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Title: Evaluation of Thermal Energy Storage Requirements for a Geothermal Based District Heating System

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The thermal energy storage requirements for a district heating system utilizing geothermal energy is evaluated with respect to the system design heating load and local climatic conditions. The local climate pattern is represented by a series of events which characterize the nature and sequence of the cold spells that can be expected during the winter. The events are defined as those days in which the average daily temperature is less than 10°F above the 97.5% design temperature. All energy storage is assumed to be accomplished by the use of a hot water storage tank.

Three different standards for evaluating the required storage capacity are used. First, the worst case storage capacity that is capable of providing the entire peak thermal energy demand above that produced by the geothermal resource is found for the most severe weather events recorded in the past 20 years for several

cities across the United States. Secondly, the storage tank capacity is sized to provide at least some thermal energy storage 99% of the days during the heating season, November 1 to March 31, by simulating the storage tank operation over the 20 year period. Finally, an economic analysis is performed which finds the lowest cost method of providing peaking energy to the district heating system, either by the incorporation of thermal energy storage or by the installation of a peaking boiler.

The ratio of the system design heating load to the maximum sustainable resource well production rate (LDRATIO) is found to have an extremely important influence on the storage requirements. A LDRATIO limit of approximately 1.6 is suggested when designing a geothermal district heating system, due to rapidly increasing peaking energy requirements and total peaking system costs for a LDRATIO above this level. The unit peaking energy is also found to be a minimum at a LDRATIO of 1.6.

District heating systems located in cities characterized as having a maritime climate were found to be better suited to the application of thermal energy storage than colder inland localities. Recommended storage tank capacities for cities in the United States are given based upon a multivariate regression analysis relating the minimum cost storage sizes as a function of several common climatic parameters. In order to help decide whether incremental additions to the system heating load should be met by drilling another resource well or by adding to the peaking system capacity estimates are made of the minimum unit peaking energy cost.

Evaluation of Thermal Energy Storage Requirements for a Geothermal Based District Heating System

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I. INTRODUCTION

Geothermal energy is one alternative source of domestic energy that shows promise for applications in the United States. Curently, there are two primary methods of tapping this resource, either electrical power generation or direct utilization of the thermal energy. If the resource temperature is high enough, then electrical energy can be generated and transmitted to wherever it is needed. Such an operation now exists in several places around the world with the largest being in the Geysers area north of San Francisco. At low resource temperatures however, electrical power production is unfavorable compared to the direct utilization of the thermal energy. This direct utilization may take the form of either industrial process heating or water and space heating of residential and commercial buildings. If a geothermal resource is supplying the thermal energy requirements for more than just a few users, then some sort of fluid distribution network to transport the thermal energy to each user must be built. This arrangement is referred to as a district heating system.

District heating is a process by which thermal energy is centrally produced and then transported to the user via a distribution system. This is analagous in some way to an electric utility network except that the energy transported is thermal instead of electrical. The user extracts the required amount of energy from a circulated distribution fluid, which is generally returned to the energy source to be reheated. In this project the primary energy source is assumed to be a geothermal resource, however, energy can be supplied to the distribution fluid by several other methods. These methods include the "waste heat" energy from the generation of electricity or directly from a boiler. A simple diagram of a geothermal based district heating system is shown in Figure 1.1.

District heating has had opposite courses of evolution in the United States and Europe. The very first reported district heating system was started in 1877 by Birdsill Holly who supplied steam to his neighbors from a boiler in his home in Lockport, New York (United States Department of Energy, 1980). District heating was rapidly accepted and systems were started in a number of American cities. Soon cogeneration systems were begun which produced steam for heating purposes as a byproduct of electricity production. However, the development of larger electrical power plants away from urban centers coupled with the accelerated use of cheap oil and natural gas for heating purposes caused a majority of this country's district heating systems to fold. Today, only a handful of these systems still exist, with the largest being operated by Consolidated Edison of New York.

In Europe however, a major expansion in the extent of district heating systems has taken place with the rebuilding after World War II. The Soviet Union has by far the greatest implementation of district heating, which is reported to supply 54% of the entire space and hot water heating demand (Karheck et al., 1977).

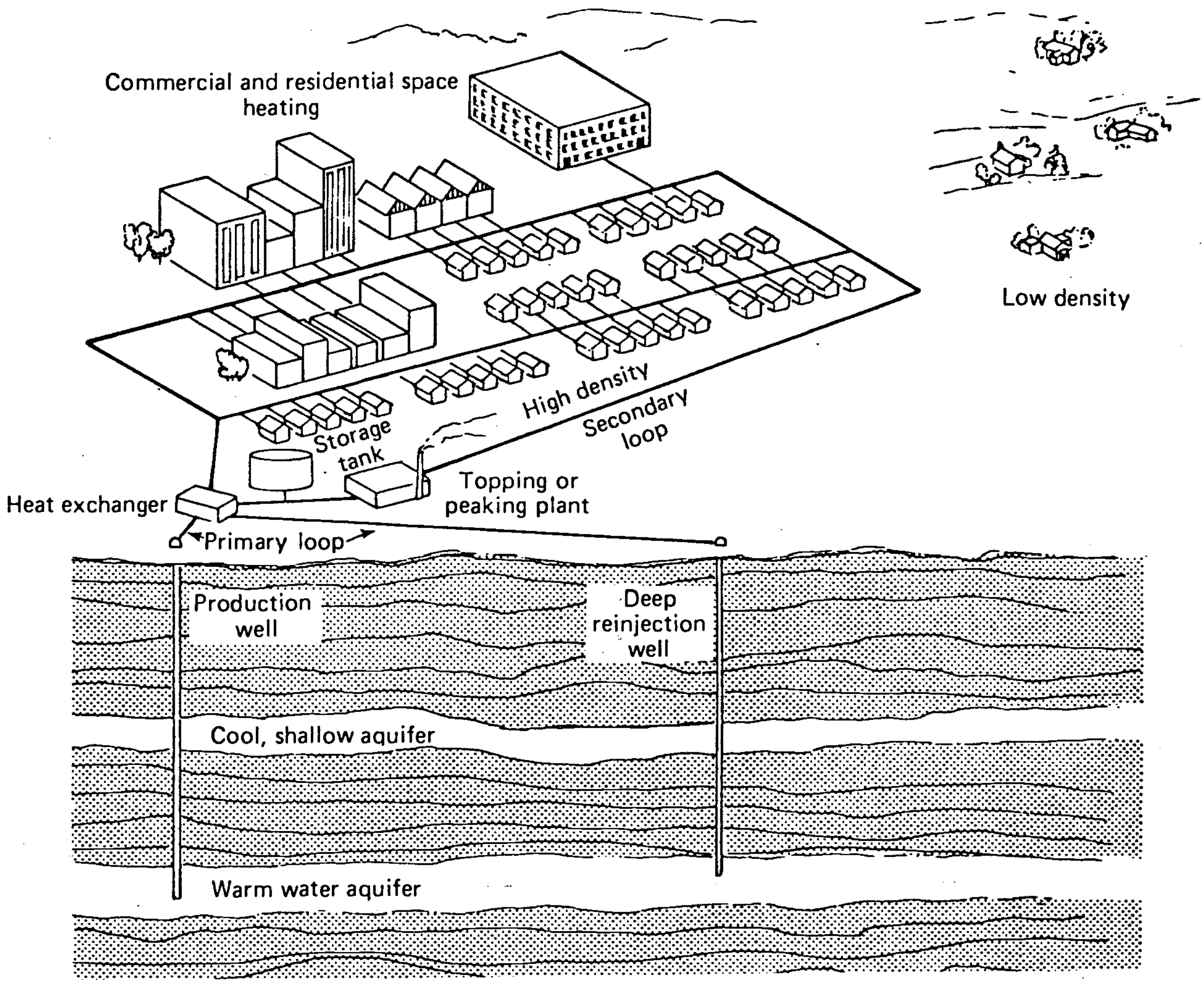

Figure 1.1 Diagram of a geothermal based district heating system. (from Barron et al., 1980)

Extensive systems also exist in West Germany, Sweden, Denmark, Finland, and the East European countries. With only a few exceptions, district heating systems in the United States use steam as the transport medium, while the systems in Europe primarily use hot water (EUS, Inc. and Hittman Associates, Inc., 1980).

A variety of factors are important in influencing the economic viability of a district heating system. One factor of primary importance is the price of energy to the district heating system operator compared to that for the individual user. The larger this difference the better the chance of the system being economically feasible, since this price differential must be large enough that the district heating system operator can supply energy to the user at a cost lower than the other alternatives available to the user while still providing enough profit to pay the system's expenses.

One of the largest front end expenses of a district heating system is the capital cost of the fluid distribution network. Consequently, areas with high heating demand densities are desired. This means that for a system that serves primarily residential heating demand, central core districts or other areas of higher population density would be best suited for district heating. In addition, for two areas of similar population density the locality with the colder climate would be expected to have a better potential for district heating.

The type of distribution fluid used is another factor highly significant in determining the cost of district heating. Both steam and hot water systems are in use, however steam has some inherent drawbacks for use, especially in the larger district heating systems. While being well suited for the transport of thermal energy, especially at higher temperatures, the use of steam becomes uneconomical if transported greater than five miles (Lindeberg, 1979). Other drawbacks of using steam as the transport media compared to hot water are larger pipe size requirements, the problem of avoiding condensation and leakage, the water quality requirements, and problems involved in the start up of a cold system. Because of these problems, steam systems will have higher distribution costs.

Quite commonly, the maximum heating load of a district heating system is allowed to be greater than the production rate of the primary energy source. The resource well is the primary energy source in a geothermal based system with the peaking requirements being met by another energy source. The use of thermal energy storage is one method that may reduce the overall cost of energy to a district heating operation. In particular for a geothermal based system, thermal energy storage will allow more users to be on the system than otherwise possible, since some of the peak demand can be supplied from the stored energy. Having more users on a system will reduce the overall cost per unit of energy by spreading the fixed charges over more customers. In addition, the use of thermal energy storage could potentially allow the geothermal well pumps to be operated at slower speeds, thereby reducing wear on the pumps.

Although the incorporation of a storage tank does have the potential to reduce the overall cost of energy, current methods of determining the proper size of a storage tank, if one is to be used, are primarily based on the system designer's best judgment. There has been very little published in the literature about how to determine the optimal amount of storage for a particular system, and consequently this decision in the past has been handled rather arbitrarily. As an example, consider two of the computer models currently available for analyzing the application of geothermal energy to district heating. Battelle's Pacific Northwest Laboratory has created GEOCITY (McDonald et al., 1977) and the Applied Physics Laboratory at Johns Hopkins University has developed GRITS (Barron et al., 1980). For both of these models, the user must define the storage size, to be provided as an input parameter, and the program does not provide any evaluation of the storage size. GEOCITY requires the storage capacity to be expressed on a total volumetric basis or as satisfying a certain number of days of heating demand. Similarly, for GRITS the user indicates the storage capacity in terms of a given number of hours of maximum output from the resource well(s).

It is the goal of this project to investigate further the effect of thermal energy storage on the overall cost of providing peaking energy for a geothermal based district heating system. The end result will be a method for estimating the desired amount of thermal energy storage as a function of the system design heating load and the climate of the locality. The amount of storage will be evaluated first from an engineering design perspective and then by using an economic analysis to find the storage capacity which will provide the peak heating load at the lowest cost.

II. REVIEW OF THERMAL ENERGY STORAGE SYSTEMS

The purpose of storing thermal energy is to allow the "production" of the energy at a different time than when it is required for use. This delay time could range from minutes to months, depending upon the particular application. Interest in the use of stored thermal energy has increased in the past decade, with applications of thermal energy storage being considered in such diverse areas as geothermal energy, solar energy, residential and commercial air conditioning systems, and electric utilities.

There are three basic means by which thermal energy may be stored, these being:

1) sensible heat - Thermal energy is stored by raising the temperature of the storage medium or by storing the hot material itself.
2) latent heat - Thermal energy is stored by changing the phase of the storage medium, for example by the melting of ice to form liquid water.
3) reversible chemical reactions - Thermal energy is stored by driving beyond equilibrium an endothermic or heat absorbing chemical reaction.

In this discussion reversible is used not in the thermodynamic sense, but rather it refers to the chemical reaction being driven in one direction or another, depending upon the operating conditions. Table 2.1 gives a list of typical possibilities in each storage category, with an approximate value of the intrinsic energy density for given operating conditions.

Table 2.1 Potential energy storage media with approximate intrinsic energy densities. Note that this assumes a reject temperature of 20°C. (from Golibersuch, 1975)

TYPE OF STORAGE	OPERATING CONDITIONS	INTRINSIC ENERGY DENSITY (MJ/m^3)
Sensible Heat		
Water	100°C	335
	50°C	125
Oil	120°C	180
Rock	120°C	130
Latent Heat		
$70NaF-30FeF_2$	682°C	1490
$ZnCl_2$	480°C	410
$Na_2SO_4 \cdot 10H_2O$ (Glauber's Salt)	32°C	11.6*
Reversible Chemical Reactions		
$CH_4+H_2O \Leftrightarrow CO+3H_2$	Temperature Range 430°C - 930°C	150 **
$C_6H_{12} \Leftrightarrow C_6H_6 3H_2$	Temperature Range 230°C - 480°C	175

* Phase change only

** Storage pressure of 1000 psi

2.1 Sensible Heat Storage Systems

A variety of materials, both liquid and solid, have been used in the storage of thermal energy in the form of sensible heat. Of these, water has a number of advantages over other liquids because of its low cost, high specific heat, and generally inert behavior, although problems are presented in avoiding corrosion. In addition, for temperature operations above 100°C, some other liquid medium besides water would have to be utilized, unless the user would be willing to pay the extra expense of a pressurized containment vessel. For a geothermal district heating system with operating temperatures usually between 30° and 100°C, pressurized vessels would not be required, and therefore water is the most practical storage medium for most applications. In fact, the hot geothermal fluid itself can be stored in some instances, eliminating the need of a heat exchanger and the associated thermal energy loss due to inefficiencies in the heat exchange process. The use of a liquid storage medium poses more of a containment problem than if a solid storage medium is used, since any leak in the containment system will cause a loss of stored thermal energy. The heat transfer loss from a storage vessel will also likely be larger for liquid media due to a generally higher heat transfer coefficient at the container walls.

Solid storage media are also being used in sensible heat storage systems. The solid particles in many applications are losely packed together in a storage unit, which is termed a packed bed. A working fluid is circulated through the packed bed for the addition or removal of thermal energy. Working fluid flow through the bed is most commonly vertical, with the flow being downward when thermal energy is being added and upward upon its removal. Since the fluid flows through the bed in essentially only one direction at a time, heat can not be simultaneously added or removed from the storage unit. This is in contrast with a storage tank using a liquid medium where the simultaneous addition and removal of thermal energy is possible.

There is essentially no difference between the design of a small liquid storage tank and that for a very large tank except for component sizing and construction differences. For a very large tank, the insulation of the tank becomes less crucial, since the volume of the tank (and hence the energy storage capability) increases faster than the surface area. If seasonal storage or any other use that requires a large amount of energy storage is being designed, then other storage methods than a storage tank should be considered. One possibility for example is the storage of heated water in underground caverns or aquifers. One particular study considered the storage of solar heated water, collected in the summer months, in confined underground aquifers for use as a heat source for a residential water-to-air heat pump during the winter (McMahon, 1981). Underground aquifers are capable of storing water at high pressures, allowing storage temperature of up to 200°C. Storage efficiencies, that is the amount of energy extracted compared to the amount actually put into storage, of the order of 70% - 80% are considered feasible with aquifer storage.

Another example of a sensible heat storage system is a solar pond (Figure 2.1). A solar pond consists of essentially two layers of water. The lowest layer has a very high salt concentration with the concentration increasing with depth. Therefore, the density of the fluid also increases with depth allowing for a very stable system with little or no convective heat transfer loss. Convective exchange can also be minimized by the addition of transparent thickening agents to the water. A solar pond has the potential to be applied to seasonal storage of thermal energy. Solar energy is collected and stored in the pond's brine layer during the warmer months, while the upper layer of fresh water acts as a thermal insulation barrier for the heated water below during the colder months. Some estimates of commercial sized solar ponds state that the energy can be provided at a cost of around \$5 - \$10 / 10^6 Btu, making it competitive with conventional energy sources at current prices (Multer, 1980).

A well designed storage system will employ the use of thermal stratification to achieve better heat transfer efficiencies. If rocks are used in a packed bed storage unit, then the heat transfer rate between the circulating fluid and the rocks will be high and the thermal conductivity of the bed when no fluid is circulating will be low, thereby aiding stratification. A high heat transfer coefficient between the fluid and the solid means that the solid material near the fluid inlet will be heated much faster than the material at the outlet. When the fluid is not being circulated, a low conductivity will allow the stratification to remain for a

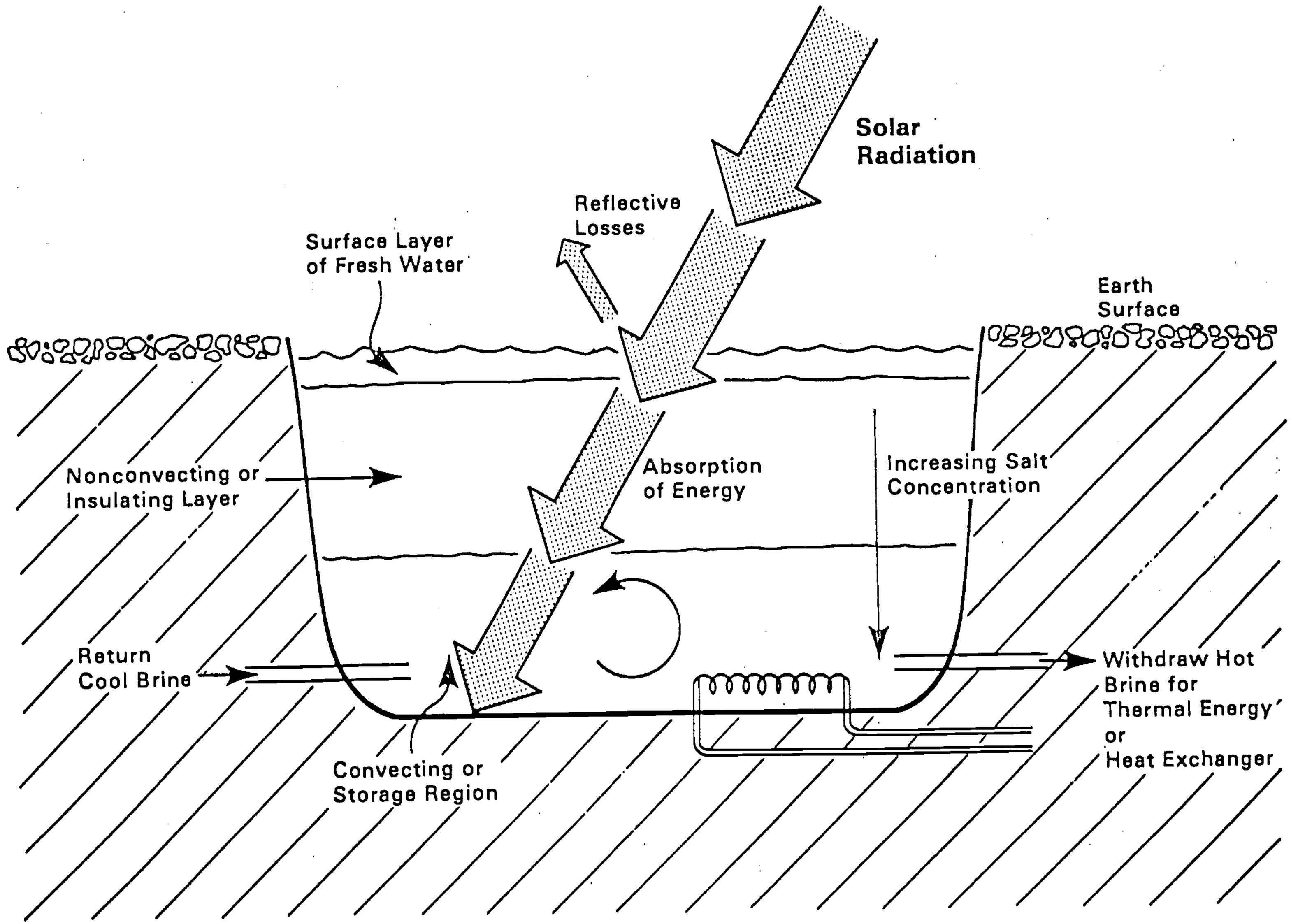

Figure 2.1 Diagram of a solar pond energy collection and storage system. (from Baylin,1979)

longer period of time.

Stratification of a liquid storage tank can be achieved if the tank's height is large compared to the cross sectional area. In this case then, cooler water can be removed from the bottom of the tank for heating and the heated water can be returned to the top of the tank. However, this is not always possible, especially for large storage capacities. For larger tanks there are several possible methods to achieve thermal stratification (Shavit, 1980). One method calls for the subdivision of the tank into a large number of individual cells (Figure 2.2a). Unfortunately, this procedure is relatively expensive to achieve significant results. Alternatively, the tank could be physically separated into hot and cold water sections by a bellow, as shown in Figure 2.2b.

2.2 Latent Heat Storage Systems

A relatively large amount of energy transfer is involved when a substance changes phase. For example, liquid water will release 336 kJ/kg when it freezes into ice. To get the same amount of energy released by the cooling of hot water would require a temperature change of nearly 80°C. Therefore, systems that take advantage of material phase changes are believed to have much potential in a number of thermal energy storage applications.

One drawback to this concept is that the process occurs only at a single temperature, adding another complication to the selection of a particular storage medium. There are several salt hydrates which have a phase change between 30° and 50°C, thus making them

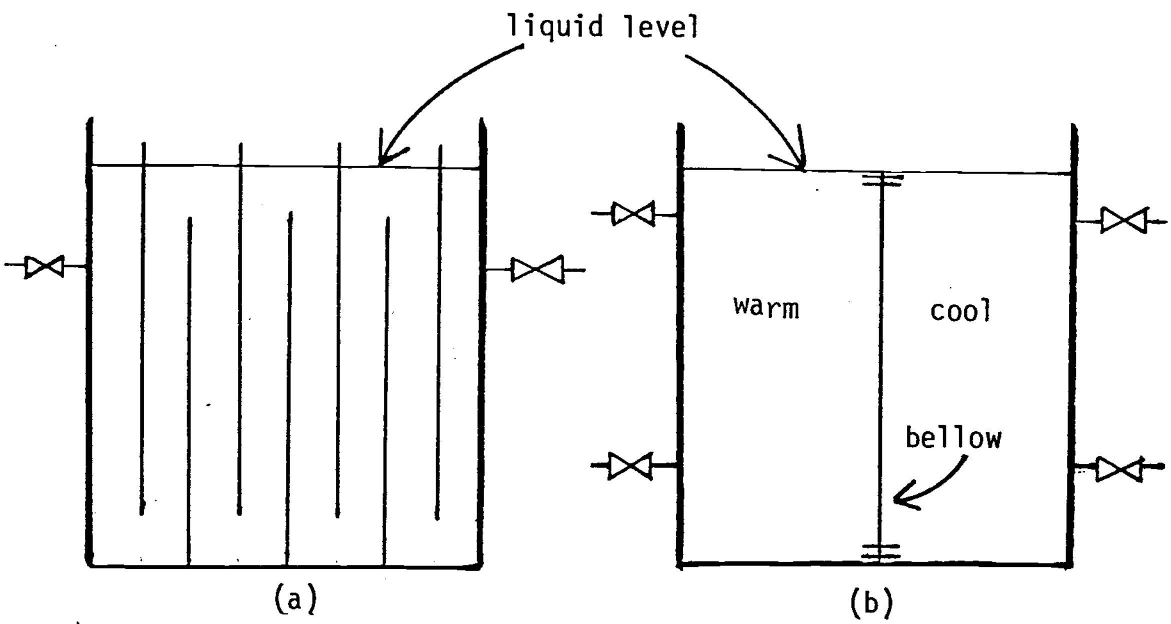

Figure 2.2 Design methods for achieving storage tank stratification in larger tanks. (from Shavit, 1980)

ideal for space heating applications. Table 2.2 lists some of the more promising salt hydrates and their approximate cost per MJ of stored thermal energy (1981 $). One example of these is Glaubers Salt, or sodium sulfate decahydrate ($Na_2SO_4 \cdot 10\ H_2O$), which changes phase at 32°C with a latent heat of fusion of 252 kJ/kg. Problems observed when salts are used for latent heat storage include the separation of the solid phase and a failure of the salts to recombine into a homogeneous liquid upon melting. Another serious problem in the use of salts for thermal energy storage is their highly corrosive nature. Extra precaution can be taken to safeguard the system components, but this will add to the overall system cost.

Table 2.2 Storage cost and total mass required of salt hydrates with the potential for latent heat energy storage at temperatures suitable for space heating. (from Lilleleht et al., 1975).

Salt Hydrate	Melting Point °C	Storage of 1 GJ $	kg
$CaCl_2 \cdot 6H_2O$	29	300	6050
$Na_2CO_3 \cdot 10H_2O$	32	290	4300
$Na_2HPO_4 \cdot 12H_2O$	36	610	4000
$Na_2SO_4 \cdot 10H_2O$	32	150	4200
$Na_2S_2O_3 \cdot 5H_2O$	120	1170	4850

The other main class of compounds being considered for latent heat storage systems is the lower molecular weight organics, primarily hydrocarbons. Most promising of these is paraffin because of its relatively low cost, safety, and high heat of fusion. The temperature range of the phase change for paraffins make them also well suited to space heating, however, the cost of these organic materials is generally more than for most salt hydrates. Figures 2.3 and 2.4 graphically show the more promising potential phase change materials and their temperature of phase change for the temperature ranges of 10° to 50°C and 50° to 90°C, respectively.

Several methods for containing these phase change materials have been devised. The simplest way is to put the material in a tank containing heat exchange coils. However, the heat transfer rate of salt hydrates and paraffins to the coils is relatively poor. The formation of a solid at the heat transfer boundary layer also tends to reduce the heat transfer rate. Another negative factor of latent heat systems is the question as to whether they will be able to maintain their effectiveness over a large number of cycles. If a particular latent heat storage system is found to show a decline in effectiveness after a period of time, then it has been suggested that this will be the primary drawback to such a system being cost effective.

Microencapsulation of the material in a non-permeable membrane will help improve the heat transfer rate of the material at the interface because of the higher surface area to volume ratio. Other packing schemes include putting the material in long thin plastic

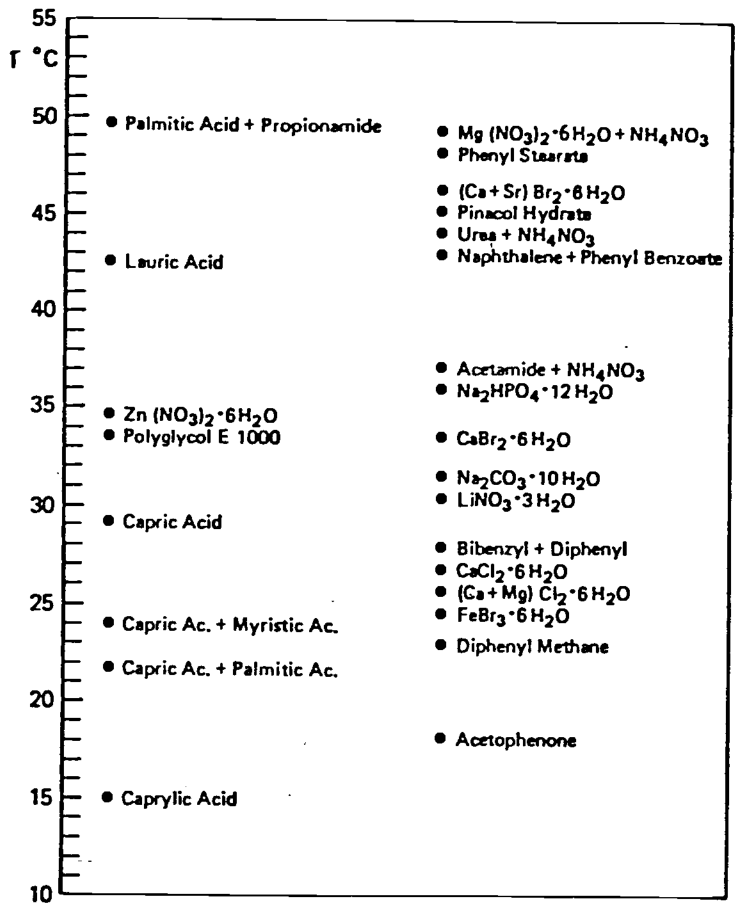

Figure 2.3 Promising phase change materials for energy storage between 10° and 50°C. Left column is for materials considered of "good" potential and right column is list of "satisfactory" materials. Temperature values are the phase change temperatures. (from Lilleleht et al., 1975)

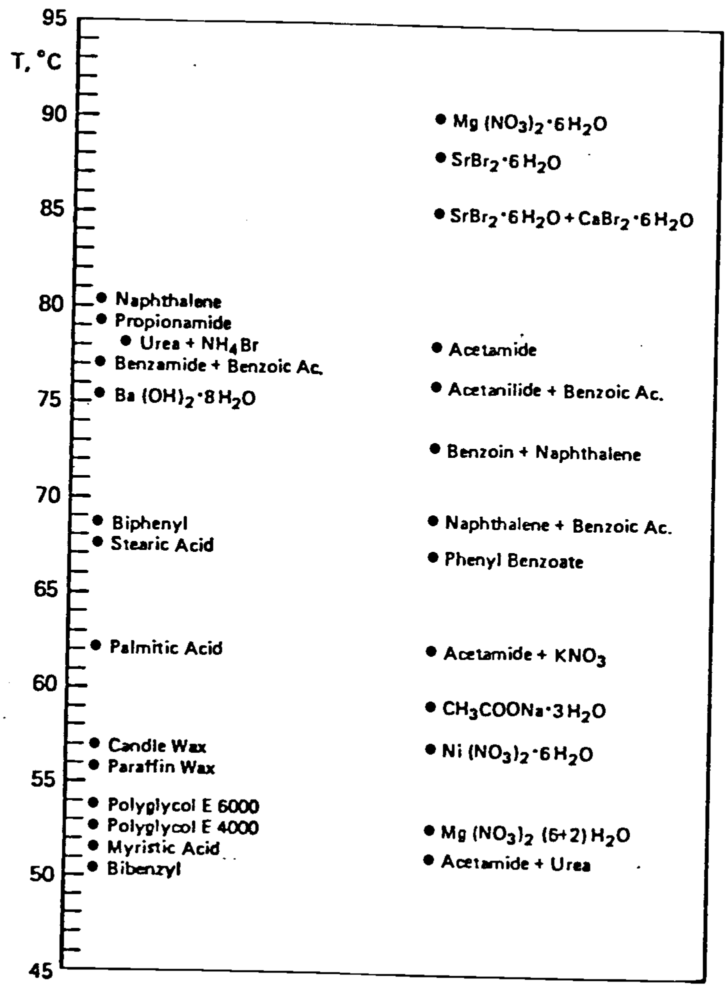

Figure 2.4 Promising phase change materials for energy storage between 50° and 90°C. Left column is for materials considered of "good" potential and right column is list of "satisfactory" materials. Temperature values are the phase change temperatures. (from Lilleleht et al., 1975)

tubes. One rather unique method that has been patented for use in electric power generation facilities to increase the heat transfer rate in high temperature salt storage systems (in this particular case around 680°C) is to drop liquid lead globules at approximately 370°C into the storage medium, with the heated lead then being collected at the bottom. Laboratory tests of a similar process found that the solid salt layers that form at the globule interface upon heat exchange are shed by dynamic distortions of the globule as it falls through the molten salt. Turnaround efficiencies of this type of system in full operation are estimated at over 90% (Golibersuch et al., 1975).

The storage of thermal energy is not necessarily restricted to heating purposes. "Coolness" can similarly be stored for use in space or other cooling operations. One obvious process is the freezing of water, where the water could be frozen by the use of heat pumps or alternatively by natural freezing in colder climates. If the winter heating and summer cooling loads are approximately the same, then an annual cycle energy storage system could be installed that would take advantage of the large latent heat of fusion of water. During the heating season, thermal energy would be extracted from a water storage tank via a heat pump forming ice. In the summer months, the cycle would be essentially reversed and the building cooled by rejecting thermal energy to the storage tank.

With the current advent of lower off-peak electric rates, diurnal ice storage for air conditioning applications are possible. During the nighttime ice is produced for use in cooling during the peak cooling load periods of the day that are associated with higher electricity costs. Annual electricity cost reductions of 41% have been estimated for such a system studied by Stubblefield (1979) designed for use in an office building and warehouse. Another possible benefit of this type of system is that the air conditioning equipment is operated during the cooler part of the day when the equipment operates more efficiently due to cooler temperatures.

2.3 Reversible Chemical Reaction Storage Systems

Any chemical reaction is accompanied by the absorption or release of thermal energy, called the heat of reaction. As a chemical reaction proceeds toward equilibrium, the heat of reaction involved can be utilized for heating if the energy is released (an exothermic reaction), or for cooling if energy is absorbed (an endothermic reaction). The operation of such a process is essentially the same as for a latent heat system, however, once at equilibrium the reaction must somehow be reversed. To do so, it is necessary to change at least one of the determining conditions of the process, either the reactant concentrations, temperature, or pressure. If a temperature change is also involved, then this part of the process behaves as a sensible heat system.

The primary advantages of reversible chemical reaction storage systems are their ability to store thermal energy for a long period of time, and their potential for much higher energy storage densities as compared to the sensible or latent heat systems. One example of a reversible chemical reaction that is currently under study for the storage, and possibly for transport, of energy is the reaction: $CH_4 + H_2O \leftrightarrow CO + 3H_2$. Heat is absorbed when this reaction goes from methane and water to carbon monoxide and hydrogen. If the products (CO and H_2) are then cooled to room temperature, the reverse reaction back to methane and water will not take place without a catalyst, even though it is thermodynamically favored. Because of this, the thermal energy has the potential of being stored for an indefinite period of time. Other reversible chemical reactions with a potential in energy storage use are listed in Table 2.3.

Table 2.3 Potential reversible chemical reactions for thermal energy storage. (data from Golibersuch, 1975).

Reversible Reaction	Temp. Range (K)	Approximate Heat of Reaction @ 298 K (Kcal)
$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	700 - 1200	59.8 *
$2CO + 2H_2 \leftrightarrow CH_4 + CO_2$	700 - 1200	59.1
$C_6H_6 + 3H_2 \leftrightarrow C_6H_{12}$	500 - 750	49.5
$C_7H_8 + 3H_2 \leftrightarrow C_7H_{14}$	450 - 700	51.0
$C_{10}H_8 + 5H_2 \leftrightarrow C_{10}H_{18}$	450 - 700	75.0
$C_2H_4 + HCl \leftrightarrow C_2H_5Cl$	420 - 770	13.4
$CO + Cl_2 \leftrightarrow COCl_2$	550 - 1000	26.9

* Includes heat of formation of water

For low temperature applications, the primary usefulness of reversible chemical reactions is in a chemical heat pump. A chemical heat pump basically consists of two storage vessels containing a liquid or a solid. A lower, approximately ambient, temperature reaction in one of the vessels produces a gas which is allowed to move into the other vessel where it reacts exothermically, thereby releasing heat. Heat is added to the storage system in the reverse process. An ammoniated salt chemical heat pump system proposed for solar energy heating applications is illustrated in Figure 2.5.

2.4 Thermal Energy Storage for Geothermal District Heating

Most of the methods of storing thermal energy discussed in this chapter are adaptable for use in a geothermal based district heating system. The simplest of these is by the incorporation of a liquid storage tank. If the hot geothermal fluid contains a relatively low concentration of dissolved minerals, then the geothermal fluid itself can be stored for peaking purposes. From this discussion it is concluded that the use of a storage tank appears to be the simplest and cheapest available alternative for storing thermal energy for a geothermal district heating system. Therefore, this project will always assume that any thermal energy storage is to be accomplished by the use of a storage tank.

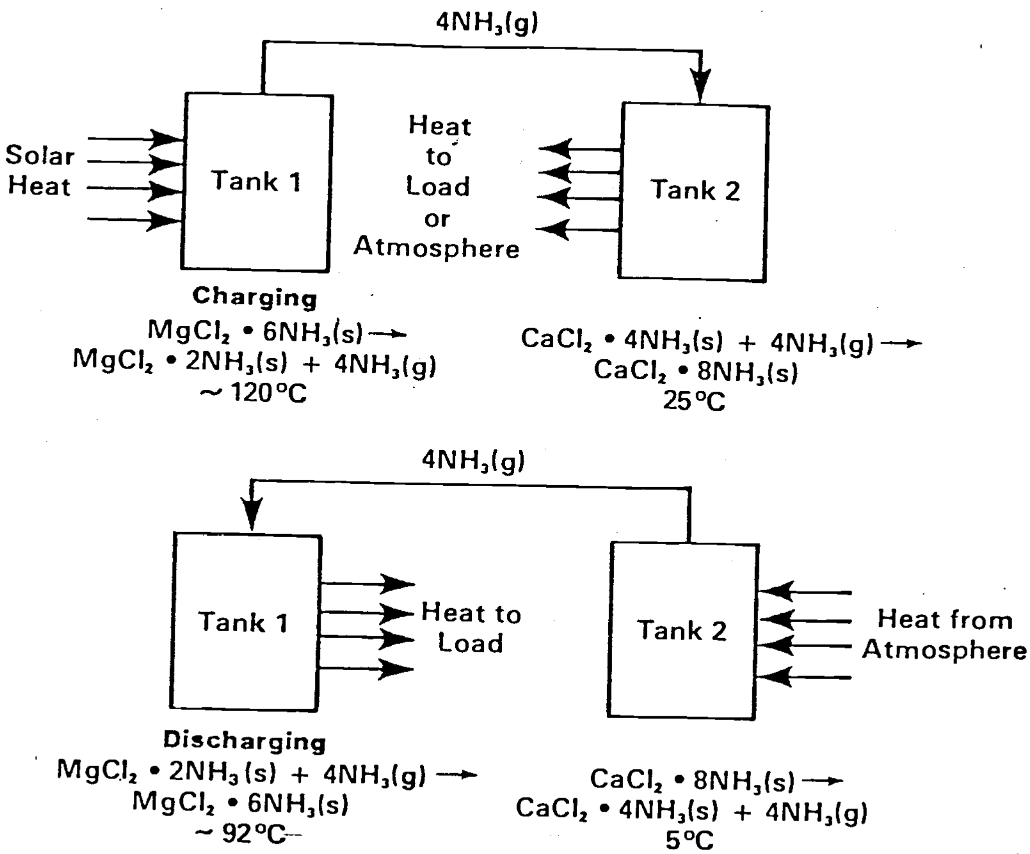

Figure 2.5 Chemical heat pump thermal energy storage system proposed for solar heating applications. (from Baylin, 1979)

III. ECONOMIC FACTORS INFLUENCING THE COST OF DISTRICT HEATING

Since the operation of a geothermal based district heating system involves a number of interrelated variables, the estimation of the economics of such a system is rather complex. However, a large percentage of the overall cost is dependent upon just a few factors, which will be discussed in detail in this chapter. These are the fluid transmission and distribution system, resource development, the local climate, and the method of providing supplemental energy during peak loads. Economic conditions also play an important role in determining the performance of a district heating system, however, many of these variables are out of the control of the engineering design team and are therefore not included in this discussion.

3.1 Transmission and Distribution System and Resource Development

While both the transmission and distribution system serve the same purpose, that is the transport of thermal energy via a hot fluid, there is a subtle distinction between the two. The transmission system is generally thought of as involving the transport of the thermal energy from the resource well(s) to the head of the distribution system. The distribution network is what actually delivers the thermal energy to the individual users. One reason that the two are sometimes considered separately is that the resource and distribution system may be operated by different companies. For example, the geothermal resource may have been developed by one company which also constructs a transmission line to the locality where it is delivered through a distribution system owned and operated by the municipal government.

The capital expenses of a geothermal based district heating system are primarily due to two components, the resource development and the transmission and distribution system. Resource development essentially refers to the drilling of the resource production and disposal wells. The incorporation of thermal energy storage will only affect the cost of the resource development and has little or no effect on the distribution and transmission costs. Storage can reduce the capital cost of the resource development by possibly allowing for fewer wells to be drilled or by reducing the well pump size requirements. Capital costs for hot fluid transport from the resource location to the user will vary more or less directly with the required transport distance. If the resource temperature is fairly high, then the amount of heat carried per unit volume of fluid will be greater, and hence the thermal energy could be transported economically over longer distances (Figure 3.1). A general rule of thumb for the maximum economical transport distance of geothermal energy for space or industrial process heating is approximately 50 miles (Bloomster et al., 1980). This 50 mile or so limit was taken into consideration in the selection of the cities used for all analyses in this project.

The size of pipe chosen will also have an influence on the cost of fluid transport. Pipe material cost per unit length essentially increases linearly with the pipe diameter, however, the fluid

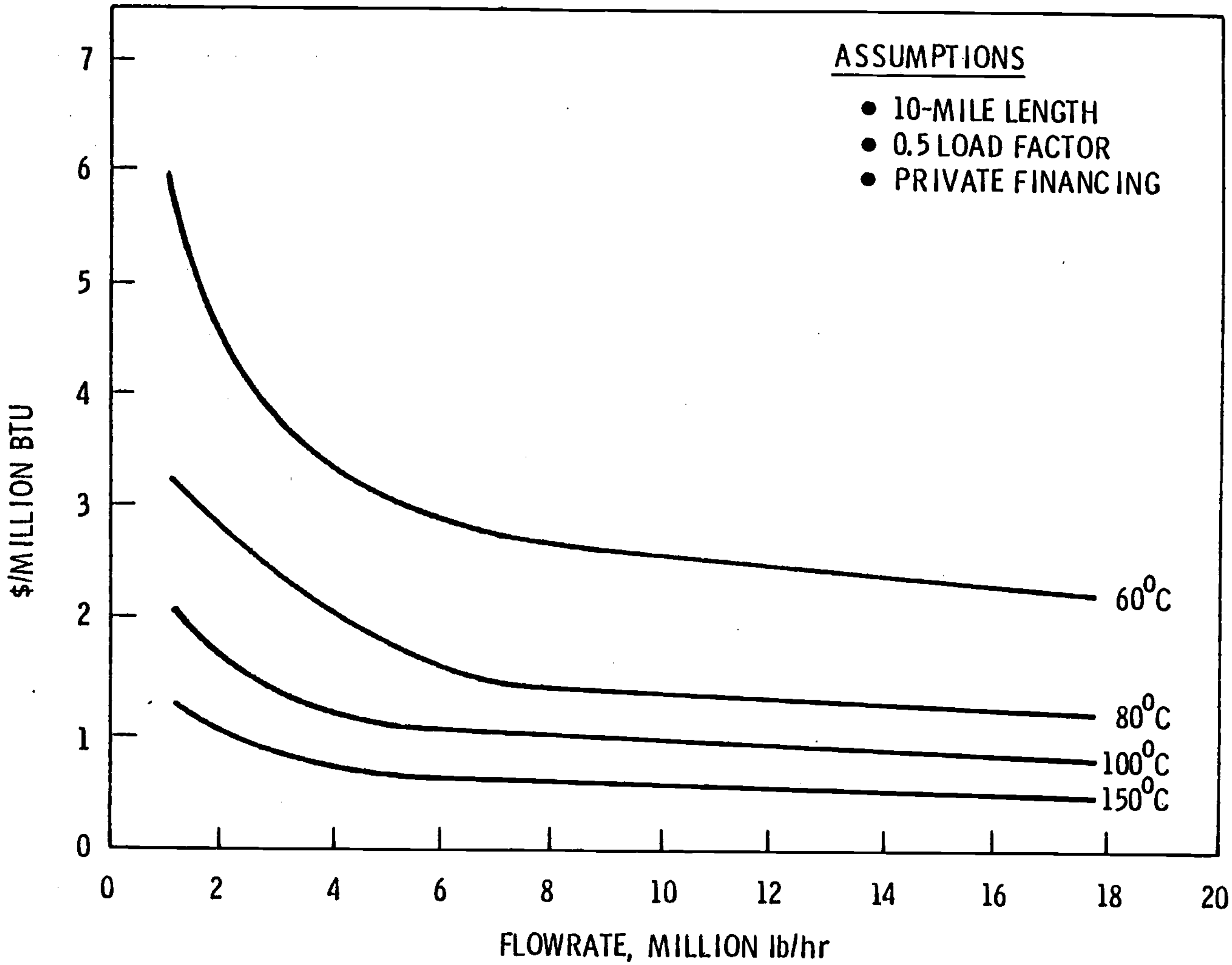

Figure 3.1 Transmission cost of thermal energy for various resource temperatures. Costs are included for comparative purposes only. Actual costs will vary according to system design. (from Bloomster et al., 1980)

transport (and hence the energy transport) capability increases with the square of the pipe diameter. The system designer may thus be tempted to oversize the pipes, allowing for the possibility of system expansion for a minimal increase in cost. Unfortunately, experience with actual systems has shown that the overall cost per unit length of a distribution system is not really a pure linear function of the pipe diameter, but rather tends to increase more rapidly for the larger (greater than 6") pipe sizes. This is illustrated in Figure 3.2 which shows costing data observed for a two pipe distribution system by Trans Energy Systems, Inc. (Christensen, 1981). Because of this, the pipe sizes should be found by an optimization procedure which balances out the initial capital cost with the operational expenses, primarily the pumping power requirements, to supply the desired amount of thermal energy.

Another extremely important variable in determining the cost of delivered energy is the system load factor, which essentially can be thought of as the equivalent fraction of designed capacity that the system is actually utilized. Since the primary expense of transporting a hot fluid is the fixed capital cost, a system with a higher load factor will be able to deliver a unit of energy for a lower cost than a similar system with a low load factor. In fact, costs can be expected to increase exponentially as the system load factor is decreased, as shown in Figure 3.3. The load factor will generally be higher for industrial process heating rather than for residential and commercial heating applications, since an industrial process usually requires a steady thermal energy demand spread over

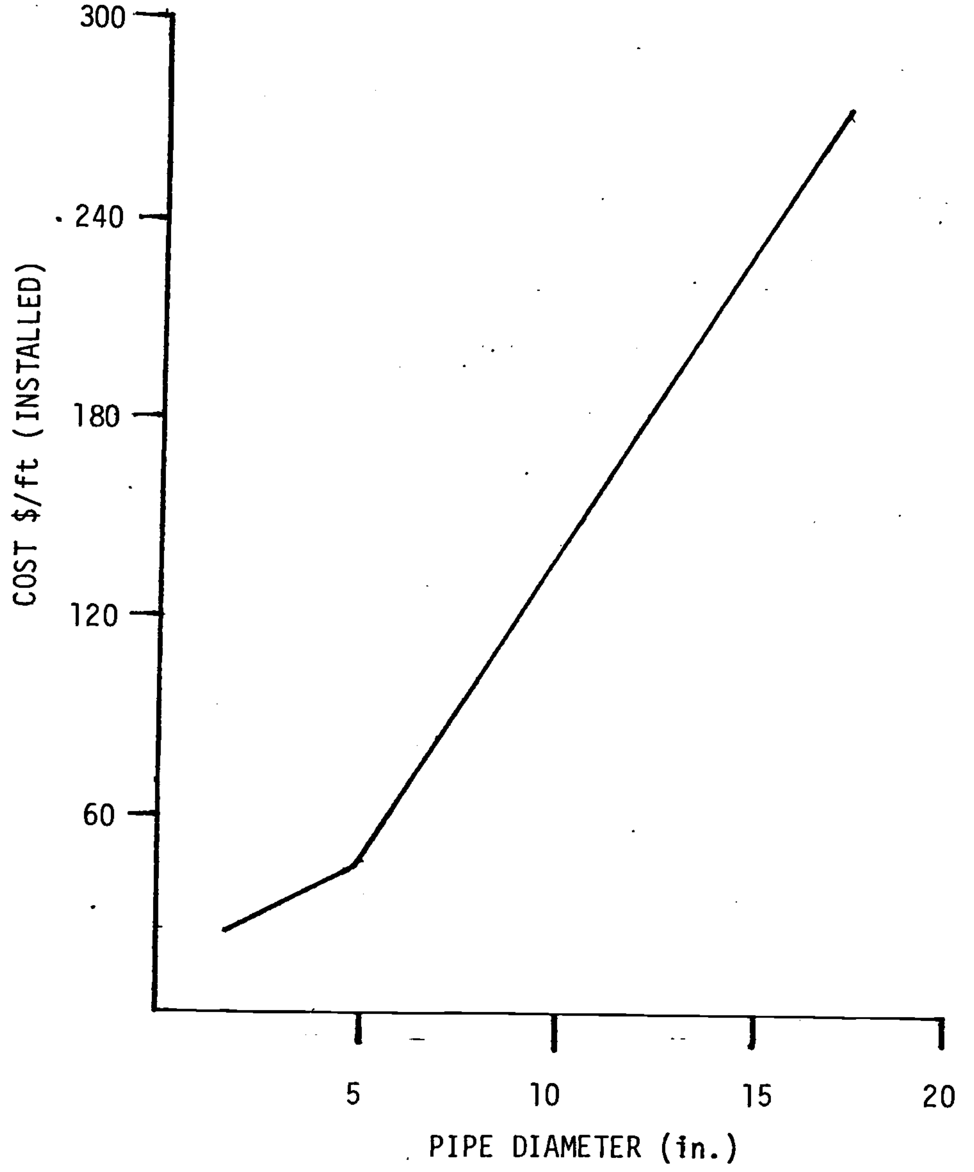

Figure 3.2 Installed cost per linear foot of trench for a two-pipe distribution system. Costs are included for comparative purposes only. Actual costs will vary according to system design. (data from Christensen, 1981)

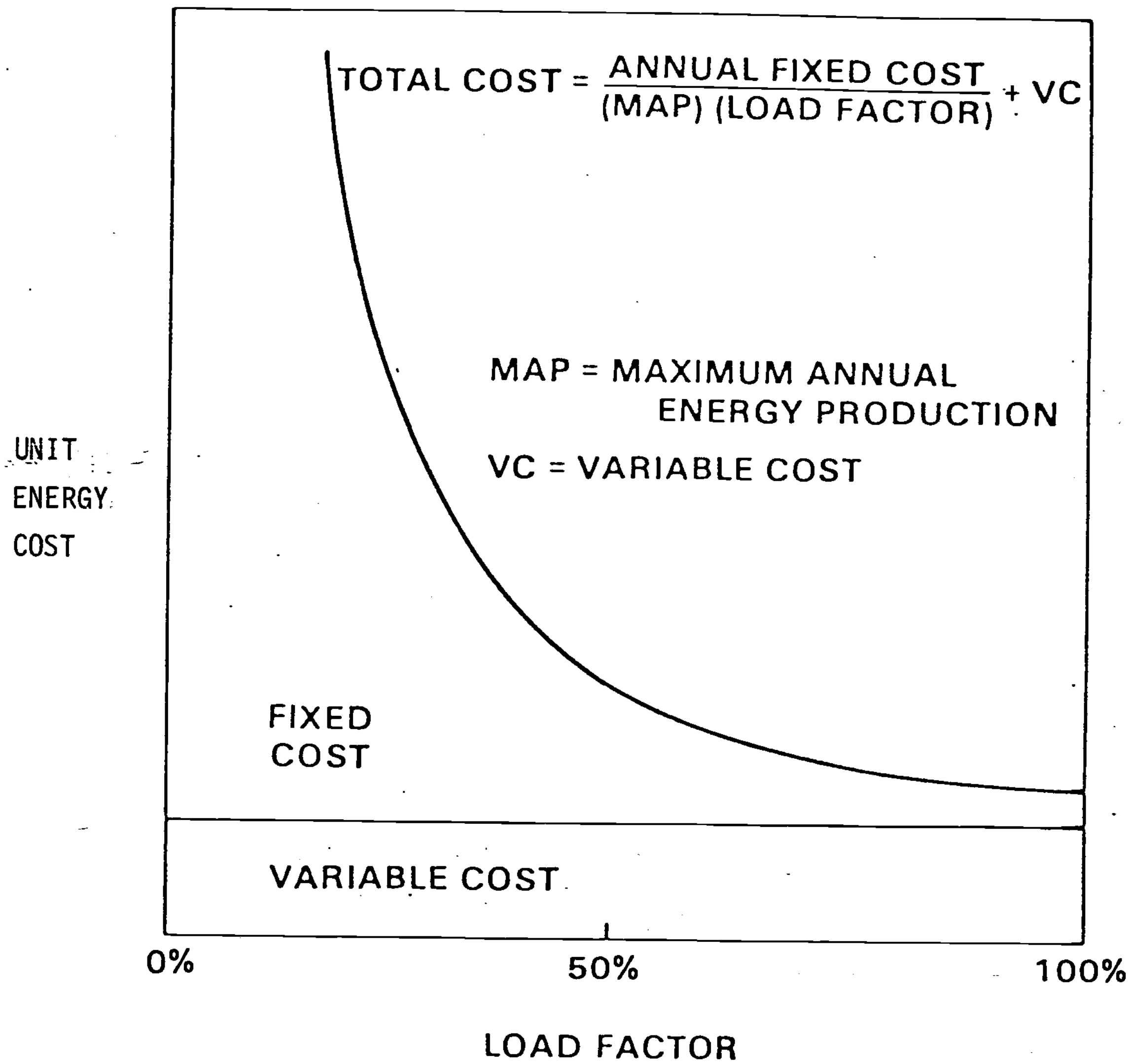

Figure 3.3 Expected variation of the unit energy cost as a function of the system load factor. (from Fassbender and Bloomster, 1979)

a good portion of the day. The particular climate type of the locality will also influence the system load factor, as discussed in section 3.3 below.

The relationship between the load size and the type of service area will also be an important factor in the determination of the cost of energy. A small load spread out over a large area, such as with a rural setting will require a larger capital expense per unit of energy, primarily as a result of distribution systems costs, than for an urban setting with the same load concentrated into a smaller area. If a system is being installed in an area currently being developed under new construction, then the cost of the system is expected to be less than if the system were being installed in an already established section of the community.

3.2 Climate

There are two basic climatic factors that influence the economics of district heating, those being the minimum or design temperature and the annual heating degree days. The design temperature determines the peak demand of the system and thus the pipe size requirements. For a system in a location with a low design temperature, higher initial capital costs will generally be necessary due to the larger pipe and pump sizes required. A colder maritime climate with energy use relatively constant throughout the year will generally lead to a higher system load factor. For example, a district heating system in Iceland is reported to have a load factor of approximately 50% (Fassbender and Bloomster, 1979), while in contrast a system in a more temperate climate can be expected to have a load factor of around 30%. The effect of increasing heating degree days on the costs of district heating is graphically illustrated in Figure 3.4. Although the design temperature and the number of heating degree days at a particular location are not entirely independent of each other, the actual relationship between the two and their combined effect upon the cost of supplying thermal energy is very difficult to accurately predict.

3.3 Storage

The primary applicability of thermal energy storage in the reduction of district heating system costs is to increase the load factor of the geothermal resource wells. Since the thermal energy is stored for use during peak demand times, more users can be served by the system than otherwise possible without storage. Hence, the system load factor will be increased, with the actual increase dependent upon the number of additional users allowed by the incorporation of storage and their total heating demand.

It is common procedure for district heating systems to be designed such that the peak energy demand is greater than the primary energy source can handle. This practice will lead to higher system load factors, but requires that some method of providing additional energy during periods of peak demand be found. The energy could be provided for a geothermal based district heating system either by storing some of the hot fluid or by the installation

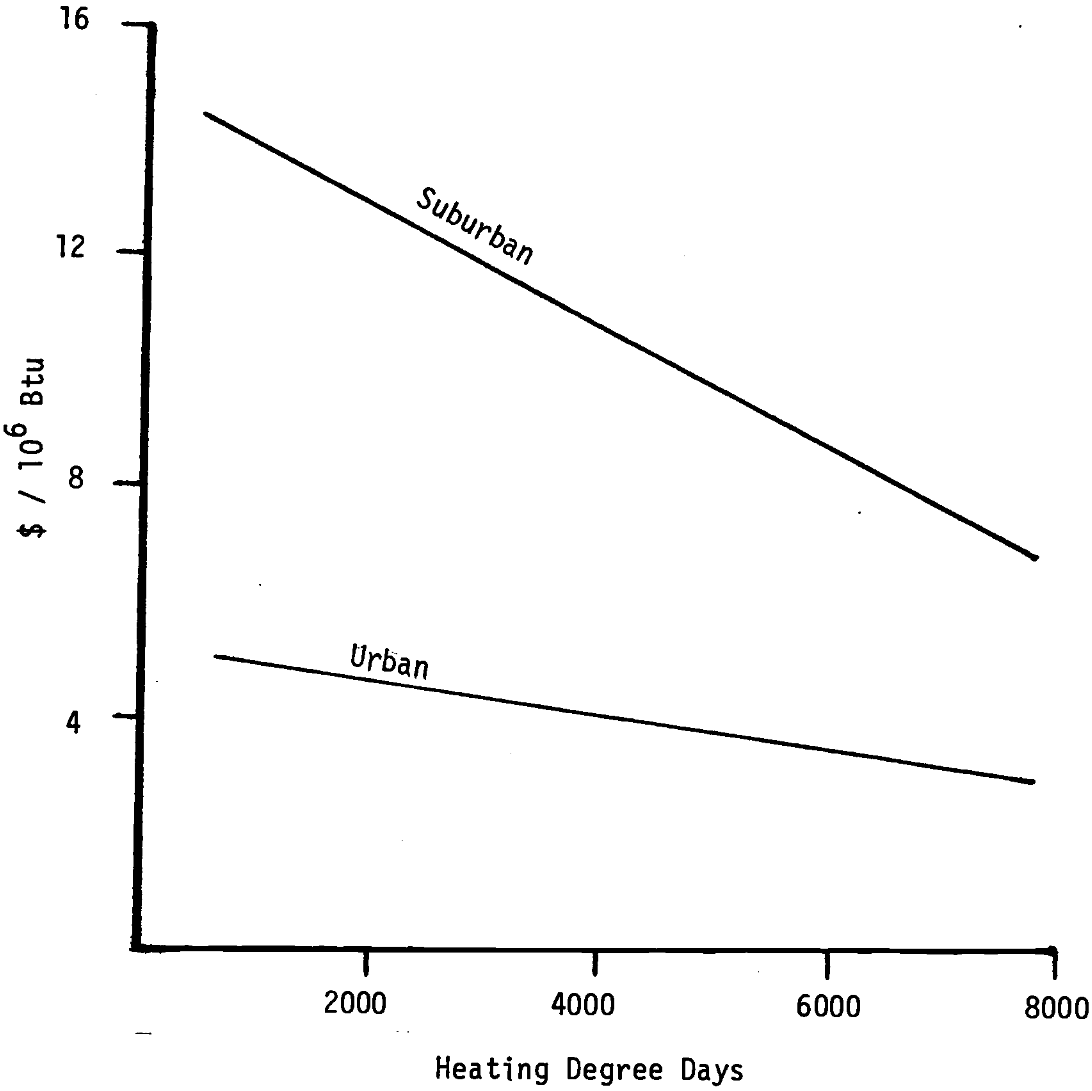

Figure 3.4 Effect of the number of yearly heating degree days on the costs of district heating for a suburban and an urban system. Suburban population density is 4000/km^2 and the urban population density is 36000/km^2. Cost are included for comparative purposes only and will vary according to the actual system design. (data from Bloomster et al., 1980)

of a peaking boiler, with perhaps both methods being incorporated to add redundancy. It is also possible that a combination of both peaking system types will be the cheapest alternative of providing the peak thermal energy demand.

The next two chapters deal with the development and application of models which are used to evaluate the effect of thermal energy storage on the cost of providing supplemental peak load energy to a geothermal based district heating system. Also included are procedures to estimate the maximum storage capacity requirements, and the storage capacity which gives the lowest overall peaking system cost with respect to the system design heating load and local climate.

IV. DEVELOPMENT OF STORAGE SIZING MODELS

This chapter describes the development of the analysis methods and computer programs used to estimate the required amount of thermal energy storage for a geothermal based district heating system. The worst case storage is found first based only on single climate events.[1] Next, a procedure is developed by which the storage required is found by taking into account all of the recorded climatic events and their sequential spacing. Finally, economic factors are considered which allow an estimate of the storage capacity that provides the required peak heating load, possibly in combination with a peaking boiler, at the lowest cost.

4.1 Analysis of Weather Data

4.1.1 Selection of Study Sites and Time Scale

The storage tank sizing analysis described in this chapter was done using weather data for Albuquerque, Indianapolis, Norfolk, Portland, San Francisco, and Salt Lake City. Each of these cities is located near a potential geothermal resource, as shown in Figures 4.1 and 4.2, and are representative of the two basic climatic types most suitable for district heating found in the continental United States, these being the cool maritime and temperate climate types.

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[1] A climatic event is defined as a period of time in which the ambient temperature is unusually cold. A more precise definition of an event as used in this project is given in section 4.1.2.

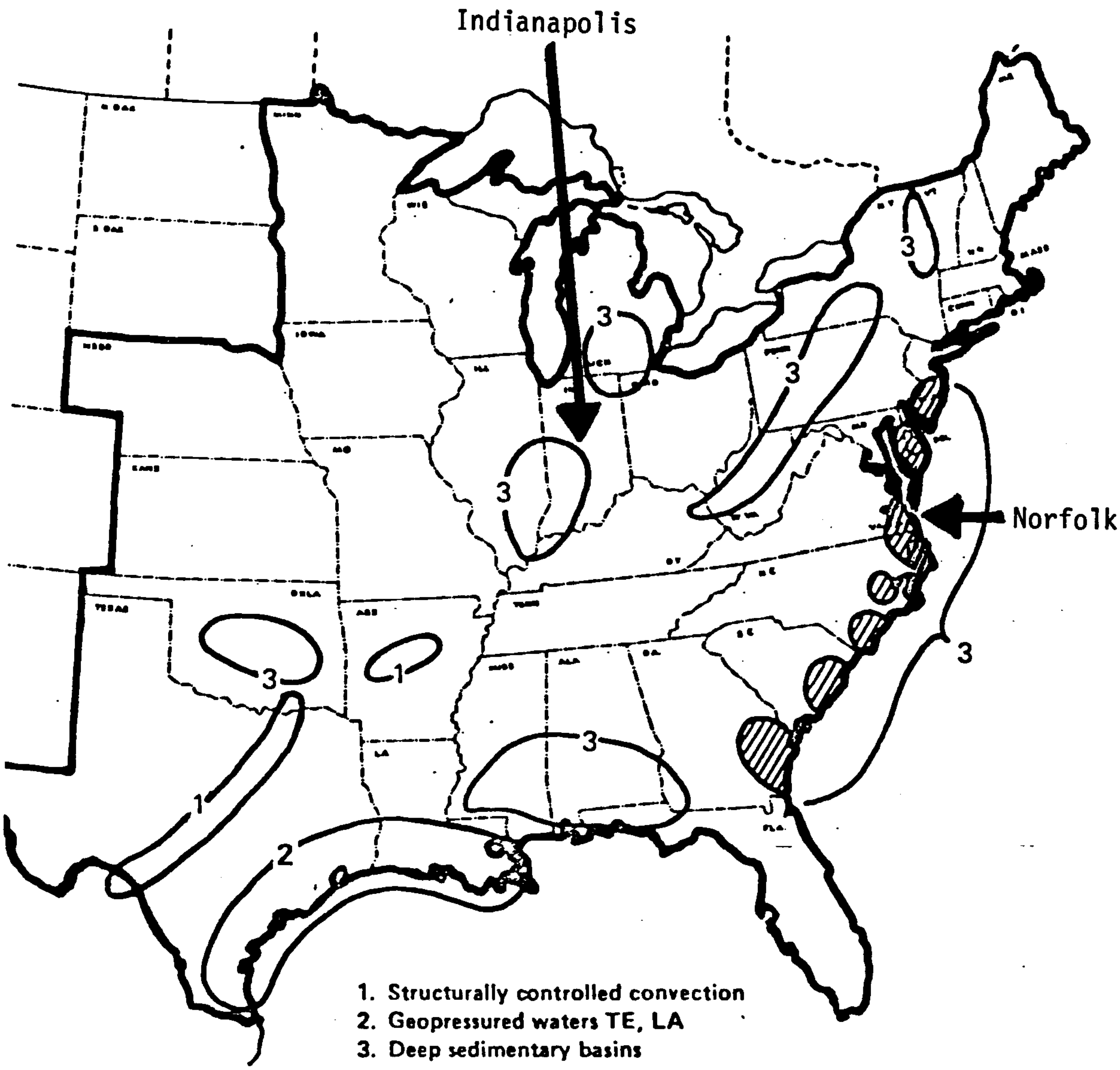

Figure 4.1 Location of cities chosen for analysis and their relation to potential geothermal resources, Eastern United States. (from Paddison et al., 1978)

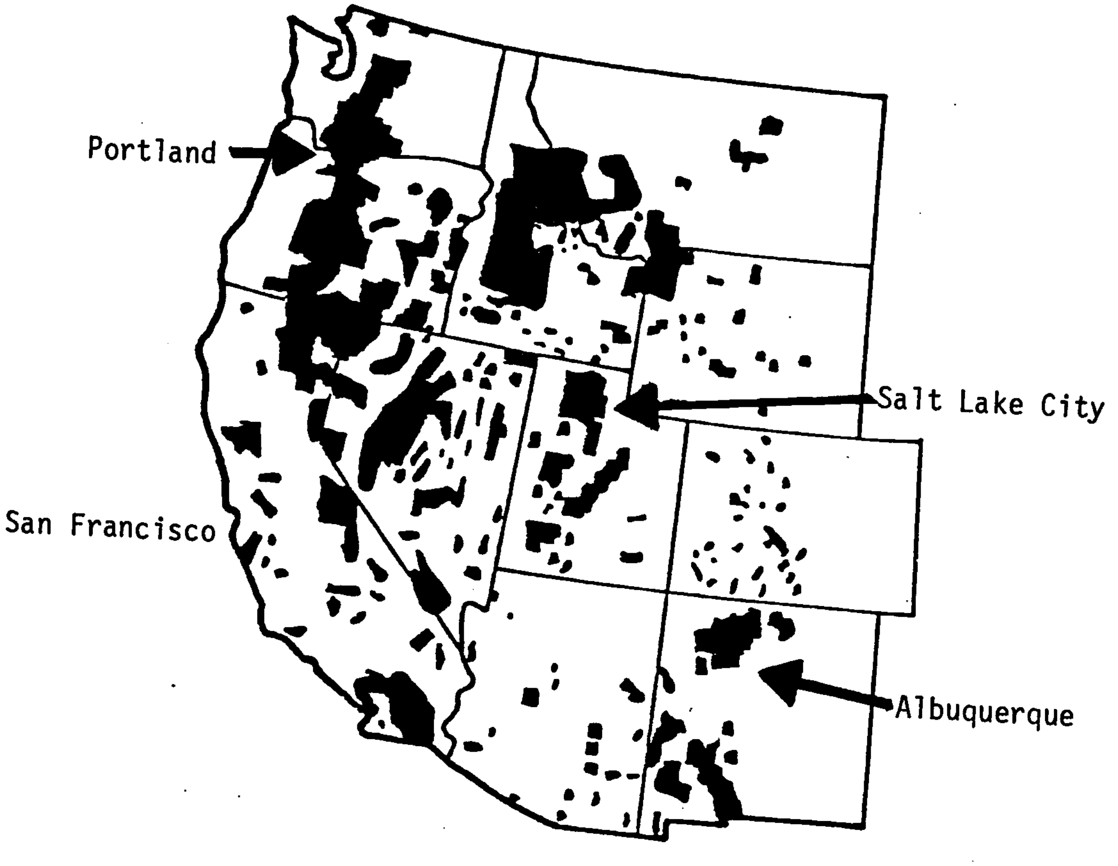

Figure 4.2 Location of cities chosen for analysis and their relation to potential geothermal resources, Western United States. (from Bloomster et al., 1980)

When performing a heating load analysis, a choice must be made regarding the time scale to be used. There are three basic time scales that could be utilized, each of which can produce reasonable results and has its own particular advantages and disadvantages. The easiest time scale from the calculational point of view is that of using a monthly summary value, such as a monthly average temperature. This will give a relatively good approximation to the climatic conditions at the particular location, but is unable to give any specific weather information outside that which is already included in the monthly averages. If a daily time scale were chosen, then data on individual climatic events could be utilized, however, the number of calculations involved is increased by a factor of approximately 30, and hence the time and cost need for the analysis will be greater. The most accurate method would be to use hourly weather data, although the number of calculations required would again be increased by a factor similar to that when going to a daily time scale from a monthly scale.

4.1.2 Procedure Used in This Project

The additional thermal energy required from storage by a district heating system during any particular weather event is a property of the event's severity, which can be expressed as a function of the temperatures involved and its duration. An event with cold temperatures and a long duration will necessitate a greater amount of stored thermal energy than a relatively milder event with less severe temperatures and/or shorter duration. Also of importance in evaluating the storage capacity for a geothermal based district heating is the spacing between events. It is during this time that the storage tank can be recharged with excess thermal energy from the resource wells that is not required for use at the present time.

For this project it was decided to work with a daily time scale. This is a compromise which allows the sensitivity needed to study the impact of individual climatic events while avoiding the prohibitively high cost of obtaining and incorporating hourly weather data into the analysis. In setting up the analytical basis for the storage sizing procedure, it was found necessary to assume a daily temperature profile based upon the daily minimum and maximum temperatures. A reasonable approximation, and the method chosen for use here, would be to assume a sinusoidal temperature profile like that shown in Figure 4.3. The average daily temperature, which is assumed to occur around midnight and noon, is then found as

$$T_{avg} = T_{min} + 1/2(\text{daily range}) \qquad (4.1)$$

It is realized that sometimes a sinusoidal daily temperature profile is far from what is actually observed, but it is believed that the use of a large number of days in the analysis will tend to average out any of these variations.

Because a daily time scale is being used and the daily temperature variation is assumed to be sinusoidal, the four variables required to describe a particular event are the minimum daily

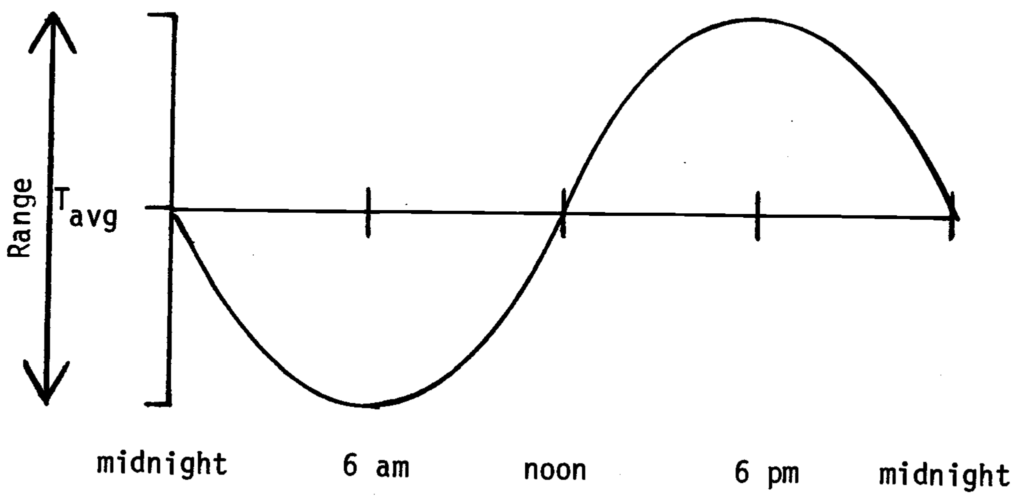

Figure 4.3 Diurnal sinusoidal temperature variation.

temperature, daily temperature range, event duration in days, and the number of days separating the events. These data are easily obtainable from U.S. Weather Bureau publications (U.S. Department of Commerce, 1960-79), from which data was gathered for the cities chosen for the years 1960 to 1979. In order to streamline the process, the minimum temperature and the temperature range were not recorded for every day of an event, rather the average values were calculated for an event and these summary values used in the analysis. It is believed that this simplication will not effect the results to any significant degree.

One question that had to be answered was the determination of what conditions actually constitute a weather event. It was decided that a specific event would be defined as a series of days in which the average daily temperature is less than or equal to the local 97.5% ASHRAE design temperature + 10°F. The design temperatures used are those listed in the 1977 Fundamentals volume (American Society of Heating, Refrigerating and Air Conditioning Engineers, 1977). The time period that incorporates the heating season also had to be defined. Initially the period from October 1 to April 30 was tried, however, after examining the weather data, it became apparent that the period from November 1 to March 31 would be sufficient without missing any events.

4.2 Worst Case Sizing

In this section, the maximum amount of thermal energy storage requirements will be found for a particular location to satisfy the heating demand given a maximum heating load at the design temperature (MAXLOAD) and the well production rate (WELL). The entire heating demand is also assumed to be supplied by the geothermal resource, meaning that no peaking boilers are to be used. The most severe events from the event data file gathered for each of the cities chosen were run in this step of the analysis. Since an event's severity is a function of both the average temperature and duration, the one event requiring the most thermal energy storage will not be easily found by inspection. Therefore, the analysis was performed on all of the events that appeared to be more severe in nature.

For all of the analysis procedures done in this project, the heating load was nondimensionalized by defining the load ratio parameter, which will be abbreviated LDRATIO. The load ratio is given by

$$LDRATIO = \frac{MAXLOAD}{WELL} \qquad (4.2)$$

where: MAXLOAD is the system heating load at the design temperature. (MW)
WELL is the well energy production rate that can be reasonably expected to be withdrawn on a continuous basis. (MW)

Additional nomenclature that is used in this section includes:

DURA - duration of the event in days

LOAD - daily system heating load during an event, in MJ/day

LOADBTW - daily system heating load in the period between events, in MJ/day

QSTORE - the additional thermal energy that must be supplied to the system above that provided by the geothermal resource

QRECHG - the excess thermal energy from the resource that is not required by the system during the time between events and therefore can be added to storage

TAVG - the event average daily temperature

TDESGN - the outdoor design temperature

For a complete listing of all nomenclature used, please refer to Appendix A.

4.2.1 Linear Heating Demand Curve

The maximum amount of thermal energy storage required will be found in this section when assuming that the system heating load is a linear function of the ambient temperature. The heating load will vary from 0 at an ambient temperature of 10°C to MAXLOAD at TDESGN (Figure 4.4). For each of the events analyzed, the storage capacity was found for LDRATIO values varying between 0.6 and 2.0, in steps of 0.05.

Using the relationship shown in Figure 4.4, the daily heating demand during an event is given by

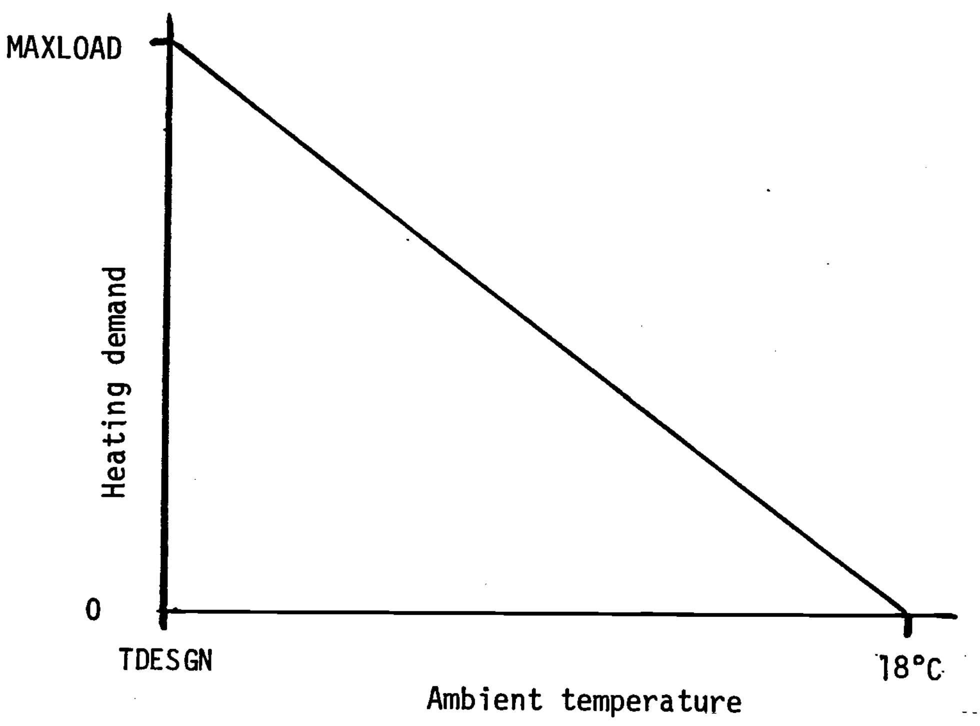

Figure 4.4 Linear relationship of heating demand and ambient temperature.

$$\text{LOAD} = 86400 \frac{\text{sec}}{\text{day}} * \frac{18. - \text{TAVG}}{18. - \text{TDESGN}} * \text{MAXLOAD} \qquad (4.3)$$

where the LOAD is in MJ/day.

The thermal energy extracted from the geothermal resource can be found in general from the expression

$$\text{WELL} = \begin{bmatrix}\text{Mass flow rate} \\ \text{from the well(s)}\end{bmatrix} * \begin{bmatrix}\text{Specific heat of} \\ \text{geothermal fluid}\end{bmatrix} * \begin{bmatrix}\text{Temeprature drop} \\ \text{across wellhead} \\ \text{heat exchanger}\end{bmatrix} \qquad (4.4)$$

A reasonable assumption of the temperature drop of the geothermal fluid through the wellhead heat exchanger is 40°C. The same ΔT was assumed to be available when removing energy from the storage tank. If the specific heat of the geothermal fluid is assumed to be close enough to that of pure water (4.184 kJ/kg °C), then equation 4.4 becomes

$$\text{WELL} = \begin{bmatrix}\text{Mass flow rate} \\ \text{from the well(s)}\end{bmatrix} * 167.36 \text{ kJ/kg} \qquad (4.5)$$

For this particular portion of the analysis a geothermal fluid production rate of 200 kg/s was assumed. This is equivalent to the combined production of roughly seven average wells. Therefore the value of WELL in the worst case analysis will be assumed to be a constant value of 200 kg/s * 167.36 kJ/kg = 33.5 MW.

The total thermal energy required from storage during the course of an event can now be found using the formula

QSTORE = DURA * (LOAD - WELL) (4.6)

However, some energy will be lost from storage as a result of losses to the environment and, if any heat exchangers are required, inefficiencies in the energy exchange process. A rough estimate of the thermal energy lost during the storage process is approximately five percent of the total amount stored (Office of Technology Assessment, 1978). The amount of storage calculated in equation 4.6 will therefore be multiplied by a factor of 1.05 to compensate for this heat loss.

In addition, it is assumed that the storage tank is required to be filled completely in time for the next event. The period between the events is assumed to have a temperature equal to that of an average January day for that locality. This temperature is then used to find the daily heating load for the time between events (LOADBTW) in the same manner as the load was found during an event. The thermal energy that can be added to storage during this time is then given by

QRECHG = SEPAR * (WELL - LOADBTW) (4.7)

If QRECHG is greater than QSTORE, then the tank will be completely filled before the next event. However, if QRECHG is less than QSTORE, then the storage becomes recharge limited. This means that any tank with a capacity greater than QRECHG would not be fully recharged in time for the next event, and thus is essentially excess capacity. Therefore, for this particular event and load size, the storage size required (QSTORE) in this case is set equal to QRECHG. It is also recognized that the heating demand for residential and commercial buildings tends to be a function of the time of day, due to daily activity patterns and work schedules. For example, a peak in energy use over that predicted strictly by the ambient temperature is generally observed in the morning hours as the occupants awake. However, Verbruggen (1980) observed that it is quite reasonable to treat the average daily heating load as a function of climatic conditions only.

4.2.2 Non-Linear Heating Demand Curve

It is generally believed that the linear demand curve assumption does not hold up well in colder temperatures, such that the actual demand is somewhat less than predicted (Nelson, 1974; Vergruggen, 1980). There are a number of possible reasons for this, including the fact that people tend to stay outdoors more or are sleeping when the ambient temperature is colder.

The procedure outlined above in section 4.2.1 was therefore repeated using a more realistic non-linear heating demand curve that was derived from data given by Verbruggen. Although not a great deal of research has been conducted studying the relationship between weather and the heating load in a district heating system, Verbruggen did find that a quadratic curve, as illustrated in Figure 4.5, best fit the data for two systems in Germany. In Figure 4.5, the linear relationship curve is like that discussed in

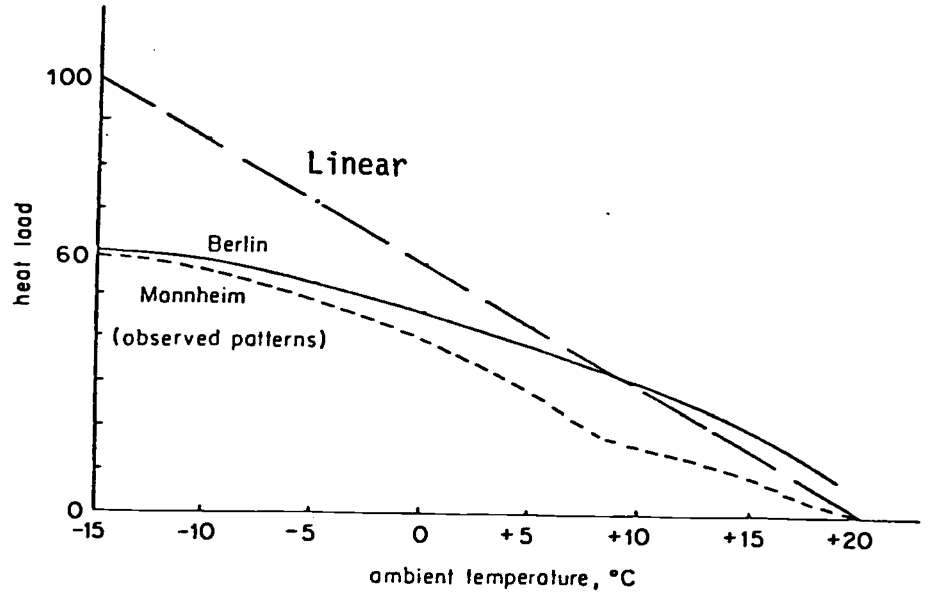

Figure 4.5 Comparison between the theoretical heating demand based on a linear relationship of load and ambient temperature to actual recorded patterns. (from Verbruggen, 1980)

section 4.2.1 where the heating load varies from 0 at an ambient temperature of 20°C to the maximum load at the design temperature.[2] The other two curves in that plot show actual heating load data observed in district heating systems in Berlin and Mannheim.

The easiest method to fit this non-linear heating demand to temperature relationship into the worst case model is to find an expression for the actual observed heating demand, shown in Figure 4.5, as a percentage of the theoretical demand if a linear heating demand to temperature relationship is assumed. As the data given in Table 4.1 show, the percentage was found to be essentially a linear function of the ambient temperature. The regression equation for this data is

$$PERCENT = 86.2 + 1.77 * T_{amb} \tag{4.8}$$

where: PERCENT = the percent of theoretical demand if linear model used

T_{amb} = ambient temperature in 0°C

The correlation coefficient for this equation is: $r^2 = 0.9776$.

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[2]Note that all calculations in this project are based on a heating load of 0 at 18°C. Since calculations during an event are generally at temperatures of 0°C or less, the error introduced by the differing temperature basis will be minimal. In fact, Verbruggen mixes discussion of heating degree days based on 18°C with this same curve (Figure 4.5) that is based on 0 load at 20°C.

Table 4.1 Non-linear heating demand curve data for the relationship between ambient temperature and the actual observed heating demand as a percentage of theoretical linear heating demand.

AMBIENT TEMP (°C)	ACTUAL DEMAND (% of LINEAR)
-15	61
-10	70
-5	76
0	83
5	90
10	103
15	117

Using this new non-linear heating demand curve relationship, the analysis was repeated for the same events as before over the same LDRATIO values used previously.

Although the worst case analysis has some merit in that it can give a quick estimate of the maximum storage requirements for a particular system, it cannot take into account the sequential spacing of the climatic events. Therefore, a model was developed to simulate the operation of the storage tank over a period of time. This model is outlined in the next section.

4.3 Engineering Design Sizing

A computer program, called FORCEIT, was written which expanded upon the worst case heating load model. FORCEIT allows the user to simulate the operation of the hot fluid storage tank over an extended period of time, in particular for this project, the simulation was run for the entire 20 years of recorded event weather data. The same non-linear quadratic heating demand curve that was incorporated into the worst case model was used in this and all subsequent procedures. A listing of this program along with the ECON program used later in this project appears in Appendix B.

Several stipulations and modifications to the worst case model were made in the development of FORCEIT. For one, the storage tank was assumed to be completely full at the beginning of the heating season on November 1. From then on until March 31, the amount of thermal energy in storage was tracked on a daily basis, with the total number of days that there was no thermal energy in the storage tank being recorded. Secondly, the heating demand during the time between events is now taken as the local mean daily temperature for the current month in the simulation. This gives a more accurate indication of the demand between events than always assuming, as was done in the worst case analysis, that the mean daily temperature is that what would be expected for the month of January.

The major modification made for FORCEIT was in the calculation of the heat loss from the storage tank. The storage tank for this model is assumed to be a cylinder with the height equal to the diameter. The structural cross section of the tank is taken to be of the simplified form shown in Figure 4.6. Since the sensitivity of the thermal energy storage requirements and the cost of peaking energy to the district heating system as a function of the amount of heat loss from the storage tank is very low (see section 5.3), any changes in the actual design of the storage tank will not have a

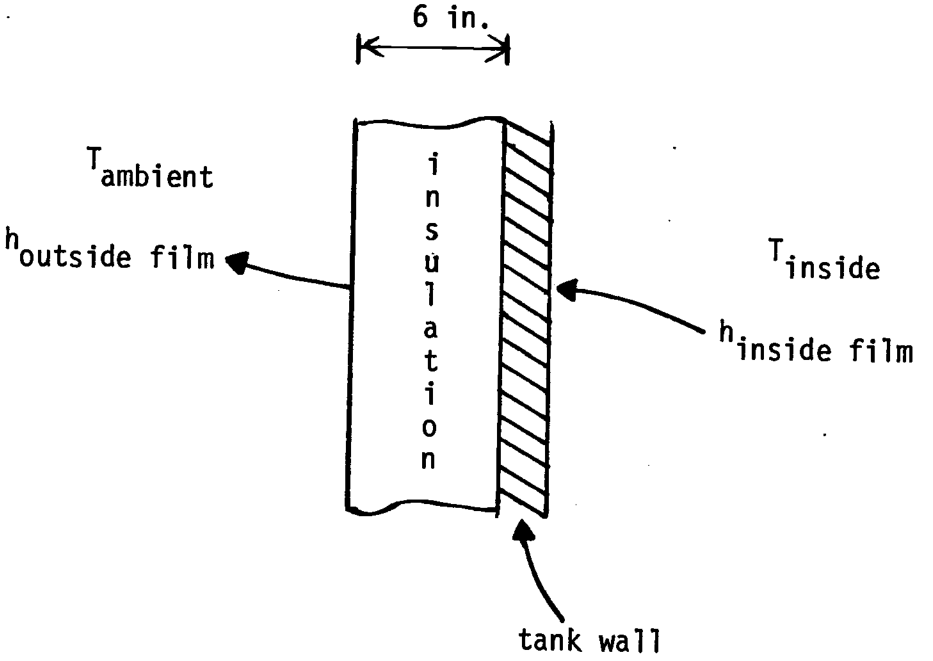

Figure 4.6 Storage tank cross section.

very significant effect.

The heat conductance terms from the tank are calculated as follows.

Base

Heat loss through the base was calculated based on perimeter length as recommended in the 1977 Fundamentals volume of ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers, 1977, Chapter 24). Assuming that the tank is built on a concrete slab with one inch of insulation extending approximately two feet below the surface, then the heat loss can be calculated using equation 4.9.

$$Q = F * P * (t_i - t_o) \tag{4.9}$$

where: $F = 0.95 \frac{W}{m°C}$

P = perimeter linear length

t_i = internal tank temperature

t_o = ambient temperature

Sides and top

Assuming an inside film coefficient of approximately 20 $\frac{Btu}{hr\ ft^2\ °F}$, an outside film coefficient of 10, an insulation conductivity of 6.25 $\frac{hr\ ft^2\ °F}{Btu\ inch}$, and that the conduction resistance in the steel plate along with radiation losses can safely be neglected, then the overall conductance value is expressed as

$$U = \frac{1}{R_{inside} + R_{insulation} + R_{outside}} \tag{4.10}$$

where: $R_{inside} = \frac{1}{h_i} = \frac{1}{20} = 0.05 \frac{hr\ ft^2\ °F}{Btu}$

$R_{insulation} = \frac{L}{K} = \frac{6\ in.}{6.25} = 0.96 \frac{hr\ ft^2\ °F}{Btu}$

$R_{outside} = \frac{1}{h_o} = \frac{1}{10} = 0.1 \frac{hr\ ft^2\ °F}{Btu}$

Therefore

$$U = \frac{1}{0.05 + 0.96 + 0.1} = 0.90 \frac{Btu}{hr\ ft^2\ °F} = 5.1 \frac{W}{m^2K} \tag{4.11}$$

The total heat loss from the sides and top is then calculated from equation 4.12.

$$Q = U * A * \Delta T \tag{4.12}$$

where: Q = total heat loss

A = total surface area of sides and top

$\Delta T = T_{inside} - T_{ambient}$

The storage tank total surface area is calculated as follows. In the program FORCEIT, the function that calculates the heat loss is given the tank size, SIZE, in millions of liters. Therefore, the volume of the tank in m^3 is

$$VOL = SIZE * 1000\ m^3/10^6\ \ell \qquad (4.13)$$

Since the cylindrical tank is assumed to have a diameter equal to its height, the diameter (X) can be found by

$$X = \left(\frac{VOL * 4}{\pi}\right)^{1/3} \qquad (4.14)$$

The perimeter length, side surface area, and top surface area are given by

$$PERIM = \pi * X \qquad (4.15)$$

$$SIDE = \pi * X^2 \qquad (4.16)$$

$$TOP = \pi/4 * X^2 \qquad (4.17)$$

Equations 4.9 and 4.12 give the heat loss out of the tank in W. To convert this to MJ per day, which is the unit used in all thermal energy calculations in FORCEIT, the heat loss rate is multiplied by a factor of 0.0864×10^6 sec/day. In all calculations involving the storage tank, the temperature of the water inside the tank was assumed to be a constant 80°C throughout.

Since the heat loss was found on a daily basis and the ambient temperature used in the equations above is the design temperature, the heat loss equations give the maximum heat loss per day from the storage tank. The problem of how to calculate the actual heat loss from the tank (LOSS) when the tank is only partially full and/or exposed to an ambient temperature different than the local design temperature had to be overcome. This was done by assuming that the actual heat loss is proportional to the fraction of capacity that the tank is currently filled. If the ambient temperature were different than the design temperature, then a ratio of the difference between the inside tank temperature and the two ambient temperatures is used. In equation form then, LOSS is expressed as:

$$LOSS = \frac{t_i - T_{avg}}{t_i - TDESGN} * \text{fraction of capacity} * MAXLOSS \quad (4.18)$$

where: T_{avg} is the event average daily temperature

t_i is the temperature of the storage water

TDESGN is the local design temperature

FORCEIT is set up to automatically find the storage tank size which gives at least some available thermal energy in storage 99% of the total heating season days. This means that the storage reserve will be 0 only 1% of the total time during the heating season.

4.4 Economic Analysis

The program FORCEIT was modified to estimate the economics of providing peaking thermal energy through a combination of thermal energy storage and a fossil fuel boiler. The prospect of incorporating a heat pump to take the place of the boiler was not considered, although such a combination is currently in common practice in France (Reistad, 1980). Since the peak energy demand will occur when the ambient temperature is at a minimum, relatively low COP values would be expected, therefore, it would seem possible that the use of heat pumps to provide peaking energy would have only marginal advantages over a fossil fueled system. When peaking energy is required, it will be assumed to be supplied from the storage tank, if thermal energy is available. Only when the storage tank no longer contains any thermal energy will the boiler be utilized to provide peaking. For redundancy the boiler will be sized to provide the entire thermal peaking energy at the design temperature (e.g. MAXLOAD).

The costs that are computed and recorded by ECON are as follows: the storage tank capilization expense, the operation and maintenance expenses for both the peaking boiler and storage tank, the boiler capitalization expense, and the boiler fuel cost. In order to get a good estimate of the initial capital cost of a storage tank and boiler, regression equations were developed that relate the component capacity to actual costing data that are available in the literature. Figure 4.7 shows a plot of data taken from the 1980 edition of "R.S. Means Building Construction Cost Data" (Godfrey, 1980) in which the total cost for an oil-fired cast iron boiler is plotted as a function of the rated heat energy output. From the data it was observed that an excellent correlation existed between the natural logarithm of the total cost ($) vs. the natural logarithm of the rated output (1000 Btu/hr), with the regression equation being

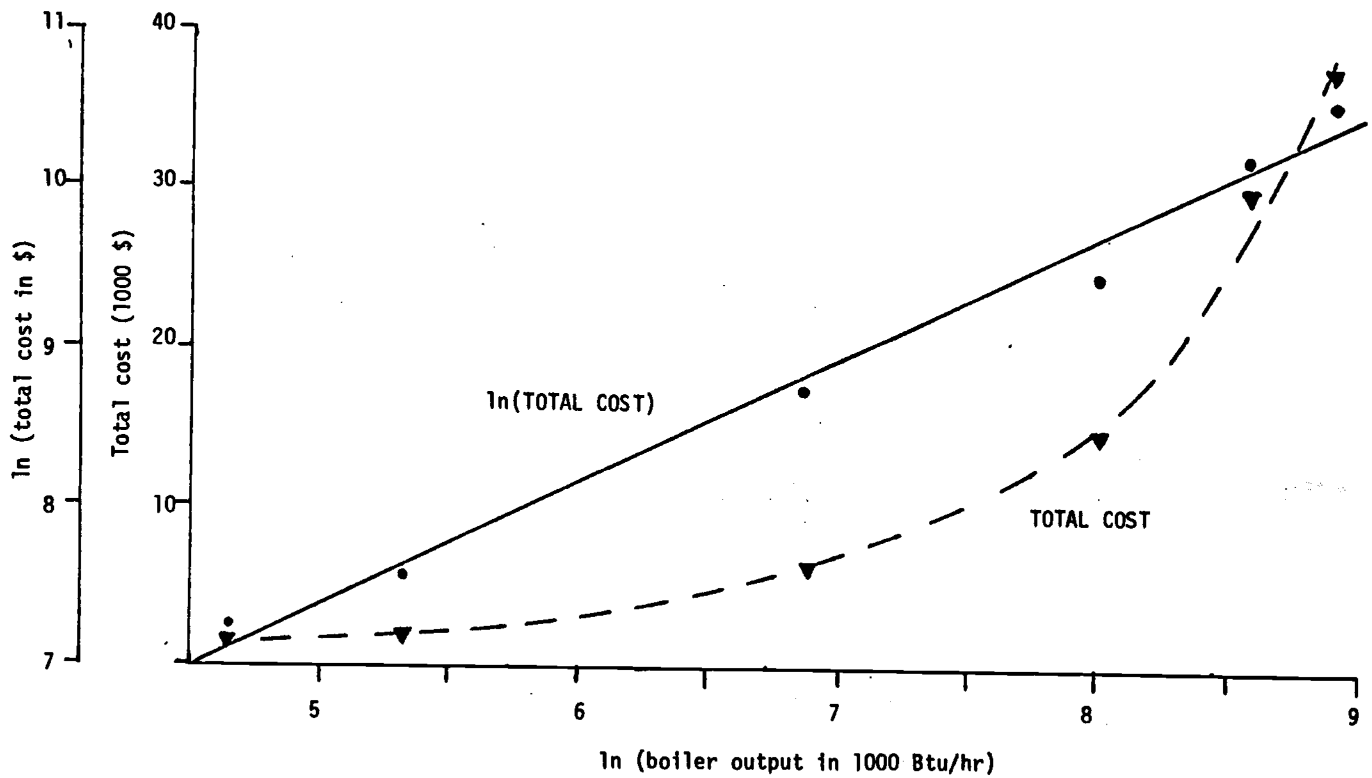

Figure 4.7 Plot of total installed cost of an oil-fired cast iron boiler versus rated boiler output, used in the development of regression equation in the economic analysis program. (Data from Godfrey, 1980)

$$\ln(\text{cost}) = 0.785 * \ln(\text{output}) + 3.45 \qquad (4.19)$$

The correlation coefficient for this equation is: $r^2 = 0.9908$

Data used in developing a regression equation for the storage tank were taken from a summary given in Chapter XI of Office of Technology Assessment (1978). A generalized plot of this data is given in Figure 4.8. Again, the best fit was for an equation relating the natural logarithm of the total cost versus the natural logarithm of the tank volume, specifically

$$\ln(\text{cost}) = -0.244 * \ln(\text{tank volume in } m^3) + 5.64 \qquad (4.20)$$

Additional parameters that are used in ECON are listed in Table 4.2, along with their respective meanings. Specific economic variables that are used in this analysis are listed in Table 4.3. ECON is set up to automatically do a sensitivity study on the effects of changes in the economic parameters on the cost of providing peak load thermal energy. The ranges of these variations for the sensitivity study are also listed in Table 4.3.

The simulation was run with the storage capacity being varied from 0 to the maximum amount determined in the previous procedures. The total cost required to provide the peaking energy over the 20 year simulation period was computed, with the goal being to find the storage capacity that will give the lowest overall cost of thermal energy. As a check on the assumption that the pumping energy at the resource well(s) could be neglected without seriously affecting the

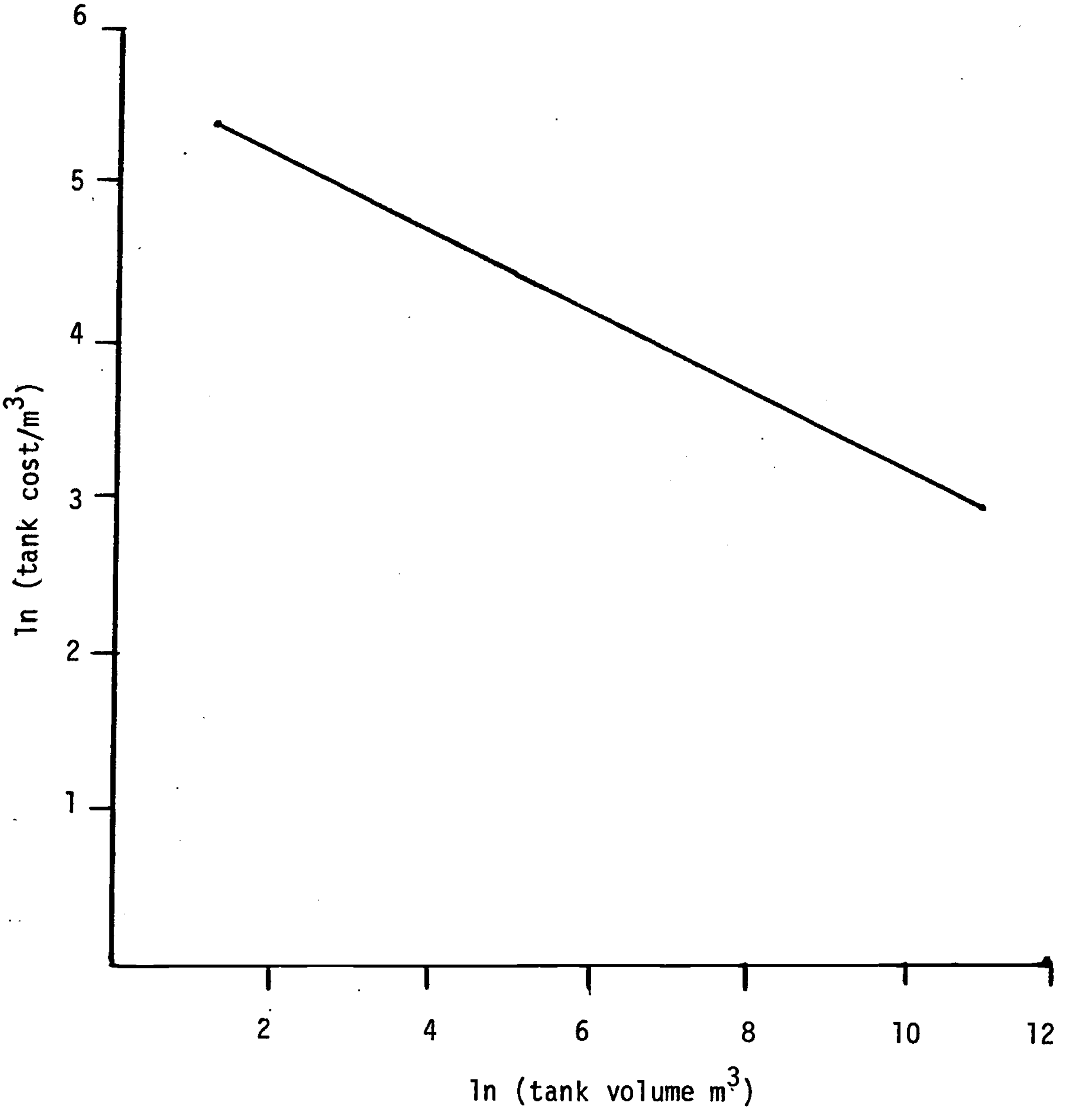

Figure 4.8 Plot of the average storage tank cost versus tank volume, used in the development of regression equation in the economic analysis program. (Data is taken from Office of Technology Assessment, 1978)

Table 4.2 Additional parameters used in the ECON program.

Parameter	Definition
ANUBCAP	Annual boiler capital cost
ANUTCAP	Annual storage tank capital cost
ANUBOM	Annual boiler operating and maintenance
ANUTOM	Annual storage tank operating and maintenance
BBUCKS	Total boiler capital cost
TBUCKS	Total storage tank capital cost
BCOST	Total boiler cost
TCOST	Total storage tank cost
BEFFIC	Boiler efficiency
FCOST	Total fuel cost (included in BCOST)
FUELMJ	Fuel used in MJ
FUELUP	Fuel escalation factor, % above inflation
FUELUSE	Yearly fuel used in 10^6 Btu
INTFUEL	Initial fuel cost in $/$10^6$ Btu
OANDMB	Boiler operating and maintenance, % of capital cost
OANDMT	Tank operating and maintenance, % of capital cost
PRIME	Interest rate, % above inflation
SYSCOST	Total peaking system cost
TFLUID	Total geothermal fluid required in kg
YEARAMT	Number of years for project amortization

Table 4.3 Economic parameters and their ranges used in ECON.

Parameter	Base case value	Range
Interest rate (%)*	2.	0.5 - 10.
Operation and maintenance (%)		
Boiler	1.5	0.75 - 3.
Tank	1.	0.5 - 2.
Initial fuel cost ($\$/10^6$ Btu)	9.00**	8. - 12.
Fuel escalation factor (%)*	3.	0. - 6.
Boiler efficiency (%)	80.	70. - 90.
Years of amortization	30.	20. - 35.

* The interest rate and fuel escalation rate are expressed as a % above inflation

** This is approximately equal to $1.30/gallon of fuel oil.

results, the total amount of geothermal fluid that was required to be pumped from the resource was determined. Results of these calculations indicate that the well pumping energy can safely be neglected (see section 5.4).

V. RESULTS AND DISCUSSION

5.1 Worst Case Sizing

The worst case model analyzed individual events to find the one event out of the entire 20 year data file which required the maximum amount of stored thermal energy, first for a linear heating demand curve, and then for a non-linear quadratic heating demand curve.

Recorded events which were felt to have the largest storage requirements were analyzed for various values of LDRATIO. Figure 5.1 gives a plot of the storage required as a function of the LDRATIO for a combined well output of 33.5 MW for a typical event using both the linear and non-linear heating demand relationships. The reduction of the maximum storage size required when assuming the non-linear heating demand curve as compared to the linear case for this particular event is typical of the results for all the events analyzed. Note that for the linear case, the peak storage requirements occur for a LDRATIO of around 1.25. Above this value, the storage size becomes limited by the recharging ability of the resource well(s), as previously discussed in section 4.2.1. All of the events had a peak thermal energy storage at a LDRATIO ranging from 1.15 to 1.35. When the non-linear demand curve was assumed though, this peak in storage requirements shifted to a higher LDRATIO value of approximately 1.6, with a range of 1.45 to 1.8 for all of the events. This shift in the LDRATIO means that more users could potentially be served by the system without the use of

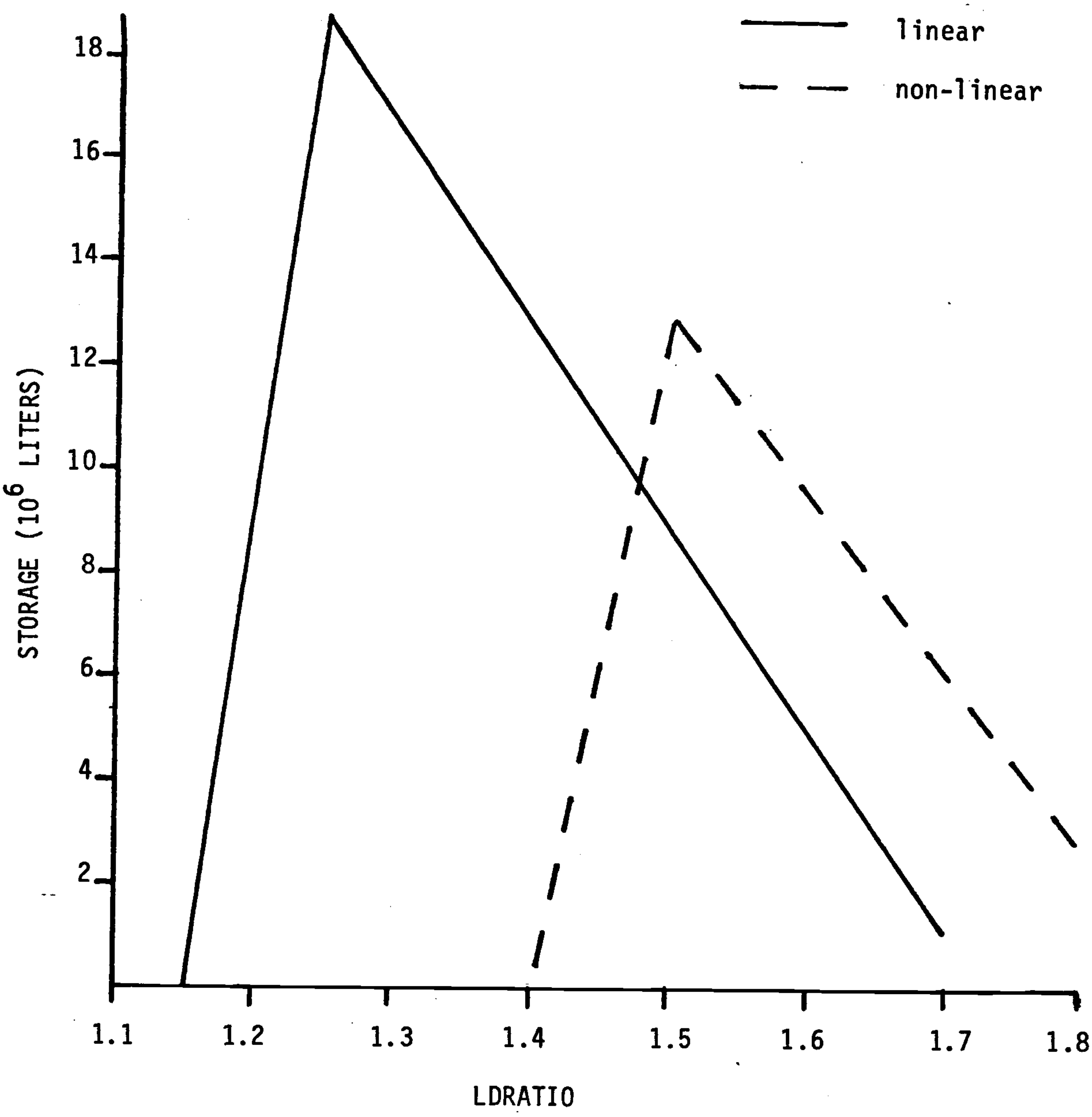

Figure 5.1 Plot of storage required as a function of LDRATIO for a typical event.

supplemental energy from a peaking boiler, and is due to the lower heating demand at a given temperature than for the linear case.

The maximum possible thermal energy storage required for an individual city was next found as a function of the design heating load, assuming a LDRATIO of 1.25 for the linear case and 1.60 for the non-linear case. A plot of this relationship for four cities, Albuquerque, Norfolk, Portland and Salt Lake City is given in Figures 5.2 (linear) and 5.3 (non-linear).

Since the LDRATIO is held constant, the storage required will vary directly with the design heating load, as observed from Figures 5.2 and 5.3. It was felt that the slope of the storage versus design heating load line could be found as a function of common climatic parameters for each city. This would give a general relationship for the slope for any other city not analyzed here given values for the climatic parameters. The specific parameters values that are used in a multivariate regression analysis of the slope are listed in Table 5.1. The slope values for each city, taken from Figures 5.2 and 5.3, are given in Table 5.2. The resulting regression equation for both the linear and non-linear heating demand curve analyses are given in Table 5.3. Of interesting note here is that since there is only one data point for each city, then the linear regression equation will give an exact fit using only the three climatic variables with the highest correlation.

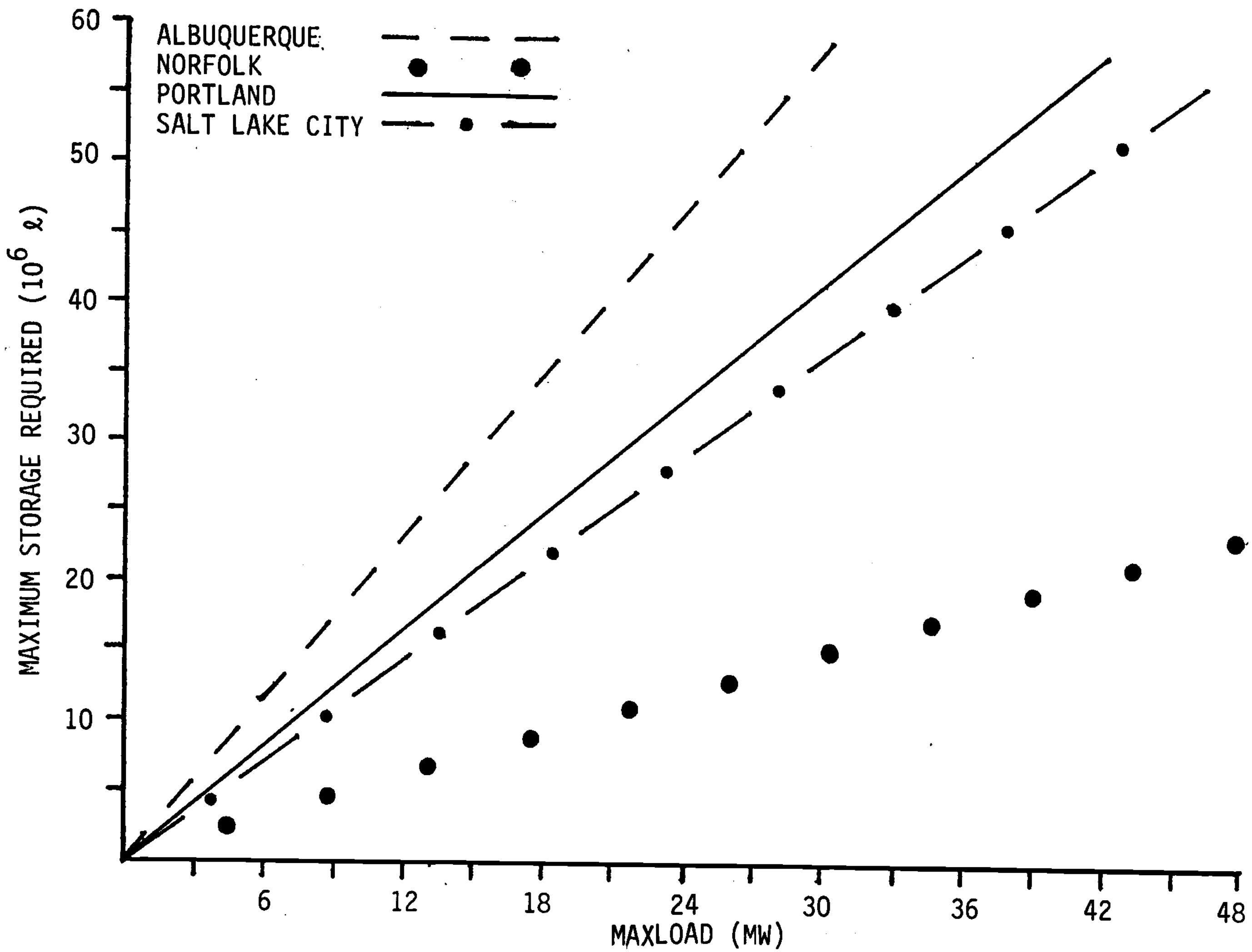

Figure 5.2 Plot of the maximum storage required as a function of design load for the various climates using the linear heating demand curve model and setting LDRATIO = 1.25.

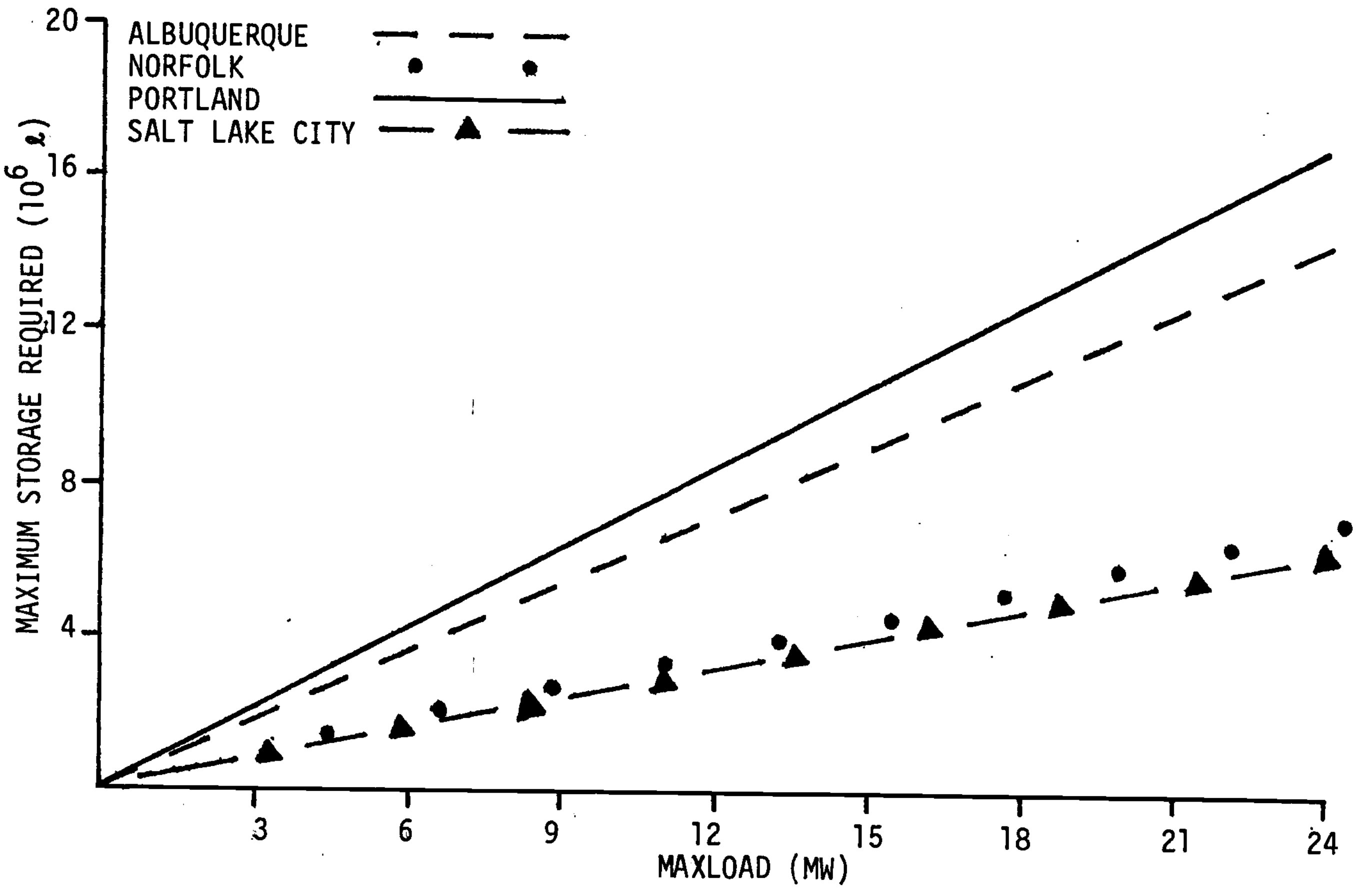

Figure 5.3 Plot of the maximum storage required as a function of design load for the various climates using the non-linear heating demand curve model and setting LDRATIO = 1.6.

Table 5.1 Climatic parameters used in storage size versus design load slope regression analysis.

City	Yearly heating degree days(°F)	97.5% Design T (°F)	99% Design T (°F)	Avg. Jan. temp (°F)	Elevation (ft)	January horizontal radiation kJ/m^2
Portland	4792	23	17	38	21	3518
Salt Lake	6052	8	3	25	4220	7253
Norfolk	3421	22	20	40	26	7698
Albuquerque	4348	16	12	35	5310	11536

Table 5.2 Slopes of the storage size versus design load line.

City	Slope (quadratic case)	Slope (linear case)
Portland	0.69	1.38
Salt Lake	0.27	1.20
Norfolk	0.28	0.49
Albuquerque	0.61	1.92

Table 5.3 Regression analysis for the relationship between storage size required and design load for both the linear and non-linear heating demand curves.

Linear case:

Slope = 0.0005366 * Yearly degree days + 0.1561 * 97.5% Design temperature + 0.0003537 * Elevation - 4.7890

R^2 = 1.000

Non-linear case:

Slope = 0.4224 * Average Jan. temperature + 0.1043 * 97.5% Design temperature - 0.3835 * 99% Design temperature - 11.2422

R^2 = 1.000

5.2 Engineering Design Sizing

The FORCEIT program was run on the 20 years of event weather data with the purpose of finding the size of storage tank which will be able to provide at least some thermal energy to the district heating system for the peak loads 99% of the total days in the heating season. Consequently, supplemental energy from a boiler will be required the other 1% of the time. The 99% figure is strictly arbitrary, and the effect of varying this percentage will be discussed later in this section.

A plot of the storage size required in relation to the system design heating load is given in Figure 5.4 for four cities. An interesting trend can be observed from this plot. Because the model incorporates a non-linear heating demand curve which tends to discount the effect of more severe temperatures on the system heating load, the cities seem to be naturally grouped according to climate type. The maritime cities, Portland and Norfolk, required a much larger storage capacity than Albuquerque or Salt Lake City. Similar results, which are not shown in Figure 5.4, are observed for San Francisco and Indianapolis with an even greater disparity between the two. This trend is attributed to the type of events which each group experiences. The maritime cities tend to have a larger number of events but rarely are they of extremely cold temperatures, while the inland cities experience fewer events but of colder temperature. Most importantly, the events, as they are defined for this project, also tend to be of a longer duration in the maritime climates.

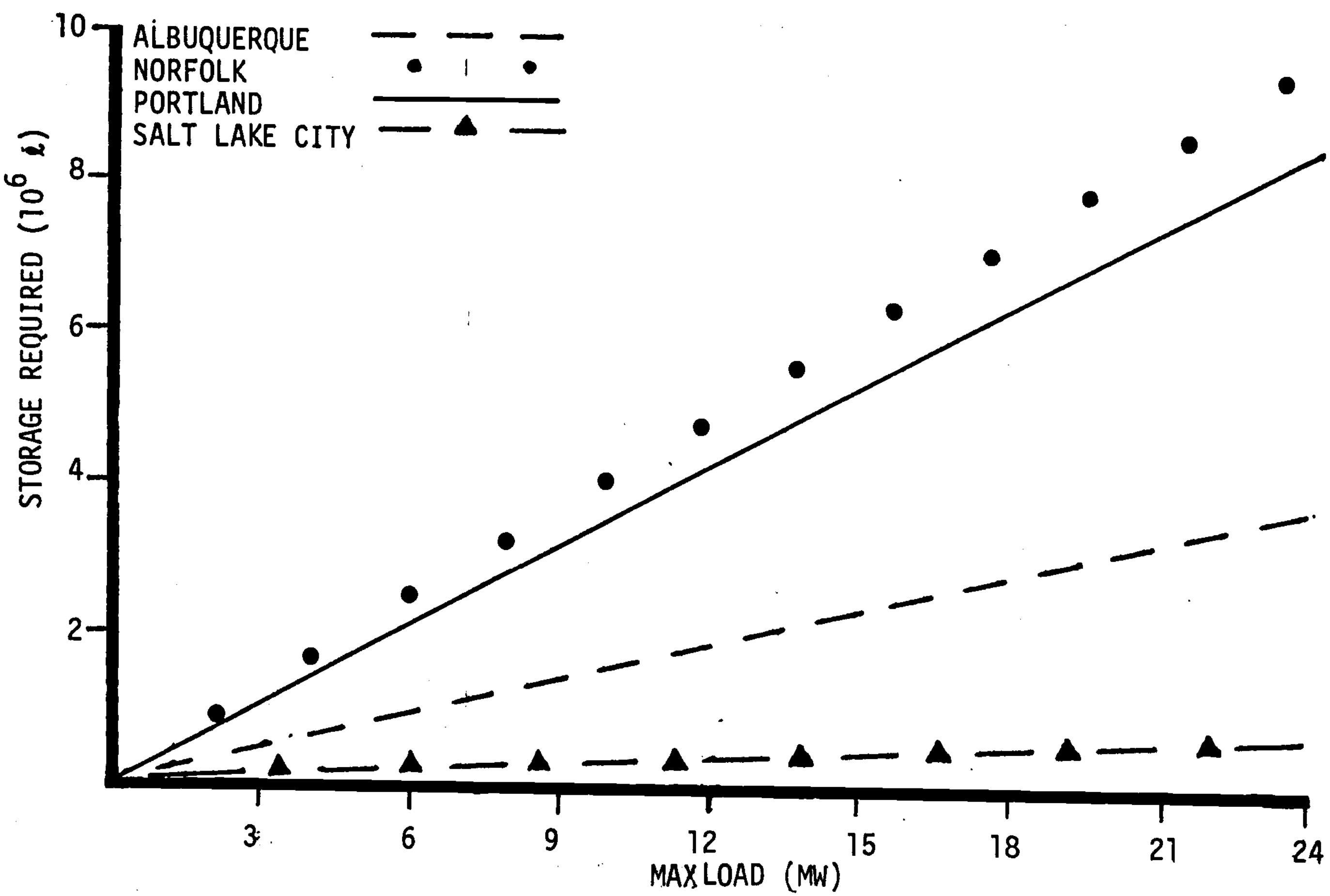

Figure 5.4 Plot of storage capacity required to supply thermal energy 99% of the total heating season days versus the design load. The LDRATIO is 1.6.

The slope of the storage size at the 1% level for all six cities studied versus the design load was found as a function of the climatic parameters by the same procedure described for the worst case analysis. The resulting regression equation is given in Table 5.4 below. Note that five climatic parameters are now necessary to give an equation of perfect fit since there are now six data points to satisfy.

Table 5.4 Regression analysis for the relationship between storage size required and design load for the results of the engineering design sizing procedure. MAXLOAD is 24 MW.

Slope = -2.3162 + 0.0006289 * yearly degree days

- 0.1006 * average January temperature

- 0.03737 * 97.5% design temperature

+ 0.236947 * 99% design temperature

+ 0.00008736 * January horizontal radiation

R^2 = 1.000

The sensitivity of the storage required for a district heating system located in Portland with respect to varying the percentage of days that the storage tank does not contain any thermal energy is given in Figure 5.5. The MAXLOAD for this case was taken as 24 MW with a LDRATIO of 1.6. It is asserted that the storage required for the percent of days to be equal to 0% would be the maximum storage capacity that would be necessary for that particular city, since any tank larger than this would not actually be fully utilized

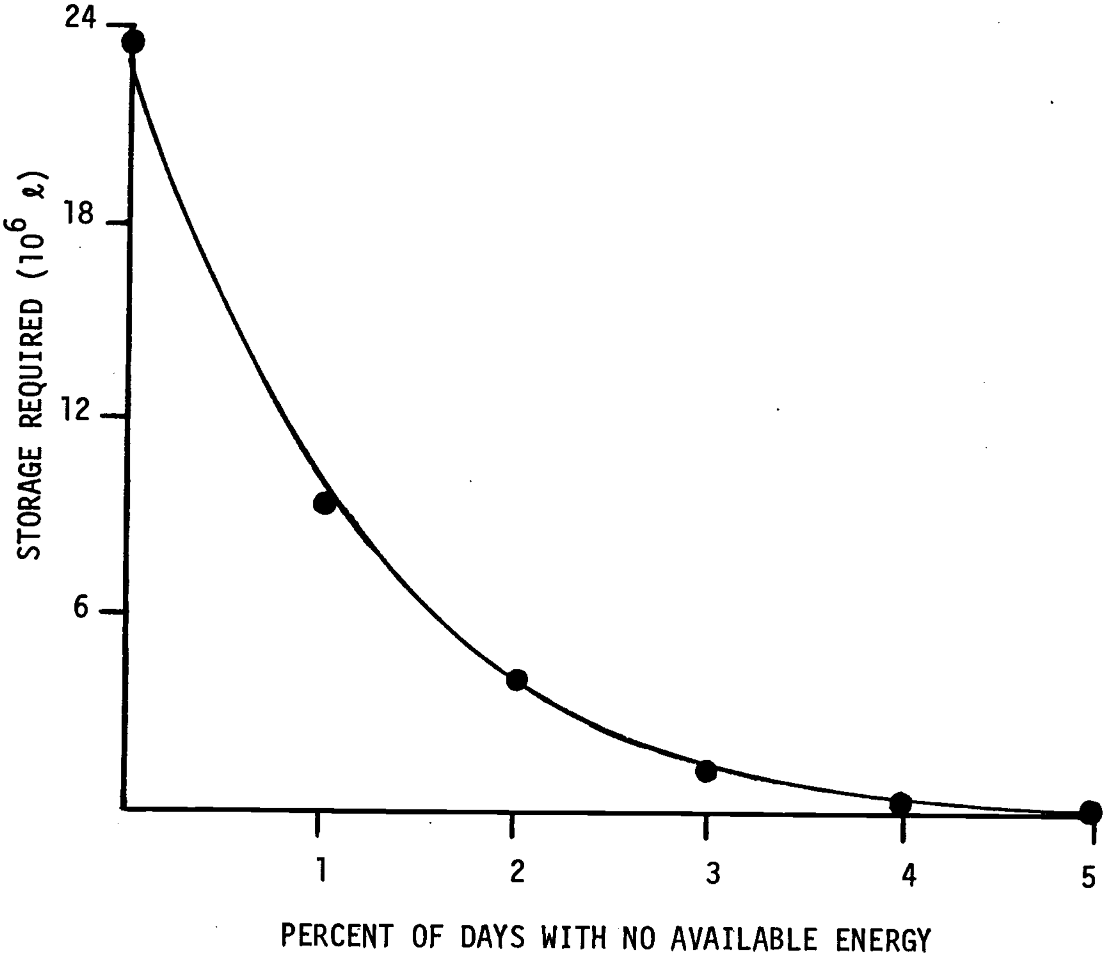

Figure 5.5 Plot of the storage required as a function of the percent of days that the tank has no available energy. System is assumed to be located in Portland with a LDRATIO of 1.6 and a MAXLOAD of 24 MW.

and therefore is excess capacity.

5.3 Sensitivity of Design Parameters in FORCEIT

The one dimensional sensitivity of the storage capacity requirements from FORCEIT as a function of changes in the LDRATIO, the heating demand curve, the percent of days that the storage tank is allowed to be empty, and the heat loss from the storage tank is plotted in Figure 5.6 for a district heating system located in Portland. The LDRATIO was varied from 1.4 to 1.8 and the percent of days the storage tank was allowed to be empty from 0% to 2%. The heat loss was varied by varying the maximum heat loss from the storage tank, MAXLOSS, from 0 to twice that originally calculated for the base case. The load curve sensitivity was found by changing the percentage of deviation from the linear heating demand curve. Recall that the non-linear heating demand curve, as observed in the German district heating systems, was found to have a relationship between the ambient temperature and the actual heating demand and is expressed as a percentage of the theoretical linear heating demand to temperature relationship (Figure 4.5). For example, at an ambient temperature of -15°C, the observed heating demand was 60% of that predicted if a linear relationship were assumed, giving a difference of 40%. In this sensitivity analysis, the difference percentage was multiplied by a factor ranging from 0.5 to 1.5, corresponding to a change in the load curve parameter as used in Figure 5.6 of -50% and +50% respectively.

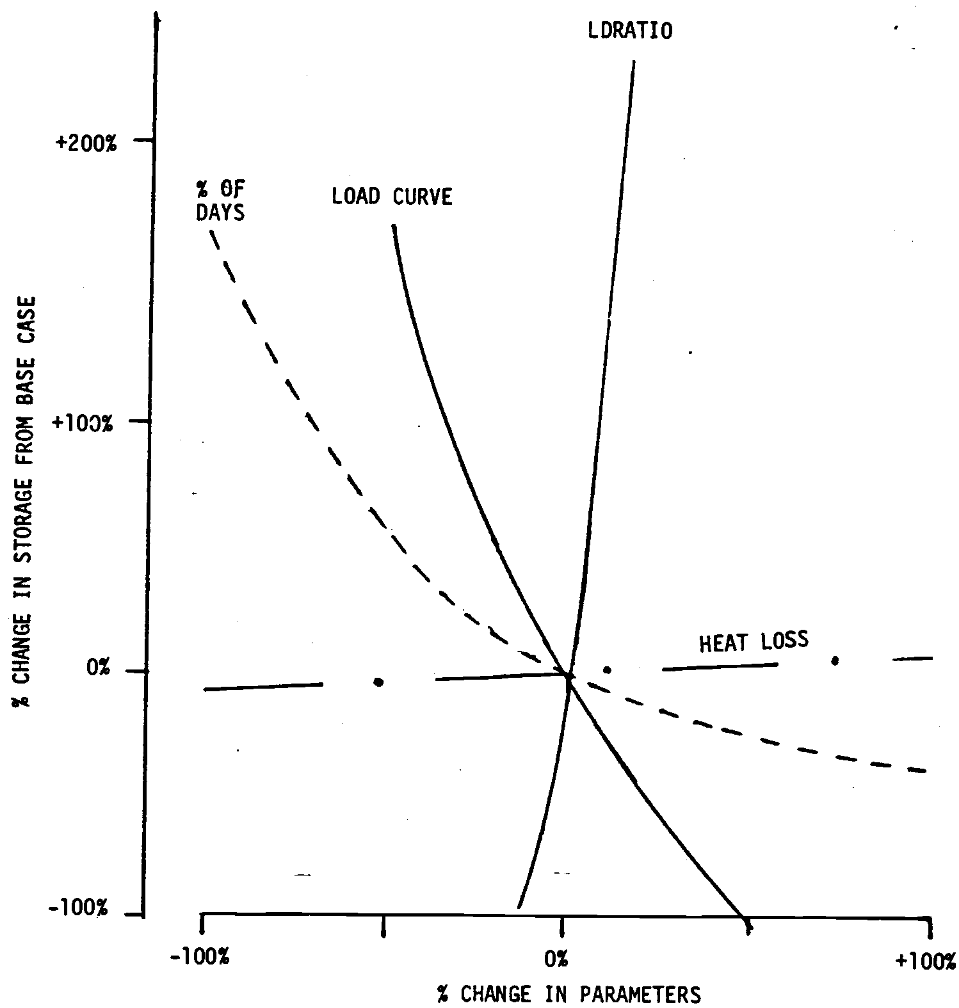

Figure 5.6 Sensitivity of storage required for changing parameters in the program FORCEIT for a district heating system located in Portland.

Changes in the heat loss from the storage tank appear to have an insignificant or at least minor impact on the storage size requirements. Thus, even if radical changes in the design of the storage tank were implemented, the storage requirements predicted as a result of this project would still be applicable. However, changes in the other parameters appear to have a fairly important effect on the storage requirements, and in particular the LDRATIO value is seen to have a major influence.

A more detailed illustration of the storage sensitivity to the LDRATIO is given in Figures 5.7 a-d for Albuquerque, Norfolk, Portland, and Salt Lake City. One general relationship that stands out is the kink in the plot of the storage requirements as a function of LDRATIO. Between a LDRATIO of 1.55 to 1.65, the slope increases in some cases rather dramatically. It would not seem to be unreasonable to suspect that it is more than coincidence that this shift in the slope occurs at the same range of LDRATIO values that was previously observed in the worst case analysis to be the point of maximum storage before recharge limitations took effect. This suggests that an upper limit of approximately 1.6 should be placed on the LDRATIO when designing a geothermal based district heating system.

5.4 Economic Analysis

The ECON costing analysis program was run for all six cities using the parameter variations listed in Table 4.3, with the intent being to find the storage size for each city which will

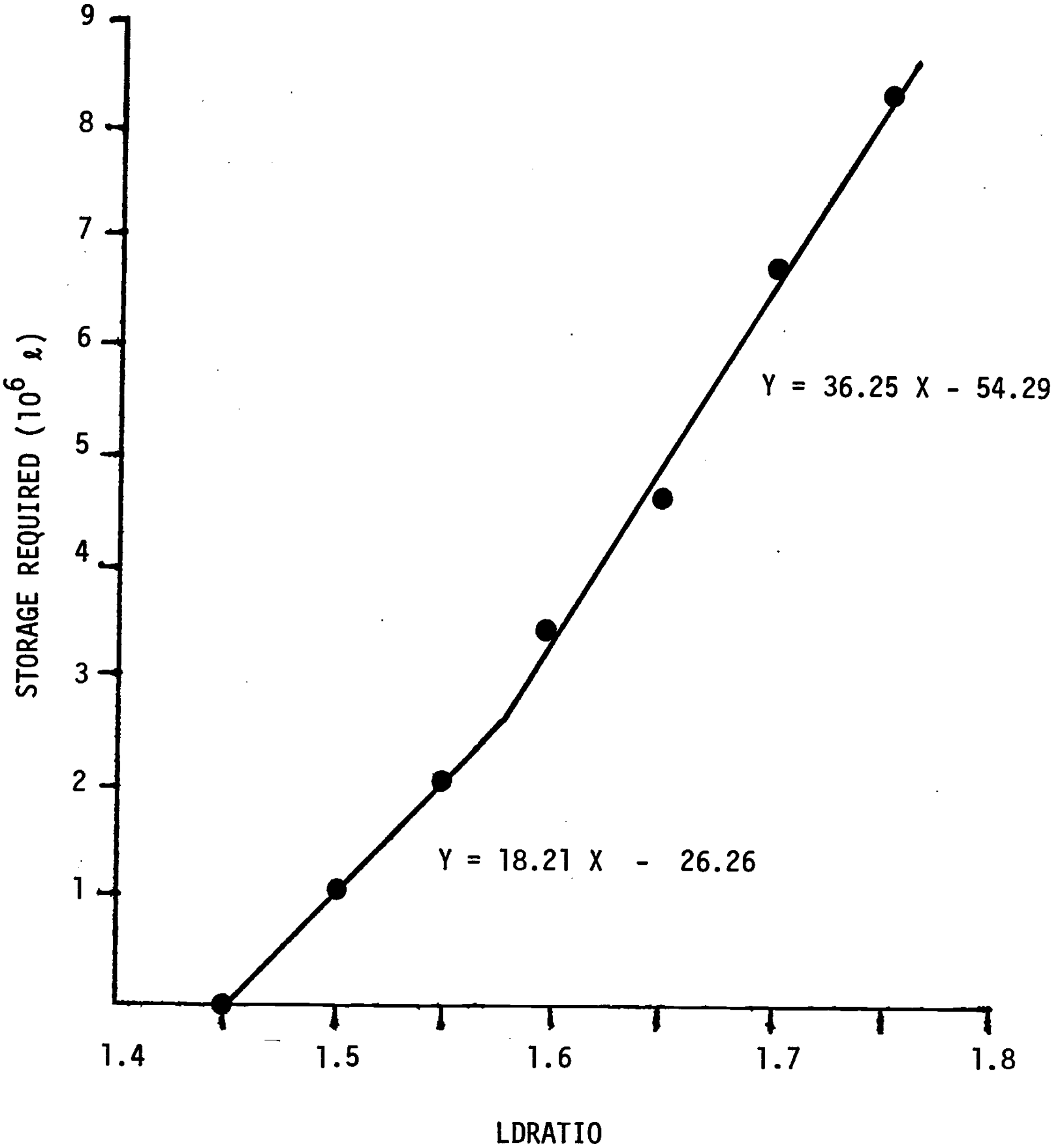

Figure 5.7 a Sensitivity of the storage required for various LDRATIO values, assuming a well production rate of 15 MW, for a district heating system located in Albuquerque.

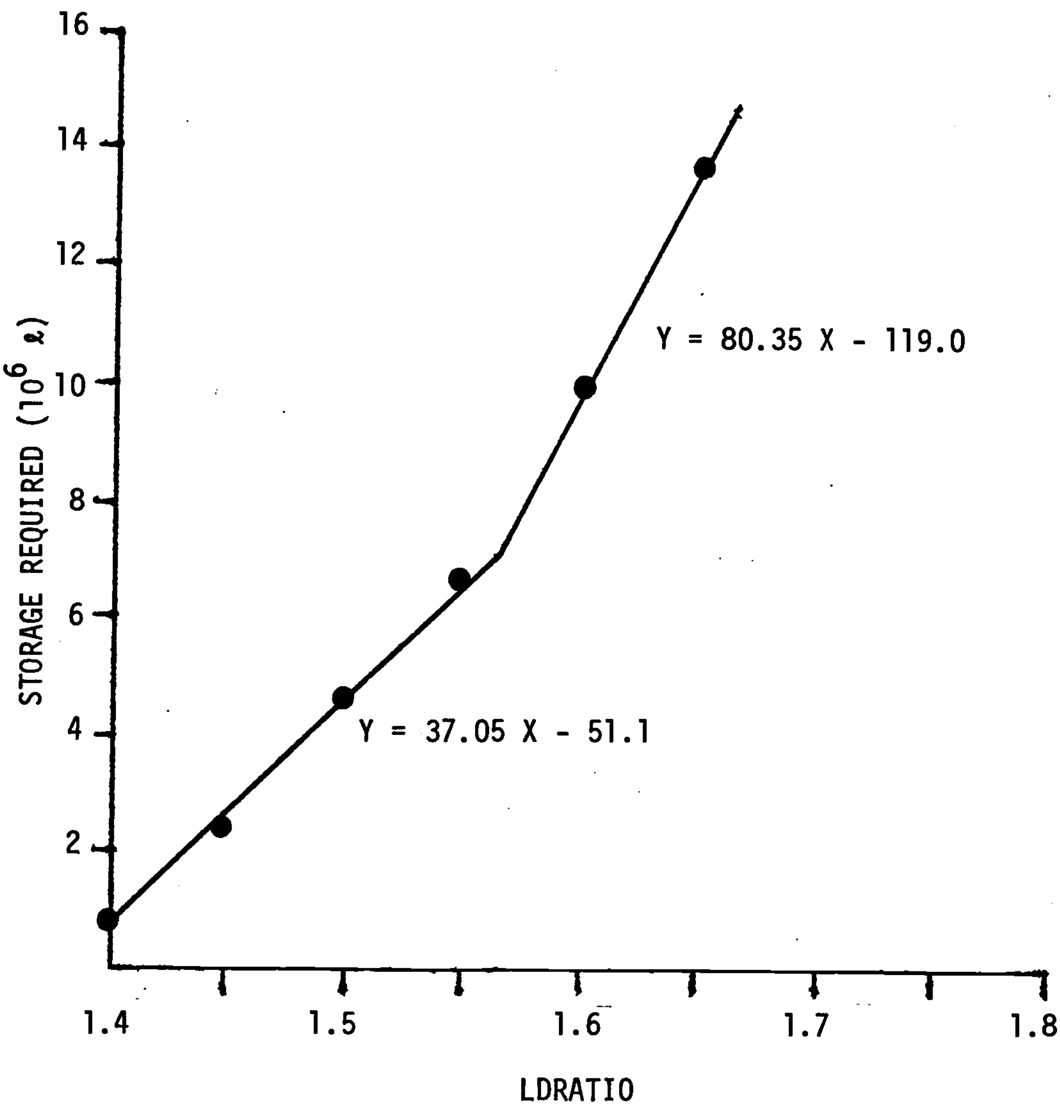

Figure 5.7 b Sensitivity of the storage required for various LDRATIO values, assuming a well production rate of 15 MW, for a district heating system located in Norfolk.

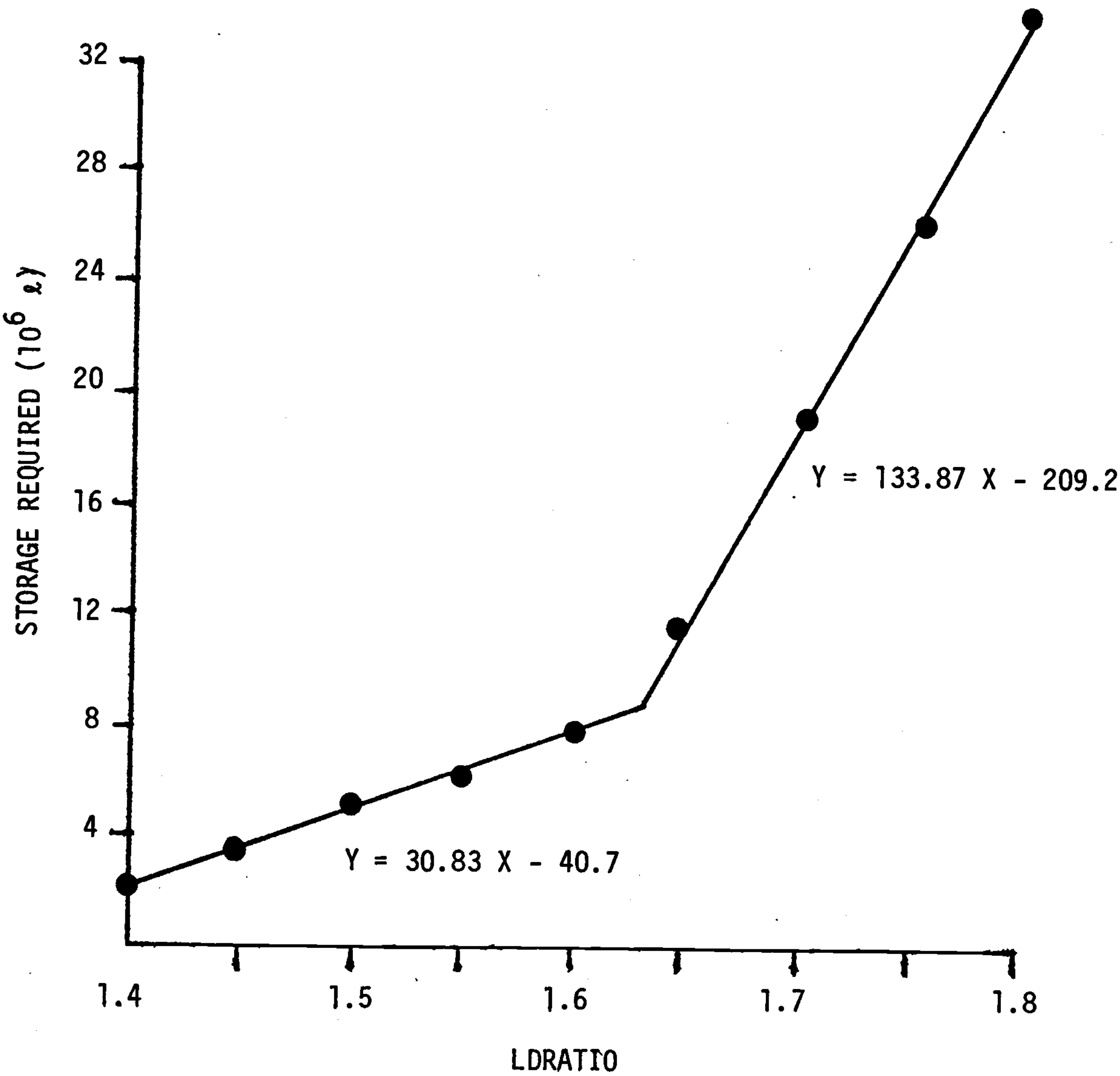

Figure 5.7 c Sensitivity of the storage required for various LDRATIO values, assuming a well production rate of 15 MW, for a district heating system located in Portland.

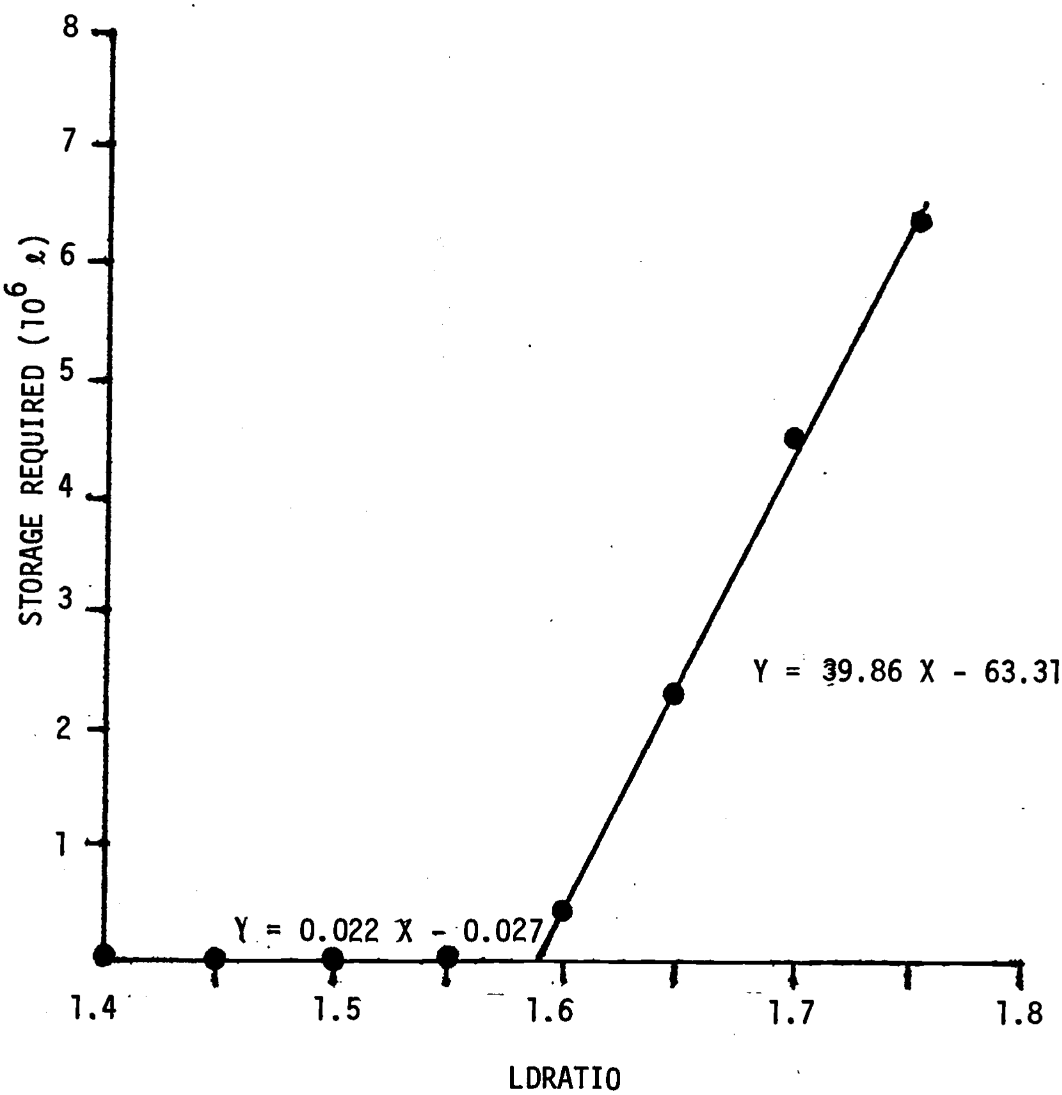

Figure 5.7 d Sensitivity of the storage required for various LDRATIO values, assuming a well production rate of 15 MW, for a district heating system located in Salt Lake City.

provide thermal peaking energy, possibly in conjunction with a peaking boiler, at the lowest cost over the 20 year simulation period. The total peaking system cost includes both the operating expenses and the capital costs required. A plot of the total peaking system costs as a function of a range of storage sizes is given in Figures 5.8 a-f. The minimum cost points are obtained by inspection of these plots, and are determined by differentiating either the equation of best fit using Newton's least square method or the local Lagrangian interpolation polynomial. The resulting equation from the Newton method is given in Figures 5.8 a-f.

In order to estimate the error introduced by ignoring the pumping energy necessary to obtain the geothermal fluid, the total amount of fluid required for the peaking heat demand over the 20 years of operation of the system was computed. Estimates of the total electrical energy input to the pumps ranged from 55 to 60 thousand KW-hr, corresponding to a cost of about $3000 (real dollars). This figure represents only 1.0% of the total peaking system cost at the minimum point, which demonstrates that the resource pumping can safely be neglected when considering the storage capacity requirements.

Calculations were also done to estimate the relative error in the storage estimates introduced by using the average daily temperature in the heating load calculations instead of the hourly temperatures. This essentially means that some diurnal storage of energy is to be provided. During the period from midnight until noon, the actual heating demand will be greater than if a constant

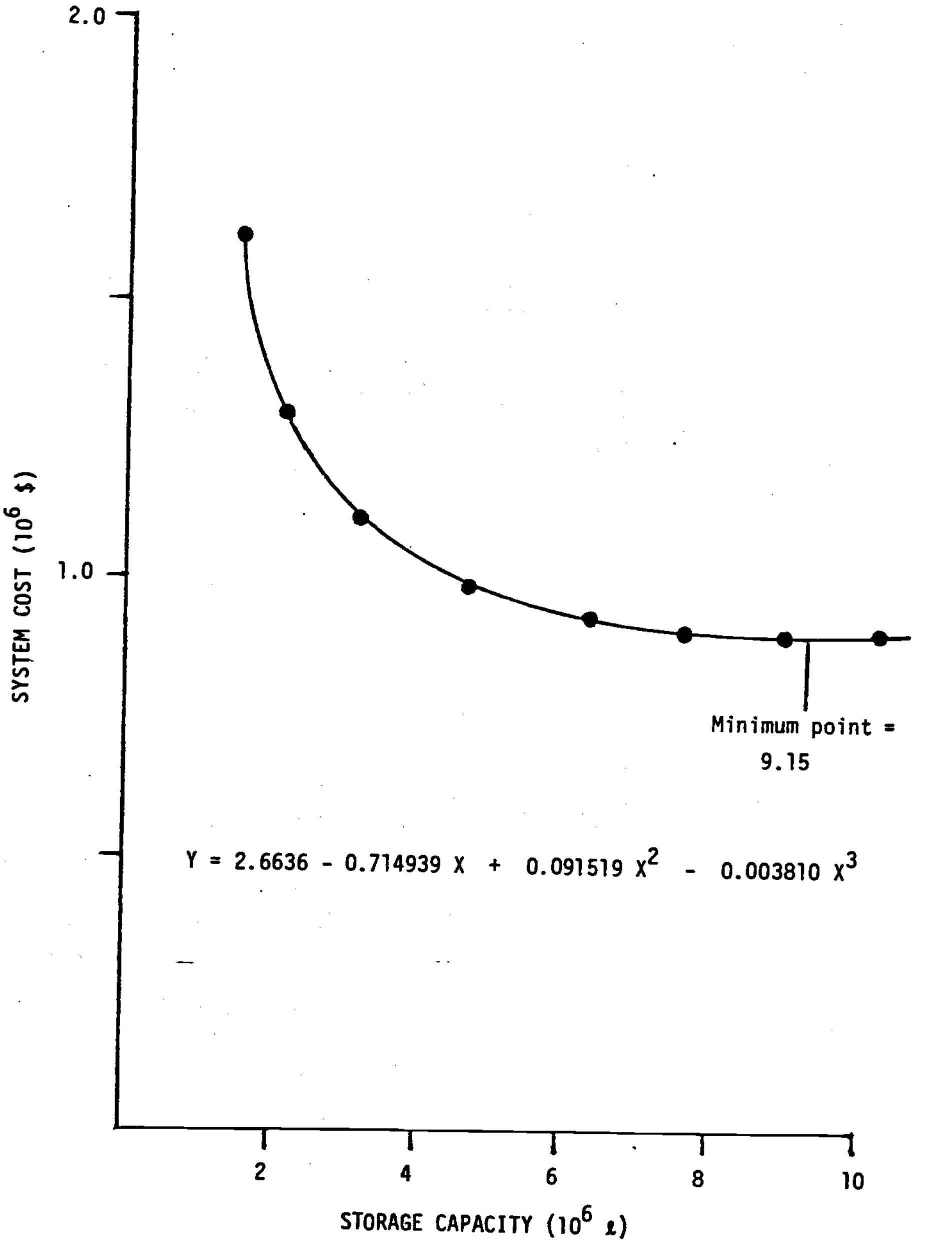

Figure 5.8 a Total lifetime peaking system cost as a function of storage capacity for a 24 MW peak load district heating system located in Albuquerque.

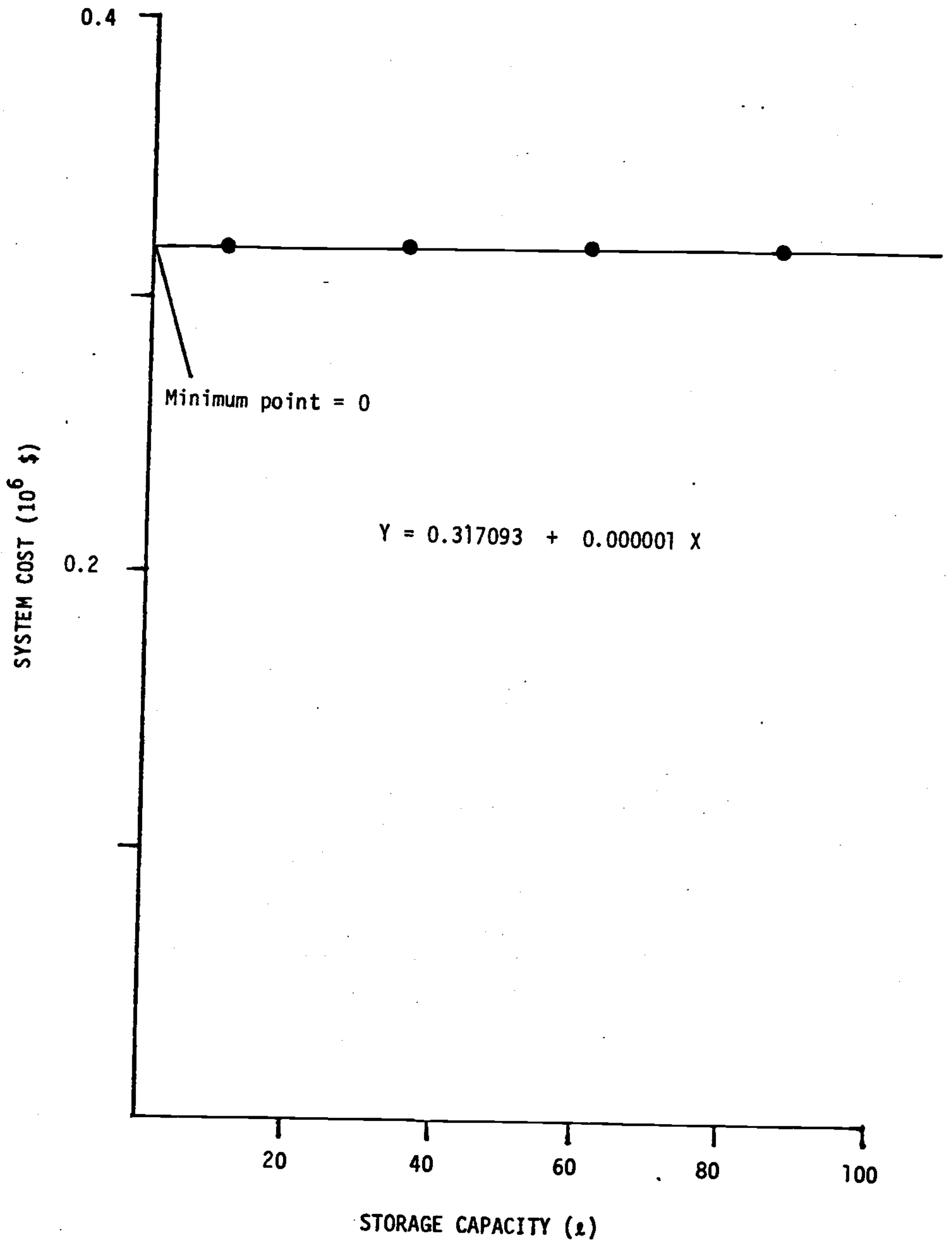

Figure 5.8 b Total lifetime peaking system cost as a function of storage capacity for a 24 MW peak load district heating system located in Indianapolis.

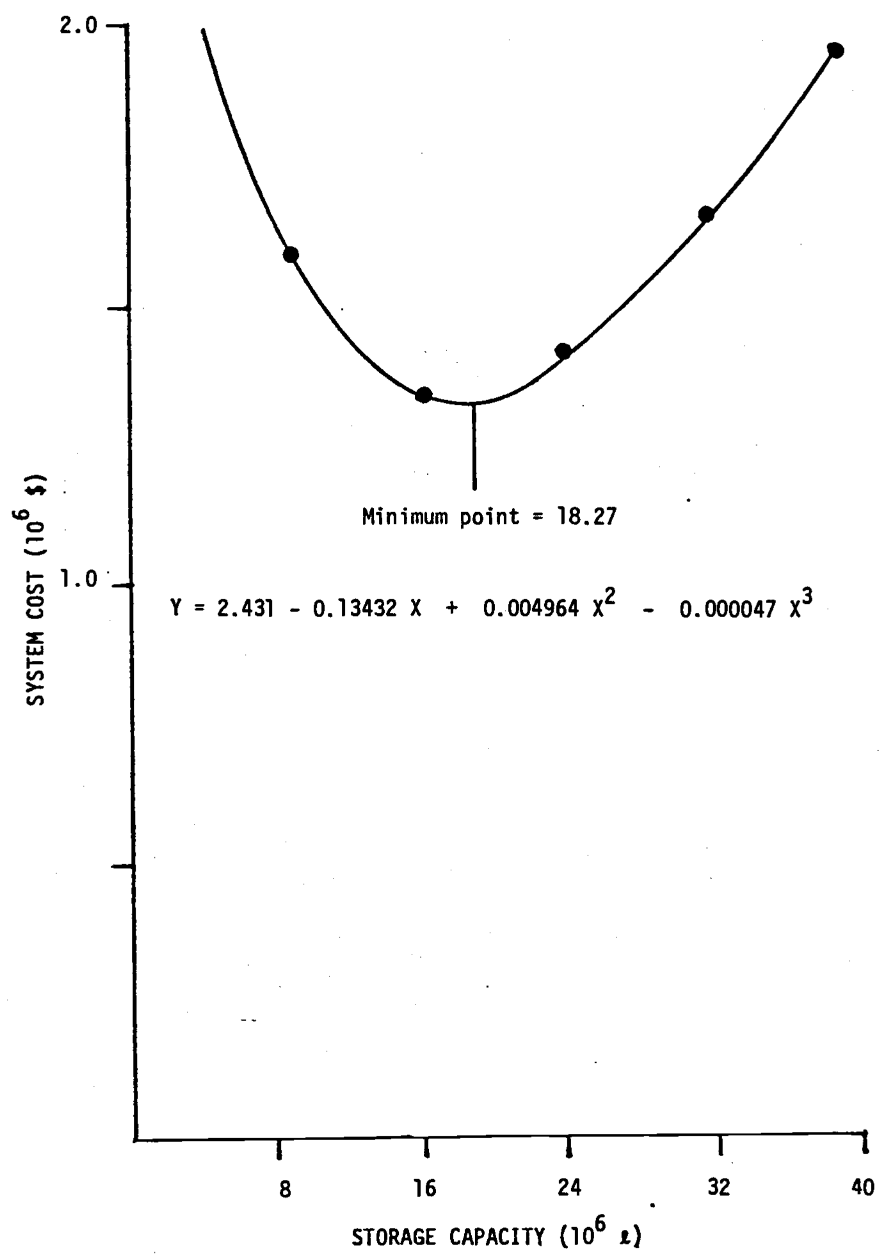

Figure 5.8 c Total lifetime peaking system cost as a function of storage capacity for a 24 MW peak load district heating system located in Norfolk.

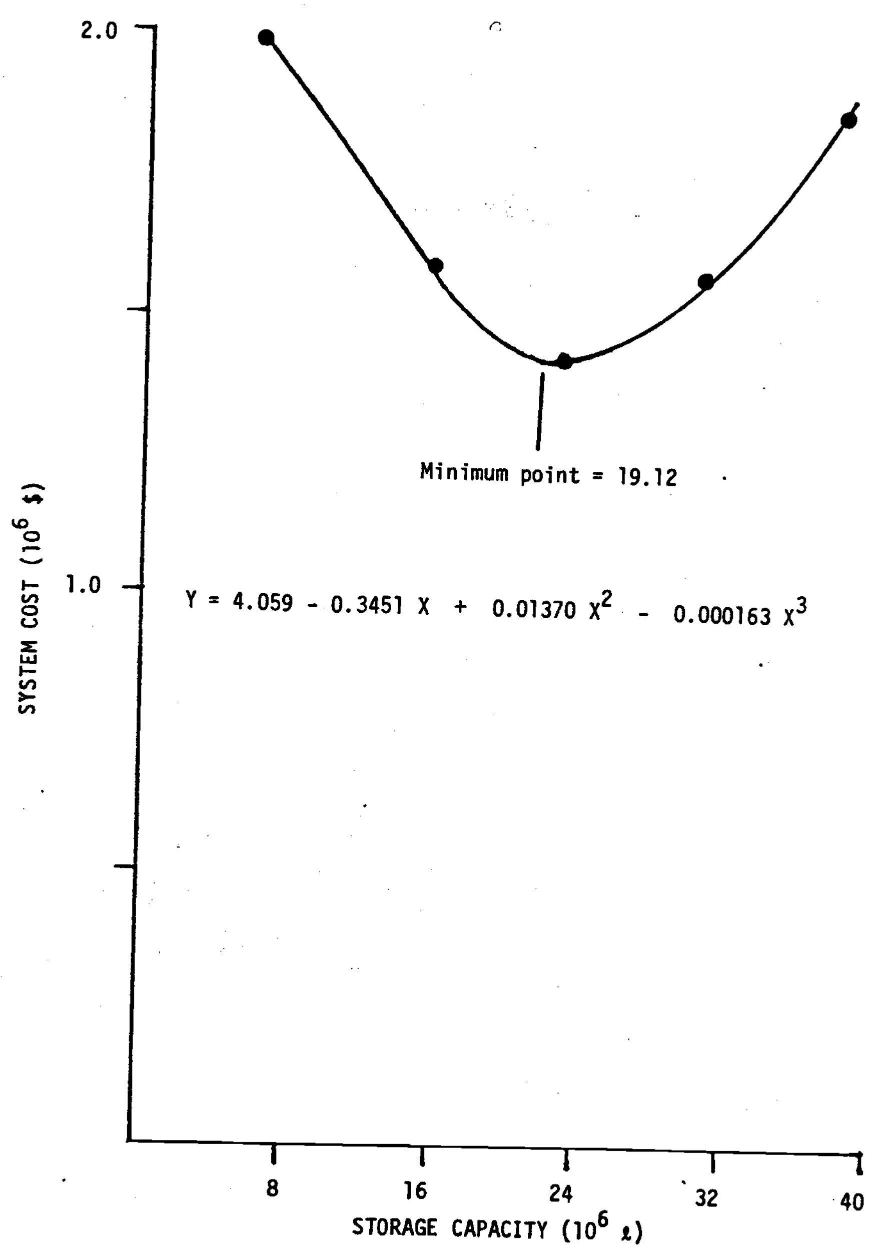

Figure 5.8 d Total lifetime peaking system cost as a function of storage capacity for a 24 MW peak load district heating system located in Portland.

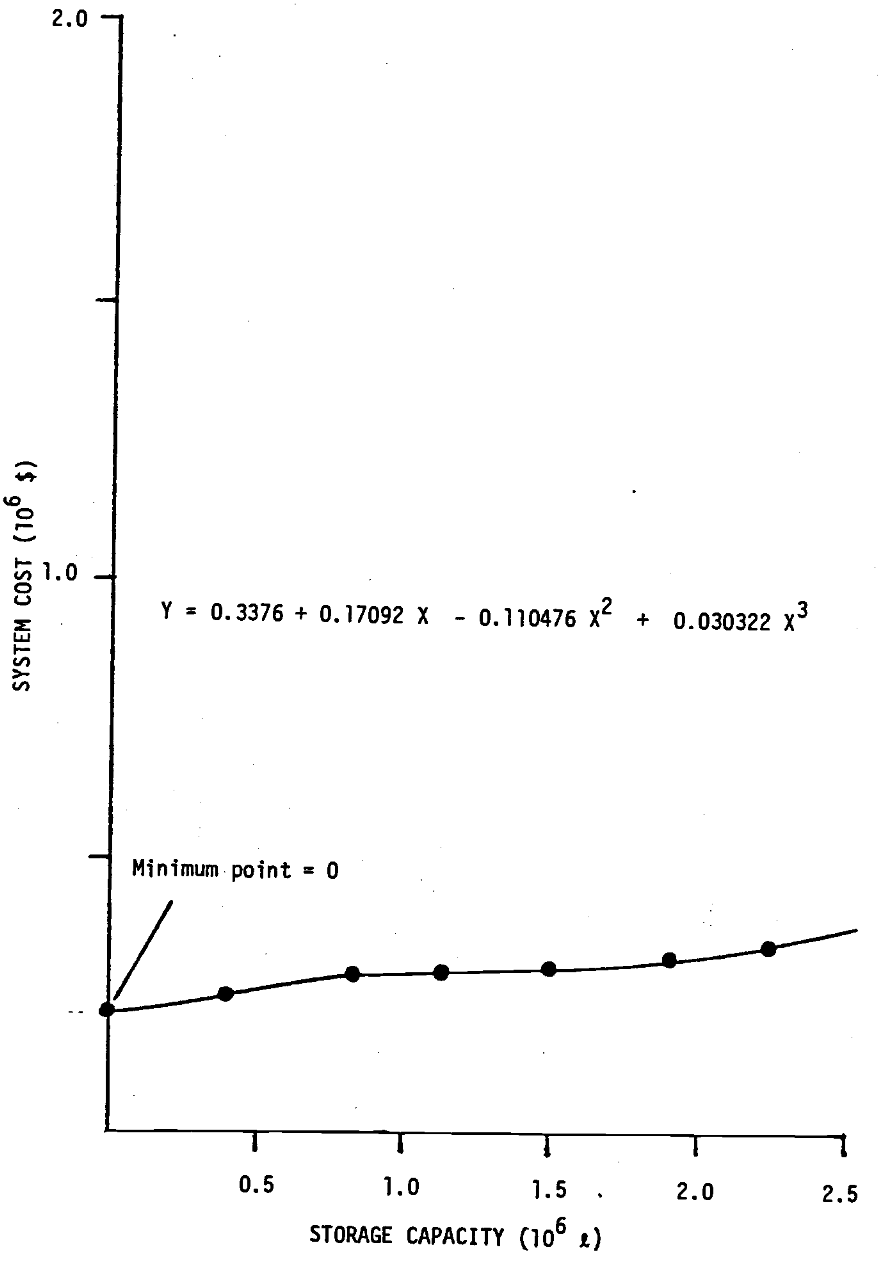

Figure 5.8 e Total lifetime peaking system cost as a function of storage capacity for a 24 MW peak load district heating system located in Salt Lake City.

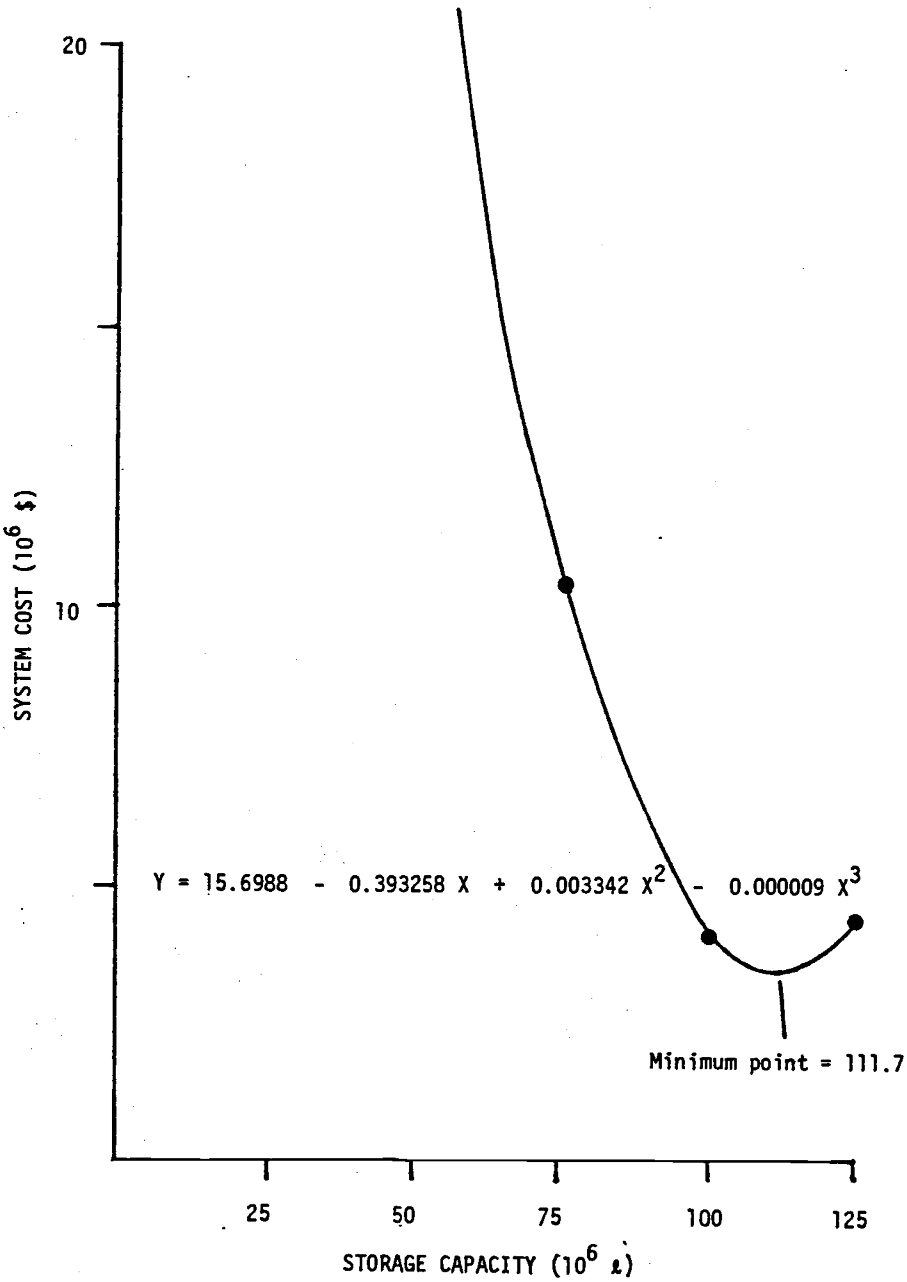

Figure 5.8 f Total lifetime peaking system cost as a function of storage capacity for a 24 MW peak load district heating system located in San Francisco.

temperature of TAVG were assumed. The total energy deficit in the morning hours is approximately the same as the surplus of energy in the afternoon. Consequently, the use of diurnal thermal energy storage will allow all long term storage calculations to be made based on the average daily temperature. The diurnal storage requirements were calculated for the worst case climatic event for Portland making the usual assumptions of WELL equal to 15 MW and LDRATIO equal to 1.6. The amount of diurnal storage required was found to be 0.245×10^6 ℓ, or approximately 1.3% of the minimum cost storage capacity of 19.12×10^6ℓ. This diurnal storage amount would be in addition to the long term storage capacities mentioned in this report. It is believed that this "assumption" of diurnal storage is the primary reason that no storage was found to be required below a LDRATIO of approximately 1.15 (see Figures 5.1 and 5.6).

Table 5.5 gives a listing of the minimum cost storage sizes for the cities studied. These minimum cost points are the primary desired result of this research project. From these data trends that are evident are used to make the following recommendations to storage sizing practices. The first observation made is that for the two localities with the coldest winter temperatures, Indianapolis and Salt Lake City, no storage facilities should be provided since the thermal peaking energy could be provided cheaper by a fossil fueled boiler. In contrast, at the three maritime cities, Norfolk, Portland and San Francisco, a storage tank will definitely reduce the cost of operating the district heating system. In fact, essentially all of the thermal peaking energy should be provided by the storage system since the minimum cost points correspond to a percent of days that the tank is empty of 0% for San Francisco and 0.5% for Norfolk and Portland. Of note here is that although the minimum cost points for the maritime cities indicate that thermal energy storage is advantageous, the total costs are higher than for the inland cities at their minimum points. This is due to the fact that more peaking energy will be required at the maritime cities.

Table 5.5 Minimum cost storage capacity and the associated cost for the six cities studied. MAXLOAD is 24 MW.

CITY	STORAGE (10^6 ℓ)	COST (10^6 \$)
Albuquerque	9.15	0.7868
Indianapolis	0.	0.3171
Norfolk	18.27	1.3473
Portland	19.12	1.3297
Salt Lake City	0.	0.3340
San Francisco	111.7	3.3265

The conclusion drawn from this is that storage tanks seem to be better suited for applications in milder climates. This is nicely illustrated in Figure 5.9, which shows an exponential increase in the minimum cost storage size in relation to the 99% design temperature. As previously done for the other sizing analyses, a multiple linear regression analysis was performed on

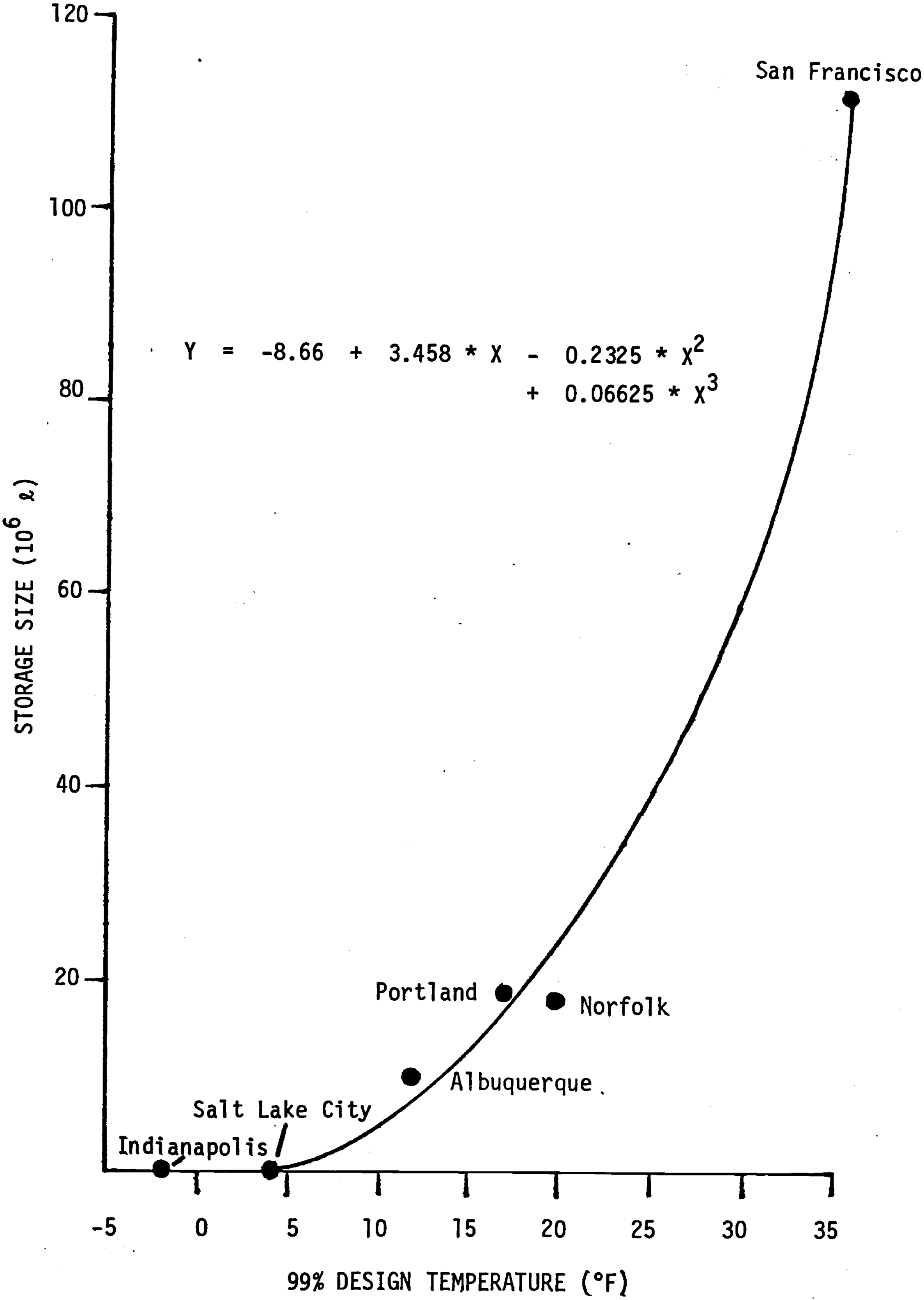

Figure 5.9 Plot of the minimum cost storage capacity as a function of the local 99% design temperature.

the storage sizes as a function of climatic parameters. Table 5.6 gives the resulting regression equation which predicts the minimum cost storage size as a function of degree days, average January temperature, design temperature, elevation and the total horizontal incident radiation from November through March.

Table 5.6 Regression equation relating the minimum cost storage capacity to local climatic parameters. MAXLOAD is 24 MW.

Storage = 0.0716215 * Degree Days (°F)

+ 3.33591 * Average January Temeprature (°F)

+ 5.34320 * 99% Design Temperature (°F)

- 0.016749 * Elevation (ft)

+ 0.0034289 * Total Horizontal Radiation, Nov. - March (KJ/m^2)

- 634.97

$R^2 = 1.000$

To get an idea of how the minimum cost storage size is affected by location throughout the United States, this regression equation was applied to 25 other U.S. cities located near known or potential geothermal resources. These cities and their resulting storage sizes are listed in Table 5.7. Note that many of the cities, especially in the East, show a negative storage size. While being facetious, these values are left in for comparative purposes. It

Table 5.7 Predicted minimum cost storage size for other cities in the United States. MAXLOAD is assumed to be 24 MW.

CITY	STORAGE CAPACITY (10^6 ℓ)
Eastern U.S.	
Albany, NY	33.15
Birmingham, AL	-43.51
Charlestown, SC	-22.08
Dallas, TX	-31.72
Detroit, MI	21.50
Evansville, IN	-47.12
Houston, TX	-31.20
Little Rock, AR	-17.39
New Orleans, LA	-14.48
Philadelphia, PA	-15.56
Savannah, GA	-3.53
South Bend, IN	-9.66
Tulsa, OK	-28.03
Washington, DC	0.70
Western U.S.	
Boise, ID	-3.31
Cedar City, UT	35.69
Denver, CO	-68.73
El Paso, TX	10.61
Flagstaff, AZ	84.26
Helena, MT	-47.19
Reno, NV	81.27
Riverside, CA	102.06
Santa Barbara, CA	83.83
Seattle, WA	22.32
Winnemuca, NV	45.02

is felt that the extreme cold of a continential climate makes storage tanks uneconomical in many of the cities due to a higher heat loss from the tank coupled with the fact that the non-linear heating demand curve was used in this program which discounts the effect of colder temperatures on the system heating load. In addition, the frequency of events differed between the climate types and seemed to influence the storage requirements. The maritime cities, while only experiencing relatively mild temperatures as compared to the inland cities, tended to have events of longer duration. In contrast, the inland cities typically experience events of colder temperatures but of a shorter duration and possibly mixed with periods of mild temperatures.

The sensitivity of the minimum cost storage sizes to differing values of the economic parameters was also checked. As can be seen from Figures 5.10 a and b, the only economic parameters that seem to have any significant influence on the costing results are the years of amortization and the interest rate on capital. Changes in the other parameters of ± 100% result in storage system cost changes of less than 10%. In all of the cases studied, the resulting changes were not enough to change the minimum cost storage capacity to any significant degree. Consequently, it is believed that these cost estimations accurately reflect what trends could be expected. The sensitivity of the storage size to the economic parameters was less than what was observed for the engineering parameters as discussed in section 5.3.

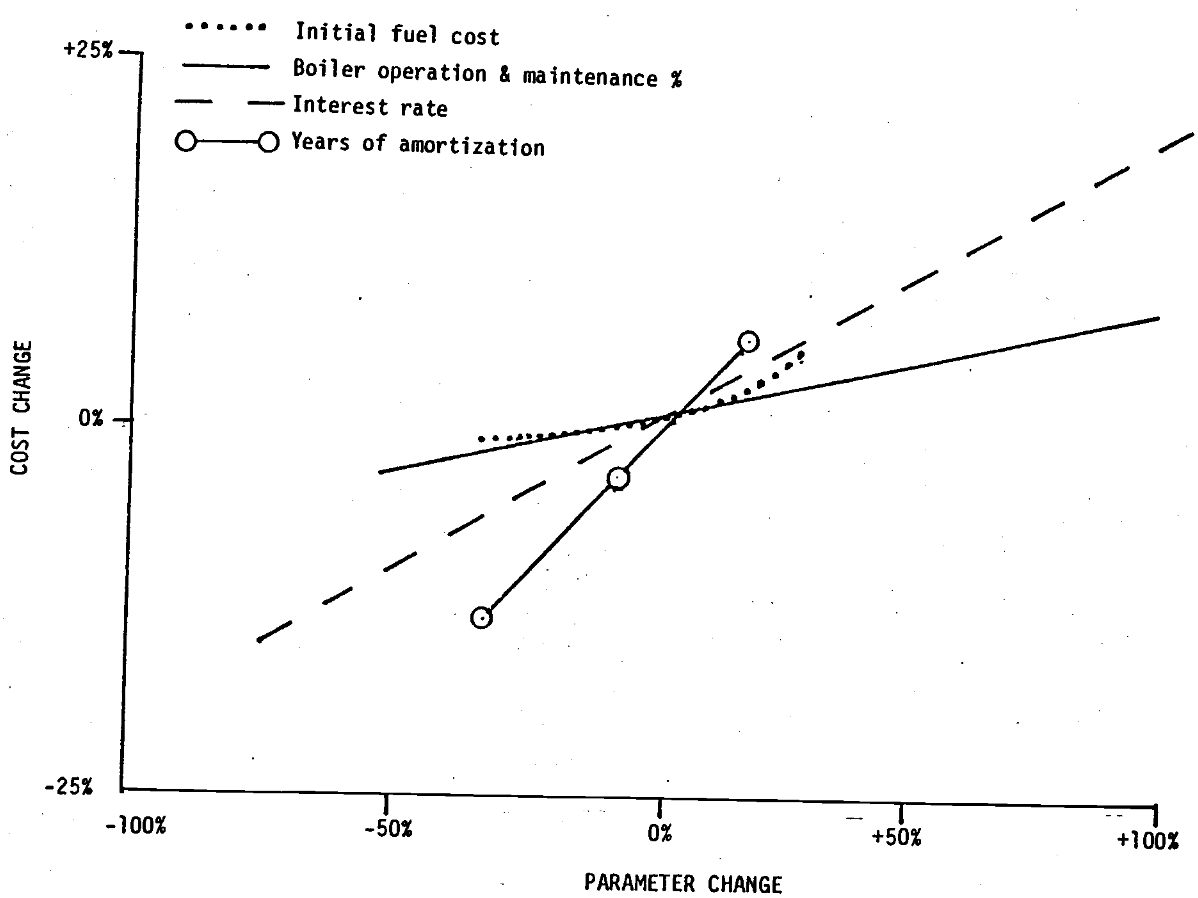

Figure 5.10 a Sensitivity of peaking system cost to changes in economic parameters. All costs are taken for a district heating system operating in Portland with a storage capacity of 22.65×10^6 ℓ.

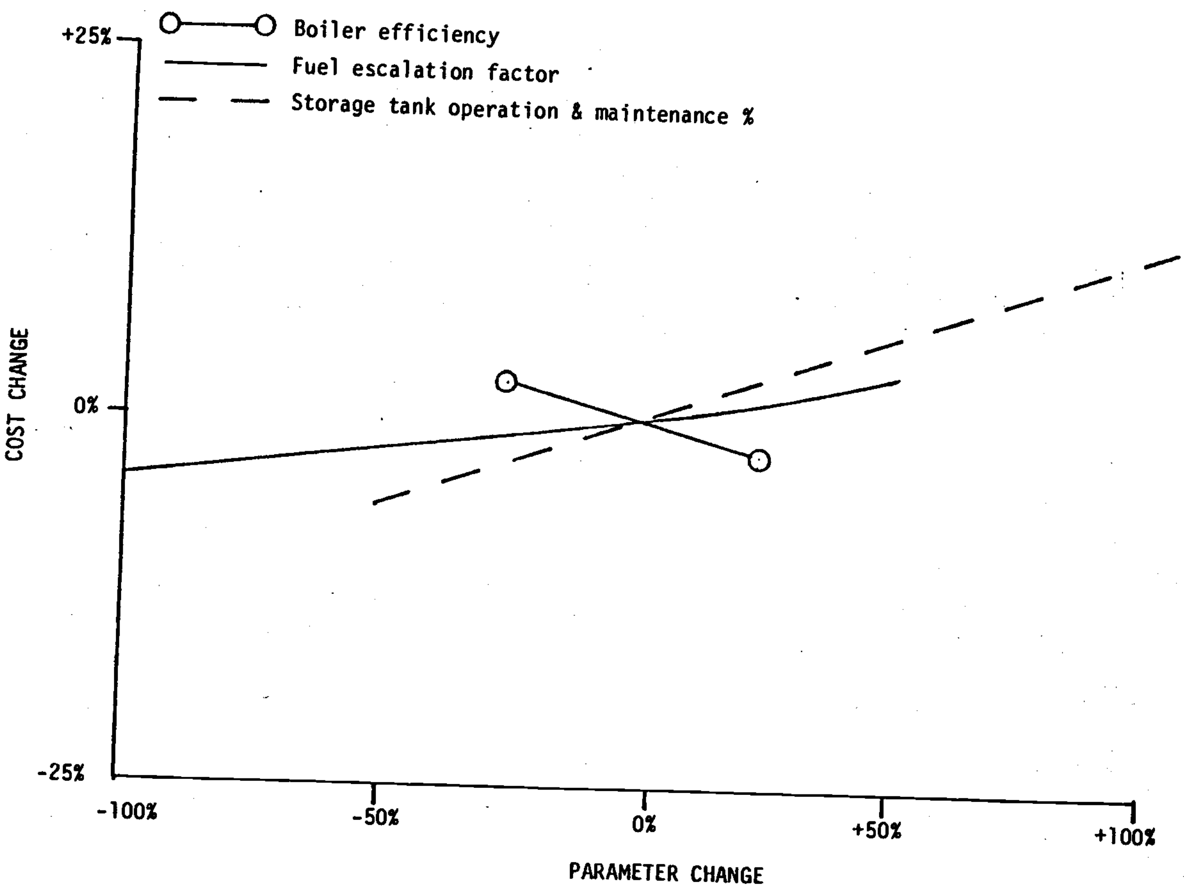

Figure 5.10 b Sensitivity of peaking system cost to changes in economic parameters. All costs are taken for a district heating system operating in Portland with a storage capacity of 22.65 x 10^6 ℓ.

5.5 Effect of the LDRATIO on System Economics

The effect on the total cost of providing peaking energy when a system has a LDRATIO different than the 1.6 value assumed in most of the results here was found to be extremely important. Figure 5.11 shows a plot of the total peaking system cost as a function of storage tank capacity for LDRATIO values of 1.2, 1.4, 1.6 and 1.8. Note that above a LDRATIO of 1.6 the peaking system costs are much higher. In fact they are about twice as high at a LDRATIO of 1.8 than the costs for the same storage capacity and a LDRATIO of 1.6.

What does it mean to the economics of a district heating system to chang[illegible]RATIO? As has been shown, the total peaking system cost decreases if a LDRATIO less than 1.6 were tried. However, this means that the total amount of energy sold by the system will also be less for a fixed number of geothermal wells, and thus the cost per unit of delivered energy will possibly be higher. As far as which LDRATIO will be best for any particular system, a final answer can not be reached based only on the results of this study. Additional information on the particular resource must be considered.

If the LDRATIO were changed after the system was in operation or already designed, then the system operator will want to know if the additional heating demand should be supplied by drilling another resource well or by expanding the peaking system capability. If the peaking system were expanded without drilling another well, then the LDRATIO will be increased. It is possible from the results of the ECON program to estimate the cost per unit of peaking energy for the cities studied. The cost per 10^6 Btu peaking energy for the

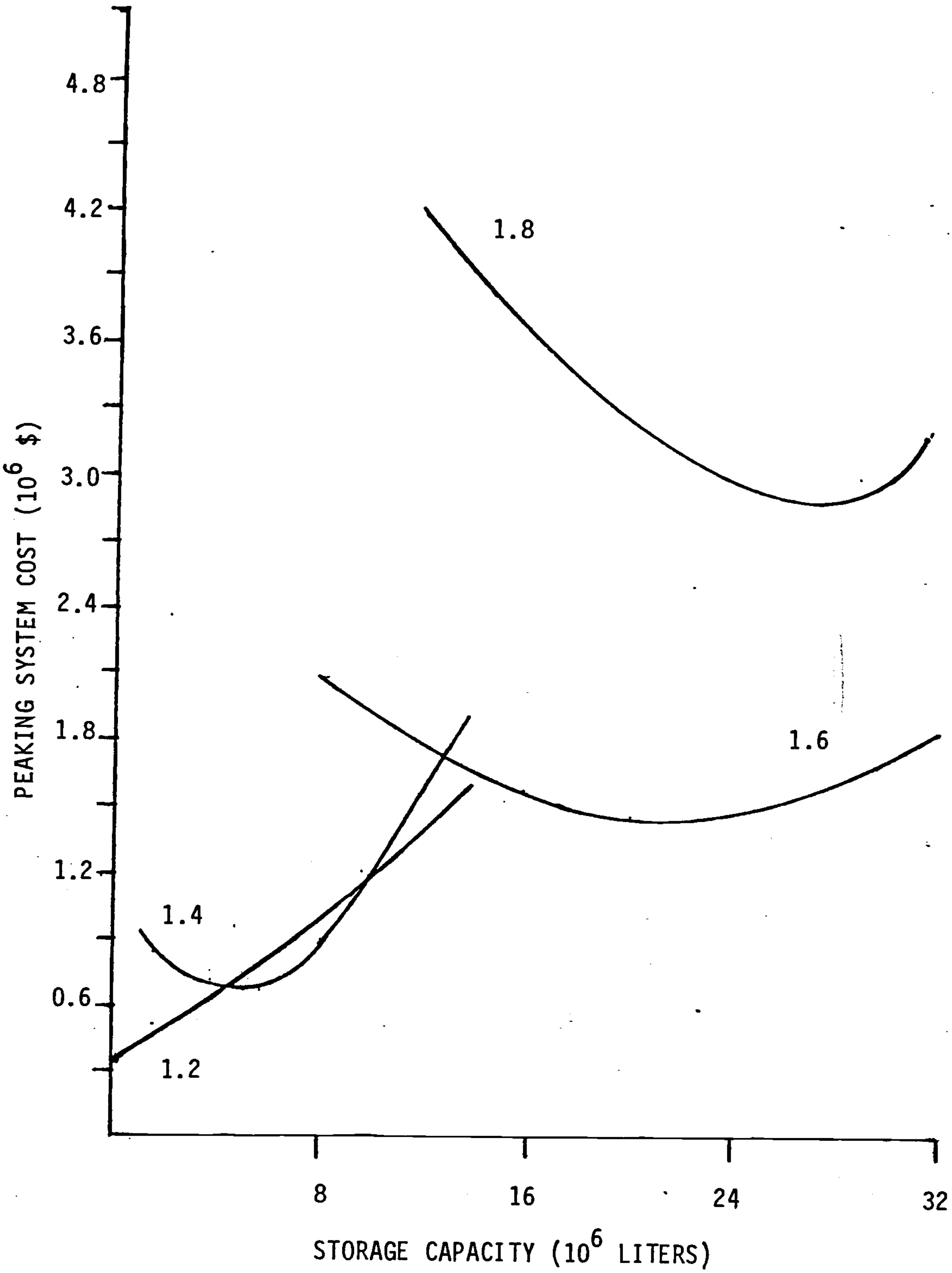

Figure 5.11 Total peaking system cost as a function of storage tank capacity for a district heating system located in Portland with various LDRATIO values. Base case economic parameters were assumed.

minimum cost storage capacities are listed in Table 5.8. Since this study did not include any analysis of the resource economics, it would be up to the system designer to decide whether the addition of another resource well would have a lower cost per unit of energy or not. However, based on the results of a comparison of the unit peaking energy costs for LDRATIO values of 1.4, 1.6 and 1.8 shown in Table 5.9, the most economic LDRATIO will probably occur close to a value of 1.6.

Table 5.8 Estimated unit peaking energy cost at the minimum cost storage capacities and for a LDRATIO of 1.6.

CITY	TOTAL PEAKING ENERGY SUPPLIED (Btu)	ESTIMATED UNIT PEAKING ENERGY COST AT MINIMUM COST STORAGE CAPACITY ($\$/10^6$ Btu)*
MARITIME		
Norfolk	3.1×10^{11}	4.20
Portland	3.1×10^{11}	4.50
San Francisco	6.3×10^{11}	6.30
INLAND		
Albuquerque	1.9×10^{11}	3.90
Indianapolis	5.4×10^{9}	59.30 **
Salt Lake City	4.5×10^{9}	73.30 **

* Does not include any resource development and operation costs, essentially meaning that the energy from the well is "free".

** These numbers do not have much relevance since the boiler was sized to meet entire system load but the cost of the boiler is assumed to be spread over only a relatively small amount of peaking energy.

Note: Fuel cost is assumed to be $\$12.10/10^6$ Btu in real 1981 dollars.

Table 5.9 Comparison of the unit peaking energy costs for a district heating system located in Portland and with varying LDRATIO values.

LDRATIO	TOTAL PEAKING ENERGY SUPPLIED (Btu)	ESTIMATED UNIT PEAKING ENERGY COST AT MINIMUM COST STORAGE CAPACITY ($/10^6 Btu)
1.4	5.9×10^{10}	12.20
1.6	3.1×10^{11}	4.50
1.8	5.0×10^{11}	5.60

(Same footnotes apply as given in Table 5.8)

VI. SUMMARY

The recommended thermal energy storage capacity for a geothermal based district heating system was estimated with respect to the system design heating load and the local climate. Although the thermal energy could be stored by a variety of methods, the analyses performed in this project assumed that storage was accomplished by the use of a storage tank filled with hot water.

The local climate was represented by a series of events which characterize the nature and sequence of the climatic events that can be expected at the particular locality. The events were defined as those days in which the average daily temperature was less than 10 degrees above the ASHRAE 97.5% design temperature, and each event was expressed in terms of the duration in days, the number of days between events, the average daily low temperature, and the average daily temperature range.

The storage size was estimated using several different models. The worst case storage capacity was first found using the most severe event for each locality. Two different relationships for the heating demand as a function of ambient temperature were used in the worst case analysis, one linear and the other non-linear. For the linear case, the peak storage requirements were found to occur at a load ratio (LDRATIO) of about 1.25, while the non-linear case exhibited peak storage sizes for a LDRATIO of approximately 1.6. The LDRATIO was defined as the ratio of the design heating load to the maximum well production rate. It was reasoned however that the use of only a single event to determine the storage requirements ignored the significance of event spacing. Therefore, the operation of the peaking system over the entire 20 year sequence of recorded events was simulated. First done was a study on the effect of engineering design parameters on the storage requirements, and then a simulation was performed from an economic perspective to find the storage size that gives the lowest cost peaking system.

The storage capacity required was found to be extremely sensitive to variations in the LDRATIO. In addition, for a LDRATIO of above 1.6, the storage requirements were found to increase more rapidly than below 1.6, suggesting that a limit on the LDRATIO of 1.6 be considered when designing a system.

The disparity in storage size requirements among the cities was first observed in the engineering design analysis and appeared quite strongly in the economic analysis. District heating systems located in cities that could be characterized by a maritime climate were found to be better suited for the use of storage tanks than colder inland climates. In fact, the results of the economic analysis model indicate that the maritime cities have a minimum peaking system cost at storage sizes close to the maximum storage capacities previously predicted, while the results for the two colder inland cities (Salt Lake City and Indianapolis) suggest that no storage tanks be included there. Recommended storage tank capacities for cities other than those studied here were found by a multivariate regression analysis relating the minimum cost storage sizes to several common climatic parameters.

To help a designer of an actual district heating system decide how to treat a system with the LDRATIO different than 1.6, a study of the peaking system cost as a function of storage capacities was done for varying LDRATIO values. The total peaking system costs were found to increase rapidly above a LDRATIO of 1.6. Additional, the unit cost of peaking energy was found to be a minimum at a LDRATIO of 1.6. These facts strengthen the recommendation of limiting the LDRATIO to a value of 1.6. Based on the total amount of energy supplied by the peaking system, an estimate was made of the unit peaking energy cost at the minimum cost points. Such information is valuable when estimating whether additional heating demand on an operational or already designed system should be supplied by the peaking system or by the addition of another resource well.

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APPENDICES

APPENDIX A

NOMENCLATURE

NOMENCLATURE

GENERAL

A	Total surface area
F	Ratio of event load to MAXLOAD based on temperature
P	Perimeter length
Q	Heat flow out of storage tank
R_{inside}	Convective heat loss resistance inside storage tank
$R_{insulation}$	Conduction resistance of storage tank insulation
$R_{outside}$	Convective resistance to outside air
T	Temperature difference of storage water and ambient
T_{amb}	Ambient temperature
T_{avg}	Average daily temperature
T_{base}	Minimum temperature at which no heating demand will occur
t_i	Storage water temperature
T_{min}	Minimum daily temperature
t_o	Ambient temperature
U	Overall heat transfer coefficient

USED IN PROGRAMS

ANUBCAP	Annual boiler capital cost
ANUTCAP	Annual storage tank capital cost

ANUBOM	Annual boiler operation and maintenance cost
ANUTOM	Annual storage tank operation and maintenance cost
BBUCKS	Total boiler capital cost
BCOST	Total boiler cost
BEFFIC	Boiler efficiency
DURA	Event duration
ECON	Economic analysis program name
FCOST	Total fuel cost
FORCEIT	Engineering design sizing program name
FUELMJ	Fuel used in MJ
FUELUP	Fuel cost escalation factor
FUELUSE	Yearly fuel used
INTFUEL	Initial fuel cost
LDRATIO	Ratio of MAXLOAD to WELL
LOAD	Daily heating load of an event
LOADBTW	Daily heating load in period between events
LOSS	Actual heat loss from storage tank
MAXLOAD	Design heating load
MAXLOSS	Maximum heat loss from storage tank at design temperature
OANDMB	Boiler operation and maintenance, % of capital cost
OANDMT	Tank operation and maintenance, % of capital cost
PERCENT	Actual heating demand as percentage of theoretical

PERIM	Perimeter of storage tank
PRIME	Interest rate on capital, % above inflation
QRECHG	Daily recharge capacity of resource well(s)
QSTORE	Daily requirement of stored thermal energy
SEPAR	Number of days until next event
SIDE	Area of storage tank sides
SIZE	Size of storage tank
SOD	Ratio of SEPAR/DURA
SYSCOST	Total peaking system cost
TAVG	Average daily temperature
TBUCKS	Total storage tank capital cost
TCOST	Total storage tank cost
TFLUID	Total geothermal fluid required
TOP	Area of storage tank top
VOL	Volume of storage tank
X	Storage tank diameter
YEARAMT	Number of years for project amortization

APPENDIX B

LIST OF COMPUTER PROGRAMS

```
      PROGRAM FORCEIT
      REAL LOW,MXSTORE,LDRATIO,MAXLOSS,MAXLOAD
      CHARACTER CITY*10,FILE*6
      COMMON TANK,WELL,TOTDAYS,DRYDAYS,EVNTDAY,YEAR,CAPACTY,MAXLOSS,
     1TDESGN,MAXLOAD
C
C  SET MAXLOAD AT INITIAL VALUE OF 24 MW
C
      LDRATIO=1.6
      WELL=15.
      MAXLOAD=WELL*LDRATIO
      WELL=WELL*86400.
C
C  INPUT CITY SPECIFIC VALUES
C
      READ 100,CITY,FILE,MXSTORE,TDESGN
 100  FORMAT(A10,5X,A6,4X,F5.2,5X,F5.0)
      READ *,AVGNTEM,AVGDTEM,AVGJTEM,AVGFTEM,AVGMTEM
      OPEN(10,FILE=FILE)
C
C  CONVERT TEMPERATURES TO C
C
      AVGNTEM=(AVGNTEM-32.)/1.8
      AVGDTEM=(AVGDTEM-32.)/1.8
      AVGJTEM=(AVGJTEM-32.)/1.8
      AVGFTEM=(AVGFTEM-32.)/1.8
      AVGMTEM=(AVGMTEM-32.)/1.8
      TDESGN=(TDESGN-32.)/1.8
C
C  SET INITIAL TANK CAPACITY AT 20% OF MAXIMUM,
C  ALSO INITIALIZE COUNTERS
C
      FUDGEF=0.20
      CAPACTY=MXSTORE*FUDGEF
      TANK=CAPACTY*167360.
      TOTDAYS=0.
      YEAR=0.
      LOOP=1
      DRYDAYS=0.
      EVNTDAY=0.
      DAYNOW=0.
      FUGHIGH=1.
      FUGLOW=0.
C
C  FIND MAXIMUM HEAT LOSS BASED ON THIS TANK SIZE
C
      MAXLOSS=HEAT(CAPACTY,TDESGN)
      CALL HEADING(FUDGEF,CITY)
```

```
C
C  ******  BEGIN SIMULATION  ********
C
C  READ IN AN EVENT'S PARAMETERS AND CONVERT
C   ---   IF END-OF-FILE, LEAVE SIMULATION
C   ---   IF NEW YEAR BEGINS, INITIALIZE FOR IT
C
 10   READ(10,*)DURA,LOW,RANGE,SEPER
      IF(DURA.LT.0.) GO TO 30
      LOW=(LOW-32.)/1.8
      RANGE=RANGE/1.8
      TAVG=LOW+RANGE/2.
      IF(SEPER.EQ.30.) THEN
         READ(10,*) STARTDY,SKIP
         SEPER=STARTDY
         IF(YEAR.LT.1.) GO TO 320
         IF(SKIP.GT.0.) THEN
            YEARN=YEAR+1.
            PRINT 300,YEARN
 300        FORMAT('0',T10,'YEAR ',F4.0,'  HAS NO EVENTS')
            ENDIF
         PRINT 310,YEAR,EVNTDAY,DRYDAYS
 310     FORMAT('0',T5,F5.0,4X,F4.0,9X,F5.0)
 320     TOTDAYS=TOTDAYS+DRYDAYS
         DAYNOW=0.
         YEAR=YEAR+1.+SKIP
         EVNTDAY=0.
         DRYDAYS=0.
         TANK=CAPACTY*167360.
         ENDIF
C
C  CALCULATE DAY OF UPCOMING EVENT
C
 20   DAYNEXT=DAYNOW+SEPER
      EVNTDAY=EVNTDAY+DURA
C
C  CHECK IF EVENT OCCURS IN NOVEMBER
C    ---   IF SO, UPDATE RECHARGING AND HEAT LOSS, SET CURRENT DAY
C
      IF(DAYNEXT.LE.30.) THEN
         TIME=DAYNEXT-DAYNOW
         CALL RECHG(TIME,AVGNTEM)
         CALL LOAD(TAVG,DURA)
         DAYNOW=DAYNEXT+DURA
         GO TO 10
      ENDIF
```

```
C
C  CHECK IF EVENT OCCURS IN DECEMBER
C    ---  IF SO, UPDATE RECHARGING AND HEAT LOSS, SET CURRENT DAY
C
      IF(DAYNEXT.LE.61.) THEN
         IF(DAYNOW.LT.30.) CALL NOVEMB(DAYNOW,AVGNTEM)
         TIME=DAYNEXT-DAYNOW
         CALL RECHG(TIME,AVGDTEM)
         CALL LOAD(TAVG,DURA)
         DAYNOW=DAYNEXT+DURA
         GO TO 10
      ENDIF
C
C  CHECK IF EVENT OCCURS IN JANUARY
C    ---  IF SO, UPDAT RECHARGING AND HEAT LOSS, SET CURRENT DAY
C
      IF(DAYNEXT.LE.92.) THEN
         IF(DAYNOW.LT.30.) CALL NOVEMB(DAYNOW,AVGNTEM)
         IF(DAYNOW.LT.61.) CALL DECEMB(DAYNOW,AVGDTEM)
         TIME=DAYNEXT-DAYNOW
         CALL RECHG(TIME,AVGJTEM)
         CALL LOAD(TAVG,DURA)
         DAYNOW=DAYNEXT+DURA
         GO TO 10
      ENDIF
C
C  CHECK IF EVENT OCCURS IN FEBRUARY
C    ---  IF SO, UPDATE RECHARGING AND HEAT LOSS, SET CURRENT DAY
C
      IF(DAYNEXT.LT.120.) THEN
         IF(DAYNOW.LT.30.) CALL NOVEMB(DAYNOW,AVGNTEM)
         IF(DAYNOW.LT.61.) CALL DECEMB(DAYNOW,AVGDTEM)
         IF(DAYNOW.LT.92.) CALL JANUAR(DAYNOW,AVGJTEM)
         TIME=DAYNEXT-DAYNOW
         CALL RECHG(TIME,AVGFTEM)
         CALL LOAD(TAVG,DURA)
         DAYNOW=DAYNEXT+DURA
         GO TO 10
      ENDIF
C
C  EVENT OCCURS IN MARCH
C    ---  SO, UPDATE RECHARGING AND HEAT LOSS, SET CURRENT DAY
C
      IF(DAYNOW.LT.30.) CALL NOVEMB(DAYNOW,AVGNTEM)
      IF(DAYNOW.LT.61.) CALL DECEMB(DAYNOW,AVGDTEM)
      IF(DAYNOW.LT.92.) CALL JANUAR(DAYNOW,AVGJTEM)
      IF(DAYNOW.LT.120.) CALL FEBRUA(DAYNOW,AVGFTEM)
      TIME=DAYNEXT-DAYNOW
      CALL RECHG(TIME,AVGMTEM)
      CALL LOAD(TAVG,DURA)
      DAYNOW=DAYNEXT+DURA
      GO TO 10
```

```
 30   PERCENT=TOTDAYS/28.69
      DIFF=PERCENT-1.
      PRINT 110,CAPACTY,PERCENT
 110  FORMAT('0',/T3,'A STORAGE CAPACITY OF',F6.2,' RESULTS IN',F5.1,
     1' % OF THE DAYS WITH ZERO RESERVE STORAGE')
      PRINT 120,(FUDGEF*100.)
 120  FORMAT('0',T20,'THE STORAGE IS ',F5.1,' % OF MAXIMUM')
C
C  CHECK TO SEE IF PERCENT OF DAYS IS WITHIN TOLERANCE
C
      IF(ABS(DIFF).LE.0.5) GO TO 99
C
C  CHECK IF STORAGE TO BE INCREASED OR DECREASED AND DO SO
C
      IF(DIFF.GT.0.) THEN
         FUGLOW=FUDGEF
       ELSE
           FUGHIGH=FUDGEF
      ENDIF
      FUDGEF=(FUGLOW+FUGHIGH)/2.
      REWIND 10
      LOOP=LOOP+1
      IF(LOOP.GT.15) GO TO 99
      CALL HEADING(FUDGEF,CITY)
      YEAR=0.
      DRYDAYS=0.
      EVNTDAY=0.
      DAYNOW=0.
      TOTDAYS=0.
      CAPACTY=MXSTORE*FUDGEF
      TANK=CAPACTY*167360.
      MAXLOSS=HEAT(CAPACTY,TDESGN)
      GO TO 10
 99   STOP
      END
      SUBROUTINE LOADBTW(T,L)
      COMMON TANK,WELL,TOTDAYS,DRYDAYS,EVNTDAY,YEAR,CAPACTY,MAXLOSS,
     1TDESGN,MAXLOAD
      REAL L,MAXLOAD
      FBTW=86400.*(18-T)/(18-TDESGN)
      QUADFBT=86.2+1.77*T
      FBTW=FBTW*QUADFBT/100.
      L=FBTW*MAXLOAD
      RETURN
      END
      SUBROUTINE HEATL(T)
      COMMON TANK,WELL,TOTDAYS,DRYDAYS,EVNTDAY,YEAR,CAPACTY,MAXLOSS,
     1TDESGN,MAXLOAD
```

```
      REAL HOWFULL,LOSS,MAXLOAD,MAXLOSS
      PORTION=(80.-T)/(80.-TDESGN)
      HOWFULL=(TANK/167360.)/CAPACTY
      PORTION=PORTION*HOWFULL
      LOSS=PORTION*MAXLOSS
      TANK=TANK-LOSS
      IF(TANK.LE.0.) THEN
         TANK=0.
         DRYDAYS=DRYDAYS+1.
      ENDIF
      RETURN
      END
      SUBROUTINE LOAD(T,D)
      COMMON TANK,WELL,TOTDAYS,DRYDAYS,EVNTDAY,YEAR,CAPACTY,MAXLOSS,
     1TDESGN,MAXLOAD
      REAL LD,MAXLOAD,MAXLOSS
      IF(TANK.LE.0.) THEN
         DRYDAYS=DRYDAYS+D
         GO TO 99
      ENDIF
      F=86400.*(18.-T)/(18.-TDESGN)
      QUADF=86.2+1.77*T
      F=F*QUADF/100.
      LD=F*MAXLOAD
      QSTORE=LD-WELL
      DO 10 I=1,D
      TANK=TANK-QSTORE
      IF(TANK.LE.0.) THEN
         TANK=0.
         DRYDAYS=DRYDAYS+(D-I)
         GO TO 99
      ENDIF
      CALL HEATL(T)
10    CONTINUE
99    RETURN
      END
      SUBROUTINE NOVEMB(DAY,TEMP)
      TIME=30.-DAY
      CALL RECHG(TIME,TEMP)
      DAY=30.
      RETURN
      END
      SUBROUTINE DECEMB(DAY,TEMP)
      TIME=61.-DAY
      CALL RECHG(TIME,TEMP)
      DAY=61.
      RETURN
      END
      SUBROUTINE JANUAR(DAY,TEMP)
      TIME=92.-DAY
      CALL RECHG(TIME,TEMP)
      DAY=92.
      RETURN
      END
```

```
      SUBROUTINE FEBRUA(DAY,TEMP)
      TIME=120.-DAY
      CALL RECHG(TIME,TEMP)
      DAY=120.
      RETURN
      END
      SUBROUTINE HEADING(F,CITY)
      CHARACTER CITY*10
      FUDGE=F*100.
      PRINT 10,CITY
 10   FORMAT('1',T6,'SIMULATION FOR ',A10,' WITH')
      PRINT 20,FUDGE
 20   FORMAT(' ',T6,'STORAGE SIZE ',F4.1,' % OF MAXIMUM')
      PRINT 30
 30   FORMAT('0',T15,'" OF',9X,'" DAYS')
      PRINT 40
 40   FORMAT(' ',T6,'YEAR   EVENT DAYS    TANK EMPTY')
      PRINT 50
 50   FORMAT(' ',11('----'))
      PRINT *
      RETURN
      END
      SUBROUTINE RECHG(TIME,TEMP)
      COMMON TANK,WELL,TOTDAYS,DRYDAYS,EVNTDAY,YEAR,CAPACTY,MAXLOSS,
     1TDESGN,MAXLOAD
      REAL LOADB,MAXLOSS,MAXLOAD
      CALL LOADBTW(TEMP,LOADB)
      QRECHG=WELL-LOADB
      IF(QRECHG.LE.0.) THEN
         DO 5 J=1,TIME
         CALL HEATL(TEMP)
 5       CONTINUE
         GO TO 99
         ENDIF
      CAPENG=CAPACTY*167360.
      DO 10 I=1,TIME
      TANK=TANK+QRECHG
      CALL HEATL(TEMP)
      IF(TANK.GT.CAPENG) TANK = CAPENG
 10   CONTINUE
 99   RETURN
      END
      FUNCTION HEAT(SIZE,TEMP)
      PI=4.*ATAN(1.0)
C
C  NOTE THAT TANK TEMPERATURE IS ASSUMED TO BE 55 DEG. C,
C    SIZE IS IN MILLION LITERS (VOL IS IN CUBIC METERS),
C    AND TANK IS ASSUMED A CYLINDER WITH HEIGHT EQUAL TO DIAMETER.
C
      DELTAT=80.-TEMP
      VOL=SIZE*1000.
      X=(VOL/PI)**(1./3.)
      PERIM=PI*X
```

```
C
C  ASSUMES F VALUE OF 0.95 W/M (LINEAR)  - K
C
      HEATB=0.95*DELTAT*PERIM
      SIDE=X*PI*X
      TOP=PI/4.*X*X
C
C  ASSUMES U VALUE OF 5.1 W/SQ. M - K
C
      HEATS=5.1*DELTAT*SIDE
      HEATT=5.1*DELTAT*TOP
C
C  FIND DAILY HEAT LOSS IN MJ
C
      HEAT=0.0864*(HEATB+HEATS+HEATT)
      END
```

```
      PROGRAM ECON
      REAL LOW,MXSTORE,LDRATIO,MAXLOSS,MAXLOAD,INTFUEL,N
      DIMENSION PARAM(7)
      CHARACTER CITY*10,FILE*6,REPEAT*3
      COMMON TANK,WELL,YEAR,CAPACTY,MAXLOSS,TDESGN,MAXLOAD,
     1FUELUSE,BEFFIC,TOTDAYS,FUELMJ,DRYDAYS,QFLUIDJ
C
C  INPUT SIMULATION VALUES FOR PRIME RATE,BOILER O&M,TANK O&M,FUEL ESCALATION
C  BOILER EFFICIENCY,YEARS OF AMORTIZATION
C
      READ*,(PARAM(I),I=1,7)
      PRIME=PARAM(1)
      OANDMB=PARAM(2)
      OANDMT=PARAM(3)
      INTFUEL=PARAM(4)
      FUELUP=PARAM(5)
      BEFFIC=PARAM(6)
      YEARAMT=PARAM(7)
C
C  SET MAXLOAD AT INITIAL VALUE OF 24 MW
C
      LDRATIO=1.6
      WELL=15.
      MAXLOAD=WELL*LDRATIO
      WELL=WELL*86400.
C
C  INPUT CITY SPECIFIC VALUES
C
      READ 100,CITY,FILE
 100  FORMAT(A10,5X,A6)
      OPEN(10,FILE=FILE)
      REWIND 10
      READ (10,*) MXSTORE,TDESGN
      READ (10,*) AVGNTEM,AVGDTEM,AVGJTEM,AVGFTEM,AVGMTEM
C
C  CONVERT TEMPERATURES TO C
C
      AVGNTEM=(AVGNTEM-32.)/1.8
      AVGDTEM=(AVGDTEM-32.)/1.8
      AVGJTEM=(AVGJTEM-32.)/1.8
      AVGFTEM=(AVGFTEM-32.)/1.8
      AVGMTEM=(AVGMTEM-32.)/1.8
      TDESGN=(TDESGN-32.)/1.8
C
C  INPUT TANK CAPACITY VALUES TO BE USED
C
      PRINT *,'INPUT THE LOWER LIMIT,UPPER LIMIT, AND STEP SIZE'
      PRINT *,'    OF THE FUDGE FACTOR.'
      READ *.A.B.N
```

```
      PRINT 250
  250 FORMAT('1')
  2   CALL HEADING(CITY)
      DO 5 FUDGEF=A,B,N
      CAPACTY=MXSTORE*FUDGEF
      TANK=CAPACTY*167360.
C
C  COMPUTE THE FIXED ANNUAL AND TOTAL CHARGES
C     INCLUDES OPERATION AND MAINTENANCE AND CAPITALIZATION COSTS
C
      CALL COSTING(TBUCKS,BBUCKS)
      ANUTCAP=AMORT(TBUCKS,YEARAMT,PRIME)
      ANUBCAP=AMORT(BBUCKS,YEARAMT,PRIME)
      ANUBOM=BBUCKS*(OANDMB/100.)
      ANUTOM=TBUCKS*(OANDMT/100.)
      BCOST=(ANUBCAP+ANUBOM)*YEARAMT
      TCOST=(ANUTCAP+ANUTOM)*YEARAMT
      QFLUIDJ=0.
      FCOST=0.
      FUELMJ=0.
      TOTDAYS=0.
      YEAR=0.
      DRYDAYS=0.
      DAYNOW=0.
C
C  FIND MAXIMUM HEAT LOSS BASED ON THIS TANK SIZE
C
      MAXLOSS=HEAT(CAPACTY,TDESGN)
C
C  ******  BEGIN SIMULATION  ********
C
C  READ IN AN EVENT'S PARAMETERS AND CONVERT
C   ---   IF END-OF-FILE, LEAVE SIMULATION
C   ---   IF NEW YEAR BEGINS, INITIALIZE FOR IT
C
  10  READ(10,*)DURA,LOW,RANGE,SEPER
      IF(DURA.LT.0.) GO TO 30
      LOW=(LOW-32.)/1.8
      RANGE=RANGE/1.8
      TAVG=LOW+RANGE/2.
      IF(SEPER.EQ.30.) THEN
         READ(10,*) STARTDY,SKIP
         SEPER=STARTDY
C
C  FIND FUEL USED IN MILLION BTU AND COMPUTE FUEL COST
C
         F=ESCA(FUELUP,YEAR)
         FUELUSE=FUELMJ/1054.4
         FCOST=FCOST+(FUELUSE*F*INTFUEL)
         DAYNOW=0.
         TOTDAYS=TOTDAYS+DRYDAYS
```

```
         YEAR=YEAR+1.+SKIP
         EVNTDAY=0.
         DRYDAYS=0.
         TANK=CAPACTY*167360.
         ENDIF
C
C  CALCULATE DAY OF UPCOMING EVENT
C
      DAYNEXT=DAYNOW+SEPER
C
C  CHECK IF EVENT OCCURS IN NOVEMBER
C    ---  IF SO, UPDATE RECHARGING AND HEAT LOSS, SET CURRENT DAY
C
      IF(DAYNEXT.LE.30.) THEN
         TIME=DAYNEXT-DAYNOW
         CALL RECHG(TIME,AVGNTEM)
         CALL LOAD(TAVG,DURA)
         DAYNOW=DAYNEXT+DURA
         GO TO 10
      ENDIF
C
C  CHECK IF EVENT OCCURS IN DECEMBER
C    ---  IF SO, UPDATE RECHARGING AND HEAT LOSS, SET CURRENT DAY
C
      IF(DAYNEXT.LE.61.) THEN
         IF(DAYNOW.LT.30.) CALL NOVEMB(DAYNOW,AVGNTEM)
         TIME=DAYNEXT-DAYNOW
         CALL RECHG(TIME,AVGDTEM)
         CALL LOAD(TAVG,DURA)
         DAYNOW=DAYNEXT+DURA
         GO TO 10
      ENDIF
C
C  CHECK IF EVENT OCCURS IN JANUARY
C    ---  IF SO, UPDAT RECHARGING AND HEAT LOSS, SET CURRENT DAY
C
      IF(DAYNEXT.LE.92.) THEN
         IF(DAYNOW.LT.30.) CALL NOVEMB(DAYNOW,AVGNTEM)
         IF(DAYNOW.LT.61.) CALL DECEMB(DAYNOW,AVGDTEM)
         TIME=DAYNEXT-DAYNOW
         CALL RECHG(TIME,AVGJTEM)
         CALL LOAD(TAVG,DURA)
         DAYNOW=DAYNEXT+DURA
         GO TO 10
      ENDIF
C
C  CHECK IF EVENT OCCURS IN FEBRUARY
C    ---  IF SO, UPDATE RECHARGING AND HEAT LOSS, SET CURRENT DAY
C
      IF(DAYNEXT.LT.120.) THEN
         IF(DAYNOW.LT.30.) CALL NOVEMB(DAYNOW.AVGNTEM)
```

```
      IF(DAYNOW.LT.61.) CALL DECEMB(DAYNOW,AVGDTEM)
      IF(DAYNOW.LT.92.) CALL JANUAR(DAYNOW,AVGJTEM)
      TIME=DAYNEXT-DAYNOW
      CALL RECHG(TIME,AVGFTEM)
      CALL LOAD(TAVG,DURA)
      DAYNOW=DAYNEXT+DURA
      GO TO 10
   ENDIF
C
C  EVENT OCCURS IN MARCH
C    ---  SO, UPDATE RECHARGING AND HEAT LOSS, SET CURRENT DAY
C
   IF(DAYNOW.LT.30.) CALL NOVEMB(DAYNOW,AVGNTEM)
   IF(DAYNOW.LT.61.) CALL DECEMB(DAYNOW,AVGDTEM)
   IF(DAYNOW.LT.92.) CALL JANUAR(DAYNOW,AVGJTEM)
   IF(DAYNOW.LT.120.) CALL FEBRUA(DAYNOW,AVGFTEM)
   TIME=DAYNEXT-DAYNOW
   CALL RECHG(TIME,AVGMTEM)
   CALL LOAD(TAVG,DURA)
   DAYNOW=DAYNEXT+DURA
   GO TO 10
30 F=ESCA(FUELUP,YEAR)
C
C  CONVERT FUEL USED FROM MJ TO MILLION BTU
C      AND GEOTHERMAL FLUID USED FROM 'J' TO KG
C
   FUELUSE=FUELMJ/1054.4
   TFLUID=QFLUIDJ/167.36
   FCOST=FCOST+(FUELUSE*F*INTFUEL)
   SYSCOST=TCOST+BCOST+FCOST
   TOTDAYS=TOTDAYS+DRYDAYS
   PRINT 110, CAPACTY,FCOST,BCOST,TCOST,SYSCOST,TOTDAYS,TFLUID
110 FORMAT('0',F7.3,F9.0,5(F10.0))
   REWIND 10
5  CONTINUE
C
C  IF ANOTHER RUN IS TO BE MADE, INPUT THE PARAMETER VALUES TO CHANGE
C
   PRINT 111,(PARAM(I),I=1,7)
111 FORMAT(' ',//7(F9.2))
150   READ *,INDEX,VALUE
      IF(INDEX.GT.10.) GO TO 999
      IF(INDEX.LE.0.) GO TO 155
      PARAM(INDEX)=VALUE
      GO TO 150
155   PRIME=PARAM(1)
      OANDMB=PARAM(2)
      OANDMT=PARAM(3)
      INTFUEL=PARAM(4)
      FUELUP=PARAM(5)
      BEFFIC=PARAM(6)
```

```
      YEARAMT=PARAM(7)
      GO TO 2
999   STOP
      END
      SUBROUTINE LOADBTW(T,L)
      COMMON TANK,WELL,YEAR,CAPACTY,MAXLOSS,TDESGN,MAXLOAD,
     1FUELUSE,BEFFIC,TOTDAYS,FUELMJ,DRYDAYS,QFLUIDJ
      REAL L,MAXLOAD
      FBTW=86400.*(18-T)/(18-TDESGN)
      QUADFBT=86.2+1.77*T
      FBTW=FBTW*QUADFBT/100.
      L=FBTW*MAXLOAD
      RETURN
      END
      SUBROUTINE HEATL(T)
      COMMON TANK,WELL,YEAR,CAPACTY,MAXLOSS,TDESGN,MAXLOAD,
     1FUELUSE,BEFFIC,TOTDAYS,FUELMJ,DRYDAYS,QFLUIDJ
      REAL HOWFULL,LOSS,MAXLOAD,MAXLOSS
      IF(CAPACTY.LE.0.) GO TO 10
      PORTION=(80.-T)/(80.-TDESGN)
      HOWFULL=(TANK/167360.)/CAPACTY
      PORTION=PORTION*HOWFULL
      LOSS=PORTION*MAXLOSS
      TANK=TANK-LOSS
      IF(TANK.LE.0.) TANK=0.
10    RETURN
      END
      SUBROUTINE LOAD(T,D)
      COMMON TANK,WELL,YEAR,CAPACTY,MAXLOSS,TDESGN,MAXLOAD,
     1FUELUSE,BEFFIC,TOTDAYS,FUELMJ,DRYDAYS,QFLUIDJ
      REAL LD,MAXLOAD,MAXLOSS
      IF(TANK.LE.0.) THEN
         DRYDAYS=DRYDAYS+D
         GO TO 99
      ENDIF
      F=86400.*(18.-T)/(18.-TDESGN)
      QUADF=86.2+1.77*T
      F=F*QUADF/100.
      LD=F*MAXLOAD
      QSTORE=LD-WELL
C
C  FIND AMOUNT OF FLUID USED:
C   1) IF LOAD IS LESS THAN WELL CAPACITY, FLUID (JOULES) = LOAD * DURA.
C   2) IF LOAD IS GREATER THAN WELL CAP., THEN FLUID USED = WELL * DURA.
C
      IF(QSTORE.LE.0.) THEN
         QFLUIDJ=QFLUIDJ+(LD*D)
         GO TO 99
      ELSE
         QFLUIDJ=QFLUIDJ+(WELL*D)
      FNDIF
```

```
      DO 10 I=1,D
      TANK=TANK-QSTORE
      IF(TANK.LE.0.) THEN
         TANK=0.
         DRYDAYS=DRYDAYS+(D-I)
C  FIND FUEL USED FOR PEAKING IN MJ, AND ADD TO TOTAL FUEL USE
         FUELMJ=(QSTORE*(D-I)/BEFFIC)+FUELMJ
         GO TO 99
      ENDIF
      CALL HEATL(T)
 10   CONTINUE
 99   RETURN
      END
      SUBROUTINE NOVEMB(DAY,TEMP)
      TIME=30.-DAY
      CALL RECHG(TIME,TEMP)
      DAY=30.
      RETURN
      END
      SUBROUTINE DECEMB(DAY,TEMP)
      TIME=61.-DAY
      CALL RECHG(TIME,TEMP)
      DAY=61.
      RETURN
      END
      SUBROUTINE JANUAR(DAY,TEMP)
      TIME=92.-DAY
      CALL RECHG(TIME,TEMP)
      DAY=92.
      RETURN
      END
      SUBROUTINE FEBRUA(DAY,TEMP)
      TIME=120.-DAY
      CALL RECHG(TIME,TEMP)
      DAY=120.
      RETURN
      END
      SUBROUTINE HEADING(CITY)
      CHARACTER CITY*10
      PRINT 20,CITY
 20   FORMAT(' ',T7,'ECONOMIC ANALYSIS FOR ',A10)
      PRINT 30
 30   FORMAT('0','STORE',5X,'FUEL ',5X,'BOILER',4X,'TANK ',5X,
     1'SYSTEM',4X,'TOTAL',5X,'FLUID')
      PRINT 40
 40   FORMAT(' ','M.LITR',4X,4('COST',6X),'DAYS',8X,'KG')
      PRINT 50
 50   FORMAT(' ',14('-----'))
      PRINT *
      RETURN
      END
```

```
      SUBROUTINE RECHG(TIME,TEMP)
      COMMON TANK,WELL,YEAR,CAPACTY,MAXLOSS,TDESGN,MAXLOAD,
     1FUELUSE,BEFFIC,TOTDAYS,FUELMJ,DRYDAYS,QFLUIDJ
      REAL LOADB,MAXLOSS,MAXLOAD
      CALL LOADBTU(TEMP,LOADB)
      QRECHG=WELL-LOADB
      IF(QRECHG.LE.0.) THEN
         DO 5 J=1,TIME
         CALL HEATL(TEMP)
         IF(TANK.LE.0) FUELMJ=(-1*QRECHG)/BEFFIC + FUELMJ
  5      CONTINUE
         GO TO 99
         ENDIF
      CAPENG=CAPACTY*167360.
      IF(CAPACTY.LE.0) THEN
         IF(QRECHG.LE.0.) THEN
            QFLUIDJ=QFLUIDJ+(WELL*TIME)
          ELSE
            QFLUIDJ=QFLUIDJ+(LOADB*TIME)
          ENDIF
         GO TO 99
      ENDIF
C
C  CHECK IF RECHARGE CAPACITY IS > 0
C  IF SO, SET FLUID USED (JOULES) TO WELL CAPACITY * TIME
C   THEN EXIT ROUTINE
C
      IF(QRECHG.LE.0.) THEN
         QFLUIDJ=QFLUIDJ+(WELL*TIME)
         GO TO 99
      ENDIF
C
C  SET FLUID USED AT LOAD BETWEEN EVENTS * TIME
C
      QFLUIDJ=QFLUIDJ+(LOADB*TIME)
      DO 10 I=1,TIME
      IF(TANK.LT.CAPENG) QFLUIDJ=QFLUIDJ+QRECHG
      TANK=TANK+QRECHG
      CALL HEATL(TEMP)
      IF(TANK.GE.CAPENG) TANK=CAPENG
 10   CONTINUE
 99   RETURN
      END
      FUNCTION HEAT(SIZE,TEMP)
      IF(SIZE.LE.0) THEN
         HEAT=0.
         GO TO 99
       ENDIF
      PI=4.*ATAN(1.0)
C
C  NOTE THAT TANK TEMPERATURE IS ASSUMED TO BE 55 DEG. C.
```

```
C     SIZE IS IN MILLION LITERS (VOL IS IN CUBIC METERS),
C     AND TANK IS ASSUMED A CYLINDER WITH HEIGHT EQUAL TO DIAMETER.
C
      DELTAT=80.-TEMP
      VOL=SIZE*1000.
      X=(VOL/PI)**(1./3.)
      PERIM=PI*X
C
C  ASSUMES F VALUE OF 0.95 W/M (LINEAR)  - K
C
      HEATB=0.95*DELTAT*PERIM
      SIDE=X*PI*X
      TOP=PI/4.*X*X
C
C  ASSUMES U VALUE OF 5.1 W/SQ. M - K
C
      HEATS=5.1*DELTAT*SIDE
      HEATT=5.1*DELTAT*TOP
C
C  FIND DAILY HEAT LOSS IN MJ
C
      HEAT=0.0864*(HEATB+HEATS+HEATT)
 99   RETURN
      END
      SUBROUTINE COSTING(TBUCKS,BBUCKS)
      COMMON TANK,WELL,YEAR,CAPACTY,MAXLOSS,TDESGN,MAXLOAD,
     1FUELUSE,BEFFIC,TOTDAYS,FUELMJ,DRYDAYS,QFLUIDJ
      REAL MAXLOAD
C ****************************************************************
C *  SUBROUTINE CONVERTS BOILER SIZE FROM MW TO THOUSAND BTU/HR*
C *    BOILER SIZE IS ASSUMED TO BE THAT REQUIRED TO SUPPLY    *
C *    THE ENTIRE SYSTEM AT THE DESIGN TEMPERATURE W/O ANY     *
C *    STORAGE.  BOILER COSTING IS APPROXIMATELY $7,700 PER    *
C *    MILLION BTU/HR CAPACITY.  TANK AND BOILER COSTING IS    *
C *    BASED ON REGRESSION EQUATION                            *
C *                                                            *
C ****************************************************************
      BSIZE=MAXLOAD*3413.
      LNSIZE=ALOG(BSIZE)
      Y=0.785*LNSIZE+3.45
      BBUCKS=EXP(Y)
      IF(CAPACTY.LE.0.) THEN
         TBUCKS=0.
      ELSE
      CUBICM=CAPACTY*1000.
      LNSIZE=ALOG(CUBICM)
      Y=-0.244*LNSIZE+5.64
      COSTPER=EXP(Y)
      TBUCKS=COSTPER*CUBICM
        ENDIF
      RETURN
```

```
      END
      FUNCTION AMORT(BUCKS,YEARS,RATE)
C
C  NOTE:  ASSUME INTEREST RATE IS GIVEN IN PERCENT
C
      PERCENT=RATE/100.
      A=(1.+PERCENT)**YEARS
      AMORT=(PERCENT*A)/(A-1.)*BUCKS
      RETURN
      END
      FUNCTION ESCA(F,YEARS)
C
C  NOTE:  ASSUMES F IS ESCALATION RATE ABOVE INFLATION IN PERCENT
C
      PERCENT=F/100.
      ESCA=(1.+PERCENT)**YEARS
      RETURN
      END
```