FEASIBILITY OF MUNICIPAL WATER MAINS AS HEAT SINK FOR RESIDENTIAL AIR-CONDITIONING

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ABSTRACT

It has been proposed that municipal water mains be used as the heat sink or the heat source for air-conditioning or heating, respectively. This paper addresses the extent of thermal contamination associated with the use of municipal water in the mains for heat rejection in residential air-conditioning applications. A small residential neighborhood in Austin, Texas was selected, and typical residential a/c loads and measured water supply rates in the main were used in the assessment.

Very substantial increases in water temperature occur in the mains for air-conditioning, even if a modest fraction of the residents opt to install such systems. No more than 1 to 2 % of residents could adopt such systems before water temperature rises in the mains become significant. The general conclusion is that, while the benefit to an individual using this concept may be positive, the impact on water temperature is excessive.

INTRODUCTION

It has been proposed that municipal water mains be used as the heat sink or the heat source for residential/commercial air-conditioning or heating, respectively. Such systems will be designated herein as "water source/sink heat pumps" (WSHP). During the air-conditioning season water from the mains would be circulated to the condenser of the a/c unit where rejected heat is absorbed by the water, and in the heating season the water would be circulated to the evaporator of a heat pump where energy is absorbed from the water. Thus, water at elevated temperature is returned to the mains during summer and water at reduced temperature is returned to the mains in the winter. The extent of this temperature elevation or reduction depends on several factors: fraction of residents using the concept, amount of water distributed in the system, the size of the thermal loads being met on the conditioned buildings, the efficiencies of the a/c equipment, length of mains as they affect heat exchange with the ground, ground thermal properties and other factors.

Proponents of the concept indicate the considerable benefit in energy efficiency and thus reduced system operating cost, while those associated with insuring the integrity of municipal water systems express concerns about both chemical and thermal contamination of the water supply. There has been considerable discussion of possible chemical contamination, but relatively little has been presented about the extent of thermal contamination. However, the thermal contamination is probably more easy to predict than is chemical contamination. Water temperature increases during the cooling season may be excessive, thereby affecting chlorine consumption and bacterial growth. The water temperature rise will also have an adverse affect on the efficiencies of units successively downstream. In the heating season the water temperature is restricted to a minimum of 32 °F and typical water supply temperatures are in the 35 to 50 °F range. Also, water demand in winter tends to be lower than in summer, and the lower water main temperatures are associated with colder periods when the heat pumping rates are greatest. The relatively small allowable temperature drop of water in the mains and the low water demands results in limited potential for heat pumping. In addition, any reduction of temperature in the mains results in greater energy requirements for downstream heat pumps and water heating. Harnish (1992) has done some valuable studies which examine the effect of water source heat pumps on the temperature in domestic water mains. His studies generally indicate that both for the cooling and heating applications the effect on water temperature is excessive due to the insufficient amount of water compared to the thermal loads involved. A number of other studies have been done which seriously question the concept in terms of the thermal impact on the domestic water supply.

This paper addresses quantitatively the thermal contamination associated with the adoption of this concept for air conditioning in a residential application. An analysis is made of a small residential neighborhood in Austin, Texas for which the number of residences is known as are the dimensions and characteristics of the water supply mains. Typical residential a/c loads were assumed for the houses in the area studied. The City of Austin Water and Waste Water Department provided actual data on the daily and hourly water flows rates into the neighborhood for a two month period during the peak of the cooling season.

Based on the test area and water supply rates, several calculations are performed to assess the resulting water temperature. The water supply rates and distributions throughout the area are variable both in time and location, and the amount of heat rejected to the water in the mains will vary with time, with the particular residence, and with the fraction of residents using the concept. Therefore, several scenarios are used to assess possible impacts on water temperature in the mains.

AREA AND SYSTEM INVESTIGATED

Following discussions with City of Austin Water and Waste Water Department personnel, they provided fairly detailed information on the water supply into a small residential neighborhood (Edgemont) in west Austin (Texas). This area, which includes 47 residences, is shown on the plot map of Figure 1. The main inlet to the area is indicated at the north border of the area and a water meter installed at this location allows for monitoring hourly flow rates. While this water network is connected to an adjacent neighborhood to the South, a valve between the two is normally closed so that all water supplied into Edgemont at Node 101 is used by residents of that area. The individual pipe sizes within the network are not presented here, but except for two short lengths of 4 inch pipe, all other pipe is 6 inch diameter. There are 32 sections of pipe totaling 3655 feet, with lengths varying from about 25 feet to as long as about 200 feet. This means about 80 feet of 6 inch main per residence. This is of interest when one considers the possible thermal energy exchange between the water and the ground.

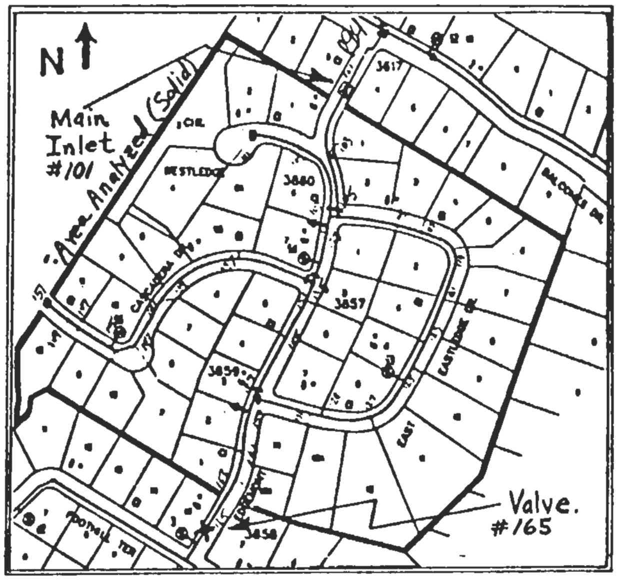

Figure 1 - Map of Edgemont Area in Austin

Figure 2 indicates the daily water supply (gpd) to the Edgemont area for the two month peak cooling period of mid-July to mid-September for 1992. These rates are actual values measured by a solar powered ultrasonic flow meter installed at node 101 by the City of Austin. It is to be noted that the daily rate flow varies markedly, from lows of about 5000 gpd to highs near 100,000 gpd. The average daily water supplied to the area during this 2 month period is about 45,000 gpd.

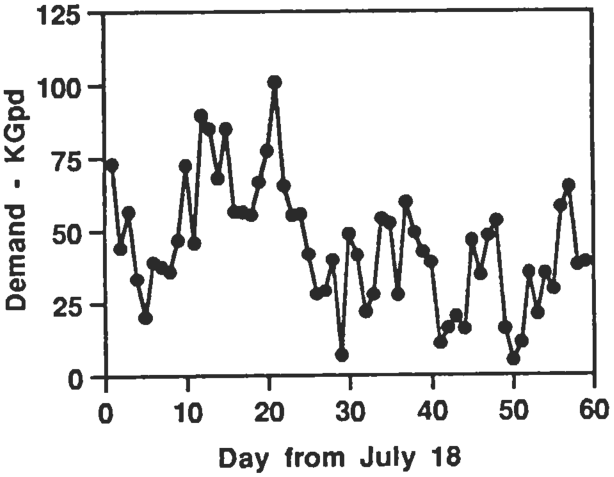

Figure 2 - Daily Water Flows (Gpd) into the Edgemont Area

Figure 3 shows hourly profiles of water flow to the area (gpm) for three specific days (July 22, Aug. 1 and Aug. 26) when the daily demands were about 20,000, 60,000 and 88,000 gpd, respectively. Again, as would be expected the variation is marked, from nil during some periods of the day to quite high flow rates at other times. It is interesting to note that the high water flow rates tend to be in the night-to-early morning periods when residents are encouraged to do lawn watering. On the other hand the high air-conditioning periods tend to be in the late afternoon-to-early evening, thus the water demand and heat loads on the mains tend to be out of sync.

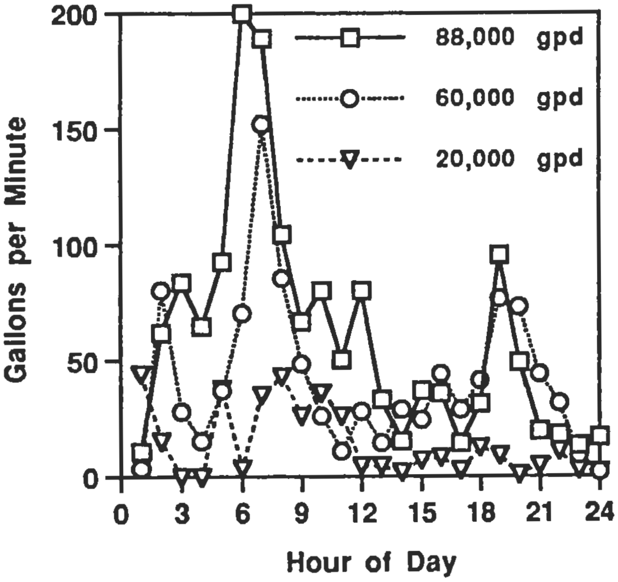

Figure 3 - Hourly Water Flows (Gpm) into the Edgemont Area for Typical Days

In the analyses which follow it is assumed that the residences in the Edgemont area have 4 ton a/c units, with each having a COP of about 3 and a duty cycle of about 50% in the summer cooling season. This is considered to be conservative in terms of potential thermal impact, since the houses in the Edgemont area (upper income families) are generally larger than average and the cooling loads are probably larger on average than the 4 tons assumed; however in lieu of a thorough survey of the a/c systems installed and their duty cycles, the assumed cooling demands have been assumed and are considered reasonable. This means that on average the heat rejected to the water mains per residence is about (4x12,000x0.5)x4/3 = 32,000 Btu/hr. Also, this being a somewhat affluent area, the water usage for lawn watering etc. is probably higher than average, and so the predicted water temperature excursions would likely be lower that in some other neighborhoods.

SIMPLIFIED THERMAL ANALYSES

Because of the variable nature of this problem, it is of interest to perform some simplified ("what if") calculations to estimate the temperature rise due to heat rejection into the water supply.

Global Analysis

Assuming an average water supply rate of 45,000 gallons per day (1875 gph) and that all of the 47 residences used the water in the mains as a sink for air-conditioning, the water temperature rise would be:

$$\frac{47\ (32{,}000\text{Btu/hr})}{(1875\text{gph})(8.33\text{lb/gal})(1.0\text{Btu/lb-F})} = 96\ \text{F}$$

Depending on what may be considered an acceptable water temperature rise, say 5 ^{O}F, then no more than about 6% of the houses (3 of the 47 houses) could install such systems.

Low Water Demand Days

Assuming the same a/c usage on a day of low water demand such as Aug. 15th (approx. 7000 gpd compared to the 45,000 gpd average), the increase in water temperature would be "much" greater. The temperature rises for average demand days are already excessive. There is also some question about the correlation between water demand and a/c demand, and this will be addressed subsequently.

Low Water Demand Periods

Consider that there are periods of very low water demand, such as the afternoon (noon to 6 pm) of July 22 nd (20,000 gpd in Figure 3) when the average water demand of around 5 gpm is about 1/3 of the average daily demand of 14 gpm. Since this three-fold decrease from the average demand appears to be typical and occurs in the afternoon when it would be expected that air-conditioning units would be operating at their highest duty cycle, then again temperature rises "much" greater than 96 °F would result. In the mid-summer the use of water for lawns is discouraged by the City of Austin and by most municipalities during the late afternoon, because of the excessive loss due to evaporation. Watering is encouraged during the late evening and early morning periods of the day. Thus the water demand and the a/c usage during the peak cooling periods of the year are in fact out of sync, as indicated earlier. A quantitative assessment of the effect of varying water and air-conditioning demands is subsequently addressed in the computer modeling.

Geometric Effect Downstream

Now consider that the area were to be served by one long main with the 47 houses connected to it uniformly along its length. Although this is not the case, since piping networks are much more complicated, as is the Edgemont network with one loop and a couple of spurs, this "linear" system allows for a simple analysis. Houses along the main would experience successively higher water temperatures, because as one proceeds along the main the water flow decreases progressively to zero as water is withdrawn, but presumably the thermal load from each house is the same. The result is that the downstream houses experience temperature rises that are much greater than the average value of the 96 °F calculated above. If one assumes the 1875 gph inlet flow rate and the 32,000 Btu/hr input from each residence, then the resulting temperature rises experienced by the 10th, 20th, 30th, 40th, and 47th houses along the main would be approximately 23, 53, 96, 178, and 427 °F, respectively. Of course the actual values are completely out of reason, but the purpose of this scenario is to emphasize the progressively greater (geometric) impact on water temperature increase for residents along the line. The 30th house experiences approximately the average temperature rise calculated above and houses further on down-line experience much greater temperature rises, with the last house experiencing almost 5 times the 96 °F average temperature rise calculated above. If some of the houses are not located "in-line" but rather on a "loop", such as the one shown on the Edgemont map (Figure 1), then there may be "null" locations along the loop as a result of the water draws of adjacent residents, even though there is flow through the main to which the loop is connected. Similar high water temperatures will be experienced at the null flow locations in these loops.

What is important about this scenario is that in a neighborhood the temperature rise experienced will be very dependent on how the water demand varies from house to house and which houses use the water sink heat pumps. In addition to the general unacceptability of these temperature increases for normal purposes, any water temperature increase partially defeats the advantage of this heat pump concept for houses further along the main. Also, the increased water temperature probably causes greater consumption of chlorine and the acceleration of any biological growth.

SIMPLIFIED ANALYSIS FOR GROUND COUPLING

One of the arguments for rejecting heat to water in the buried mains is that much of the energy is dissipated to the ground and thus the water temperature increases projected above may be excessive. The process of heat diffusion into the soil from a heated object is one that has been researched by others. Schneider (1963) provides an analytical solution for the case of a very long heated cylinder that is buried in an infinite medium at a different, but uniform temperature. The cylinder surface temperature is assumed to be suddenly raised above that of the surrounding medium and his solution provides the rate of heat flow with time into the surrounding medium.

A simplified global case is now considered where only 10 % of the residences are assumed to use this concept, and for this 10 % penetration the resulting average water temperature rise with no heat transfer to the ground would be $0.1 \times 96\ ^{\circ}F = 9.6\ ^{\circ}F$. The question is: "For this assumed 9.6 °F difference between the water and the ground, does the heat transfer into the ground represent a significant fraction of the $47 \times 0.10 \times 32{,}000 \cong 150{,}000$ Btu/hr that is rejected into the water mains".

As noted earlier, the total buried pipe length in the Edgemont area is 3655 feet and except for two short sections the line diameter is 6 inch. Soil properties (thermal conductivity, density and specific heat), particularly thermal conductivity, vary considerably, but the values used in the following analysis are:

$k = 0.5$ Btu/hr-ft-°F
$\rho = 100$ lb/ft^3
$c_p = 0.40$ Btu/lb-°F
$\alpha = 0.0125$ ft^2/hr

Incropera and DeWitt (1990) list the following thermal conductivity values for a variety of soils: 0.16, 0.30, and 0.75 Btu/hr-ft-°F for sand, soil, and clay, respectively. The above assumed value of 0.5 is reasonable and probably a conservatively high value, since lines are usually laid in sandy/gravel type fill. That is, transfer into the ground is probably over-predicted by using the 0.5 value. The specific heats are 0.19, 0.44 and 0.21 Btu/lb-°F for sand, soil and clay, respectively, so a value of 0.40 is reasonable.

Figure 4 presents as a function of Fourier number, the dimensionless thermal gradient dT/dR at the surface of a long cylinder that is buried in an infinite medium. This figure is developed from the work of Schneider (1963). The dimensionless gradient is:

$$\frac{dT}{dR} = \left(\frac{dt}{dr}\right)\left[\frac{r_p}{(t_p - t_g)}\right]$$

and the Fourier number is defined as:

$$Fo = \alpha \, \Delta\tau \, / \, r_p^2$$

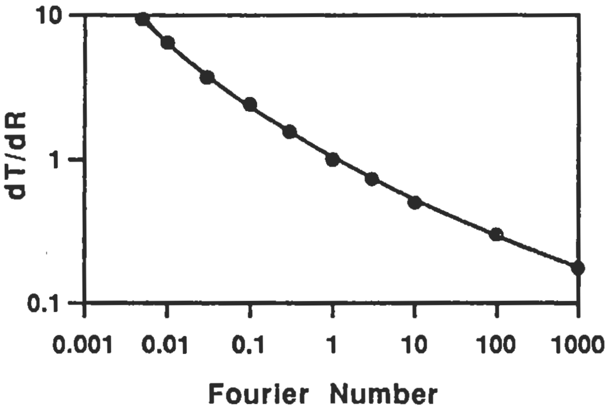

Figure 4 - Dimensionless Thermal Temperature Gradient at Pipe Surface as Function of Fourier Number (Adapted from Schneider, 1963)

Here t_p and t_g are the pipe surface and ground temperatures, r_p is the pipe radius, α is the ground thermal diffusivity, $k/(\rho \, c_p)$, and $\Delta\tau$ is the time from the sudden rise in temperature.

For our case of $r_p = 0.25$ ft and $\alpha = 0.0125$ ft^2/hr, $Fo = 0.20 \, \Delta\tau$. The heat transfer into the ground as a function of time can be calculated and compared to the total heat input of 150,000 Btu/hr from the 10% percent of the houses using the water source heat pumps. For example, after 1 hour the Fourier number is 0.20, for which $dT/dR \cong 1.8$ and the heat transfer into the ground is therefore:

$$q = k_g \, (dT/dR)[(t_p - t_g)/r_p] \times 2\pi \, r_p \, L$$

$$= (0.5)(1.8)(9.6/0.25)(2\pi \text{x} 0.25 \text{x} 3655)$$
$$\cong 198{,}000 \text{ Btu/hr.}$$

compared to the 150,000 Btu/hr rejected to the water in the mains. Thus, the ground initially can absorb more heat than needed, i.e. by a 1.3 factor. However, if one considers extended times of operation typical of the use over a season (2880 hr for a four month cooling season), then ground absorption falls off greatly during that period. Figure 5 indicates the approximate fraction of the heat rejected to the mains that can be absorbed by the ground as a function of time. After one day the fraction falls to 0.48, after a week to about 0.3, after a month to about 0.2 and after 120 days to about 0.15. Thus, for times of interest (a month or more) the ground absorption is less than about 20 % of the heat rejected to the mains. The effect of varying ground properties is considered subsequently.

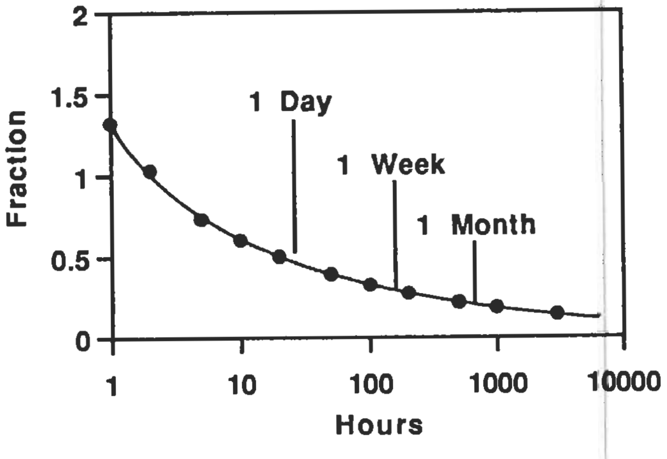

Figure 5 - Fraction of Energy Absorbed by Ground with Time

COMPUTER MODELING

A computer model was developed to simulate the water and surrounding ground temperatures as functions of time for the case of a "straight" main serving 20 houses, each of which would possibly use the WSHP concept. The straight main geometry was analyzed because in a more complex network such as Edgemont details of the water flows for each house made it difficult to assess the flow rates and flow directions in various sections of the main. Also, only 20 houses were considered for convenience. The water demand per house, the WSHP heat rejection per house, the mains diameter and the length of main per house were those used in the above analyses based on Edgemont. For the analysis it was assumed the inlet water temperature and the unaffected surrounding ground temperatures are both 70 °F. Seven radial nodes out into the ground and 20 nodes along the main (one for each house) were used. For most of the results which follow the ground properties are those listed above However, to also assess the effect of prevailing ground conditions, several ground property scenarios are considered in one of the following sections.

Effect of WSHP Penetration

Figure 6 shows the variation with time of the water main temperature for the 10th and the 20th houses along the line for various percentages of the homes (100, 50, and 10%) having water source heat pumps that reject heat to the main. The modeling was simplified by assuming all houses had WSHPs but that they operated at these partial loads.

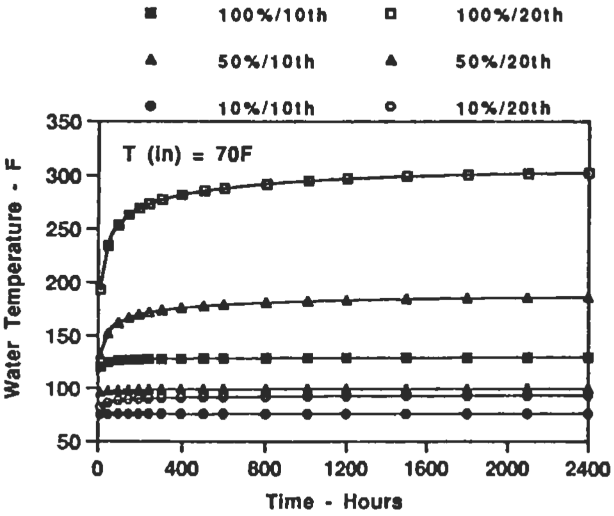

Figure 6 - Effect of WSHP Penetration on Water Temperature Increase.

It is seen that the water temperature rises occur mainly during the first week or two. This is consistent with the use of Schneider's analysis above which indicated that the fraction of energy absorbed by the ground reduced to less than 20% after about one month. The water temperature increase for the 10th (middle) house is only about 25% of that experienced at the last house, i.e. the geometric effect discussed earlier. It is also seen that to limit water temperature increases to less than about 20 °F, fewer than 10% of the houses may have WSHPs using the main water for heat rejection. This is consistent with the earlier simplified analysis which showed that the 5th of the 47 houses (or about 10% along the main) experienced an 11 °F rise in water temperature.

Figure 7 shows more details of the water temperature variation for the case of 10% WSHP penetration. The water main temperatures experienced by the 5th, 10th 15th and 20th (last) houses along the main are shown over the duration of a cooling season (about 3 to 4 months). The temperature rises after a few weeks are about 2.5, 6, 11 and 23 °F respectively. Several other considerations are examined in the results which follow, and for these comparisons it will be assumed that only 10% of the houses have WSHPs connected to the water mains.

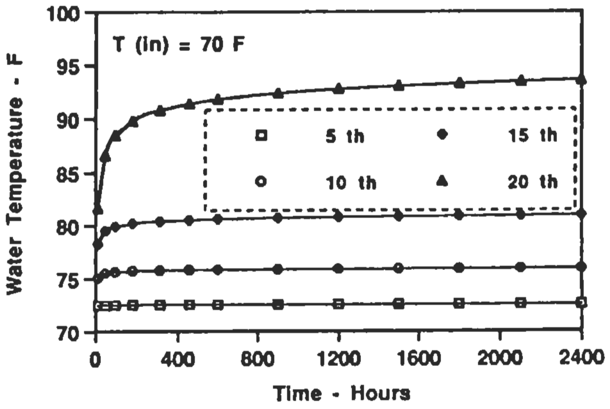

Figure 7 - Transient Water Temperature in Mains (with 10% WSHP's)

Effect of Ground Properties

As indicated earlier, proponents of this concept suggest that a large portion of the rejected heat is absorbed by the ground. Using the above simplified analysis based on the work of Schneider it was seen that the ground is only important early in the process and this is confirmed by the results shown in Figures 6 and 7. However, "What is the effect of varying the properties of the ground ?" The 'ground' conditions vary greatly, so several scenarios are considered here, and the properties assumed (k, r, c_p and α) are listed in Table 2. The 'rock' scenario considers the average properties of solid rock such as granite, limestone and sandstone, as obtained from Incropera and DeWitt (1990). The properties for the 'nominal' scenario are those used in the above analyses. The 'good' scenario uses a set of properties that are averages between those of solid rock and the nominal condition. The cases of 'sand' (poor ground absorption) and 'insulated' (no ground absorption) are also shown for comparison. The five cases are identified by the thermal conductivity used for each, since thermal conductivity is the most important of the properties.

Table 2 - Ground Property Scenarios

	Ground Type				
Property	Rock	Good	Nom	Sand	Insul
k - B/h-ft-F	1.5	1.0	0.5	0.16	0
ρ - lb/ft^3	155	128	100	95	-
c_p - B/lb-F	.20	.30	.40	.19	-
α - ft^2/h	.048	.026	.0125	.0089	0

Figure 8 shows the terminal (last house) water temperature during a cooling season for the five scenarios. While the water temperature rise is about 23 °F for the "nominal" case, even if the most optimum case of solid rock is assumed, the temperature rise would still be about 15 °F. At the same time, even if the main were insulated, so that "no" energy is absorbed by the ground, the water temperature rise is about 35 °F. That there is not as much difference between these extreme scenarios is a result of the fact that for times of interest (several weeks) the ground is unable to absorb much heat, so ground properties are really not as important as might be expected.

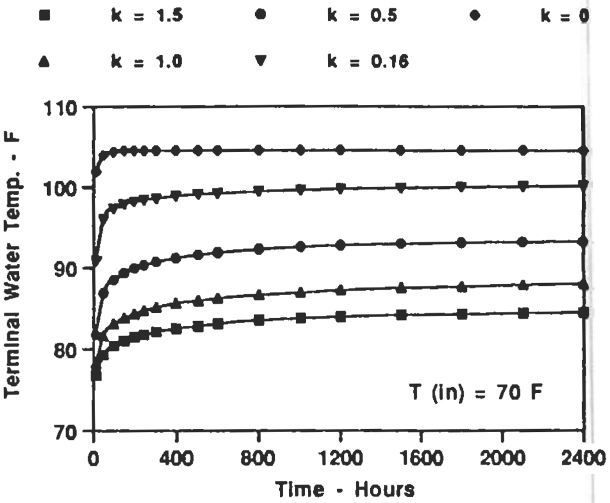

Figure 8 - Influence of Ground Properties on Terminal Water Temperatures (with 10 % WSHP's)

Figure 9 presents the same results in a slightly different format, where the terminal water temperature rise is shown as a function of ground thermal conductivity for three times (2, 10 and 100 days) after the process begins. The conclusion is that, while the ground does have an effect on the temperature in the mains, it is small and the 'nominal' ground conditions used should give reasonably accurate predictions.

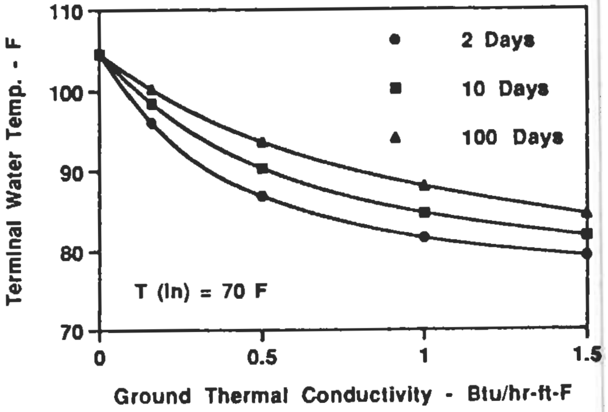

Figure 9 - Effect of Ground Thermal Conductivity (Properties) and Time on Terminal Water Temperature (with 10 % WSHP's)

Effect of Varying Water Demand and A/C Use

As indicted earlier, the demand for water and the need for air-conditioning tend not to be in sync. During the summer cooling season water demand tends to be high during the night/early morning and low in the late afternoon/early evening. On the other hand, air-conditioning tends to be highest during the late afternoon and very early evening. Although actual air-conditioning demand has not been modeled, it is assumed in the case which follows that the air-conditioning demand undergoes a sinusoidal variation from a maximum of about three times its minimum, with the daily average being that used in the above analyses where constant heat rejection to the water in the mains was assumed. The variation assumed was such that the peak occurs at 4 pm and the minimum at 4 am.

The water demand is also assumed to be sinusoidal, but approximates the variation seen in Figure 3. It is assumed to vary from 30% of the average to 170% of the average, with the maximum occurring at 8 am and the minimum occurring at 8 pm. The numerical model was run for 10% WSHP penetration under the constant water demand / constant heat load scenario until 2000 hours when the heat loads and water demands were assumed to take on these sinusoidal variations. After only a few days the water temperature variation with time became reasonably 'repeating' from day to day and this variation is shown in Figure 10 over a 24 hour period for four locations along the main. It is seen that the temperature increase at the end of the main approached 30 °F in the early evening, compared to about a 23 °F rise for the constant a/c and constant water demand scenario. It would at first seem that the high a/c demand and low water demand during the late afternoon-early evening would result in much greater temperature increases during this period compared to the constant scenario. However, the ground conduction tends to dampen the effects of these short time transients, resulting in only about a 30% increase in the water temperature rise as a result of the variations of water and a/c demands.

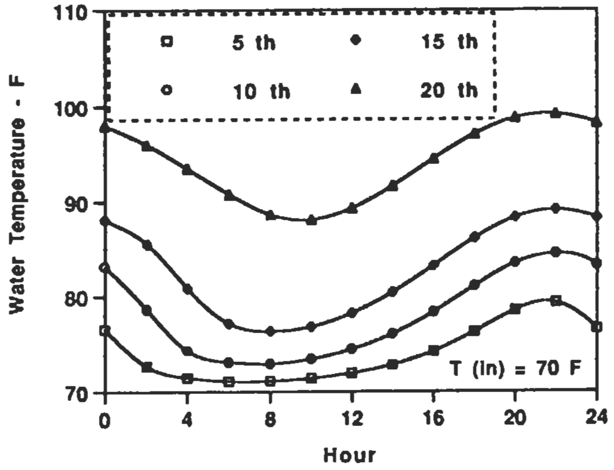

Figure 10 - Transient Water Main Temperatures for Variable Heat Loads and Water Flows (for 10 % WSHP's)

General Comments

Most of the above results are based on the assumption that 10% of the houses have WSHPs using water in the mains for heat rejection. Under this assumption water temperature rises varying up to about 30 °F are experienced, depending on the location along the main, the type of ground, the miss-match between a/c and water demands, and the water distribution network. Considering that water temperature rises of only a few degrees could be assumed reasonable, say 5 °F, then no more than about 1 or 2 percent of the houses could reasonably be allowed to use the water in the mains for heat rejection. Considering the limited application and the problems associated with regulating the installment and operation of such systems, such an application in any residential neighborhood seems to be very unattractive.

CONCLUSIONS

The concept of using municipal water in the mains for heat rejection from air-conditioning systems has been assessed quantitatively for a residential application by simple analysis and by computer modeling. The results indicate that for as little as a 10% penetration of such WSHPs connected to the main the water temperature increases are expected to be as large as about 30 °F. In addition to the percent penetration of WSHPs, the water temperature increase is affected by a number of factors including: water demand rate, size of a/c units used, the timing between water demand and a/c use, the location along the main, and the ground properties. The heat absorption by the ground represents less than about 20% of the rejected heat for the extended times of interest. Water demand and a/c use tend to be out of sync. for this application, resulting in even greater temperature increases than experienced under constant demand conditions. The location along the main or in the network has a very large affect on the water temperatures experienced.

Considering that only about a 5 °F increase in water temperature in the mains is likely to be considered acceptable, this means that no more than about 1 to 2 % of the houses could be allowed to install such systems. Considering this limited application and the problems associated with regulating the installation and operation of such systems, application in any residential neighborhood seems to be very unattractive.

ACKNOWLEDGEMENT

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