# PERFORMANCE OF
# THE BRAMPTON ADVANCED HOUSE

**PREPARED FOR:**

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## NOTE

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# *EXECUTIVE SUMMARY*

In 1989 the "Advanced House" in Brampton Ontario was built to demonstrate innovative residential energy-efficient technologies. This house is Canada's contribution to the research segment of the International Energy Agency Task XIII Advanced Solar/Low Energy Residential Buildings. This house was also the catalyst for Energy, Mines and Resources Canada Advanced Houses Program begun in 1991.

House construction was completed in late February, 1990, open for public viewing from March 1990 through February 1991, the house was sold in June 1991.

The energy performance of the house was predicted through detailed computer simulation using the ENERPASS computer program. A monitoring system was installed to assess the actual energy performance of the house and its innovative energy-conserving technologies. Monitoring of the house began in the summer of 1990 and continued until October 1992. This report examines the performance of the house over its first two and a half years.

The Advanced House was designed to use 12500 kWh per year or 31 kWh per $m^2$ of floor area in a degree day climate of 4200 °C-days. This is approximately 30% the energy consumption of a similar house built to the 1985 insulation standards of the Ontario Building Code and using conventional electric mechanical systems.

Tests of the building shell show that the building heat loss coefficient (199 W/°C) and airtightness (0.9 ACH at 50 Pa) are close to design targets. Some decrease in building airtightness over time was noted. Maximum formaldehyde and radon concentrations were measured at 0.048 ppm and 0.002 WLU respectively, well within accepted guidelines.

Hot water use for the three-person family averaged 164 litres per day at 45°C. The water-conserving appliances are credited with reducing the water heating requirement to 60% of the typical residential load. An average of 260 litres per day was used for normal cold water demands; in addition 140 cubic metres of water was dumped during the cooling season to maintain Integrated Mechanical System (IMS) cooling capacity.

Monthly lighting and receptacle loads averaged 400 kWh; of this, 125 kWh per month were used by the major appliances. Fan energy use averaged 134 kWh per month. These loads are close to design values.

Monitored energy consumption was 28% higher than computer-predicted values during the demonstration period and 60% higher than predicted when the house was occupied. The annual energy use during the occupied period was 19834 kWh or 49 kWh per square metre of heated floor area.

The higher-than-expected energy use is attributed to five factors. First, high exhaust air flow rates and higher-than-expected air leakage from the house to the sunspace (thereby reducing the effectiveness of the sunspace preheating) resulted in high ventilation air heating load. Second, the average indoor air temperature over the heating season was 23°C, 2 C° above the 21°C setting assumed at the design phase.

The three remaining factors relate to the IMS. The Seasonal Performance Factor (SPF) over the heating season averaged 1.54 (or as high as 1.74 including monitoring uncertainties). This is between 13 and 23% lower than the predicted value of 2.0. The average heat output from the IMS ranged from 4 to 5.5 kW, less than the 6 kW expected. The lower output meant that the heating system had to use more back-up electrical energy than predicted. The high parasitic energy required for fans, pumps and controls contributed to the reduced SPF. The pumps, fans and controls consumed 400 to 500 Watts continuously. Over the year, this represents an energy use of 3750 kWh or 30% of the total house energy consumption.

The peak electrical demand was 8.7 kW. This is 13% below the 10 kW required to activate the load-shedding.

In summary, monitoring of the Advanced House has shown that extremely energy-efficient buildings are achievable. A wide range of commercially available energy-saving products were successfully used to reduce energy consumption in all systems in the house. Although there were a few minor problems with the prototype Integrated Mechanical System, this technology has the potential to offer large energy savings.

# *ACKNOWLEDGEMENTS*

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- the homeowners, Shirley and Percy DeSouza, for the generous co-operation in data collection and providing access to the house.

# SOMMAIRE

En 1989, on construisait la «Maison performante» à Brampton, en Ontario, dans le but de faire la démonstration de technologies innovatrices d'efficacité énergétique dans des immeubles résidentiels. Contribution du Canada au segment recherche du projet XIII de l'Agence internationale de l'énergie, «Advanced Solar/Low Energy Residential Buildings», cette maison a aussi donné le coup d'envoi au Programme de la maison performante d'Énergie, Mines et Ressources Canada, lancé en 1991.

La maison, terminée vers la fin de février 1990 et ouverte au public de mars 1990 à février 1991, a été vendue en juin 1991.

Le rendement énergétique prévu de la maison a été calculé à l'aide d'une simulation détaillée rendue possible par le programme informatisé ENERPASS. Un système de suivi a été installé afin d'évaluer le rendement énergétique réel de la maison et de ses technologies de conservation d'énergie. La maison fut ainsi étudiée de l'été 1991 à octobre 1992, période couverte par le présent raport.

La maison performante a été conçue pour consommer 12 500 kWh d'électricité par an, soit 31 kWh par mètre carré, à une température ambiante de 4 200 °C-jours, ce qui ne représente qu'environ 30 % de la consommation d'une maison semblable construite selon les normes d'isolation du Code du bâtiment de l'Ontario de 1985 et équipée de systèmes électro-mécaniques de type classique.

Des tests effectués sur l'enveloppe du bâtiment ont révélé que son coefficient de déperdition (199 W/°C) et son étanchéité à l'air (0,9 ACH à 50 Pa) étaient près des normes établies à la conception. Une certaine perte d'étanchéité a été enregistrée avec le temps. Les concentrations maximales de formaldéhyde et de radon étaient de 0,048 ppm et de 0,002 WLU respectivement, bien en deçà de normes établies.

Les occupants, au nombre de trois, on consommé en moyenne 164 litres d'eau chaude (45 °C) par jour, quantité qui, grâce aux économiseurs d'eau, ne représente que 60 % de celle d'une résidence type. La même famille a écoulé 260 litres d'eau froide par jour, auxquels se sont ajoutés les plus de 140 mètres cubes d'eau déversés chaque année pour maintenir les capacités refroidissantes du Système mécanique intégré pendant la période de climatisation.

La consommation mensuelle moyenne d'électricité pour l'éclairage et les appareils a été de 400 kWh, dont 125 kWh pour les principaux appareils ménagers. Le système de ventilation a utilisé 134 kWh par mois, soit à peu près ce qui avait été prévu à la conception.

La consommation réelle d'électricité a été de 28 % plus élevée que ce qui avait été prévu par simulation en période de démonstration, proportion qui a grimpé à 60 % lorsque la maison est devenue habitée. Au cours de la période d'occupation, la consommation annuelle s'est chiffrée à 19 834 kWh, soit 49 kWh par mètre carré d'espace chauffé.

Cette consommation plus forte que prévue est attribuable à cinq facteurs. Tout d'abord, un débit élevé de circulation de l'air vicié et un taux plue élevé que prévu de fuite d'air entre la maison et l'espace-serre (réduisant ainsi l'efficacité du préchauffage de l'espace-serre) se sont traduits par une demande accrue en chauffage de l'air. Ensuite, la température ambiante moyenne au cours de la période de chauffe a été de 23 °C au lieu du 21 °C prévu à l'étape de la conception.

Les trois autres facteurs sont liés au SMI. Le coefficient de rendement saisonnier (CRS) au cours de la saison de chauffe a été de 1,54 (ou jusqu'à 1,74 si l'on tient compte de la marge d'erreur que comporte l'étude), soit de 13 à 23 % en deçà du 2,0 prévu. En moyenne, le SMI n'a produit que de 4 à 5,5 kW de chauffage à consommer plus d'électricité d'appoint. La forte consommation des ventilateurs, des pompes et des dispositifs de régularisation ont également contribué à la baisse du CRS. Ces éléments ont consommé de 400 à 500 W de façon continue, soit 3 750 kWh pour l'année, ou 30 % de la consommation totale de la maison.

En aucun temps la demande en électricité n'a excédé 8,7 kW, soit 13 % de moins que les 10 kW requis pour activer le dispositif de délestage.

Bref, l'observation de la Maison performante a révélé qu'il était possible de construire des bâtiments extrêment efficaces sur le plan énergétique. Une vaste gamme de produits à faible consommation d'énergie, qui sont d'ailleurs offerts sur le marché, ont été utilisés pour tenter, avec succès, de réduire la consommation énergétique de tous les systèmes de la maison. En dépit de quelques problèmes mineurs avec le prototype du SMI, cette technologie a le potentiel requis pour faire réaliser de grandes économies d'énergie.

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# 1. INTRODUCTION

In 1989 a unique house was constructed in Brampton, a city just northwest of Toronto. It was built as an example of advanced energy-efficient housing. Referred to as the "Advanced House", it is Canada's most recent demonstration of leading-edge residential energy-efficient technologies. It is Canada's contribution to the research portion of the International Energy Agency Task XIII Advanced Solar/Low Energy Residential Buildings, which examines innovative methods of reducing residential energy consumption. This house was also the catalyst for Energy, Mines and Resources Canada Advanced Houses Program begun in 1991.

The house was constructed by the Fram Building Group with financial support from Energy, Mines, and Resources Canada, the Ontario Ministry of Energy, and Ontario Hydro. Many commercial firms donated products and services to the project. House construction was completed in late February, 1990. The house was open for public viewing from March 1990 through February 1991. The house was then sold and the homeowners took possession in June 1991.

The energy performance of the house was predicted using the detailed computer simulation program, ENERPASS. A monitoring system was installed to assess the actual energy performance of the house and its innovative energy-conserving technologies.

This report presents the monitored performance results of the Advanced House over a 2 1/2 year period: June 1990 to October 1992. The monitored results are compared to computer predictions to determine whether the systems are performing to specifications. Performance predictions are also presented for different house designs and climates to demonstrate the potential for repeating the innovative Advanced House technologies worldwide.

The first-year monitored results (June 1990 to June 1991) are for the period when the house was open as a public demonstration (and therefore was not operated as a "typical" single family home). For the remainder of the monitoring period (June 1991 to October 1992) the house was occupied by a three-person family. In the first year, numerous commissioning problems with the Integrated Mechanical System (IMS) and the monitoring system resulted in only a few months of complete monitored data being available. These systems operated reliably when the house was in the occupied mode.

## *1.1 General House Description*

Designed to fit into a conventional upscale suburban subdivision, the Advanced House has 284 square metres of above-grade floor area. The total conditioned floor area is 408 square metres, which includes the full basement, but not the south-facing sunspace. Building floor plans are given in Figures 1.1 and 1.2. Although the house appearance is conventional, the house contains many novel energy-efficient features:

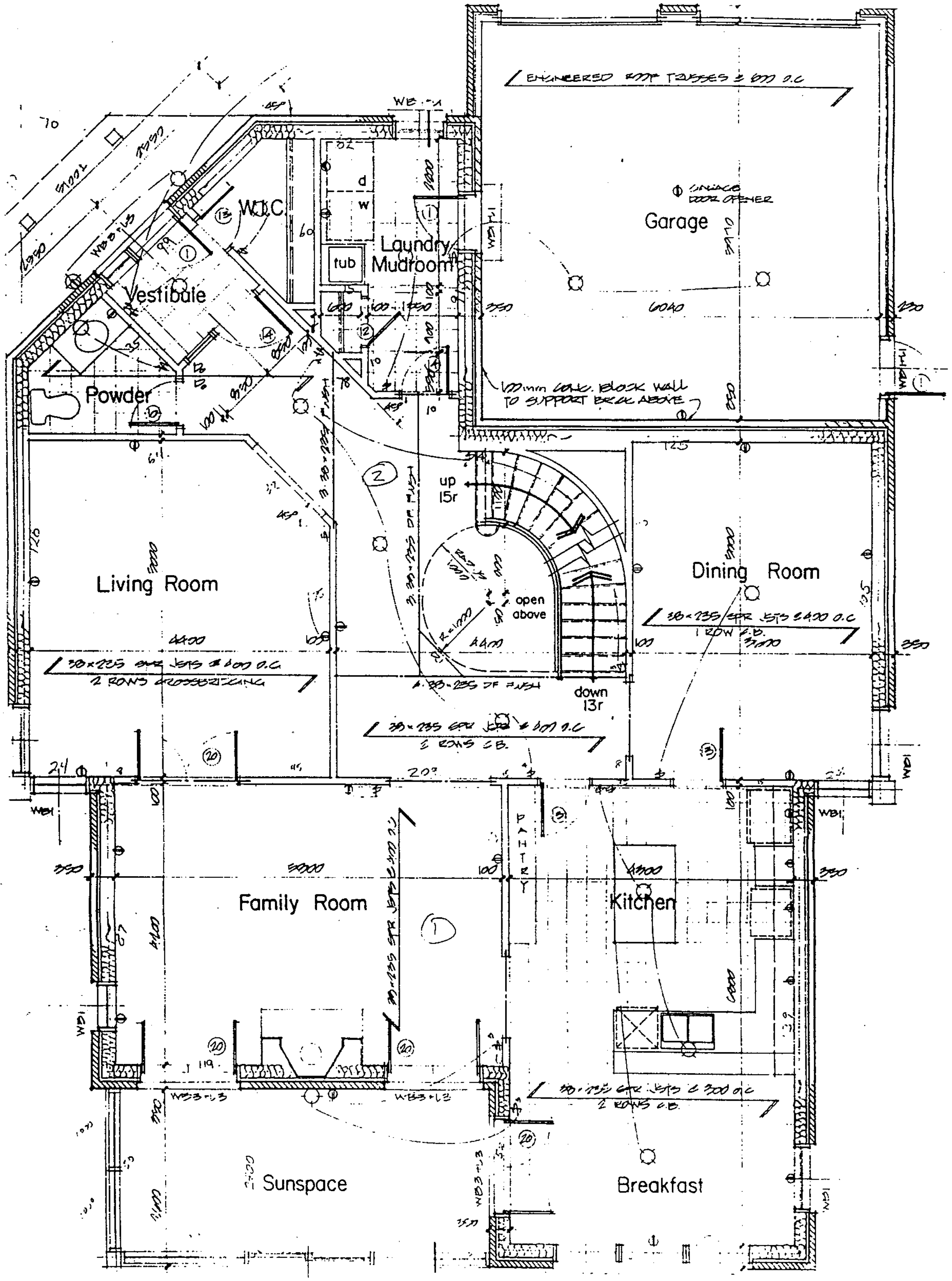
- high levels of insulation
- airtight construction
- high-performance windows
- passive solar sunspace
- an integrated mechanical system (IMS) for space and water heating, ventilation and space cooling
- energy-efficient lighting and appliances, and
- a high-efficiency masonry fireplace.

A description of each of these features are given in the following sections.

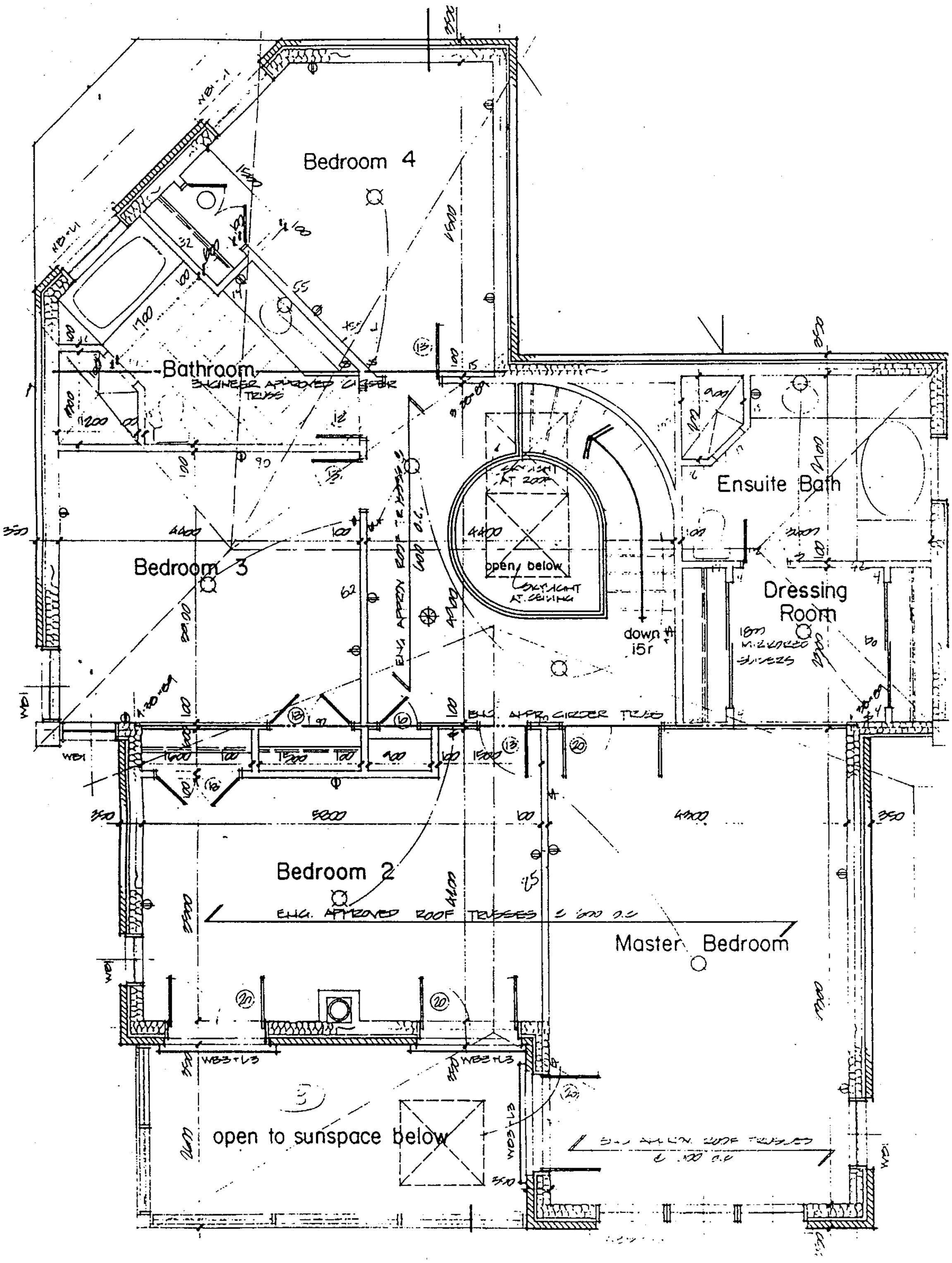
### *1.1.1 Building Shell*

The walls are constructed of 13 mm of drywall, 240 mm of wet blown cellulose, 25 mm of rigid fibreglass wall sheathing (Glasclad), and a brick veneer (see Figure 1.3). The ceiling consists of 13 mm of drywall and 300 mm of blown cellulose. The basement walls comprise of 13 mm of drywall, 175 mm of blown cellulose, poured concrete wall and 50 mm of rigid fibreglass sheathing foundation (Baseclad). The basement floor is 100 mm of poured concrete with 50mm of rigid fibreglass foundation sheathing (Baseclad) underneath. The sunspace floor is uninsulated slab-on-grade. The wall between the living area and the sunspace is insulated with 100 mm of cellulose insulation. The calculated RSI values for these house components (including stud

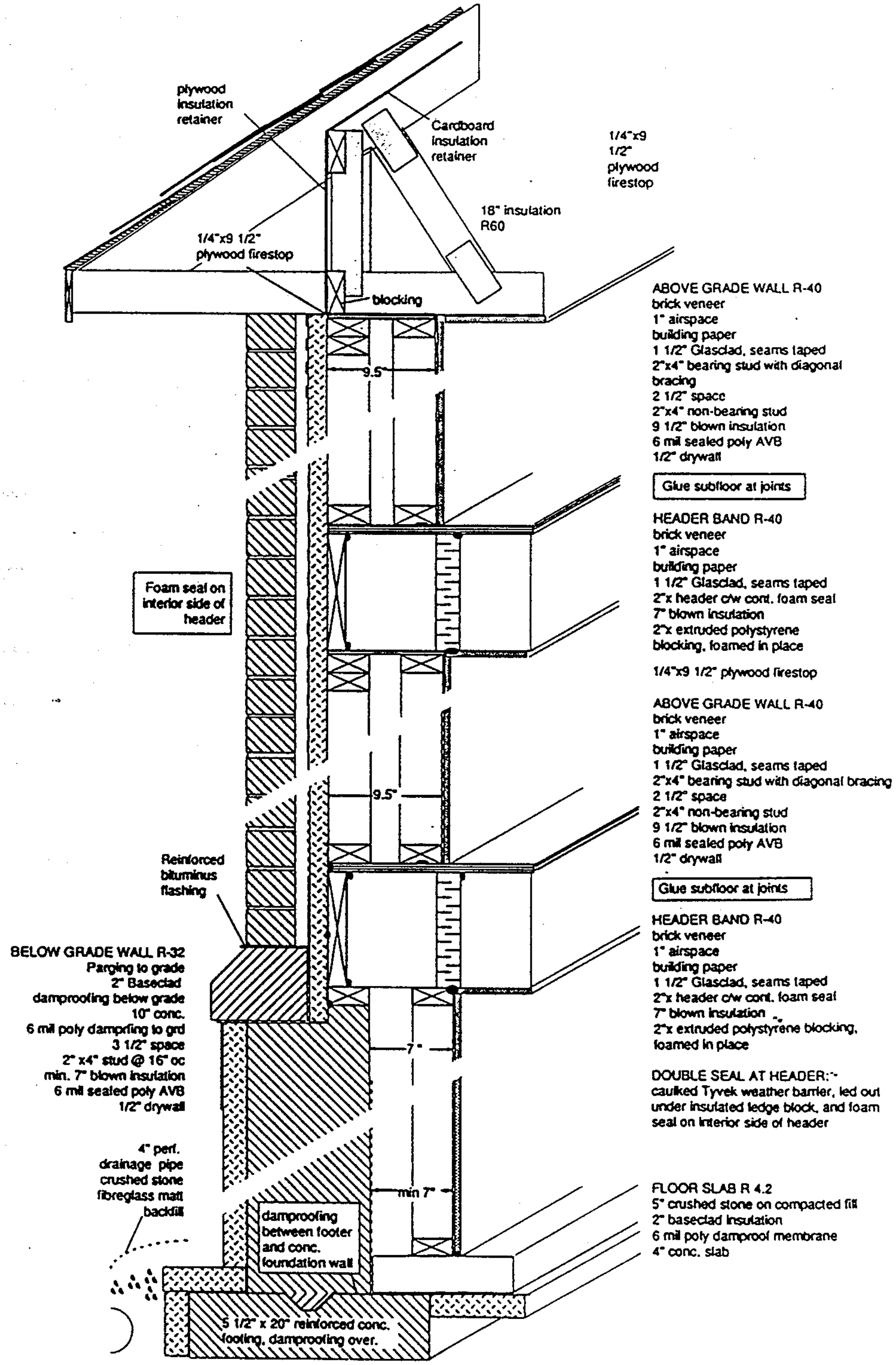
## Figure 1.1 Advanced House Main-Floor Plan



## *Figure 1.2 Advanced House Second-Floor Plan*



# Figure 1.3 Wall Construction



effects and film coefficients) are listed in Table 1.1. The thermal resistance of the cellulose was assumed to be RSI 26.4 m-C/W (R 3.81 per inch), from the manufacturers specifications.

The primary air/vapour barrier is 6-mil polyethylene located directly behind the drywall. All seams and headers are caulked. The house was designed to have an airtightness of 0.75 air changes per hour at 50 Pascals pressure difference; this corresponds to a natural air leakage rate of approximately 0.05 air changes per hour.

## *Table 1.1 Building Shell Insulation Levels*

| | RSI | R |
|---|---|---|
| Basement Above-Grade Walls | 6.55 | 37.2 |
| Remaining Above-Grade Walls | 6.89 | 39.1 |
| Basement Below-Grade Walls | 6.55 | 37.2 |
| Ceiling | 10.57 | 60.0 |
| Basement Floor | 1.6 | 9.1 |
| Sunspace - Living Area Wall | 2.1 | 11.9 |

With the exception of the sunspace skylight, all the windows in the house are wood-framed, triple-glazed, with two low-emissivity coatings, two argon-gas fills and butyl-rubber edge spacers. Including frame and edge-of-glazing effects, the living area windows were calculated to have a U-value of 1.14 W/($m^2$-°C) (based on 20% frame area), and the sunspace windows were calculated to have a U-value of 1.05 W/($m^2$-°C) (based on 10% frame area). The glazing shading coefficient was calculated to be 0.57. The operable and fixed windows have CSA Energy Ratings (ER) of -4 and +9 respectively.

## *1.1.2 Passive Solar Sunspace*

The majority of south-facing glass area is located in the sunspace. Because temperatures are allowed to float (the sunspace has no heating or cooling system), glass areas can be increased without energy penalty. Passive solar gains are stored in the concrete floor slab, in the backfill under the slab, and in the masonry surrounding the fireplace. The heat is transferred to the living space through the common walls and through the glass doors which connect the two spaces.

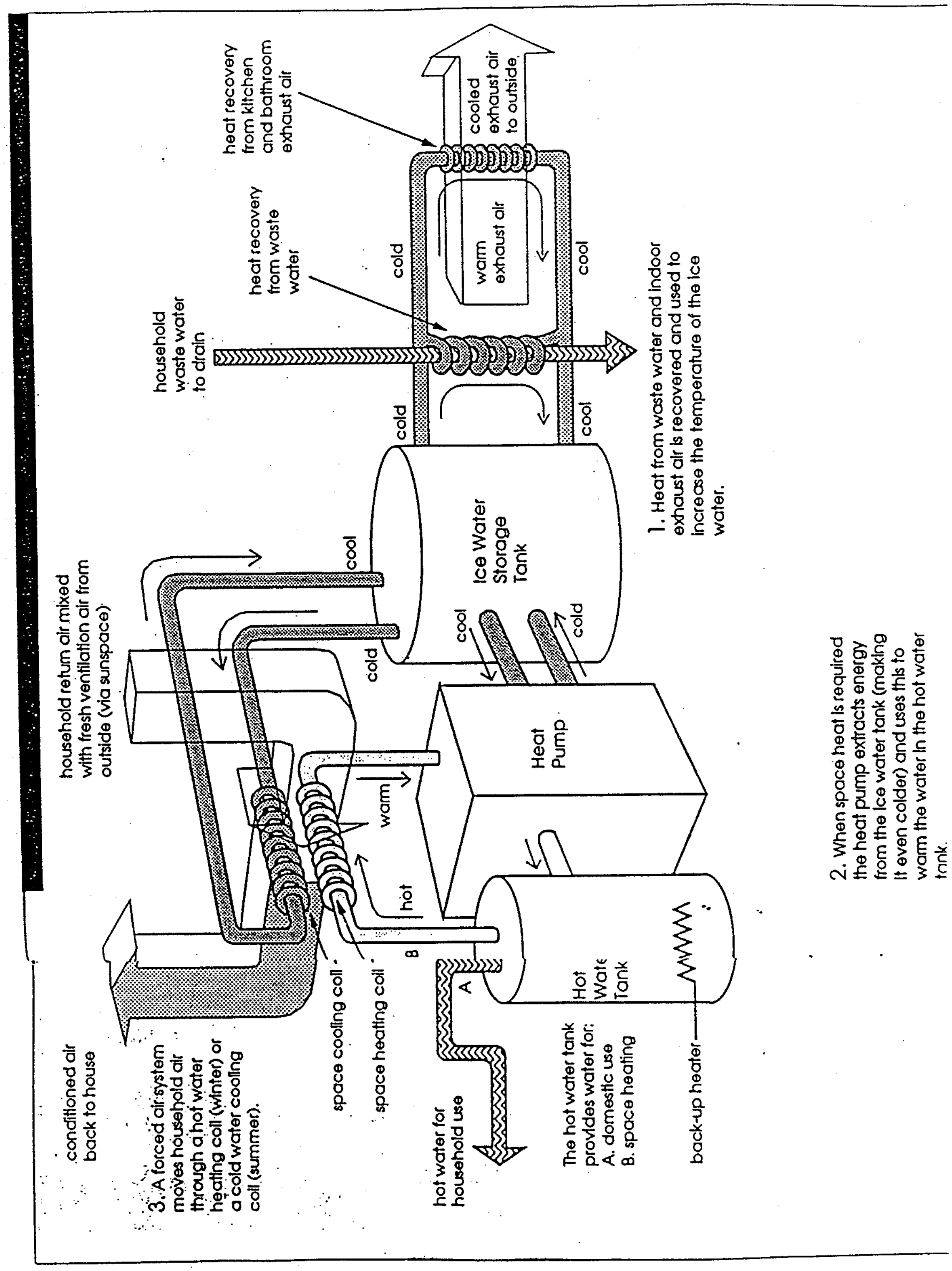
The sunspace also provides passive preheating of fresh ventilation air. Outdoor air is ducted into the sunspace through ceiling diffusers. A return-air duct mounted high on the wall pulls the fresh, preheated air down to the floor slab, where it is circulated through a series of parallel-flow ducts and then to the IMS where it is mixed with house air and distributed to each room. The floor slab acts to temper the fresh air and reduce day/night temperature swings. When the sunspace temperature exceeds a set-point, the skylight opens automatically to provide passive cooling. Reflective blinds and exterior trellis work provide summer shading for the sunspace.

## *1.1.3 Integrated Mechanical System*

One of the most innovative features of the Advanced House is the integrated mechanical system (the "Solmate", developed by Allen Associates) which provides heating, ventilating, cooling, and water heating for the house. The integrated mechanical system (IMS) was an engineering prototype specifically built for this project. Although similar systems were installed in a few earlier homes, the Advanced House was the first detailed assessment of this technology.

The system (see Figure 1.4) comprises a hot-water (or DHW) tank and a cold-water (or ice storage) tank thermally connected by a heat pump. The hot-water side supplies heat to meet space- and water-heating loads. Hot-water demand is met by taking hot water from the top of the DHW tank directly to the taps. Cold mains water enters the bottom of the DHW tank to replace the water used. To provide space heating, a

## Figure 1.4 Integrated Mechanical System Schematic



pump circulates water from the hot-water tank through the heat pump condenser and a fan coil. Heat is delivered to the space by circulating air over the fan coil.

The air circulation fan operates continuously (at 285 l/s) to ensure good air circulation and a constant supply of outdoor air to all rooms. The IMS maintains a continuous exhaust of 68 l/s from kitchen and bathroom areas. Outdoor make-up air enters the house via an intake grille in the sunspace. The ventilation air is pulled into the return air duct of the IMS, and mixes with 217 l/s of recirculated building air.

The DHW tank is maintained hot by operating the heat pump. The heat pump transfers heat from the ice tank to the DHW tank. Heat is added to the ice tank by circulating a 33% ethylene glycol-water mixture through a grey-water heat exchanger and an exhaust air coil. If there is no heat in the ice tank (i.e., it is almost all ice), the heat pump shuts off and a 6.0 kW electric element is used to heat the hot-water tank.

Cooling is provided from the ice tank. When the house thermostat indicates cooling is required, a three-way valve opens to direct the IMS glycol mixture through the house cooling coil. House circulation air is cooled as it passes through the coil. The glycol mixture transfers its heat to the ice storage tank via a heat exchanger in the tank. This system allows heat removed from the house air to be stored in the ice tank for use when water heating is required.

In the summer, heat removed by the cooling coil will cause the cold tank temperature to rise. To maintain adequate cooling capacity, hot water from the DHW tank is discharged. Dumping hot water causes the compressor to turn on to supply hot water. Running the compressor removes heat from the cold-side tank, thereby allowing the cooling system to continue to operate. The discharged hot water is mixed with cold water and used in the under-ground yard irrigation system.

A standard Honeywell heat/cool thermostat is used to control room air temperature. Night set-back is not used for two reasons. First, because of the long building time constant, the building temperature would not drop significantly overnight. Second, returning the house to normal temperatures in the morning would require expensive resistance electric heating. Because the higher efficiency heat pump maintains the temperature overnight, less electricity is used.

The IMS was designed to provide 2.3 kW of cooling and 6 kW of heating. Although this cooling capacity might be sufficient for small homes, it was not intended to meet the full cooling load of the Advanced House. No back-up cooling system was installed.

The IMS heating output is also slightly low for the expected house heating load of approximately 8 kW. It was expected, however, that the long building time constant would allow the building to coast through extremely cold periods and the energy-efficient fireplace would provide sufficient auxiliary heating. The fireplace incorporates several advanced design features: sealed combustion chamber with outdoor supply air, convoluted chimney to increase heat transfer area, and large masonry shell for heat storage. Nevertheless, in-duct electric heating coils were installed in the fall of 1991 to ensure that the house temperature could be maintained at the thermostat setting.

The IMS was expected to have an instantaneous COP of between 2.5 and 3.0 depending on the temperature of the ice tank. Energy to operate the exhaust-air and recirculation fans was estimated to be 1400 kWh annually (based on a continuous draw of 160 Watts).

### *1.1.4 Energy-Efficient Appliances and Lighting*

The house has all the major appliances found in most Canadian homes. In this case, however, energy-efficient appliances are used instead of standard products. The appliances used in the house are listed in Table 1.2. The energy ratings in Table 1.2 include the electrical energy required to operate the appliances and the energy required to provide hot water, if required.

No incandescent lighting was used in the house. Most lighting was tube and compact fluorescent, except for the Halogen lights in the kitchen and front hall. Lighting and receptacles loads were expected to consume approximately 1500 kWh annually.

## Table 1.2 Appliance Energy Consumption

| Appliance | Manufacturer | Rating (kWh/yr) | Features |
|---|---|---|---|
| Refrigerator | Sun Frost | 240 | |
| Dishwasher | AEG Favorit | 672 | |
| Range | Thorn ceramic cooktop | - | Halogen bulb |
| Oven | AEG B88L | 348 | Double wall with convection |
| Clothes Washer | AEG Lavamat | 708 | front loading |
| Clothes Dryer | AEG Lavatherm | 612 | |
| TOTAL | | 2580 | |

Monitoring of R2000 homes has shown that the average house consumes approximately 8000 kWh of electricity for lights and appliances. It was estimated that the Advanced House would use only half this amount.

### 1.1.5 Control System

A PC-based control system was designed for the house to help reduce energy and peak demand. These controls were in addition to those of the IMS. The control system provides the following functions:

- Demand Limiting. The strategy was to shed electric load, specifically the 6.0 kW back-up heater in the DHW tank, if the demand in the house rose above 10 kW.
- IMS Seasonal Switch. The IMS operates differently in the summer and winter (no heat recovery in summer). The control system was to automatically switch the IMS based on date and the weather history for the preceding two weeks.
- IMS Water Dump. To meet cooling loads during times of low hot-water demand the control system was to automate the water dump so that the heat pump could operate and maintain the cooling capacity of the ice tank.

- Motorized Skylight. To ensure that the sunspace does not overheat, the control system was to monitor sunspace temperature and open the skylight based on a programable temperature.
- Security Lighting. The control system was to operate two security lighting circuits. They were to be independently programmable and wall switches would provide a manual override.

The control system was constructed and installed at the same time as the monitoring system. The control system was a prototype developed specifically for the Advanced House. The system was never fully installed or commissioned. The IMS seasonal switch, skylight control and security lighting control were never fully operational.

During the first few months of operation, several observations were made. First, load-shedding never took place because the electrical demand never went over 10 kilowatts. In addition, it is unlikely that the electric tank element could be shut off long enough to shift the load to Ontario Hydro's off-peak period (11PM to 7AM). Second, control of the water dump was found to be erratic sometimes dumping more water than necessary and sometimes dumping no water at all.

Initial data analysis indicated that a large proportion of the internal heat gains were from the two computers operating the control and the monitoring systems. Each system had a continuous draw of approximately 75 Watts for a total of 150 Watts.

Because many of the original control system functions were not operational or not required, the steering committee decided to disconnect the system. The control computer was disconnected November 15, 1990. A separate temperature controller was installed to control the skylight. An independent water-dump control was added to the IMS. The IMS seasonal switch was changed to manual operation.

# 2. EXPECTED PERFORMANCE

## 2.1 Performance Predictions

The ENERPASS computer program was used to predict the energy consumption of the Advanced House as described in Section 1. ENERPASS is an hour-by-hour building energy analysis program that includes a model of the performance of the IMS. The predicted energy consumption over a typical year with the house located in Toronto (4257 Celsius Degree-Days) is shown in Table 2.1.

### Table 2.1 Predicted Energy Performance

| Component | Annual Consumption (kWh) | |
|---|---|---|
| Space Heating | 4822 | (Compressor power, pumps and Back-up) |
| Hot Water | 2016 | (Compressor power to supply a 5130 kWh load) |
| Lights/Appliances | 4042 | |
| Air Conditioning | 225 | (Compressor power to heat dumped water) |
| Fans | 1402 | |
| TOTAL | 12507 | |

Because the IMS links various energy loads in the building, the monitored distribution of compressor energy may differ from the numbers given above, but the total should be correct. Thus, the house is expected to consume 30.7 kWh/m$^2$ of conditioned floor area, of which 11.8 kWh/m$^2$ is for space heating. According to the simulations, the IMS is expected to have a Seasonal Performance Factor (SPF) of 2.0

over the heating season. Seasonal Performance Factor, the ratio of useful energy delivered divided by all energy input, is defined more fully in Section 4.4.

A Sankey diagram showing the energy flows in the house is given in Figure 2.1. The annual passive solar contribution is 10,060 kWh. The IMS recovers 8,690 kWh of heat to meet space and water heating needs.

## *2.2 Comparison to Conventional House Designs*

To put the energy consumption of the Advanced House in perspective, simulations were made as if the house were built to the 1985 Ontario Building Code (OBC) and R2000 standards. The differences between these methods of construction and the Advanced House are summarized in Table 2.2. Other than these differences, the three house types simulated were identical (i.e., same floor area and house layout). For the OBC and R2000 houses it was assumed that the sunspace did not preheat ventilation air and the connecting doors to the houses were kept closed.

In the simulations of the R2000 and OBC houses, it was necessary to increase the heating system output and air flow rate to meet the peak heating load. It was also necessary to adjust the air flows to each house zone to maintain the same temperature distribution in the houses. The Heat Recovery Ventilator (HRV) for the R2000 house was assumed to use 150 Watts continuously. The R2000 house would also require a 340 W furnace fan operated continuously. The OBC House would use a larger 500 W furnace fan to meet the higher heating load but it would probably cycle as necessary to meet the heating load. If the OBC house used continuous air circulation, the fan energy use would be significantly higher.

The energy consumption of the three houses is shown in Table 2.3.

The Advanced House is expected to save two-thirds of the energy used in the same house built to OBC standards. At 1991 electricity rates (6.66 cents/kWh), this represents an annual savings of over $1,800.

The space heating energy consumption should be only 21% that of a house built to the 1985 Ontario Building Code.

## *Table 2.2 Comparison of House Designs*

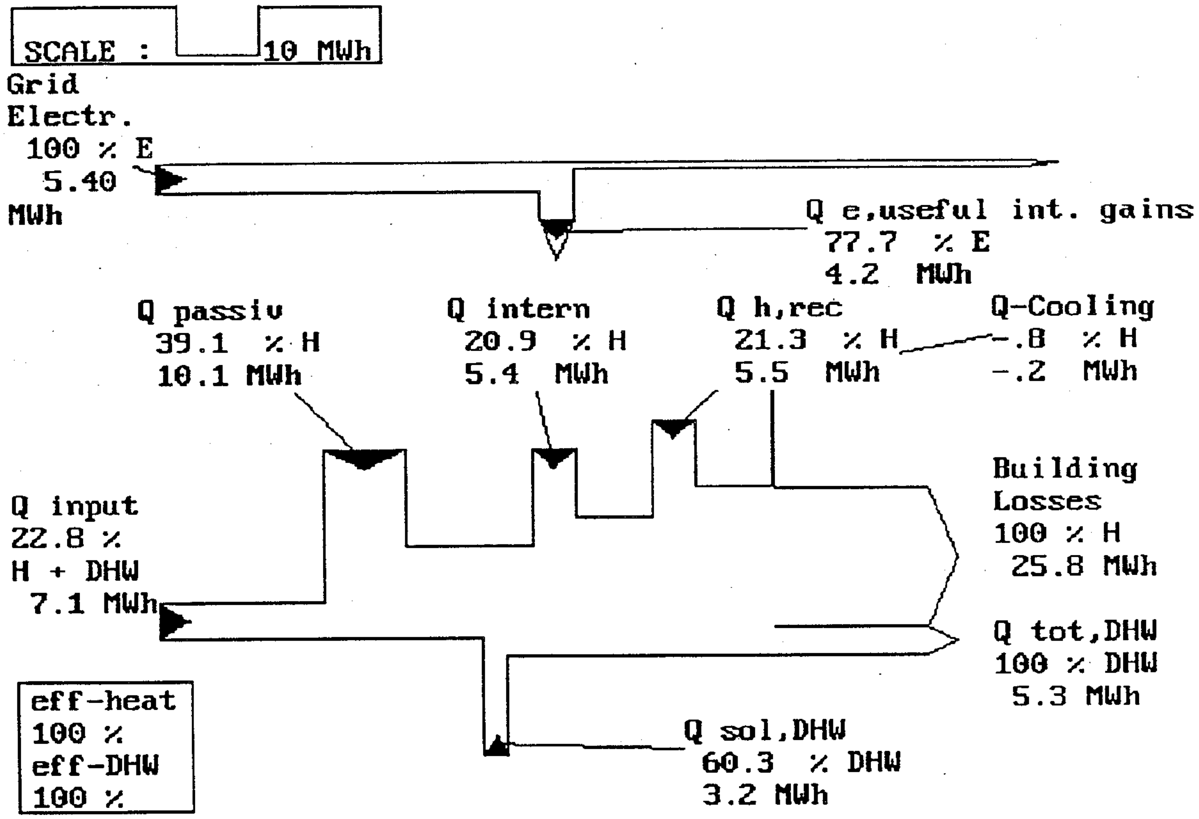
| | Advanced House | R2000 House | 1985 OBC House |
|---|---|---|---|
| Insulation (RSI, in $m^2$-°C/W) | | | |
| Basement Above-Grade Walls | 6.55 | 3.52 | 1.4 |
| Remaining Above-Grade Walls | 6.89 | 3.52 | 2.1 |
| Basement Below Grade Walls | 6.55 | 3.52 | 1.4* |
| Ceiling | 10.57 | 7.0 | 5.5 |
| Basement Floor | 1.6 | 0.2 | 0.2 |
| Windows (U-Value) | 1.2 | 2.0 | 2.85 |
| Air Exchange | | | |
| - mechanical (l/s) | 66 | 66 | 0 |
| - natural | 15 | 15 | 97 |
| Heat Recovery Effectiveness | 0.75 | 0.7 | 0.0 |

* to 0.6m of depth, RSI 0.2 for remaining depth (uninsulated)

## *Table 2.3 Comparison of Energy Predictions (kWh)*

| Load | Advanced House | R2000 House | 1985 OBC House |
|---|---|---|---|
| Space Heating | 4822 | 8826 | 23438 |
| Domestic Hot Water | 2016 | 5261 | 5277 |
| Lights / Appliances | 4042 | 8085 | 8085 |
| Air Conditioning | 225 | 1828 | 1568 |
| Fans | 1402 | 4292 | 1402 |
| TOTAL | 12507 | 28292 | 39769 |
| Increase over Ad. House | | 15785 | 27262 |

*Figure 2.1 Sankey Diagram of Energy Flows at the Brampton Advanced House*



Thermal Load (Annual) = 7.10 MWh/a
Electricity Load (Annual Requirement) = 5.40 MWh/a

# 3. MONITORING PROCEDURE

Monitoring of the Advanced House is divided into two categories: short-term or one-time tests and long-term or continuous monitoring. The one-time tests are used to determine the thermal characteristics of a variety of building and building component features. The second category is long-term or continuous monitoring of performance characteristics of the house and various systems within the house. Special emphasis was placed on the Integrated Mechanical System (IMS). Long-term monitoring was done using a PC-based electronic data acquisition system and several manually read meters.

## 3.1 One-Time Tests

Several of the features incorporated into the Advanced House were novel components, new to the construction industry. Wet-blown insulation and high-performance windows did not have well-documented performance characteristics. Thus, an independent assessment of the manufacturer's claimed performance values were required. Building envelope airtightness required verification to determine if the design criteria had been met.

Table 3.1 lists the one-time tests that were performed. Items 1 through 8 were performed to assess the thermal effectiveness of the building shell. Items 9 and 10 were performed to assess the air quality and ventilation system effectiveness.

The thermal effectiveness of the building shell was evaluated by testing the thermal resistance of the individual components (i.e., insulation, wall system and windows) and by measuring the airtightness and building heat loss coefficient. The airtightness of the building shell and the sunspace were evaluated using a standard blower door. Experience has shown that dividing the air leakage rate at 50 Pa by 15 gives a reasonable estimate of the expected natural air infiltration rate. The building heat loss coefficient was measured using a co-heating test.

## Table 3.1 One Time Tests Conducted at the Advanced House

| Parameter Measured | Test Used |
|---|---|
| 1. Building Heat Loss Coefficient | Co-heating |
| 2. Building Time Constant | Thermal Decay |
| 3. Air Tightness of Building Shell | CAN2-149.10-M86 (Blower Door) |
| 4. Infiltration to Sunspace (2 Tests) (with Fresh Air Vents Open and Blocked) | CAN2-149.10-M86 (Blower Door) |
| 5. Wood Moisture Content | Embedded Moisture Pins and Thermistors |
| 6. Thermal Resistance of Insulation Only | ASTM C-518 |
| 7. Thermal Resistance of Insulation in Mock Wall Assembly | Guarded Hot Box to ASTM C-236 |
| 8. Window Thermal Resistance | NRC Method |
| Window Dew Point | Modified CAN/CGSB 12.8 |
| Window Assembly Air Leakage | CSA A440 (@ 75 Pa) |
| Glazing Solar Transmittance | ASTM E-424 |
| 9. Formaldehyde Concentration | Exposure Monitor |
| 10. Radon Concentration | Etched Plate Survey Meter |

Any significant discrepancy between the tested value and the ENERPASS predicted value could indicate a potential flaw in the thermal efficiency of the house shell.

There was a concern that the use of wet-blown insulation may prevent the wood framing from drying out which could possibly lead to wood rot. Twenty-four moisture pins and five thermistors were embedded in various locations in the wall framing of the above-grade portions of the house to check the wood moisture content.

Although there are many potential indoor pollutants, the most commonly measured contaminants are formaldehyde and radon. The testing program called for these contaminants to be measured several times during the monitoring program to identify trends in the results. Formaldehyde levels were tested using two exposure meters, one installed on the main floor in the dining room and the other placed in the master bedroom on the second floor. An etched-plate surveymeter was used to measure radon gas concentrations in the basement. All instruments were in place for a one-week period, as required to obtain a time-averaged value.

## 3.2 Long-Term Monitoring

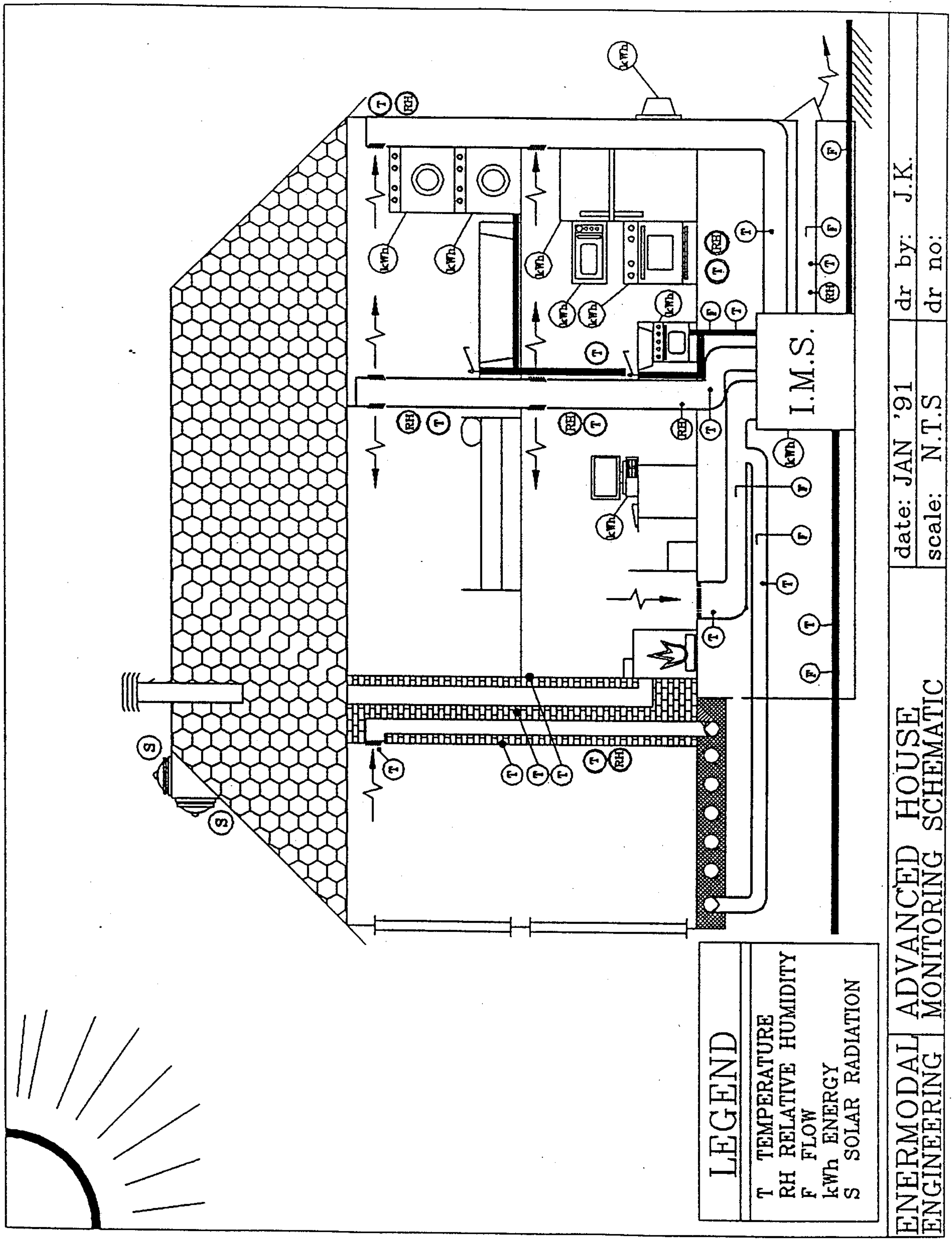
A PC-based data acquisition system (DAS) measuring 66 digital, analog and pulse-counting points was installed in the Advanced House. The DAS monitors the energy use patterns within the house with special regard for the performance characteristics of the IMS. Appendix A lists all the points that are being monitored. These points are schematically represented in Figures 3.1 and 3.2 . The measured points can be characterized as shown in Table 3.2.

### Table 3.2 Monitoring Points Classified

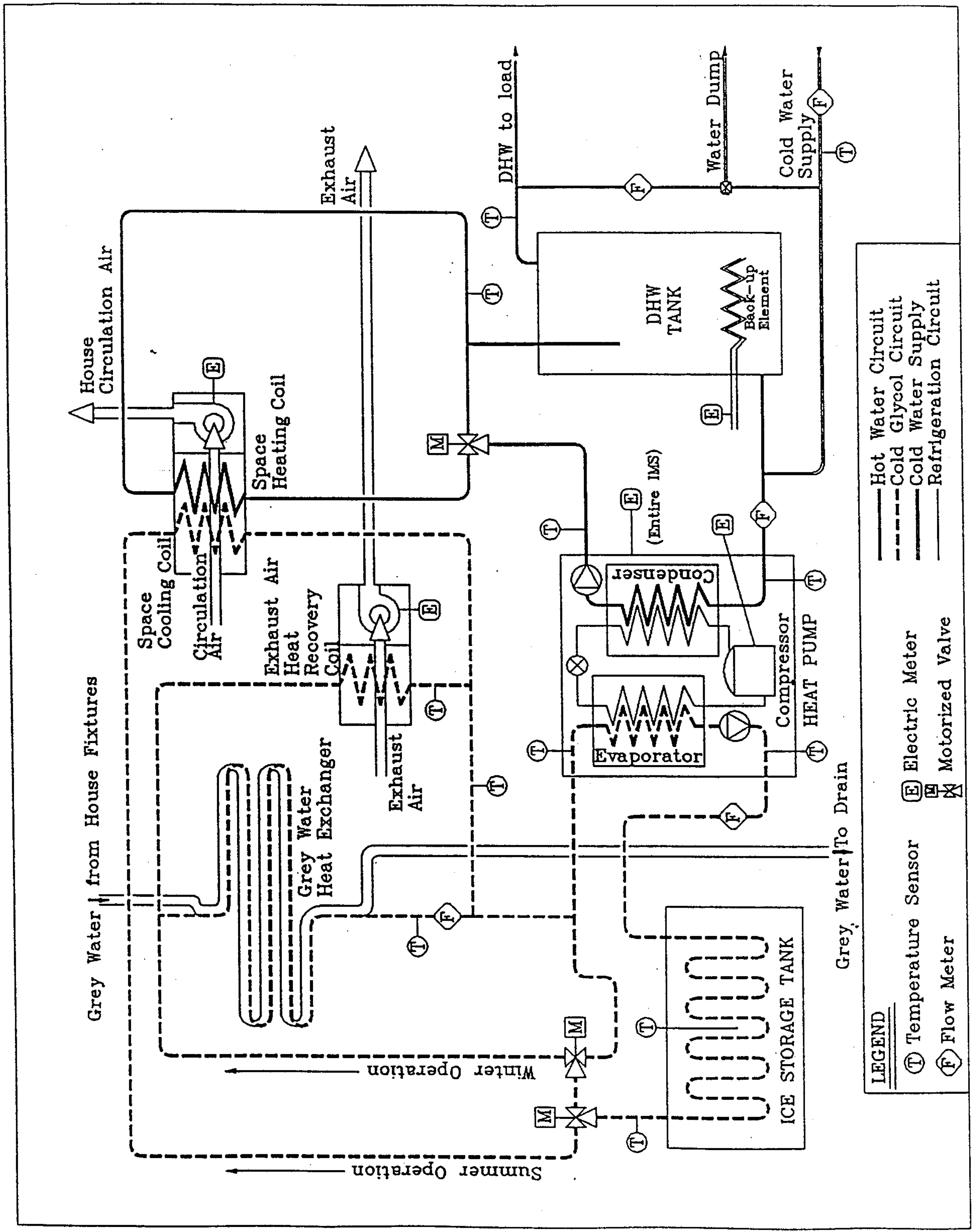
| | |
|---|---|
| Atmospheric Conditions | 4 Points |
| Indoor Comfort Conditions | 12 Points |
| Sunspace Conditions | 6 Points |
| IMS Operating Parameters | 24 Points |
| IMS Comfort Conditioning Parameters | 7 Points |
| House Electrical Consumption Breakdown | 13 Points |

The DAS samples all points at 15-second intervals. At every sample interval heat flows relative to comfort conditions and IMS performance are calculated and stored at hourly intervals.

*Figure 3.1 Advanced House Monitoring Schematic*



## Figure 3.2 IMS Monitoring Schematic



The eight watt-hour meters and six water meters connected to the DAS have accumulating dials. These meters maintain a permanent record of cumulative energy and water use. The meters are read manually at least once a month. The manual readings provide a permanent record in case the data acquisition system fails and data is lost.

The data acquisition system provides detailed performance data on a wide range of energy-consuming and -conserving elements. This particular DAS was approximately 9 years old and is no longer produced commercially but was donated to the project. A sophisticated software package called COPILOT was used to operate the DAS.

A contractor was hired to install the instrumentation and the DAS. The installation began in the spring of 1990 and was essentially completed by June 1990. Enermodal Engineering's role was to analyze the data produced by the monitoring system. The initial data collected was used by the installation contractor to commission the system. The installation contractors work was completed by the end of August, 1990.

## 3.3 Monitoring System Commissioning

Examination of August and September 1990 data revealed a number of inconsistencies. There were several causes for these inconsistencies. Some temperature sensors were installed in incorrect locations, and others in a manner that allowed the reading to be adversely affected by conditions surrounding the sensor (e.g., ambient air adjacent to a sensor measuring the skin temperature of a pipe). The pulse step for some water meters and watt-hour meters was found to be too large to accurately track energy consumption. Pulse counters connected to the various watt-hour meters and flow meters were found to be sensitive to electrical noise, and more pulses than produced by the meters were being counted by the DAS. The power used in some electrical circuits was measured by toroidal coils which had threshold requirements higher than the level to be measured. Wet-bulb thermometers, installed in two locations to track humidity conditions, often dried out and consequently gave inaccurate readings. Because of the configuration of the ducting, one air-flow sensor provided reasonable results at only one flow value. Several problems with the programming were also found.

At the beginning of October 1990, Enermodal Engineering was contracted to commission and maintain the system. Commissioning involved correcting the problems described above and repairing system hardware that had been damaged by lightning strikes.

A major part of the commissioning was to ensure that IMS heat flows were balancing. All temperature sensors within the IMS were checked for accuracy, and were found to be within a few tenths of a °C. The sensors needed to be re-located, however, to provide more representative readings. Water flow meters were checked using a graduated bucket and found to be accurate. Both short- and long- term stability of the pulse counters was checked by comparing the manual readings from the DAS against the meter dials. Good agreement was found once repairs were made to overcome electrical noise. The heat capacity of the IMS glycol solution was sent to Ortech for analysis. The test value of 3.7 kJ/(m$^3$-K) is very close to the textbook value.

In order to ensure that monitored data was reasonable, a heat balance was performed on the various components in the system. Three heat balances were performed using the monitored data for the three month period December 1991 to February 1992. A long time period is required to minimize any thermal storage effects of the IMS.

On the cold side of the IMS (Table 3.3), a heat balance requires that heat added to the glycol loop from grey-water and exhaust-air heat recovery and the cooling coil and heat gains from the basement air be equal to the heat removed by the heat pump evaporator. It is very difficult to measure the heat gains from the basement, but since the tank and glycol lines are well insulated, this quantity should be small.

## *Table 3.3 Cold-Side Three-Month Heat Balance*

| Heat Removed by Evaporator (MJ) | Heat Added by Grey Water and Exhaust Air (MJ) | Heat Added by Cooling Coil (MJ) | Ambient Gains/Errors (MJ) |
|---|---|---|---|
| 13493 | 12679 | 29 | 695 |

On the cold side, there appears to be a small gain into the glycol loop and ice tank system. The 695 MJ corresponds to an average continuous heat gain of 89 Watts, a reasonable value for heat gains. This value is approximately 5% of the average evaporator capacity.

On the hot side of the IMS (Table 3.4), a heat balance requires that the heat put into the water loop by the condenser and the electrical back-up must equal the heat delivered to the loads and losses from the loop to the basement air. As with the cold side, it is difficult to measure the heat loss but it should be small.

## Table 3.4 Hot-Side Three-Month Heat Balance

| Heat Output by Condenser (MJ) | Heat Output by Back-up (MJ) | Heat to Space (MJ) | Heat Losses/Errors (MJ) |
|---|---|---|---|
| 20673 | 5878 | 25043 | 1199 |

On the hot side, there appears to be a small loss from the hot water tank and piping to the space. The 1199 MJ corresponds to a continuous heat loss of 154 Watts. The water heater would have a heat loss of approximately 100 Watts. Because much of the hot water piping is uninsulated, it is conceivable that piping heat loss could account for most of the remaining 54 Watts of heat loss. Thus, there appears to be a reasonable heat balance on the hot side.

The third heat balance (Table 3.5) examines the heat transfer across the heat pump. The heat removed by the evaporator and the energy consumed by the compressor should equal the heat delivered by the condenser and system heat losses.

## *Table 3.5 Heat Pump Three-Month Heat Balance*

| Heat Removed by Evaporator (MJ) | Energy Consumed by Compressor (MJ) | Heat Supplied by Condenser (MJ) | Heat Loss/Error (MJ) |
|---|---|---|---|
| 13493 | 11112 | 20673 | 3932 |

Across the heat pump, there appears to be a large loss of 505 Watts while the heat pump is operating. This represents 16% of the energy input to the heat pump (evaporator plus compressor). For residential heat pump systems (typically 2 to 3 tons output), approximately 5% of the evaporator capacity ends up as heat loss [Hawken, 1989]. Although the small IMS (less than one ton) would have a smaller heat loss in absolute terms, the percentage heat loss could be higher. Thus, approximately half of the 505-Watt loss can be attributed to component heat loss. The remaining discrepancy could be other system losses or instrumentation error. Careful inspection and calibration checks of the instrumentation suggest that the monitored values are reasonably accurate. Nevertheless, the uncertainty in monitoring the IMS could result in an underprediction of condenser output of 0.25 kW and 0.1 in the heat pump COP.

Final commissioning of the monitoring system was completed in mid-December 1990. All systems were functioning properly except for a few torodial coils measuring small currents (e.g., lighting circuits). It was decided that because the power used in these circuits was small, it was not important to accurately know the value. Other problems have occurred and were corrected as monitoring continued. Some examples include sensors unplugged by visitors or construction workers, power supply for humidity switched off during construction work, and malfunctioning of sensors. In a few instances the pulse counters have incorrectly registered zero. It has yet to be determined whether this is a software, hardware or electrical noise problem.

In summary, the manually-read electrical meters have produced reliable data for the period July 1990 to present. Full monitored data is available after mid-December 1990.

# *4. MONITORED RESULTS*

## *4.1 House and System Operation over the Monitoring Period*

### *4.1.1 House Operation*

Construction of the Advanced House was completed in February, 1990. The house was open for public viewing from March 1990 to March, 1991. During the demonstration phase, the house was open Wednesday through Sunday for a total of 26 hours per week. When the house was open, many of the lights were on in order to highlight the innovative products and display boards. Most of the appliances, with the exception of the refrigerator, were not used. The thermostat was set to 21 °C in the winter and 25 °C in the summer.

Demonstration activities were stopped in March 1991 and the house was put up for sale. The house was subsequently sold and the homeowners took possession in June 1991. For the three-month period March 1st to June 1st, the house was empty (i.e., lights and appliances were not used). For the most of this period, the IMS was being adjusted and the backup heating element was providing space heating.

The new homeowners, a family of two adults and a teenage daughter, took possession of the house on June 1st, 1991. They were not, however, completely moved in until June 20th. They operated the house in a consistent manner over the remainder of the monitoring period. In periods of cold weather, they used the fireplace to maintain the house temperature; the electric in-duct heaters were never operated.

The exhaust air flow rate was originally set to 68 L/s in accordance with CSA-F326 Ventilation Requirements for Houses. The homeowners, however, found the house stuffy. The ventilation rate was increased to 87 L/s on July 26, 1991.

The summer of 1992 was unusually cool and little air-conditioning was required. The homeowners never shut-off the IMS heat recovery (i.e., switch system to bypass) for the summer. Thus the IMS cold-side tank was hotter than expected and in some instances, hot water was dumped to reduce the cold tank temperature.

A time-line of significant events in the operation of the house is shown in Figure 4.1.

### *4.1.2 House Equipment Operation*

Several malfunctions of the equipment in the house reduced the amount of valid data available. Figure 4.2 shows a time-line of the significant events over the monitoring period. These events are discussed in the following paragraphs.

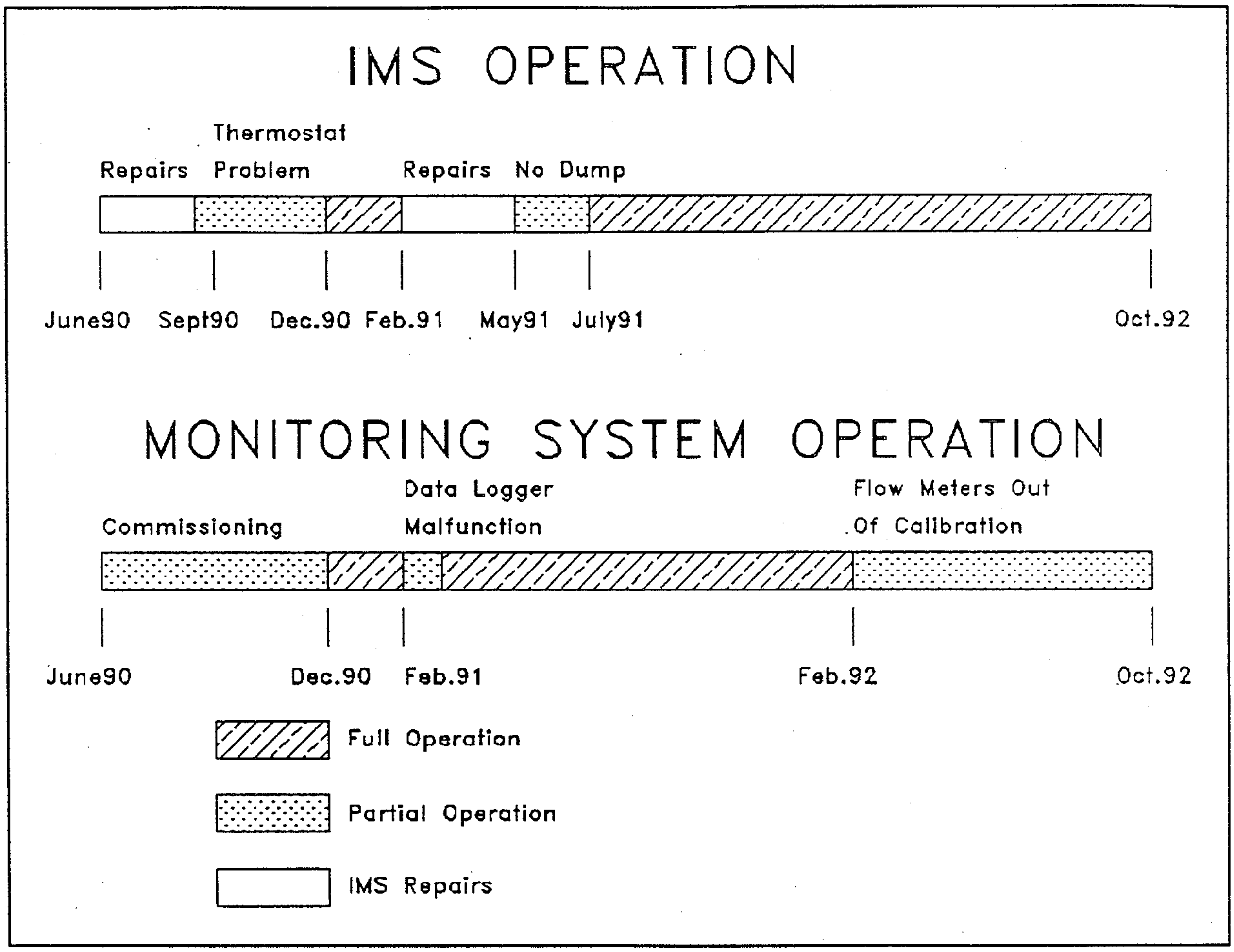
The IMS manufacturer replaced parts and made adjustments to the system throughout June and July, 1990. The system was not operating for most of this period. The system returned to operation in August 1990.

As was discussed in Section 1.1.4, the house control computer was never fully operational. The water-dump control failed in late August, 1990. This meant that the IMS was not able to dump hot water to allow the cooling system to operate. Thus, the energy consumption for the tail end of the cooling season is lower than would otherwise be expected. The control computer was removed on November 15, 1990. A hot water dump control was added to the IMS on July 14, 1991.

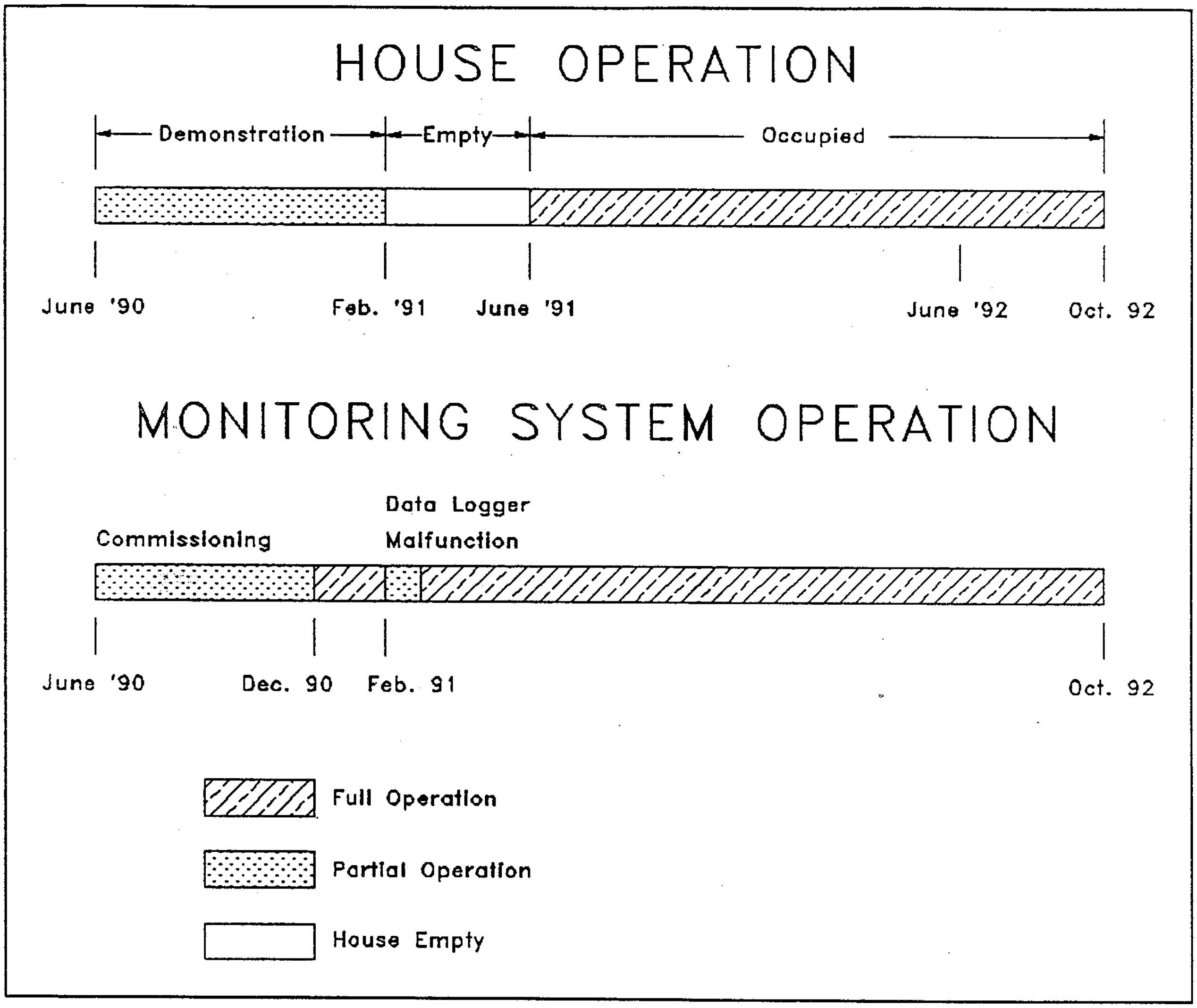
As the heating season approached, it became apparent that the heating system was not functioning properly. An investigation revealed that the house thermostat anticipator was causing the heating system to turn off prematurely. The anticipator was disabled in mid-December (as had been originally specified) and the IMS functioned correctly in heating mode thereafter.

In March, 1991 the house was closed to the public and put up for sale. At approximately the same time an electrical problem caused the IMS to shut down. At the same time, analysis of monitoring results from

## *Figure 4.1 Timeline of IMS Operation*



## Figure 4.2 Timeline of House Operation



this first winter showed that no heat was being recovered from grey water. This was not critical because very little hot water was used in the first year. The grey-water heat exchanger was found to be improperly plumbed causing the grey water to bypass the heat exchanger. The heat exchanger was replumbed and some minor improvements made to the system. The system was put back in operation in mid-April, 1991.

### *4.1.3 Monitoring System Operation*

As discussed in Sections 3.2 and 3.3, a long-term monitoring system was installed in the spring of 1990; and installation was complete by June 1990. Commissioning of the monitoring system took five months to November 1990. Manual electric kilowatt-hour meter readings were available from June 1990, but complete monitored data was not available until December 1990.

Once commissioned, the monitoring system operated reliably throughout the monitoring period with only a few missed days and a few faulty sensors that required replacement. The significant events in the operation of the monitoring system are summarized in Figures 4.1 and 4.2.

The periods for which valid monitored data are available are summarized on a time-line in Figures 4.1 and 4.2. During the demonstration phase, there is only a modest amount of valid monitored data. For the period June through November 1990, problems with the monitoring system and IMS were being resolved. Monitored data for the period March through May 1990 is of limited value because the house was empty and most systems were shut down or not used.

For the 1 and 1/2 years when the house was occupied, there is almost a full set of monitored data. Detailed information on the IMS performance is not available for February, March and April 1992 because of a broken flow meter on the IMS hot side.

In April 1990, a problem occurred in the measurement of evaporator glycol flow. The flow meter was repaired in June, 1990, but readings for the remainder of the monitoring period showed the heat removed by the evaporator to be over-estimated.

### 4.1.4 Weather Data over the Monitoring Period

Figure 4.3 shows the site-measured monthly average ambient temperature and the Typical Meteorological Year for the Toronto International Airport. With the exception of the summer of 1992, the site is consistently 2 to 3 C° degrees warmer than the Toronto Airport. The warmer conditions at the site may be due to sheltering of the ambient temperature sensor at the site and/or urban heat gains. The summer of 1991 was exceptionally warm and the summer of 1992 was abnormally cool.

Figure 4.4 shows the site-measured south-side vertical solar radiation and the TMY solar radiation (as computed by ENERPASS). In general, there is good agreement between the measurements. The site-measured solar radiation in 1991 tends to be higher than the TMY data and the site data for 1992 tends to be lower than the TMY data.

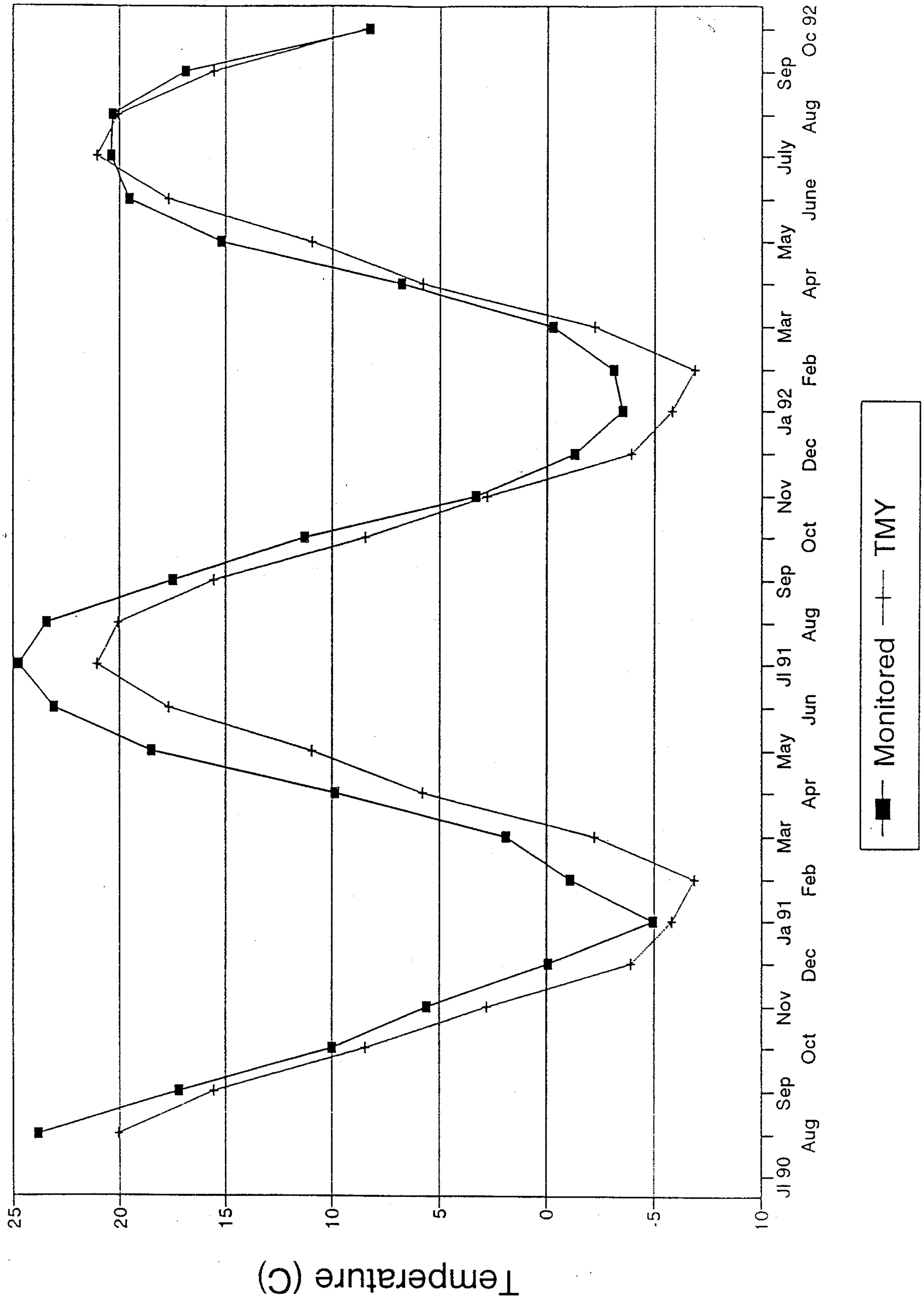
The temperature and solar radiation measurements show that the 1991 cooling load was high and the 1992 cooling load low.

## 4.2 Building Loads

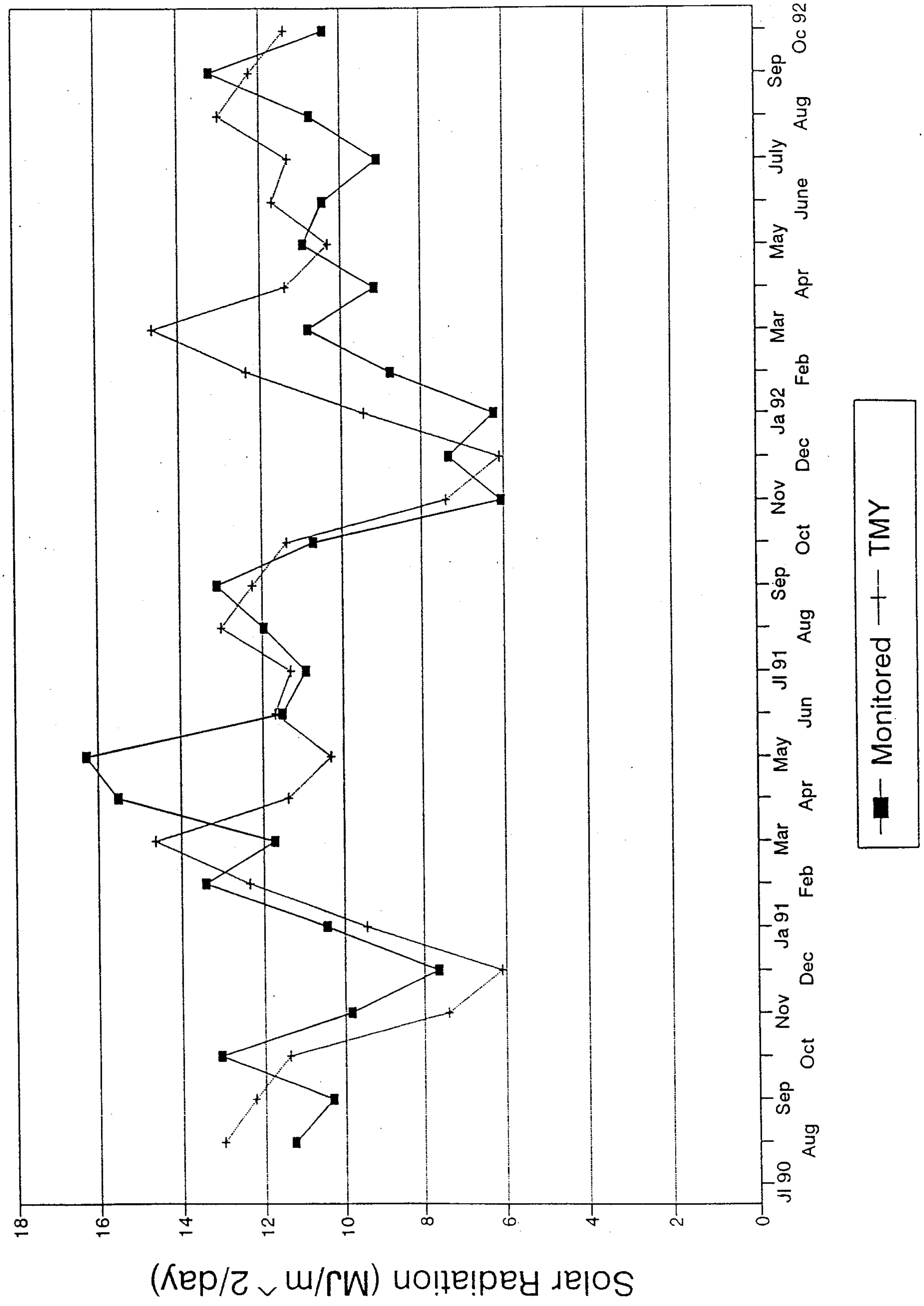
### 4.2.1 Building Heat Loss Characteristics

As was discussed, the thermal resistances of the entire building shell and various shell components were assessed by performing one-time tests. Testing laboratories measured the thermal resistance of the windows, insulation and a mock wall section. The building heat loss coefficient was measured using a co-heating test. The building time constant was obtained by measuring the temperature decay of the building. The results of these tests are discussed in this section.

## Figure 4.3 Ambient Temperature



## Figure 4.4 Global Solar Radiation



### *Wall Thermal Resistance*

In November 1989, a 153.6-mm-thick sample of the wet-blown cellulose was sent to Ortech International for determination of its thermal resistance. It was tested in its "wet" state upon receipt. In May 1990, after the sample had dried to a constant weight, it was retested in a "dry" state. All tests were conducted in accordance with ASTM Standard C-518. During the test a temperature differential of 22C° at a mean specimen temperature of 24°C was maintained. The results are shown in Table 4.1.

### *Table 4.1 Conductivity of Wet-Blown Cellulose*

| Test Condition | Conductivity (W/m-C) | Moisture Content (%/wt) |
|---|---|---|
| Wet | 0.055 | 69.9 |
| Dry | 0.044 | N/A |
| Manufacturers' Data | 0.036 | N/A |

The tests show that there is a significant decrease in thermal conductivity once the material has dried. In the dry state the material was found to have a thermal conductivity 18% above the manufacturers' specifications. The accuracy of the measurement is quoted (in units of conductivity) at ±0.003 W/m-°C (or about ±5% of the reading in this case) [Bauer, 1991].

A full-scale model of a wall section, identical to the above grade walls using double-wall construction and wet-blown cellulose, but with interior and exterior finishes not included, was built to provide an insight into the capacity of wet-blown insulation to dry and the behaviour of the insulation in a wall assembly. The mock section was stored in the garage of the Advanced House for one year to allow drying of the assembly. The assembly was a nominal 2.06 meters wide by 2.46 meters high by 273 mm thick. A clear 6-mil polyethylene vapour barrier covered the indoor side of the model and 25 mm of rigid fibreglass wall sheathing with a spunbonded polyolefin air barrier covering the exterior surface.

The thermal resistance of this wall section was tested in accordance with ASTM C236 by Warnock Hersey in May 1991 (Table 4.2). Two tests were conducted at different steady-state temperature conditions and the results are listed in the first row of the table below. These results are for the surface-to-surface temperature difference across the specimen and do not include any contribution from interior or exterior air films. To compare these values to the values used in the simulations, the thermal resistances of an interior air film, gypsum board, exterior air film, brick veneer, and air space need to be added. The total thermal resistance for these items is 0.71 $m^2$-C/W when computed in accordance with ASHRAE recommended procedures. The second row of the table incorporates the additional resistance values.

## *Table 4.2 Thermal Resistance of Wall Assembly ($m^2$-C/W)*

| Test Conditions | -8.3°C Exterior<br>21.7°C Interior<br>($m^2$-°C/W) | -33.0°C Exterior<br>21.1°C Interior<br>($m^2$-°C/W) |
|---|---|---|
| Results for Mock Wall Assembly | 6.11 | 5.29 |
| Total for Complete Wall | 6.82 | 6.00 |
| Total Wall Using Manufacturers' Data | 6.9 (calculated) | |
| Total Wall Using Table 4.1 Dry Data | 5.7 (calculated) | |

The thermal resistances of the total wall assembly appears to be between RSI 5.7 and 6.9 depending on temperature differential. Decreases in thermal resistance of wall assemblies with colder outdoor temperatures have also been noted by other researchers [Besant, 1991]. The upper end of this range is consistent with the manufacturers performance claims. Since the time of testing, the thermal resistance of cellulose has been re-rated at 7 to 15% lower values. Nevertheless, the thermal resistance of the wall assembly appears to be close to design specifications.

### *Wood Moisture Content*

Twenty-four moisture pins and five thermistors were embedded in various locations in the wall framing of the above grade portions of the house. These were checked on two occasions during the first year of operation of the house. On both occasions very low readings of wood moisture content were recorded. The maximum reading was 12%. It has been found that the chemical content in wood depresses the moisture readings. Still, it is felt that the walls had successfully dried out and were below the 35% threshold where wood rot is a serious concern and likely below the 19% fibre saturation point of wood [CHBA, 1989]. On a third attempt to read the moisture pins the meter was found to be malfunctioning. No further measurements are planned because of the cost of a new meter and the requirement for calibrating the electrodes.

### *Windows*

The thermal resistance of a sample window was measured at the National Research Council of Canada using the NRC Method. This methodology is referenced in CSA Preliminary Standard A440.2 Method for Determining the Energy Performance of Windows. The test was conducted at an outdoor temperature of -18°C, and provided an overall window U-value (RSI) of 1.10 W/($m^2$°C). The thermal performance of the window assembly was also simulated using the FRAME [Enermodal, 1990] and VISION [Wright, 1989] computer programs. The simulated value was within 2% of the measured value. The test value and simulation results meet the design requirement of 120 W/($m^2$°C).

Four other tests were conducted on the sample window at Ortech International to fully characterize the window's performance. These tests and the results are shown in Table 4.3.

### *Building Heat Loss Coefficient*

A co-heating test was conducted over two nights to determine an "as-built" building heat-loss coefficient (UA-value). Two different test modes were used. Over the first night, the sunspace doors were left open and the sunspace was treated as a heated room in the house.

## Table 4.3 Window Test Results

| TEST NAME | STANDARD/PROCEDURE | RESULT |
|---|---|---|
| Window Dew Point | Modified CAN/CGSB 12.8 | -73°C |
| Window Assembly Air Leakage | @ 75 Pa Pressure Difference | 0.019 $(m^3/h)/m$ |
| Glazing Solar Transmittance | ASTM E-424 | 41.6% |
| Thermal Break: Condensation occurred at sill/jamb corner on glass stop | | -29.4°C |

Over the second night, the sunspace doors were closed to allow the house to operate as designed. The average nighttime temperature for the tests was -3°C.

The results of the co-heating tests are shown in Table 4.4. The co-heating test results show that the house shell is performing very close to predictions. The monitored results are 16% and 5% below the ENERPASS predictions with the sunspace doors open and closed respectively. These results are probably within the accuracy of the simulation and the experiment. The design heating load of 8.0 kW at an outdoor temperature of -19°C obtained using ENERPASS (sunspace doors closed) appears to be a reasonable estimate of actual house performance.

## Table 4.4 Building UA-Value in W/°C

| | Co-Heating Test | ENERPASS |
|---|---|---|
| Sunspace Doors Open | 224 | 268 |
| Sunspace Doors Closed | 199 | 209 |

### *Building Time Constant*

A test to determine the building time constant was also conducted. The heating system was shut off and the rate of house temperature decrease was measured. Over a cold period between 3:30 a.m. and 7:30 a.m., the time constant was determined to be 54 hours. This value compares favourably with the value of 48 hours predicted by ENERPASS.

## *4.2.2 Building Airtightness*

A blower-door test was performed in early 1990. The tests were conducted in accordance with CGSB test Standard CAN2-149.10-M86. The original target airtightness was 0.75 ACH at 50 Pa, excluding the sunspace. Because of difficulties in isolating the sunspace for the test, and because it was believed that during occupancy the doors between the house and the sunspace would be open, it was decided to include it as part of the envelope for the test. The result was 0.9 ACH @ 50 Pa or 0.60 $cm^2/m^2$ normalized leakage area @ 10 Pa.

A second air leakage test was performed on September 18, 1991. Tests were performed with both the doors between the sunspace and the house open and closed. The sunspace doors had been weatherstripped since the first blower-door test. The measured airtightness was 1.34 ACH @ 50 PA or 0.77 $cm^2/m^2$ normalized leakage area @ 50 Pa with the sunspace doors open to the house. The airtightness was only slightly less with the sunspace doors closed (1.29 ACH @ 50 Pa). The airtightness of the building shell appears to have decreased between the two test periods. No obvious leakage areas were identified.

While examining monitored data, it was found that overnight sunspace temperatures remained higher than was expected. In fact, on a night when computer simulation predicted that the sunspace temperature would drop below 10°C the measured temperature remained above 16°C. It was suggested that one possible reason for the high temperature was that house air was leaking into the sunspace. To test this hypothesis, two blower door tests were done.

The blower door was installed in the sunspace patio door leading to the outdoors. All French doors leading to the house were weatherstripped properly and kept closed. One test was done with the fresh air supply grilles uncovered so that a total equivalent leakage area (ELA) for the sunspace including vent area could be determined. For the second test the fresh air grilles were sealed to determine what fraction of the ELA from the first test was associated with the fresh air grilles.

Simultaneously a smoke pencil was used to inspect for significant leakage locations. The smoke-pencil test qualitatively identified the frames around the doors between the sunspace and the house as the largest area of leakage. The quantitative test results are in Table 4.5.

## Table 4.5 Sunspace Leakage Area

| | Design | Measured ($ELA_{10}$) |
|---|---|---|
| Sunspace to House wall ($cm^2$) | 26.3 | 159 |
| Sunspace Air Vent Area ($cm^2$) | 365 | 40.9 |

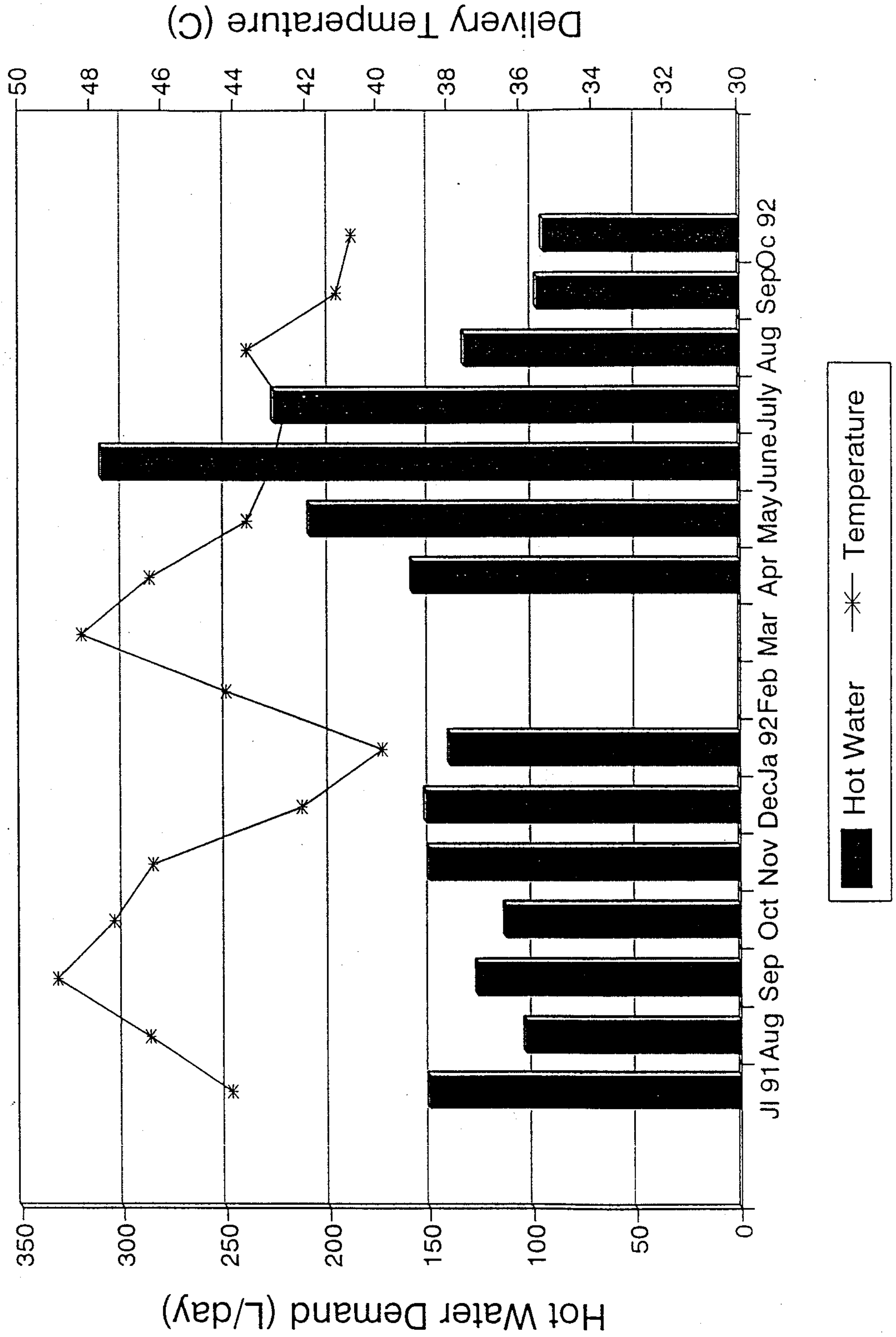
If the wall between the sunspace and the house had the same air-tightness as the rest of the house it should have an ELA of 26.3 $cm^2$, but, the test indicates 159 $cm^2$. The design specifications called for 365 $cm^2$ of fresh air vent area, but, the test indicates 40.9 $cm^2$. The dual effect of a large leakage area from the house to the sunspace and a constricted vent opening from the outdoors combine to limit ventilation air being drawn in through the sunspace.

Ventilation air is drawn through the sunspace into the IMS through a duct that is connected to the return air (suction) side of the house circulating fan. The air flow through this duct is 34 L/s. If it is assumed that the sunspace shell has the same ELA as the house, then it can be calculated that 15 L/s is outside air and the remainder is air drawn into the sunspace from the house. The total exhaust air is 68 L/s; therefore, 53 L/s of outdoor air filtrates through the building shell. Thus, the hypothesis appears correct.

### 4.2.3 Water Usage

Figure 4.5 shows monthly values of daily average hot water use (in litres/day) for the period when the house was occupied. The average daily hot water demand was 164 litres per day at an average delivery temperature of 45°C. Very little water was used during the demonstration period and as such is not reported.

## Figure 4.5 Hot Water Load



The hot water demand at the Advanced House is very low, indicating the impact of the water conserving appliances in the house. A study by Ontario Hydro showed the average family uses 236 litres/day of hot water at 55°C [Perlman and Mills, 1985]. The CSA standard for testing solar water heaters uses a value of 225 litres per day at 55°C as representative of a three to four person family. The hot water heating demand at the Advanced house is only 60% that of a typical family.

The average hot water delivery temperature varies between 40°C and 50°C depending on the time of year. In the summer, hot water is dumped to allow the compressor to operate and maintain a cool ice storage tank. If there is a large hot water demand during or after a water dump, the delivery temperature can be below the hot water setpoint. In the winter, during periods of peak space heating demand, the compressor and back-up element cannot maintain the tank temperature. IMS winter operation is discussed in more detail in Section 4.3.2. It should be noted that the homeowners never complained about lack of hot water. The amount of cold water was probably adjusted to provide the desired temperature at the taps.

Daily cold water use, for the months when no water was dumped to maintain cooling capacity, was 264 litres per day. Ignoring dumped water, the total daily water use was 428 litres per day, of which 38% was for hot water. A typical Canadian house uses 683 l/day of cold water [Carpenter and Kokko, 1993]. In the summer, however, cold water use (including dumped water for cooling) was typically 1500 litres per day. Averaging the two cooling seasons, it is estimated that 143 cubic metres of water are dumped per season to maintain cooling capacity.

## *4.3 Air Quality Test Results*

Although there are many potential indoor pollutants, the most commonly measured are formaldehyde and radon. Contaminant levels were measured over the first week of February 1991. Formaldehyde levels were tested using two exposure meters, one installed on the main floor in the dining room and the other placed in the master bedroom on the second floor. An etched-plate surveymeter was used to measure radon gas concentrations in the basement. All instruments were in place for a one-week period, as required to obtain a time-averaged value. All measurements were well below the applicable standards.

Formaldehyde concentration was measured at 0.048 ppm in the master bedroom and 0.026 ppm in the dining room, both values are well below the Canadian guideline of 0.10 ppm. The radon concentration was 0.002 working level units, well below the conservative U.S. guideline of 0.02 WLU (4 picocuries/litre). The exhaust ventilation rate was set at 68 L/s in accordance with the Draft Canadian Ventilation Standard F326. The results show that air quality in the Advanced House to be satisfactory.

## 4.4 IMS Performance

### 4.4.1 Total Performance

The total energy used by the IMS for the demonstration and occupied periods are shown in Figures 4.6 and 4.7 respectively. When the house was in demonstration mode (July, 1990 through February, 1991), there was very little hot water use. Data for March, April and May 1991 are not shown because the IMS was shut-off for modifications and the house was unoccupied.

On an annual basis, the IMS consumed 13,287 kWh during the period when the house was occupied. The compressor is the largest energy user, representing 65% of IMS energy use. The back-up element energy use in the three coldest months (December, January and February) is significant especially in the first year (demonstration mode). The lower back-up element use in year two can be attributed to the homeowner use of the wood fireplace. The fireplace provided an estimated 1700 kWh of space heating in the second winter (see Section 4.7).

Perhaps somewhat surprising is the high energy use for pumps, fans and controls. The supply and exhaust fans operate continuously at a combined power draw of between 180 and 200 Watts. The two circulating pumps and controls consume a total of between 230 and

## *Figure 4.6 Monitored Performance of the IMS (Unoccupied Mode)*

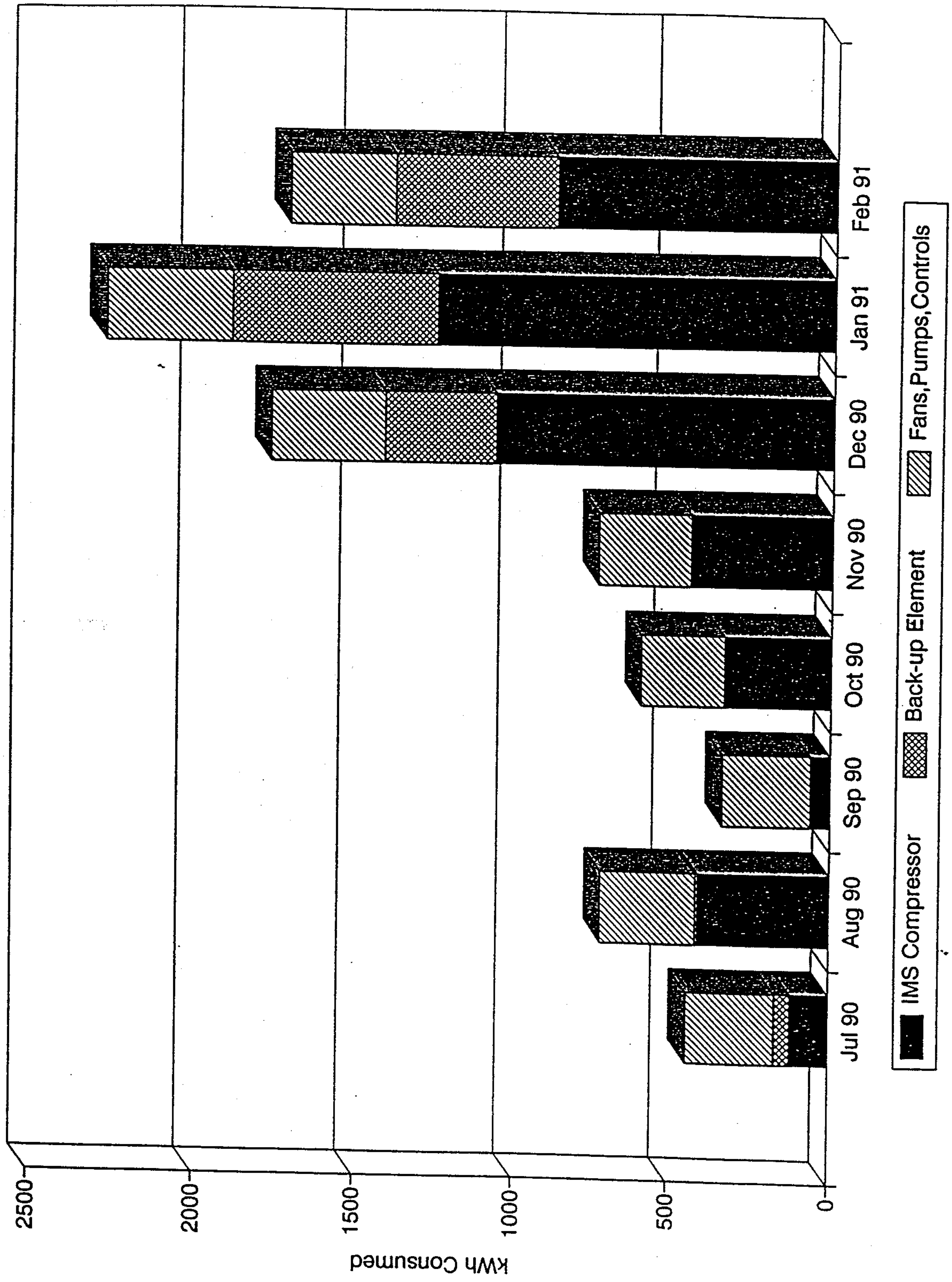
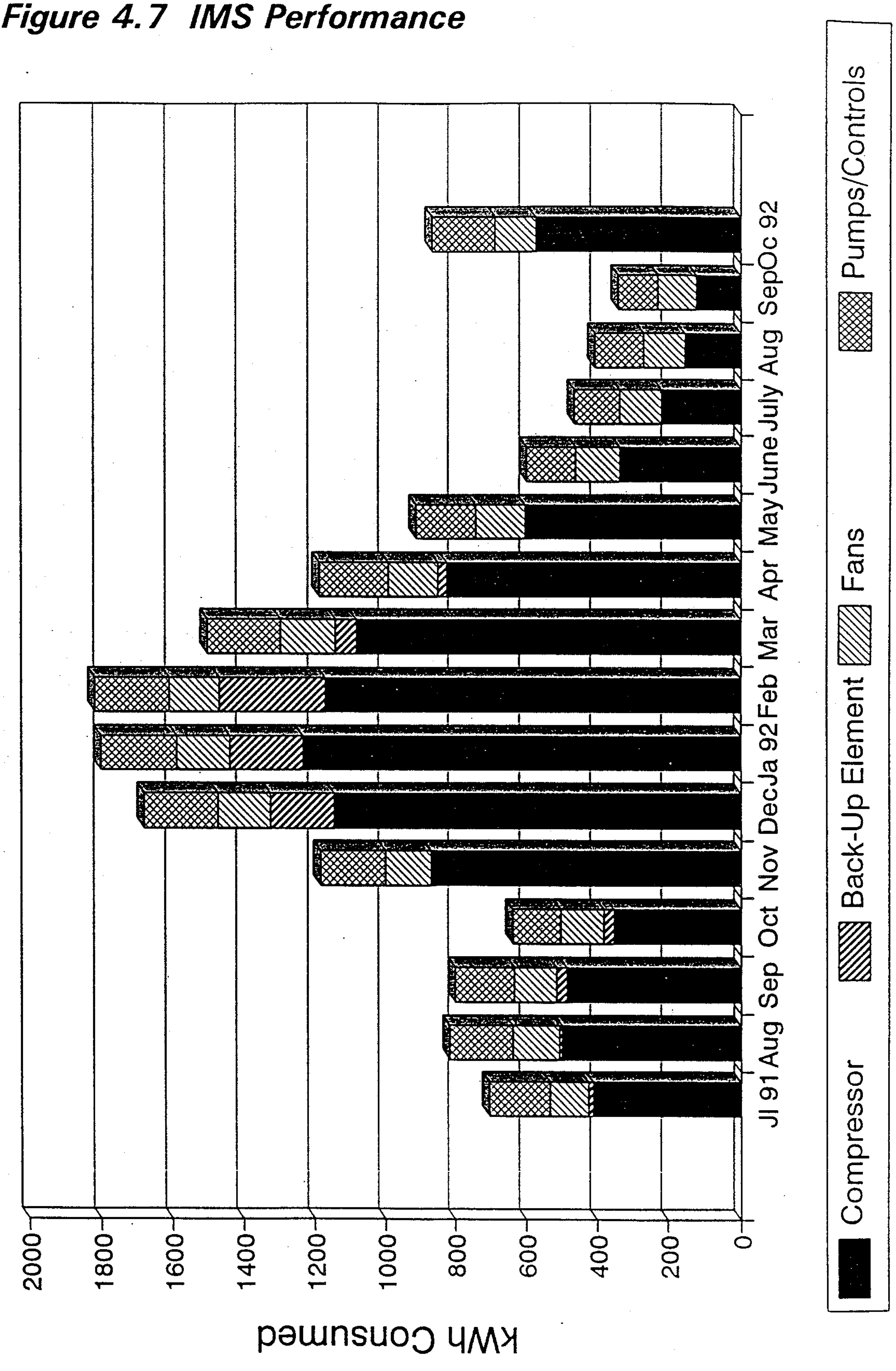


***Figure 4.7 IMS Performance***



310 Watts depending on the temperature of the glycol. The parasitic energy accounts for 3,750 kWh of electricity use per year, or 30% of the predicted energy use for the total house.

Although parasitic energy use represents a significant proportion of total house energy use, it is only slightly higher than that for a conventional house. A typical HRV could be expected to consume between 900 and 1300 kWh annually and a furnace would consume approximately 1200 kWh (if operated intermittently) or 3000 kWh (if operated continuously) [Ontario Hydro, 1990]. In a conventional house, parasitic energy use would represent less than 10% of total energy use, but in the Advanced House, approximately the same energy use accounts for 30% of the total.

To characterize the performance of the system, a Seasonal Performance Factor or SPF was defined. The definition for this parameter was derived from accepted standards [Cane, 1992]. There are no standards, however, for rating integrated mechanical systems.

Seasonal Performance Factor is a measure of how the IMS is performing in the Advanced House over the heating and cooling seasons. It is a measure of the performance of the entire system relative to the load placed on it. It is defined as the useful heating and cooling energy supplied divided by the total energy used by the IMS including auxiliary heating. The SPF can be written:

$$SPF = \frac{\text{Space Heating} + \text{Water Heating} + \text{Circulating Fan Heat} + \text{UsefulCooling}}{\text{Compressor} + \text{Pumps} + \text{Fans} + \text{Back-Up}}$$

Circulating Fan energy is treated as a credit (positive value) when the IMS is space heating and as a liability (negative value) when the IMS is providing space cooling. Any heating from the fireplace is not included in the SPF formula.

Monthly values of the daily average heat flows and SPF of the IMS are listed in Tables 4.6 and 4.7 for the months of valid monitored data. The quantities are given as average values excluding the days when the IMS was shut off. A range is given for the SPF reflecting the uncertainties in the monitoring of the IMS as discussed in Section 3.3.

## Table 4.6 IMS Monthly Average Performance - Demonstration Period

| Quantity | December | January | February |
|---|---|---|---|
| Total Heat Recovery (W) | 1627 | 1939 | 1343 |
| Evaporator Energy (W) | 1781 | 2016 | 1374 |
| Compressor Energy (W) | 1464 | 1664 | 1130 |
| Condenser Energy (W) | 2650 | 3124 | 2153 |
| Compressor Run Time (hrs/day) | 16.5 | 19.9 | 14.5 |
| Space Heating (W) | 2970 | 3716 | 2949 |
| Water Heating (W) | 35 | 46 | 46 |
| Back-Up Heating (W) | 449 | 888 | 949 |
| Fans (W) | 206 | 198 | 201 |
| Pumps/Controls (W) | 286 | 313 | 281 |
| SPF | 1.29 to 1.39 | 1.26 to 1.34 | 1.21 to 1.31 |

Figure 4.8 shows the monthly values of the SPF when the house was occupied. The SPF averaged 1.54 over the heating season and 0.85 over the cooling season for the period when the house was occupied. Because of the uncertainties in the monitoring discussed in Section 3.3, the SPF could be up to 0.1 higher. During the demonstration mode, the SPF values were lower because the back-up electrical element was used instead of the wood fireplace. The reader is cautioned not to compare the SPF values over the cooling season to a conventional air-conditioning system. The values quoted in this report include the energy required to supply hot water and circulate and exhaust air; these energy quantities that are not normally included in air-conditioning COP's.

## 4.4.2 Heating Season Performance

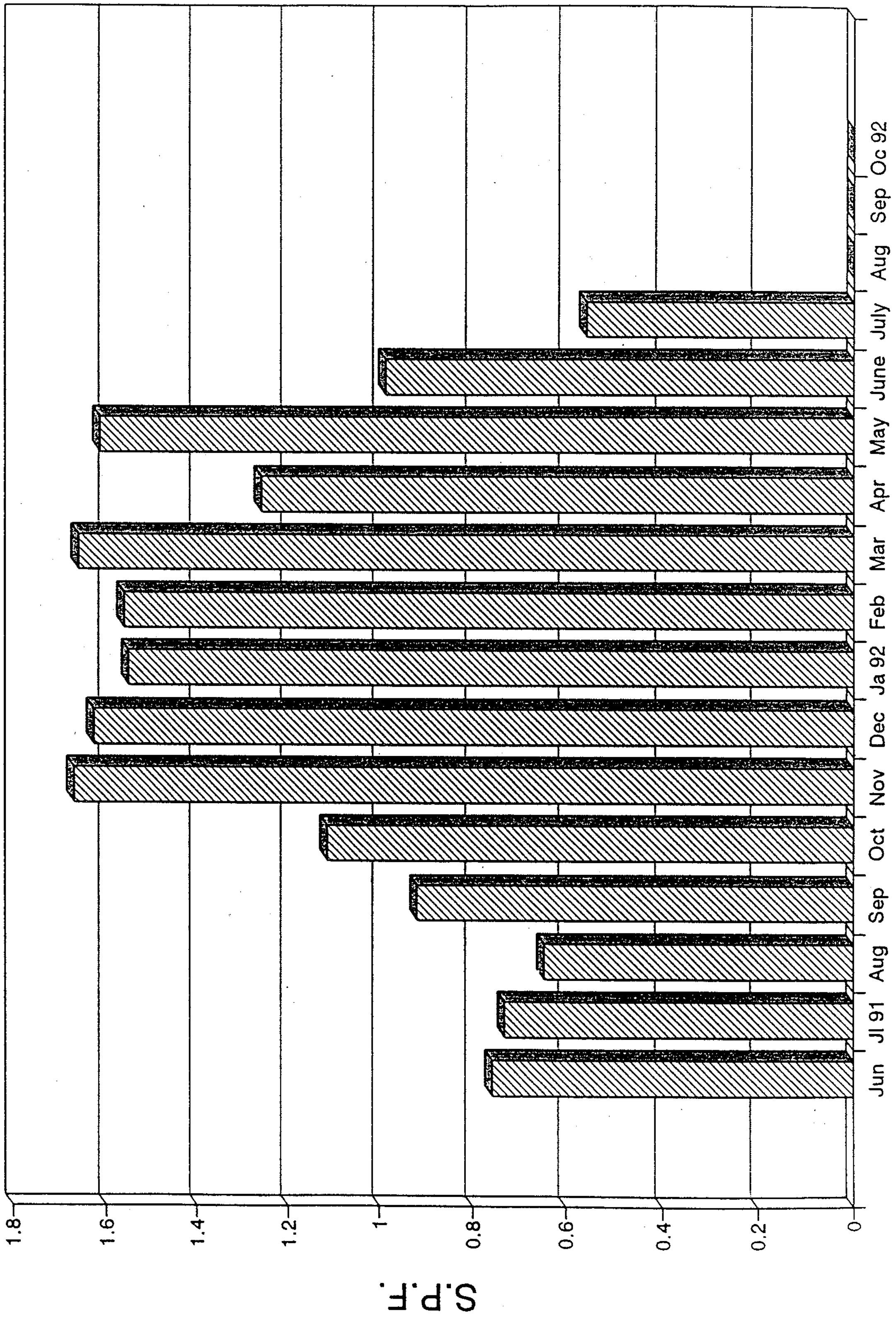
To characterize the instantaneous heating performance of the IMS, a heat pump COP was defined. It is defined as heat output from the condenser divided by the electricity consumed by the compressor, hot

## Table 4.7 IMS Monthly Average Performance - Occupied Period

| Quantity | July 91 | Aug. 91 | Sept. 91 | Oct. 91 | Nov. 91 | Dec. 91 | Jan. 92 | Feb. 92 | Mar. 92 | Apr. 92 | May 92 | June 92 | July 92 | Aug. 92 | Sept. 92 | Oct. 92 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total Heat Recovery (W) | 0 | 0 | 66 | 329 | 1063 | 1325 | 1347 | 1226 | 1150 | 855 | 648 | 473 | 297 | 145 | 117 | 592 |
| Evaporator Energy (W) | 961 | 1181 | 1107 | 673 | 1785 | 2137 | 2277 | 2363 | 2092 | 1683 | 1206 | 666 | 446 | 351 | 254 | 1087 |
| Compressor Energy (W) | 559 | 675 | 677 | 478 | 1218 | 1540 | 1655 | 1683 | 1454 | 1149 | 811 | 471 | 301 | 217 | 177 | 777 |
| Condenser Energy (W) | 1084 | 1530 | 1596 | 977 | 2634 | 3212 | 3238 | *3352* | *2912* | *1823* | *1643* | 886 | 518 | 382 | 14 | 0 |
| Compressor Run Time (hrs/day) | 2.0 | 2.4 | 2.6 | 1.8 | 4.9 | 6.4 | 7.0 | 7.9 | 6.1 | 4.7 | 3.2 | 2.0 | 1.2 | 0.8 | 0.7 | 3.0 |
| Space Heating (W) | 0 | 0 | 380 | 679 | 2363 | 3285 | 3384 | *3752* | *2987* | *1662* | *1493* | 162 | 43 | 28 | 1 | 0 |
| Space Cooling (W) | 522 | 638 | 478 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 25 | 0 | 0 |
| Water Heating (W) | 250 | 165 | 211 | 202 | 302 | 306 | 274 | 233 | 258 | 324 | 408 | 579 | 394 | 226 | 163 | 170 |
| Back-Up Heating (W) | 21 | 11 | 42 | 39 | 0 | 245 | 274 | 430 | 80 | 37 | 3 | 4 | 1 | 0 | 0 | 0 |
| Fans (W) | 146 | 176 | 164 | 167 | 179 | 200 | 203 | 205 | 207 | 202 | 189 | 174 | 161 | 159 | 152 | 154 |
| Pumps/Controls (W) | 232 | 245 | 231 | 182 | 254 | 284 | 290 | 303 | 277 | 272 | 234 | 191 | 178 | 186 | 158 | 242 |
| SPF | 0.73 | 0.65 | 0.92 | 1.11 | 1.67 | 1.63 | 1.55 | 1.56 | 1.66 | 1.26 | 1.61 | 0.99 | 0.56 | N/A | N/A | N/A |

Note: *Italicized* - estimated

***Figure 4.8 IMS Seasonal Perf. Factor***



water pump, glycol pump, and controls. The pump and control energy is included because these components are necessary for the operation of the refrigeration system. Fan energy is not included because alternative heating systems (e.g., forced-air furnace) would also require this energy. Back-up energy is also excluded from the definition of COP. Mathematically, the heat pump COP can be written:

$$\text{Heat Pump COP} = \frac{\text{Condenser Heat}}{\text{Compressor} + \text{Pumps}}$$

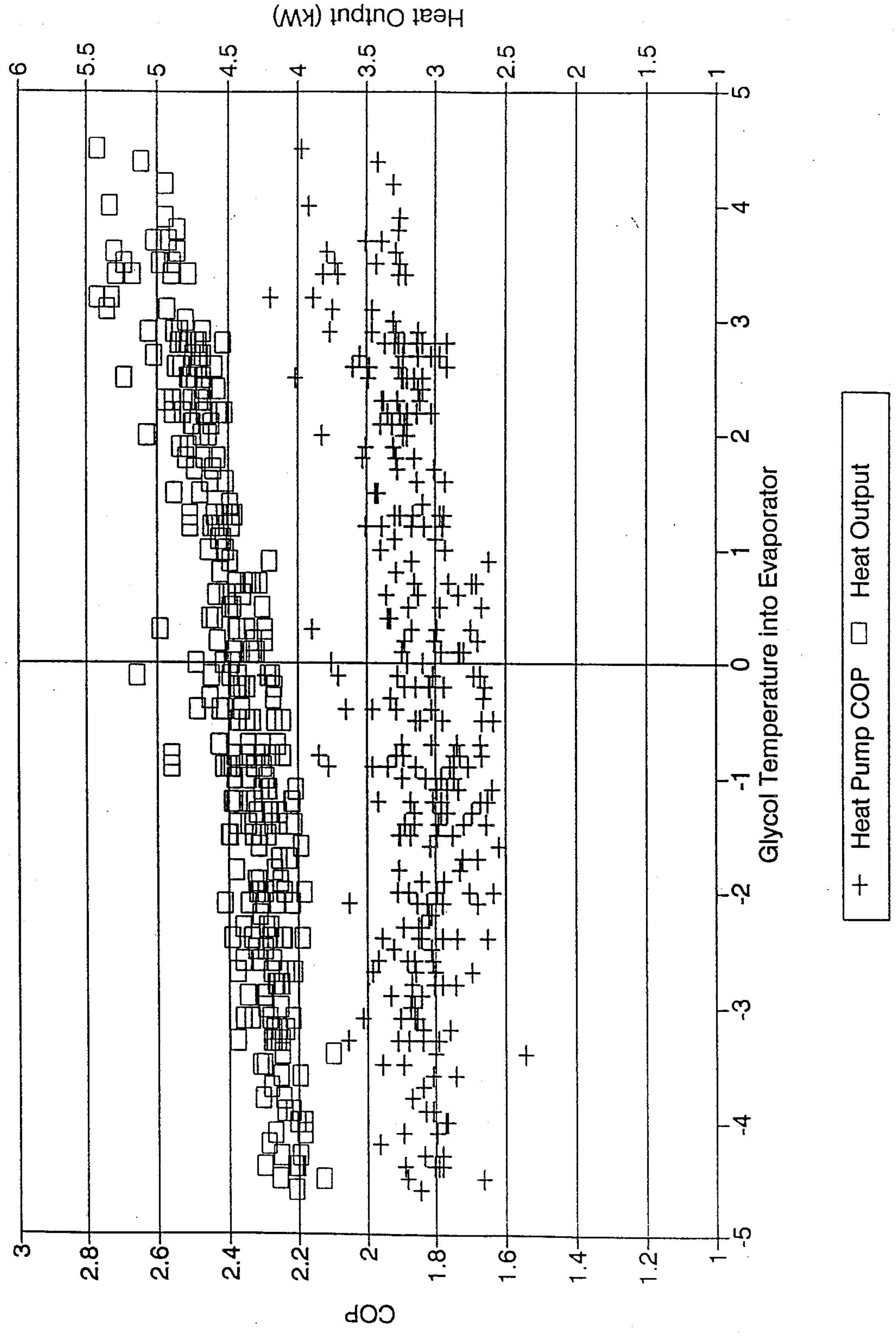
Figure 4.9 shows hourly values of heat pump COP and heat output from the condenser for those hours in the 1991/92 heating season when the compressor operated for the full hour. The results show that both condenser output and heat pump COP improve with higher glycol temperatures. Like most other heat pumps, the IMS will perform best when the temperature difference between the hot and cold sides is kept to a minimum.

The performance of the heat pump appears to be slightly below design expectations. The condenser output ranged from 4 to 5.5 kW at COP values of between 1.7 to 2.1. (Design values were 6 kW at a COP of 2.5 to 3.0.)

A 6-day period from January 20th to the 25th, 1991 was examined in detail to gain insight into the operation of the house and the IMS during cold weather. Ambient temperatures for this period varied from +4°C to -19°C. The 20th and 23rd were overcast and the other four days were sunny. Indoor temperatures appear to be significantly affected by outdoor temperatures overnight and solar radiation during the day. From the afternoon of the 20th to mid-morning of the 21st the average indoor temperature experienced a 4C° drop. Over the next five days, indoor temperatures fluctuated between 19°C and 25°C.

The IMS operated continuously over the 6-day period. The thermostat was set at 26°C or higher; the data shows that the IMS continued to operate in heating mode even when the temperature in the dining room (where the thermostat was placed) reached 25.5°C. Presumably, the elevated temperature setting allowed the mass of the house to be

## *Figure 4.9 Hourly IMS Performance*



recharged when the heating load was small. The stored heat will help the house to coast through colder periods when the heat load is greater than the IMS output.

The hourly IMS heating output varied from a high of 4.4 kW to a low of 3.0 kW (see Figure 4.10) with an average of 3.7 kW. (These values could be as much as 0.25 kW higher because of instrumentation uncertainties - see Section 3.3.) The variation in heating was caused by changes in the heating coil inlet water temperature. Figure 4.10 shows that the DHW tank and coil inlet temperatures drop when the compressor is running. This implies that heat is being delivered to the house at a rate faster than is being made up by the compressor. When the DHW tank becomes cool, the compressor shuts off and the back-up element comes on. The rise in tank temperature indicates that the back-up element is supplying heat faster than is being delivered to the house. The electrical resistance element in the DHW tank has a measured output capacity of 5.5 kW.

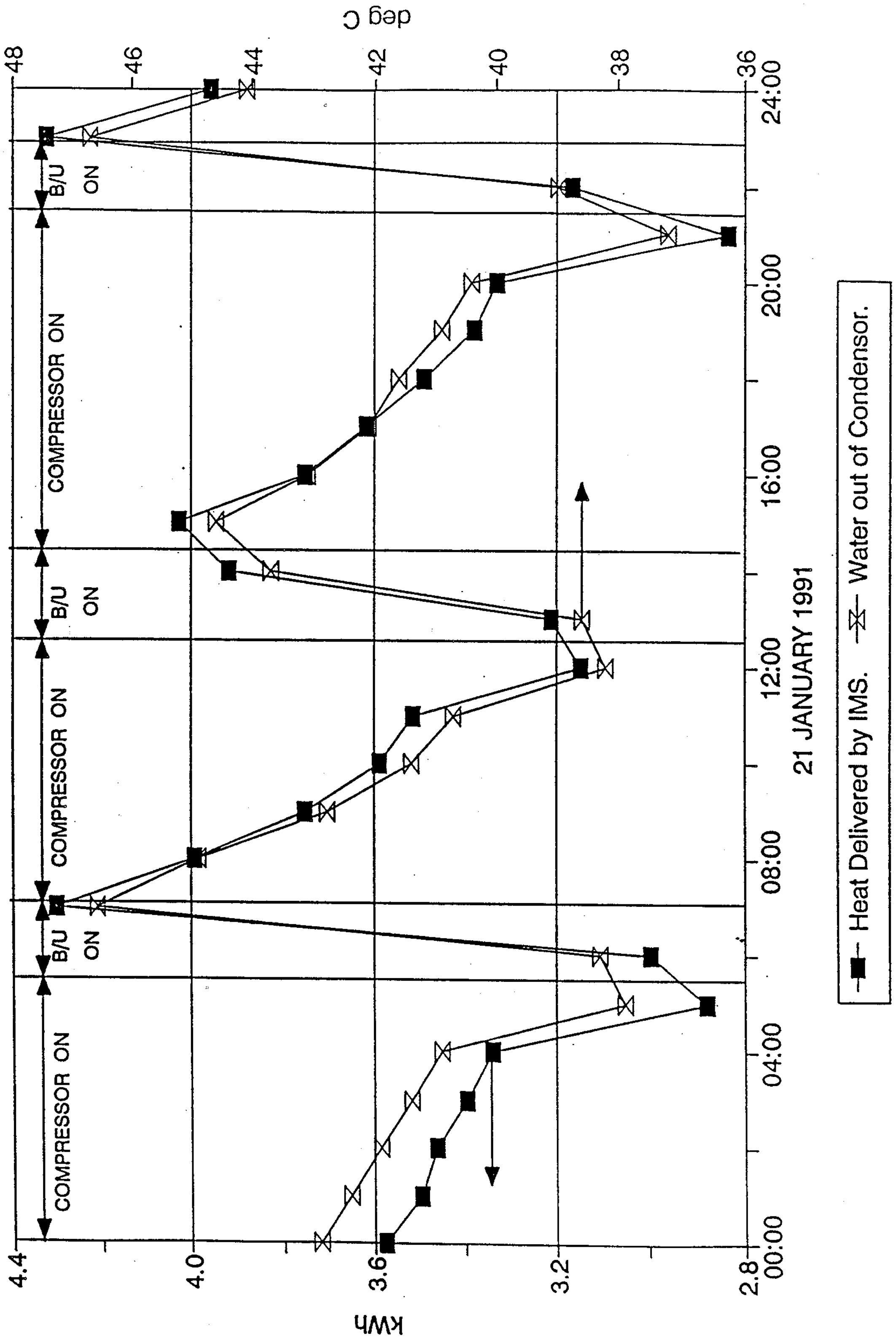
The output from the back-up element and the compressor suggest that the capacity of the heating coil is between 4.4 and 5.5 kW at a coil inlet temperature of 55°C. This capacity is slightly lower than the design value of 6 kW. The low heating-coil capacity was traced in part to low house circulation airflow. The specified flow was 360 L/s at an external pressure of 75 Pa., and the measured flow is about 285 L/s at a measured external pressure of 25 Pa. The low COP values are due to lower than expected heat output and higher than expected pump power.

The exhaust-air heat-recovery coil appears to be working very well. At an air flow of 75 L/s, the system had a heat recovery 1.7 kW for the month of January. The coil sensible heat effectiveness was 0.74 over this time period where:

$$\epsilon = \frac{T_{air after coil} - T_{coil}}{T_{air before coil} - T_{coil}}$$

The grey-water heat exchanger also appears to be working quite well. Over the 1991/92 heating season, the heat exchanger recovered heat equivalent to 63% of the water heating load. The amount of heat

## *Figure 4.10 Advanced House - IMS Operation*



recovery varies with the temperature of the glycol solution; ranging from over 80% in February to 20% in May and October. The heat exchanger is bypassed in the summer.

### *4.4.3 Cooling Season Performance*

The ability of the IMS to provide cooling is dependent on three components: the cooling coil, the evaporator and the water dump. The cooling capacity of the system will be the lesser of; the heat transferred from the house air to the cooling coil; glycol to the heat pump evaporator, or hot water dumped to drain, allowing the heat pump to operate and maintain the cooling capacity of the heat pump.

Figure 4.11 shows hourly performance values for those hours in August 1991 in which the compressor ran continuously. The evaporator heat removal rate is approximately 4.5 kW, at a cooling COP of 1.7. Cooling COP is defined as heat removed by the evaporator divided by electrical energy required to operate the compressor, pumps and controls.

Performance data from August 29th was examined to assess IMS cooling performance. The high outdoor temperature and solar radiation meant that there was a continual demand on the cooling system. The average indoor temperature was 27°C. The dump control system was able to dump sufficient hot water to maintain a hot water tank at an average of 47°C, below the DHW setpoint. The system dumped over 1,100 litres of water that day. Despite the large water dump and 24 hours of cooling system operation, the compressor operated only 10.1 hours that day. This implies that the evaporator can remove heat at a higher rate than the cooling coil. Over this day the average IMS cooling rate was 1.85 kW at an average ice tank temperature of 8.7°C.

## *4.5 Appliances*

The energy consumptions of four appliances were monitored independently: refrigerator, washer/dryer, dishwasher and stove. The energy consumption of the microwave oven and small appliances was included in the general electricity use of the house (see next section).

***Figure 4.11 IMS Steady State Performance***

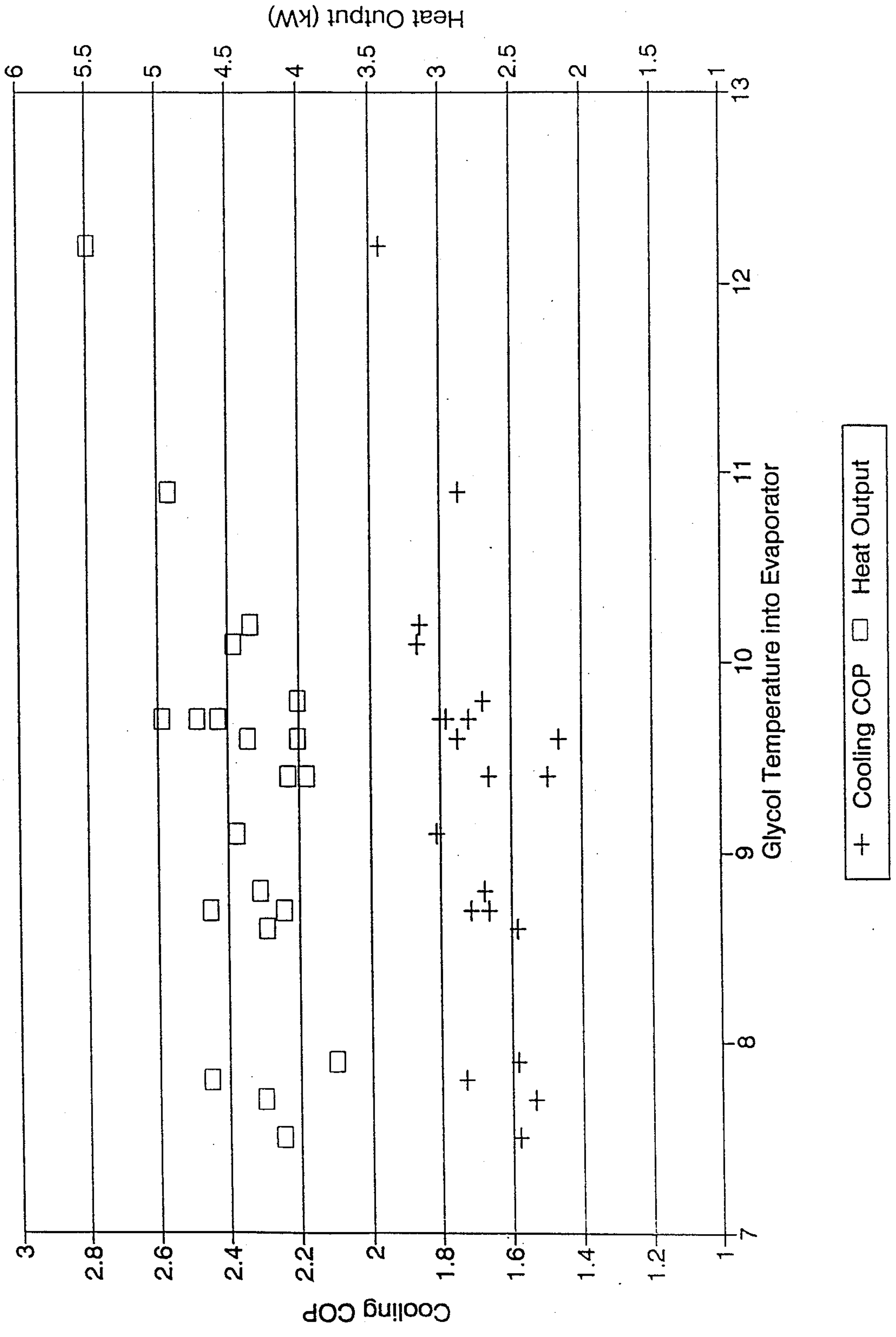


Figure 4.12 shows the monthly energy use of the four main appliances when the house was occupied. (Energy use during the demonstration mode is not relevant because the appliances were rarely used.) The appliance load averages 125 kWh per month (or 1502 kWh/year). This figure is for the electricity used by the appliance only and does not include energy required to supply hot water to the appliances.

Table 4.8 compares the monitored energy use to the energy ratings for the appliances. Standard appliance energy ratings include the energy required to heat water, whereas the monitored values do not include water heating requirements. To enable a comparison of monitored values and appliance ratings, a modified energy rating excluding water heating energy was estimated. These estimates were based on the distribution of energy found in typical appliances.

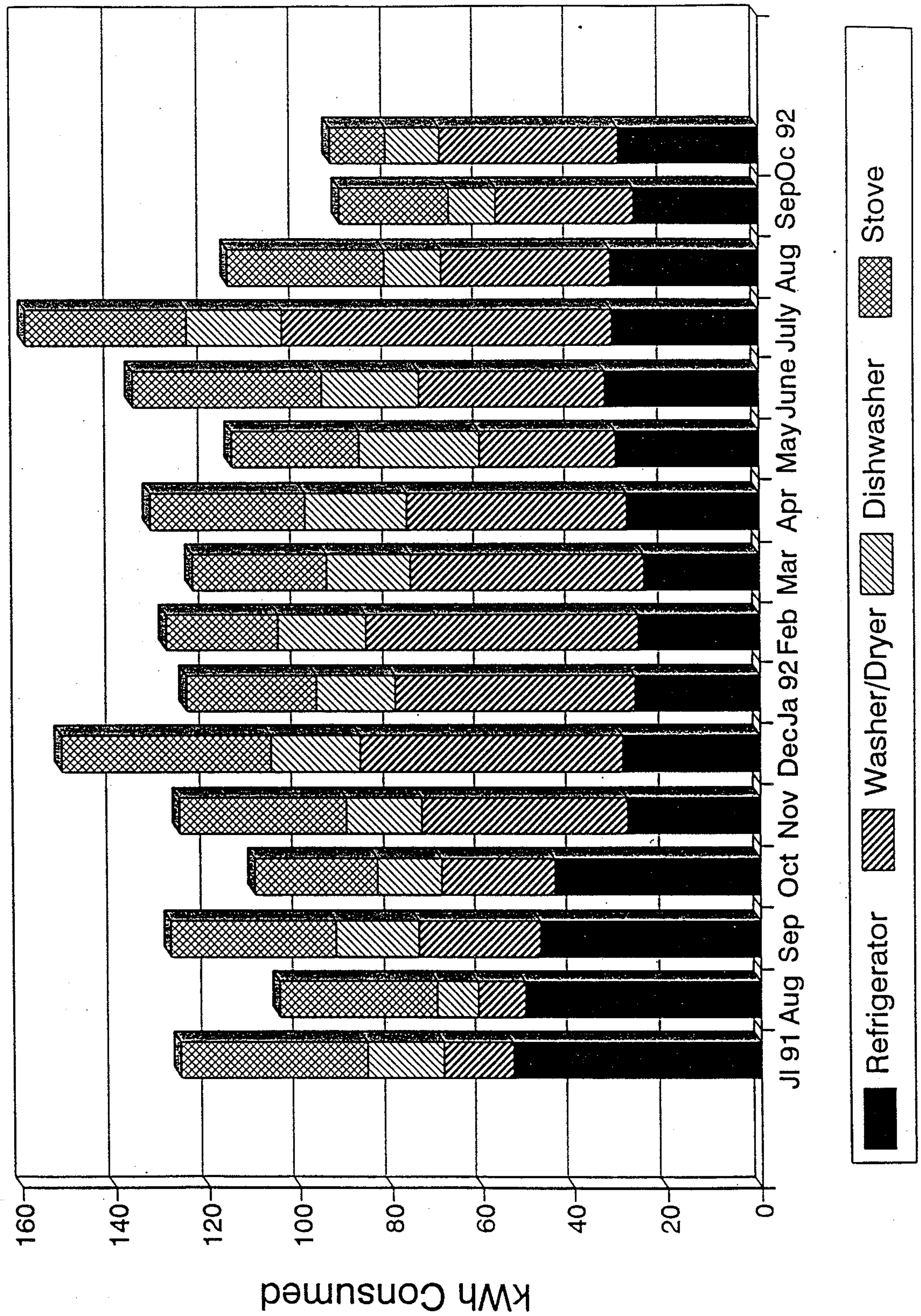
In general, there is fairly good agreement between the adjusted energy ratings (1608 kWh) and monitored energy use (1502 kWh). It should be noted, however, that appliance energy use is highly dependent on its usage. The Table 4.8 comparison is not a measure of whether the appliance meets its rating, but is, rather an indication of whether the energy rating testing procedure has relevance to this and similar households. The biggest discrepancies are with the washer/dryer combination and the refrigerator. The reasons for these discrepancies are discussed in the following paragraphs.

## *Table 4.8 Appliance Energy Use*

| Appliance | Annual Energy Rating Including Hot Water (kWh) | Adjusted Annual Energy Rating[1] (kWh) | Monitored Energy Use[1] (kWh) |
|---|---|---|---|
| Refrigerator | 240 | 240 | 385 |
| Washer/Dryer | 1320 | 762 | 512 |
| Dishwasher | 672 | 258 | 217 |
| Stove | 348 | 348 | 388 |
| Total | 2580 | 1608 | 1502 |

[1] - excludes energy required to supply hot water

## Figure 4.12 Appliance Energy Use



The SunFrost refrigerator is rated as the most energy-efficient commercially-available unit in North America. The refrigerator is rated at 20 kWh/month (or 240 kWh/year) by the manufacturer. The refrigerator was operated over the entire monitoring period, although in the demonstration phase there was very little food loading.

The average energy use of the refrigerator over the 9-month period demonstration period (June 1990 through February 1991) was 26 kWh/month. For the first three months of operation (June, July, and August 1990), the refrigerator consumed an average of 33 kWh/month. During this period ice formed in the refrigerator and manual defrosting was required. Based on these results, the manufacturer suggested the controls required adjusting to optimize operation. After the controls were adjusted in accordance with the manufacturers specifications, September 1990 energy consumption dropped to 26 kWh.

A problem with the refrigerator door developed. The door would not latch closed. October 1990 consumption rose to 45 kWh. After the door catch was repaired the consumption dropped to 24 kWh for November. Energy consumption in December, January and February all averaged 13 kWh/month. The reason for this low consumption level is not known. Part of the explanation could be that the kitchen temperatures were lower than during the summer months. Low air temperature reduces the heat gain through the cabinet and improves the efficiency of the refrigeration cycle.

For the occupied period (July, 1991 to October 1992), the refrigerator used 32 kWh per month. The higher energy use than in the demonstration mode is probably due to food loading and possibly increased door openings. The energy use in the first four occupied months was almost 50 kWh per month. This high value was due to warm kitchen temperatures and cold refrigerator temperature setting. The refrigerator temperature setting was adjusted and energy use averaged 29 kWh for the remainder of the monitoring period, still higher than the energy rating.

The washer/dryer energy use varies significantly from month to month. The low energy use for the summer of 1991 is because the dryer was not connected. Had the dryer been operational, the monitored value would have been 562 kWh; closer to the adjusted energy rating. The homeowner indicated that clothes were often air dried in the sunspace or outdoors on a clothes line.

## *4.6 Other Electrical Systems*

The final category for electricity consumption is lighting and loads connected to wall receptacles (e.g., monitoring computers, lights, a fax machine, television and small appliances).

The energy consumption of the monitoring system should not be included in the assessment of the house performance because it is included for information purposes and not as a system required for building operation. The monitoring system was located in the basement where it had the least direct impact on the heating and cooling loads experienced by the IMS. The monitoring system consumed an average of 70 kWh per month.

Excluding the monitoring system energy consumption, lighting and receptacle energy use was 3340 kWh annually (or 278 kWh/month) significantly above the annual design value of 2434 kWh. Receptacle loads used more than twice the energy of the major appliances in the house (not including any hot water requirements).

The design target for the combined appliance and receptacle energy use was 4042 kWh per year or half that of a typical house. The monitored annual energy use was 4842 kWh; 20% above the target.

## *4.7 Whole House Analysis*

Whole house energy consumption was examined for two periods of operation. The energy consumption of the house for the demonstration period (July 1990 to February 1991), is presented in Figure 4.13. The line shows the predicted values for the same water load and internal gains (but with TMY weather data). In general, there is good agreement with the monthly trends in predicted and monitored values. The monitored energy consumption, however, is 28% higher than predicted.

## Figure 4.13 Monitored Energy Consumption

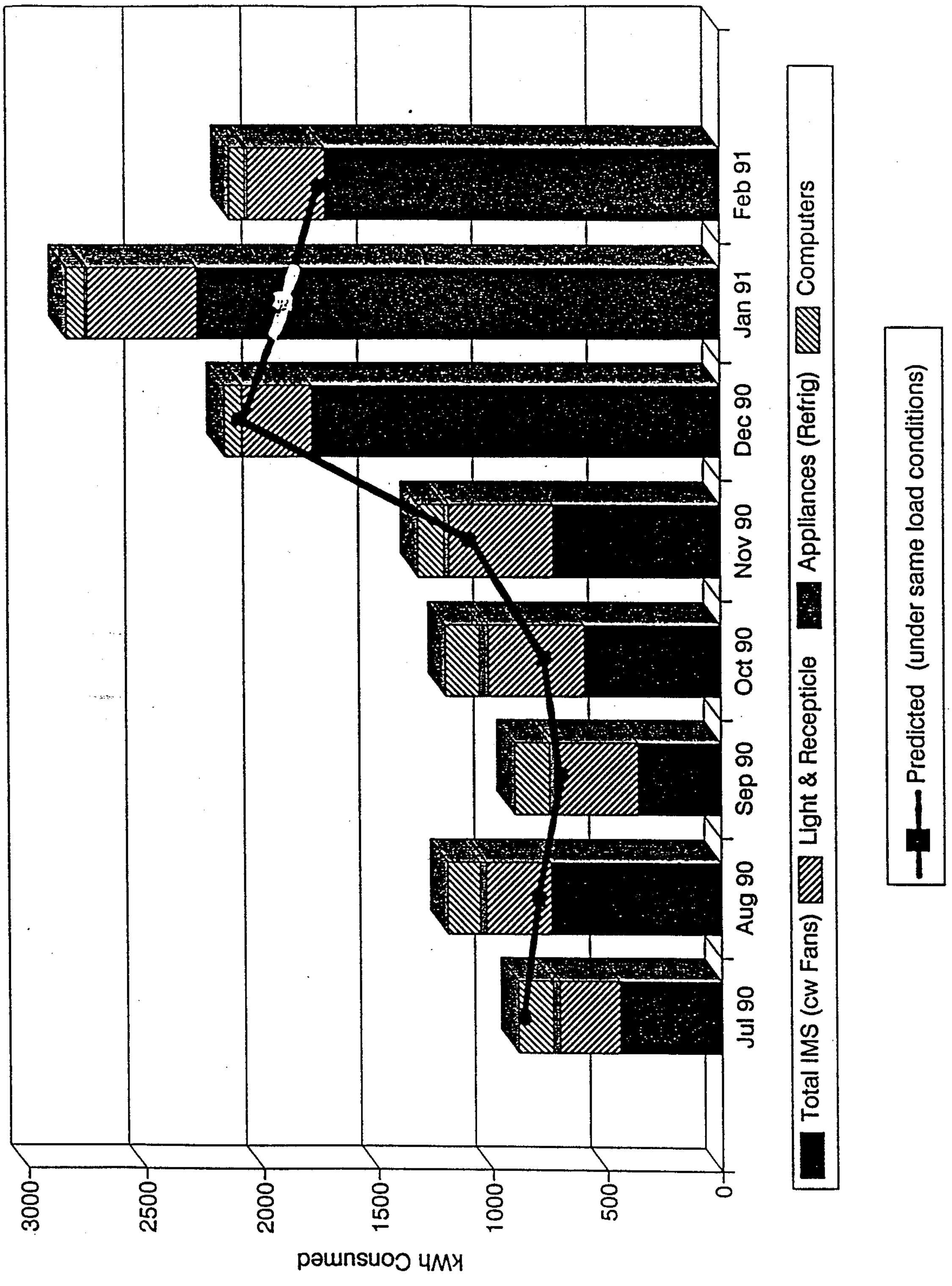


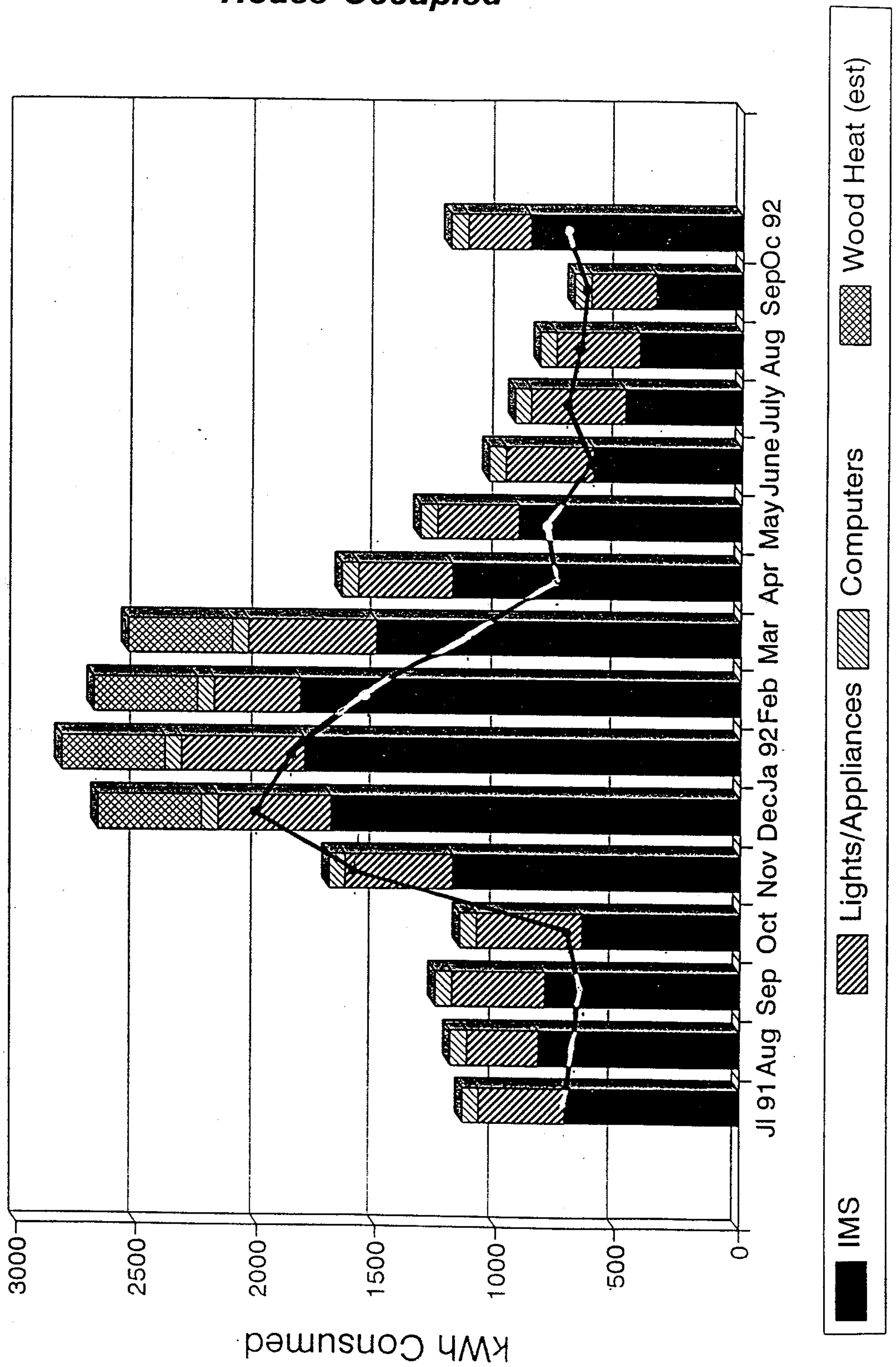
Figure 4.14 shows the house energy use for the occupied period (July 1991 to October 1992). The line in Figure 4.14 shows the predicted performance as described in Section 2.1. Again there the monitored energy use has the same trend as the predicted energy use, but is much higher. The monitored energy use includes an estimate of the useful heating supplied by the wood fireplace. According to the homeowner, approximately two face cords of wood were burned over the 1991/92 winter. The fireplace was assumed to have a heat conversion efficiency of 75% (as quoted by the fireplace manufacturer).

Monitored annual energy use (including the contribution from wood heat) is 19834 kWh; almost 60% higher than the predicted value. Figure 4.15 shows a comparison of the predicted and monitored energy usages on a component basis. The major difference is with the compressor and pump energy; the monitored value for this component is more than twice the predicted value. Energy required for back-up heating (including wood), fans and combined receptacle/appliance loads are reasonably close to predictions. Nevertheless, even this higher than expected energy use is half the value of the average R2000 home [Martin, 1989].

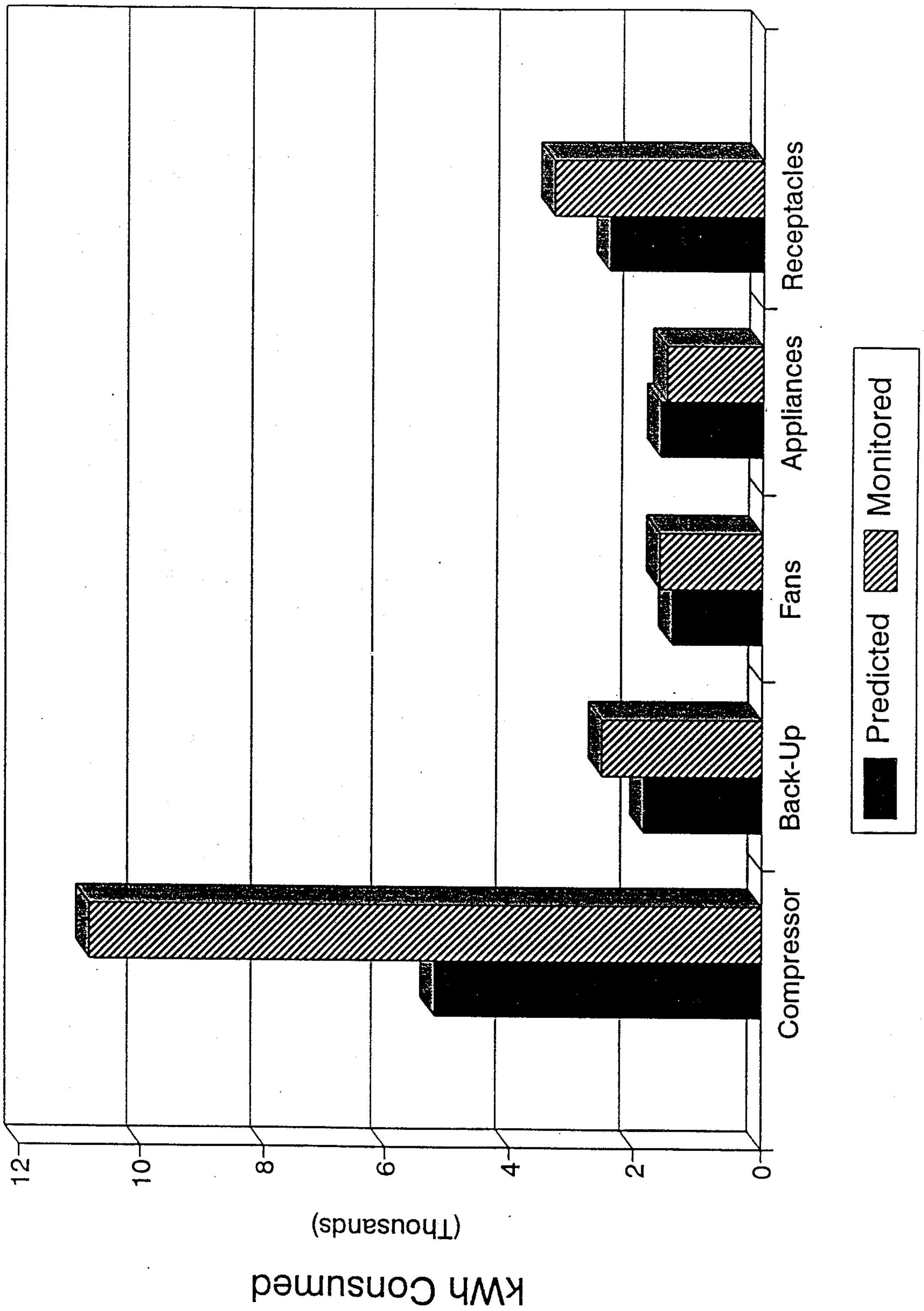
There appears to be five factors that contributed to the discrepancy between predicted and monitored energy use. These factors caused larger than expected space heating loads and lower than expected IMS performance. These factors are discussed in the following paragraphs.

Two factors contributed to the space heating load being 35% higher than was predicted: high ventilation air heating load and high building air temperature. First, the high ventilation heating load was caused by higher than design exhaust air flow rate (see Section 4.1) and problems with the operation of the sunspace preheat. Blower-door tests on the sunspace showed that there is considerable air leakage around the six sets of single-glazed double French doors connecting the sunspace to the house. The net effect is that only 45 % of the air being pulled into the sunspace is from the outside (the remainder is air leaking from the house into the sunspace). Measurements showed that the air flow in the sunspace preheat air duct to the IMS is only half the design value. The

Figure 4.14 House Total Energy Use - House Occupied



## Figure 4.15 Comparison of Predicted and Monitored Energy Use



net result is that only 15 L/s of outdoor air is being preheated by the sunspace, the remaining 53 L/s of supply air comes from infiltration through the building shell.

The second factor was high building temperatures. According to the monitoring system, the average air temperature in the above-grade portions of the house was 23°C. The original energy predictions assumed that the house would be maintained at 21°C.

The three remaining factors relate to the IMS and result in lower than expected Seasonal Performance Factor over the heating season. The SPF was expected to be 2.0 but the monitored value was 1.54. The low SPF is a result of higher than expected pump energy and lower than expected heat output and compressor COP. As discussed in Section 4.4.2, the average IMS heating output is below the design value. The low heating output resulted in either extra back-up element or fireplace use.

The pumps, fans, and controls in the IMS consume an average of 428 Watts continuously. Over the year, this represents an energy use of 3750 kWh, or 30 % of the total house energy budget. Parasitic energy consumption is usually 5% to 10% of total energy consumption in a standard house; however, total energy consumption at the Advanced House is much lower then a standard house, and parasitic consumption comparable. The combined effect is to make parasitic energy consumption a very significant portion of the whole house load.

Finally, The heat pump steady-state COP varied from 1.7 to 2.1. Even excluding pump energy, the COP is 1.9 to 2.3, significantly below the expected value of 2.5 to 3.0.

The peak electrical demand during the occupied was 8.7 kW in January, 1992. This value is below the 10 kW peak which would have activated load-shedding.

# 5.0 CONCLUSIONS

The Advanced House was designed to use 12500 kWh per year, approximately 30% the energy consumption of a similar house built to the insulation standards of the 1985 Ontario Building Code and using conventional electric mechanical systems.

Tests of the building shell show that the building heat loss coefficient and airtightness are close to design targets. Some decrease in building airtightness over time was noted. Formaldehyde and radon concentrations are well within accepted guidelines.

Hot water use for the three-person family averaged 164 litres per day at 45°C. The water-conserving appliances are credited with reducing the water heating requirement to only 60% of the typical residential load. An average of 260 litres per day was used for normal cold water demands; in addition 140 cubic metres of water was dumped during the cooling season to maintain IMS cooling capacity.

Monthly lighting and receptacle loads averaged 400 kWh, of this 125 kWh per month were used by the major appliances. Fan energy use averaged 134 kWh per month, close to the design value.

Monitored energy consumption was 28% higher than computer-predicted values during the demonstration period and 60% higher than predicted when the house was occupied. The annual energy use during the occupied period was 19834 kWh or 49 kWh per square metre of heated floor area.

The higher-than-expected energy use is attributed to five factors. First, high exhaust air flow rates and higher-than-expected air leakage from the house to the sunspace (thereby reducing the effectiveness of the sunspace preheating) resulted in high ventilation air heating load. Second, the average indoor air temperature over the heating season was 23°C, above the 21°C setting assumed at the design phase.

The three remaining factors relate to the IMS. The Seasonal Performance Factor (SPF) over the heating season averaged 1.54 (or as high as 1.74 including monitoring uncertainties), lower than the predicted value of 2.0. The average heat output from the IMS ranged from 4 to 5.5 kW, less than the 6 kW expected. The lower output meant that the heating system had to use more back-up energy than predicted. The high parasitic energy required for fans, pumps and controls contributed to the reduced SPF. The pumps, fans and controls consumed 400 to 500 Watts continuously. Over the year, this represents an energy use of 3750 kWh or 30% of the total house energy consumption.

The peak electrical demand was 8.7 kW, below the 10 kW required to activate the load-shedding.

In summary, monitoring of the Advanced House has shown that extremely energy-efficient buildings are achievable. A wide range of commercially available energy-saving products were successfully used to reduce energy consumption in all systems in the house. Although there were a few minor problems with the prototype Integrated Mechanical System, this technology has the potential to offer large energy savings.

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# APPENDIX A:

# MONITORING SYSTEM

| Function | Abbrev. | Type | Location |
|---|---|---|---|
| Air Flow | | | |
| (1) exhaust air | FlExhA | Anem. | exhaust duct from IMS |
| (2) space heat | FlSpHt | Anem. | return duct into IMS |
| (3) fresh air | FlFrsh | Anem. | sunspace duct |
| Air Temperatures | | | |
| (4) dining room | Tdin | Tcpl | dining room |
| (5) master bedroom | Tbed | Tcpl | master bedroom |
| (6) basement | Tbase | Tcpl | below Kitchen |
| (7) kitchen | Tkitch | Tcpl | kitchen |
| (8) ambient | Tamb | Tcpl | garage eaves |
| (9) sunspace | Tsun | Tcpl | N. wall - lower level |
| (10) ex. into IMS | TexhIn | RTD | IMS exhaust duct |
| (11) ex. out of IMS | TexhOu | RTD | IMS exhaust duct |
| (12) return Air | Tretrn | RTD | IMS return duct |
| (13) supply Air | Tsuply | RTD | IMS supply duct |
| (14) sunspace (top) | TsunDc | RTD | sunspace duct at grill |
| (15) fresh air to IMS | TfrsIm | Tcpl | exit from slab |
| Wall Temperatures | | | |
| (16) sunspace wall | TsunWs | Tcpl | north sunspace wall |
| (17) wall midpoint | TsunWm | Tcpl | north wall midpoint |
| (18) house wall | TsunWh | Tcpl | north wall |
| Liquid Temperatures | | | |
| (19) mains water | TmainW | Tcpl | IMS DHW tank inlet |
| (20) DHW | T_DHW | Tcpl | IMS DHW tank outlet |
| (21) brine from IMS | TbrIMS | Tcpl | IMS brine outlet |
| (22) brine from grey water | TbrGrW | Tcpl | brine grey water out |

| | | | |
|---|---|---|---|
| (23) brine from coils | TbrCol | Tcpl | brine coil outlets |
| (24) brine to evaporator | TbrEvI | Tcpl | brine into evaporator |
| (25) brine from evaporator | TbrEvO | Tcpl | brine out of evaporator |
| (26) ice tank | Tice | Tcpl | middle of ice tank |
| (27) into condenser | TconIn | Tcpl | water into condenser |
| (28) out of Condenser | TconOu | Tcpl | water out of condenser |
| (29) return from heater coil | TcolOu | Tcpl | outlet of heat coil |
| Relative Humidity Readings | | | |
| (30) living room | RHliv | RH | living room |
| (31) master bedroom | RHbed | RH | master bedroom |
| (32) sunspace | RHsun | RH | sunspace |
| (33) basement | RHbase | RH | basement |
| (34) exhaust from IMS* | TwExht | RH | IMS exhaust duct |
| (35) supply air* | TwSupl | RH | IMS supply duct |
| (36) ambient | RHamb | RH | |
| * these were changed to humidity readings from wet bulb temperatures in December 1990 | | | |
| Electrical Consumption | | | |
| (37) total house | Ehouse | kWh | near main panel |
| (38) total IMS | EIMS | kWh | near IMS |
| (39) IMS compressor | EIMScp | kWh | near IMS |
| (40) DHW backup element | EDHWbk | kWh | near IMS |
| (41) supply fan | EsupFn | kWh | near IMS |
| (42) exhaust fan | EexhFn | kWh | near IMS |
| (43) microwave | Eoven | coil | near panel |
| (44) washer | Ewash | kWh | near panel |
| (45) dryer | Edry | coil | near panel |
| (46) dishwasher | Edish | kWh | near panel |
| (47) refrigerator | Efridg | kWh | near panel |
| (48) stove | Ecookt | coil | near panel |
| (49) counter 1 | Ecntr1 | coil | near panel |
| (50) counter 2 | Ecntr2 | coil | near panel |

| | | | |
|---|---|---|---|
| (51) lights 1 | Elite1 | coil | near panel |
| (52) lights 2 | Elite2 | coil | near panel |
| (53) computers | Ecompt | kWh | near IMS |
| (54) voltage | Volts | | near panel |
| Liquid Flow | | | |
| (55) DHW | DHW | pulse | IMS DHW inlet |
| (56) IMS brine return | FbrRtn | pulse | brine into tank |
| (57) brine from grey water | FbrGry | pulse | brine grey water out |
| (58) IMS water loop | FimsWt | pulse | water to condenser |
| (59) cold water | Fwater | pulse | mains inlet |
| (60) dump | Fdump | pulse | dump line |
| Solar Energy | | | |
| (61) horizontal solar | SolarH | pyran. | sunspace roof |
| (62) south vertical | SolarV | pyran. | sunspace wall |
| Status Switch | | | |
| (63) IMS cooling | IMScol | - | IMS controls |
| (64) IMS grey water | IMSgry | - | IMS controls |
| (65) IMS space/DHW | IMSspc | - | IMS controls |
| (66) compressor on | CmpOn | - | IMS controls |

# APPENDIX B:

# IEA TASK XIII

# ACTIVITIES

In 1989, The International Energy Agency (IEA) Solar Heating and Cooling Programme established a task (Task XIII) to study advanced low-energy homes. Fourteen countries, including Canada, are participating in that task. Each country was to design, build, monitor and report on a low-energy residential building. The Brampton Advanced House was chosen as Canada's contribution.

To assist the other IEA countries in comparing the Brampton Advanced House to their house designs, computer simulations were repeated for a variety of climatic regions worldwide. A discussion of the other IEA buildings and their expected performances are included in the attached paper.

Only one minor change was made to the Brampton house design for simulations in other climates. For those regions where cooling is not normally used (e.g., northern Europe) the cooling system was removed and hydronic space heating added. Given the low heat loss from the house, 55°C water would be warm enough to meet the heating load. For warm climates (e.g., Trapani, Italy it was necessary to increase the supply air flow to meet the high cooling load).

Table B.1 summarizes the results of the simulations. The results show an interesting trend with respect to the performance of the IMS: energy consumption is at a minimum for locations with approximately 4000 degree-days (20°C Base). In fact, the design of the IMS is probably not appropriate for locations with high cooling or high heating loads. For locations with high cooling and low space heating requirements, the grey-water and exhaust-air heat recovery of the integrated mechanical system is not used. For very cold locations, the integrated mechanical system must use straight electric resistance heating when recovered heat has been depleted. Economics probably favours air-to-air heat exchangers over the coil-and-ice-tank method of heat recovery in cold locations. Nevertheless, the IMS design appears to perform reasonably well for most of northern European, northern U.S.and southern Canadian climates.

## Table B.1 Performance of the Advanced House in Other Regions

| | Degree Days (Base 20°C) | | | | |
|---|---|---|---|---|---|
| Location | Trapani | Denver | Stuttgart | Copenhagen | Helsinki |
| | 1351 | 3953 | 3988 | 4313 | 5744 |
| Load | Energy Consumption (kWh) | | | | |
| Space Heating | 36 | 1319 | 3429 | 4065 | 9229 |
| Water Heating | 1604 | 1564 | 1833 | 1877 | 1895 |
| Lights/App. | 4042 | 4042 | 4042 | 4042 | 4042 |
| Fans | 2453 | 350 | 350 | 350 | 350 |
| Cooling | 2453 | 0 | 0 | 0 | 0 |
| Total | 10588 | 7275 | 9654 | 10334 | 15516 |
| Total (kWh/m$^2$) | 26.0 | 17.8 | 23.7 | 25.3 | 38.0 |

One criticism of the Advanced House is that it is too large to be a practical alternative for European or low and middle-class housing. To address this issue, a number of design changes were made to the model.

The house floor area can be reduced by one-third by eliminating the basement. Although consumer demand in Canada makes basements essentially mandatory, basements are not common in the rest of the world. The interior partitions would have to be redesigned slightly to accommodate a main floor mechanical room and a second floor storage room. Eliminating the basement reduces energy consumption of the Advanced House by only 110 kWh and increases the per unit area consumption to 45.6 kWh/m$^2$.

Appendix C contains floor plans for the house duplexed and the house four-plexed. In the duplex design, there is a main floor apartment and a second floor apartment. They share the basement and the sunspace (a floor would be added to the sunspace to separate the first and second storeys). The floor area of each unit is 204 square metres with the basement, 136 square metres without. The mechanical systems could also be reduced in size without any loss in performance.

In the four-plex design, a mirror image of the building would be built to the east of the floor plans shown. Note that the east wall has been straightened and the south-facing windows lost have been moved to the west half of the house. The energy consumption of each half of the four-plex is reduced because of the smaller exposed wall area. The simulated energy consumption is 11508 kWh or 42.3 kWh/m$^2$ above grade floor area.

Presented at SESCI'92 Conference, Edmonton, Alberta, July 4-8, 1992.

# ENERGY-EFFICIENT BUILDINGS OF IEA TASK XIII

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## ABSTRACT

As a part of the International Energy Agency Task XIII, fourteen countries are designing, building and monitoring the performance of low-energy residential buildings. This paper presents an overview of the designs including some of the more innovative systems. The expected performance of the buildings are compared in terms of heating load, appliance energy use, water heating and total energy. The comparison shows that very low-energy-use buildings can be built regardless of location.

## INTRODUCTION

Task XIII of the International Energy Agency's Solar Heating and Cooling Programme was formed to provide international collaboration on the design of low-energy residential buildings. Each country is expected to design, build, monitor and report on at least one building. The buildings are expected to have extremely low energy use, incorporate innovative energy concepts and be locally applicable. Representatives from 14 countries meet semi-annually to discuss progress on their national project. The Advanced House in Brampton, Ontario is Canada's contribution to the task. The task was started in late 1989 and is scheduled to run until 1994. This paper summarizes the progress of the Task to date and presents some of the more interesting building concepts being investigated.

## PROJECT STATUS

Task XIII is made up of 11 European countries, Japan, U.S. and Canada. Eleven buildings from nine countries are scheduled to be built (see Table 1). The Canadian house has been constructed and is in the monitoring phase. Eight buildings will be constructed in 1992 and another two in 1993. In addition, the United Kingdom will be retrofitting at least three houses at its contribution and two other countries have designs but no construction plans as yet. The building types vary according to the predominant housing type of each country. There will be five single-family, six row houses and two multi-unit buildings.

Table 1: Status of National Projects

| Country | Building Type | Heated Floor Area ($m^2$) | Construction Status |
|---|---|---|---|
| Austria (A) | undecided | - | - |
| Belgium (B) | Row House | - | late 1992 |
| Canada (C) | Single Family | 408 | completed |
| Denmark (DK) | Row House 1 | 105 | late 1992 |
| | Row House 2 | 98 | late 1992 |
| Finland (SF) | Single Family | 166 | - |
| Germany (D) | Row House | 175 | * |
| | Duplex | | * |
| Italy (I) | Multi-unit | - | 1993 |
| Japan (J) | Single Family | 125 | * |
| Netherlands (NL) | Multi-unit | 95 | * |
| Norway (N) | Row House | 142 | * |
| Sweden (S) | Single Family | 114 | - |
| Switzerland (CH) | undecided | - | - |
| United Kingdom (UK) | Housing Retrofit | - | renovation started |
| United States (US) | Single Family | 125 | 1993 |

* under construction

## SUMMARY OF BUILDING DESIGNS

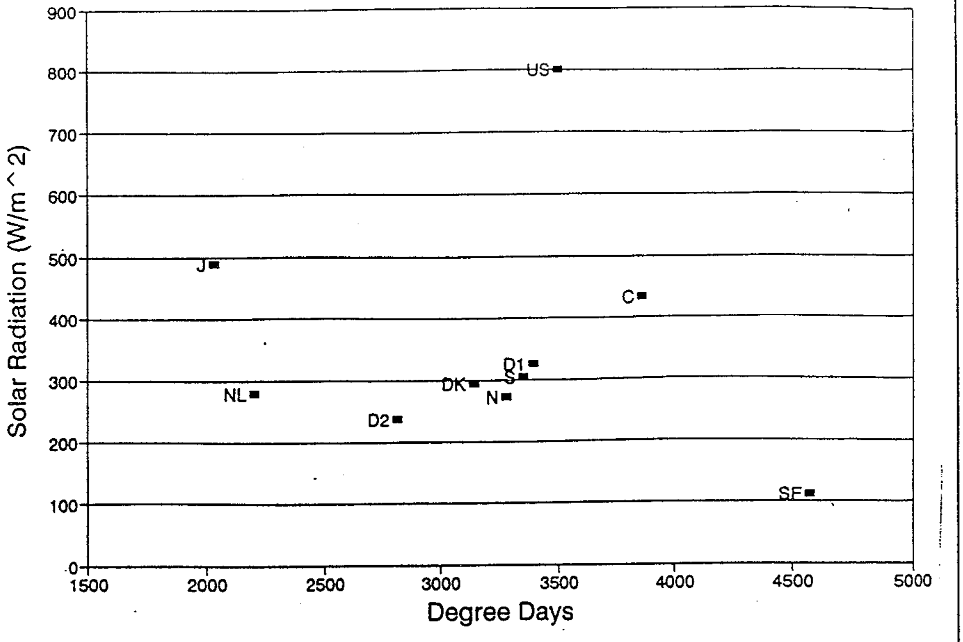


FIG. 1
Comparison of Climates

The various houses will be located in widely differing climates. Figure 1 shows the degree-days (base 20°C) and south-facing vertical solar radiation for the six-month period October through March. (Note: degree-days base 20°C for the six-month winter period is approximately equal to the Canadian degree-day method of base 18°C for the full year.) The climates range from cold and overcast (Finland) to mild (Japan).

Despite the range of climates seen in Figure 1, there are many similarities in the house designs. With the exception of the Canadian house, all the housing units are modest in size with an average total heated floor area of 130 square metres. All buildings, except the Japanese house, are super-insulated (usually using wood-stud wall construction). All have oriented most of the windows to the south and most use high-performance windows (U-value below 1.5 $W/m^2{}^\circ C$). The buildings are of airtight construction and all have a mechanical ventilation system with some sort of heat recovery.

Many of the designs incorporate sunspaces, although through the design process they have been reduced in size and been made more functional. The Canadian and Dutch designs use the sunspace as a preheater for ventilation air. The Norwegian house uses the sunspace as an entrance area and airlock.

The type of space heating systems vary according to the predominant heating source. Finland, Canada, Japan and Norway use electric heat pumps, whereas most of the other European buildings are connected to district heating systems. Norway and Canada use a heat-pump system to supply domestic hot water, whereas all the remaining countries have chosen a solar DHW system.

## INNOVATIVE SYSTEMS

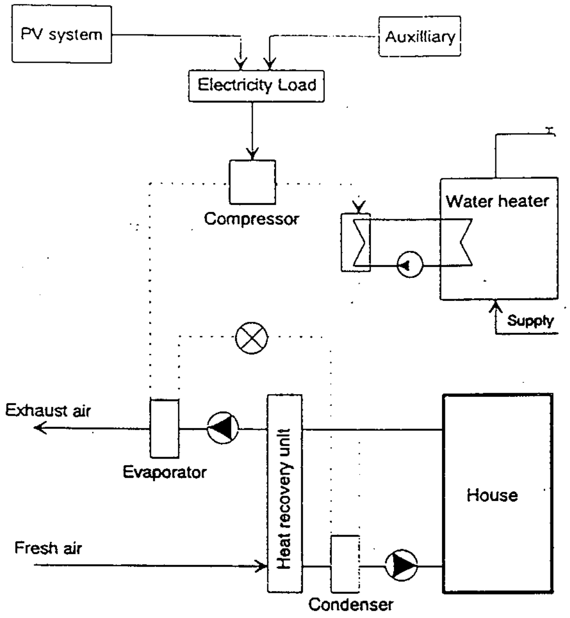
There are a number of innovative systems that are being incorporated into the house designs. The most innovative aspect of the Canadian Advanced House (in Brampton, Ontario) is the integrated mechanical system. This system uses a heat pump to meet the space heating, space cooling, water heating and ventilation requirements of the house. The design and performance of the Advanced House and the integrated mechanical system have been presented at previous conferences and will not be discussed further [White, 1990; Carpenter, 1991].

The Norwegian House will also feature an integrated mechanical system (see Figure 2). The system has a combined air-to-air heat exchanger and heat-pump heat-recovery unit. Heat from the exhaust air is used to heat domestic water and meet space-heating needs. The COP of the system should be fairly high because the evaporator temperature is high and the condenser temperature will be low (especially when space heating). A photovoltaic system is expected to supply almost 2000 kWhr towards the electric load of the house.

The Dutch building uses a sunspace to connect three small apartment blocks. The six-storey high sunspace will be used to preheat ventilation air for the individual suites. A high-efficiency air-to-air heat exchanger will be used to provide supplemental ventilation air heating. The Dutch work has shown that the sunspace preheat virtually eliminates any possibility of frosting in the heat exchanger. The sunspace has a venting system and a shading device to prevent overheating in the summer.

The German team is investigating the use of a water-cooled active-solar shading device to control solar gains in their sunspace. The system resembles a venetian blind with the slats replaced by solar collector fin

FIG. 2 Norwegian House Heating System



tubes. The fin tubes have a selective surface on the one side and are painted white on the other side. At night, the blinds are closed with the selective surface facing out, in effect creating a triple-glazed window with a low-e coating. The window heat loss with the blind in this position was measured to be 1.69 W/m$^2$°C [Schuler, 1992]. During winter days, the blinds can be adjusted to vary the amount of solar radiation entering the sunspace and the amount absorbed by the selective surface. Water is circulated through the tubes in the blinds to supply domestic hot water and cool the blinds.

To prevent summertime overheating the blinds can be switched to have the white side facing out. The white surface reflects most of the solar gain, the water keeps the blinds cool and the inward-facing selective surface reduces radiative heat gain to the room. Tests have shown that this shading system is superior to all other interior shading devices and equal in performance to an exterior venetian blind (but without the problems associated with exterior shuttering systems).

The Swedish design has an innovative approach for using hollow-core floor slabs as a combined heating/ventilation system (see Figure 3). The house is slab-on-grade. Insulation is placed above and below the hollow core floor slab. A thin slab incorporating a low-temperature hydronic floor-heating system is placed on top of the assembly. The hollow cores in the floor slab are ducted so as to serve as a 70% efficient air-to-air heat exchanger and are connected to alternate between carrying outdoor supply air and building exhaust air. A hydronic coil ensures that the entering air temperature is always above -4°C. By adjusting the flow pattern in the floor slab, the homeowner can select the amount of fresh air delivered to each room. There is no need to add additional heat to the supply air because it's temperature never drops below 13°C.

The hydronic system supplies space heating, ventilation air preheating and domestic water preheating. The radiant floor heating system can meet the house heating demand at a water supply temperature of 30°C. The return water flow is split into two parallel circuits for ventilation air and domestic water preheating. The return temperature to the heating system is approximately 10°C. The low return temperature means that back-up heat can be supplied from low-temperature heat sources such as active solar or industrial waste heat. The Swedish team is also investigating whether waste heat from automobiles could be used as the heating source.

## BUILDING ENERGY PERFORMANCE

Energy performance estimates are available for eleven of the house designs. Figure 4 shows the predicted heating load for the eleven buildings normalized to heated floor area. Despite the wide range in climates, house size and building type, the heating loads fall within a relatively narrow band with the average of approximately 20 kWhr/m$^2$. (The low heating load for the Danish houses can be attributed to the high internal heat gains for a small floor area and well-insulated shell.) The lack of climate dependency is due to the natural tendency for increasing insulation levels in colder climates: Finland and Canada have the highest insulation levels and Japan the lowest. The average heating load is a significant reduction from the average values for R2000 energy-efficient housing, which are approximately 46 kWhr/m$^2$ [Martin, 1989].

Figure 5 shows the back-up water heating use and electricity use for appliances, lighting and fans. Given that the average Canadian home uses approximately 5000 kWhr for water heating and 8000 kWhr for electrical loads, the IEA houses offer quite a dramatic reduction. The savings in water heating energy use is due in most part to the use of solar water heating systems. Also, Europeans tend to use slightly less hot water than Canadians, although the Japanese use almost twice as much.

Two main factors affect the range of electricity use for appliances and fans: lifestyle and method of heat delivery. Europeans favour hydronic heating systems, whereas in Canada forced-air heating is the system of choice. A water-circulating pump will draw only 100 Watts, whereas a furnace fan will draw over 500 Watts. As the building shell is made more efficient, heating/ventilating parasitic energy use becomes a larger percentage of the total house energy bill. For example, in the Canadian house, parasitic energy use for pumps and fans accounts for 25% of the energy use [Enermodal, 1992]. In terms of lifestyle, Europeans tend to use smaller appliances and use more fluorescent lighting.

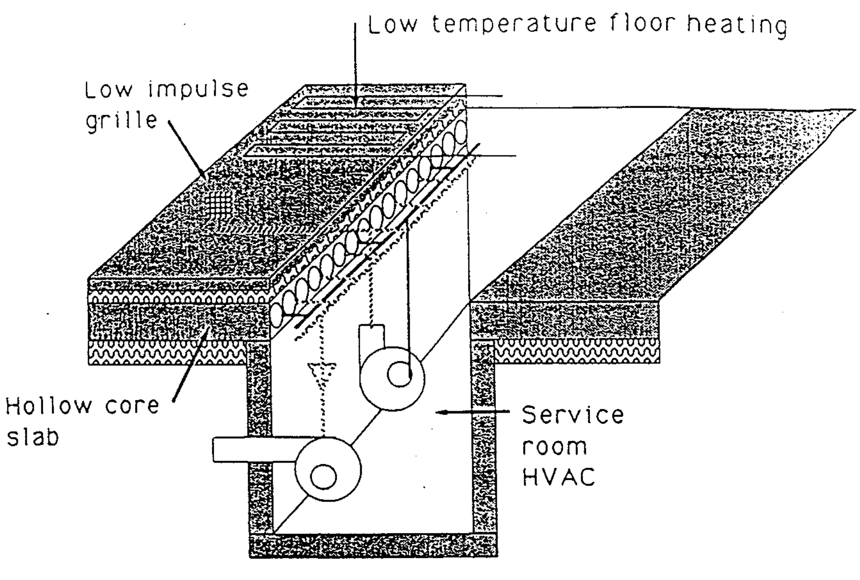
Figure 6 presents the predicted total house energy use for the eleven buildings. Interestingly, the energy consumption of seven of the eleven buildings fall within the narrow band of 30 to 36 kWhr/m$^2$. The German Ultra-Haus is predicted to use only 15 kWhr/m$^2$ because it will use an active solar heating system with seasonal storage to supply all the space and water heating load. The high energy use of the Japanese house is due to the high water-heating load and relatively high appliance energy use.

At 39 kWhr/m$^2$, the average total energy use of the IEA buildings is only one-third that of a typical R2000 house at 106 kWhr/m$^2$ [Martin, 1989]. The average energy use of the 12 houses being constructed as part of Energy, Mines and Resources Canada Advanced Houses Program is only slightly higher at 49 kWhr/m$^2$ [Dumont, 1992].

## CONCLUSIONS

Over the next few years, thirteen very-low-energy houses will be constructed as a part of the International Energy Agency's Task XIII. The average total energy use for the buildings is predicted to be 39 kWhr/m$^2$. This represents a two-thirds reduction in the energy use of a typical R2000 home. Monitoring will determine if these targets can be met.

FIG. 3a Swedish Floor Slab Heating System



Energy use is not climate-dependent. Designers tend to adjust insulation levels according to the climatic location of the house. In very-low-energy houses, parasitic energy (for pumps and fans) can be a major portion of the total energy use.

FIG. 3b Swedish Floor Slab Heating System

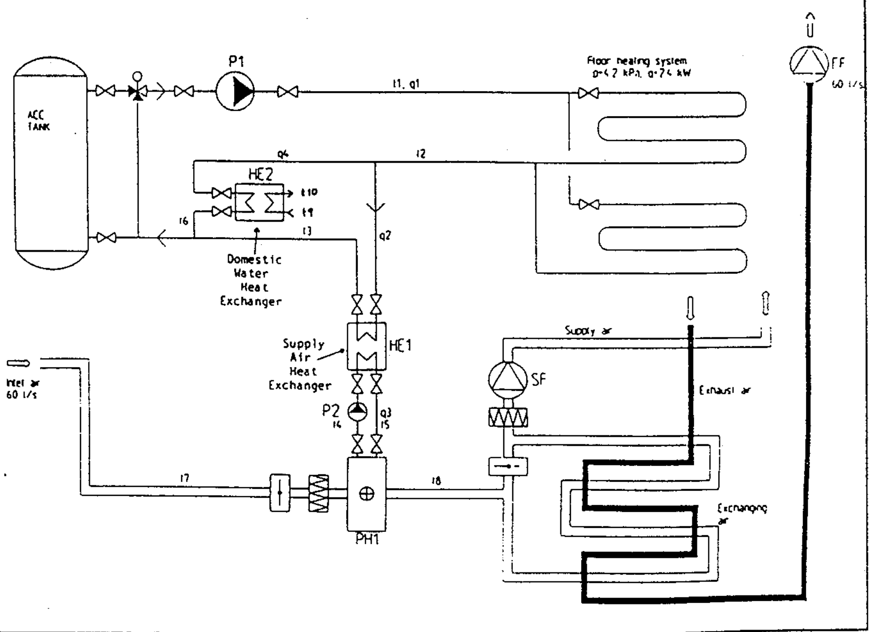


FIG. 4
Heating Load for IEA Task XIII Buildings

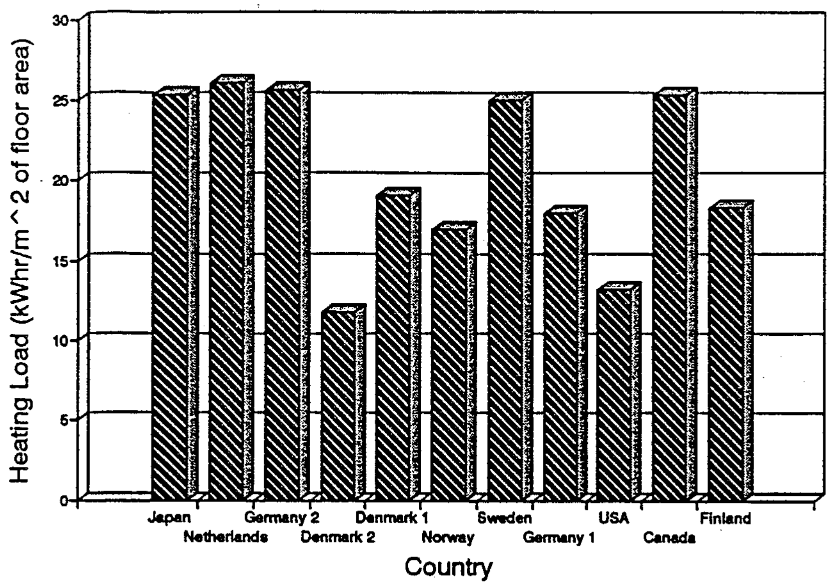
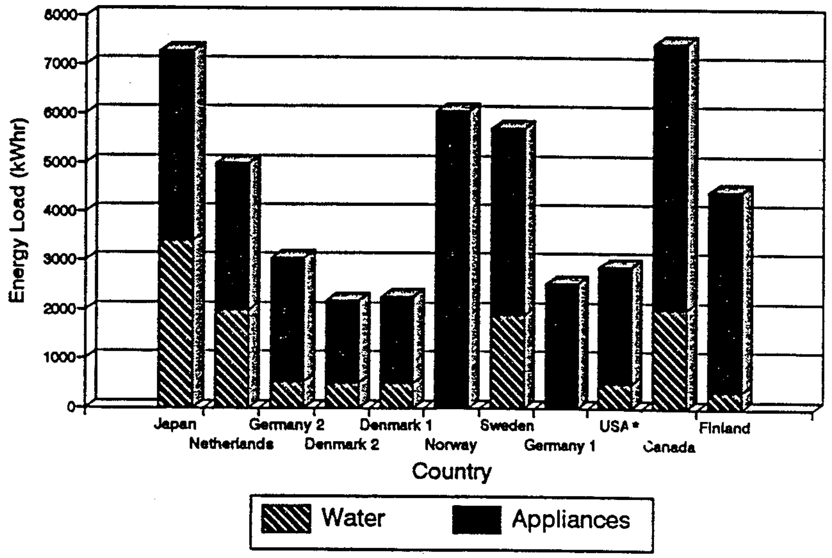


FIG. 5
Energy Load for IEA Task XIII Buildings



* Estimated Water Use

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## ACKNOWLEDGEMENTS

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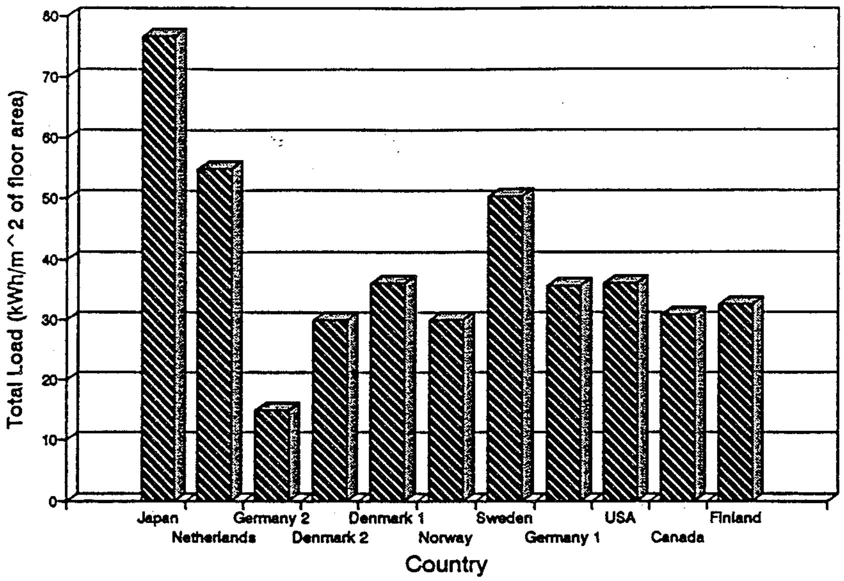
FIG. 6
Total Energy use for IEA Task XIII Buildings



# APPENDIX C:

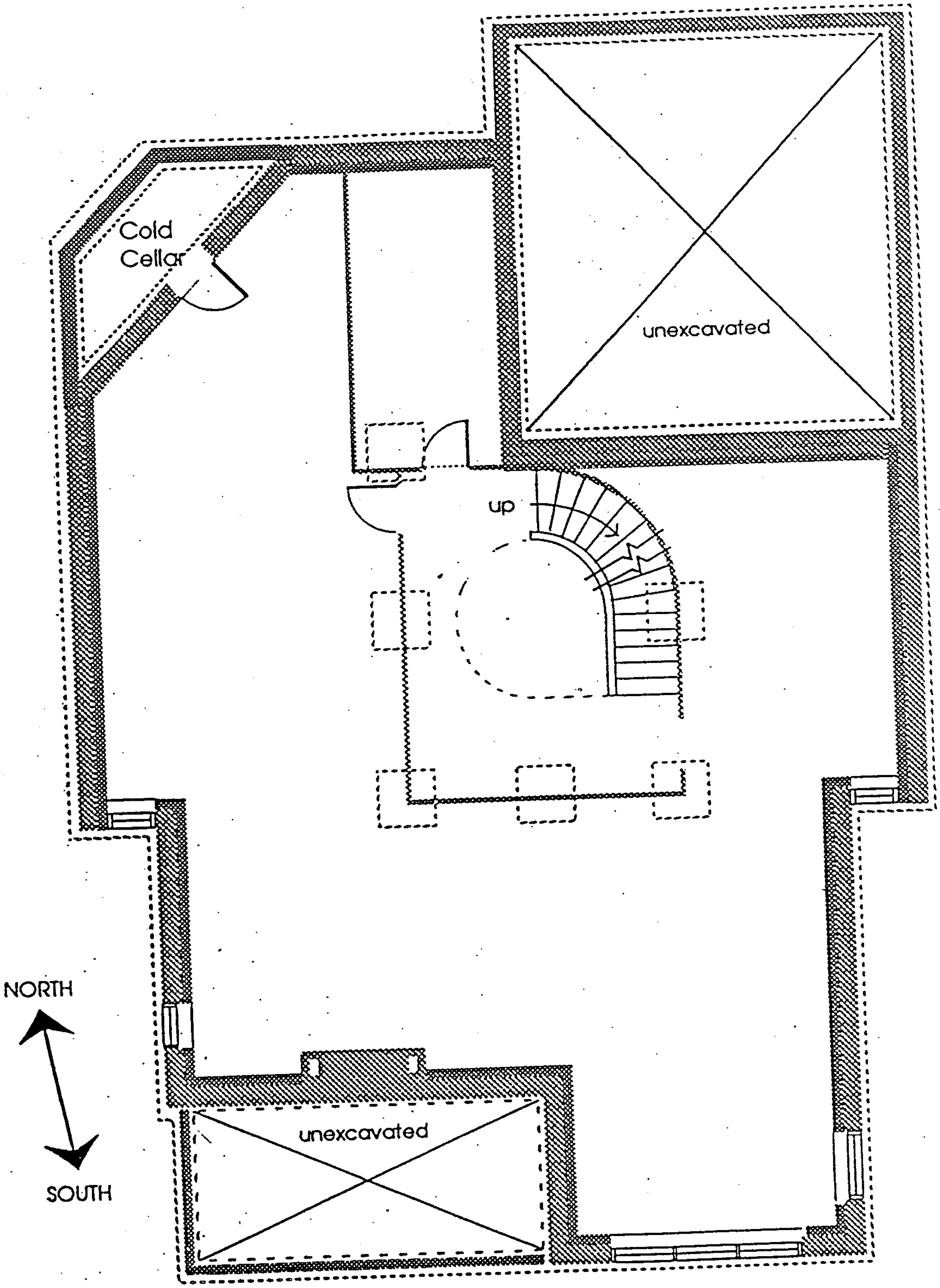
# FLOOR PLANS

Scale: 1:100

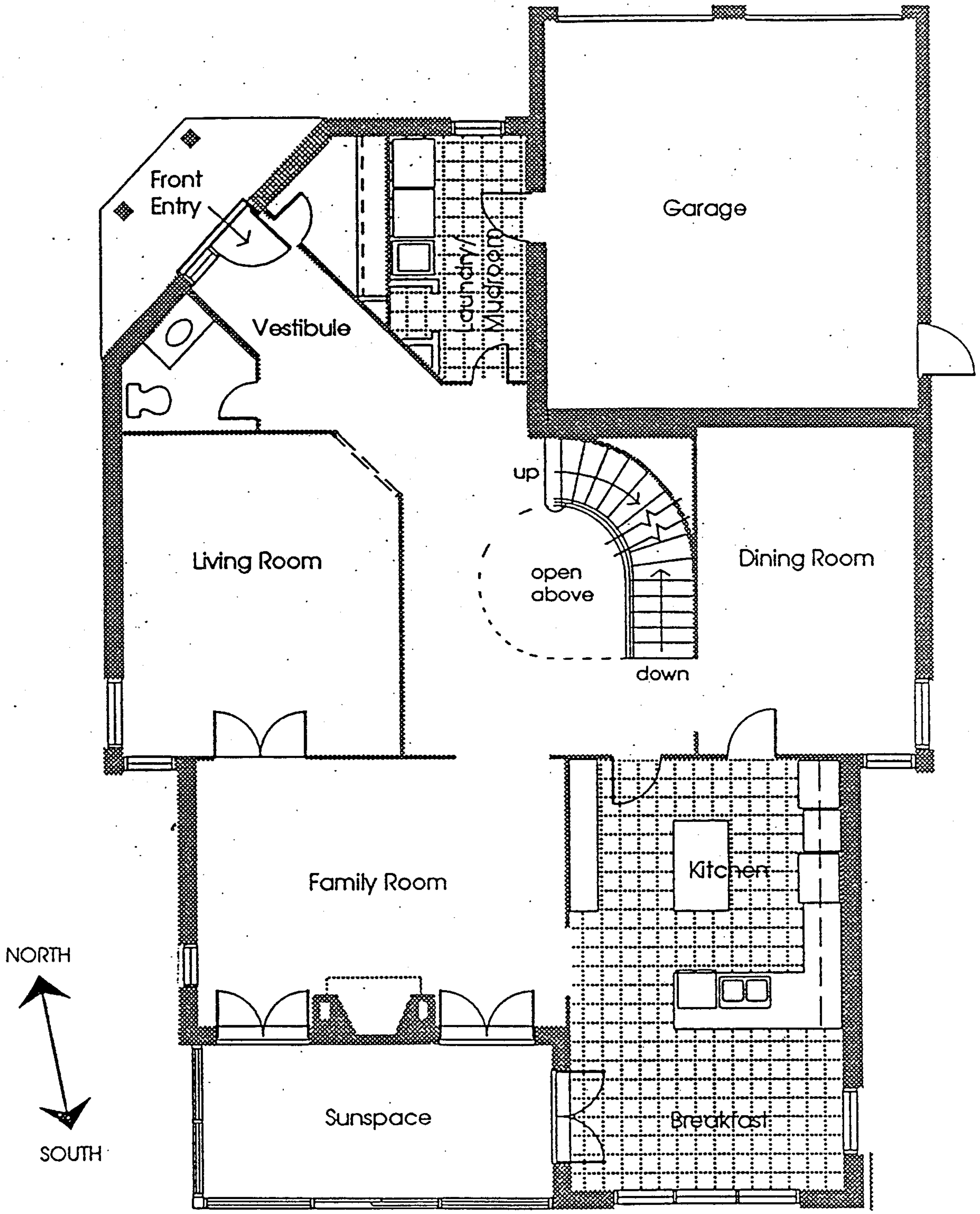
- A1 Advanced House Floor Plans
- A4 Duplex Advanced House Floor Plans
- A7 Fourplex Advanced House Floor Plans (West Units Only)

# BASEMENT FLOOR PLAN

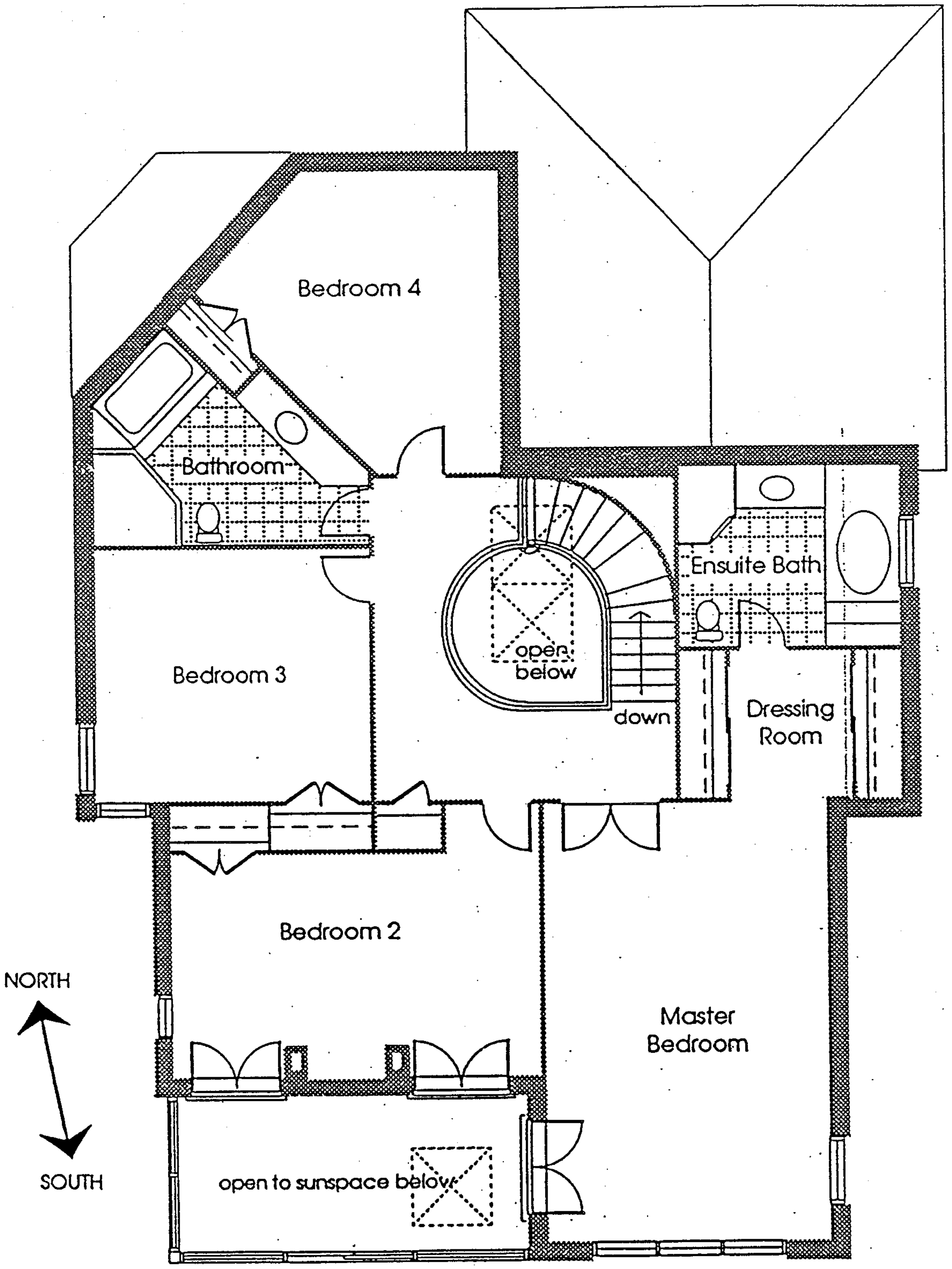
A1

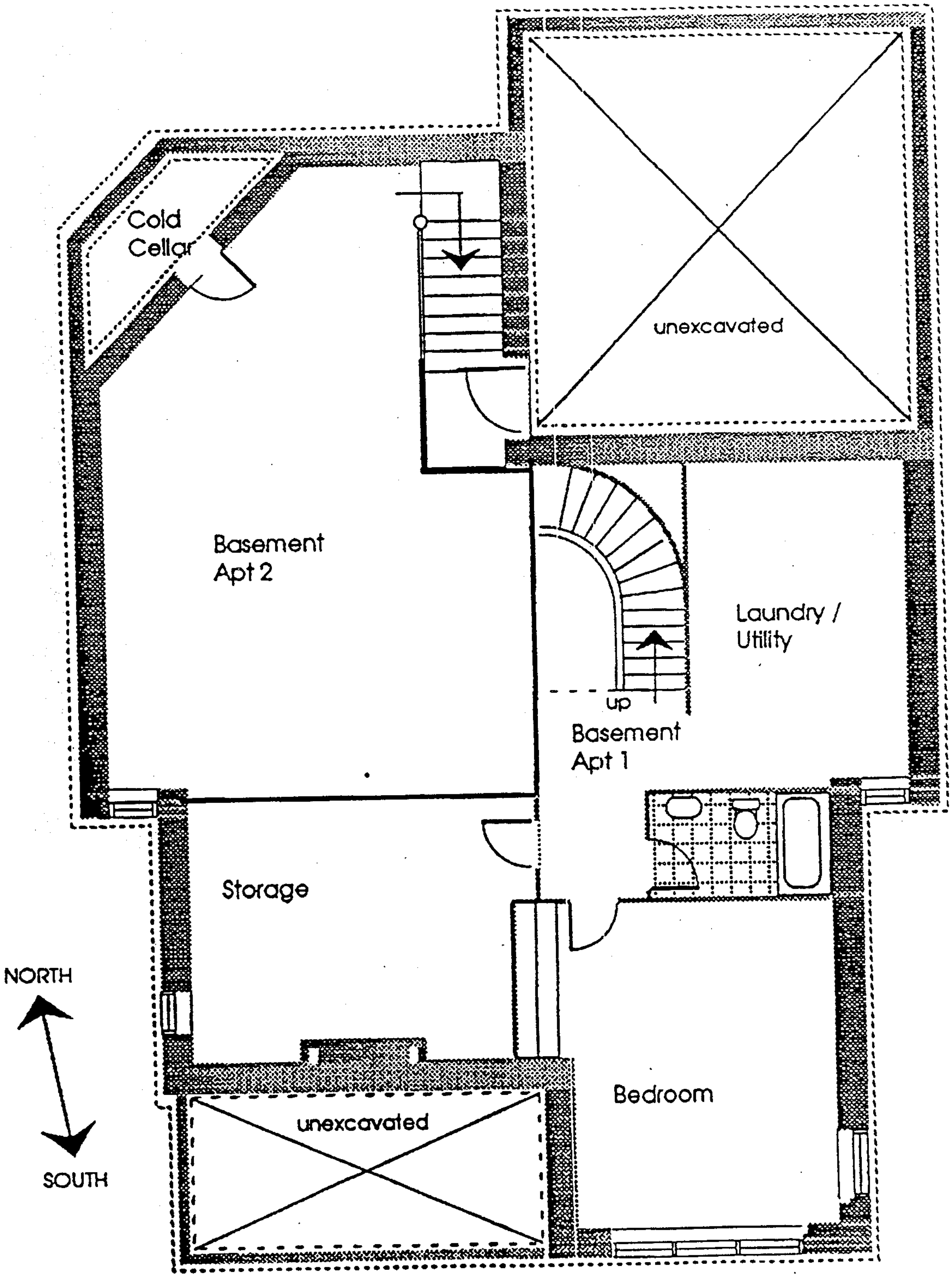


# GROUND FLOOR PLAN



# SECOND FLOOR PLAN

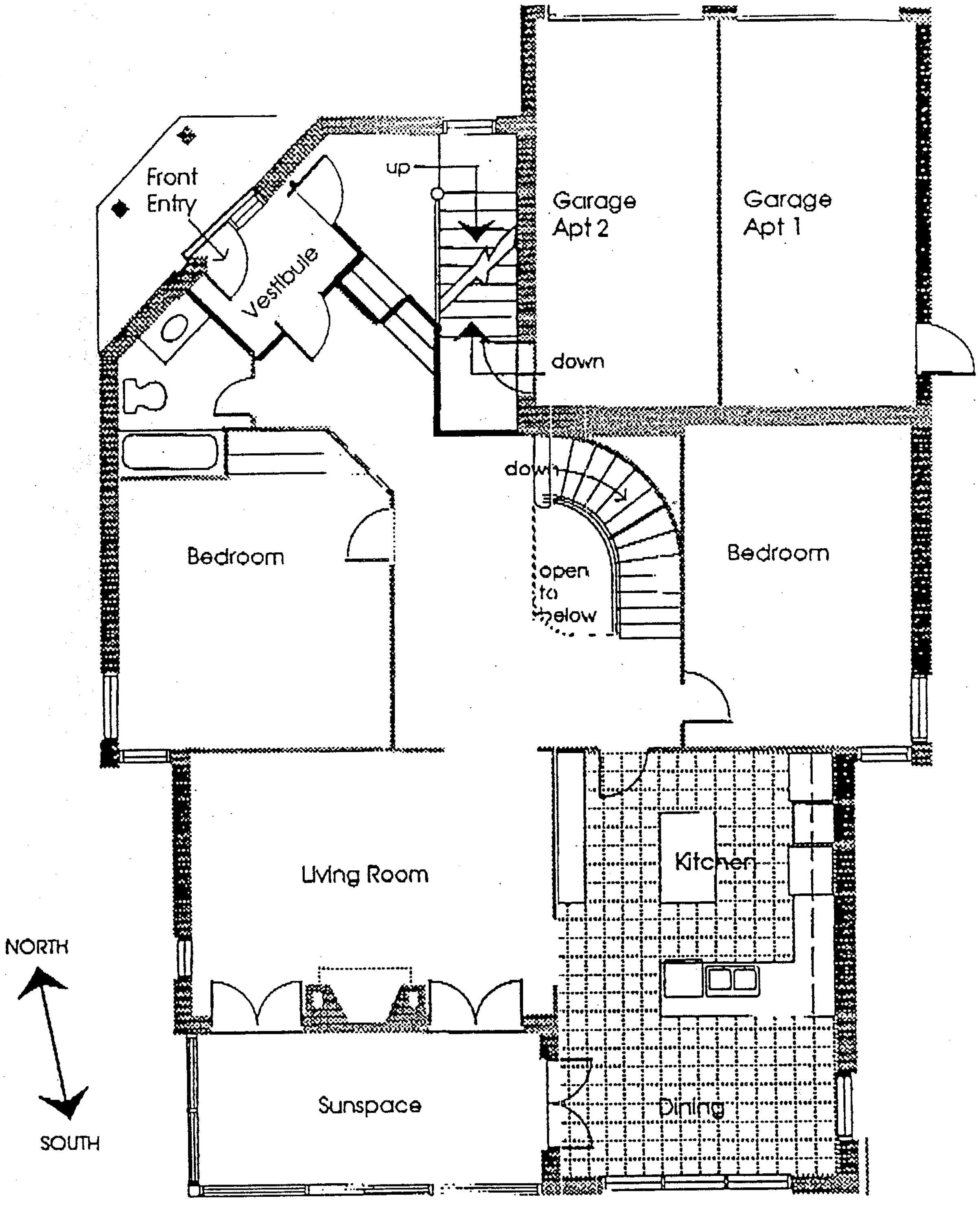




**ADVANCED HOUSE —IEA design variations —I. Duplex**

(Two three-bedroom apartments, zero changes to envelope)

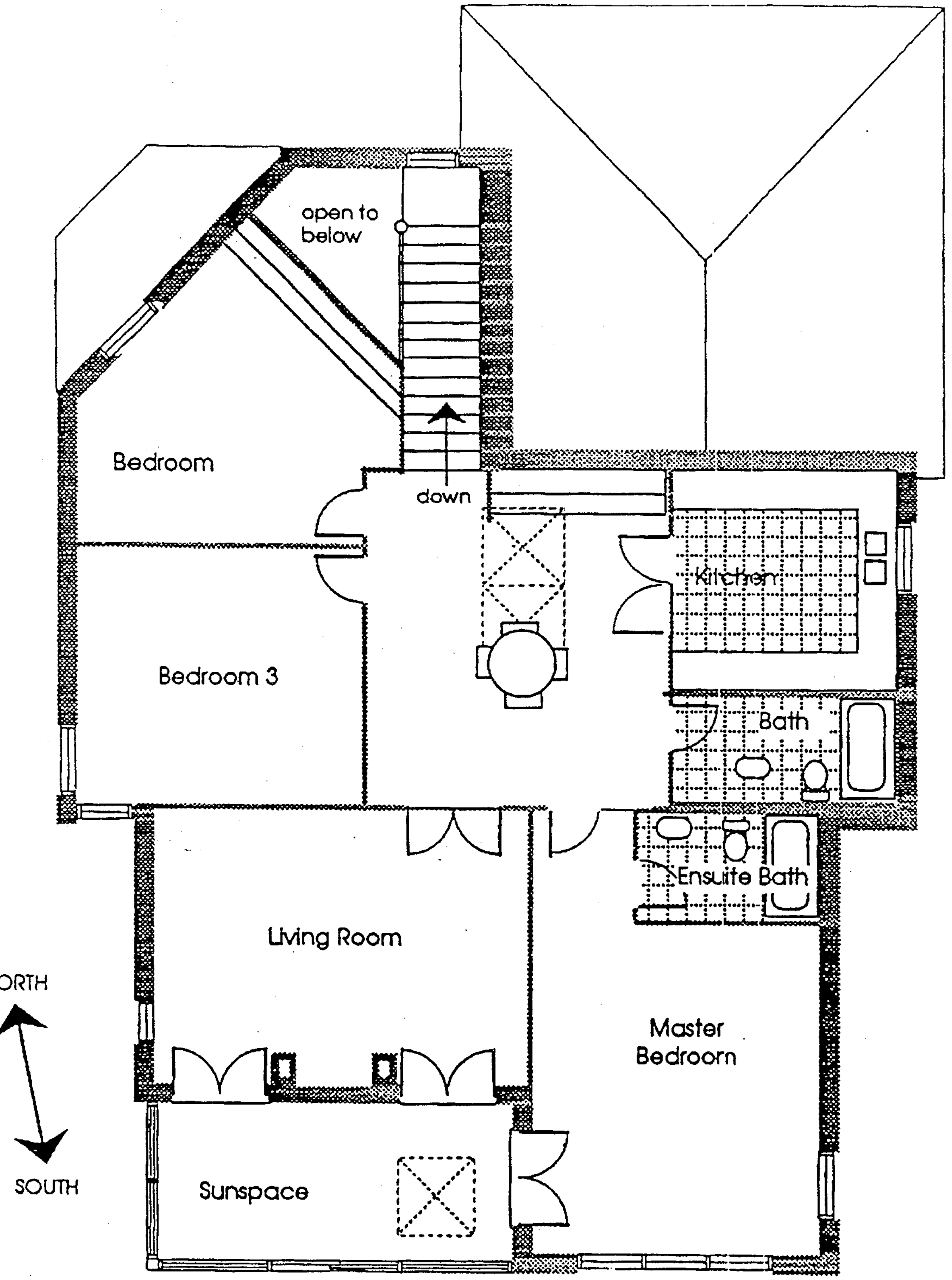
Basement Plan



**ADVANCED HOUSE —IEA design variations —I. Duplex**

(Two three-bedroom apartments, zero changes to envelope)

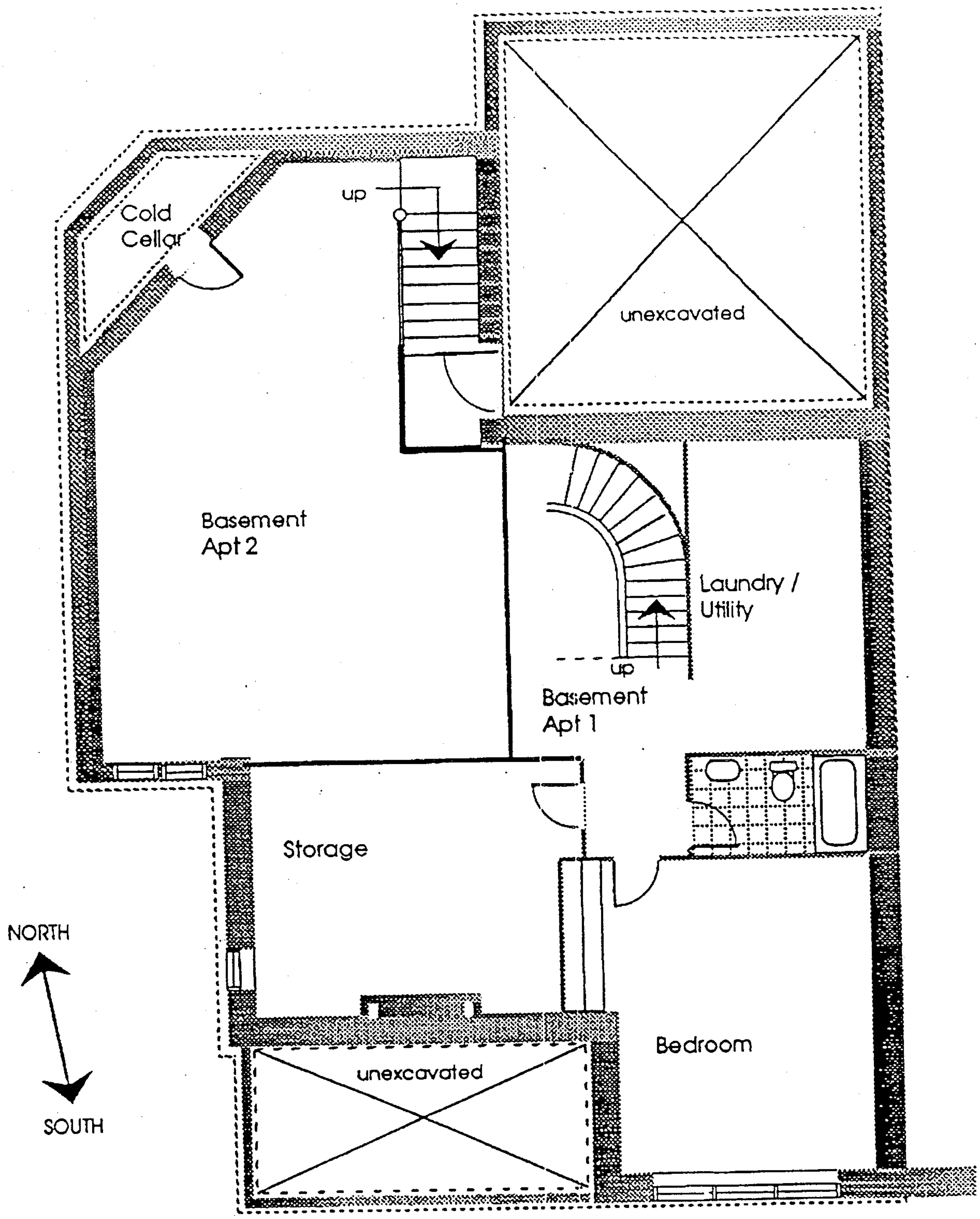
First Floor Plan



**ADVANCED HOUSE —IEA design variations —I. Duplex**

(Two three-bedroom apartments, zero changes to envelope)

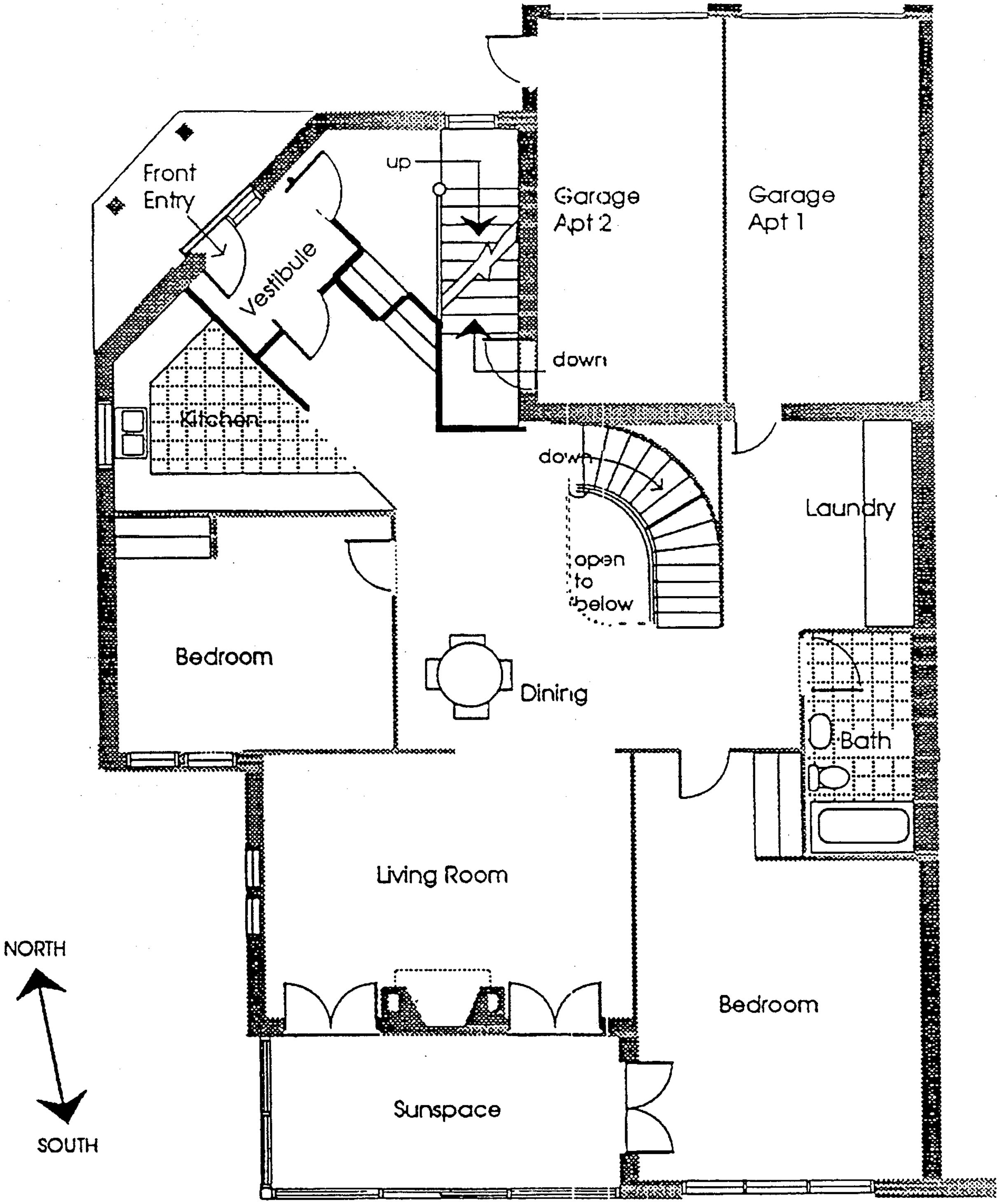
Second Floor Plan



**ADVANCED HOUSE —IEA design variations —II. Fourplex**

(Four three-bedroom apartments, zero changes to floor area and volume, envelope changes as shown)

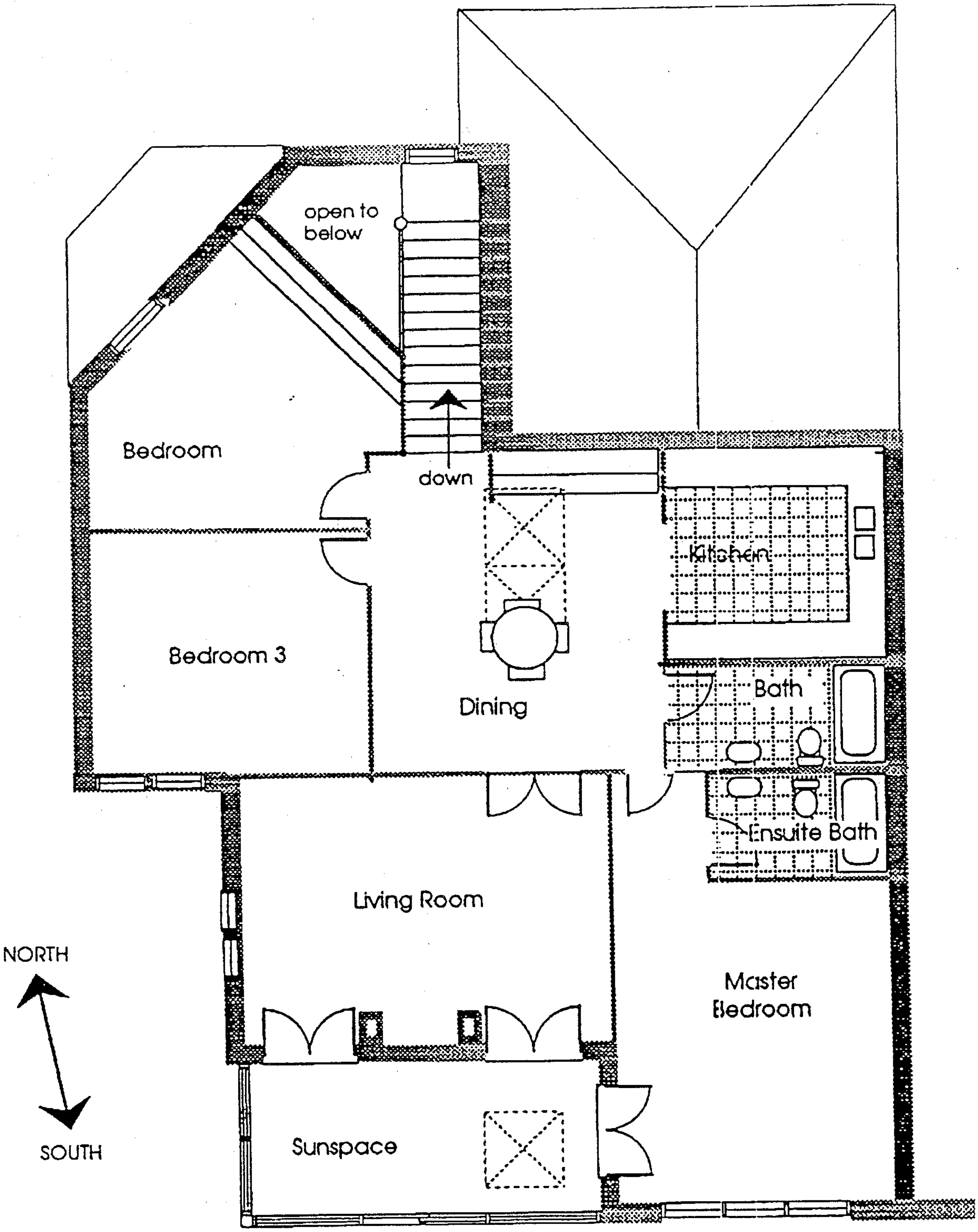
Basement Plan



**DVANCED HOUSE —IEA design variations —II. Fourplex**

our three-bedroom apartments, zero changes to floor area
nd volume, envelope changes as shown)

rst Floor Plan



**ADVANCED HOUSE —IEA design variations --II Fourplex**

(Four three-bedroom apartments, zero changes to floor area and volume, envelope changes as shown)

Second Floor Plan

# APPENDIX D:

# MONTHLY SUMMARIES OF MONITORED DATA

(Under Separate Cover)