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GROUND-WATER HEAT PUMPS: AN EXAMINATION OF HYDROGEOLOGIC, ENVIRONMENTAL, LEGAL, AND ECONOMIC FACTORS AFFECTING THEIR USE

Main Text and Appendices A, B, C

By
Dana M. Armitage
Douglas J. Bacon
John T. Massey-Norton
James M. Miller

November 12, 1980

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National Water Well Association
Worthington, Ohio

U. S. DEPARTMENT OF ENERGY

Division of Buildings and Community Systems

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Dana M. Armitage, Douglas J. Bacon,
John T. Massey-Norton, James M. Miller

National Water Well Association
500 West Wilson Bridge Road
Worthington, Ohio 43085

Prepared for the

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Assistant Secretary for
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Office of Building and Community Systems
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EXECUTIVE SUMMARY

Ground water is attractive as a potential low-temperature energy source in residential and commercial space-conditioning applications. When used in conjunction with a heat pump, ground water can serve as both a heat source (for heating) and a heat sink (for cooling). The temperature of the ground water varies little, if at all, on a seasonal basis, regardless of the temperature extremes on the surface. Thus, it is warmer than the outside air in winter and cooler in summer. Since heat pump capacity and efficiency vary significantly with the heat source/sink temperature (or temperature difference between the source/sink and the conditioned space), a ground water-source heat pump system should, in principle, offer considerable advantages over the more widely used air-source heat pump system.

However, the use of ground water (well water) is not without potential technical problems or economic and institutional constraints. First, is the well cost and the availability of an adequate supply of suitable quality well water. Second, the removal of significant quantities of well water without suitable recharge may deplete the underground aquifer. Also, plans to reinject or return the water underground may be precluded by legal restrictions. And if permitted, it could entail additional costs for the disposal well. Special provisions to prevent thermal alteration of the underground source may be required. This study was designed to answer these and other questions related to:

- ground-water quality and availability
- potential environmental effects
- legal restrictions
- energy use and economics of ground-water heat pump use

SCOPE OF STUDY

In more detailed terms, the study project included three main elements, or tasks, as follows:

Task 1. Collection of Hydrogeologic and Climatologic Data - This task involved assessing the availability and characteristics of ground water supplies throughout the United States for use with ground water-source heat pumps. This assessment was made on a state-by-state basis and included evaluation maps for each state. Water quality was considered, as it affects the performance and life-expectancy of the water-to-refrigerant heat exchanger and, in extreme cases, the technical viability of the ground-water heat pump option. Depth-to-water and ground-water temperature were considered, as they affect the operational efficiency of the heat pump system. Data regarding ground water availability were considered, as a minimum water flow rate is necessary for proper operation of a ground-water heat pump. Weather data for each of nine test cities were acquired for use in the Task 2 analysis (for heating and cooling load calculations and source temperatures for the conventional air-to-air heat pump).

Task 2. Economic and Energy Analysis of Ground-Water Source Heat Pumps - Using information and data collected in Task 1, together with manufacturers' performance data on water-source heat pump performance, a comparative analysis of the energy consumption and owning and operating cost of ground-water heat pumps was undertaken. The analysis was based on an hour-by-hour computer simulation of the performance of the ground-water heat pump and more conventional heating/cooling systems in a typical single-family residence in nine cities representative of the various geographic and climatic regions. The conventional systems were electric resistance heating with electric air conditioning, fossil-fueled (oil and gas) furnaces in combination with electric air conditioning, and the air-to-air heat pump. The results of this analysis include seasonal performance factors, equipment costs, operating costs, simple payback, and total life cycle costs.

Task 3. Environmental and Legal Consequences of Using Ground Water as an Energy Source - This task involved evaluating the environmental problems that can potentially result from expanded use of ground-water source heat pumps and conducting a survey of Federal, state, and local regulations that might affect the potential use of ground-water heat pumps. In examining the potential environmental impact, consideration was given to thermal alteration of ground-water temperatures, ground-water chemistry aspects, alternative methods of disposal, methods of of recharge (if used), and varied hydrologic conditions which limit discharge options to be considered. The environmental parameters that influence the feasibility of ground-water heat pump use were also examined for each of the nine test cities (in Task 2) to illustrate technical problems and favorable potential on a case study basis. To evaluate the potential legal problems involving ground-water use and water quality control, a state-by-state review was conducted of water use restrictions, well construction standards, and waste disposal regulation. Major Federal programs on waste water disposal were analyzed. Examples of pertinent local county and municipal regulations were also examined for their potential impact on ground-water heat pump use.

A major contribution of this study is the economic evaluation which compares the initial purchase/installation and operating costs of ground-water heat pumps to conventional space-conditioning systems. However, it must be recognized that the energy use and economics are evaluated only for residential size units and only for an individual end-user. This is a significant limitation. Economics would probably be more favorable for applications other than single-family residences requiring their own supply wells, pump/piping systems, and discharge provisions. Applications in the commercial building sector or possibly "community wells" serving several residences are potentially more cost-effective than the single-family residence application.

On the other hand, the information and data developed to characterize ground water as an energy resource and to define the legal and environmental problems associated with its use seem to be more broadly applicable to all ground-water heat pump systems, regardless of size or configuration.

The applicability of ground-water heat pumps is determined by hydrogeologic, economic, legal, and environmental factors. The results of this study will, therefore, be useful in identifying those areas in each state where ground-water heat pumps may be capable of supplying a portion of residential space-conditioning. Examination of these data, supplemented by appropriate site specific analysis, should enable planners, developers, and/or utility companies to assess the feasibility of using or promoting ground-water heat pumps in a specific area. In addition, manufacturers and distributors of ground-water heat pumps may use this information to plan market strategies in select areas. However, detailed site-specific analyses of all relevant factors should be conducted prior to any large-scale implementation. The hydrogeologic data shown on the state maps in Appendix D are locally variable. The maps are meant to indicate major trends only. These maps should not be used for design criteria or for determining the suitability of a particular site.

CONCLUSIONS

The major conclusions reached during the course of this study involved both the subjective results from the Task 1 and Task 3 data collection and assessment activities and the more quantitative results from the Task 2 energy use and economic analyses. These conclusions are given in summary form below, and the results are presented and discussed in more detail in subsequent sections of this Executive Summary report.

1. Results of computer simulations indicate that in nine test cities, reflecting a variety of climatological conditions, the ground-water heat pump uses less energy and operates at higher efficiencies than conventional heating/cooling equipment.

    - Simulations indicate that the ground-water heat pump uses from 20 to 60 percent less energy for heating than the air-source heat pump.

    - If the energy required for both heating and cooling is taken into account, the ground-water heat pump uses from 10 to 60 percent less energy than the air-source heat pump.

2. The economics of owning and operating a ground-water heat pump depends on consideration of the alternate heating/cooling system choices and on well cost options included in the ground-water heat pump system. The following can be concluded:

    - Based on U.S. Department of Energy projections of energy costs, a gas heating/electric cooling system is the most economically attractive of current system choices in most parts of the United States.

- The ground-water heat pump system, with no well costs included, has an economic advantage over all other systems evaluated (including conventional air-source heat pump systems, electric heating/electric cooling systems, and oil heating/electric cooling systems) in eight of the nine test cities (Houston, Texas is the exception).

- With the cost of an injection well included, payback of incremental first costs for installation of a ground-water heat pump system is usually achieved within a 20-year life cycle period. The shortest payback periods are indicated for northern climate installations. Using the air-source heat pump or the electric heating/electric cooling system as the alternate choice, payback periods range from 4 to more than 20 years and from 1.5 to 17 years, respectively. Using the oil heating/electric cooling system as the alternate, payback period ranges from 1 to more than 20 years.

- With the cost of both a supply and injection well included, the ground-water heat pump generally does not achieve payback within a 20-year life cycle period when compared to alternative systems.

It is recognized that in some areas, shallow, small-diameter wells can be used for both supply and injection wells at substantially lower costs than those used in this study. These circumstances are considered atypical and were not evaluated.

3. Water use and discharge methods are important in the consideration of ground-water heat pump installations. Improper design may lead to a decrease in system performance or environmental problems or both.

   - Ground-water depletion and local lowering of water tables should be avoided. Thus, in most areas recharge to the subsurface (usually via injection wells) is recommended.

4. Corrosion and incrustation of the water-side heat exchanger are potential problems under certain water quality conditions. Corrosion appears to be a greater potential problem than incrustation.

5. County and municipal controls on well construction and water use are often stricter than state or Federal regulations. These rules represent the most significant restrictions on ground-water heat pump development in some areas.

In general, recharge using an injection well is the preferred method of water discharge. However, due to regulations at the state and/or local level(s) of government and to geologic influences, alternative methods (e.g., leach fields, dry wells, discharge to surface water bodies) could be investigated.

The review of existing legislation affecting ground-water heat pump development presented in this report can represent only a "snapshot in time" of relevant Federal and state laws. It is recognized that these laws are in a state of flux and will undoubtedly change in the future to accommodate further market development. Federal regulations pertaining to ground-water quality will not pose a serious impediment to ground-water heat pump use. Permit requirements for water use and waste water disposal will be the primary method of ground-water heat pump control at the state level. Most state permit requirements will not severely restrict heat pump use, although large-scale heat pump development may be subject to stringent rules in some areas.

It can be concluded from this study that ground-water heat pumps are an economically feasible and environmentally sound alternative to conventional heating/cooling systems. Monitored installations where meaningful data can be accumulated are needed to substantiate this. Energy requirements under recorded climatologic conditions and a quantification of environmental impact would be helpful to further investigate the market potential of these devices.

GROUND-WATER RESOURCES IN THE U.S.

Water temperatures in shallow wells not affected by geothermal activities in the conterminous United States range from approximately 44°F in the north-central regions to near 80°F in southern Texas and Florida (Figure 1). This range is within the minimum and maximum entering water temperature requirements of currently marketed ground-water heat pumps. There are vast reservoirs of underground water in the U.S., and they contain large quantities of useful heat energy. Figure 2 shows the types and locations of these aquifers. Every aquifer will yield water; in general, aquifers composed of unconsolidated or semiconsolidated clastic materials (i.e., sands and gravels) are more productive and reliable sources of ground water than are aquifers composed of consolidated materials such as limestones, shales, and sandstones. Dense rocks such as granites, schists, and slates contain water in interconnected fractures and generally do not yield large supplies of water to individual wells.

State-by-state maps of major aquifers and of ground-water chemistry characteristics, including a description and evaluation of select hydrogeologic parameters, can be found in Appendix D.

WATER-SOURCE HEAT PUMP EQUIPMENT

Most water-to-air heat pumps currently available commercially appear to have been developed for use in commercial building applications. The technology is similar to that of air-to-air systems, except that the outdoor fan-coil unit is replaced by a coiled, coaxial water-to-refrigerant heat exchanger. Such systems are typically designed to operate with a water source/sink temperature in the range of 60°F to 90°F. That is, where heating is needed, 60°F to 90°F water is used as the heat source; if cooling is required, the same water loop serves as the heat sink. With the

Figure 1

Ground Water Temperatures
in Wells Ranging from 50' to 150' in Depth

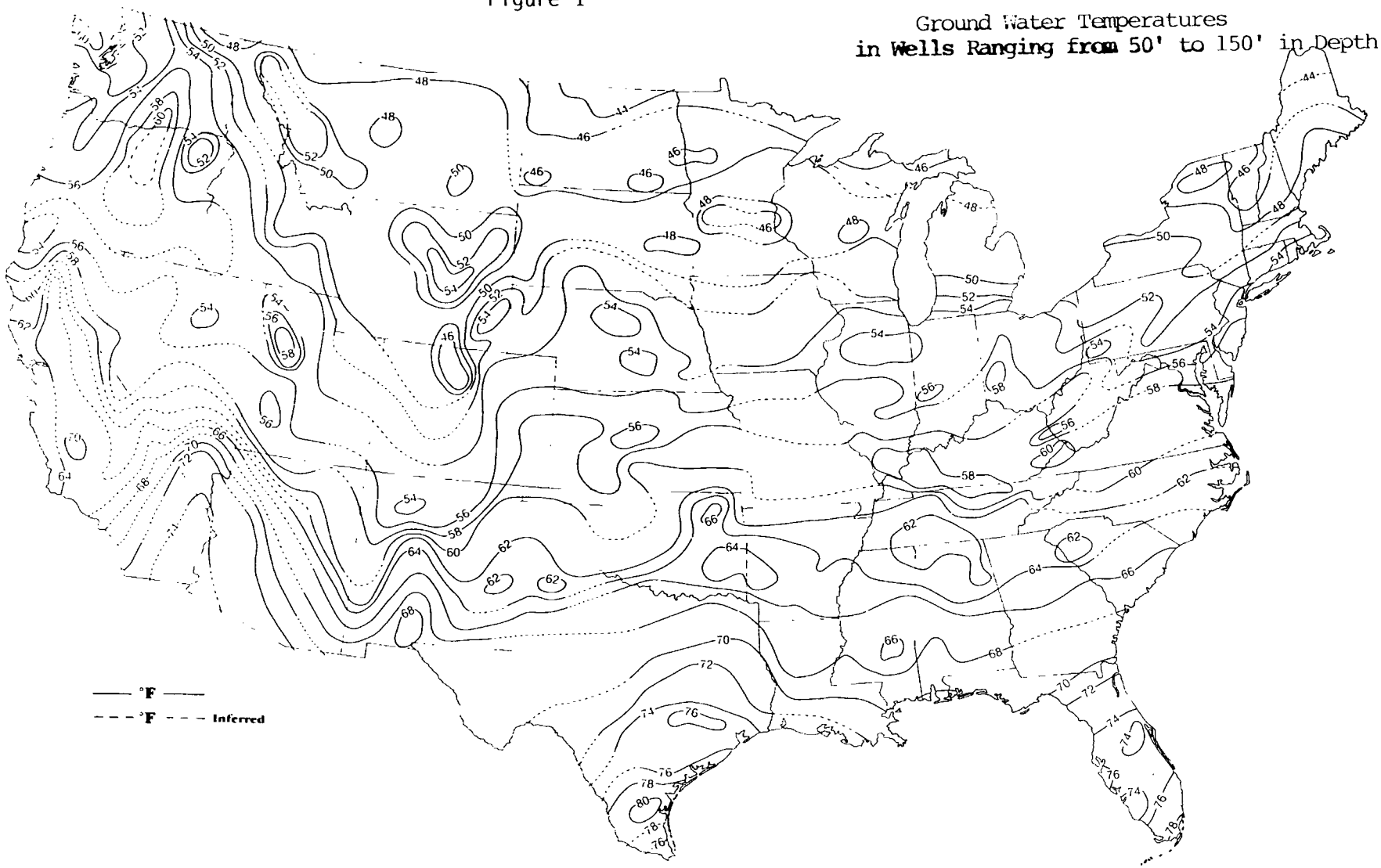
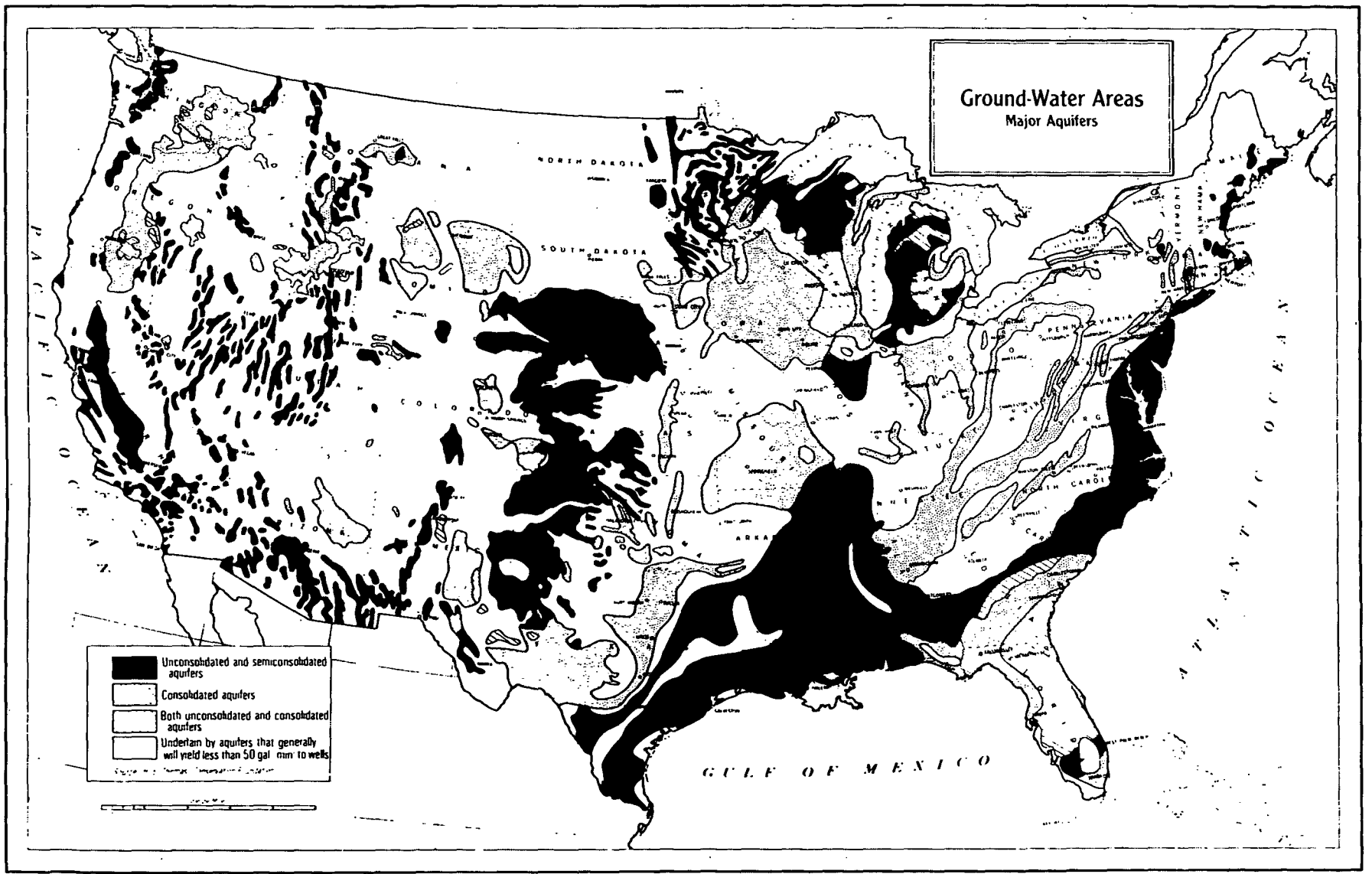


Figure 2



Base Map by USGS

WATER INFORMATION CENTER INC

addition of a boiler and cooling tower to the water loop, the net heating or cooling requirements can be met while the individual water-to-air heat pumps provide zoned heating or cooling, whichever is required.

Most such heat pumps apparently have been designed for low equipment cost. Rated heating COPs with a 60°F water source are generally no better than those of high-efficiency air-source systems at 47°F. These systems may not be suitable for use with cooler ground-water sources, which may be as low as 45°F. However, with proper controls and component matching, water-source heat pumps can be used with 45°F sources. In addition, a number of such smaller specialty manufacturers and at least one major manufacturer have announced new water-source heat pump models featuring substantially improved efficiency at ground water temperatures (45°F-60°F). Also, optional cupro-nickel alloy heat exchangers are available for service where ground-water chemistry conditions warrant.

Ground-water heat pumps offer the potential advantages of almost constant capacity and higher seasonal COPs, compared to air-to-air units employing similar technology. Reliability of the refrigerant system should be superior because of the narrower range of operating conditions and the elimination of frosting. However, the water system may require some maintenance above that required for air-to-air units.

Figure 3 is a schematic diagram of a ground-water heat pump operating during a heating cycle. The refrigerant reversing valve directs a gaseous refrigerant from the compressor to a heat exchanger coil. Heat is removed by air passing over the coil, and the gaseous refrigerant is cooled and condensed to a liquid. The liquid refrigerant then travels through the expansion device to a second heat exchanger where heat is extracted from the ground water. The liquid refrigerant absorbs the heat and evaporates, and the cycle begins again.

During the cooling cycle (Figure 4), the position of the refrigerant reversing valve is reversed. Hot air blowing over the air-to-refrigerant heat exchanger coil gives up heat to the liquid refrigerant, causing it to evaporate. Cool air then passes out the ventilation duct of the system. The gaseous refrigerant is directed by the refrigerant reversing valve into the compressor and is then pumped to the water-to-refrigerant heat exchanger. The refrigerant gives up heat to the water and condenses. After the water is warmed it is subsequently discharged. In the last step, the liquid refrigerant passes through the expansion device and returns to the air-to-refrigerant heat exchanger coil to extract more heat from the air and continue the cooling cycle.

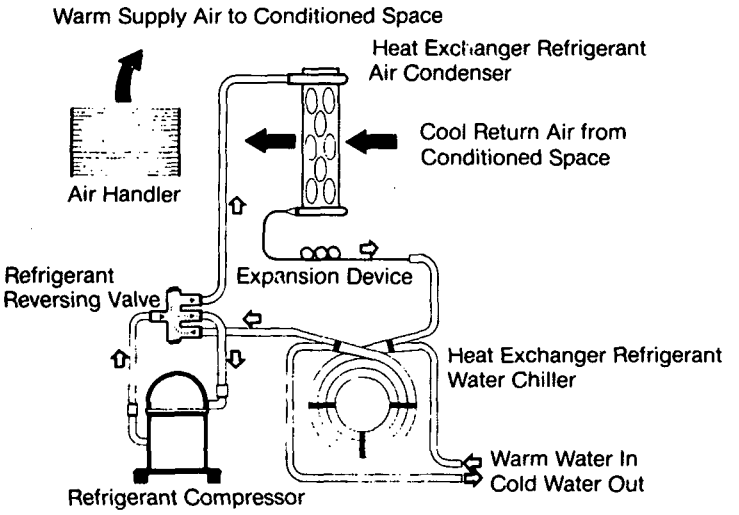


Fig. 3 Heating mode operation

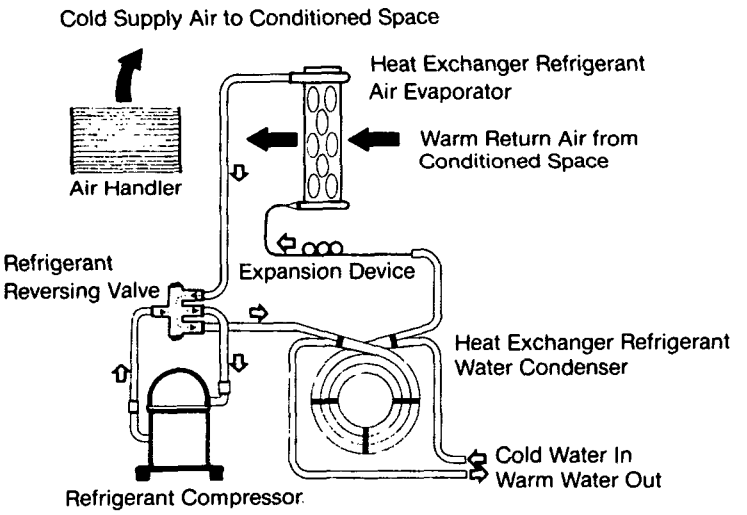


Fig. 4 Cooling mode operation

ENERGY USE COMPARISONS

A measure of efficiency of the heat pump is the seasonal performance factor (SPF). For heating mode operation, the number is defined by:

$$(SPF)_H = \frac{\text{Quantity of heat energy delivered}}{\text{Quantity of energy supplied to operate device}}$$

For cooling mode operation, the SPF is defined by:

$$(SPF)_C = \frac{\text{Quantity of heat energy removed}}{\text{Quantity of energy supplied to operate device}}$$

The SPF of the heat pump varies according to the heating/cooling load, heat pump capacity/sizing, heat source/sink temperature, flow rate, and the design and operational characteristics of the particular heat pump equipment used.

Computer-simulated SPF values for residential air-source and ground-water heat pumps in nine different test cities, representing various climatological conditions in the U.S., are shown in Table 1. Included are the SPF values for a heat-only ground-water heat pump sized to design heating load. Cooling, in that case, is accomplished by direct heat exchange with ground water.

The annual coefficient of performance (ACOP) can be used to compare the performance of various heating/cooling equipment combinations. This measure of operational efficiency is defined as:

$$ACOP = \frac{\text{Annual heating and cooling requirement}}{\text{Total annual energy used for heating and cooling}}$$

Figure 5 graphically shows the relationship of the ACOP to the ratio of annual heating load to total load (Q_H/Q_T). An electric air conditioner is included in the electric/electric system, while both heat pumps provide cooling as described previously. It is evident that as the value of Q_H/Q_T increases, the performance of the air-source heat pump and the electric/electric system decreases while the performance of the ground-water heat pump remains relatively stable.

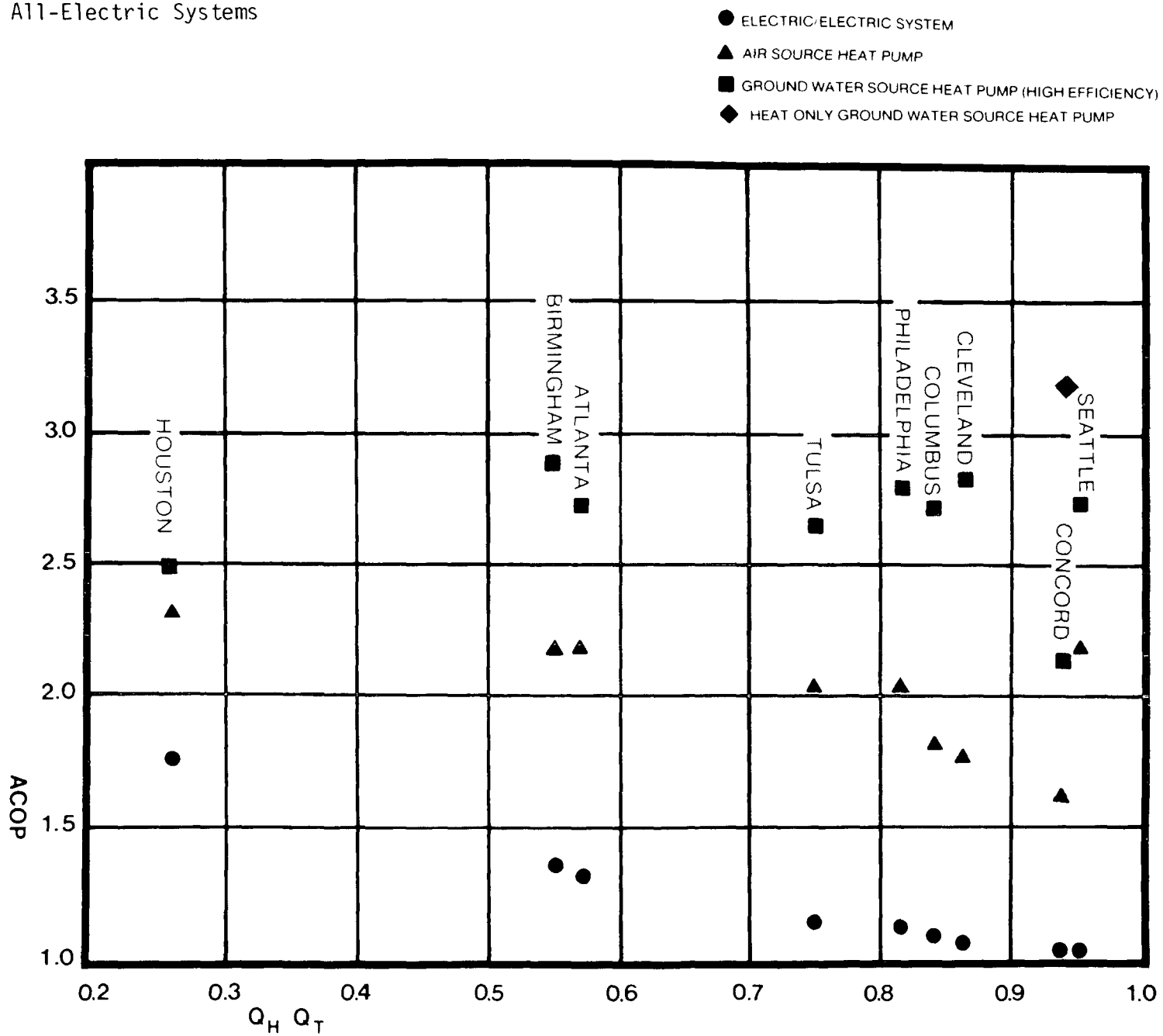
The lowest efficiency rating (ACOP = 2.2) was obtained in the Concord, New Hampshire test city where the annual heating load constitutes 94 percent of the total load. In the Concord test city, 10 percent of the total annual energy consumed by the ground-water heat pump was used for supplemental electric strip heat while the air-source heat pump required 40 percent for the same purpose. The simulation of a heat-only ground-water heat pump and direct heat-exchange cooling (with ground water) resulted in a 30 percent reduction in energy requirements compared to the reversible-cycle model. This is a result of sizing to full heating design load rather than cooling load. Using this strategy, the use of supplemental electric strip heat is substantially reduced or eliminated.

TABLE 1

HEAT PUMP SEASONAL PERFORMANCE FACTORS

CITY	HEATING		COOLING	
	AIR-SOURCE	WATER-SOURCE	AIR-SOURCE	WATER-SOURCE
Atlanta	2.10	2.67	2.30	2.83
Birmingham	2.04	2.84	2.28	2.99
Cleveland	1.74	2.81	2.31	2.90
Columbus	1.75	2.48	2.29	2.80
Concord	1.58	2.14	2.30	2.33
Heat-Only w/ Direct Cooling		3.05		10.87
Houston	2.24	2.74	2.31	2.43
Philadelphia	1.96	2.77	2.29	2.91
Seattle	2.17	2.72	2.29	3.06
Tulsa	1.94	2.70	2.26	2.48

Fig. 5
ACOP vs QH/QT for
All-Electric Systems



Otherwise, the highest efficiency rating (ACOP = 2.9), utilizing heat pump operation for both heating and cooling and conventional cooling load sizing methods, was obtained under conditions in which the annual heating load was approximately one-half the total annual load (Birmingham, Alabama). Under these conditions, the ground-water heat pump required 50 percent less energy than an electric heating/electric cooling system and 25 percent less than an air-source heat pump. The lowest efficiency rating vis-a-vis the air-source heat pump was obtained under conditions in which the annual heating load was approximately one-fourth the total load (Houston, Texas). Under these conditions, the ground-water heat pump used only 8 percent less than the air-source heat pump. The ACOP value for the ground-water heat pump in Houston is 2.5.

ECONOMICS OF GROUND-WATER HEAT PUMPS

The initial cost of a ground-water heat pump and its annual operating cost must be evaluated for an accurate economic picture. Table 2 compares ranges of installed costs for the ground-water heat pump and other conventional heating/cooling systems. Computer simulations indicate that the ground-water heat pump is not economically attractive when compared to a gas/electric system at the Department of Energy's current projected natural gas prices. (Deregulation and resulting increases in the price of natural gas could change this conclusion.) That cost model (gas/electric system) is therefore not included in this summary discussion of life-cycle cost comparisons and payback.

With the cost of an injection well included in the ground-water heat pump cost, the system is generally more expensive to install, but the benefits of lower annual operating costs make it economically competitive. The ground-water heat pump system, including both supply and injection well costs, is generally not economically viable.

Table 3 shows present worth of total life-cycle costs for two ground-water heat pump cost models (no well or injection well costs included) and conventional heating/cooling systems. These costs include installed, operation and maintenance, and fuel costs for a projected 20-year life cycle period. Using a 2 percent real discount rate, simulated total life-cycle costs for the ground-water heat pump ranged from $8,900 (Seattle) to $20,500 (Concord). This cost included the initial expense of an injection well in the ground-water heat pump system. This model was taken to be typical (or at least desirable) in most installations. (It is recognized that, in some areas, shallow, small-diameter wells can be used for both supply and injection wells at a substantially lower cost than those presented here. These circumstances are considered atypical and were not included in this work.) As a comparison, the air-source heat pump showed a total life cycle cost of $7,600 in Seattle and $24,100 in Concord. Costs for the electric heating/electric cooling system for the same cities were $11,800 and $35,300, respectively. The heat-only heat pump with direct cooling in the Concord test city showed a total cost of $17,400, substantially less than any other system.

TABLE 2

Installed Costs of Heating/Cooling Equipment

	*Ground-Water Heat Pump	*Air-Source Heat Pump	Oil/Electric System	Electric/Electric System
HEATING	$1300-2100	$2300-3200	$ 1300	$ 600- 700
COOLING			$1600-1900	$1600-1900
DUCTWORK	$ 800-1000	$ 800-1000	$ 800-1000	$ 800-1000
FLUE			$ 400	
PLUMBING/WIRING	$ 400- 500	$ 100	$ 200	$ 100
TOTAL	$2500-3600	$3200-4300	$4300-4800	$3100-3700
With Injection Well	$3900-6100			
With Supply and Injection Wells	$6000-9300			

*Since the heat pump provides both heating and cooling, the costs are not separated as they are for the other systems.

Table 3

Present Worth of Total Life Cycle Costs (1979 Dollars x 10^{-3})

City	Electric/ Electric	Air-Source Heat Pump	Oil/ Electric	GWHP* (0 Wells)	GWHP* (1 Well)
Atlanta	$13.7	$9.9	$13.6	$7.8	$9.5
Birmingham	13.3	9.8	13.3	7.8	9.5
Cleveland	25.1	16.9	19.2	12.0	13.7
**Columbus d = 2%	23.0	15.6	17.8	11.6	13.3
**Columbus d = 10%	13.3	9.6	11.1	7.5	9.1
Concord	35.3	24.1	21.1		
Reversible-cycle				18.6	20.5
Heat-only w/Direct Cooling				15.5	17.4
Houston	13.5	11.3	13.4	10.2	13.1
Philadelphia	21.3	13.9	17.4	10.9	12.8
Seattle	11.8	7.6	15.9	6.8	8.9
Tulsa	19.5	13.9	15.7	10.7	13.1

* Ground-water heat pump

** The Columbus, Ohio test city was used to test the sensitivity of Life Cycle Costs to changes in the real discount rate (d).

Table 3 also shows the effect on present worth values when a 10 percent real discount rate is applied in the cost model, using the Columbus test city as an example.

Payback periods of incremental costs resulting from the installation of the ground-water heat pump system (including no wells, injection well only, and supply and injection wells) rather than conventional systems are shown in Tables 4 and 5.

Table 4 shows payback periods using the electric heating/electric cooling system or the air-source heat pump as the alternative choice. With no well costs included in the ground-water heat pump system, the installed cost of that system is usually less than that of the alternatives. Thus, there is no payback period. Inclusion of the injection well cost in the ground-water heat pump model results in payback periods ranging from 1.5 to 17 years for the electric heating/electric cooling system comparison and from 4 years to more than 20 years (the life cycle period used in the study) for the air-source heat pump comparison. With both supply and injection well costs included in the cost model, payback period ranges from 4 years to more than 20 years and is more than 10 years for most of the test cities using the electric heating/electric cooling system as the alternative. Payback is rarely achieved within the life-cycle study period using this cost model and the air-source heat pump for the comparison.

Table 5 shows payback periods using the oil heating/electric cooling as the alternative choice. For all but one test city, the oil heating/electric cooling system costs more to install than the ground-water heat pump if no well costs are included. For that circumstance, a payback period is not defined. If the injection well cost is included in the ground-water heat pump system cost, payback period ranges from less than 1 year to more than 20 years relative to the oil heating/electric cooling system. Payback of incremental costs with both wells included in the cost model is achieved in less than 15 years in only three test cities.

ENVIRONMENTAL AND WATER QUALITY ASPECTS

Temperature changes in the vicinity of the recharge well will usually result from injection of the heat pump discharge water. If the discharge water from the heat pump is recharged to the supply aquifer, proper well spacing must be maintained to avoid thermal interference of supply and recharge waters. This "short circuiting" is not a significant detrimental environmental impact, but could lower the operating efficiency of the ground-water heat pump. If the discharge water is recharged to an aquifer other than the supply aquifer and the two aquifers are separated by a thickness of low-permeability material, thermal interference should be minimal or non-existent. Supply and recharge aquifers must be chemically compatible to assure that mixing of the two water types does not result in precipitation of salts or hydroxides from solution, which might lead to eventual "plugging" of the aquifer surrounding the recharge well.

Table 4

Simple Payback Period (years)

Ground-Water Heat Pump System

vs.

All-Electric Systems

CITY	WITH NO WELLS		WITH INJECTION WELL		WITH SUPPLY & INJECTION WELLS	
	Elec. Htg./ Elec. Clg.	Air-Source Heat Pump	Elec. Htg./ Elec. Clg.	Air-Source Heat Pump	Elec. Htg./ Elec. Clg.	Air-Source Heat Pump
Atlanta	*	*	3.1	11.9	11.0	>20
Birmingham	*	*	4.4	14.3	12.7	>20
Cleveland	*	*	2.0	5.2	5.2	15.7
Columbus	<0.1	*	2.6	7.3	6.2	20.0
Concord						
Reversible-cycle	*	*	1.5	4.4	3.7	12.5
Heat-Only w/Direct Cooling	0.7	1.2	2.1	4.3	3.8	8.6
Houston	*	*	17.2	>20	>20	>20
Philadelphia	*	*	2.7	10.2	6.9	>20
Seattle	*	*	7.4	>20	>20	>20
Tulsa	*	*	4.4	11.3	11.0	>20

* Payback period is undefined (Ground-Water Heat Pump system costs less to install and operate)

† Payback period is undefined (Ground-Water Heat Pump system costs more to install and/or operate)

Table 5

Simple Payback Period (years)

Ground-Water Heat Pump System

vs.

Oil Heating/Electric Cooling System

CITY	WITH NO WELLS	WITH INJECTION WELL	WITH SUPPLY & INJECTION WELLS
Atlanta	*	*	13.1
Birmingham	*	*	16.3
Cleveland	*	*	14.4
Columbus	*	1.1	>20
Concord			
Reversible-cycle	†	†	†
Heat-Only w/Direct Cooling	*	19.9	>20
Houston	*	>20	>20
Philadelphia	*	0.3	>20
Seattle	*	0.6	9.5
Tulsa	*	4.7	>20

* Payback period is undefined (Ground-Water Heat Pump system costs less to install and operate)

† Payback period is undefined (Ground-Water Heat Pump system costs more to install and/or operate)

Corrosion of the water-side heat exchanger is inhibited by the formation of an oxide or hydroxide film. Any ground-water constituent that prevents the formation of this film or removes it will cause degradation of the metal. Hydrogen sulfide (H_2S) is the most common corrosive agent with the water-side heat exchangers. Although the cupro-nickel alloy (No. 706) heat exchanger is more resistant than the copper variety to mechanical erosion and corrosion by brackish waters, neither metal shows acceptable resistance to dissolved hydrogen sulfide. Concentrations as little as 0.5 parts per million are known to cause corrosion of the metals. Chemical incrustation has not been a significant problem in existing installations. Analytical techniques are available to predict the tendency of a water sample to corrode or scale. Biological incrustation (fouling), if encountered, is likely to be a problem throughout the entire domestic water supply system. If bacterial infestation and subsequent blockage of the heat exchanger is a chronic problem, water treatment before passage through the heat exchanger would be required. Due to the large volumes of water used, this would substantially increase system operating costs.

Environmental impacts associated with the usage of ground-water heat pumps are minimal or non-existent when the properties of the hydrologic system are evaluated and taken into consideration. However, in areas where well yields are low, consumptive use of ground water due to overpumping can lead to water depletion in the aquifer. In environmentally sensitive ground-water regions, careful planning is required in order to minimize environmental impacts.

Whenever possible, the consumptive use of ground water for heat pump applications should be avoided. The problems associated with widespread, high density use of this method are usually too numerous to warrant its use.

A possible alternative to consumptive use is the implementation of earth-coupled well systems. These closed-loop units do not withdraw water from the well avoiding problems of aquifer depletion.

Some problems are associated with the non-consumptive use of ground-water supplies. The most serious of these is the thermal alteration of the aquifer system. However, the environmental effects of thermal alteration are minimal. The greatest effect will be in the performance of the heat pump system. Management of the heat balance within an aquifer is essential in urban areas where heat transfers between several users may have to be coordinated. Spacing of private domestic wells is likely to depend on property boundaries rather than the hydrologic characteristics of the aquifer under development. Random installation of ground-water heat pumps could lead to thermal interference through improper well spacing. Efficiency of the heat pump system would be considerably reduced where a sufficient amount of interference exists.

Through careful planning and analysis of the aquifer prior to housing construction, it is possible to avoid the problem of well interference. Production and injection wells can be spaced for optimum dissipation of

thermal energy within the aquifer. Well spacing should be based on the heating and cooling loads for the proposed number of residential units to be built at a given location, as well as the hydrologic properties of the aquifer to ensure the efficient utilization of ground water for the operation of ground-water heat pumps. A computer model is currently being developed at the University of Missouri for NWWA under U.S. EPA Grant #R806 465-01-1. This model will be validated with experimental data obtained from a test installation and will be used to predict thermal alteration under varied hydrogeologic conditions. The information can then be used to plan optimum spacing of production and injection wells. The projected completion date for this work is July 1981.

In a single aquifer system, both the production and injection wells utilize the same aquifer. This may limit the number of heat pumps in a given area. A greater volume of the aquifer is needed for thermal reconditioning of the injected water as it is transmitted from the injection well to the production well.

A dual aquifer system enhances the feasibility of operating a greater number of heat pumps in a smaller area. This type of system can operate effectively only where there exist two or more aquifers of sufficient capacity and chemical compatibility. In addition, care must be taken so that the quality of the water in the supply aquifer is at least as good as that in the recharge aquifer.

REGULATORY RESTRICTIONS

Federal, state, and local regulations impose restrictions and mandate various requirements for well construction, ground-water use and quality, and effluent disposal, but they will not significantly obstruct the implementation of ground-water heat pump technology.

The Safe Drinking Water Act was enacted to insure that public water systems are adequately supervised by the states. This act requires the EPA to adopt regulations for state underground injection programs. Heat pumps which use a reinjection system or discharge water in a manner which could affect drinking water supplies may be subject to regulations as a Class V well discharge system. States are required to participate in inventory and impact assessment of all Class V wells. This may include heat pump reinjection wells, depending upon the state's interpretation of the Act.

At the state level, well construction requirements may be numerous or nonexistent. Concern here is more a matter of cost than of limitation; the expense involved in meeting such requirements can rule out the feasibility of heat pump utilization. Where water-use restraints exist, usually in the form of permit requirements, they are not serious deterrents to heat pump use. The disposal of effluent to a recharge well is uncontrolled in some states and prohibited in others. Where this disposal method is forbidden, heat pump viability may suffer. Alternative disposal methods are available, however, and are generally subject to less regulation than are recharge wells. Since other disposal methods, such as discharge to land,

Table 6

Summary of Ground Water Heat Pump Water Use and Effluent Disposal Regulations by State*

State	Water Use	To Recharge Well	To Surface Water	To Land	To Septic Tank	To Sewer
Alabama	No permit needed to use water for H-P under domestic category	Notification and perhaps a permit needed from Water Improvement Commission	Theoretically covered by NPDES-however this system is usually not equipped to consider small domestic use so in most cases could just discharge w/o a permit	Not a problem if discharge to land owned by H-P user	A loophole in regulations--this type of discharge is allowed if tank is big enough and far enough from well	Would probably be allowed almost anywhere--although in many areas would be cost-prohibitive
Alaska	No problem to obtain water rights	No mechanism to require a permit or to prevent this type of injection well	1	2	3	4
Arizona	Falls into domestic category--permit needed	Discharge is prohibited to any well that penetrates water-bearing strata	1	2	3	4
Arkansas	No permit needed for water use of this type	Apparently no program exists to control recharge wells of this type	1	2	3	4
California	32 counties out of 53 total require permits for all wells--no real problems	Waste disposal under control of Water Quality Control Board, which does not regulate H-P return wells at this time	1	2	3	4
Colorado	Permit needed for all wells	Permit required for recharge	1	2	3	4
Connecticut	No permit needed--falls into private domestic well category	Permit is required from Department of Environmental Protection for all types of discharge				
Delaware	Well construction permit required	Strict rules exist regarding reinjection --however, would probably be able to get a permit for a H-P return well	1	2	3	4
Florida	A permit would be required for this volume of water use--but not a serious problem in most parts of state	A permit would be required for a disposal well of this type--not a serious problem to obtain	1	2	3	4
Georgia	No permit needed for use under 100,000 gpd (378,500 l/day)	Reinjection of cooling water is only type allowed in state. No permit is required for this	1	2	3	4
Hawaii	Classified as a domestic well --no problem to obtain water use	A regulation exists that requires permission for disposal wells and wastewater disposal --however, not enforced at present	1	2	3	4

1, 2, 3, and 4 regulations pertaining to this type of discharge are similar to those in Alabama

*Small scale domestic heat pump utilization only

Idaho	No permit needed for a domestic use except in critical ground-water area--need a permit for any use over 13,000 gpd (49,205 l/day)	Theoretically required to obtain permit for any type of disposal or injection well but permit mechanism does not exist at present	No problem except in critical ground-water areas where recharge back to the aquifers would be required			
Illinois	Domestic use classification--no permit needed	Under control of the state EPA which at present has no mechanism to regulate wells of this type	1	2	3	4
Indiana	Domestic use--no permit needed	Conventional and cooling water recharge wells not regulated--though Stream Control Board has theoretical authority	Board of Health permit, no special problem to obtain	2	3	4
Iowa	No permit needed for domestic use	No permit needed for discharge of this type	1	2	3	4
Kansas	A water appropriation permit would be needed	A permit would be required but not a problem--mostly for record-keeping purposes	1	2	3	4
Kentucky	Private use--no permit required	No permit required	1	2	3	4
Louisiana	No permit required	Might eventually need a permit from Department of environmental Control but no official policy at present	1	2	3	4
Maine	No permit needed for this type of water use	At the present time no underground injection of any type is allowed in this state	1	2	3	4
Maryland	A permit is needed for use of this type	A permit is required for discharge into surface or underground waters of the state		2	3	4
Massachusetts	No permit needed for this type of water use	Permit would be needed from Division of Water Pollution Control to discharge heated or cooled water		2	3	4
Michigan	No permit needed for this type of water use	Discharge permit required from Water Resources Commission for all units with heat exchange capacity greater than 120,000 BTU per hour (35,172 W). Permit also required for any unit using chemical additives.				
Minnesota	No permit required	Reinjection of this type is generally prohibited but could apply for a variance permit.	1	2	3	4
Mississippi	No permit required	No permit needed	1	2	3	4
Missouri	No permit needed	No permit required for small-scale domestic use	1	2	3	4
Montana	Certificate of water right is needed--no serious problem to obtain	Permit would theoretically be needed--but no mechanism is set up to issue them at this time	1	2	3	4

Nebraska	No permit needed	No regulations exist to cover a permit process	1	2	3	4
Nevada	Permit would be required	Regulations exist and a permit would be required for this type of injection	1	2	3	4
New Hampshire	No permit needed	Permit theoretically required but at this time notification would suffice	1	2	3	4
New Jersey	No permit needed	No permit required	1	2	3	4
New Mexico	Permit needed for use of this magnitude	Notification and a simple permit required	1	2	3	4
New York	No permit needed	No permit needed to cover this type of discharge	1	2	3	4
North Carolina	No permit required	Permit needed--at present time this disposal method is discouraged	1	2	3	4
North Dakota	Standard appropriation permit needed	No policy exists to cover this type of discharge	1	2	3	4
Ohio	No permit needed for domestic use	A permit is needed for all types of well injection	1	2	3	4
Oklahoma	No permit needed for domestic use	Discharge into water-bearing strata prohibited under law--but Water Resources Board won't enforce it if no necessary	1	2	3	4
Oregon	Less than 15,000 gpd (56,775 l/day)--no permit required	Return water must be reinjected into the same formation	1	2	3	4
Pennsylvania	No permit needed	A simple permit might be required (just notification) but no specific regulations	1	2	3	4
Rhode Island	No permit needed	Recharge wells not required to obtain permit	Rhode Island Pollution Discharge Elimination System may require a simple permit	2	3	4
South Carolina	No permit needed	No regulations exist at this time	1	2	3	4
South Dakota	No permit needed	No program to regulate this type of well exists at this time	1	2	3	4
Tennessee	No permit needed for water use under 50,000 gpd (189,250 l/day)	Permit would be required from Department of Health--no special problem to obtain		2	3	4

Texas	No permit needed for water use	Permit granting procedures do not exist for recharge wells--no permit needed	1	2	3	4
Utah	Permit needed for use of any type	No permit program exists for this type of reinjection --no permit needed	1	2	3	4
Vermont	No permit needed	Permit theoretically needed	1	2	3	4
Virginia	No permit needed	Non-injection of waste water is a policy in the state at present--would be a complicated permitting procedure for H-P return well	1	2	3	4
Washington	Permit needed for use over 5,000 gpd (18,925 l/day)	Necessary to obtain a discharge permit from the Department of Ecology		2	3	4
West Virginia	No permit needed	No real policy exists requiring permits at this time	1	2	3	4
Wisconsin	No permit needed	No reinjecting allowed in state	1	2	3	4
Wyoming	No permit needed	The method of disposal would have to be indicated on the use permit but otherwise no special requirement for any type of discharge				

surface water, septic tank, or sewer, are usually possible, state limitations on recharge wells should not hinder heat pump utilization. Table 6 shows existing water use and effluent regulations pertaining to ground-water heat pump use for each state.

Some local controls on well construction, ground-water use and quality, and waste disposal may adversely affect heat pump utilization. Most local regulations, however, will not seriously impede widespread development of this alternative energy source.

Most regulations and restrictions enacted at the Federal, state, and local levels will not present serious obstacles. Knowledge of their existence and their legal implications is vital to the implementation of ground-water heat pump technology.

CHAPTER 1
HYDROLOGIC ASPECTS WHICH INFLUENCE THE OPERATION OF GROUND-WATER HEAT PUMPS

I. INTRODUCTION

Certain general design criteria related to the hydrologic system have a profound influence on the operation of ground-water heat pumps. Depending on the mode of operation and the manufacturer, a ground-water heat pump has a flow rate requirement of 1.5 - 3.0 gpm/ton (0.03 to 0.06 l/s/kw) (A ton is defined as 12,000 BTU/hr or 3.5 kw). The minimum entering water temperature for residential units manufactured at the time of this writing range from 40 to 55°F (4.4 to 12.8°C) for heating mode operation. Maximum entering water temperature for cooling mode operation is flexible, but in general, performance decreases with increasing water temperature. The presence of certain chemical elements in the water may result in corrosion or incrustation of the water-side heat exchanger. For these reasons, aquifer characteristics such as permeability, ground-water temperature, and chemical quality of the water, among others, require consideration.

In its natural state, ground water is in chemical equilibrium with the subsurface environment. Chemical reactions that occur are responding to changes in temperature, pressure, and mineral composition of the aquifer. These changes are generally gradual in space and time, thus allowing ground water to maintain equilibrium conditions with the surrounding rock body.

In theory, the relatively rapid alteration of physical or chemical ground-water qualities by man-made devices has the potential to upset this natural equilibrium. This could change the ground water's capacity to dissolve or retain in solution certain chemical elements or compounds. (A detailed analysis of the parameters that affect corrosion and incrustation of a ground-water heat pump heat exchanger is presented in Section 1.III and Appendix A.

The intent of this section is to describe the nature and origin of the major constituents of ground-water chemistry, as well as describing the basic hydrologic principles governing the availability of ground water. The reader is referred to Johnson Division, UOP, 1966; Bouwer, 1978; Lohman, 1972, Freeze and Cherry, 1979; and Hem, 1970, for a

more definitive treatment of the concepts and principles discussed herein.

II. GENERAL CHEMICAL AND PHYSICAL PARAMETERS

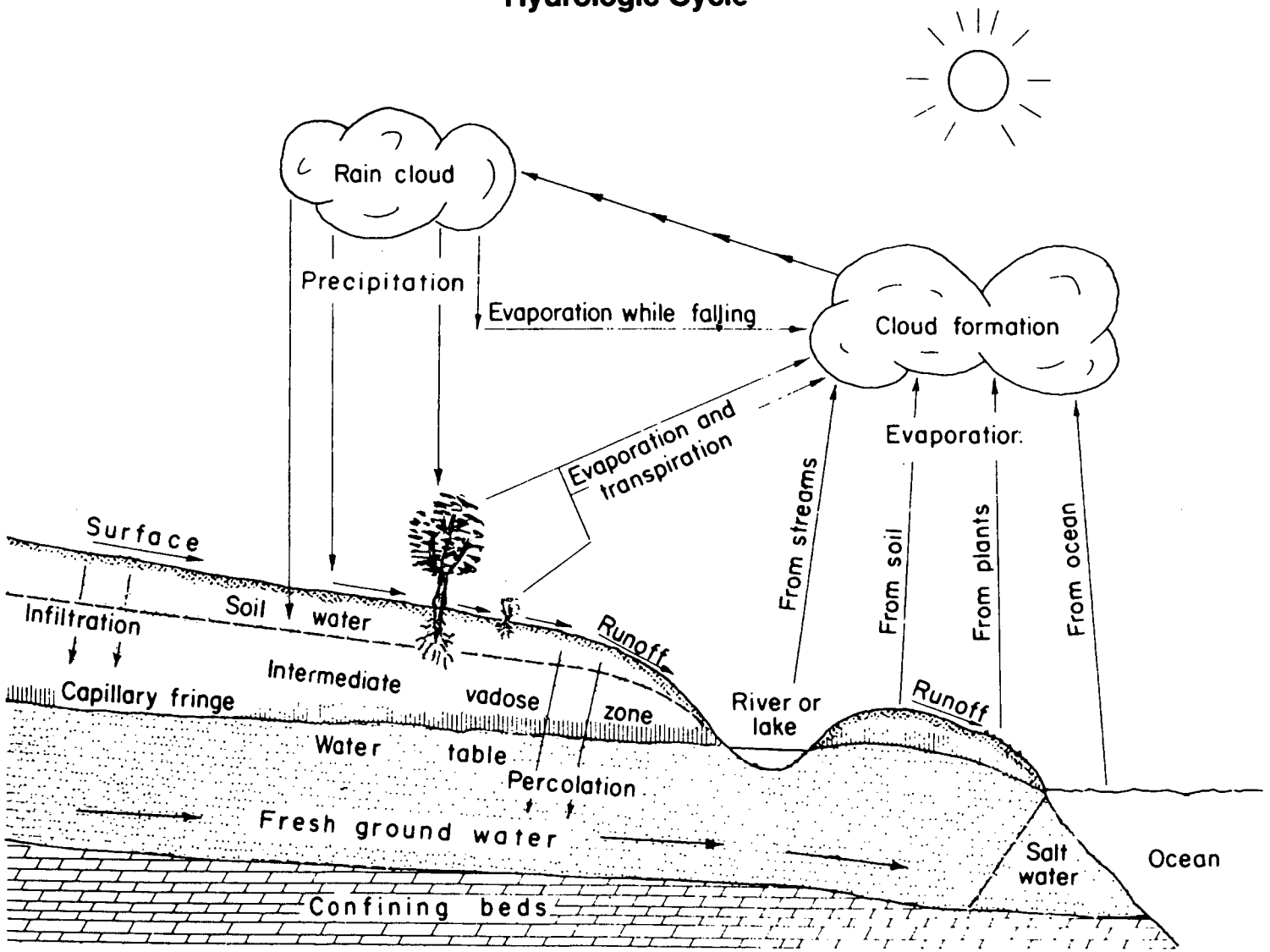
The hydrologic cycle controls the quantity and quality of ground water available for heat pump utilization at a given time in a particular area. The hydrologic cycle is defined as, "...the constant circulation of water from the sea, through the atmosphere, to the land, and its eventual return to the atmosphere by way of evaporation from the sea and (other water and) land surfaces" (American Geological Institute, 1980). The sun is the driving force behind this cycle; it controls global weather patterns and provides the energy needed to evaporate water from the land and water surfaces. Figure 1.1 illustrates the methods by which the water moves through the cycle.

The chemical constituents normally found in ground water display considerable regional variations in concentration. The major concern of dilute solution chemistry as it affects the performance of heat pumps is the chemical disequilibrium that favors incrustation or corrosion of the heat exchanger. In addition, precipitation of mineral salts or the dissolution of the aquifer matrix (under extreme conditions) also influences the ability of the aquifer to transmit and yield water. The chemical equilibrium of ground-water systems is extremely complex due to the number of interacting variables. As such, it is difficult and sometimes impossible to predict the behavior of the chemical equilibrium of ground-water systems. Where such predictions are made, equilibrium conditions are often simplified.

The physical parameters that affect the performance of ground-water heat pumps refer to the hydrologic properties of bedrock formations or unconsolidated deposits. The ability of subsurface formations to store, transmit, and yield water is influenced by its lithology, thickness, areal distribution, structural configuration, and engineering properties.

Appendix D contains a brief description of ground-water availability and quality for each state. Accompanying each description is a set of maps depicting well yields, depth to water, temperature, and the concentration of common ground-water constituents. The concentration of each chemical is illustrated by isograms (lines of equal chemical

Figure 1.1
Hydrologic Cycle



Schematic diagram of the earth's water cycle — the hydrologic cycle.

concentration) for most of the ground-water quality maps. The contour interval is determined by the natural range of each chemical parameter, as well as the density of data points in a given area. Each map represents the general trend of a chemical constituent or parameter and can only show approximate values in any particular region. Wide variations in each parameter may occur. In some regions (usually mountain ranges), no data were available, thus precluding the use of contour lines. In general, the greatest density of data points coincided with the more populated regions of the country. The states of Alaska and Hawaii were omitted from this study because climatic conditions in these areas make the potential for heat pump development questionable. Also, pertinent data were lacking for these states.

A. Withdrawal Rates

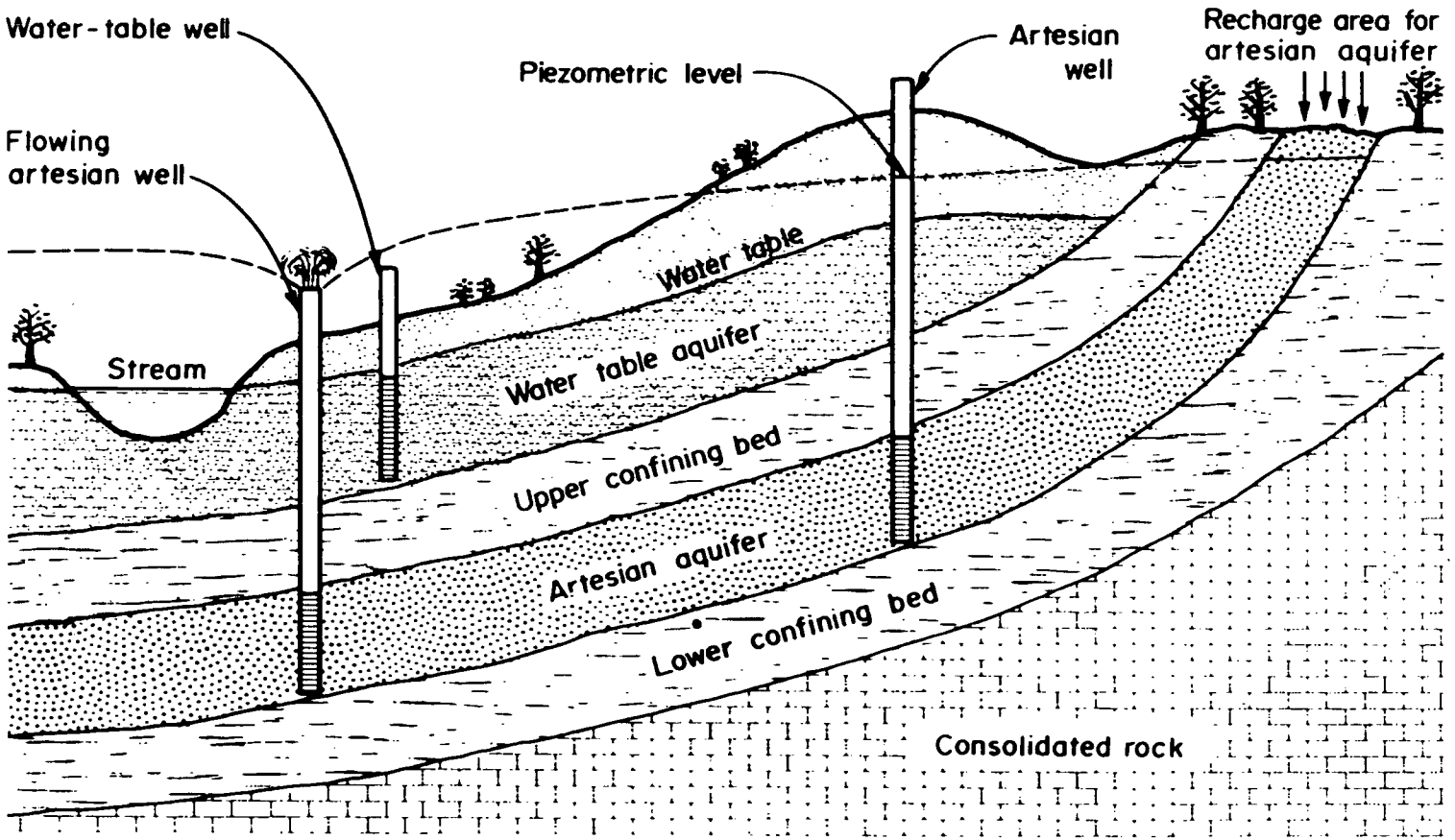
Ground water originates from precipitation falling on the land surface. Once the soil is saturated with water, excess water runs into ditches or streams and infiltrates into the soil by gravity toward the water table. The water table forms a continuous surface of water at the top of completely saturated rocks and sediments. The shape of the water table is generally an attenuated reflection of the land surface.

The pumping rate of a well is dependent on the hydrogeologic properties of the aquifer and the physical design of the well. An aquifer is a body of rock that contains sufficient saturated permeable material to conduct ground water and yield economically significant quantities of ground water to wells and springs. An aquifer is generally classified as either confined or unconfined (a water-table aquifer). Some aquifers exhibit characteristics of both classifications and are referred to as semi-confined.

An unconfined aquifer receives direct recharge from the land's surface. The water table in these aquifers fluctuates in response to changes in barometric pressure, tidal effects, or seasonal variations in evapotranspiration and recharge rates.

A confined aquifer is a completely saturated formation overlaid by relatively impermeable formations such as clays or shales. Water in a confined aquifer occurs under

Figure 1.2
Potentiometric Surface of Various Aquifer Systems



Subsurface and ground-water phase of the hydrologic cycle.

pressurized conditions. This type of pressure is referred to as hydrostatic pressure or feet of head. When a well penetrates an aquifer of this type, the water level in the well rises above the aquifer from which the water is stored. Flowing wells result when hydrostatic pressures in artesian aquifers are sufficient enough to force water up to the land's surface. Other artesian wells are non-flowing; that is, the water level in the well rises to the piezometric surface below land surface. The piezometric or potentiometric surface is a theoretical boundary whose position depicts an equilibrium between atmospheric and hydrostatic pressures. Figure 1.2 illustrates this concept.

Unconsolidated and bedrock aquifers contain minute pore spaces that retain and transmit water. Porosity is the ratio of the volume of these pore spaces to the volume of the aquifer (porosity is a dimensionless quantity). Table 1.1 gives typical porosity values of some common materials. A material's porosity can be developed in two ways. Its primary porosity consists of the pore spaces that occur between the grains in a clastic sediment. For this reason, primary porosity is also known as intergranular porosity. Primary porosity is proportional to the degree the material has been sorted. Thus, a well-sorted deposit will generally hold and yield large quantities of water because of the large volume in the pore spaces. In a poorly-sorted deposit, however, the pore spaces are often choked by finer grained material which substantially reduces the aquifer's porosity. Figure 1.3 illustrates this concept. The diagenetic history of the sediment also affects the porosity. Those clastic sediments that have a greater quantity of cementing material in the intergranular voids have lower porosities.

Aquifers can also exhibit secondary porosity that develops after lithification of the sediments. Typical examples of secondary porosity include fractures, joints, bedding planes, and solution channels. Since many different geologic factors act to develop secondary porosity, its occurrence is difficult to predict. Figure 1.4 depicts the development of fractures and joints in a bedrock aquifer.

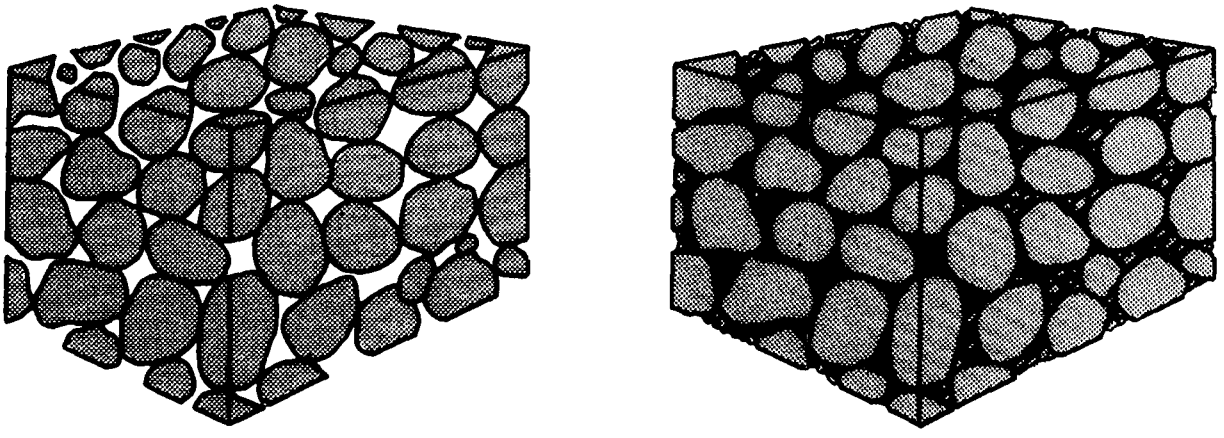
A highly porous aquifer, however, is not necessarily highly productive. For example, an aquifer may consist of fine-grained material containing many small pores which retain water by capillary forces. Such aquifers may hold

Table 1.1

APPROXIMATE AVERAGE POROSITY, SPECIFIC YIELD, AND PERMEABILITY OF VARIOUS MATERIALS

Material	Porosity %	Specific yield %	Permeability		Intrinsic permeability, D
			gpd/ft^2	m^3/dm^2	
Clay	45	3	0.01	0.0004	0.0005
Sand	35	25	1,000	41	50
Gravel and sand	25	22	100,000	4,100	5,000
Sandstone	20	16	10,000	410	500
Dense limestone and shale	5	8	100	4.1	5
Quartzite, granite	1	0.5	0.01	0.0004	0.0005

Figure 1.3
Primary (Intergranular) Porosity

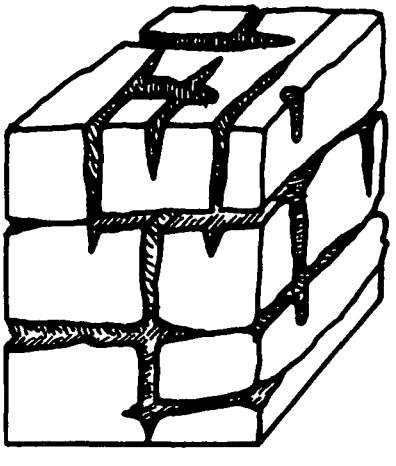


A. Well-sorted deposit

B. Poorly sorted deposit

Well-sorted deposits have more open space than poorly sorted deposits.

Figure 1.4
Secondary Porosity



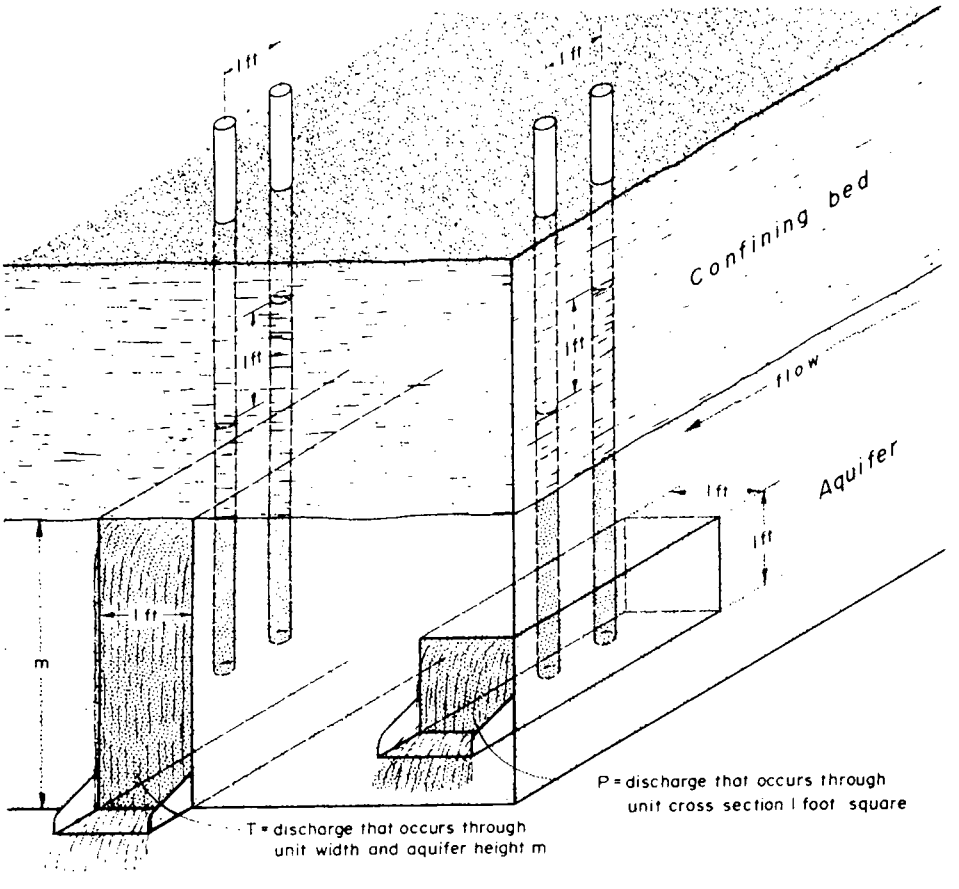
The water-bearing openings in bedrock consist of a network of interconnected fractures.

relatively large quantities of water but produce little. The effective porosity or specific yield indicates what portion of an aquifer is able to yield water under the influence of gravity. This value is expressed as the ratio of the volume of water which will drain freely from the material to the total volume of the material. Thus, it is a dimensionless quantity. The specific yield cannot exceed the porosity because the capillary forces will always retain some water within the pore spaces. Specific yields of fine-grained materials are less than the specific yields of coarser-grained materials due to the greater capillary forces of the fine-grained sediments.

The quantitative measure of available water in an aquifer system is the storage coefficient. In unconfined aquifers, the storage coefficient is equal to the specific yield. Thus, in an unconfined aquifer with a porosity of 30 percent and capillary forces retaining 20 percent, the storage coefficient (specific yield) equals 0.30 minus 0.20. Thus, 10 percent of the total aquifer volume represents recoverable ground water. Storage coefficients for typical unconfined aquifers range from 0.05 to 0.30. Because the storage coefficients for confined aquifers rely on a combination of fluid and aquifer-pressure dynamics, they generally range from 0.001 to 0.000001.

Permeability refers to the aquifer's ability to transmit water. The coefficient of permeability, also known as hydraulic conductivity, is the quantity of water that will flow through a cross-sectional area of a porous material per unit of time under a hydraulic gradient of 1.00 at a specified temperature. The transmissivity of an aquifer indicates the quantity of water that will flow through a vertical section of the aquifer one foot wide with a height equal to the saturated thickness of the aquifer. Transmissivity is the product of the coefficient of permeability (or hydraulic conductivity) and the saturated thickness of the aquifer. Figure 1.5 illustrates these concepts. In essence, aquifers which have both large porosity values and large coefficients of permeability (hydraulic conductivity) will generally yield significant quantities of water. Table 1.1 also lists typical permeabilities of different materials. High permeability values indicate that the aquifer is capable of transmitting large quantities of water. Highly permeable materials include unconsolidated sand, sand and gravel deposits, carbonates, and sandstones. Igneous, metamorphic,

Figure 1.5
Permeability and Transmissivity



Graphical concepts of the coefficients of permeability and transmissibility. Coefficient of permeability multiplied by the aquifer thickness equals coefficient of transmissibility.

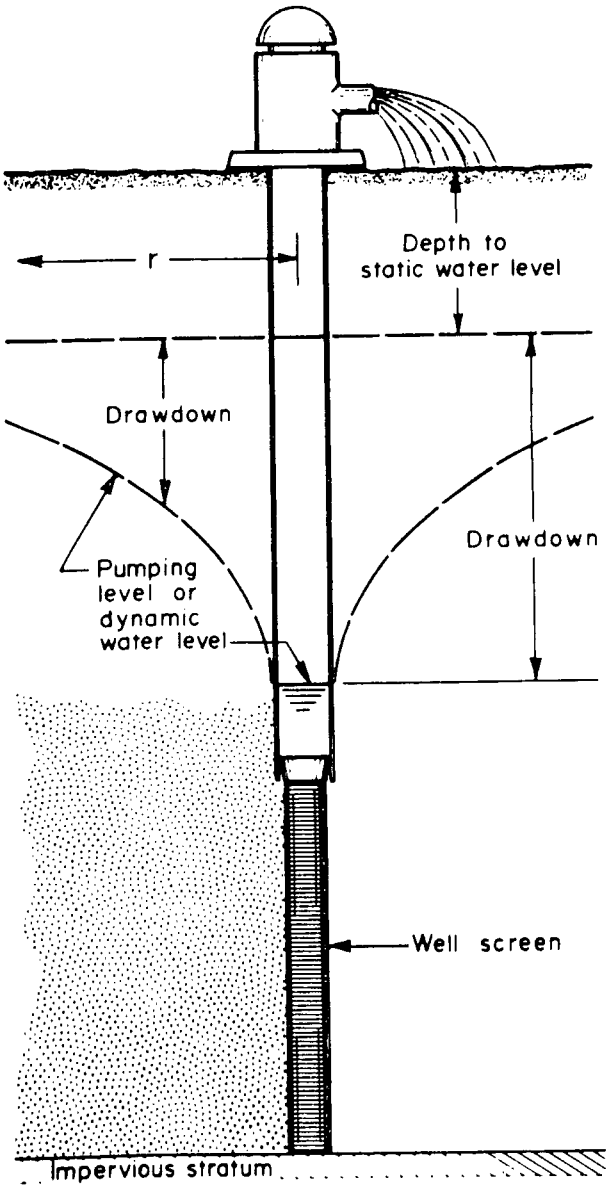
fine-grained clastic rocks, and fine-grained unconsolidated deposits also serve as aquifers, but their permeability is generally quite low and may provide inadequate quantities of ground water to a well.

When a well is pumped to withdraw water from an aquifer, a cone of depression forms around the well (Figure 1.6). The drawdown is the vertical depth from the original level of the water table to any point in the cone. The aquifer's transmissivity controls the shape of the cone of depression that forms around a pumping well. If the transmissivity is low, ground water will flow slowly toward the well. As transmissivity increases, there is a corresponding increase in the flow rate. The magnitude of drawdown is therefore inversely proportional to the transmissivity (Figure 1.7). The storage coefficient also affects the rate at which a cone develops around a pumping well. A large storage coefficient indicates a well with a slowly expanding cone of depression. In these wells, water is released from aquifer storage at nearly the same rate it is being pumped from the well. The small coefficient typical of a confined aquifer produces a rapidly expanding cone of depression.

The shape and extent of the cone of depression is very important when several wells are pumped in the same vicinity. If the wells are improperly spaced, their cones of depression will coalesce and considerably depress the water level. Under extreme conditions, the water level may be depressed below the depth of some wells, resulting in loss of production. The sustained yield of a well is the rate ground water can be continuously withdrawn without lowering water levels to critical stages, or without establishing new hydraulic gradients that would induce the migration of inferior quality water to the well.

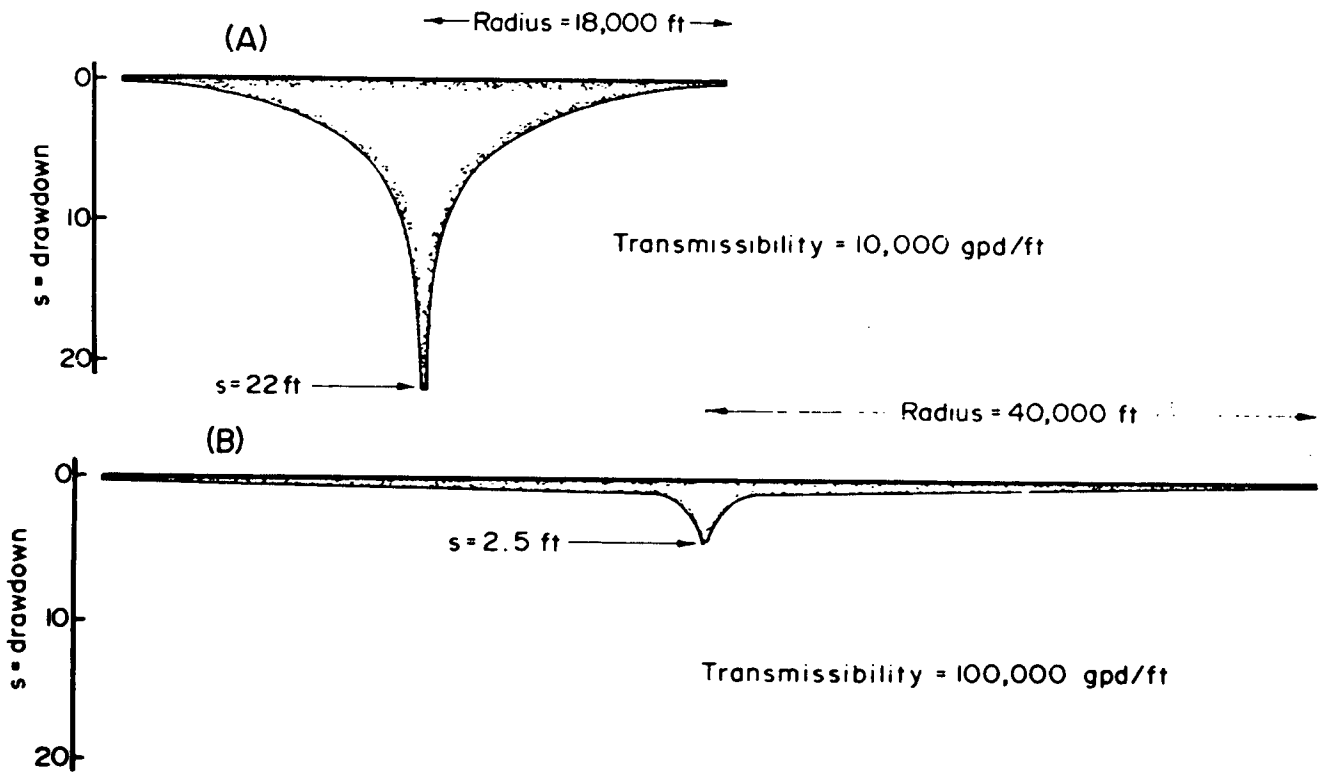
Computations of the practical sustained yield of aquifers require a complete hydrogeologic systems analysis. This analysis requires hydrogeologic maps describing: (1) coefficient of permeability and/or transmissivity of the aquifer; (2) the aquifer's coefficient of storage; (3) area of the aquifer; (4) saturated thickness of the aquifer; (5) coefficient of permeability and storage of existing semipermeable formations; (6) saturated thickness of existing semipermeable formations; and (7) location, extent, and nature of aquifer and semipermeable foundations. Limitations of data and funds often make such detailed studies impractical for large areas. However, generalized

Figure 1.6
Cone of Depression Around A Pumping Well



Measurements related to well performance and pumping tests of wells and aquifers.

Figure 1.7
Transmissivity Values and Cones of Depression



Effect of differing coefficients of transmissibility upon the shape, depth and extent of the cone of depression, pumping rate and other factors being the same in both cases.

maps of aquifer yield can be made using basic geologic data and yield data from existing wells. Those maps can be used to estimate the well yield at a certain location within a specified range.

B. Water Depth

The level at which water stands in a nonpumping well is known as the static water level. This level coincides with the water table for an unconfined aquifer or the piezometric surface for a confined aquifer. The static water level in unconfined aquifers fluctuates in response to recharge, withdrawals from wells, discharge to streams, and evapotranspiration. Water levels in confined aquifers are also affected by recharge, although the effect may not be noticed immediately.

Records of water level fluctuations in the form of hydrographs show diurnal, weekly, and seasonal changes, as well as long-term trends. Normally, static water levels may fluctuate several feet in response to seasonal recharge. During drought periods, water levels may be depressed several additional feet.

The depth to water may also be illustrated by a potentiometric map of an aquifer. This type of map can be used to indicate the direction of flow, recharge and discharge areas, and depth to ground water. The depth to water is a primary factor in estimating well construction and pumping costs.

Wells perpendicular to the direction of flow are able to intercept a greater quantity of ground water, with minimal interference, than wells constructed parallel to the direction of movement. In addition, wells located in discharge areas are generally less expensive to construct and operate because the water table is closer to the land surface. Conversely, wells constructed in recharge areas generally cost more because ground-water levels are usually far below the surface. Other factors which affect well costs include the type of drilling method employed, type of lithologies penetrated, season of the year, diameter of the well, and type and amount of well casing used. The depth to water is also necessary to determine the optimum pump size needed once the water requirements for the heat pump and domestic consumption are known.

C. Ground-Water Temperatures

Ground-water temperatures vary considerably throughout the United States depending on the location and well depth. Figure 1.8 is an isothermic contour map of ground-water temperatures for the conterminous United States. At shallow depths in recharge areas, ground-water temperatures may vary as much as 10 to 15 F° (5.6 to 8.3 C°)in response to seasonal temperature changes. This temperature variation, however, generally disappears at depths greater than 20 to 40 feet (6.1 to 12.2 m). Below these depths, ground-water temperatures approach a steady-state condition.

Local anomalies in ground-water temperatures result from natural and man-made causes. These anomalies are not depicted in Figure 1.8 because of their local nature. Ground-water temperatures may be altered from the regional norm by the recharge of spent water used for cooling through injection wells or from the recharge of thermally-polluted surface water. Variations in the geothermal gradient, magmatic activity, or concentration of radiogenic elements may also create temperature anomalies. Figure 1.9 shows contour lines of equal geothermal gradients and anomalous areas where higher gradients are located. An attempt was made to exclude the influence of anomalously high temperatures at depth in the isotherms of Figure 1.8. However, since many hydrothermal and ground-water reservoirs are hydraulically connected, there is a high probability that at least some areas are affected by high gradients. Interconnected fault zones, typical of hydrothermal areas, may provide a conduit which allows the mixing of hot fluids with the cooler, shallow ground waters (Moran, 1979). Ground-water temperature anomalies are also associated with some active faults. The heat generated by frictional forces along a fault plane is dissipated through the circulation of ground water.

D. Ground-Water Quality

Numerous ground-water heat pumps have successfully operated under various ground-water quality conditions. In general, the natural chemical quality of ground water in most regions poses no problem to heat pump operation. Problems can arise from improper installation, improper selection of plumbing materials, or poor well construction. Highly mineralized or naturally aggressive ground water may also affect the performance of the heat pump or supply well.

Figure 1.8
Ground Water Temperatures
In Wells Ranging from 50ft to 150ft (15m to 30m) in Depth

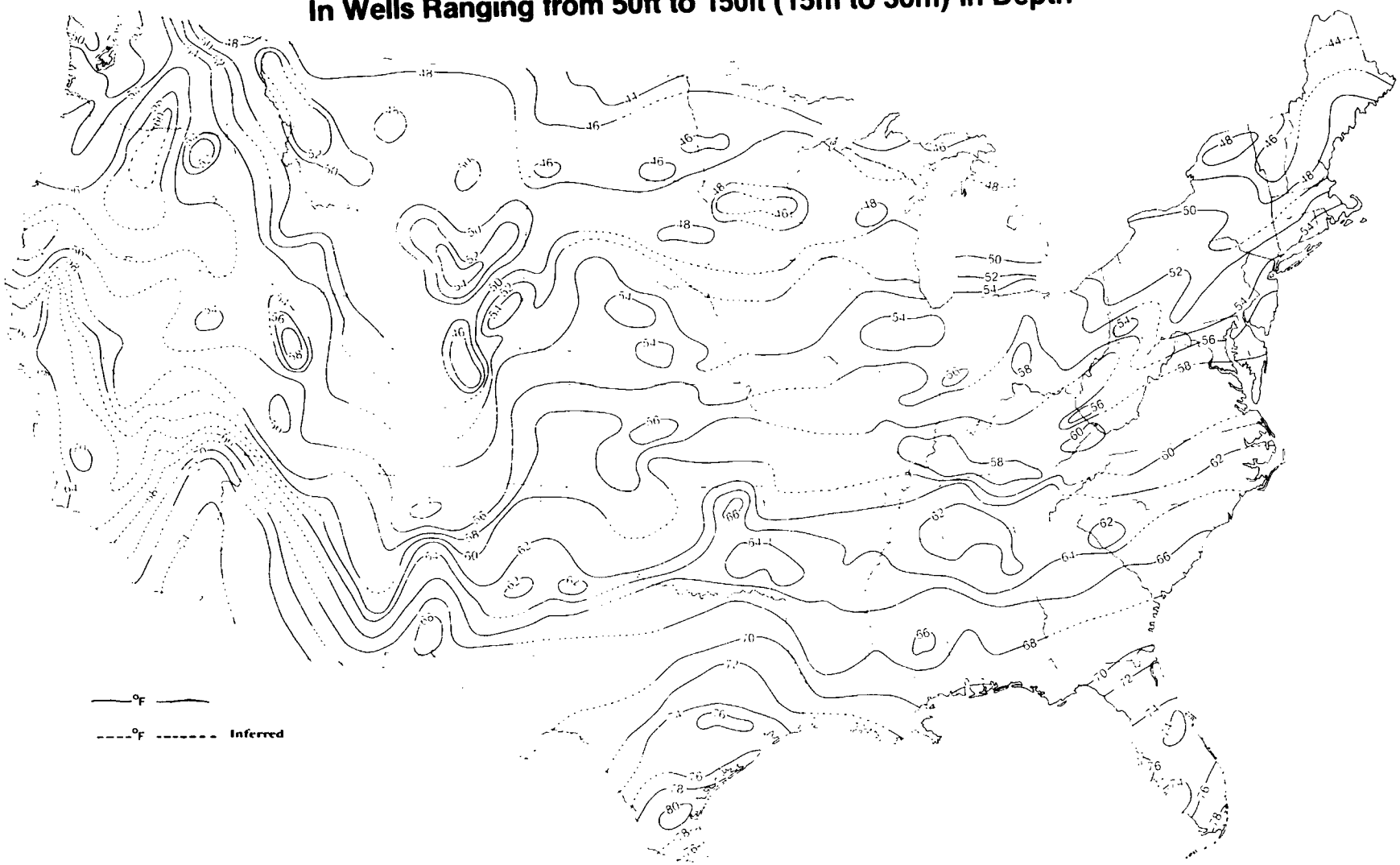
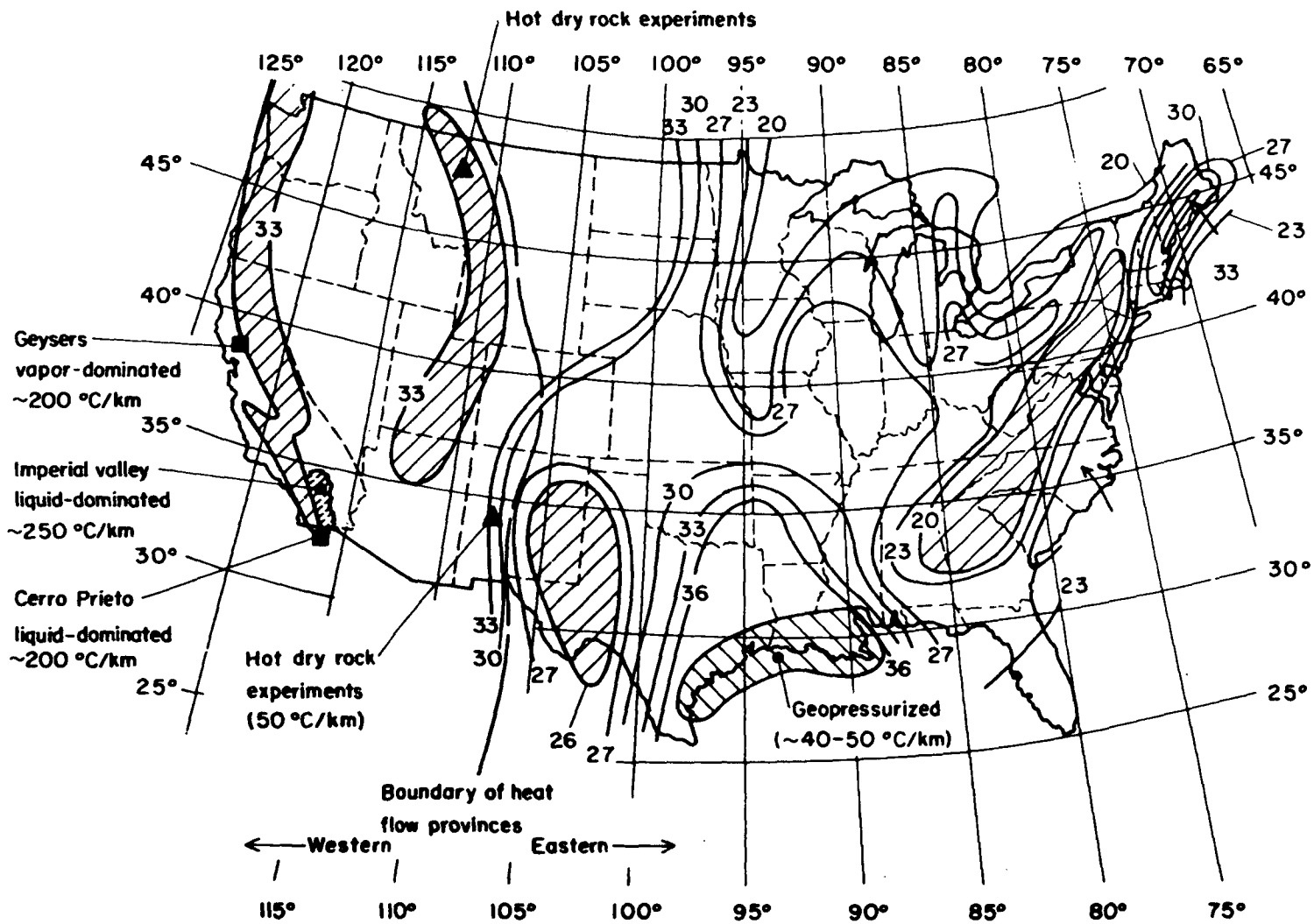


Figure 1.9
Geothermal Temperature Gradient Contours, °C/km
(average gradient to 6 km)



Contained in Appendix D are ground-water quality maps for each state depicting the following constituents: calcium, magnesium, sodium, potassium, sulfate, chloride, bicarbonate, iron, manganese, hardness, total dissolved solids, and pH. A brief review of each parameter describing its origin and effect on ground-water heat pump installations is discussed in the following sections.

The chemical properties of ground water are highly variable, depending on location. As a general rule, the dissolved solids content increases with depth, as well as with the time and distance the water has traveled through the ground. The chemical quality of ground water is also closely related to precipitation. In general, the least mineralized water occurs in areas of abundant rainfall. Exceptions may occur where ground-water quality has been altered by unusual hydrogeologic conditions, or where man's activities have polluted the environment.

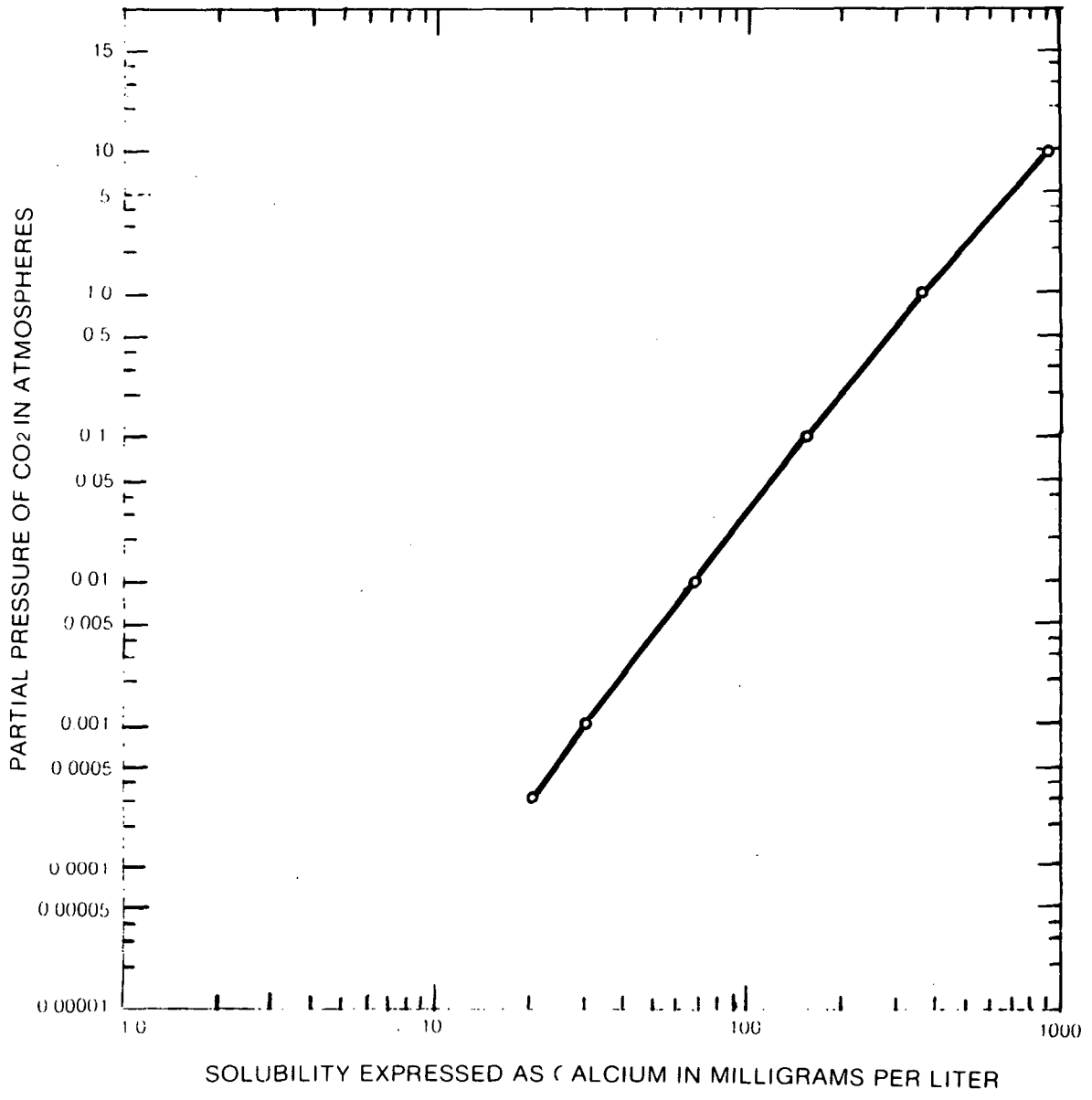
Calcium Calcium is the principal cation commonly found in most ground waters. It is an essential constituent of many minerals, particularly the chain silicates, pyroxenes, amphiboles, and feldspars. The slow decomposition of these minerals, however, restricts the amount of calcium available for solution. In general, most of the calcium available for solution is derived from calcite or aragonite (both having the formula $CaCO_3$) and dolomite [$(Ca,Mg)CO_3$]. These minerals are commonly found in sedimentary rocks and comprise the principal constituents of limestone and dolomite formations. Other calcium minerals include gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_4$), and fluorite (CaF_2). Calcium is also commonly found in some clays. Within sandstone and other detrital rocks, calcite is present as a cement between particles or a partial filling of the interstices.

The chemical equilibria involving carbonates are the major factors limiting the solubility of calcium in most natural waters. The solubility of calcite is expressed as:

$$CaCO_3 + H^+ \rightleftharpoons Ca^{2+} + HCO^-_3$$

The hydrogen ion supply, a function of the available carbon dioxide, is most likely to control calcite solubility. The amount of carbon dioxide present in air is 0.03 percent or, in terms of partial pressure, 0.003 atmosphere. The relationship of calcite solubility to partial pressure of carbon dioxide is illustrated in Figure 1.10. Carbon

Figure 1.10
Calcite Solubility vs. Partial Pressure of Carbon Dioxide



Solubility of calcium carbonate (calcite) in water at 25°C in the presence of carbon dioxide.

dioxide contained within the soil is primarily derived from plant respiration and the decay of organic material. Because of this, carbon dioxide concentration is greatest in environments which support dense vegetation. Partial pressures of carbon dioxide within soils are commonly one to two orders of magnitude higher than the level measured in the atmosphere. These partial pressures, however, decrease with increasing depth.

A high calcium content contributes to the hardness of water and, in this sense, increases the potential for scale formation in the heat exchanger.

Magnesium Magnesium is a typical constituent of the dark-colored ferromagnesium minerals. Sedimentary forms of magnesium include carbonates like magnesite and dolomite. The magnesium ion, Mg^{+2}, is normally the predominant form in solution. Waters in which magnesium is the predominant cation only occur in brines associated with evaporite deposits. Magnesium equilibria are somewhat complex due to the diverse forms of magnesium carbonates and hydroxycarbonates which may not reversibly dissolve. As such, it is impossible to make any broad generalizations concerning the effect of magnesium equilibria on the operation and performance of ground-water heat pump installations. However, magnesium, like calcium, contributes to the hardness of water and increases the potential for scale formation.

Sodium The principal source of sodium is the decomposition of feldspars. In resistate sediments, sodium may be present as an impurity in the cementing material of unaltered mineral grains. Sodium may also be present as crystals of readily soluble sodium salts deposited in sediments by saline water. Sodium is derived from the dissolution of evaporite minerals such as halite (NaCl), trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$), mirabilite ($Na_2SO_4 \cdot 10H_2O$), and thenardite ($NaSO_4$).

The sodium content of ground water can range from a few mg/l to more than 100,000 mg/l when found in brines in closed basins. The sodium ion generally occurs in Na^+ state where total dissolved solids concentrations are less than 1,000 mg/l. In more concentrated solutions, however, a variety of complex ions and ion pairs are possible. In general, the exchange of calcium or magnesium ions for sodium ions reduces the hardness of water and decreases the potential for scale formation.

Potassium In sediments, potassium is present in unaltered feldspar or mica particles and is a common constituent of some clay minerals. Evaporite rocks locally include beds of potassium salts which constitute a source of high potassium concentration in brines.

In general, potassium is less soluble than sodium. Potassium is liberated with greater difficulty from silicate minerals and exhibits a strong tendency to be reincorporated into solid weathering products, particularly certain clay minerals. In most cases, the potassium concentration is much lower than the sodium concentration and generally does not exceed a few tens of milligrams per liter. Because of its very low concentrations, the effect of potassium on ground-water heat pumps is negligible.

Sulfate When dissolved in water, sulfur generally occurs in the fully oxidized (S^{+6}) state with oxygen as the anion sulfate, $(SO_4)^{-2}$. Sulfur is not a major constituent of the earth's crust, but it is widely distributed in a reduced state as metallic sulfides. During the decomposition of these minerals, sulfides are oxidized to yield sulfate ions, which are then carried off with the water. Pyrite and marcasite are commonly found in sedimentary rocks and are often associated with biogenic deposits such as coal, which were deposited under reducing conditions. Sulfate is also derived from certain minerals in the feldspathoid group. The most extensive occurrence of sulfate is in evaporite sediments, such as gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$). Sulfate is derived to a lesser extent from barite ($BaSO_4$).

The principal complications in sulfate chemistry concerning ground-water heat pump use are the reactions of sulfate with certain bacteria. Sulfate ions are metabolized by sulfate-reducing bacteria and produce hydrogen sulfide gas as a by-product. Sulfate ions can also combine with calcium ions, contributing to total hardness and forming a scale under certain conditions. As such, increasing concentrations of sulfate may produce a scale or liberate hydrogen sulfide under appropriate conditions which could adversely affect a heat pump installation.

Chloride Chloride in ground water may originate from evaporite deposits or from sea water trapped in sediments when they were deposited. It may also be concentrated by

evapotranspiration in arid and semiarid climates. Excessive pumping of coastal or island aquifers may result in salt water intrusion. Another major source of chloride in some areas is pollution from oil field brines, road salt, septic tanks, and irrigation return flow. High chloride levels can affect galvanic corrosion rates and cause the removal of protective films on metal surfaces.

pH The hydrogen ion concentration of water is expressed in terms of the pH value. The pH scale ranges from a highly acidic pH of 1 to an extremely basic or alkaline pH of 14. Water with a pH of 7 is said to be neutral. The pH of water is influenced by the amount of carbon dioxide, carbonate, and bicarbonates in solution. Temperature and pressure affect the solubility of carbon dioxide and therefore affect the pH. Natural ground water generally ranges in pH from 6 to 8.5. Values lower than 4.5 are usually the result of acid mine drainage or industrial processes. The effect of pH on ground-water heat pumps is discussed in greater detail in Section 1.VB.

Bicarbonate Bicarbonate ions are derived from the solution of carbonate minerals. Bicarbonate concentrations vary considerably in ground water from one region to the next. These concentrations are generally higher than those of carbonate, particularly when calcium and magnesium concentrations are low. High concentrations of bicarbonate and carbonate can combine with calcium or magnesium ions to form a scale when the water temperature approaches its boiling point. This problem, however, is not encountered at the anticipated operational temperatures of ground-water heat pumps.

Iron Iron is an abundant and widespread constituent of the earth's crust. The oxide and sulfide species of iron minerals are usually the principal sources of dissolved iron in ground water. These minerals include pyrite, marcasite, hematite, and goethite.

Ferrous iron, Fe^{+2}, is the most common form of iron in ground water. The complex $FeOH^{+}$ may occur in solutions very low in dissolved carbon dioxide content. Ferric iron, Fe^{+3}, can generally be formed in acid solutions, but these solutions rarely occur naturally.

The principal variables influencing iron solubility include pH, redox potential (Eh), amount of dissolved carbon

dioxide, and sulfur species. A considerable concentration of ferrous iron can be maintained in equilibrium within the usual pH range of ground water and an Eh range below 0.20 and above -0.20 volts. However, as the Eh increases (primarily from the dissolved oxygen as ground water is exposed to air), iron is oxidized and forms a precipitate, usually ferric hydroxide.

Recharge reaching the water table is generally oxygenated after coming in contact with air. Any reduced iron minerals, particularly pyrite, coming into contact with the oxygen-rich water will oxidize to form ferric iron and sulfate. The oxygen in the circulating water is ultimately depleted by this and other reactions.

Bacteria also play an important part in the occurrence of iron. Bacteria may act as catalysts to speed reactions which are thermodynamically favorable but which normally occur at much slower rates. Crenothrix and Leptothrix are common forms of iron bacteria. Both genera require oxygen, thus living in environments where ferrous iron is already unstable. This type of bacteria may produce a gelatinous substance which can clog the well screen or the aquifer in the immediate vicinity of the well. This problem more often affects the well rather than the heat exchanger, and usually results in reduced well yields. Automatic devices are activated that shut off the heat pump if there is an insufficient flow rate.

Iron bacteria are a fairly common problem that can be easily treated and controlled. Shock chlorination of the well and piping system generally eradicates these bacteria.

Manganese Manganese is less abundant than iron in the earth's crust. However, it is a common element widely distributed in rocks and soils. Small concentrations of manganese (0.05 mg/l) constitute an objectionable impurity in domestic water supplies. Manganese in ground water exhibits a chemical behavior similar to that of iron. In solution, manganese bicarbonate oxidizes when exposed to air and changes to an insoluble black precipitate, manganese hydroxide. Various genera of bacteria, similar to iron bacteria, may also cause the oxidation of manganese compounds to an insoluble form. In general, concentrations of manganese in ground water do not pose significant problems. It is unusual to encounter ground water in which manganese predominates over iron.

Hardness The total hardness of ground water may be divided into two types, carbonate and noncarbonate. Carbonate hardness is generally greater than noncarbonate hardness. Carbonate hardness consists of the calcium and magnesium content that may combine with bicarbonate or carbonate. This type of hardness is also referred to as temporary hardness.

Permanent hardness results from calcium and magnesium combining with sulfate, chloride, or nitrate ions. This type of hardness in water cannot be removed by boiling. The effect of hardness on heat pumps is discussed in greater detail in Section 1.IVA.

Dissolved Gases Dissolved gases are generally not included in a routine water analysis. This analysis must be made at the well site immediately after acquiring the sample in order to mimimize the dissipation of the gases into the atmosphere. The presence of dissolved gases in substantial concentrations may result in corrosion or incrustation under various conditions. The most common types of dissolved gases include oxygen, hydrogen sulfide, carbon dioxide, nitrogen, sulfur dioxide, methane, and ammonia. Of these, the first three are most typically found in ground water.

The dissolved oxygen content of ground water generally decreases with increasing depth or time. Most of the oxygen is consumed through the oxidation of organic matter as it percolates through the soil. Dissolved oxygen accelerates the corrosive attack of water upon iron, steel, galvanized iron, or brass. The corrosive properties of dissolved oxygen in ground water are more fully discussed in Section 1.VA of this chapter.

Hydrogen sulfide gas in ground water is recognized by its "rotten egg" odor. Hydrogen sulfide in water forms a weak acid capable of corroding many metals. Sulfate-reducing bacteria are capable of producing hydrogen sulfide as a by-product through the reduction of sulfate ions. The corrosive nature of hydrogen sulfide is examined in greater detail in Section 1.VA of this chapter.

Carbon dioxide is derived from the atmosphere as well as through the decay and respiration of plants. In a pumping well, a pressure drop may cause carbon dioxide to come out of solution as gas bubbles. The equilibrium of the water

then favors the precipitation of calcium and magnesium carbonate scale. This process may continue until the scale completely clogs the well and causes well failure. This problem can be alleviated through proper well design and periodic well maintenance. Other aspects of carbon dioxide are discussed in greater detail in Section 1.VA.

III. CORROSION AND INCRUSTATION OF THE HEAT PUMP WATER-SIDE HEAT EXCHANGER

The effects of corrosion and incrustation have long plagued modern technology. No specific rules govern the choice of materials for a particular water-handling application, but a decision is usually based on chemical and physical properties, availability, and relative cost. These factors, plus the effects of corrosion and fouling, must be weighed when considering the use of any metal or alloy in a water-handling application.

This study examines, to a limited extent, the fouling or corrosion of metals in direct contact with aqueous solutions. This degradation of metal often results from the interaction of chemical and physical parameters in the system. For example, high oxygen and carbon dioxide content of supply water, when occurring separately, will degrade copper heat exchangers. With both conditions present, the severity of attack increases, resulting in rapid failure. Because of the complexity of the interactions, treatment techniques and preventive maintenance are often based on past experience rather than laboratory test results.

Ground water in most areas of the country contains chemical constituents that can lead to corrosion or incrustation. However, the two phenomena rarely occur simultaneously on the same surface. The rapid dissolution of a metal prohibits the formation of scale or protective film at the metal/water interface. Products of corrosion in one area of a metal surface can accumulate in another area, causing fouling. In addition, the accumulation of incrusting materials or a protective film may prohibit contact between the metal and water, thus eliminating or minimizing metallic corrosion. One exception should be noted. In some instances, the incrusting material may not form a uniform layer on the metal surface. This condition, coupled with the introduction of a corrosive water, may lead to deterioration of the metal. This type of situation, however, is probably rare.

Case histories of fouling or corrosion of the water-side heat exchangers in ground-water heat pumps are not common. This may be due to the fact that during the last five years, heat exchangers have been made available which are highly resistant to these effects. Exchangers which experienced severe corrosion or fouling problems prior to the introduction of these new units are probably no longer in service. It appears that these difficulties arose from a lack of understanding of the principles of corrosion or fouling, resulting in faulty design. Installations also failed in areas where ground water is severely corrosive to most economically available metals.

Many older heat exchangers were fabricated from admiralty brass. These are adequate in areas that have ground water of good quality. In some areas, especially in brackish water environments with high dissolved solids content, admiralty brass led to corrosion problems. Aluminum was also used in some installations built during the 1950s. These deteriorated rapidly, probably because of galvanic corrosion.

Installations in areas of extremely poor quality water also result in corrosion. For instance, high concentrations of hydrogen sulfide in supply water can result in a direct chemical attack of the metal. Also, some ground waters near swamps and other areas of organic decay contain organic acids which are corrosive to nearly all commercially available heat exchangers. However, these conditions are isolated and need not be considered factors in all regions.

A general description of the effects of various ground-water parameters on the corrosion and fouling of the water-side heat exchanger is presented in the following sections. This is to offer guidelines to assist those who may be experiencing problems with heat exchangers fabricated from a number of different metals.

IV. INCRUSTATION OF THE WATER-SIDE HEAT EXCHANGER

In the context of this report, incrustation can be defined as the exsolution of a chemical out of the supply water and subsequent deposition on the heat exchanger surface. As mentioned previously, a certain amount of

incrustation is necessary for many metals to form a protective layer to inhibit corrosion. For example, stainless steel forms an oxide or hydrate film, which technically can be termed an incrusting layer. Therefore, this report will refer to incrustation as any significant build up of scale which impedes the function of the heat exchanger.

The effects of incrustation on the function of the heat pump depend on the thickness and extent of the incrusting material. The accumulation of a substantial thickness of scale on the heat-exchanger surface lessens the effective diameter. This can result in:

1) a lower volume of water available for use as a heat source/sink

2) a higher flow velocity which produces a higher pressure drop through the coil

3) increased friction losses caused by the irregular surface of the scale layer

4) a change in the rate of heat transfer between water and refrigerant caused by the added layer of material with low thermal conductance

Over a period of time, points 1 through 3 will cause excessive wear on the supply-water pump. The fourth factor affects the operating efficiency of the unit.

A. Chemical Incrustation

The most common cause of scaling in water-handling equipment is hardness in the water supply. Calcium and magnesium salts account for nearly all of the hardness in natural waters. The common varieties of these mineral salts are:

$$(Ca, Mg)\ (HCO_3)_2$$
$$(Ca, Mg)\ SO_4$$
$$(Ca, Mg)\ Cl_2$$
$$(Ca, Mg)\ (NO_3)_2$$

Changes in temperature and/or pressure through the heat exchanger can result in the release of carbon dioxide and exsolution of the scale material. For example, the Changes in temperature and/or pressure through the heat exchanger

can result in the release of carbon dioxide and exsolution of the scale material. For example, the following overall equation describes the reaction which can result in the deposition of calcium carbonate as scale on heat exchangers.

$$Ca(HCO_3)_2 \rightleftharpoons CaCO_3 + H_2O + CO_2 \text{ (Equation 1)}$$

The carbon dioxide content in water plays an important role in determining whether the water has an incrusting or corroding tendency. Equation 1 shows that soluble calcium bicarbonate requires excess carbon dioxide to remain in solution.

In relation to the carbon dioxide/calcium bicarbonate equilibrium, Shreir (1963) classifies water into four categories based on carbon dioxide content:

1. The amount required to produce carbonate
2. The amount required to convert carbonate to bicarbonate
3. The amount required to keep calcium bicarbonate in solution
4. Any excess over that accounted for in 1, 2, and 3.

With a concentration of carbon dioxide lower than that required for condition 3 and none available for condition 4, the water will be supersaturated with calcium carbonate, and a slight increase in pH may cause precipitation and deposition on the metal surface. If this forms a nonporous, thin, continuous surface, the metal will be protected from corrosive attack without significantly affecting the heat transfer properties of the heat exchanger. Corrosive conditions exist if a type 4 concentration of carbon dioxide is present, preventing the accumulation of calcium carbonate and possibly causing degradation of the metal.

Another source of chemical incrustation is the precipitation of iron and manganese compounds, primarily the oxides and hydroxides. Ferrous iron, Fe^{2+}, is highly soluble in water. However, when oxidized to ferric iron (Fe^{3+}), insoluble oxides or hydroxides of iron are precipitated from solution and may adhere to the metal surface. This is common near well screens but should not occur in properly installed heat pump heat exchangers.

If a water supply with high iron and manganese content was exposed to the atmosphere prior to use in the heat pump, incrustation of the heat exchanger could occur. Any source of air entrainment into the supply water could result in the oxidation and subsequent precipitation of the iron oxides or hydroxides.

For a further discussion of the chemical incrustation of water-side heat exchangers, refer to Appendix A. This includes information regarding the fouling resistance resulting from mineral scale formation from natural waters on metal surfaces. Also included is a discussion of procedures used to determine the scale-forming tendency of waters.

B. Mechanical Incrustation

Mechanical incrustation results from the accumulation of suspended clay and silt-size particles on a surface. It is unlikely that this would occur singularly in heat exchangers. It is more probable that these particles would be found as grains in a matrix of a chemical precipitant such as calcium carbonate or iron oxide. These fouling substances would function as a cementing agent for the grains. There is a relatively high incidence of this type of incrustation on well screens. However, a properly developed well is unlikely to produce substantial amounts of suspended particles at the point of use. Thus, purely mechanical incrustation is not considered a problem in the function of heat exchangers.

C. Biological Incrustation

The presence of certain strains of bacteria in the supply water can lead to fouling by chemical and biological substances. The most common problem-causing bacteria are the iron and sulfate-reducing varieties.

Iron bacteria thrive in ground waters of relatively high dissolved iron content (0.2 to 14.0 ppm) (Cullimore and Mc Cann, 1979). The metabolic functions of the bacteria transform soluble iron into insoluble compounds which precipitate on the metal surface. The result is a slimy accumulation of iron hydroxide deposits. Some of these bacteria are able to utilize manganese as well as iron in a similar function. Sulfate-reducing bacteria are a potential problem in the water supply, but their functions usually result in corrosion rather than incrustation problems.

V. CORROSION OF THE WATER-SIDE HEAT EXCHANGER

Few metals found in the earth's crust occur in the metallic state. The common exceptions are copper, gold, and silver. The other more common metals occur as compounds, often as oxides, hydroxides, and insoluble salts. This demonstrates that these metals are more stable in the combined form than in the metallic state. From the thermodynamic standpoint, most metals are more likely to transform to a more stable state (i.e. to corrode). As a result, most studies of corrosion are concerned with the rates of corrosion and the factors that influence these rates. Identifying the cause and controlling the rates of corrosion by proper selection of metals and proper water treatment is the main thrust of most engineering studies. The intent of this section is to identify the types and causes of metallic corrosion that commonly occur at a ground water/metal interface.

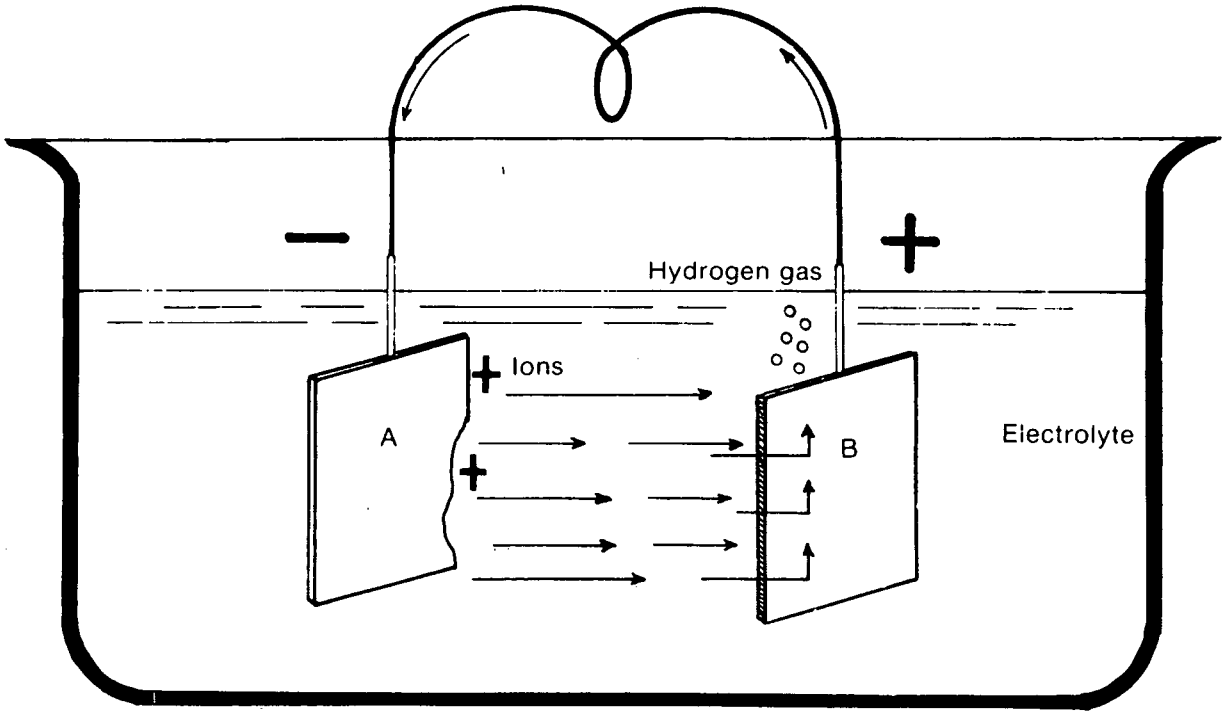
The corrosion of metals in aqueous solutions can be regarded as electrochemical in nature, i.e., there exists a chemical change accompanied by a flow of current (Borgmann et al., 1946; Shreir, 1963). In Figure 1.11, metals A and B are immersed in an electrolyte and connected by a conductor. The spontaneous degradation of metal A is accompanied by the solution of metallic ions and the flow of current in the wire. Metal A is called the anode, and it is at this metal where corrosion occurs. In addition to the physical degradation of metal A, the electrochemical action displaces hydrogen from the electrolyte. The hydrogen ions migrate to metal B, which is termed the cathode. Atomic hydrogen combines at the cathode to form hydrogen gas. The general reactions in a corrosion cell, then, are:

$$\text{Anode:} \quad M \rightleftharpoons M^{++} + 2e^-$$
$$\text{Cathode:} \quad 2H^+ + 2e^- \rightleftharpoons H_2$$

Some of the hydrogen gas forms bubbles and escapes to the surface, while some forms a thin protective layer on the cathode. This action is termed cathodic polarization and inhibits further corrosion. The cathode can be polarized by other means, such as the formation of a thin film of metal oxide or hydroxide, or from the precipitation and adherence to the metal surface of insoluble salts.

Depolarization occurs when this protective film is removed from the metal, allowing the recurrence of the corrosion process.

Figure 1.11
Electrochemical Cell



An electrochemical reaction implies the existence of an anode, cathode, and electrolyte. Thus, these components should be capable of being identified. This is the case in many corrosion processes where one area of the metal surface is anodic and another area of the same or dissimilar metal is primarily cathodic. Distances between these areas can be as small as fractions of a millimeter. In some reactions, however, the anodic and cathodic areas cannot be distinguished, and their existence is postulated by theory alone (Shreir, 1963).

The mechanism, rate, and intensity of metallic corrosion is dependent on a number of factors. The corrosion process is due to a dominant or controlling factor or a combination of factors. The most important of these are:

1. Composition of the corroding media
2. pH
3. Velocity of water
4. Tube wall temperature
5. Bimetallic couples
6. Mechanical/thermal stress
7. Biological effects

A. Composition of the Corroding Media

Oxygen Cathodic depolarization is the primary function of oxygen in the corrosion process. The removal of the protective blanket at the cathode allows the corrosion process to continue. Apparently, nearly any metallic surface can catalyze the reaction of oxygen and hydrogen at the cathode to form water (Borgmann, et al., 1946). Thus, the extremely slow rate of reaction of the two gases when combined without a catalyst is not observed in field applications. The rate of corrosion is, in many instances, almost directly dependent on the rate at which oxygen reaches the interface. This is true, however, only under conditions in which the chemical character of the water prevents the formation of a protective film on the metal

surface. In this sense, then, oxygen can perform a dual function in the presence of certain metals and aqueous solutions. It is necessary for the formation of a protective oxide film but, under some circumstances, acts as a depolarizing agent. Experiments indicate that as the availability of dissolved oxygen increases, the probability of attack decreases. However, if corrosion does occur, the intensity will be much higher at higher oxygen concentrations (Mears and Evans, 1935).

Carbon Dioxide Carbon dioxide is dissolved in ground water primarily by two mechanisms. During exposure of recharge precipitations to the atmosphere, the gas is dissolved in the water. The recharge water infiltrates through the unsaturated zone and eventually reaches the water table. The other source is from the decay of organic matter in the soil or in swampy areas. Carbon dioxide is released and subsequently dissolved in the recharge water as it infiltrates the soil horizon to the zone of saturation.

Carbon dioxide dissolved in ground water forms carbonic acid that is relatively weak, but which accelerates corrosion. The corrosion rate is accelerated by the presence of oxygen in solution.

Hydrogen Sulfide Hydrogen sulfide, when dissolved in water, forms a weak acid (hydrosulfuric acid) that can corrode most metals. The gas is common in mineral waters and is generated in peaty soils by bacteria. It is often associated with organic shale deposits that were formed under reducing conditions. In the presence of oxygen, hydrogen sulfide can react to form sulfurous or sulfuric acid.

Industrial Pollutants Man-made solutions that have entered the ground-water system can cause corrosion damage to heat exchangers. For example, acid mine drainage that infiltrates into ground water may (if concentrations are sufficiently high) cause serious damage. Dissolved ammonia also corrodes most metals including copper. Although the previous conditions will not apply on a regional scale, these and similar adverse conditions should be considered when installing a ground-water heat pump in an area that is known to have, or suspected of having, problems with industrial pollution.

Dissolved Mineral Salts The principal ions found in natural ground waters are calcium, magnesium, nitrate, sodium, bicarbonate, chloride, and sulfate. The solubility of the ion is important to the corrosion process in that it influences the conductivity of the solution. Solutions with high conductivities result from strong concentrations of highly soluble substances. Dissolved solids of relatively low solubility may retard corrosion by depositing a protective layer on the metal surface.

Because of its small ionic radius, the chloride ion is often able to penetrate the lattice structure of protective layers at some metal surfaces. This can enhance the corrosion process by causing depolarization.

The sulfate ion, in general, behaves in a similar manner. The corrosion rate relative to that of chloride solutions depends on the metal under consideration and the concentration of the salt in solution.

B. pH of the Solution

Generally speaking, the pH value of a solution is not in itself a measure of its tendency to corrode a given metal. A metal may react differently to chemically dissimilar solutions of the identical pH value. The difference is apparently due to the compounds that influence the pH value and the presence or absence of other chemical constituents in the solution (Scovill Manufacturing Company, 1950).

The pH of ground water generally ranges from 6.0 to 8.5. At low levels (pH <4.0) gaseous evolution of hydrogen may occur, indicating anodic degradation. This is not normally found in nature but may be found in areas of acid mine drainage or industrial pollution. The effect of pH in relation to the scale-producing tendency of waters is described in Appendix A.

C. Velocity of Water

The flow velocity of water in a tubular heat exchanger can affect the nature of corrosion in a number of ways. Varying the flow rate directly varies the availability of oxygen at the water/metal interface in waters that contain a significant quantity of oxygen. The effect of oxygen was covered in Section 1.VA. Increased velocity creates more friction at the metal/water interface, causing mechanical

erosion of the protective film. This problem is enhanced by the presence of suspended solids or entrained gas bubbles in the water flow. The erosion of the metal surface as a result of this can cause severe pitting in heat exchangers. Extremely low flow rates may produce concentration cells in which differences in solution concentration or dissolved oxygen distribution result in a potential difference on a metal surface. This produces current flow which intensifies a corrosion process locally.

D. Tube Wall Temperatures

Within the range of heat pump operating temperatures, no definite relation can be established between temperature and corrosion rates. Factors which may increase the rate as a result of a rise in temperature are an increase in diffusion rates, electrical conductivity, and ionization. In some instances, however, an increase in temperature may decrease the corrosion rate. Figure 1.12 shows the relationship of temperature and oxygen solubility. An increase in temperature results in exsolution of oxygen. Increases in temperature may also be conducive to the formation of some protective films.

E. Bimetallic Couples

If two dissimilar metals are in contact and immersed in an electrolyte, a galvanic cell will be produced and corrosion will probably result. This bimetallic corrosion is probably not a problem in the heat exchanger itself but may be troublesome at connections to the heat exchanger. The rate of corrosion depends on three factors: the nature of the metals in contact, the conductivity of the electrolyte, and the availability of oxygen or other oxidizing agents.

In the electromotive series (Table 1.2), contact of two dissimilar metals in an electrolyte produces a galvanic cell. Metals near the top of the series (reactive metals such as zinc or aluminum) act as anodes and are corroded when in contact with metals near the bottom of the series. These are the more noble or passive metals which act as cathodes and are protected by polarization. As an example, connecting a copper pipe to a brass fitting would be relatively safe, while a connection of copper to aluminum would probably result in corrosion. The farther apart the two connected metals are in the series, the greater the

Figure 1.12
Corrosion Rate:
Temperature vs. Oxygen Solubility

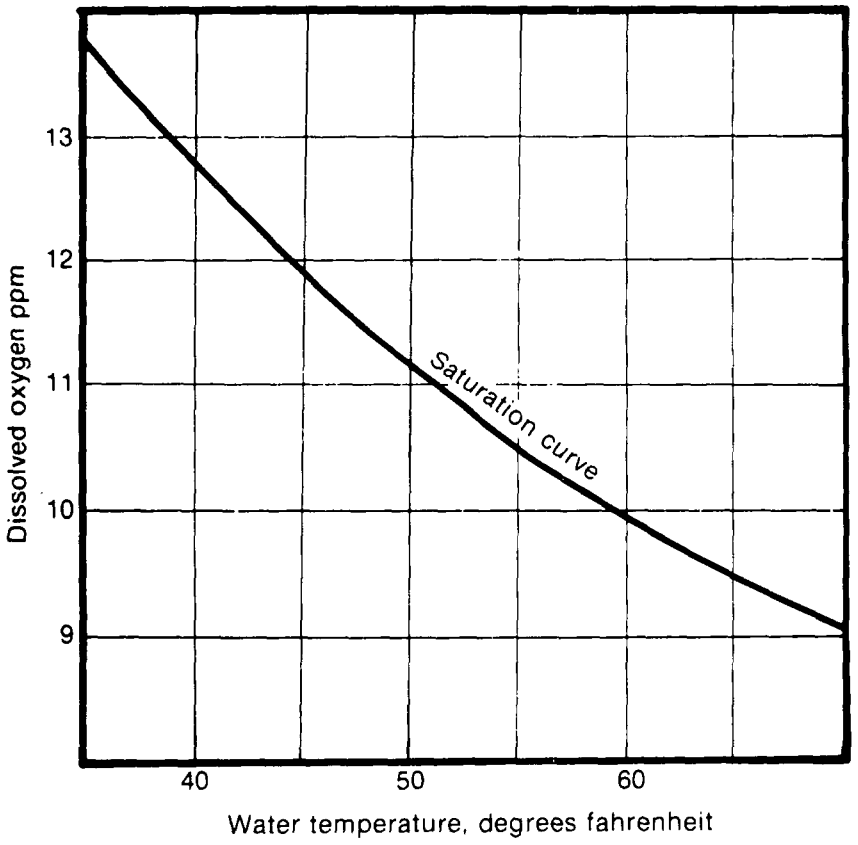


Table 1.2
Electromotive Series of Metals

Corroded End *(Anode)*	Magnesium Magnesium Alloys
	Zinc
	Aluminum 25
	Cadmium
	Aluminum 17ST
	Steel or Iron Cast Iron
	Chromium-Iron (Active)
	Ni-Resist
	18-8 Chromium-Nickel-Iron (Active) 18-8-3 Chromium-Nickel-Molybdenum-Iron (Active)
	Led-Tin Solders Lead Tin
	Nickel (Active) Inconel (Active)
	Brasses Copper Bronzes Copper-Nickel Alloys Monel
	Silver Solder
	Nickel (Passive) Inconel (Passive)
	Chromium Iron (Passive) 18-8 Chromium-Nickel-Iron (Passive) 18-8-3 Chromium-Nickel-Molybdenum-Iron (Passive)
Protected End *(Cathode)*	Silver Gold Platinum

DECREASING CORROSION RESISTANCE

(After the International Nickel Co., Inc.)

potential difference developed in the cell, and the greater the intensity of corrosion.

The conductivity of the electrolyte, i.e. the total dissolved solids content, has an important effect on the distribution of corrosion on the anode. In highly conductive waters, there is a uniform degradation of the anodic metal over a greater surface area, and total weight loss is high. In waters of low total dissolved solids, the conductivity is correspondingly lower. Under these circumstances, the anodic corrosion is primarily concentrated at the junction of the two metals. Total weight loss is low, but rapid penetration could result because of the loss in a small area.

F. Mechanical/Thermal Stress

Cycling of mechanical stress and/or thermal gradients in conjunction with a corrosive environment can lead to rapid failure of metallic components. The stresses that may contribute to failure in heat pump heat exchangers are most likely to occur as cyclic stresses set up by vibration resulting from compressor operation. In those cases where the process appears to be predominantly mechanical in nature and initiated electrochemically, the rate of crack propagation is characteristically much higher than corrosion rates that are purely electrochemical in nature (Shreir, 1963). Corrosion of this nature is usually of the pitting type rather than a uniform thinning.

G. Biological Effects

Bacteria in the heat pump supply water can create corrosion and incrustation problems.

Iron bacteria live in low-temperature waters containing soluble iron salts. Dissolved oxygen tolerances vary, but generally range from 0.3 to 0.9 ppm. In their metabolic processes, the bacteria oxidize the soluble ferrous iron in the water to the insoluble ferric state. The gelatinous slime that forms on the metal face can then entrap small suspended particles, compounding the incrustation problem. In addition, the deposition of the slime material can form the basis of concentration cells. These cells are produced when the electrolyte concentration varies on adjacent areas of the metal surface. This condition is known to accentuate electrochemical attack.

Although aerobic strains of sulfate-reducing bacteria exist, the anaerobic variety is believed to be the cause of most corrosion problems in water supply systems. These bacteria utilize sulfate as a primary energy source and produce hydrogen sulfide, which is a known corrosive in metal-aqueous systems. In addition, the products of the metabolic processes of certain strains of these bacteria depolarize cathodic areas by the removal of hydrogen, allowing electrochemical corrosion to occur.

VI. MANUFACTURED HEAT EXCHANGERS

A. Physical Structure

The water-side heat exchangers available in commercially produced ground-water heat pumps are of two physical configurations. The most common is a coiled, coaxial structure. Of the eight manufacturers sampled, the majority use the configuration in which the inner tube is fabricated from either copper or a cupronickel alloy and contains the water. The heat exchangers, supplied by two manufacturers, use booster fins on the refrigerant side of the inner coil. The outer tube is fabricated from steel and contains the refrigerant. The other coaxial configuration also uses the copper or cupronickel inner tubes which contain the refrigerant, while the outer polybutylene tube contains the water.

One manufacturer uses a shell-and-tube assembly in which water is passed through straight copper tubes, and the refrigerant surrounds the tube bundle. The end plates of this design are removable to allow cleaning of the tubes in case incrusting materials affect the performance of the heat exchangers. Other manufacturers include this feature but only on commercial-sized units.

B. Materials

Copper and alloys of copper have been used in heat exchanger applications for decades. The high thermal conductivity and resistance to corrosion are the primary reasons for the widespread use of these materials in heat exchangers. Generally speaking, copper is adequate for use in natural freshwater applications due to the formation of protective films at the liquid/metal interface. Exceptions to this are examined in the following section.

Condenser tube failures in marine vessels during World War I necessitated research into copper alloys for these applications. This led to the introduction of the copper-nickel alloys which offer high resistance to corrosion. The addition of iron to these alloys produces a protective film that is highly resistant to impingement attack resulting from high velocities.

Four of the eight manufacturers sampled offer the copper-nickel variety heat exchanger as standard equipment, whil the remainder offer the copper heat exchanger as standard equipment. The apparent reason for this is to offer a lower cost heat exchanger where corrosion problems are not anticipated. If these problems are suspected, the more corrosion-resistant, copper-nickel model is supplied at an extra cost.

The resistance to corrosion and incrustation of each of the metals is examined in the following sections.

Copper Copper is noble with respect to the hydrogen electrode in the electromotive series. Under normal conditions, it does not displace hydrogen ions in aqueous solutions. It exhibits low rates of corrosion in nonoxidizing acids, providing oxygen or other depolarizing agents are not present.

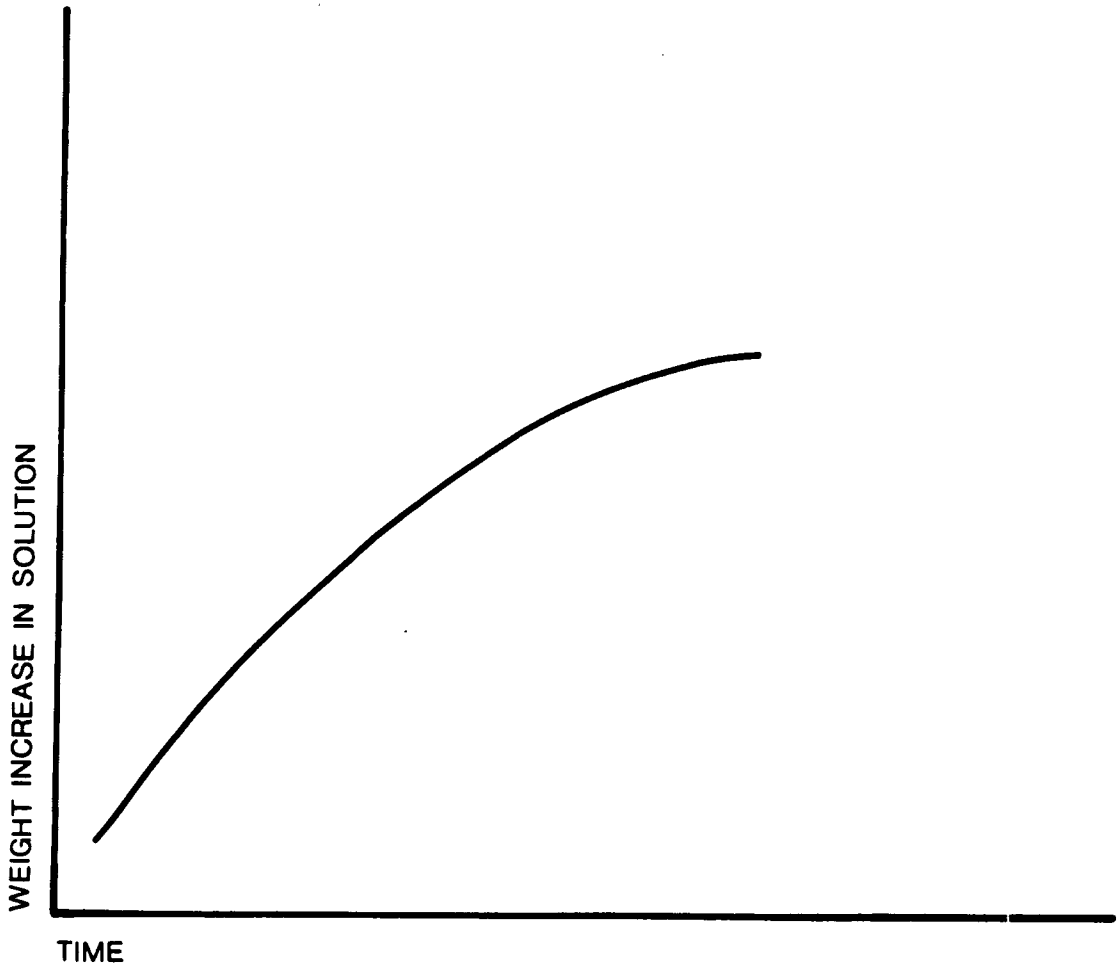
In the presence of oxygen and oxidizing acids, the overall corrosion reaction may be considered to be:

$$2\ Cu + 4H^{+} + O_2 \rightleftharpoons 2\ Cu^{++} + 2H_2O \qquad \text{(Equation 2)}$$

(Leidheiser, 1971)

The rate of reaction is non-linear with respect to time and the rate of oxygen supply because the formation of a stable film on the metal surface prevents the diffusion of oxygen to the surface. In aerated natural waters low in carbon dioxide and anions, the protective film is cuprous oxide and cupric hydroxide. The corrosion rate is known as a parabolic relationship with time and is represented qualitatively in Figure 1.13. Oxygen, then, performs a dual role in its reaction with copper by enhancing corrosion at cathodic areas and by forming oxygen-bearing protective films. In this sense, a limited amount of oxygen may result in a more corrosive condition than an abundant supply (Uhlig, 1948). Any factor which changes the solubility of

Figure 1.13
Corrosion Rate of Copper



oxygen in solution would change the corrosion rate. The effect of temperature on the solubility of oxygen was examined in Section 1.VD.

The presence of carbon dioxide in solution with oxygen greatly accelerates the corrosion rate and alters the configuration of the corrosion curve. Figure 1.14 shows the time relationship of oxygen and copper in solution for different carbon dioxide concentrations in tap water. The apparent reason for this is the formation of carbonic acid from the reaction of water and the dissolved carbon dioxide. This weak acid degrades and prevents the formation of protective films on the metal surface. The metal surface is then subject to attack as described in Equation 1.

Copper shows a low resistance to corrosion in the presence of sulfur and sulfur compounds in polluted or brackish water environments. Hydrogen sulfide is probably the most important of these compounds in these environments.

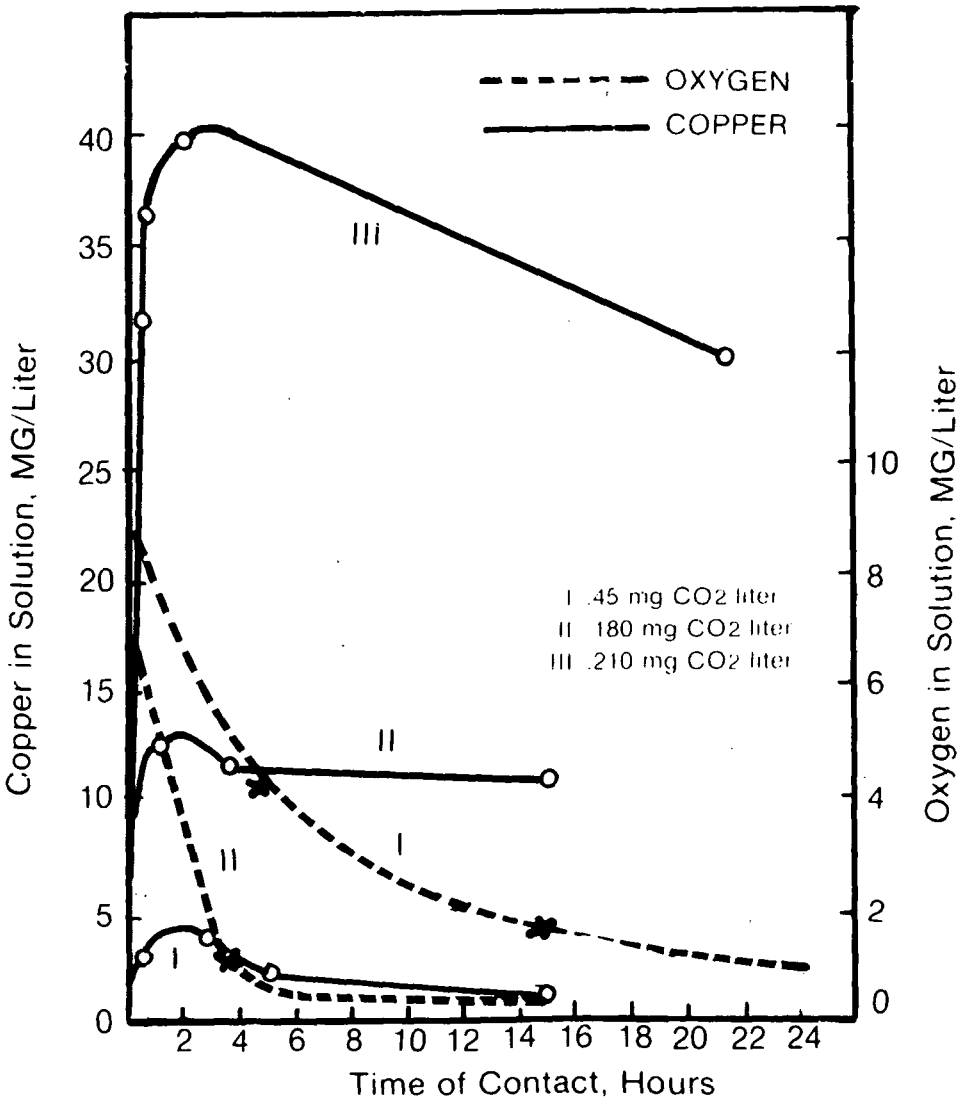
In field terminology, the reference to "sulfur water" is due to the presence of hydrogen sulfide in the water. When dissolved, the compound forms hydrosulfuric acid, a weak acid with a dissociation constant of 1.0×10^{-7}. Apparently, the acid is of sufficiently high strength to cause rapid deterioration of copper by preventing the formation of the protective film.

Copper is also susceptible to impingement attack, especially at high velocities in conjunction with suspended particles or air bubbles. If impingement attack is anticipated, the copper-nickel heat exchanger is preferred because it offers a higher resistance to erosion-corrosion. Recommended velocities for fluids in copper tubing range from 2.5 to 9.9 feet per second (0.8 to 3.0 m/sec) (Scoville Mfg. Co., 1950).

Galvanic coupling of copper with reactive metals (see Table 1.2) should be avoided. Those metals are anodic to copper and are subject to galvanic corrosion. In industrial applications, coupling of copper with galvanized steel or iron has resulted in failure.

Figure 1.15 shows the effect of pH on the corrosion rates of copper in chloride and sulfate solutions. For pH values less than 7.0 found in natural ground waters, concentrations of this magnitude do not appear to present problems.

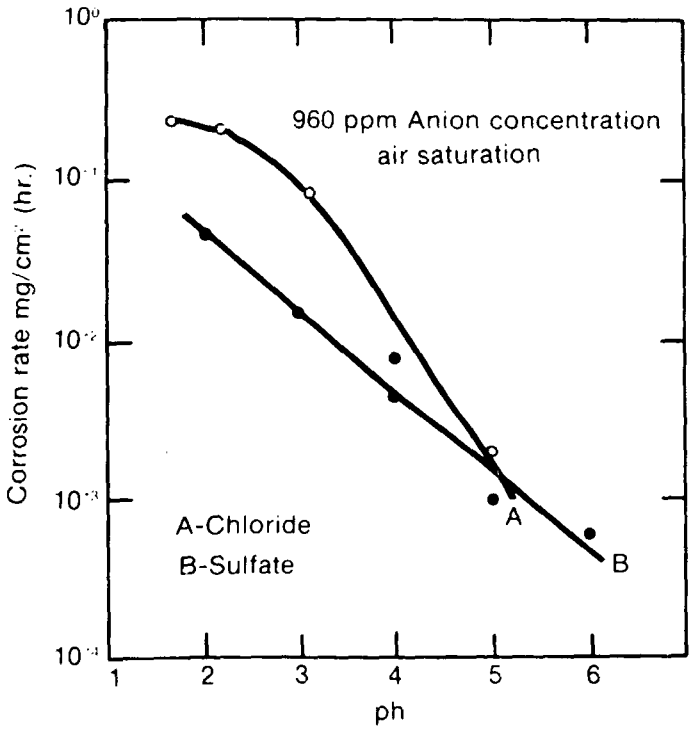
Figure 1.14
Corrosion Rate of Copper in Solutions Containing Oxygen and Carbon Dioxide



Copper and oxygen contents of tap water containing varying amounts of added carbon dioxide, after standing for different periods of time in copper pipes at 20 C

Source: Uhlig, 1948

Figure 1.15
Corrosion Rates of Copper in Chloride and Sulfate Solutions



Source: Leidheiser, 1971

Cupronickel The cupronickel alloys are solid solutions in which copper is the predominate constituent. Copper content ranges from approximately 54 percent to nearly pure copper. The copper-nickel alloys used in the residential heat pump heat exchangers are exclusively the 90:10 variety, alloy No. 706.

The cupronickel heat exchangers offer many of the same advantages as the standard copper variety. The primary advantage of the cupronickel alloy lies in its resistance to impingement attack, especially in these alloys containing iron (0.3 to 5 percent).

Corrosion rates in fresh waters are difficult to predict in detail because of the differences in concentrations of many constituents. Dissolved mineral matter, organic matter, gases, and suspended solids all interact, making it difficult to predict the actual course and rate that corrosion follows. Copper-nickel alloys generally exhibit excellent corrosion resistance to both polluted and fresh waters, with corrosion rates less than 0.001 inches per year (0.003 cm per year), (Uhlig, 1948).

Similar to copper and other metals, the corrosion resistance of the cupronickel metals results from the formation of the protective film at the metal/liquid interface. The addition of trace amounts of iron not only inhibits impingement corrosion but also appears to stifle attack by polluted or brackish waters that are allowed to stand in unused heat exchangers for long periods of time.

Galvanic coupling of cupronickel alloys to other copper alloys generally does not result in substantial corrosion. In applications where the water is low in total dissolved solids, conductivity is low, and galvanic corrosion does occur, it is usually at or very near the metal-to-metal junction. As with copper heat exchangers, the coupling of cupronickel with reactive metals such as aluminum and zinc should be avoided, especially if the ground water is high in total dissolved solids. Coupling with steel should be avoided under the same conditions.

The 90:10 copper-nickel alloy shows good resistance to stress corrosion from vibration in both fresh water and salt water applications. Of ten copper and copper alloy metals, this variety ranked second to 60:40 brass in resistance to

corrosion under severe vibration conditions. With proper design of vibration isolation, however, copper is acceptable.

Corrosion by microorganisms Sulfate-reducing bacteria have a corrosive effect on copper and copper alloy metals. The primary effect is that hydrogen sulfide evolves from metabolic processes of the bacteria. A study undertaken by Gilbert (1947) indicates severe corrosion of copper and its alloys in the presence of sulfate-reducing bacteria. Although the test was not conducted under design conditions for ground-water heat pump applications, the biochemical environment may have been similar. The hydrogen sulfide produced by the bacteria prevents the accumulation of the protective film which enhances the corrosion process.

As pointed out in Section 1.VG, the accumulation of slime in heat exchangers could lead to the formation of concentration cells which could result in further damage. However, this phenomenon has not been observed in field installations.

Incrustation of copper and alloy 706 For the operating temperature range of ground-water heat pump applications, little literature has been published regarding the behavior of copper and cupronickel metals in scaling environments in natural waters. The Stability Index can only be used as a guide to determine the tendency to corrode or form scale, as discussed in Section 1.IVA.

When questioned as to the mechanism by which the metals resist scale, most of the manufacturers' engineers were unsure as to the exact process. A possible explanation is that scale exfoliation was due at least in part to the expansion and contraction characteristics of the metals. Furthermore, it is possible that the adherence of carbonate or oxide scale to the protective oxygen-bearing film is not as strong as that of the metal to the film. This factor, in conjunction with the expansion characteristics, may explain the low rate of incidence of scale formation. However, this is not substantiated by available published literature. Further investigation into the chemical thermodynamics of this explanation is outside the scope of this study.

Survey of operating heat pumps A telephone survey was conducted in April, 1979, to obtain information regarding corrosion and incrustation problems that occurred in

existing residential and commercial installations. Engineering personnel, homeowners, and HVAC contractors were interviewed. The ten interviews accounted for a total of approximately 240 installations. Information for approximately 130 of these was obtained from manufacturers and distributors in Ohio. Information for approximately 100 was obtained from an installing contractor in Florida. The remaining information was obtained from homeowners and engineering designers in the Northeast and Midwest. The problems and probable causes experienced for these installations are described below.

One residential installation in Florida experienced blockage of a cupronickel heat exchanger due to the accumulation of bacterial slime. Continuous chlorination at the well screen solved the problem. Although high concentrations of chlorine are corrosive to copper and cupronickel, sufficient dilution apparently takes place before the supply water enters the heat exchanger.

Another residential installation in Florida experienced scaling of the heat exchanger as a result of overheating. Apparently, an undersized pump was used in the installation. Flow rate was not adequate for sufficient heat rejection in the cooling mode, resulting in exsolution of a sulfate scale. Cleansing of the heat exchanger and the installation of a pump with proper capacity rectified the problem.

The same contractor reported that installations operating in his area utilized ground water with an iron content as high as 36 ppm. At the time of this writing, he had not received any reports of iron oxide or iron hydroxide incrustation on the cupronickel heat exchangers.

One distributor in Ohio reported an accumulation of iron bacteria on the cupronickel heat exchanger of a hot water generator. Flushing with chlorinated water every three months prevented a significant accumulation of the material.

All four commercial installations examined had developed a yearly maintenance and inspection program. None of the inspections showed a significant accumulation of scale or slime on the heat exchangers in the year period. Chemical and mechanical cleaning are used to remove any slight accumulation of scale.

Nearly all installations examined had been installed within three years of the time of this writing. Therefore, long-term effects cannot be examined yet. The manufacturers appear to be confident that effects will not be significant. In fact, most manufacturers warrant the cupronickel heat exchanger for either five or ten years. One commercial installation that has been in operation for twenty years has not experienced any corrosion problems.

Additional information regarding the corrosion of copper and cupronickel can be obtained from industrial studies. Table 1.3 shows some examples of corrosion rates of those materials under varying conditions.

VII. MAINTENANCE OF WATER-SIDE HEAT EXCHANGERS

For installations in which water quality results in scaling of the heat exchangers, periodic draining and flushing with suitable chemicals is recommended. The frequency of maintenance will vary depending on the severity of scaling.

The use of water pressure gauges at the high and low pressure sides of the coil is recommended to determine the need for descaling. The heat exchanger is designed to produce a narrow range of pressure drop at a given flow rate. Pressure drop through manufactured units generally range from 2 to 10 psig (1.37×10^4 to 6.87×10^4 N/m^2) as a function of flow rate. A substantial increase in pressure drop indicated by the pressure gauges signals a high probability of mineral and/or biological incrustation in the heat exchanger.

One heat exchanger manufacturer recommends the use of two compounds for chemical treatment. A dilute caustic soda ($Na(OH)_2$) solution is used to remove bacterial slime and entrapped sediment from the heat exchanger surface. The solution is prepared by mixing 5 ounces (0.1 l) of the commercial powdered chemical with 1 gallon (3.9 l) of warm water. The other compound used in the process is a 15 percent by volume solution of inhibited hydrochloric acid. The solution is prepared by diluting 1 pint (0.5 l) of the commercial acid solution with 3 quarts (2.8 l) of water. The solution is used to remove chemical scale from the metal surface.

Table 1.3

Corrosion Rates

Condition of Exposure	Duration of Test (days)	Corrosion rate, in/yr (cm/yr)	
		Cu	90:10 Cu:Ni
Water side of tubular cooler, pH 7.8 alkalinity is $CaCO_3$ 165 ppm T = 66°F (19°C)	40	.004 ([illegible])	
Outlet at condenser water box, pH 5, at times as low as 3	240	.004 (.010)	.0[illegible] (.015)
Well water high in free CO_2, low temperature	630	.001 (.003)	
Open tank handling well water, 85 ppm CO_2, 65 ppm H_2S 120 ppm NaCl	104	.002 (.005)	
Well water, low pH, high CO_2, near 1 ppm O_2, 50°F - 68°F (10°C-20°C)	—	.015 max. (.038)	

Source: Modified after Leidheiser, 1971

These solutions can be used on both the shell-and-tube and coaxial heat exchangers. Units with the coaxial design must incorporate isolating valves so that the solution can be circulated through the heat exchanger without circulation through the entire water system. A small positive displacement pump can then be used in the application.

The same solutions can be used for descaling the shell-and-tube heat exchangers. For this design, the water supply to the unit must be turned off. The end plates of the heat exchanger can be removed, and a soft, metal-brush cleaning rod can then be used with the chemicals to remove slime and scale material.

Both of these solutions are potentially corrosive to the heat exchangers, especially the copper variety. Therefore, it is important that the solutions are not left in contact with the metal surface for extended periods of time.

CHAPTER 2
ENVIRONMENTAL ASPECTS OF GROUND-WATER HEAT PUMP USE

I. INTRODUCTION

The use of ground water for the operation of ground-water source heat pumps is expected to have a minimal impact on the environment. In fact, in some cases positive effects can be expected. The effect on the environment depends on the following factors:

(1) whether water is recharged
(2) variations in heating and cooling load
(3) density of use

The consumptive use of ground water involves the withdrawal and subsequent remote disposal of the spent heat pump water. Remote disposal can be accomplished in several ways, including discharge into nearby streams, ditches, and reservoirs. Without proper planning, this type of ground-water use may have certain undesirable effects on the environment.

The non-consumptive use of ground water involves the removal of water from the aquifer and its subsequent reinjection into an aquifer near the site of withdrawal. This method eliminates many of the problems associated with the consumptive use of ground water but creates several of its own. Being reinjected, the water will have been thermally altered (that is, its temperature will have been raised or lowered several degrees). The effect of this thermal pollution on the aquifer should be considered. However, previous studies (Andrews, 1978; Schaetzle and Brett, 1974) have indicated that the non-consumptive use of ground water for heating and cooling demonstrates no serious environmental impacts.

II. CONSUMPTIVE USE OF GROUND WATER

The consumptive use of ground water in heat pumps involves the withdrawal of water and its subsequent surface disposal by any of several methods. The term "consumptive" is misleading in that it implies permanent removal of the ground water. Actually, the water is eventually returned to the hydrologic cycle. On a small scale or when density of

utilization is low, the consumptive use of ground water will have minimal effects. It is only when high density usage occurs that the impacts may be serious.

Once water has passed through the heat pump system various alternatives for surface disposal include discharge into nearby ditches, streams, storm drains, sewers, septic tanks, or cesspools. Disposal into septic tanks and cesspools is considered surface discharge only in areas where the water table is not present at shallow depths. In areas where the water table is close to the surface, discharge into septic tanks and cesspools is a form of recharge.

A. Problems Associated with Consumptive Use

The most common problem to be anticipated is the effect of well interference where wells are closely spaced. This interference situation is most likely to occur where there is high density usage of heat pumps on relatively small lots. When water is discharging from a flowing well, the local water level is lowered. In an area where there are numerous wells, the water table may be depressed to the point where some of the shallower wells no longer produce sufficient quantities of water.

The consumptive use of ground water on a large scale along coastal areas may establish new hydraulic gradients that favor the intrusion of salt water. In other areas, the establishment of new gradients may result in the upward coning of saline or connate waters from deeper zones. Saline waters are derived from the solution of evaporite formations such as gypsum, halite, or anhydrite. Connate water is composed of water that remains in the formation after burial and lithification of the sediments. These types of water would be unsuitable for use in the domestic water supply.

In areas where withdrawal exceeds available natural recharge and storage, land subsidence may present a problem. This subsidence is caused by an increase in pressure which compacts the aquifer matrix. For unconfined aquifers, this increase results from a loss of buoyancy of the aquifer matrix in the dewatered zone. For confined aquifers, the increase in pressures is a result of decrease in hydrostatic pressures against the bottom of the upper confining layer. Bouwer (1977) has calculated that the rate of subsidence

will range from 2 to 20 inches (5 to 50 cm) for every 33 foot (10 m) drop in ground-water levels for unconsolidated deposits. Surface cracks or faults may result from nonuniform subsidence induced by differential water declines or differences in compressivity of subsurface materials. These faults may act as fluid barriers. The effect of these surface cracks on the ability of the aquifer to transmit water warrants further study.

A more localized form of land subsidence occurs in areas underlain by carbonate formations. In humid regions where carbonate formations have undergone extensive karstification, subsidence occurs through the development of sinkholes. Joints and fractures within these formations may be widened by solution-formed cavities. When water levels decline, there is a reduction in hydrostatic pressure. The roof of a cavity may slowly lose its underlying support to the point where it collapses under its own weight.

Several decades of pumping in areas such as Houston, Texas; south-central Arizona; and the San Joaquin Valley in California have resulted in the lowering of ground-water levels and accompanying land subsidence (Kreitler, 1976; Gabrysch, 1976; Lofgren, 1969; Schumann, 1969). Unfortunately, once land subsidence has occurred, it is essentially irreversible. The rebound of the land surface is normally insignificant even if the ground-water levels are restored to pre-subsidence heights (Bouwer, 1977). However, land subsidence can be limited by halting water level declines and, where necessary, replenishing the ground water to prevent residual compression of clay layers.

Since the consumptive use of ground water involves surface discharge, high density heat pump usage may lead to a number of problems. A discharge of 1.4 mgd (5.3×10^3 m^3/day) can be generated by 100 homes where each installation continuously discharges 10 gpm (0.6 l/s). This discharge can tax the capacity of sewer systems, overload the capacity of the treatment plant, or inadvertently flood low areas.

Problems with erosion may also occur when water is discharged into streams and ditches. Increased discharge can lead to increased erosion and therefore, sediment load. The effects of increased sediment load (suspended solids) include: (1) mechanical (abrasive) action, (2) loss of light penetration, (3) blanketing action (deposition of sediments), (4) availability as a surface for growth of

microorganisms, (5) adsorption or absorption of various chemicals or both, and (6) change in temperature fluctuations (Cairns, 1978). Any or all of these can have an effect on the aquatic life in a stream.

The water being discharged from a heat pump installation will not be chemically altered, but its temperature will have been raised (10° to 20°F/6° to 11°C while operating inthe cooling mode) or lowered (5° to 10°F/3° to 6°C while operating in the heating mode). The effect of the discharge for thermally altered water must be considered. The aquatic biosphere is normally exposed to some thermal variations. Problems occur when there are high frequency changes or extreme temperature variations. In the situation of disposal of heat pump water, the change would be consistent. In this case, alteration of species distribution may be expected near the discharge, only where more tolerant species can exist.

The consumptive use of ground water in environmentally sensitive regions may aggravate and even directly contribute to the imbalance of the hydrologic system. Additional stress imposed by ground-water heat pumps within such regions may create a situation where ground-water withdrawals exceed storage or recharge or both. Under such conditions, the ground water is mined; thus, priorities and goals must be established so that this limited resource can be efficiently utilized. The removal of ground water and method of disposal must be evaluated on a site-specific basis. The monitoring and careful management of ground-water resources can avoid many of the problems associated with the intense development and consumptive use of ground water.

III. NON-CONSUMPTIVE USE OF GROUND WATER

The non-consumptive use of ground water for the operation of heat pumps entails the discharge of water into an injection well (or other subsurface disposal device) after it has passed through the system. The hydrologic system would maintain an equilibrium between inflow and outflow where the heat pump water is reinjected. However, the discharge water will be thermally altered, that is, the temperature of the water will be raised or lowered, depending on the mode of operation of the heat pump. The effect of this thermal alteration on the aquifer's

hydrologic properties is the primary environmental concern associated with non-consumptive use.

A. Problems Associated with Non-Consumptive Use

Several studies have examined cyclic heat extraction or heat transfer through aquifer systems. Andrews (1978) simulated the impact of heat pump use for residential heating and cooling of ground-water temperature by means of a mathematical model. A hypothetical case using data for southern Wisconsin was considered. Ten years of operation of a dual well system in a subsurface aquifer produced a change in water temperature of less than 1.8°F (1°C) at a distance greater than 132 feet (40 m) from the wells. This evidence indicates that reinjection of spent heat pump water would not adversely affect ground-water temperatures if use was restricted to areas of low population density.

High-density usage of ground-water heat pumps could have a more pronounced effect on the environment. In one study done in northeastern Illinois, the wells for cooling installations penetrated sandstone aquifers. The aquifers showed no evidence of undesirable effects related to the injection of higher temperature water. Four installations each recharged 25,000 to 345,000 gpd (1.1 to 15.1 l/s) at an initial temperature of 85° to 110°F (29.4° to 43.3°C) (Sasman, 1972). Another study concerned the use and subsequent recharge of ground water for air conditioning of commercial buildings on Long Island (Brashears, 1941). In several cases, thermal well interference occurred between the production and injection wells. The increased ground-water temperature resulted in lowered efficiency of the cooling system, which therefore increased operating costs. However, no adverse effects on the aquifer were noted. In light of Brashears's work, it is the opinion of the authors of this report that no serious environmental impacts were encountered on Long Island.

The transfer of thermal energy within an aquifer is accomplished by convection, hydrodynamic dispersion, and conduction. The areal extent of thermal alteration within an aquifer depends on the rate of ground-water movement, the amount of thermal energy added to or subtracted from the system, as well as the thermal properties of the aquifer. Variations in heat transfer can result from changes in porosity, transmissivity, or lithology. Other perturbations of the thermal regime can result from the recharge of phreatic waters in an unconfined aquifer (Werner and Kley,

1977). By proper spacing of wells, thermal interference can be avoided.

Thermal alteration of ground water may also have an effect in the chemical equilibrium of the aquifer system. The chemical composition of ground water is subject to a variety of complex interactions that are dependent on its geologic, hydrologic, and biologic characteristics, as well as the presence of man-made contaminants. Of concern is the extent to which temperature changes affect water-rock or water-water chemical reactions. However, the environmental consequences of altering the chemical equilibrium of ground water through heat pump operation is not well documented.

The effects of thermal alteration on the natural chemical equilibrium of ground water can best be understood when the chemical factors involved are considered. In ground-water systems, the types of chemical reactions that are reversible and rapid enough to be of concern here include:

(1) Adsorption or desorption of cations or anions held at the surface of the aquifer matrix
(2) Solution or precipitation of mineral salts
(3) Oxidation, reduction, or hydrolysis of certain metals (Hem, 1963)

The most serious potential impact would be the precipitation of mineral salts that could clog the pore spaces of the aquifer, inhibiting ground-water movement. However, the solubility of common salts, mainly magnesium and calcium, is highly dependent on pH-Eh conditions, and only to a lesser extent on temperature. Therefore, the impact of changing the solubility of salts in aquifers at the anticipated temperature ranges, resulting from the discharge of heat pump water, could only be measured in terms of geologic time (Schaetzle and Brett, 1979). It is unlikely that the operation of the heat pump units would affect the pH-Eh of the aquifer system. The units would therefore not alter the existing chemical equilibrium of the system.

The Research Facility at the National Water Well Association (NWWA) is currently conducting research for the U.S. Environmental Protection Agency (Grant #R806 465-01-1) that will provide experimental data regarding the thermal and chemical alteration of ground water used for heat pump

supply water. In this project, the heat pump discharge water of a residential installation is routed underground to a recharge well. There the water temperature and depth to water are monitored. In addition, various chemical parameters are measured weekly from four observation wells to obtain data regarding the time-dependent changes (if any) of numerous water constituent concentrations. After seven months of operation, no noticeable change in water quality has been detected for the parameters tested.

The temperature and water depth measurements provide data to delineate the spatial and temporal distribution of the thermal plume that results from the injection of thermally altered water. A computer simulation is being developed which will be validated with experimental data obtained from the site. This simulation will be used to predict the thermal alteration under varied hydrogeologic conditions. The projected completion date for this work is July 1981.

IV. GROUND-WATER QUALITY

Ground-water quality must be considered in the operation of heat pumps. Where the ground water has been previously polluted, such contamination could be spread further via the heat pump supply and injection wells. For example, in a dual aquifer system, polluted ground water from the upper aquifer is cycled through the heat pump and subsequently reinjected into a lower aquifer. The introduction of contaminants into the lower aquifer would certainly degrade its potability. In this case, discharge of the spent heat pump water into the producing aquifer would have the least detrimental effect. However, contaminants may also be spread into different portions of a single aquifer system. Any detrimental influences can most likely be mitigated by chemical treatment of the discharge prior to reinjection. Further research into this area is necessary to fully determine the possible effects.

The areal extent in which contaminants are spread throughout an aquifer depends on the density of heat pump units operating in any given area. Ground-water pollution is more likely to be severe and widespread where the greatest density of wells supplying heat pumps exist. In these circumstances, it may be advisable to use the ground water consumptively or treat it prior to reinjection.

Another consideration is the mixing of chemically incompatible waters from one aquifer into another. This situation could occur in a dual well system where water is withdrawn from one aquifer and discharged into another or where surface waters are artificially injected. Precipitation of calcium carbonate could occur where ground water containing high concentrations of calcium, bicarbonate, and carbonate are injected into an aquifer deficient in carbon dioxide. Similarly, the injection of oxygen-rich waters into reducing waters may cause the precipitation of ferric hydroxide (Sniegocki, 1963). In general, a greater number of problems would be encountered when the Eh-pH equilibrium of the native ground water is radically different from the injected water. The possible precipitation of salts or dispersion of clay colloids could close the aquifer pore spaces and substantially reduce its permeability. In a multi-aquifer situation, especially where there is significant leakage between the aquifers, waters are more likely to be chemically compatible. The problem would tend to be more severe in situations in which recharge water is imported, of surface origin, or radically different from ground waters.

V. POSITIVE ENVIRONMENTAL IMPACTS

The non-consumptive use of ground water for heat pump operation is expected to have some positive effects on the environment. Ground-water source heat pumps conserve energy and reduce pollution produced by more conventional systems (Schaetzle and Brett, 1979). Particulate, gas, and thermal pollution in urban and industrial areas has been shown to modify weather patterns by altering temperatures and rainfall (Huff and Changnon, 1973). It appears that these favorable environmental impacts more than offset the slight and often insignificant thermal-fluid alterations that occur through the operation of ground-water source heat pumps (Lehr, 1977).

VI. MANAGEMENT SUGGESTIONS

Optimum utilization of ground water as an energy source can be achieved by careful planning. Many of the problems associated with the intensive development of ground-water resources can be prevented.

Whenever possible, the consumptive use of ground water in heat pumps should be avoided. The problems associated with widespread, high density use of this method are usually too numerous to warrant its use. Situations in which the consumptive use would be desirable include the case in which ground-water supply has been previously contaminated. In this case, the reinjection of heat pump water (as in non-consumptive use) could spread the pollution into other aquifers. Under these circumstances, the consumptive use of ground water would be preferable.

A possible alternative to consumptive use is the implementation of earth-coupled well systems. These closed loop units do not withdraw water from the well and thus avoid problems of aquifer depletion.

Some problems are associated with the non-consumptive use of ground-water supplies. The most serious of these is the thermal alteration of the aquifer system. However, the environmental effects of thermal alteration of the aquifer are minimal; the greatest effect will be on the performance of the heat pump system. Management of the heat balance within an aquifer is essential in urban areas where heat transfer between several users may have to be coordinated. The spacing of private domestic wells is likely to depend on property boundaries rather than hydrologic characteristics of the aquifer under development. Random installation of ground-water heat pumps could lead to thermal well interference through improper well spacing. The efficiency of the heat pump system would be considerably reduced where a sufficient amount of interference exists.

Through careful planning and analysis of the aquifer prior to housing construction, it is possible to avoid the problem of well interference. Favorable site locations can be depicted from a regional composite of overlays where each overlay displays a select environmental characteristic of the aquifer in the proposed construction area (Dove and Schreuder, 1979). Production and injection wells can be spaced for optimum dissipation of thermal energy within the aquifer. Well spacing should be based on the heating and cooling loads for the proposed number of residential units to be built at a given location. Planning should also include a consideration of the aquifer's hydrologic properties to ensure the efficient utilization of ground water for the operation of ground-water heat pumps. To

review this area, NWWA is currently working with the University of Missouri to develop a model under the U.S. EPA Grant #R806-465-01-1 previously discussed. This model will be validated with experimental data obtained for the test installation and will be used to predict thermal alteration under varied hydrogeologic conditions. Information can then be used to plan optimum spacing for production of injection wells.

Renovation of existing housing subdivisions could utilize a cluster well concept. A group of houses, each with its own heat pump unit, could be supplied by a common production and injection well (Schaetzle and Brett, 1979). This system is analogous to a small rural water supply system in that each home would connect with central distribution mains. Such a system would avoid well interference through the construction of strategically located high-capacity wells.

In a single aquifer system, both the production and injection wells use the same aquifer. This may limit the number of heat pumps in a given area. A greater aquifer volume is needed for thermal reconditioning of injected water as it is transmitted from the injection to the production well.

A dual aquifer system enhances the feasibility of operating a greater number of heat pumps in a smaller area. This type of system can operate effectively only where two or more aquifers exist of sufficient capacity and chemical compatibility. Several commercial scale ground-water heat pump installations using a dual aquifer system have been operating in Oregon and Washington since the early 1960s (Price et al., 1965). In general, one aquifer is used for storing cold water, while another aquifer is exclusively used for storing warm water. Alternate aquifers could then be used during the heating and cooling seasons, increasing system efficiency. Under ideal circumstances, this type of system could operate indefinitely. However, most areas would experience an alteration of ground-water temperature after several years of operation due to an imbalance between heating and cooling loads. The recharge must be controlled in order to maintain thermal equilibrium in a multiple aquifer system.

VII. SUMMARY

Environmental impacts associated with the high density usage of ground-water heat pumps are minimal or non-existent when the properties of the hydrologic system are evaluated. However, in areas where well yields are low, consumptive use of ground water under high density usage conditions can lead to depletion of the aquifer. In environmentally sensitive ground-water regions, careful planning is required in order to minimize environmental impacts. Ideally in such areas, the artificial recharge of the spent heat pump water is the most efficient method of reducing most adverse impacts. The slight thermal alteration of ground-water temperatures within the aquifer is insignificant when compared to the substantial energy savings of ground-water source heat pumps.

CHAPTER 3
LEGAL ASPECTS OF GROUND-WATER HEAT PUMP USE

I. INTRODUCTION

The use of ground-water source heat pumps may meet with a number of legal problems involving water use and water quality control. Federal, state, and local laws and regulations may obstruct the utilization of this alternative energy source.

This problem is analyzed through a study of federal and state legislation concerning ground-water use and wastewater disposal. The two major Federal programs for ground-water quality control -- the National Pollutant Discharge Elimination System (NPDES) and the Underground Injection Control program (UIC) -- are analyzed, and a state-by-state review of water use restrictions, well construction standards, and waste disposal regulations is presented. To the extent possible, pertinent county and municipal regulations also are examined for their potential to affect heat pump use. While the sheer number of local ordinances precludes their incorporation in this report, examples of local control are presented to illustrate potential problem areas.

This study takes as strict an interpretation of legislation as is practical. That is, if the literal interpretation of a law indicates that it may affect utilization of a residential ground-water heat pump, the law is reviewed. This does not mean that all laws applicable to heat pump use would be enforced if a heat pump were installed. Water use and water quality protection laws suffer from lax enforcement in some areas and virtually no enforcement in others.

In situations involving only a small volume of ground-water heat pumps, users probably will not be forced to comply with all applicable legislation. Nevertheless, an understanding of this legislation is crucial in preparing for the widespread application of heat pump technology. As water use and effluent discharge increases, stricter regulation of the water use and disposal aspects of ground-water heat pumps will likely evolve.

In the review of legislation, many ambiguities were noted in the use of terms such as law, act, statute, regulation, and ordinance. For the purpose of this study, the terms law, act, and statute are used interchangeably to denote a legislative enactment of a federal or state legislative body. The word "ordinance" refers to county or local government enactments. Regulation ordinarily means an administrative action rather than an enactment of a legislative body. In some cases, however, regulations may be adopted by legislative bodies, as will be indicated in the text.

The NWWA Legislative Research Division's extensive legislative files proved invaluable in the preparation of this report. Where necessary, state and local regulatory officials were contacted to answer questions concerning content and enforcement of regulations.

A. Ground-Water Use

The use of a ground-water source heat pump for residential heating requires a well that can provide up to 15 gallons of water per minute (0.9 l/s), depending on the size of the house, the type and efficiency of the system, and the climatic conditions. This presents certain legal problems. The installation or use of the type of well needed to supply a ground-water heat pump is prohibited in some areas of the country. This prohibition may have been enacted to require use of public water supply, to prevent lowering of ground-water levels or the depletion of the ground-water resource, or to prevent the use of contaminated ground water. Whatever the reason for the prohibition, development of ground-water heat pumps will not be possible in these areas.

A loophole in these regulations may permit the installation of ground-coupled heat pump systems in some areas where conventional units are prohibited. Many of these rules are written to prevent the withdrawal of water from a well for domestic purposes. The ground-coupled system does not actually withdraw water from the well and may thus be exempt from this prohibition.

In other instances, however, the restriction exists against the installation of wells for domestic use. Ground-coupled systems would be prohibited in these situations, as conventional heat pump units would be.

Many areas that allow the drilling of a well require that a permit be obtained for the installation or use of a well. The procedure involved in acquiring a permit can sometimes be too expensive or too complicated to be considered a reasonable option for the individual homeowner. However, certain types of wells qualify for exemptions that simplify the permit procedure or waive the permit requirement entirely. A standard for exemption found in many areas is based on a maximum allowable volume of pumpage per day. This volume limitation is often high enough to include heat pump use. For example, the maximum pumpage allowed without a permit in New Jersey is 100,000 gallons per day (gpd) (378,500 l/day). Nevada, by contrast, allows a volume of only 1,800 gpd (6,813 l/day) to be used without obtaining a permit, significantly less than the amount needed for successful heat pump operation. Other states have values within the range of Nevada and New Jersey. The major problem areas for heat pump use are found in the more arid Western states.

Several states exempt wells used for domestic purposes from permit requirements. The definition of "domestic purposes" can cause problems for heat pump development. Domestic use is most commonly defined as use for the ordinary household purposes of drinking, bathing, cleaning, and cooking. The problem with this standard definition is that it does not include heating or cooling as an ordinary domestic use. In most cases, this results not from intentional exclusion, but from inadvertent failure to recognize home heating and cooling as a domestic water use. Therefore, except where other definitions, statutes, or regulations indicate a separate classification, home heating and cooling via ground-water heat pumps will be considered a domestic use of water.

Some states combine a maximum volume limitation and a definition in their classification of domestic use, while others use well diameter or location to determine permit requirements. These limitations and their effects on heat pump use will be examined in a later section.

B. Disposal of Water

The operation of a domestic ground-water source heat pump requires the disposal of up to 22,000 gpd (83,270 l/day) of slightly heated or cooled water. Water may be discharged to an aquifer recharge well, to a surface water

body, to a leach field, or to a sewer, depending upon the heat pump system used. Each of these disposal methods is subject to statutes and regulations.

Discharge to surface water is regulated in every state by the National Pollutant Discharge Elimination System. Individual states may supplement NPDES with their own strict standards of surface-water quality that affect the method of discharge of heat pump effluent.

Though discharge to a well is the most environmentally sound method of disposal in that it creates a non-consumptive use of water, it meets frequently with legal problems. Several states limit or prohibit the discharge of any waste to a well. Others have complicated monitoring and permit procedures that can prove burdensome to the individual homeowner. These requirements, along with water use restrictions, well construction standards, and effluent disposal regulations, are examined in detail in the following sections. This assessment of federal and state controls of ground water yields an evaluation of the real and potential impact of these controls on the implementation of ground-water heat pump technology.

II. FEDERAL CONTROLS

There are no Federal controls on ground water use that will have a significant impact on heat pump development. The Federal government allows the states to control allocation of the resource and limits its influence to ground-water quality control programs. Two of these programs, the National Pollutant Discharge Elimination System and the Underground Injection Control program, have the potential to influence heat pump utilization.

A. NPDES Program

The NPDES program was created by Section 402 of the Federal Water Pollution Control Act Amendments of 1972. In 1977, new amendments were passed, and the Act is now known as the Clean Water Act. The NPDES permit program is designed to control all discharge of pollutants into U.S. waterways. Permits may be issued by either the EPA or an approved state. The Clean Water Act establishes that the states have the primary responsibility to control water pollution. The Act provides that states shall be approved

to operate the NPDES program if their state system conforms to federal specifications. The majority of states have been approved by the EPA to operate the program within their boundaries. The EPA conducts the program in the other states and territories.

Permit System The NPDES and the state programs it has created utilize a permit system to impose detailed pollution control requirements on waste discharges to surface waterways. These regulations stipulate that any owner or operator of a source that discharges pollutants into the surface waters of the United States must have a permit. Exemptions to this rule are granted to: irrigation return flows, vessels being used for transportation, dischargers of dredged or fill material, and agricultural and silvicultural operations producing pollutants through runoff.

The permits limit discharges of effluents, impose schedules of compliance, and require permittees to monitor their discharges, and report results to the permitting agency. NPDES permits are valid for up to five years. The permit terms and conditions may be modified or revoked during the permit period. Permittees are required to apply for renewal before their permit expires.

Dischargers must apply to the EPA or approved state agency for an NPDES permit. Permit terms and conditions vary according to the nature and extent of the discharge. The conditions of the permits are based on national and state guidelines for water quality protection. Permit decisions may be appealed by the applicant or by interested parties seeking different permit conditions.

Implications for Heat Pump Use This program has serious implications for ground-water heat pump use. Heat is defined as a waste product under the NPDES system. Heat discharges are limited through requirements that state the temperature of the receiving surface-water body not be altered by more than a few degrees centigrade. The permissible temperature alteration varies with location and is dependent upon factors such as stream flow, water use, and surrounding discharges.

Most ground-water heat pump installations discharge water at relatively moderate temperatures. The temperature of the water used is altered from ambient ground-water temperatures. However, the resulting effluent is not

extremes hot or cold. It is unlikely, therefore, that most heat pump disposal will cause an impermissible alteration of surface water temperatures. The possibility does exist, however, that in instances of low surface water flow, large volume discharges, or extremely narrow temperature restrictions, disposal of heat pump effluent to surface water will be restricted or prohibited.

Enforcement of Permit Requirements Regardless of the degree of temperature alteration, an NPDES permit would be required for heat pump disposal to a United States waterway. Realistically, however, it is unlikely that this requirement will be enforced for the individual homeowner in most states. The NPDES program is fairly comprehensive, and over 50,000 discharge permits have been issued at this time. Nevertheless, the program, especially as administered by the Federal EPA, is not equipped to handle permits for small-scale domestic situation. The law does apply to these instances, but at the present time in areas administered by the Federal EPA or in most states, it could not realistically be enforced for the single, domestic heat pump discharge. If ground-water heat pump development increases, however, this situation may not continue, and some form of permit may be required for domestic use. There are, at this time, some states that do require a permit for this type of discharge under their NPDES program. The restrictions on these permits are usually minimal and often just notification is required. These instances will be discussed in a later section, but it is likely that these requirements will eventually be enforced in other states.

Enforcement of permit regulations is more likely for large-scale heat pump installations such as industrial systems or subdivision community developments. Effluent disposal to waterways will be more closely regulated in these instances. However, NPDES permit requirements are somewhat flexible, and it is likely that the restrictions associated with the permit will not be too extensive due to the negligible amount of contamination associated with heat pump discharges. In many cases, notification and a small amount of volume and temperature monitoring may be the only requirements.

In summary, the NPDES program has significant implications for ground-water heat pump development through its permit requirement for all discharge to surface waterways. This requirement may not be enforced at this time, however, for individual domestic units.

B. UIC Program

The Underground Injection Control program has been developed under authority of the Safe Drinking Water Act of 1974 (P.L. 93-523). This act instructed the U.S. EPA to establish a national program to prevent underground injections that may endanger drinking water sources. Thus, this program has an effect on underground disposal of heat pump effluent.

The Safe Drinking Water Act requires the EPA to: publish minimum national requirements for effective State Underground Injection Control programs; list deadlines for states to establish these programs; and make grants to states for developing and implementing UIC programs. The EPA is further instructed to review proposed state policies and approve or disapprove them. The Agency must then enforce UIC programs in states that choose not to participate, develop, and operate an approved program.

The UIC program is similar to the NPDES in that the individual states are expected to assume primary responsibility for fashioning and operating their own programs. EPA is required to administer the program only if a state chooses not to participate or fails to develop an effective program.

The UIC program is further required not to interfere with or impede oil and gas production unless necessary to protect underground sources of drinking water; not to unnecessarily disrupt effective existing state programs; and not to fail to consider local variations in geology, hydrology, and history.

The regulations propose that all aquifers or portions of aquifers currently serving as drinking water sources be designed for protection. Furthermore, any other aquifer or portion of it which is capable of yielding water containing 10,000 or fewer milligrams per liter of total dissolved solids will also be designated. However, not all underground water sources are considered suitable for providing drinking water. Some aquifers are used for producing minerals, oil, gas, or high-temperature geothermal energy. Others are so contaminated or located in such a manner that recovery of water for drinking purposes is neither economically practical nor technologically feasible. Such sources will not be designated for protection unless they already serve as sources of drinking water.

Injection Well Classifications To implement its proposed technological controls, EPA categorized well injection activities into five classes. Each class includes wells with similar functions, construction, and operating features. The technical requirements can then be applied consistently to each class.

The five classes of injection wells developed for the implementation of the UIC program are:

Class I Wells - Those wells that are used to inject industrial, nuclear, and municipal wastes beneath the deepest stratum containing an underground drinking water source.

Class II Wells - Those wells that are used to dispose of fluids brought to the surface in connection with oil and gas production, to inject fluids for the enhanced recovery of oil or gas, or to store hydrocarbons.

Class III Wells - Those wells that are used for injecting fluids for the solution mining of minerals, for *in situ* gasification of oil, shale, and coal, and for the recovery of geothermal energy.

Class IV Wells - Those wells that are used by operators of hazardous wastes or by owners and operators of hazardous waste management facilities to inject into or above strata that contain underground drinking water sources.

Class V Wells - Those wells that are not incorporated in classes I-IV. Typical examples of such wells are recharge wells and air-conditioning return flow wells.

A brief summary of the general underground injection controls proposed for each class is shown in Table 3.1.

TABLE 3.1

Type of Controls Applicable to Injection Well Classes

TYPE OF CONTROL	CLASS I	CLASS II	CLASS III	CLASS IV	CLASS V
Area of Review	Yes	New Wells	Yes	Not Applicable	No
Mechanical Integrity Requirements	Yes	Yes	Yes	Not Applicable	No
Construction Requirements	Strict	Flexible	Moderate	Banned	To be Defined
Monitoring	Continuous	Periodic	Continuous	Varied	To [illegible] Def[illegible]
Reporting	Quarterly	Annual	Quarterly	Quarterly	Not Applicable
Form of Regulation	By Permit	By Rule or Permit	By Permit	By Permit	By Rule

Implications for Heat Pump Use The UIC program is still in its formative stages, and the classification of some wells is unclear, as are many of the eventual regulatory controls. Heat pump effluent return wells are, however, most likely to be placed under a Class V restriction. These wells will probably be classified as either cooling water return or recharge wells. It is possible that they will fall under the geothermal injection well category in some states. The disposal wells would then be subject to the requirements for Class III injection wells. These controls are stringent and specify that the well owner must obtain the appropriate injection permit.

Class III wells must inject into strata that are below the deepest underground source of drinking water and must have an adequate confining layer above the injection zone. These wells must also be cased and cemented to prevent fluid

migration and must inject through tubing with a suitable packer set immediately above the injection zone (or an equivalent alternative).

The technical integrity of these wells must be demonstrated initially and every five years thereafter, and corrective action must be taken on improperly plugged or completed wells within the area of review.

Class III well operators are further required to monitor continuously and to measure volumes and annular pressures. Class III operators must also periodically test the composition of injected fluids and provide the permitting authority with quarterly operating reports.

These requirements are restrictive and would discourage most underground disposal of heat pump effluent. It would also be extremely difficult to enforce those regulations with the advent of widespread heat pump development.

It is more likely and more reasonable to expect that heat pump return wells will be categorized as Class V injection wells. These wells are to be regulated by rule rather than by permit. The precise regulatory approach to these wells is uncertain. At present, the EPA has too little information on the extent, operation, and impact of Class V wells to propose a suitable comprehensive program. The proposed regulation, therefore, would require states to conduct an assessment of such wells and submit recommendations to the EPA within two years. Specific regulatory requirements will be fashioned after the completion of the assessments.

At this time, states are required to take immediate action on any Class V well that poses a significant risk to human health.

It would not be difficult to enforce the UIC regulations applicable to heat pump return wells that are placed under Class V restrictions. These rules are not prohibitively strict and, as shown, no permit program would be required. A simple control by rule with little if any monitoring requirements would not impede ground-water heat pump development or discourage the use of recharge wells as a method of disposal. These regulations could be enforced at all levels from individual domestic to large-scale commercial or municipal installations, and they would have

the benefit of controlling recharge wells without discouraging their use.

III. STATE CONTROLS

Various state regulations affect or have the potential to affect ground-water heat pump utilization. Well construction standards, water use restrictions, and ground-water effluent disposal regulations can all influence the development of this alternate energy source. Ground-water heat pumps are rarely specifically mentioned in these regulations. However, the applicability of these controls is not diminished by a lack of reference to heat pump units.

Well construction standards vary widely among the states. Some states have no standards for the construction of individual domestic supply wells, while others mandate a multitude of requirements including the filing of a notice of intent, a drilling permit, drilling code compliance, completion reports, and water quality analyses.

Many states impose no restrictions on the use of water for domestic purposes, which, unless otherwise indicated, includes the use of water for household heat pump operation. Several states require permits for water use of any type, and others require permits for pumpage exceeding some set volume limitation.

Included in each description of state controls are the requirements for using a recharge well for disposal of heat pump effluent. Unless otherwise noted, the following holds true for other methods of disposal:

To Surface Water: This disposal method is theoretically controlled by the National Pollution Discharge Elimination System. However, this system is usually not equipped to monitor small-scale domestic discharge, allowing for such disposal without a permit.
To Leach Field: Disposal of heat pump effluent is not a problem if the land is owned by the heat-pump user.

To Septic Tank: A loophole in most state regulations allows this type of discharge if the tank is big enough and if it is located far away enough from the well.
To Sewer: Discharge of effluent to a sewer would be allowed almost anywhere, although cost considerations would rule out the feasibility of this disposal method in many areas.

As noted in the introduction to this section, some regulations applicable to ground-water development, use, and quality control suffer either from lax enforcement or no enforcement. Regardless of whether or not they are enforced, all regulations and requirements that touch on these areas are included in this section in order to present a realistic assessment of the present and future legal environment of heat pump operation.

A. State-By-State Review of Water Use Restrictions, Well Construction Standards, and Waste Disposal Regulations

Alabama Alabama law does not specify standards for domestic well construction. Public supply wells, however, must be inspected and meet established construction criteria. A notice of intent and a completion report must be filed for all well construction, both public and domestic. This requirement poses no special problem to heat pump utilization.

The use of water for household heat pumps falls under the domestic use category and therefore requires no permit. However, the disposal of heat pump effluent to a recharge well must be preceded by notification of the Water Improvement Commission. At present, no permits are required, but as ground-water heat pump use expands, the Commission reserves the right to require permits for the disposal of heat pump effluent to recharge wells.

Alaska Site selection and installation of individual domestic wells must be approved by the Department of Health and Social Services. In addition, a well log must be filed with the Department of Natural Resources for all new wells. Public supply wells must meet the construction standards of the Department of Environmental Conservation.

Alaska law requires that water rights be obtained prior to water use. These rights are granted as a matter of course for domestic use. The simple application process presents no obstacle to household heat pump utilization, since this is considered a domestic use. At present, no permit is required for the disposal of heat pump effluent to recharge wells. However, combined on-site water supply and waste disposal facilities are permitted only on lots

measuring 40,000 square feet (372 square meters) or larger.

Note: At present, Alaska's low ground-water temperatures rule out the viability of ground-water heat pump use. However, rapidly expanding technology promises to extend the applicability of ground-water heat pumps to colder climates.

Arizona The State Land Department of Arizona enforces construction regulations for all wells and special requirements for those within critical ground-water areas. The construction of public supply wells is regulated by the Department of Health Services and the Arizona Water Commission.

Securing water rights for household heat pump utilization presents no special problems, although a permit is required under the domestic use category. However, disposal of heat pump effluent can pose problems; Arizona prohibits discharge to "any well, either abandoned or constructed for that purpose, that is carried to such a depth as to penetrate water-bearing strata." This presents a serious impediment to heat pump effluent disposal.

The state further prohibits the discharge of effluent into "any crevice, sink hole, or other opening, either natural or artificial, or in a rock formation which will permit the pollution or contamination of ground water." This rule is difficult to enforce because the Water Quality Control Council has not yet adopted any ground-water quality standards.

Arkansas Construction standards are enforced for all wells in Arkansas by the Committee on Water Well Construction. The State Department of Health imposes additional regulations for public supply wells.

No permit is necessary to use water for household heat pump utilization, since such usage is considered domestic in nature. There is currently no program to control the type of recharge wells necessary for the disposal of heat pump effluent.

California A notice of intent and a completion report for all wells is required by the Contractor's State License Board. The Department of Water Resources requires submission of specific information on all wells and

promulgates recommended water well construction standards which are adopted at local levels. Public supply systems having greater than 200 connections are regulated by the State Department of Health. None of these regulations pose special problems in the construction of wells for heat pump systems.

Of California's 58 counties, 32 require permits for all wells. These permits are not difficult to obtain for domestic heat pump use. Waste discharge is controlled at the state level by the Porter-Cologne Water Quality Control Act, which requires that any person discharging waste apply for a permit from the Regional Water Quality Control Board. There are nine of these throughout the state. Other than requiring a permit for disposal, the Water Quality Board does not regulate heat pump recharge wells at this time.

Colorado All water wells constructed in Colorado must meet set standards for water well construction. The State Department of Health requires well inspection and water quality tests for all wells. These requirements do not present any problems unique to the construction of wells for ground-water heat pump use.

As far as water use is concerned, a permit is required for all wells. Permits are also needed for disposal of heat pump effluent into a recharge well. Colorado prohibits discharge of waste underground unless it can be established "beyond a reasonable doubt that there will be no pollution". Under these restrictions, all permit applications will be thoroughly evaluated with respect to all legal, geological, and hydrological parameters. Submitted applications will need to include as much supporting data as possible including system specifications, return flow methods, and well drilling procedures and specifications.

Connecticut The State Well Drilling Board enforces construction standards for all wells. Public supply wells are regulated by the State Health Department.

Connecticut does not require permits for the use of private domestic wells, so use of water for household heat pump use would not require a permit. However, heat pump discharge is subject to stricter regulations. Connecticut state laws require permits for subsurface as well as surface water discharges (including discharges to sewers). Titles 22 and 25 of the Connecticut General Statutes define the authority of the Commissioner of Environmental Protection to

regulate these discharges. Section 25-54i describes the permit process through which such discharges are handled. At this time, all thermal discharges arising from the operation of heat pump units must obtain a state discharge permit. The Department anticipates the possibility of exempting certain domestic uses; however, at this time, insufficient experience and information exists with which to allow for a reasonable judgment regarding those uses which can be exempted from the permit process.

The submission of a Section 25-54i permit discharge application initiates the permit process. Submission of the application is the responsibility of the heat pump owner, who must also provide sufficient information regarding the proposed discharge so that the Department can make an evaluation as to whether the proposed discharge will or will not cause pollution (in this case, harmful thermal effect) to the waters of the state.

For domestic heat pump discharge applications, extensive information concerning the heat pump system, water source, water sink, and water quality must be submitted. A permit will not be granted until this information has been received.

Delaware The Department of Natural Resources and Environmental Control has detailed construction specifications and requires a well construction permit for all wells. The State Department of Health Services maintains water quality standards for public supplies. The Department of Natural Resources and Environmental Control also enforces strict reinjection rules. However, because disposal of heat pump effluent has minimal environmental impact, a permit for a recharge well should not be difficult to obtain.

Florida The Department of Environmental Regulations controls all well construction in the state. The Department has divided the state into six water management districts, which can enact stricter construction codes than those applying state-wide. Public supply wells require the additional approval of the State Department of Health and Rehabilitative Services.

Florida law requires that a permit be obtained for water use of over 5,000 gpd (18,925 l/day). The use of most household heat pump units would require this permit. Permits are also required for waste disposal wells in

Florida. Heat pump return wells fall under this category and must meet specifications and conditions outlined by the Department of Environmental Regulation.

Georgia The Department of Natural Resources regulates well construction for public supplies and all other wells exceeding 100,000 gpd (37,850 l/day) except those used for irrigation and poultry processing. Since wells for ground-water heat pumps require less than the 100,000 gpd (37,850 l/day) limit imposed by the Department, no permit is necessary for their use. The Department of Human Resources requires that domestic well owners submit water samples for bacterial analysis.

Reinjection of cooling water is the only type of reinjection allowed by the state. Ground-water heat pump effluent falls under this category and is thus allowable. No permit is needed.

Hawaii In Hawaii, the Department of Land and Natural Resources requires the filing of a notice of intent to drill and a well completion report for all wells. The Department of Health must approve the site and design of public supply wells.

The use of water for household heat pump operation would be considered domestic in nature, so obtaining water use rights would not be difficult. Hawaii has a regulation requiring permission for disposal wells and wastewater disposal; however, this regulation is not presently enforced. A permit to dispose of heat pump effluent in a recharge well should therefore not be difficult to obtain.

Idaho All wells drilled in Idaho must meet the construction standards of the Idaho Water Resources Board.

No permit would be necessary for water used for a household heat pump operation, since domestic water use is ordinarily uncontrolled. An exception is water used in locations considered critical ground-water areas. Here, a water use permit is needed when pumpage exceeds 13,000 gpd (49,205 l/day). This should pose no serious problems to heat pump use, since most residential heat pumps require less than 12,000 gpd (45,420 l/day). Idaho law requires a permit for the use of any type of disposal or injection well, but no permit mechanism exists at present. Approval of heat pump effluent discharge to a recharge well should not be difficult to secure.

Other methods of effluent disposal--to surface water, to land, to septic tanks, or to sewers--should not present problems. However, if a heat pump is operating in a critical ground-water area, recharge back to the aquifer would be the required method of disposal.

Illinois A drilling permit is required by the Department of Mines and Minerals for all wells constructed in Illinois. In addition, all wells must meet construction standards imposed by the Department of Public Health. Public supply wells must be approved by the Illinois Environmental Protection Agency.

The use of water for household heat pumps falls under the category of domestic use; thus, no permit to dispose of heat pump effluent is necessary. The use of recharge wells is under the control of the state EPA, but at this time this agency has no mechanism to regulate wells of this type. Thus, water use for heat pump operation and the discharge of effluent to recharge wells should meet with no obstacles in Illinois.

Indiana No water well construction regulations exist in Indiana, but the State Board of Health has published a manual of recommended construction practices for private wells. A completion report is required for every newly constructed well. The State Board of Health must approve the well site and specifications and requires a water quality analysis for all public supply wells.

No permits are necessary for domestic water use, and the use of water for household heat pump operation is considered domestic in nature. Theoretically, the Stream Control Board has authority over recharge wells, but conventional cooling-water recharge wells are not currently regulated. There would be no regulatory impediment to the discharge of heat pump effluent to a recharge well.

Permission to dispose of effluent in a surface water body must be obtained from the Board of Health. However, because of the minimal environmental impact of heat pump effluent disposal, a permit could be easily secured.

Iowa The only restrictions on well drilling in Iowa are approval of specifications and bacterial analyses required by the Environmental Quality Department for public and

quasi-public supply wells. Individual domestic supply wells are monitored by the Department of Health, but no controlling regulations exist at this time.

A permit would not be required for household heat pump use, since this use of water is domestic in nature and uncontrolled by the State. Neither is a permit required for the discharge of heat pump effluent to a recharge well. The lack of restrictive regulation in Iowa would facilitate conversion from traditional heating and cooling to ground-water heat pump use.

Kansas All wells must meet the well construction regulations of the Department of Health and Environment. Well logs and bacterial and chemical analyses are included among the requirements of the Department.

The State Board of Agriculture requires a water-right permit for all water use. There are five ground-water management districts under the auspices of the Division of Water Resources, and each may impose its own regulations such as well spacing and yield requirements. These districts are responsible for recommending the approval or denial of a permit, though the decision is made by the Division of Water Resources. Because the size and yield of a well for heat pump operation need not be large, obtaining a permit should not be a problem.

A permit is likewise required for the discharge of heat pump effluent to a recharge well. The state must determine that the proposed discharge will not subject water resources to 'preventable' pollution. Since environmental impact of heat pump effluent disposal is minimal, a permit could be easily obtained. In the case of recharge wells for heat pumps, this permit system would be necessary merely for record keeping purposes.

Kentucky There are no construction regulations for individual domestic supply wells in Kentucky. Public and semi-public supply wells are restricted by the Department of Natural Resources and Environmental Protection to the extent that specification approval and bacterial and chemical quality analyses are required.

The use of water for domestic heat pump operation is considered private use, and no permit is required. Neither is a permit required for the use of recharge wells for heat pump effluent disposal.

Louisiana Individual domestic supply wells are not regulated in Louisiana unless pumpage exceeds 50,000 gpd (189,250 l/day), in which case the well must be registered with the Department of Transportation and Development. The Department also requires that all public supply wells be registered and comply with established construction standards. Public supply wells are further regulated by the Department of Health and Human Resources.

No permit is needed for domestic water use, which includes the use of water for household heat pump operation. Although there is no official policy concerning the use of recharge wells for the disposal of heat pump effluent at present, the Department of Environmental Control may eventually require permits for discharge. This should pose no special problems to heat pump users.

Maine No regulations exist for individual domestic supply wells in Maine; only public supply wells are regulated. For these, the Department of Human Services requires the filing of a notice of intent, inspection during and upon completion of construction, and bacterial and chemical analyses.

No permit is necessary for domestic water use, which includes the use of water for heat pump operation. Discharge of heat pump effluent disposal to a recharge well is prohibited by the state's restrictive ruling against underground injection of any type. This presents a real obstacle to effluent disposal through recharge.

Maryland Ground-water heat pump installations in Maryland are subject to the following permit regulations:

1) Well Drilling Regulations - COMAR .08.05.02. This requires a well drilling permit for drilling all wells and details certain specifications for the wells. The permit must be obtained by a Master Well Driller licensed by the Maryland State Board of Well Drillers.

2) State Water Appropriation Regulations - COMAR 08.05.02. This requires a State Water Appropriation Permit for withdrawal of ground and/or surface water for all uses, except domestic and farm use. Use of water for heat pump applications requires a permit.

3) State Discharge Permit Regulations - COMAR .08.05.04. This requires a Ground-Water Discharge Permit for discharge of any waters or wastewaters into the

underground waters of the state and an NPDES permit for discharge of waters or wastewaters into surface water bodies.

Thus, permits are necessary both for the use of water for a ground-water heat pump and for the disposal of heat pump effluent to surface or underground waters. Neither of these permits should be difficult to obtain.

Massachusetts The Massachusetts Water Resources Commission requires the submission of completion reports for all wells. Public supply wells are further regulated by the Department of Public Health, which must approve site selection, well installation, and water quality analyses.

No permit is needed to use water for a household heat pump, since this falls under the "domestic use" category.

The discharge of heated or cooled water to recharge wells or surface waters requires a permit from the Division of Water Pollution Control. Obtaining permits for either of these effluent disposal methods should not be a problem for heat pump users, however.

Michigan A completion report and bacteria analysis are required for all wells by the Department of Public Health. The Department further requires a drilling permit and a chemical quality analysis for all public supply wells. Industrial wells must pass chemical quality tests, and community public supply wells are subject to site inspection. The simple requirements for an individual domestic supply well for heat pump use should pose no problems.

No permit is needed for the domestic use of water, which includes household heat pump use. Regarding discharge, it is the policy of the Michigan Water Resources Commission that heat pump facilities with a heat exchange capacity of 120,000 BTU per hour (35 kw) or less are not required to have a discharge permit provided there are no chemical additives used in the system.

Systems having a heat exchange rate greater than 120,000 BTU per hour (35 kw) or systems having a heat exchange rate of 120,000 BTU per hour (35 kw) or less that use chemical additives must file with the Commission an application for discharge permit. These applications are reviewed and

permit conditions established, if necessary, to protect the waters of the state.

Minnesota The Minnesota State Board of Health enforces a construction code and requires a completion report, a notice of intent, a drilling permit, and a water quality analysis for all wells. These requirements pose no special problems to the construction of a well for ground-water heat pump use.

The domestic use of water does not require a permit in Minnesota, and water for household heat pump use falls under the definition of domestic use.

Minnesota generally discourages and prohibits underground injection. This could present obstacles to the discharge of heat pump effluent to recharge wells. However, the state agency officials contacted said that individual homeowners could apply for variance permits that would allow the use of recharge wells for household heat pump systems.

Mississippi The only restriction on water well construction in Mississippi is the requirement that a completion report be filed with the Board of Water Commissioner for all wells drilled.

No permit is required for domestic water use, which includes water used for heat pump operation. Likewise, no permit is necessary to use a recharge well for the disposal of heat pump effluent.

Missouri Only individual domestic supply wells that are federally financed are subject to regulation in Missouri. These wells, and public supply wells, are subject to location and installation approval by the Department of Social Services. The Department of Natural Resources requires a notice of intent, drilling permit, site inspection, completion report, and water quality analysis for all public supply wells. These requirements will not apply to supply wells for individual domestic heat pump systems.

No permit is needed for domestic water use, which includes the use of water for household heat pump operation. In addition, no permit is required for:

1) Any ground-water heat pump injection/withdrawal well that is limited to a single family residence

2) Any ground-water heat pump injection/withdrawal well that is limited to eight or less single family residences as long as the combined injection/withdrawal rate is less than 600,000 BTU/hour (176 kw)

All other uses of ground-water heat pump injection/withdrawal wells shall be subject to a permitting procedure as established and regulated by the clean water commission pursuant to chapter 204, RSMo.

Montana A well log must be submitted to the Department of Natural Resources and Conservation for each well drilled. The Department also requires a drilling permit for all wells in controlled ground-water areas and for wells with an expected capacity in excess of 100 gpm (6.3 l/s). None of these requirements should adversely affect construction of wells for ground-water heat pumps because the well yield necessary for heat pump operation is well below the 100 gpm (6.3 l/s) limit. Even if the well is in a controlled ground-water area, the use of recharge wells allows for favorable non-consumptive water use.

A certificate of water right, needed for water use, is easily obtainable. Theoretically, a permit is needed to discharge heat pump effluent to a recharge well. However, there is no enforcement of this permit system at this time.

Nebraska There are no standards for individual domestic well construction in Nebraska. However, a number of Water Resources Districts have authority to implement ground-water and drilling regulations if the locality is designated a control area. Public supply wells are regulated by the Department of Health, and the Department of Water Resources requires registration upon completion for all except individual domestic wells.

No permit is needed for domestic water use, which includes heat pump operation. Reinjection of heat pump effluent to a recharge well is not controlled; at present, no regulations exist to cover a permit process. This lack of restrictive regulation will facilitate heat pump use in Nebraska.

Nevada A notice of intent and a completion report are required for all wells in Nevada. Public supply wells must meet additional requirements imposed by the Department of Human Resources. The Division of Water Resources within the Department of Conservation and Natural Resources has specific requirements for management of "wells being drilled for heating and cooling purposes" as follows:

1. The intake well and return well should be located not over 100 feet (30.5 m) apart, with the return well located down-gradient from the intake well.

2. Both wells must be the same depth with the same construction. The size of the casing, however, can be different.

3. The return water must be returned to the same aquifer within which it originates.

4. Care must be exercised in perforating the casings of both wells so that there is not a mixture of high- and low-quality water.

5. Before a driller starts work on such a job, he must report verbally to the well supervisor or State Engineer's office and submit his plan of construction.

6. The pipe system must be completely closed, and all pipes above the ground surface must be painted red.

A permit is required to use any well which exceeds the 1,800 gpd (6,813 l/day) limitation for domestic wells. Since the use of a heat pump calls for more than 1,800 gpd (6,813 l/day), a permit would be necessary. The above regulations exist, and a permit is also required for disposal of heat pump effluent to a recharge well.

These restrictions must be taken into consideration when evaluating the benefits of heat pump use. The cost and time involved in meeting these requirements may detract from the attractive aspects of heat pump use.

New Hampshire There are no permit or construction requirements for individual or domestic supply wells in New Hampshire. Public water supply systems must meet design standards and water quality criteria imposed by the Water Supply and Pollution Control Commission.

No permit is needed for domestic water use which includes the use of water for household heat pump operation. Theoretically, a permit is required to use a recharge well for disposal of heat pump effluent. However, this requirement is not enforced, and simple notification will suffice.

New Jersey The Department of Environmental Protection requires a drilling permit and a completion report for all wells. Further requirements include a water allocation permit for all wells with a capacity over 69 gpm (4.4 l/s) and inspection and water quality analysis for all potable supply wells supplying 69 gpm (4.4 l/s) or more. These last two requirements would not ordinarily pertain to domestic supply wells for heat pump use because the volume of water indicated far exceeds that needed for domestic applications.

A permit is not needed for domestic water use, including water use for heat pump operation. Recharge wells may be used for the disposal of heat pump effluent; there are no restrictions on their existence at present.

New Mexico A construction code is enforced for all wells by the State Engineer. This office also requires a drilling permit and a completion report for all wells drilled in declared ground-water basins. Wells constructed with state loans and grants must meet certain additional construction regulations, as must all public supply wells.

A permit is necessary to use the volume of water required by a household heat pump, but this is not difficult to obtain. Similarly, a permit is needed to use a recharge well to dispose of effluent. None of the requirements noted should inhibit heat pump use in New Mexico.

New York Individual domestic supply wells are regulated only on Long Island, where the Department of Environmental Conservation requires drilling permits and completion reports for all wells that yield more than 45 gpm (2.8 l/s). The Department enforces additional regulations for public supply wells throughout the state.

A permit is unnecessary for domestic water use, which includes the use of water for household heat pump operation. Neither is a permit required to use a recharge well for the discharge of ground-water heat pump effluent. In New York, the lack of restrictive regulation makes ground-water heat pumps a favorable alternative to traditional heating/cooling systems.

North Carolina The Department of Natural Resources and Community Development promulgates a well construction code and requires a completion report for all wells. Wells with a pumpage to exceed 100,000 gpd (378,500 l/day) require a permit, as do all wells other than individual domestic supplies in capacity-use areas. Public supply wells are further regulated by the Department of Human Resources, which must approve well plans and specifications and results of water quality analyses. The construction of individual domestic supply wells for heat pump use should present no special problems in meeting the requirements of the construction code and the well completion report.

A water use permit is required for the withdrawal of water in excess of 100,000 gpd (378,500 l/day) and for all wells in capacity-use areas.

A permit is needed for the use of a recharge well to discharge heat pump effluent. This disposal method is presently discouraged by the State Department of Natural Resources. The use of alternative effluent disposal methods are subject to less regulation.

North Dakota Completion reports are required for all wells by the Board of Water Well Contractors, and the Department of Health requires water quality analyses for all wells. Public supply wells must meet specifications and construction codes enforced by the Department of Health.

A standard appropriation permit is necessary for water use, but this is easily obtainable when water use is for domestic purposes, which includes household heat pump operation. The use of recharge wells for disposal of heat pump effluent is unregulated in this state.

Ohio A well log must be submitted for all wells. The Ohio Environmental Protection Agency enforces a construction code for all wells and regulates public supply wells through requirements for a notice of intent, design approval, and bacterial analyses.

Domestic use of water, including that used for heat pump operation, does not require a permit. Recharge wells are controlled by the Ohio EPA, which has developed the following policy on the use of return wells in conjunction with ground-water heat pump systems:

1. Supply wells and return wells used in conjunction with ground-water source heat pumps must be constructed, operated, maintained, and abandoned in compliance with the Water Well Regulations OAC 3745-9.

2. Heat pump source water of an objectionable quality should not be returned to an aquifer or portion of an aquifer containing water of a higher quality.

3. Water returned to the subsurface through a well should be of essentially the same quality both chemically and bacteriologically as it was prior to use except for the temperature differential.

4. The heat pump system should be equipped with an automatic device to shut down the entire system if a leak occurs in the refrigeration system.

5. An approved backflow prevention device must be installed immediately ahead of the heat pump unit to protect both the supply well from contamination and the water use.

6. Anyone planning to install a ground-water source heat pump system utilizing a return well must inform the appropriate Ohio EPA District Office by letter. The letter should describe the proposed system and address the above items. The location of the supply and return wells should be shown in respect to nearby roads on an accompanying map. A letter indicating the acceptability of the proposal will be sent from the District Office to the applicant.

Oklahoma The Water Resources Board of the Division of Ground Water enforces a construction code, requires the filing of completion reports for all wells, and specifies additional requirements for industrial and irrigation wells. Public supply wells are regulated by the Department of Health, which has also published recommended standards for the construction of individual supplies. The requirements for domestic wells should create no special problems in the construction of wells for heat pump use.

No permit is needed to use water for household heat pump operation, since domestic use of water is unregulated. Oklahoma prohibits discharge into wells, pits, holes, or into water-bearing strata from which a domestic or public supply is drawn. This law theoretically restricts the use of recharge wells for the discharge of heat pump effluent, but the Water Resources Board has advised that this

restriction will not be enforced for domestic heat pump use unless problems develop as a result of injection.

Oregon All wells are governed by a construction code enforced by the Water Resources Department. The Department also mandates submission of notice of intent and a completion report for all wells. Community and public systems must meet location and installation approval of the Department of Human Resources and are subject to water quality analyses.

No permit is required for domestic water use, including heat pump operation, unless pumpage volume exceeds 15,000 gpd (56,775 l/day). The only limitation imposed on recharge wells is that return water must be reinjected into the same formation from which it was withdrawn. Neither of these requirements should deter heat pump use in Oregon.

Pennsylvania The Department of Environmental Resources requires a notice of intent and a completion report for all wells. While the Department promulgates construction standards for individual water supplies, these are mandatory only for service establishments that provide water to the public. Numerous other regulations apply to public supply wells. The state geologist further requires drilling logs for all new wells. Rules relating to individual domestic water supplies should not prove restrictive to the construction of wells for ground-water heat pump use.

Use of water for domestic purposes, including heat pump operation, requires no permit. A permit is necessary for use of a recharge well to dispose of heat pump effluent. No specific regulations restrict this disposal method, though the Pennsylvania Clean Streams Act authorizes the Department of Environmental Regulation to regulate all activities which have the potential to pollute. Because of the ground-water heat pump's minimal environmental impact, there should be no problem in obtaining a permit for recharge of effluent.

Rhode Island A completion report is required for all wells by the Water Resource Board, which, together with the Department of Health, specifies additional requirements for all public supply wells.

Domestic water use, which includes the use of water for household heat pump operation, requires no permit. Neither is a permit required to discharge heat pump effluent to a

recharge well. The Rhode Island Pollution Discharge Elimination System requires a simple permit to dispose of heat pump effluent in a surface water body. This permit is easy to obtain, and neither this requirement nor any other Rhode Island regulation should impede heat pump use.

South Carolina There are no regulations affecting individual domestic supply wells in South Carolina. Public supply systems must meet criteria imposed by the Department of Health and Environmental Control.

The use of water for ground-water heat pumps would require no permit because this is considered a domestic use, which is unregulated. Recharge wells for the disposal of heat pump effluent are not limited at this time. Since South Carolina has no regulations concerning individual domestic supply and recharge wells, heat pump use in this state should meet with no problems.

South Dakota The Department of Natural Resource Development enforces construction standards and requires the submission of a notice of intent to drill, a completion report, and a well log for all wells. Public water supply systems must meet additional specifications mandated by the Department of Environmental Protection.

No permit is needed for domestic water use, including water used for household heat pump operation. Reinjection wells are not limited at this time, so use of a recharge well to discharge heat pump effluent presents no obstacles.

Tennessee The Department of Conservation promulgates a construction code and requires inspection upon completion and a completion report for all wells. Public supply wells are regulated by the Department of Health through requirements for location and construction approval.

No permit is needed for domestic water use under 50,000 gpd (189,250 l/day). Since household water requirements for domestic and heat pump use do not ordinarily exceed this limit, no permission is required for water use. The Department of Health requires permits for the discharge of heat pump effluent to recharge wells or to surface water bodies. Securing these permits should pose no special problems to heat pump users.

Texas Completion reports are required by the Department of Water Resources for all wells constructed in Texas. Public supply wells must meet standards and requirements promulgated by the Department of Health Resources. In addition, all wells financed by the Farmers Home Administration are regulated through inspection and water quality analysis requirements.

Permits are not needed for the domestic water use represented by household heat pump operation. Recharge wells are not controlled by any permit mechanism, facilitating this method of heat pump effluent discharge.

Utah The Office of the State Engineer enforces a construction code and requires a notice of intent, a drilling permit, and a completion report for all wells. Public supply wells are subject to additional regulation by the Department of Social Services.

All types of water use require a permit in Utah. The State Engineer may limit or prohibit drilling in a particular area because of excessive ground-water use. This situation has the potential to severely restrict heat pump use in Utah.

No permit is needed to use a recharge well for reinjection. While heat pump users will not encounter obstacles in effluent disposal, they may have problems in securing water rights.

Vermont A completion report must be submitted, and a water quality analysis performed on all wells, according to the Department of Water Resources. Both the Department of Health and the Division of Environmental Protection specify additional standards for public supply wells.

Domestic water use, which includes water use for household heat pump operation, is not restricted and requires no permit. Theoretically, a permit is needed to use a recharge well for disposal of heat pump effluent, but this requirement is not enforced at this time.

Virginia The State Water Control Board requires a completion report and well cuttings from all wells. Public supply wells fall under the regulation of the State Department of Health, which enforces a construction code and requires a notice of intent, a drilling permit, inspection upon completion, and water quality analyses.

No permit is necessary for domestic water use; use of water for heat pump operation is included in this definition. Injection of wastewater is prohibited in Virginia at this time, ruling out disposal of heat pump effluent via recharge wells. While well construction and water use pose no special problems to heat pump users, the prohibition of recharge wells limits effluent disposal methods.

Washington Requirements for well construction of all types include submission of a completion report and a drilling permit for wells with a capacity exceeding 5,000 gpd (18,925 l/day). These requirements are not difficult to meet and should pose no problems to construction of individual domestic wells for heat pump use. Public supply wells are subject to requirements imposed by the Department of Social and Health Services.

Domestic water use (including water for the operation of a ground-water heat pump) in excess of 5,000 gpd (18,925 l/day) requires a permit, which is easily obtainable. To discharge heat pump effluent to a recharge well or surface water body, a permit must first be secured from the Department of Ecology. This should create no special problems for heat pump users.

West Virginia Only those individual domestic supply wells financed by federal loans are subject to regulation. For these wells, the Department of Health requires site inspection upon completion and water quality analyses. Requirements for public supply wells are more stringent.

The use of water for ground-water heat pump operation is considered a domestic use and, therefore, requires no permit. No policy exists concerning the use of recharge wells to dispose of heat pump effluent at this time.

Wisconsin The Wisconsin Department of Natural Resources enforces a construction code and requires a drilling permit and inspection of grouting for all wells with a capacity exceeding 70 gpm (4.4 l/s). A completion report must be submitted for all potable wells and for all non-potable wells exceeding 70 gpm (4.4 l/s). This means that completion reports will be necessary for all heat pump wells that also supply potable water for household use. Water quality analyses are required for all wells except irrigation and stock-watering systems.

No permit is needed to use the volume of water required for domestic use, which includes household heat pump operation. Use of a recharge well to discharge effluent is not a viable disposal method, as all reinjection is prohibited in Wisconsin. Hence, it will be necessary for heat pump users to adopt alternative disposal methods.

Wyoming The Office of the State Engineer promulgates a construction code and requires a drilling permit and a completion report for all wells. The State Engineer further mandates special procedures for public supply wells and for all wells in ground-water control areas. The Department of Health and Social Services regulates individual domestic and semi-public well systems through water quality analyses and requirements for approval prior to construction. Public supply wells must meet further specifications of the Department and receive location and specification approval from the Department of Environmental Quality. The time and expense involved in meeting the substantial requirements imposed on well construction in Wyoming will be a factor in determining whether or not to install a ground-water heat pump system.

No permit is needed for the use of water for heat pumps since this is considered domestic use, which is not regulated. There are no restrictions on heat pump effluent disposal; the method selected must simply be indicated on the discharge permit.

B. Large-Scale Utilization

Thus far, this section has focused on regulations affecting small-scale individual domestic heat pump use. Large-scale operations in most cases would be subject to additional constraints and requirements at the state level. Large-scale use would include housing subdivision developments and municipal water systems. These applications are most often classified as public water supply systems, although this term has various meanings throughout the country. The Federal EPA defines public water supply as a system having more than 15 connections or serving more than 25 persons for at least 60 days per year. Many states have adopted this definition. Other states distinguish public supply solely by the number of connections. Some state codes also distinguish between large-capacity and small-capacity public supplies or between public and semi-public or quasi-public supplies. These

Table 3.2

General Well Construction Requirements

State	Wells Restricted	Requirements
Alabama	All	Notice of Intent Completion Report
	Public Supply	Notice of Intent Drilling Permit Inspections Bacterial and Chemical Quality Completion Report
Alaska	Public Supply	Approval of Plans Bacterial and Chemical Quality Completion Report
	All	Copy of Well Log
Arizona	All	Equipment Installed Completion Report
	All Outside Critical Ground Water Area	Notice of Intent
	Irrigation within Critical Ground Water Area	Drilling Permit
	Public Supply and Semi-Public	Approval of Plans Site Inspection Well Log
	Public Supply Subdevelopments	Sufficient Water Supply
Arkansas	All	Completion Report
	Public Supply	Approval of Site and Installation
	Individual Domestic	Separation from Septic Tank
California	All	Notice of Intent Completion Report

cont.

State	Wells Restricted	Requirements
Colorado	All	Drilling Permit Completion Report
	Public Supply	Inspection Upon Completion
	Public Supply	Inspection Bacterial and Chemical Quality
Connecticut	All	Drilling Permit
	Public Supply	Notice of Intent Drilling Permit Inspection during and upon Completion Completion Report Bacterial and Chemical Quality
Delaware	All	Drilling Permit
	Public Supply	Bacterial and Chemical Quality
Florida	All	Drilling Permit Completion Report
	Public Supply	Inspection during and upon Completion Bacterial and Chemical Quality
	Public Supply	Approval of Site and Installation
Georgia	All exceeding 100,000 gpd (378,500 l/day) except Irrigation and Poultry Processing	Drilling Permit by Ground Water Use Report
	Public Supply	Approval of Plans and Specifications Well Data Report
	Individual Domestic	Bacteria

cont.

State	Wells Restricted	Requirements
Hawaii	All	Notice of Intent Completion Report
	Public Supply and Individual Domestic	Approval of Site and Installation
Idaho	All	Completion Report
	Public Supply Industrial, Irrigation, and Waste Disposal	Drilling Permit
Illinois	All	Completion Report
	All Pumps	Notice of Intent to Install a Pump Pump Completion Report
	All	Drilling Permit
	Public Supply	Approval of Plans Bacterial and Chemical Quality
Indiana	All	Completion Report
	Public Supply	Approval of Site and Plans Bacterial and Chemical Quality
Iowa	Public and Quasi-Public Supply	Approval of Plans and Specifications Bacterial Analysis
Kansas	All	Well Log Bacterial and Chemical Quality
	All Water Use	Appropriation of Water Right Permit
Kentucky	Public and Semi-Public Supply	Approval of Plans Bacterial and Chemical Quality

cont.

State	Wells Restricted	Requirements
Louisiana	Public Supply	Approval of Plans and Specifications Bacterial and Chemical Quality
	All exceeding 50,000 gpd (189,250 l/day)	Registration
	Public Supply	Registration
Maine	Public Supply	Notice of Intent Inspection During and upon completion Bacterial and Chemical Quality
Maryland	All	Drilling Permit Completion Report
	All exceeding 10,000 gpd (37,850 l/day) except Individual Domestic and Agricultural	Appropriation Hearing for Drilling Permit
Massachusetts	All	Completion Report
	Public Supply	Approval of Site and Installation Bacterial and Chemical Quality
Michigan	All	Completion Report Bacterial Analysis
	Public Supply (Community and Noncommunity)	Drilling Permit
	Public Supply (Community and Noncommunity) and Industrial	Chemical Quality
	Public Supply (Community)	Inspection of Site Prior to and During Construction

cont.

State	Wells Restricted	Requirements
Minnesota	All	Completion Report Bacterial and Nitrate Analysis
	Public Supply	Notice of Intent Drilling Permit Bacterial and Chemical Quality
Mississippi	All	Completion Report
Missouri	Public Supply	Notice of Intent Drilling Permit Inspection of Site During and After Construction Completion Report Bacterial and Chemical Quality
	Public Supply	Approval of Site and Installation
	Individual Domestic if Federally Financed	Approval of Site and Installation
Montana	All	Well Log
	All in Controlled Ground-Water Area	Drilling Permit
	All if Expected Capacity Exceeds 100 gpm (6.3 l/s)	Drilling Permit
	Public Supply	Approval of Site and Installation
Nebraska	All except Individual Domestic	Registration Upon Completion
	Public Supply	Designed by a Registered Engineer Approval of Site and Installation Inspection of Site Upon Completion Bacterial and Chemical Quality

cont.

State	Wells Restricted	Requirements
Nevada	All	Notice of Intent Completion Report
	Public Supply Industrial Irrigation	Drilling Permit
	Public Supply	Approval of Site and Installation
	Individual Domestic When FmHA or VA Loan; Same as Public Supply Regulations	Bacterial and Chemical Quality
New Hampshire	Public Supply	Approval of Design and Specifications Bacterial and Chemical Quality
New Jersey	All	Drilling Permit Completion Report
	All Exceeding 69 gpm (4.4 l/s)	File for Water Allocation
	Potable Supply Exceeding 69 gpm (4.4 l/s)	Inspection Bacterial and Chemical Quality
New Mexico	All in Declared Ground Water Basin	Drilling Permit Completion Report
	Public Supply	Approval of Site and Installation Bacterial and Chemical Quality
	Public Supply Seeking Funding under Water Supply Construction Act	Special Standards
New York	Public Supply	Notice of Intent Drilling Permit Site Inspection Upon Completion Completion Report Bacterial and Chemical Quality

cont.

State	Wells Restricted	Requirements
New York (cont.)	All Long Island Exceeding 45 gpm (2.8 l/s)	Drilling Permit Completion Report
	Industrial Long Island Exceeding 45 gpm (2.8 l/s)	Notice of Intent Chemical Quality
North Carolina	All	Completion Report
	All Wells or Systems Exceeding 100,000 gpd (378,500 l/day)	Drilling Permit Approval of Location and Design
	All in Certain Geographic Areas	Well Cutting Samples
	All in Capacity-Use Area	Permit of Quantity of Use
	Public Supply	Approval of Plans and Specifications Bacterial and Chemical Quality
North Dakota	All	Completion Report
	All	Bacterial and Chemical Quality
	Public Supply	Approval of Plans and Specifications
Ohio	Public Supply	Notice of Intent Approval of Design Bacterial Analysis
	All	File Well Log
Oklahoma	All	Completion Report
	Industrial and Irrigation	Drilling Permit Inspection Upon Completion
	Public Supply	Engineer's Plans and Specifications
	Individual Domestic	Bacterial and Chemical Quality

cont.

State	Wells Restricted	Requirements
Oregon	All	Notice of Intent Completion Report
	Community Greater than 3 Households or Connections	Approval of Site and Installation Bacterial and Chemical Quality
	Public Supply greater than 1 Facility (Restaurant, Trailer Park, Etc.)	Bacterial and Chemical Quality
Pennsylvania	All	Notice of Intent Completion Report (Site Inspection and Cuttings Sample if Necessary) Notice of Intent to Abandon
	Public Supply	Drilling Permit Engineer's Report Drill Survey Cuttings Sample Bacterial and Chemical Quality
Rhode Island	All	Completion Report
	Public Supply	Approval of Site and Installation
	Public Supply	Bacterial and Chemical Quality
South Carolina	Public Supply	Notice of Intent Drill Permit Site Inspection During and After Completion Completion Report Bacterial and Chemical Quality
	Industrial for Potable Supply	Bacterial and Chemical Quality

cont.

State	Wells Restricted	Requirements
South Dakota	All	Notice of Intent Completion Report Well Log
	All except Individual Domestic	Application to Water Right Proposal for Appropriation
	Irrigation	Chemical Analysis for Soil-Water Compatability
	Public Supply	Approval of Site and Installation Bacterial and Chemical Quality
Tennessee	All	Inspection Upon Completion Completion Report
	Public Supply	Approval of site, Engineers Report and Plans, and Construction
Texas	All	Completion Report
	Public Supply	Notice of Appointment Approval of Plans Completion Report
	All Financed by FmHA	Inspection During and After Construction Bacterial and Chemical Quality
Utah	All	Notice of Intent Drilling Permit Completion Report
	Public Supply (exceeding 49 People of 9 Homes or Restaurants, etc.)	Approval of Plans Bacterial and Chemical Quality

cont.

State	Wells Restricted	Requirements
Vermont	All	Completion Report Bacterial and Chemical Quality
	Public Supply	Plan Approval Bacterial and Chemical Quality
	Public Buildings, Subdivisions and Mobile Home Parks	Plan Approval
Virginia	All	Completion Report Well Cuttings
	Public Supply	Notice of Intent Drilling Permit Inspection Upon Completion Bacterial and Chemical Quality
Washington	All	Completion Report
	All Exceeding 5,000 GPD (18,925 l/day)	Drilling Permit
	Public Supply (Greater than one) Single Family Residence	Approval of Site and Installation
West Virginia	Public Supply	Approval of Plans Construction Permit Inspection Upon Completion Completion Report Bacterial and Chemical Quality
	Individual Domestic Financed by FHA, VA, or FmHA Loans	Inspection of Site Upon Completion Bacterial Analysis by County Department of Health

cont.

State	Wells Restricted	Requirements
Wisconsin	All Exceeding 70 gpm (4.4 l/s)	Approval (Permit)
	All Exceeding 70 gpm (4.4 l/s) Public Supply	Inspection of Grouting Procedure
	All Non-Potable Exceeding 70 gpm (4.4 l/s) All Potable	Completion Report
	All Except Irrigation and Stock Watering	Bacterial Analysis
	Public Supply	Chemical Quality
Wyoming	All	Drilling Permit Completion Report
	All in Control Area Public Supply	Special Procedure
	Industrial and Irrigation	Inspection Upon Completion
	Individual Domestic and Semi-Public	Approval Prior to Construction Bacterial Analysis
	Public Supply	Approval of Plans and Specifications Bacterial Analysis

distinctions and other differences from the standard EPA definition are indicated in Table 3.2, a summary of well construction requirements.

Commercial and industrial heat pump utilization would also fall under the large-scale category. These systems are subject to more rules than are domestic systems but are not as closely controlled as are public supply systems.

Construction requirements applicable to large-scale heat pump installations are usually more stringent than those required of domestic units. This is especially true for those wells that fall under the public supply category. Agency approval of location and construction plans is often mandated. In addition, chemical and bacteriological analyses are often required. The additional construction restrictions on these wells are indicated in Table 3.2. These rules will not present a serious impediment to heat pump development. The degree of enforcement of these regulations varies, but it is important that large-scale installations with sizeable investments in this technology comply with the provisions of these rules.

Water use for large-scale heat pump installations will also be more strictly controlled than domestic water use. The larger volumes of water involved are more likely to be subject to permit requirements. Table 3.2 indicates the instances in which permits will be required. These rules may cause some temporary difficulty for heat pump installation but in most cases should not seriously impede development of this alternate energy source. Fewer problems are likely to occur if an approved recharge well is used to provide a non-consumptive water use.

The regulations governing underground disposal of effluent for large-scale heat pump installations are similar to those for domestic units. Permit requirements and general prohibitions against recharge are indicated in Table 3.3, a summary of regulations applicable to heat pump use. However, the state agency issuing the recharge well permit may place stricter conditions on large-scale use permits. Most of these agencies have a number of options concerning the conditions set on permits of this type. A number of restrictions may or may not be applied.

For example, a permit for a recharge well in Pennsylvania must be obtained from the Bureau of Water

Quality Management. This agency has indicated that these permits will not be difficult to obtain for domestic use. However, the Bureau has the authority under the Pennsylvania Clean Streams Act to impose severe restrictions on a recharge well permit. These potential restrictions include:

1) Applicant's Geologic/Engineering Consultant must complete a ground-water model and submit additional requested information

2) Newspaper announcement to determine necessity for public hearing

3) Public hearing in which all interested parties may participate

4) Permit revocation if pollution occurs or if conditions of permit are not maintained

These requirements may not be fully invoked. However, large-scale heat pump operations are likely to encounter strict recharge well regulations. This will be true for all aspects of the legal control of large-scale heat pump utilization. The large volume of water use will lead to increased permit requirements and more stringent construction restrictions. The use of recharge wells will be more closely regulated, although severe problems may be alleviated as regulatory agencies become familiar with these systems. These regulations will not preclude large-scale ground-water heat pump operation in most cases.

IV. LOCAL CONTROLS

There are thousands of county and municipal regulations throughout the United States that relate to the development of ground-water source heat pumps for domestic use. Although the volume of these regulations precludes comprehensive coverage in this study, it is important to recognize the various forms that the rules may take. These local controls often impede heat pump development more than applicable Federal or state legislation.

A. County Regulations

Ground-water regulations at the county level are most often promulgated by the local Health Department. In many

instances, this agency is an arm of the State Health Department and acts as the local enforcement agency for the state codes. Sometimes, however, local Health Departments devise and enforce their own regulations, which are often stricter than those promulgated by the state. For example, the Health Department of Kern County, California, enforces a stringent set of well construction standards. The empowering ordinance which is based partly on the California Water Well Standards mandates that well drillers must be licensed and that well permits are required. It specifies standards for construction and sealing of wells and stipulates required minimum distances from potential sources of pollution. The section on disposal wells mandates the following:

1. The disposal water shall not cause the temperature of the adjacent ground water to increase more than 8°F (4.4°C).

2. The discharge shall not contain certain toxic materials or other substances which will alter the existing ground-water quality in the disposal area.

3. The discharge shall not cause a public nuisance.

4. A sampling tap shall be installed at the disposal well site in such a manner that water representative of the water entering the well may be withdrawn for laboratory analysis.

The rules of the Dade County (Florida) Health Department are another example of strict local regulation. Ordinance No. 72-76 of October 31, 1972, contains several sections related to sampling and protection of ground water. The ordinances dictate water quality standards for Dade County and prohibit the discharge of sewage, industrial wastes, cooling water, solid wastes, or any other wastes in such quantities and of such characteristics as may cause surface water, tidal salt water estuaries, or ground water to be of poorer quality after mixing with the waste streams than specified in the water quality standards.

In cases of waste discharge into the ground, the regulations require that samples be taken from the wells nearest to and encircling the point of a waste stream's entry into the ground-water table. The installation and maintenance of test wells may be required if the Pollution

Control Officer judges existing sampling points to be inadequate.

Deep disposal wells, defined as any conduit designed or operated to discharge wastewater, sewage, or any deleterious substances into the ground at depths greater than 2,000 feet (610 m), must meet requirements regarding floatable and suspended solids and coliform bacteria. Discharge of septic tank wastes into aquifers or on the ground surface is prohibited.

The Dade County Plumbing Code has regulations on supply and disposal wells. Paragraph "P" states that "wells shall be so located as to be free of danger of contamination from unsafe water supply or shall be at least 50 feet (15 m) from a septic tank, drain field, soakage pit, or discharge well, and of sufficient depth to provide pure and wholesome water". The minimum depth of domestic water wells is specified at 20 feet (6 m).

The Dade County Sewer Code (1972) states that "no unauthorized person shall cause storm water or ground water ...to enter the sanitary sewer system". Included in the code are maximum allowable values for certain materials in, or characteristics of, wastewater entering the sewage systems.

The Dade County and Kern County ordinances are representative of the types of control exerted at the county level. There are many other such county level regulations that govern well construction and effluent disposal. Some of these will adversely affect heat pump utilization; however, the majority will not seriously impede widespread development of this alternate energy source. It is important to recognize the existence of these regulations and the restrictions they place on heat pump development. The degree of enforcement of these rules varies with location, but they are often stringently enforced by local Health Departments.

B. Municipal Regulations

Regulations regarding ground-water use and development are found in municipal codes throughout the country. One of the most common rules is a prohibition against the drilling of water supply wells in areas served by public water supply. These regulations limit the development of other

sources of water and present a significant impediment to heat pump utilization. It is often possible, however, to get a variance permit that will allow the drilling of a well that is to be used strictly for heating and cooling purposes. Application for this permit must be made to the local Board of Supervisors or to a similar governing board. It will usually not be difficult to obtain approval if the application clearly states that the well will be used solely for heating and cooling purposes and will not infringe upon the role of the public water supply.

Another restriction in some municipalities is the requirement that water used for heating or cooling purposes be reinjected into the aquifer from which it was withdrawn. This regulation prevents depletion of ground-water supplies in areas of high-volume ground-water use. This type of regulation will not cause serious problems for heat pump utilization. It is important, however, to recognize that this type of regulation can be promulgated at the municipal level and has no applicability at the state or county level.

Other regulations at the municipal level include domestic well permit requirements, wetland and other special protection area restrictions, and waste disposal prohibitions. Most of these will not seriously affect heat pump development. It is important to recognize and satisfy all applicable local regulations; problems will arise if heat pump users are unaware of local regulations and local officials are uninformed about heat pump development. Communication between the parties involved and an assessment of the potential impact of local rules will facilitate widespread heat pump utilization.

V. CONCLUSION

Federal, state, and local regulations impose restrictions and mandate various requirements for well construction, ground-water use and quality, and effluent disposal, but they will not significantly obstruct the implementation of ground-water heat pump technology.

Federal regulations pertaining to ground-water quality will not prove burdensome as long as the wells used for heat pump operation are Class V wells under the Underground Injection Control Program.

At the state level, well construction requirements may be numerous or nonexistent. Concern here is more a matter of cost than of limitation; the expense involved in meeting such requirements can rule out the feasibility of heat pump utilization. Where water-use restraints exist, usually in the form of permit requirements, they are not serious deterrents to heat pump use. States whose restrictions pose potential problems are noted in Table 3.4. The disposal of effluent to a recharge well is uncontrolled in some states and prohibited in others. Where this disposal method is forbidden, heat pump viability may suffer. States in which this may be a problem are included in Table 3.4. Alternative disposal methods are available, however, and are generally subject to less regulation than are recharge wells. Since other disposal methods, such as discharge to land, surface water, septic tank, or sewer, are usually possible, state limitations on recharge wells should not hinder heat pump utilization. State restrictions placed on various effluent disposal methods are summarized in Table 3.3.

Some local controls on well construction, ground-water use and quality, and waste disposal may adversely affect heat pump utilization. Most local regulations, however, will not seriously impede widespread development of this alternative energy source.

Although most regulations and restrictions promulgated at the Federal, state, and local levels will not present serious obstacles, knowledge of their existence and their legal implications is vital to the implementation of ground-water heat pump technology.

Table 3.3

Summary of Ground-Water Heat Pump Water Use and Effluent Disposal Regulations by State*

State	Water Use	To Recharge Well	To Surface Water	To Land	To Septic Tank	To Sewer
Alabama	No permit needed to use water for H-P under domestic category	Notification and perhaps a permit needed from Water Improvement Commission	Theoretically covered by NPDES-however this system is usually not equipped to consider small domestic use; in most cases could discharge w/o a permit	Not a problem if discharge to land owned by H-P user	A loophole in regulations--this type of discharge is allowed if tank is big enough and far enough from well	Would probably be allowed almost anywhere--although in many areas would be cost-prohibitive
Alaska	No problem to obtain water rights	No mechanism to require a permit or to prevent this type of injection well	1	2	3	4
Arizona	Falls into domestic category--permit needed	Discharge is prohibited to any well that penetrates water-bearing strata	1	2	3	4
Arkansas	No permit needed for water use of this type	Apparently no program exists to control recharge wells of this type	1	2	3	4

1, 2, 3, and 4 regulations pertaining to this type of discharge are similar to those in Alabama

*Small-scale domestic heat pump utilization only

California	32 counties out of 58 total require permits for all wells--no severe problems	Waste disposal under control of Water Quality Control Board, which does not regulate H-P return wells at this time	1	2	3	4
Colorado	Permit needed for all wells	Permit required for recharge	1	2	3	4
Connecticut	No permit needed--falls into private domestic well category	Permit is required from Department of Environmental Protection for all types of discharge				
Delaware	Well construction permit required	Strict rules exist regarding reinjection --however, would probably be able to get a permit for a H-P return well	1	2	3	4
Florida	A permit would be required for this volume of water use--but not a serious problem in most parts of state	A permit would be required for a disposal well of this type--not a serious problem to obtain	1	2	3	4

Georgia	No permit needed for use under 100,000 gpd (378,500 l/day)	Reinjection of cooling water is only type allowed in state. No permit is required for this	1	2	3	4
Hawaii	Classified as a domestic well --no problem to obtain water use	A regulation exists that requires permission for disposal wells and wastewater disposal --however, not enforced at present	1	2	3	4
Idaho	No permit needed for a domestic use except in critical ground-water area--need a permit for any use over 13,000 gpd (49,205 l/day)	Theoretically required to obtain permit for any type of disposal or injection well but permit mechanism does not exist at present	No problem except in critical ground-water areas where recharge back to the aquifers would be required			
Illinois	Domestic use classification--no permit needed	Under control of the state EPA which at present has no mechanism to regulate wells of this type	1	2	3	4
Indiana	Domestic use--no permit needed	Conventional and cooling water recharge wells not regulated--though Stream Control Board has theoretical authority	Board of Health permit, no special problem to obtain	2	3	4

Iowa	No permit needed for domestic use	No permit needed for discharge of this type	1	2	3	4
Kansas	A water appropriation permit would be needed	A permit would be required but not a problem--mostly for record keeping purposes	1	2	3	4
Kentucky	Private use--no permit required	No permit required	1	2	3	4
Louisiana	No permit required	Might eventually need a permit from Department of Environmental Control but no official policy at present	1	2	3	4
Maine	No permit needed for this type of water use	At the present time no underground injection of any type is allowed in this state	1	2	3	4
Maryland	A permit is needed for use of this type	A permit is required for discharge into surface or underground waters of the state		2	3	4
Massachusetts	No permit needed for this type of water use	Permit would be needed from Division of Water Pollution Control to discharge heated or cooled water		2	3	4

Michigan	No permit needed for this type of water use	Discharge permit required from Water Resources Commission for all units with heat exchange capacity greater than 120,000 BTU per hour (35 kw). Permit also required for any unit using chemical additives.				
Minnesota	No permit required	Reinjection of this type is generally prohibited but could apply for a variance permit.	1	2	3	4
Mississippi	No permit required	No permit needed	1	2	3	4
Missouri	No permit needed	No permit required for small-scale domestic use	1	2	3	4
Montana	Certificate of water right is needed--no serious problem to obtain	Permit would theoretically be needed--but no mechanism is available to issue them at this time	1	2	3	4
Nebraska	No permit needed	No regulations exist to cover a permit process	1	2	3	4
Nevada	Permit would be required	Regulations exist and a permit would be required for this type of injection	1	2	3	4

New Hampshire	No permit needed	Permit theoretically required but at this time notification would suffice	1	2	3	4
New Jersey	No permit needed	No permit required	1	2	3	4
New Mexico	Permit needed for use of this magnitude	Notification and a simple permit required	1	2	3	4
New York	No permit needed	No permit needed to cover this type of discharge	1	2	3	4
North Carolina-	No permit required	Permit needed--at present time this disposal method is discouraged	1	2	3	4
North Dakota	Standard appropriation permit needed	No policy exists to cover this type of discharge	1	2	3	4
Ohio	No permit needed for domestic use	A permit is needed for all types of well injection	1	2	3	4

Oklahoma	No permit needed for domestic use	Discharge into water-bearing strata prohibited under law--but Water Resources Board won't enforce it if unnecessary	1	2	3	4
Oregon	Less than 15,000 gpd (56,775 l/day)--no permit required	Return water must be reinjected into the same formation	1	2	3	4
Pennsylvania	No permit needed	A simple permit might be required (notification) but no specific regulations	1	2	3	4
Rhode Island	No permit needed	Recharge wells not required to obtain permit	Rhode Island Pollution Discharge Elimination System may require a simple permit	2	3	4
South Carolina	No permit needed	No regulations exist at this time	1	2	3	4
South Dakota	No permit needed	No program to regulate this type of well exists at this time	1	2	3	4

Tennessee	No permit needed for water use under 50,000 gpd (189,250 l/day)	Permit would be required from Department of Health--no special problem to obtain		2	3	4
Texas	No permit needed for water use	Permit granting procedures do not exist for recharge wells--no permit needed	1	2	3	4
Utah	Permit needed for use of any type	No permit program exists for this type of reinjection --no permit needed	1	2	3	4
Vermont	No permit needed	Permit theoretically needed	1	2	3	4
Virginia	No permit needed	Non-injection of wastewater is a policy in the state at present--would be a complicated permitting procedure for H-P return well	1	2	3	4
Washington	Permit needed for use over 5,000 gpd (18,925 l/day)	Necessary to obtain a discharge permit from the Department of Ecology		2	3	4
West Virginia	No permit needed	No real policy exists requiring permits at this time	1	2	3	4

Wisconsin	No permit needed	No reinjecting allowed in state	1	2	3	4
Wyoming	No permit needed	The method of disposal would have to be indicated on the use permit but otherwise no special requirement for any type of discharge				

Table 3.4

SUMMARY OF STATES THAT PRESENT POTENTIAL PROBLEMS FOR DOMESTIC HEAT PUMP DEVELOPMENT

Water Use

State	Potential Problem
Arizona	Permit required
California	32 counties require permits for all wells
Colorado	Permit required
Delaware	Permit required
Florida	Permit required
Idaho	Permit needed in critical ground-water area
Kansas	Permit needed
Maryland	Permit needed
Montana	Water right certificate needed
New Mexico	Permit needed
North Dakota	Appropriation permit needed
Utah	Permit needed

Reinjection

Permit Required:	Alabama	Idaho	New Mexico
	California	Kansas	North Carolina
	Colorado	Maryland	Ohio
	Connecticut	Massachusetts	Pennsylvania
	Delaware	Michigan	Tennessee
	Florida	Nevada	Vermont
	Hawaii	New Hampshire	Washington

Reinjection Prohibited

Arizona
Maine
Minnesota
Oklahoma
Virginia
Wisconsin

CHAPTER 4
COMPUTER MODEL OF RESIDENTIAL HEATING/COOLING SYSTEMS: DESCRIPTION OF METHODOLOGY AND INPUT DATA

I. INTRODUCTION

The purpose of Chapters 4, 5, and 6 of this report is to provide a comparative energy use and economic assessment for installing and operating a ground-water heat pump as a space-conditioning system. Monitoring a field installation will provide useful information for a specific location and weather year; however, data resulting from demonstrations are very space-time dependent, making the universal application of the results questionable.

Computer simulation of various space-conditioning systems offers a useful comparison. Effects of climate can be varied by simulating equipment operation in different areas of the country. User and structure characteristics can also be varied to test the dependence of energy use on those related variables. In addition, the effect of energy and installed equipment costs on users within regions can be assessed.

The energy use and system cost analyses for this study were accomplished entirely by computer simulation. A model was originally developed by the Honeywell Corporation to simulate operation of an Annual Cycle Energy System (ACES) and to compare it with conventional equipment under UCC-ND Subcontract No. 7470 (Honeywell, 1979). Considerable model modification was required to fulfill the goals of this study.

Although a program listing is not included in this report, it is currently available. The study consists of three program modules: LOADS, SIMULATION, and ECON. The LOADS module provides hourly heating, cooling, and domestic hot water loads for a user-specified structure. Based on energy requirements read from LOADS, the SIMULATION subprogram simulates the operation of various space-conditioning systems. Using the required energy for each system along with installed equipment costs, current and projected energy cost rates, and operation and maintenance costs, the ECON module provides a comparison of economic parameters for systems being analyzed.

Each of the following systems are of primary interest to this study.

Heating	Cooling
Electric Furnace	Electric Central Air-Conditioning
Oil Furnace	Electric Central Air-Conditioning
Natural Gas Furnace	Electric Central Air-Conditioning
Air-Source Heat Pump	Reversible cycle
Ground-Water Source Heat Pump	Reversible cycle

A heat-only ground-water heat pump with direct heat exchange cooling was also studied to determine effects of sizing strategies.

Although the program has the capability of including the energy required for domestic hot water generation, this area of study is addressed only to a limited extent in this report. A comparison of energy requirements is made for the ground-water heat pump using an electric resistance element or an optional desuperheater for the generation of domestic hot water. The simulation output is the time-dependent history of energy usage of the systems listed above.

The program was run on two Digitel Equipment Corporation PDP 11/03 computers. These 16 bit mini computers are at the National Water Well Association Research Facility. Core storage and disk storage consist of 64K and 10M, respectively. The program is written in FORTRAN IV language.

II. CALCULATION OF HOURLY LOADS

A. Methodology

Methodology used in determining hourly heating and cooling loads of the residence is similar to techniques used by Honeywell, Inc., in the ACES program. However, the subroutine COIL in the Honeywell ACES program has been totally deleted from the deliverable NWWA computer program. This portion of the program used 32°F (0°C) ice-slush water in association with the ACES ice-storage system.

A totally new ground-water heat pump subroutine was written around manufacturers' data of a residential

ground-water heat pump. In this subroutine, performance depended upon the dry bulb and wet bulb temperatures of the air entering the airside coil, as well as the flow rate of the water through the water-side coil. The data for each variable were normalized and reduced into a linear equation with complex forms for the slope and intercept coefficients.

With the above mentioned modifications, the LOADS module was run for all locations. Heating and cooling loads were determined as in the Honeywell Program, except cooling loads were produced from the new ground-water heat pump subroutine. First, these were calculated by determining a dynamic hourly humidity ratio for the structure, which was then used to calculate an hourly wet bulb temperature. Knowing these values, the total cooling load (consisting of sensible and latent) was calculated each hour by entering the new ground-water heat pump subroutine at the current water flow rate (gallons per minute), water temperature, air-side flow rate (cubic feet per minute), and dry bulb and wet bulb temperatures.

Loads determined for the residence in each city were used as a base for simulating the cooling systems. The work approach was similar to the Gordian project; it was "based upon simulating the load on a single residential structure synthetically located (by means of the computer) in various climatological regions of the country and then estimating the energy required to balance the load by simulating the performance of different heating and cooling systems" (Gordian Associates, 1978).

B. Computer Program

Input House construction information was identical to that in the Honeywell report. Basic construction details for the residential home were not changed for each city. With this technique, NWWA was essentially able to simulate the various types of heating and cooling plants while simultaneously comparing the effects of different climates on the performance of the heating and cooling plants.

Input parameters having the greatest effect on output were:

1) latitude and longitude of installation
2) inside and outside surface heat transfer film coefficients for walls and roof

3) overall heat transfer values (U values) for walls, floors, and ceilings
4) well water temperature and flow rate through heat pump
5) air handler CFM
6) areas of walls, floors, ceilings, and roof
7) thermal capacitance and internal mass of structure components.

Design Conditions Data For each city, ASHRAE 95 1/2 percent and 2 1/2 percent dry bulb design temperature data were used for input as the design weather day for heating and cooling modes, respectively. The computer program used this data along with the thermostat set point (70°F/21.1°C winter, 78°F/25.6°C summer) plus the construction details, and it performed winter heat loss and summer heat gain calculations of the residence for the design heating and cooling days. Once these loads were determined, the correctly sized ground-water heat pump was selected by the computer through the use of a scaling routine. A reversible heat pump was sized for the design summer cooling load, and the shortage of winter heating capacity was made up of strip heat. However, the heat-only heat pump with direct ground-water cooling for summer was sized for the design winter heating load rather than the design summer cooling load. Cooling equipment was sized independently.

Weather Data Hourly weather data, required for the computer simulation of heating and cooling, were: dry bulb, wet bulb, dew point, wind speed, barometric pressure, type of clouds, cloud cover, wet precipitation, and dry precipitation. NWWA criteria used in selecting weather data were the same as in the Gordian study. The selection procedure of cities representing the broad range of climatic conditions in the United States was based on the concept of the heating degree day. A list of the cities and associated heating degree days is shown below:

City	Heating Degree Days
Houston, TX	1290
Birmingham, AL	2483
Atlanta, GA	2821
Tulsa, OK	3670
Philadelphia, PA	4508
Seattle, WA	4407
Columbus, OH	5476
Cleveland, OH	6097
Concord, NH	7377

Average daily temperatures at every weather station were routinely converted into degree days. Monthly and annual summaries were readily available. However, after selecting the nine cities, a problem arose in the degree-day concept when deciding what year of weather data represented the long-term average for each city. The use of an average year was mandated by consideration of extreme deviations which occur from year to year.

To limit these extreme weather variations, each city's weather data were analyzed. The procedure used followed the method described in Noyes Data Corporation's Heat Pump Technology for Saving Energy (Collie, 1979). Briefly stated, an average year of weather data was compiled for each city. Individual months were not necessarily in the same calendar year. However, yearly totals and individual monthly degree days of heating and cooling represented the long-term, 30-year average for each city. For the nine cities, the smallest range of deviation from the average varied from ± 3 to ± 10 percent.

III. SIMULATION OF HEATING/COOLING SYSTEMS

A. Simulation Theory

The methodologies used to simulate different heating and cooling systems are identical to the Honeywell program. Once the LOADS module determined the hourly heating or cooling loads, they were used as input for the SIMULATION program. The output of the SIMULATION program were time-dependent histories of all gas, oil, and electric consumption of each of the simulated heating and cooling systems. Changes to the SIMULATION program included the deletion of the ACES heat pump using 32°F (0°C) ice-slush water. New subroutines (Water-to-Air Heat Pump and Air-to-Water Heat Pump) were written around manufacturers' data of a residential ground-water heat pump. Performance data, COP, heating capacity, cooling capacity, compressor power consumption, well water flow rate and temperature, air handler flow rates, and entering air thermodynamic state points were reduced into linear equations with complex forms for the slope coefficient and intercept coefficient. These equations were used in the new subroutines to simulate a ground-water heat pump.

Three types of ground-water heat pumps were simulated. Two were residential, reverse-cycle, heating and cooling heat pumps. The third was a heat-only heat pump with cooling provided by a direct ground-water cooling coil.

The two reverse-cycle ground-water heat pumps were similar in many respects. One was a standard unit for use with moderately warm ground water commonly found in the middle and southern latitudes of the United States. The other unit was a higher performance model for use with the colder ground water found in the northern United States.

The standard, four-ton, ground-water heat pump consisted of a 208/230 volt, single-phase compressor and a 3/4 horsepower (0.56 kW), direct drive, multi-speed blower motor. The refrigerant-to-air heat exchanger surface area was 4.17 ft^2 (0.39 m^2) with 14 fins per inch (2.5 cm). Supplemental strip heat was provided in each unit as auxiliary heaters to meet the winter design load. The modeled unit used disposable type air filters. As an option, a hot water generator was included.

The high-performance ground-water heat pump consisted of the above features. However, modifications were made to exchanger and compressor sizes so that heating and cooling performance would be maintained at cooler ground-water temperatures.

The final type of simulated ground-water heat pump was a heat-only heat pump consisting of a 230 volt, single-phase compressor with a blower unit, a refrigerant-to-air heat exchanger, back-up supplemental electrical resistance strip heaters, direct ground-water cooling coils, and disposable type air filters.

The air-source heat pump modeled in the original computer program was replaced with a high-performance, split-system heat pump. This heat pump had an indoor air-handling system complete with electrical supplementary heaters, a refrigerant indoor heat exchanger coil, throw away filters, and an indoor fan with direct-drive multi-speed motor. Its outdoor components consisted of a compressor, an outdoor refrigerant coil, an outdoor fan with direct-drive motor, and an outdoor thermostat.

B. Comparative Equipment Modeled

The other types of simulated heating systems were an oil-fired furnace, a gas-fired furnace, and an electric furnace. These pieces of equipment were identical to the equipment used in the Honeywell ACES project. For comfort cooling in the summer, identical split-system air conditioners were used for each of the above heating systems. The split-system air conditioner had the same components as the air-source heat pump when operated in the cooling mode without the outdoor thermostat required for defrosting in the heating mode.

C. Simulation Program Output

Simulation output listed the residence energy requirements by total heating load, total hot water, and total cooling load in BTUs for the entire year. The output listed five various heating and cooling systems and the associated energy required to meet the residence load.

By comparing the residence load with the energy required for equipment operation, yearly COPs of each system may be obtained.

IV. INPUT DATA

In order to assess the energy use and economic feasibility of using ground-water heat pumps under different operating conditions, nine test cities reflecting varying climatological/hydrogeological and economic conditions are chosen. The primary consideration in the selection of the cities was climate. Each city selected had to represent a reasonable number of climatological conditions. However, these conditions had to be limited in number because of the high cost of data input and computer runs per city.

Selected cities are identical to those described in "Evaluation of the Air-to-Air Heat Pump for Residential Space-Conditioning," prepared by Gordian Associates, Inc. (1976). The choice, as reported in that study, is made on a degree-day basis. The reader is referred to the Gordian Associates report for a more complete discussion of the selection procedure.

Table 4.1 shows the selected cities and associated degree-day and design temperature data. Although Seattle

TABLE 4.1

REPRESENTATIVE DESIGN TEMPERATURE, DEGREE-DAY, AND GROUND-WATER DATA FOR THE NINE TEST CITIES

Test City	Summer Design Temperature °F (°C)	Winter Design Temperature °F (°C)	Representative Heating Degree Day Range	Ground-Water Temperature °F (°C)	Pumping Head Ft. (m)
Atlanta	92 (33)	23 (-5)	2500 - 3500	64 (18)	25 (8)
Birmingham	94 (74)	22 (-6)	2000 - 3000	64 (18)	25 (8)
Cleveland	89 (32)	7 (-14)	6000 - 7000	54 (12)	25 (8)
Columbus	88 (31)	7 (-14)	5000 - 6000	55 (13)	50 (15)
Concord	88 (31)	-7 (-22)	7000 - 8000	48 (9)	200 (61)
Houston	94 (34)	32 (0)	500 - 2000	75 (24)	100 (30)
Philadelphia	90 (32)	15 (-9)	4000 - 5000	54 (12)	25 (8)
Seattle	79 (26)	32 (0)	4000 - 5000	51 (11)	25 (8)
Tulsa	99 (37)	16 (-9)	3000 - 4000	64 (18)	100 (30)

lies in the same degree-day range category as Philadelphia, it is included to represent regions of the Pacific Northwest typified by long rainy periods with generally high humidity.

Water pumping levels (Table 4.1) in wells used for ground-water heat pump supply are obtained from U.S Geologic Survey Water Supply Papers. Because of the depth and function of the wells listed in these sources, a high degree of variability exists in the water levels. Data from wells that would most closely depict average domestic wells in each region were included whenever possible.

To determine the ground-water temperatures (Table 4.1), data sources include numerous U.S. Geological Survey Water Supply Papers and state and regional hydrologic investigations. Space limitations and practicality preclude the listing of all data sources employed. Only wells between 50 and 150 feet (15.3 and 45.8 meters) are used in the selection of the water temperature data, since these depths reflect those typical of domestic wells in most regions of the United States.

In order to determine energy usage for any heating/cooling system configuration, a number of components are included. Energy use of fossil fuel-fired equipment (natural gas and oil furnaces) consists of a fossil fuel input to the burner and an electrical input to the air handler. The split-system electric cooling and air-source heat pump input consists of electrical energy to operate the compressor, the air handler, and the outdoor coil fan.

The electric furnace requires electric energy input to the heating elements and to the air handler, and the ground-water heat pump requires electric input to the air handler, compressor, and well pump.

Supply air delivery for the fossil fuel-fired equipment and air-source heat pump are held constant at 1000 cubic feet per minute (cfm) (0.5 m^3/s) and 1200 cfm (0.57 m^3/s), respectively.

Supply air and water delivery to the heat exchangers for the ground-water heat pump are varied for each city. A combination of these components used in the simulation and economic analysis require the least energy while satisfying the required heating and cooling load. In general, for those locations in which high pumping heads are required, the water flow rate is held to a minimum, reducing the energy required by the well pump.

Water and air flow rates used for the ground-water heat pump simulation and economic analysis are shown in Table 4.2.

Electric strip heat is added to all reversible-cycle heat pumps. A capacity equal to the design heat loss is added to the air-source heat pump, while the capacity added to the ground-water heat pump equals the difference of design heat loss and equipment heating capacity at the design conditions for each city-year combination.

As a matter of convenience, it is assumed that the well pump is activated at the same instant and for the same period of time as the heat pump itself. The rate of energy input to the well pump was calculated from the formula:

$$kW = \frac{(1.88 \times 10^{-4})\ Q \cdot H}{E_0}$$

Q = discharge flow rate, gallons per minute
H = total pumping head, feet of water
E_0 = wire-to-water efficiency of the well pump, expressed as a numerical fraction. This factor is assigned a constant value of 0.30 for this study. Although higher capacity pumps generally operate at higher efficiencies, this value reflects typical efficiencies of domestic-size submersible pumps currently on the market.

The value of Q in the above equation is the flow rate through the water-side heat exchanger during heat pump operation as reported in Table 4.2.

Variables concerning long-term owning and operating costs can be divided into three categories: installed equipment costs, energy and maintenance costs and escalation rates, and assumed economic parameters such as real discount rates.

Equipment costs used in the analysis are reported in Table 4.3. With the exception of the ground-water heat pump, installed HVAC equipment costs are obtained from a local heating/cooling contractor in Columbus, Ohio. These costs include the cost of the space-conditioning plant, ductwork, and any required plumbing and wiring. The cost of

TABLE 4.2

WATER AND AIR FLOW RATES USED
IN GROUND-WATER HEAT PUMP SIMULATION

CITY	SUPPLY AIR DELIVERY cfm (m^3/s)	WATER FLOW RATE gpm (l/s)
Atlanta	1050 (0.5)	14 (0.9)
Birmingham		
Standard Model	1050 (0.5)	14 (0.9)
High-Efficiency Model	1050 (0.5)	14 (0.9)
Cleveland	1050 (0.5)	10 (0.6)
Columbus	1050 (0.5)	10 (0.6)
Concord		
Reversible-Cycle	1050 (0.5)	6 (0.4)
Heat-Only w/ Direct Cooling	1800 (0.8)	4 (0.3)
Houston		
Standard Model	1050 (0.5)	6 (0.4)
High-Efficiency Model	1050 (0.5)	6 (0.4)
Philadelphia	1050 (0.5)	10 (0.6)
Seattle	1050 (0.5)	14 (0.9)
Tulsa		
Standard Model	1190 (0.6)	8 (0.5)
High-Efficiency Model	1190 (0.6)	6 (0.4)

an oil storage tank and a triple-walled flue are included in the cost of the oil heating system. For the natural gas furnace system, the cost of a standard flue is included. The local contractor was unable to provide installed equipment costs for the remaining test cities. Therefore, in order to account for the effect of variations in local economies, costs for equipment are indexed by test city using Columbus, Ohio, as the reference city. HVAC costs in the nine cities were comparatively indexed (Means, 1978). It should be noted that installation labor cost variances make up the greatest portion of the regional price differences. The actual equipment retail price structure varies much less across the country, especially when local contractors choose to install locally or regionally manufactured equipment. Thus, the effect of shipping costs is seldom a major factor in any of the nine test cities. Cost indexes for each city are listed in Table 4.3.

Costs of all ground-water heat pumps are obtained from the manufacturers. Prices quoted are suggested prices for homeowners in Columbus, Ohio. Plumbing and wiring costs are added to the equipment costs. Electric strip heat prices are obtained from engineering personnel at the Thermal Energy Transfer Corporation of Powell, Ohio. These costs are included in the installed costs of all heat pump systems.

Regional water well cost data (Table 4.3) are taken from the Water Well Drilling Cost Survey (1979), prepared by the National Water Well Association for the U.S. Department of Energy. The data results from actual water well contractors' reports of well diameter and depth pricing for various geographic regions. It should be noted that these costs are based on average regional hydrologic conditions; extremely localized hydrogeologic anomalies could result in considerably cheaper or more expensive drilling costs. Since most metropolitan areas included in this study cover a fairly large physical area, an average figure is both fair and representative.

Residential energy costs for gas, electric, and fuel oil are obtained from the U.S. Department of Energy. Projected energy costs in 1975 dollars per million BTUs for each year from 1980 to 1995 are used in a linear regression program. Each cost is multiplied by a factor of 1.3 to reflect 1979 dollars. (A 1980 multiplier was not available, but was assumed to be similar to the 1979 multiplier.) Conversion factors are then used to transform the costs to

TABLE 4.3

INSTALLED COSTS FOR HEATING/COOLING SYSTEMS

Test City	Gas System	Oil System	A-A H.P. System	Electric System	Electric Cooling
Atlanta	$1660	$2860	$3370	$1580	$1650
Birmingham	$1600	$2750	$3240	$1520	$1590
Cleveland	$1920	$3300	$3880	$1820	$1900
Columbus	$1790	$3080	$3425	$1700	$1600
Concord	$1630	$2810	$3190	$1550	$1460
Houston	$1770	$3050	$3520	$1680	$1760
Philadelphia	$1880	$3230	$3770	$1790	$1860
Seattle	$1880	$3230	$3515	$1790	$1860
Tulsa	$1760	$3020	$4340	$1670	$1940

cont.

TABLE 4.3 (Continued)

INSTALLED COSTS FOR HEATING/COOLING SYSTEMS

Test City	G.W.H.P. System No Well	Injection Well	Supply Well	Cost Index
Atlanta	$2650	$1400	$2070	-7.0%
Birmingham	$2340	$1500	$2130	-10.6%
Cleveland	$3560	$1500	$2270	7.0%
Columbus	$3320	$1500	$2220	0.0%
Concord	$3040	$1600	$2250	-8.8%
Houston	$2820	$2500	$3210	-0.9%
Philadelphia	$3450	$1650	$2420	4.9%
Seattle	$3450	$1800	$2550	5.0%
Tulsa	$2990	$2000	$2700	-1.9%

appropriate units for each fuel type. These results are reported in Table 4.4.

Factor n in the equation is the year number in question using 1980 as year 0. The coefficient of n is the slope of the straight line relating the year number to the energy cost. Units for the coefficient, then, are dollars per energy unit per year. The second term in the expression is the y intercept of the line depicting 1980 energy costs. Units are dollars per energy unit.

Correlation coefficients for the least-squares fit ranged from 0.87 to 0.99. The line was extrapolated to the year 2000 to supply energy costs for the 20-year life cycle period.

The value of operation and maintenance costs is assumed to be constant from year to year and is assigned a value of 1 percent of the total installed cost according to findings of Economic Evaluation of the Annual Cycle Energy System (ACES) Vol. 2, p. 4-4, as part of a U.S. Department of Energy study produced by Honeywell, Inc. (Contract No. 7470, 1979).

The real discount rate used in the study is 2 percent, reflecting an assumed opportunity cost of capital in the private sector. Although a value of 10 percent is generally used by Federal agencies, privately owned electric utilities use a figure close to 2 percent (1.9 percent) in making energy-related investment decisions (Department of Energy, 1980). The 10 percent figure is used for comparison purposes in the Columbus test city and is discussed in Chapter 6.

TABLE 4.4

ENERGY RATES*

CITY	ELEC (KWH)	GAS (MCF)	OIL (Gal.)
Columbus, Cleveland	7.50×10^{-4} (n) + 0.049	1.29×10^{-1} (n) + 2.80	3.21×10^{-2} (n) + 0.69
Seattle	5.01×10^{-4} (n) + 0.020	1.53×10^{-1} (n) + 4.30	3.14×10^{-2} (n) + 0.67
Houston, Tulsa	1.11×10^{-3} (n) + 0.049	1.76×10^{-1} (n) + 2.85	3.25×10^{-2} (n) + 0.72
Philadelphia	4.79×10^{-4} (n) + 0.053	1.33×10^{-1} (n) + 3.25	3.42×10^{-2} (n) + 0.74
Birmingham, Atlanta	6.52×10^{-4} (n) + 0.040	1.26×10^{-1} (n) + 2.77	3.62×10^{-2} (n) + 0.73
Concord	3.86×10^{-4} (n) + 0.069	1.47×10^{-1} (n) + 4.38	3.16×10^{-2} (n) + 0.73

* 1979 Dollars per Energy Unit

n = year number using 1980 as the base year

CHAPTER 5
BUILDING LOAD AND ENERGY CONSUMPTION RESULTS OF COMPUTER SIMULATIONS IN NINE CITIES

I. INTRODUCTION

Comparisons made in this study involve equipment currently available and marketed in the United States. In the most general sense, the equipment can be classified into types requiring fossil fuels and electric energy and types requiring only electrical input.

The results of simulating the space-conditioning equipment in the nine test cities are reported in this section. For each system, the energy required annually to satisfy the heating or cooling load is reported in millions of BTUs. In addition, two measures of efficiency are calculated.

The on-site annual coefficient of performance (ACOP) is calculated by dividing the total annual heating and cooling load by the total energy required to satisfy that load at the point of use. However, since electric energy generation from fossil fuels is not 100 percent efficient and is not generated on-site, a number reflecting the measure of on-site efficiency for the oil/electric and natural gas/electric systems would be somewhat meaningless. Thus, these values are not provided.

The source ACOP is calculated using a similar procedure. In this calculation, however, the electric energy required at the site is multiplied by a factor of three to account for efficiencies of power generation at the power plant. Power plant efficiency was assumed to be 0.33.

Seasonal Performance Factors (SPF) are calculated for the ground-water heat pump and for the air-source heat pump only. The performance factor for either season is the ratio of the load for that season divided by the energy required to satisfy that load for a specific equipment type.

Because of differences in ambient ground-water temperatures in the nine test cities, two ground-water heat pump models (standard and high efficiency) are simulated. In the northern cities, the high-efficiency unit is

generally required because of low ground-water temperatures. These cities include Seattle, Concord, Philadelphia, Columbus, and Cleveland. The standard model is used in the remaining cities. The Houston, Tulsa, and Birmingham test cities are used to examine the energy use effectiveness and economic feasibility of installing the high efficiency model at a higher initial cost in a given city.

II. TABULATED RESULTS

Examination of Table 5.1 indicates that the ratio of annual heating to cooling loads is closer to unity for Birmingham than for any other test city. Thus, the operating conditions of the equipment in Birmingham have minimal bias to heating or cooling mode operation.

Simulation results for all systems in Birmingham, including the standard model and high-efficiency ground-water heat pumps, are shown in Table 5.2. The results indicate a clear advantage of both ground-water heat pumps over the other systems in terms of energy usage and annual performance factors. The air-source heat pump is closest to the ground-water heat pump in terms of performance, requiring 27 percent more energy than the standard model. In addition, the electric heating/electric cooling uses 104 percent more energy than the standard model ground-water heat pump. Moreover, the comparison of the high-efficiency ground-water heat pump with the standard model shows that the high-efficiency unit offers only a moderate advantage in terms of performance (the economic benefits resulting from the installation of this unit are examined in Chapter 6).

A comparison of energy use and ACOP values for Birmingham and Atlanta indicates a high degree of similarity for all equipment types. The standard ground-water heat pump is used in Atlanta (Table 5.3). The nearly identical loads for each city raise some question as to the utility of the method used to select the test cities outlined in Chapter 4.

A comparison of the two models of ground-water heat pumps can also be made using Tulsa as the test city with a 3:1 ratio of annual heating to cooling load. The same trend is exhibited in Table 5.4, which shows less than an eight percent reduction in energy usage for the high-efficiency model. It must be noted that these results are obtained

TABLE 5.1

HEATING AND COOLING LOADS
FOR THE NINE TEST CITIES

	ANNUAL ($BTU \times 10^{-6}$)		DESIGN ($BTU/HR \times 10^{-3}$)	
CITY	Heating	Cooling	Heating	Cooling
Atlanta	33.7	24.5	40.1	34.7
Birmingham	31.7	26.4	40.8	35.9
Cleveland	73.3	9.3	52.4	31.4
Columbus	66.0	12.5	52.2	30.7
Concord	88.8	5.6	62.0	30.7
Houston	14.8	42.8	33.3	35.9
Philadelphia	55.9	13.4	46.7	32.0
Seattle	62.6	2.5	34.3	25.1
Tulsa	46.6	15.7	44.4	39.0

TABLE 5.2
SIMULATION RESULTS

City: Birmingham

Ground-Water Heat Pump Model: Standard
High-Efficiency

HVAC SYSTEM HEATING/COOLING PLANT	YEARLY ENERGY CONSUMPTION (BTU X 10^{-6}) Electric	Fossil	ON-SITE ACOP	SOURCE ACOP
Natural Gas/Electric	12.46	49.65		0.67
Oil/Electric	12.46	43.39		0.72
Air-source Heat Pump	27.03		2.14	0.72
Electric/Electric	43.27		1.34	0.45
Ground-Water Heat Pump Standard Model	21.23		2.74	0.91
High-Efficiency Model	20.21		2.87	0.96

TABLE 5.3
SIMULATION RESULTS

City: Atlanta

Ground-Water Heat Pump Model: Standard

HVAC SYSTEM HEATING/COOLING PLANT	YEARLY ENERGY CONSUMPTION (BTU X 10^{-6}) Electric	Fossil	ON-SITE ACOP	SOURCE ACOP
Natural Gas/Electric	11.61	52.72		0.66
Oil/Electric	11.61	46.11		0.72
Air-source Heat Pump	26.71		2.18	0.73
Electric/Electric	44.35		1.31	0.44
Ground-Water Heat Pump	21.29		2.73	0.91

TABLE 5.4
SIMULATION RESULTS

City: Tulsa

Ground-Water Heat Pump Model: Standard
High-Efficiency

HVAC SYSTEM HEATING/COOLING PLANT	YEARLY ENERGY CONSUMPTION (BTU X 10^{-6}) Electric	Fossil	ON-SITE ACOP	SOURCE ACOP
Natural Gas/Electric	8.17	72.83		0.64
Oil/Electric	8.17	63.95		0.70
Air-source Heat Pump	31.05		2.01	0.67
Electric/Electric	53.57		1.16	0.39
Ground-Water Heat Pump Standard Model	25.53		2.44	0.81
High-Efficiency Model	23.61		2.64	0.88

from the simulation of one manufacturer's equipment. Even though the high-efficiency model has performance ratings at the higher range on an industry-wide scale of performance, it would be inaccurate to assume that the identical results would be obtained for all manufacturers' equipment.

For the Houston test year, the ratio of annual cooling to heating load approaches three to one. Under these conditions, the air-source heat pump requires slightly less energy than the standard model ground-water heat pump and nine percent more energy than the high-efficiency model (Table 5.5). For all cities tested, in which there is a mild heating load and no supplemental electric strip heat added, the ground-water heat pump displays the poorest performance in Houston. This is due to the fact that the unit shows a substantial difference in seasonal performance factors (SPF) for the climatological conditions represented by Houston. For the standard model ground-water heat pump, the heating SPF is 2.51 compared to a cooling SPF of 2.17 (Table 5.6). This factor and the fact that the energy required for the well pump accounts for eight percent of the total energy used explains the relatively low ACOP values obtained for the standard model ground-water heat pump in Houston. The air-source heat pump shows the highest ACOP values in Houston for all cities tested. In contrast to the ground-water source heat pump, the SPF values for cooling are slightly higher than for heating (2.31 and 2.24, respectively). It can be concluded, then, that for the equipment modeled, the air-source heat pump performs equally or as well on an annual basis in a climatological setting represented by Houston.

The high-efficiency ground-water heat pump shows a substantially higher heating SPF compared to the air-source heat pump, while there is only a slight improvement in cooling performance.

Concord shows the highest annual and design heating loads of all the test cities, which results in the greatest energy consumption for each system (Table 5.7). Under these conditions, the air-source heat pump uses 33 percent more energy than the ground-water heat pump, and the electric/electric system uses 107 percent more.

The low ACOP values for the heat pumps in Concord can be attributed to their reliance on supplemental electric resistance heating to make up the difference in design

TABLE 5.5
SIMULATION RESULTS

City: Houston

Ground-Water Heat Pump Model: Standard
High-Efficiency

HVAC SYSTEM HEATING/COOLING PLANT	YEARLY ENERGY CONSUMPTION (BTU X 10^{-6}) Electric	Fossil	ON-SITE ACOP	SOURCE ACOP
Natural Gas/Electric	19.00	23.45		0.72
Oil/Electric	19.00	20.14		0.75
Air-source Heat Pump	25.08		2.30	0.77
Electric/Electric	33.30		1.73	0.58
Ground-Water Heat Pump				
Standard Model	25.62		2.25	0.75
High-Efficiency Model	23.01		2.50	0.83

TABLE 5.6

HEAT PUMP SEASONAL PERFORMANCE FACTORS

CITY	HEATING AIR-SOURCE	HEATING WATER-SOURCE	COOLING AIR-SOURCE	COOLING WATER-SOURCE
Atlanta	2.10	2.67	2.30	2.83
Birmingham	2.04		2.28	
Standard Model		2.68		2.81
High-Efficiency Model		2.84		2.99
Cleveland	1.74	2.81	2.31	2.90
Columbus	1.75	2.48	2.29	2.80
Concord	1.58		2.30	
High-Efficiency Model		2.14		2.33
Heat-Only w/ Direct Cooling		3.05		10.87
Houston	2.24		2.31	
Standard Model		2.51		2.17
High-Efficiency Model		2.74		2.43
Philadelphia	1.96	2.77	2.29	2.91
Seattle	2.17	2.72	2.29	3.06
Tulsa	1.94		2.26	
Standard Model		2.47		2.35
High-Efficiency Model		2.70		2.48

TABLE 5.7
SIMULATION RESULTS

City: Concord

Ground-Water Heat Pump Model: High-Efficiency

Heat-only Heat Pump with
Direct Heat-Exchange Cooling

HVAC SYSTEM HEATING/COOLING PLANT	YEARLY ENERGY CONSUMPTION (BTU X 10^{-6}) Electric	Fossil	ON-SITE ACOP	SOURCE ACOP
Natural Gas/Electric	4.16	138.95		0.62
Oil/Electric	4.16	122.61		0.70
Air-source Heat Pump	58.53		1.61	0.54
Electric/Electric	91.22		1.03	0.34
Ground-Water Heat Pump				
High-Efficiency Reverse-Cycle	43.99		2.15	0.72
Heat-Only Heat Pump with Direct Heat Exchange Cooling	29.59		3.19	1.06

capacity and unit heating capacity. This has a greater effect on the performance of the air-source heat pump than on the water-source heat pump due to its inverse relationship of heating capacity and outside air temperature. The water-source heat pump performs substantially better in this climate because it operates at constant capacity independent of outside air temperature and requires no defrost cycle.

The relatively high pumping heads used in the model account for the large fraction (16 percent) of total required energy to operate the well pump. The depth to water in any location, then, is an important factor regarding total energy used by the system.

The low ACOP values for the air-source and ground-water source heat pumps are also partially due to sizing procedures. The method for sizing the heat pumps in Concord is the same as that in the other cities. Units are sized to satisfy the cooling load, which, under Concord's climatological conditions, leaves a substantial heating deficit that is accommodated by supplemental electric resistance heat. This condition could be partially alleviated with the air-source heat pump by choosing a low balance point for a specific application. In areas with severe heating loads, light cooling loads, and consistently low humidity, dehumidification would probably not be a problem. However, the unit would still suffer from frequent cycling, which may result in premature mechanical failure.

This sizing procedure also accounts for the low ACOP for the ground-water heat pump. The use of a heat-only ground-water heat pump offers distinct advantages in terms of energy consumption since the unit could be sized to any desired fraction of full design capacity, independent of cooling load. If cooling is required, direct heat rejection to the ground water could be achieved using a properly designed water-to-air coil. Results of the simulation involving the heat-only heat pump and direct heat exchange cooling coil are shown in Table 5.7.

A 33 percent decrease in energy consumption compared to the reverse-cycle ground-water heat pump and the 49 percent decrease compared to the air-source heat pump illustrate the advantage of independently sizing equipment to heating and cooling loads. It is unlikely that the effect would be as pronounced as heating and cooling loads approach similar

values, as in milder climates. In the northern areas, however, the advantage is clear.

The heat-only heat pump is sized to full design heating load for this study. Long-term economics of using this strategy under some conditions is questionable. In many areas, sizing to some fraction of the total design load and making up the deficit in heating capacity with strip heat may be attractive. For the short periods of time when the extra capacity is needed, the long-term costs incurred in installing and operating the strip heat may be notably less than operating a design-capacity unit. This effect would be substantial if installation of a small capacity of strip heat would allow smaller components to be used in the heat pump.

The direct heat exchange cooling coil offers extremely efficient cooling under relatively light cooling loads and low ground-water temperatures (Table 5.7). For more severe latent loads, a two-stage cooling operation could be used. A direct heat exchange coil would be used until it could not satisfy the total load. At this time, the heat pump would begin operation, using the direct heat exchange coil as a pre-cooler. Climatological conditions and ambient ground-water temperatures for which these systems would be an option require further research.

Climates represented by Cleveland, Columbus, and Philadelphia (Tables 5.8, 5.9, and 5.10, respectively) present milder annual heating loads and heavier cooling loads than those in Concord. Under these conditions, both the air-source heat pump and ground-water heat pump operate at higher efficiencies. However, the ground-water heat pump uses less energy and operates at substantially higher efficiencies than the air-source heat pump in all three cities.

Effects of design load on heat pump operation can be seen by comparing the simulation results of Seattle (Table 5.11) with those of another test city having annual heating loads and pumping heads similar to those of Seattle but with dissimilar design loads, e.g. Philadelphia. The heating SPFs for the ground-water source heat pump in the two cities are nearly identical, while the performance of the air-source heat pump is 13 percent lower in Philadelphia (Table 5.10). Cooling SPFs remain nearly constant for each equipment type.

TABLE 5.8
SIMULATION RESULTS

City: Cleveland

Ground-Water Heat Pump Model: High-Efficiency

HVAC SYSTEM HEATING/COOLING PLANT	YEARLY ENERGY CONSUMPTION (BTU X 10^{-6}) Electric	Fossil	ON-SITE ACOP	SOURCE ACOP
Natural Gas/Electric	5.71	114.52		0.63
Oil/Electric	5.71	100.94		0.70
Air-source Heat Pump	46.03		1.79	0.60
Electric/Electric	77.38		1.07	0.36
Ground-Water Heat Pump	26.28		2.82	0.94

TABLE 5.9
SIMULATION RESULTS

City: Columbus

Ground-Water Heat Pump Model: High-Efficiency

HVAC SYSTEM HEATING/COOLING PLANT	YEARLY ENERGY CONSUMPTION (BTU X 10^{-6}) Electric	Fossil	ON-SITE ACOP	SOURCE ACOP
Natural Gas/Electric	6.97	103.13		0.63
Oil/Electric	6.97	90.84		0.70
Air-source Heat Pump	43.10		1.82	0.61
Electric/Electric	71.47		1.10	0.37
Ground-Water Heat Pump	28.81		2.72	0.91

TABLE 5.10
SIMULATION RESULTS

City: Philadelphia Ground-Water Heat Pump Model: High-Efficiency

HVAC SYSTEM HEATING/COOLING PLANT	YEARLY ENERGY CONSUMPTION (BTU X 10^{-6}) Electric	Fossil	ON-SITE ACOP	SOURCE ACOP
Natural Gas/Electric	7.25	87.29		0.64
Oil/Electric	7.25	76.78		0.70
Air-source Heat Pump	34.37		2.02	0.67
Electric/Electric	61.77		1.12	0.37
Ground-Water Heat Pump	24.83		2.79	0.93

TABLE 5.11
SIMULATION RESULTS

City: Seattle

Ground-Water Heat Pump Model: High-Efficiency

HVAC SYSTEM HEATING/COOLING PLANT	YEARLY ENERGY CONSUMPTION (BTU X 10^{-6}) Electric	Fossil	ON-SITE ACOP	SOURCE ACOP
Natural Gas/Electric	3.21	96.74		0.61
Oil/Electric	3.21	85.16		0.69
Air-source Heat Pump	29.90		2.18	0.73
Electric/Electric	63.68		1.02	0.34
Ground-Water Heat Pump	23.81		2.73	0.91

Table 5.12 reports the percentage of total energy used in the heating season for electric strip heating for all heat pumps. The percentage of total annual energy used for well pump operation to supply water to the ground-water heat pump is also shown.

This table also shows that the ground-water heat pump uses a substantial quantity of energy for strip heating only in the Concord test city (11 percent). Requirements for peak heating load days did not surpass heating capacity in the other cities. Thirty-eight percent of the energy used for heating with the air-source heat pump was used to operate the electric strip heat required to supplement the deficit in heating capacity.

The percentage of energy required for strip heat operation of the air-source heat pump ranges from 0 percent in Houston to 38 percent in Concord. A comparison of strip heat use in Seattle and Philadelphia shows the effect of design conditions even though the annual heating loads are within 12 percent of each other. Since the ground-water heat pump operates at constant capacity regardless of ambient air temperature, no strip heat is required. Peak load is less than capacity for the test years selected for those cities.

The percentage of energy required for well pump operation for the reversible-cycle ground-water heat pump ranges from a low of 4 percent in Cleveland and Philadelphia to a high of 16 percent in Concord. The high percentage in Concord is due to the relatively long run times and high pumping heads used in the simulation.

Figures 5.1 and 5.2 are plots of ACOP values versus the ratio of annual heating load to total load (Q_H/Q_T) for each system type. Examination of Figure 5.1 shows that for the nine cities tested, on-site performance of the ground-water heat pump remains relatively constant, independent of Q_H/Q_T. The reversible cycle ground-water heat pump falls substantially below this trend in the Concord test city, in part due to the use of electric strip heat to make up the heating capacity deficit. The more frequent use of this supplemental heat during severe heating demand periods results in the lower efficiency values. However, this loss of efficiency is apparently due to the sizing techniques used. These techniques did not take full

TABLE 5.12

	PERCENT OF TOTAL ENERGY TO STRIP HEAT		PERCENT OF TOTAL ENERGY TO WELL PUMP
	GROUND-WATER HEAT PUMP	AIR-SOURCE HEAT PUMP	
Atlanta	0.0%	6.5%	5.2%
Birmingham		7.9	
Standard Model	0.0		5.1
High-Efficiency Model	0.0		5.3
Cleveland	0.0	27.0	4.2
Columbus	0.8	27.0	7.9
Concord		38.0	
High-Efficiency Model	11.0		15.5
Heat-Only w/Direct Cooling	0.0		8.7
Houston		0.0	
Standard Model	0.0		7.9
High-Efficiency Model	0.0		8.1
Philadelphia	0.0	13.7	3.8
Seattle	0.0	0.3	5.1
Tulsa		11.7	
Standard Model	0.0		9.8
High-Efficiency Model	0.0		7.0

Figure 5.1
ACOP Versus Q_H/Q_T
for All-Electric Systems

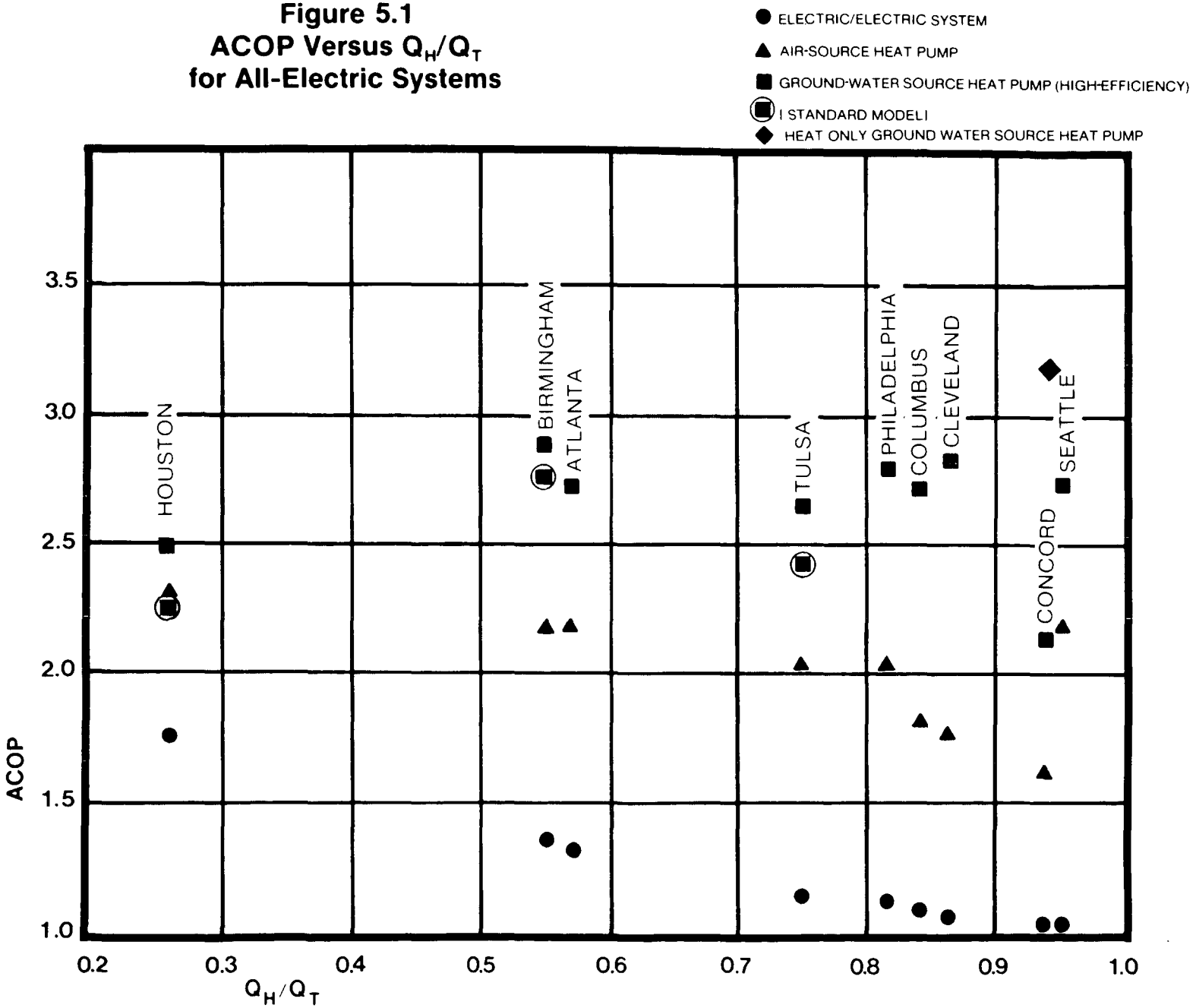
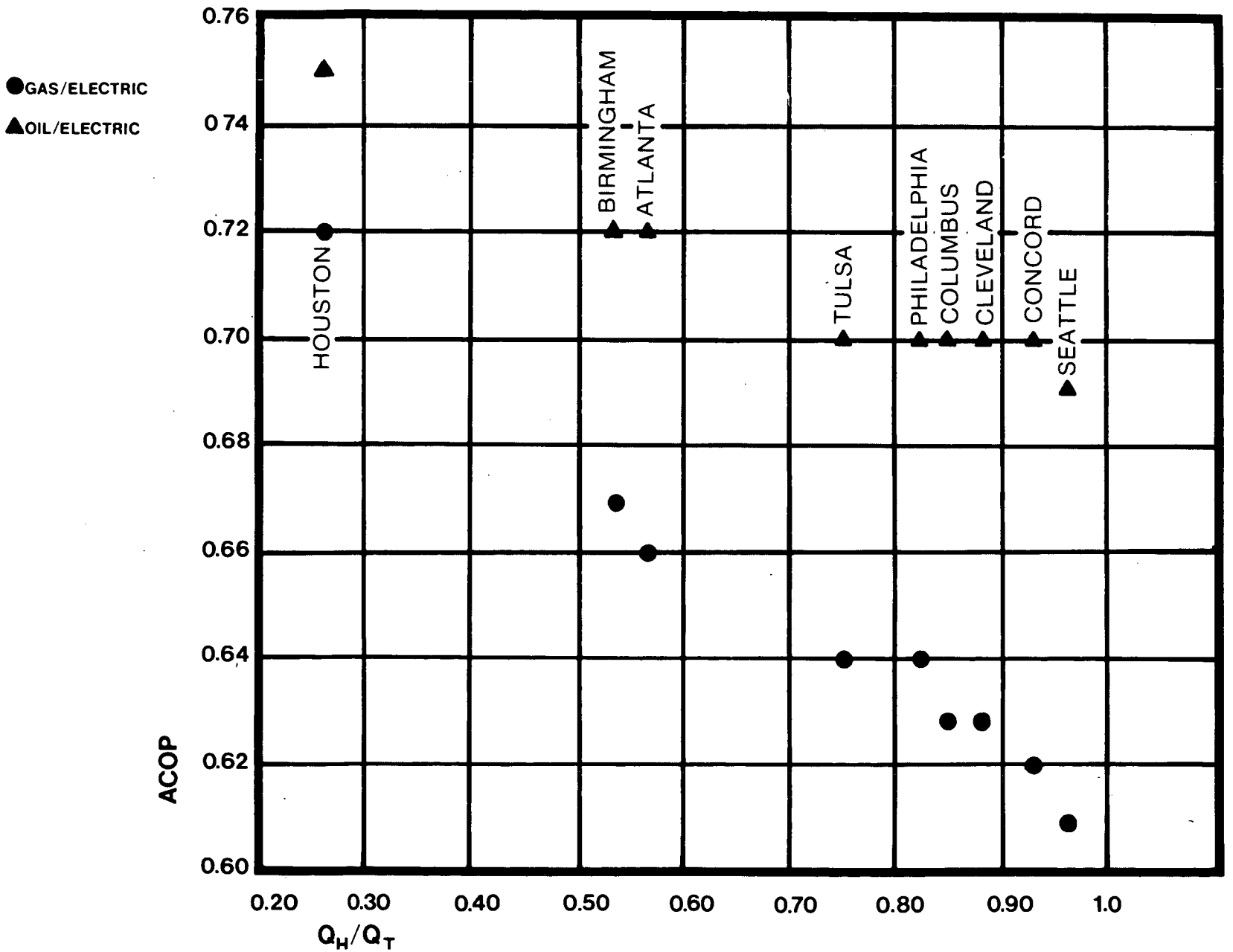


Figure 5.2
ACOP versus Q_H/Q_T
for Fossil Fuel Systems



advantage of the ability of the ground-water heat pump to operate at full capacity independent of outside air temperature.

As illustrated by Figure 5.1, the simulation of the heat-only heat pump with direct heat exchange cooling shows a substantial increase in the ACOP value in Concord and the highest for all cities tested.

The high pumping head used in the simulation is also influential in lowering the ACOP value for the ground-water heat pump in Concord. However, the effect is not as severe for the heat-only heat pump which has a lower water requirement and shows a considerable decrease in run time.

Performance of the air-source heat pump and the electric heating/electric cooling system decreases with an increase of Q_H/Q_T. In the case of the air-source heat pump, this is due to the unit's reliance on electric strip heat to supplement the heating deficit resulting from sizing the system to design cooling load. The more severe the design heating load, the greater the fraction of energy used by the electric strip heat compared to the total energy used (Tables 5.1 and 5.12). In the case of the electric heating/electric cooling, the system operates at an efficiency near 1.0 for a greater fraction of total annual running hours as the Q_H/Q_T ratio increases. Thus, although the cooling unit operates at a substantially greater efficiency, the effect of that operation on the system efficiency is inversely related to the ratio of annual heating load to total annual load.

The gas/electric system and the oil/electric system exhibits trends similar to the electric/electric system. Examination of Figure 5.2 indicates that there exists a lesser ACOP dependence on the ratio of annual heating load to total load for the fossil fuel-fired equipment systems than for the other systems. This is apparently due to the fact that for these equipment types, heating capacity is independent of outside air temperature, and the unit operates at a constant capacity. As the value of Q_H/Q_T increases, the effect of the higher efficiency operation of the cooling unit becomes less significant. The least sensitive to the ratio is the oil/electric system.

Table 5.13 shows energy use and performance data for each system in the Columbus test city with annual energy

TABLE 5.13
SIMULATION RESULTS
INCLUDING HOT WATER GENERATION

City: Columbus

Ground-Water Heat Pump Model: High-Efficiency

HVAC SYSTEM HEATING/COOLING PLANT	YEARLY ENERGY CONSUMPTION (BTU X 10^{-6}) Electric	Fossil	ON-SITE ACOP	SOURCE ACOP
Natural Gas/Electric	6.97	130.96		0.65
Oil/Electric	27.84	90.84		0.57
Air-to-Air Heat Pump	63.97		1.55	0.52
Electric/Electric	92.34		1.08	0.36
Ground-Water Heat Pump				
Electric Hot Water	49.68		2.00	0.67
Desuperheater	43.54		2.28	0.76

required for domestic hot water generation included in the analysis. All systems used an electric-fired hot water generator except for the gas/electric system, which used a gas-fired unit in the simulation. Energy use for the ground-water heat pump is listed for an electric-fired unit and for hot water generation using an optional desuperheater.

Except for the electric/electric system, there is a substantial lowering of on-site ACOP values when hot water usage is included in the model. There is a marked improvement in the performance of the ground-water heat pump when the desuperheater is used for hot water generation compared to the electric-fired unit. The simulation shows a decrease in annual energy consumed by 12 percent. Using the desuperheater, the ground-water heat pump system uses 53 percent and 32 percent less energy than the electric/electric system and the air-source heat pump, respectively. Similar equipment is available which operates with the air-source heat pump. Although not included in this study, the difference in energy use between the two systems would, no doubt, not be of the magnitude shown in Table 5.13.

CHAPTER 6
ECONOMIC EVALUATION AND COMPARISON OF SYSTEM INSTALLATION AND OPERATION

I. INTRODUCTION

The heating/cooling systems discussed in the previous sections are compared in terms of a number of economic parameters. For the purposes of simplicity and uniform comparison, the ground-water heat pump system with an injection well is chosen to represent the most typical (or at least the most desirable) installation. For this system, it is assumed that a supply well is required, but the capital expenditure for that well is assigned to the domestic water system rather than the heating/cooling system. Also, listed in the output is the owning and operating cost comparison using the installed cost of the heating/cooling unit only. It is assumed that, for this installation, the water is discharged in some manner that does not require a substantial capital expenditure and that the supply well cost is again assigned to the domestic water supply cost. This cost model is obviously the least expensive and, for that reason, probably represents many present day installations. The most expensive cost model is one in which the costs of the supply and injection wells are assigned to the ground-water heat pump system. For this study, a 6 percent discount on the total well costs is used. An informal survey of area well drillers indicates that, when a discount is given, it would usually range from 5 to 10 percent, reflecting the need for travel and setup time for the first well, but reduced costs for these items for the second well.

II. ECONOMIC MODEL DESCRIPTION

The output of the model used in this study consists of the present worth of total life cycle cost for each system. Using the electric/electric system as a reference, total net benefit is reported. In addition, simple payback of incremental capital expenditure, resulting from installation of the ground-water heat pump system in favor of each alternate system, is calculated.

The present value of total life cycle cost includes cost incurred upon equipment installation, and those

incurred during the life cycle period (20 years). These include fuel costs and operation and maintenance costs (O_M). The present value of total life cycle cost for a heating/cooling system can be expressed as:

$$PV = E + O_M + FC$$

$$= E + (0.01)E \quad \Sigma_{i=1}^{N} \frac{1}{(1 + d)^N}$$

$$+ \quad \Sigma_{k \text{ fuel types}} \quad \Sigma_{i=1}^{N} \frac{(mN + b)_k}{(1 + d)^N}$$

PV = Present value
E = Installed equipment cost
O_M = Present value of total life cycle operations and maintenance costs
FC = Present value of total life cycle fuel cost
d = Real discount rate (two percent)
N = Life cycle period (20 years)
$(mN + b)_k$ = Cost of fuel type k in year N. The values of m and b in the equation are the slope and y-intercepts (year 0), respectively, of the fuel cost escalation curve for fuel type k.

As indicated by the above expression, those costs that are periodically charged over the life cycle period (O_M and fuel costs) are discounted to present value. Values used in the expression above are discussed in Chapter 4.

Simple payback period (PP) of incremental costs is calculated by dividing the difference in installed costs by the difference in first year fuel and operation and maintenance costs of the alternate system and the groundwater heat pump system. The formula is expressed as:

$$PP = \frac{\Delta E}{(FC_1 + O_{M1})}$$

$$= \frac{E_G - E_A}{(\{FC_1\}_A + \{O_{M1}\}_A) - (\{FC_1\}_G + \{O_{M1}\}_G)}$$

E = Installed equipment cost
FC_1 = First year fuel cost
O_{M1} = First year operation and maintenance costs

Subscripts G and A refer to the ground-water heat pump system and alternate system, respectively.

III. RESULTS

Table 6.1 reports the present worth of total life cycle costs for all systems in all cities. The gas/electric system incurs the lowest cost of all systems (using the ground-water heat pump with an injection well to represent that system) in Cleveland, Columbus, Concord, Houston, and Tulsa. Even though the ground-water heat pump operates at a higher efficiency than the gas/electric system, the comparative energy rates in these cities accounts for lower life cycle costs for the later.

For Cleveland and Columbus, the difference is due to the low initial gas cost ($2.82/MCF) and low escalation rate used in the model ($0.129/MCF · yr.). In addition, electrical energy cost in these cities is relatively low ($0.049/KWH); the escalation rate is high ($7.5 x 10^{-4}/KWH · yr.).

For Concord, the extensive use of strip heat with the high-efficiency ground-water heat pump coupled with the high electric rates results in the lower total life cycle cost of the gas/electric system. The heat-only heat pump with direct cooling shows a lower cost than all other systems due to a substantially lower total fuel cost. This can be attributed to the elimination of strip heat use resulting from sizing the unit to design heating load rather than design cooling load.

For Houston and Tulsa, the initial gas costs ($2.85/MCF) and escalation rates ($0.176/MCF · yr.) are relatively low. Even though the initial electric energy cost is also low ($0.049/KWH), the escalation rate is higher than any other test city ($1.11 X 10^{-3}/KWH · yr.).

The air-source heat pump shows a lower total life cycle cost compared to the ground-water heat pump system in the Seattle and Houston test cities. In the climates

representative of these cities, the air-source heat pump operates at high efficiencies with little use of supplemental electric strip heat. Thus, the difference of total fuel costs of the two systems is minimal for these cities. Even though the fuel costs are less for the ground-water heat pump, the differences are not sufficient to offset the increase in capital expenditure resulting from the high injection well costs used in the model.

With the exception of the high-efficiency unit in Concord, total life cycle costs for the ground-water heat pump with no well costs included are less than that for any other system in all cities. In Concord, the extensive use of supplemental electric strip heat coupled with the high electric energy rates results in a lower total fuel cost for the gas/electric system. The difference in fuel cost is greater than the slightly higher installed cost compared to the ground-water heat pump. The use of the heat-only heat pump in Concord alters this condition substantially. Savings incurred in total fuel costs make the heat-only heat pump (with the injection well cost included) favored when compared to all other systems in Concord.

The cost model represented by the ground-water heat pump with supply and injection well costs included is attractive compared to the air-source heat pump only in the Cleveland and Concord test cities. It is in these locations that the simulation showed the greatest percentage of energy used by electric strip heat in the air-source heat pump (27 percent and 38 percent respectively). As a result, a comparison of total fuel costs for the life cycle period of the air-source heat pump and water-source heat pump in these cities shows the greatest difference, ranging from $4,500 to $5,000. This variance in life-cycle costs offsets the incremental capital investment of both supply and recharge wells in the ground-water heat pump system.

The ground-water heat pump system with both supply and injection wells included in the cost, is preferred only in the Seattle test city when compared to the gas/electric system. This is due to the relative costs of the two energy sources (Table 5.4) and the extreme bias of annual heating load to total load in the area (Q_H/Q_T = 0.96). Because of these factors, the difference in total life cycle fuel costs is $6,700. As in the comparison of the air-source heat pump above, this cost offsets the cost incurred by the installation of the supply and injection wells.

Table 6.1 Present Worth of Total Life Cycle Costs (1979 Dollars x 10^{-3})

City	Electric/ Electric	Air-Source Heat Pump	Oil/ Electric	Gas/ Electric	GWHP* (0 Wells)	GWHP* (1 Well)	GWHP* (2 Wells)
Atlanta	$13.7	$9.9	$13.6	$9.9	$7.8	$9.5	$11.7
Birmingham	13.3	9.8	13.3	9.8			
Standard Model					7.7	9.5	11.7
High-Efficiency Model					7.8	9.5	11.7
Cleveland	25.1	16.9	19.2	13.6	12.0	13.7	16.1
Columbus d = 2%	23.0	15.6	17.8	12.7	11.6	13.3	15.7
Columbus d = 10%	13.3	9.6	11.1	8.0	7.5	9.1	11.3
Concord	35.3	24.1	21.1	18.3			
High-Efficiency Model					18.6	20.5	22.8
Heat-only w/Direct Cooling					15.5	17.4	19.7
Houston	13.5	11.3	13.4	11.3			
Standard Model					10.6	13.5	16.9
High-Efficiency Model					10.2	13.1	16.4
Philadelphia	21.3	13.9	17.4	12.9	10.9	12.8	15.4
Seattle	11.8	7.6	15.9	13.9	6.8	8.9	11.6
Tulsa	19.5	13.9	15.7	12.1			
Standard Model					10.8	13.1	15.9
High-Efficiency Model					10.7	13.1	15.9

* Ground-water heat pump

This cost model is also not appealing when compared to the oil/electric system in Concord, Houston, and Tulsa and when compared to the electric/electric system in Houston. For Concord, however, the heat-only heat pump with both well costs included is attractive when compared to all other systems because of the fuel cost savings accrued over the life cycle study period.

Table 6.1 shows the present worth of total life cycle costs for each system for the Columbus test city using a 10 percent real discount rate. Although present value of both O_M and total fuel cost cash flows are influenced by the choice of the real discount rate, the change in the latter typically accounts for more than 80 percent of the difference in present value of total life cycle costs when comparing the 2 percent and 10 percent real discount rate values.

It is evident that if a private homeowner is able to realize a 10 percent return on an alternative investment, then the present worth of the total life cycle costs associated with any of the listed HVAC installations is substantially less compared to that with only a 2 percent return.

Simple payback periods for the ground-water heat pump system, compared to other systems, are reported in Table 6.2 through 6.5. Payback periods are reported for system costs including heating/cooling equipment only, equipment plus injection well, and equipment plus supply and injection wells.

The footnotes indicate those cost conditions in which a payback period is not defined. If the installed cost of the ground-water heat pump is less than that for the comparative system, there is no incremental cost to be considered in a payback period. Also, if the sum of fuel costs and operations and maintenance costs for the ground-water heat pump is greater than that for the alternate system, the former cannot accrue savings over any number of years.

Examination of Table 6.2 indicates that for most test cities, the ground-water heat pump (with no well costs included) is cheaper to install than the electric/electric system. Exceptions are the Columbus and Concord test cities. For Concord, the heat-only heat pump shows a

Table 6.2

Simple Payback Period (years)

Ground-Water Heat Pump System

vs.

Electric/Electric System

CITY	WITH NO WELLS	WITH INJECTION WELL	WITH SUPPLY & INJECTION WELLS
Atlanta	*	3.1	11.0
Birmingham			
High-Efficiency Model	*	4.4	12.7
Standard Model	*	3.7	12.3
Cleveland	*	2.0	5.2
Columbus	<0.1	2.6	6.2
Concord			
High-Efficiency Model	*	1.5	3.7
Heat-Only w/Direct Cooling	0.7	2.1	3.8
Houston			
High-Efficiency Model	*	17.2	>20
Standard Model	*	>20	>20
Philadelphia	*	2.7	6.9
Seattle	*	7.4	>20
Tulsa			
High-Efficiency Model	*	4.4	11.0
Standard Model	*	3.6	10.5

* Ground-Water Heat Pump system costs less to install and operate.

† Ground-Water Heat Pump system costs more to operate, therefore, payback period is undefined.

substantially higher installed cost than the electric/electric system. But this incremental cost is retrieved in less than one year of operation because of the large difference in first year fuel cost. For the Columbus test city, the small increment in installed cost is retrived in a very short period of time. The Houston test city shows the longest payback periods when the cost of an injection well is included. This results from the high cost of the injection well ($2,500) used in the analysis. In addition, first-year fuel costs are similar because of the relatively high cooling SPF values for the air-source heat pump and the high annual cooling load. The shortest payback period of 1.5 years is calculated for the Concord test city using the high efficiency model ground-water heat pump as the comparison. This is due to a large difference in first-year fuel costs between the two systems.

Using the ground-water heat pump cost model that includes both the supply and injection wells, payback is achieved within the life cycle period for most test cities. Exceptions are again Houston, in which well costs used in the study are substantially higher than for other test cities, and Seattle, where the difference in first year fuel costs for the two systems is small in comparison to that in other cities. The Concord test city again shows the shortest payback period as a result of the difference in first-year fuel costs.

Table 6.3 reports payback periods of incremental costs incurred by the ground-water heat pump system compared to the air-source heat pump. For most cities, payback period is undefined because of the lower installed cost of the ground-water heat pump system with no wells. For the standard model in Houston, however, payback period is undefined because of the lower first-year fuel cost for the air-source heat pump. The increased capital expenditure for the heat-only heat pump in the Concord test city is recovered in a short period of time because of the large difference in fuel cost. This is a direct result of the high expenditure required for supplemental electric strip heat used by the air-source heat pump that is not needed by the heat-only ground-water heat pump. With the cost of the injection well included in the ground-water heat pump system, payback periods are realized within the life cycle study period for most test cities. Exceptions are for the high-efficiency ground-water heat pump in Houston and Seattle. For both cities, the small difference in first-

Table 6.3

Simple Payback Period (years)

Ground-Water Heat Pump System

vs.

Air-Source Heat Pump System

CITY	WITH NO WELLS	WITH INJECTION WELL	WITH SUPPLY & INJECTION WELLS
Atlanta	*	11.9	>20
Birmingham			
High-Efficiency Model	*	14.3	>20
Standard Model	*	13.3	>20
Cleveland	*	5.2	15.7
Columbus	*	7.3	20.0
Concord			
High-Efficiency Model	*	4.4	12.5
Heat-Only w/Direct Cooling	1.2	4.3	8.6
Houston			
High-Efficiency Model	*	>20	>20
Standard Model	†	†	†
Philadelphia	*	10.2	>20
Seattle	*	>20	>20
Tulsa			
High-Efficiency Model	*	11.3	>20
Standard Model	*	9.0	>20

* Ground-Water Heat Pump system costs less to install and operate.

† Ground-Water Heat Pump system costs more to operate, therefore, payback period is undefined.

year fuel costs does not compensate for the difference in installed costs of the two systems. The shortest payback period is reported in the Concord test city where 38 percent of the total energy consumed by the air-source heat pump is used to operate the electric strip heat (Table 5.12). This is compared with 11 percent for the high-efficiency model ground-water heat pump and 0 percent for the heat-only heat pump. With the cost of both the supply and injection wells included in the ground-water heat pump system, payback of incremental costs is achieved within the life cycle study period in three of the nine test cities, again with the shortest payback period calculated in Concord for the heat-only heat pump.

Table 6.4 reports the payback period of incremental costs for the installation and operation of ground-water heat pump systems rather than the oil/electric systems. For all test cities except Concord with the high-efficiency model ground-water heat pump, the installed cost of the ground-water heat pump is less than that for the oil/electric system. For that test city, however, first-year fuel cost is less for the latter system. Thus, the payback period is undefined for that comparison. With the injection well cost included in the model, the installed cost of the ground-water heat pump system is less than that for the oil/electric system in Atlanta, Birmingham (both standard and high-efficiency models), and Cleveland. The increased cost of the triple-walled flue for the oil system accounts for the relatively high cost for this equipment in all test cities. This factor, plus the fact that these three test cities show the lowest injection well costs accounts for the cost increment of the oil/electric system over the ground-water heat pump system. Payback periods in the remaining test cities range from less than one year to nearly 20 years as in the Concord test city using the heat-only ground-water heat pump for the comparison. The small difference in first-year fuel costs requires a considerably longer payback period in this test city. In the Houston test city, neither model of the ground-water heat pump shows a payback period less than the life cycle period. Because of the bias toward the cooling mode operation and the favorable performance of the electric cooling system compared to that of the ground-water heat pump operating in the cooling mode, first-year fuel costs for the two systems are similar. Even though these costs are lower for the ground-water heat pump, they are not sufficiently low to realize a payback of incremental costs

Table 6.4

Simple Payback Period (years)

Ground-Water Heat Pump System

vs.

Oil/Electric System

CITY	WITH NO WELLS	WITH INJECTION WELL	WITH SUPPLY & INJECTION WELLS
Atlanta	*	*	13.1
Birmingham			
High-Efficiency Model	*	*	16.3
Standard Model	*	*	16.0
Cleveland	*	*	14.4
Columbus	*	1.1	>20
Concord			
High-Efficiency Model	†	†	†
Heat-Only w/Direct Cooling	*	19.9	>20
Houston			
High-Efficiency Model	*	>20	>20
Standard Model	*	>20	>20
Philadelphia	*	0.3	>20
Seattle	*	0.6	9.5
Tulsa			
High-Efficiency Model	*	4.7	>20
Standard Model	*	0.4	>20

* Ground-Water Heat Pump system costs less to install and operate.

† Ground-Water Heat Pump system costs more to operate, therefore, payback period is undefined.

within the life cycle study period. For the majority of the test cities, payback is not realized within the life cycle period when both well costs are included in the ground-water heat pump system. The lowest period for those test cities in which payback is realized is Seattle showing the shortest time period at 9.5 years. This results from the low initial electric energy costs and the bias toward the heating mode operation in the climatological conditions represented by Seattle.

Payback periods of incremental costs compared with the gas/electric system are reported in Table 6.5. For Atlanta, Birmingham, Seattle, Philadelphia, and Houston (high-efficiency model only), installed costs of the ground-water heat pump without well costs included are less than that for the gas/electric system. The only test city in which payback is realized is Concord for the heat-only heat pump. For the rest of the test cities, operating costs of the ground-water heat pump are greater than that of the gas/electric systems, thus payback period is undefined for all system cost options. With the cost of the injection well only or both wells included in the model, payback of incremental costs is realized within the life cycle period only in the Seattle test city. This is due to the low initial electric rates ($0.02/KWH) and high initial gas rates ($4.30/MCF) used in the model.

In general, the ground-water heat pump installation (with no well costs included) is economically favorable because the installation cost is less than that for other systems. With the cost of the injection well included, payback is usually achieved within the life cycle study period. The exception to this is the comparison with the gas/electric system. With both well costs included, the ground-water heat pump system generally does not achieve payback within the life cycle study period when compared to alternative systems.

Table 6.5

Simple Payback Period (years)

Ground-Water Heat Pump System

vs.

Gas/Electric System

CITY	WITH NO WELLS	WITH INJECTION WELL	WITH SUPPLY & INJECTION WELLS
Atlanta	*	>20	>20
Birmingham			
High-Efficiency Model	*	>20	>20
Standard Model	*	>20	>20
Cleveland	†	†	†
Columbus	†	†	†
Concord			
High-Efficiency Model	†	†	†
Heat-Only w/Direct Cooling	17.0	>20	>20
Houston			
High-Efficiency Model	*	>20	>20
Standard Model	†	†	†
Philadelphia	*	>20	>20
Seattle	*	5.4	14.7
Tulsa			
High-Efficiency Model	†	†	†
Standard Model	†	†	†

* Ground-Water Heat Pump system costs less to install and operate.

† Ground-Water Heat Pump system costs more to operate, therefore, payback period is undefined.

CHAPTER 7
RECOMMENDATIONS FOR FURTHER STUDY

Based on the findings of this report, the following recommendations for further investigation are presented. Some of the areas of study were investigated in this report, but due to the scope of the work, they could be covered only superficially.

1. Based on the material in Chapter V, it appears that substantial energy savings could be realized by using the heat-only ground-water heat pump with direct ground-water cooling in northern climates. Useful information would include the delineation of those heating and cooling loads and ground-water temperatures for which this system is more suited than the reversible-cycle unit. Additional energy and dollar savings may be realized by sizing the heat pump to some fraction of design load, especially for the heat-only heat pump. For some installations, resistance heat could be used to satisfy the load deficit during design load conditions. If lower capacity equipment components could be used, total life cycle costs could be lessened. These studies could best be accomplished by computer simulation thus allowing the flexibility and ease of parameter alteration.

2. Domestic hot water loads comprise approximately 25 percent of total energy used in residential and multifamily dwellings. Computer simulations showing energy use for varying combinations of heating/cooling/hot water generation equipment would be useful. Hot water generators (desuperheaters) installed on both ground- water source and air-source heat pumps would be of special interest.

3. Energy-use monitoring of conventional heating/cooling equipment has been well documented. Realiable energy use data from monitored ground-water heat pump installations are lacking. Monitored field installations under varying climatological and hydrogeologic conditions would yield useful information regarding actual energy usage. This information could also be used to validate existing computer programs.

4. A national survey of ground-water heat pump market potential is needed to assess the possible impact on further research and development work performed by manufacturers on regulatory requirements and on electric utility loading.

5. A computer simulation could be developed to show the effect of varying ground-water heat pump market penetration on peak load characteristics of power generating facilities within their networks.

6. A ground-water heat pump applications manual suitable for contractors would be useful. The focus of the manual would be on:
   A) Hydrologic assessment to determine feasibility
   B) Equipment sizing
   C) Installation considerations
   D) Start-up procedures
   E) Follow-up maintenance

7. It was shown in this report that the energy required to pump water to the heat pump constitutes a considerable portion of the total energy required to operate the entire system. A sensitivity analysis could be performed to determine the lower pumping level at which the ground-water heat pump is not economical to operate under a range of heating and cooling loads and ground-water temperatures.

8. Many laws and regulations were enacted at the state, Federal and local levels which restrict water use and water disposal methods. In most instances, this was done when ground-water heat pumps were relatively obscure in the HVAC market. At that time, there was no need to consider their use in the context of these laws. In some areas, they do restrict heat pump development. These laws and regulations should be reviewed and, where appropriate, provisions made to exempt these systems from excessive control. In a similar sense, a model program of laws and regulations designed to control (but not restrict) heat pump development should be adopted at state and local levels where a substantial market penetration is anticipated.

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APPENDIX A
CHEMICAL INCRUSTATION OF THE WATER-SIDE HEAT EXCHANGER

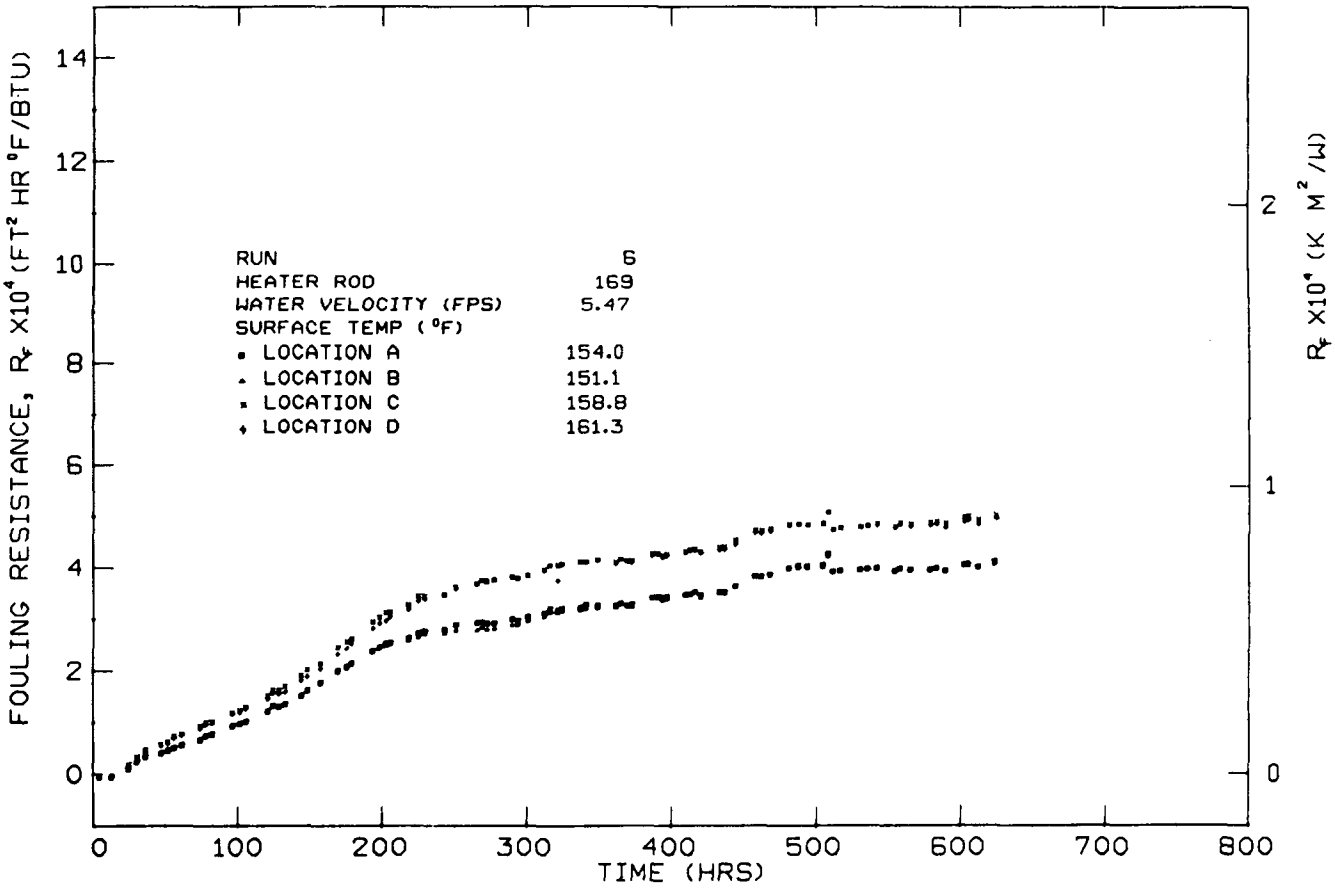
Water tube scaling is a serious problem in boiler applications. However, research indicates that this will have a minimal effect on the performance of water-to-refrigerant heat exchangers of ground-water heat pumps. Figure A1 shows typical rates at which fouling resistance increases as a result of mineral accumulation on a condenser. Water quality, velocity, and condenser temperatures are also depicted. Direct comparisons with aquifer water quality cannot be made with water quality data for this particular experiment. However, these concentrations are similar to those found in natural ground water.

The fouling resistance, R_F, is expressed in ft^2 hr °F/BTU (m^2 °C/W), which is the reciprocal of the heat transfer coefficient, BTU/hr °F ft^2 (W/m^2 °C). Apparently, mineral scale accumulates and is simultaneously eroded off the metal surface until a dynamic equilibrium condition is reached. In a report by Schaetzle and Brett (1974) a maximum value of R_F of approximately 4.0×10^{-4} ft^2 hr °F/BTU (7.0×10^{-5} m^2 °C/W) was noted. Heat transfer coefficients for water-to-refrigerant heat exchangers range from 60 to 150 BTU/hr °F ft^2 (340 to 850 W/m^2 °C). Corresponding values of R_F range from 2×10^{-2} to 7×10^{-3} ft^2 hr °F/BTU (3×10^{-3} to 1×10^{-3} m^2 °C/W).

Calculations show the decrease in performance due to mineral scale formation ranges from two to six percent at the experimental temperatures. Condensing temperatures for this data are approximately 30F° (17C°) less than those expected in the heat pump heat exchangers. It is not known at this time what the theoretical effect of this temperature differential is on the value of R_F. Past performance of existing heat pumps indicates that the effect is minimal.

Several nomographs have been formulated that can determine the scale-forming tendency of water (Langlier 1936; ASHRAE 1973). The Langlier Saturation Index takes into account pH, temperature, total dissolved solids, calcium hardness, and carbonate (carbonate alkalinity). The saturation index number,

Figure A1
Time Effect on Heat Exchanger Fouling



$$SI = pH - pH_S$$

is a measure of calcium carbonate saturation in the solution. If SI exceeds +0.5, calcium carbonate is usually insoluble in solution and will precipitate as scale. The pH value must lie between 6.5 and 9.5. In the above equation, pH_S is the pH at which the water is in equilibrium with calcium carbonate and is determined by adding values read from the nomograph (Figure A2). A higher positive number indicates a greater tendency to form scale. A negative number indicates solution of calcium carbonate and a low tendency to form scale. It must be emphasized that the saturation index number indicates only a tendency to dissolve or precipitate calcium carbonate. There may be other factors that interfere with the mechanism on which the nomograph is based.

The nomograph is read as follows: parts per million (mg/l), calcium hardness, and M alkalinity (carbonate and bicarbonate) are read on the abcissa. Diagonals labeled pALK and pCa define these values which are read on the left ordinate axis. Total solids are read from the abcissa to the appropriate temperature curve. The value for C is then read on the right ordinate scale.

For example, consider water with the following characteristics:

Ca Hardness = 600 ppm
M Alkalinity = 100 ppm
Total Dissolved Solids = 400 ppm
pH = 8.0

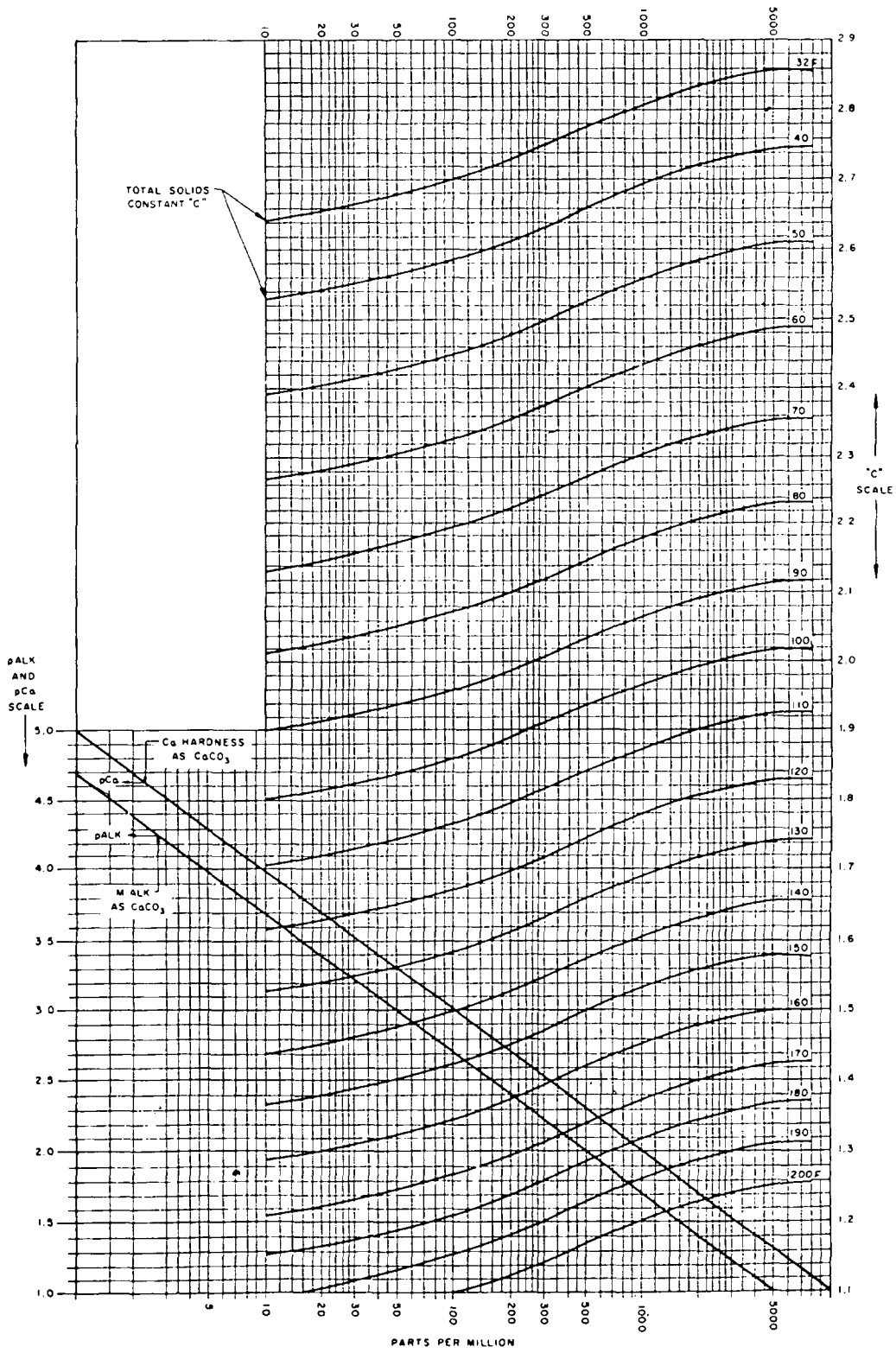
When the heat pump operates in the heating mode, water temperature in the water-to-refrigerant heat exchanger will be near measured ground-water temperatures. Thus, 55°F (12.8°C) will be used as the water temperature entering the heat exchanger for this example.

Reading the nomograph as described above:

$$\begin{array}{rl} pCa = & 2.23 \\ pALK = & 2.70 \\ + \text{ C at } 55°F = & 2.45 \\ \hline pH_S = & 7.38 \approx 7.4 \end{array}$$

$$SI = pH - pH_S = 8.0 - 7.4 = +0.6$$

Figure A2
Nomograph: Langelier Saturation Index



This water has a slight tendency to form scale. However, increasing water temperature at the condensing coil increases the tendency to form scale. In the cooling mode, thermal energy is rejected to the ground water. The superheated refrigerant at the high-pressure (discharge) side of the compressor will be at a temperature approximately 80° to 100°F (40° to 60°C) above the saturated condensing temperature. Thus, the temperature of the water/metal interface at the refrigerant-inlet end of the water-side heat exchanger will range from approximately 180° to 220°F (80° to 110°C). The temperature at this surface will steadily drop with increasing distance from the inlet side. The saturated condensing temperature will be reached when all the superheat has been rejected to the water. These temperatures range from approximately 100° to 120°F (40° to 50°C). Thus, scale will most likely form at the refrigerant-inlet end of the heat exchanger where the desuperheating takes place. If a domestic hot water generator (desuperheater) is used in the system, the scale will most likely form at that point in the cycle.

Using 200°F (93.3°C) as the water temperature with the same water quality characteristics, the value of C in the example is 1.16. With the same calculation procedure,

$$pH_s = 6.09$$
$$SI = +1.91$$

This water has a strong tendency to be scale-forming, indicated by the high index number. If the metal used in this application is not resistant to scaling, periodic maintenance may be required to prevent excessive scale formation and poor performance.

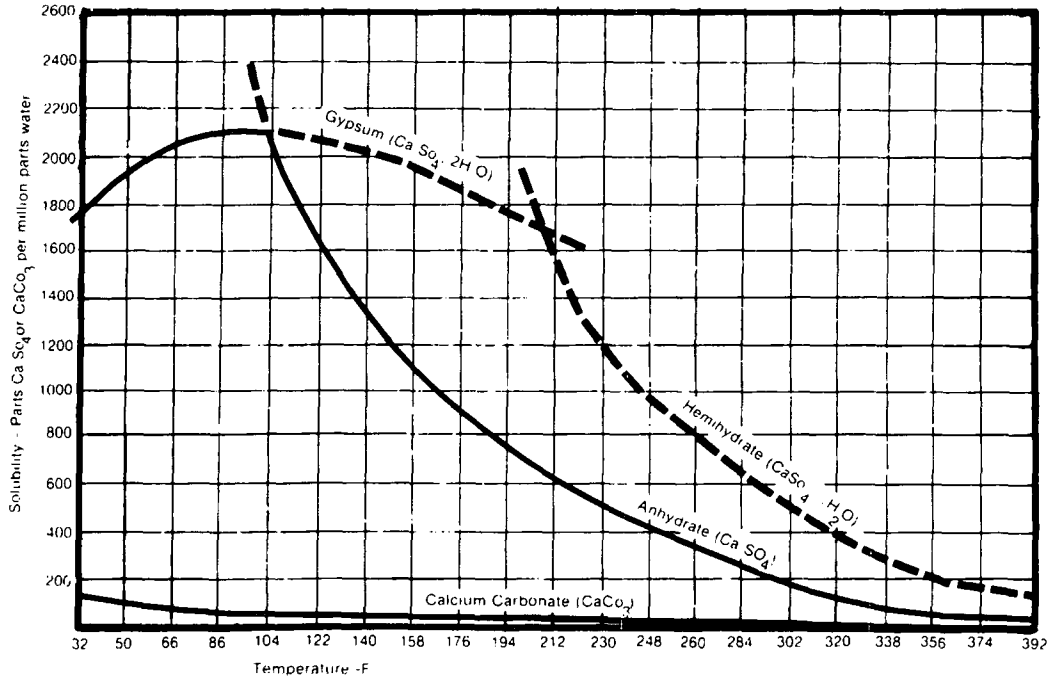
A modification of the saturation index known as the Stability Index was developed by Ryznar (ASHRAE 1973; Ryznar, 1944).

The Stability Index,

$$SI = 2\ pH_s - pH$$

is always positive. For values less than 6.0, scale formation is possible. The tendency to form scale increases with lower values.

Figure A3
Temperature Dependent Solubilities of Calcium Sulfate and Calcium Carbonate



Source: ASHRAE 1976 SYSTEMS

Similar methods have been developed for various other hardness constituents such as calcium sulfate. However, this compound is highly soluble at the condensing temperatures of ground-water heat pumps. Figure A3 indicates that for the temperature range considered, calcium carbonate has a much lower solubility than calcium sulfate, and is a more common scaling compound.

APPENDIX A
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APPENDIX B
PROJECTED ENVIRONMENTAL IMPACTS FOR NINE TEST CITIES

I. INTRODUCTION

The environmental parameters that influence ground-water heat pump utilization in nine major U.S. cities will be discussed in this appendix. The objective of this discussion is to provide an environmental evaluation of the potential for successful implementation of ground-water heat pump technology. This evaluation is based on an analysis of the general characteristics of each city (including geographic location, climate, population, and agricultural and industrial activity) and the geologic nature of the area (including topography, composition of underlying formations, and water resources, particularly ground-water availability and quality).

The nine cities evaluated include:

(a) Houston, Texas
(b) Birmingham, Alabama
(c) Atlanta, Georgia
(d) Tulsa, Oklahoma
(e) Seattle, Washington
(f) Philadelphia, Pennsylvania
(g) Columbus, Ohio
(h) Cleveland, Ohio
(i) Concord, New Hampshire

These cities were chosen to represent varying climatologic, hydrogeologic, and economic conditions. The selected cities were identical to those described in "Evaluation of the Air-to-Air Heat Pump for Residential Space Conditioning" prepared by Gordian Associates, Inc. (1976). As reported in that study, the choice was made on a degree-day basis. However, the cities also represent a wide range of hydrogeologic conditions.

II. HOUSTON, TEXAS

Houston is located in Harris County in the northeastern Texas Gulf Coast region. The study area includes Harris County and sections of Waller, Fort Bend, Montgomery, and Galveston Counties.

The climate is subtropical humid with weather predominantly influenced by steady south-southeast winds from the Gulf of Mexico. Precipitation is evenly distributed throughout the year, varying between 44 to 49 inches (111.8 to 124.5 cm). Summers are characteristically long, hot, and humid; winters are typically short and mild with only 15 to 30 days below freezing. The natural vegetation consists of various grasses, legumes, and deciduous trees.

The area supports a wide variety of agriculture and industry. The principal crops are cotton, grain, sorghum, rice, and soybeans. Industries of the area include petroleum refineries, organic chemical producers, plastics and synthetics, and steel mills.

The population of the study area was 1.9 million people in 1974 and is expected to increase to 3.4 million by the year 2000. About 95 percent of the present population resides in Harris County. However, growth patterns suggest that adjacent Montgomery County will experience the greatest increase in the future.

A. Geologic Setting

The Houston district is located in the west Gulf Coastal Plain which displays a gently undulating topography. Stream drainage is typically dendritic, although some segments are aligned along shallow surface faults or traces of deeper subsurface faults.

The coastal plain is divided into two distinct parts by the Hockley Escarpment, the most prominent of a series of southeast-facing escarpments. A featureless plain extends from the coast to the foot of the escarpment 80 miles (128.7 km) inland, reaching an altitude of 16.5 feet (5.0 m). Northwest of the escarpment, the area is characterized by a gently rolling topography.

Formations of Miocene, Pliocene, and Pleistocene age underlie the study area. These formations were deposited during several cycles of marine and continental transgressions. They consist of relatively impermeable clays and shales interbedded with permeable sand, gravel, and sandstone. The formations dip 25 to 35 feet per mile (4.7 to 6.6 m/km) southeastward with considerable thickening downdip (White, et al., 1944).

The presence of faults in the area results from natural geologic forces. However, fault movement has been accelerated by the withdrawal of ground water (Kreitler, 1976). The faults are associated with salt tectonism and sediment mass movements. Salt domes, resulting from the upward movement of lower density salt masses, penetrate aquifers and nearly reach the surface in some areas. Salt structures are responsible for several distinct types of faulting including normal faulting, grabens, horsts, radial faulting, and reverse faulting. Depositional loading of sediments, enhanced by gulfward creep of the sediment mass, is responsible for another class of faults (Bornhauser, 1956; Bruce, 1972). This type of normal faulting is a result of sedimentary overload with the downthrown block and sedimentary thickening towards the coast.

B. Ground-Water Availability

The Houston district obtains its water supply from formations composed of sand, silt, gravel, and clay which were deposited in lagoonal and deltaic environments. For this reason, the beds are not continuous in lithology or thickness but grade into each other both laterally and vertically within short distances (Wood and Gabrysch, 1965).

There are two major aquifer systems in the Houston district. One consists of the Goliad Sand and part of the Fleming Formation, and is known as the Evangeline Aquifer. The other principal aquifer, referred to as the Chicot Aquifer, is composed of the Willis, Bently, Montgomery, and Beaumont Formations, as well as Quaternary alluvium (Gabrysch, 1968, Jorgenson, 1975).

The basis for separating the Chicot Aquifer from the underlying Evangeline Aquifer is primarily a difference in hydraulic conductivity, which partially causes the difference between the potentiometric surfaces of the two aquifers. The average hydraulic conductivity in the Chicot Aquifer, estimated from several pumping tests, is approximately 600 gpd/ft^2 (263.2 m/d) (Wood and Gabrysch, 1965). Average hydraulic conductivity values for the Evangeline Aquifer tend to be lower, ranging from 209 to 310 gpd/ft^2 (91.7 to 136 m/d) (Gabrysch, 1968). However, transmissivity values of the Evangeline tend to be higher due to its greater thickness.

Municipal, industrial, and irrigation wells are constructed in both the Chicot and Evangeline Aquifers. The Evangeline is the most heavily pumped aquifer in the Houston metropolitan area, but most domestic and stock wells are drilled into the Chicot Aquifer. These wells, 4 to 6 inches (10.2 to 15.2 cm) in diameter, are capable of yielding upward of 100 gpm (6.3 l/s). Maximum well depths generally do not exceed 600 feet (182.9 m) (Naftel, et al., 1976). The depth to ground water in the outlying areas (areas not influenced by large ground-water withdrawals) generally ranges from 20 to 50 feet (6.1 to 15.2 m).

The major source of recharge in the Houston area is through precipitation. The mean annual rainfall is approximately 44 to 49 inches (111.8 to 124.5 cm), 11 inches (27.9 cm) are lost to runoff, and evapotranspiration consumes another 34 inches (86.4 cm), leaving 4 inches (10.2 cm) for recharge. Another source of recharge, although only practiced on a limited scale, is the artificial injection of water to arrest land subsidence problems (Garza, 1977).

C. Ground-Water Quality

The quality of the ground water in the Houston area is good to excellent. Reports indicate that shallow aquifers are predominantly moderate to very hard calcium carbonate types. Deeper aquifers are generally of sodium bicarbonate type and yield soft to moderately hard water (Winslow, et al., 1953). The ground water is moderately mineralized, although a few deeper wells yield highly mineralized water. Variable amounts of iron and manganese are present, but concentrations tend to be low. Chloride and sulfate concentrations generally do not exceed 180 mg/l and 50 mg/l, respectively, except in areas near salt domes or where salt water encroachment is a problem. Table B1 illustrates the range of chemical constituents of the ground water.

Ground water temperatures are approximately 75° F (23.9° C). Shallow wells tapping water table aquifers in outlying portions of the Houston district may experience slight seasonal fluctuations in ground-water temperature. However, the temperature normally varies little below a depth of 15 to 20 feet (4.6 to 6.1 m) and tends to reflect the mean annual air temperatures of the region.

Table B1

Typical Ground-Water Quality

Houston, Texas

SiO_2 mg/l	Fe micro-gram/liter	Mn micro-gram/liter	Ca mg/l	Mg mg/l	Na mg/l
24	49	78	29	8	97
24	91	14	46	6	50
16	176	23	25	4	108
16	230	25	25	4	120

K mg/l	HCO_3 mg/l	CO_3 mg/l	SO_4 mg/l	Cl mg/l	F mg/l
1.5	261		20	42	0.7
4.7	206		6.7	40	0.3
2.3	282		9.0	54	1.7
	291		10	55	0.82

N mg/l	B mg/l	TDS micro-gram/liter	HARD mg/l	pH	Temp °C
0.14	111	380	115	7.9	22.8
0.3	100	274	135	7.5	24.3
0.17	162	356	78	7.7	26.0
0.19		366	80	7.7	27.2

Depth (in feet)

0-350
350-700
700-1050
1050-1400

D. Environmental Evaluation

The ground water resources of the Houston area have already been extensively developed, and future water demands must be met by the development of surface water resources.

Declining water levels in southern Harris and Galveston Counties have initiated salt-water intrusion. Due to this intrusion, increasing chloride concentrations have necessitated the abandonment of Galveston's "old" well field and the establishment of a new well field further inland. The operation of numerous, closely-spaced heat pumps in these counties could aggravate and contribute to the problem by enlarging existing cones of depression which aid salt water intrusion. This problem can be avoided by recharging all water used by ground-water heat pumps.

The consumptive use of ground water has already led to severe regional land subsidence in the Houston district. Land subsidence has caused critical problems with inundation of low-lying areas by normal tides, and much of the region may be subject to catastrophic flooding during hurricane tides.

Associated with land subsidence is an extensive network of surface faults. The Houston-Galveston area is interlaced with over 240 active faults. Gabrysch (1976) suggests that faulting consists of natural as well as man-induced stresses caused by the removal of large quantities of oil, gas, and ground water. Kreitler (1976) suggests that these faults act as fluid barriers. The impact of surface faulting on the aquifers' ability to transmit ground water warrants further study, as attempts to arrest subsidence in the Houston area have gained only limited success.

The consumptive use of ground water for the operation of heat pumps in areas already experiencing active land subsidence can only contribute to the problem. The extent to which artesian pressures are lowered depends on the density of installations, water requirements of each installation, and their location with respect to existing cones of depression.

The development of ground water is less troublesome in the northern part of the Houston district. It may be possible to consumptively use ground water for heat pump operations in this area. The spent heat pump water could be discharged to surface reservoirs, thereby supplementing their storage, or be used for irrigation purposes.

The non-consumptive use of ground water to operate heat pumps would avoid the adverse environmental impacts associated with the consumptive use of ground-water resources. A greater number of ground-water heat pumps can operate in a smaller area when each installation incorporates an injection well, or when the discharge from a number of installations is injected through a large-capacity well. As each installation operates, the water could be reinjected back into the aquifer and thus maintain a dynamic equilibrium within the aquifer between withdrawal and recharge. The number of installations operating in any given area primarily depends upon the sphere of thermal alteration within the aquifer with respect to production and injection wells. Hilderbrandt, et al. (1979) performed a study of five domestic heat pump systems that have operated since 1959 within a Houston subdivision. He concluded that such operation had negligible environmental impacts on the aquifer system. Since cooling loads greatly exceed heating loads, ground water temperatures would become progressively warmer after operating a number of years. This effect could be partially mitigated through the temporary surface discharge of the water.

When reinjected into the same aquifer, the injection of spent heat pump water should pose minimal problems. The spent heat pump water will essentially be unaltered (except for its temperature) and will be chemically compatible with the ground water. The potential for salt precipitation is considerably reduced when the injected water is not oxygenated or allowed to decrease its carbon dioxide content. The anticipated operating temperatures of the heat pump are expected to have insignificant effects on the chemical equilibrium of the ground water.

E. Conclusion

Population growth and the future development of industry and agriculture in the Houston district will create an increased demand for water. These demands will be satisfied through the conjunctive use of surface and ground water. In the past, the majority of the area's water requirements have been satisfied through the region's ground-water resources. The extensive development of these resources has led to serious environmental problems. The consumptive use of ground water for domestic heating and cooling could aggravate existing problems of salt-water intrusion and land

subsidence. Artificial recharge of the heat pump water would alleviate these problems, but may introduce a thermal imbalance in the aquifer due to the high ratio of cooling to heating degree days. Careful planning and management of ground-water resources would be required to implement large-scale use of ground-water heat pumps in the greater Houston area.

III. BIRMINGHAM, ALABAMA

Birmingham is located in Jefferson County in northern Alabama. Situated in the Cahaba and Black Warrior River basins, it is one of the four most populated areas in the state.

The climate is subtropical humid, characterized by long, hot, humid summers and short, mild winters. The mean annual temperature is approximately 65° F (18.3° C). Warm, moist air from the Gulf of Mexico as well as cooler, drier air masses from the North influence the weather. Mean annual precipitation is about 53 inches (134.6 cm). The natural vegetation consists of various short grasses, legumes, hardwoods, and conifers.

The Birmingham area supports a diverse agricultural and industrial economy. Some of the area's leading industries include coal mining, iron-ore mining, iron and steel manufacturing, lumbering, chemicals, textiles, and meatpacking. Cotton, soybeans, and dairy and truck-farming operations comprise some of the principal agricultural industries.

Birmingham's population has increased from 652,000 in 1950 to 740,000 in 1970. The population continues to grow and is expected to reach 916,000 by the year 2000.

A. Geologic Setting

Birmingham lies in a valley three to seven miles (4.8 to 11.3 km) wide that extends northeastward across Jefferson County. A low-lying ridge divides the valley into two parallel flat-bottomed valleys. Several tributaries of the Black Warrior River cut through the valley walls and drain the area.

The bedrock in the Birmingham area is approximately 15,000 feet (4,572 m) thick, ranging in age from Cambrian to Pennsylvanian. The older rocks are carbonates that were deposited as stable shelf-type sediments, while the younger rocks are clastics of fluvio-deltaic origin (Simpson, 1965). The presence of several unconformities indicates that deposition was periodic, followed by intermittent episodes of erosion. The Appalachian Mountains underwent four major orogenic episodes, the last of which (the Appalachian Orogeny) had a profound influence on the area. Stresses from the southeast folded the rocks into elongated anticlines and synclines, thus forming the Valley and Ridge province.

A fault striking northeast separates the two major structures of the Birmingham area: the Black Warrior basin (of the Appalachian Plateau province) and the Birmingham Anticline (of the Valley and Ridge province) (Butts, 1910). The Birmingham Anticline is asymmetrical, slightly overturned to the northwest, and marked by a line of low-angle thrust faults that dip away to the southeast. Several smaller folds are superimposed and have axes that strike northeast, sympathetic to the major structure. A regional joint pattern composed of conjugate sets that strike N18°E-E and N2°E-N68°W is developed only in the more competent beds (Simpson, 1965).

B. Ground-Water Availability

The availability of ground water in the Birmingham area is influenced by the geology, topography, impact of urbanization and industrialization, and hydrologic properties of the aquifer under development. The most productive aquifers in the study area are limestone, dolomite, chert, and sandstone formations (Knight, 1976).

The Pottsville Formation of Pennsylvanian age is the most extensive formation underlying the Birmingham area. It ranges from 750 to 5,000 feet (228.6 to 1,524 m) thick, and underlies approximately two-thirds of the northern and western portions of the study area. Well yields tend to be low, ranging from one-half to 10 gpm (0.03 to 0.63 l/s). However, yields up to 170 gpm (10.7 l/s) have been recorded.

Mississippian-age carbonate aquifers are developed extensively throughout the Birmingham Valley. Well depths range from 250 to 350 feet (76.2 to 106.7 m) (Knight, 1976).

Low to moderately large well yields have also been developed from Paleozoic sandstone and carbonate formations. Cambrian carbonates generally yield large amounts of very hard water. These aquifers are capable of yielding 50 to 300 gpm (3.2 to 18.9 l/s) (Simpson, 1965; Robinson, et al., 1953). Well depths generally exceed 200 feet (61 m), which preclude their use as a source of domestic ground water except in outcrop areas.

The major source of recharge to the Birmingham area is precipitation. The mean annual precipitation is about 53 inches (134.6 cm), runoff is approximately 21 inches (53.3 cm), and evapotranspiration accounts for 31 inches (78.7 cm). Most of the recharge occurs in February, March, and April due to the heavy rainfall in winter and early spring when evapotranspiration is at its lowest.

The deformation of the bedrock, as well as major lithologic facies, serves to complicate the movement and occurrence of ground water within the hydrologic system. In general, ground water flows from the northeast to the central part of the Birmingham Anticline. In the southwest part of the anticline, the direction of movement is diverted northeast towards a topographic low (Simpson, 1965).

Natural discharge areas consist of several perennial streams and underflow into adjacent areas. Man-made discharge areas are centered around major pumping locations where large cones of depression exist. In some areas, local overdevelopment has lowered the water level by 148.1 feet (45.1 m), initiating the development of sinkholes (Newton, and Hyde, 1971), Newton, 1976). Such problems will continue unless the water table recovers to its former position.

C. Ground-Water Quality

The ground water of Jefferson County is generally of good chemical quality. Overall, wells tapping limestone and dolomite formations generally yield a calcium or magnesium bicarbonate type of water. Water obtained from wells in the Birmingham metropolitan area contains high concentrations of sulfate, nitrate, and dissolved solids (Knight, 1976).

Wells developed in sandstone aquifers tend to yield soft to moderately hard water which is moderately mineralized. In general, the water quality of the Birmingham area is good

Table B2

Average Values (mg/l) for Chemical Constituents of Ground Water in the Birmingham Area

SiO_2	Fe	Ca	Mg	Na
11.43	0.65	35.01	9.39	16.71

K	HCO_3	CO_3	SO_4
1.19	148.35	0.29	19.17

Cl	F	NO_3	TDS	Temp	pH
10.22	0.13	3.66	196.42	17.4°C	7.3

and will not impede the use of ground-water heat pumps. Table B2 lists average values for chemical constituents throughout the study area.

Ground-water temperatures vary from 59° to 71° F (15° to 21.7° C) and generally average 63° F (17.2° C) (Knight, 1976; Avrett, 1968).

D. Environmental Evaluation

Carbonate aquifers have long supplied large quantities of ground water for public, industrial, and domestic use in the Birmingham area. The unplanned development of these aquifers by excessive withdrawals of ground water, improper well spacing, and improper well construction has resulted in serious localized environmental problems. Overdevelopment has resulted in turbidity problems and land subsidence.

Land subsidence in the Birmingham area will most probably occur in highly-weathered carbonate formations since they are most likely to be developed for ground-water supplies because of their high permeability. Declining water levels in these areas may be accompanied by a reduction of the buoyant force provided by ground water. When this occurs, the land surface may collapse and create a sinkhole. Approximately 4,000 sinkholes have developed throughout Alabama since 1900, most of which have formed since 1950 as a result of man's activities. The largest sinkhole recorded [270 feet (82.4 m) in diameter and 90 feet (27.5 m) deep] developed in a matter of seconds in adjacent Shelby County (Newton, 1976). This rapid form of land subsidence can pose a serious threat to human welfare.

Turbidity problems are also associated with wells drilled in karst aquifers. These problems are due to the migration and suspension of clay colloids in the aquifer. Turbidity problems and the development of sinkholes can be avoided if wells are drilled on the periphery of the weathered carbonate zones. Another alternative is to drill into a deeper aquifer that is overlain by a more competent formation (Spigner, 1974). The overlying bedrock prevents sinkhole development by providing a structurally-competent support medium.

Industrialization or urbanization in recharge areas presents another serious problem. Extensive earth works and construction has limited the amount of recharge available to

some aquifers, which has resulted in decreased well yields. However, the degree to which urbanization affects domestic ground-water production in the area is not fully known yet.

The chemical quality of ground water in the area is generally good. There are some areas where high concentrations of iron may present a problem, but this can be treated and probably would not affect heat pump performance.

E. Conclusion

In the past, water demands in the Birmingham area have been met primarily by surface water sources. Only about five percent of the water supply has been derived from the area's ground-water resources. Future demands will most likely be met by further development of surface-water supplies.

Birmingham has adequate ground-water supplies for the operation of heat pump systems. However, serious environmental problems have already resulted in some areas from the withdrawal of water from carbonate aquifers. With proper planning and nonconsumptive ground-water use, these problems could be avoided. While high-density usage of heat pumps may present a problem, the outlook for moderate density usage in the Birmingham area is favorable.

IV. ATLANTA, GEORGIA

Atlanta is located in the north central part of Georgia. The study area includes Fulton, Cherokee, Cobb, Dekalb, Rockdale, and Gwinnett Counties. Atlanta serves as the state capitol and is also a major metropolitan area in the Southeast.

The climate of the Atlanta area is a humid temperate type. The mean annual temperature is about 60°F (15.6°C), and July, August, and September are usually the warmest months. The average annual precipitation is 48 to 49 inches (122 to 124.5 cm), and the driest months are usually September through November.

Agriculture is the major industry of the study area, which includes corn, wheat, and cotton production and the raising of cattle. The manufacture of monumental stone,

such as granite and marble, is another leading industry. Atlanta is the center of an extensive network of highways and railroads, and has one of the nation's busiest airports.

The population of Atlanta's metropolitan area was 729,000 in 1950, and increased to 1.39 million in 1970. Future growth is estimated at 2.5 million by 2000, and 3.2 million by the year 2020.

A. Geologic Setting

Atlanta is located in the Piedmont province of the Appalachian Uplands. The area displays a mature well-drained topography, broken locally by residual erosional remnants (monadnocks).

The rocks underlying the study area are largely igneous and metamorphic. The bedrock is composed chiefly of biotite gneiss and muscovite schist into which igneous rocks have been intruded (Herrick and LeGrand, 1949). The intrusive rocks are chiefly granites, with intrusions of pyroxenite and pegmatite being fairly common. Thin diabase dikes intrude all other rock types.

Several periods of deformation have altered the character of the original rocks. Intensive folding and overthrust faulting occurred in the late Paleozoic, with displacement of beds to the northwest. Exfoliation, or sheeting structure, occurs as major parting planes and is widespread throughout the study area.

B. Ground-Water Availability

The Atlanta region enjoys moderately abundant ground-water resources. As such, future water supplies may be supplemented with the development of ground-water supplies. This development would require careful planning and consideration of topography, geology, and hydrologic parameters in order to construct efficient high-capacity wells. In most areas, adequate well yields can be obtained for heat pump operation.

The occurrence and movement of ground water in the metamorphic rocks of the area is largely influenced by secondary porosity in the bedrock, which generally occurs as joints and fractures. In more competent rocks having little structure, these fractures may extend for considerable

distances and are referred to as sheeting planes. Sheeting planes develop when the weight of overlying bedrock is removed by erosional processes. The rock body adjusts to the reduced load stresses by fracturing. In this manner, imperfect shallow pseudo-synclinal basins are formed in valleys and act as reservoirs for ground water that percolates along sheeting planes from nearby upland slopes.

In most parts of the study area, the depth to ground water is generally less than 60 feet (18.3 m). Drilled domestic wells range from 150 to 250 feet (45.7 to 76.2 m), while industrial and municipal wells are sometimes drilled an additional 200 feet (61 m). Domestic well yields range from one-half to 25 gpm (0.03 to 1.6 l/s). Maximum well yields for large-capacity wells range up to 500 gpm (31.5 l/s).

Some high-yield wells tap intense fracture zones, but most tap permeable contact zones between rocks of contrasting character. The largest yields are obtained from contacts between quartzite and amphibolite or gneiss; granite and gneiss or amphibolite; and granite and schist. It should be possible to obtain well yields of 80 to 500 gpm (5 to 31.5 l/s) by selecting sites in topographic locations that favor recharge, and by determining the exact locations and attitudes of such contact zones.

High well yields are also obtained from alluvial deposits along the Chatahootchee River. Well depths here are generally less than 150 feet (45.7 m). However, the limited areal extent of these deposits restricts their importance as major aquifers in the Atlanta area.

C. Ground-Water Quality

The chemical quality of ground water in the Atlanta area is governed by the solubility of rock types. In general, the relatively insoluble nature of most crystalline rocks produces ground water that is soft and low in total dissolved solids. Total dissolved solids is generally less than 150 mg/l -- higher concentrations may indicate the presence of contamination. The pH varies throughout the area, but generally ranges from 7.1 to 6.0.

The most troublesome quality problem encountered in the study area is excessive concentrations of iron where water is used for domestic consumption. Table B3 illustrates the

range of chemical constituents normally encountered in the Atlanta area:

Table B3

Concentration Ranges in Atlanta's Ground Water (mg/l)

SiO_2	Fe	Ca	Mg	Na	K
13-46	0.0-4.0	2.4-18	0.9-4	2.1-12	0.7-2.2

HCO_3	SO_4	Cl	F	NO_3	TDS	Hardness
8-98	0.0-40	0.0-5.0	0.0-0.2	0.0-12	58-150	10-100

pH
6.0-7.2

Ground-water temperatures of the area vary considerably. Depending on well depths, temperatures range from 59° to 66°F (15° to 18.9°C). Wells less than 15 feet (4.6 m) deep showed considerable temperature fluctuations corresponding to seasonal weather changes. Recorded temperatures for wells deeper than 40 feet (12.2 m) approach steady-state conditions and generally range from 60° to 62° F (15.6° to 16.7° C).

D. Environmental Evaluation

The greatest problem in the Atlanta area is associated with the crystalline nature of the bedrock. Due to the interlocking nature of the minerals, crystalline rocks readily yield an adequate supply of water only in areas of high secondary porosity (which occurs as joints and fractures). For this reason, yielding capacity varies greatly from place to place. In the past, wells in the study area have been located with three considerations in mind: quantity of water available, convenience of location, and quality of the water. However, these factors do not necessarily complement each other (Herrick and LeGrand, 1949). The location of a successful well in an area underlain by crystalline rocks such as Atlanta must be carefully planned to ensure maximum well yields.

Another problem also related to the crystalline nature of the bedrock may be the inability of the rocks to accept recharge. Ground water would have to be used consumptively in this case. Unfortunately, since the ground-water supplies are limited at best, the potential for dewatering the aquifer exists. While adequate supplies of ground water

are available for domestic use, high-density usage of heat pumps would not be feasible except in unconsolidated aquifers along major streams. In this case, stream infiltration into the aquifer would provide sufficient water for heat pump operation. Spent heat pump water could be discharged into the stream to maintain flow.

The chemical quality of ground water in the study area is generally good. Locally high iron content can be treated, thus avoiding any complications with heat pump operation. Some high concentrations of nitrate are also a local problem, but this would not affect utilization of heat pumps.

E. Conclusion

The limited ground-water supplies of the Atlanta area restrict the high-density usage of ground-water heat pumps. The greatest potential for heat pump operation lies in alluvial deposits along major streams. However, their areal extent is rather restricted. With proper planning and careful development of ground-water resources, low to moderate density usage of heat pumps is possible.

V. TULSA, OKLAHOMA

Tulsa is located along the Arkansas River in northeastern Oklahoma. The study area includes Tulsa County and portions of adjacent counties.

The climate in the study area is subhumid and temperate. Spring and autumn are mild with warm days and cool nights. Summers are long and often hot; winters are generally mild with brief cold spells. The mean annual temperature varies between 60° and 63°F (15.6 to 17.2°C). Precipitation occurs throughout the year but is most intense during May. The native vegetation consists of little and big bluestems, Indian grass, and switchgrass. Scrub oaks and cottonwood trees are common along streams.

Tulsa's chief industries relate to oil and gas development and associated petrochemical industries. Food processing, meat packing, printing, publishing, and the manufacture of transportation equipment are also leading industries of the area, as well as the mining of various mineral resources. The area's agricultural industries

include the production of corn, hay, sorghum, and other produce. Livestock, such as hogs, cattle, and chicken, are raised. The number of farms have decreased over the years, but the size of individual farms has increased.

The population of the Tulsa Standard Metropolitan Statistical Area (SMSA) was 478,000 in 1979, and is projected to increase to 535,000 in 1980. By the year 2020, the population is expected to reach 671,000. A rural to urban shift has occurred over the past 10 years, since people are attracted by the large variety of employment opportunities and the easy access to many facilities in the city.

A. Geologic Setting

The Tulsa area is situated in the Prairie Plains Homocline physiographic province. The area consists of a gently eastward-sloping plain which is underlain by westward-dipping Pennsylvanian rocks (Oklahoma Water Resources Board, 1979). The plain has an average elevation of 750 feet (228.6 m). The drainage is dendritic except where it occurs as a modified trellis pattern along faults.

Mississippian-age rocks crop out to the north and northeast and are overlain by Pennsylvanian-age rocks throughout the remainder of the study area. The Pennsylvanian rocks are approximately 7,000 feet (2,134 m) thick and are comprised of limestones and coal beds in a sandstone-shale sequence.

Uplift of the Ouachita Mountains during the Pennsylvanian age caused folding and faulting of rocks in the basin area. Emplacement of nepheline syenite and other igneous intrusives is thought to account for mineralization in the mountains.

Melting glaciers during the Quaternary period in the Rocky Mountains initiated the major streams present today. At that time they flowed southward as tributaries of the Mississippi, and have since shifted to follow bedrock structures. Alluvial deposits of gravel, sand, clay, and silt range up to 100 feet (30.5 m) thick.

B. Ground-Water Availability

The principal aquifers in the study area are the Vamoosa and Ada bedrock formations and the alluvium along the

Arkansas and Verdegris Rivers. Adequate well yields for domestic use can also be developed from thinner alluvial deposits along numerous tributaries.

Wells in the Vamoosa Formation produce yields up to 500 gpm (31.5 l/s) in Seminole County. Well yields tend to decrease northward from 250 gpm (15.8 l/s) to 10 to 20 gpm (0.6 to 1.26 l/s) (OWRB, 1976). This decrease may reflect a corresponding decrease in the aquifer's permeability due to the increase of shale in the north. Well depths vary considerably throughout the formation and may range upwards of several hundred feet.

Overlying and cropping out slightly further west, the Ada Aquifer runs parallel to the Vamoosa Formation. Wells penetrating this formation generally yield 25 to 35 gpm (1.6 to 2.2 l/s). In Creek County, the aquifer thickens locally into a medium coarse-grained sandstone where yields may be as much as 50 gpm (3.2 l/s). In the southern half of Osage County, the base of the fresh water extends 200 to 300 feet (61 to 91.4 m) below the land surface.

Other bedrock formations which serve as minor aquifers in the Tulsa area are the Burgen, Warner, Chelsea, and Bluejacket Sandstones (Marcher, 1969), and (Marcher and Bingham, 1971). Wells drilled in areas where these formations thicken locally and intersect a sufficient number of fractures, joints, and bedding planes may yield more than 20 gpm (1.3 l/s). However, well yields tend to be lower throughout the rest of these formations.

Greater well yields are generally obtained from unconsolidated sediments, chiefly terrace and other coarse-grained alluvial deposits, situated along major rivers in the Tulsa area. Alluvial deposits along the Arkansas River generally average 30 feet (9.1 m) thick, but reach 60 feet (18.3 m) in some areas. Well yields vary considerably and are dependent on the type and thickness of the deposit penetrated, its inherent hydrogeologic properties, and the hydraulic connection between the well and the river. Wells penetrating alluvium along the Arkansas River yield 200 to 1,000 gpm (12.6 to 63.1 l/s). Well yields along the Verdegris River vary from 10 to 30 gpm (0.6 to 1.9 l/s) and may reach a maximum of 75 gpm (4.7 l/s) in favorable locations (Tanaka, 1972).

Mean annual precipitation varies from 42 inches (106.7 cm) in the eastern portion of the study area to 36 inches (91.4 cm) in the western half. Precipitation accounts for most of the recharge to the ground-water system. Mean annual runoff ranges between 5 and 10 inches (12.7 and 25.4 cm) in different parts of the study area. Evapotranspiration and runoff is estimated to account for 80 percent of total precipitation.

Movement of ground water through the unconfined aquifer system is largely influenced by the topography of the area. The configuration of the flow pattern indicates that the Verdegris and Arkansas Rivers are the principal natural discharge areas. Local well fields and domestic wells act as points of discharge on a smaller scale.

C. Ground-Water Quality

The chemical quality of ground water in the study area ranges from good to poor. The major aquifers most suitable for supplying water for the operation of heat pumps generally yield moderately mineralized water that is very hard. Alluvial aquifers along the Arkansas and Verdegris Rivers yield a sodium or calcium bicarbonate water (OWRB, 1976). Wells tapping either of the major aquifers in local areas, however, yield water with high concentrations of nitrate, chloride, and/or sulfate. Ground-water supplies developed from extensive Pennsylvanian bedrock yield fair to poor quality water. The least mineralized water is obtained from local thickening of sandstone aquifers, while coal seams yield highly mineralized water (Oklahoma Water Resources Board, 1979). Table B4 lists chemical constituents encountered in some of the area's formations.

Ground-water temperatures generally range between 59°F (15°C) and 68°F (20°C) (Havens, 1978). Higher values are obtained from bedrock wells that are deep enough to be substantially affected by the geothermal gradient. Colder temperatures may be obtained from shallow wells which are more likely to be influenced by daily or seasonal weather changes. Temperature fluctuations are also apparent from wells tapping alluvial deposits that induce considerable stream infiltration.

Table B4
Ground-Water Quality: Tulsa, Oklahoma
(mg/l)

Specific Conductivity*	pH	Ca	Mg	Na	HCO_3	SO_4	Cl	F	NO_3	TDS	HARDNESS Ca-Mg	HARDNESS Non-Carbonate	B**	Fe**	
2156	7.8	172	18	336	511	397	126		1.5	1605	363		710		Boggy Fm
1433	7.9	106	31	188	357	200	124	0.2	33.0	1230	520	437	270	146	Senora Fm
1913	7.9	18	25	209	238	623	223	0.5	0.8	1444	599			78	Calvin Ss
3238	8.1	137	69	559	391	128	704	0.7	1.0	1686	482	1570	580		Wewoka Fm
1539	8.0	46	30	266	389	130	253	0.2	12.4	1111	259				Seminole Fm
2126	8.0	101	61	238	351	160	298		2.6	1235	565	139			Coffeyville Fm
813	7.8	33	48	84	249	157	43	0.6	35.0	559	223	88			Nellie Bly Fm
773	7.6	46	24	78	204	72	90	0.4	35.0	498	238	96	870		Wann Fm
851	7.5	15	6	183	202	274	30		13.0	562	102	15			Barnsdall Fm
726	7.2	21	11	52	121	115	80	0.3	74.0	489	266	167			Tallant Fm
1132	7.6	80	28	115	219	172	110		13.2	659	246	207		78	Vamoosa Fm
773	7.8	36	22	42	257	45	41	0.2	5.8	387	319	49	66	172	Quatenary Alluvium & Terrace Deposits

*units of micromhos

**units of micrograms per liter

D. Environmental Evaluation

Several aquifers in the Tulsa area are capable of sustaining the operation of many heat pumps in a relatively small area with no adverse effects on the environment. Alluvial deposits of sand and gravel along the major rivers are the most productive aquifers in the study area, and would be able to support high-density heat pump usage. Ground water could be used consumptively in these areas and discharged into the river. The anticipated temperatures of the discharged water is not expected to adversely affect the aquatic ecosystem.

The abundant ground-water supplies of the Vamoosa and Ada bedrock aquifers are also capable of supporting high-density operation of heat pumps. However, it would be necessary to recharge water to avoid dewatering the aquifers. Proper well-spacing is also necessary to allow proper thermal readjustment of the injected water.

In areas underlain by Pennsylvanian shales and dense sandstones, well yields may be insufficient to support heat pump usage. However, alternative designs using supplemental storage or closed-loop, earth-coupled, heat exchange may be implemented. Installations using only ground water would have to be spaced farther apart due to the poor hydrogeologic properties of the aquifer. High-density usage would not be possible in such areas, even with nonconsumptive ground-water use. Using recharge wells to increase the density of installations may not be successful due to the inability of the aquifer to accept recharge.

Inferior ground-water quality encountered in some formations may also inhibit the performance of heat pumps. In a few localized areas, highly mineralized ground water is present. In general, poor water-quality conditions are associated with coal deposits and may contain excessive iron, hydrogen sulfide, and dissolved solids concentrations. The recharge of poor quality water into other parts of the aquifer would result in the general degradation of the ground-water quality. Similarly, the surface discharge of the inferior quality water may infiltrate into other aquifers or adversely affect the aquatic biosphere of surface-water bodies.

E. Conclusion

Municipal and industrial water demands in the Tulsa area have been satisfied chiefly by surface water, while ground

water has been utilized in the production of oil and gas through secondary operations. Future demands will probably be met by further development of surface water. Hence, the ground water resources of the Tulsa area are largely untapped.

There is considerable potential for the utilization of heat pumps in the Tulsa area. However, limited aquifer capacity of Pennsylvanian formations that underlie most of the study area would confine usage to moderate density of installations, except along the more productive Vamoosa, Ada, and alluvium aquifers.

VI. SEATTLE, WASHINGTON

Seattle is located in King County along the eastern shore of Puget Sound in Washington. The 1970 census reported 1.4 million people residing in Seattle's Standard Metropolitan Statistical Area (SMSA). Growth patterns indicate that the population will increase to 1.5 million by 1980, 1.8 million by 2000, and two million by 2020.

The climate in the Seattle area is strongly modified by its proximity to the Pacific Ocean. Prevailing ocean winds make temperature extremes uncommon. The mean annual temperature of Seattle is 53.2° F (11.8° C), with July being the warmest month and January the coldest. Annual precipitation in King County averages 80 inches (203.2 cm) with most of the precipitation falling as snow along the western front of the Cascade Range. Along the Puget Sound lowland, precipitation ranges from 30 to 35 inches (76.2 to 88.9 cm). Most precipitation falls during the autumn and winter months; summers are typically hot and dry.

The native vegetation of the Seattle area is predominantly conifers. Extensive logging has virtually removed all the native evergreen timber, which has been replaced by big leaf maple, vine maple, red adler, black cottonwood, and willow. Of these, the cottonwood, red alder, and particularly the willow are predominant in lowland areas where there is a shallow water table.

Principal industries of the study area include the manufacture of transportation equipment, food processing, fabrication of metal products, and lumber. In addition, coal, sand, and gravel are mined. Dairy and truck-farming

operations are located in the Duwanish, Snoqualine, and Sammanish River Valleys. The silty clay and sandy loam soils of the valleys are more conducive to agricultural development than the stony soils of the intervening drift plains.

A. Geologic Setting

The western half of King County is located in the Puget Sound lowland, a topographic basin that extends from the Cascade Range to the Olympia Mountains. The area consists of gently rolling plains separated by well-developed north-trending river valleys. The southern and eastern portions of the county display a rugged topography.

Most of the bedrock is of Tertiary age, ranging from Eocene to Miocene. Pre-Tertiary age bedrock, remnants of a former mountain chain, outcrop only in the northeastern section of the county (Richardson, et al., 1968). The Tertiary bedrock consists of marine and continental sediments interbedded with volcanic flows and tuffs.

The Tertiary rocks have been folded and faulted, and most of the deformation occurred during the Miocene period. The most prominent structure is the Newcastle Hills anticline, which extends from eastern King County south through Seattle and across the Puget Sound. Minor folds occur along the flanks which are parallel to the major structure.

The Puget Sound lowland was glaciated at least four times during the Pleistocene epoch by the Puget glacial lobe. The Puget lobe is an extension of the Cordilleran ice sheet that formed in British Columbia. The deep troughs and intervening plateaus of the lowland were formed by ice scour. The glaciation resulted in a complex stratigraphic sequence of glacial deposits which are the principal aquifers of King County.

Post-glacial deposits derived from the reworking of older glacial deposits are accumulated along the river valleys. In addition, a large volcanic mudflow occurred about 4,800 years ago. The Osceola mud flow descended from the northeast flank of Mount Rainier and down the White River Valley, resulting in significant changes in drainage and depositional patterns.

B. Ground-Water Availability

Abundant ground-water supplies can be developed throughout the Seattle area and Puget Sound Lowland. In general, unconsolidated sediments and sand and gravel deposits are the principal aquifers of the area. The development of bedrock aquifers is limited to areas where unconsolidated sediments are lacking or well yields are inadequate. The most productive domestic wells are drilled in a variety of sand and gravel aquifers.

Oligocene- and Miocene-age sandstones and conglomerates are the most productive bedrock aquifers. These formations are extensively developed in the Newcastle Hills area. Well yields generally range from 35 to 75 gpm (2.2 to 4.7 l/s), and depths vary between 125 and 250 feet (38.1 to 76.2 m) (Liesch, et al., 1963). The development of ground water in Newcastle Hills is limited by the areal distribution of sandstone and conglomerate aquifers. Lower well yields or inadequate yields are not uncommon for the fine-grained shale and siltstone formations.

Unconsolidated deposits of Oligocene and Miocene age commonly display erratic well yields. Wells tapping a substantial thickness of sand and gravel are capable of yielding upwards of 750 gpm (47.3 l/s). Domestic wells, however, tend to yield considerably smaller amounts, typically less than 10 gpm (0.6 l/s). The irregular distribution of the more permeable sand and gravel lenses makes these formations' unconsolidated deposits less favorable for the development of ground-water supplies.

The Orting Gravel attains a maximum thickness of 200 feet (61 m). It occurs extensively throughout the Seattle area and is a major aquifer. Average well depths in the drift plains of northern King County are about 135 feet (41.1 m). Average well yields are about 150 gpm (9.5 l/s) for large diameter wells.

The Esperance Sand and stratified deposits of the Vashon drift are extensively developed for their ground-water supplies. Moderate to large supplies of ground water can be developed from the stratified drift deposits. Domestic wells, 4 to 8 inches (10.2 to 20.3 cm) in diameter, generally yield from 5 to 25 gpm (0.3 to 1.6 l/s) (Liesch, et al., 1963; Luzier, 1969). The Salmon Springs drift is an important aquifer in southwestern King County. Well yields

for these deposits are comparable to those in the stratified drift.

Low well yields are typically encountered in glacial till deposits. Wells tapping compact glacial till generally yield a fraction of a gallon to a few gallons per minute. One distinction of the Vashon till is that the upper portion is more permeable than the lower till. This results in perched or semi-perched water tables which generally yield adequate supplies for domestic use.

Post-glacial deposits of coarse-grained sands and gravels are found along the major river valleys. Wells tapping deposits that are hydraulically connected to the river yield several hundred to a few thousand gallons per minute. Another post-glacial deposit, the Osceola mudflow, is not a principal ground water source due to its low permeability.

Readily available supplies of ground water can generally be developed throughout the Puget Sound lowland. Well depths vary considerably over the region. Well yields range from a fraction of a gallon per minute for till and lacustrine deposits, to several thousand gallons per minute for sand and gravel deposits.

Recharge to the ground water system is largely by precipitation during autumn and winter. At this time, evapotranspiration is at its lowest point and precipitation is at a maximum. These conditions allow a great amount of water to be available for recharge. Injection wells are used locally to recharge the ground water system.

The complex stratigraphy of the Pleistocene deposits make it difficult to predict ground water movement and occurrence. In general, ground water in the Vashon till and deeper Pleistocene deposits under artesian conditions moves from the drift plains and discharges into rivers and the Puget Sound as base flow. Ground water is also discharged by springs and seeps along bluffs, as well as by evapotranspiration from plant activity.

C. Ground-Water Quality

The Seattle area ground water is of fair to excellent chemical quality, generally of a slightly mineralized, calcium bicarbonate type. The water varies from soft to

hard. Excessive amounts of sodium, sulfate, and chloride are typical for areas along the Puget Sound experiencing intrusion of saline or connate waters, but the extent of encroachment is not known.

Many domestic wells penetrating peat or coal seams commonly yield poor quality water. The decay of organic matter produces humic acids along with various corrosive gases. Carbon dioxide and hydrogen sulfide tend to react with iron sulfides and locally increase iron concentrations as high as 9 ppm. The utilization of heat pumps may be impaired where these quality problems are encountered. Table B5 lists the average concentration of some common ground-water constituents of the Seattle area.

TABLE B5
Average Concentrations of Common Ground-Water Constituents in the Seattle Area
mg/l

SiO_2	31.0	SO_4	11.0
Fe	0.11	Cl	5.3
Cd	8.8	F	0.1
Mg	8.0	NO_3	4.3
Na	5.5	pH	7.3
K	1.2	TDS	100.0
HCO_3	54.0		

Ground water temperatures range from 50° to 55° F (10° to 12.8° C). In general, the temperature of ground water remains fairly constant below a depth of 15 to 20 feet (4.6 to 6.1 m). Exceptions to this may occur where a considerable amount of stream infiltration is induced. The extent and magnitude of such fluctuations is primarily dependent on the distance between the well and the recharge boundary. Temperature fluctuations also occur near injection wells, where the injected water is thermally altered by use in heat pump systems.

D. Environmental Evaluation

Deterioration of ground water quality in Seattle results primarily from salt water encroachment along the Puget Sound, and leachate from refuse sites. The extent and magnitude of the pollution is not well known, but it is believed to be local in nature.

Improper design of landfill sites is a problem. Rainfall entering the landfill through its exposed surface comes in contact with refuse. Organic and inorganic substances are dissolved, forming a noxious solution. This leachate then percolates downward, contaminating the underlying ground water. These sites are capable of polluting the ground water for several decades to several centuries.

In addition to improper landfill sites, inadequate domestic disposal systems have also locally impaired the ground-water quality. For example, many unsewered housing developments in the Tacoma-Seattle area have resulted in significant ground water pollution. The contaminated ground water discharges as base flow to nearby surface water bodies, thus spreading the pollution (van der Leeden, et al., 1975).

Several commercial ground-water heat pumps have been operating in the Puget Sound area since the early 1960s. Generally, they utilize a two-well system, with each well penetrating a different aquifer. The most frequent problem encountered, technological rather than environmental in nature, results from the clogging of the injection well. When the capacity of the well is inadequate, the water is temporarily discharged into storm sewers. In general, the utilization of heat pumps has not demonstrated any adverse effects on the hydrogeologic system.

The West Coast Telephone Company Building in Everett is an example of an installation heated and cooled by a ground-water heat pump. The problems encountered in this installation are typical of other systems in the area. During the first few months of operation, the specific capacity of the injection well decreased drastically. This decrease was attributed to serious clogging of the aquifer in the vicinity of the well. The clogging probably resulted from entrained air bubbles that became lodged in pore spaces, reducing the permeability. In addition, permeability may have been reduced through the precipitation of iron.

The capacity of the injection well was partially restored by redevelopment and treatment with sodium hexametaphosphate, a common dispersing agent. Future treatments will be necessary to ensure continued operation. Other heat pump systems have similar problems and generally follow the same corrective measures. The operation of the heat pump has not impaired the chemical quality of the

ground water, nor has it significantly hampered the hydrologic properties of the aquifer.

E. Conclusion

The majority of wells in the study area are used for individual domestic supplies. Future water demands will be satisfied through the development of additional surface and ground water resources.

Adequate ground water supplies for the operation of heat pumps are available throughout most of the study area. Ground-water heat pumps have been operating for several years in the Seattle area, and further development is favorable.

VII. PHILADELPHIA, PENNSYLVANIA

Situated along the Delaware River in southeastern Pennsylvania, Philadelphia serves as the state capitol and is the largest city in the study area. Included in the study area are Philadelphia, Bucks, Montgomery, Delaware, and Chester Counties in Pennsylvania, and Camden County in New Jersey.

The climate in the study area is continental temperate with moderate to mild winters and long warm summers. The mean annual air temperature varies from 49° F (9.4° C) in the north to 55° F (12.8° C) in the south. The weather is generally pleasant and is strongly influenced by moist air masses from the Atlantic Gulf Stream. The orographic effects of the Appalachian Mountains, along with air masses from the west, exert a strong climatic influence on the weather patterns.

The topography of the area varies in response to several geologic features and erosional processes. A gently rolling plain gradually rising from sea level to about 223 feet (68 m) characterizes part of the area, becoming more hilly and rugged toward the west. The natural vegetation consists of various deciduous hardwoods, short stem grasses, and legumes.

The area supports a wide variety of industry and agriculture. The principal agricultural industries include dairy farming, croplands (corn, soybeans), orchards, and

some truck-farming operations. The manufacture of petrochemicals, pharmaceuticals, synthetics, and transportation equipment, plus steel and milling foundries, are typical industries of the area.

Philadelphia is a major metropolitan center. The area experienced a substantial population growth during and immediately following World War II. The population increased from 3.6 million in 1950 to 4.8 million by 1970. By the year 2000, the population is expected to reach six million. As with most major cities, the upper and middle classes, as well as some industries, are moving to suburban areas.

A. Geologic Setting

The study area lies in two major physiographic provinces: the Appalachian Uplands and the Atlantic Coastal Plain. The provinces are separated by a fall line that runs northeastward through Philadelphia. The Appalachian Uplands are further subdivided into the Piedmont province and the Jersey Highlands. The Piedmont province is an extensive, gently undulating province that generally slopes southeastward. It has undergone prolonged erosion so that much of its former plateau-like appearance has been modified to slopes and gently rounded hills. The Atlantic Coastal Plain is a relatively flat plain with minor topographic variations.

The area displays a variety of complex geologic structures and lithologies. Several periods of mountain building, subsidence, and changing depositional environments have contributed to this complexity. Metamorphic rocks and igneous intrusives are found throughout the southwestern and western portions of the study area. Coarse to fine-grained clastics and carbonates are found in the rest of the area.

The Peach Bottom Synclinorium, the Brandywine Synclinorium, and the West Chester Prong are the dominant structures in the south. Several minor anticlines and synclines occur as sympathetic structural features and have axes that strike in a northeasterly direction, parallel to the major structures. In general, the anticlines display a gneissic core that is often intruded by ultramafics. The synclines are generally composed of phyllite and/or schist.

The Triassic basin is located to the north and west. Several anticlines and synclines are superimposed on a large homocline. In the north, several major faults with displacements up to 3,000 feet (914.4 m) show contacts of Paleozoic and Precambrian rocks with Triassic formations. A wedge-shaped mass of Cretaceous sediments crop out along the Delaware River. These formations dip southeast and thicken considerably downdip where they unconformably overlie the Cambrian basement complex. Overlying the Cretaceous-age sediments are Pleistocene deposits of marine origin which were deposited during interglacial periods when sea levels rose. Outwash sands and gravels were also deposited in the area by glacial meltwaters during the retreat of the Wisconsin glacier.

B. Ground-Water Availability

The diverse geology of the Philadelphia area is responsible for a wide variety of hydrologic systems. These complex systems have evolved in response to changes in lithology and structural deformation of the bedrock. Numerous reports have described the abundant ground-water resources around Philadelphia (Greenman, et al., 1961; Parker, et al., 1964; Longwill and Wood, 1965; Poth, 1968; and Farlekas, et al., 1976), and adequate domestic supplies capable of sustaining ground- water heat pumps can be developed throughout much of the area.

Crystalline bedrock of Precambrian to Lower Cambrian age underlies most of the southwest portion of the study area. The rocks in the Glenarm Series and the Baltimore Gneiss display a wide range of well yields and depths as a result of diverse lithologies, topographies, and geologic structures. Despite this diversity, a few generalizations concerning the hydrogeologic properties of the bedrock can be made:

(1) Little or no intergranular porosity exists except in the weathered saprolite zone near the surface;
(2) Solution openings are generally developed only in rocks with a high carbonate mineral assemblage (e.g., marble);
(3) The ground water zone exists as a complex network of fractures.

The porosity of crystalline rock decreases with depth more rapidly than any other rock type in the study area, and

little water is obtainable (except locally) below a depth of 300 feet (91.4 m) (Parker, et al, 1964). Above the bedrock is a mantle of saprolite ranging from 20 to 40 feet (6.1 to 12.2 m) thick. The character of the saprolite tends to reflect the composition of the parent rock, which is usually an unsorted mixture of clay, silt, and sand with low to moderate permeability.

Well yields vary from 0 to 300 gpm (0 to 18.9 l/s), but generally average 11 gpm (0.7 l/s) in the Glenarm Series and 17 gpm (1.1 l/s) in the Baltimore Gneiss. Wells range from 100 to 200 feet (30.5 to 61 m) in depth (Poth, 1968).

Adequate domestic supplies of ground water can be developed from the Cambrian- to Ordovician-age bedrock. These formations are predominantly carbonates that have been subjected to various degrees of metamorphism. Most carbonates are susceptible to solution (karstification) which enhances their porosity and permeability. Carbon dioxide absorbed from the soil and atmosphere forms a weak acid which can make small cavities by dissolving the carbonate rocks. The distribution of these cavities is very irregular, thus making it difficult to ensure that two wells pumping in the same area will not interfere with each other. Well yields in these rocks generally range from 3 to 30 gpm (0.2 to 1.9 l/s) with a maximum of 500 gpm (31.5 l/s) (Parker, et al., 1964; Poth, 1968). Higher yields can be obtained in extensive networks of solution-enhanced openings near perennial streams. Well depths vary from 42 to over 400 feet (12.8 to 121.9 m), but generally average 90 to 150 feet (27.4 to 45.7 m).

The western and northern portions of the study area are situated in the Triassic lowlands and are underlain by rocks of the Newark Group. These are clastic rocks that have undergone intrusion by diabase sills and dikes, some of which form prominent ridges. Adequate supplies of ground water to sustain heat pump operation can generally be developed throughout the area. Notable exceptions are wells constructed in the sills and dikes. Contact metamorphism resulting from these intrusions has altered the surrounding shales to tough hornfels. Well yields of 3 gpm (0.2 l/s) are typical of diabase sills (Longwill and Wood, 1965). Well yields in the rest of the Newark Group average between 10 to 85 gpm (0.6 to 5.4 l/s) in the various formations.

Readily available ground water supplies can be obtained from the unconsolidated sediments of the Atlantic Coastal Plain. These sediments consist of Upper Cretaceous and Pleistocene-age sands, silts, and clays that thicken considerably seaward. The reported yield of wells tapping Pleistocene deposits show a range from 8 to 7,000 gpm (0.5 to 441.6 l/s). Transmissivity values are moderately high for the Pleistocene deposits.

The Cretaceous-age formations form a seaward thickening wedge of marine sediments and consist of lenticular beds of sand, silt, clay, and small amounts of gravel. Sand members are separated by thick, impermeable clay layers which create artesian conditions. Wells generally yield upward of 1,000 gpm (63.1 l/s) (Farlekas, et al., 1976; Greenman, 1961).

Recharge to the ground water system comes principally from precipitation. Most recharge occurs in late winter and early spring by melting snow and infiltrating rainfall; evapotranspiration is at its lowest during this period. Recharge areas are not identified where the Precambrian, Paleozoic, and Mesozoic rocks crop out. The structural deformation, as well as their complex lithology, complicates the movement and occurrence of ground water within the system.

Recharge areas within the unconsolidated aquifer system have significantly shifted their position in response to the development of ground water resources in the area. Prior to this extensive development, the recharge area was a narrow band which exposed these formations at the surface. Other areas of recharge have developed over topographic high points in Camden County's Cherry Township. However, the exact area of recharge cannot as yet be identified, even with the aid of isotopic carbon studies (Winograd and Farlekas, 1974).

C. Ground-Water Quality

Quality of ground water varies considerably throughout the Philadelphia area. In general, ground-water quality is strongly influenced by the soluble constituents of the aquifer, and numerous and diverse lithologies in the study area account for the variability in ground water qualities. In addition, local land-use practices affect water conditions.

The Precambrian to Paleozoic bedrock aquifers yield excellent quality water that is low in dissolved solids and soft to moderately hard. The Mesozoic rocks yield moderately mineralized water that is moderate to very hard. Carbonate aquifers typically yield moderately mineralized water that varies from moderately hard to very hard.

The unconsolidated sediments of the Atlantic Coastal Plain illustrate drastic changes in ground water quality, largely due to man's impact on the hydrologic system. Typically, a calcium or sodium bicarbonate water is obtained in the outcrop area. The pH of the water varies from 7.6 to 5.5, and excessive iron concentrations constitute the single most troublesome problem. Table B6 contains a chemical analysis of wells tapping aquifers in the Philadelphia area.

TABLE B6

Average Chemical Analyses of Ground Water in Consolidated Rocks in the Philadelphia Area

	ppm
SiO_2	18.02
Fe	0.64
Cd	37.50
Mg	10.43
Na + K	11.20
HCO_3	103.87
SO_4	35.45
Cl	11.29
F	0.08
NO_3	9.50
TDS	199.41
pH	7.1
temperature	11.9°C

In general, ground water in the Philadelphia area is of good to excellent quality, but excessive iron concentrations are frequently encountered. However, this iron can easily be treated by various methods and should not impede the utilization of ground-water heat pumps. On the other hand, heat pump usage may be seriously hampered in areas where the ground water quality has been drastically altered by industrial, municipal, and domestic forms of pollution.

D. Environmental Evaluation

Ground water pollution in the study area is presently limited to the outcrop areas of the Pleistocene aquifers. However, the types of pollution in these areas may seriously affect the operation of ground-water heat pumps.

The largest known area of ground water pollution from industrial wastes is located in the League Island Trough. A lower artesian aquifer of sand and gravel is hydraulically connected to the water table aquifer. Withdrawal of water from the lower aquifer regionally affects the potentiometric surface, establishing a new hydraulic gradient. This favors the intrusion of poor quality water into the lower aquifer.

Pollution may also be spread from one aquifer to another by artificial injection of spent heat pump water. In a dual aquifer system where water is taken from one aquifer and discharged into another, poorer quality water from a polluted aquifer could be spread via the injection well.

The water table aquifer in tidelands and adjacent lowland areas in south Philadelphia consists of river silts and landfill from the city. The concentration of organic material has resulted in the generation of methane and other gases, but the extraordinary concentration of iron and carbon dioxide poses the most significant problem. Dissolved carbon dioxide could cause serious corrosion within the heat pump system, which could severely limit heat pump use in such areas.

Near the Five Mile Point area in northern Philadelphia, ground-water pollution results from three sources: (1) contamination by industrial brines yield highly mineralized sodium chloride waters; (2) numerous industrial wastes generate moderately mineralized calcium bicarbonate and sulfate water; (3) inadequate local sanitary waste systems cause water to be moderately mineralized with high concentrations of nitrate. Contamination of the artesian system occurs where it is hydraulically connected to the water table aquifer. Variations in ground water quality result from local recharge through vertical leakage near centers of pumping, or through the mixing of superior quality water from the Delaware River.

A chemical analysis of Camden City's public supply wells showed excessive chromium concentrations. The source of the

chromium is not known, but at least three metal-plating companies are located within a radius of 1,600 feet (488 m) (Farlekas, et al, 1976). Two potential areas of salt-water intrusion occur within Camden County: one is along the Delaware River, the other is near the fresh-salt water interface in Winslow Township.

The Delaware River is tidal in the Philadelphia area. Salt water does not normally reach this vicinity except during extended droughts. The reduced stream discharge during these periods favors the invasion of salt water upstream. Prolonged intrusion of salt water would eventually contaminate aquifers that are hydraulically connected to the Delaware River.

Another potential area of salt water encroachment derives from the vertical and/or lateral migration of the salt-fresh water interface. The interface itself is actually a broad diffusion zone where salt water mixes with fresh water. Normally, there is little movement of the interface. However, changes in hydraulic gradient may induce the movement of salt water toward centers of pumpage.

E. Conclusion

Future water supplies in the Philadelphia area will be developed primarily from the Delaware and Schyulkill Rivers. Any development of ground-water resources will be more extensive in the unconsolidated aquifers of the coastal plain than in the bedrock aquifers. In general, ground water supplies are readily available and of good quality. However, there are serious local problems with pollution. The potential utilization of ground-water heat pumps is favorable except in these areas. The storage of thermal energy in aquifers is already practiced commercially on a limited scale. Throughout the Atlantic Coastal region, several deeper geothermal areas have been identified and exploratory drilling has been initiated.

VIII. COLUMBUS, OHIO

Columbus is located in Franklin County in central Ohio. It ranks as one of the three largest cities in the state, and serves as the state capitol. The population of Columbus resembles a micro-America and serves as an ideal test market for many new products and services.

The climate is continental temperate. Generally, the winters are short and cold with moderate to light amounts of snowfall. Summers are typically long, hot, and humid. The average temperature for Columbus is 53.1° F (11.7° C); the average precipitation is 35.7 inches (90.7 cm). Most of the precipitation is widespread and occurs in the spring, with local intense thundershowers characterizing summer and early autumn rainfall. The natural vegetation consists of woodlands, short grasses, and legumes. Hemlock is also native to the area as a reminder of the colder climates during continental glaciation.

Presently, the Columbus area supports a diversified agricultural and industrial economy. Principal crops include corn, soybeans, cereals, and some truck-farming operations. Other agricultural industries are hog, cattle, and dairy farming. Several limestone quarries, sand and gravel pits, and shale (for clay products) constitute the nonmetallic mineral resources of the area. The major industries are food processing and printing.

The population of the Columbus area has nearly doubled in the past 20 years. However, future growth is expected to be slower. By the year 2000, population is projected to be 1.5 million.

A. Geologic Setting

The topography of the Columbus area reflects a rolling to hummocky surface with well-defined stream valleys that typify areas of continental glaciation. Most of the study area is located in the Till Plains section of the Central Lowlands physiographic province, with the remainder in the Appalachian Plateau. The two provinces are separated by a series of north-south scarps and terraces which lie in the eastern extremity of Franklin County.

The consolidated rocks underlying Franklin County are sedimentary in origin. The rocks range in age from late Silurian to early Mississippian and consist of dolomitic limestone, black shale, and alternating beds of shale and sandstone.

Unconsolidated deposits of Pleistocene age overlie a mature, finely-dissected bedrock surface. Glacial outwash deposits of sand and gravel are generally found in the southeast portion of Franklin County. Lacustrine deposits

of silt and clay occur in many buried valleys in the area. Overlying the silt and clay deposits are deposits of sand and gravel left by glacial meltwaters. These deposits are stratified and commonly cross-bedded. A thick mantle of ground moraine, along with several terminal moraines, were deposited during a later period of glaciation. Generally, 50 feet (15.2 m) of till overlie the bedrock and more than 250 feet (76.2 m) of sediments in the buried valleys.

The Cincinnati Arch is the dominant structure of the area. Its axis strikes northeast and extends from Toledo, Ohio, to Louisville, Kentucky. The bedrock beneath the Columbus area lies on the east flank of the arch and dips south-southeast at 25 to 32 feet per mile (4.7 to 6.1 m/km) (Schmidt and Goldthwait, 1958). In some areas, the dip is altered by small folds or local variations in formation thickness.

B. Ground-Water Availability

Moderate to abundant ground-water supplies can be developed from a variety of glacial deposits and bedrock aquifers. Over three-fourths of Franklin County is underlain by aquifers capable of sustaining ground-water heat pumps.

Bedrock aquifers underlying the western half of Franklin County consist of Silurian and Devonian carbonates. The Delaware Limestone generally yields smaller quantities of water than the underlying Columbus Limestone. Cumulative yields for wells penetrating both of these formations range upward of 175 gpm (11 l/s). Industrial wells tapping the Silurian Bass Island Dolomite are capable of producing 400 gpm (25.2 l/s) (Schmidt and Goldthwait, 1958). Ground water is transmitted through solution-enhanced fractures, joints, bedding planes, and interconnected solution cavities. Well depths in the bedrock generally do not exceed 200 to 400 feet (61 to 122 m).

The Olentangy, Ohio, and Bedford Formations comprise approximately 40 percent of the bedrock beneath the study area, and consist of black to blue argillaceous shales interbedded with thin siltstones and sandstones. Low to submarginal well yields are typical of these formations, although wells that yield moderate supplies are not uncommon. In general, ground water is transmitted along a weathered zone in the upper part of the formations where it is overlain by unconsolidated till and sediments.

In the northwest portion of the Columbus area, the principal bedrock aquifers are the Berea Sandstone, Sunbury Shale, and the lower part of the Cuyahoga Formation. Wells tapping the Berea Sandstone yield 9 to 70 gpm (0.6 to 4.4 l/s) and average 17 gpm (1.1 l/s). A slightly lower average, 13 gpm (0.8 l/s), is obtained from wells penetrating the Cuyahoga, Sunbury, and more shaly members of the Berea Sandstone. Secondary porosity in the form of joints, fractures, and bedding planes transmit the ground water through the aquifer. Intergranular porosity of the sandstone members supplements the secondary porosity of the aquifers.

The most productive aquifers are Pleistocene deposits that occur extensively throughout Franklin County. Sand and gravel deposits occur in the southeastern quarter of the county. Wells tapping these deposits have recorded maximum yields of 500 gpm (31.5 l/s). Similar deposits along Little Walnut Creek, Big Walnut Creek, and the Scioto River are capable of producing over 1,000 gpm (63.1 l/s) (Schmidt and Goldthwait, 1958). The permeable nature of these deposits induces stream infiltration which enables wells tapping these deposits to produce high yields. Along the Olentangy River and Alum Creek, wells penetrating coarse-grained sand and gravel deposits yield 250 to 300 gpm (15.8 to 18.9 l/s). In general, well depths are less than 150 feet (45.7 m).

Most of the area is mantled by glacial till. The composition of the till generally reflects the nature of the bedrock from which it is derived (Flint, 1971). The till consists of a heterogenous mixture of fine to boulder-sized materials in which the fine-grained faction predominates. As such, glacial till may have very high porosity but very low hydraulic conductivity values. Wells tapping more permeable sand stringers within the glacial till are capable of yielding 5 to 10 gpm (0.3 to 0.6 l/s). Where the till is predominantly clay, maximum well yields are typically less than 5 gpm (0.3 l/s).

Recharge to the ground-water system occurs in late winter and early spring. Melting snow and early rainfall infiltrate into the ground. Toward late spring, much of the infiltrating water is intercepted by vegetation and returned to the atmosphere through evapotranspiration. Recharge rises again in autumn when the vegetation is dormant and the rate of evapotranspiration drops.

The mean annual precipitation varies from 36 to 40 inches (91.4 to 101.6 cm) over the area. Of this, approximately 32 to 34 inches (81.3 to 86.4 cm) is returned to the atmosphere by evapotranspiration.

The direction and movement of ground water depends on the following factors: topography; character and permeability of the various geologic materials through which the water moves; and location of intake and discharge areas. The complex stratigraphy and rapid vertical as well as lateral variations of the Pleistocene deposits serve to complicate the occurrence and movement of water within the system. In general, ground water moves downslope and is eventually discharged into the major rivers that traverse the area.

C. Ground-Water Quality

The ground water of Franklin County is of fair to moderately good chemical quality. In general, the water is moderately to highly mineralized and very hard with locally high concentrations of hydrogen sulfide, iron, and manganese. Ground-water temperatures average 55° F (12.8° C) which is slightly above the mean annual air temperature.

The bedrock aquifers typically yield calcium sulfate water with some hydrogen sulfide. Glacial deposits generally yield a calcium bicarbonate water with excessive concentrations of iron. Table B7 gives a more complete chemical analysis of the ground water.

TABLE B7

Average Values for Chemical Constituents (ppm) from Selected Wells in Franklin County

pH	7.2
SiO_2	13.74
Fe + Mn	1.45
Cd	182.80
Mg	65.34
Na + K	56.50
HCO_3	394.91
SO_4	450.66
H_2O	7.20
Cl^-	28.63
F	.79
NO_3	3.52
TDS	1036.9

D. Environmental Evaluation

Presently, most of the municipal water supply comes from three surface reservoirs situated along Alum Creek, Big Walnut Creek, and the Scioto River. Ground water contributes only a minor portion to the municipal supply. Smaller, separate water systems have joined the Columbus municipal system in the past. This trend is likely to continue in light of recent federal legislation. The water demand is estimated to increase to 160 mgd (0.7 m^3/s) in 1990 and 263 mgd (1.2 m^3/s) by the year 2000. The construction of additional surface reservoirs and other projects have been proposed to be added in increments so that if growth or consumption rates change substantially, one or more of these latter projects need not be built.

Additional ground-water supplies may be developed through the expansion of the South Well Field. The addition of five well sites by 1985 would bring the total well field capacity up to 75 mgd (0.3 m^3/s). The addition of 12 more well sites could bring the total to 150 to 200 mgd (0.7 to 0.9 m^3/s) by 2020.

Problems with the chemical quality of water may be encountered in areas with high concentrations of iron and hydrogen sulfide. The presence of these chemicals could impair heat pump operation if the water is not properly treated.

The Battelle Memorial Institute in Columbus has used a commercial-scale heat pump system for approximately 20 years. The system uses 350 gpm (22.1 l/s) obtained from six 16-inch (40.6 cm) wells drilled to a depth of 50 feet (15.2 m) into a gravel aquifer. Problems with iron bacteria contamination and galvanic corrosion were encountered. Buildup of iron bacteria in some of the smaller diameter tubes was treated by adding a chlorinator to the system. Corrosion of the coils was remedied by the periodic installation of sacrificial anodes. Neither of these problems adversely affected the local environment. After the water passes through the heat pump system, it is discharged into the nearby Olentangy River. No detailedstudies have been made, but there has been no apparent harm to the environment in the heat pump's 20 years of operation.

E. Conclusion

In 1974, the average daily water demand in the Columbus area was approximately 102 mgd (0.5 m^3/s). Future needs are estimated at 243 mgd (1.1 m^3/s) by the year 2020, which must be met by a combination of surface and ground-water resources. Adequate supplies of ground water are available for the operation of heat pumps. The chemical quality of the water is generally good, and any local problems with high iron or hydrogen sulfide content can be treated to ensure proper heat pump performance. The outlook for high density utilization of ground-water heat pumps in the Columbus area is favorable, as evidenced by the successful operation of systems currently in use.

IX. CLEVELAND, OHIO

Cleveland is located in Cuyahoga County along the southern shore of Lake Erie. The surrounding metropolitan area is one of the most densely populated regions in Ohio.

The study area has a continental temperate climate with a mean annual air temperature of 49.2° F (9.6° C). Winters are generally cold with a moderate amount of precipitation. The summers are typically long, hot, and humid. The climate is somewhat modified by the proximity of Lake Erie, since most large bodies of water influence weather through cooling by evaporation in summer and heat gain during the winter. The natural vegetation consists of various deciduous trees, legumes, and grasses.

A variety of light and heavy industries are located in the Cleveland area. The manufacture of iron, steel, automotive parts, and machined tools are some of the leading industries. In the surrounding area, a diversified agriculture exists. Orchards, alfalfa, wheat, corn, oats, hogs, cattle, and truck farming operations are the principal agricultural industries.

The population has grown steadily as people are attracted by the employment opportunities in Cleveland. The population has increased from 1.5 million in 1950 to two million in 1970. Future projections estimate that the population will reach 2.2 million in 1980, 2.4 million in 2000, and 2.7 million by the year 2020.

A. Geologic Setting

The Cleveland area is situated in two physiographic provinces: the Appalachian Uplands and the Interior Central Lowlands. The line of demarcation between the two provinces is the Portage Escarpment which strikes northeast through Cuyahoga County. A sharp contrast in topography exists between the two areas. The Eastern Lake and Till Plains section of the Interior Central Lowlands is relatively flat and gradually rises to the southeast. A series of long, linear, sandy ridges mark former strand lines of several preglacial lakes. The glaciated section of the Appalachian Plateau is characterized by a mature topography that has been deeply dissected by many streams. The valley floors of the major rivers are typically 100 to 150 feet (30.5 to 45.7 m) below the general land surface.

The bedrock beneath Cuyahoga County, which was deposited during the mid-Paleozoic era, is relatively flat. Devonian shales are the oldest rocks exposed in the study area. The next sequence of rocks is of Mississippian age and consists of the Cuyahoga Group, Berea Sandstone, and Bedford Shale. This is overlain by the Sharon Conglomerate of Pennsylvanian age. Deposition continued throughout the Pennsylvanian, but the sediments have since eroded away.

Unconsolidated sediments of Pleistocene age overlie the bedrock and attain a thickness of over 200 feet (61 m) in buried preglacial and glacial valleys. Outwash deposits of sand and gravel are generally located in the three major buried valleys. Generally, the location of these buried valleys is coincident with present-day major river valleys.

Both the Nebraskan and Kansan glaciers are believed to have traversed the area (Winslow, et al., 1953), but the bulk of the unconsolidated sediments were deposited during the Wisconsin glaciation. Several long, sinuous ridges found in the northeastern part of the county represent beach deposits of former glacial lakes. Deposits of sand and gravel make up these ridges, while fine sand, silt, and clay settled out in the deeper, calmer waters of the lake.

Recharge to the ground-water system is derived principally through precipitation and underflow into the region. Annual precipitation averages 34 inches (86.4 cm) in the Cleveland area. Evapotranspiration and runoff consume two-thirds to three-fourths of the total.

Generally, recharge occurs during late autumn and early spring. The movement and occurrence of ground water is complicated by the complex stratigraphic variation of the Pleistocene glacial deposits, which are characterized by discontinuity and limited areal extent. For the most part, ground water moves through the system and eventually discharges into a stream that intersects the water table.

B. Ground-Water Availability

Adequate ground-water supplies can be developed from sandstone formations and glacial sand and gravel deposits. Lower well yields are obtained from shale formations and fine-grained glacial deposits that occur extensively throughout Cuyahoga County.

The Sharon Conglomerate of Pennsylvanian age is a coarse to medium-grained quartzitic sandstone. The average well yield for 4 to 6-inch (10.2 to 15.2 cm) diameter wells ranges from 5 to 10 gpm (0.3 to 0.6 l/s). Large-capacity wells have yielded upwards of 230 gpm (14.5 l/s) (Winslow, et al., 1953). The areal extent of the aquifer, however, is limited to the southern half of the county.

The Cuyahoga Group consists of shale and sandstone members which underlie the southern half of Cuyahoga County. Domestic wells 6 inches (15.2 cm) in diameter generally yield 3 to 5 gpm (0.2 to 0.3 l/s).

The most productive bedrock aquifer is the Berea Sandstone. It underlies the Cuyahoga Group and forms a prominent escarpment trending northeast-southwest through Cuyahoga County. Domestic wells penetrating this formation generally yield 5 to 10 gpm (0.3 to 0.6 l/s) (Winslow, et al., 1953); industrial wells have produced as much as 260 gpm (16.4 l/s). Well depths vary and tend to increase towards the southern portion of the county.

C. Ground-Water Quality

The quality of ground water in the Cleveland area varies from fair to good. It is typically a calcium or magnesium bicarbonate type that ranges from hard to very hard. Some wells yield highly mineralized water, and there may be high local concentrations of iron and manganese.

Table B8 lists maximum and minimum values of some chemicals found in the Cleveland area ground water:

Table B8 - Maximum and Minimum Values for Some Chemicals Found in Cleveland's Ground Water

	Minimum (mg/l)	Maximum (mg/l)
Na	6.4	2974
HCO_3	112	1124
SO_4	1.2	682
F	0.1	1.2
Fe	0.13	17
Mn	0.0	0.82
TDS	228	7404
Hardness	11	889

Ground-water temperatures vary between 51° to 53° F (10.6° to 11.7° C). In general, the annual temperatures are constant below depths of 15 to 20 feet (4.6 to 6.1 m). Exceptions may occur in wells experiencing stream infiltration. The magnitude of such temperature fluctuations depends on the distance between the well and recharge boundary, as well as the hydraulic conductivity of the aquifer. In general, such fluctuations are not of sufficient magnitude to affect the utilization of ground-water heat pumps.

D. Environmental Evaluation

In general, the ground-water resources of the Cleveland area are largely undeveloped. Several aquifers within the area are capable of sustaining high-density usage of ground-water heat pumps with minimal environmental impacts.

Glacial outwash deposits of sand and gravel are the most productive aquifers of Cuyahoga County. These deposits are generally located in buried valleys which coincide with the present location of the Cuyahoga, Chagrin, and Rocky Rivers. The consumptive use of ground water would have minimal impact where the aquifer is hydraulically connected to a river. Wells tapping such an aquifer could establish a hydraulic gradient that favors induced recharge from the stream. The spent heat pump water could then be discharged into the stream in order to maintain stream flow.

In areas where the potential for induced recharge from the stream is inadequate, the discharge water could be reinjected into the aquifer. The equilibrium in the hydrologic system would thus be maintained. Production and injection wells should be properly spaced to avoid thermal well interference. Minimal effects are anticipated if the spent heat pump water is recharged to the aquifer, since it is chemically compatible with the native ground water.

Local variations in the chemical quality of ground water in Cuyahoga County may present a problem in utilizing heat pumps. Hydrogen sulfide and excessive iron may impair heat pump performance. Since these high values are local in nature, they would not restrict heat pump usage throughout the area.

E. Conclusion

The high-density usage of ground-water heat pumps will have minimal environmental effects in the more productive aquifers of Cuyahoga County. Generally, a sufficient amount of ground water can be developed from glacial deposits or underlying bedrock. However, in some cases, the development of adequate storage may be necessary to supply both heat pump and domestic needs. Overall, the ground-water resources of the Cleveland area have a moderate to good potential for sustaining ground water heat pumps.

X. CONCORD, NEW HAMPSHIRE

Concord is situated along the Merrimack River in south-central New Hampshire. It serves as the state capitol and is the county seat of Merrimack County. Concord consists of a central urban section with five outlying urban villages.

The Concord area experiences a semi-continental, moderately moist climate. The average mean temperature is 46° F (7.8° C). However, the average temperature maxima and minima vary greatly for any given month. Precipitation is distributed evenly throughout the year with a mean snowfall of 61.6 inches (156.5 cm) and a mean rainfall of 38 inches (96.5 cm).

The industry of the Concord area is the most extensively diversified in New Hampshire. Major products manufactured

in the area include electrical and electronic equipment, mobile and modular homes, nonferrous foundry products, and heat treatment equipment. Principal agricultural industries include orchards, corn, and dairy farms.

The population of Concord increased 16.7 percent from 30,000 in 1970 to 35,000 in 1977. In Merrimack County, the population increased by 18.8 percent to a total of 909,000 in 1977. Future growth for the county is projected to be .10 million in 1980, .11 million in 1990, and .12 million in 2000.

A. Geologic Setting

The bedrock underlying the Concord area originally consisted of a thick sequence of sediments deposited in a eugeosyncline during the Silurian. These sediments were derived from the Canadian Shield to the north and a volcanic island arc complex to the south. Deformation and metamorphism of these sediments occurred during the Acadian Orogeny in the Devonian, and was accompanied by the intrusion of granites and quartz monzanites.

One of the most prominent features of the granites in the study area is large-scale exfoliation or sheeting. Sheet structure has been described as "the division of granite into 'sheets' or 'beds' by jointlike fractures which are variously curved or nearly horizontal, being generally parallel with the granite surface". It is believed that the relief of confining pressure (to which the rock has become adjusted) by removal of superincumbent load is the most probable cause of this structure (Jahns, 1943). Sheeting fractures are an important type of secondary porosity in the study area. Ground water is transmitted along these planes, and tends to accumulate in topographically low areas where sheeting planes, fractures, and joints intersect.

The last major geologic event to occur in the Concord area took place during the Pleistocene epoch. During this time, several major continental glaciers advanced over the area. Various glacial sediments were deposited throughout the northeast, and the topography was significantly modified in some areas. Numerous outwash and lacustrine deposits were distributed throughout the Merrimack Valley and its major tributaries. In addition, ground moraine blankets the surrounding hills, generally averaging 10 to 30 feet (3.1 to 9.1 m) in thickness.

B. Ground-Water Availability

Adequate supplies of ground water for domestic use can be developed throughout Merrimack County. Higher yields are generally obtained from wells tapping unconsolidated Pleistocene deposits. Under favorable conditions, bedrock wells are capable of producing well yields upwards of 30 to 50 gpm (1.9 to 3.2 l/s) (Cotton, 1976).

Glacial till is the most widespread type of unconsolidated deposit, reaching up to 100 feet (30.5 m) thick. In general, till consists of lodgement and ablation drift. Lodgement till is deposited at the basal portion of a glacier and is more compact and less permeable than ablation drift. Wells developed in glacial till tend to yield only a fraction to a few gallons per minute.

Thicker unconsolidated deposits occur in many of the stream valleys. These deposits are fine-grained sands, silts, and clays of lacustrine origin that are interbedded with thin lenses of sand and gravel which were deposited during the discharge of glacial meltwaters. These areas hold a low potential for the development of municipal or industrial ground water supplies, but should be adequate for domestic needs.

Well yields of 210 to 500 gpm (13.2 to 31.5 l/s) can be developed from glacial outwash deposits located below the confluence of the Merrimack and Soucook Rivers. Most wells penetrating the unconsolidated deposits along the Merrimack River and its tributaries are generally less than 100 feet (30.5 m) deep.

Adequate domestic ground water supplies can be developed from the crystalline bedrock that underlies most of the Concord area. Bedrock well yields tend to be smaller in diameter than wells developed in the unconsolidated sediments. The difference in well yield results from the lack of intergranular porosity due to the interlocking nature of the crystals that comprise the bedrock. The dominant form of porosity in these types of rocks is secondary porosity in the form of joints and fractures. Bedrock wells situated in topographic lows tend to have higher yields than similar wells a short distance away that are located on topographic highs. Low areas are more likely to accumulate a greater volume of sediments which allow runoff from higher areas to infiltrate and be retained.

Recharge to the ground-water system is derived principally through precipitation. During autumn, the ground-water table tends to rise as vegetation becomes dormant and evapotranspiration is reduced. Water levels continue to rise until spring. The movement of ground water through the subsurface depends on a number of factors: topography; character and distribution of permeable materials through which the water moves; and location of intake and discharge areas. Generally, water moving through the shallow, unconfined aquifer is discharged into a stream that intersects the water table and eventually flows into the Merrimack River in the Concord area. Water is also discharged through the municipal well field and several domestic wells.

C. Ground-Water Quality

Ground water in the middle Merrimack River Basin is generally of excellent to good chemical quality. The ground water is slightly acidic (pH = 6.5) and varies from soft to moderately hard. Locally high concentrations of iron and manganese may impair the quality of the water. Naturally high fluoride concentrations are also encountered in the area (Miller, et al., 1974). Table B9 illustrates average values for some of the chemical constituents in the Concord area.

TABLE B9
Ground-Water Quality for Concord, New Hampshire

	Average Concentration (mg/l)
NO_3	0.13
F	0.10
Fe	0.10
Mn	0.07
Na	7.74
Cl	13.0
pH	6.5

Ground-water temperatures vary from 46° to 48° F (7.8° to 8.9° C). Variations from the regional values may occur in recharge and discharge areas. Wells tapping the unconsolidated deposits in stream valleys may experience temperature and chemical quality fluctuations. The degree of fluctuation depends on the distance between the well and the recharge boundary and the hydraulic conductivity of the aquifer.

D. Environmental Evaluation

Ground-water pollution in the middle Merrimack River Basin is localized and generally reflects land-use practices within the area. Local degradation of ground water quality occurs near unsewered residential and village areas, waste disposal sites, or along highways where deicing salts are applied or stored (Miller, et al., 1974). In general, ground-water pollution in the Concord area is limited and does not constitute a serious problem. The greatest potential for high-density usage of ground-water heat pumps is from wells tapping glacial outwash deposits along the river valleys. These areas would experience the least degradation to the environment. It may be possible to use ground water consumptively in areas where the aquifers are capable of inducing a substantial amount of stream infiltration. Wells tapping these aquifers could establish a new hydraulic gradient favorable to stream infiltration. Stream flow would be maintained by discharging the spent heat pump water back into the stream.

Wells tapping crystalline bedrock generally yield less than 10 gpm (0.6 l/s). As such, some heat pump installations may require supplemental storage in order to maintain an adequate water supply. However, the low permeability of crystalline rock would somewhat restrict the recharge capacity. This leaves considerable potential for dewatering of the aquifer. In these areas, moderate to low-density heat pump usage would have the least environmental impact.

E. Conclusion

Domestic ground-water supplies can be developed from glacial outwash deposits and from bedrock where the well intersects a sufficient number of water-bearing fractures. In general, minimal adverse environmental impacts are encountered from high density usage when the more productive glacial outwash deposits are the primary aquifers. Overall, the potential for utilizing ground-water heat pumps in the Concord area is favorable.

APPENDIX B
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APPENDIX C
LIST OF GROUND-WATER HEAT PUMP MANUFACTURERS

It was considered that, in the interest of completeness, a current list of ground-water heat pump manufacturers be included in this report.

The following list includes those manufacturers with whom the authors of this report are at least familiar. Due to the relative infancy of the industry, it is likely that some smaller manufacturers have entered the market and are not included on this list.

The attempt was also made to exclude from this list those companies which produce equipment that was originally designed for closed-loop system operation but may be suitable for ground-water applications in some areas of the country.

TRADE NAME	HEAT PUMP MANUFACTURERS COMPANY AND ADDRESS
Ener Con System	American Air Filter 215 Central Avenue Louisville, KY 40201
Command Aire	Command Aire Corp. P.O. Box 7916 Waco, TX 76710
Energy Miser Vantage Series	Florida Heat Pump Corp. 610 Southeast 12th Avenue Pompano Beach, FL 33060
Geo-thermal Heat Pump	Friedrich 2000 West Commercial Blvd. Fort Lauderdale, FL 22209
Geo Systems	Geo Systems 3623 N. Park Drive Stillwater, OK 74074
Century/Comfort Aire	Heat Controller, Inc. Losey at Wellworth Jackson, MI 49203
Koldware	Heat Exchanger, Inc. 8100 N. Monticello Avenue Skokie, IL 60076
Phoenix	Phoenix Enviro-Temp 651 Vernon Way El Cajon, CA 92020
TempMaster	International Energy Conservation Systems, Inc. 1775 Central Florida Parkway Regency Industrial Park Orlando, FL 32809
Ground Water Heat Exchanger	Tetco Heat Extractor 378 W. Olentangy Street P.O. Box 397 Powell, OH 43065
Solargy System	WESCORP, Inc. 15 Stevens Street Andover, MA 01810
Vanguard	Vanguard Energy Systems 9133 Chesapeke Drive San Diego, CA 92123

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