Design and Analysis of A Residential Greywater Heat Recovery System

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DISCLAIMER

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EXECUTIVE SUMMARY

A prototype residential greywater heat recovery system was designed, installed and evaluated for a period of one year in the Manitoba Advanced House in Winnipeg. Using data gathered from field tests performed on the prototype, coupled with an analysis of the maximum theoretical savings achievable by such systems, a thermal simulation model was developed for predicting the performance of greywater systems for various design configurations and operational conditions.

The theoretical analysis showed that the maximum possible savings which could be achieved by an ideal greywater system are a function of the inlet water and greywater temperatures, domestic hot water (DHW) tank setpoint, DHW load and DHW tank efficiency. A general procedure was also developed for estimating the maximum theoretical savings for specific applications. Using typical values for the input parameters, the analysis found that the maximum savings which a residential greywater heat recovery system could achieve would be about 50% of a typical family's annual DHW load.

The simulation model was then used to predict the technically achievable savings from various greywater systems, i.e., the savings which would result using an actual, rather than ideal, system. Using typical operating and environmental conditions, the practical performance limit for a greywater system was found to be about 42% of the annual DHW load. This system would be approximately the same as the prototype used in the Manitoba Advanced House but would have increased tank insulation, reduced greywater mass, increased cold water mass and an increased heat transfer coefficient between the cold water and greywater.

The impact of a number of design and operational variables was also studied using the model and categorized as having either a minor or major impact on system performance. Minor variables were found to be: tank insulation levels (provided a minimum level is used), greywater mass and room temperature. Major variables were: cold water mass, cold water inlet temperature, greywater temperature, DHW tank setpoint, AU1 (the overall heat transfer coefficient between the cold water and the greywater), the greywater and cold water flow rates (acting together) and the greywater flow rate (acting in isolation).

It was also concluded that the success of a greywater heat recovery system depends as much, or more, on proper selection of the application as it does on the design of the system. Ideal applications are those which have large DHW loads and have not, or can not, take advantage of conservation measures designed to reduce DHW consumption.

RÉSUMÉ

On a conçu, installé et évalué (pendant un an) un prototype de système de récupération de la chaleur à partir des eaux ménagères dans la maison de technologie de pointe du Manitoba (*The Manitoba Advanced House*), à Winnipeg. Grâce aux données obtenues à la suite d'essais effectués sur le prototype et à une analyse des économies théoriques maximales réalisables avec ce système, on a développé un modèle de simulation thermique pour prévoir le rendement des systèmes d'eaux ménagères ayant divers modèles de conception et de conditions de fonctionnement.

L'analyse théorique a montré que le maximum d'économies réalisables avec un système idéal est fonction de la température de l'eau à l'entrée et de celle des eaux ménagères, du point de réglage du chauffe-eau, de la charge d'eau chaude domestique et de l'efficacité du réservoir d'eau chaude. Une procédure générale a également fait l'objet d'une élaboration dans le but d'évaluer les économies maximales réalisables avec des applications données. Selon les conclusions qu'on a tirées de l'analyse, en prenant des valeurs typiques comme paramètres d'entrée, les économies maximales qu'un système permettrait de réaliser correspondraient à environ 50 % des besoins annuels en eau chaude d'une famille ordinaire.

Le modèle de simulation a servi à déterminer les économies techniquement réalisables avec divers systèmes d'eaux ménagères, c'est-à-dire les économies qui résulteraient de l'utilisation d'un système réel et non idéal. Dans des conditions environnementales et de fonctionnement typiques, on a trouvé que la limite pratique de rendement atteindrait environ 42 % de la charge annuelle d'eau chaude domestique. Le système serait à peu près le même que le prototype utilisé dans la Maison performante du Manitoba, mais avec une meilleure isolation du chauffe-eau, une masse d'eaux ménagères réduite, une plus grande masse d'eau froide et un plus grand coefficient de transfert de chaleur entre l'eau froide et les eaux ménagères.

Le modèle a également permis d'étudier l'incidence d'un certain nombre de variables de conception et de fonctionnement qui ont été catégorisées selon leurs répercussions mineures ou majeures sur le rendement du système. Les variables mineures étaient le degré d'isolation du chauffe-eau (avec isolation minimale), la masse d'eaux ménagères et la température de la pièce. Les variables majeures étaient la masse d'eau froide, la température d'entrée de l'eau froide, la température des eaux ménagères, la température de consigne du chauffe-eau, le coefficient de transfert de chaleur entre l'eau froide et les eaux ménagères, le débit de l'eau froide et des eaux ménagères (combiné) et le débit des eaux ménagères (non combiné).

Selon les conclusions, le succès d'un système de récupération de la chaleur à partir des eaux ménagères dépend autant, si ce n'est plus, du bon choix de l'application que de la conception du système. Les applications idéales sont celles où la charge d'eau chaude est élevée et qui ne tirent pas avantage (ou est dans l'impossibilité de le faire) des mesures d'économies d'énergie conçues pour réduire la consommation d'eau chaude.

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SECTION 1
RESIDENTIAL GREYWATER HEAT RECOVERY SYSTEMS

1.1 THE OPPORTUNITY

A typical Canadian family in a conventional, new house uses about 250 litres (l) to 400 l (55 imperial gallons (I.G.) to 88 I.G.) of domestic hot water (DHW) per day. This requires about 5,000 kWh to 8,000 kWh (net) of energy to heat. Depending on the type of fuel, the efficiency of the DHW tank, the price of energy, the temperature of the incoming mains water, etc., this will cost between $150 and $700 per year.

Since the 1970's, researchers have recognized that the average Canadian household wastes a significant amount of the hot water used for baths, showers, washing machines and other fixtures. The vast majority of this energy is lost down the drain once the bath is over, the washing cycle is complete, etc. Some heat is picked up by the interior air, which reduces the space heating load, but the quantity of this recovered energy is relatively small. For many years, greywater heat recovery systems have been proposed as a method to reduce the DHW load. Despite the tantalizing prospect of recovering energy from waste water, only a handful of such systems are known to exist. These have generally been one-off systems designed for demonstration purposes and data on their performance has been sketchy or non-existent.

A considerable amount of energy is contained in residential greywater however, from a thermodynamic perspective, it is very low grade energy. That is, the available energy exists at a low temperature which means that recovering it is difficult - or to be more precise - expensive, since the heat recovery area, and hence the device, have to be large or incorporate some other means to facilitate heat transfer. Further, DHW usage is very sporadic, meaning that some form of thermal storage has to be used. Also, several of the main users of hot water (baths, washing machines and dishwashers) are batch flow devices which draw and discharge water in segmented lumps rather than on a continuous basis (such as occurs with ventilation systems equipped with Heat Recovery Ventilators). This batch flow characteristic also dictates some type of thermal storage. All of these factors have combined to result in negligible market penetration for residential greywater heat recovery systems.

1.2 THE MANITOBA ADVANCED HOUSE GREYWATER HEAT RECOVERY SYSTEM

This report discusses the design and analysis of a prototype residential greywater heat recovery system which was installed in the Manitoba Advanced House in Winnipeg. This structure is one of ten houses constructed across Canada as part of the Advanced Houses Program to demonstrate and evaluate innovative housing technologies which reduce energy consumption, conserve water, improve indoor air quality, facilitate home recycling and reduce construction waste. The Manitoba Advanced House is a two storey, 186 m^2 (2000 ft^2) home with a full basement. It uses a high efficiency (94%) gas hot water heater to provide space and DHW heating. The house was built in 1992 with the final components and systems installed in early 1994, after which the house was sold and occupied.

All Advanced Houses have to meet an energy target which is calculated on the basis of their size and the severity of the local climate. This target has been designed to result in a total, annual energy consumption which is about one-half that which would result if the house were designed to the R-2000 energy target. In addition to the overall target, sub-targets are included for each of the major energy end-uses. In the case of the Manitoba Advanced House, the target and sub-targets were:

Space Heating	7303 kWh
DHW Heating	5520 kWh
Space Cooling	0 kWh
Appliances	3838 kWh
Lighting	352 kWh
Outdoor Electrical	183 kWh
Energy Target (Total)	17,196 kWh

The Manitoba Advanced House was designed to incorporate various measures to reduce DHW consumption including low-flow showerheads and faucet aerators on major hot water fixtures. However, after evaluating the impact of these measures during the design phase, it became apparent that additional steps would have to be taken to reduce DHW energy consumption. After considering various alternatives, it was decided to include a greywater heat recovery system in the house.

A background review was carried out of other greywater systems but the available information was found to be limited. Dumont described an early system installed in the Saskatchewan Conservation House in 1977 (Dumont) and Nelson developed an improved design in 1981 (Nelson). Although these provided useful information, there was still a paucity of detailed information, including an absence of design tools to aid in sizing and the evaluation of alternatives.

1.3 OBJECTIVES

This project was carried out to document the experiences, lessons and performance of the greywater heat recovery system installed in the Manitoba Advanced House. The specific objectives were:

1. To construct, commission and evaluate (under real-world conditions) a greywater heat recovery system.

2. To measure its performance under controlled conditions and to evaluate its internal heat transfer characteristics.

3. To use the empirically derived data to develop a model capable of simulating greywater heat recovery systems in different configurations and under various operational situations.

1.4 REPORT OVERVIEW

After the greywater system was designed and installed (Section 2), operational data was collected (Section 3) and trials carried out to measure its performance. Using this information, a computer model was developed (Section 4) and used to predict the behaviour of the system for a wide range of design configurations, usage characteristics and ambient air and water conditions (Section 5). This information was then synthesized to provide some general observations on the capabilities of residential greywater heat recovery systems. Final comments on the savings, costs and applications of greywater systems are provided in Section 6 and conclusions are offered in Section 7.

SECTION 2
DESIGN AND CONSTRUCTION

2.1 BASIC PERFORMANCE EQUATIONS

The prototype greywater heat recovery system used in the Manitoba Advanced House is basically a simple heat exchanger, approximating a counter-flow design. Outgoing greywater is stored in the preheat tank where it is close thermal contact with the incoming mains water. Using basic heat exchanger terminology and ignoring thermal losses from the tank to the surrounding space, the amount of heat transfer is expressed by:

$$Q = m_c \, c_p \, (T_{co} - T_{ci}) = m_h \, c_p \, (T_{hi} - T_{ho}) \qquad (1)$$

where:

Q = Heat transferred
m_c = Mass flow rate of the cold water
m_h = Mass flow rate of the hot water (i.e., greywater)
c_p = Specific heat of water
T_{ci} = Temperature of the cold water entering the preheat tank
T_{co} = Temperature of the cold water leaving the preheat tank
T_{hi} = Temperature of the greywater entering the preheat tank
T_{ho} = Temperature of the greywater leaving the preheat tank

The maximum possible heat transfer, Q_{max}, which can take place is equal to:

$$Q_{max} = C_{min} \, (T_{hi} - T_{ci}) \qquad (2)$$

where:

C_{min} = the lesser of $(m_c \, c_p)$ or $(m_h \, c_p)$

The thermal effectiveness, ϵ, is defined as:

$$\epsilon = \text{(actual heat transfer) / (maximum possible heat transfer)}$$

For most greywater applications, C_{min} will be established by the cold water flow, thus:

$$\epsilon = m_c \, c_p \, (T_{co} - T_{ci}) \, / \, C_{min} \, (T_{hi} - T_{ci}) \qquad (3)$$

$$\epsilon = (T_{co} - T_{ci}) \, / \, (T_{hi} - T_{ci}) \qquad (4)$$

The DHW load, Q_{dhw} is defined as:

$$Q_{dhw} = m_c\, c_p\, (T_{setpoint} - T_c) \qquad (5)$$

where:

$T_{setpoint}$ = Setpoint temperature of the DHW tank
T_c = Temperature of the incoming mains water

If Eqs. (2) and (5) are combined, then the maximum amount of energy which the greywater system can recover, expressed as a percentage of the total DHW load, is obtained. For most applications, $C_{min} = m_c\, c_p$ and $T_{ci} = T_c$, so:

$$Q_{max}/Q_{dhw} = [C_{min}\, (T_{hi} - T_{ci})] \;/\; [m_c\, c_p\, (T_{setpoint} - T_c)]$$

$$Q_{max}/Q_{dhw} = (T_{hi} - T_{ci}) \;/\; (T_{setpoint} - T_{ci})$$

$$Q_{max}/Q_{dhw} = (T_g - T_{ci}) \;/\; (T_{setpoint} - T_{ci}) \qquad (6)$$

where:

T_g = Temperature of the greywater

The implications of Eq. (6) become apparent once typical values are substituted into the formula. For example, if:

$T_g = 35$ °C

$T_{ci} = 12$ °C

$T_{setpoint} = 60$ °C, then

$$Q_{max}/Q_{dhw} = (35 - 12) \;/\; (60 - 12) = 0.48$$

This means that the maximum possible energy which an ideal preheat tank could recover from the outgoing greywater is 48%, or about one-half, of the annual, DHW load.

The input assumptions used in this example are reasonably typical of actual conditions for most Canadian applications. Therefore, as a general estimating guideline, the maximum theoretical energy which can be recovered by a residential greywater system is about 50% of the DHW load.

It is obvious that Eq. (6) provides an extremely useful tool for assessing the maximum potential savings from greywater systems.

2.2 DESIGN PROCESS

Since little design information or guidelines could be found to assist with the design of the prototype system, the design process relied heavily on fundamental heat transfer analysis and numerous assumptions about DHW usage patterns, etc. The limitation of this approach is that a greywater system is very dynamic and time-varying, which is difficult to emulate without a detailed computer model.

2.3 SYSTEM DESCRIPTION

The system schematic of the Manitoba Advanced House greywater system is shown in Fig. 1 and the construction of the preheat tank is described in Fig. 2. Photographs of the completed installation are shown in Fig. 3.

Greywater is plumbed through a separate drainage system from five fixtures and appliances which were judged to be the dominant producers of high temperature greywater: shower/bath (second floor bathroom), jacuzzi (ensuite), shower (ensuite), washing machine (main floor) and the dishwasher (main floor). The separate drainage system was included to prevent thermal dilution of the greywater by cold water from sinks, etc. Consideration was originally given to plumbing all the greywater to the preheat tank through a thermostatically controlled valve which would only permit water above some preset temperature into the tank (the rest being dumped directly to the drain). However, this idea was abandoned because of concerns about reliability and the valve's ability to operate with sufficient temperature resolution.

2.4 PREHEAT TANK

The preheat tank was constructed from high density polyethylene (HDPE) and has a removable top to permit access for cleaning. Its exterior dimensions are (length, width and height) 77 cm x 77 cm x 122 cm (30.25" x 30.25" x 48"). The sides and top were insulated with 25 mm (1") of rigid glass fibre insulation with an aluminum facing. Inside the preheat tank is a coil of 34.1 m (112 ft) of 32 mm (1.25") copper tubing through which the incoming mains water flows. The copper tubing extends the full height of the tank to increase the surface area available for heat transfer. The mains water is preheated by the outgoing greywater and then plumbed to the inlet side of the conventional hot water tank. The preheat tank holds about 386 kg (850 lbm) of greywater and 27 kg (60 lbm) of mains water. Total tank weight (filled) is approximately 455 kg (1000 lbm). It is plumbed so that it can be isolated, using shut-off valves, from the cold water and greywater lines without shutting down the operation of either line. The tank is located in the basement mechanical room.

2.5 SAFETY CONSIDERATIONS

The major safety concern with a greywater heat recovery system is contamination of the potable water by the greywater. Not only is the possibility of leakage between the two sides of the system a concern, but also the possibility that any leakage will go undetected, resulting in continuous contamination of the fresh water. To limit the chances of this occurring, most plumbing inspectors require that a double-wall heat exchanger be used to separate greywater and fresh water (this is usually enforced as part of the requirements for backflow prevention).

The prototype system in the Manitoba Advanced House was designed with several layers of protection against contamination. First, the design of the preheat tank creates a double-wall heat exchanger through the use of a polyethylene liner between the greywater and the copper tubing. Second, the bottom of the storage tank was designed with drainage holes so leakage from either the greywater liner or the fresh water tubing would drain out onto the floor alerting the homeowner to a problem. Finally, the copper tubing is pressurized relative to the greywater (by mains pressure) which would impede leakage from the greywater to the fresh water.

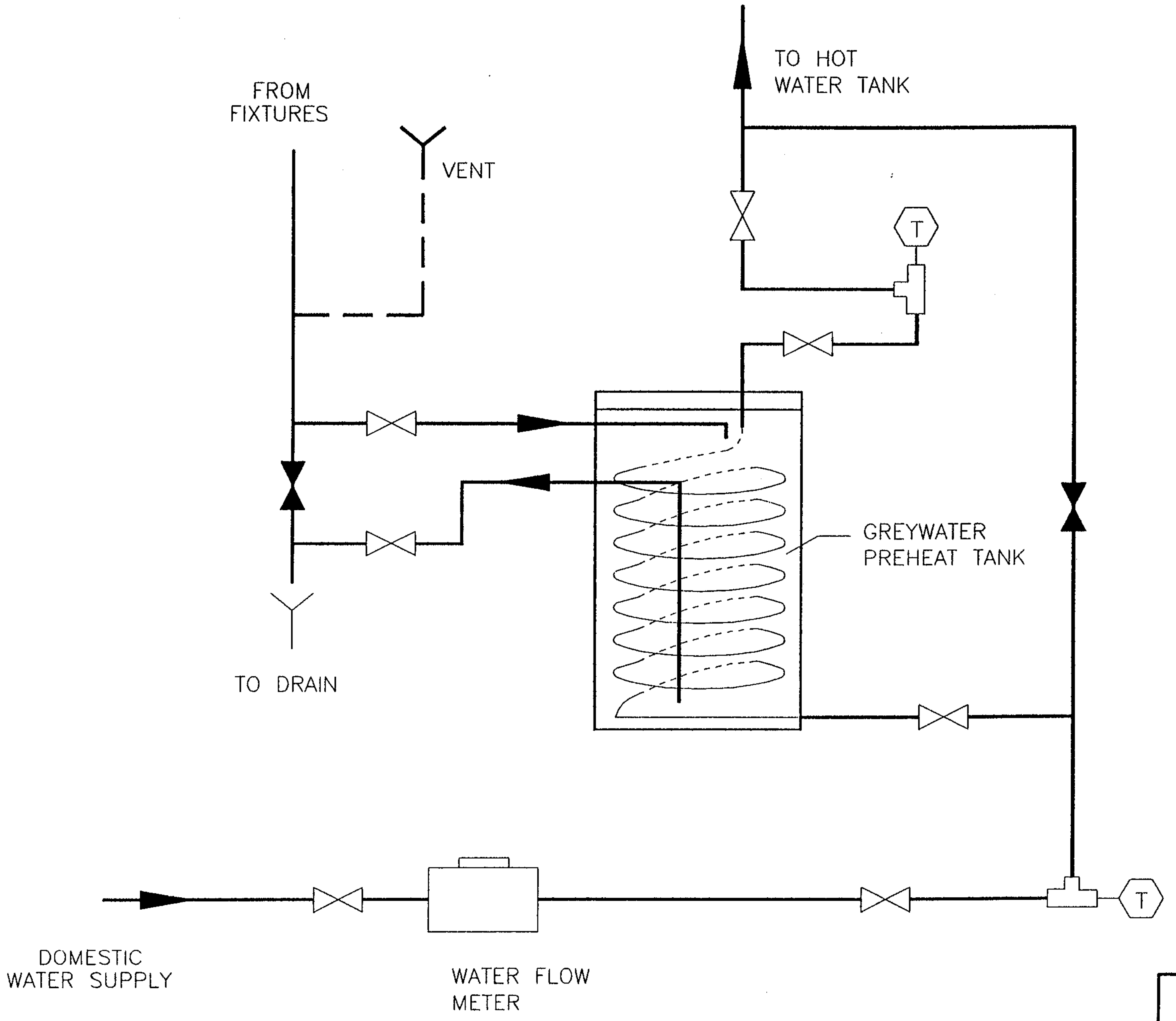


Fig. 1

GREYWATER HEAT
RECOVERY SYSTEM

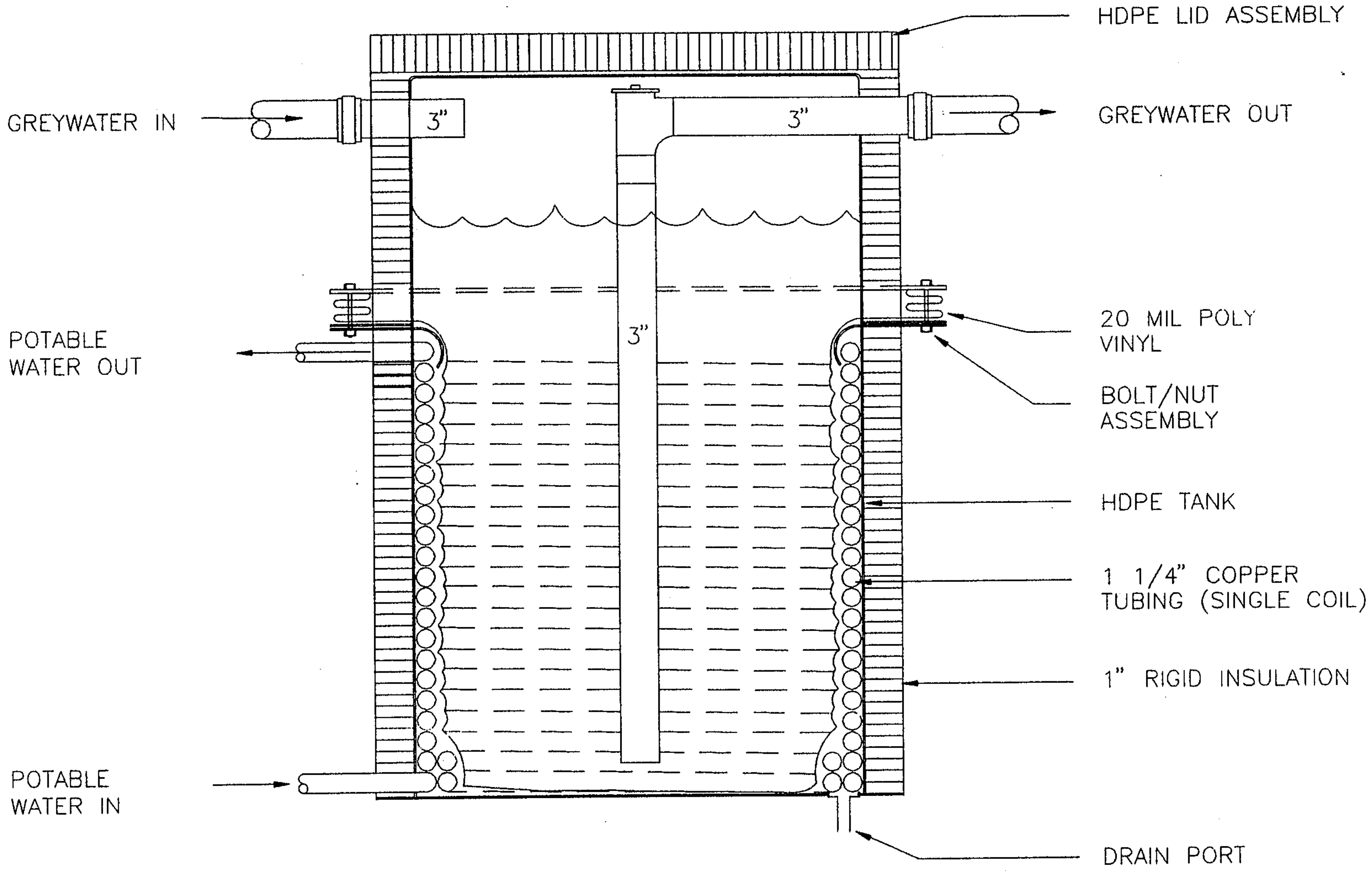
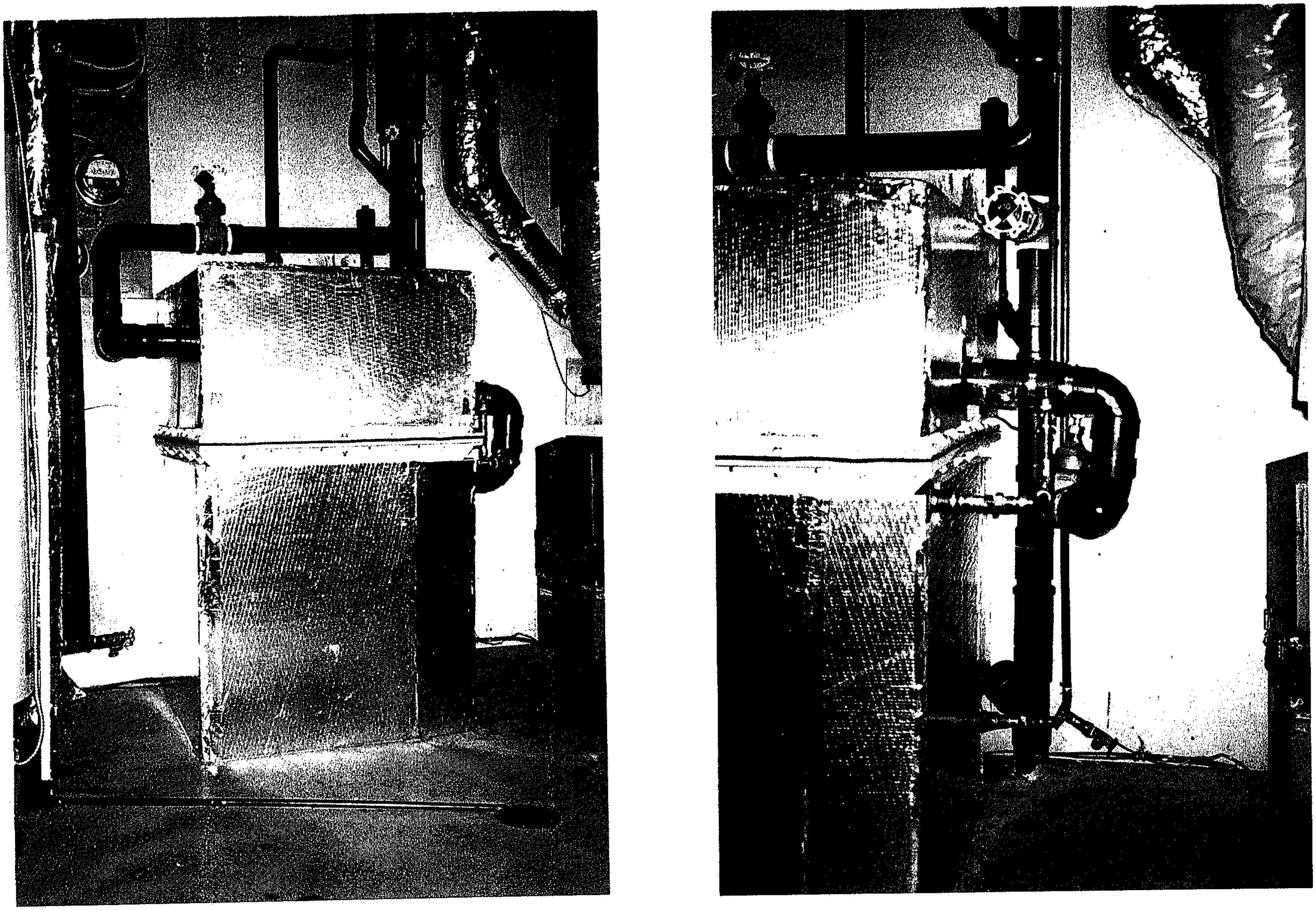


Fig. 2

GREYWATER
PREHEAT TANK



3(a)

3(b)

Fig. 3 PREHEAT TANK

SECTION 3
OPERATIONAL EXPERIENCES

3.1 ODOURS AND WATER LEAKS

A concern of any design of this type is the possibility of odours penetrating into the living space or of water leaking from the tank. So far, neither problem has arisen. No odours have been detected or reported by the homeowners and no leakage has been found. At the time of writing, the preheat tank has been in operation for approximately one year (and the house occupied for about 10 months). During the unoccupied period, it was used for the continuous flow trials.

3.2 SPACE CONSIDERATIONS

The preheat tank is physically large and occupies a significant amount of floor space in the mechanical room. In the case of the Manitoba Advanced House, this is not a serious problem since the house is relatively spacious. However, for smaller houses, particularly those without a basement, the space requirements would have to be considered.

3.3 LOCATION

From a design perspective, the preheat tank has to be located below the level of the lowest fixture which drains into it. For houses with basements, this would not normally be a problem. However, for bungalows with crawl spaces or slab-on-grade construction, it might not be possible to use a system layout of the type described herein.

The preheat tank must also be located so as to facilitate connection to the house's sewer line and to permit connection to a plumbing vent. This also has to be considered at the design stage.

3.4 MAINTENANCE

To date, the preheat tank has not required any maintenance. Unfortunately, the prototype is a little cumbersome from a maintenance perspective. Gaining access to the tank interior is time-consuming since approximately 20 fasteners on the sides have to be removed and the greywater outlet pipe disconnected. Reassembly has to be carefully performed to ensure there are no leaks between the top and the bottom since one of the sealing gaskets is wet, i.e., is under a hydrostatic head, when the tank is full. If the tank were redesigned, an alternate arrangement would be used to facilitate maintenance. Finally, because of its weight (455 kg), the tank has to be drained before it can be moved.

SECTION 4
COMPUTER MODEL

4.1 MODEL STRUCTURE AND DESCRIPTION

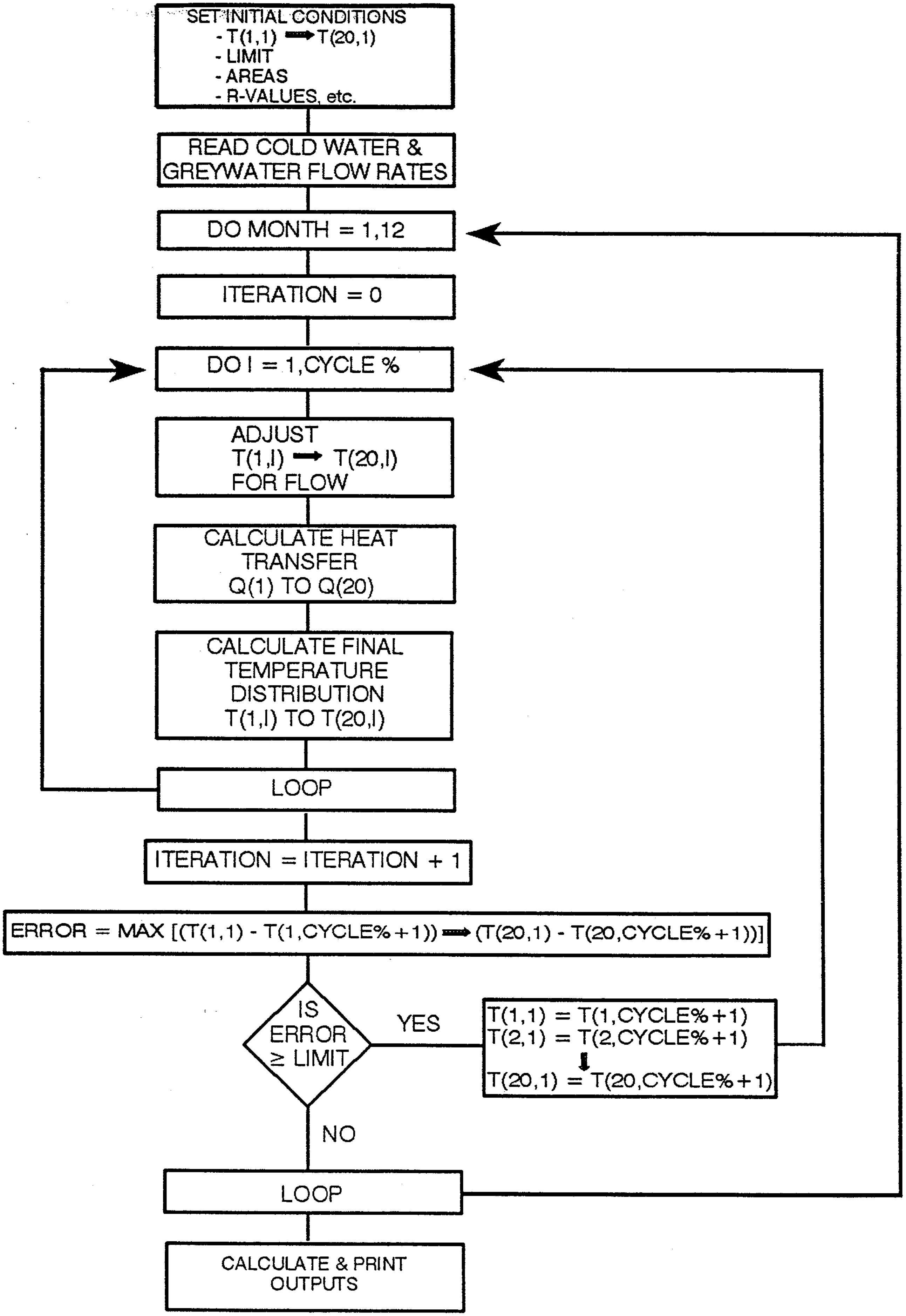
A finite-difference thermal model was developed to simulate the performance of the greywater heat recovery system in different configurations and under various operational situations. After development, the model was validated using empirical data. The model was then used to develop a series of annual performance predictions.

The finite-difference model subdivides each of the greywater and cold water volumes in the preheat tank into 10 thermal strata of appropriate mass. Thermal communication is permitted between greywater and cold water nodes at the same strata level but not between different levels thereby accounting for the effects of thermal stratification within a dynamic operating environment. Heat transfer is also permitted between the greywater/cold water nodes and the room air and the floor. Since DHW usage is very dynamic, the model has to operate with comparatively fine time increments. For the performance evaluations described in Section 5, a time increment of one minute was used. This resulted in (24 x 60) 1440 time steps per day.

The model performs an energy balance by reading the mass flows of greywater and cold water for each time increment in the day. The thermal impact of these flows upon the existing temperature distribution within the tank is then evaluated. The resulting temperature distribution is then used to calculate the nodal heat flux over the time increment. This produces the temperature distribution at the end of the increment. The process then continues on to the next time increment until the last one is reached at the end of the day. A single day is used to characterize each month. Summations are then calculated and the model advances to the next month. A system schematic is shown in Fig. 4.

Key input variables which can be altered in the model include:

- o Greywater flow schedule
- o Cold water flow schedule
- o Tank insulation levels (top, bottom and sides)
- o Greywater-to-cold water heat transfer coefficient
- o Monthly mains water temperature
- o Mass of greywater stored in the tank
- o Mass of cold water stored in the tank
- o Greywater temperature entering the tank
- o Room temperature
- o Floor temperature



MODEL SCHEMATIC
Fig. 4

The greywater system model is written in QuickBASIC and is designed to be run from within the Smart Editor. It operates reasonably quickly, typically performing an annual simulation in two to three minutes on a 80486 personal computer operating at 66 MHz.

Considerable effort was expended evaluating the model under various scenarios to establish confidence in its performance. The only major problem encountered was that care has to be exercised in the selection of the time increment to prevent violations of the Second Law of Thermodynamics, i.e., ensuring that heat is not inadvertently flowing from one node to a second node which is at a higher temperature. This turned about to be more problematic than originally anticipated because the possibility of Second Law violations is affected by the time increment chosen, the nodal masses and other variables which can be altered by the user. The possibility of violations was minimized by using small time increments, such as one minute.

4.2 COLD WATER AND GREYWATER USAGE SCHEDULES

A domestic hot water usage schedule was developed for use in the performance evaluations using an assumed net energy consumption of 14 kWh/day or 4939 kWh/yr. This is equivalent to heating 240 litres (53 I.G.) of water per day from 12 °C to 60 °C (53 °F to 140 °F). This daily usage was then proportioned to each hour using the consumption profiles in the Canadian Electrical Association "Electric Water Heating Manual" (CEA) The minute-by-minute consumption was calculated by assuming it occurred as a single draw commencing at the beginning of the hour at a rate of 2 litres per minute (0.44 I.G. per minute). The cold water flow rate was set equal to the DHW flow rate by assuming there was no significant removal or storage in the hot water supply system.

The greywater draw was assumed to occur coincident with the hot water usage but at a higher mass flow rate to account for dilution of hot water with cold water at the plumbing fixtures. Based on an analysis of fixture flows and usage in the CEA manual, it was assumed that the flow rate of greywater would, under typical circumstances, be 50% larger than the flow of hot water. The temperature of the greywater would, of course, be lower than that of the hot water because of the fixture mixing.

4.3 MODEL VALIDATION

The model was validated by comparing its predicted performance to that measured during a set of field trials conducted during May, 1994 using the prototype system installed in the Manitoba Advanced House. During these trials, the greywater system was operated under steady-state conditions by maintaining a continuous greywater flow through the system while key variables were monitored. Due to the large thermal mass of the storage tank, it took approximately 200 hours of continuous operation to establish thermal equilibrium. The house was unoccupied during the field trials and all water usage carefully controlled and accounted for in the calculations.

A comparison of the predicted performance and the measured results from the May, 1994 field trials is given in Table 1. This showed good agreement for the two critical outlet temperatures and the resulting heat exchanger thermal effectiveness, which is calculated from the inlet and outlet temperatures and the water flow rates.

In addition to the steady-state field trials, some key performance variables were monitored by the Data Acquisition System installed in the Manitoba Advanced House. These included total domestic hot water consumption, the temperature of the cold water entering the preheat tank and the temperature of the greywater leaving the preheat tank. Analysis of this data showed that DHW consumption for the house, once it was occupied, was very low, averaging 50 kg/day (110 lbm/day). This represents about 20% of the usage of an average family (and of that which was used in the performance analysis).

The temperature of the cold water entering the preheat tank was also checked for some typical days during the 1994/95 winter and found to compare quite closely to the values used in the performance analysis.

TABLE 1
COMPARISON OF MEASURED AND PREDICTED PERFORMANCE UNDER STEADY-STATE CONDITIONS

	T_{ci}	T_{co}	T_{hi}	T_{ho}	ϵ
MEASURED	8.4 °C (input)	29.2 °C	50.9 °C (input)	27.9 °C	0.50
PREDICTED	8.4 °C (input)	30.2 °C	50.9 °C (input)	28.6 °C	0.51
DIFFERENCE		-1.0 °C		-0.7 °C	0.01

Nomenclature:

T_{ci} = Temperature of the cold water entering the preheat tank
T_{co} = Temperature of the cold water leaving the preheat tank
T_{hi} = Temperature of the greywater entering the preheat tank
T_{ho} = Temperature of the greywater leaving the preheat tank
ϵ = Thermal effectiveness

SECTION 5
PERFORMANCE ANALYSIS

5.1 VARIABLES STUDIED

Following completion and validation of the model, a series of annual simulations were carried out to explore the impact of various design parameters and operational variables on the system's performance. The prototype system installed in the Manitoba Advanced House was defined as the Base Case and then, for each variable, annual simulations were performed using the Base Case conditions and a range of alternate values for that variable. The variables studied were:

- Tank insulation
- Greywater mass
- Cold water mass
- Greywater temperature
- Cold water inlet temperature
- DHW setpoint temperature
- AU1 (heat transfer variable)
- Greywater and cold water flow rates
- Room temperature
- Greywater flow rate
- Design optimization

The results of this analysis are described on the following pages. For each variable, a short description is provided of its impact on the annual performance. The two key output parameters reported are: the percentage savings produced by the preheat system (i.e., the fraction of the total DHW load supplied by the greywater system) and the absolute energy savings (which defines the value of the recovered energy).

5.2 IMPACT OF TANK INSULATION

The prototype preheat tank was insulated on the top and sides with 25 mm (1") of rigid glass fibre insulation with an aluminum facing; all joints were sealed with aluminum tape. This gave an effective RSI value of 0.70 (R-4). The bottom was uninsulated.

As shown in Table 2 and Figs. 5 and 6, increasing the insulation levels by 50% relative to the Base Case produced a small decrease in heat loss from the tank resulting in a slight improvement in performance. Further increases in the amount of tank insulation, and the addition of an RSI 0.88 (R-5) extruded polystyrene bottom board produced modest, additional savings. However, if the tank were uninsulated, a significant degradation in performance would have resulted since the average tank temperature was higher than the basement air temperature most of the time. Note that no credit was given to the greywater system for the reduction in the space heating load due to losses from the tank to the basement air.

Based on these results, it was concluded that the tank insulation levels should have been higher than those used on the prototype. Also, an insulated bottom board should have been included.

TABLE 2

CASE	DHW LOAD (kWh/yr)	RECOVERED ENERGY (kWh/yr)	THERMAL EFFECTIVE-NESS	PERCENT DHW LOAD SUPPLIED
0. Base Case. RSI 0.70 (R-4) sides & top; bottom uninsulated.	4939	1789	0.759	36.2%
1. RSI 1.06 (R-6) sides & top; bottom uninsulated.	4939	1862	0.790	37.7%
2. RSI 1.41 (R-8) sides & top; bottom uninsulated.	4939	1902	0.807	38.5%
3. RSI 1.41 (R-8) sides & top; RSI 0.88 (R-5) bottom.	4939	1905	0.809	38.6%
4. Tank uninsulated.	4939	1482	0.629	30.0%

FIGURE 5

IMPACT OF TANK INSULATION

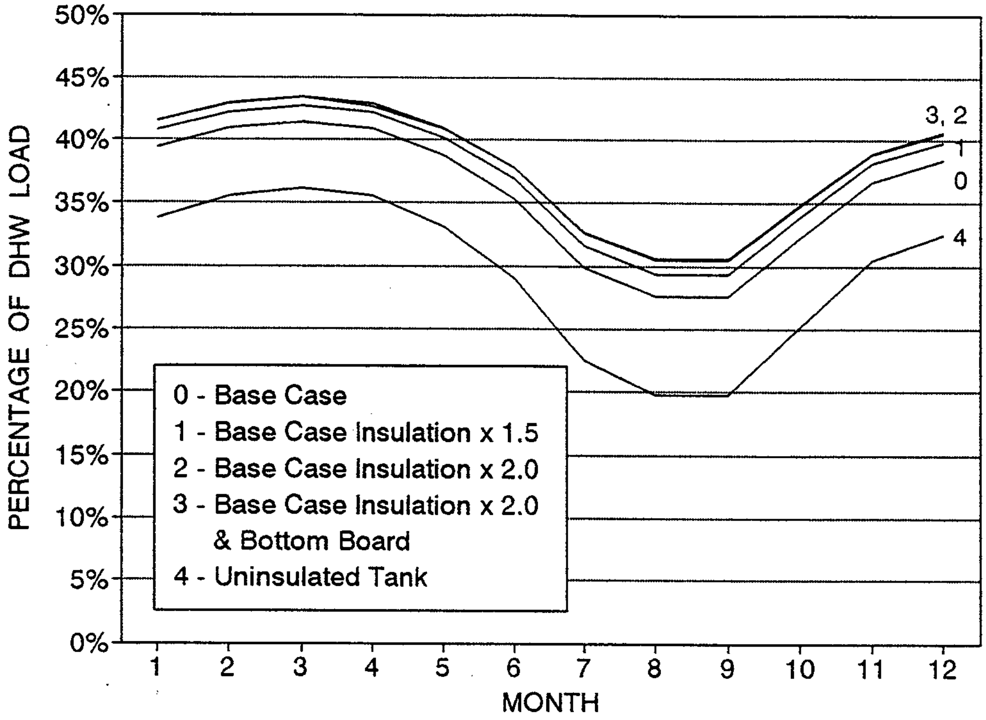
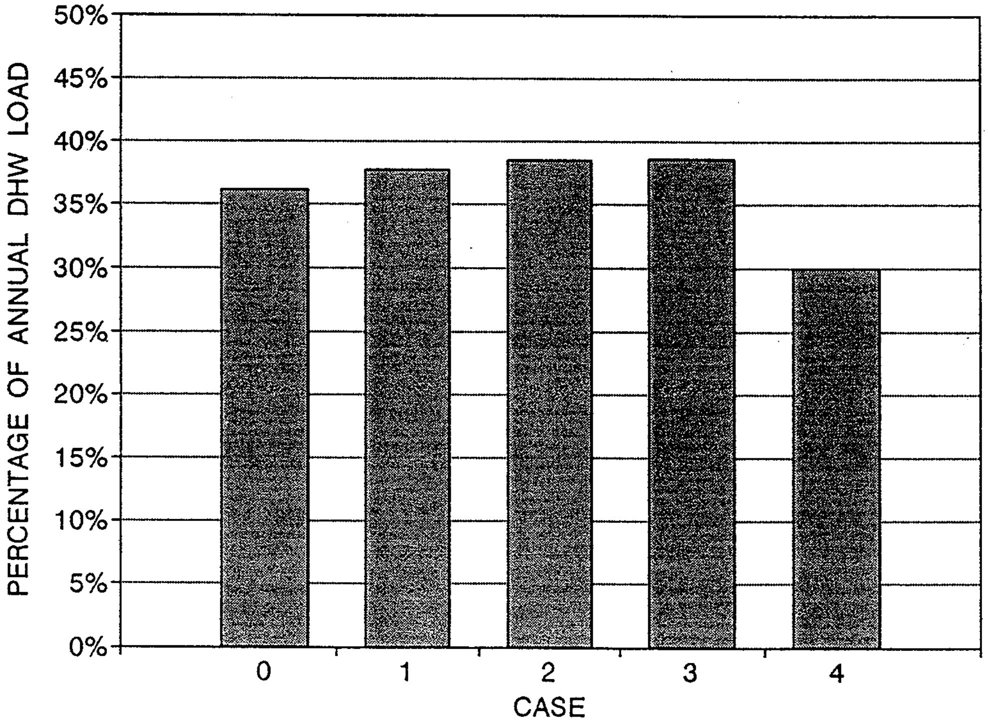


FIGURE 6

IMPACT OF TANK INSULATION



5.3 IMPACT OF GREYWATER MASS

The mass of greywater stored in the prototype was 386 kg (850 lbm). This was originally selected so as to provide storage for approximately one day's production of greywater under typical occupancy conditions. Altering the storage capacity affects the amount of heat available for recovery, influences the level of thermal stratification achievable within the tank and impacts skin losses from the tank to the space.

Modelling showed that there was an optimum level of greywater storage which could be achieved depending on the usage characteristics. Enlarging the greywater storage tank from that used on the prototype increased the energy available for recovery but degraded the benefits of thermal stratification. When the storage tank capacity was doubled, the percentage of the DHW load supplied by the preheat system decreased. By reducing the greywater mass to between one-quarter and one-third that used in the prototype, slight performance gains were achieved. This would permit a smaller and hence less expensive tank to be used.

Based on these results, it appears that a greywater storage volume of between about 100 kg and 130 kg (220 lbm and 286 lbm) would be optimum for typical, residential usage conditions.

TABLE 3

CASE	DHW LOAD (kWh/yr)	RECOVERED ENERGY (kWh/yr)	THERMAL EFFECTIVE-NESS	PERCENT DHW LOAD SUPPLIED
0. Base Case. Greywater mass equal to 386 kg (850 lbm)	4939	1789	0.759	36.2%
5. Base Case mass x 0.50	4939	1872	0.795	37.9%
6. Base Case mass x 0.33	4939	1896	0.805	38.4%
7. Base Case mass x 0.25	4939	1904	0.808	38.5%
8. Base Case mass x 2.00	4939	1640	0.696	33.2%

FIGURE 7

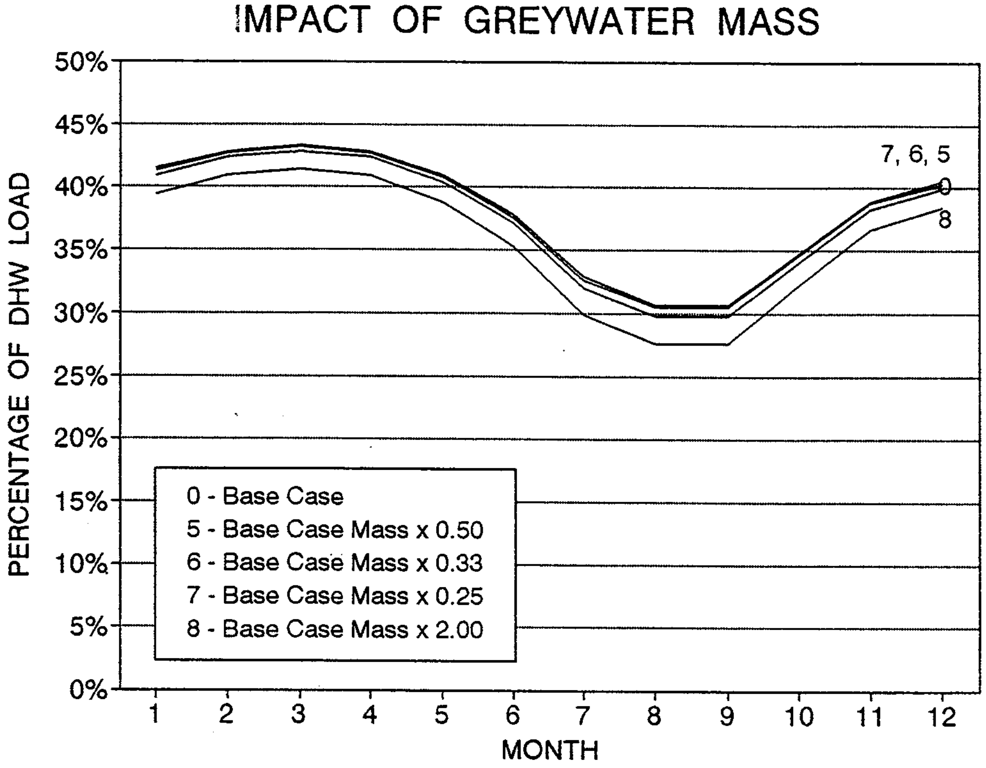
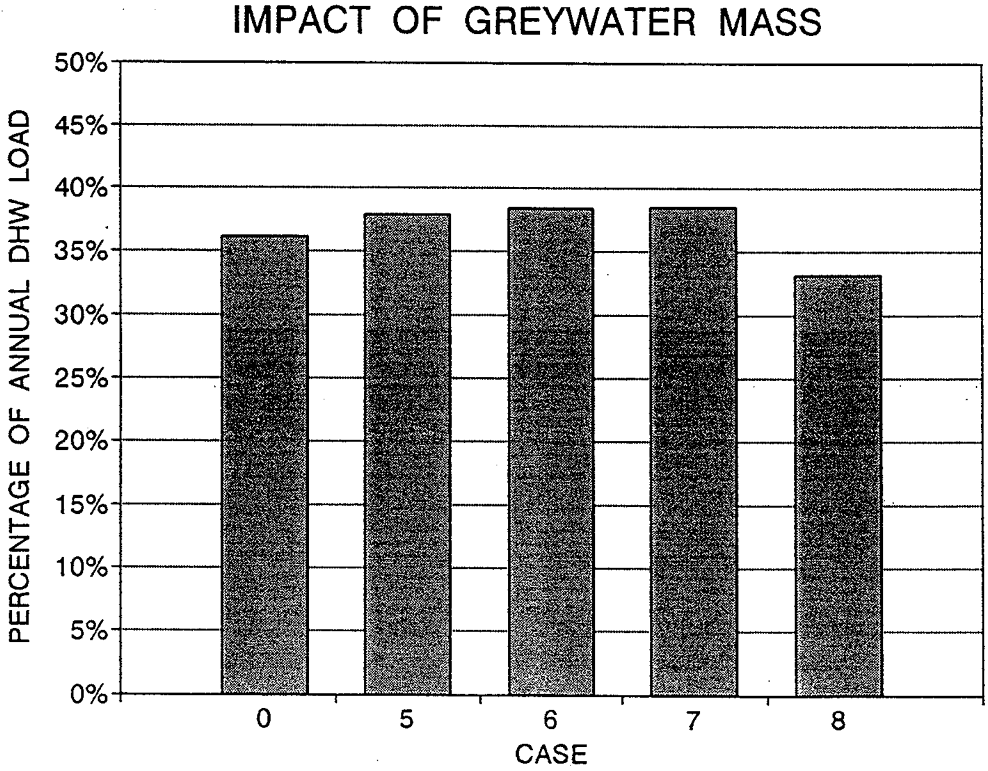


FIGURE 8



5.4 IMPACT OF COLD WATER MASS

The mass of cold water stored in the prototype preheat tank was 27 kg (60 lbm). This quantity was selected based on the available space within the tank and the cost of the tubing. Modifying the cold water mass has two effects; it alters the thermodynamic interaction between the cold water and the greywater and, for most instances, changes the available heat transfer area between the two since the coil dimensions change. Selecting the correct length of coil is important because it can be a relatively expensive part of the overall system if a material such as copper is used.

The analysis found that varying the mass of cold water had a much more pronounced effect than corresponding changes to the mass of greywater in the tank. As shown in Figs. 9 and 10, reducing the cold water mass by 50% reduced the annual percentage savings from 36.2% for the Base Case to under 30%. Increasing the cold water mass increased performance although the benefits reached a plateau at a mass equal to about twice that used in the prototype tank. Based on these results, it appears that a cold water storage mass of about 55 kg (120 lbm) would be optimum for a typical, residential application. It was also concluded that the mass of cold water, and the corresponding heat transfer area between the two fluids, was one of the key variables affecting performance of the greywater heat recovery system.

TABLE 4

CASE	DHW LOAD (kWh/yr)	RECOVERED ENERGY (kWh/yr)	THERMAL EFFECTIVE-NESS	PERCENT DHW LOAD SUPPLIED
0. Base Case. Cold water mass equal to 27 kg (60 lbm)	4939	1789	0.759	36.2%
9. Base Case mass x 0.5	4939	1465	0.621	29.7%
10. Base Case mass x 2.0	4939	1926	0.818	39.0%
11. Base Case mass x 3.0	4939	1950	0.828	39.5%
12. Base Case mass x 4.0	4939	1950	0.828	39.5%

FIGURE 9

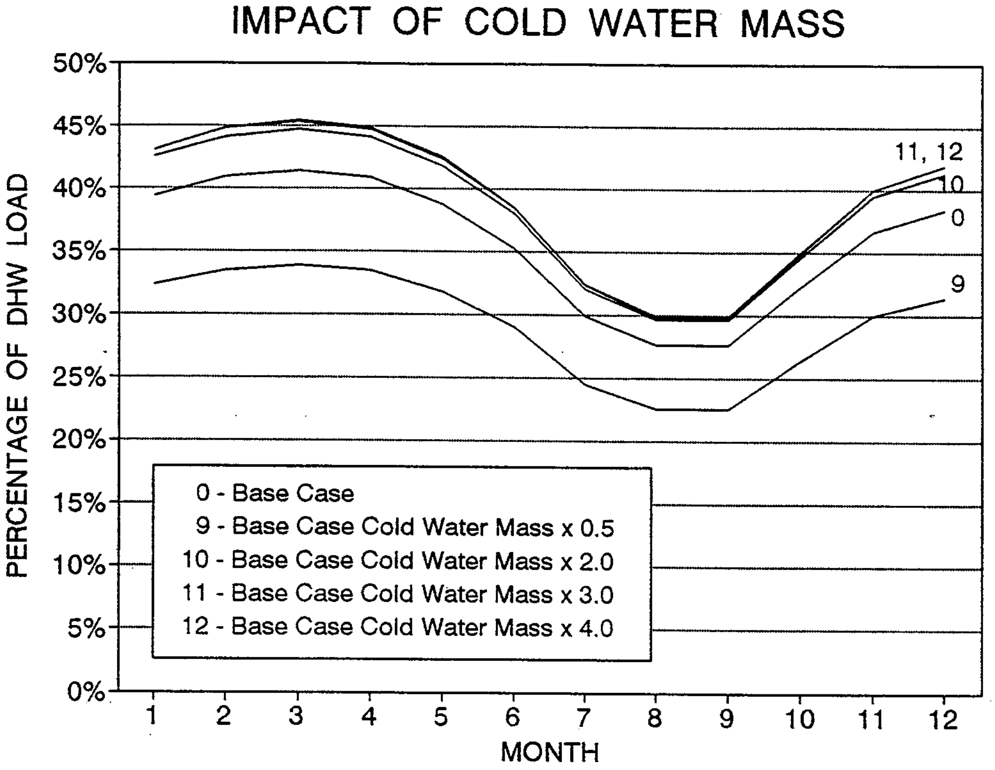
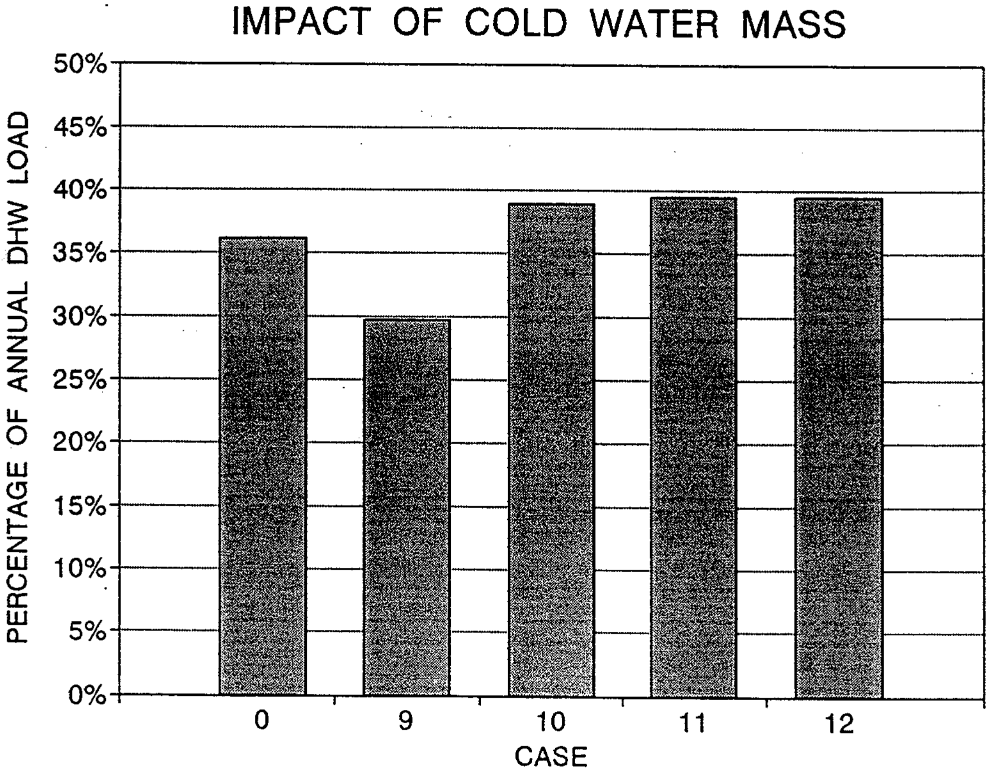


FIGURE 10



5.5 IMPACT OF GREYWATER TEMPERATURE

The temperature of the greywater reaching the preheat tank will vary depending on which fixtures and appliances are plumbed to the tank and which are discharging at any given moment. For modelling the Base Case, a constant greywater temperature of 35 °C (95 °F) was used based on sample measurements of typical discharge temperatures in residential applications. However, this variable is dependent on lifestyle, particularly the temperature settings used on the washing machine. For the analysis, it was assumed that a warm wash/cold rinse cycle was used.

The analysis found that the greywater temperature had a major impact on system performance. The percentage of the DHW load supplied by the greywater system decreased roughly 1.4% for each 1 °C (or 0.8% for each 1 °F) reduction in the greywater temperature. Thus, when 27 °C (80 °F) was used instead of 35 °C (95 °F), the annual contribution dropped from 36.2% to 24.3 %, representing a one-third reduction in recovered energy. This means that the selection of fixtures and appliances plumbed into the greywater system is critical. Unfortunately, it also makes proper design of the system more difficult given the uncertainties of predicting homeowner lifestyle patterns.

TABLE 5

CASE	DHW LOAD (kWh/yr)	RECOVERED ENERGY (kWh/yr)	THERMAL EFFECTIVE-NESS	PERCENT DHW LOAD SUPPLIED
0. Base Case. Greywater temperature 35.0 °C (95 °F).	4939	1789	0.759	36.2%
13. Greywater temperature 32.2 °C (90 °F).	4939	1593	0.767	32.2%
14. Greywater temperature 29.4 °C (85 °F).	4939	1397	0.776	28.3%
15. Greywater temperature 26.7 °C (80 °F).	4939	1201	0.789	24.3%
16. Greywater temperature 37.8 °C (100 °F).	4939	1985	0.754	40.2%

FIGURE 11

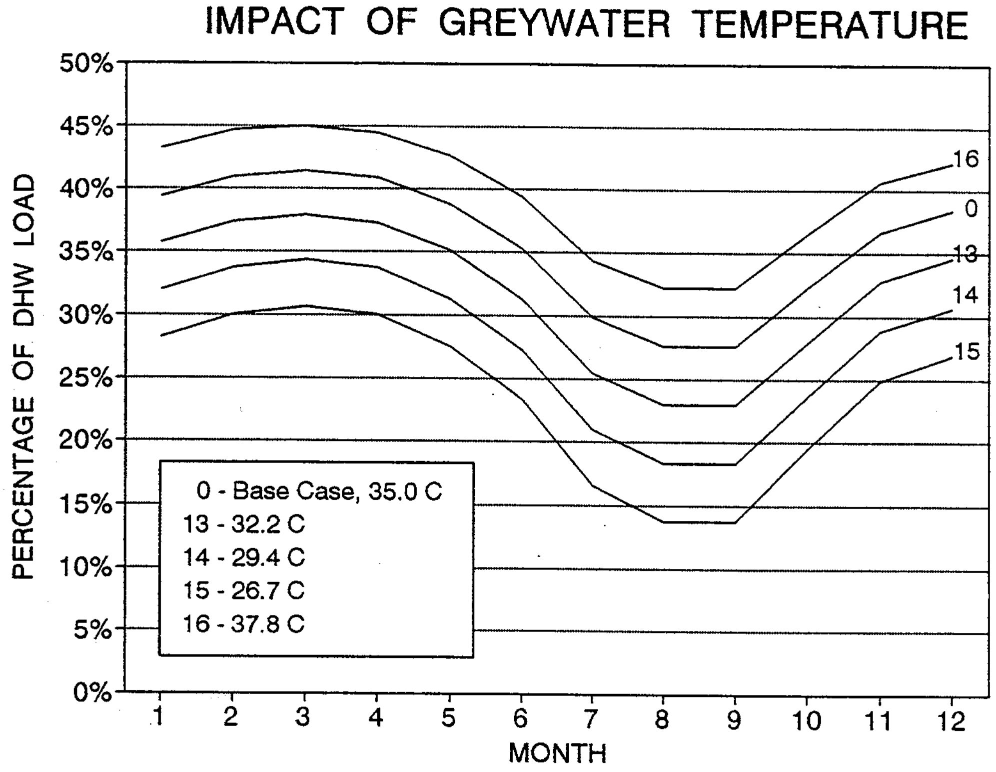
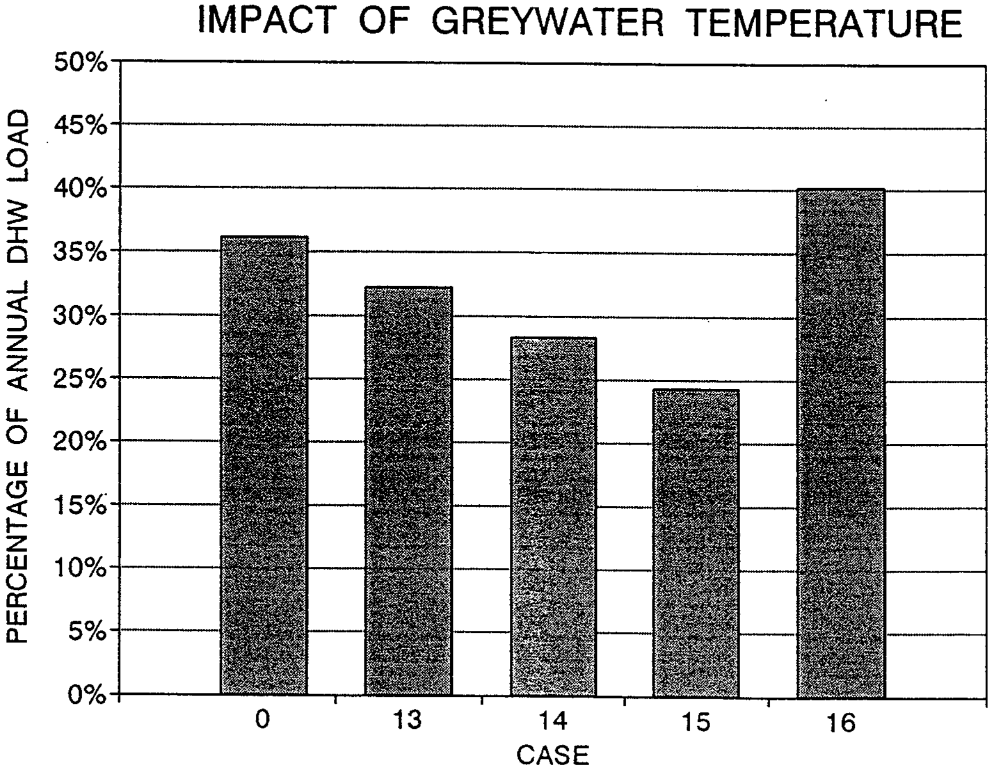


FIGURE 12



5.6 IMPACT OF COLD WATER INLET TEMPERATURE

The temperature of the cold water entering the preheat tank from the water mains typically varies in harmony with the deep-ground temperature and lags that of the ambient air by about two months. As the mains temperature increases, the performance of the greywater system degrades because the temperature differential between the cold water and the greywater is reduced (see Section 2). For modelling, measured monthly water temperatures, obtained from the local water utility were used for the Base Case (City of Winnipeg). This ranged from 6.1 °C to 18.3 °C (43 °F to 65 °F), with an average monthly temperature of 11.5 °C (53 °F). Four additional scenarios, created by raising or lowering each of the monthly values in increments of 1.1 °C (2 °F), were evaluated. This range of cold water temperatures would include the deep-ground temperatures for most sites in southern Canada. The analysis assumed negligible preheating of mains water by house air.

The analysis showed that the cold water temperature had a modestly strong impact on performance, although not as pronounced as variations in greywater temperature. The maximum variation in the percentage of DHW load met was about 5%. As the inlet water temperature increased, the variations in seasonal performance also became more pronounced. Variations in monthly performance were somewhat larger than had been anticipated and reinforced the decision to design the model with variable water inlet temperatures.

TABLE 6

CASE	DHW LOAD (kWh/yr)	RECOVERED ENERGY (kWh/yr)	THERMAL EFFECTIVE-NESS	PERCENT DHW LOAD SUPPLIED
0. Base Case. Average cold water temperature 11.5 °C (53 °F).	4939	1789	0.759	36.2%
17. Cold water temperature equal to Base Case - 1.1 °C (2 °F).	5052	1889	0.765	37.4%
18. Cold water temperature equal to Base Case + 1.1 °C (2 °F).	4825	1689	0.752	35.0%
19. Cold water temperature equal to Base Case + 2.2 °C (4°F).	4712	1589	0.745	33.7%
20. Cold water temperature equal to Base Case + 3.3 °C (6°F).	3052	1489	0.736	32.3%

FIGURE 13

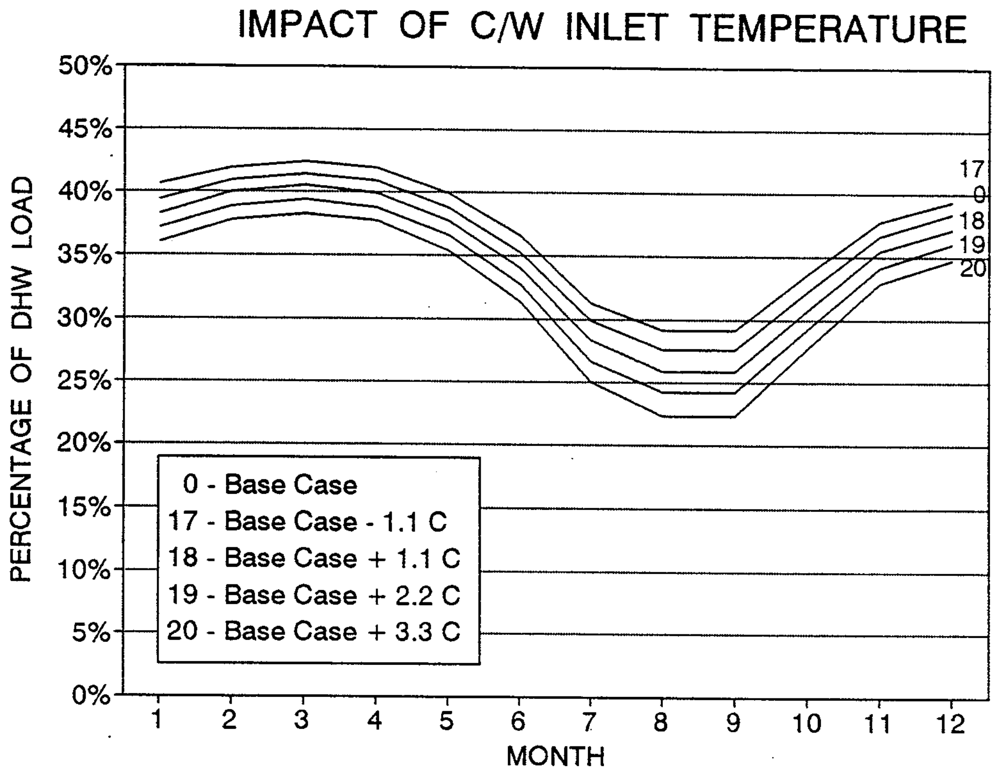
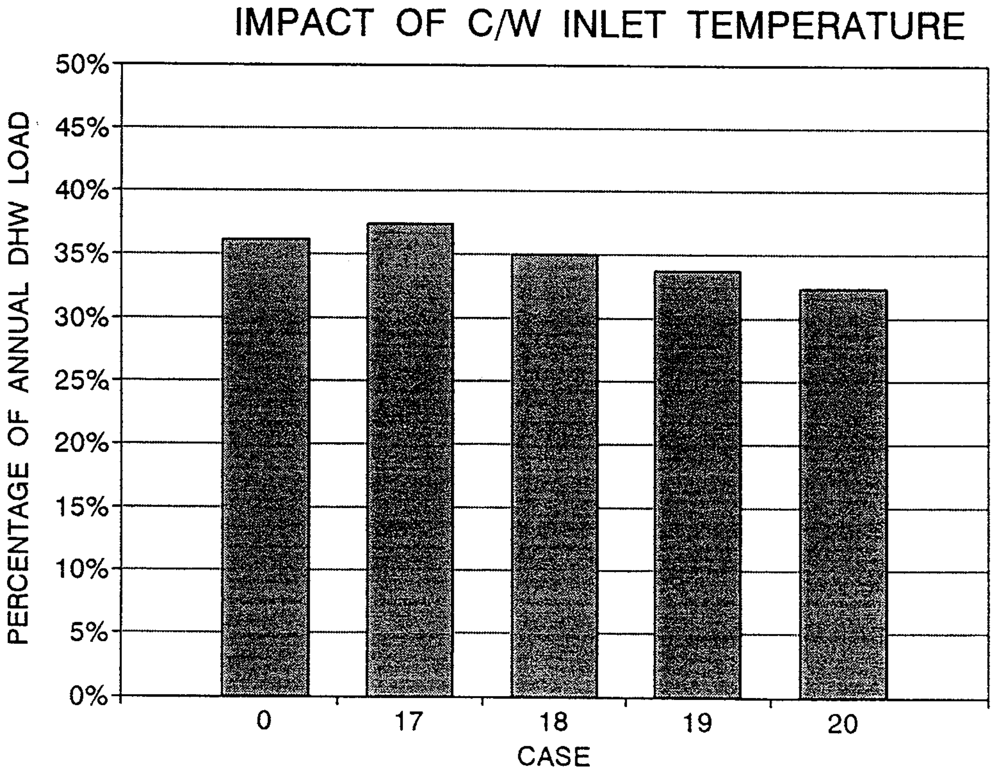


FIGURE 14



5.7 IMPACT OF THE DHW SETPOINT TEMPERATURE

The DHW tank setpoint temperature has no impact on the absolute quantity of energy recovered by the greywater system, but it does affect the percentage of the total load which can be supplied by preheating. Theoretically, to maximize the recoverable energy, a low setpoint is preferable since this places a larger percentage of the total DHW load within the temperature range of the greywater. A lower limit of 60 °C (140 °F) is often recommended to reduce the risk of bacteria colonization. However, lower temperatures are used by some homeowners to save energy. It has also been argued that tanks heated by natural gas or oil can be run at lower setpoints because of the more pronounced thermal stratification, within the tank, which temporarily exposes the water to high temperatures when it is near the burner. No comment is offered about the validity of these arguments; however, the impact of lower DHW setpoints was investigated. The upper temperature limit is defined by the need to reduce the probability of scalding and extend tank life. For the analysis, DHW setpoint temperatures of 48.9 °C to 71.8 °C (120 °F to 160 °F) were studied.

As expected, the percentage performance declined with higher setpoint temperatures. Each 1 °C (1.8 °F) increase in the setpoint temperature reduced the percentage of the DHW load met by about 0.8% (absolute).

TABLE 7

CASE	DHW LOAD (kWh/yr)	RECOVERED ENERGY (kWh/yr)	THERMAL EFFECTIVE-NESS	PERCENT DHW LOAD SUPPLIED
0. Base Case. DHW setpoint temperature 60.0 °C (140 °F).	4939	1789	0.759	36.2%
21. DHW setpoint temperature 48.9 °C (120 °F).	3808	1789	0.759	47.0%
22. DHW setpoint temperature 54.4 °C (130°F).	4373	1789	0.759	40.9%
23. DHW setpoint temperature 65.6 °C (150 °F).	5504	1789	0.759	32.5%
24. DHW setpoint temperature 71.1 °C (160 °F).	6070	1789	0.759	29.5%

FIGURE 15

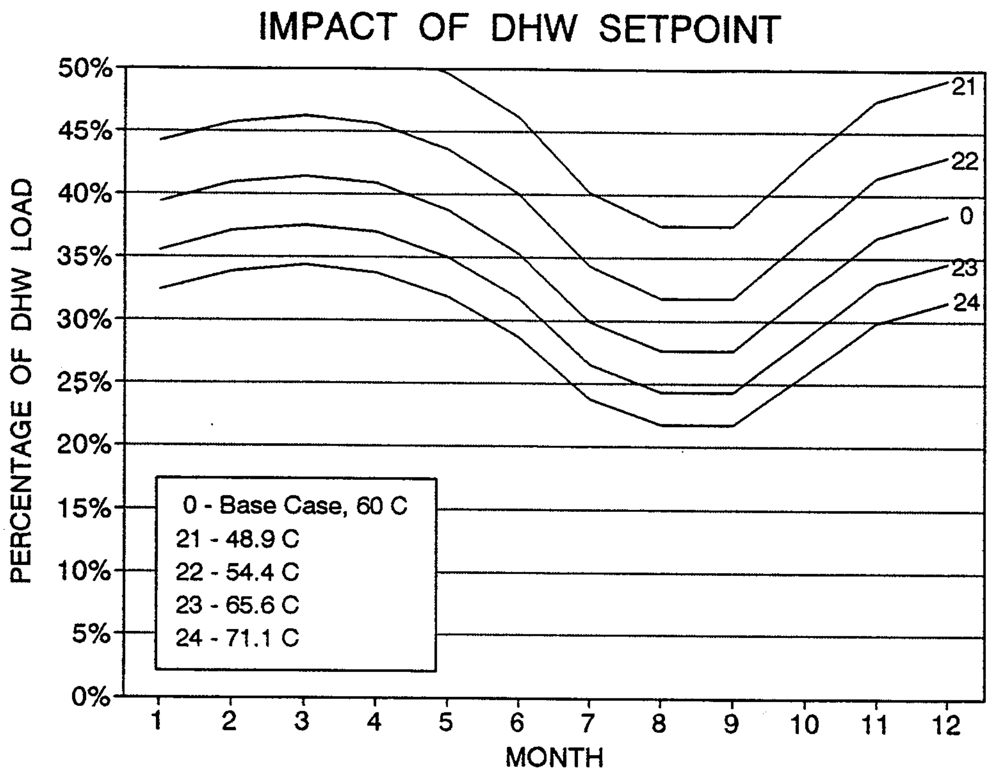
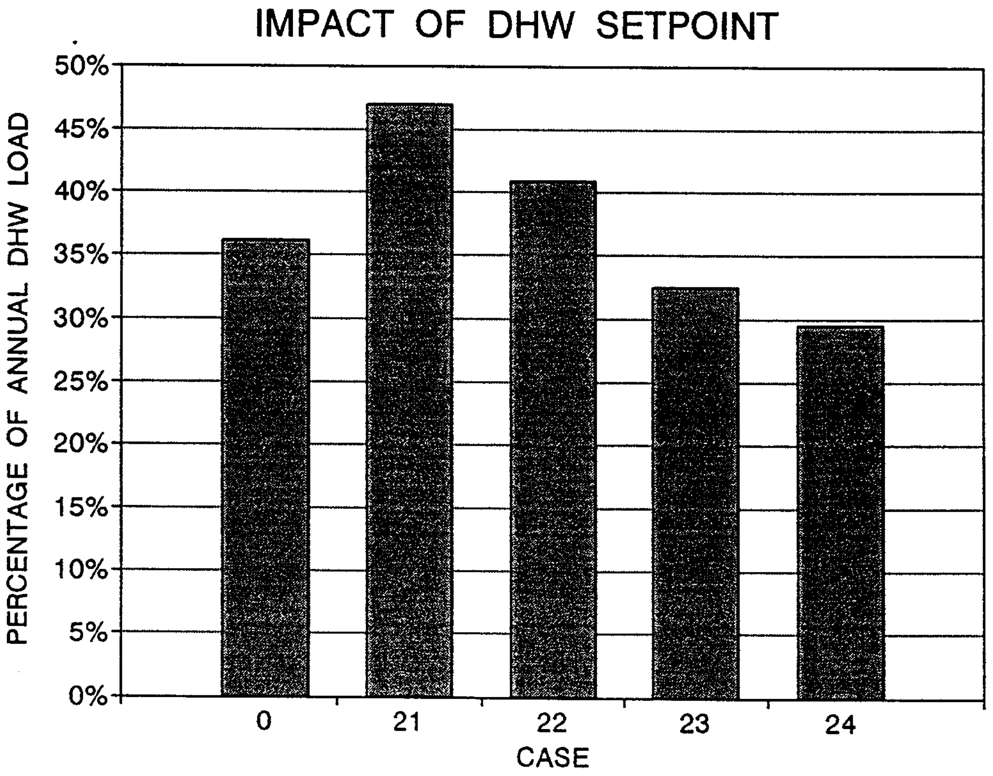


FIGURE 16



5.8 IMPACT OF AU1

AU1 is the term used within the model to describe the thermal conductance between the cold water and greywater. It is the product of the area over which the heat transfer takes place and the unit thermal conductance. It accounts for the effects of the two water-to-surface thermal resistances as well as the resistance of the tube wall, tank liner and the tube-to-liner contact resistance. AU1 can be altered by changing the heat transfer area (i.e., the size or length of the copper tubing in the tank) or by altering the average flow velocity within the tube. It can also be modified by employing some form of extended surface on the tubing, although this was not studied. The value used for AU1 in the prototype, 139 W/°C (263 Btu/hr-°F), was experimentally determined during the steady-state field trials.

The analysis found that the value of AU1 used in the prototype was reasonably close to the optimum level. Modest performance gains could be attained by increasing AU1 by 50% to 100% although the cost-effectiveness of this action has to be weighed against the extra tubing cost if an expensive material such as copper is being used. However, if AU1 were decreased significantly, there would have been a potentially significant reduction in performance. It should also be acknowledged that cheaper materials such as plastic tubing might offer an inexpensive means of increasing AU1.

TABLE 8

CASE	DHW LOAD (kWh/yr)	RECOVERED ENERGY (kWh/yr)	THERMAL EFFECTIVE-NESS	PERCENT DHW LOAD SUPPLIED
0. Base Case. AU1 equal to 139 W/°C (263 Btu/hr-°F).	4939	1789	0.759	36.2%
25. Base Case AU1 x 0.50.	4939	1670	0.709	33.8%
26. Base Case AU1 x 0.25.	4939	1447	0.614	29.3%
27. Base Case AU1 x 1.50.	4939	1840	0.781	37.2%
28. Base Case AU1 x 2.00.	4939	1878	0.797	38.0%

FIGURE 17

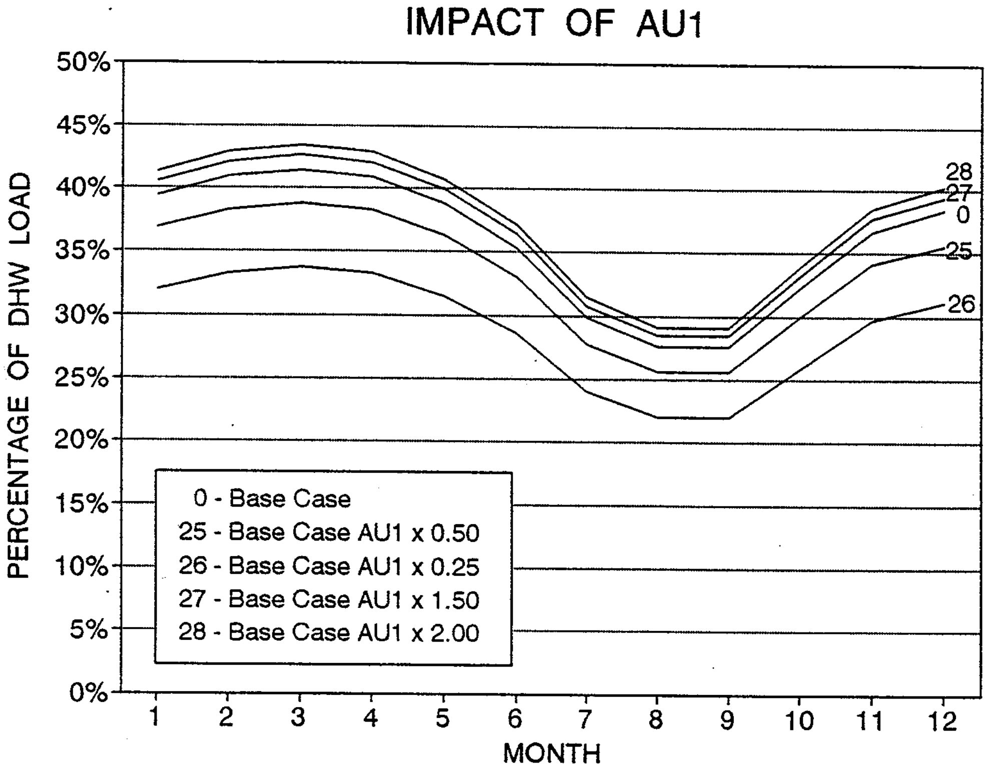
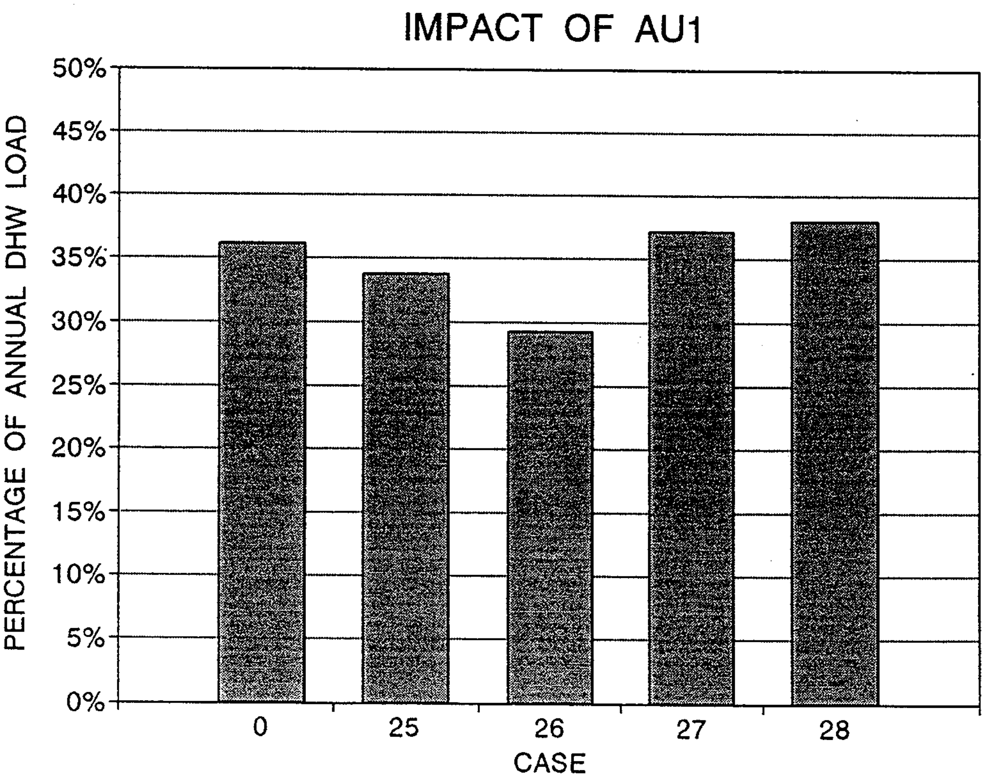


FIGURE 18



5.9 IMPACT OF GREYWATER AND COLD WATER FLOW RATES

The daily mass flow rates of cold water and greywater through the preheat system are largely determined by homeowner lifestyle and can vary widely. Changing these two variables not only affects the internal performance of the preheat tank but also changes the total DHW load since the cold water flow determines the mass of water which has to be heated. For the Base Case, the cold water consumption was derived from the hot water usage patterns described in the CEA Water Heating Manual, while the greywater flow rate was assumed to be 50% greater. Total daily cold water and greywater flow rates for the Base Case were 240 kg/day and 358 kg/day (530 lbm/day and 787 lbm/day), respectively. Hourly profiles were also derived from the CEA manual. For the analysis, the daily cold water and grey water flows were adjusted by up to ±50%.

The analysis showed that the major effect of adjusting the two flow rates was to alter the absolute value of energy recovery by the preheat system, as shown in Table 9 below. This would have a major impact on the system's cost effectiveness and basically illustrates that the best applications for greywater preheat systems are those which have large DHW loads. Measures which reduce DHW consumption, such as low-flow showerheads, would degrade the savings achievable by the preheat system. The percentage of the total DHW load met by the preheat system was relatively constant over the range of flows examined.

TABLE 9

CASE	DHW LOAD (kWh/yr)	RECOVERED ENERGY (kWh/yr)	THERMAL EFFECTIVE-NESS	PERCENT DHW LOAD SUPPLIED
0. Base Case flow rates.	4939	1789	0.759	36.2%
29. Base Case flows x 0.75.	3704	1357	0.768	36.6%
30. Base Case flows x 0.50.	2469	889	0.755	36.0%
31. Base Case flows x 1.25.	4445	2183	0.741	35.4%
32. Base Case flows x 1.50.	7568	2517	0.712	34.0%

FIGURE 19

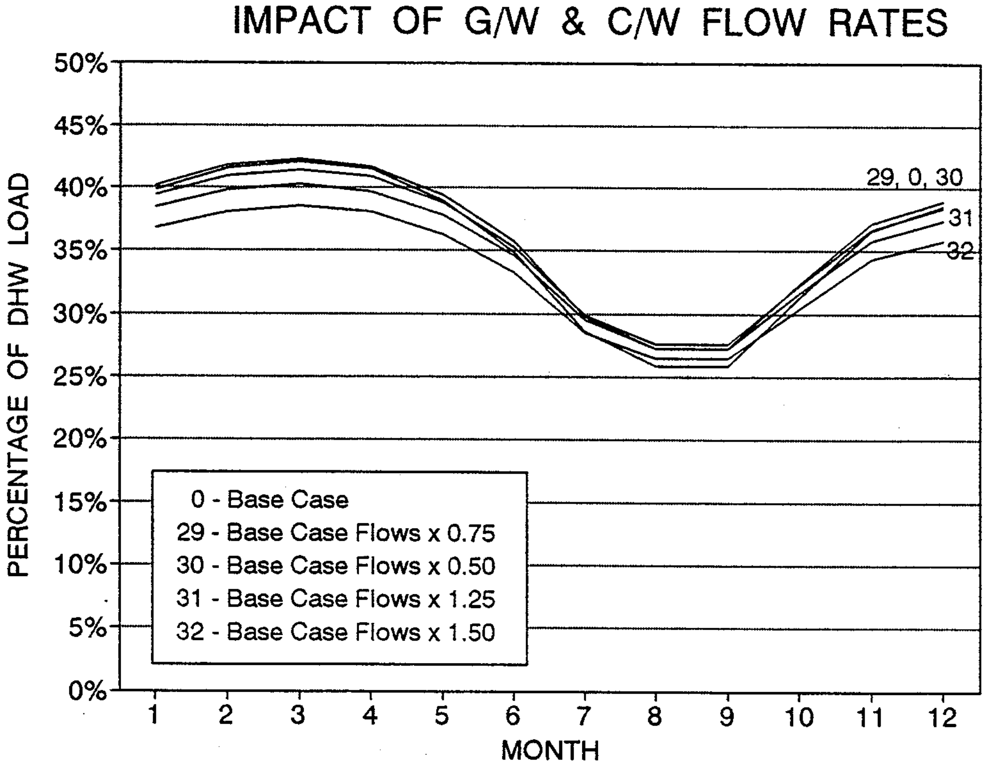
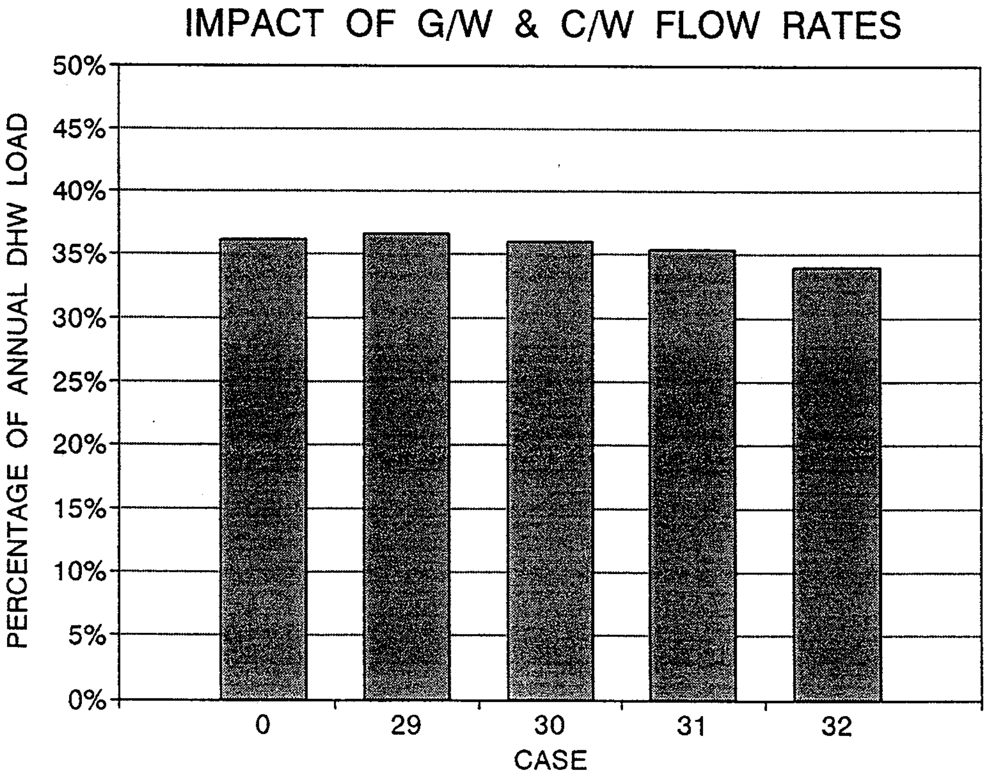

IMPACT OF G/W & C/W FLOW RATES

FIGURE 20


IMPACT OF G/W & C/W FLOW RATES

5.10 IMPACT OF ROOM TEMPERATURE

Room temperature affects the performance of the preheat system by altering the skin losses from the storage tank to the air. In most applications, room temperature is a fixed variable determined by the use of the room in which the tank is located. For the Base Case, the preheat tank was assumed to be located in a basement at 18.3 °C (65 °F). The floor temperature was assumed to be constant at 16°C (60°F). Skin losses from the sides and top of the tank offset the space heating load of the house (and possibly increase the cooling load), however no credit for these losses to the space was included in the analysis.

As shown in Figs. 21 and 22, room temperature had a modest impact on overall performance. The temperature range explored, 18.3 °C to 23.9 °C (55 °F to 75 °F) would cover most potential applications. These results were calculated assuming the Base Case levels of insulation on the tank. If greater amounts of insulation were used, the variation in performance with room temperature would be less pronounced.

TABLE 10

CASE	DHW LOAD (kWh/yr)	RECOVERED ENERGY (kWh/yr)	THERMAL EFFECTIVE-NESS	PERCENT DHW LOAD SUPPLIED
0. Base Case. Room temperature 18.3 °C (65 °F).	4939	1789	0.759	36.2%
33. Room temperature 15.6 °C (60 °F).	4939	1739	0.738	35.2%
34. Room temperature 12.8 °C (55 °F).	4939	1689	0.717	34.2%
35. Room temperature 21.8 °C (70 °F).	4939	1839	0.781	37.2%
36. Room temperature 23.9 °C (75 °F).	4939	1889	0.802	38.3%

FIGURE 21

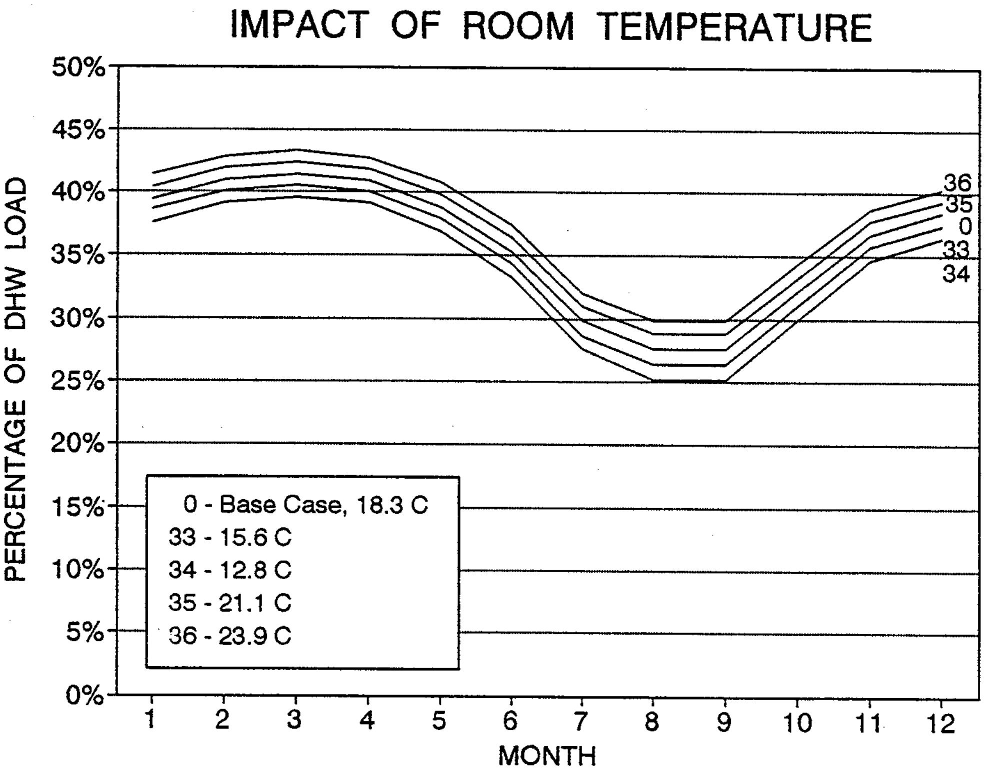
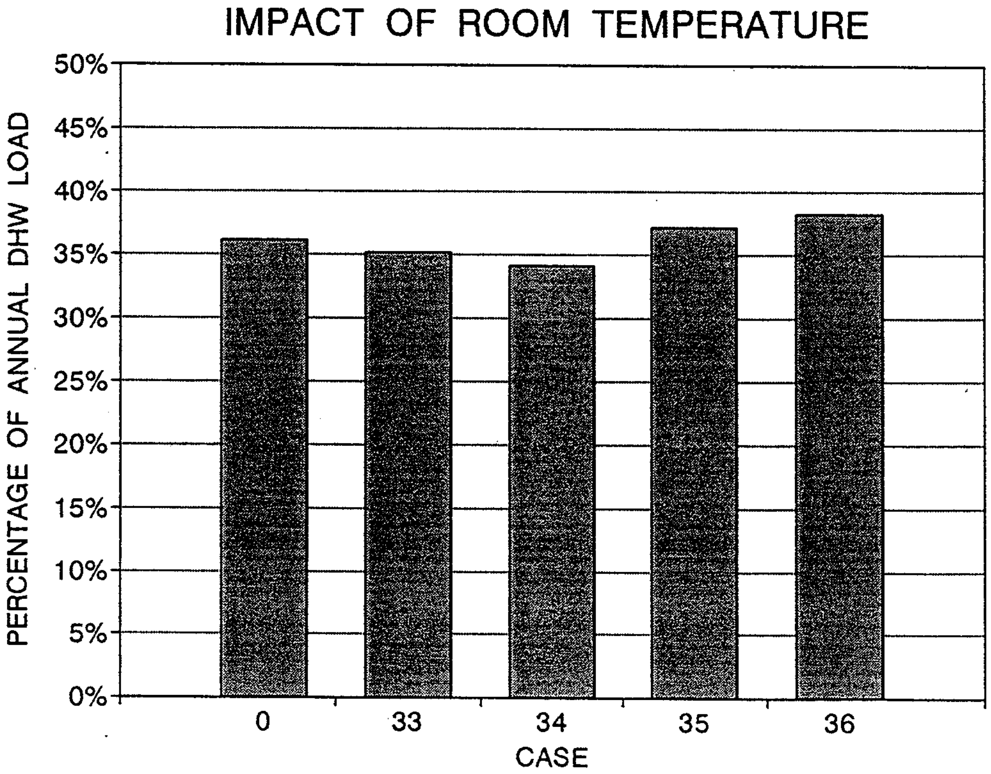


FIGURE 22



5.11 IMPACT OF GREYWATER FLOW RATE

The greywater flow rate is a key variable affecting system performance because it determines the maximum potential energy which is available for recovery by the preheat system. The flow rate will vary based on the number and types of fixtures which are plumbed into the greywater system. For example, if the washing machine was not connected, for example because cold water washes and rinses were used, then a significant amount of energy would not be available relative to the case for (say) a connected washer using a hot wash/cold rinse cycle. The flow rate used for the Base Case analysis was 358 kg/day (787 lbm/day). Variations of up to ±50% were explored with the cold water flow rate held constant at 240 kg/day (530 lbm/day).

The greywater flow rate was found to be a very significant performance variable. Both the absolute energy and percentage of the DHW load varied significantly over the range of conditions studied. For example, when the greywater flow rate was cut in half, the percentage savings dropped from 36.2% to 25.3%. This highlights the fact that one of the most critical factors impacting the cost effectiveness of a greywater heat recovery system is selecting applications which have a large resource of available greywater, preferably at a high temperature.

TABLE 11

CASE	DHW LOAD (kWh/yr)	RECOVERED ENERGY (kWh/yr)	THERMAL EFFECTIVE-NESS	PERCENT DHW LOAD SUPPLIED
0. Base Case. Greywater flow equal to 358 kg/day (787 lbm/day)	4939	1789	0.759	36.2%
37. Base Case flow x 0.75	4939	1587	0.858	32.1%
38. Base Case flow x 0.50	4939	1250	0.986	25.3%
39. Base Case flow x 1.25	4939	1914	0.812	38.8%
40. Base Case flow x 1.50	4939	1997	0.846	40.4%

FIGURE 23

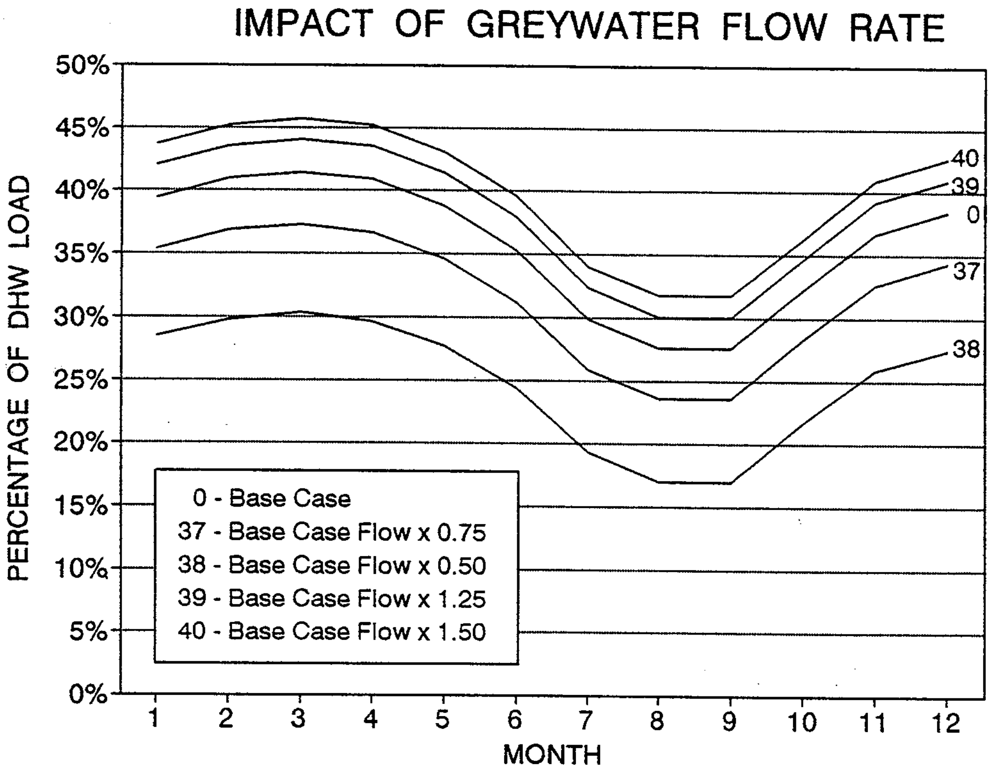
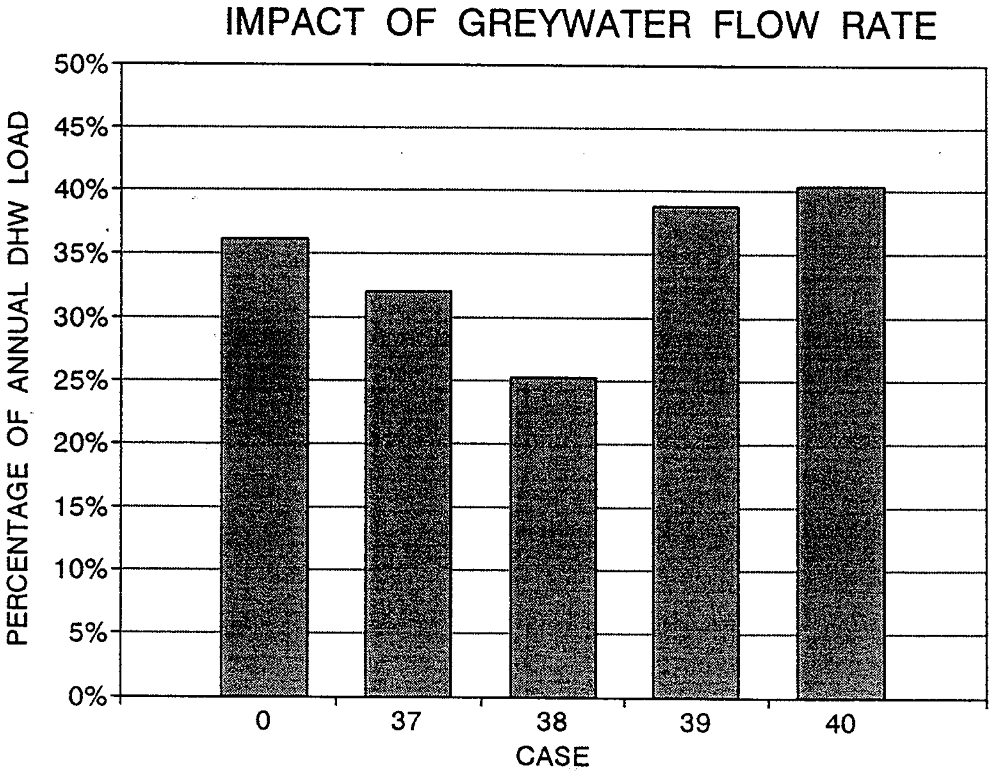


FIGURE 24



5.12 IMPACT OF DESIGN OPTIMIZATION

The prototype greywater system used in the Manitoba Advanced House was designed without benefit of the simulation model described in this report or the understanding acquired through its use. In some cases, the initial design assumptions proved reasonable while in other instances, better choices could have been made. Therefore, after the simulations described in this section had been completed, some additional runs were performed to illustrate how the system design could have been better optimized. The results of the two most significant runs are shown in Table 12 and Figs. 25 and 26.

Run #41 modified the Base Case system by increasing the insulation levels (by 50% on the top and sides plus the addition of a bottom board) and reducing the mass of greywater stored in the preheat tank to 50% of the Base Case amount. This increased the absolute energy recovered by 134 kWh/yr and raised the percentage of DHW load provided from 36.2% to 38.9%. The combination of these two measures would also reduce the overall system costs since the tank size would be reduced.

Run #42 consisted of the two measures used in Run #41 plus an increase in the mass of cold water stored in the preheat tank along with a doubling of AU1, the overall heat transfer coefficient between the cold water and greywater. This increased the annual contribution of the preheat system to 42.0% of the DHW load. Given that the maximum theoretical savings (for conditions approximating those used in the analysis), was calculated to be 48% in Section 2, Run #42 can be regarded as being close to the practical limit of expected performance for this type of greywater heat recovery system.

TABLE 12

CASE	DHW LOAD (kWh/yr)	RECOVERED ENERGY (kWh/yr)	THERMAL EFFECTIVE-NESS	PERCENT DHW LOAD SUPPLIED
0. Base Case	4939	1789	0.759	36.2%
41. Base Case plus optimization	4939	1923	0.816	38.9%
42. Base Case plus further optimization	4939	2072	0.879	42.0%

FIGURE 25

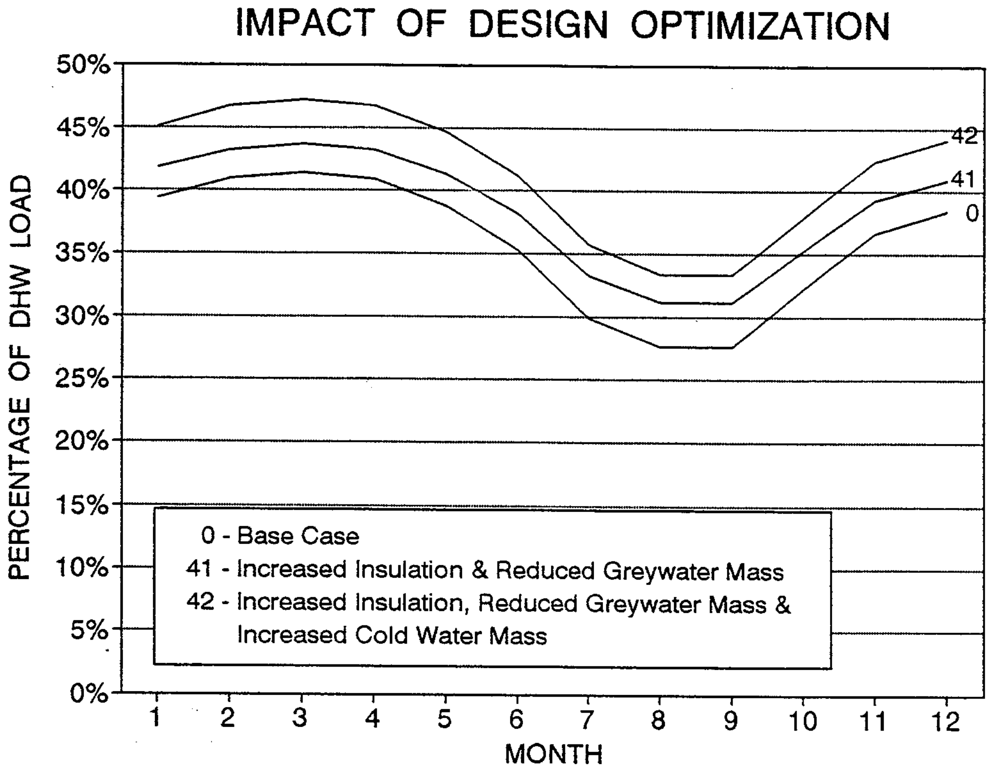
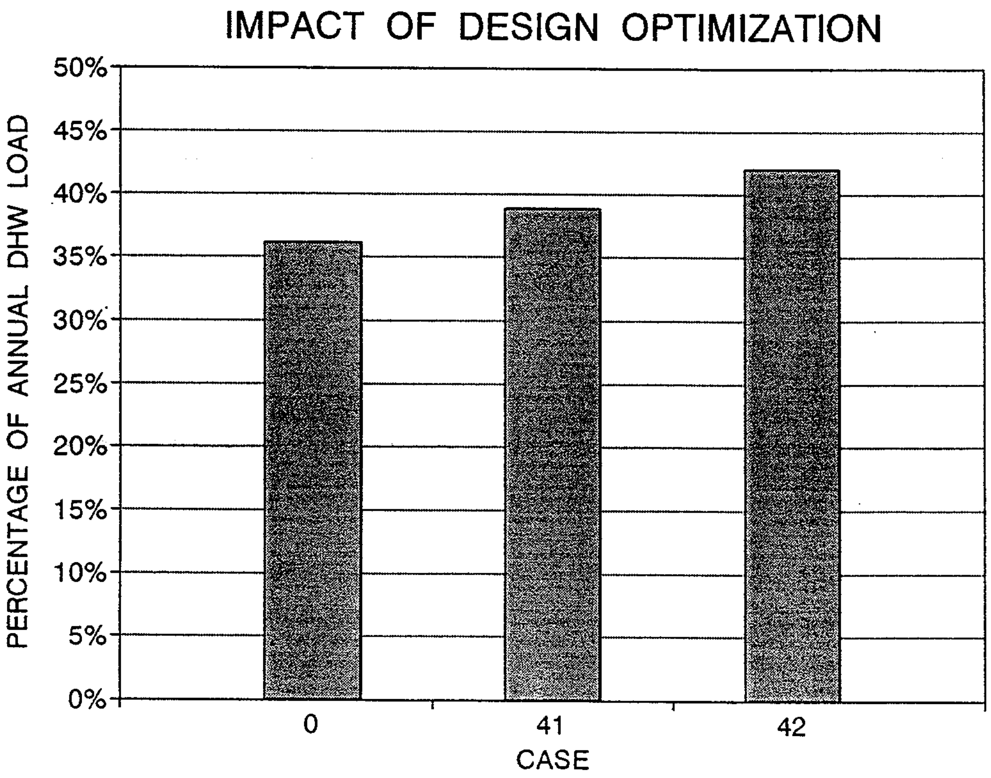


FIGURE 26



SECTION 6
SAVINGS, COSTS AND APPLICATIONS

6.1 MAXIMUM THEORETICAL SAVINGS

The maximum theoretical energy savings which an ideal greywater heat recovery system could deliver can be estimated using Eq. (6):

$$Q_{max}/Q_{dhw} = (T_g - T_{ci}) / (T_{setpoint} - T_{ci}) \tag{6}$$

$$Q_{max} = [(T_g - T_{ci}) / (T_{setpoint} - T_{ci})] \times Q_{dhw} \tag{7}$$

Note that Q_{max} represents the net energy savings, i.e., before consideration of the conversion efficiency of the conventional DHW tank. By introducing the tank efficiency, η, and the cost of energy, C, a corresponding dollar value for the maximum theoretical dollar savings can be calculated:

$$S_{max} = Q_{max} \times C / \eta \tag{8}$$

where:

S_{max} = Maximum dollar savings
C = Unit cost of energy
η = Efficiency of the conventional DHW tank

Equations (7) and (8) provide useful tools for estimating the maximum theoretical energy and dollar savings which can be achieved based on a few, readily available parameters. As described in Section 2, if typical temperature values for the greywater, mains water and the DHW tank setpoint are substituted into Eq. (6), the maximum heat recovery would be about 50% of the total DHW load. For most residential applications, this value would not change significantly with different input parameters.

6.2 TECHNICALLY ACHIEVABLE SAVINGS

The technically achievable savings are those which would be produced by an actual, as opposed to an ideal, greywater system. These can be estimated using the simulation model described in this report, with the appropriate inputs. If a rough estimate of the savings is acceptable, then one of the scenarios described in Section 5 can be used. As a benchmark, it appears that the practical performance limit for a greywater system, under typical operating and environmental conditions, is about 42% of the annual DHW load, as described in Section 5.12.

6.3 GREYWATER SYSTEM COSTS

The prototype system developed as part of this project was a one-off design intended as a technology demonstrator and research tool. For this reason, little effort was made to save costs, or to even accurately quantify them during the project. However, a few comments can be made regarding ways to reduce the installed costs of future systems.

First, less expensive materials should be used for the cold water coil and the tank. The 32 mm (1.25") copper tubing is expensive and could, in a production model, by replaced by polybutylene tubing, which is acceptable for such applications. Because of the poorer heat transfer characteristics, a longer length of polybutylene tubing would probably be necessary. Likewise, the high density polyethylene case used for the preheat tank was custom manufactured at considerable expense and could have been constructed more economically using either plastic, moulded fibreglass or a metal tank with a suitable insulating scheme.

6.4 PROCEDURE FOR EVALUATING THE COST EFFECTIVENESS OF A SPECIFIC APPLICATION

To evaluate the cost effectiveness of a specific, potential greywater heat recovery application, or to assess the amount of capital which can be invested in an application, the following procedure can be used:

1. Estimate the DHW load from existing information or by using design handbooks such as the CEA Water Heating Manual, the ASHRAE Handbook of Applications (1991), etc.

2. Calculate the maximum theoretical energy and dollar savings using Eqs. (7) and (8). This will require estimates of the greywater temperature, mains temperature, DHW tank efficiency, the cost of energy and the DHW system efficiency.

3. Using the simulation model described in this report or the results discussed in Section 5, estimate the net, technically achievable energy savings, Q. As a check, the energy savings should be less than those calculated in Step 2. The actual, annual dollar savings can be calculated as:

$$S = (Q \times C) / \eta \qquad (9)$$

4. Apply the appropriate economic multiplier to the annual savings, or other economic criterion as deemed appropriate, to estimate the maximum investment which can be justified in the system.

6.4.1 Example 1

Step 1. Estimate the DHW load.

Assume a residential application with electric DHW heating, at 8 ¢/kWh, with a system efficiency of 90%. Also, assume that the net, annual DHW load (Q_{dhw}) is 5000 kWh/yr (14 kWh/day).

Step 2. Calculate the maximum possible savings.

Assume $T_g = 35$ °C, $T_{ci} = 11.4$ °C (avg.), $T_{set} = 60$ °C. Using Eq. (7):

$$Q_{max} = [(T_g - T_{ci}) / (T_{setpoint} - T_{ci})] \times Q_{dhw}$$

$$Q_{max} = [(35 - 11.4) / (60 - 11.4)] \times 5000$$

$$= 0.49\ (5000) = 2450 \text{ kWh/yr.}$$

Using Eq. (8),

$$S_{max} = Q_{max} \times C / \eta$$

$$S_{max} = (2450 \times 0.08) / 0.9 = \$218/\text{yr.}$$

Step 3. Calculate the actual savings using the greywater model.

Using the assumptions described above, a simulation was performed using the greywater model. It predicted that the greywater system would supply 36.4% of the annual DHW load, which is equal to 1819 kWh/yr. Note that this does not exceed the theoretical, maximum savings of 2450 kWh/yr. The dollar value of the actual savings is calculated from Eq. (9).

$$S = (Q \times C) / \eta$$

$$= (1819 \times 0.08) / 0.9 = \$162/\text{yr.}$$

Step. 4 Calculate the maximum justified investment.

Assume that the system's potential owner has decided that the investment can be justified provided the simple payback period does not exceed five years. Therefore, the maximum, allowable installed cost is:

$$\$162 \times 5 = \$810.$$

6.4.1 Example 2

Step 1. Estimate the DHW load.

Assume a residential application with natural gas DHW heating, at 2 ¢/kWh$_e$ (kilowatt-hours equivalent), with a system efficiency of 50%. Also, assume that the net, annual DHW load (Q_{dhw}) is 8000 kWh$_e$/yr (22 kWh$_e$/day).

Step 2. Calculate the maximum possible savings.

Assume $T_g = 35$ °C, $T_{ci} = 11.4$ °C (avg.), $T_{set} = 60$ °C. Using Eq. (7):

$$Q_{max} = [(T_g - T_{ci}) / (T_{setpoint} - T_{ci})] \times Q_{dhw}$$

$$Q_{max} = [(35 - 11.4) / (60 - 11.4)] \times 8000$$

$$= 0.49\ (8000) = 3920 \text{ kWh}_e\text{/yr.}$$

Using Eq. (8),

$$S_{max} = Q_{max} \times C / \eta$$

$$S_{max} = (3920 \times 0.02) / 0.5 = \$157\text{/yr.}$$

Step 3. Calculate the actual savings using the greywater model.

Using the assumptions described above, a simulation was performed using the greywater model. It predicted that the greywater system would supply 33.5% of the annual DHW load, which is equal to 2681 kWh$_e$/yr. This does not exceed the theoretical, maximum savings of 3920 kWh$_e$/yr. The dollar value of the actual savings is calculated from Eq. (9).

$$S = (Q \times C) / \eta$$

$$= (2681 \times 0.02) / 0.5 = \$107\text{/yr.}$$

Step. 4 Calculate the maximum justified investment.

Assume that a five year payback period is also required for this system. Therefore, the maximum, installed cost which can be justified is:

$107 x 5 = $535.

In both examples, the five year simple payback period was used simply for illustrative purposes and does not necessarily represent an actual economic criterion. This would have to be made on an individual basis and should preferably consist of a more complete and rigorous analysis which would include consideration of the life cycle costs and any other factors deemed relevant.

6.5 APPLICATIONS

Analysing the various simulations discussed in Section 5 from an economic perspective, the best greywater heat recovery system applications appear to be those which have a large load since this increases the maximum attainable savings. The capital costs of a system installed in a house with a large DHW load will be the same as those in a house with a small load. A house which uses conservation features designed to control hot water usage (low-flow showerheads, faucet aerators, etc.) will, all else being equal, be a poorer application for a greywater system than an equivalent structure without these measures. In most instances, these conservation measures are very inexpensive, so would normally be considered first.

The focus of this report has been residential uses of greywater systems, specifically single family residences. However, it is worth noting that other applications are also worth considering and may offer some excellent applications for the technology. These include commercial laundries, dormitories, swimming pools, hotels, restaurants and any other large users of hot water. Several of these have the added advantage of possessing DHW loads which are relatively constant, as opposed to the sporadic loads found in houses. The basic performance equations and the simulation model discussed in this report can all be used to assess the potential savings obtainable in these applications.

6.6 LIMITS OF THE TECHNOLOGY

The preceding discussion has identified the useful limits of this technology, i.e., greywater systems which rely upon passive heat recovery technology. Achieving improved performance is possible, but would require the use of other technologies such as heat pump heat recovery systems which are capable of achieving greater heat recovery, although with attendant operating costs and (perhaps) at a higher capital cost. They are mentioned here to acknowledge their potential and as a possible area for future study.

SECTION 7
CONCLUSIONS

7.1 MAXIMUM THEORETICAL SAVINGS

The maximum theoretical savings which could be achieved by an ideal greywater heat recovery system were found to be a function of the mains water temperature, greywater temperature, DHW tank setpoint, DHW load and the efficiency of the DHW tank. They can be calculated for a specific application using Eqs. (6) to (9). The maximum savings achievable by a residential greywater system were found to be about 50% of the annual DHW load, assuming typical values for the input variables.

7.2 TECHNICALLY ACHIEVABLE SAVINGS

The technically achievable savings, i.e., those which would be produced by an actual, rather than an ideal, greywater system, can be estimated using the simulation model described in this report with the appropriate inputs. If a rough estimate of the savings is acceptable, then one of the scenarios described in Section 5 can be used. As a benchmark, it appears that the practical performance limit for greywater systems, under typical operating and environmental conditions, is about 42% of the annual DHW load. Such a system would be similar to the prototype used in the Manitoba Advanced House but with increased tank insulation, reduced greywater mass, increased cold water mass and an increased heat transfer coefficient between the cold water and greywater.

7.3 MINOR PERFORMANCE VARIABLES

The following design and operating variables were found to have a minor effect on the performance of greywater heat recovery systems: tank insulation (provided a minimum amount is used), greywater mass and room temperature.

7.4 MAJOR PERFORMANCE VARIABLES

The following design and operating variables were found to have a relatively major impact on the performance of greywater heat recovery systems: cold water mass, cold water inlet temperature, greywater temperature, DHW tank setpoint, AU1 (the overall heat transfer coefficient between the cold water and greywater), the greywater and cold water flow rates (acting together) and the greywater flow rate (acting in isolation).

7.5 APPLICATIONS

The success of a greywater heat recovery system depends as much, or more, on proper selection of the application as it does on the design of the system. Ideal applications are those which have large DHW loads and have not, or can not, take advantage of conservation measures designed to reduce DHW consumption.

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