter must be changed if the insulation option IO is changed from its default value of calcium silicate.

TG Average year-round ground temperature (⁰K). The default is 283⁰K (50⁰F).

VMBTU Value of one million Btu of heat in base year January PRINDX dollars. This parameter is used in determining the value of lost heat for optimizing the insulation thickness around the distribution pipes. The default is \$8/MBtu in January 1980 dollars.

AGFACT(I) Age factor to increase (multiply) friction losses in distribution system pipes due to the increase in relative roughness caused by the deterioration of pipes with age. Three multipliers are used, depending upon the nominal outer pipe diameters. The default values of the age factor were selected to correspond approximately to a pipe age of 10 years.^(a)

The default values are as follows:

	Range I of Nominal Outer Pipe Diameters		
	1 (<4 in.)	2 (4 to 9 in.)	3 (>9 in.)
Age Factor AGFACT(I)	5.	3.6	1.8

(a) Hydraulic Handbook, Colt Industries, Fairbanks Morse Pump Division, 4th Edition, 1965.

The estimated pressure drop in a pipe equals the pressure drop calculated for new pipe times the age factor. This factor applies to all distribution system piping: mains, laterals, street, and house pipes.

WLEAK Fraction of fluid lost by leakage in the distribution system.
The default is 0.01.

3.4.8 Point Demand

The simulation of a single point demand (i.e., a district consisting of one point of heat or chill demand) is implemented by using district number 1 with its district type set to 6. Recall from Section 3.4.6.2 that district type 6 is reserved for defining a single point demand. The default values defining the characteristics of district type 6 were previously summarized in Table 8 of Section 3.4.6.2.

The two key parameters used to define the annual heating or cooling energy requirements for a single point demand are the peak heat or chill demand and the annual load factor. The peak heat or chill demand is input using the district type parameter HQ(6) or CQ(6) expressed in MBtu of heat or chill per hour. Contrary to the simulation of residential districts, the annual load factor for a single point demand is not calculated by the code from climatic data, but instead is defined by the input parameter PF.

GEOCITY calculates the average heat (chill) demand during the year and the annual heat (chill) demand for the single point demand as follows:

- 1) Average heat (chill) demand (MBtu/hr) = peak heat (chill) demand (MBtu/hr) * annual load factor [i.e., Average heat (chill) demand (MBtu/hr) = $HQ(6) * PF$ (or $CQ(6) * PF$)].
- 2) Annual heat (chill) demand (MBtu/yr) = average heat (chill) demand (MBtu/hr) * number of hours per year [i.e., Annual heat (chill) demand (MBtu/yr) = $HQ(6) * PF * 24. * 365.25$ (or $CQ(6) * PF * 24. * 365.25$)].

Several restrictions are present in the code when simulating a point demand. These are as follows:

- 1) Only one point demand can currently be simulated at a time.

- 2) No sanitary hot water heating requirements and no supplemental heating or cooling are simulated for a point demand.
- 3) Retrofit cost for the heating or cooling system for the single point demand is input using district type 6 and the parameters CRTF(6) or CRTFC(6) as described in Section 3.4.6.2. Lithium bromide/water absorption chillers and a fluid mixing tank are used to provide cooling for the single point demand, as previously described for the residential districts in Section 3.4.5.

The parameters described previously for defining the operational mode (Section 3.4.1), optional distribution heat exchanger (Section 3.4.4), and distribution system piping design (Section 3.4.7) also apply to the simulation of a single point demand. Parameters defining climatic data, such as heating degree days or cooling degree hours, do not apply.

The values that must be input for the geometric and district type parameters to simulate a single point demand are defined below. The district type parameters not mentioned below should be left set to their default values (Table 8 of Section 3.4.6.2).

District Geometry

NDTR	= 1 ... Number of districts
IDTYPE	= 1 ... Generic type of district is point demand
IDTR(1)	= 6 ... District type 6 for point demand
AREA(1)	= 1 ... District area
WIDTH(1)	= 1 ... District width
XLNGTH(1)	= 1 ... District length
DDTR(1)	= User Input ... Length of main pipe (and optional return pipe) serving district number 1 (miles).

District Type Characteristics

HQ(6)	= User Input ... Peak heat or chill demand (MBtu/hr) for the
or CQ(6)	single point demand
PF	= User Input ... Annual load factor (fraction)

TREJ(6) = User Input ... Temperature ($^{\circ}\text{F}$) of the return water
or
TREJC(6) from the point demand heating or
cooling system.

CRTF(6) = User Input ... Retrofit cost (January PRINDX dollars)
or
CRTFC(6) for the heating or cooling system for the
single point demand.

3.4.9 Branching Pipe Mains Network for Multi-Residential Districts

A variety of main pipe configurations can be simulated to service multi-residential districts in GEOCITY. The configuration of pipe mains is defined by means of two matrices: DDTR (district M), $M = 1$ to number of districts NDTR; and DNET (district M, main MM), $M = 1$ to NDTR, $MM = 1$ to number of mains. The matrices DDTR and DNET are dimensioned 20 and 20×20 , respectively. The Mth element, DDTR (M), defines the length (miles) of the main servicing district M. Lengths are measured from either the inlet to the distribution system or the last junction in the main, to the center of district M.

The matrix DNET defines the districts serviced by each main. The element DNET (M, MM) is set to one of the following values:

- 2, if main MM connects directly to district M
- 1, if main MM transports flow to district M but does not connect directly to district M
- 0, if main MM does not transport flow to district M in any way.

The procedure for setting up this matrix is defined later in this section. Two options which are available for defining the configuration of mains are described below.

Option 1. Each Main Services One and Only One District

Option 1 is used to simulate a simple layout of mains in which each main from the distribution inlet services one and only one district. The configuration of mains is illustrated by sample configuration 1 in Figure 15. The matrix DDTR (M), $M = 1$ to NDTR, is used to define the length (miles) of the main serving district M. The matrix DNET (M, MM), $M = 1$ to NDTR, $MM = 1$ to number of mains, can be left set to its default value of all zeroes. As an alternative approach, configuration 1 can also be simulated using the procedure

OPTION 1: EACH MAIN SERVES ONE AND ONLY ONE DISTRICT

CONFIGURATION 1

OPTION 2: AT LEAST ONE MAIN SERVES MORE THAN ONE DISTRICT

CONFIGURATION 2
SERIES

CONFIGURATION 3
BRANCHES

CONFIGURATION 4
COMBINATION
OF SERIES AND
BRANCHES

NOTES: A MAIN INTERSECTION MAY OCCUR INSIDE A DISTRICT OR OUTSIDE A DISTRICT

WATER PUMPED FROM DISTRIBUTION INLET TO OUTLYING DISTRICTS

• MAIN INTERSECTION

◻ DISTRICT

M_i MAIN NUMBER *i*

DDTR(*j*) = l_j LENGTH OF MAIN SERVING DISTRICT *j*

FIGURE 15. Examples of Main Configurations Servicing Multi-Residential Districts

discussed in option 2 below. Using option 2 to simulate configuration 1, the element DNET (M, MM) is set to 2 whenever main MM connects directly to district M in configuration 1, and set to 0 otherwise.

Option 2. At Least One Main Services More Than One District.

Option 2 is used to simulate more complex configurations of mains in which at least one main services more than one district. With this option, the following main configurations can be simulated.

- One or more mains service several districts in series, (i.e., one or more mains servicing a district continue beyond that district to service additional districts, as illustrated by sample configuration 2 in Figure 15).
- One or more mains branch (subdivide) into two or more mains to service additional districts, as illustrated by sample configuration 3 in Figure 15.
- Combinations of the above two configurations (combinations of series and branches), as illustrated by sample configuration 4 in Figure 15.

The following steps are suggested for defining option 2:

- Step 1. Number all districts serviced by a main and all main intersections outside a district, beginning with the districts furthest away from the distribution inlet and proceeding toward the distribution inlet.^(a) The number assigned to a given district or main intersection outside of a district must be greater than that assigned to any district or main intersection outside a district further down the main away from the distribution inlet. Figure 15 shows several configurations that illustrate the numbering scheme for districts and main intersections outside a district. In addition, a main intersection outside a district must be defined as a district with zero area and zero heat (chill) demand in the input data.

(a) A main intersection may occur inside a district (as number 9 in configuration 4 of Figure 15) or outside a district (as numbers 4 and 8 in configuration 4).

- Step 2. Number the mains beginning with main number 1 at the distribution inlet and proceeding away from the distribution inlet. At every main intersection that branches (divides) into 2 or more mains, number each branch with a new main number. This numbering scheme for mains is illustrated in Figure 15. Observe that a main that does not divide into 2 or more branches, such as main number 1 in configuration 2 or main number 4 in configuration 4, can retain the same main number in its next leg.
- Step 3. Set up the matrix DDTR (M), M = 1 to NDTR, defining the distance (miles) from the next higher number district on the same main or from the main intersection immediately preceding the district to district number M. The sample configurations in Figure 15 illustrate the definition of the lengths of the mains.
- Step 4. Set up the matrix DNET (M, MM), M = 1 to NDTR, MM = 1 to number of mains, defining the districts serviced by each main. Set the element DNET (M, MM) to one of the following values:
- 2, if main MM connects directly to district M
 - 1, if main MM transports flow to district M but does not connect directly to district M
 - 0, if main MM does not transport flow to district M in any way.

In defining the 20 x 20 two-dimensional matrix DNET through the NAMELIST input data, the user should be careful to input the array values by columns, [i.e., define all rows (district numbers) for the first column (main number 1), next all rows (district numbers) for the second column (main number 2), and so on]. The user should also define the entire 20 rows for each column, inputting zeros if necessary to complete the 20 entries for each column. Additionally, zeros should be input if necessary to complete the entries for all 20 columns. This will result in a matrix with values defined for all 400 entries.

The matrices DNET (district number, main number), DDTR (district number), and AREA (district number) are shown in Table 9 for sample configurations 2 through 4 in Figure 15 to illustrate the procedure for defining option 2. These matrices are defined for sample configurations 2 through 4 using NAMELIST input data as follows:

TABLE 9. Matrix Examples for Branching Mains Network

CONFIGURATION 2

		<u>DNET</u>	<u>DDTR</u>	<u>AREA</u>
		Main Number		
District	1	1		
	2	2	l_1	a_1
Number	2	2	l_2	a_2

CONFIGURATION 3

		<u>DNET</u>	<u>DDTR</u>	<u>AREA</u>
		Main Number		
District	1	1 2 3		
	1	1 0 0	l_1	a_1
Number	2	1 2 0	l_2	a_2
	3	2 0 0	l_3	0

CONFIGURATION 4

		<u>DNET</u>	<u>DDTR</u>	<u>AREA</u>
		Main Number		
District	1	1 2 3 4 5 6 7 8		
	1	1 1 0 2 0 0 0 0	l_1	a_1
Number	2	1 1 0 2 0 0 0 0	l_2	a_2
	3	1 1 2 0 0 0 0 0	l_3	a_3
	4	1 2 0 0 0 0 0 0	l_4	0
	5	1 0 0 0 1 0 2 0	l_5	a_5
	6	1 0 0 0 1 0 0 0	l_6	a_6
	7	1 0 0 0 1 2 0 0	l_7	a_7
	8	1 0 0 0 2 0 0 0	l_8	0
	9	2 0 0 0 0 0 0 0	l_9	a_9

Sample Configuration 2

DNET = 2*2, 18*0, 380*0,

DDTR = l_1 , l_2 , 18*0,

AREA = a_1 , a_2 , 18*0,

Sample Configuration 3

DNET = 1, 1, 2, 17*0, 0, 2, 0, 17*0, 2, 0, 0, 17*0, 340*0,

DDTR = l_1 , l_2 , l_3 , 17*0,

AREA = a_1 , a_2 , 0, 17*0,

Sample Configuration 4

DNET = 8*1, 2, 11*0, 3*1, 2, 16*0, 2*0, 2, 17*0, 2*2, 18*0, 4*0, 3*1,
2, 12*0, 6*0, 2, 13*0, 4*0, 2, 15*0, 5*0, 2, 14*0, 240*0,

DDTR = l_1 , l_2 , l_3 , l_4 , l_5 , l_6 , l_7 , l_8 , l_9 , 11*0,

AREA = a_1 , a_2 , a_3 , 0, a_5 , a_6 , a_7 , 0, a_9 , 11*0,

3.5 FINANCIAL INPUT DATA

GEOCITY can simulate a wide range of financial and tax structures through input parameters that vary the rates of return on equity and debt, the debt-equity ratios, tax rates, interim capital replacement rates, investment tax credits, property insurance rates, and depreciation schedules. Both private enterprise and municipal utility systems can be simulated. The reservoir and fluid transmission system and the distribution system may have the same or different financial structures and costs of capital. The project lifetime can be varied over a long period, currently up to 50 years.

The financial parameters for the reservoir and fluid transmission system are input through the NAMELIST group \$RESVOR. Distribution system financial parameters are input through the NAMELIST group \$DISTRB. Described within Sections 3.5.1 through 3.5.6 are financial data concerning both the reservoir and fluid transmission system and distribution system, well drilling costs, trenching costs, and pre-development, development, and operational costs for the reservoir and fluid transmission system.

The majority of capital costs of the reservoir and fluid transmission system and distribution system are calculated by the code using the capital cost

models described in Appendices D and B, respectively. The O&M costs for the reservoir and fluid transmission system and distribution system are calculated by the code as fractions of their respective capital costs, as described in Section 3.5.1 and Appendix B. The rates (fractions) for interest, return on equity, taxes, capital replacement, property insurance, and maintenance are specified through the input data (Sections 3.5.1 and 3.5.3). The cost of thermal energy delivered by the reservoir and fluid transmission system to the distribution system is calculated by the code.

The base year for calculating capital and O&M costs for the reservoir and fluid transmission system and distribution system is defined in Section 3.5.5.11. Parameters for inflating and escalating the calculated capital and O&M costs over the project lifetime are defined in Section 3.5.5.2. The unit cost of supplemental heat to the distribution system is defined in Section 3.5.5.3. The electrical pumping costs for the reservoir and fluid transmission system and distribution system are calculated using parameters defined in Section 3.5.5.3.

3.5.1 Reservoir and Fluid Transmission System Financial Data

This section describes the input array DINPUT(N), N = 1, to 35, which is used to define the financial and tax data for the reservoir and fluid transmission system. Other parameters described here include the investment tax credit for the reservoir and fluid transmission system, and the option to either capitalize or expense all the intangible reservoir pre-development costs which are described in Section 3.5.6.

An appropriate discount rate is required to calculate present worth and levelized costs. The discounted cash flow submodels in GEOCITY use mid-year discounting with the after-tax cost of capital as the discount rate. The discount rate for the reservoir and fluid transmission system is calculated by the code as follows:

$$\begin{aligned} \text{After-tax discount rate} = & \text{bond interest rate} * [1 - \{(\text{federal tax rate}) * \\ & (\text{1-state tax rate}) + \text{state tax rate}\}] * \\ & \text{fraction of investment in bonds} + \\ & \text{equity return rate} * \text{fraction of investment in equity} \end{aligned}$$

The parameters defined below are input through the NAMELIST group \$RESVOR. The values of DINPUT(N) not mentioned below are not input into the code.

N	Description of DINPUT(N)
4	Fraction of initial investment in bonds; default is 0.42.
5	Bond interest rate (fraction); default is 0.08.
6	Earning rate on equity after taxes (fraction); default is 0.15.
7	Federal income tax rate (fraction); default is 0.46 (but 0 for a municipal utility, i.e, when DINPUT(4) = 1).
8	Peak thermal energy capacity (MWth) of the reservoir. The default is 250 MWth. This number is used to calculate the reservoir exploration costs (Appendix A). The input value should normally be equal to or slightly larger than the calculated peak thermal energy requirements (MWth) from the reservoir production wells.
9	Depreciable life of reservoir production and replacement wells (years); default is 10 years. This value must be less than or equal to the average production well life (AVGWL) defined in Section 3.3.1.
14	Startup year for operation of the distribution system; default is 1985. The same year must also appear for DINPUT(49) (Section 3.5.3).
15	State income tax rate (fraction); default is 0.07 (but 0 for a municipal utility).
16	State gross revenue tax rate (fraction); default is 0.
17	Property tax rate (fraction); default is 0.025 (but 0 for a municipal utility).
18	Fluid transmission system interim capital replacement rate, (fraction of fluid transmission system capital cost); default is 0.015. This is also the fluid injection system interim capital replacement rate, (fraction of fluid injection system capital cost and cost of drilling injection wells).
19	Property insurance rate (fraction); default is 0.0012.
26	Depreciable life of fluid transmission system (years); default is 15 years. This value must be less than or equal to the fluid transmission system and distribution system operating life DINPUT(61) defined in Section 3.5.3.
27	Royalty payments, (percentage of reservoir and fluid transmission system annual sales); default is 10%.

<u>N</u>	<u>Description of DINPUT(N)</u>
28	Fluid transmission system maintenance rate, (fraction of fluid transmission system capital cost); default is 0.05.
29	Fluid injection system maintenance rate, (fraction of fluid injection system capital cost); default is 0.05.
DA	Percentage depletion allowance for the reservoir. The default is 15% (but 0 for a municipal utility, i.e., when DINPUT(4) = 1).
PIVTCR	Percent investment tax credit for the reservoir and fluid transmission system; default is 10% (but 0 for a municipal utility).
IEXPNS	Option to capitalize (IEXPNS=0) or expense (IEXPNS=1) all the reservoir pre-development costs described in Section 3.5.6. The default is IEXPNS=0. With the default option, all reservoir pre-development costs are capitalized and amortized on a straight line basis.

3.5.2 Reservoir Well Drilling Costs

Well drilling costs are either input directly or calculated by the drilling model in the code. The option for the user to input the drilling costs is described first. This option is implemented by defining the three well cost input parameters described below through the NAMELIST group \$RESVOR.

IDRILL	Set to 0 to input the well drilling costs directly. This is the default value. The drilling costs should be input in the same base year dollars in which the capital costs are calculated in the code (January PRINDX dollars, defined in Section 3.5.5.1, with default value of January 1980 dollars).
DCPW	Total cost (January PRINDX dollars) of all tasks involved in drilling one production well. The default is \$1,000,000 in January 1980 dollars.
DCNPW	Total cost (January PRINDX dollars) of all tasks involved in drilling one nonproducing (dry) well. The default is \$800,000 in January 1980 dollars.

DCINJW Total cost (January PRINDX dollars) of all tasks involved in drilling either one exploratory well or one injection well. The default is \$1,000,000 in January 1980 dollars.

PERCNT(N)
N=1,2 Fraction (not percentage) tangible and intangible parts, respectively, of the drilling costs for production and injection wells. The optional breakdown into tangible and intangible parts is provided because of possible differential tax treatment. The tangible part is capitalized, with costs recovered through the well depreciation account. The intangible part is expensed immediately. Nonproducing (dry) wells are expensed. The default values for the PERCNT array are as follows:

PERCNT(1) = 1/3, fraction tangible
PERCNT(2) = 2/3, fraction intangible.

The option for the code to calculate the drilling costs using the drilling model (subroutine DRILL) is implemented by setting the parameter IDRILL to 1 and defining four other input parameters through the NAMELIST group \$RESVOR: the fraction of the well that is cased (CASFR), the well diameter (DIA), the rock hardness to be drilled, and the drilling depth (NUMTYP, STRATA(M,N), M = 1,2; N = 1,10). The drilling costs calculated in subroutine DRILL are a function of the wellhead temperature. The parameters CASFR, DIA, NUMTYP, and STRATA(M,N), M = 1,2; N = 1,10, were previously defined in Section 3.3.1. All input parameters are input through the NAMELIST group \$RESVOR.

IDRILL Set to 1 to let the code calculate the drilling costs using the drilling model in subroutine DRILL. The calculated drilling costs are automatically updated to the base year dollars (January PRINDX dollars) using drilling price indices obtained from drilling publications.^(a)

The drilling model also calculates the parameters PERCNT(1) and PERCNT(2), which represent the tangible and intangible fractions, respectively, of the drilling costs for production and injection

(a) June 1975 report of the Independent Petroleum Association of America (IPAA) Cost Study Committee and February 15, 1981 issue of World Oil.

wells. The well diameter, rock hardness to be drilled, drilling depth, wellhead temperature, and fraction of the well to be cased are required when calculating the drilling costs using the drilling model. These parameters were previously defined in Section 3.3.1.

The drilling costs are calculated by the drilling model as the weighted sum of 20 separate categories described below. The costs in each category are first calculated relative to July 1969 as the base year. These costs are then brought up to date by separate drilling price indices stored in subroutine DRILL for each of the 20 categories. The drilling price indices are defined relative to January PRINDX as the base year. Currently, the parameter PRINDX cannot be increased beyond its default value of January 1980 without first updating the drilling price indices stored in subroutine DRILL for January 1980. However, this is an easy subroutine modification. The cost calculated in each category is updated by subroutine DRILL using the drilling price index for that category as follows:

$$\begin{aligned} \text{Cost of category(I) in January PRINDX dollars} = \\ \text{Cost of category(I) in July 1969 dollars} * \\ \text{Drilling Price Index(I) / 100.} \end{aligned}$$

The 20 categories and their drilling price indices stored in subroutine DRILL for January 1980 drilling cost updates are as follows:

<u>Drilling Cost Category</u>	<u>Drilling Price Index for January 1980</u>
1-Payments to Contractors	378.0
2-Road & Site Preparation	218.9
3-Transportation	216.9
4-Fuel	488.5
5-Drilling Mud and Additives	334.4
6-Well Site Logging	214.6

(continued)

<u>Drilling Cost Category</u>	<u>Drilling Price Index for January 1980</u>
7-All other Physical Tests	262.3
8-Logs	281.8
9-Directional Drilling	229.5
10-Perforate	231.9
11-Formation Treating	221.4
12-Cement	248.1
13-Casing	323.1
14-Special Tools	226.1
15-Drill Bits	263.5
16-Wellhead Equipment	292.7
17-Plugging	246.4
18-Other Equipment and Supplies	274.7
19-Supervision	239.9
20-All Other Expenses	233.8

3.5.3 Distribution System Financial Data

This section describes the input array DINPUT(N), N=36 to 70, which is used to define the financial and tax data for the distribution system. Other parameters described include the construction time for the distribution system and the investment tax credit.

The after-tax discount rate is calculated by the code from the input parameters defined below in an analogous manner as described for the reservoir and fluid transmission system in Section 3.5.1. The capital investment schedule during the construction time period was previously described in Section 2.9.

The parameters defined below are input through the NAMELIST group \$DISTRB. The values of DINPUT(N) not mentioned below are not input into the code.

N	Description of DINPUT(N)
39	Fraction of initial investment in bonds; default is 0.59.
40	Bond interest rate (fraction); default is 0.08.
41	Earning rate on equity after taxes (fraction); default is 0.12.
42	Federal income tax rate (fraction); default is 0.46 (but 0 for a municipal utility, i.e., when DINPUT(39) = 1).
44	Depreciable life of distribution system (years); default is 15 years. This value must be less than or equal to the distribution system operating life [DINPUT(61)].
49	Startup year for operation of the distribution system; default is 1985. The same year must also appear for DINPUT(14) (Section 3.5.1).
50	State income tax rate (fraction); default is 0.07 (but 0 for a municipal utility).
51	State gross revenue tax rate (fraction); default is 0.04.
52	Property tax rate, (fraction of distribution system capital investment); default is 0.025 (but 0 for a municipal utility).
53	Interim capital replacement rate, (fraction of distribution system capital investment)); default is 0.015.
54	Property insurance rate, (fraction of distribution system capital investment); default is 0.0012.
61	Distribution (also reservoir and fluid transmission) system operating life (years); default is 30 years.
63	Distribution system maintenance rate, (fraction of distribution capital cost); default is 0.05.
NYC	Number of years to construct the distribution system. The default is 3 years.
PIVTC	Percent investment tax credit for the distribution system. In the first year of operation, the investment tax credit is computed as a fraction (PIVTC*.01) of the total construction period capital cost and interim capital replacements. In any subsequent year of operation, the investment tax credit is computed as a fraction of the interim capital replacements for that year. The default is 10% (but 0 for a municipal utility).

3.5.4 Distribution System Trenching Costs

Trenching costs for the distribution system are calculated by summing five component costs of trenching in a trenching cost model represented by the capital cost equations in Table B-1 of Appendix B. The five components of the trenching cost model are as follows:

- 1) Excavation
- 2) Bedding fill, including the purchase and delivery of sifted fill material
- 3) Back fill, including the purchase and delivery of sifted fill material
- 4) Finish fill, using the excavated material to fill and pack to grade with a bulldozer
- 5) Resurfacing

The physical layout of the trenches used in the trenching cost model for the different pipe and casing options described in Section 3.4.7 is shown in Figure 16.

The trenching cost model assumes vertical slopes with excavation through a dirt and rock mixture. The trenches are assumed to be dug in residential areas, requiring some hand excavation and relocation of existing utilities. Two inches of bedding fill hauled to the site is placed under the pipe casing. Sifted backfill material is hauled to the site and hand-filled and tamped in 8-inch lifts until the distribution pipe casing is covered by 2 inches of fill. The rest of the trench is filled and packed by a bulldozer. Resurfacing consists of 2 inches of pavement on top of 2 inches of gravel. The 2 inches of fill on top of the casing is at the specified burial depth DPTH below the surface of the ground (Section 3.4.7).

The five component costs of trenching can be individually adjusted through the cost parameters defined below. These costs are input in January 1977 dollars through the NAMELIST group \$DISTRB and then escalated by the code to January PRINDX base-year dollars using the Chemical Engineering Plant Cost Index for the category of "construction labor". Section 3.5.5.1 provides a description of these indices.

EXCC Excavation cost of trenching, $\$/\text{meter}^3$. The default value of $\$26.16/\text{meter}^3$ is based on excavation through a dirt and rock mixture. These costs assume: 1) union labor and 2) that the

COMMON CASING
PIPE OPTIONS PO = 1, 2, 3, AND 6 AND CASING OPTIONS CO = 1, 2

SEPARATE CASINGS
PIPE OPTIONS PO = 4, 5 AND CASING OPTIONS CO = 1, 2

CONCRETE CASING
CASING OPTION CO = 3

FIGURE 16. Physical Layout of Buried Pipe Trenches Used in the Trenching Cost Model

trenches are being dug in residential areas, requiring some hand excavation and relocation of existing utilities.

- BEDC Bedding fill cost, $\$/\text{meter}^3$. The default value of $\$13.10/\text{meter}^3$ is based on the use of sifted fill material hauled 10 miles to the site. Two inches of bedding fill is placed in the trench underneath the pipe casing.
- BACKC Backfill cost, $\$/\text{meter}^3$. The default value of $\$13.10/\text{meter}^3$ is based on the use of sifted fill material hauled 10 miles to the site and hand tamped in 8-inch lifts until the top of the pipe casing is covered by 2 inches.
- FINC Finish fill cost, $\$/\text{meter}^3$. The default value of $\$1.30/\text{meter}^3$ is based on using excavated material filled and packed to grade with a bulldozer.
- RESRFC Resurfacing cost, $\$/\text{meter}^2$. The default value of $\$8.40/\text{meter}^2$ is based on a 2-inch layer of pavement on top of 2 inches of gravel.
- TRDF Trenching difficulty factor, used to increase (multiply) the total cost of trenching, depending on local conditions at the simulated site. The default value is 1.

3.5.5 General Economic Parameters

3.5.5.1 Base Year of Capital and O&M Costs and Depreciation Options

All capital and O&M cost estimates stored in the internal cost data bases for GEOCITY or calculated by the capital and O&M cost models described in Appendices B and D are defined in January 1977 dollars. This section describes an input parameter PRINDX, defined through the NAMELIST group \$DISTRB, which automatically updates these costs to January PRINDX base-year dollars. The default value of PRINDX is 1980. This automatic updating is performed using nine Chemical Engineering (CE) plant cost indices published monthly in Chemical Engineering and described below.

The following cost parameters must also be input in January PRINDX base-year dollars:

- 1) The drilling costs DCPW, DCNPW, and DCINJW (Section 3.5.2) if the drilling model is not used. If the drilling model is used, GEOCITY automatically updates the drilling costs it calculates to January PRINDX base-year dollars using the price index adjustments for drilling previously described in Section 3.5.2.
- 2) The unit electrical cost of operating the transmission and distribution system pumps COPUMP (Section 3.5.5.3).
- 3) The unit cost of supplemental heat CSBTU (Section 3.5.5.3).
- 4) The value of supplemental heat VMBTU (Section 3.4.7).
- 5) The building retrofit costs CRTF(N) and CRTFC(N) $N = 1$ to 8 (Section 3.4.6.2).
- 6) The reservoir and fluid transmission system unit costs UNITO(N), $N = 1$ to 39 (Section 3.5.6).

In addition, if the trenching cost parameters described in Section 3.5.4 are changed from their default values, they must be estimated in January PRINDX dollars and then deflated to January 1977 dollars using the price index adjustment for the category "construction labor" (see below) before they are input. This is due to the fact that GEOCITY automatically updates the trenching cost parameters from January 1977 dollars to January PRINDX base-year dollars.

The capital cost updates implemented through the input parameter PRINDX are programmed in subroutine UPDATE of the code using nine CE plant cost indices. Currently, the parameter PRINDX cannot be increased beyond its default value of January 1980 without first modifying subroutine UPDATE. However, this is an easy programming modification, since subroutine UPDATE is a small routine. In addition, if the drilling model is used, the drilling price index adjustments in subroutine DRILL (Section 3.5.2) must be modified if the parameter PRINDX is increased beyond January 1980.

The nine CE plant cost indices are defined in subroutine UPDATE as follows:

<u>Generic Cost Category</u>	<u>CE Index Jan 1977</u>	<u>CE Index Jan 1980</u>	<u>Index Ratio (Adjustment)</u>
1 - Buildings	194.0	234.8	1.210
2 - Fabricated Equipment (Including Heat Exchangers)	208.3	274.9	1.320
3 - Process Machinery	205.8	263.7	1.281
4 - Pipes, Valves & Fittings	236.6	317.6	1.342
5 - Pumps & Compressors	234.6	293.8	1.252
6 - Electrical Equipment	154.0	196.9	1.279
7 - Structural Support & Misc. (Including Insulation & Casing)	219.3	285.5	1.302
8 - Construction Labor (Including Site Work)	178.5	199.2	1.116
9 - Engineering & Manpower	162.1	204.3	1.260

The cost index ratio for each generic category is the ratio of the CE cost index for the user-specified year PRINDX to the 1977 CE cost index for that category. Subroutine UPDATE updates the capital cost for a capital cost item using its appropriate generic cost category and the following equation:

$$\text{Cost (Jan. PRINDX\$)} = \text{Cost (Jan. 1977\$)} * \text{CE Cost Index Ratio}$$

As pointed out in Section 3.5 and Appendix B, the O&M costs are calculated in the code as fractions of the capital costs. The fractions, such as interim capital replacement rate, maintenance rate, property insurance rate, etc., are specified through the input data. Therefore, updating the capital costs to January PRINDX base-year dollars also automatically updates the O&M costs to the same base-period dollars.

Two depreciation options are available in GEOCITY for recovering the capital costs and interim capital replacements for the reservoir and fluid transmission system and distribution system: straight-line depreciation or double declining balance (DDB) accelerated depreciation with switch over to straight line. The switch is made in the year when the depreciation calculated by the DDB method becomes less than it would be by the straight-line method.

The parameters input through NAMELIST group \$DISTRB to implement the options described in this section are summarized below.

PRINDX Base year (January 1) in which GEOCITY calculates the capital and O&M costs of the reservoir and fluid transmission system and

distribution system. The default is 1980. Any value beyond 1980 will require modifications to subroutines UPDATE and DRILL.

LL2 Depreciation option for the reservoir and fluid transmission system and distribution system.
 1 = straight line
 3 = double declining balance with switch over to straight line.
 The default option is LL2 = 3.

3.5.5.2 Inflation and Escalation

GEOCITY allows for the effects of inflation and price escalation in calculating the cost of thermal energy from the reservoir and fluid transmission system and the cost of heat (chill) from the distribution system to the end-user. Input parameters are provided to define the general inflation rate and price escalation rates for four generic categories in the reservoir and fluid transmission system and distribution system: capital equipment, O&M expenses, electricity expenses for pumps, and supplemental thermal energy. Another input parameter is provided to define the financial mode of operating the code that permits either current-dollar analysis with inflation and escalation or constant-dollar analysis without inflation and escalation.

The four price escalation rates allow the user to escalate costs in the four generic categories at annual compound rates over the project lifetime to reflect a combination of inflation, supply/demand, and other effects such as environmental and engineering considerations. This definition of price escalation allows inflation to be just one of several factors that can contribute to price escalation.

The current-(inflated) dollar analysis is the default mode of operating the code. This mode calculates the unit costs (\$/MBtu) of energy from the reservoir and fluid transmission system and the unit costs (\$/MBtu) of heat (chill) from the distribution system to the end-users for each year of the project lifetime in current dollars. The sale of thermal energy to the distribution system and heat (chill) to the end-users generates the revenues needed by the reservoir and fluid transmission system and the distribution system, respectively, to exactly recover all costs in current dollars, including return on investment, over the project lifetime. Finally, based on the

general inflation rate and after-tax discount rate, GEOCITY levelizes and deflates the year-by-year costs of thermal energy and heat (chill) in current dollars to obtain a life-cycle levelized cost (\$/MBtu) of thermal energy and heat (chill), respectively, expressed in January PRINDX base-year dollars. Operation of the code with constant dollars over the project lifetime generates a life-cycle levelized cost (\$/MBtu) of thermal energy and a life-cycle levelized cost (\$/MBtu) of heat (chill) expressed in January PRINDX base-year dollars without inflation and escalation.

The values selected for interest rates and return on equity must be consistent with the financial mode of operating the code and the inflationary assumptions. For example, the default values selected for the interest rate (0.08) and return on equity (0.15) for the financial entity operating the reservoir and transmission system reflect market rates for the current-dollar analysis (default mode) based on a default value of 6% for the general inflation rate (PIFALL = 6% below). If the code is operated in constant dollars without inflation or in current dollars with a lower general inflation rate, a lower interest rate and return on equity should be defined in the input data.

The input parameters needed to simulate the effects of inflation and price escalation in the reservoir and fluid transmission system and distribution system are defined below. These parameters are input through the NAMELIST group \$RESVOR.

ICOST Option to calculate the cost of thermal energy from the reservoir and fluid transmission system and the cost of heat (chill) from the distribution system using either constant-dollar analysis or current-dollar analysis.

0 = Constant-dollar analysis. This is the mode used with inflation and escalation rates set to 0.

1 = Current-dollar analysis (default mode). This is the default mode used with the inflation and escalation rates set greater than 0.

PIFALL Percent general inflation rate. The default is 6%.

PIFCAP Percent price escalation rate for capital equipment and interim capital replacements. The default is 6%.

- PIFCSB Percent price escalation rate for purchased supplemental energy. The default is 8%. This parameter escalates the cost of supplemental heat purchased by the distribution system (CSBTU, Section 3.5.5.3).
- PIFELR Percent price escalation rate for purchased electricity needed for operating the transmission and distribution pumps. The default is 7%.
- PIFOM Percent price escalation rate for O&M expenses. The default is 6%.

3.5.5.3 Cost of Supplemental Heat, Pumping Efficiency, and Pumping Electrical Costs

This section describes the input parameters used to define the cost of supplemental heat, the pumping efficiency, and the pumping electrical cost. Supplemental heating is used by the distribution system when the outdoor winter temperature falls below the winter outdoor design temperature used in sizing the reservoir and fluid transmission system and distribution system. Recall that the design heating degree days DDGDAY(1) and the winter outdoor design temperature TDES(1) (Section 3.4.2) are usually input to design the system to meet slightly less than the extreme peak heating energy requirements. This undersizing of the capacities of the reservoir and fluid transmission system and distribution system improves the system load factor. In this way, the system is not being sized at a large incremental cost to meet extreme peak heating demands that occur only a small fraction of the time during the winter. As previously described in Section 3.4.1, no supplemental cooling is provided by the code for either a residential district or a point demand.

The costs of supplemental heating to meet the heating shortfalls are calculated by the code as the product of the calculated MBtu of heating shortfall times the unit cost of supplemental heating (\$/MBtu). Supplemental heat is included in calculating the annual MBtu of thermal energy sold by the distribution system to the end-users, but is also treated as an annual operating expense for the distribution system.

The pumping efficiency and unit cost of electricity to operate the pumps apply to all pumps in the reservoir and fluid transmission system and distribution system including:

- Downhole pumps that provide the vertical lift and restore the frictional pressure losses in the production wells and surface wellfield piping.
- Surface pumps that restore the frictional pressure losses in the surface transmission piping of the reservoir and fluid transmission system.
- Surface pumps at both the tube and shell sides of the optional heat exchanger located at the inlet to the distribution system.
- Surface pumps that restore the frictional pressure losses in the distribution system piping.

The parameters summarized below are input through the NAMELIST group \$DISTRB.

CSBTU	Cost of supplemental heat, expressed in January PRINDX base year dollars. The default is \$8/MBtu.
ETA	Combined motor and pump efficiency (fraction) of reservoir and fluid transmission system and distribution system pumps. The default is 0.65.
COPUMP	Unit cost of electricity for operating the reservoir and fluid transmission system and distribution system pumps (\$/kWh), expressed in January PRINDX base-year dollars. The default is \$.029/kWh.

3.5.6 Pre-Development, Development, and Operational Time Schedules and Costs for Reservoir and Fluid Transmission System

Among the parameters described below are the time arrays used to schedule the times over which the activities comprising the pre-development, development, and operation of the reservoir and fluid transmission system are to take place. The expenditures for these activities are distributed uniformly over the times in which they are scheduled to occur.

This section also describes a cost array used to calculate the costs of all activities comprising the pre-development (exploration) of the reservoir and the annual field operating costs for production well abandonment, production and injection well maintenance, and production well redrilling due to scale buildup. This array defines costs for these activities on a unit basis, primarily per target reservoir site, acre, or well. The total costs associated

with these activities are calculated in the code by multiplying the appropriate unit costs by the number of target reservoir sites, acres, or wells calculated for that activity.

The costs of all other activities in the development and operation of the reservoir and fluid transmission system are defined or determined from parameters described in previous sections. This includes the major costs such as drilling production and injection wells, the capital costs of the transmission system and disposal (injection) system, and all other annual operating costs labeled "computed" in the right-hand column of Table 10A.

This section also describes an array that defines the fraction of reservoir sites to retain at each of six major decision points in the step-by-step process of reducing the number of prospective reservoir sites during pre-development (exploration) to one reservoir site for development and operation. The size of prospective reservoir sites leased for exploration is also defined below.

The parameters defined below are input through the NAMELIST group \$RESVOR.

- ACRES Size (acres) of each prospective geothermal site leased for reservoir exploration. This parameter is multiplied by the input unit costs per acre associated with lease cost (UNITO(N), N = 6, 7, 8 in Tables 10A and 10B) to calculate the lease cost per site. Appendix A gives the cost equations for calculating lease cost. The default value is 15,000 acres.
- LAGS (ITEX(N), K), ITEX(N) = 1, ..., 22; K = 1, 2 - Time array to schedule the expenditures and times over which the activities defining the pre-development, development, and operation of the reservoir and fluid transmission system in Tables 10A and 10B are to take place. An internal array in subroutine RESVOR, ITEX(N), N = 1, ..., 39, currently groups the 39 activities in Tables 10A and 10B into 22 subgroups of activities as shown in Table 11. All activities within a given subgroup are presumed to occur parallel in time. However, the user has the flexibility to schedule the different subgroups of activities either sequentially or parallel in time.

TABLE 10A. Activities and Input Costs for Supply System Pre-Development, Development, and Operation of Reservoir and Fluid Transmission System

Index for Itemizing Individual Activities N	Index for Grouping Activities IGP = GROUP(N)	Description of Grouped Activities	Unit Costs (Dollars)(a) for Individual Activities UNITO(N)
		RESERVOIR EXPLORATION ACTIVITIES	
	1	Identification of Targets	
1		Literature Search	100./site
2	2	Preliminary Land Check	250./site
	3	Preliminary Reconnaissance	
3		Literature Search	700./site
4	4	Geological Reconnaissance	1000./site
5	5	Detailed Land Check	1200./site
	6	Detailed Reconnaissance	
6, 7, 8(b)		Lease Cost	10./acre, 10./acre/year, 2./acre
9	7	Field Geology	5000./site
	8	Geochemical Examination	6000./site
10	9	Geophysical Examination	10000., 15000./site
11,12(b)		Identification of Drillable Sites	
	10	Heat Flow Wells (4 per site)	3000./well
13	11	Temperature Gradient Wells (10 per site)	1250./well
14	12	Electrical Resistivity	3500./well
15	13	Microseismic	5000./site
16	14	Detailed Geochemistry	7500./site
17		Exploration Drilling	
	15	Well Drilling	DCINJW/well
18,19,20,21(c)	16	Well Testing	10000./site
22		FIELD DEVELOPMENT ACTIVITIES	
	17	Production Well Drilling	DCPR/well or drilling model
23,24(c)	18	Nonproduction Well Drilling	DCMPW/well or drilling model
25(c)	19	Injection Well Drilling	DCINJW/well or drilling model
26,27(c)	20	Transmission System & Downhole Pumps	Computed in Subroutine TRANS
28	21	Disposal System	Computed in Subroutine INJECT
29		FIELD OPERATION ACTIVITIES	
	22	Replacement Well Drilling	Computed - see Appendix A
30	23	Nonproduction Well Drilling	Computed - see Appendix A
31	24	Well Abandonment	10000. * No. of Production Wells/ Well Life
32		Well maintenance	1000./production or injection well
33	25	Overhead and Management	5000./production well
34	26	Well Redrilling due to Scaling	Computed - see Appendix A
35	27	Replacement or Downhole Pump	Computed - see Appendix A
36	28	Pumping Electricity Costs	Computed - see Appendix A
37	29	Transmission System Maintenance	Computed - see Appendix A
38	30	Disposal System Maintenance	Computed - see Appendix A
39	31		

(a) NAMELIST input array -- default values.

(b) Activities done at the same time that were consolidated into one aggregate activity, as follows:

Lease Cost

6) Bonus payment to leaseholder

7) Annual payment to leaseholder

8) Administrative procurement cost.

(c) Drilling activities were also consolidated into aggregate activities with input variables in NAMELIST or the drilling model determining drilling costs for each type of well:

Exploratory Well Drilling

18), 19), DCINJW with default value \$1,000,000

20), 21).

Nonproduction Well Drilling

25) DCMPW with default value \$800,000./well

Production Well Drilling

23), 24) DCPW with default value \$1,000,000./well

Injection Well Drilling

26), 27) DCINJW with default value \$1,000,000./well

TABLE 10B. Activities, Input Times, and Success Ratios for Pre-Development, Development, and Operation of Reservoir and Fluid Transmission System

Index for Itemizing Individual Tasks	Index for Grouping Tasks	Index for Time Grouping	Start Month Relative to N=1 (a)	Duration in Months (a)	Index for Decision Grouping	Success Ratio (a)	Number of Favorable Sites
N	IGP=GROUP(N)	ITEX(N)	LAGS[ITEX(N),1]	LAGS[ITEX(N),2]	NTARG(N)	FTF[NTARG(N)-1]	FAVSIT(IGP)
1	1	1	0	6	1		128
2	2	↓	↓	↓	↓		↓
3	3	2	1	7	2	0.5	64
4	4	↓	↓	↓	↓		↓
5	5	↓	↓	↓	↓		↓
6,7,8	6	3,3,3	2	11	3	0.5	32
9	7	4	4	10	4	0.67	21
10	8	↓	↓	↓	↓		↓
11,12	9	↓	↓	↓	↓		↓
13	10	5	11	24	5	0.75	16
14	11	↓	↓	↓	↓		↓
15	12	↓	↓	↓	↓		↓
16	13	↓	↓	↓	↓		↓
17	14	↓	↓	↓	↓		↓
18,19,20,21	15	6,6,6,6	23	24	6	0.25	4
22	16	7	47	1	↓	↓	↓
23,24	17	8,8	47	42	7	0.25	1
25	18	9	47	42	↓	↓	↓
26,27	19	10,10	89	27	↓	↓	↓
28	20	11	89	27	↓	↓	↓
29	21	12	89	27	↓	↓	↓
30	22	13	116	348	↓	↓	↓
31	23	14	116	348	↓	↓	↓
32	24	15	116	360	↓	↓	↓
33	25	16	116	360	↓	↓	↓
34	26	17	116	360	↓	↓	↓
35	27	18	116	360	↓	↓	↓
36	28	19	116	360	↓	↓	↓
37	29	20	116	360	↓	↓	↓
38	30	21	116	360	↓	↓	↓
39	31	22	116	360	↓	↓	↓

(a) NAMELIST input arrays -- default values.

TABLE 11. Subgrouping of Activities Occurring Parallel in Time for Reservoir and Fluid Transmission System

	Reservoir Pre-Development																					
Activity N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
ITEX(N)	1	1	2 →			3 →			4 →				5 →					6 →				7
LAGS[ITEX(N),1]	0			1			2					4					11				23	47
LAGS[ITEX(N),2]	6			7			11					10					24				24	1

Field Development							
ACTIVITY N	23	24	25	26	27	28	29
ITEX(N)	8	8	9	10	10	11	12
LAGS[ITEX(N),1]		47	47		89	89	89
LAGS[ITEX(N),2]		42	42		27	27	27

Field Operation											
Activity N	30	31	32	33	34	35	36	37	38	39	
ITEX(N)	13	14	15	16	17	18	19	20	21	22	
LAGS[ITEX(N),1]	116	116	116	116	116	116	116	116	116	116	
LAGS[ITEX(N),2]	348	348	360	360	360	360	360	360	360	360	

The startup month and duration in months (≥ 1) for each set of activities grouped together are defined by means of the input time array LAGS(ITEM(N), 1) and LAGS(ITEM(N), 2), respectively, indexed by the array ITEM. The startup month for each subgroup of activities is defined relative to the first activity, which is given the reference value 0. The startup date for the first activity, defining the beginning of reservoir pre-development (exploration), is back calculated by subroutine RESVOR from the startup date input for the operation of the distribution system using the durations in months for the pre-developmental and developmental activities. GEOCITY schedules the startup date for the operation of the distribution system in January of the year defined in NAMELIST by DINPUT(14) and DINPUT(49). The default value is January 1985. The back calculation ensures that the last activity in the pre-development and development ends in the month prior to the startup date input for the operation of the distribution system. With the default values, this date is December 1984.

Regardless of the duration in months specified for the activities in the operation of the reservoir and fluid transmission system ($N = 30$ to 39), subroutine RESVOR schedules the duration based upon the operating life of the distribution system. Table 11 lists the subgrouping of the activities presumed to occur parallel in time by the array ITEM and the default values of the array LAGS.

The time sequences of the activities corresponding to the default values of the LAGS array and default distribution system startup date of January 1985 are delineated in the horizontal bar graph of Figure 17. A discussion of the use of these arrays for calculating annual expenditures in subroutine RESVOR is given in Appendix A.

UNITO(N), $N = 1, \dots, 39$ - Cost array defining costs (January PRINDX base-year dollars) for the activities in the pre-development, development,

FIGURE 17. Default Time Sequences of Pre-Development, Development, and Operational Activities for Reservoir and Fluid Transmission System

and operation of the reservoir and fluid transmission system on a unit basis, primarily per target reservoir site, acre, or well, based upon industry estimates. The total cost associated with each activity is calculated in subroutine RESVOR by multiplying the appropriate unit cost in the UNITO array by the number of favorable target sites, acres, or wells calculated by GEOCITY for that activity. The cost equations based on the UNITO array are given in Appendix A. The default values for the UNITO array are shown for each of the activities in Table 10A.

FTF[NTARG(N) - 1], NTARG(N) = 1, ..., 7 - Success ratios (fractions), indexed by the array NTARG(N), associated with the major decision points in the step-by-step process of reducing the number of prospective reservoir sites. The process converges on one site for development and operation. An internal variable NUMFTF in subroutine RESVOR currently sets the number of major decision points in the reservoir exploration process to six. An internal array, NTARG(N), N = 1, ..., 39, groups the 39 activities in Table 10B into 7 groups of activities (one more than the number of decision points) according to the major decision points. The calculation of the initial number of target sites to identify for exploration, and the number of sites to retain at each decision point for further exploration (based upon the success ratios FTF NTARG(N) - 1), is described in Appendix A. Table 12A shows the subgrouping of the activities by the array NTARG, the corresponding decision points, and the default values of the array FTF. Table 12B describes the decision points.

3.6 OUTPUT SELECTION OPTIONS

Several output options (i.e., print switches) are available to select various levels of detail in the printout from the GEOCITY code. The most detailed printout (i.e., all print switches set to their maximum value) shows the input data, all techno-economic iterations between the reservoir and fluid transmission system and distribution system, full economic (cash flow) output

TABLE 12A. Subgrouping of Activities for Reservoir and Fluid Transmission System by Decision Points

Activity N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
NTARG(N)	1	1	2	→	3	→	4	→	5	→	→	→	5	→	→	→	→
NTARG(N)-1= Decision Point					1		2					3					4
FTF[NTARG(N)-1]					0.5		0.5					0.07					0.75

Activity N	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
NTARG(N)	6	→	→	→	7	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
NTARG(N)-1= Decision Point					5																	6
FTF[NTARG(N)-1]					0.50																	0.50

TABLE 12B. Description of Decision Points

Decision Point	Description
1	Fraction of sites to retain for preliminary reconnaissance after identification of target sites
2	Fraction of sites to lease after preliminary reconnaissance
3	Fraction of leased sites to retain for detailed reconnaissance
4	Fraction of sites to evaluate for subsequent exploratory drilling
5	Fraction of sites to retain for exploratory drilling
6	Fraction of sites to develop and operate

for the reservoir and fluid transmission system and distribution system, and a financial summary of the simulation results. This option is generally used only as a trouble-shooting guide to debug the code because of the voluminous printout.

The most condensed printout (i.e., all print switches set to their minimum value) shows the input data, the input districts for the distribution system summary, the year-by-year costs of thermal energy and heat (chill), and a financial summary of the simulation results. This option is generally used only with multiple production runs to reduce the volume of the printout. nomic (cash flow) output for the reservoir and fluid transmission system and distribution system, and the financial summary of the simulation results.

Another printout option allows the user to display printer plots calculated from several of the key capital cost equations described in Appendix B for the distribution system. These plots show in graphical form the capital costs estimated for various components of the distribution piping system, such as pipes, insulation, and casing, over a wide range of pipe diameters. The printer plots are displayed as part of the input data since the underlying capital cost equations constitute an internal data base stored in the code. The printer plots are not part of the default printout.

Finally, an option is available to print results from the drilling model when it is implemented by the parameters previously defined in Section 3.5.2. The results from the drilling model are included in the default printout if the well drilling model is used (Section 3.5.2).

The definitions of the print switches generating the various levels of detail in the printout are given below. The print switches LL6, LL11, LL12, IPLIT, IDRPNT, and IPCOMB are input through the NAMELIST group \$RESVOR. The other print switch DFLAG is input through the NAMELIST group \$DISTRB. The description of the output generated by the setting of the print switches is described below in terms of the pages of output generated by the default printout in Appendix G. The first six print switches -- LL6, LL11, LL12, IPLIT, IDRPNT, and IFLAG -- apply to all simulation modes: heating, cooling, and combined heating and cooling. The final print switch, IPCOMB, applies only to the combined heating and cooling mode.

LL6 Print switch for selecting the iteration printout between the reservoir and fluid transmission system and the distribution system demand.

- 0, suppresses printout of the iterations
- 1, prints only the last iteration upon convergence (pages G-16 to G-20)
- 2, prints all iterations

The default is 1.

LL11, LL12 Print switches for selecting the reservoir and fluid transmission system and distribution system economic (cash flow) printout.

- LL11 = 1, LL12 = 1, prints full economic (cash flow) output (pages G-78 to G-91)
- LL11 = 1, LL12 = 0, prints an economic summary of the reservoir and fluid transmission system and distribution system, including the breakdown of thermal energy costs from the reservoir and fluid transmission system and heat (chill) costs from the distribution system, but excluding the annual statements of operating costs, cash flow, tax deductible expenses, income, and payout of investments.
- LL11 = 0, LL12 = 0, suppresses all economic (cash flow) output.

The default is full economic (cash flow) output.

IPLLOT Print switch to display printer plots of capital costs estimated for various components of the distribution piping system, including pipes, insulation, and casing. Costs are plotted as a function of pipe diameter ranging from 1 to 40 inches. The underlying capital cost equations are part of the internal data base stored in the code.

- 0, suppresses display of the printer plots
- 1, displays the printer plots after the input data

The default is 0.

IDRPNT Print switch to print the results from the well drilling model, which is employed if the parameter IDRILL (Section 3.5.2) is set to 1.

0, suppresses printout from the drilling model

1, prints results from the drilling model

The default is 1.

DFLAG Print switch for selecting the distribution system printout. The parameter DFLAG is declared logical in the code. The default is .TRUE.

DFLAG = .TRUE., prints the full distribution system output (pages G-24 to G-65)

DFLAG = .FALSE., prints only the first two pages of the distribution system output (pages G-24 to G-26) entitled "Definition of Distribution Districts" and "District Populations", and the last page (page G-65) entitled "Distribution System Description".

IPCOMB Print switch to control the level of printout in the combined heating and cooling mode. Further reductions in the level of printout can be obtained by appropriate settings of the six print switches above in conjunction with the setting of the print switch IPCOMB.

1, abbreviated printout

2, intermediate printout

3, full printout, primarily for debug purposes.

The default is 2, which generated the printout for the combined heating and cooling mode in Appendix G.

4.0 DESCRIPTION OF OUTPUT

Appendix G lists the computer output generated by GEOCITY using the sample input data in Section 3.2 for simulating geothermal district heating and cooling of a small city (population 29,000) in the western United States. The 106 pages of printout show the input data, the techno-economic output from the final iteration between the reservoir and fluid transmission system and the distribution system, the annual cash flows for the reservoir and fluid transmission system, the annual cash flows for the distribution system, and the summary of the simulation results. The output results are printed in an easy-to-read format with an accompanying description. Table 13 presents an overview of the output, identifying the pages of output generated by the major submodels of GEOCITY. For the sake of brevity, a more detailed description is provided below only for output results that may require further explanation.

The input parameters for the sample GEOCITY simulation are shown on pages G.1 through G.7. Printer plots of equations in the code for estimating the capital costs of piping, insulation, and casing for the distribution system are displayed on pages G.8 through G.14. The equations are defined in Appendix B.

In simulating combined space heating, space cooling, and sanitary water heating, the peak fluid requirements of the distribution system are calculated separately for two modes: 1) space heating and sanitary water heating, and 2) space cooling and sanitary water heating. Initial requirements are calculated based on fluid conditions at the production wellheads. Subsequent calculations of the peak fluid requirements are based on fluid conditions at the inlet to the distribution system. These calculations reflect the fluid degradation during transmission to the distribution system in an iterative process that is described below. The peak fluid requirements of the distribution system, after convergence of the final iteration, are given for the two modes on pages G.15 and G.66.

The mode with the larger peak fluid requirement is designated the major mode (space cooling and sanitary water heating in the sample case). The other mode is designated the minor mode. The simulation of the reservoir and fluid transmission system and the distribution system for providing combined space

TABLE 13. Summary of Computer Output from GEOCITY

<u>Description of Computer Output</u>	<u>Pages</u>
<u>1. GEOCITY Input Parameters</u>	
● Reservoir and Fluid Transmission System Parameters	G.1
● District Heating and Cooling Distribution System Parameters	G.2 to G.5
● Financial Parameters	G.6
● Well Drilling Costs, General Economic Parameters, and Output Selection Options	G.7
● Printer Plots of Internal Capital Cost Equations for Distribution System	G.8 to G.14
<u>2. Determination of Major and Minor Modes for Designing and Sizing System for Combined Space Heating, Space Cooling, and Sanitary Water Heating</u>	
● Simulation of Major Mode to Design and Size System - (includes one-half of sanitary water heating during the year)	G.15
<u>Iteration History Between Production Wellfield, Fluid Transmission System, and Distribution System for Major Mode (only final iteration shown in sample case)</u>	
● Reservoir and Fluid Transmission System Key Input Parameters	G.16
● Production Wellfield and Fluid Conditions, Capital Costs, and Pumping Requirements of Fluid Transmission System	G.17 to G.19
● Convergence Test for Geothermal Flow Requirements of Distribution System from Production Wellfield	G.20
<u>Design and Cost of Heat Exchanger and its Pumps at Inlet to Distribution System for Major Mode</u>	G.20 to G.21
<u>Fluid Conditions, Capital Costs, and Pumping Requirements of Injection System from Heat Exchanger to Injection Wellfield for Major Mode</u>	G.21 to G.23
<u>Distribution System for Major Mode</u>	
● Definition of Districts	G.24 to G.25

TABLE 13. (continued)

Description of Computer Output	Pages	
● District Populations	G.26	
● Piping Network and Fluid Conditions for District M	Repeats for M=1 to NDTR (no. of districts)	G.27 to G.62
● Capital Costs and Material Requirements of Piping Network for District M		
● Branching Mains Network and Fluid Conditions for Each District	G.63	
● Total Capital Costs, Material Requirements, and Operating Expenses of Distribution System Summed over all Districts for Major Mode	G.64	
● Summary of Thermal Energy and Peak Fluid Requirements of Distribution System by District for Major Mode; Piping System and Retrofit Costs by District for Major Mode; Load Factor for Major Mode	G.65	
3. <u>Simulation of Minor Mode Using System Designed and Sized by Major Mode</u> (includes other half of sanitary water heating during the year)		
● Peak Fluid Requirements of Distribution System in Minor Mode (final iteration value)	G.66	
<u>Operation of Reservoir and Fluid Transmission System in Minor Mode</u>		
● Reservoir and Fluid Transmission System Key Input Parameters	G.67	
● Summary of Fluid Conditions Delivered from Production Wellfield by Transmission System in Minor Mode; Total Capital Costs and Pumping Requirements of Transmission System (totaled over major and minor modes)	G.68	
● Summary of Fluid Conditions Delivered by Injection System in Minor Mode; Total Capital Costs and Pumping Requirements of Injection System (totaled over major and minor modes)	G.69	
<u>Operation of Distribution System in Minor Mode</u>		
● Definition of Districts	G.70 to G.71	

TABLE 13. (continued)

Description of Computer Output	Pages
<ul style="list-style-type: none"> • Total Capital Costs, Material Requirements, and Operating Expenses of Distribution System Summed Over All Districts (totaled over major and minor modes) 	G.72
<ul style="list-style-type: none"> • Summary of Thermal Energy and Peak Fluid Requirements of Distribution System by District for Minor Mode; Total Piping System and Retrofit Costs by District (totaled over major and minor modes); Load Factor for Minor Mode; Combined Load Factor (summed over major and minor modes) 	G.73
<u>Technical Characteristics and Discounted Cash Flow Analysis of Reservoir and Fluid Transmission System for Combined Space Heating, Space Cooling, and Sanitary Water Heating</u>	
<ul style="list-style-type: none"> • Reservoir Characteristics and Well Properties 	G.74
<ul style="list-style-type: none"> • Well Drilling Costs Calculated by Drilling Model 	G.75 to G.76
<ul style="list-style-type: none"> • Exploration, Development, and Operation Costs for Reservoir and Fluid Transmission System 	G.77
<ul style="list-style-type: none"> • Financial and Tax Input Data 	G.78
<ul style="list-style-type: none"> • Annual Operating Costs 	G.79
<ul style="list-style-type: none"> • Annual Cash Flow Statement 	G.80
<ul style="list-style-type: none"> • Annual Tax Deductible Expense Statement 	G.81
<ul style="list-style-type: none"> • Annual Income Statement 	G.82
<ul style="list-style-type: none"> • Annual Payout of Investments (capitalization) 	G.83
<ul style="list-style-type: none"> • Annual Cost of Thermal Energy from the Reservoir and Fluid Transmission System 	G.84
<u>Discounted Cash Flow Analysis of Distribution System for Combined Space Heating, Space Cooling, and Sanitary Water Heating</u>	
<ul style="list-style-type: none"> • Financial and Tax Input Data 	G.85
<ul style="list-style-type: none"> • Annual Operating Costs 	G.86
<ul style="list-style-type: none"> • Annual Cash Flow Statement 	G.87

TABLE 13. (continued)

Description of Computer Output	Pages
● Annual Tax Deductible Expense Statement	G.88
● Annual Income Statement	G.89
● Annual Payout of Investments (capitalization)	G.90
● Annual Cost of Combined Space Heating, Space Cooling, and Sanitary Water Heating from the Distribution System to the End-User	G.91
<u>Financial Summary of Combined Space Heating, Space Cooling, and Sanitary Water Heating Simulation</u>	G.92
4. <u>Simulation of Space Heating and All Sanitary Water Heating During the Year (Without Space Cooling; Used to Calculate Incremental Cost of Space Cooling on Final Summary Page)</u>	
● Peak Fluid Requirements of Distribution System for Space Heating and Sanitary Water Heating (final iteration)	G.93
<u>Reservoir and Fluid Transmission System for Space Heating and Sanitary Water Heating (final iteration)</u>	
● Reservoir and Fluid Transmission System Key Input Parameters	G.94
● Summary of Fluid Conditions Delivered from Production Wellfield by Transmission System; Capital Costs and Pumping Requirements of Transmission System	G.95
● Summary of Fluid Conditions Delivered by Injection System; Capital Costs and Pumping Requirements for Injection System	G.96
<u>Distribution System for Space Heating and Sanitary Water Heating</u>	
● Definition of Districts	G.97 to G.98
● Capital Costs, Material Requirements, and Operating Expenses of Distribution System Summed Over All Districts	G.99

TABLE 13. (continued)

Description of Computer Output	Pages
<ul style="list-style-type: none"> Summary of Thermal Energy and Peak Fluid Requirements of Distribution System by District; Piping System and Retrofit Costs by District; Load Factor for Space Heating and Sanitary Water Heating 	G.110
<u>Technical Characteristics and Annual Cost of Thermal Energy from the Reservoir and Fluid Transmission System for Space Heating and Sanitary Water Heating</u>	
<ul style="list-style-type: none"> Reservoir Characteristics and Well Properties 	G.101
<ul style="list-style-type: none"> Exploration, Development, and Operation Costs for Reservoir and Fluid Transmission System 	G.102
<ul style="list-style-type: none"> Annual Cost of Thermal Energy from the Reservoir and Fluid Transmission System 	G.103
<u>Annual Cost of Space Heating and Sanitary Water Heating from the Distribution System to the End-User</u>	G.104
<u>Financial Summary of Space Heating and Sanitary Water Heating Simulation</u>	G.105
<u>Final Summary of Costs for 1) Combined Space Heating, Space Cooling, and Sanitary Water Heating, 2) Space Heating and Sanitary Water Heating, and 3) Incremental Cost of Space Cooling</u>	G.106

heating, space cooling, and sanitary water heating is performed in two steps based on these modes. The major mode is simulated in the first step to design and size the two systems based on the thermal energy and peak fluid requirements, thermal losses, pressure drops, and pumping requirements calculated for the major mode. The simulation of the major mode determines all capital costs of the reservoir and fluid transmission system, all capital costs of the distribution system (except for retrofit costs associated with the minor mode), the load factor for the major mode, and that portion of operating costs for the two systems associated with the major mode (based on its load factor). The output for the major mode is presented on pages G.16 to G.65.

Key input parameters to the reservoir and fluid transmission submodel (such as the wellhead temperature, well flow capacity, well spacing, fraction

excess production wells, and fraction dry wells) are listed on page G.16. The output from the final iteration between the production wellfield, the fluid transmission system, and the distribution system is summarized for the major mode on pages G.17 to G.20. The output describes the peak fluid flow rate, pipe diameters, pipe schedules, insulation thickness, thermal losses, pressure drops, pumping requirements, capital costs, and operating costs of the reservoir and fluid transmission system for the major mode.

The code initially calculates the peak geothermal flow requirement of the distribution system from the production wellfield based on the wellhead conditions. After the initial calculation, the geothermal flow requirement of the distribution system is recalculated to account for fluid degradation which occurs during transport from the production wellfield to the inlet of the distribution system. The reservoir and fluid transmission submodel supplies the increased flow requirement by adding production wells and determining the new temperature and enthalpy drops during fluid transmission. The convergence criterion requires that the flow requirement of the distribution system estimated in the current iteration differ by less than 2% from the flow requirement estimated in the previous iteration. The peak flow rate and fluid conditions entering the heat exchanger at the inlet of the distribution system are presented on page G.19 for the major mode after convergence of the final iteration.

The output describing the production wellfield and the fluid degradation during collection and transmission to the distribution system is presented for the major mode on pages G.17 to G.19. The geometry of the production wellfield for the sample case is illustrated in Figure 18. Twelve production wells are equally spaced as nodes on a triangular grid, with an effective well spacing of 30 acres, after allowance for two dry wells, resulting in a distance of 374 meters between the production well nodes. The pipe runs connecting the well nodes are routed parallel to the horizontal X-axis in Figure 18, joining with one manifold line leading to the distribution system. The distance of the manifold line from the first column of wells in the sample case was set in the input data to one meter. The distance from the outlet of the production wellfield to the inlet of the distribution system was set in the input data to 10 miles.

FIGURE 18. Production Wellfield Nodes and Exiting Temperature Degradation on a Nodal Basis During Cooling Mode

The nodal fluid degradation (temperature and enthalpy drops) during collection and transmission to the distribution system is calculated in the order shown on pages G.17 and G.18. The fluid is maintained in a compressed liquid state during collection and transmission by the use of downhole pumps in the production wells and surface pumps along the final leg from the outlet of the production wellfield to the inlet of the distribution system. Although the fluid pressure drop is calculated internally by the code on a nodal basis, it is summarized in the printout on pages G.18 and G.19 only from the furthest well in the wellfield (well number 12 in Figure 18) to the outlet of the wellfield.

Figure 18 depicts the fluid temperature degradation on a nodal basis during the cooling mode for the sample case, corresponding to the output on pages G.17 and G.18. The calculations begin with the perimeter well nodes (row $I = 5$ and column $J = 2$ in Figure 18) and proceed downstream to the distribution system.

The output from the first iteration at a node (iteration 1 on pages G.17 and G.18) shows the condition of the fluid exiting the node. The letter M is used to indicate the mixture of two inlet fluid flows at a node. Fluid exiting a well node ($J > 1$ in Figure 18) is a mixture of fluid from the wellhead and degraded fluid transmitted from upstream well nodes. Fluid exiting a manifold node ($J = 1$ in Figure 18) is a mixture of degraded fluid from the upstream manifold line and degraded fluid from the row of wells leading into the manifold node. The exit enthalpy is estimated as the mass-weighted average of the inlet enthalpies. The exit temperature is calculated using the steam library function TPHL for compressed liquid, based upon the exit enthalpy and pressure.

The output from the last iteration at a node on pages G.17 and G.18 shows the degraded condition of the fluid immediately prior to its entry into the next downstream node. Fluid degradation between neighboring nodes is a function of the internal pipe diameter. Inversely, the optimization algorithm used to calculate the internal pipe diameter is a function of the mass flow rate and fluid conditions. The initial estimate of the internal pipe diameter is calculated assuming no fluid degradation between neighboring nodes. The fluid degradation is then calculated as a function of the internal pipe diameter. Using the degraded fluid conditions, the internal pipe diameter is recalculated. The

iteration continues until the degraded fluid temperature at the entry into the downstream node changes by less than 0.10°F from the temperature calculated in the previous iteration. The internal diameters of the pipes are shown on a nodal basis on pages G.17 and G.18.

The basic design characteristics, capital costs, and operating costs of the heat exchanger specified at the inlet to the distribution system are presented for the major mode on page G.20. The pressure drops calculated for the tube- and shell-sides of the heat exchanger are shown on pages G.20 and G.21. The electrical consumption and capital costs of tube- and shell-side pumps are shown on page G.21.

The fluid injection system from the outlet of the heat exchanger to the injection wellfield is summarized for the major mode on pages G.21 to G.23. The output describes the peak fluid injection rate, pipe diameters, pipe schedules, pumping requirements (based on one large conceptual pump at the outlet of the heat exchanger), capital costs, and operating costs of the fluid injection system for the major mode.

The geometric layout of the injection wellfield is analogous to that of the production wellfield (Figure 13). Only five injection wells are required in the sample case (versus 12 production wells), since the maximum flow capacity of each injection well is input as twice the maximum flow capacity of each production well (and 2 of the 12 production wells are spare wells). Observe that no insulation is used in the design of the injection piping system in order to reduce the costs of the fluid injection system. Thermal losses and pressure drops are currently not calculated for each individual pipe section, as was previously done for the production wellfield and fluid transmission system.

The input characteristics to the distribution system submodel defining the residential districts in the sample case served by the district heating and cooling system are given on page G.24 in English units and on pages G.24 and G.25 in metric units. The district populations are shown on page G.26; however, the information on population per se is not directly used in the distribution system submodel.

The design, fluid conditions, capital costs, and material requirements of the distribution piping network in each district are summarized for the major mode on pages G.27 to G.62. The length of pipe, number of fittings, valves, and expansion loops, and the capital costs of pipes, fittings, valves, insulation, casings, expansion loops, and trenches are summarized for up to 23 nominal outer pipe diameters that can be used throughout the piping network. These costs are summed over all pipe sizes and combined with the cost of meters and pumps to give the total capital costs for each district piping system for the major mode.

The layout of the piping network and the fluid conditions for each district are output in a condensed format. Since the piping network is designed symmetrically by subroutine GRAPH about the main and lateral, the output for one building, one half-street (above or below the lateral), one half-lateral (to the left or right of the main), and the main is sufficient to summarize the layout of the entire piping network and the fluid conditions for the district.

The layout of the piping network for district 7, which has 54 multiple-family apartments (corresponding to 54 meters on page G.40), on page G.39 is depicted in Figure 19. The layout was constructed from the output on page G.39 together with the number of buildings (54) to illustrate the interpretation of the condensed output for the district piping networks. The output on page G.39 summarizes the layout of the piping network and fluid conditions for the following sections of pipe:

- street-to-building pipe for each building
- pipe sections down each half-street connecting building pairs 1 through 3
- pipe sections across the half-lateral connecting full streets 1 through 3
- main pipe connecting the midpoint of district 8 with the midpoint of the full lateral in district 7 of Figure 12.

Note that two short half-streets are used in Figure 19, one on each end of the lateral, to obtain 54 buildings, while preserving the symmetry of the piping network about the main and lateral. The four full streets account for 48 buildings (4x12), leaving a remainder of six buildings, which is not enough to fill out a full street.

FIGURE 19. Layout for District 7 with 54 Buildings in Sample Case

In interpreting the condensed output for the piping network, another observation is worthy of comment. The zero thermal loss and zero pressure drop for building pair four on page G.37 indicate that the lateral in district 6 is directly below the 4th building pair. If the thermal loss and pressure drop are nonzero for the last building pair on a half-street, as in district 7, the location of the lateral is half way between building pairs of the two half-streets, as illustrated in Figure 19. The location of the lateral is determined by subroutine GRAPH to preserve the symmetry of the piping network about the lateral and main.

GEOCITY uses input data on peak thermal energy requirements of a typical building in district 7 for the major mode (space cooling and sanitary water heating in the sample case) to determine the peak hot water flow requirement of each building in district 7. Working down the piping network, the peak hot water flow requirements are computed for each section of pipe based on the number of buildings served. The peak flow requirements are used as the basis for selecting the diameter of each section of pipe. Material requirements, thermal losses, and pressure drops are determined for each section of the piping network. Construction costs, material costs, operating costs, and costs for pumps, meters, and control equipment are derived based on the distribution system design and size determined for the major mode. These results are summarized for district 7 on pages G.39 and G.40.

The output summarizing the design and fluid conditions for the branching mains and the districts served by each main (Figure 12) is presented for the major mode on page G.63. The capital costs and material requirements of the piping networks for all districts are summarized for the major mode for up to 23 nominal outer pipe diameters on page G.64. The capital costs summed over all pipe sizes, the cost of meters and pumps, and the operating expenses of the distribution system are given for the major mode on page G.64. The thermal energy and peak hot water requirements and the capital costs of the piping network for each district, together with the system load factor, are summarized for the major mode on page G.65.

This completes the description of the output for the reservoir and fluid transmission system and the distribution system for the major mode (simulated

in the first step). The minor mode is simulated in the second step. It uses the system design and sizes determined by the major mode to calculate the thermal losses, pressure drops, incremental capital costs, incremental pumping requirements, load factor, and incremental operating costs for the minor mode (based on its load factor). In these calculations, the thermal energy and peak fluid requirements of the minor mode are used.

The output for the minor mode is presented on pages G.67 to G.73. The default printout (IPCOMB = 2) reduces the volume of output for the minor mode, but still minimizes the impact on its clarity and interpretation. The walk-through of the condensed output is similar to that of the major mode. The output summarizes the capital and operating costs of the reservoir and fluid transmission system and the distribution system after they are totaled over both modes, the load factor for the minor mode, and the combined system load factor (summed over major and minor modes). The peak flow rates and fluid conditions are summarized for the transmission system, injection system, and distribution system. However, the detailed printout of peak flow rates and fluid degradation in the production wellfield, fluid transmission system, heat exchanger, injection wellfield, and individual districts of the distribution system is not presented for the minor mode, unless the full printout (IPCOMB = 3) is requested.

Following the output for the reservoir and fluid transmission system and the distribution system, page G.74 lists the reservoir characteristics and well properties. The well properties include the following information:

- 1) Number of production wells
- 2) Number of dry wells
- 3) Number of injection wells
- 4) Peak thermal energy capacity per well relative to 100°F sink
- 5) Actual flow rate per production well in major mode

Descriptions of the calculations of these quantities are given below: fractional results for the first three quantities are rounded up to the next largest integer.

- 1) Number of production wells =

$$\left\{ \left[\text{total flow rate (lb/hr) of distribution system in major mode} \right] / \text{maximum flow rate (lb/hr) per well} \right\} * (1. + \text{fraction excess production wells})$$
 where:
 The maximum flow rate per well is input as the parameter FLORAT. The fraction excess production wells is input as the parameter FRCEPW.
- 2) Number of nonproduction wells =

$$(\text{number of production wells}) * (\text{fraction of nonproduction wells})$$
 where:
 The fraction of nonproduction wells is input as the parameter FRCNPW.
- 3) Number of injection wells =

$$\left[\text{flow rate (lb/hr) from distribution system or its optional heat exchanger in major mode} \right] / \left[\text{maximum injection well flow rate (lb/hr)} \right]$$
 where:
 The maximum injection well flow rate =

$$\left[\text{ratio of injection well to production well flow rate, input as PRDRAT} \right] * \text{maximum production well flow rate, input as FLORAT}.$$
- 4) Peak thermal energy capacity (MWth) per well relative to 100°F sink =

$$\left[\text{maximum flow rate (lb/hr) per well} \right] * \left[\text{enthalpy at the wellhead} - \text{enthalpy at 100°F sink} \right] / (3.41443 * 10^6)$$
- 5) Actual flow rate (lb/hr) per production well in major mode =

$$\left[\text{total flow rate (lb/hr) of distribution system in major mode} \right] / \left[\text{number of production wells} \right].$$

The well drilling costs calculated by the optional drilling model are presented for production, nonproduction, and injection wells in January base-year dollars on pages G.75 and G.76. The capitalized, expensed, and total costs incurred in the exploration, development, and operation of the reservoir and fluid transmission system are given in January base-year dollars on page G.77. The times over which these expenditures are uniformly distributed are also shown on page G.77.

The total thermal energy requirements, capital costs, operating costs, and system load factor calculated for space heating, space cooling, and sanitary

water heating are input at this point to the discounted cash flow submodels of the reservoir and fluid transmission system and the distribution system. The output from these two submodels is on pages G.78 to G.84 and G.85 to G.91, respectively.

Page G.78 lists the financial and tax input data for the discounted cash flow submodel of the reservoir and fluid transmission system. Page G.79 shows the annual operating costs for the reservoir and fluid transmission system. Annual cash flow data for major expenses are shown on page G.80. Summary accounts of tax-deductible expenses are shown on page G.81. A simplified income statement is shown on page G.82, and the net cash flow and investment position for the reservoir and fluid transmission system are shown on page G.83.

The cost of thermal energy from the reservoir and fluid transmission system is shown on page G.84. Annual costs are presented in current dollars for each operating year of the reservoir and fluid transmission system. The life-cycle levelized cost is given in January base-year dollars. The thirty-year levelized cost in January 1980 dollars for the sample case is \$5.44/million Btu of thermal energy delivered to the distribution system.

Page G.85 lists the financial and tax input data for the discounted cash flow submodel of the distribution system. Pages G.86 to G.90 present the same cash flow and accounting information for the distribution system as pages G.79 to G.83 present for the reservoir and fluid transmission system. Observe that the energy sales (page G.82) by the operator of the reservoir and fluid transmission system are energy costs (page G.87) to the operator of the distribution system.

The cost of combined space heating, space cooling, and sanitary water heating from the distribution system to the end-user is shown on page G.91. Annual costs are presented in current dollars for each operating year of the distribution system. The life-cycle levelized cost is given in January base-year dollars. The thirty-year levelized cost in January 1980 dollars for the sample case is \$21.76/million Btu of heat delivered to the end-user for space heating, space cooling (using absorption chillers at each household), and sanitary water heating.

Before proceeding to the financial summary, several technical statistics of interest from the simulation of combined space heating, space cooling, and sanitary water heating for the sample case are summarized below:

Peak heat demand:	3.65×10^8 Btu/hr (occurs during space heating and sanitary water heating, page G.73)
Annual heat demand:	9.6369×10^{11} Btu/yr (combined total for space heating, space cooling, and sanitary water heating, page G.89)
Peak geothermal flow rate:	3.68×10^6 lb/hr (occurs during space cooling and sanitary water heating, page G.15)
Combined load factor:	0.27 (page G.73)
Number of production wells:	12 (page G.74)
Peak flow rate per well:	306,716 lb/hr (occurs during space cooling and sanitary water heating, page G.74)
Number of dry wells:	2 (page G.74)
Number of injection wells:	5 (page G.74)
Injection temperature from heat exchanger:	183°F during space cooling and sanitary water heating (page G.23); 110°F during space heating and sanitary water heating (page G.69)

The financial summary of the simulation results is presented on page G.92. The small western city in the sample case served by the geothermal district heating and cooling installation consists of 29,000 people, residing in 11,066 households and 9013 buildings. The thirty-year levelized cost in January 1980 dollars for combined space heating, space cooling, and sanitary water heating is \$1,895 per household per year.

The geothermal district heating and cooling system for this small city is capital-intensive. This is underscored by the fact that the levelized cost of the total capital investment accounts for 75.9% of the total cost of district heating and cooling to the end-user. The initial capital investment in January

1980 dollars for the geothermal installation is 119 million dollars. The distribution system and end-use (retrofit) equipment account for 43.6% and 41.9% of the initial capital investment, respectively. However, the levelized costs of O&M and electricity for pumping account for only 22.3% and 1.9% of the total cost of district heating and cooling to the end-user. As previously noted in Section 3.2, no supplemental thermal energy is purchased by the distribution system in this sample case for heating below the winter outdoor design temperature (-15°F) or cooling above the summer outdoor design temperature (95°F).

The simulation of combined space heating, space cooling, and sanitary water heating is followed by a second simulation for space heating plus all of the sanitary water heating required during the year (i.e., excluding space cooling). The results from the second simulation are used in calculating the incremental cost of space cooling, presented in the final summary on page G.106. The output for the simulation of space heating and all of the sanitary water heating during the year is shown on pages G.93 to G.105. The default printout (IPCOMB = 2) reduces the volume of output for this simulation below that of the full printout (IPCOMB = 3). The walk-through of the condensed output is similar to that conducted for the first simulation.

The financial summary of the results from the second simulation is presented on page G.105. The thirty-year levelized cost in January 1980 dollars for space heating and all of the sanitary water heating during the year is \$11.14/million Btu of heat delivered to the end-user. The equivalent annual levelized cost in January 1980 dollars is \$907 per household per year.

The incremental cost of space cooling is presented in the final summary on page G.106. In terms of the annual levelized cost per household, the incremental cost of space cooling is computed as the difference between the annual cost of combined space heating, space cooling, and sanitary water heating (first simulation) and the annual cost of space heating and sanitary water heating (second simulation). The incremental cost of space cooling in January 1980 dollars for the sample case is \$988 per household per year.

In terms of the levelized cost per MBtu of heat delivered to the absorption chiller, the incremental cost of space cooling in January 1980 dollars can be computed as follows:

Incremental cost of space cooling (\$/MBtu of heat delivered to absorption chiller) =

Incremental annual cost of space cooling per household per year
(\$/household-yr) * Number of households/Annual heat demand by all
absorption chillers (MBtu/yr)

For the sample case, this yields:

\$988/household-yr * 11,066 households/62,620 MBtu/yr =
\$175/MBtu of heat delivered to the absorption chiller.

The annual heat demand by all absorption chillers (62,620 MBtu/yr) is obtained by computing the difference between the annual heat demand in the first simulation (963,690 MBtu/yr on page G.89) and the annual heat demand in the second simulation (901,070 MBtu/yr on page G.100).

The high incremental cost of space cooling, when expressed in \$/MBtu of heat delivered to the absorption chiller, results from the low annual cooling demand by the small western city in the sample case, the high initial capital cost of the chillers, and the high interim capital replacement cost of the chillers. The incremental cost of space cooling, in \$/MBtu of chill delivered to the household (last line on page G.106), is obtained by dividing the incremental cost of space cooling in \$/MBtu of heat delivered to the absorption chiller by the coefficient of performance (0.72) for the absorption chiller.

The city and climate used in the sample case were selected solely to illustrate the input and output of the GEOCITY model. Thus, the results should not be interpreted as representing average district heating and cooling costs, which are by nature site-specific. Nevertheless, several strategies could significantly lower district heating and cooling costs to the end-users in the sample case. The system load factor for combined space heating, space cooling, and sanitary water heating in the sample case is only 27%. Since district heating and cooling systems are capital-intensive, a higher system load factor (i.e., higher system capacity utilization throughout the year) would reduce the unit cost of heating and cooling to the end-user. The increased year-round use of the system, once it has been designed, would then effectively spread the total capital cost over a larger quantity of energy sales, resulting in a lower unit cost per Btu of energy.

Higher annual residential heating and cooling loads than those required by the small city in this sample case would increase the system load factor. However, this is site-specific and depends to a large extent on the climate. Combining residential space heating, space cooling, and sanitary water heating with contra-seasonal industrial process heating or cooling is another means for increasing the system load factor.

Population density is another important factor affecting district heating and cooling costs. The distribution system piping network accounts for 75.9% of the initial capital investment of 119 million dollars. Increasing population density reduces district heating and cooling costs by reducing the average length of distribution piping runs. With very high population densities, as in large multi-story apartment buildings, significant economies-of-scale are also realized by the use of larger diameter pipe. Thus, future growth in high-density developments would make district heating and cooling a more attractive option for the small city in the sample case. Of course, the ultimate density is realized by a single point demand, such as an industrial factory, that is a large user of thermal energy for process heating or cooling throughout the year.

Currently, the cost of using absorption chillers at each individual residence is relatively expensive. The retrofit cost is 41.9% of the initial capital investment for the sample case, most of which is due to the absorption chillers. This suggests that either further research and development be undertaken to reduce their costs, or that the use of central chillers in the city be investigated for economies-of-scale. The latter approach would require a three-pipe system to provide combined space heating, space cooling, and sanitary water heating: 1) one pipe to supply hot water for space heating and sanitary water heating, 2) another pipe to supply chilled water for space cooling, and 3) a third pipe for returning the used water from the residences.

The cost of the distribution system accounts for 43.6% of the initial capital investment, much of which is due to the cost of the large number of small supply and return pipes between the streets and buildings. We are currently investigating whether the use of other piping material between the streets and buildings (e.g., pre-fabricated and pre-insulated copper tubes used between streets and buildings in European district heating systems) offers significant

cost savings over the combined cost of carbon steel pipes, calcium silicate insulation, and steel casing used in the sample case.

These are only a few possibilities for reducing district heating and cooling costs in the sample case. Other important factors affecting district heating and cooling costs include the geothermal resource temperature, well drilling costs, average well life, installed cost of downhole pumps, service life of downhole pumps, downhole and surface pumping costs, distance between the geothermal resource and end-users, and financing costs for the developers of the reservoir and fluid transmission system and the distribution system.

5.0 ACKNOWLEDGMENTS

The authors gratefully acknowledge the work of C. L. McDonald, S. C. Schulte, Bobi Garrett-Price, and D. R. Brown for their contributions toward the development and application of GEOCITY.

6.0 REFERENCES

1. L. J. P. Muffler, Assessment of Geothermal Resources of the United States - 1978. U.S. Geological Survey Circular 790, February 1979.
2. C. H. Bloomster, L. L. Fassbender, and C. L. McDonald, Geothermal Energy Potential for District and Process Heating Applications in the U.S. - An Economic Analysis, BNWL-2311, Pacific Northwest Laboratory, Richland, WA, August 1977.
3. R. B. McClintock and G. T. Silvestri, Formulation and Iterative Procedures for the Calculation of Properties of Steam, The American Society of Mechanical Engineers, New York, NY, 1968.
4. C. A. Meyer, R. B. McClintock, G. T. Silvestri, and R. C. Spencer, Jr., 1969 ASME Steam Table--Thermodynamic and Transport Properties of Steam Comprising Tables and Charts for Steam and Water, The American Society of Mechanical Engineers, United Engineering Center, New York, NY.
5. CRC Handbook of Tables for Applied Engineering Science, R. E. Boltz and G. L. Tuve, Editors, The Chemical Rubber Co., Cleveland, OH, 1970.
6. CRC Handbook of Chemistry and Physics, 50th Edition, R. C. Weast, Editor, The Chemical Rubber Co., Cleveland, OH, 1969.
7. ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating, and Air Conditioning Engineers, New York, NY, 1977.
8. ASHRAE Handbook of Systems, American Society of Heating, Refrigerating, and Air conditioning Engineers, New York, NY, 1980.
9. Ibid.
10. Op Cit. ASHRAE Handbook of Fundamentals.
11. Chemical Engineer's Handbook, R. H. Perry and C. H. Chilton, Editors, McGraw-Hill Book Co., New York, NY, 1973.

Do Not
Microfilm

PNL-4422 Vol I
UC-66i

DISTRIBUTION

No. of
Copies

No. of
Copies

OFFSITE

OFFSITE

A. A. Churm
DOE Patent Office
9800 S. Cass Avenue
Argonne, IL 60439

John Lund
Geo-Heat Utilization Center
Oregon Institute of Technology
Klamath Falls, OR 97601

3 Eric Peterson
Department of Energy
Office of Solar Technologies
Washington, D.C. 20545

Bill Johnson
WESTEC Services, Inc.
3211 Fifth Avenue
San Diego, CA 92103

10 Jim Bresee
Department of Energy
Office of Renewable Technologies
Washington, D.C. 20545

Gordon Bloomquist
Washington State Energy Office
400 East Union
Olympia, WA 98504

27 DOE Technical Information Center

ONSITE

Dave Anderson
Geothermal Resources Council
PO Box 1350
Davis, CA 95616

DOE Richland Operations Office

H. E. Ransom

Vasel Roberts
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304

44 Pacific Northwest Laboratory

Craig McDonald
Synergic Resources Corp.
Suite 820
4th & Pike Building
Seattle, WA 98101

C. H. Bloomster (8)
D. R. Brown
D. E. Deonigi
L. L. Fassbender (8)
H. D. Huber (13)
B. A. Garrett-Price
L. D. Williams
J. K. Young
Economics Library (3)
Technical Information Files (5)
Publishing Coordination (2)

Gordon Reistad
Department of Mechanical Engineering
Oregon State University
Corvallis, OR 97331