FLAIR ENERGY DEMO PROJECT
ENERGY MONITORING PROGRAM
AND VALIDATION OF HOT 2000
- VERSION 6.0 -

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SUMMARY

A monitoring program consisting of sub-metering of major energy flows, spot measurements of energy-related variables, and a variety of detailed studies was used to characterize energy consumption rates at a monthly time scale in 23 occupied new houses constructed as part of the Flair Homes Energy Demo/ Canadian Home Builders Association Flair Mark XIV Project in Winnipeg. Eighteen of the houses were built to the R-2000 Standard and five to conventional energy conservation standards. Monitoring periods ranged from 16 to 39 months between late 1985 and early 1990, depending on date of construction and circumstance. A batch version of HOT2000 6.0, enhanced to allow for monthly resolution of critical model inputs and non-fixed solar shading, was used together with quantitative information arising from the monitoring program to estimate actual monthly energy usage for each house.

Sets of meter readings and other data describing the occupied homes were accumulated manually by project personnel during regular monthly site visits and as a result of additional access opportunities associated with special studies. As the chosen monitoring strategy, it provided an economical means to examine a larger sample of houses and develop a useful familiarity with the manner in which each dwelling was operated. For the level of scrutiny required in the monthly analysis reported herein, the data collection effort yielded a rather limited number of monitored variables and an inconvenient time scale for meter readings in comparison to that which could be obtained using an automated data acquisition system.

On the whole, the month-by-month space heating and total house energy requirements were reasonably well predicted for most of the occupied Flair project houses. In most cases, the difference between the observed total house energy consumption over any twelve contiguous months and the corresponding HOT2000 prediction was less than ± 2000 kWh, or about 10 percent of total annual consumption. Explanations or extenuating circumstances could be suggested for most of the exceptions, but not all. Within the set of project houses, there was a greater tendency for the model to underpredict the annual energy requirement than for the reverse to occur.

Among the findings of the analysis was a notable month-to-month and year-to-year variation in the difference between predicted and measured energy use. The predictability was seasonal, but usually non-linear with respect to outdoor temperature. The seasonality differed from house to house, and it drifted from year to year. The range of the drift in the 12-month total prediction error over the full monitoring period was typically 1000 to 2000 kWh, or 5 to 10 percent of the typical annual total energy consumption. This meant that, despite the apparent changes in predictability as time passed, a house which was over- or under-predicted tended to remain that way throughout the monitoring period.

Significant monthly variations in the energy-consuming activities of the occupants appeared in the records for the majority of the houses. These possibly affected model performance in the shoulder seasons and summer months when consumption by non-heating system appliances made up the majority of the total energy usage in the houses. In that part of the year, the validity of sub-model representations of the operation of appliances and ventilation systems and the availability and utilization of their waste energy as space heat became critical to overall model success. It was recommended that, for planned use of HOT2000 in applications needing better resolution than the standard low-energy design exercise, further capability for temporal variation of occupancy factors be built into the program and, further, that validation or improvement of the various non-heating sub-models be carried out.

The noticeable seasonalities which remained in the monthly prediction errors despite the implementation of extended capability for handling variables on a monthly basis in the analysis were taken as indication that there could still be room for refinement in the energy modelling of the 23 homes. The available data probably would be insufficient for more intensive study, however. Uncertainty in particular input variables, specifically the interior temperature regimes of the houses and the management of available solar radiation by the occupants, was found to have enough influence on overall space-heating energy requirements that monthly estimation errors of the magnitudes encountered in the analysis were judged to be realistic. It was concluded that the limitation to accuracy in estimating the actual monthly energy consumption in the project's houses using HOT2000 Version 6.0 should be attributed, most of all, to the coverage of energy-use processes in the houses and the resolution in time afforded by the data collection method that was used, and to a lesser degree, to the capability for fair representation of the energy-use processes in the houses using only the simple one-pass monthly model and its algorithms.

A variety of individual topics related to energy use and modelling in the project houses was also addressed in the study.

Demand metering in a few of the houses confirmed that unfavourable electrical load distributions relative to the total quantities of energy delivered to a single address throughout the course of a day should only be expected to worsen with the growing adoption of practices which reduce residential space-heating requirements. At certain hours, the occupants of low-energy houses still tend to wash, cook, and dry clothes, activities for which the power requirements are very high relative to the more steady demand for heat in the houses.

Actual Winnipeg weather for the period 1985-90 was used in the analysis. Despite some unusual conditions which occurred within the monitoring period, notably, warm months in some winters, extended drought, and changes to incident solar radiation levels which accompanied both of these phenomena, the predictability of the resulting patterns of energy consumption in the 23 houses using HOT2000 did not appear to be affected.

An heuristic electric clothes dryer energy-use model was prepared for, and used in, the analysis. Because it has become standard practice to exhaust the automatic dryer to the outdoors, the amount of metered energy which typically is rendered unavailable for secondary use as space heat within the home is quite significant. Estimation of the importance of clothes dryer energy within the overall energy balance in project houses provided support for a recommendation that effort be directed toward development of mainstream measures for recovery of clothes dryer heat, and that specific recognition and handling of clothes dryer energy be incorporated within HOT2000.

Energy used by the occupants of each house to operate interior lighting and electrical appliances other than ventilation systems, domestic water heaters, air conditioners and clothes dryers was estimated from sub-metered data. Lifestyles and the number of people living under one roof were evidently both partly responsible for the patterns noted. A seasonal variation was clearly evident in many of the houses, along with an upward trend in some which was probably more attributable to acquisitions than to increased usage. The arrival of a family's first child and the associated change in lifestyle resulted in a slight increase in home appliance use in the set of project houses.

Consumption of energy for the heating of water in the homes was found to be even more strongly related to the number of occupants than was appliance usage. Examination of the reasonableness of the water-heating sub-model of HOT2000 Version 6.0 indicated clearly a need for improvement of the representation of the DHW process within the program.

Larger HOT2000 underpredictions in three of the electrically heated houses were attributed to the use of windows and doors for ventilation instead of the installed mechanical ventilation systems, which were monitored, but which were not often operated by the respective occupants. Passive one-week tracer gas studies in the three houses yielded estimates of total ventilation rates which were significantly higher than those derivable from the clocking of mechanical ventilation equipment usage and the approximation of uncontrolled building envelope leakage. Energy-use predictability for the three houses improved to levels more typical of the other houses of the group when the higher measurement-based ventilation rate estimates were substituted.

Furnace flue air flows were estimated to be the dominant air exchange mechanism in the two project houses which had naturally aspirating gas furnaces and water heaters. The modelling of flue losses was found from comparison of tracer gas test results and the energy simulations for the houses to be a weak point within Version 6.0 of HOT2000.

The most difficult of HOT2000's sub-models to apply in realistic fashion during the analysis of actual energy usage was found to be the simulator for heat-recovery ventilator operation. Major problem areas were equipment layouts and control strategies which differed from the one assumed within the HRV sub-model and actual ventilation air flow rates which varied significantly from the standard values reported from laboratory performance testing of commercial products.

Finally, comparison of simulation results for three project houses which had each been monitored through most of a heating season without occupants, as well as through a following period of normal occupancy, provided support for the idea that the tendency for underprediction of monthly and annual energy consumption in the full set of occupied houses may have been due in part to the people being present. In this view, the normal everyday activities of the occupants, including their reactions to the dynamic interior environment of the house, can be accompanied by, for example, significant unmetered energy losses via window and door openings. The monthly residual simulation errors for two of the three houses were very small and almost random throughout the unoccupied period. Anomalous energy usage in the third of these houses proved to be unexplainable with the information available.

RÉSUMÉ

Ce rapport rend compte des résultats d'un programme d'observation qui visait à établir les caractéristiques de la consommation d'énergie mensuelle dans 23 maisons occupées qui avaient été construites récemment dans le cadre du projet Flair Mark XIV réalisé conjointement à Winnipeg par Flair Homes Energy Demo et l'Association canadienne des constructeurs d'habitations. L'étude comportait plusieurs volets : comptage divisionnaire des flux d'énergie, mesures ponctuelles de diverses variables influant sur la consommation d'énergie et études détaillées de toutes sortes. Dix-huit de ces maisons avaient été construites selon la norme R-2000, et les cinq autres selon des normes d'économies d'énergie traditionnelles. Les observations ont été effectuées entre la fin de 1985 et le début de 1990, pendant des périodes de 16 à 39 mois, selon la date de construction et les circonstances. On a utilisé une version par lots du programme HOT2000 6.0 — que l'on avait cependant modifiée pour pouvoir ramener à une période d'un mois les données d'entrée des modèles critiques et les données concernant l'ombrage non fixe — et de l'information quantitative découlant du programme d'observation pour estimer la consommation mensuelle réelle d'énergie dans chaque maison.

Les lectures de compteurs et d'autres données caractéristiques des maisons occupées ont été relevées manuellement par le personnel du projet au cours des visites mensuelles régulières et dans le cadre de certaines études spéciales qui ont créé d'autres possibilités d'observation directe. Cette stratégie a permis d'examiner à peu de frais un plus large échantillon de maisons et d'acquérir des connaissances utiles sur le mode de fonctionnement individuel des maisons. Compte tenu du niveau de précision que requiert l'analyse mensuelle dont il est rendu compte ici, le nombre de variables observées est plutôt limité et l'intervalle de lecture des compteurs est peu commode, en comparaison de ce que l'on aurait pu obtenir avec un système automatisé d'acquisition de données.

Dans l'ensemble, les prévisions des besoins mensuels en énergie de chauffage des locaux et en énergie totale étaient assez bonnes pour la plupart des maisons occupées du projet Flair. Dans la plupart des cas, l'écart entre la consommation totale d'énergie observée sur une période de douze mois consécutifs et la prévision du modèle HOT2000 a été inférieure à ± 2 000 kWh, soit environ 10 % de la consommation annuelle totale. On peut expliquer et justifier la plupart des exceptions, mais pas toutes. À l'intérieur de l'échantillon de maisons témoins, le modèle prévisionnel est plus porté à sous-estimer qu'à surestimer la consommation d'énergie annuelle.

Entre autres résultats de l'analyse, on constate une variation marquée, de mois en mois et d'année en année, de l'écart entre les prévisions et les consommations mesurées. La prévisibilité est saisonnière, mais sa relation avec la température

extérieure n'est pas linéaire. La saisonnalité variait d'une maison à l'autre, et dérivait d'une année à l'autre. Pendant toute la période d'observation, l'ampleur de la dérive dans l'erreur de prévision totale sur 12 mois s'est située généralement entre 1 000 et 2 000 kWh, soit 5 à 10 % de la consommation annuelle moyenne totale d'énergie. Donc, les variations apparentes de la prévisibilité avec le temps n'ont rien changé aux surestimations et aux sous-estimations de la consommation d'énergie.

Pour la majorité des maisons, on constate des variations mensuelles importantes dans les activités consommatrices d'énergie des occupants. Ces variations pourraient avoir influé sur le rendement du modèle dans les inter-saisons et dans les mois d'été, lorsque le gros de la consommation totale d'énergie est attribuable à des appareils autres que le système de chauffage. Dans cette période-là de l'année, la validité des sous-modèles et la justesse avec laquelle ils représentent le fonctionnement des appareils et des systèmes de ventilation ainsi que la disponibilité et l'utilisation de l'énergie résiduelle pour le chauffage des locaux revêtent une importance déterminante pour le rendement global du modèle. Pour utiliser le modèle HOT2000 dans des applications exigeant une résolution supérieure à celle dont on peut s'accommoder lorsqu'il s'agit de bâtiments à faibles besoins énergétiques standard, il a été recommandé de doter le programme d'une fonction lui permettant de mesurer la variation temporelle des facteurs d'occupation des locaux, puis de valider ou d'améliorer les divers sous-modèles qui représentent autre chose que le système de chauffage.

Les saisonnalités marquées qui subsistent dans les erreurs de prévision mensuelles, malgré l'implantation de fonctions étendues permettant de ramener les variables à une échelle mensuelle au cours de l'analyse, semblent indiquer que la modélisation énergétique des 23 maisons pourrait encore être améliorée. Les données disponibles ne seraient probablement pas suffisantes, toutefois, pour procéder à une étude plus détaillée. On a jugé que l'incertitude qui entoure certaines variables d'entrée, en particulier les régimes de températures intérieures des maisons et l'utilisation du rayonnement solaire disponible par les occupants, avait suffisamment de poids dans l'estimation des besoins en énergie de chauffage des locaux pour justifier des erreurs d'estimation mensuelles de l'ordre de grandeur rencontré dans l'analyse. On a conclu que l'exactitude de l'estimation de la consommation d'énergie mensuelle réelle dans les maisons témoins au moyen de la version 6.0 du modèle HOT2000 était limitée principalement par la couverture des processus d'utilisation de l'énergie dans les maisons, par la résolution temporelle des données issues de la méthode de collecte utilisée et, dans une moindre mesure, par la capacité de bien représenter les processus d'utilisation de l'énergie dans les maisons en utilisant uniquement le modèle mensuel monopasse et ses algorithmes.

Diverses questions reliées à l'utilisation de l'énergie et à la modélisation de la consommation d'énergie dans les maisons témoins ont également été examinées au cours de l'étude.

Le comptage de la consommation dans quelques-unes des maisons a confirmé que l'adoption de pratiques réduisant les besoins en énergie de chauffage ne ferait vraisemblablement qu'accentuer l'inégalité de la répartition de la demande d'électricité au cours d'une journée. Les occupants des maisons à faibles besoins énergétiques continuent à réserver certaines heures à des activités énergivores, comme le lavage, le séchage et la cuisson, alors que la demande de chaleur est plus constante.

Pour les besoins de l'analyse, on s'est servi des températures mesurées à Winnipeg entre 1985 et 1990. Il s'est produit certains phénomènes inhabituels au cours de la période d'observation, notamment des mois chauds certains hivers, une longue période de sécheresse et les variations concomitantes de la quantité de rayonnement solaire incident, mais la prévisibilité de la consommation d'énergie dans les 23 maisons témoins ne semble pas en avoir été affectée.

Au cours de l'analyse, on a utilisé un modèle heuristique de la consommation d'énergie des sécheuses électriques, que l'on avait élaboré expressément à cette fin. Comme il est d'usage d'évacuer à l'extérieur la vapeur des sécheuses automatiques, la quantité d'énergie mesurée qui n'est pas recyclée pour servir au chauffage des locaux est assez importante. La part de la quantité d'énergie produite par les sécheuses dans le bilan énergétique global des maisons témoins a amené les analystes à recommander que des efforts soient faits pour mettre en place des mesures de récupération de la chaleur résiduelle de ces appareils et que le programme HOT2000 soit doté de fonctions qui tiennent compte spécifiquement de cette énergie.

À partir des données du comptage divisionnaire, on a estimé la quantité d'énergie consommée dans chaque maison pour faire fonctionner les lumières intérieures et les appareils électriques autres que les systèmes de ventilation, les chauffe-eau, les climatiseurs et les sécheuses. Le style de vie et le nombre de personnes vivant sous le même toit sont évidemment des facteurs importants des profils de consommation. Dans un grand nombre de maisons, on a observé une nette variation saisonnière; dans certaines, la consommation présente une tendance à la hausse que l'on peut sans doute attribuer davantage à l'acquisition de nouveaux équipements qu'à une intensification de la consommation. La venue d'un premier enfant et le changement de style de vie qui en résulte se sont traduits par une légère augmentation de l'utilisation des appareils dans les maisons témoins.

On a constaté que le nombre d'occupants a encore plus d'influence sur la consommation d'énergie pour le chauffage de l'eau que sur l'utilisation des appareils. Le contrôle de la vraisemblance des résultats du sous-modèle du chauffage de l'eau dans la version 6.0 du modèle HOT2000 indique clairement la nécessité d'améliorer la représentation du processus de chauffage de l'eau domestique au sein du modèle.

La sous-estimation est nettement plus marquée dans trois des maisons chauffées à l'électricité. Ce résultat s'explique par le fait que la ventilation dans ces trois maisons s'effectue par les fenêtres et les portes plutôt que par les systèmes de ventilation mécanique qui y sont installés; ces systèmes ont fait l'objet d'un contrôle, mais ils n'ont pas été souvent utilisés par les occupants. Des études par gaz de dépistage ont été faites durant des périodes d'une semaine; dans les trois maisons, les estimations du débit de renouvellement d'air étaient beaucoup plus élevées que les estimations obtenues par chronométrage de l'utilisation des systèmes de ventilation mécanique et par approximation des fuites non contrôlées de l'enveloppe du bâtiment. La prévisibilité de la consommation d'énergie dans les trois maisons se rapproche de la prévisibilité moyenne des autres maisons témoins quand on substitue les estimations mesurées aux estimations dérivées.

Les conduits d'air des appareils de chauffage constituaient le principal mécanisme d'échange d'air dans les deux maisons témoins équipées d'appareils de chauffage et de chauffe-eau à gaz à aspiration naturelle. Une comparaison des résultats des essais au gaz de dépistage avec ceux des simulations énergétiques a permis de constater que la modélisation des pertes par les conduits d'air est un des points faibles de la version 6.0 du modèle HOT2000.

Le sous-modèle le plus difficile à appliquer de façon réaliste au cours de l'analyse de la consommation d'énergie réelle est celui qui simule le fonctionnement du ventilateur-récupérateur de chaleur. Les principaux problèmes tenaient au fait que la disposition des équipements et les stratégies de contrôle étaient différentes de ce qui était prévu dans le sous-modèle en question, et à l'écart considérable entre les débits mesurés d'air de ventilation et les valeurs standard produites par les essais en laboratoire de produits commerciaux.

Finalement, la comparaison des résultats des simulations exécutées pour trois maisons témoins qui avaient été observées, d'abord en l'absence d'occupants pendant la majeure partie d'une saison de chauffage, puis pendant une période d'occupation normale, confirme la thèse suivant laquelle la tendance à sous-estimer la consommation d'énergie mensuelle et annuelle dans l'ensemble des maisons occupées pourrait s'expliquer en partie par l'absence ou la présence d'occupants. Dans cette optique, les activités courantes des occupants et leurs réactions à l'environnement intérieur dynamique de la maison peuvent s'accompagner, par exemple, d'importantes pertes d'énergie non mesurées par les portes et les fenêtres. Les erreurs de simulation résiduelles obtenues sur une base mensuelle pour deux des trois maisons en question étaient très faibles et presque aléatoires sur toute la période sans occupants. Les données disponibles ne permettent pas d'expliquer la consommation d'énergie anomale mesurée dans la troisième maison.

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INTRODUCTION - FLAIR ENERGY DEMO PROJECT'S ENERGY MONITORING PROGRAM

1.1 BACKGROUND

Organized pre-market field testing of residential energy conservation strategies, construction techniques and products would seem to make good sense. With a few hundreds of thousands of housing starts annually across the country and a renovation market which is possibly even larger, a great deal is at stake with the possible implementation of new energy-conserving technologies. Manufacturers of energy-consuming domestic appliances and other components have long been familiar with field trials and certification testing within the development stream for new products. At the whole-house level, i.e., the energy-efficient dwelling together with all its component parts, construction codes and bylaws perform a regulating function, but this system is not configured to be the developer of new practice. Trial and error, complemented by word-of-mouth, continues to dominate as the means by which a diverse housing industry adapts and adopts new technologies and methods.

Change in the industry evolves in increments, with false steps commonplace. Consequently, it is probably safe to say that most Canadians could point out an example within their own home of an energy-saving idea or product that, in their opinion, had not quite matured by the time it was built. In most cases, the result has been merely a degree of inconvenience; in some, the industry's former lessons have turned out to be highly regrettable. We seek a more optimal path. Unfortunately, the cost and schedule are not often favourable when it comes to the evaluation of technology which might affect whole-house performance.

The real effect of energy-saving innovations is likely to be most fully appreciated only after real occupants have reacted to them and discovered their limitations. For suitable full-scale testing of a single concept, a dedicated building and at least several heating seasons might be the minimum requirement. In practice, the complete experiment is rarely done. Over the last twenty years or so, there have been only a limited number of examples of this kind of evaluation carried from the design stage through to construction and occupancy.

Quite naturally there has arisen a preference to assess residential energy conservation alternatives using simulation rather than physical experiment. Mathematical models for building energy-use simulation abound, and many of them can be used to represent small buildings. The HOT2000 Energy Analysis Program is one such simulation model developed in Canada. However, relative to the level of resolution and flexibility desired by users, there is ample room for improvement of this model. At the same time it cannot be said that there is an excess of applicable calibration and verification data to assist the process.

Multi-year series of sub-metered energy consumption data for 23 occupied houses have been collected as part of the Flair Homes Energy Demo/CHBA Flair Mark XIV Project. Early on, it was envisioned with the foresight of the day that these data would be used in the development of a better understanding of some of the processes that contribute to the total energy bill of houses, particularly those which incorporate low-energy technologies, and also that they would be a good set of data for use in verifying the simulation of the interaction of those processes using HOT2000.

Since the energy monitoring component of the project was designed in 1985, the R-2000 Home Program and other initiatives have led to the rapid accumulation of much experience with basic residential energy-conservation measures in Canada and elsewhere, and the establishment of a growing level of confidence in their effectiveness and reliability. Some of the early uncertainties about different building envelope materials and constructions have been alleviated or confirmed in that time through the natural interaction of building officials, the industry and its market, and through specific investigations such as the Flair project.

The scale and potential impact of residential energy savings have also become much more fully defined than they were in the mid-eighties. It is notable that, as the value of demand reduction has begun to be appreciated at a wide level, as the physical and related economic implications of envelope improvements have been explored and more fully rationalized, and as the role of occupant activities has been at least partially clarified, the technological focus in the new decade has shifted toward conservation of non-heating energy expenditures in the home. Need has arisen to understand and quantify energy-use processes that were formerly considered to be insignificant. Pressure for refinements to the representation of such processes within simulation programs like HOT2000 has kept program developers active and intensified the requirement for suitable real-world observations.

Despite the fact that it was being outpaced by rapid advancements in low-energy housing technology at the same time as it was being compiled, the energy-monitoring data set from the Flair project houses remains relatively unique in that it is a continuous record of several years of occupancy. As such, it provides a clear view of the seasonal dispensation of end-use energy in some typical homes built to the R-2000 standard, and some more conventional homes as well. Further, the completeness of the data set renders it useful for the purpose of validation of some residential energy-use algorithms and whole-house models.

1.2 SCOPE

The present report outlines the findings of a study intended to examine:

(a) the energy consumption patterns in the 23 occupied homes of the Flair Homes Energy Demo/CHBA Flair Mark XIV project, and

(b) the predictability of those patterns when the HOT2000 Energy Analysis Program is used to simulate them.

1.3 THE FLAIR HOMES ENERGY DEMO/CHBA FLAIR MARK XIV PROJECT

The work described in this report was conducted as part of the Flair Homes Energy Demo/CHBA Flair Mark XIV Project. This project was created in 1985 to provide a demonstration of various energy conservation technologies, products and systems which might be suitable for the Canadian home building industry. The specific objectives of the project were:

1. To demonstrate and evaluate the performance of various low energy building envelope systems.

2. To demonstrate and evaluate the performance of various space heating, hot water heating and mechanical ventilation systems.

3. To transfer the knowledge gained in the project to the Canadian home building industry.

Support for the project was provided by Energy, Mines and Resources Canada under the Energy Demo Program and by Manitoba Energy and Mines under the Manitoba/Canada Conservation and Renewable Energy Demonstration Agreement (CREDA). Project management was the responsibility of Flair Homes (Manitoba) Ltd. Project monitoring and reporting were effected by UNIES Ltd., consulting engineers, of Winnipeg.

The project was also intended to provide technical support to the R-2000 Home Program, which is funded by Energy, Mines and Resources Canada and administered by the Canadian Home Builders Association (CHBA). The CHBA's "Mark XIV" designation was acquired when a major portion of the research priorities identified by the CHBA's Technical Research Committee was incorporated into the work plan.

To meet the project's objectives, 24 houses were constructed in Winnipeg by Flair Homes Ltd. and monitored for periods of up to three years. Their energy conservation levels ranged from those of conventional houses to those which met or exceeded the R-2000 Standard.

1.4 PROJECT HOUSES AND THE ENERGY MONITORING PROGRAM

The 24 project houses were constructed between 1985 and 1989. Descriptions of the houses and their envelope and mechanical systems are summarized in Tables 1 and 2. Further detail is given in Proskiw (1992a).

Observations of energy-use patterns in the homes were acquired mainly through sub-metering, with reading of meters being done manually on an approximately monthly frequency as part of regular access visits.

Houses #1 through #10, built in 1985, were monitored from late 1985 to March 1989. Houses #11 to #20 were completed in 1986 and were monitored from early- to mid-1986 through to March 1989. All of the above homes were

TABLE 1
DESCRIPTION OF PROJECT HOUSES

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HOUSE	BUILDING ENVELOPE					MECHANICAL SYSTEMS		YEAR COMPLETED	ENERGY STANDARD
	WALL CONSTRUCTION	EXTERIOR WALL FINISH	BASEMENT CONSTRUCTION	CEILING/ATTIC CONSTRUCTION	WINDOWS	SPACE HEATING SYSTEM	VENTILATION SYSTEM		
1-6	38x140 (2x6), Rigid Glass Fibre Insulated Sheathing (Reversed) c/w SBPO Air Retarder	Stucco with Wood or Brick Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed, Awning & Casement	Electric Forced Air Furnace	Heat Recovery Ventilator	1985	R-2000
7,8	38x140 (2x6)	Stucco with Wood Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed, Awning & Casement	Electric Forced Air Furnace	Central Exhaust with Make-Up Air Duct	1985	Conventional
9,10	38x140 (2x6)	Stucco with Stone & Wood Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed, Awning & Casement	Gas Forced Air Furnace	Bathroom Exhaust Fan	1985	Conventional
11-14	38x140 (2x6), Rigid Glass Fibre Insulated Sheathing c/w SBPO Air Retarder	Stucco with Wood, Brick or Stone Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning & Casement	Electric Baseboards or Forced Air Furnace	Exhaust-only Heat Pump or Heat Recovery Ventilator	1986	R-2000
15,16	Double Wall	Stucco with Wood Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning & Casement	Air-to-Air Heat Pump	Integrated with Space Heating System	1986	R-2000
17,18	Double Wall	Stucco with Brick, Wood or Stone Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning & Casement	Electric Baseboards	Heat Recovery Ventilator	1986	R-2000
19,20	38x89 (2x4), Rigid Extruded Polystyrene Sheathing	Stucco with Wood & Brick Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning & Casement	Electric Baseboards	Heat Recovery Ventilator	1986	R-2000
21	Predominately 38x140 (2x6) with Interior Strapping	Vinyl & Wood Siding	Cast Concrete	Cathedral & Truss Ceilings	Several Types	Several Types	Several Types	1989	R-2000
22	38x140 (2x6)	Stucco with Wood & Brick Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed & Awning	Electric Forced Air Furnace	Central Exhaust	1988	Conventional
23	38x140 (2x6) with Interior Strapping	Stucco with Wood Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed & Awning	Electric Forced Air Furnace	Heat Recovery Ventilator	1988	R-2000
24	38x140 (2x6) with Rigid Glass Fibre Sheathing	Stucco with Wood & Brick Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed, Awning & Casement	Electric Baseboards & Radiant Panels	Heat Recovery Ventilator	1988	R-2000

TABLE 2
AIR AND VAPOUR BARRIER DETAILS

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HOUSE	AIR BARRIER							VAPOUR BARRIER		
	TYPE	SEALING METHOD					CREW			
		HEADERS	CANTILEVERS	PARTITION WALLS AT CEILING	WINDOW & DOOR ROUGH OPENINGS	ELECTRICAL OUTLETS		WALLS	CEILING	BASEMENT
1-6	ADA	Closed Cell Polyethylene Gaskets	Closed Cell Polyethylene Gaskets	Gaskets	Gaskets	Poly-Pan Boxes & Gaskets	A	Paint	Paint	Paint
7,8	ADA	Closed Cell Polyethylene Gaskets	Closed Cell Polyethylene Gaskets	Gaskets	Gaskets	Poly-Pan Boxes & Gaskets	A	Paint	Paint	Paint
9,10	4 mil Polyethylene	None	None	Unsealed Polyethylene	Unsealed Polyethylene	Unsealed Polyethylene	A	Polyethylene	Polyethylene	Polyethylene
11-14	Simplified ADA	None	None	None	Ethafoam Rod Gaskets	Poly-Pan Boxes & Gaskets	B	Paint	Paint	Paint
15,16	6 mil Polyethylene	Caulking	Caulking	Sealed Polyethylene	Sealed Polyethylene	Sealed Polyethylene	B	Polyethylene	Polyethylene	Polyethylene
17,18	6 mil Polyethylene	Caulking	Caulking	Sealed Polyethylene	Sealed Polyethylene	Sealed Polyethylene	B	Polyethylene	Polyethylene	Polyethylene
19,20	ADA	Closed Cell Polyethylene & Neoprene Gaskets	Closed Cell Polyethylene & Neoprene Gaskets	Neoprene Gaskets	Ethafoam Rod Gaskets	Poly-Pan Boxes & Gaskets	B	Paint	Paint	Paint
21	Primarily 6 mil Polyethylene	Sealed Polyethylene	Sealed Polyethylene & SBPO Air Retarder	Sealed Polyethylene	Various	Sealed Polyethylene	C	Polyethylene	Polyethylene	Polyethylene
22	Primarily 6 mil Polyethylene	Sealed Polyethylene & SBPO Air Retarder	Sealed Polyethylene & SBPO Air Retarder	Saturated Urethane Open Cell Gaskets	Various	Polyethylene	D	Polyethylene	Polyethylene	Polyethylene
23	6 mil Polyethylene	Sealed Polyethylene & SBPO Air Retarder	Sealed Polyethylene & SBPO Air Retarder	Sealed Polyethylene	Various	Sealed Polyethylene	D	Polyethylene	Polyethylene	Polyethylene
24	6 mil Polyethylene	Sealed Polyethylene & SBPO Air Retarder	Sealed Polyethylene & SBPO Air Retarder	Saturated Urethane Open Cell Gaskets	Various	Polyethylene	D	Polyethylene	Polyethylene	Polyethylene

occupied soon after completion, so the monitored performance is almost exclusively that of occupied conditions.

Project houses #22, #23 and #24 were completed in the autumn of 1988, were all first occupied around mid-1989, and were monitored from late 1988 to March 1990, so short periods of observation under both unoccupied and occupied conditions have been acquired for these homes.

Project house #21 was completed in 1989 and served as an unoccupied test facility until late 1990. Due to the experiments going on in this building, its energy usage patterns were unrepresentative of occupied conditions. Consequently, House #21 has been excluded from the analysis reported herein.

SECTION 2

DATA ACQUISITION

2.1 RESOURCES

An application-specific, random-access database and companion database management tools were prepared in 1986 and were used throughout the monitoring period to handle the incoming energy and other data. The resulting collection of data is the main data resource used in this investigation of energy performance and energy simulation in the homes.

Other information used in the analysis was compiled from the Atmospheric Environment Service of Environment Canada, Winnipeg, from project event journals and "as-built" documentation, and from the homeowners themselves through interviews repeated approximately semi-annually throughout the monitoring period.

The basic energy monitoring program for each house is described in Appendix A, beginning with a list of the major energy-related variables which were sampled during the site visits. Electricity, natural gas, and water metering were accomplished using utility-standard analog meters which had been serviced prior to installation in the houses. The device run-time monitors that were used were application-specific, and were designed and fabricated directly for the project.

Besides the continuously sub-metered variables shown in Appendix A, other relevant quantities that were spot-sampled regularly included indoor dry-bulb and wet-bulb air temperatures, thermostat and dehumidistat settings and readings, fan speed-control settings, and ventilation system air flow rates at the various operating speeds (observed at permanently installed flow measurement stations). Recording analog hygrothermographs were also operated in the houses over periods of about a month, at approximately semi-annual intervals.

In addition, some measurements taken as part of special studies were also applicable to the energy analysis. For example, estimates of total house air exchange rates were obtained during periodic air quality studies. Regular blower door tests of the buildings' envelopes provided statistics on changes in the characteristics of non-forced air leakage.

The homeowner interviews provided insight into unmetered factors related to the occupants' reactions to and their control of the interior environments of the homes. This included use of operating windows and window coverings, usage of car heaters and lawn and gardening equipment, clothes dryer operation, temperature setbacks, changing use of interior appliances, and hours spent in the house. Of limited quantitative consistency, this information was used as a guide in the analysis.

Finally, from the frequent contact of project personnel over the several years of monitoring, there arose a general knowledge of the houses, including the character of their mechanical systems and the behaviour of their occupants. Through a merging of this information with that from all of the above-described sources, with a bit of judgment as binder material, a quantitative/qualitative appreciation of the house energy environment was gradually developed for each dwelling. This understanding was invaluable in the setting up of the energy simulations and in the analysis of energy flows in the houses. The use of non-metered monitoring data in the analysis evolved through the need to maintain pace with the maturation and changes in focus in housing energy research that have transpired since the monitoring components of the Flair project were conceptualized.

The manual method of data collection followed during the project had an advantage of cost and reliability, and, by its nature, forced the acquiring of the familiarity that turned out to be valuable in the analysis. What also evolved from the frequent contact with the homeowners was a modest level of awareness and trust concerning control systems and mechanical equipment, such that each of the project houses came to be operated by the occupants with attention to the advice of project personnel. Thereby, the inherent difficulty of carrying out studies in occupied housing was partially mitigated.

During the 1988-89 heating season, eight months of parallel hourly monitoring (computerized data acquisition) experience were accumulated in one of the dwellings (House #24), providing verification of the longer-term energy quantities observed manually. Further description of the special hourly monitoring program is provided in Appendix B. The exercise served to demonstrate that more frequent meter readings in all houses, theoretically obtainable with a trouble-free system of automated data acquisition, would have facilitated the energy analysis by allowing greater freedom in the choice of times for "taking" readings. The occupant-related noise would still have necessitated a firm understanding of the human presence in the houses, however. Indeed, the less tangible aspects of residential energy usage will likely further increase in importance as the overall energy consumption in new Canadian homes continues to decline in response to the commercialization and uptake of new conservation measures.

2.2 PRE-CONDITIONING

As part of the analysis of the recorded energy data, pre-adjustment of meter readings and spot measurements to align with calendar month ends was done. This step was included in order to facilitate comparisons with the simulation results generated using the HOT2000 Energy Analysis Program, a monthly model.

For variables strongly correlated with the heating season, such as the rate of energy usage by the main space heating appliance in the house, the pre-adjustment first involved the estimation of piecewise-linear correlation functions for the observed data, based on the average outdoor temperature (local weather station) during each meter reading interval. This was followed by the application of the newly derived functions to the existing record of mean daily outdoor temperatures to produce equivalent daily meter reading series (the procedure conserves total consumption over all actual meter reading intervals). Calendar month-end "readings" from the derived daily series were then selected and assembled into new monthly meter reading series. Resolution of energy usage rates is reduced slightly by this pre-adjustment step as the result of shifting from actual meter readings to estimated month-end readings.

For metered variables having weaker seasonal dependence, e.g., the appliances or domestic hot water load, new month-end meter-reading series were created through simple day-weighting among the actual meter readings. For non-metered variables, such as temperatures and forced-air flow rates, for which measurements taken during a site visit can be non-representative of average longer-term operating conditions, a combination of numerical day-weighting and qualitative judgment was used in the preparation of the new month-end data series.

SECTION 3

ANALYSIS OF ENERGY PERFORMANCE - MODELLED VS ACTUAL

HOT2000 was used to simulate the time-behaviour of energy consumption in the 23 conventionally operated project houses. A primary objective of this activity was to assess the validity of the model, given the availability of a comprehensive (multivariate over several heating seasons) set of verification data.

The original model evolved mainly as a design tool. Used in that capacity, a standard operating environment (temperatures, ventilation rates, appliance and hot water usage, etc.) is usually assumed for the house undergoing energy system design. Application of HOT2000 with the assumed standard occupancy, a description of the house, and a set of monthly data which describes a normal weather year at the locality results in an estimated annual energy consumption profile for the house. Adoption of a realistic group of occupancy-related input values can be expected to be adequate for the comparative purposes of a design exercise.

The fact that energy usage may vary depending on the real weather and the house operating conditions unfortunately precludes easy assessment of the model's capabilities in simulating the typical <u>occupied</u> house. Some detailed monitoring is required to track energy flows so that various portions of the house energy load can be estimated more closely. In the Flair project, the sub-metered energy consumption data for 23 homes provide one such opportunity for a less-obscured examination of HOT2000's validity.

A modified batch version of HOT2000 6.0 was prepared for use in the analysis. All energy-calculation algorithms in the commercially available version were retained unaltered in the modified version, but special provision was made to allow for monthly and year-to-year variations in weather, house physical description, and operating inputs over the 1985 to 1990 monitoring period. Also incorporated was an extension to the program's window sub-model to allow for the representation of fractional external shading devices such as draperies, trees, and other buildings. The resulting model was then run with the best inputs that could be defined from the monitored data, and the predicted and actual energy requirements were compared. A summary of the monthly model inputs and resources is given as Table 3.

Errors normally would be expected in the results of any model simulation. In simplest form, the errors could be assigned to either of two broad categories: (a) model or systematic errors, and (b) random or non-systematic errors. During development of a physically based model such as HOT2000, it is ideally expected that its conceptual part would be improved until remaining total prediction errors could no longer be identified as anything but randomness, and hopefully would constitute only some small portion of the output value being calculated. Usually, however, it is accepted that some model or algorithmic limitations must remain in the finished product. It is then left to the user's experience to make sense out of the combined model and random error.

HOT2000 at the present time is still undergoing refinement in many of its algorithms where deficiencies are appreciated, and there is new development in areas where a need for modelling capability has been identified. Thus, there are some sources of potential error remaining in the most recent releases of the program.

In this analysis, the main focus is on the overall predictive capability of the program, with the acknowledgment that a deviatory outcome may be contributed to variously from multiple sources. Individual model errors are naturally inherent in all of the internal sub-models/algorithms for estimation of the space- and water-heating loads, the solar and internal gains and their utilization, and the performance of energy-handling mechanical equipment.

Adding to this imbroglio is the fact that the various parts of HOT2000 interact, thereby making it more difficult to isolate and remedy individual problems. Study of contributing sub-models may lead to their improvement. However, the agglomeration of sub-model errors within HOT2000's calculation of the auxiliary (net) space-heating requirement, as the difference between the total losses and the total gains, normally would make this derived quantity more uncertain than other constituents of the total house energy requirement.

The above situation is not ameliorated by the southern Canadian context for low-energy houses where the auxiliary heating requirement calculation becomes the difference between two numbers of similar magnitude. Along with being the most important calculation, the estimation of auxiliary heating requirement therefore also may be the most sensitive basic indicator of net program accuracy. Quantification and understanding of individual errors and their sources may require deeper analysis. Below, HOT2000's performance is examined through comparison of observed and predicted auxiliary space heating energy usage and total purchased energy for the house.

TABLE 3

REVIEW OF THE HOT2000 INPUTS USED IN THE ENERGY SIMULATIONS

Weather File.

Environment Canada Atmospheric Environment Service observations for Winnipeg International Airport. The weather station is approximately 16 km from Houses #1 through #20, and 8 km from Houses #21 to #24. Data used for HOT2000 simulations and for pre-processing of monitored data.

Outdoor Temperature.

Mean daily temperatures derived as unweighted averages of hourly dry bulb temperature readings as reported by AES. Longer-term means, e.g., monthly, taken as unweighted averages of daily means.

Wind Speed and Direction.

Mean daily windspeed and prevailing direction as reported by AES. Longer-term windspeed means, e.g., monthly for HOT2000 weather files, taken as unweighted averages of daily means.

Solar Radiation.

Total incident global and diffuse radiation on a horizontal surface as reported by AES. Where monthly observations unavailable within the period 1985 to 1990: global radiation estimated from AES monthly total bright sunshine hours on the basis of de-seasonalized correlation of monthly values over the period 1957 to 1984; diffuse radiation input as zero and calculated internally by HOT2000.

Deep Ground Temperature.

Calendar year averages of AES monthly mean ground temperature at 3 metre depth.

All Other Weather File Parameters.

Default values from HOT2000 Winnipeg standard weather file.

House Physical Description.

Variable monthly to accommodate changes during the monitoring period, such as installation of storm doors, changes to draperies or their time open and closed, etc. Dimensions taken off as-built drawings, or site-measured. Envelope considered to be at interior surface of exterior walls, ceilings, floors, etc.

Sub-Component R-values.

Net R-value of assembly on basis of assumption of parallel energy flows through framing and insulation.

TABLE 3 (continued)

Windows.

According to HOT2000 Version 6.0 format, window opening area, type, frame material, number and spacing of glazings, spacer type, and inter-lite gas fill according to as-built condition.

Window R-value and unobstructed shading coefficient calculated internally by the program's algorithms.

Overhangs according to as-built geometry.

Shading due to draperies: based on ASHRAE Fundamentals Handbook, 1989 (ref.), Chap. 27, the shading factor approximated as a fraction to be applied to the solar heat gain coefficient determined for an undraped window:

- no draperies, or draperies opened fully	1.00
- light-coloured, sheer-type draperies, fully closed	0.69
- light-coloured, heavy-weave draperies, fully closed	0.50

Drapery materials used by the homeowners were assigned to one of these categories. For draperies open during a percentage of daylight hours as derived from interview responses, shading factors were prorated between the fully open and fully closed values. The modified batch version of HOT2000 6.0 used in the study included provision for accepting drapery shading factors as inputs for each defined window.

Obstruction due to trees and adjacent buildings estimated from site inspection as fraction of incident radiation not reaching particular window due to obstruction; solar heat gain coefficient for that window correspondingly derated for HOT2000 simulation through adjustment of drapery shading factor.

Operating Temperatures.

Representative monthly main floor and basement temperature settings for each house estimated from simultaneous main and basement spot measurements, thermostat settings and readings ("click" points) and main floor temperature readings from recording hygrothermograph traces, all recorded during site visits, and from the day-to-day temperature behaviour as shown in the month-long hygrothermograph records.

Thermostat data generally concurred closely with spot measurements. Hygrothermograph results usually could contribute only an understanding of temperature pattern rather than quantity due to logistics of instrument placement in occupied homes. Most were sited either on top of kitchen cupboards or living/dining room shelving units or they were on the floor out of the way of travelled areas. The resulting temperature readings from these units were correspondingly too high or too low.

TABLE 3 (continued)

Forced Air Flow Rates.

Average air changes (house volumes) per hour, supply and/or exhaust, derived from ventilation system flow rates measured at the various operating speeds and the lengths of time spent operating at those speeds.

Houses 1-6, 13, 14, 19, 20, 23, 24: nearly balanced HRV systems; supply and exhaust rates used in calculation for each month. For House #13, forced ventilation rates derived using monitored flowrates and run times were consistently lower than the values implied by perfluorocarbon tracer (PFT) passive monitoring studies, the reason being that actual HRV system usage by the occupants was infrequent and intentional ventilation for the house was largely provided through other means (likely the use of operating windows, an unmonitored variable).

Houses 7, 8, 22: exhaust-only systems; exhaust rate used in calculation; additional monthly mean air change due to fresh air intake estimated for Houses #7 and #8 on basis of measured inflow rates and furnace on-times. Actual exhaust system usage by occupants was infrequent; total air change rates indicated by tracer gas studies suggest significant unmonitored ventilation means were substituted.

Houses 9, 10: bathroom fans only; average forced air flowrates assumed zero due to infrequent usage.

Houses 11, 12: exhaust-only Habitair heat pump ventilator systems, run continuously; exhaust rate used in calculation.

Houses 15, 16: Peach furnace, heat pump DHW/ventilator system (nearly balanced flows); only PFT air change estimates available; warm and cold season operating flowrates are consistent and agree with control system operating protocol; therefore, PFT-derived average flowrate values assumed for forced flows in calculations, with natural airchange rates set close to zero.

Houses 17, 18: Nilan heat pump HRV, run continuously; nearly balanced flows; only rates of flow monitored (but not high/low times), low speed flows 2/3 to 3/4 of high speed flows; humidities remained low relative to setpoints maintained, so not much demand (high speed) time; therefore, forced air change approximated by assuming continuous low speed operation.

Natural Air Change.

Monthly average air changes (house volumes) per hour, determined internally by the program, on the basis of house airtightness data inputs derived from semi-annual blower door tests and AES records of local daily outdoor temperature, wind speed and wind direction during the monitoring period.

Occupancy.

Monthly interior presence of adults and children for occupancy sensible heat gain calculation; estimated from reported hours in the house per day for each person.

TABLE 3 (continued)

Interior and Exterior Appliance and Lighting Loads.

HOT2000 accepts separate inputs for total appliance electrical energy usage rate and exterior (i.e., outdoor) electrical energy usage rate; the latter is subtracted from the former by the program to yield an interior appliance electricity usage rate.

Monthly values estimated from monitoring data; in most cases, sub-metered quantity included exterior usage (e.g., car plugs), ventilation fans, and clothes dryer usage.

Automobile block heater, car interior warmer electricity and other outdoor electricity usage for lawn and gardening equipment, etc., either sub-metered or estimated; monthly values input as exterior usage.

Ventilation system fan energy estimated and subtracted from monitored total appliance energy data, because HOT2000 handles fan power as a separate input, and it calculates and distributes fan energy usage.

Electrical clothes dryer input energy (resistance heaters plus drum/blower motor) assumed to be fully exhausted from the house if the dryer is vented outdoors (most cases); monthly electricity consumption estimated using external clothes dryer model based on occupancy and typical load cycle (Sec. 4.3.3), and added to exterior usage for input.

Houses 11, 12, 17, 18. Exterior usage sub-metered; clothes dryer exhaust energy estimated and added to exterior energy usage; total appliance energy sub-metered; both values used as inputs, with interior usage derived within HOT2000 by subtraction from total.

Remaining houses. Total appliance electricity consumption rates and corresponding outdoor temperatures compared; winter car heater usage estimated from correlation between the two variables at non-car-heater temperatures and according to interview responses. Non-car-plug exterior energy usage was minor, mostly summertime. Except for stock overhead lighting at entrance doors, exterior lighting minimal for all the houses. Clothes dryer exhaust energy estimated and added to estimated car heater energy for exterior sub-total; total appliance energy sub-metered; interior usage derived by subtraction within HOT2000.

Ventilation Fan Power.

Monthly estimates of average input fan power, obtained from monthly average forced air change rates via estimated fan power vs flowrate curves which are close to manufacturers' data for typical installations and also close to the fan power inputs recently observed in some Toronto-area monitored houses (ORTECH International, 1990). Ventilation equipment not sub-metered in most houses, so the daily energy in kWh/d corresponding to the average fan power subtracted from the observed total appliance electricity consumption rate to yield the net total appliance consumption rate used for program input.

TABLE 3 (continued)

Domestic Hot Water Consumption.

Monthly values estimated from monitoring data.

Houses 1-8, 13, 14, 17-20, 22-24: HOT2000 algorithm for DHW calculations, including built-in assumptions and standard efficiencies, used in back-calculation of monthly volumetric hot water pseudo-usage rates (litres/day) equivalent to the observed electricity inputs (kWh/day); the former usage rates, when used as input during simulations, lead to DHW energy requirements equal to the observed consumption.

Houses 9, 10: Natural gas hot water heaters; monthly litres/day for input estimated using same procedure as above, except natural gas instead of electricity.

Houses 11, 12, 15, 16: Hot water usage sub-metered (integrated mechanical systems). Monthly hot water consumption rates estimated directly from monitoring data. (note: Houses 23, 24 also sub-metered for hot water volumetric usage, but model inputs derived from above back-calculation method to maintain consistency with standard procedure followed for other conventional electric DHW systems)

Mechanical System Performance Specifications.

Electric Furnaces, Baseboard Heaters, "Radiant" Ceiling Panels, Duct Heaters, Natural Gas Furnaces, Electric and Natural Gas Hot Water Tanks (Houses 1-10, 13, 14, 19, 20, 22-24). Default HOT2000 seasonal efficiencies used for all months.

Central Exhaust Fans, Conventional Heat-Recovery Ventilators (Houses 1-8, 13, 14, 19, 20, 22-24). Standard monthly average ventilation fan power and energy input calculation as above; heat-recovery efficiency specified according to standard HOT2000 input requirements, based on CAN/CSA-C439-88 test result convention (reporting sensible recovery efficiency at 55 or 30 litres/sec and two test temperatures); low temperature ventilation reduction set to zero for input and partially taken into account elsewhere in calculation of average forced ventilation rate from run-time sub-metering including defrost cycle.

Habitair Heat Pump DHW/Ventilator System with backup Baseboard Heaters (Houses 11 & 12), Peach Electric Furnace/Heat Pump DHW/Ventilator System (Houses 15 & 16), Nilan Heat Pump HRV with Baseboard Heaters (Houses 17 & 18). Suitable energy simulation algorithms lacking in HOT2000, therefore these systems modelled as conventional electric space and water heating systems with no heat recovery on forced ventilation. Monthly average heat-recovery effects estimated separately from sub-metered and other data.

SECTION 4

RESULTS - EVALUATION OF HOT2000 SIMULATIONS

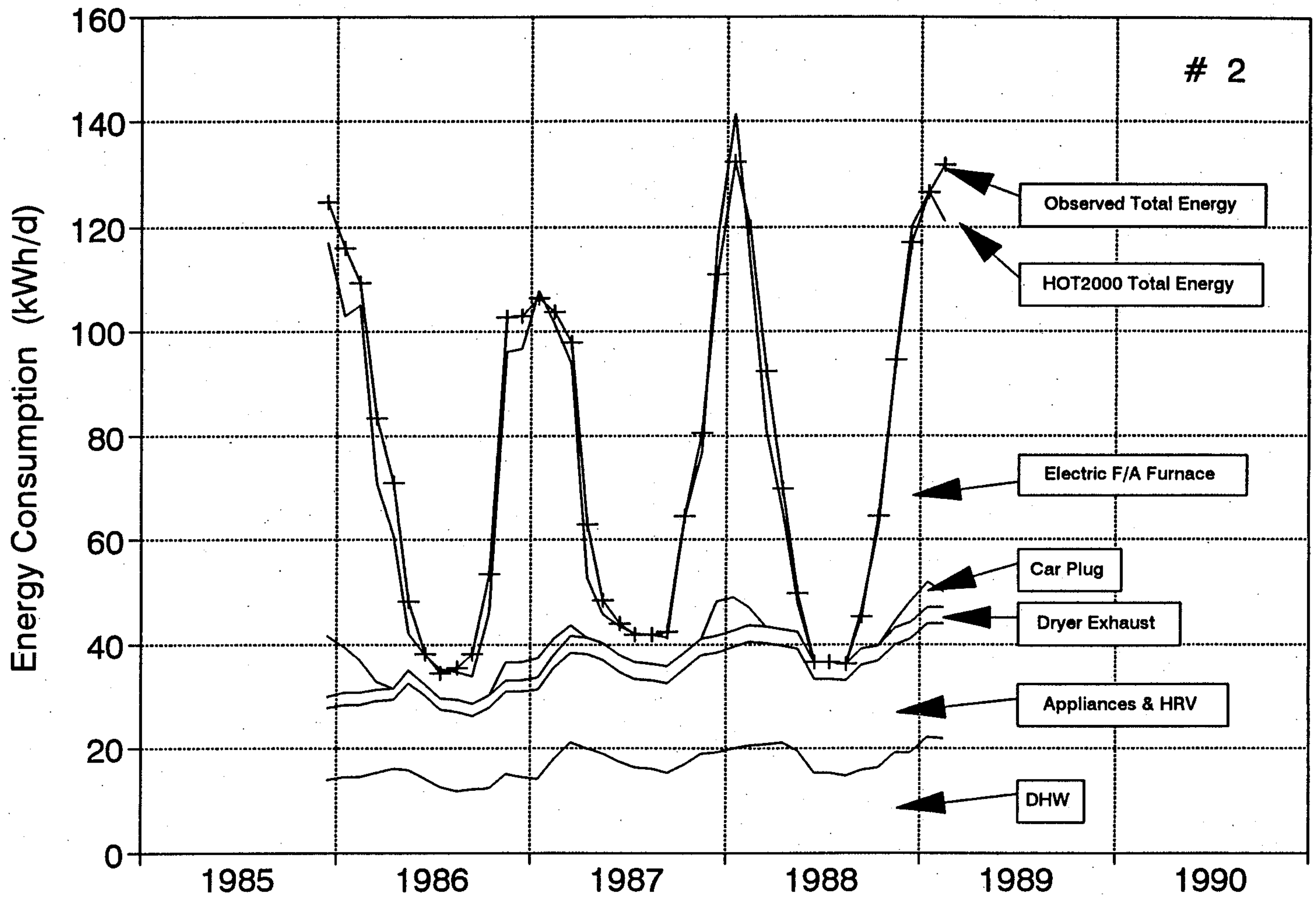
Seventeen of the 23 test houses can be considered to be highly suited to energy systems modelling with HOT2000 at its current stage of development. They all are of simple rectangular plan with basement and main levels, and they have separate space heating, water heating, and air handling systems of conventional type which can be explicitly described in terms of standard program inputs.

Capability for representing the more unusual mechanical systems of the other 6 houses, whose space heating, water heating and ventilation energy management functions are integrated, is not directly available as a HOT2000 feature as yet. However, these homes can be modelled approximately, using a two-part analysis which combines HOT2000 simulations, assuming conventional mechanical equipment, with separate analyses of the effects of the houses' actual integrated mechanical systems. Sufficient tracking of the internal energy flows associated with the various integrated systems has been provided in most cases through the energy sub-metering programme and spot observations.

The results of simulating each of the group of 23 houses through their monitoring periods as described above are shown in Appendix A (Figures A.1 through A.24 (note: the figure numbers within Appendix A correspond to the identification numbers for the houses, with House #21 not reported; for illustration within this section, Figure 1 comprises a repetition of the results for House #2, which are typical within the Flair project group). The set of plots for each house includes the following, respectively:

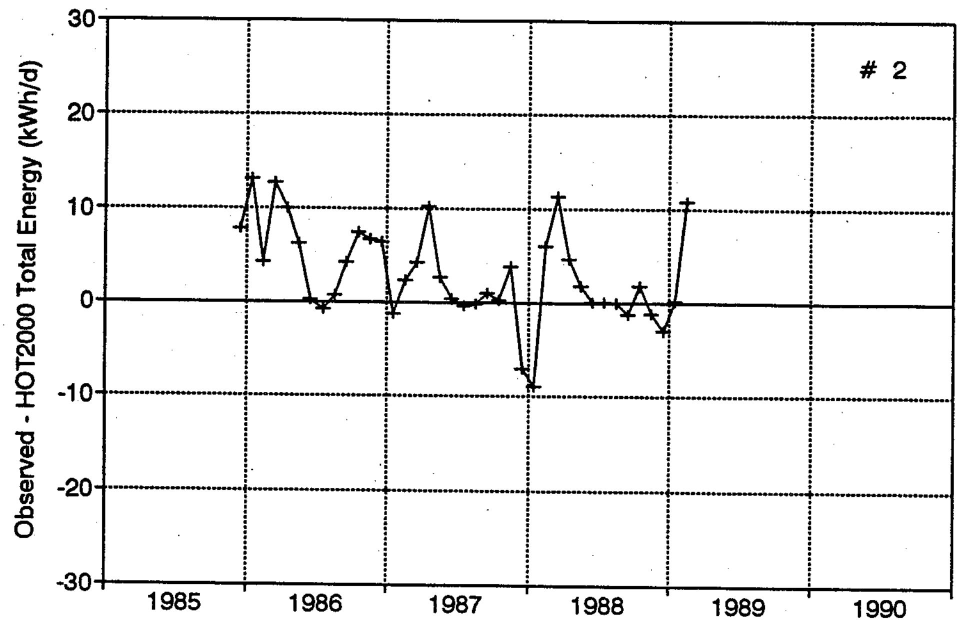
(a) a monthly breakdown of the total purchased energy for the house into the various end uses, with both recorded and simulated results shown.

Unless otherwise indicated in this figure, the monthly average rates of energy consumption for all uses except the space heating portion are identical in both the modelled and actual cases, because the monthly sub-metering data have been used for the HOT2000 inputs. Where it has been necessary to estimate the quantities of electrical energy wasted to the outdoors via car plug or exhausted from the clothes dryer, for example, the estimates have been portioned out of the metered appliance energy consumption rates, so that the analysis preserves the appliance sub-total as observed. In the case of domestic hot water (DHW) usage, observed rates of energy consumption in a standard tank-type water heater have been back-calculated using the HOT2000 algorithm to yield a volumetric usage rate for DHW. When used as program input, this quantity results in an energy usage rate for DHW the same as the observed value. Discussion of aspects of individual sub-models and the Flair houses follows later in this report.

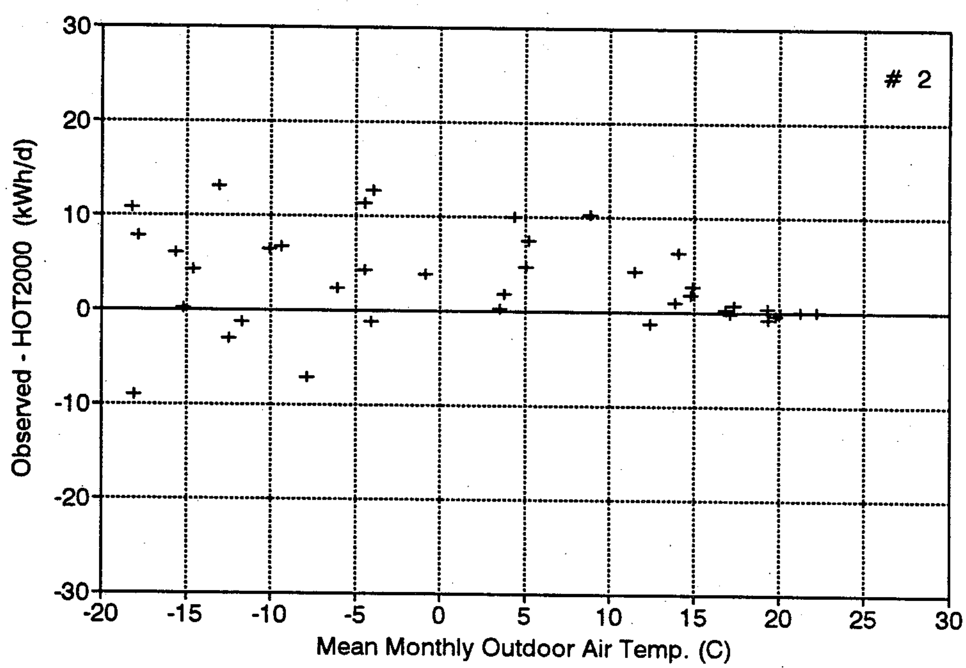


(a)

Figure 1 Example of Energy Modelling Results - House #2
(a) Energy Profile, (b) Model Performance, (c) Occupancy Factors

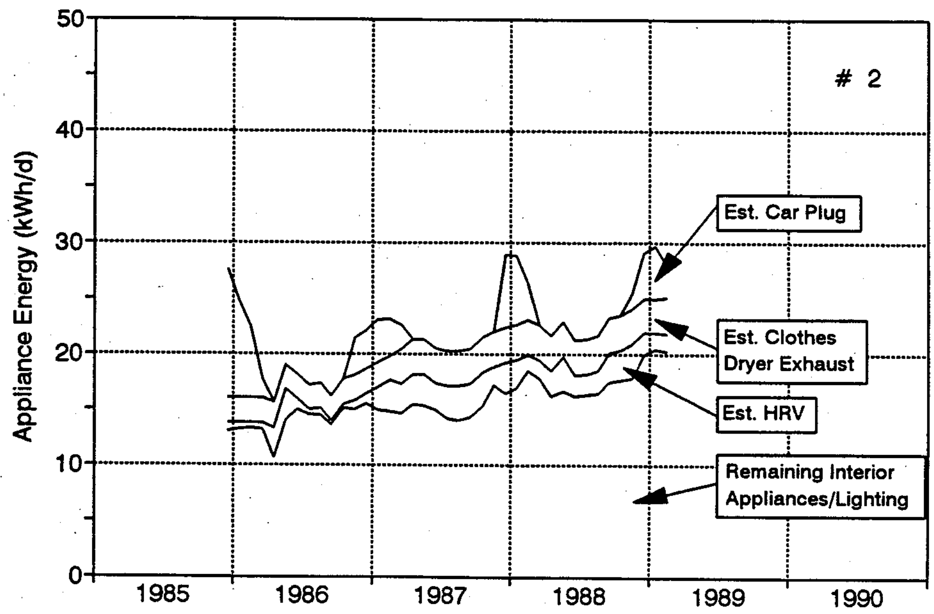


(i)

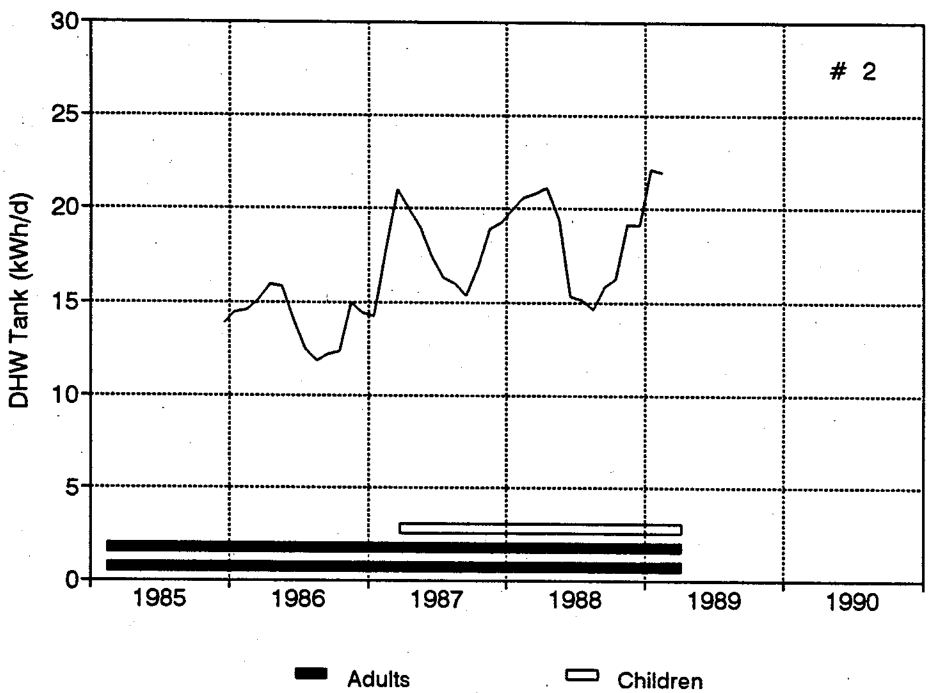


(ii)

Figure 1 (continued) (b) Monthly HOT2000 Performance
(i) Difference Between Observations and Predictions
(ii) Seasonality of Energy Predictability



(i)



(ii)

Figure 1 (continued) (c) Occupancy Factors
(i) End-Use Distribution of Non-Heating Energy
(ii) Domestic Hot Water and Number of Occupants

In the breakdown shown in the energy-profile plot for each house, the two highest traces represent the monthly total purchased energy for the house, one line being the observed total, the other being the total predicted using HOT2000. For the six houses with complex mechanical systems, the total purchased energy prediction includes a HOT2000 simulation result combined with analytical results derived from the monitored data. For all houses, the difference between the two top lines represents the prediction error, which is the error in the estimation of total purchased energy requirement.

(b) the HOT2000 prediction error, observed minus predicted:

(i) a monthly trace of the errors;

(ii) an illustration of the characteristics of the prediction error, shown as the correlation of the monthly error with monthly average outdoor temperature.

(c) selected occupancy-related variables, as monthly averages:

(i) the so-called "base electricity" consumption, or the total lighting and appliance electricity which is used inside the house, and which, in its leftover form as waste heat, is eligible to contribute to satisfaction of part of the dwelling's space heating load. Net values shown in the figures are estimates resulting from subtracting any sub-metered or estimated non-contributing electricity usage from the basic metered quantity. The subtracted energy includes that which is delivered to the engine block and interior heaters of automobiles, exterior lighting and electrical garden equipment, central air conditioners, ventilation equipment and fans, and electric clothes dryers;

(ii) the domestic hot water (DHW) consumption in terms of the electricity consumed (or the electrical equivalent of the natural gas used) for water heating in conventional tank systems (most of the houses), or, instead, the metered quantity of heated water produced and used in the unconventional systems. Also shown within the DHW plot for each house are the numbers of children and adults ("adults" includes older children) normally resident in the house.

Rates of energy usage and errors in their prediction are expressed in the figures in average kilowatt hours per day over the month (kWh/d).

4.1 OVERALL ASSESSMENT

It is evident from Figures A.1 through A.24 that, on the whole, the month-by-month space heating and total house energy requirements are reasonably well predicted for most of the occupied Flair project houses. In perspective, this is an encouraging result because although the largest single end use in both the conventional and low-energy project houses usually is the space heating system, the calculated space heating energy is merely the amount needed to satisfy the leftover heating demand once the levels of utilization of all the available contributions of energy originating in non-space-heating end uses have been determined. The space heating energy calculation thus suffers from the accumulated effect of deficiencies in all the other process sub-models.

Numerical summary statistics of the analysis are shown in Table 4, with a visual indication of overall modelling performance given as Figure 2. From a basis within the sets of characterizing model inputs which could be derived from the monitoring data, the long-term averages of measured minus predicted energy usage in the project's houses generally turned out to be not far from zero. In most cases, the total, or net, difference between the observed total house energy consumption over twelve contiguous months and the corresponding HOT2000 prediction is less than 2000 kWh, or about 10 percent of total annual consumption. Within the set of project houses, there is greater tendency for the model to underpredict the annual energy requirement than for the reverse to occur. Exceptions and other aspects of energy use and its prediction in project houses are discussed further in this and following sections. The Table 4/Figure 2 results should be viewed carefully in context, because (a) the monitoring periods vary from house to house, and (b) the general levels of space heating and other energy consumption vary among the houses depending upon building envelope design, mechanical systems, and occupancy.

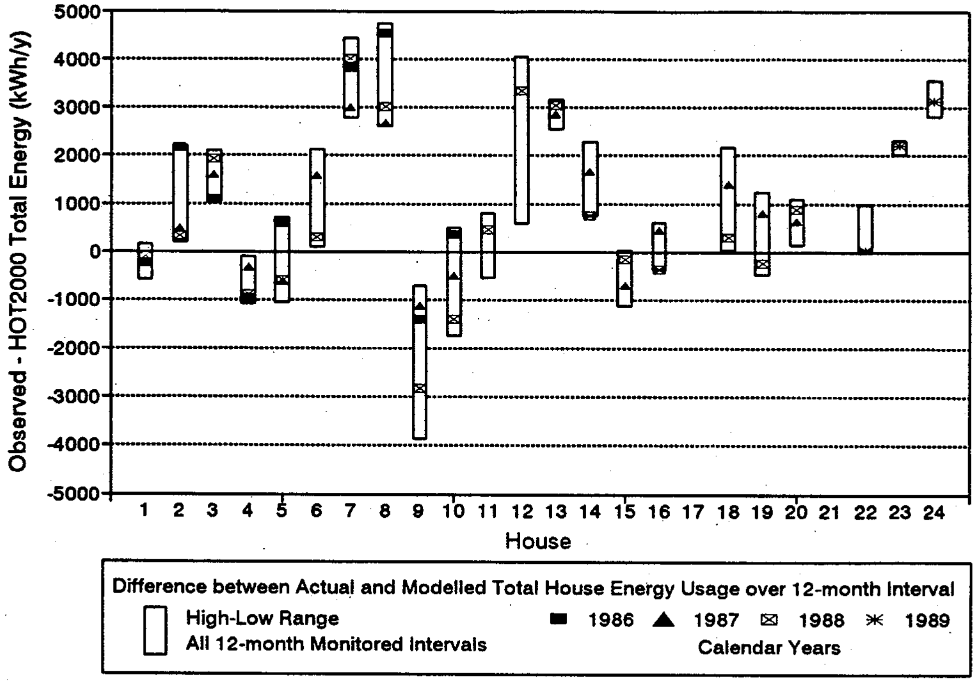
Most notable among the findings of the analysis is the indication of month-to-month and year-to-year variation in energy-use predictability, as exemplified in Figures A.1(b) through A.24(b) and in Figure 2. The predictability is seasonal, but usually is non-linear with respect to outdoor temperature. A tendency for underprediction of a house's actual energy consumption in the shoulder (spring and fall) months seems to be at least partially counterbalanced by a tendency for overprediction at the coldest time of the year. The seasonality differs from house to house, and there is some drift from year to year. In some cases, the monthly patterns are similar among sub-groups of the houses; however, these trends cannot be considered to be definitive at the present level of analysis, since there are almost as many exceptions to the patterns as there are similarities.

The monitoring records also reveal significant monthly variations in the energy-consuming activities of the occupants (e.g., Figures A.1(c) through A.24(c) and Figure 2). These may be large enough to have an impact on month-to-month predictability, due at least partly to the magnitude of non-heating energy usage relative to the total house heat loss. For many months of the year, consumption by non-heating system appliances can make up the majority of the total energy usage in the house, even though the annual energy total is dominated by space heating energy. As a result, sub-model representation of the operation of those appliances and the availability and utilization of their waste energy as space heat can be the major component affecting overall model performance for a good part of the year. If appliance usage is decidedly non-steady at such times, then predictability may also lack uniformity. With its smaller space heating

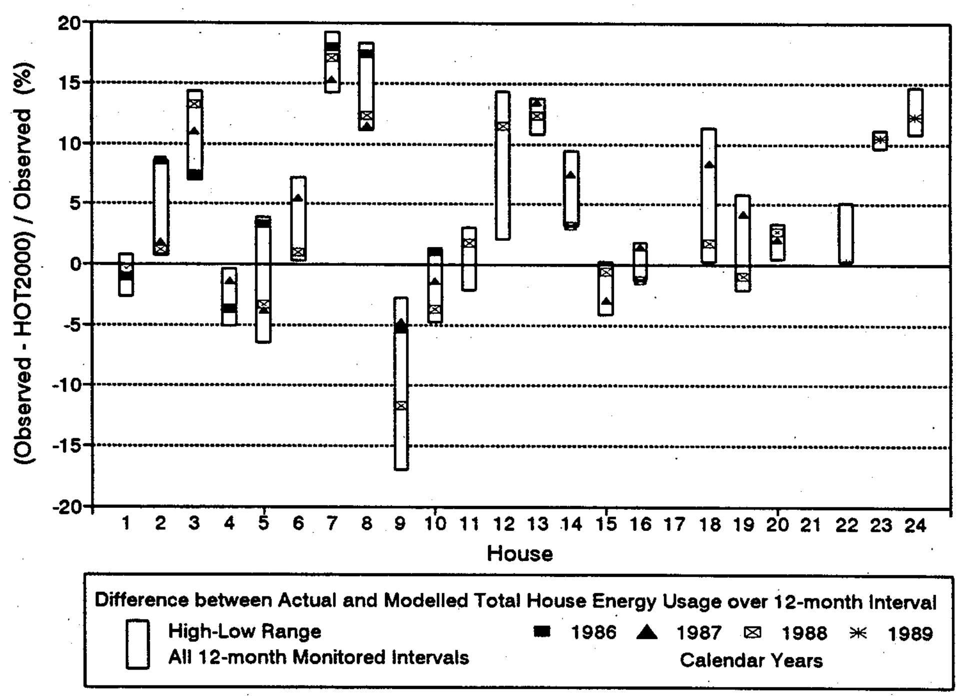
TABLE 4
MONTHLY SIMULATION PERFORMANCE SUMMARY - TOTAL PURCHASED ENERGY IN FLAIR PROJECT HOUSES

NET DIFFERENCE OVER INDICATED 12-MONTH PERIOD IN kWh[1]										
House	Monitoring Period Start-End	Months	8601-8612	8609-8708	8701-8712	8709-8808	8801-8812	8901-8912	Highest	Lowest
1	8512-8902	39	-223	-577	-245	71	-91		169	-577
2	8512-8902	39	2165	1301	479	375	327		2208	203
3	8512-8902	39	1097	1202	1597	2057	1922		2105	1045
4	8512-8902	39	-952	-879	-334	-121	-871		-101	-1069
5	8512-8902	39	579	319	-607	-1011	-598		704	-1056
6	8512-8902	39			1588	664	295		2123	109
7	8512-8902	39	3835	2801	3011	4433	4019		4449	2801
8	8512-8902	39	4539	3624	2677	3080	3027		4749	2623
9	8512-8902	39	-1397	-953	-1118	-1704	-2816		-706	-3854
10	8512-8902	39	373	-639	-480	-22	-1399		511	-1746
11	8705-8902	22				-437	477		812	-533
12	8705-8902	22				661	3340		4054	598
13	8608-8902	31		2688	2864	3122	3036		3164	2549
14	8608-8812	29		2234	1670	1046	751		2299	751
15	8609-8902	30		-1120	-683	-95	-145		48	-1120
16	8609-8902	30		-188	446	235	-370		609	-370
17	8603-8902	36								
18	8609-8902	30		2160	1393	85	295		2170	37
19	8606-8902	33		870	814	416	-218		1245	-457
20	8609-8902	30		144	625	684	896		1104	144
22	8812-9003	16						45	982	45
23	8812-9003	16						2206	2306	2029
24	8810-9002	17						3144	3571	2815
NET DIFFERENCE OVER INDICATED 12-MONTH PERIOD AS PERCENTAGE OF OBSERVED TOTAL HOUSE ENERGY[2]										
1	8512-8902	39	-1.0	-2.7	-1.2	0.3	-0.4		0.8	-2.7
2	8512-8902	39	8.6	5.1	1.9	1.4	1.2		8.6	0.8
3	8512-8902	39	7.5	8.1	11.1	13.9	13.2		14.4	7.0
4	8512-8902	39	-3.7	-3.6	-1.4	-0.5	-3.7		-0.4	-5.1
5	8512-8902	39	3.3	1.9	-3.8	-5.8	-3.3		3.9	-6.5
6	8512-8902	39			5.5	2.2	0.9		7.2	0.4
7	8512-8902	39	18.0	14.3	15.3	19.1	17.1		19.2	14.3
8	8512-8902	39	17.4	14.7	11.5	12.8	12.4		18.3	11.1
9	8512-8902	39	-5.4	-3.7	-4.7	-7.0	-11.7		-2.7	-17.0
10	8512-8902	39	1.0	-1.8	-1.4	-0.1	-3.7		1.4	-4.8
11	8705-8902	22				-1.7	1.8		3.1	-2.1
12	8705-8902	22				2.3	11.5		14.4	2.1
13	8608-8902	31		12.2	13.5	13.3	12.3		13.8	10.8
14	8608-8812	29		9.0	7.5	4.6	3.2		9.4	3.2
15	8609-8902	30		-4.1	-3.0	-0.4	-0.6		0.2	-4.2
16	8609-8902	30		-0.6	1.4	0.8	-1.3		1.9	-1.3
17	8603-8902	36								
18	8609-8902	30		11.2	8.4	0.5	1.8		11.4	0.2
19	8606-8902	33		4.2	4.2	2.0	-1.0		5.8	-2.1
20	8609-8902	30		0.5	2.1	2.2	2.8		3.4	0.5
22	8812-9003	16						0.2	5.1	0.2
23	8812-9003	16						10.5	11.2	9.7
24	8810-9002	17						12.3	14.7	10.8

Note: 1. Observed Total Energy - HOT2000 Estimate of Total Energy
2. (Observed Total Energy - HOT2000 Estimate of Total Energy) / Observed Total Energy * 100



(a)



(b)

Figure 2 Summary of Modelling Results
(a) Differences between Observations and HOT2000 Predictions
(b) Differences as Percentage of Total Energy Usage

requirements, the typical low-energy house especially could be subject to this effect.

It would appear, then, that the non-heating system sub-models of HOT2000 should be allotted due scrutiny in the overall scheme of the energy-use simulations. Where necessary, they should be reviewed for representativeness and upgraded. Further capability for temporal variation of the human factors of energy use also should be included within HOT2000 if the program is to be applied for analytical purposes needing better resolution than the standard low-energy design exercise.

The drift range of the year-to-year meandering of energy-use predictability over the monitoring period is typically 1000 to 2000 kWh, or 5 to 10 percent of the magnitude of the average annual total for a house. It is possible that longer-term observation would show even greater variation than noted herein. For defensible evaluation of HOT2000 and other residential energy simulation models which use average weather or other parameters, the findings of the current analysis provide good reason for requiring clear specification of the verification interval that is used, including the year. A prediction error associated with the month of January one year seems very likely to be significantly different, both in its magnitude and in its cause, from errors arising in April or July of the same or some other year.

Reasons can be suggested for many of the cases of larger error magnitudes or larger changes in magnitudes which are shown in Figures A.1(b) through A.24(b) and Figure 2, although the analysis has not yielded a complete explanation for all of the behaviour.

For example, House #9 exhibits a sizeable overprediction for the 1988-89 heating season, attributable to a significant drop in observed natural gas space heating energy consumption in comparison to its earlier years. To a lesser extent the same phenomenon can be seen in the results for House #10. Consistent data returns from the sub-metering of natural gas usage in the houses indicate no loss of gas meter function. Minor differences in recorded interior temperature settings and readings, which are, of course, included in the month-by-month simulations reported in the figures, are the only significant changes to occupancy and operating conditions that were noted during monitoring. Otherwise the collected data suggest no reason to expect a decreased space heating requirement. The fact that the effect is common to the two gas-heated houses may be indicative of a response to something external, such as unusual environmental conditions affecting the combustion/venting process, variation in the energy content of mains gas, etc.

A trending discrepancy between observed and estimated energy requirements for House #12 over the monitoring period is not paralleled in the results for the identically equipped House #11 next door. Sub-metering of the integrated mechanical system installed in the house provides some indication that the drift in House #12 may be attributable to system performance degradation resulting from a gradual loss of refrigerant from the heat pump sub-component. However, flow metering records show that DHW usage in the house declined significantly over the same period, so non-linearities in integrated system performance may have had something to do with it. Heat pump characteristics assumed for the entire period of the simulations are based on testing done shortly after the unit was commissioned.

For House #18, heating requirements during the first winter of occupancy are significantly underpredicted, while the next two winters are very closely simulated. No explanation is suggested in the information available for this house. Unfortunately, homeowner intervention in mechanical system operation has rendered infeasible any parallel simulation of the matching House #17.

At least one of the individually thermostatted basement baseboard heaters in House #19 remained at a high thermostat setting beyond the beginning of summer in 1986, the first year of occupancy for the house, resulting in an underprediction of the heating load.

Houses #7, #8, and #13 exhibit consistently high underpredictions throughout the study period. This may be partially explained by the fact that the estimated air change rates that result from the standard simulation protocol used for the analysis of all houses, which includes the forced flowrates derived from ventilator flow monitoring and the natural leakage based on airtightness test results, are significantly lower than the total airchange rates inferred from tracer gas studies. Windows probably replaced fans as the preferred means of ventilation in the three houses.

Both computerized hourly and manual monitoring of House #24 in the period prior to its being occupied provide virtually the same HOT2000 input data, thereby failing to discredit the large underprediction which is experienced for that house under operating conditions of zero hot water heating energy requirement and almost no non-space heating appliance or lighting energy usage. Monthly modelling performance is better for this house during the following period of occupancy by several adults. Houses #22 and #23 also were monitored during extended intervals of no occupancy over the 1988-89 winter, but do not replicate the large prediction error of their counterpart.

The above is a quick peek at the more noticeable among the prediction problems which appear in the results of the standardized application of monthly energy-use simulations for the project houses. The cited difficulties are mostly related to differences between the data that were actually collected and the information that is needed to provide fair representation of processes in the simulation. For these cases, either the phenomenon is not easily characterizable with the information available (e.g., suspected freon loss in House #12 in the absence of parallel performance testing), or the data do not adequately describe the process (e.g., unmetered air exchange in Houses #7, #8, #13). The larger errors suggest more about monitoring tactics than modelling capabilities.

Smaller, or non-outlying, errors understandably do not attract the same level of scrutiny. For this project, the mass of relatively non-descript, probably characteristic, HOT2000 prediction errors peaks at about ± 2000 kWh per any twelve-month period between the start and completion of the monitoring program, and averages somewhat less. For some of the houses, the best twelve-month performance has a cumulative difference between model and observations of essentially zero, with the contributing monthly errors also all very small.

The annual modelling performance for each house varies, depending upon which 12-month interval is selected. For a single house, it typically floats within an error band 1000 to 2000 kWh wide as noted above, somewhere between a 12-month overprediction of 2000 kWh and a 12-month underprediction of 2000 kWh. Some houses vary as little as 500 to 1000 kWh over the monitoring period. The differences in error level among the houses thus tend to be greater than the drift in predictability shown in the results for each. In other words, project houses tend to be overpredicted or underpredicted relatively consistently throughout the monitoring period, some more, some less.

Residual modelling error is therefore not random. Since room for improvement or enhancement of the input data can still be seen as possible (examples below), the next logical level of error correction would evidently lie more with the individual house, its operation, and its representation in the model, and somewhat less with the possible accuracy and interaction of model algorithms. Despite its length, completeness and reliability, the descriptive data set appears to be the present limit to capability for simulating energy use patterns in the Flair project houses using HOT2000.

At a general level, the analytical experience of this project provides reaffirmation of a familiar tenet: the importance of good monitoring data cannot be overemphasized. In this case, the data quality was adequate for the subsequent purpose of modelling monthly energy usage. However, due to the limited number of monitored variables, the resolution of energy flows for even the simplest of the envelope/mechanical system combinations encountered in the project houses still leaves some questions. A sparse set of observation points sampled per house may permit a greater degree of replication within a group of monitored houses, but the metering of as many variables as possible within each house is probably the more desirable approach for future projects of this type. The need for more monitoring stations is especially supported by the growing recognition that individual minor processes (and also the interactions among all minor and major processes) are important both to understanding and to overall energy-use predictability.

Further, whereas an automated system of data collection may be subject to unfortunate lapses and breakdowns necessitating some circumventive analysis, and also may lead to a lower level of familiarity with the non-digital way of life within the test building, the high frequency of recorded measurements which can be obtained through computerized data acquisition is a significant advantage in any subsequent analysis. Reliability, flexibility, and economy of the hardware/software packages required to carry on comprehensive monitoring of an occupied unit's energy flows presently need to be improved, however. As the electronic revolution continues, the necessary changes probably will happen and manual data collection may in time be rendered uncompetitive from the double perspective of site-visit logistics and cost. This eventuality would be acceptable provided that future monitoring programs could include allowance for sufficient site visitation to ensure that unprogrammed human understanding of the monitored interior environment is at hand at the time of analysis.

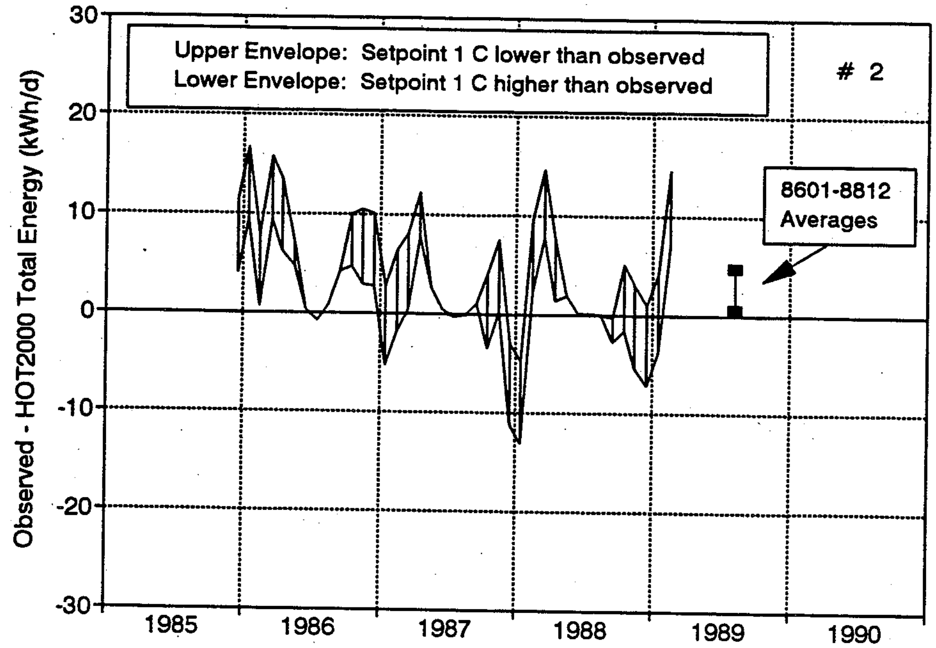
Finally, the Flair house energy monitoring program and subsequent analysis of simulation capabilities discussed in this report have verified that the energy flows within an occupied home comprise a phenomenon whose complexity can be far from trivial. With a relatively comprehensive data set giving consistent coverage of several years of occupied operation of the 23 homes, residual energy-use estimation errors under 10 percent can be achieved using HOT2000 Version 6.0, which is a simple monthly representation of the major processes. Improvements to this outcome look possible, and there is a thirst for still more accuracy, but the latter is tempered by the apparent cost of the data collection necessary to pin down the vagaries of occupancy. The project experience fails to lead one to the conclusion that there is a good substitute for trial-and-error testing of energy-conserving products and construction techniques, since occupant activities appear to be very important to the patterns of purchased energy usage in the house.

4.2 PERSPECTIVE ON THE PREDICTION ERRORS IN THE FLAIR HOUSES

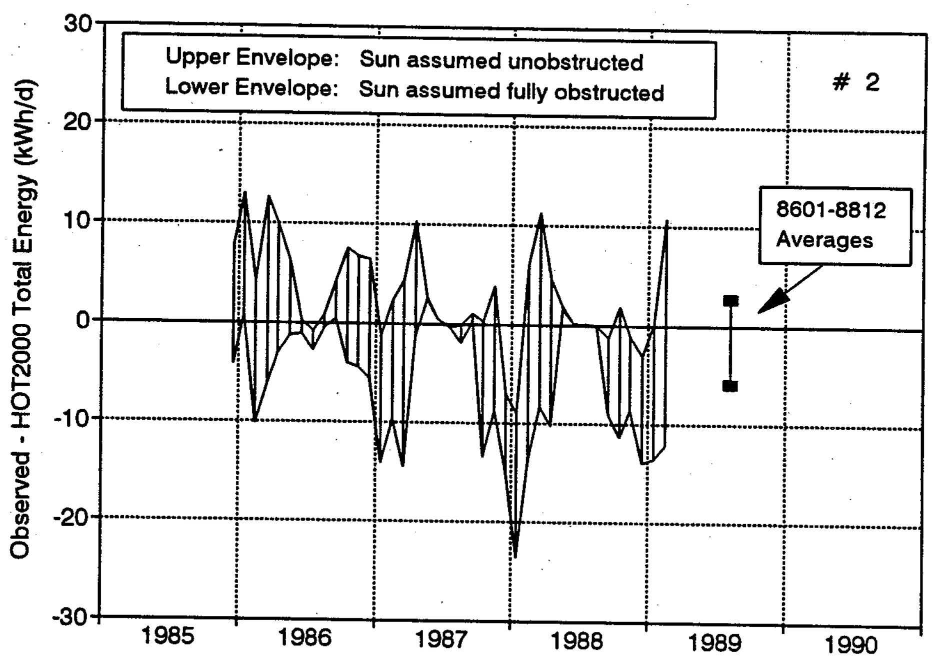
In terms of the deployment of HOT2000 both as a design and as an analytical tool, the essential question for the present investigation is: are the variations between the HOT2000-predicted energy requirements and the recorded energy requirements significant on a month-to-month basis, and, if so, what program improvements are suggested by the results? Collectively, the outcomes of the energy simulations for the 23 Flair project houses clearly indicate that the remaining monthly differences between the observed and predicted energy usage rates do exhibit non-trivial patterns. However, further examination reveals that there is no parsimonious explanation for their presence and size, a large number of factors being involved.

A simplified view of the relative magnitude of the residual differences is shown in Figure 3, continuing the example of House #2 from Figure 1. As evidenced in the earlier figure, the errors of prediction for the example house exhibit both a seasonality and a noticeable non-systematic element which are typical of many of the Flair project test houses.

House #2 is a rectangular, electrically heated, 100-square-metre-class bungalow, with insulation levels of RSI 7.0, 4.7, and 3.5 in the ceiling, main walls, and basement walls, respectively, and an air-to-air heat-recovery ventilator. Occupancy is by two adults, both employed outside the home until the arrival of their first child, partway through the monitoring period. There is no air conditioner, a significant amount of electricity is delivered outdoors to the automobile block



(a)



(b)

Figure 3 Sensitivity of HOT2000 Simulation to Input Variables (House #2)
(a) Effect of Interior Setpoint Temperature
(b) Effect of Incident Solar Radiation

heater in winter, and the forced-air furnace blower is operated continuously during the winter and sometimes continuously during the summer. The interior thermostat setting is maintained near 22°C during the heating months with a 2°C night setback applied during many, but not all, nights, and window draperies are normally open during the day and drawn closed at night.

Of the uncertain quantities dealt with during the energy modelling of House #2 and the others, two of the most significant would be (a) the "real" effective temperature setting, and (b) the effect of drapery operation on solar gains. Both variables provide a characteristic degree of difficulty to the linking of the monitoring and modelling processes.

Version 6.0 of HOT2000 retains the two-zone, point-process model of energy usage in the house. The space heating system is assumed to respond to a setpoint temperature representing the above-grade levels as well as to one representing the basement, if present. Even with the enhanced batch HOT2000 capability that allows monthly changes in the setpoints to be used within this study, it is easy to see that this does not ensure a realistic representation of the interior temperature regime. Control at a central thermostat in the project houses could commonly be disrupted and influenced by hourly variations in horizontal and vertical stratification within the space, localized overheating and temporary energy storage in south-side rooms, and so on. Further, some of the houses (#'s 17, 18, 19, 20, 24) have individual controls for each baseboard heater.

Drapery operation in a house is typically a partly scheduled, partly reactive activity, with resulting seasonal tendencies. In this study, monitoring of drapery materials and manipulations was non-rigorous and qualitative, handled almost incidentally within semi-annual interviews. HOT2000 has been extended for the purposes of this investigation to account for non-fixed shading through input specification of a single value, which can be varied monthly along with the other parameters.

In Figure 3(a), simulation results are shown for a pair of cases in which the input interior setpoint temperatures for House #2 have been adjusted uniformly upward or downward by one degree from the actual estimates determined during the study for each month of the monitoring period. All other input parameters retain the final values they have been assigned during the course of the analysis. Similarly, Figure 3(b) is an illustration of the simulation outcomes for two other extreme test cases in which, through use of the augmented HOT2000 provision for non-fixed shading (draperies, trees, etc.), either the entire incident solar radiation has been allowed to enter the house unimpeded via the windows (i.e., no shading other than by the building's exterior geometry), or all incident solar radiation has been blocked from entering the house (i.e., full shading).

Both of the input adjustments shown in Figure 3 are systematic, for illustrative purposes only, so, while they help to demonstrate the magnitude of the model's sensitivity to input variations, they result primarily in a shift in the simulation results (e.g., months with unusual simulation results relative to others in the study period tend to retain their positions). In contrast, the errors which normally could be introduced into the modelling of the houses' energy performance due to data difficulties and/or model shortcomings are more likely to be made up of season-related or quasi-cyclical effects (problems with the representation of the energy processes) and/or single-month effects (phenomenological randomness or interpretive errors).

The two-degree setpoint adjustment range is small relative to the usually dominant indoor/outdoor temperature difference for heating months, so that the range in the two results is more or less constant during those months (around 8 kWh per day, or 4 kWh/d per °C). Fewer heating hours occur during the shoulder seasons, with the effect being a smaller range in the simulation results shown for those months in Figure 3(a). Heating setpoint has no impact in summer.

Over three full annual cycles of monitoring (January 1986 to December 1988), each 1.0°C of setpoint adjustment for House #2 averages to an impact of about 2.2 kWh/d, or 3.1 percent in terms of total purchased energy. This may be compared to the overall prediction error obtained for this house of +2.4 kWh/d, or +3.3 percent (i.e., actual whole-house consumption for the three years is higher than predicted consumption by 2.4 kWh/d).

Based upon the interior temperature setting and reading data collected during the project and upon the level of confidence which these data engender regarding knowledge of the prevailing interior conditions (the coverage was mainly by spot measurements, whereas thermostats were controlled by occupants), estimation of the actual monthly setpoint temperatures to the nearest one degree Celsius would have to be considered to be the best that one could realistically accomplish. Further, there is nothing within the setpoint estimate which imitates the actual spatial distribution of temperatures in the various rooms.

The effect of uniform shading on predicted solar gain is much more seasonal in nature, as evidenced in Figure 3(b). For House #2, the difference between no shading and full shading can be close to 20 kWh/d in terms of displaced space heating during the most highly impacted months, February and March, when incident angle is low (unobstructed windows), strength of the incoming radiation is higher than during the early and mid-winter months, and demand for heating energy is high. Overall, the opportunity for solar gain through the windows of the example house has the equivalent value of about 8.3 kWh/d of space heating on average over the same 36-month period covering calendar years 1986 through 1988, or about 11.6 percent of total purchased energy.

From an underprediction of 2.4 kWh/d (+3.3 %), with draperies assumed to be open during the day (similar to the actual reported operation for this house), the modelled throttling of solar gain through partial or full shading therefore trends toward a maximum average overprediction of 5.9 kWh/d (-8.2 %). In reality, the latter condition would be difficult to achieve with draperies alone, however.

If the lightweight draperies utilized in House #2 were always drawn, it is estimated that the difference would be an effective filtering (rejection) of about 30 percent of the energy that would have been captured via the unobstructed windows. Aside from the lack of rigour used here to arrive at the degree of filtering by drapery materials, the sensitivity due solely to the occupants' reporting of their operation of the draperies therefore might be only about 2.5 kWh/d at the extreme, which is similar in its effect to a 1.0°C uncertainty in setpoint temperature. The actual uncertainty regarding drapery operation for House #2 is significantly less than this, because of a high degree of consistency in its occupants' reports about their use of the window coverings during the more than three years of monitoring. For other houses, uncertainty about drapery operation usually would be larger.

Total energy consumption and energy model prediction error patterns for most of the other houses resemble those for House #2. Over the multi-year period of monitoring, this means an average discrepancy between observation and prediction of less than 10 percent usually, as shown in Figure 2 and Table 4. Individual sensitivity to the most highly suspected among all the input variables derived from field data is suggested by the above results to be around a maximum of about two or three percent at the level of precision achieved for these variables. Combinations of data uncertainty effects such as those explored above, together with basic failings in the energy process model, therefore could feasibly result in total errors of the same magnitudes as have been obtained for these homes.

The fact that a noticeable seasonality remains in the monthly prediction errors indicates that there is still room for refinement in the energy modelling of the 23 homes. This result has occurred despite the more extensive list of variables which have been taken into account on a monthly basis during the analysis, and the care which was taken in the preparation of the input data sets. The patterns of the fluctuations in predictability both vary and show similarities among the houses, and, in so doing, they invite deeper probing of causes and effects within both the monitoring process and the modelling process for a HOT2000-based analysis. Understanding the modelling of contributing processes through further delving will be restricted by the fact that the encountered estimation errors in this analysis are net of the combination of several sub-models. The monitoring data provide some insights nevertheless. The latter part of this report summarizes certain of the findings which may be useful to the low-energy housing industry, building officials, researchers, and modellers.

Additional model investigations with selected houses and the available data may help to explain some of the remaining non-random patterns in the errors of prediction. Overall, however, it is believed that the present study's standardized evaluation of all 23 houses using HOT2000 has exposed the useful application limit for the Flair project energy-use database. With lesser certainty, through its detailed consideration of monitored variables including their measurement and deployment as part of the energy-use simulations, the analytical process has also raised a few points about the simplified process representation within some of the program's sub-models and algorithms. It would appear that, in order of importance, both (a) the level of energy-use data coverage and its resolution which have resulted from the project's monitoring program, and (b) the capability for resolving the energy-use processes in the houses using a one-pass monthly model, may be constraints to further refinement of the energy-use characterizations for the group of project houses.

It therefore may be inferred from the results of this analysis that in order to achieve smaller modelling errors of only a few percent of purchased energy when using Version 6.0 of HOT2000 for occupied residences, both of the following probably would be required: (a) a refinement of the program to take more account of some of the energy-related processes which are relevant at a sub-daily time scale, and (b) an increase in the level of the monitoring effort to acquire the necessary and sufficient calibration and verification data.

HOT2000 development has been ongoing throughout the execution and analysis of the Flair Energy Demo Project. Initiatives to improve certain of its algorithms and sub-models have been suggested partly as a result of the experiences and requests of the program's users. It is hoped that what has been revealed through the present analysis of the project's monitoring database will be of assistance to the users in selecting appropriate values for certain input quantities, and also will constitute useful feedback for the program's developers.

4.3 SELECTED TOPICS

4.3.1 Magnitude of Total and Peak Energy Requirements of Project Houses

Auxiliary space heating consumption in the houses is generally low, typically averaging about 2.5 to 4.5 kW for the coldest part of a Winnipeg winter when outdoor temperature averages about -20°C during a month. Part of the variation among the houses is due to difference in size of the two basic house plans included in the group and to the variety of different envelope and mechanical system designs utilized; however, much of the encountered range is simply a function of the quantity of non-space-heating energy consumed in each house, which in each case defrays direct space heating energy consumption. The sets of Figures A.1 through A.24 illustrate the extreme variability of lifestyle-related energy usage from one house to the next, and its overshadowing effect in comparison to the differences in heating energy requirements associated with the various envelope constructions that were demonstrated in the houses. In fact, although the houses were for the most part replicated in pairs according to building envelope, the replication has ultimately delivered negligible insight to the project.

Total purchased energy usage during the year's cold month ranges from about 3.5 to 6.0 kW, the equivalent continuous non-heating part of it ranging from less than 1.0 to more than 2.0 kW, depending on the house. Space heating therefore continues to make up the largest portion of the energy pie for the group of mainly low-energy project houses. However, due to the relatively low envelope heat losses in most of them, peak total loads in the winter do not often occur during the middle of the night when outdoor temperatures are lowest. Instead, maximum loads are most commonly experienced on relatively cold days when heating demand happens to be simultaneous with the energy requirements of one of the following normal occupant activities: (a) at the end of an overnight thermostat setback interval when the space heating system could be running at capacity and there may also be some water heating load; (b) at times of heavy morning or afternoon hot water usage, especially clothes washing and drying; or (c) when the electric range is being utilized for meal preparation sometime during the late afternoon or evening.

Among Houses #1 to #8, for example, the peak 15-minute annual load in the four smaller project homes (280 cubic metres heated, 10 kW typical space heating capacity) was found to be in the range 14 to 18 kW, while in the four larger units (450 cubic metres, 15 kW) the range was 19 to 24 kW (Manitoba Hydro, 1989). Corresponding load factors on the peak days ranged from 0.16 to 0.30 (i.e., ratio of 24-hour average power to highest 15-minute average power). The lower end of the load ranges represents homes designed to meet the R-2000 energy standard, while the higher end reflects the conventional homes in the group. Due to the non-coincidence of weekly schedules for washing clothes and cooking large meals, the days on which the largest peaks occurred varied among the houses, and the magnitude of individual peaks varied widely from day to day in a given house.

The above demand metering data do not provide any surprises. While space heating should continue to make up a sizeable portion of the seasonal peak energy demand in all-electric homes as basic low-energy construction gains market share and/or as more stringent energy standards are applied, residential peaks are unlikely to change their times of occurrence away from the times of the day that the typical Canadian electrical utility with a diverse load presently experiences its peaks, i.e., the traditional morning and afternoon/evening periods. Short-term demands for non-heating power in the home are already quite influential at the utility level. Reduction in residential space-heating energy requirements therefore will only contribute to a sharpening of the spikes. Use of diurnal thermostat setbacks will enhance the effect; further development and introduction of energy-saving technologies and load management for non-space-heating appliances will likely mitigate it. Unknown at this time is the realistic potential for the latter.

The absolute error in predicting the energy consumption (space heating or total) as determined during this investigation ranges up to more than 20 kWh/d (equivalent to over 0.8 kW continuous) in some winter months for some houses, but is usually less than half that amount (i.e., less than 10 kwh/d or 0.4 kW). Below are discussed some of the possible factors which may be contributing to the remaining differences between the actual and the predicted usage.

4.3.2 Actual Weather

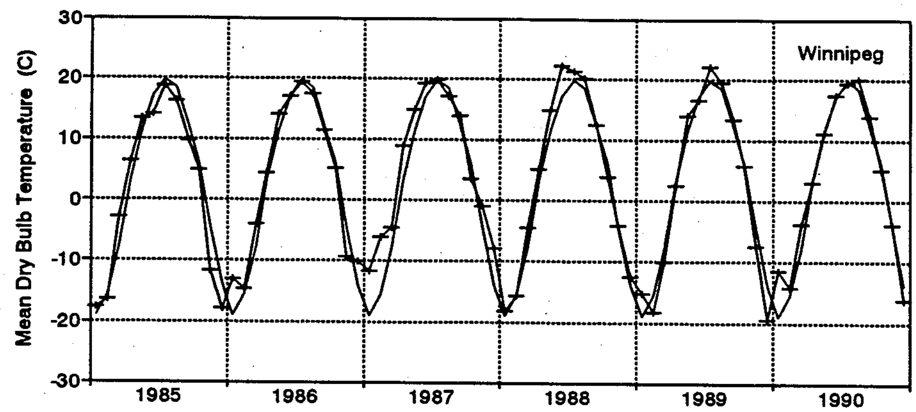
The balance between the basic elements of space heating demand and supply in a modern Canadian house essentially consists of the outdoor/indoor temperature difference on the one side and the utilizable portions of the captured, incident solar radiation and interior non-space-heating energy usage on the other, with the space heating system making up the difference. The two major external elements driving the space heating system are highly seasonal, and they vary inversely according to the sun's annual passage. Thus the relative importance of the major elements within the overall balance also changes considerably from month to month throughout the annual cycle.

For most of the project houses, residual prediction error shows a strong seasonal pattern (Figures A.1(b) through A.24(b)). To realize only random errors in all months, house-energy model algorithms and sub-models must correctly represent and integrate the strong seasonality of the subject phenomena. Determination of the fractional utilization of internal and passive solar heat gains in the house is one example of a procedure whose seasonal validity could elicit some suspicion. The internal gain utilization factor for a month, or the fraction of internal heat gain to be utilized as heating energy, is assumed in HOT2000 to be a polynomial function of the ratio of total available energy to gross space heating demand energy, where the internally available energy includes that from occupants, appliances and lighting, and domestic hot water usage. Coefficients and form of the polynomial remain the same for all months. Calculation of the solar heat gain utilization factor follows a similar procedure, with an additional wrinkle to account for thermal mass of the building (CHBA, 1991b).

It seems reasonable to expect that, if there is significant seasonal bias in the net accuracy of HOT2000 due to problems in the waste energy utilization calculation or any other algorithm, then unusual deviations from the normal monthly balance of major elements may be borne out as inconsistencies in the usual seasonal error patterns. In order to be visible, such effects would have to be larger than other residual prediction errors caused by input data deficiencies.

Long-term average Winnipeg weather is compared, in Figure 4, to that which occurred during the Flair project monitoring period. The 30-year averages shown in the figure are incorporated within HOT2000 Version 6.0 as part of the normal or default weather file for Winnipeg. All simulations reported herein were done with the recorded monthly values shown in the figure for the years 1985 through 1990. It is notable that, despite what will likely be remembered as extreme excursions from normality at different times of that period, the familiar annual cycle of monthly outdoor temperatures and available solar radiation remains the preeminent feature of the weather. This has a lot to do with the predictability of actual space heating requirements using simple models.

Within the weather records outlined in Figure 4 can be seen several significant departures from the usual pattern. In particular, the months of January in 1986, 1989, and 1990 were exceptionally warm and in all cases were preceded



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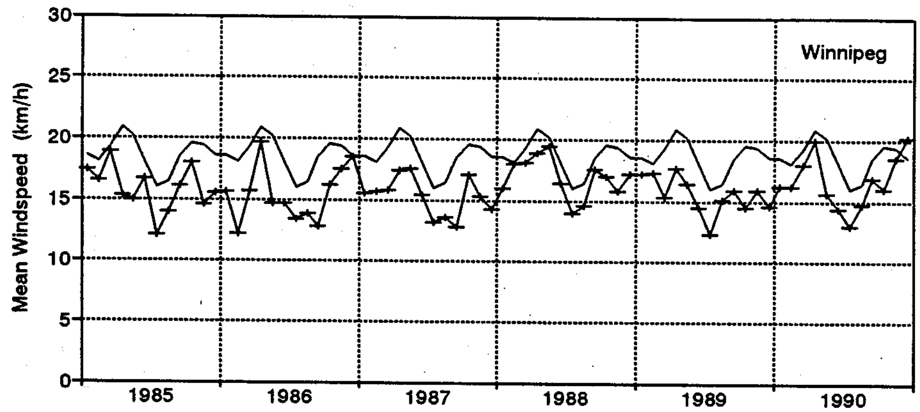

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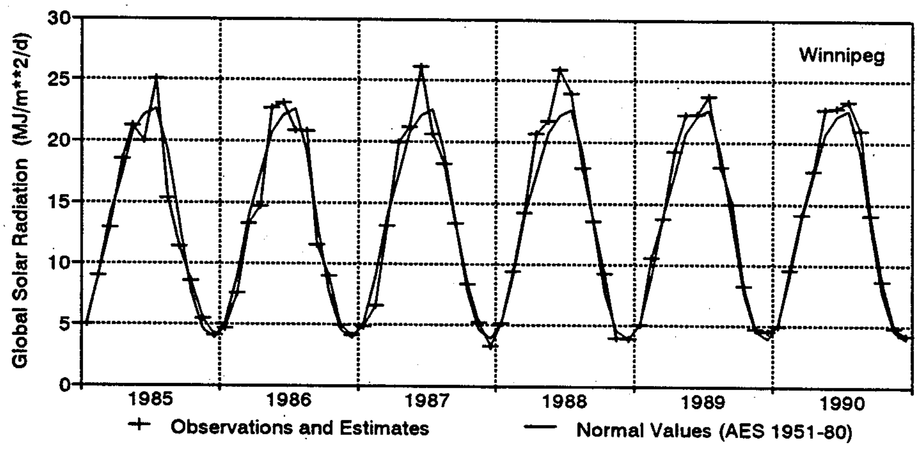


(c)

Figure 4 Monthly Weather: Monitoring Period Compared to 30-Year Normal
(a) Dry Bulb Temperature, (b) Mean Windspeed,
(c) Total Solar Radiation on a Horizontal Surface

and followed by near- or below-normal months. The entire winter of 1986-87 was well above normal in terms of temperatures. Available solar energy was apparently quite close to normal values for most winter months in the monitoring period.

The latter half of the 1980's was one of generally above-average temperature and well-below-average precipitation in southern Manitoba. In particular, most of the 1986-87 winter and all of the following winter were characterized by low snowfall. Probably this translated into a lower-than-usual ground albedo, which might have had some effect on the amount of solar energy reaching the windows of the project houses.

Spring and summer of 1987 and 1988 were among the warmest on record and were also dry with clearer than normal skies. Recorded ground temperatures at Winnipeg moved slightly upward relative to long-term normals in response to the extended period of warmer weather which occurred during the monitoring phase of the project. Published windspeeds (Figure 4(b)) covering the project period are consistently below long-term averages. Correlation between mean windspeed and space heating energy for averaging intervals down to as low as two or three days in a relatively tight house is usually very weak, however, so no discernible impact of the apparently calmer-than-normal (up to 20 percent) conditions should be expected to show up in the monthly HOT2000 results. In any case, one would be expecting the model to respond in a realistic manner to all these deviations from the normal weather pattern.

Subjective examination of the month-to-month simulation performance for the 23 project houses (Figures A.1 through A.24, (a) and (b)) with the above-noted weather anomalies in mind returns a null result. Prediction errors in the unusual months, such as the three abnormal Januaries, exhibit neither consistent patterns among houses nor discernible differences from the errors experienced in adjacent near- and below-normal months. Instead there can be seen a strong tendency for entire winters to be either over- or under-predicted for individual houses, and for just about as many houses to be over-predicted as under-predicted throughout any single winter.

The actual weather's deviations from long-term normality therefore provide no simple clue that the strong seasonal fluctuations of simulation performance found in the study might depend in major part on a seasonal bias introduced through the program's algorithms.

Not examined herein are the effects of the actual distributions of weather parameters within each month in comparison to the assumptions utilized within HOT2000. For most variables, a single value is used to characterize the month within the calculations, so estimation using an average observation for the month should be a reasonable practice. The exception to this is the distribution of outdoor temperatures for the month which, in the program, is constrained to take a particular shape that can be parametrized by the mean and standard deviation of the set of hourly temperatures for the month (CHBA, 1991b). Actual hourly temperatures for a month often exhibit a distribution which is significantly deviant from the assumed one. Further, the shape of the distribution of hourly temperatures in a month varies in a seasonal manner, so the difference between it and the assumed shape also varies seasonally. The possibility that this effect may be contributing to the seasonal fluctuations in the HOT2000 results for the project houses is a subject which should be investigated. Ultimately, it may be desirable to abandon the artificial distribution which describes temperatures within the month in favour of a set of empirical or characteristic distributions.

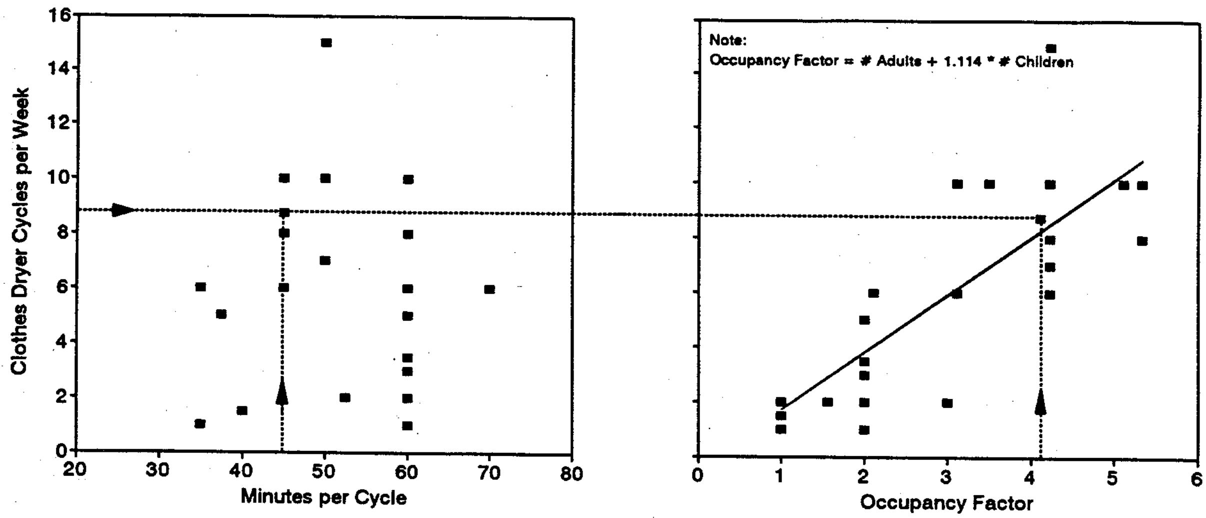
4.3.3 Clothes Dryers

Purchased energy consumed by clothes dryers can constitute a significant portion of the total appliance energy usage in a home. Almost all of the project households operated electric dryers regularly during most of the monitoring period. With dryer exhaust flow normally directed outdoors for purposes of internal dust and moisture management, a significant amount of the purchased appliance energy therefore never became available to substitute as space heating energy.

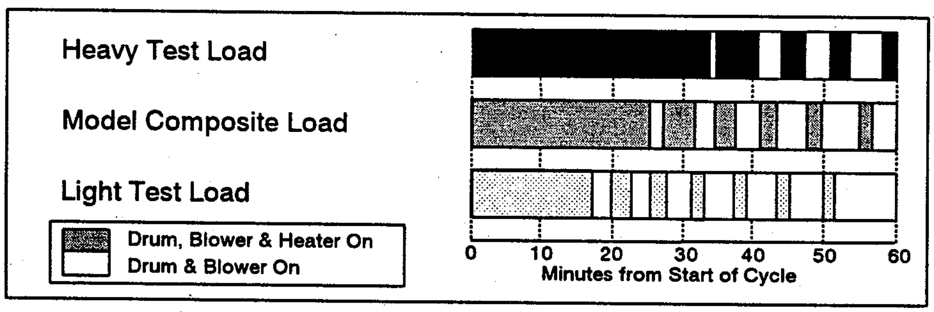
Sub-metering or other measuring of dryer energy usage in the houses was not carried out, perhaps the single most unfortunate shortcoming of the original monitoring program design. It was only at the time of this analysis, following the completion of monitoring, that the potential importance of this excluded energy relative to the other energy quantities was fully appreciated. In the absence of monitoring data, retrospective estimation of dryer energy in each project house becomes intrinsically difficult, being subject to short memories and further complicated by the changes in family status and home ownership which occurred during the monitoring period and later. As an alternative, an heuristic clothes dryer energy sub-model has been prepared, and has been applied uniformly to all houses as a part of this analysis. The elements of the model are illustrated in Figure 5.

A straw poll was taken of 27 households, including the occupants of 14 of the project houses, to ascertain dryer usage patterns under conditions of the families' lifestyles at the time of the interviews. Two statistics were derived for each house: (a) the typical length of one dryer cycle, and (b) the number of dryer cycles or loads per week.

Most people indicated they rarely varied the length of the cycle and didn't think much about it; optimization in their case had been restricted to a once-through, trial-and-error process leading to a cycle duration which proved suitable most of the time. For many, the adopted duration was the maximum available crank-timer setting, commonly 60 minutes. The range reported among all households was 35 to 70 minutes (Figure 5(a)). CAN/CSA-C361-M89, a Canadian standard test method for determining energy consumption ratings for conventional household electric clothes dryers (CSA, 1989), includes a uniformly applied, field-conditions correction which, for timer-controlled units, presupposes an overconsumption of 18 percent of the basic energy expended to dry a standard load to a certain final moisture content.



(a)



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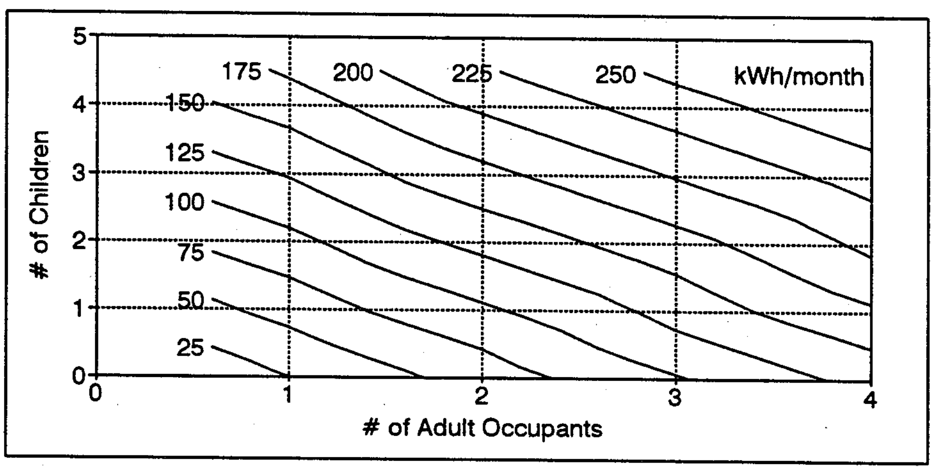


(c)

Figure 5 Straw Poll Clothes Dryer Model
(a) Poll Results (n=27), including Expected Frequency-of-Use
(b) Duty Cycle Characteristics
(c) Expected Clothes Dryer Energy Usage Rate, Model Duty Cycle

Figure 5(a) also shows that, for the polled group, dryer usage is quite noticeably a function of the number of residents. Multiple linear regression of number of cycles per week against the number of adults and the number of young children normally living in the 27 houses results in the least-squares line shown in the figure and described as follows:

Expected Cycles per week = -0.369 + 2.100 * # Adults + 2.336 * # Children
(R^2 = 0.59)

When the poll responses regarding typical cycle length are used to determine a similar best-fit relationship for duration of dryer usage, the following is the result:

Expected Hours per week = -0.983 + 2.275 * # Adults + 1.866 * # Children
(R^2 = 0.57)

The poll results may be interpreted to imply that the presence of children tends to lead to more dryer loads of shorter average duration or, in other words, more frequent clothes washing with consequently smaller individual loads.

As part of the clothes dryer model, the above expressions are used on a monthly basis to estimate the frequency and duration of dryer usage in the project homes. The expected schedule of a dryer's operation thus changes with the number of occupants served by it. CAN/CSA-C361-M89 incorporates the assumption of an average 416 dryer cycles per year, or eight per week. For the straw poll sample and current dryer sub-model, this would be the expected result for a family of 2.0 adults and 1.8 children, which seems about right.

For convenience, an arbitrary expression of the estimated length of one operating cycle is adopted:

Probable Cycle Duration = Expected Hours per Week / Expected Cycles per Week

The above yields slightly different estimates and slightly more variability than does a simple regression of cycle duration against occupancy, but neither expression is very sensitive to the occupancy due to the low correlations associated with this statistic. In the main, with most dryers relatively alike, a certain amount of energy and time will be required to render a typical load (the contents of a single, relatively large load recently removed from an automatic washer) to more or less the same level of dryness. Total clothes dryer energy usage is mostly a function of the number of people whose clothes are passing through it, at the rate of about 2 loads per week per person.

Several typical dryer installations were examined to get an idea of performance. Exhaust flow rates measured at the exterior wall hoods during winter were found to be 27, 27, 28, and 37 litres per second respectively for four dryers in three different homes. The first two results are for the same house and both a 30-year old and a new (ca. 1989) dryer at different times, with exhausting from a deep basement installation via slightly more than two metres of the common 100 mm plastic-covered, wire-coil flexible duct. In the second house, the dryer setup is similar to the first, except that straight-walled galvanized 100 mm ducting is used, with two right-angles in the flow path. The third installation resembles the second one, except that the total length of galvanized ducting is well under two metres as a consequence of the house foundation being fairly shallow. All of the hoods have working flaps.

A standard clothes dryer exhaust flow rate of 30 litres/sec is adopted for the present analysis. In the monthly HOT2000 simulations of the project monitoring period, the dryer flow is considered as an equivalent continuous exhaust rate which is additional to any provided via a ventilation system, and it is determined by factoring in the expected number of operating hours for the month, derived as above. For most houses, the result works out to be an equivalent steady flow of only a few litres per second. On a monthly basis this can be considered as a reasonable representation from the perspective of the space heating load associated with the induced air leakage, but it says nothing about short-term flow imbalance and depressurization attributable to the clothes dryer.

Limited monitoring of one of the test installations produced the energy-use patterns shown in Figure 5(b). The subject dryer is a conventional tumble-type domestic unit of standard size, loads from the front, and carries a CAN/CSA-C361-M89 ("Energuide") rating of 94 kWh/month. Controls are manual (time-termination system). Most of the project house dryers are very similar to this, some a few years old, some relatively new. The legible CSA Energuide stickers among them read 111, 78, and 89 kWh/month.

Peak metered draw by the test unit is almost 5.5 kW including about 5.0 kW for the heater and the rest for controls and the drum/blower motor. With heater "on" in this type of dryer, it appears that evaporative cooling restrains the temperature rise in the drum until much of the moisture originally in the clothes has been removed. Once short cycling begins, the durations of intervals with heater energized gradually shorten as the total thermal mass of the dryer's contents requires less input energy to be raised from the lower to the upper temperature setpoint. Similarly, as the drying proceeds, phase-change cooling becomes less and less of a factor during the intervals with heater disabled, and the durations of these intervals lengthen.

The "heavy" test load shown in Figure 5(b) included in its relatively large volume several bulky items which retained a significant amount of water at the end of the normal spin-dewatering process which completes the conventional automatic washer cycle. The "light" load was characterized by looser-woven bed linens and a smaller total dry volume. Somewhere between them may be considered to be a "typical" load. For modelling purposes, the composite load cycle shown in the figure is arbitrarily fixed at midway between the two observed ones. It is assumed that the model dryer, when running, consumes energy at the rate of 5.5 kW with the heater on, and at 0.5 kW when the heater is off.

In the clothes dryer model, an estimate of the duration of one dryer cycle and the frequency of dryer usage in a time period are both determined on the basis of the occupancy functions. These are combined with the adopted duty cycle to yield an estimate of the total dryer input energy consumption. Figure 5(c) illustrates the expected values for a month. According to this procedure, a lone adult would be estimated to use about 25 kWh/month in 1.7 dryer loads per week, each of duration 44.8 minutes. Similarly, in 8.0 loads of 51.7 minutes duration per week, the family of 2.0 adults and 1.8 children would be expected to use about 125 kWh/month in its dryer, which seems to be not unreasonable.

For outdoor venting of electric clothes dryers it has been assumed in the HOT2000 simulations that all the input energy is ejected. Otherwise, dryer input energy is considered to be available for utilization in the same manner as that from other interior appliances. In perspective, McQuiston (1984) approximates typical dryer heat loss to space as 0.29 kWh per cycle, which would correspond to about 8 percent of the input energy for the model duty cycle and the 3.8-person family of this analysis.

Hot water used for clothes washing is given no special treatment in the HOT2000 analysis, being monitored elsewhere as part of the DHW system input energy, or as part of the water which is drawn into the DHW heating system.

The clothes dryer energy-use model prepared for use in this analysis is an introductory attempt to fairly represent the major elements of the process, but is nevertheless an inferior substitute for sub-metered data. Therefore, it must be considered that the estimation of the clothes dryer fraction within the sub-metered appliance energy falls below the standard of rigour applied in this analysis to other components of the home energy balance. Derivation of expected value functions for dryer usage based on numbers of occupants does, however, make possible the uniform use of the model for all project homes and all months, with forfeiture of resolution in the cases of houses where the interviews provided direct statements about frequency of dryer use.

The estimated effect of dryers exhausting outdoors can be seen in Figures A.1 through A.24, (a) and (c)(i), to be several kWh/d, significant in comparison to total energy consumption, and a quantity for which explicit provision probably should be included within a future release of HOT2000. When contemplating the default or user-defined input value for appliance load, many users may not now consider a distinction between the clothes dryer and other appliances. In recent years it appears that exterior venting has become the standard practice for dryer installations. Wider appreciation of the quantities of energy involved may stimulate further development and implementation of measures to recapture some of it. Simulation models may have a role in the process. Possibly some of the ideas from the conceptual dryer sub-model formulated herein would be useful.

4.3.4 Appliance Energy

Sub-metering of appliance/lighting energy in project houses during the monitoring period usually amounted to a difference calculation between the total electricity measured at the main meter and the sum of all other specifically sub-metered appliances, including space heating equipment and water heaters.

Direct exterior uses such as car engine block and interior heaters, electrical lawn and garden equipment, and Christmas lights were sub-metered in a few homes, but mostly they have been estimated for purposes of the HOT2000 simulations, as noted in Table 3. The sub-metering on a few houses showed that non-winter exterior electricity consumption could be safely ignored in simulations (i.e., casual usage was insignificant in terms of total energy). Further, there were no installations, during the monitoring period, of exterior devices such as security lighting systems, driveway heating cables, hot tubs, or pottery kilns which could be expected to use a significant amount of purchased energy).

Clothes dryer energy usage has been estimated as described in Sec. 4.3.3.

Porch lighting and other exterior electricity consumption drawn from interior circuits has been ignored in the analysis.

Ventilation system fan input energy lost via the exhaust air stream is normally handled in the ventilation system sub-models, as is the calculation of total fan energy. Depending on the system, some or all of the fan energy may be exhausted. In general, ventilation system input energy was not sub-metered in project houses. Therefore, as part of the analysis of energy flows in the project houses, appropriate estimated monthly fan powers and corresponding energy usage rates have been derived from monitored flowrates and subtracted from the sub-metered total appliance energy usage rates in advance of the simulations.

The preparatory fan power calculations also include consideration of the location of fans and motors in the air streams of the various ventilation systems in order that the HOT2000 Version 6.0 algorithms account realistically for both the energy which is exhausted and also the energy which is utilizable within the building. The adopted procedure ensures that the program total for appliance plus ventilator energy adds up to the observed values.

Central air conditioners, where installed, also were not sub-metered. The air conditioner sub-model of HOT2000 is somewhat persnickety in terms of the permissible combination of descriptive input values, so trial and error with interactive HOT2000 Release 6.02 has been used to select acceptable unit descriptions which fairly closely match those of the actual systems. In the absence of reliable cooling thermostat settings, a standard 25°C has been adopted for the simulations. In the Winnipeg climate, home air conditioner operation is rarely continuous during the summer, so establishment of a single realistic setpoint temperature for energy simulation on a monthly time step is less than straightforward.

Iteration has been used to preserve the total appliance energy balance: the air conditioner input energy estimate is subtracted from the sub-metered total appliance energy prior to each simulation run. It should be noted that there is a double-counting of energy with the Version 6.0 algorithms in the case where the space heating and air conditioner blowers are the same fan (integrated system) and the space heating fan is assumed to be running continuously. Among project houses with air conditioners the double-counting problem is applicable only to House #6, and only during the summer months of 1987 and 1988; no correction is made in this analysis.

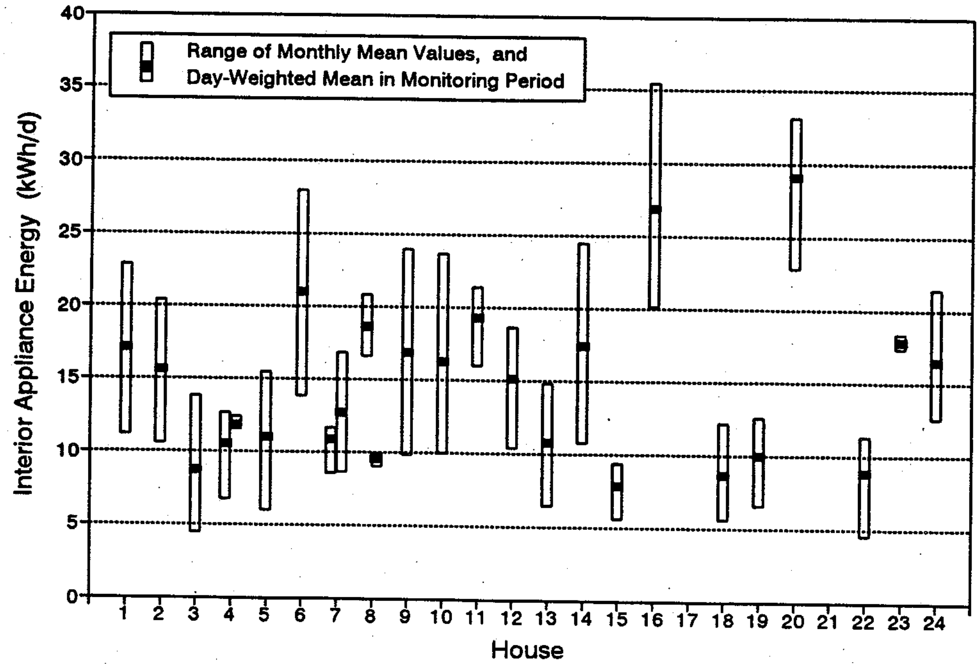
Iteration is also used in the HOT2000 simulations for Houses #9 and #10, which have natural gas heating and DHW systems. Furnace fan energy is included with the monthly sub-metered total appliance energy but is calculated within the space heater algorithms during the model run. Estimated fan energy from each previous iteration is therefore subtracted from the input total appliance energy to ensure an appliance energy balance once the iterations have converged.

Breakdowns of interior appliance/lighting energy for each house appear in Figures A.1 through A.24, (a) and (c)(i), with a summary given as Figure 6. There is a significant seasonal pattern indicated for basic electrical usage in many of the houses, and there is a gradual increase in the consumption over the monitoring period in some. For many of the homeowners, the project homes were their first, so the initial years of occupancy could be expected to be marked by the arrival of children and some acquisition of electrical appliances.

The typical range of the monthly averages within the monitoring period is shown in Figure 6(a) to be 10 to 15 kWh/d, the same order of magnitude as the typical mean value for a house. Overall, the monthly value ranges from about 5 to 35 kWh/d in the twenty-two houses for which results are shown. What this serves to indicate is the influence of occupancy on overall energy consumption patterns. It is often easy for the designer and prospective owners of a low-energy dwelling to develop a comfortable expectation about the expenditure of energy, based on simulations, which is subsequently not realized as lifestyle evolves.

Choice of appropriate estimates of appliance energy consumption rates to be used in design exercises may be feasibly developed from improved resolution of the expected occupancy. As a first step, Figure 6(b) illustrates the variation due simply to the number of people living in the house. There does not seem to be much difference among the several forms of a basic family unit for these relatively compact houses (average is 12 to 15 kWh/d). Possibly the arrival of the first child has some effect (most of those families appearing in the 2/1 group [adults/children] also were members of the 2/0 group earlier in the monitoring period).

For this set of households, additional interior appliance energy usage tends to come about when there is at least a third adult or child present. Within all of the occupancy groups, however, there is still significant variability, lifestyle apparently being a major cause. Nevertheless, one could relatively easily visualize in



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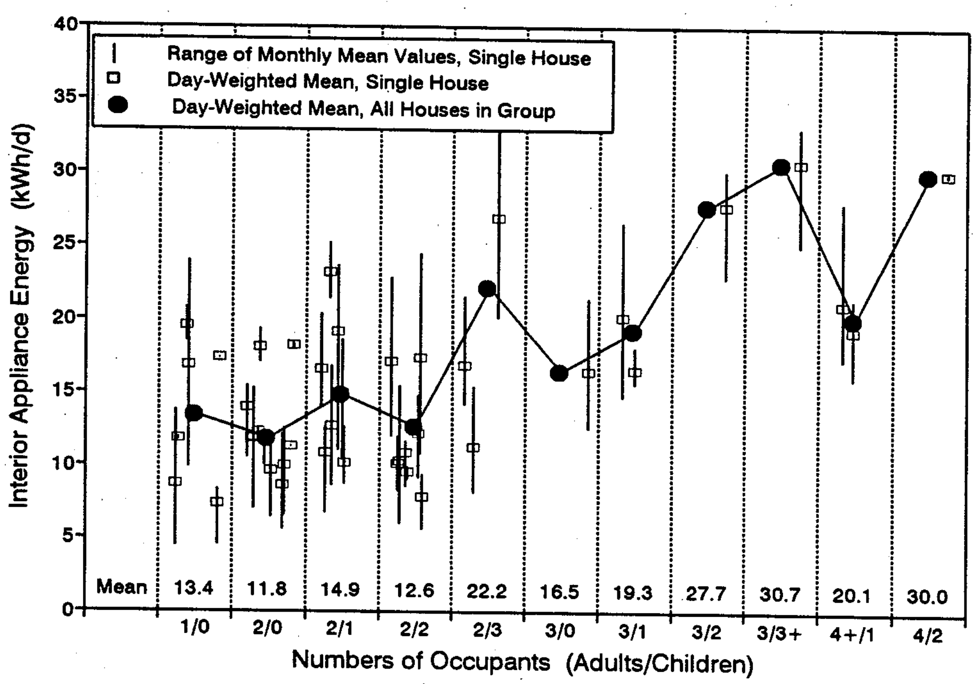


(b)

Figure 6 Interior Appliances and Lighting Energy Consumption, excluding Space Heaters, Clothes Dryer, Ventilation System, Air Conditioner (a) Summary by House and Ownership, (b) Occupancy Effects

Figure 6(b) a line which trends from near 10 kWh/d to near 30 kWh/d across the groups. If typical of the project group represented in the figure, a family of 2 adults and 1.8 children could be interpreted to be using about 13 kWh/d (localized interpolation) or 15 kWh/d (trend line approximation) for lights and interior appliances. With further examination and a larger sample, it may be possible to develop a useful algorithm to replace the present method which requires the user to specify a simple constant value.

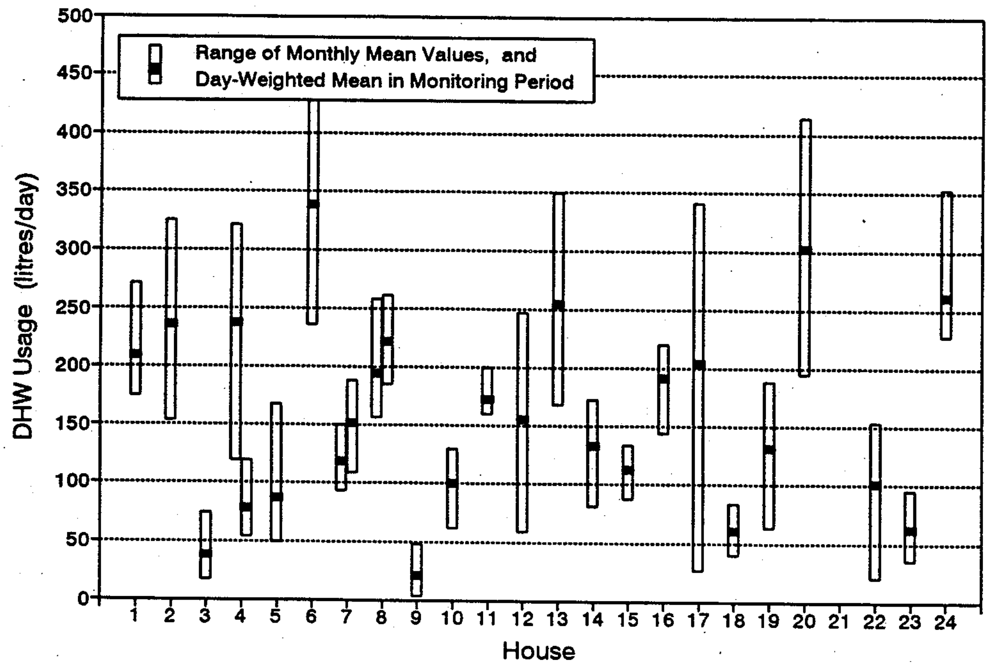
4.3.5 Water Heating Energy

Shared consumption of non-space heating appliance and lighting energy obviously would serve to blur the correlation between that usage and the number of occupants. For example, several family members may routinely get up from the dinner table and plop down in front of the TV in the family room. In the case of water heating energy, dish and clothes washing could be associated with a similar joint-use effect, but generally the consumption of hot water in the home by other than young children would be expected to be more of an individual pursuit.

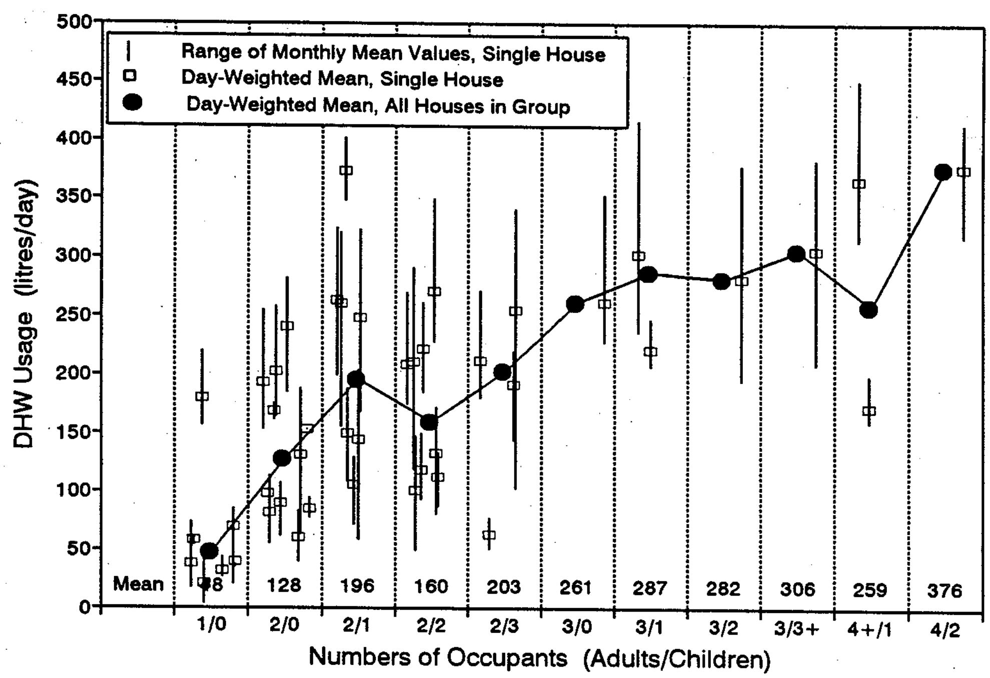
Figure 7, which is a compilation of DHW usage characteristics for all 23 project homes, indeed indicates relatively greater quantitative ranges within individual houses, and stronger relationship to occupancy, than is shown in Figure 6 for basic electricity usage. Figures A.1 through A.24, (a) and (c)(ii), illustrate the monitored water heater usage for each house. Seasonal variation is notable, partly attributable to the annual cycle in the mains water temperature, and possibly also including some element of human reaction to the seasons. Most striking, however, are the non-seasonal occupancy effects: (a) variations due to changes in the number of people present and using hot water in a house as the monitoring period evolved (including the "first child" effect), and (b) the differences in quantities of hot water used by different families of the same size (some people may have a greater penchant for dirt).

The HOT2000 Version 6.0 algorithm for water heating energy derives an energy requirement out of the volumetric rate of use of hot water specified by the user as part of program input, on the basis of an assumed constant input mains temperature of 7.5°C, an average released hot water temperature of 55°C, and an assumed inefficiency for the water-heating equipment (CHBA, 1991b). While much of it will go down the drain as it does in practice, a portion of the purchased DHW energy ultimately is rendered available for utilization as waste interior energy. There is room for improvement of this sub-model.

For example, a provision to allow choice of the water temperatures would improve the sub-model's flexibility for users without requiring change to the basic structure of the algorithm. Such a change could naturally be integrated within an overall move toward monthly varying inputs for a greater variety of entered quantities. For the present study, coverage by spot monitoring of raw and heated water temperatures in the 23 homes was non-uniform, so turned out to be only of incidental value in the standardized analysis.



(a)



(b)

Figure 7 Domestic Hot Water Consumption, Observations and Estimates
(a) Summary by House and Ownership
(b) Occupancy Effects

Beyond user-chosen water temperatures, it may be further worthwhile to increase the complexity of the water-heating sub-model in HOT2000 if a realistic representation of the process can be formulated to complement the overall monthly focus of the program. The wide range in the average rates of flow of hot water encountered in the project houses provides a clue that the following elements of a dwelling's DHW subsystem could be among those which vary significantly in importance from house to house: (a) there is energy used simply to keep hot water at the ready, and the amount is only weakly affected by the amount of heated water used in the house, (b) there are transient interactions between the space and water heaters (i.e., both the preheating of inflowing mains water from space, and the loss to space from heated water standing in the pipes leading from tank to fixture), and (c) the behaviour of the water heater itself varies (heated water leaves the tank over a range of temperatures up to the setpoint, depending on the quantities and schedule of use). Among these factors, standby energy usage is one which, due to its nature, could be appended to the existing sub-model simply, yet realistically.

Houses #22, #23 and #24 were monitored both while occupied and unoccupied. All have standard electric water heaters with tank sizes 182, 114 and 182 litres, respectively. House #23 was also fitted with a prototype air-to-water heat pump system with 220 litre storage tank, but this was not operated during the monitoring period, so the small standard tank downstream was used to meet all hot water demands. Mains water passing through the larger storage tank along the way would have been warmed by exposure to the interior house environment on average more than the incoming water for a conventional DHW setup, due to the length of time spent in the house before reaching the water heater; this effect is ignored in the analysis. Tank electricity consumption was recorded in all three dwellings, and hot water usage rates were also metered in Houses #23 and #24.

Consumption during the time of negligible hot water usage was steady at about 2.75 kWh/d for the 182 litre unit in House #22, and at about 2.50 kWh/day for the 114 litre tank in House #23. House #24's DHW system was activated only upon the imminent arrival of its occupants. In order to harmonize their hot water demands with the capacity of the small system, the occupants of House #23 adjusted the temperature setpoint upward to 70°C. For the others, adjustments to setpoints may have been made from time to time by the occupants, but scheduling and settings were not tracked. Water heating characteristics for the three houses are shown in Figures A.22(c)(ii), A.23(c)(ii), and A.24(c)(ii), respectively.

The above-referenced data presentations for Houses #23 and #24 also include the estimated electricity requirement which would be determined with the water heating algorithm of HOT2000 Version 6.0, given the flowrates, and with a modified HOT2000 algorithm which allows for specification of water temperatures and a constant value for standby energy. In the latter calculation, a steady 2.75 kWh/d is allocated to standby in House #24 and the 55°C heated water temperature is accepted in lieu of actual measurements. For House #23, both an elevated delivery temperature and standby energy are included. Estimates for both houses are fairly close to the observed values. This cannot be considered a rigorous comparison, but it serves to show that the standby losses can be significant relative to the total energy requirement for cases of low hot water consumption. It therefore would be advisable to make improvements to the water heating sub-model; the above could provide a basis.

Except for project houses #11, #12, #15, and #16, where water and space heating systems are integrated and detailed sub-metering was carried out, all other houses have been assumed for the HOT2000 simulations reported in Appendix A to conform to the 7.5 and 55 °C water temperature regime. Monthly pseudo-usage rates have been estimated by inverting the simple HOT2000 algorithm, in order to ensure that, with these rates used as inputs, the normal calculation for hot water energy comes up with the values actually observed. Program algorithms which distribute the heated water energy as waste heat lost, or alternatively as waste heat available for application to the space heating demand, thus "see" the correct quantity.

In Houses #11 and #12, part of the water heating demand is met with heat recovered from ventilation air, thereby reducing the amount of direct electrical resistance heating that is applied. System control logic for the integrated mechanical systems of Houses #15 and #16, in contrast, permits the transferring of part of the energy supplied to the water heating sub-system across to the space heating sub-system. Distributions of water and space heating energy for these unusual systems are included within the results for each home in Appendix A. Commercial production of both systems has been discontinued.

To arrive at the estimated quantities of hot water shown for each house in Figure 7, either the sub-metered quantity is used (Houses #11, #12, #15, #16, #23 and #24), or else a back-calculation from the sub-metered electricity is used (all others). In the latter case, all DHW tanks are 182 litres and a constant 2.75 kWh/day is used to account approximately for standby energy. Part of the variation shown within Figure 7(a) for an individual house therefore may be attributable to changing water heater thermostat settings over time. For a given family size within Figure 7(b), part of the difference between houses similarly may be due to differences in settings. Nevertheless, a strong trend is indicated in the latter figure; hot water usage in this group of homes appears to be highly correlated to the number of persons served. The family of 2 adults and 1.8 children would be expected to use about 170 litres per day. Examination of a larger sample which contains a greater variety of house and family sizes may nevertheless lead to further insight and possibly a useful algorithm for estimating hot water usage.

4.3.6 Phantom Air Leakage

Perfluorocarbon tracer (PFT) passive monitoring studies to estimate total air exchange rates in the project houses #1 to #20 were repeated six to eight times in each house during the monitoring period. The air change rate estimates that resulted were averages over the time the monitors were in place, typically seven days. In most cases, the one-week averages for air exchange correspond fairly well to the values derivable at a monthly scale from ventilation-system timer and flowrate observations and from airtightness test results, when the measurements are combined according to the protocol of HOT2000 Version 6.0 (CHBA, 1991b).

The monthly monitoring data lead to consistent underestimation of total air change rates for Houses #7, #8, and #13, however. These are the three dwellings in which the installed mechanical ventilation systems (central exhaust systems for the first two, HRV for the third) were scarcely used by the five occupant families (2, 2, and 1, respectively) during the monitoring period. During some months, run timers indicated almost no mechanical ventilation in the three houses. Further discussion of ventilation system usage in the project houses, and the effects, appears in Proskiw (1992b,c).

Air leakage which is inferred from tracer gas tests in the three homes to be in excess of the amount of natural air leakage expected on the basis of airtightness test results most likely should be attributed to the opening of doors and windows. Many of the test house occupants reported opening windows during winter days. Nighttime use of open windows in winter was minimal. During shoulder seasons, windows were frequently opened to mitigate solar overheating. Door usage for passage may, of course, be frequent in any house, all year; use of door openings for supplementary ventilation is also possible. These are instances of air change which are not naturally included with either forced or non-forced ventilation rates as HOT2000 inputs, nor are they easily quantified.

The fact that total air change estimates from both the PFT studies and the regular monthly monitoring program agree quite well in most cases probably indicates that casual and unavoidable opening of doors and windows is not a factor significantly affecting either total average air change rates or total heating energy consumption. Therefore, for houses and ventilation systems of this type, it is probably safe in most cases to consider window and door opening as a non-essential variable for metering and for explicit treatment in residential energy-use simulations.

When the preferred ventilation system is windows and doors (especially includes the case where they are the only means available), or an explicit attempt is made to use them as such, as is inferred by the PFT results for Houses #7, #8, and #13, specific consideration of this variable will be required in future energy-use studies. In the standard analysis, which is reported in Appendix A and Figure 2, the same approach to air flow quantities was used for the three houses as for the others. The unmetered air exchange via window and doors is therefore ignored, with the expected consequence being a HOT2000 underprediction of the actual heating and total energy usage rates. In fact, the three houses do exhibit underpredictions which are consistently among the largest within the project group.

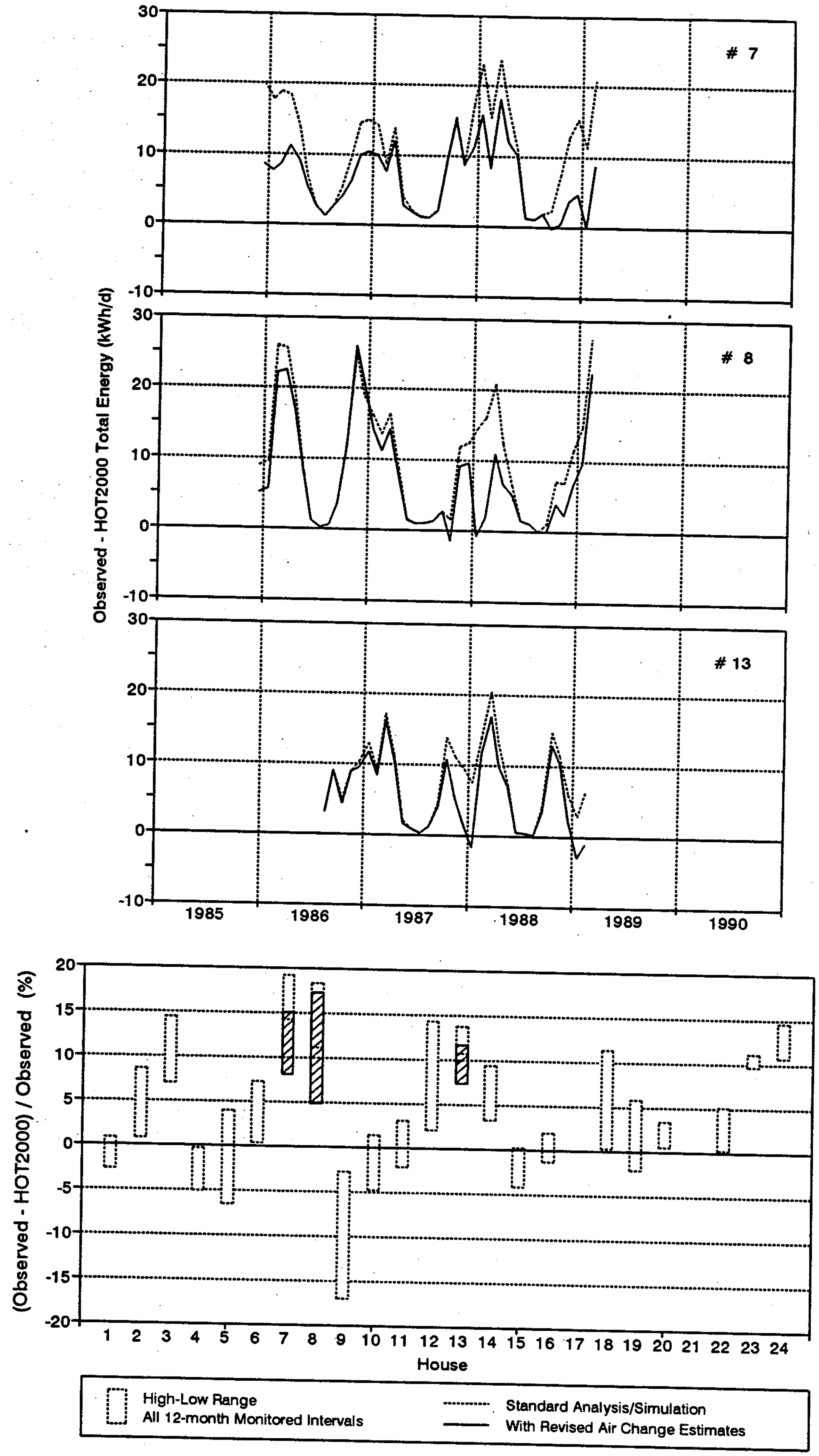


Figure 8 Unmonitored House Air Changes: Impact on Energy Simulations

A rough idea of the true air exchange history for the houses is provided within the sets of tracer gas results, which effectively amount to sparse series of spot measurements taken during the monitoring period. For purposes of comparison, highly approximate monthly total air change rates for the three houses have been estimated on the basis of the PFT results. Figure 8 is an overlaying of the standard energy simulation results with the results of modified analyses in which the total air change rate estimates are achieved in the revised simulations through appropriate control of forced and non-forced air flowrates. It is implied from Figure 8 that, while utilization of better air change rate estimates would improve the simulation performance significantly (the three houses would be moved more within the envelope of performance of the other houses), there is clearly other residual error in the analysis for these dwellings.

4.3.7 Flue Flows

The two conventional houses of the project group which use natural gas for space and water heating are shown in Figure 2 and Appendix A to be modellable, energy-wise, to within a few percent of the observed energy consumption using the standard algorithms of HOT2000 Version 6.0. In both cases, the model overpredicts the winter of 1988-89, and shows in Figures A.9(a),(b) and A.10(a),(b) a radical departure from the simulation performance indicated for the remainder of the monitoring period. Other than this effect, which is discussed in Section 4.1, simulation outcomes for House #9 exhibit a modest seasonal overprediction (greater in winter) which is absent from the results for House #10.

There are two major aspects of modelling the gas-heated houses with HOT2000 which make the total purchased energy-use calculations for Houses #9 and #10 unique and subject to error in comparison to the energy simulations for all the other project houses.

First, a fossil fuel energy conversion efficiency is assumed. In this analysis, steady state conventional furnace efficiency of 76 percent is adopted (the HOT2000 default value). The program's default water heater efficiency of 45 percent is also used, but any impact of this choice on the analysis has been circumvented in the analysis through use of the observed DHW gas consumption as described above in Section 4.3.5. No equipment testing was done to verify furnace combustion efficiencies, so there is potential for error in the assumption.

Second, specification of a fuel-burning appliance necessitates consideration of air leakage via the system's exhaust flue. HOT2000 Version 6.0 incorporates flue flow sub-models based on Ferguson and Sullivan (1984). With the monitoring information available, a definitive separation of the energy-usage effects of the above two processes on simulation performance is infeasible.

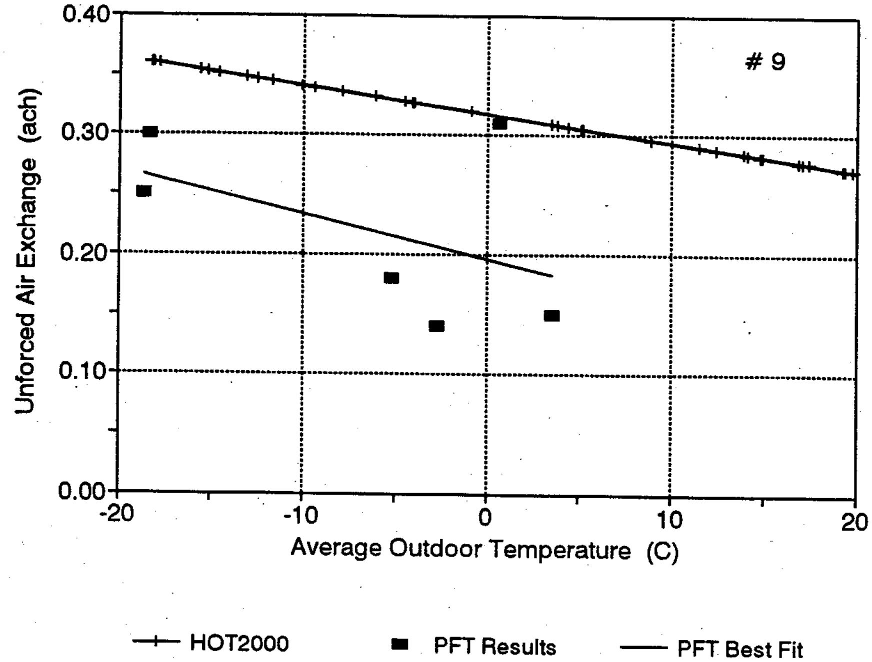
The HOT2000 algorithms for total air changes deal with flow in the unheated chimney (the so-called "off-cycle" losses), natural infiltration through the building envelope, and the incremental effect of a hotter flue and exhaust stack during the on-cycle. For conventional natural gas and propane furnaces (i.e., natural draft), a 125 mm diameter flue is assumed in the model, and the effect, if any, of the DHW heater is ignored. Houses #9 and #10 have 125 mm diameter flues.

An empirical equation which depends only on outdoor temperature, the furnace's output capacity and steady state efficiency, and the assumed flue diameter is used to calculate a base off-cycle flue flowrate. For the oversized furnaces in Houses #9 and #10 (design factor of three or more), approximately 5 percent of the estimated time-averaged off-cycle flow is in effect attributed by the algorithm to the presence of the excess capacity. The estimated monthly average flow (using the standard normalized temperature distribution) falls within a summer-to-winter range of 21 to 27 litres/second. This is not affected by house airtightness or its envelope area, heated volume, or shape.

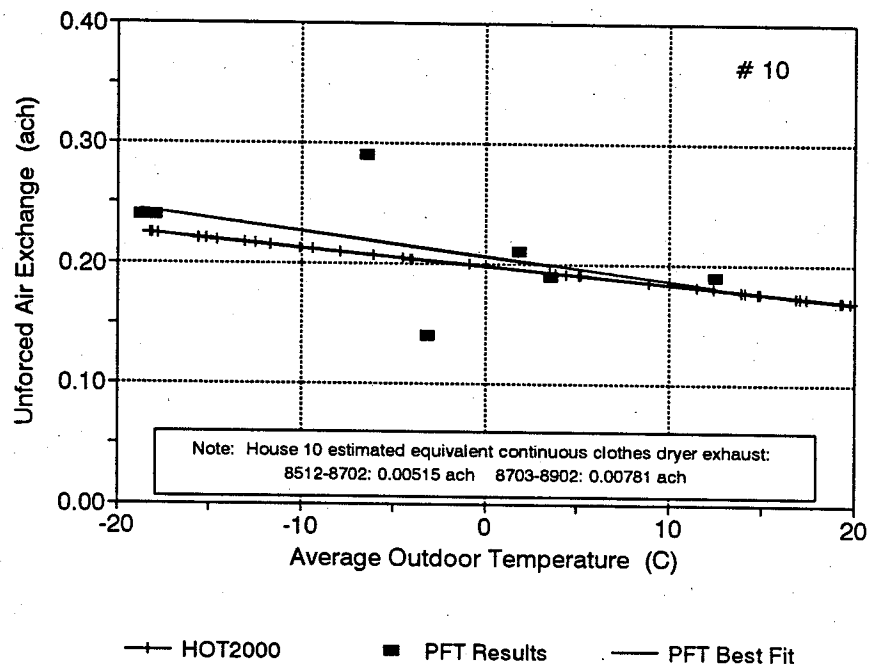
Wind- and temperature-induced infiltration, as calculated for the two houses according to the modified Shaw method (CHBA, 1991b), is always sufficiently small as to have zero effect when combined with the off-cycle chimney flow in the format implemented within the HOT2000 6.0 sub-model. Total unforced air leakage becomes simply the off-cycle flue flow. Mechanical exhaust flows (the only significant one is the clothes dryer in House #10) are added, with the result being the total estimated air change rate for each house. The HOT2000 estimates of unforced air leakage for Houses #9 and #10 are shown in Figure 9. The equivalent continuous exhaust flows estimated for House #10 are very small in comparison, as are the estimated on-cycle flue-flow increments in both.

Perfluorocarbon tracer test results for both houses are also shown in Figure 9. Excluded from the observations shown in the figure are the tests done for intervals when the occupants reported simultaneous opening of windows or doors for ventilation purposes (warmer periods, mostly). Consequently, it is fair to compare the displayed sets of PFT results of total air exchange to the HOT2000 sub-model estimates. The correspondence of measured and modelled flue-dominated flows for House #10 would have to be called a fortunate coincidence, since deployment of the algorithm leads only to a narrow calculated range of volumetric flowrates. A smaller heated space of similar airtightness and identical mechanical equipment setup, e.g., the 279 cubic metres of House #9, is assigned the same flow, which is evidently too high. The reasonableness and flexibility of the HOT2000 Version 6.0 flue loss calculations therefore should be reviewed.

The energy requirement associated with the difference between the observed and simulated air change rates for House #9 approximates to a daily space heating load increment of 5 kWh at an outdoor temperature of 0°C, and 8 kWh at -20°C. This works out to an overprediction of the purchased energy requirement of about 9 kWh/d at 0°C and 12 kWh/d at -20°C. The differences are similar in magnitude to the total residual modelling errors shown in Figure A.9(b) for the standard analysis, so it is probable that a realistic sub-model estimate for unforced air leakage in this house would lead to revised HOT2000 simulation performance close to that which resulted for House #10. Acceptance of the default furnace efficiency (76 %) for both thus does not appear to be an unreasonable choice.



(a)



(b)

Figure 9 Air Exchange in Project Houses with Natural Draft Flues and No Ventilation Systems - Tracer Gas Studies and HOT2000 Algorithm: (a) House #9, (b) House #10.

4.3.8 Simulation of HRV Operation

Over the last decade, recovery of heat from ventilation air has become synonymous with low-energy housing in Canada. The interval has also encompassed almost the entire evolution of the technology so far. Flair Project houses contain off-the-shelf HRV equipment representing the industry's offerings at various times during this developmental period. Twelve of the 23 houses examined herein have conventional air-to-air equipment, while 6 more are fitted with less mainstream heat-pump heat-recovery units (Table 1, Appendix A).

HOT2000 Version 6.0 includes an HRV sub-model for estimation of the equipment's effect on the comings and goings of house energy. Presently, only one conceptual arrangement of core, fans, and preheater is schematized (CHBA, 1991b). The user supplies only sensible heat-recovery efficiencies and the unit's fan power requirements for two outdoor temperatures, a pre-heater capacity, and a throttling factor for frost-affected flow at low core temperatures. Model algorithms are based on an expectation of published results from standard laboratory tests of commercially available units, done according to CAN/CSA-C439-88 (CSA, 1988). Assumed in the model are balanced operation, linearized unit performance curves tied to the set of inputs, no latent heat transfer, and no impact due to energy exchanges occurring along the attached ductwork.

The above representation is compromised by (a) the modelled process being more complex than can be realistically characterized with only a few parameters, and (b) the maturity of understanding of the process by both the manufacturer and the analyst which has led to the present preferred characterization being empirical measurements from a test bed. As a result there can be little confidence in the validity of the HOT2000 HRV sub-model where the actual system differs from the model layout (most of the time), and where operating conditions vary from the assumed conditions (usually the case).

For the standard analysis reported herein, there is sufficient unavoidable variation from the assumptions of the HRV sub-model that it is unclear whether all or part of the remaining seasonal tendency in the residual energy simulation errors should be attributed to the modelling of HRV operation. In order to find out definitively, it first may be required to study, and ultimately characterize, HRV behaviour at greater depth than at present.

In the analysis, it has been attempted to work around some of the weaknesses of the HRV sub-model to provide as fair a representation of the ventilation behaviour as possible with the monitored data. The most obvious problem lies with the fact that ventilation flow rates over the monitoring period in almost all homes with heat-recovery ventilators averaged significantly lower than the consistent 55 (or 30) litres/second reporting level for the CAN/CSA-C439-88 tests. The quoted performance figures have been used for lack of better numbers, even though it is clear that heat recovery is sensitive to the rate of air flow.

Fan power magnitudes commensurate with the actual monthly average air flow rates, rather than the test values, have been used, estimated from typical fan power curves applicable to each device. Fan locations within the HRV systems are different from the model's assumptions, so model inputs for fans have been prepared individually. Equivalent fan power/energy calculations have been completed on the side, and have been entered via appropriate adjustment of fan and appliance energy inputs.

Defrost cycle simulation has also been handled as a side calculation, with overall supply and exhaust airflow rates adjusted according to the defrost strategies utilized in the various HRV designs. For identical models the defrost periods varied among the houses, due at least partly to differences in interior moisture levels (in comparison, CAN/CSA-C439-88 tests are done with house-side air conditioned to 22°C and 40 percent relative humidity). As an extreme example, defrosting action in the first generation HRV's installed in Houses #1 to #6 is activated within a pre-set temperature band for the warmed supply-side air, so some units in the more humid houses would remain in defrost (exhaust only, no heat recovery) for as many as half the hours during the coldest months.

As rationalization of the industry shakes out the better design strategies for heat-recovery ventilators, the task of characterizing the processes for purposes of simulation, such as within HOT2000, will become simpler. It will probably be most feasible to provide support for the few most common HRV system layouts; however, valid characterization of any one system, even in a monthly model, will probably require a significantly greater number of input variables.

4.3.9 Anomaly

Simulation performance for House #24 over the winter of 1988-89 is particularly puzzling, since the lack of occupants and hot water usage, low non-heating energy consumption, and tight control on thermostat settings should have been highly favourable conditions for HOT2000 trials. The model's underprediction for this period is almost the highest encountered in any of the project houses throughout the monitoring period (Figures 2, A.24(a),(b)).

Total energy usage by the other two unoccupied-then-occupied dwellings (22, 23) is, in contrast, very closely simulated through the first post-construction winter (1988-89), while each was also devoid of occupants and furnishings and was infrequently entered (Figures A.22(a),(b) and A.23(a),(b)). For the later period of inhabitation, each reverts to a schedule of energy use and an associated HOT2000 seasonal predictability which resemble those of most of the other houses in the study group. The shift from an almost trendless prediction error pattern to that of the characteristic underprediction found for most of the electrically heated project houses may be indication of the importance of occupancy effects. A significant part of the difference conceivably could be due to unmonitored energy usage associated with both intentional and unintentional ventilation through windows and doors. Future residential energy-monitoring studies should explicitly take the quantification of this effect into consideration at the project-design stage.

House #24, on the other hand, appears to be anomalous. It is instructive to compare the 1988-89 winter simulations for House #24 to those of House #23, a similar R-2000 unit. Dimensions and floor plans are the same. Nominal thermal resistance of ceilings, main and basement walls, and basement floor slabs are very similar. Solar orientation of the two homes is the same but the south windows of House #23 are larger and, per unit area, lose more heat and admit more radiation than do those of their House #24 counterparts. Airtightness, as characterized through the periodic depressurization tests, is almost the same (1.4 air changes at 50 Pa). HRV designs and corresponding CAN/CSA-C439-88 test results are also similar. Only the heating systems are notably different: electric furnace in House #23 versus electric baseboards in the basement and baseboards and ceiling heating panels on the main floor in House #24.

Interior operating temperatures during the period October 1988 to March 1989 were nearly the same in the two houses. Draperies were not present in either house. Continuous mechanical ventilation rates via HRV were similar (both houses: about 30 litres per second, entire period, except for House #24: almost 50 litres per second on demand [October and November 1988 only]). The DHW heater of House #23 was in a standby condition almost exclusively during the entire comparison period, whereas that of House #24 was not energized. Used on an alternating schedule, the two main floor heating systems in House #24 supplied about half the total space heating energy for the house during the period, the basement heaters providing the other half (Appendix B). The electric furnace of House #23 met all its space heating requirements.

The HOT2000 Version 6.0 algorithm for internal gain utilization indicates maximum uptake of the gains from non-space-heating electricity usage for both houses in each of the six comparison months. That is, 95 percent of the available energy is utilized [description of algorithm is given in CHBA, 1991b], which is a small number in both cases, due to the lack of occupants. Similarly, the estimated solar gain utilization is exactly unity, or a bit less, in all six months of the comparison period. In the end, the monthly HOT2000 estimates for total (mostly space heating) energy in the two houses are quite similar. Except for one month, predictions for House #23 are close to the observations; for House #24, the predictions are consistently 15 kWh/day low (equivalent to more than 600 Watts continuous), regardless of which of the main floor heating systems was active.

A systematic difference of the magnitude found, since it has occurred under unoccupied conditions, must be considered non-accidental. Whether the underprediction determined for the later period of occupancy (starting April 1989) is fully typical of that found for other project houses, or is dominated by the same prediction problem which exhibits itself in the unoccupied period, is not clear from the results of this study. The error for the unoccupied period is larger than could be reasonably attributed to inappropriate characterization of an envelope component such as wall thermal resistance, or glazing properties.

Unfettered suspicion should not be applied to the ceiling panel heating system either, since (a) the same energy disparity occurs in months where only baseboard heaters were being operated, and (b) the expected increase in main floor heater electricity usage for the case of ceiling panel heaters being operated full-time has been estimated from the hourly energy monitoring program to be about 3.0 kWh/d (5.9 percent) at -20°C and 0.8 kWh/d (3.1 percent) at 0°C (Appendix B). Through a normal October-to-April Winnipeg heating season, this result works out to about 4.6 percent more energy consumption than would have been expected with the main floor baseboard heaters in operation.

In comparison, the HOT2000 default seasonal efficiency for radiant ceiling panels is 95 percent. For House #24 simulations, electric heating system inefficiencies of up to 2.5 percent have been applied in each month, depending on the fraction of time that the ceiling panels were activated (about half of the total energy delivered by space heating appliances in the house went through the basement baseboard heaters).

Although review of the representation of House #24 which has been adopted for the analysis does not reveal any serious deficiencies, the energy simulation results indicate that the model and actual houses are somehow significantly different. For reasons so far undetermined, the actual heating energy consumption in House #24 over the 1988-89 winter was higher than expected. It may be possible to unravel the mystery through further investigation; suggested components of such an examination would include a field inspection and, if necessary, an additional program of energy sub-metering in the house.

SECTION 5

CONCLUSIONS

Examination of energy consumption rates and energy flows in 23 occupied homes of the Flair Homes Energy Demo/CHBA Flair Mark XIV Project, using

(a) data from a program of regular monitoring of house operation over a period ranging from 16 to 39 full months between 1985 and 1990, and

(b) the energy-use simulator HOT2000 6.0, with enhancements to allow greater monthly resolution of program inputs,

has led to the following conclusions and recommendations:

1. Energy consumption in the R-2000 and conventional houses of the test group was heavily influenced by the presence of the occupants, in that:

    - non-space heating energy usage accounted for a significant part of the total purchased energy in all but the coldest winter months.

    - peak annual power demands occurred not necessarily on the coldest day, but at predictable times when the stacked total of occupancy-based demands was several times as large as that required solely to maintain interior space temperature; activities contributing to the peaks included thermostat set-up, DHW draw, clothes drying, and cooking.

    - use of energy for appliances, water heating, and automobile block heaters varied significantly from month to month, year to year, and house to house:

        - monthly average appliance energy usage in 22 houses through 674 occupied months of monitoring ranged between 5 and 35 kWh/d, excluding the energy used in ventilation systems, space heating fans, clothes dryers, and air conditioners.

        - monthly average hot water usage in 23 houses through 710 occupied months of monitoring ranged from almost zero up to 450 litres per day.

    - appliance usage and hot water consumption were related to the number of people normally resident in the homes and to the mix of adults and children:

        - for groupings of houses occupied by either a single adult or by 2 adults and zero, one or two children, the average appliance energy usage ranged between 12 and 15 kWh/d, with significant variation above and below the averages in the cases of individual families; average appliance energy usage ranged upward from these values for households made up of more than two adults or more than two children.

• daily hot water consumption averaged near 50 litres for single-occupant houses, between 125 and 200 litres for occupancy by two adults and up to two children, and higher for houses with at least three adults or children.

• electric clothes dryer usage was significant, averaging about two drying cycles per week per person, with most of the energy used for clothes drying being exhausted to the outdoors.

• supplemental and unintentional ventilation via windows and doors induced a non-metered heating energy load which was significant relative to total energy requirements in at least some of the houses.

2. The quality of the standardized monthly HOT2000 simulations of house energy consumption was compromised by the combined effect of:

• variation in occupant activities and house operation through time and the difficulty of tracking the variations with a system of monthly site visits, and

• the limits to how well the actual energy-use processes in the homes could be characterized using only the monitoring-based data and the algorithms of Version 6.0.

3. Energy-use predictability varied from house to house and year to year and was highly seasonal, yet the monthly differences between observations and simulations were non-linear relative to outdoor temperature. In the absence of the extenuating circumstances of known or suspected cause which affected the energy-use characterizations for some of the test homes, the analysis indicated annual total energy consumption in the project houses could be predicted to within about 2000 kWh, or around 10 percent. Overall there was a tendency for underprediction of total energy consumption in the occupied low-energy and conventional electrically heated homes in the project group, and for overprediction of energy use in the two conventional gas-heated houses.

4. Better simulation performance would be expected with better house data; however, in the course of the analysis some capabilities of HOT2000 6.0 were identified as needing review and/or improvement or were suggested as areas where enhancements could contribute to making the program more useful in both design and analytical applications, among them the following:

• expansion of capability for utilization of input variables on a month-by-month basis.

• allowance for selection of realistic appliance energy and hot water usage rates from basis in occupancy functions.

- improvement of sub-model which estimates the DHW energy usage requirement on the basis of the quantity of hot water used.

- improvement of model representation of HRV operation and performance.

- review and improvement of flue losses estimation and the interactions of the various contributing sources of air exchange.

- treatment of clothes dryers and other previously non-quantified energy losses.

- improvement to the characterization of the hourly outdoor temperature distributions for each month.

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APPENDIX A

RESULTS OF ANALYSIS - HOUSES #1 TO #24

UNIES Ltd.

A.1 House # 1

A.1.1 Thumbnail Sketch

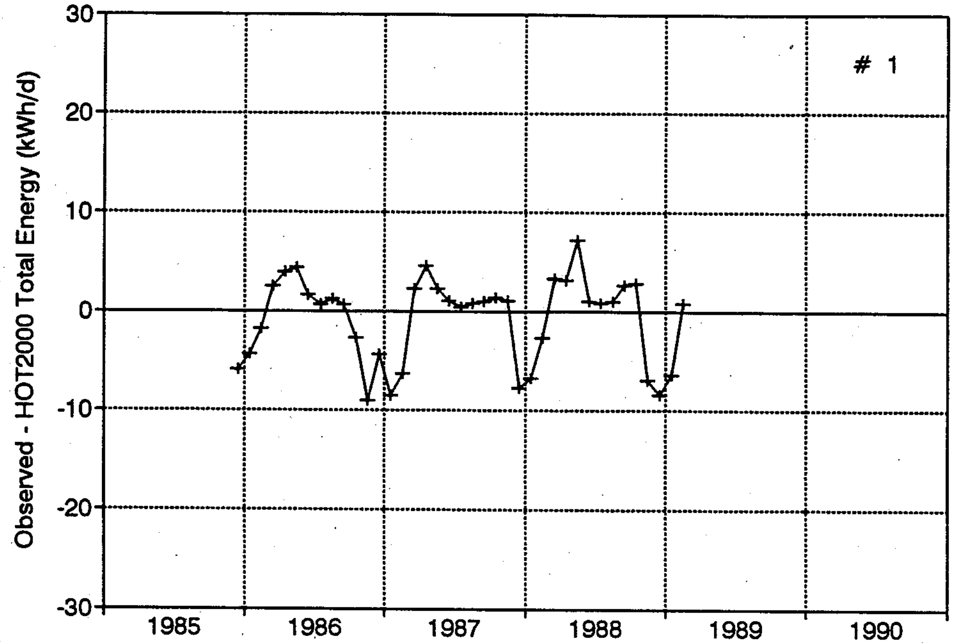
Type:	one-storey wood frame over full basement
Footprint:	63 square metres
Heated Volume:	283 cubic metres
Construction:	Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in cellulose)
	glass fibre batts over vaulted ceiling portion
Main Walls:	R 4.7 (glass fibre, batts plus semi-rigid sheathing)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric forced air furnace
Ventilation system:	HRV (double crossflow, 1st generation, shared ducts)
DHW system:	electric tank

A.1.2 Energy Sub-Metering Schedule

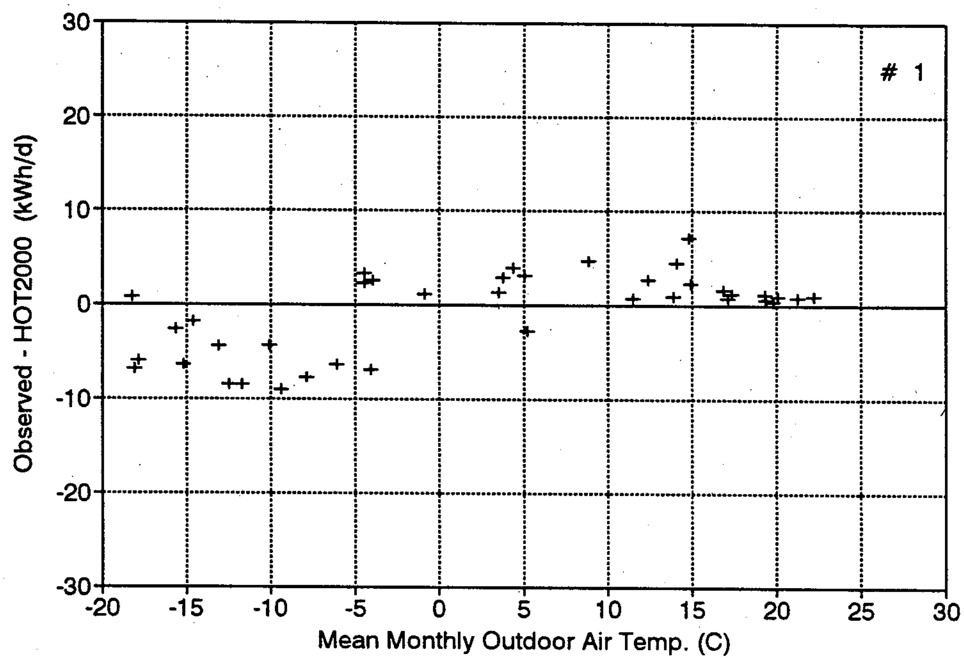
Main Electric
- Electric Furnace
- Domestic Hot Water Tank
- Appliances incl. HRV and Exterior Receptacles (derived)

HRV Total Run Time
- Demand Time
- Defrost Time
- Low Speed Time (derived)

Mains Water



(i)



(ii)

Figure A.1(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
(ii) Model Performance Signature

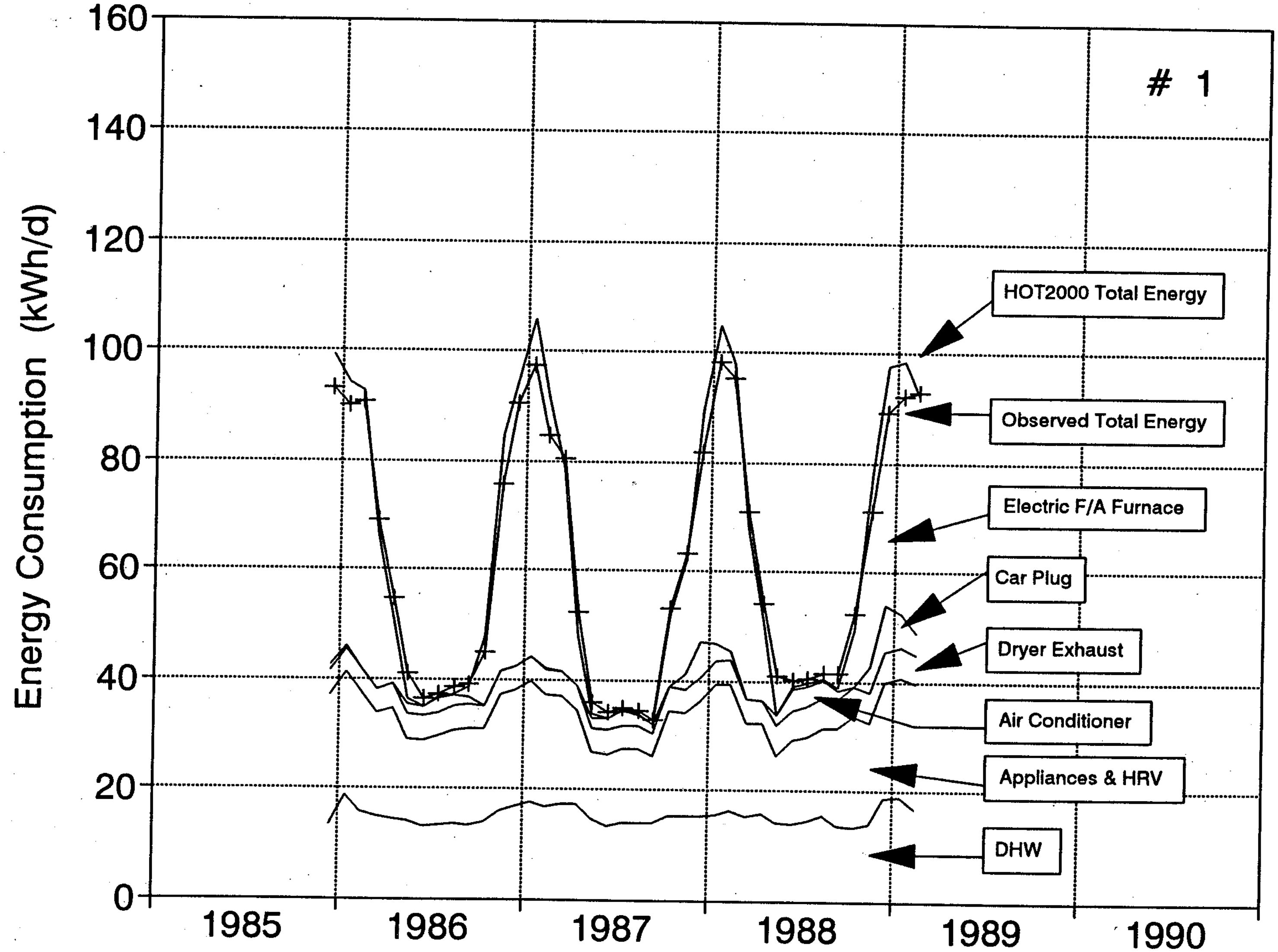
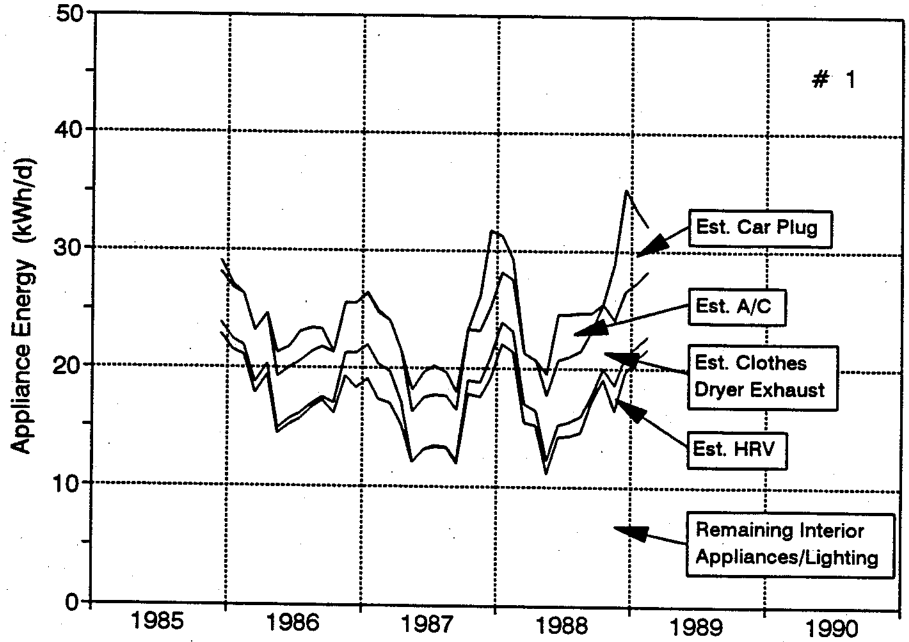


Figure A.1(a) Energy Profile



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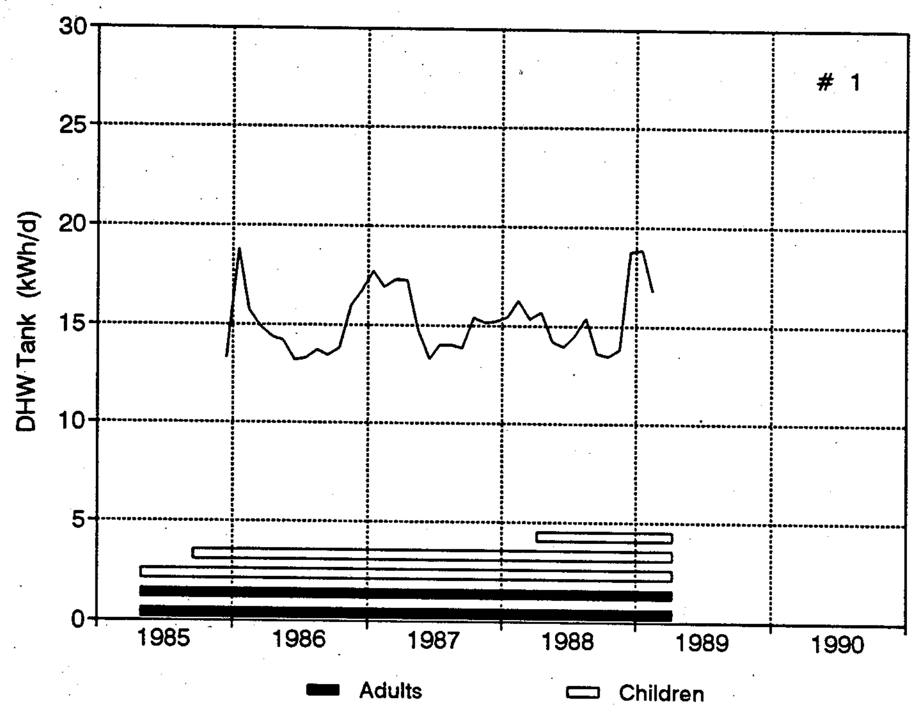


(ii)

Figure A.1(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.2 House # 2

A.2.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	450 cubic metres
Construction:	Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in cellulose)
	glass fibre batts over vaulted ceiling portion
Main Walls:	R 4.7 (glass fibre, batts plus semi-rigid sheathing)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric forced air furnace
Ventilation system:	HRV (double crossflow, 1st generation, shared ducts)
DHW system:	electric tank

A.2.2 Energy Sub-Metering Schedule

Main Electric
- Electric Furnace
- Domestic Hot Water Tank
- Appliances incl. HRV and Exterior Receptacles (derived)

HRV Total Run Time
- Demand Time
- Defrost Time
- Low Speed Time (derived)

Mains Water

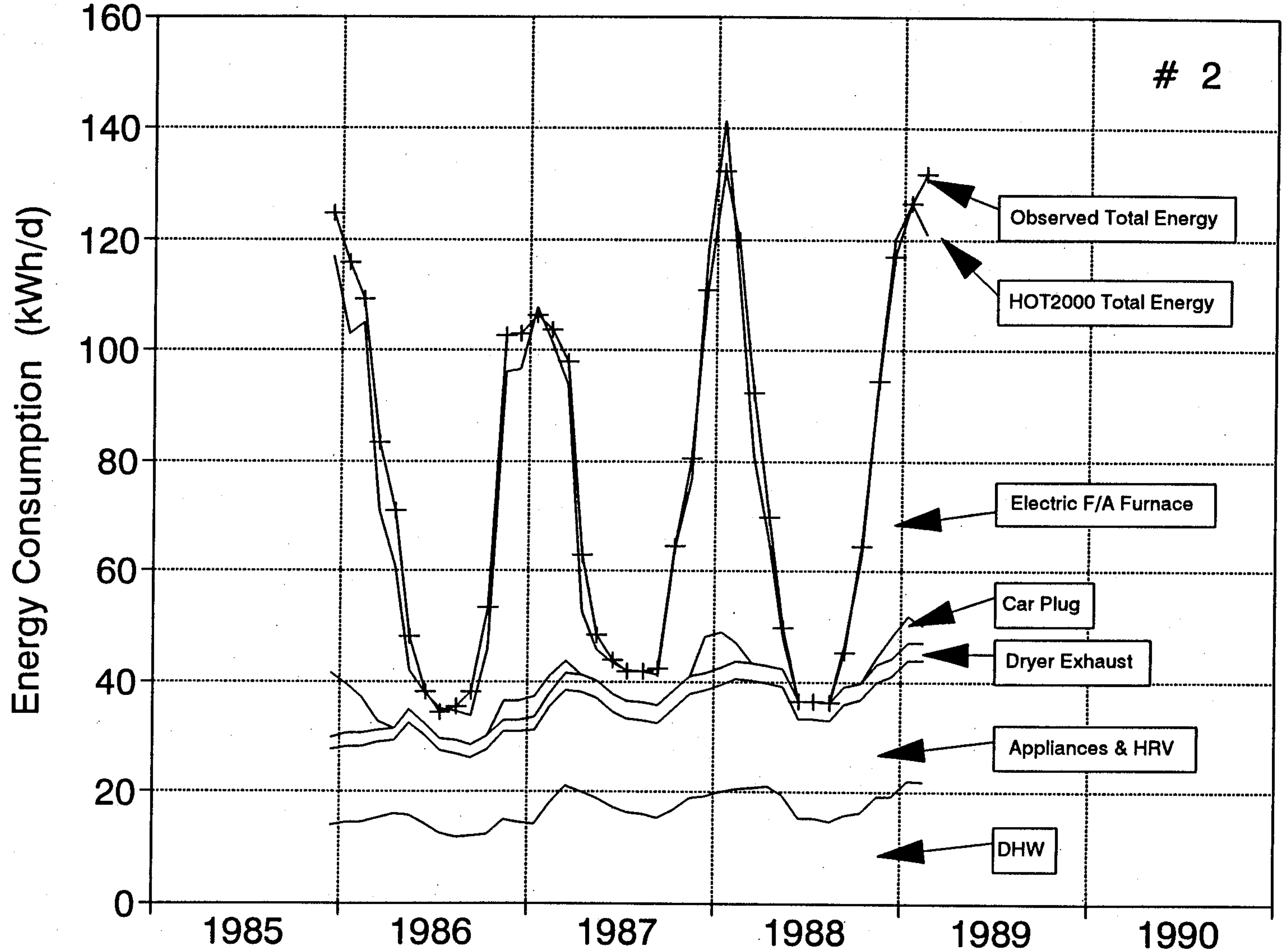
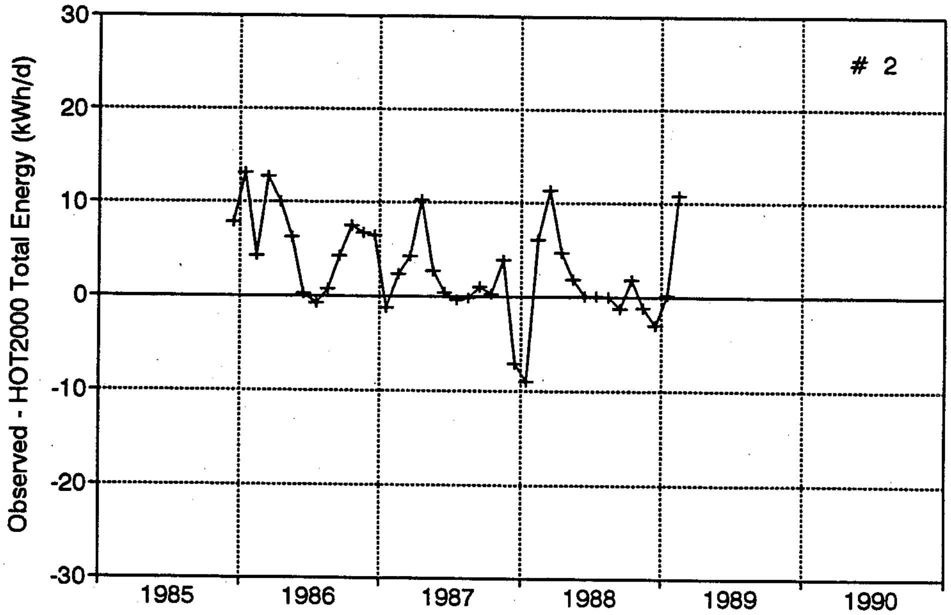


Figure A.2(a) Energy Profile



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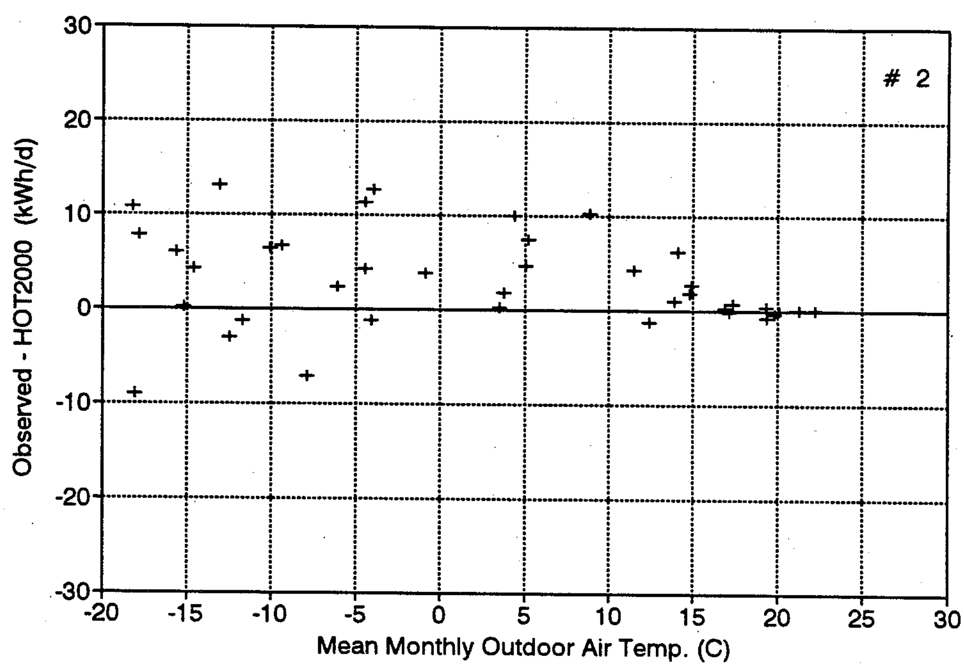

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Figure A.2(b) Energy Model Performance
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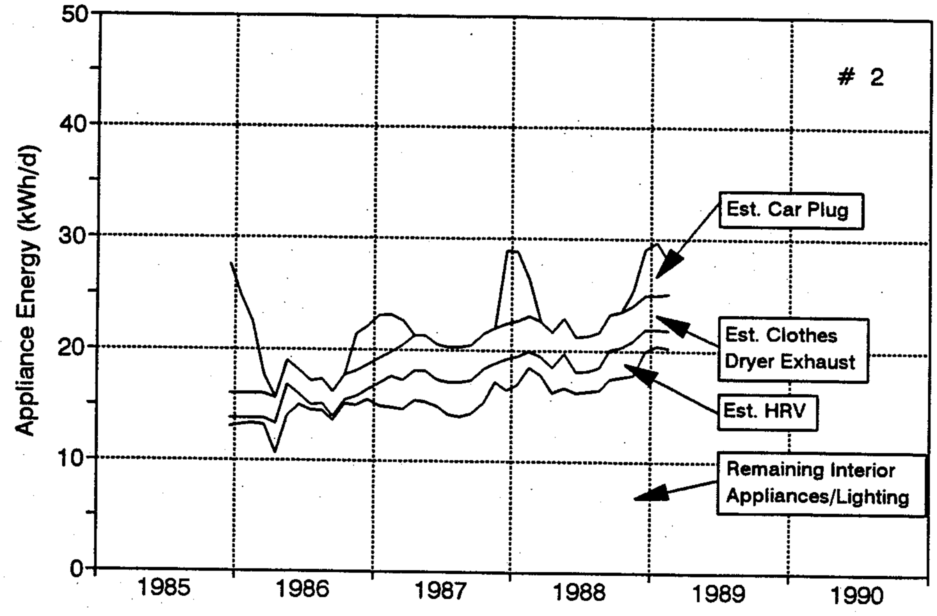
(ii) Model Performance Signature



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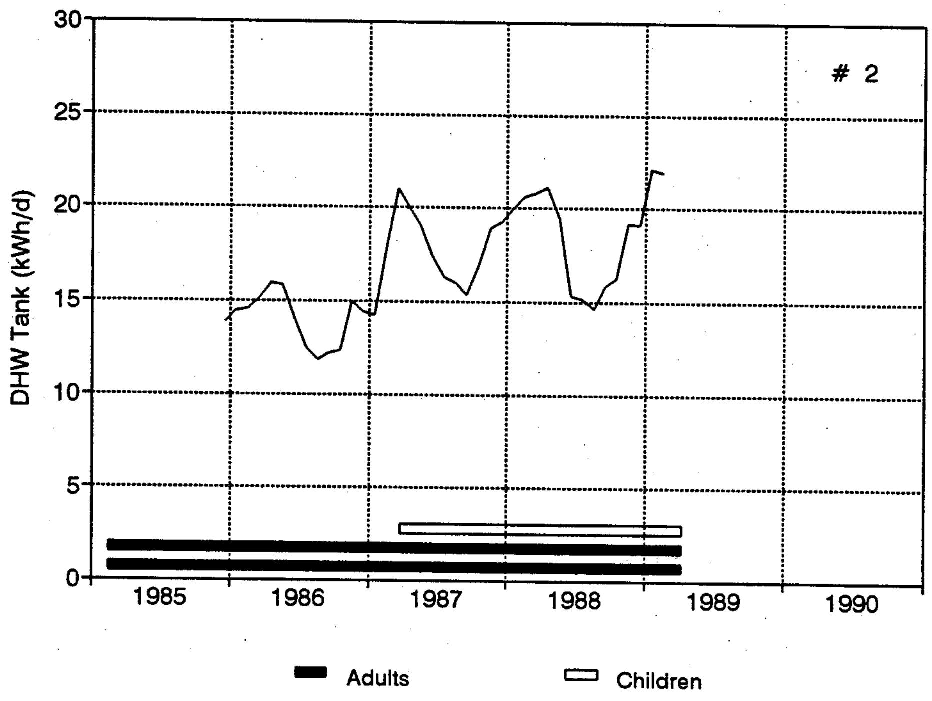


(ii)

Figure A.2(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.3 House # 3

A.3.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	63 square metres
Heated Volume:	283 cubic metres
Construction:	Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in cellulose)
	glass fibre batts over vaulted ceiling portion
Main Walls:	R 4.7 (glass fibre, batts plus semi-rigid sheathing)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric forced air furnace
Ventilation system:	HRV (double crossflow, 1st generation, shared ducts)
DHW system:	electric tank

A.3.2 Energy Sub-Metering Schedule

Main Electric
- Electric Furnace
- Domestic Hot Water Tank
- Appliances incl. HRV and Exterior Receptacles (derived)

HRV Total Run Time
- Demand Time
- Defrost Time
- Low Speed Time (derived)

Mains Water

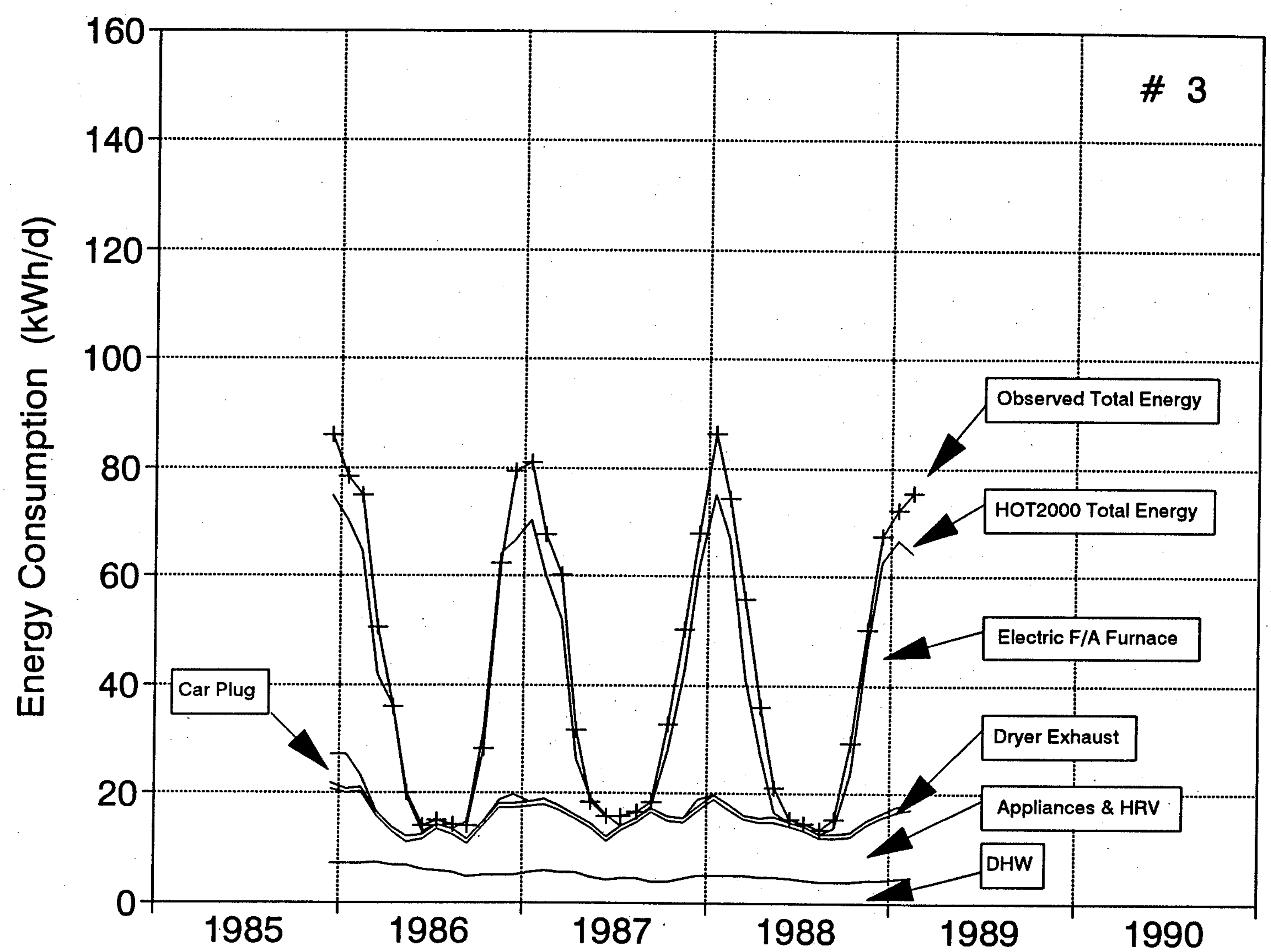
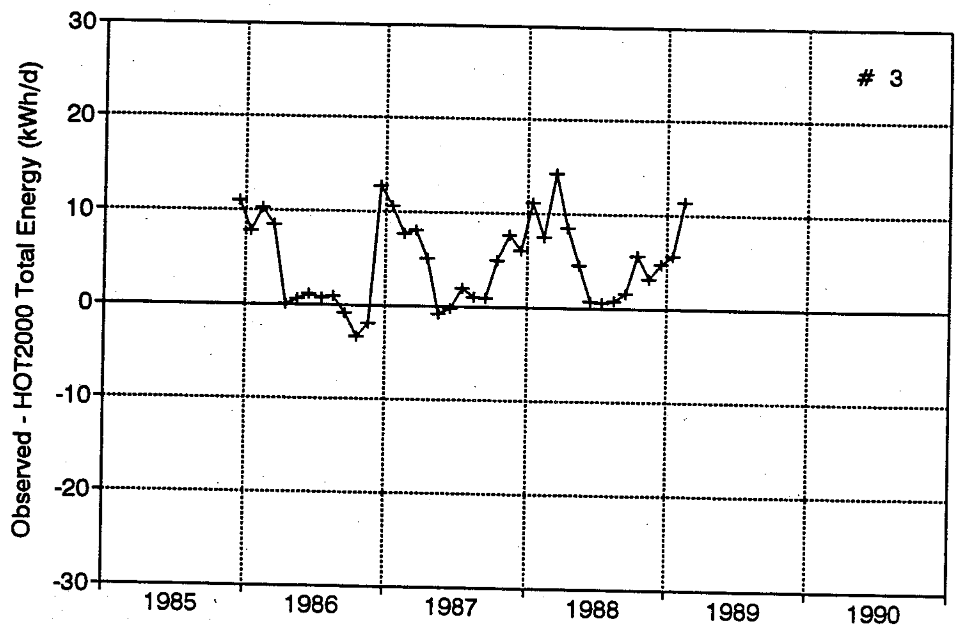


Figure A.3(a) Energy Profile



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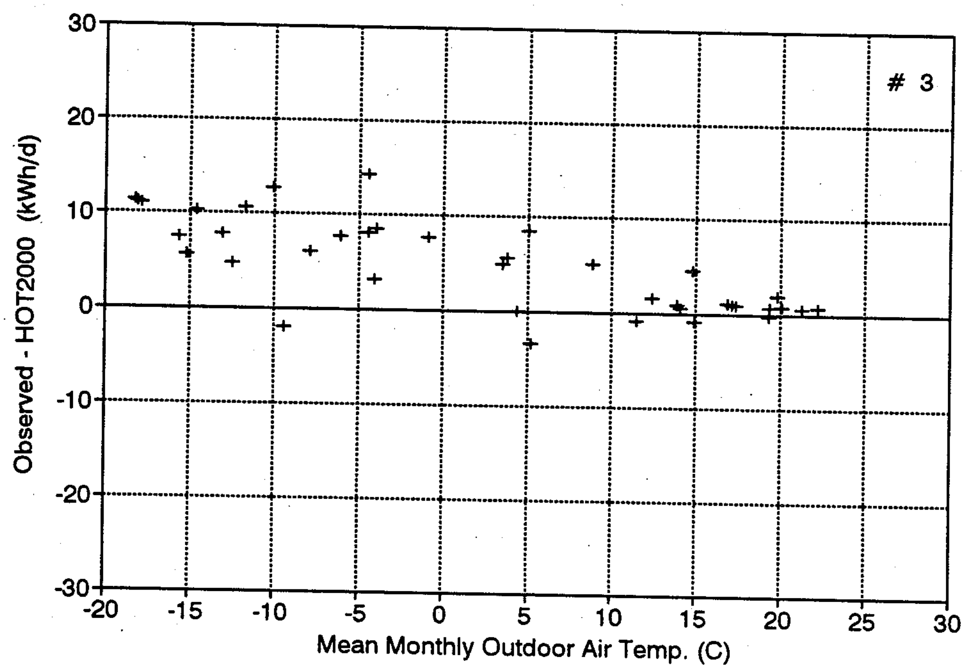

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Figure A.3(b) Energy Model Performance
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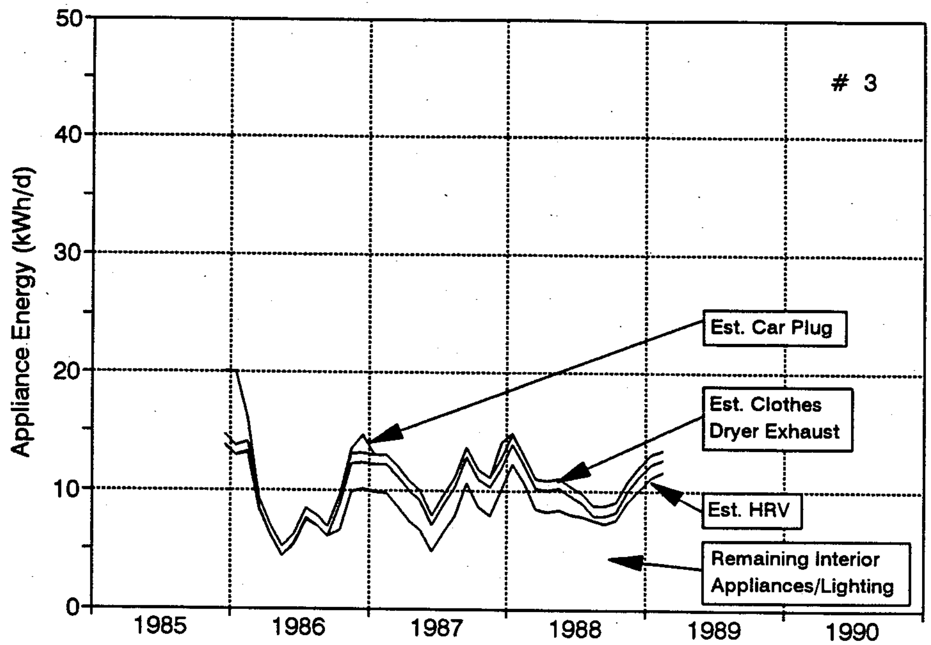
(ii) Model Performance Signature



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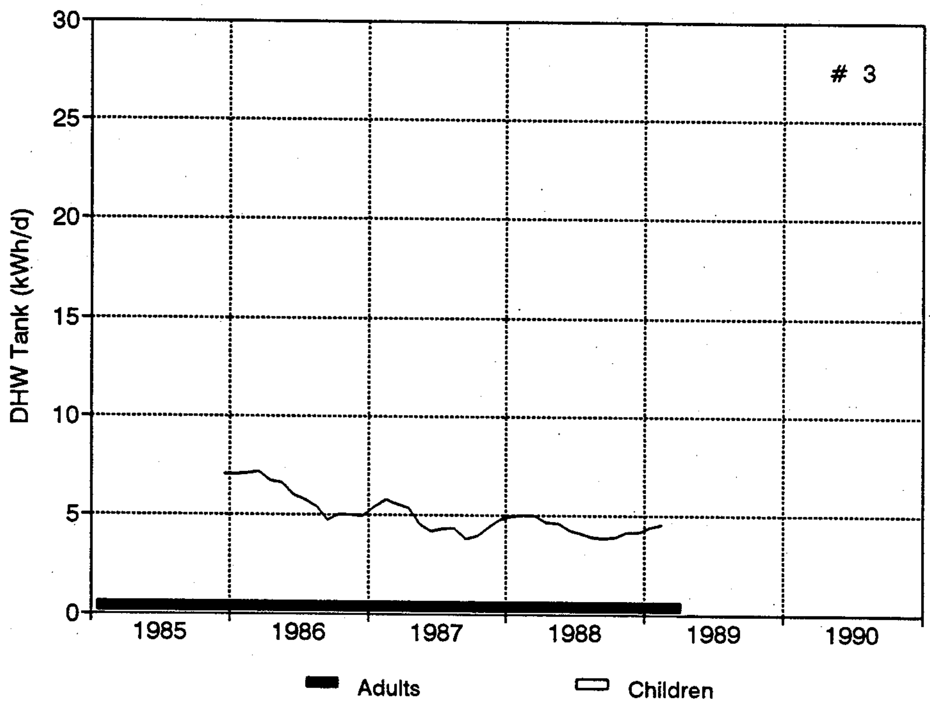


(ii)

Figure A.3(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.4 House # 4

A.4.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	450 cubic metres
Construction:	Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in cellulose) glass fibre batts over vaulted ceiling portion
Main Walls:	R 4.7 (glass fibre, batts plus semi-rigid sheathing)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric forced air furnace
Ventilation system:	HRV (double crossflow, 1st generation, shared ducts)
DHW system:	electric tank

A.4.2 Energy Sub-Metering Schedule

Main Electric
- Electric Furnace
- Domestic Hot Water Tank
- Appliances incl. HRV and Exterior Receptacles (derived)

HRV Total Run Time
- Demand Time
- Defrost Time
- Low Speed Time (derived)

Mains Water

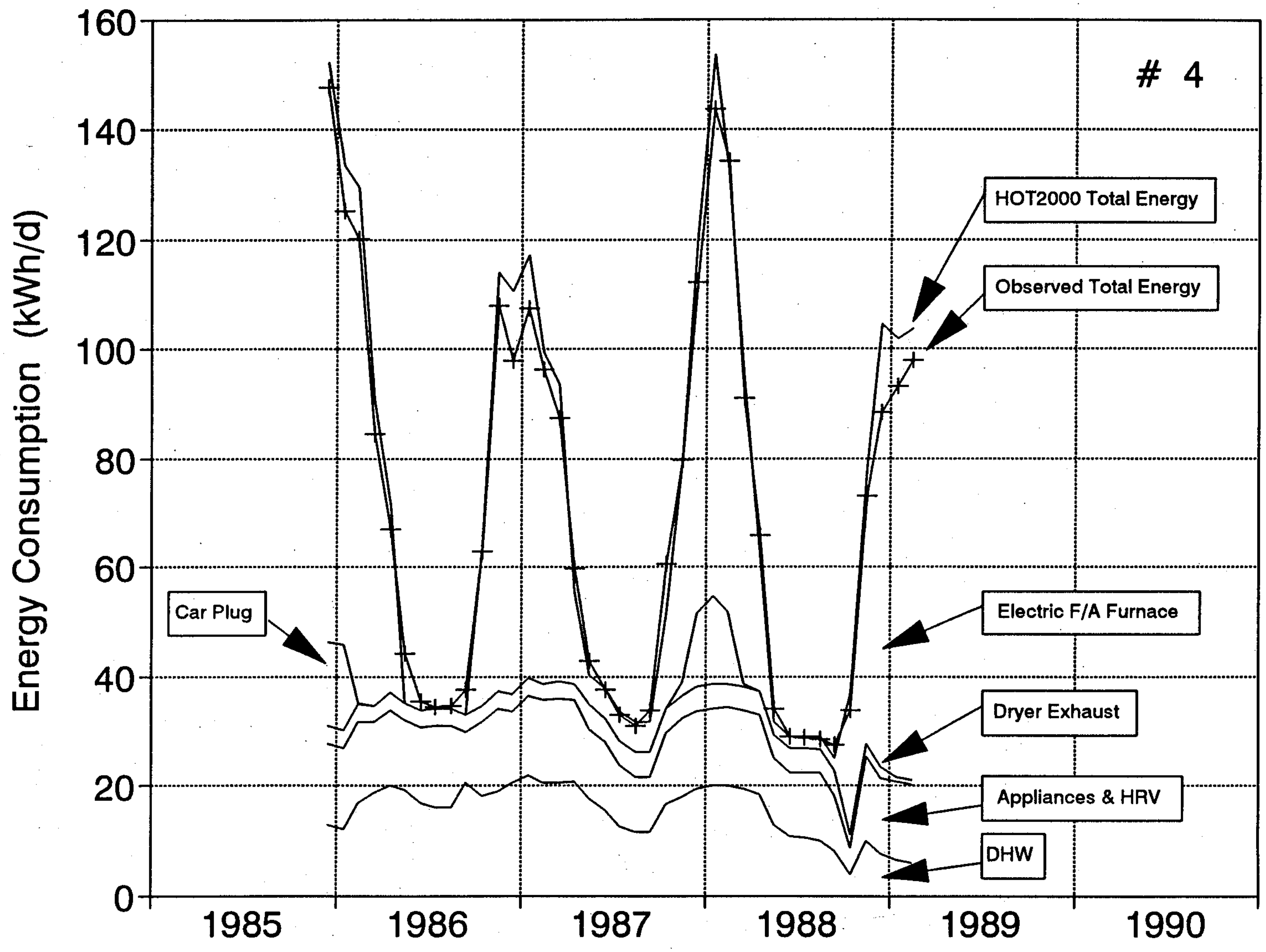
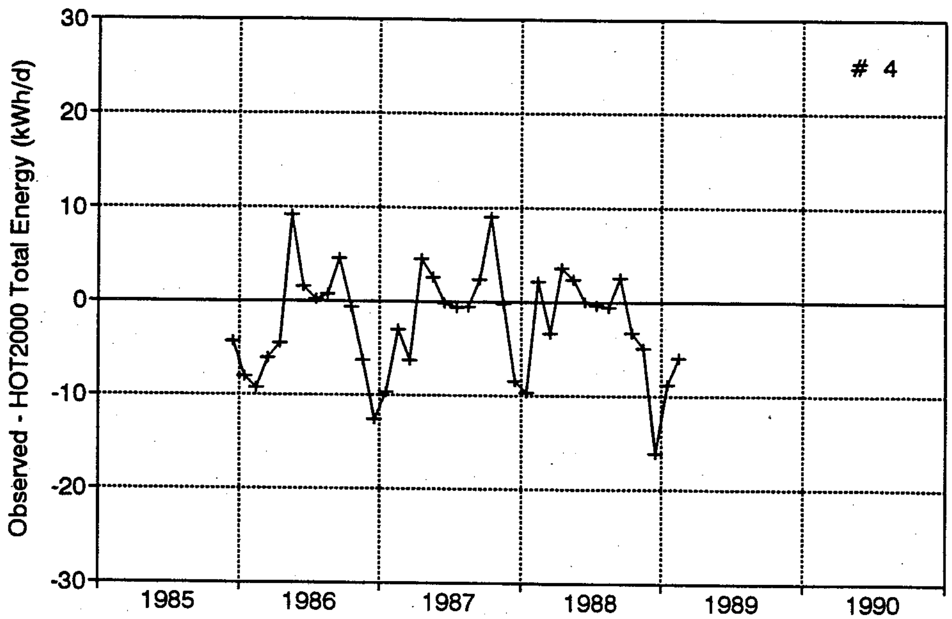


Figure A.4(a) Energy Profile



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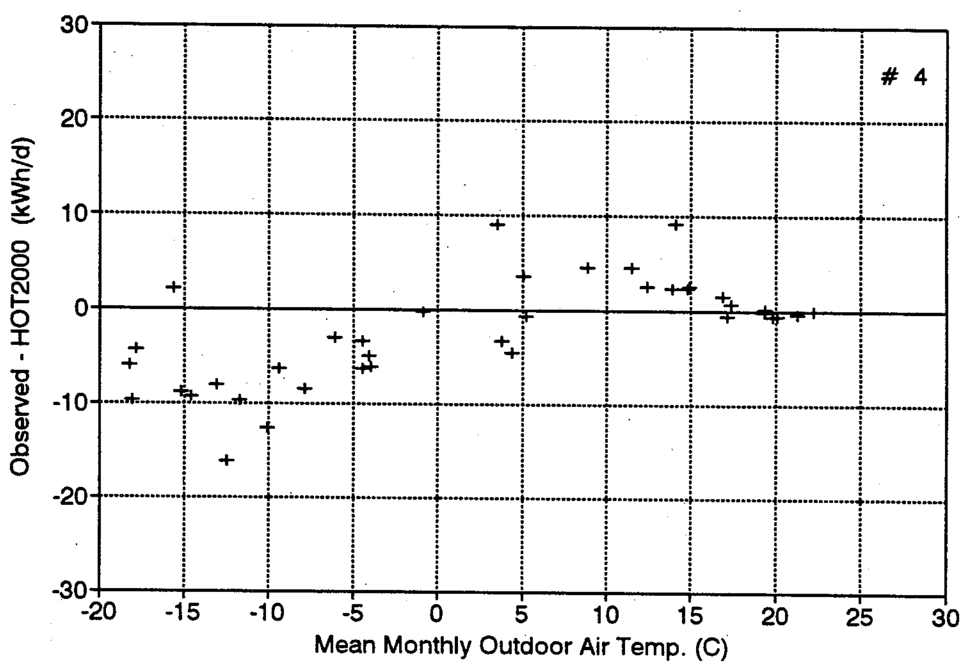

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Figure A.4(b) Energy Model Performance
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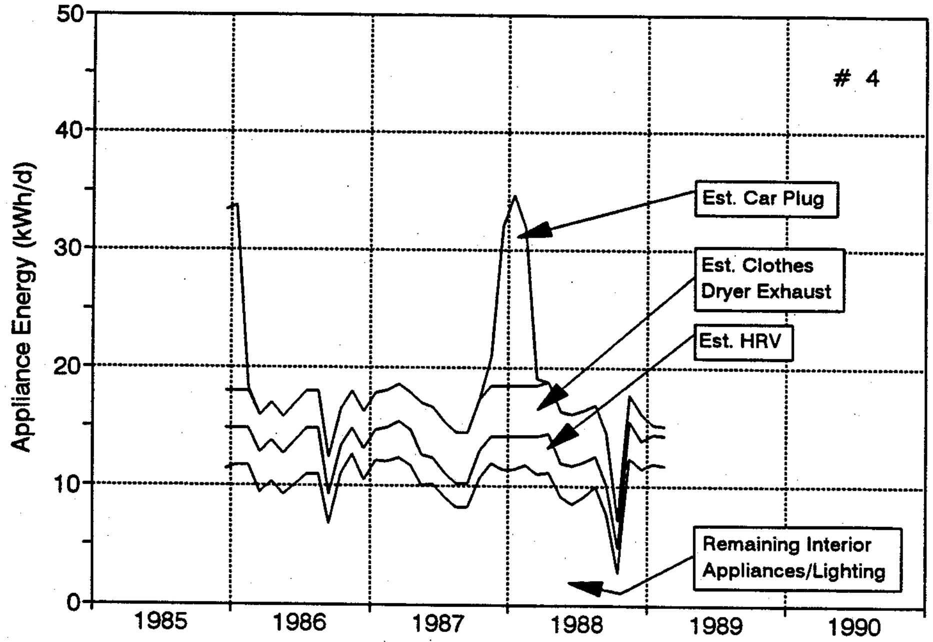

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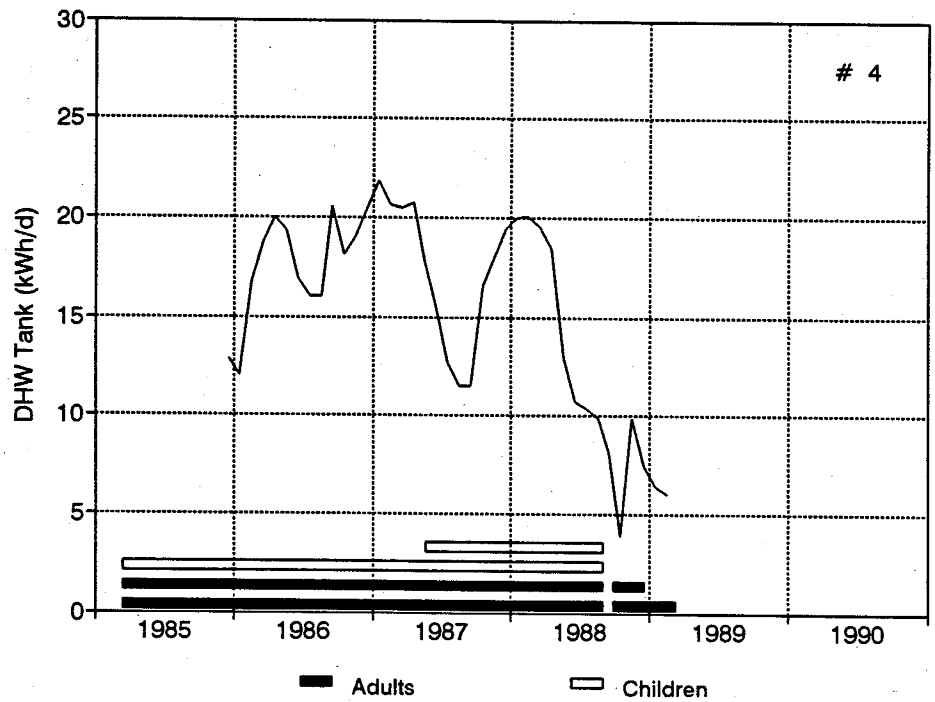


(ii)

Figure A.4(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.5 House # 5

A.5.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	63 square metres
Heated Volume:	279 cubic metres
Construction:	Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in cellulose) glass fibre batts over vaulted ceiling portion
Main Walls:	R 4.7 (glass fibre, batts plus semi-rigid sheathing)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric forced air furnace
Ventilation system:	HRV (double crossflow, 1st generation, shared ducts)
DHW system:	electric tank

A.5.2 Energy Sub-Metering Schedule

Main Electric
- Electric Furnace
- Domestic Hot Water Tank
- Appliances incl. HRV and Exterior Receptacles (derived)

HRV Total Run Time
- Demand Time
- Defrost Time
- Low Speed Time (derived)

Mains Water

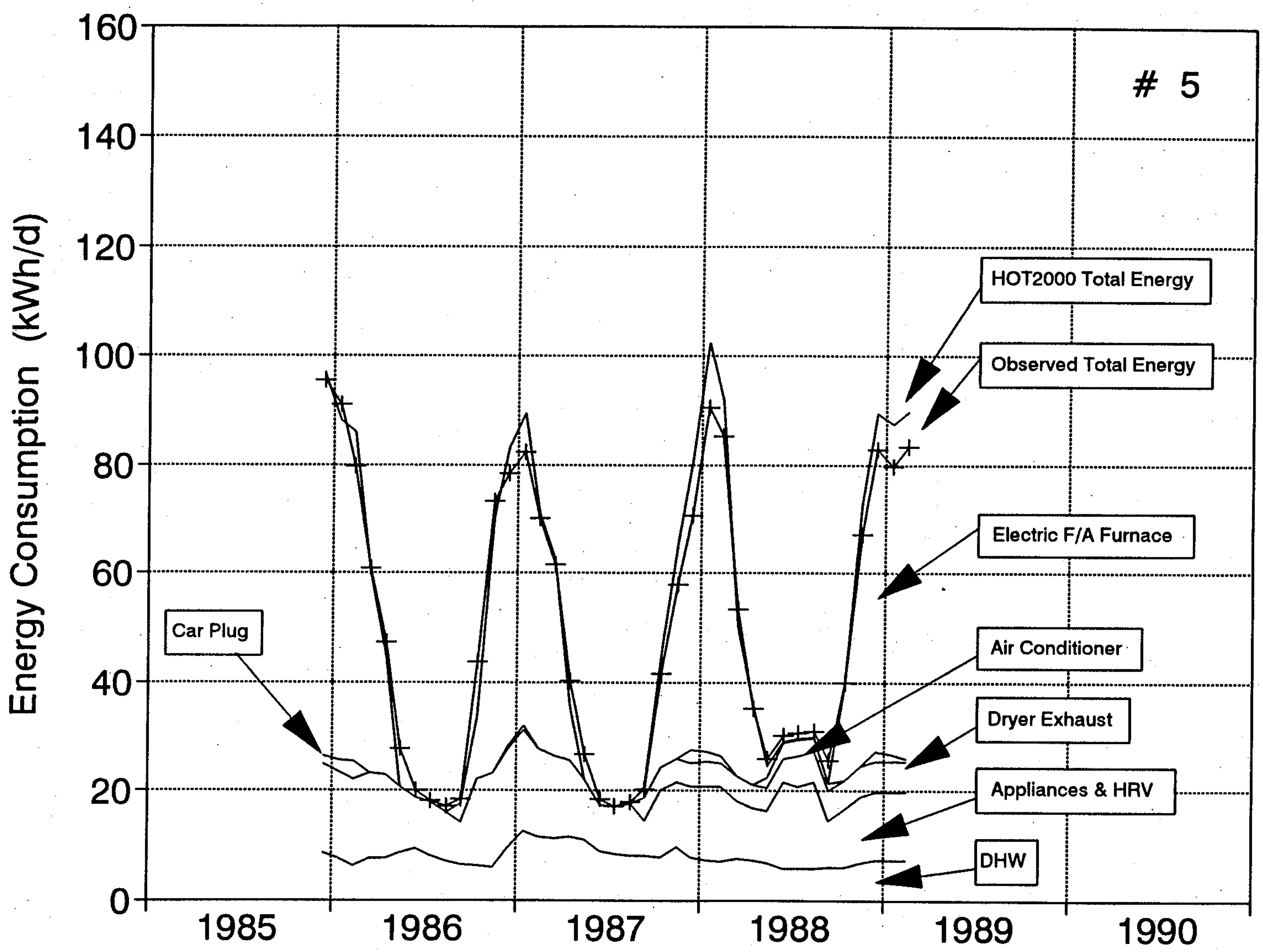
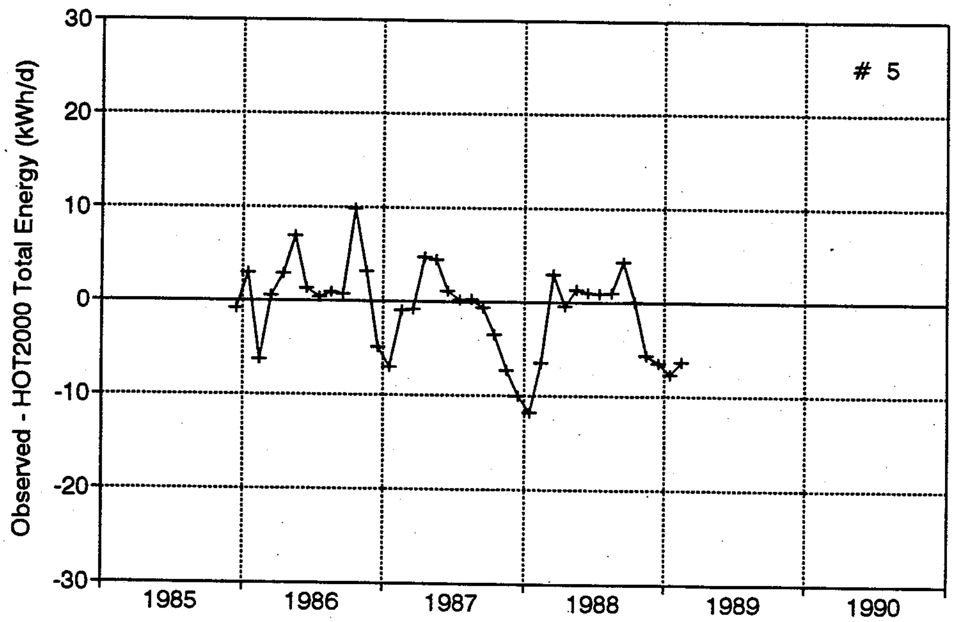


Figure A.5(a) Energy Profile



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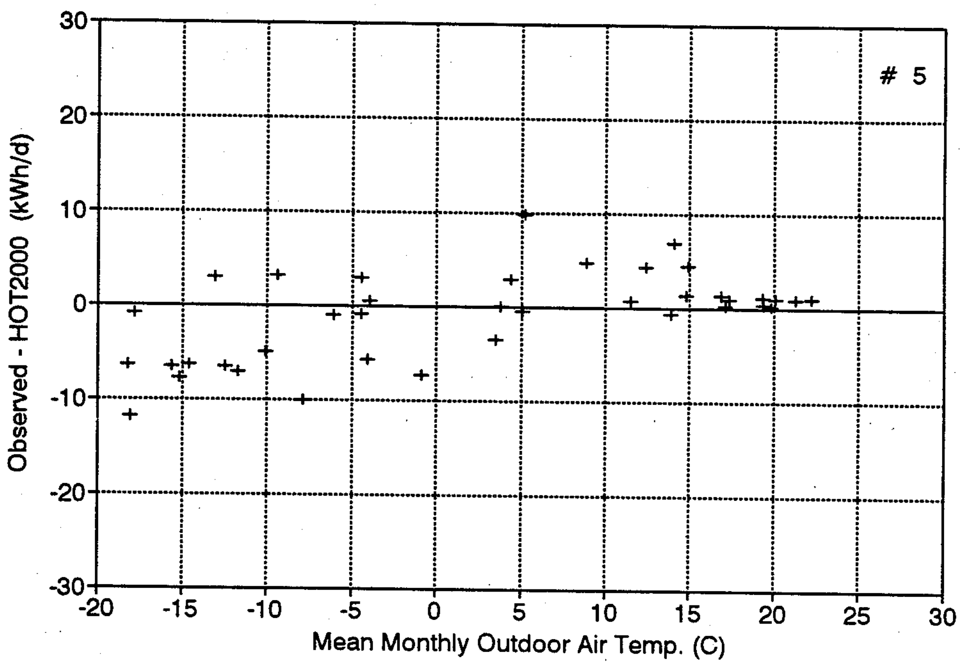

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Figure A.5(b) Energy Model Performance
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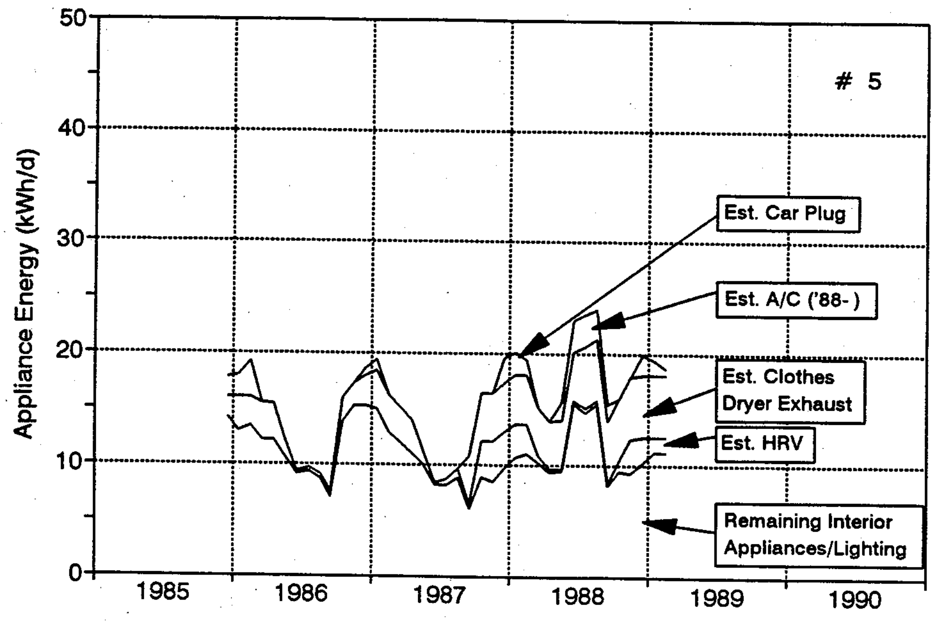

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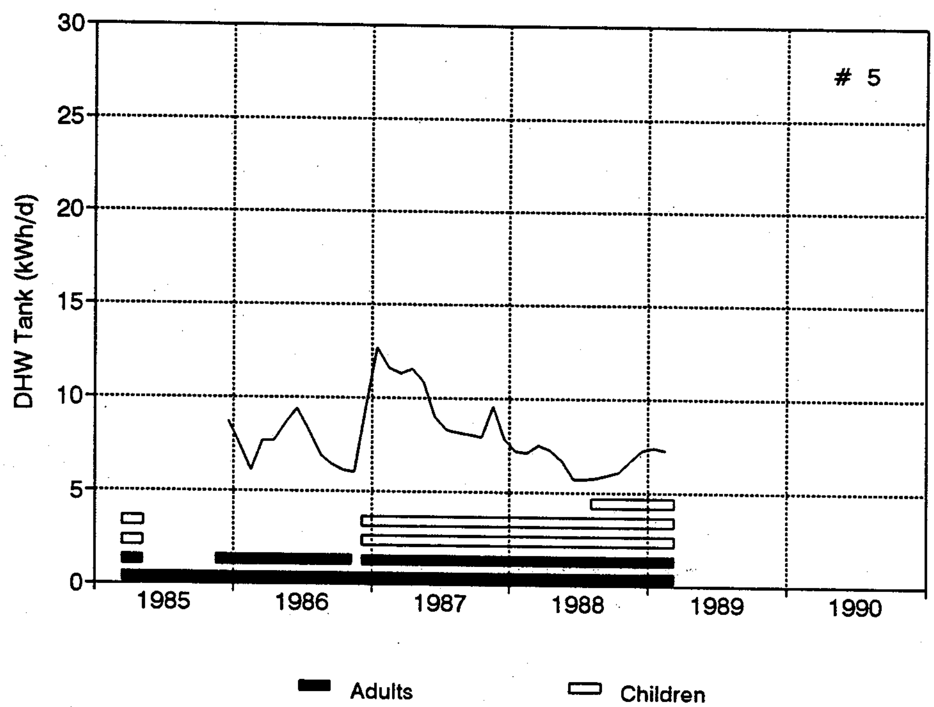


(ii)

Figure A.5(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.6 House # 6

A.6.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	444 cubic metres
Construction:	Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in cellulose)
	glass fibre batts over vaulted ceiling portion
Main Walls:	R 4.7 (glass fibre, batts plus semi-rigid sheathing)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric forced air furnace
Ventilation system:	HRV (double crossflow, 1st generation, shared ducts)
DHW system:	electric tank

A.6.2 Energy Sub-Metering Schedule

Main Electric
- Electric Furnace
- Domestic Hot Water Tank
- Appliances incl. HRV and Exterior Receptacles (derived)

HRV Total Run Time
- Demand Time
- Defrost Time
- Low Speed Time (derived)

Mains Water

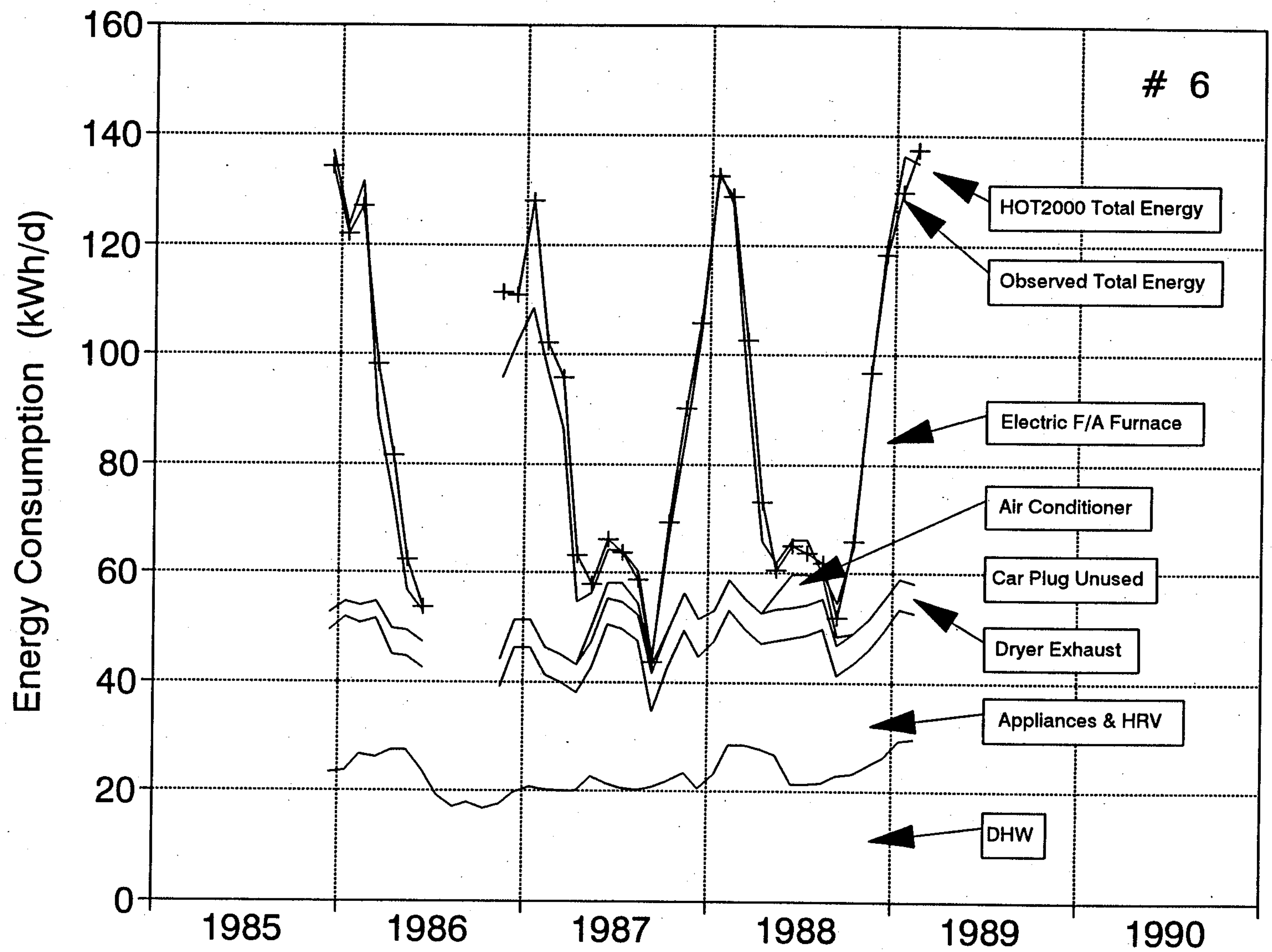
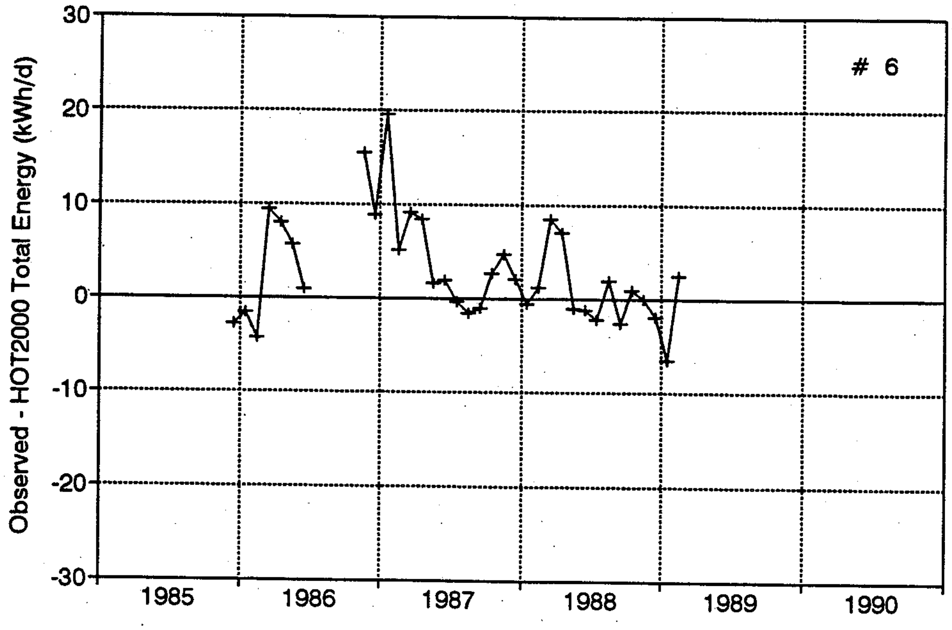


Figure A.6(a) Energy Profile



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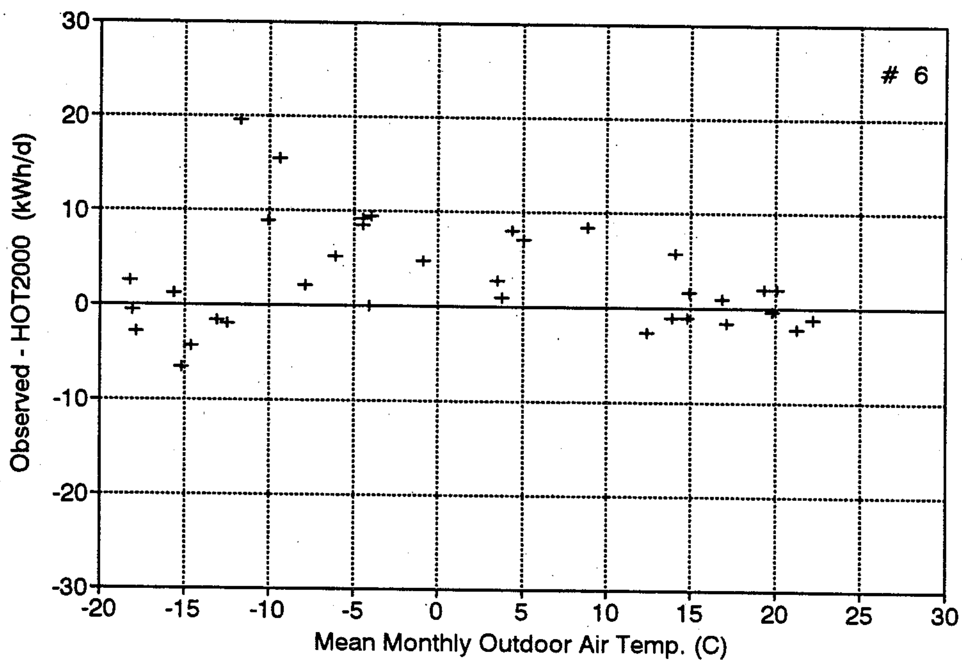

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Figure A.6(b) Energy Model Performance
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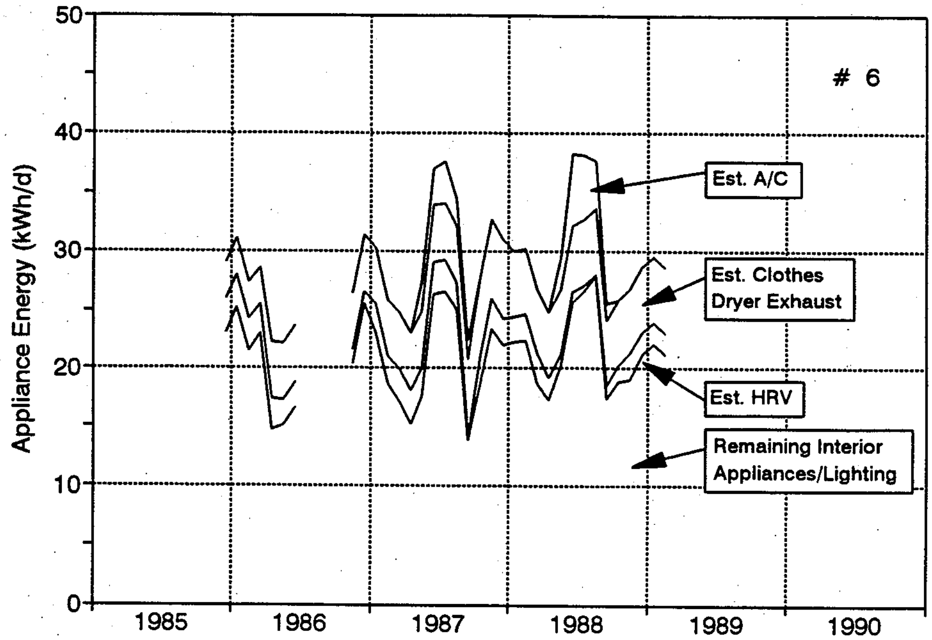

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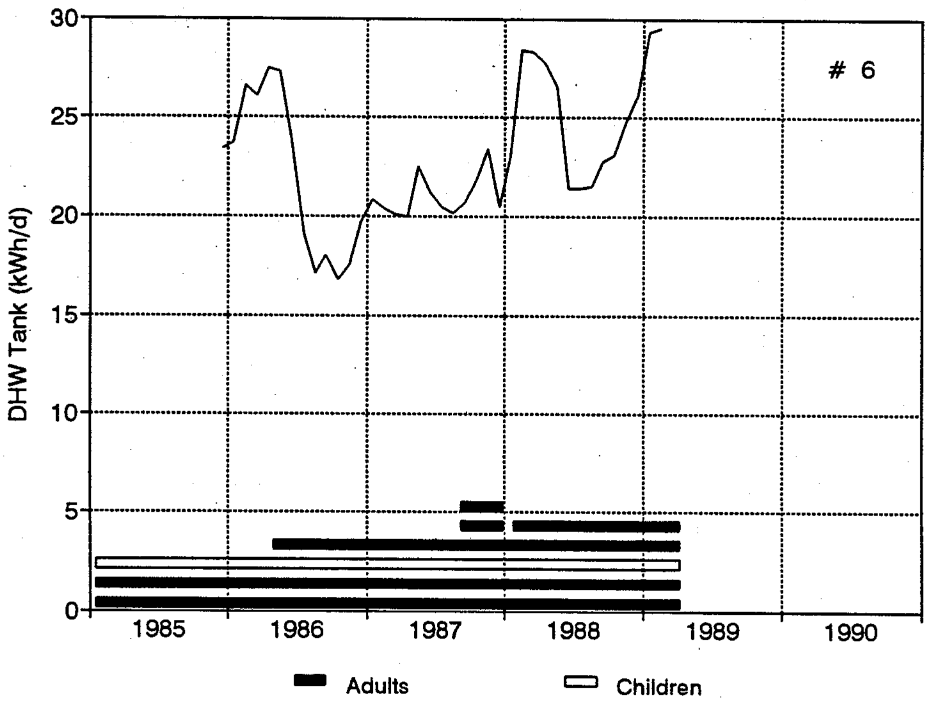


(ii)

Figure A.6(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.7 House # 7

A.7.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	63 square metres
Heated Volume:	283 cubic metres
Construction:	Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in cellulose)
	glass fibre batts over vaulted ceiling portion
Main Walls:	R 3.5 (glass fibre batts)
Basement Walls:	R 1.8 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric forced air furnace
Ventilation system:	central exhaust plus fresh air intake to heating system
DHW system:	electric tank

A.7.2 Energy Sub-Metering Schedule

Main Electric
- Electric Furnace
- Domestic Hot Water Tank
- Appliances incl. Central Exhaust Fan and Exterior Receptacles (derived)

Central Exhaust Fan Total Run Time

Mains Water

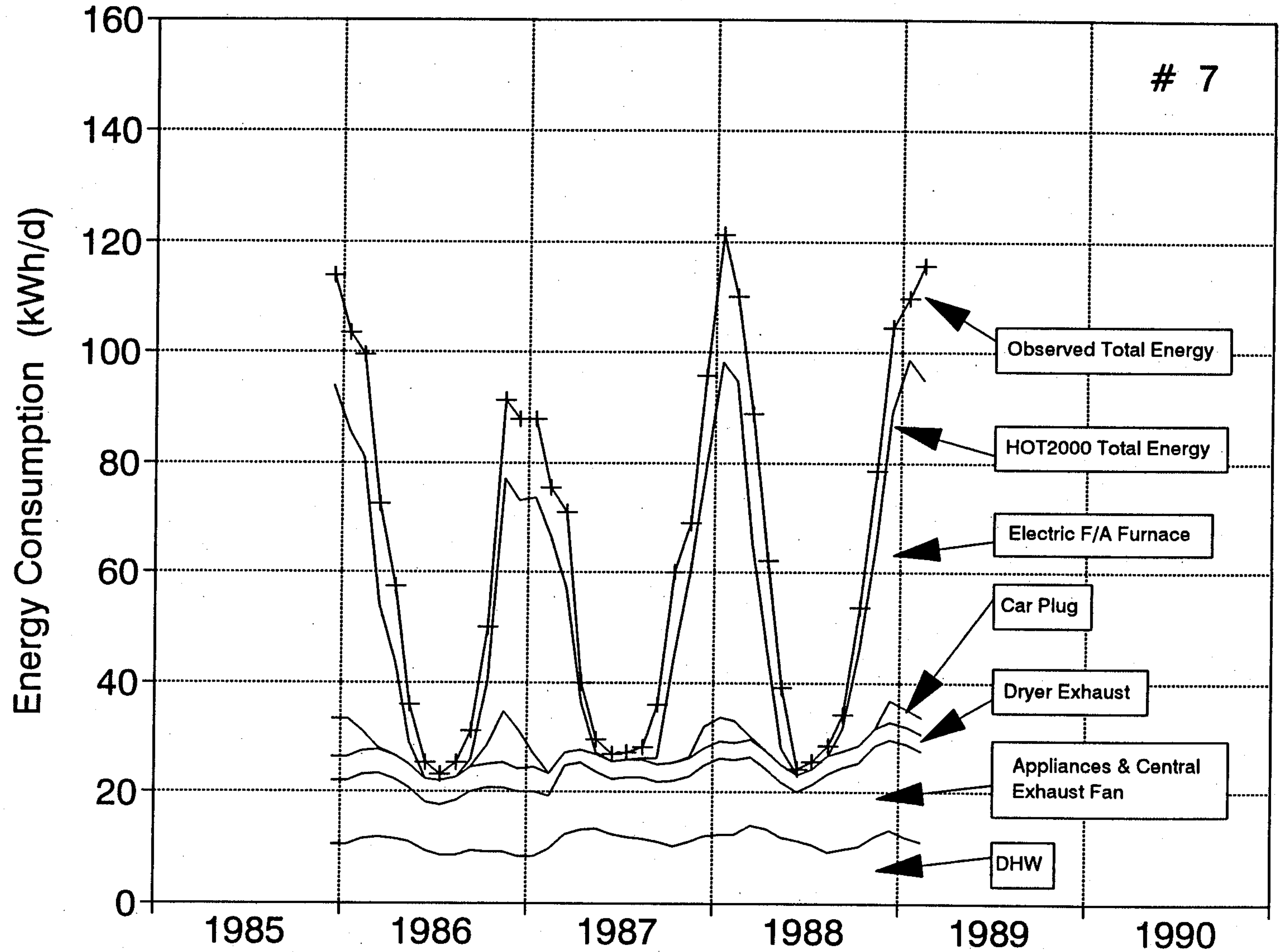
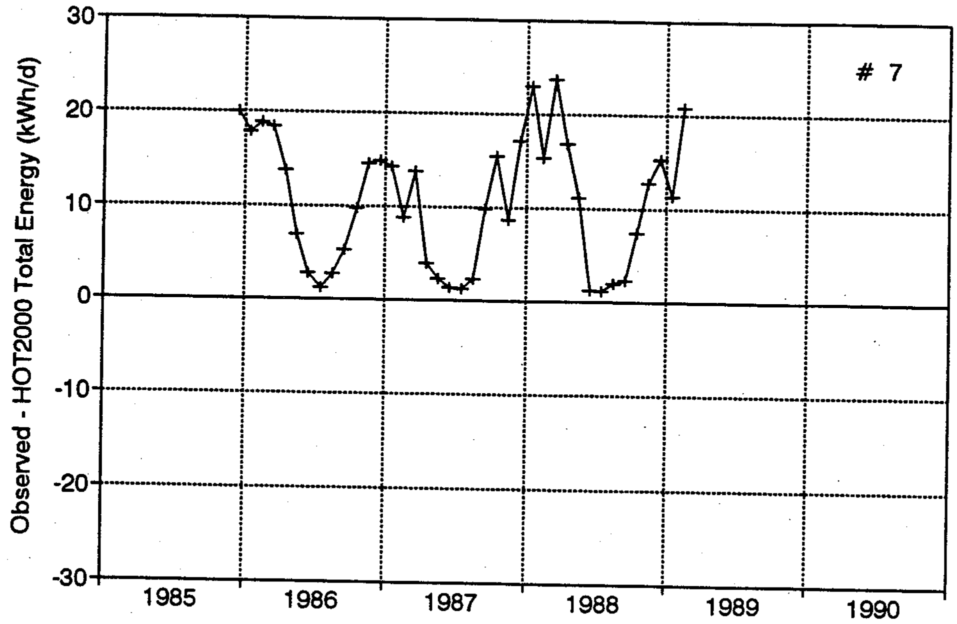


Figure A.7(a) Energy Profile



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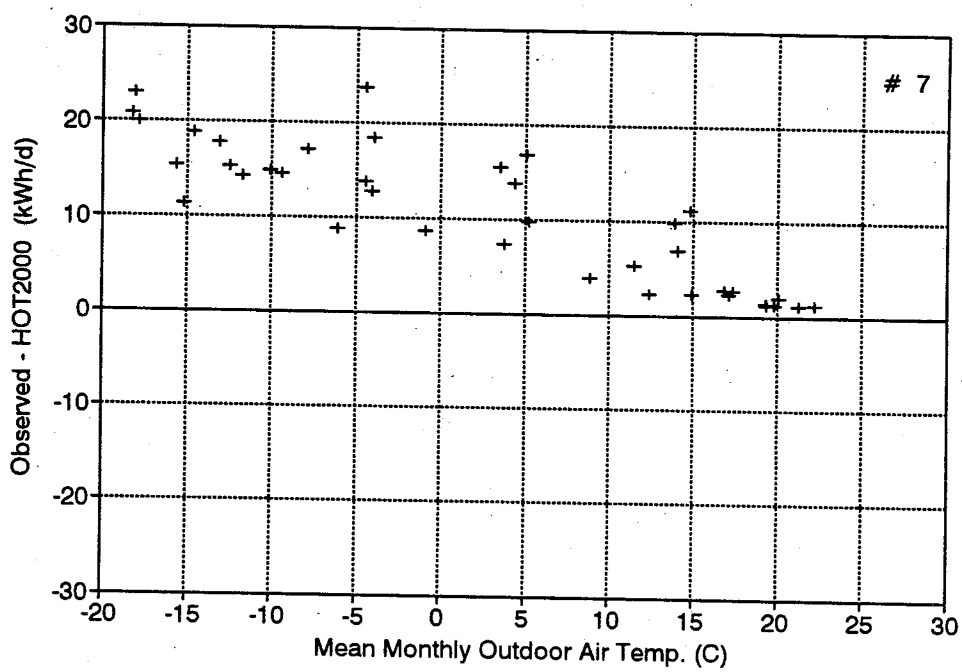

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Figure A.7(b) Energy Model Performance
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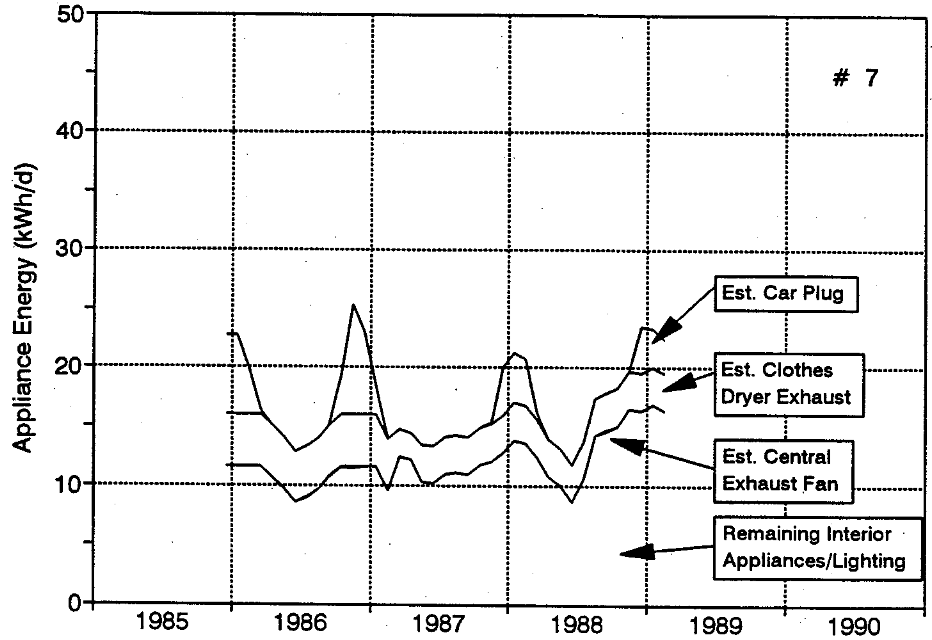

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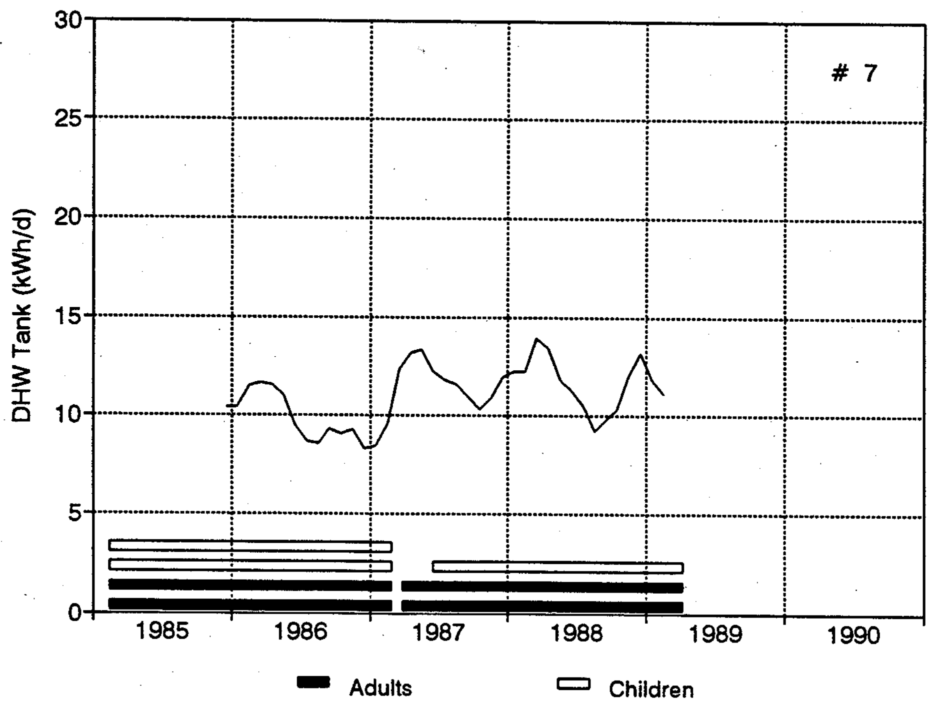


(ii)

Figure A.7(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.8 House # 8

A.8.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	444 cubic metres
Construction:	Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in cellulose)
	glass fibre batts over vaulted ceiling portion
Main Walls:	R 3.5 (glass fibre batts)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric forced air furnace
Ventilation system:	central exhaust plus fresh air intake to heating system
DHW system:	electric tank

A.8.2 Energy Sub-Metering Schedule

Main Electric
- Electric Furnace
- Domestic Hot Water Tank
- Appliances incl. Central Exhaust Fan and Exterior Receptacles (derived)

Central Exhaust Fan Total Run Time

Mains Water

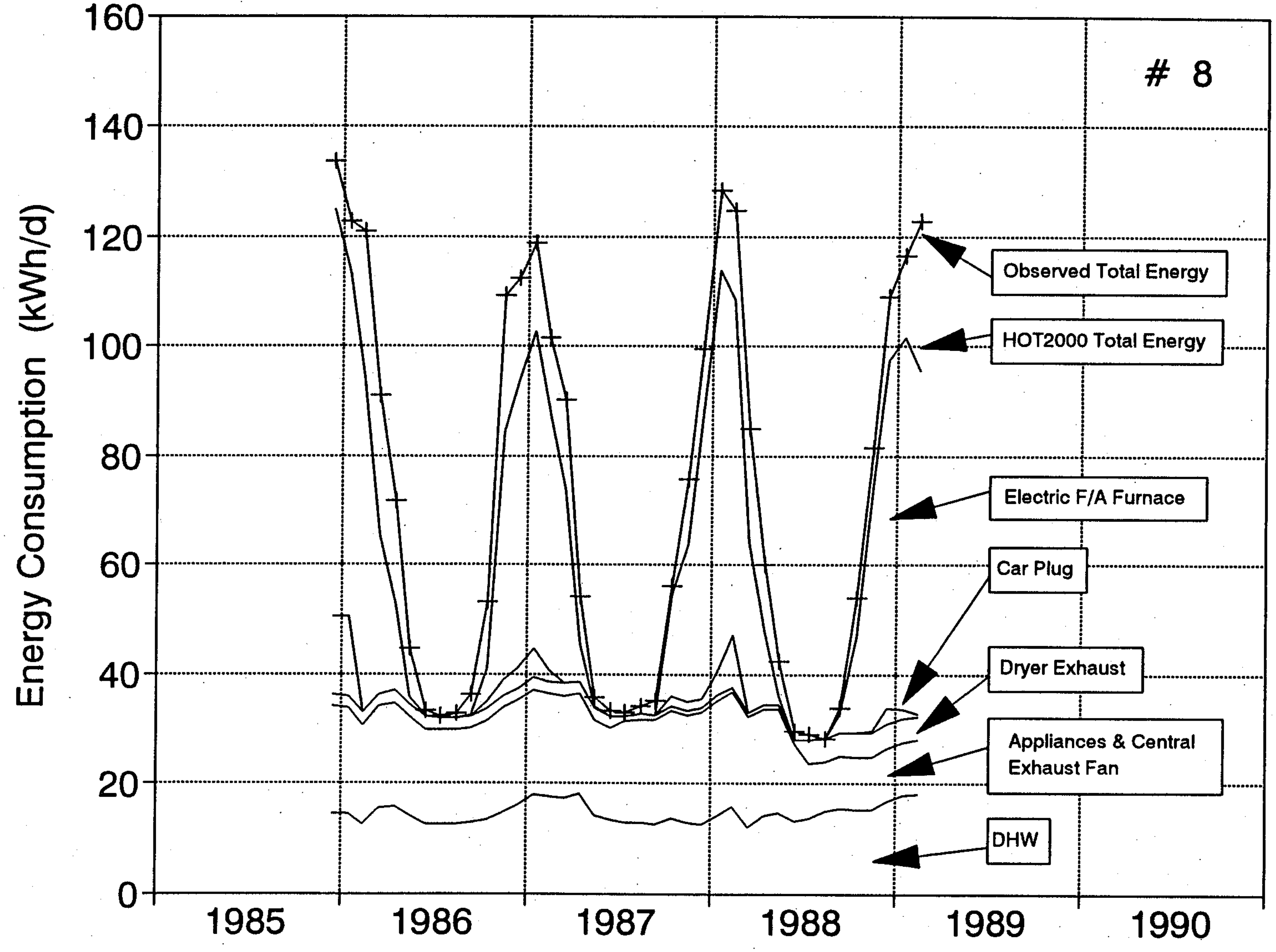
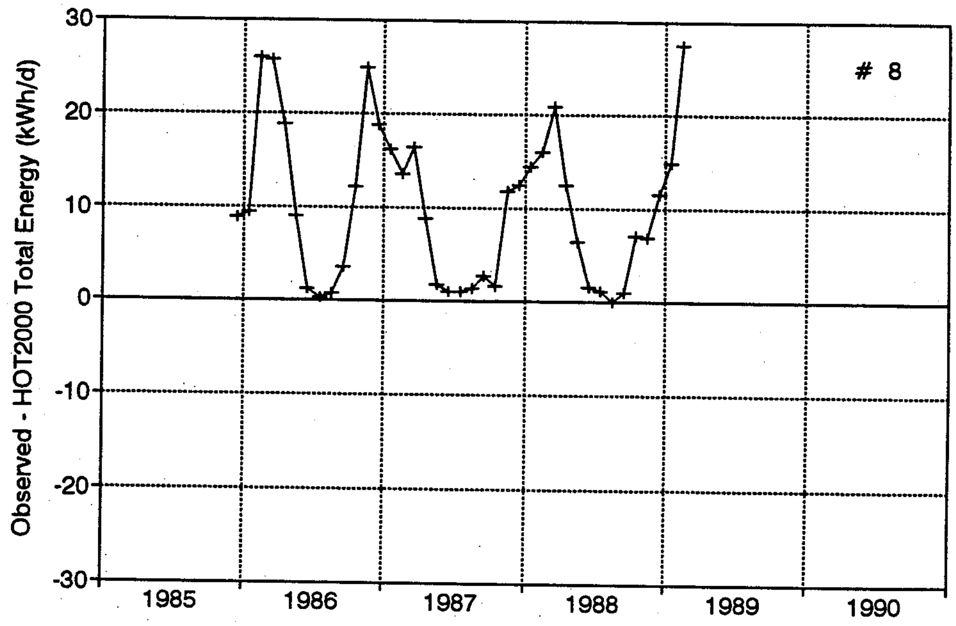


Figure A.8(a) Energy Profile



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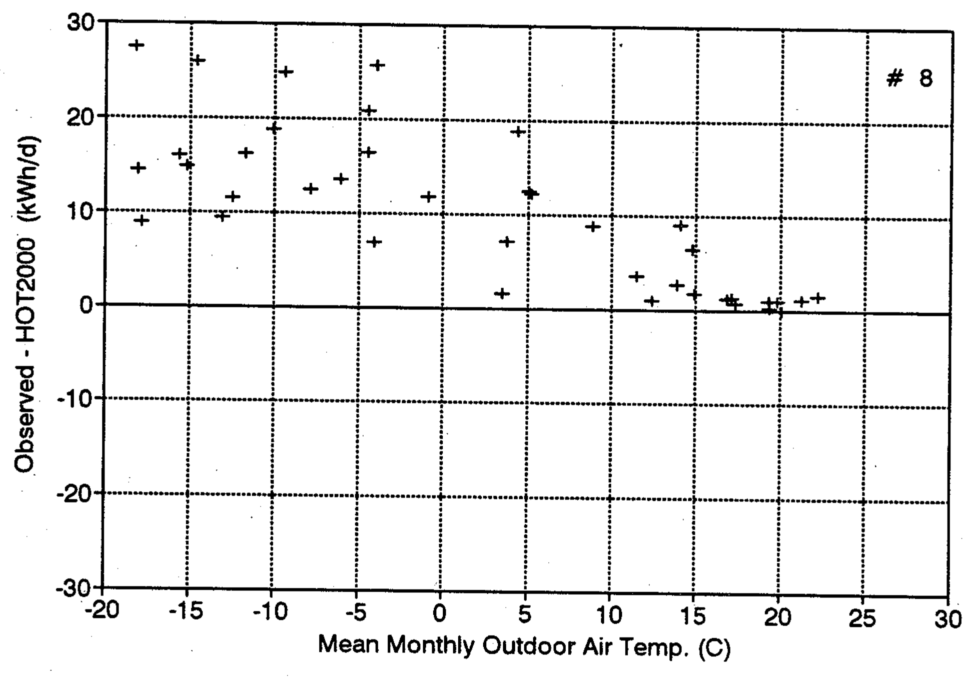

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Figure A.8(b) Energy Model Performance
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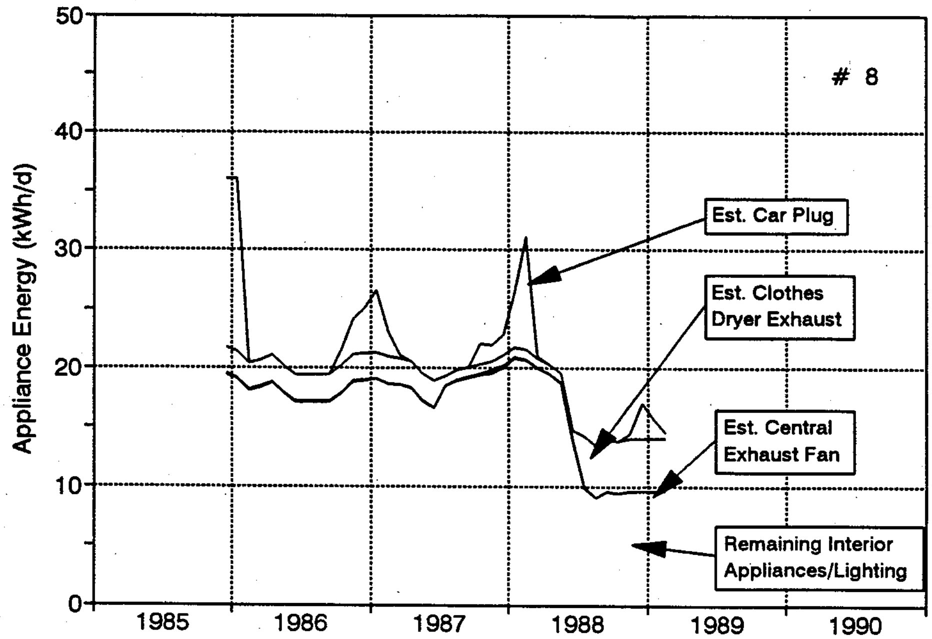

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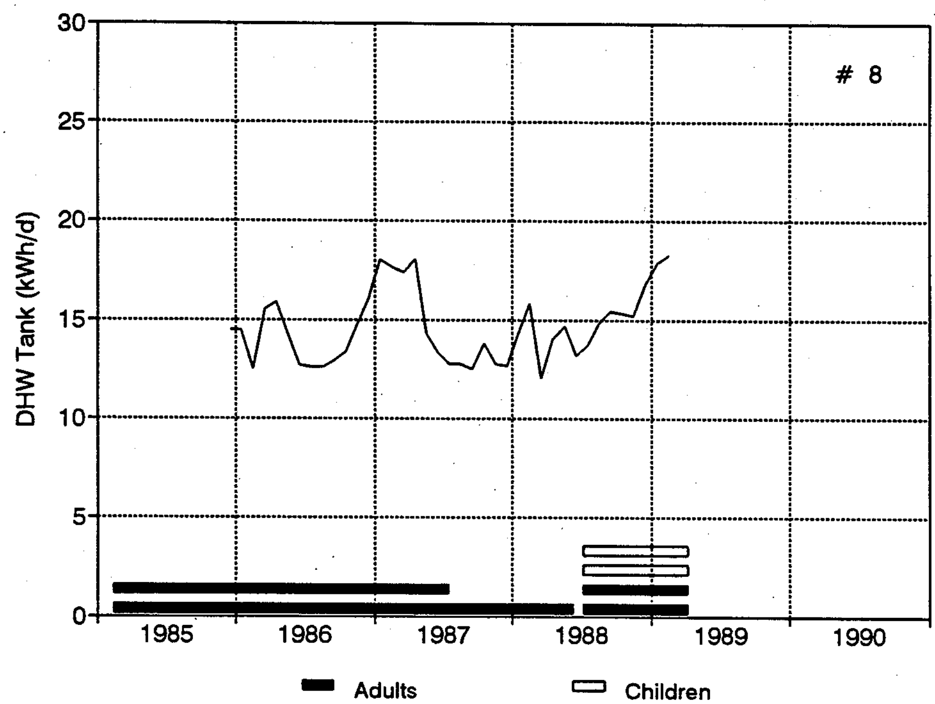


(ii)

Figure A.8(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.9 House # 9

A.9.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	63 square metres
Heated Volume:	279 cubic metres
Construction:	conventional, with 4 mil poly air/vapour barrier
Ceiling:	R 7.0 (blown-in cellulose)
	glass fibre batts over vaulted ceiling portion
Main Walls:	R 3.5 (glass fibre batts)
Basement Walls:	R 1.8 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	conventional natural gas forced air furnace
Ventilation system:	bathroom exhaust fan
DHW system:	conventional natural gas tank

A.9.2 Energy Sub-Metering Schedule

Main Electric (incl. appliances, bathroom exhaust fan, exterior receptacles)

Main Natural Gas
- Natural Gas Furnace
- Natural Gas Domestic Hot Water Tank (derived)

Mains Water

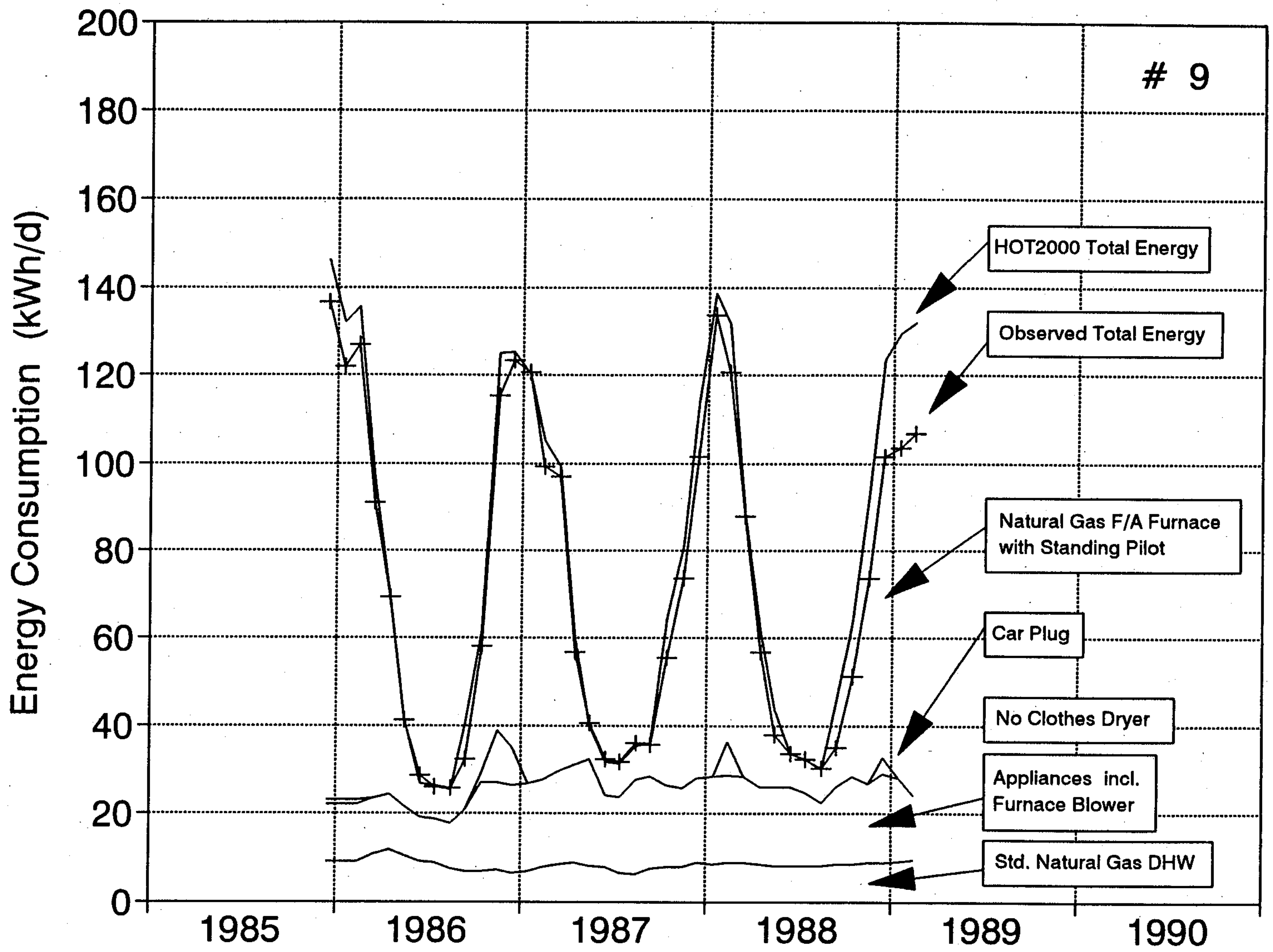
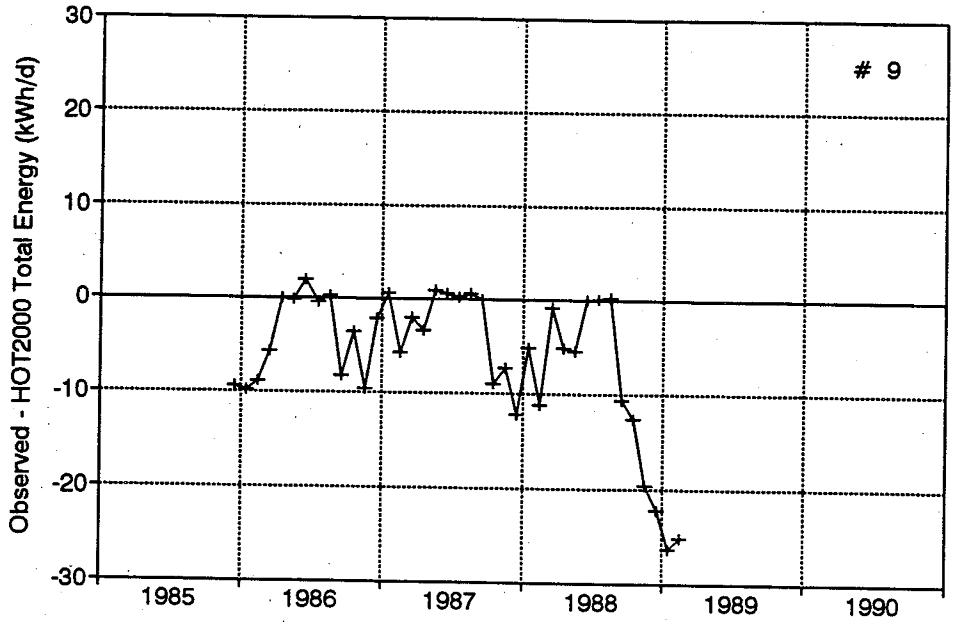


Figure A.9(a) Energy Profile



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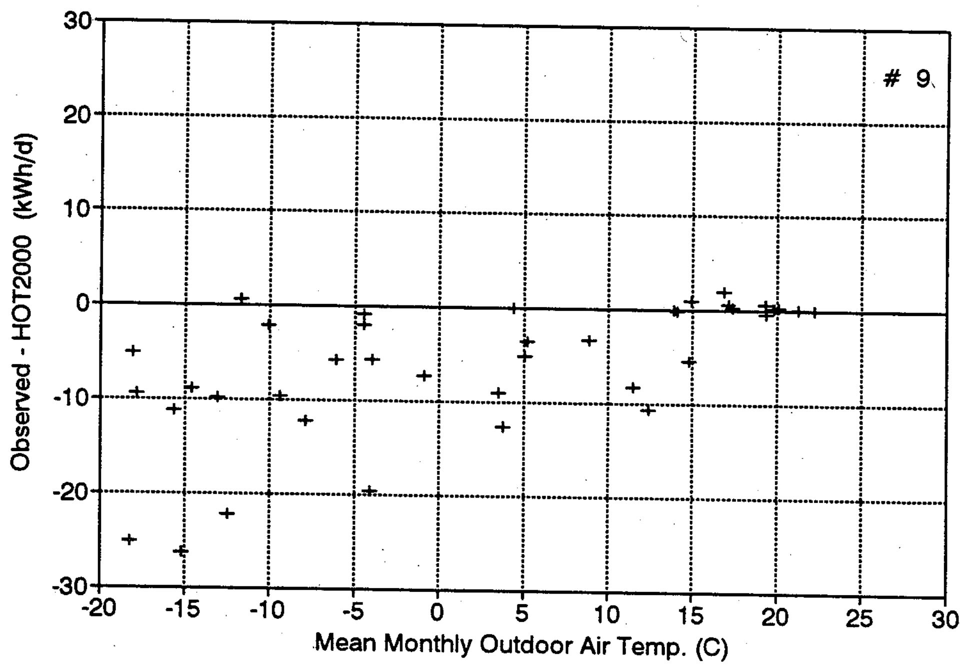

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Figure A.9(b) Energy Model Performance
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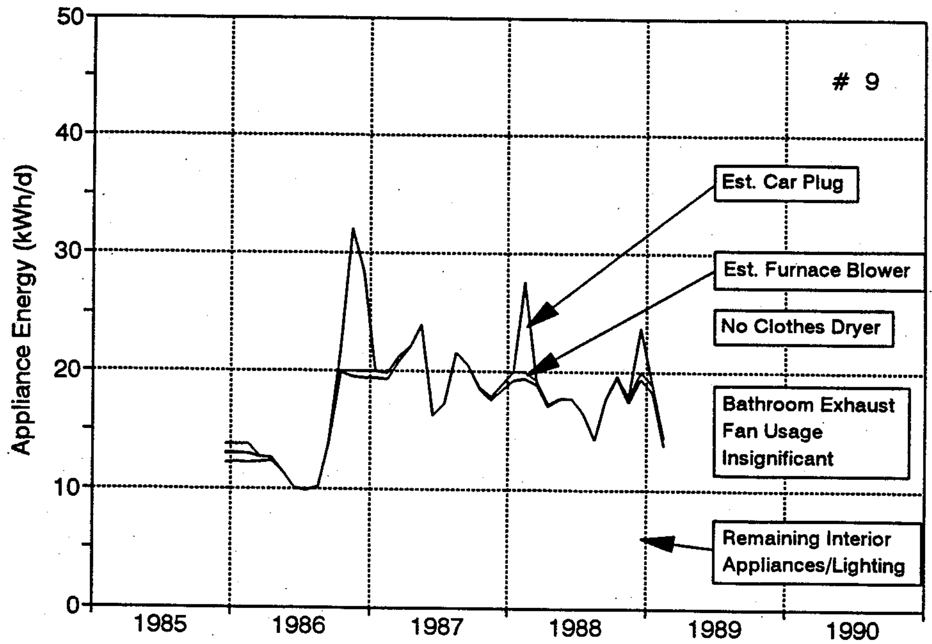

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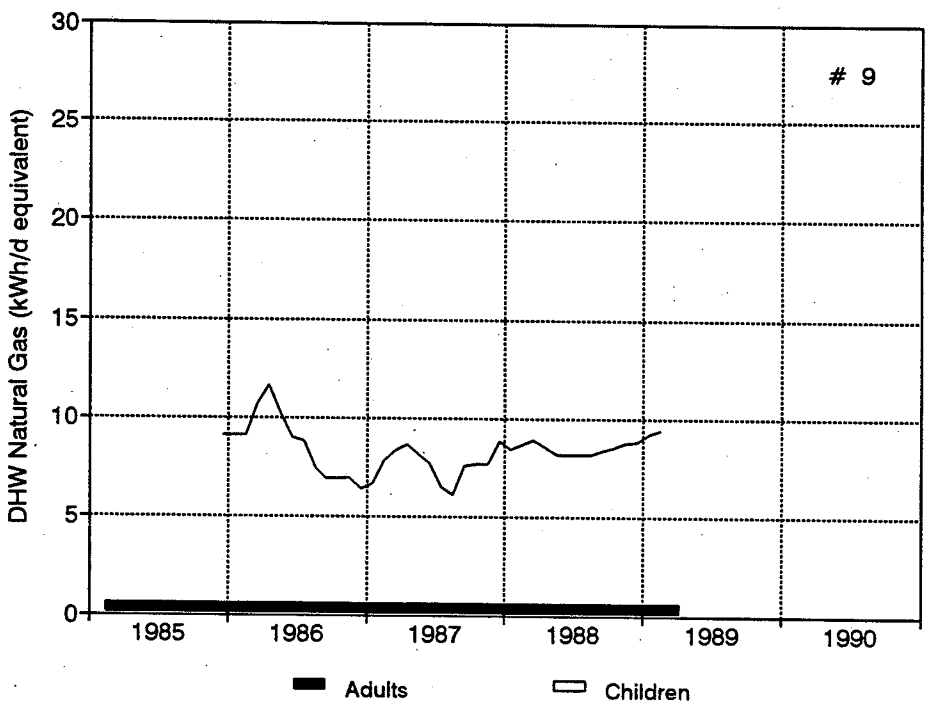


(ii)

Figure A.9(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.10 House # 10

A.10.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	447 cubic metres
Construction:	conventional, with 4 mil poly air/vapour barrier
Ceiling:	R 7.0 (blown-in cellulose)
	glass fibre batts over vaulted ceiling portion
Main Walls:	R 3.5 (glass fibre batts)
Basement Walls:	R 1.8 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	conventional natural gas forced air furnace
Ventilation system:	bathroom exhaust fan
DHW system:	conventional natural gas tank

A.10.2 Energy Sub-Metering Schedule

Main Electric (incl. appliances, bathroom exhaust fan, exterior receptacles)

Main Natural Gas
- Natural Gas Furnace
- Natural Gas Domestic Hot Water Tank (derived)

Mains Water

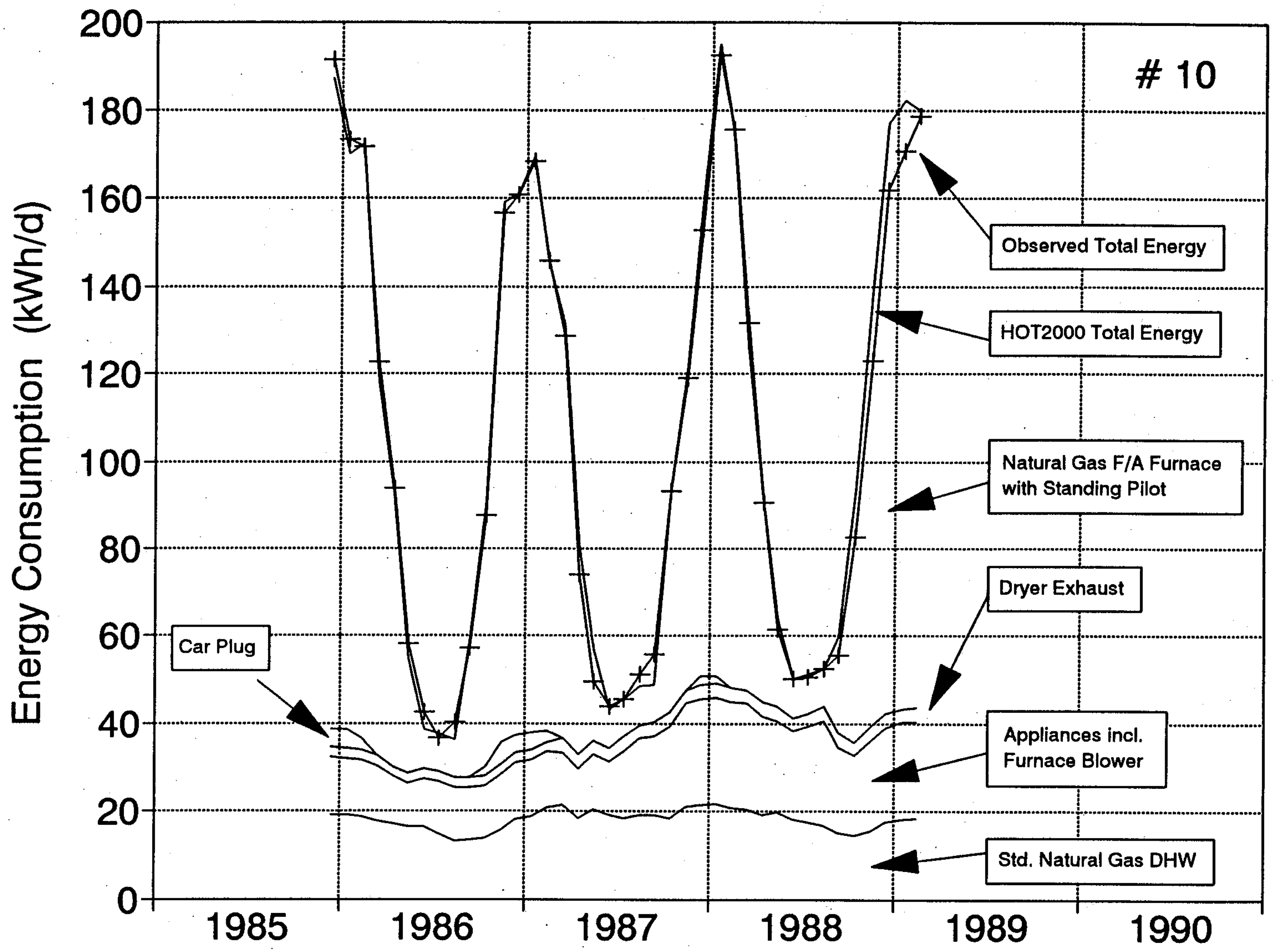
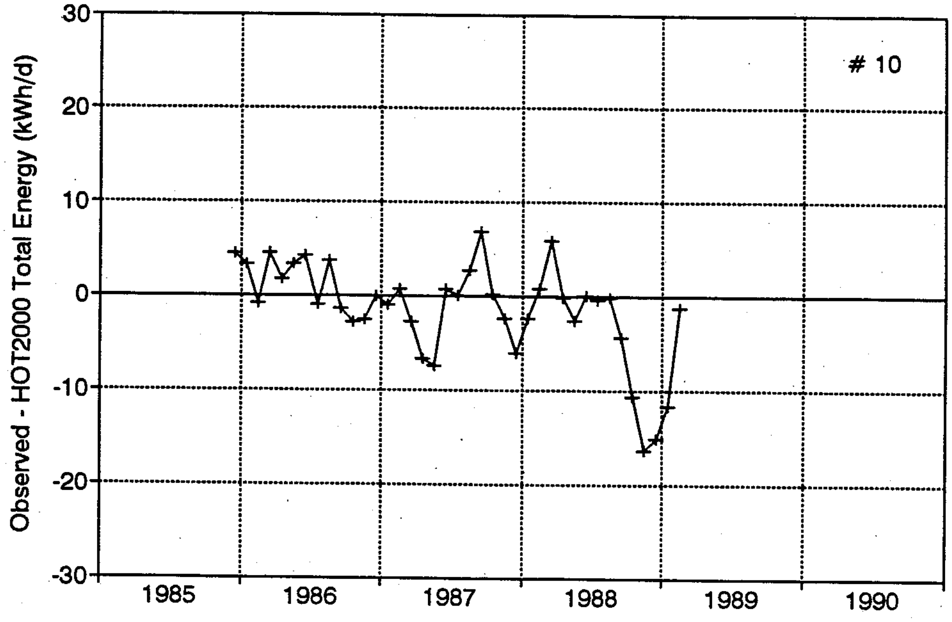


Figure A.10(a) Energy Profile



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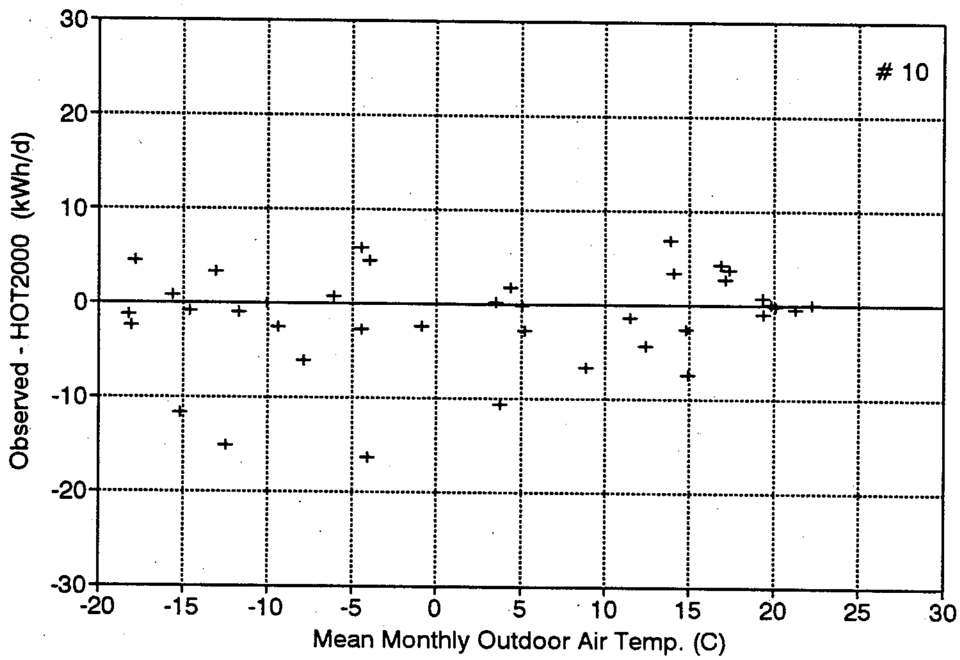
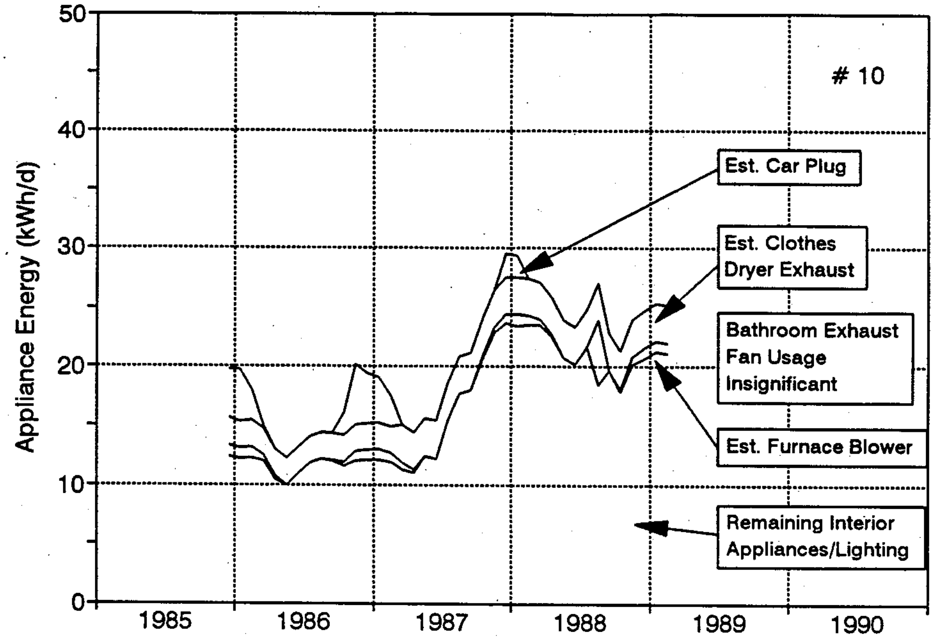


(ii)

Figure A.10(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
(ii) Model Performance Signature



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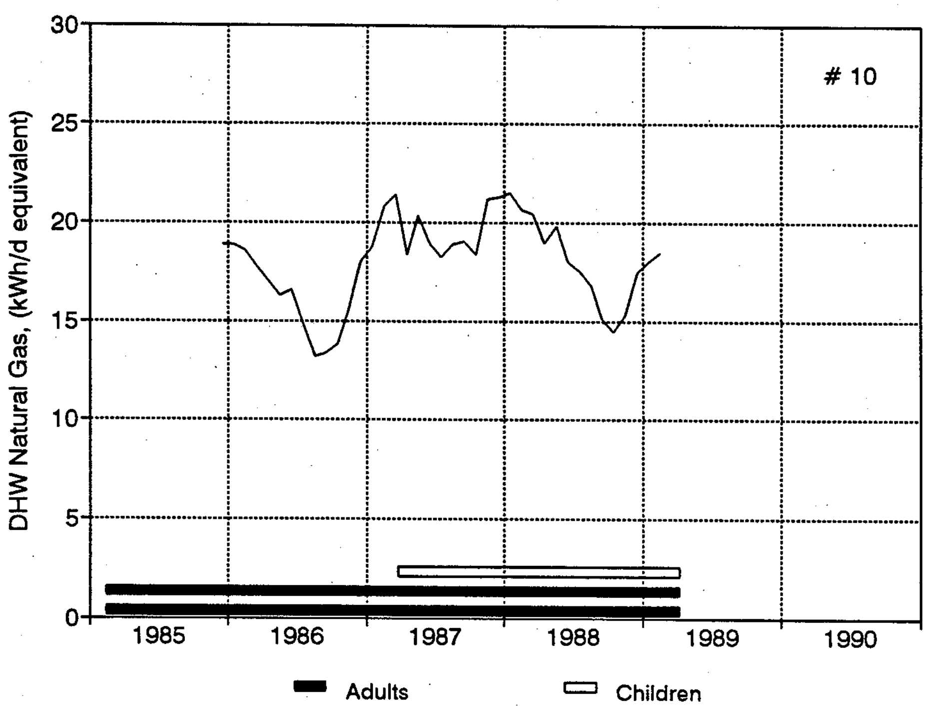


(ii)

Figure A.10(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.11 House # 11

A.11.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	454 cubic metres
Construction:	Simplified Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in glass fibre)
Main Walls:	R 5.1 (glass fibre, batts plus semi-rigid sheathing)
Basement Walls:	R 2.3 (glass fibre semi-rigid sheathing, exterior)
Basement Floor:	R 1.2 (glass fibre semi-rigid sheathing below slab)
Windows:	conventional wood-framed tripane units
Mechanical Systems:	Integrated primary system: exhaust-only heat pump HRV, contributes to DHW heating and space heating/cooling; Supplementary systems: electric baseboard heaters and conventional electric DHW tank

A.11.2 Energy Sub-Metering Schedule

Main Electric
- Baseboard Heaters
  - Basement Heaters
  - Main Floor Heaters (derived)
- Habitair Heat Pump, DHW Tank & Ventilator System
- Downstream Domestic Hot Water Booster Tank
  (in line between Habitair tank and point of use)
- Exterior Receptacles
- Interior Appliances (derived)

Habitair Heat Pump Run Time
Habitair Domestic Hot Water Heater Run Time
Habitair Domestic Hot Water Circulation Pump Run Time
Bathroom Fan Run Time

Mains Water
- Hot Water

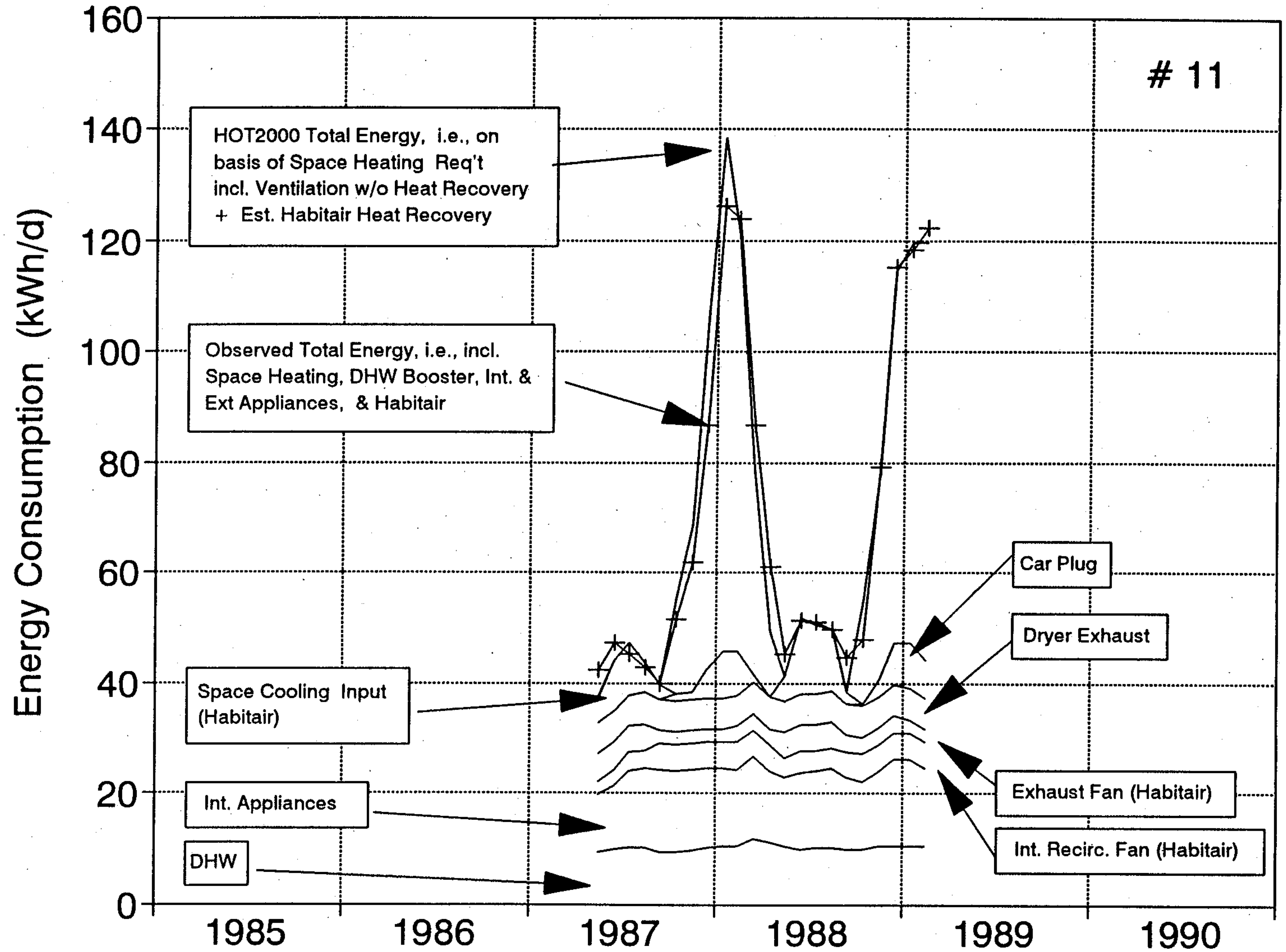
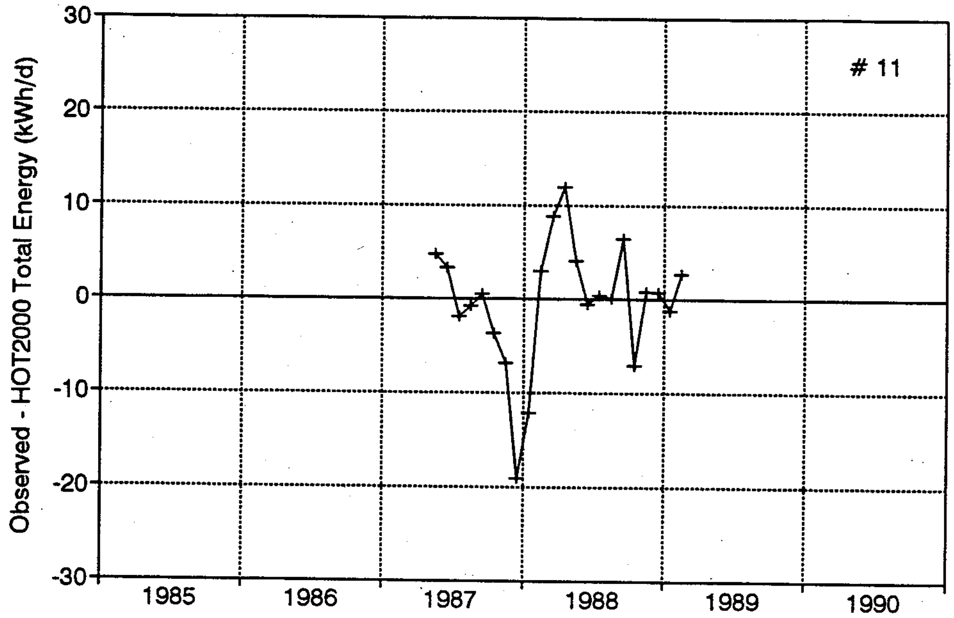


Figure A.11(a) Energy Profile



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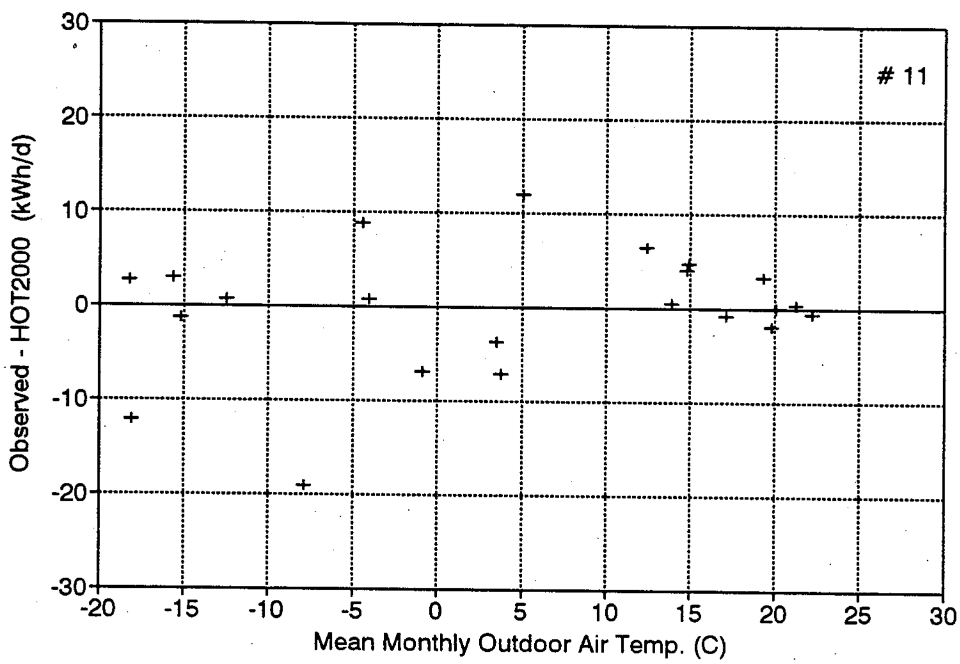

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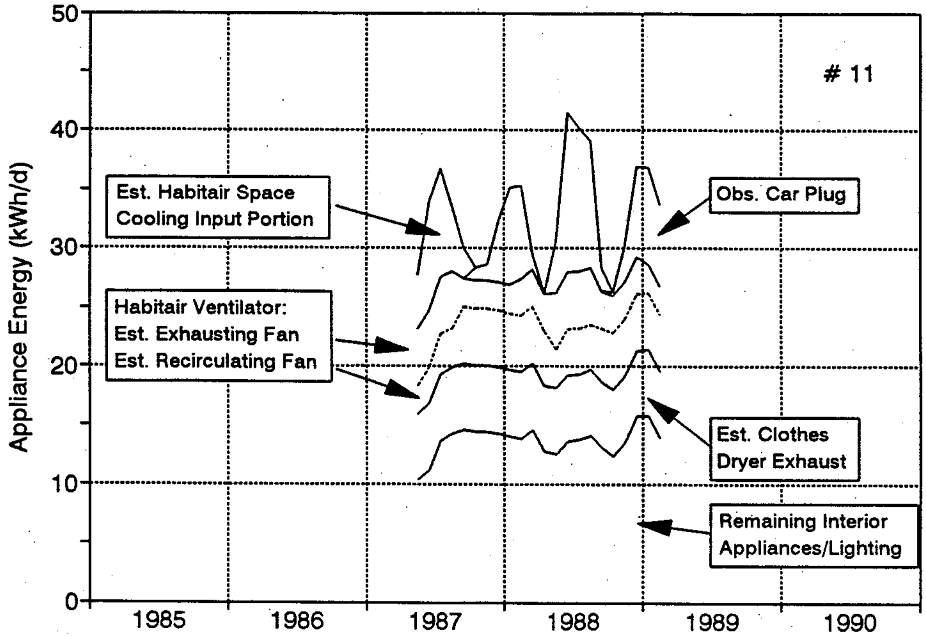
Figure A.11(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
(ii) Model Performance Signature



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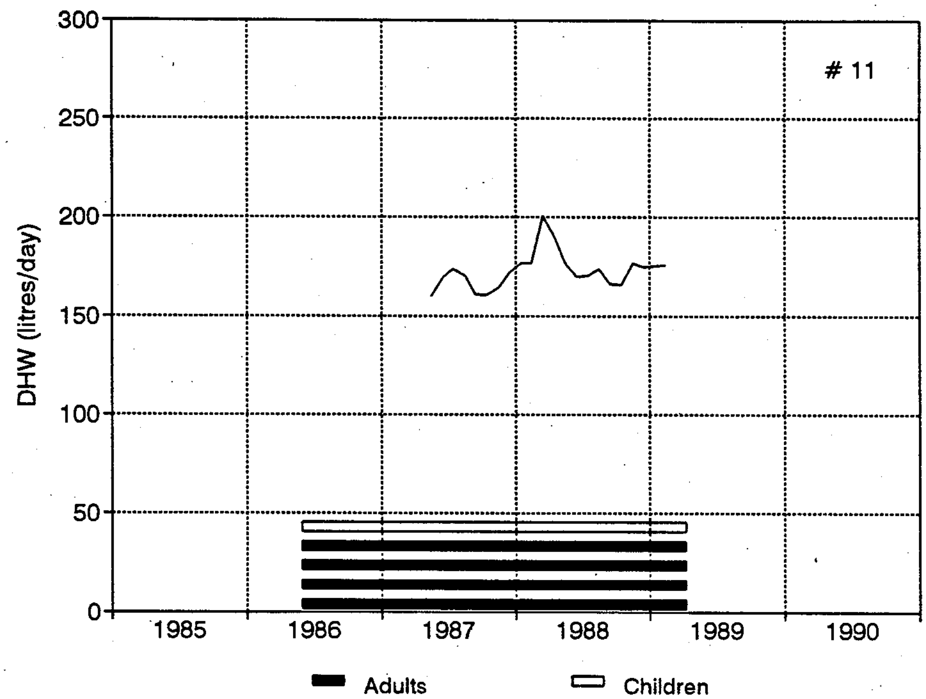


(ii)

Figure A.11(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Hot Water Usage and Number of Occupants

A.12 House # 12

A.12.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	454 cubic metres
Construction:	Simplified Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in glass fibre)
Main Walls:	R 5.1 (glass fibre, batts plus semi-rigid sheathing)
Basement Walls:	R 2.3 (glass fibre semi-rigid sheathing, exterior)
Basement Floor:	R 1.2 (glass fibre semi-rigid sheathing below slab)
Windows:	conventional wood-framed tripane units
Mechanical Systems:	Integrated primary system: exhaust-only heat pump HRV, contributes to DHW heating and space heating/cooling; Supplementary systems: electric baseboard heaters and conventional electric DHW tank

A.12.2 Energy Sub-Metering Schedule

Main Electric

- Baseboard Heaters
  - Basement Heaters
  - Main Floor Heaters (derived)
- Habitair Heat Pump, DHW Tank & Ventilator System
- Downstream Domestic Hot Water Booster Tank
  (in line between Habitair tank and point of use)
- Exterior Receptacles
- Interior Appliances (derived)

Habitair Heat Pump Run Time

Habitair Domestic Hot Water Heater Run Time

Habitair Domestic Hot Water Circulation Pump Run Time

Bathroom Fan Run Time

Mains Water

- Hot Water

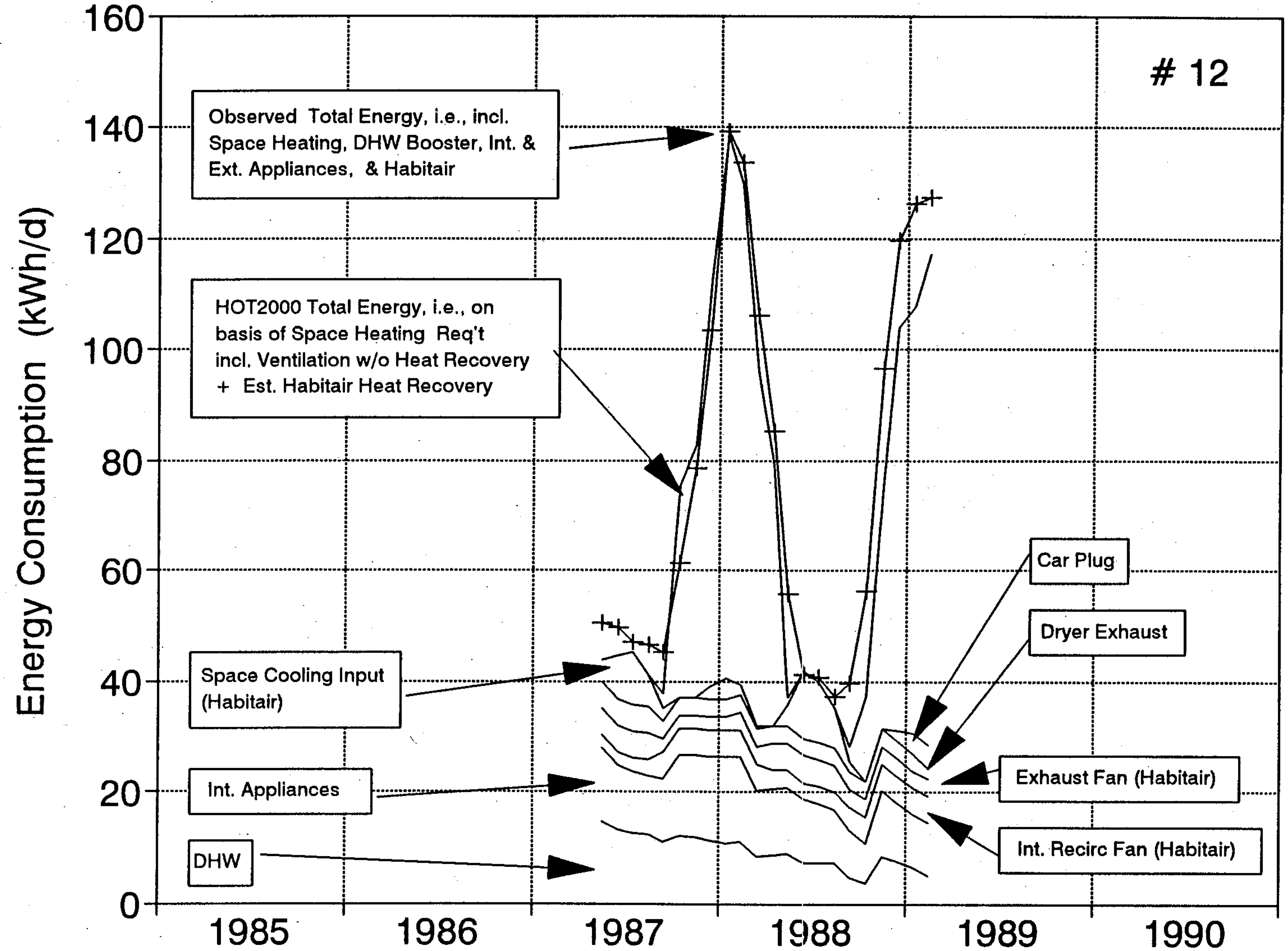
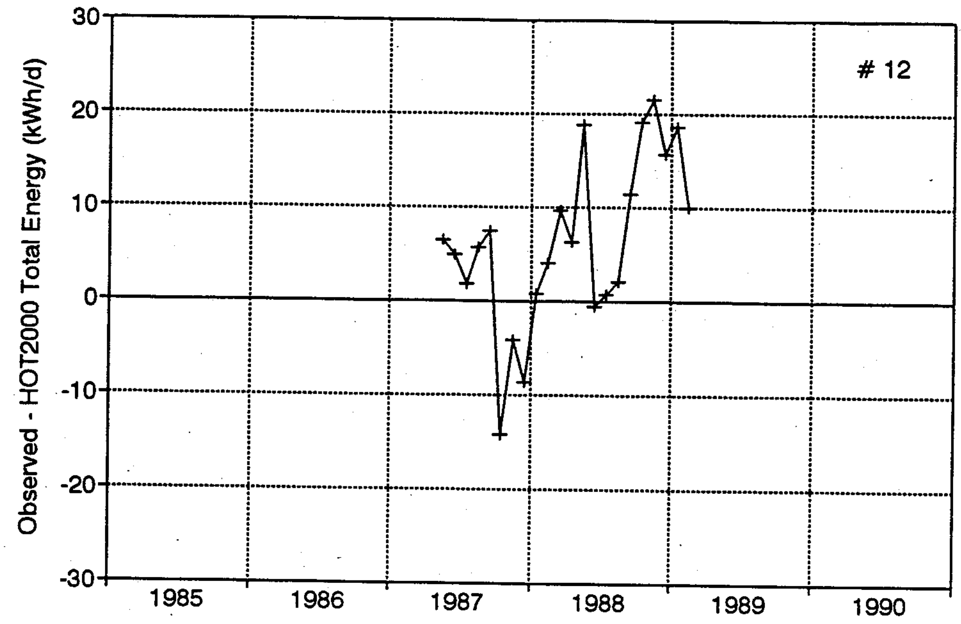


Figure A.12(a) Energy Profile



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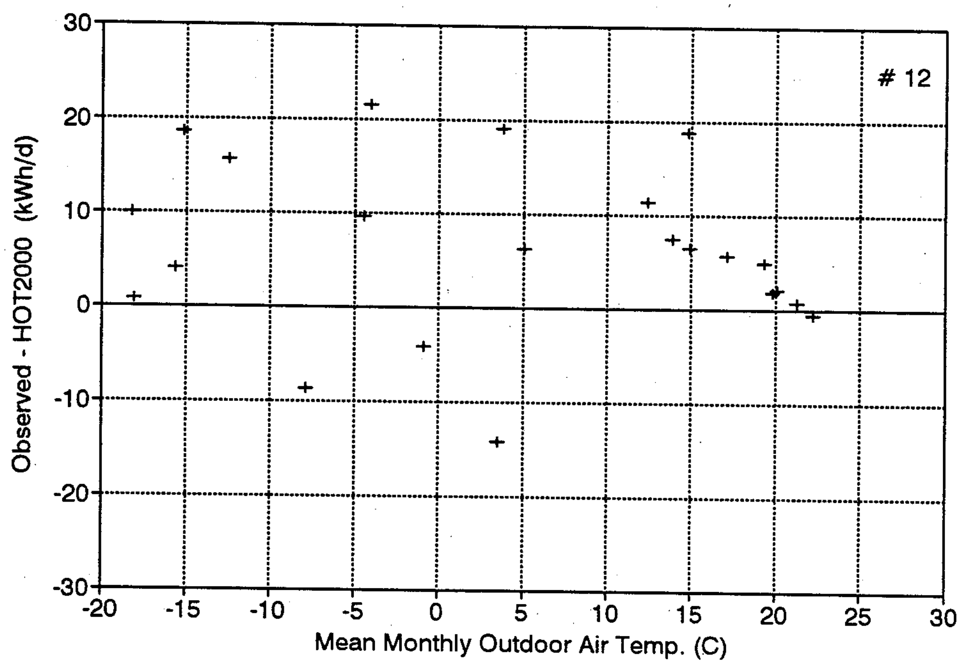

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Figure A.12(b) Energy Model Performance
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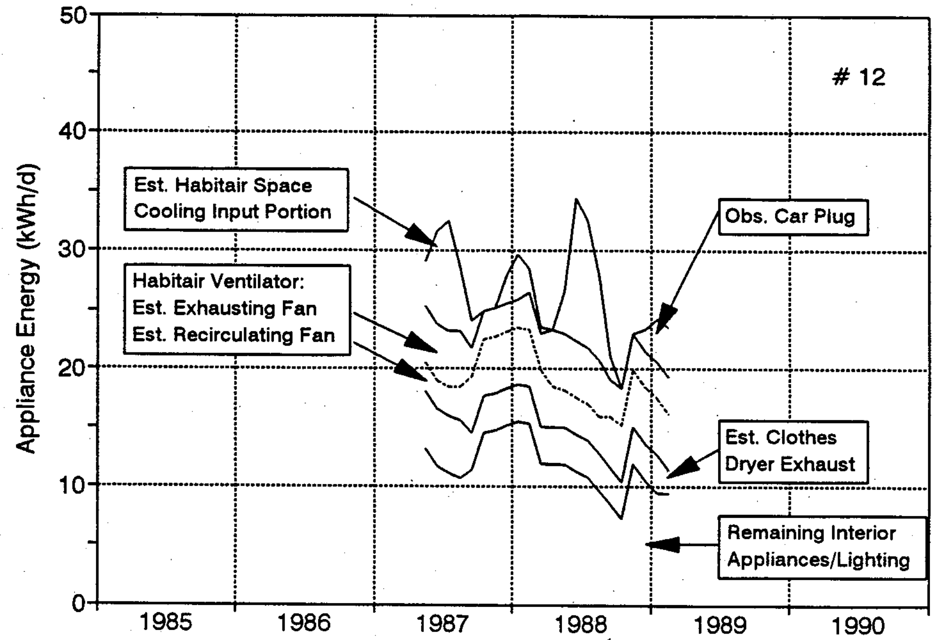
(ii) Model Performance Signature



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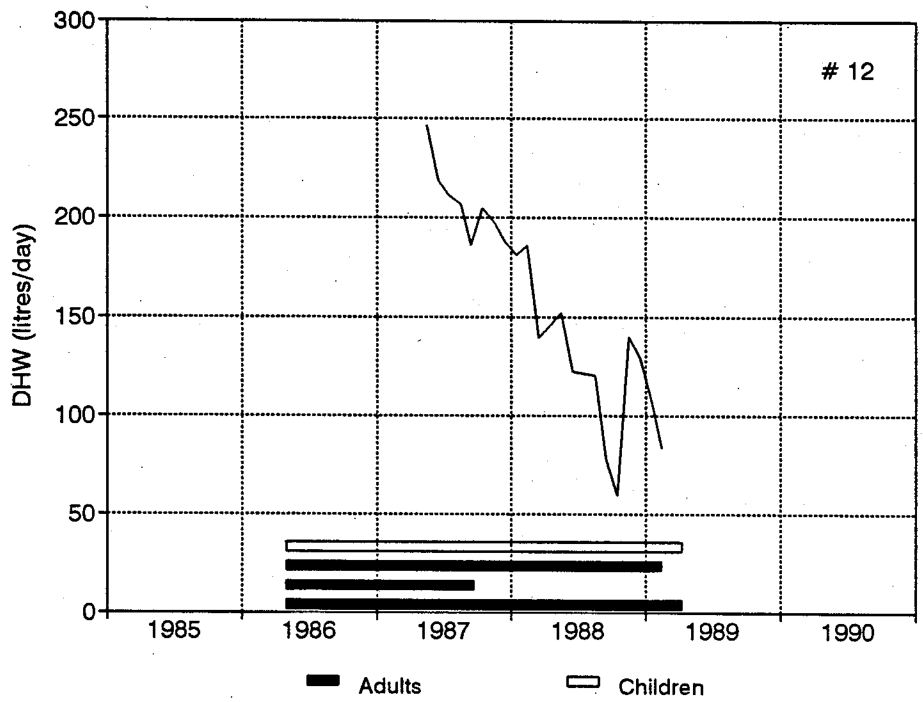


(ii)

Figure A.12(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Hot Water Usage and Number of Occupants

A.13 House # 13

A.13.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	439 cubic metres
Construction:	Simplified Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in glass fibre)
Main Walls:	R 5.1 (glass fibre, batts plus semi-rigid sheathing)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric forced air furnace
Ventilation system:	HRV (single crossflow, 2nd generation, shared ducts)
DHW system:	electric tank

A.13.2 Energy Sub-Metering Schedule

Main Electric
- Space Heating (derived)
  - Electric Furnace
  - Duct Heater
- Domestic Hot Water Tank
- Appliances incl. HRV and Exterior Receptacles (derived)

HRV Total Run Time
- Demand Time
- Defrost Time
- Low Speed Time (derived)

Mains Water

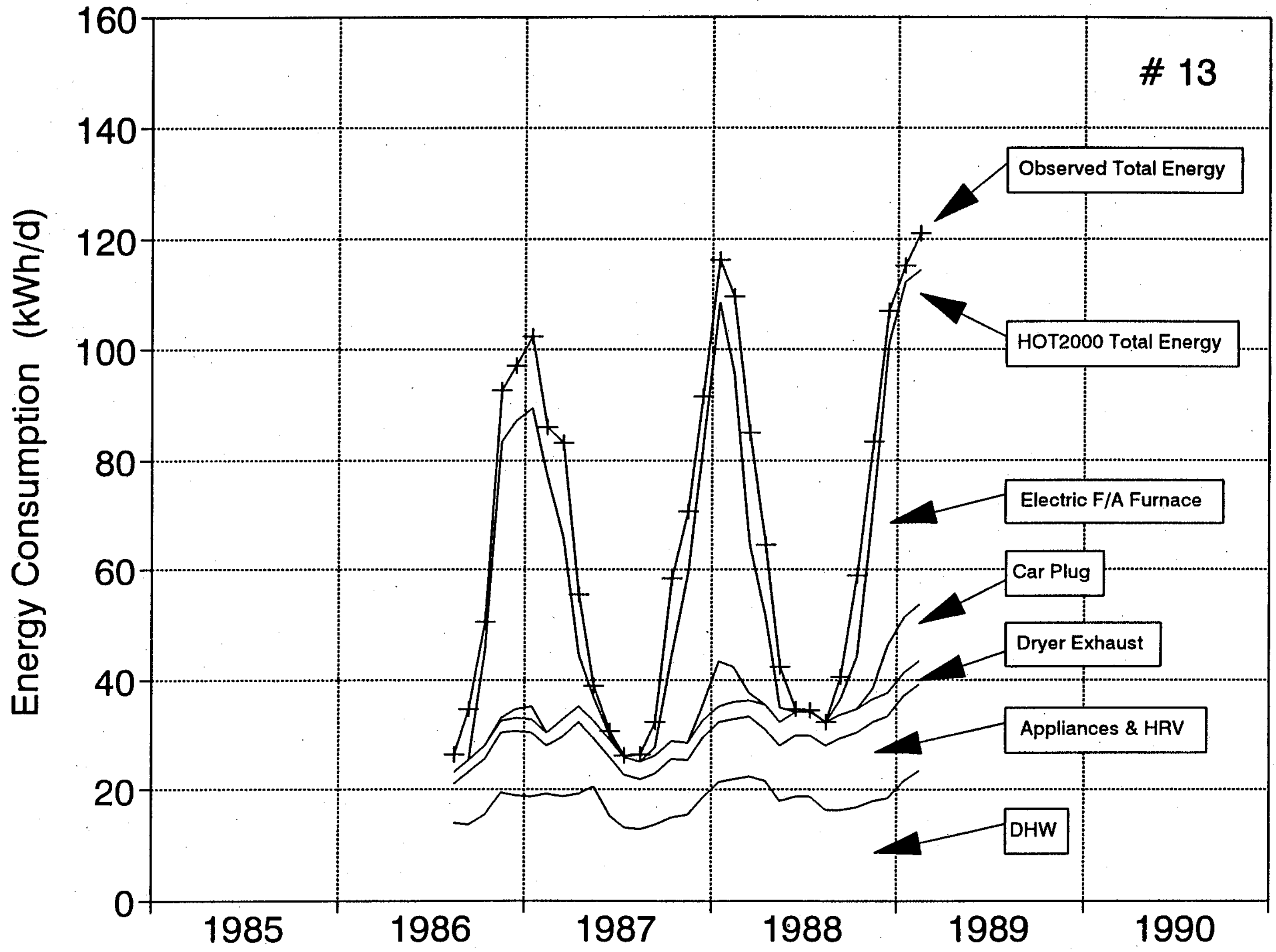
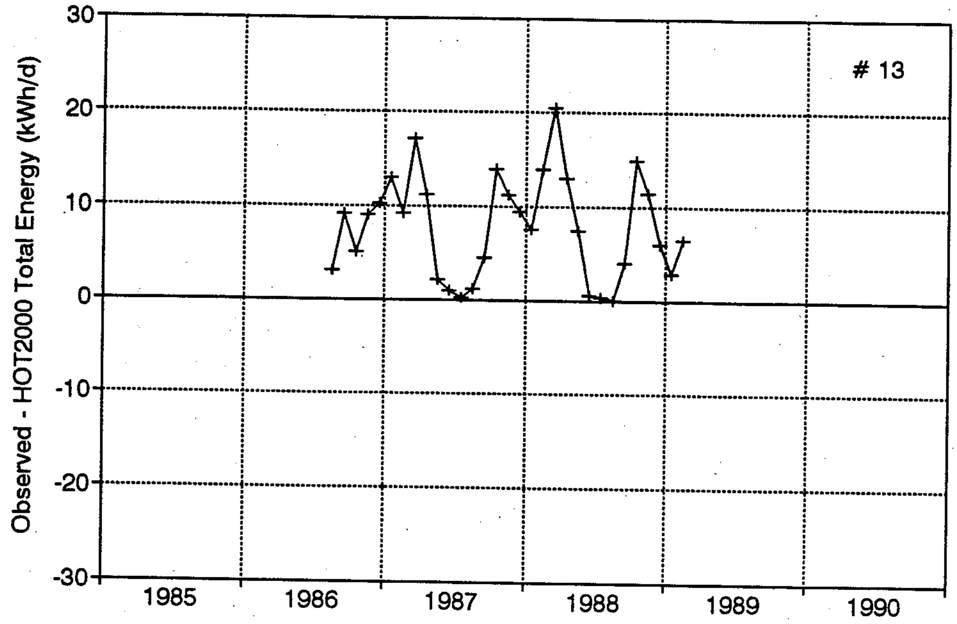


Figure A.13(a) Energy Profile



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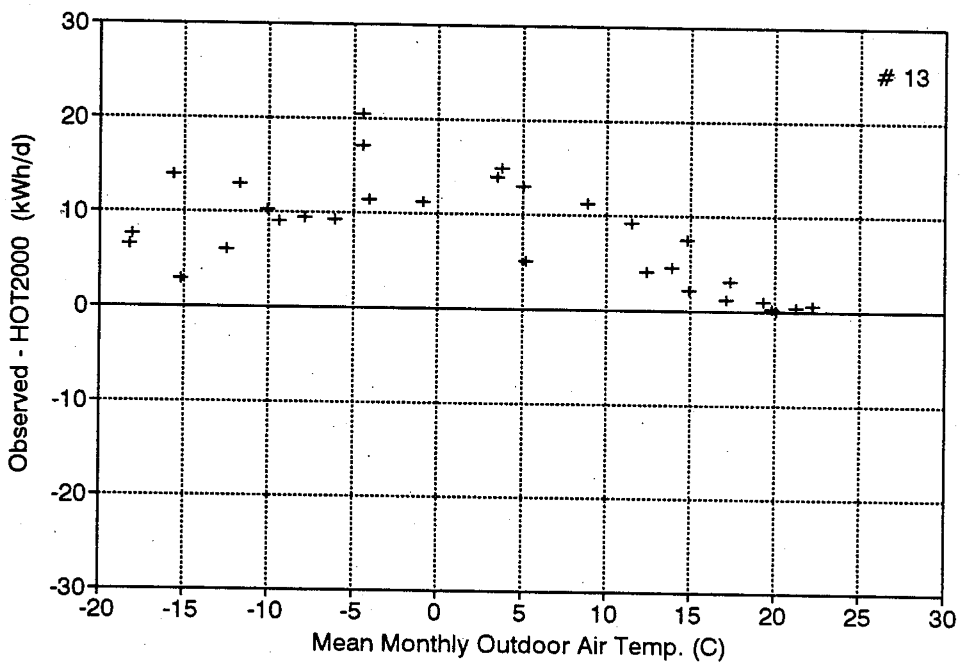

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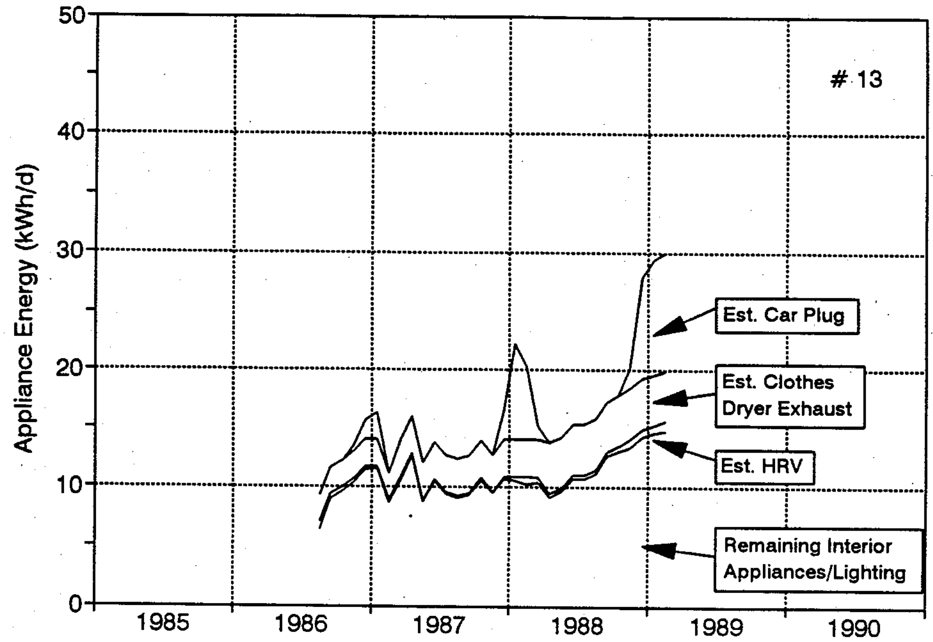
Figure A.13(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
(ii) Model Performance Signature



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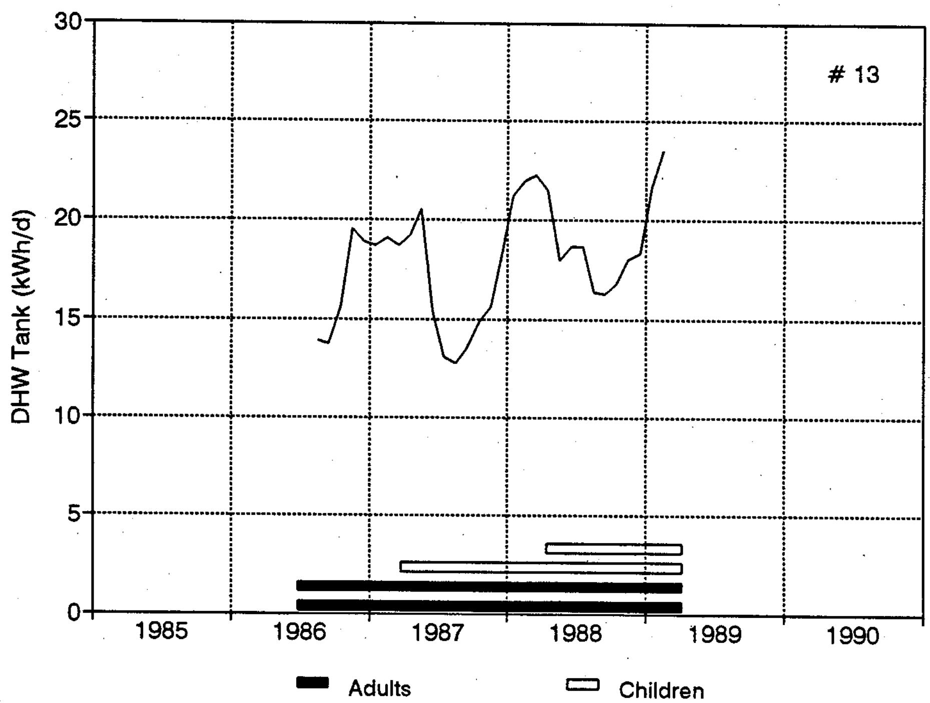


(ii)

Figure A.13(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.14 House # 14

A.14.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	442 cubic metres
Construction:	Simplified Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in glass fibre)
Main Walls:	R 5.1 (glass fibre, batts plus semi-rigid sheathing)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric forced air furnace
Ventilation system:	HRV (single crossflow, 2nd generation, shared ducts)
DHW system:	electric tank

A.14.2 Energy Sub-Metering Schedule

Main Electric

- Space Heating (derived)
  - Electric Furnace
  - Duct Heater
- Domestic Hot Water Tank
- Appliances incl. HRV and Exterior Receptacles (derived)

HRV Total Run Time

- Demand Time
- Defrost Time
- Low Speed Time (derived)

Mains Water

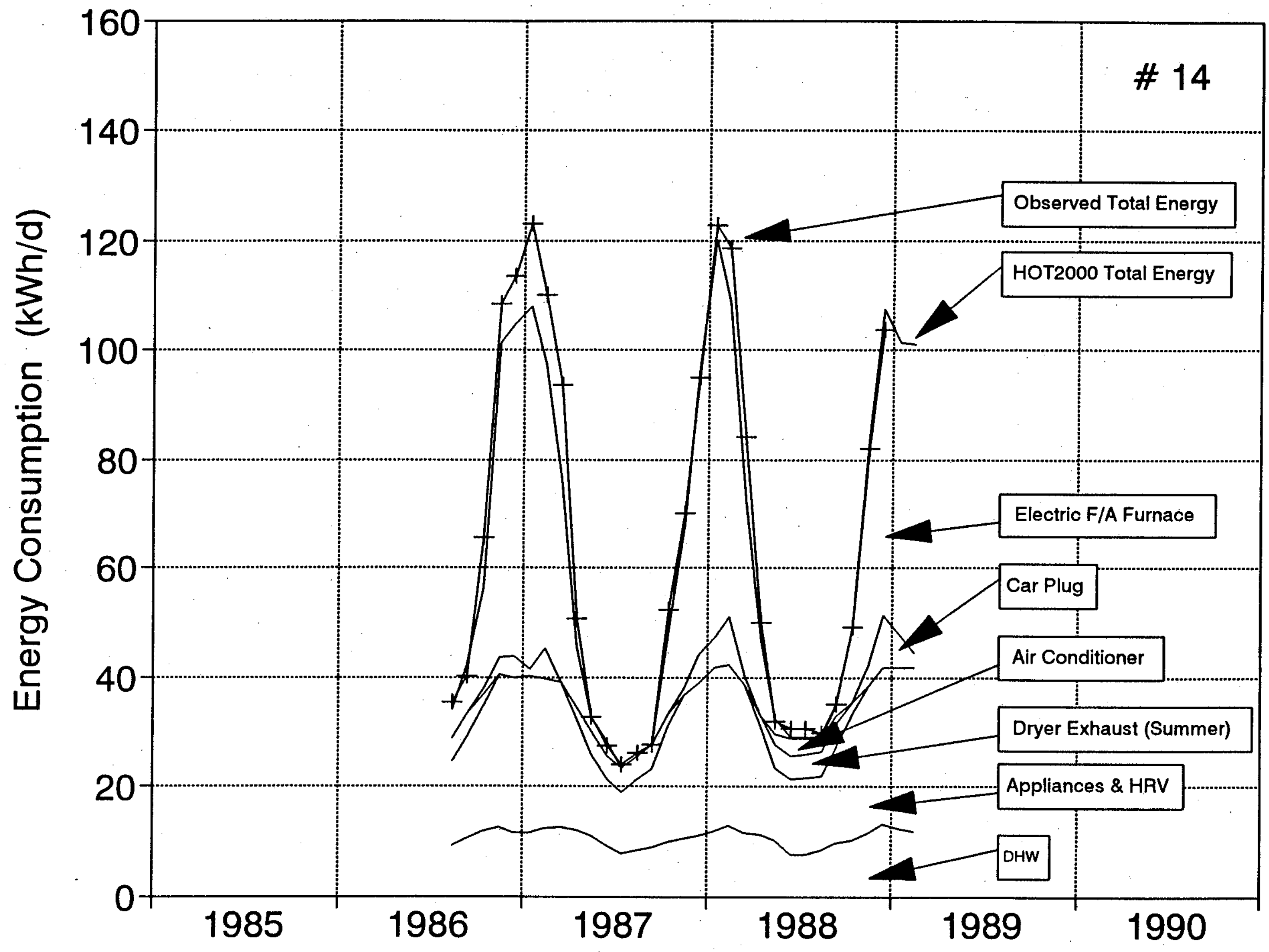
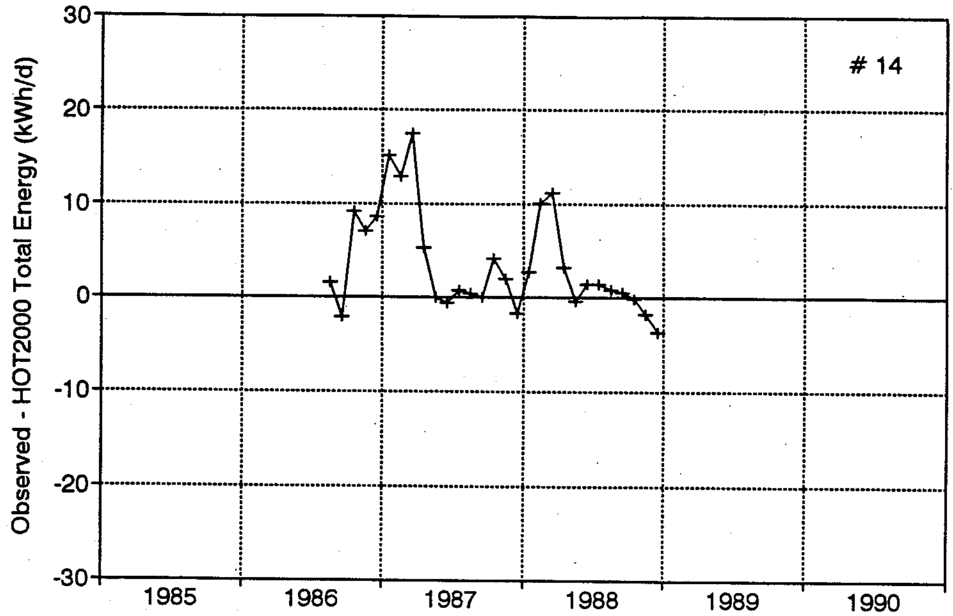


Figure A.14(a) Energy Profile



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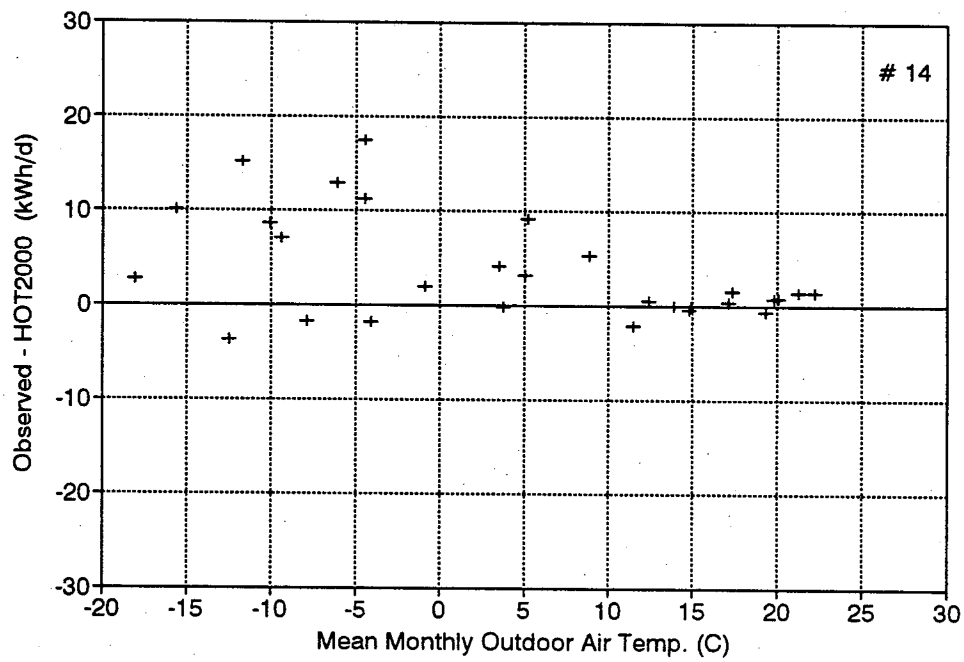

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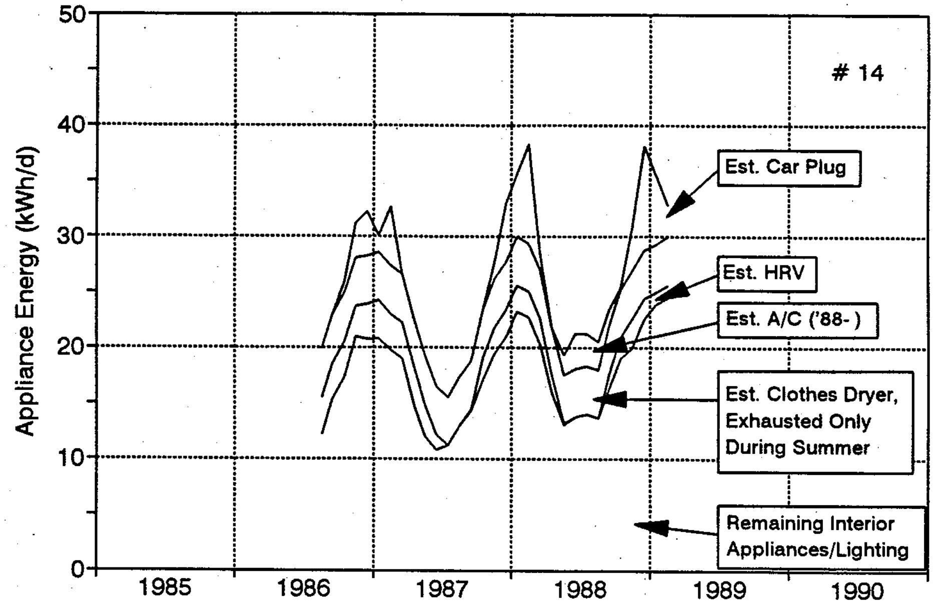
Figure A.14(b) Energy Model Performance
(i) Difference Between Monthly Observations and Prediction
(ii) Model Performance Signature



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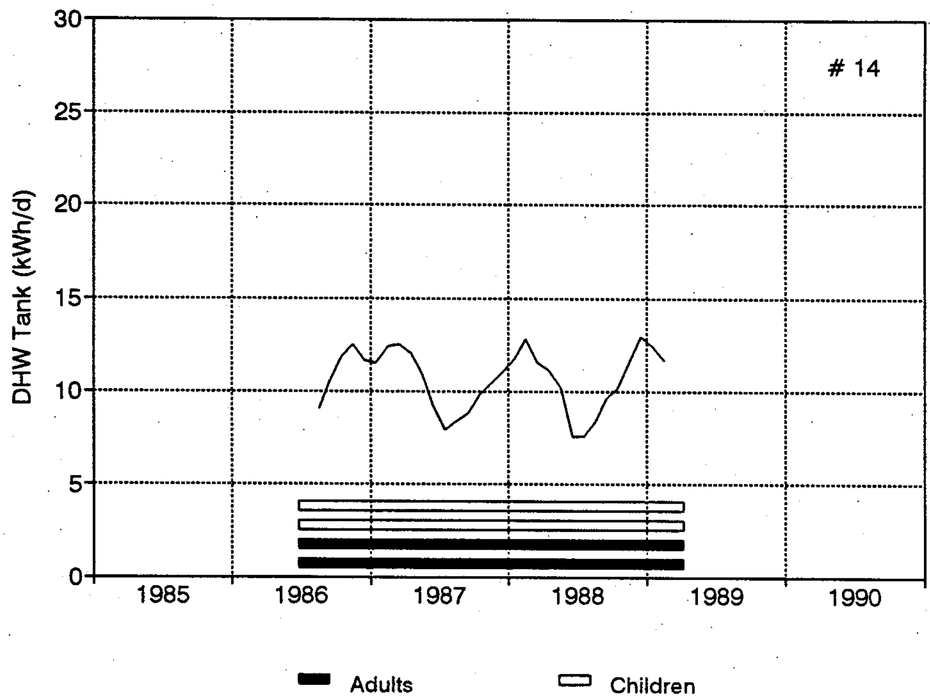


(ii)

Figure A.14(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.15 House # 15

A.15.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	454 cubic metres
Construction:	Double Wall
Ceiling:	R 7.0 (blown-in cellulose)
Main Walls:	R 7.0 (glass fibre batts)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Mechanical Systems:	Integrated system: air-to-air heat pump HRV, DHW pre-heater and electric forced air furnace; Supplementary systems: separate fans for peaking exhaust capacity, and conventional electric DHW tank

A.15.2 Energy Sub-Metering Schedule

- Main Electric
  - Peach System
    - Peach Electric Furnace
    - Peach Heat Pump Compressor
    - Peach Auxiliary Electricity Input including outdoor and indoor ventilation fans and DHW recirculation pump (derived)
  - DHW Resistance (derived)
    - Domestic Hot Water Pre-heater Tank (in recirculation loop with heat pump)
    - Domestic Hot Water Booster Tank (between pre-heater and point of use)
  - Appliances including Exterior Receptacles (derived)

- Mains Water
  - Hot Water

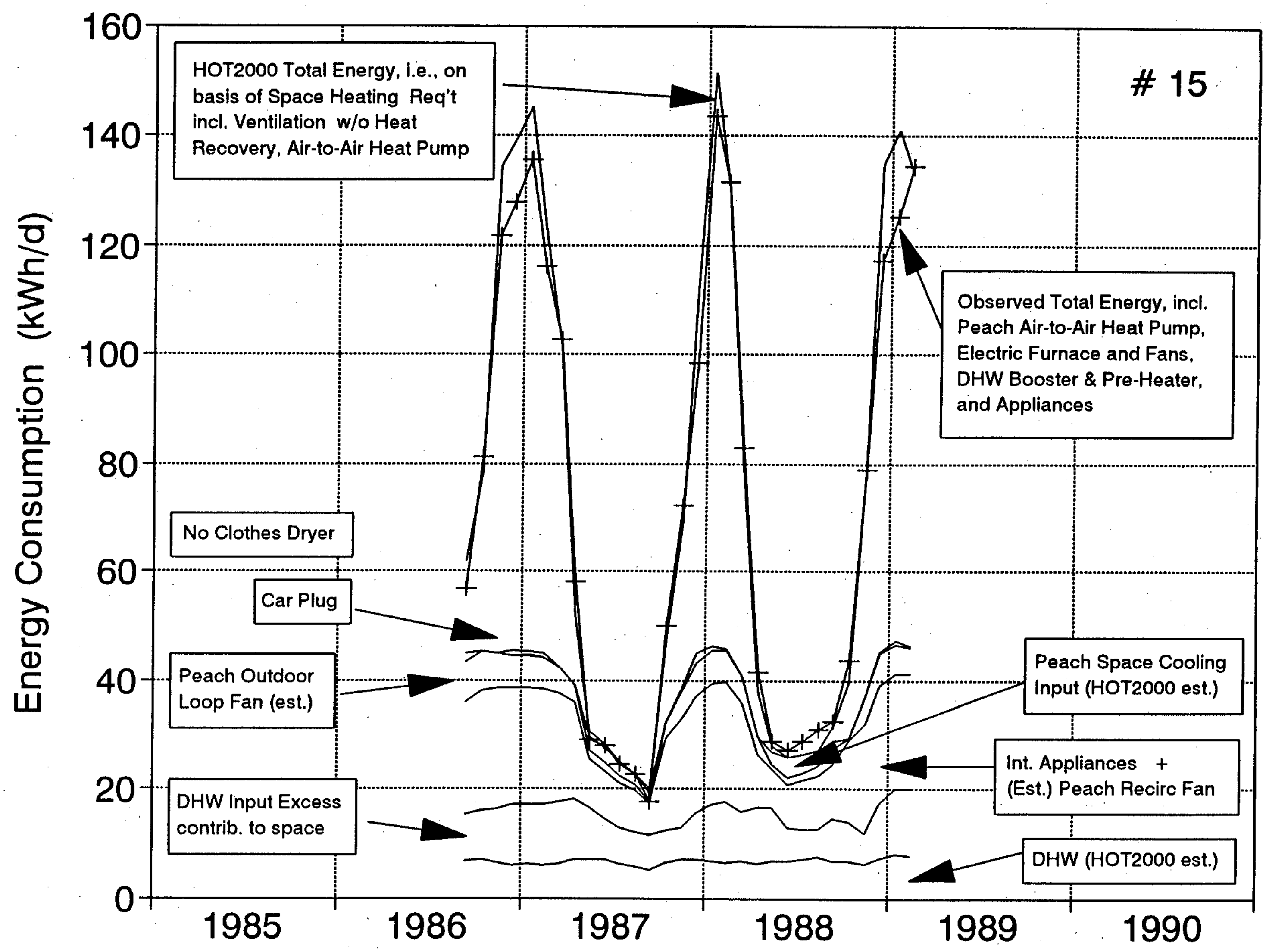
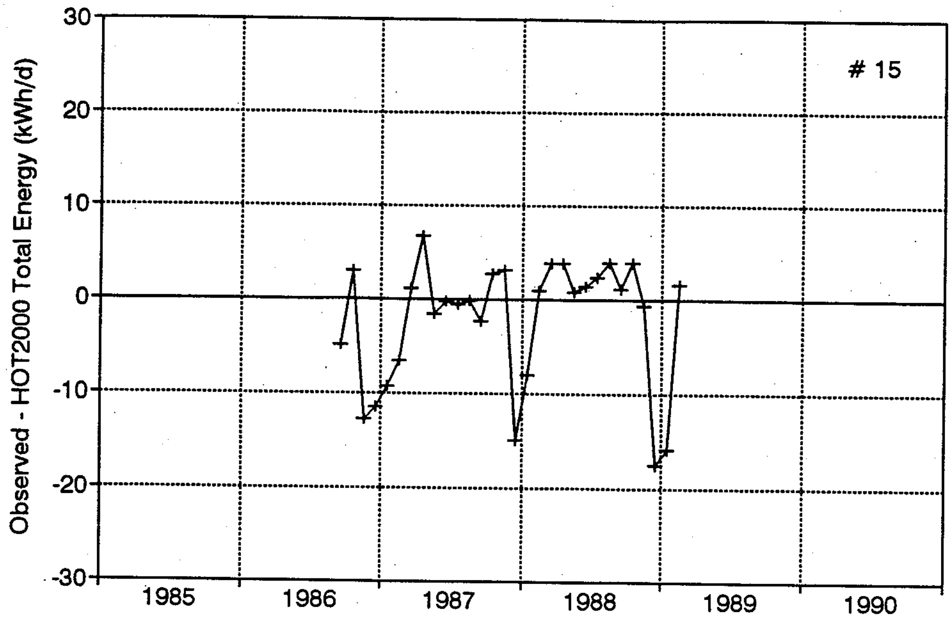


Figure A.15(a) Energy Profile



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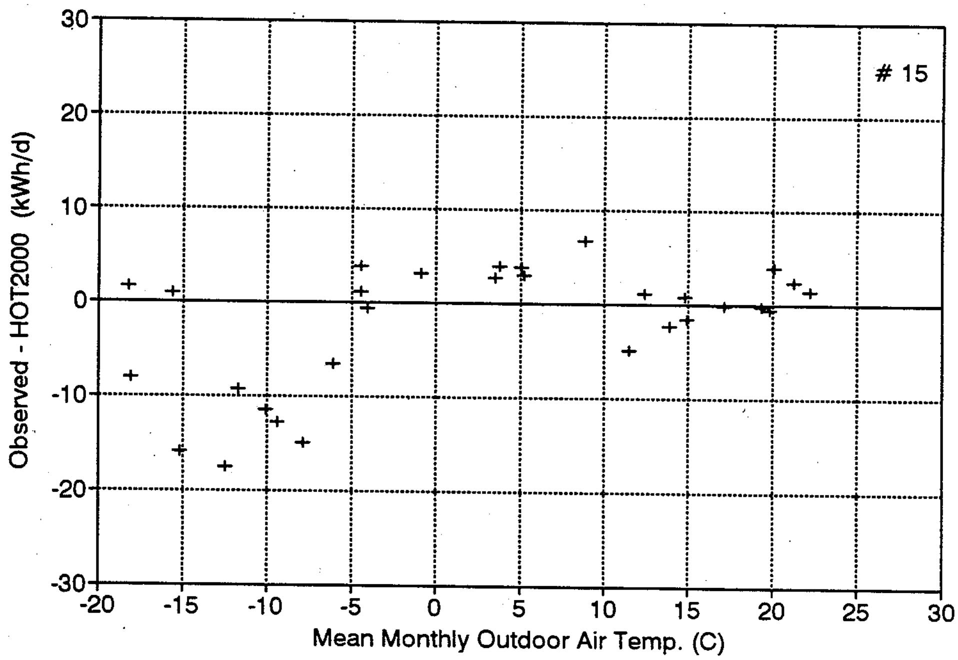
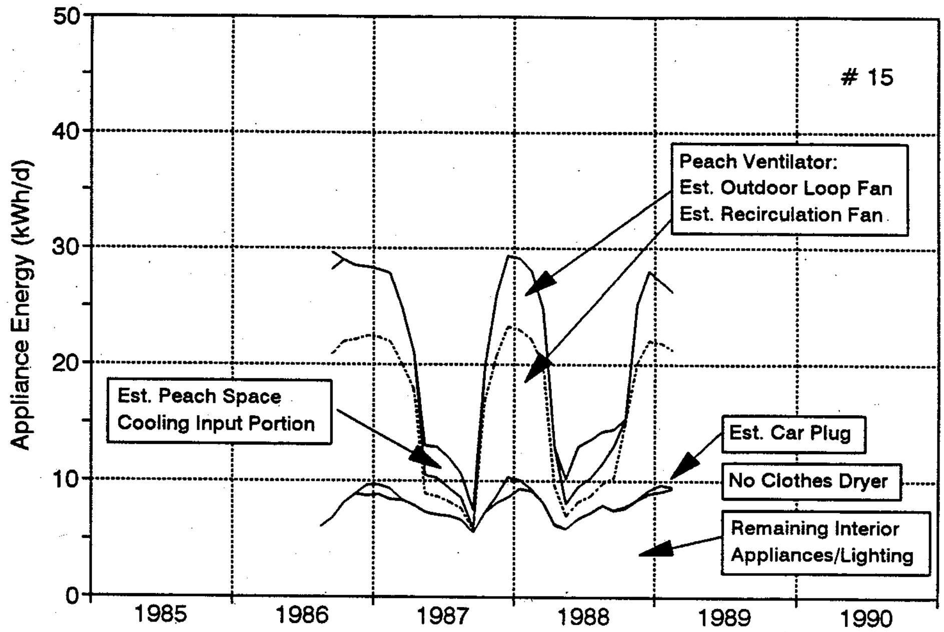


(ii)

Figure A.15(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
(ii) Model Performance Signature



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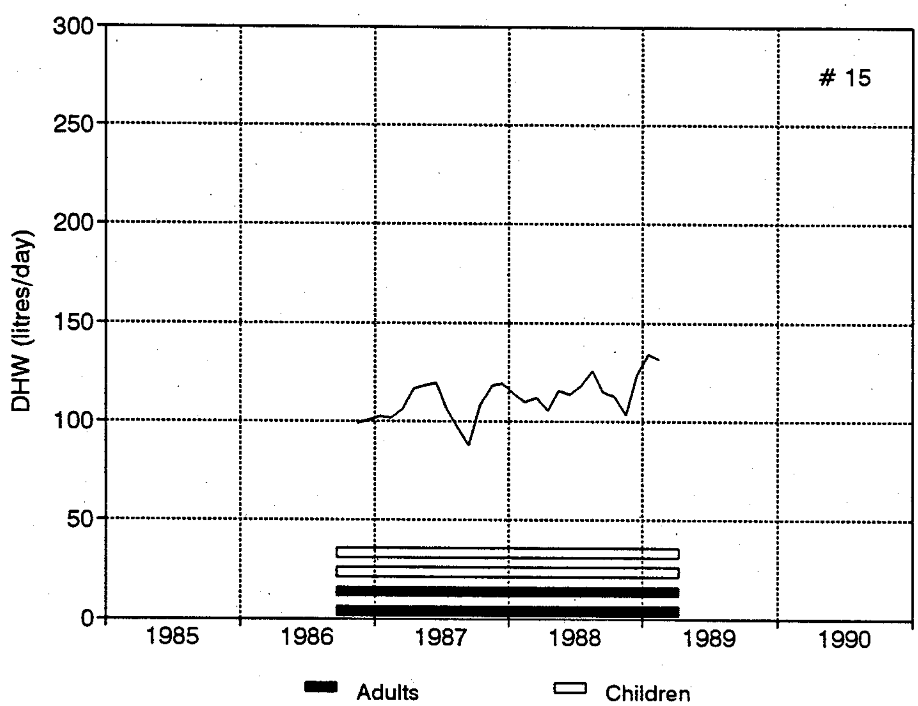


(ii)

Figure A.15(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Hot Water Usage and Number of Occupants

A.16 House # 16

A.16.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	456 cubic metres
Construction:	Double Wall
Ceiling:	R 7.0 (blown-in cellulose)
Main Walls:	R 7.0 (glass fibre batts)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Mechanical Systems:	Integrated system: air-to-air heat pump HRV, DHW pre-heater and electric forced air furnace; Supplementary systems: separate fans for peaking exhaust capacity, and conventional electric DHW tank

A.16.2 Energy Sub-Metering Schedule

Main Electric
- Peach System
  - Peach Electric Furnace
  - Peach Heat Pump Compressor
  - Peach Auxiliary Electricity Input including outdoor and indoor ventilation fans and DHW recirculation pump (derived)
- DHW Resistance (derived)
  - Domestic Hot Water Pre-heater Tank (in recirculation loop with heat pump)
  - Domestic Hot Water Booster Tank (between pre-heater and point of use)
- Appliances including Exterior Receptacles (derived)

Mains Water
- Hot Water

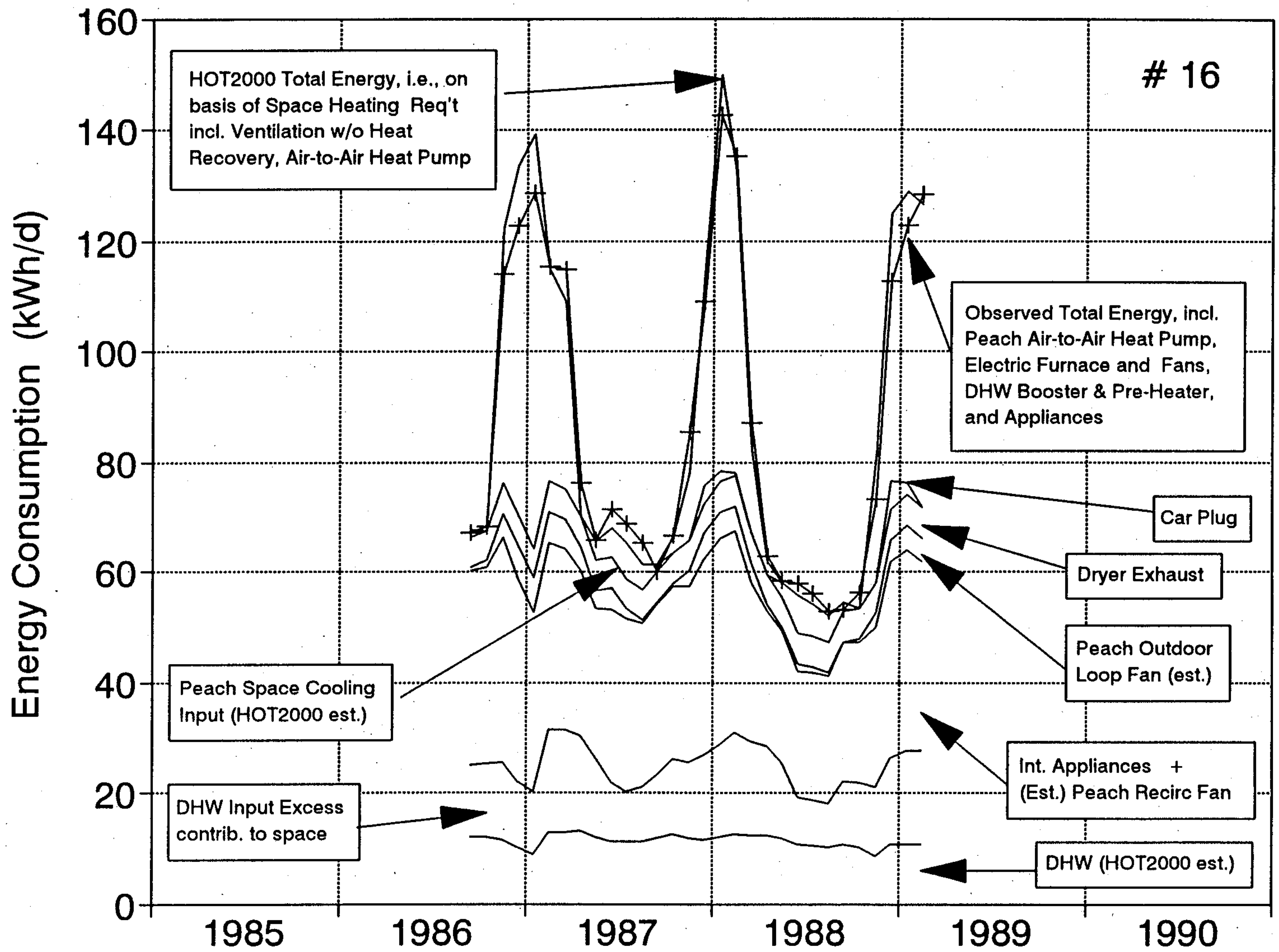
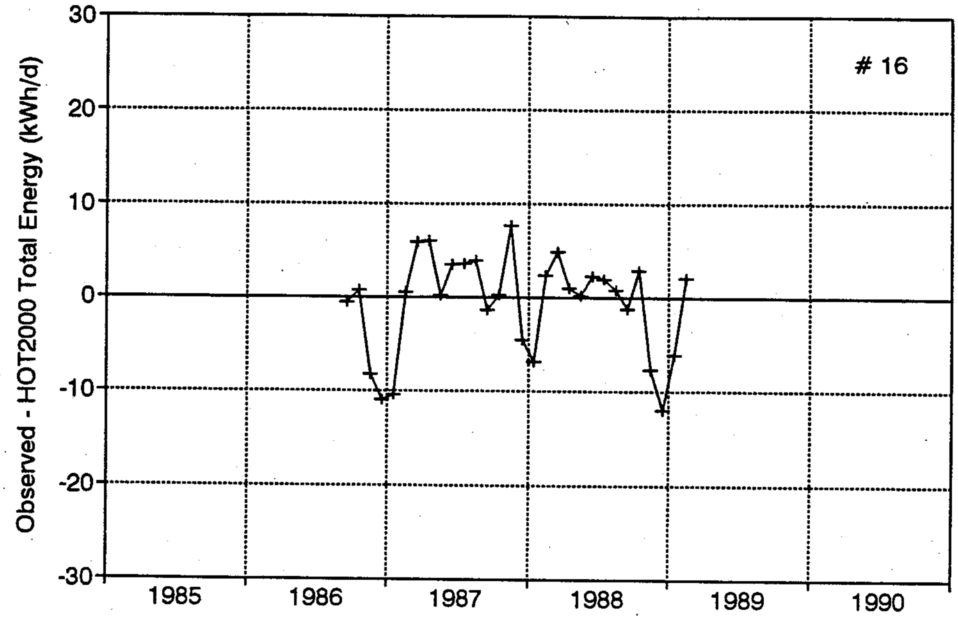


Figure A.16(a) Energy Profile



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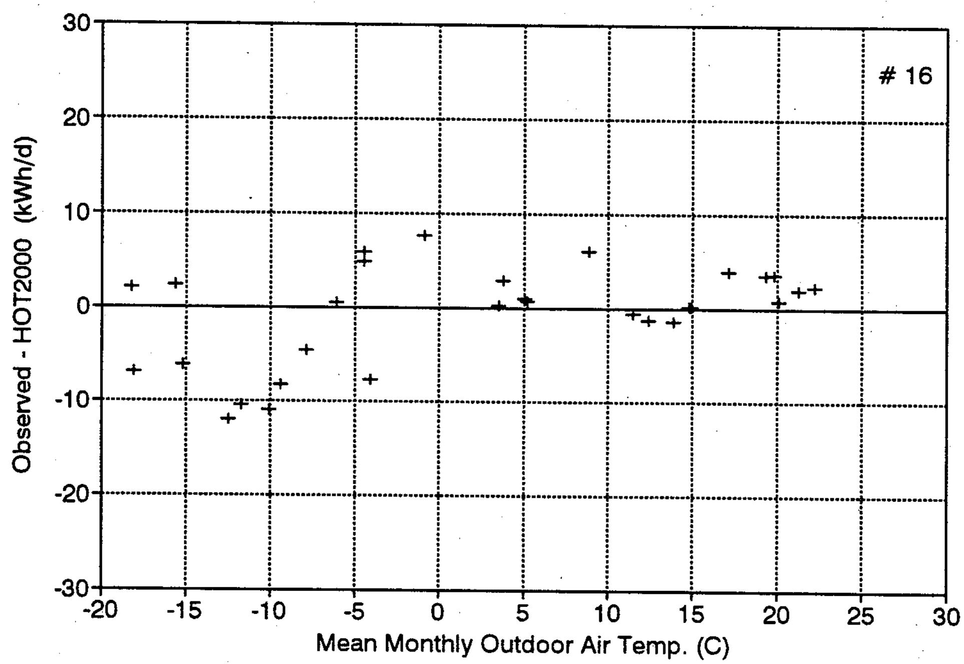

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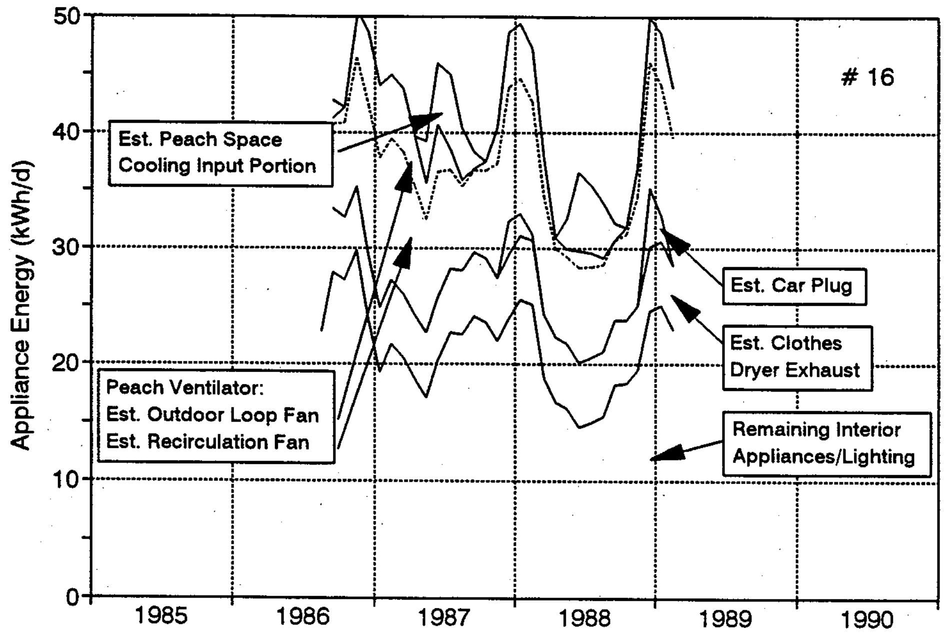
Figure A.16(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
(ii) Model Performance Signature



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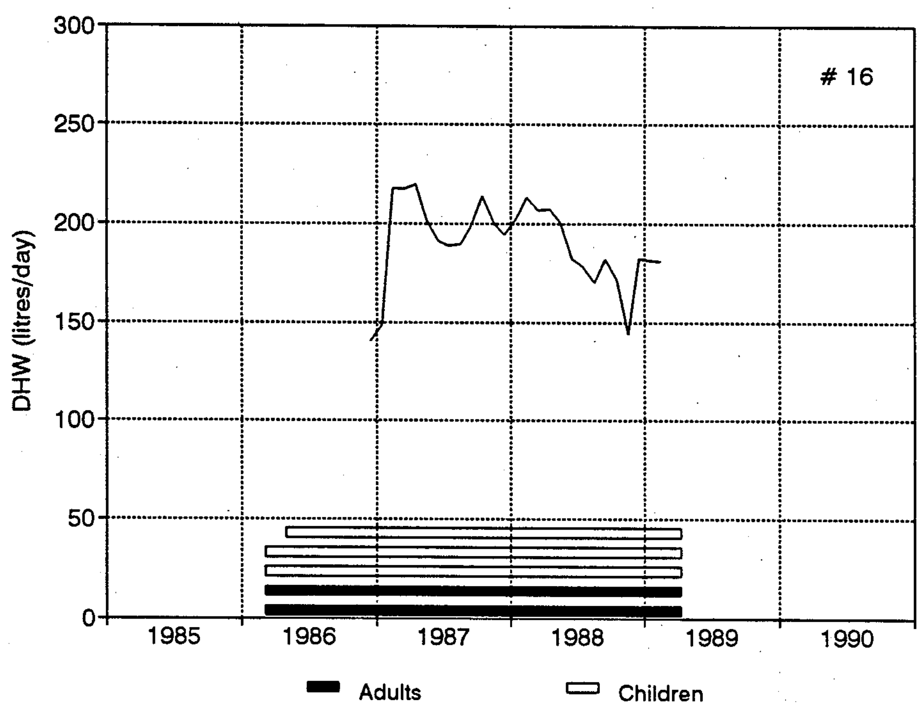


(ii)

Figure A.16(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Hot Water Usage and Number of Occupants

A.17 House # 17

A.17.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	454 cubic metres
Construction:	Double Wall
Ceiling:	R 7.0 (blown-in cellulose)
Main Walls:	R 7.0 (glass fibre batts)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric baseboard heaters
Ventilation system:	heat pump HRV with dedicated ducts
DHW system:	electric tank

A.17.2 Energy Sub-Metering Schedule

Main Electric

- Space Heating (derived)
  - Baseboard Heaters
  - Duct Heater
- Domestic Hot Water Tank
- Exterior Receptacles
- Interior Appliances (including Nilan) (derived)

Mains Water

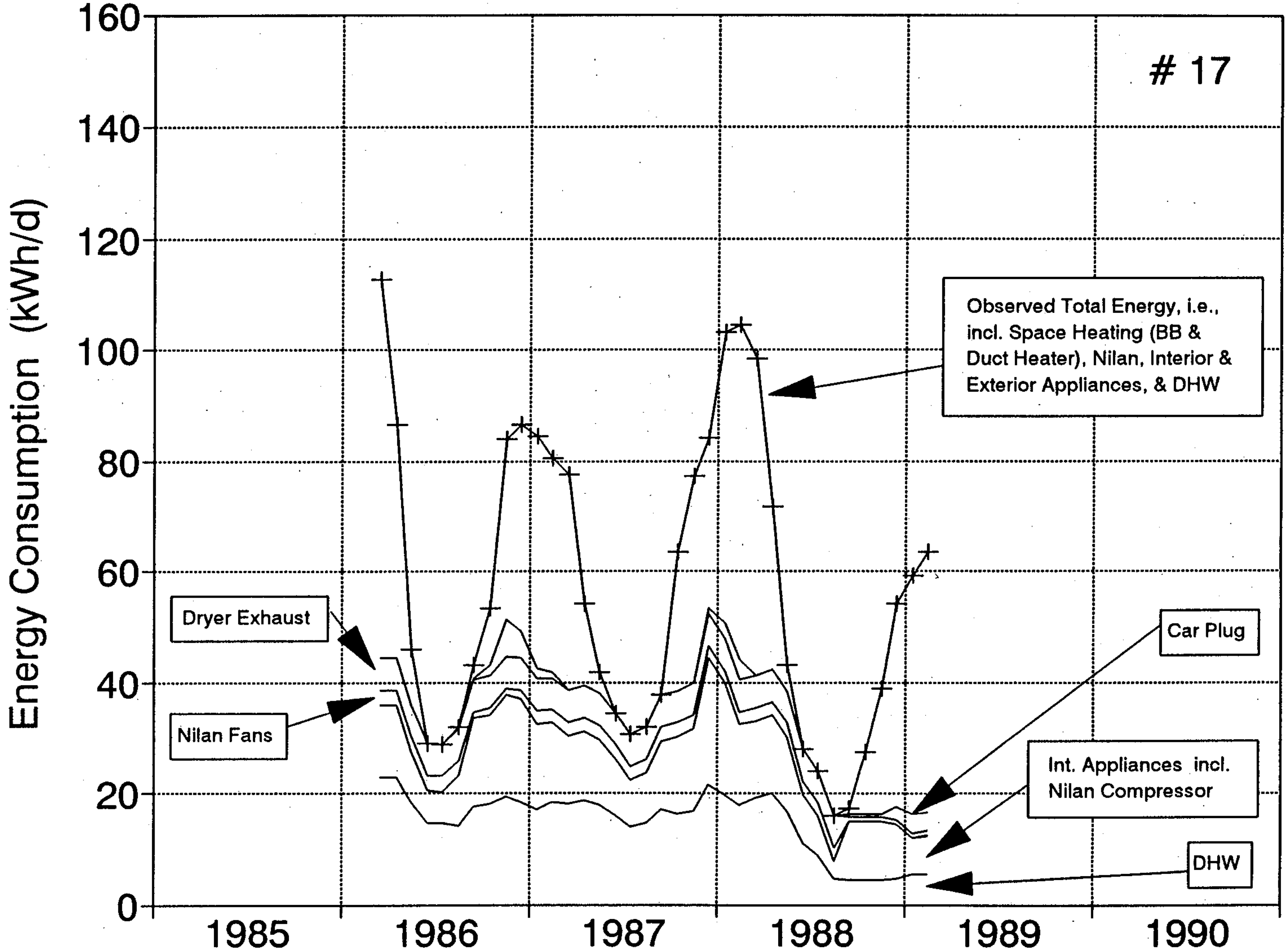
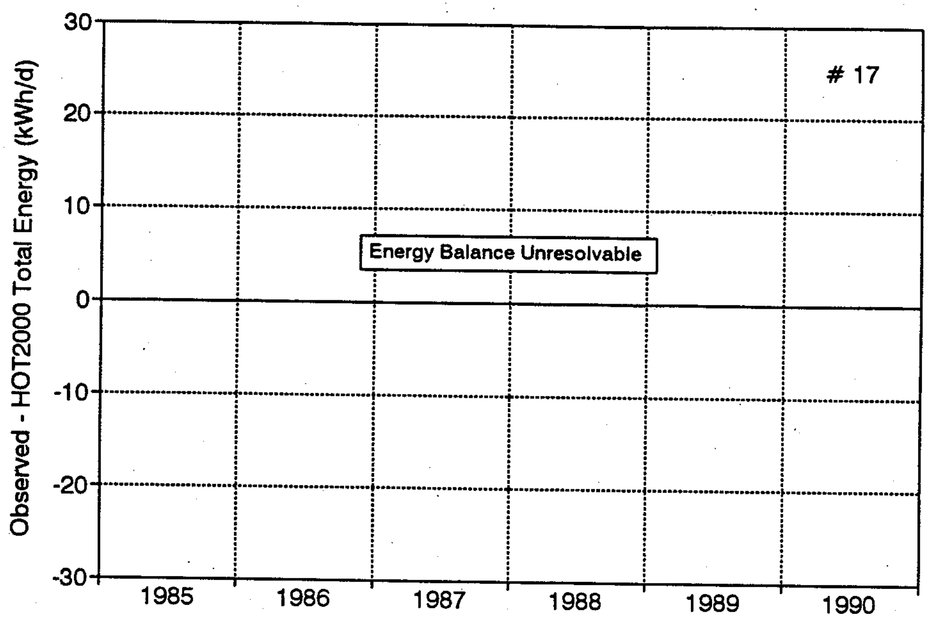


Figure A.17(a) Energy Profile



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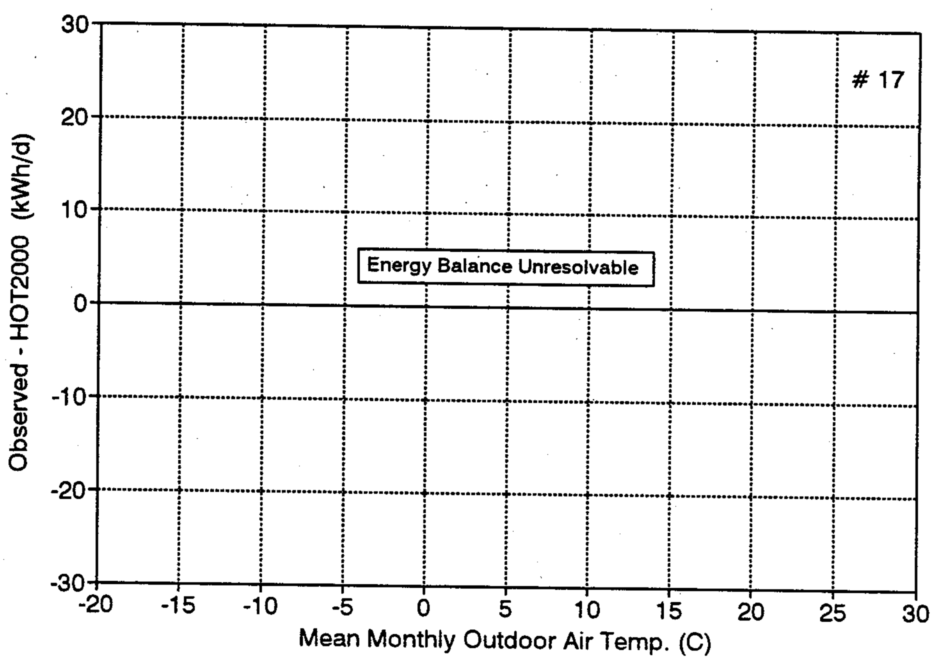
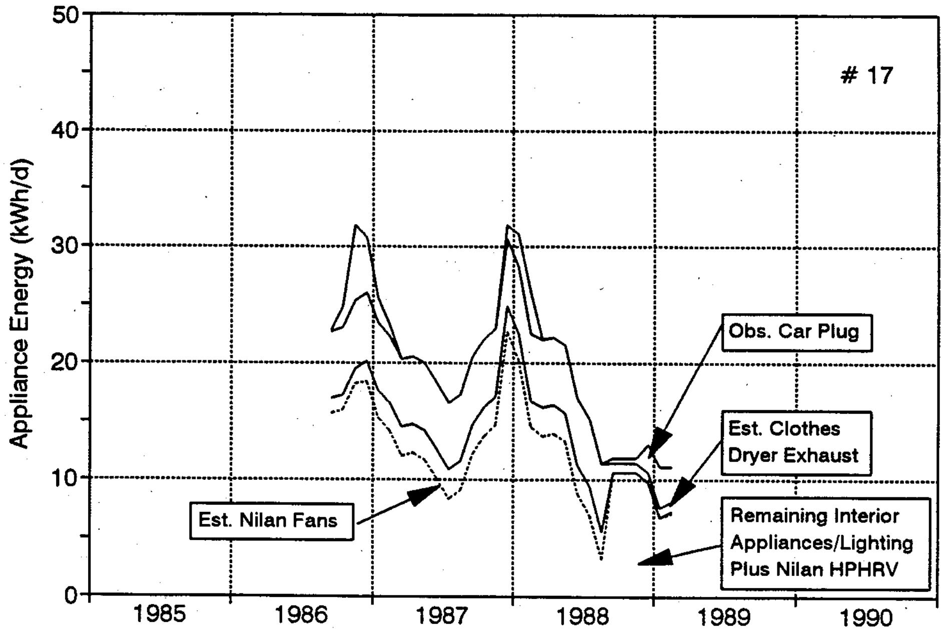


(ii)

Figure A.17(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
(ii) Model Performance Signature



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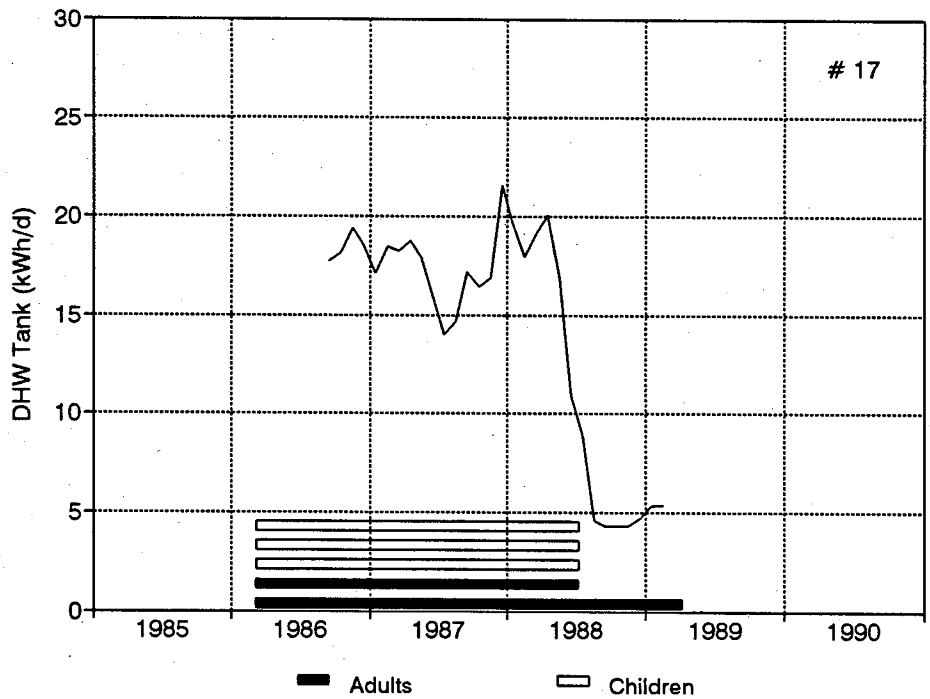


(ii)

Figure A.17(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.18 House # 18

A.18.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	454 cubic metres
Construction:	Double Wall
Ceiling:	R 7.0 (blown-in cellulose)
Main Walls:	R 7.0 (glass fibre batts)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric baseboard heaters
Ventilation system:	heat pump HRV with dedicated ducts
DHW system:	electric tank

A.18.2 Energy Sub-Metering Schedule

Main Electric

- Space Heating (derived)
  - Baseboard Heaters
  - Duct Heater
- Domestic Hot Water Tank
- Exterior Receptacles
- Nilan Heat Pump HRV
- Interior Appliances (derived)

Mains Water

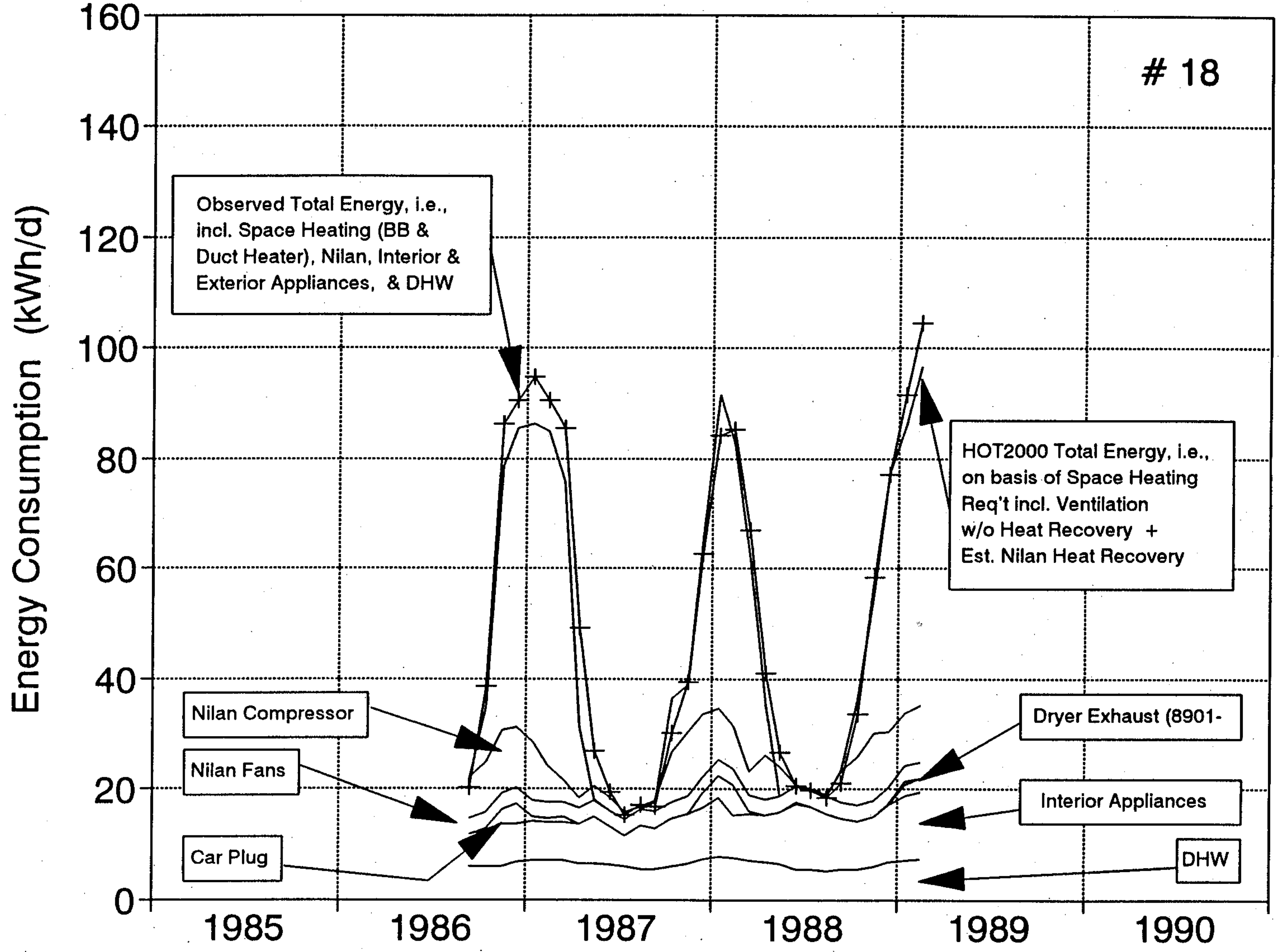
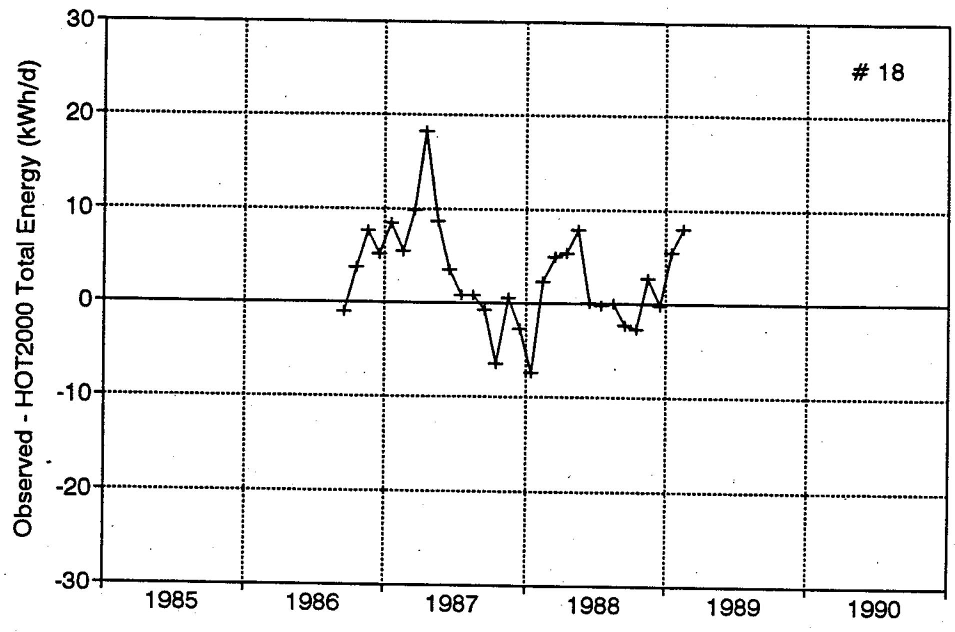


Figure A.18(a) Energy Profile



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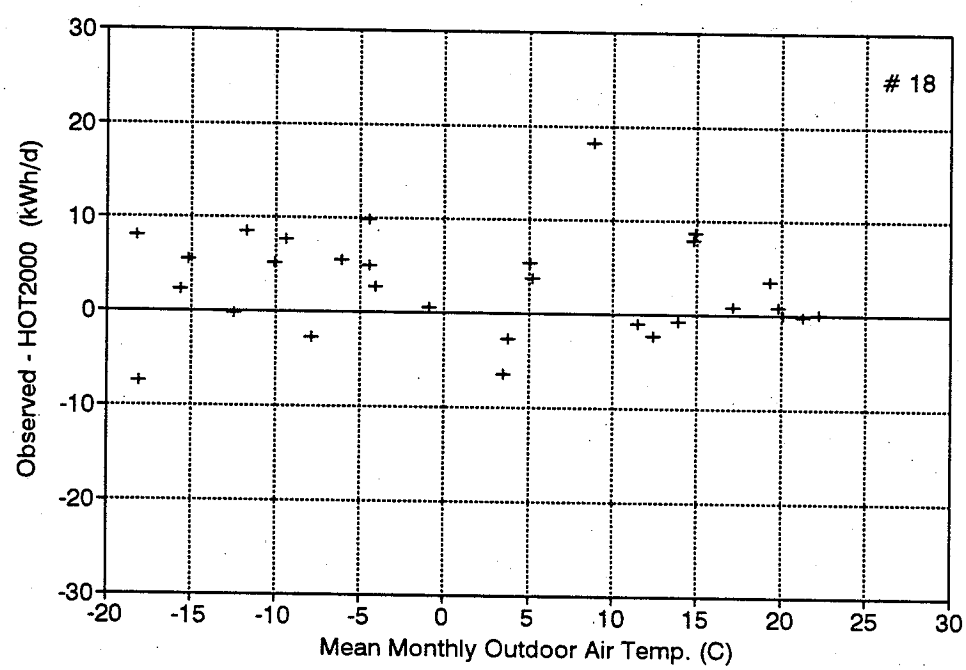
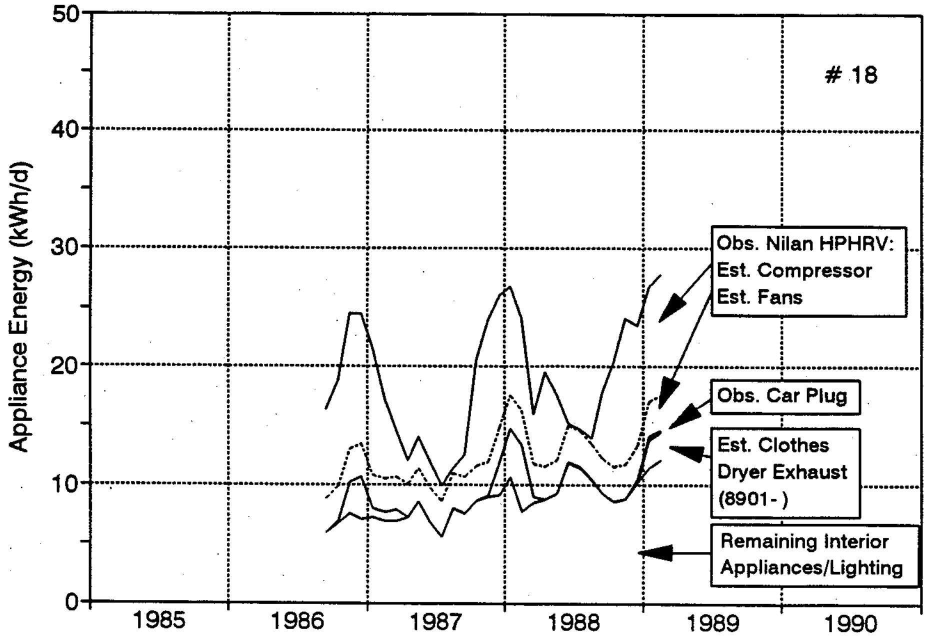


(ii)

Figure A.18(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
(ii) Seasonal Dependence of Model Performance



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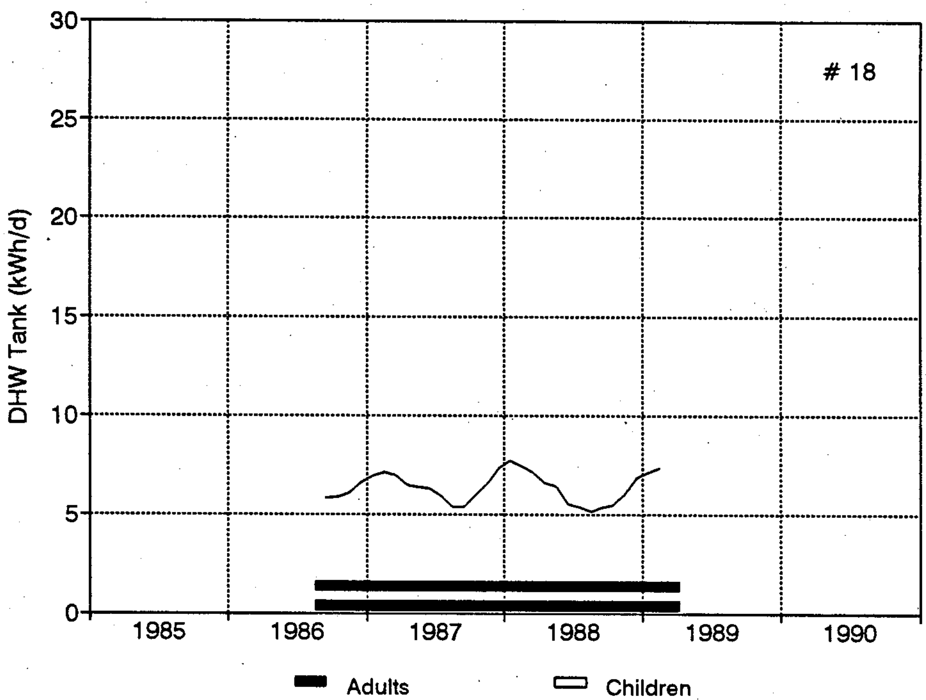


(ii)

Figure A.18(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.19 House # 19

A.19.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	444 cubic metres
Construction:	Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in cellulose)
Main Walls:	R 3.9 (glass fibre batts plus extruded polystyrene sheathing)
Basement Walls:	R 3.9 (glass fibre batts, interior, with extruded polystyrene sheathing, exterior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric baseboard heaters
Ventilation system:	HRV (single crossflow, 2nd generation, dedicated ducts)
DHW system:	electric tank

A.19.2 Energy Sub-Metering Schedule

Main Electric
- Space Heating (derived)
  - Baseboard Heaters
  - Duct Heater
- Domestic Hot Water Tank
- Appliances incl. HRV and Exterior Receptacles (derived)

HRV Total Run Time
- Demand Time
- Defrost Time
- Low Speed Time (derived)

Mains Water

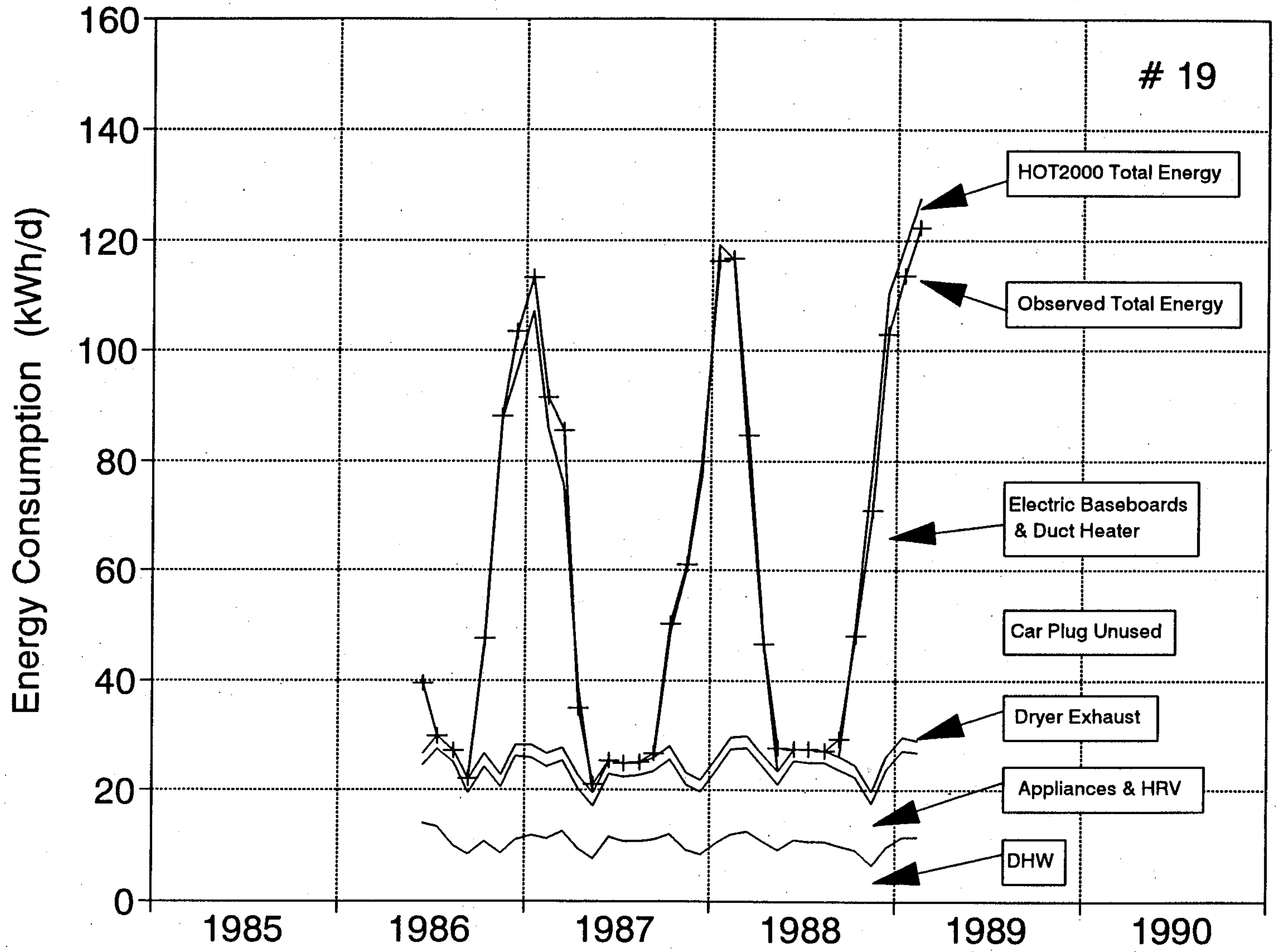
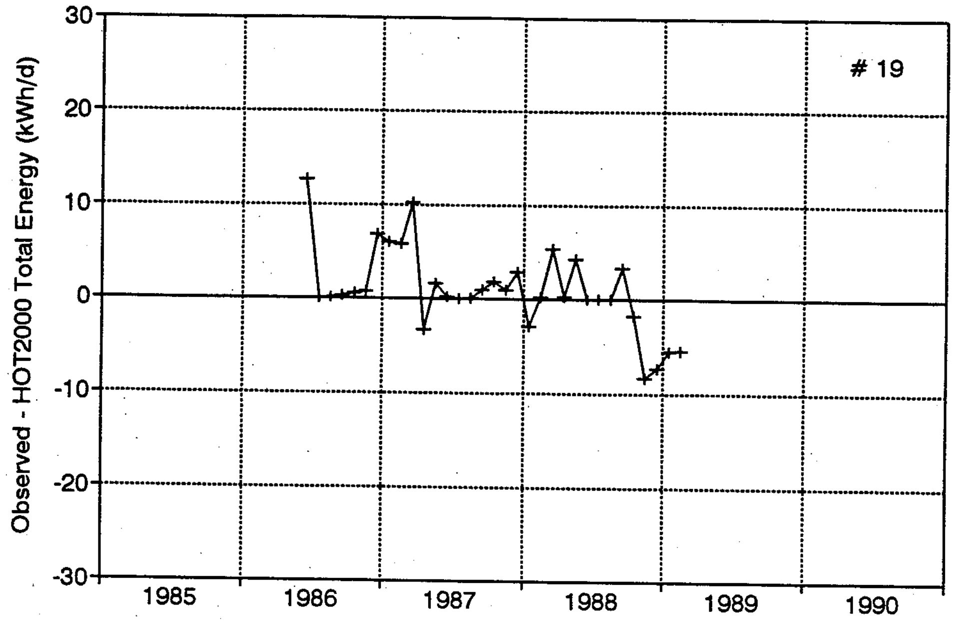


Figure A.19(a) Energy Profile



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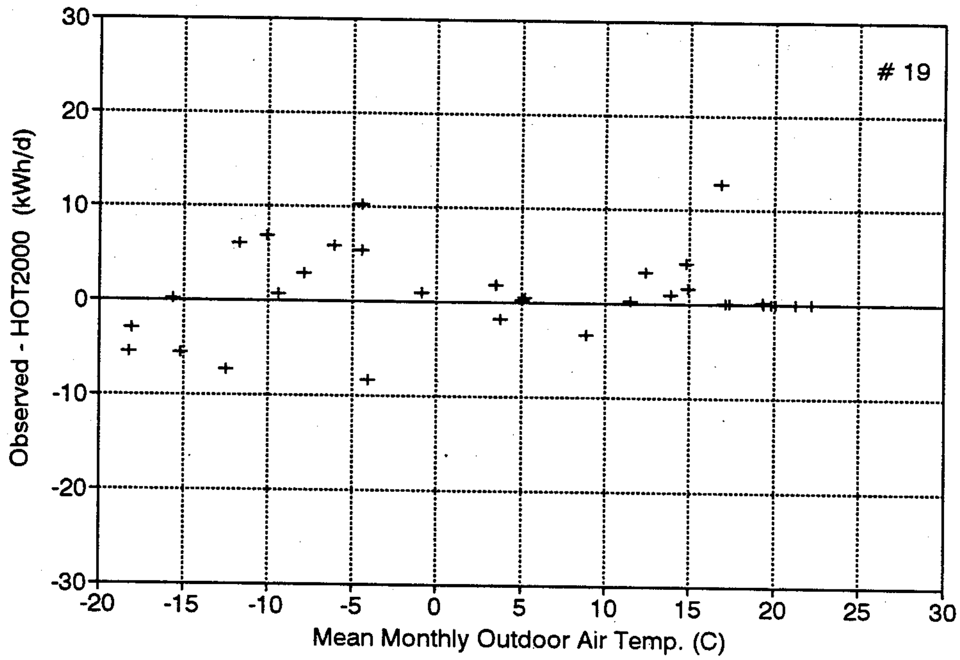
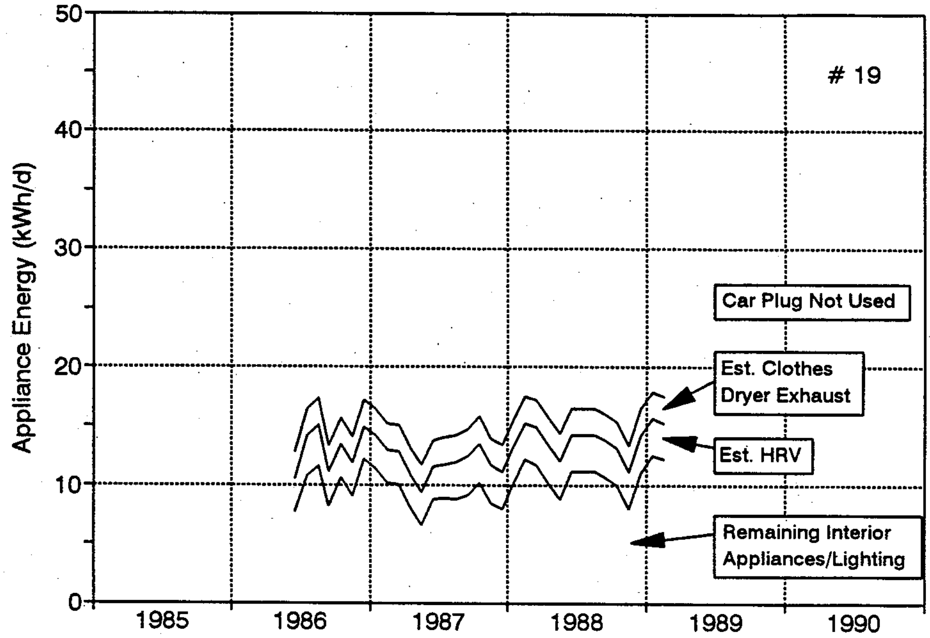


(ii)

Figure A.19(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
(ii) Model Performance Signature



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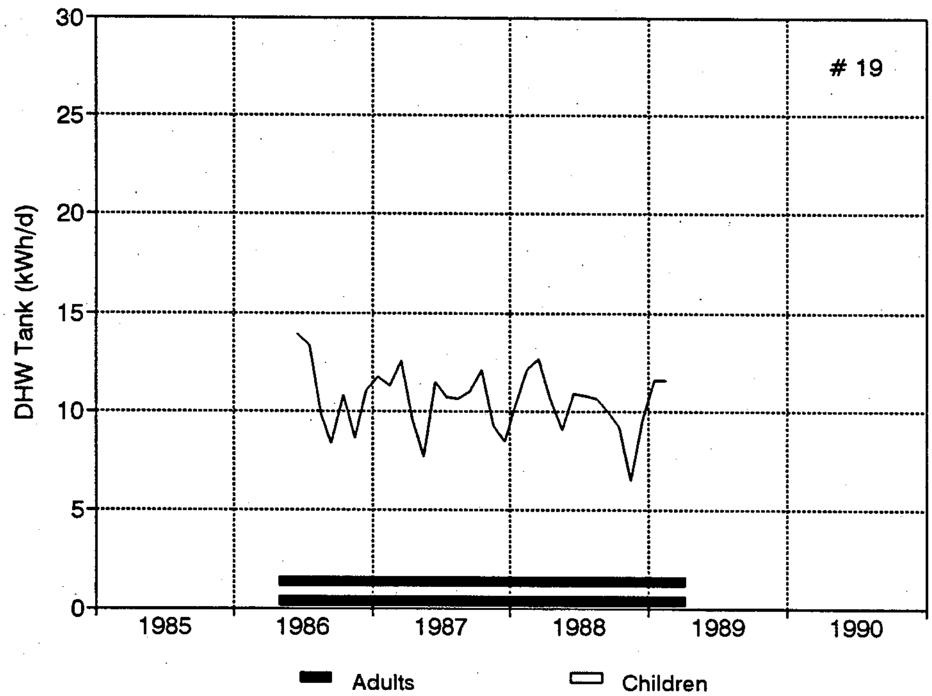


(ii)

Figure A.19(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.20 House # 20

A.20.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	444 cubic metres
Construction:	Airtight Drywall Approach
Ceiling:	R 7.0 (blown-in cellulose)
Main Walls:	R 3.9 (glass fibre batts plus extruded polystyrene sheathing)
Basement Walls:	R 3.9 (glass fibre batts, interior, with extruded polystyrene sheathing, exterior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units
Heating system:	electric baseboard heaters
Ventilation system:	HRV (single crossflow, 2nd generation, dedicated ducts)
DHW system:	electric tank

A.20.2 Energy Sub-Metering Schedule

Main Electric
- Space Heating (derived)
  - Baseboard Heaters
  - Duct Heater
- Domestic Hot Water Tank
- Appliances incl. HRV and Exterior Receptacles (derived)

HRV Total Run Time
- Demand Time
- Defrost Time
- Low Speed Time (derived)

Mains Water

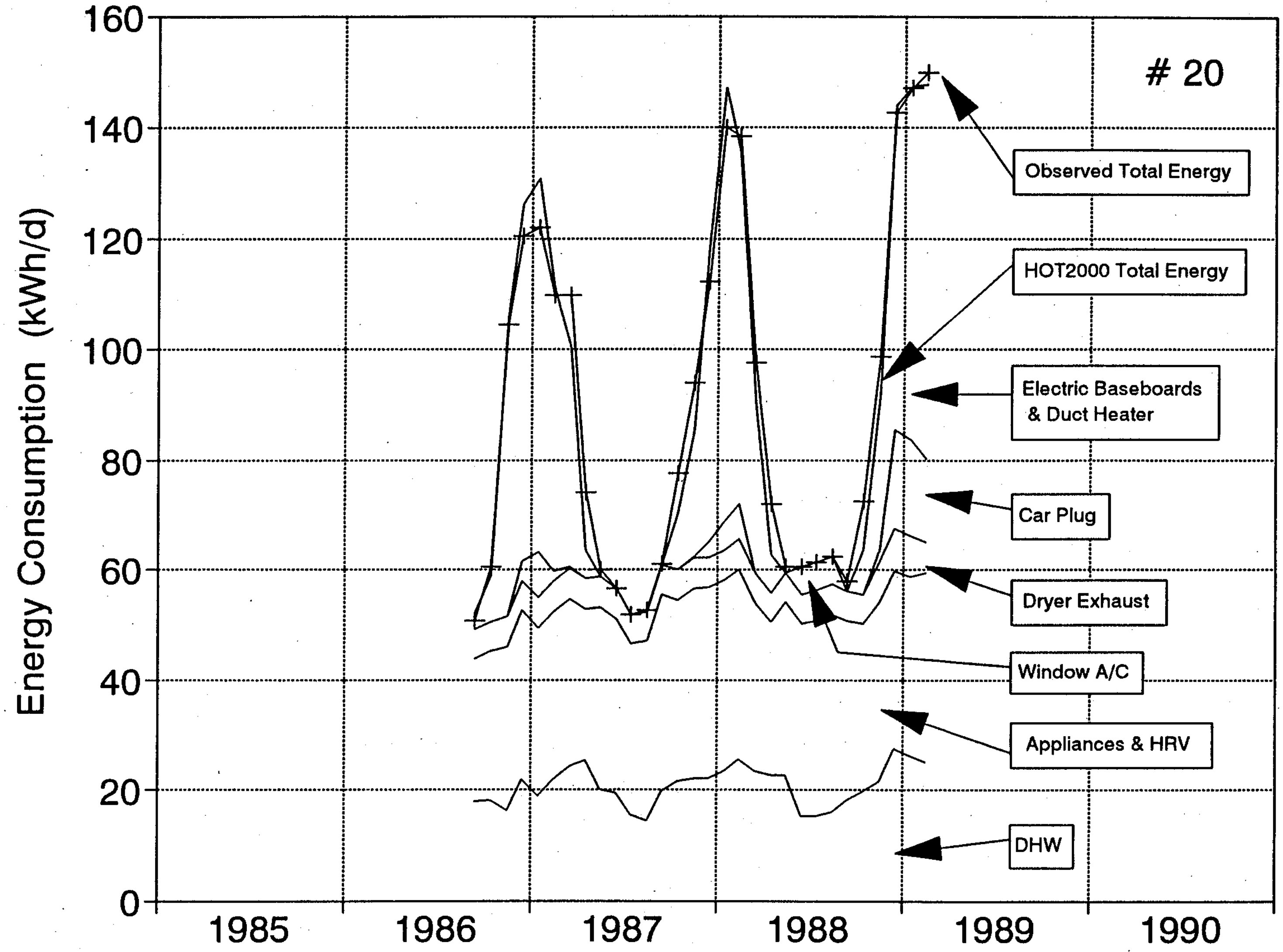
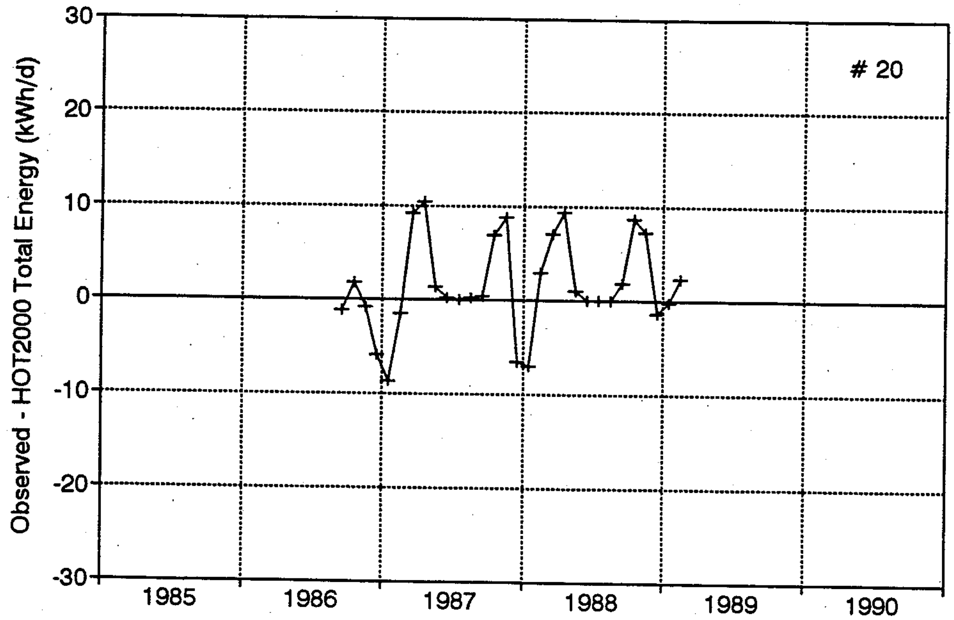


Figure A.20(a) Energy Profile



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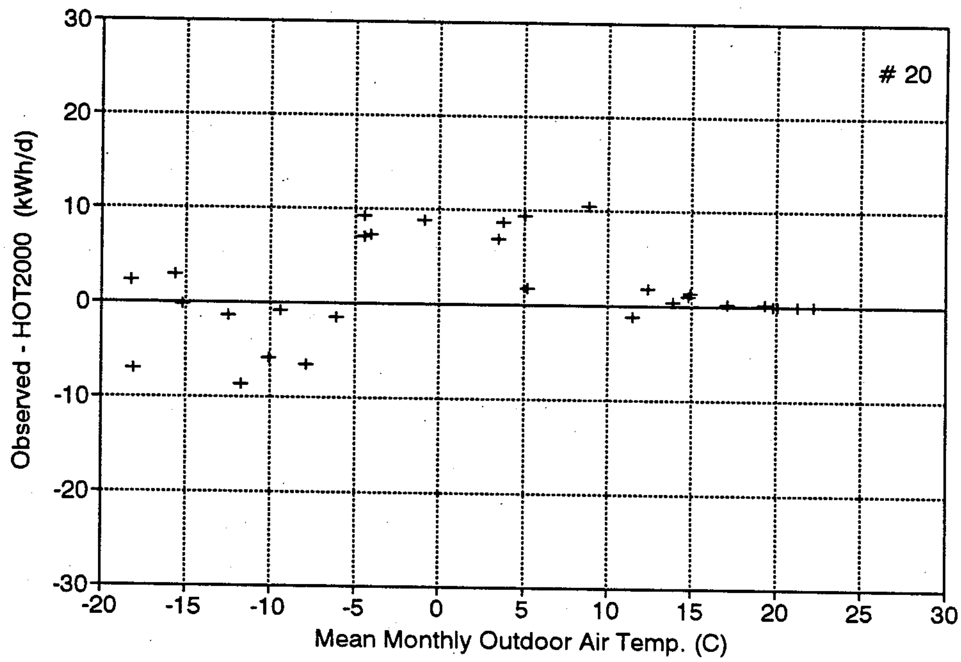

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Figure A.20(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
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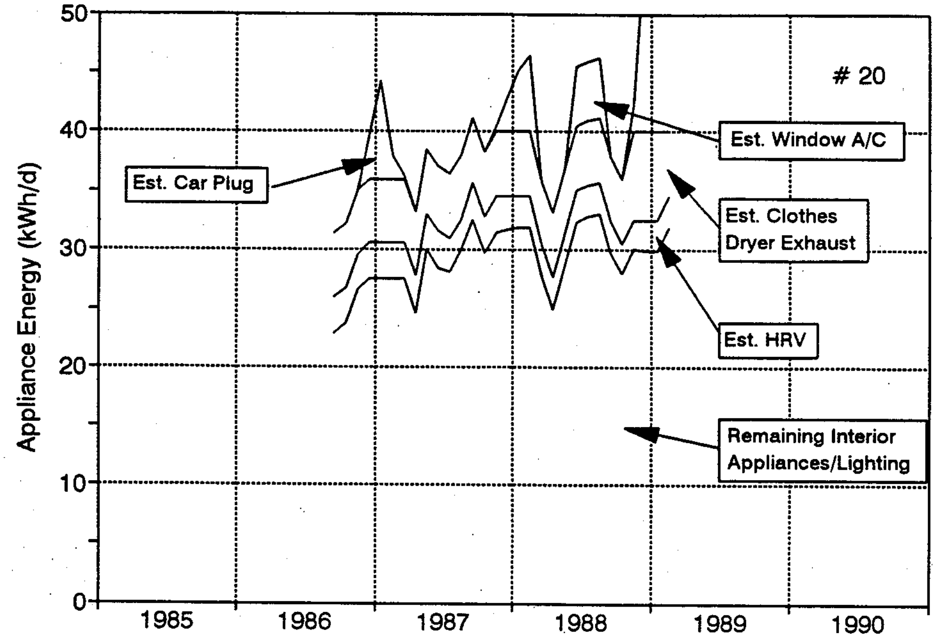

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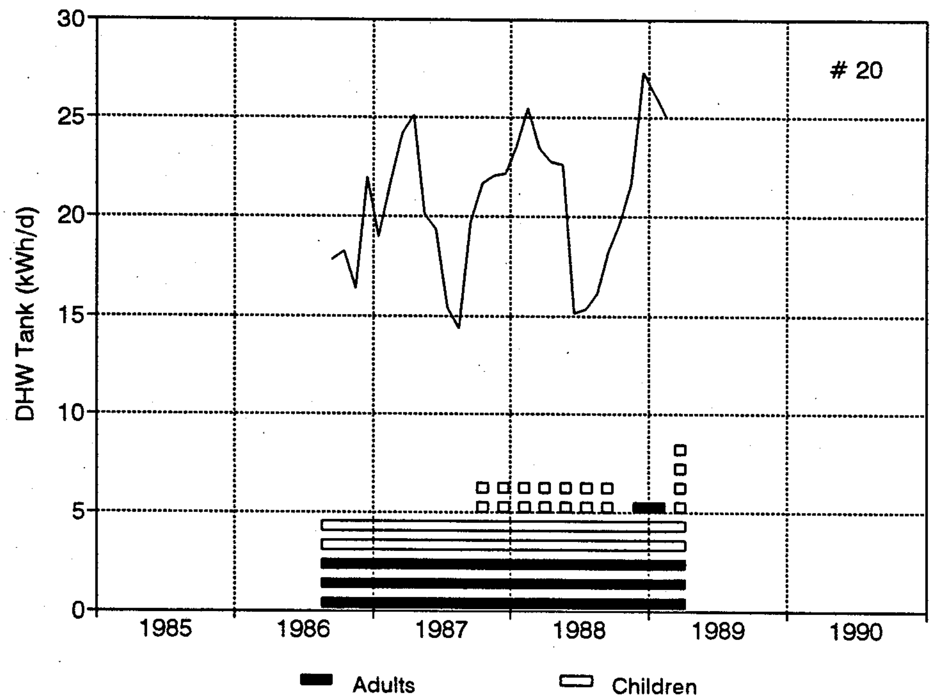


(ii)

Figure A.20(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.22 House # 22

A.22.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	464 cubic metres
Construction:	conventional, with 6 mil poly air/vapour barrier
Ceiling:	R 7.0 (blown-in cellulose)
	glass fibre batts over vaulted ceiling portion
Main Walls:	R 3.5 (glass fibre batts)
Basement Walls:	R 2.1 (glass fibre batts, interior)
Basement Floor:	uninsulated concrete slab
Windows:	conventional wood-framed tripane units, also wood-framed, quad-glazed (two suspended films) units
Heating system:	electric forced air furnace
Ventilation system:	central exhaust fan with fresh air intake
DHW system:	electric tank

A.22.2 Energy Sub-Metering Schedule

Main Electric
- Electric Furnace
- Domestic Hot Water Tank
- Appliances incl. Central Exhaust Fan and Exterior Receptacles (derived)

Central Exhaust Fan Total Run Time

Mains Water

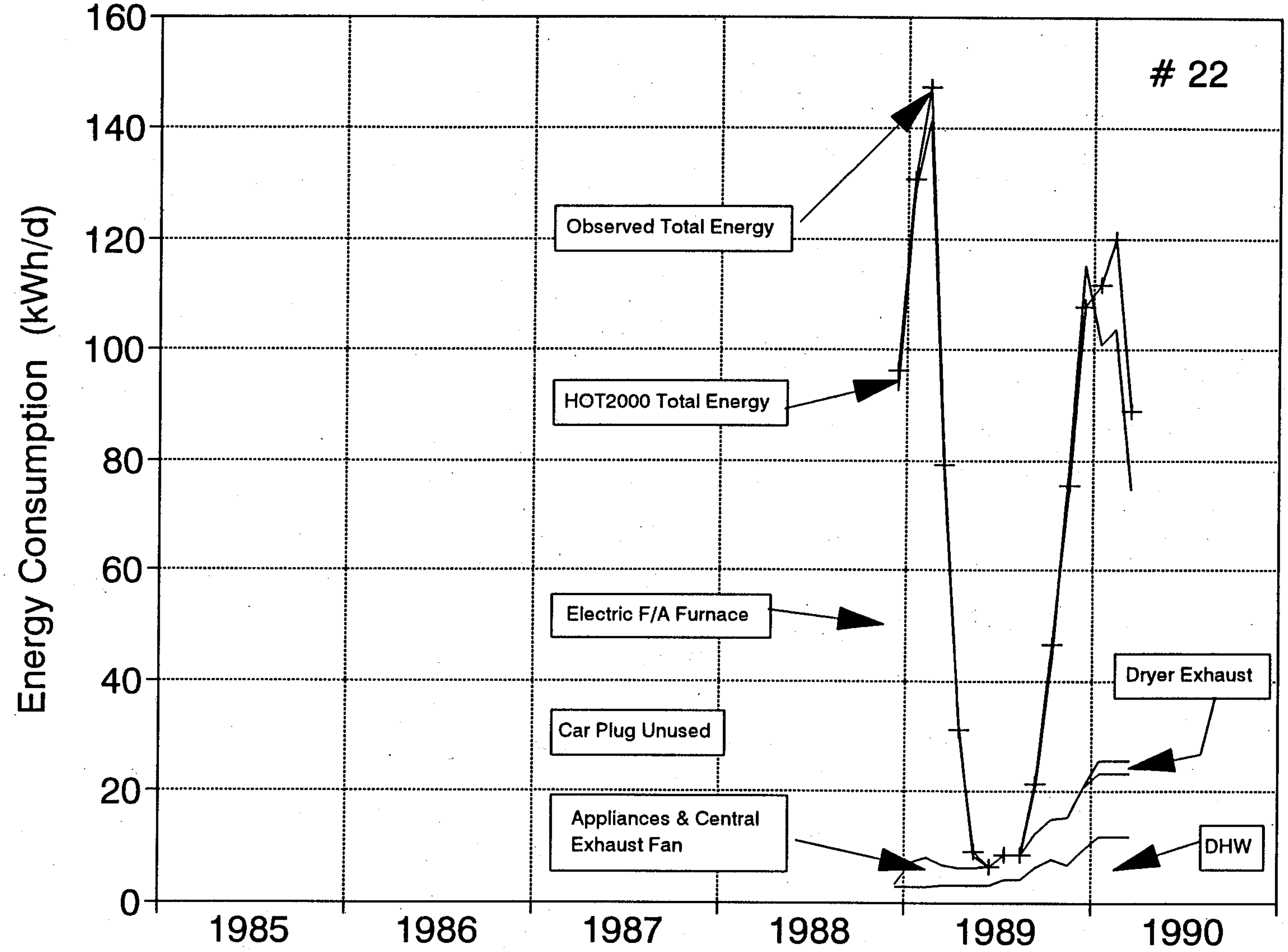
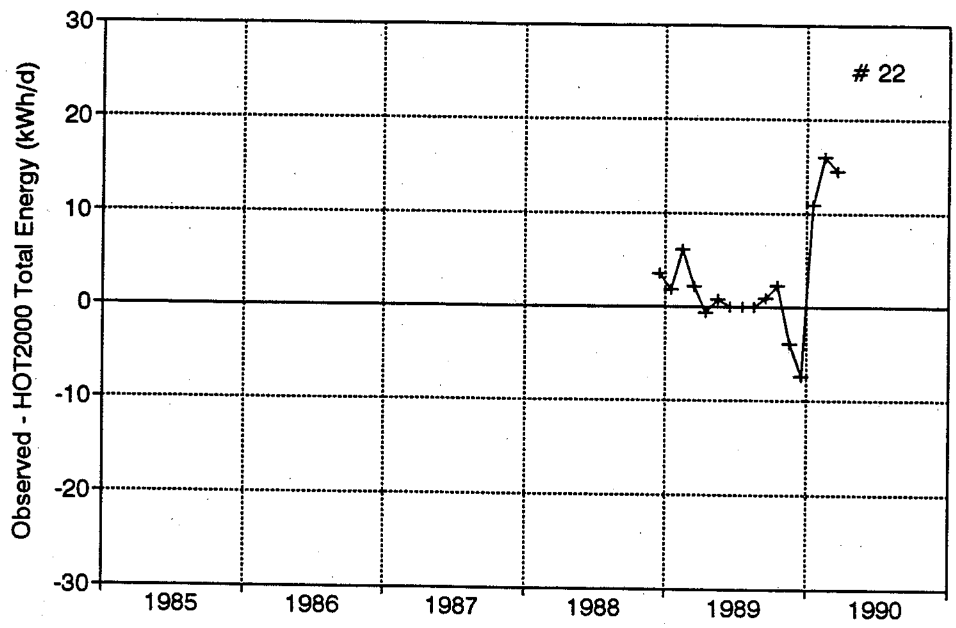


Figure A.22(a) Energy Profile



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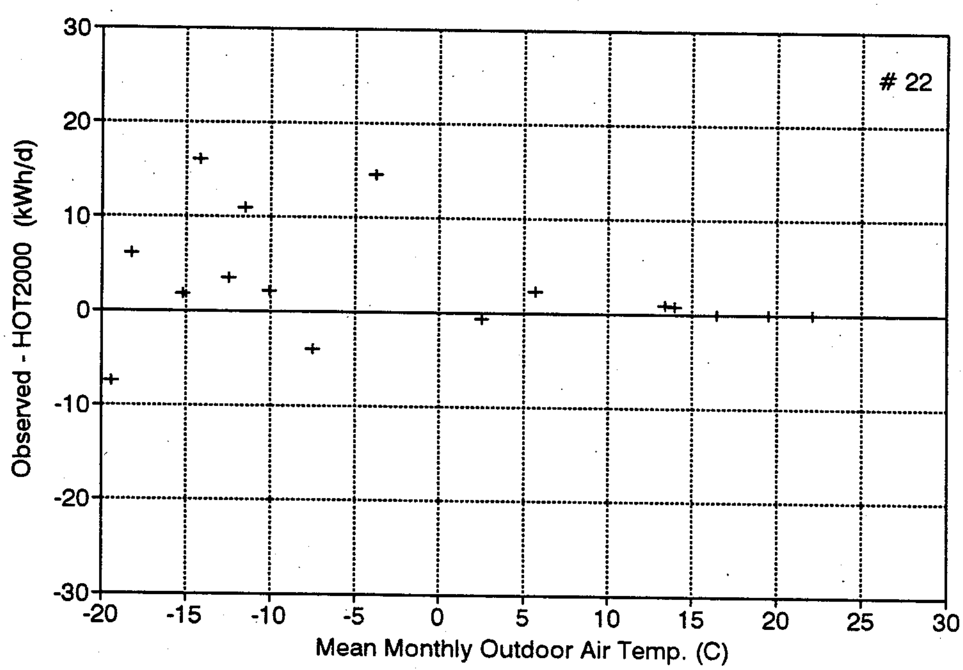

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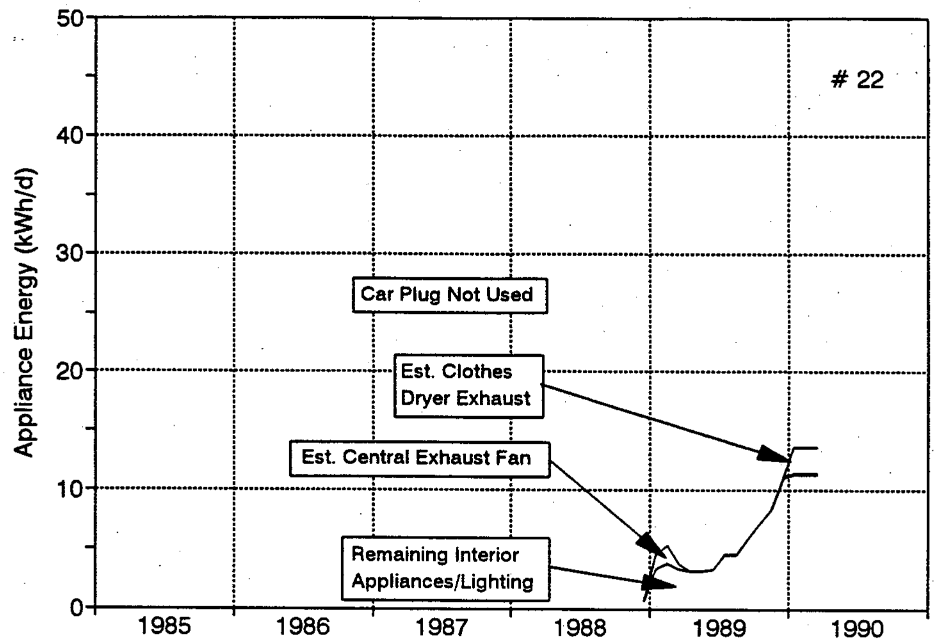
Figure A.22(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
(ii) Model Performance Signature



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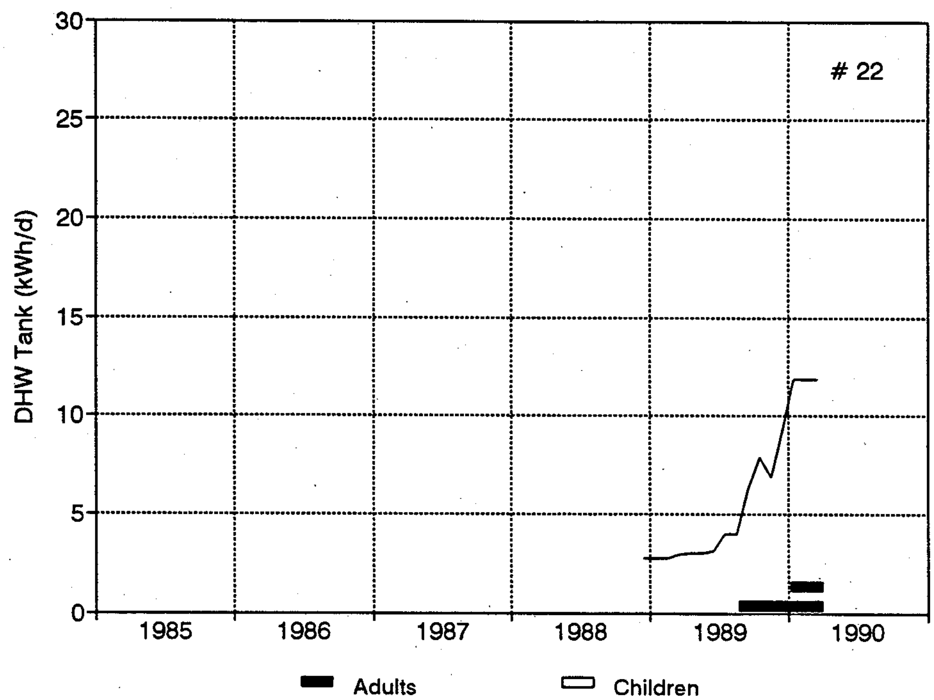


(ii)

Figure A.22(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Water-Heating Energy and Number of Occupants

A.23 House # 23

A.23.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	449 cubic metres
Construction:	conventional, with 6 mil poly air/vapour barrier
Ceiling:	R 7.0 (blown-in cellulose) glass fibre batts over vaulted ceiling portion
Main Walls:	R 4.8 (glass fibre batts with interior strapping)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	R 0.9 (extruded polystyrene rigid sheathing below slab)
Windows:	conventional wood-framed tripane units, also wood-framed tripane units with two low-e coatings and argon gas fill
Heating system:	electric forced air furnace
Ventilation system:	HRV (low-capacity, single crossflow, shared ducts), plus kitchen range hood exhaust fan
DHW system:	electric tank

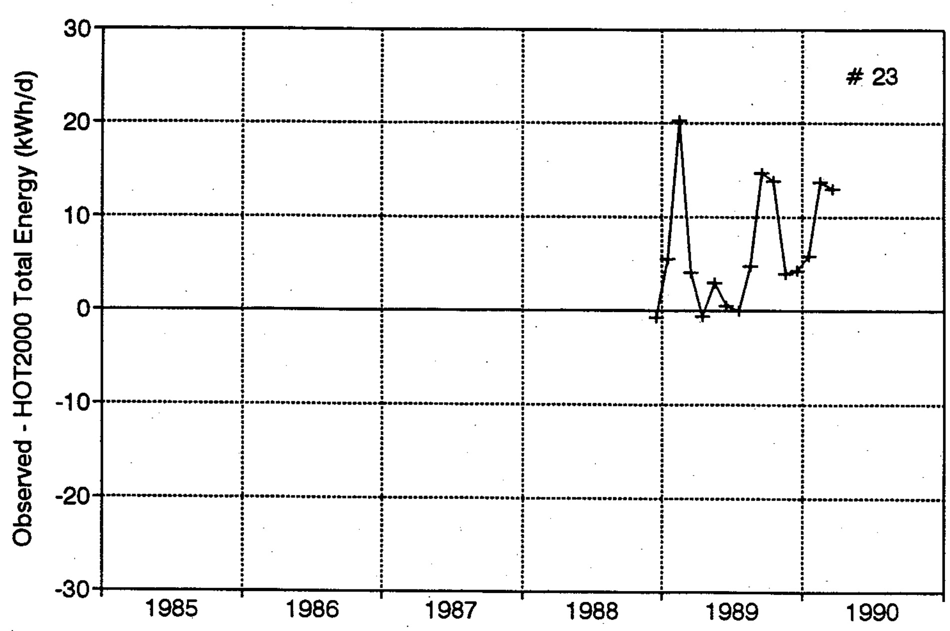
A.23.2 Energy Sub-Metering Schedule

Main Electric
- Electric Furnace
- Domestic Hot Water Tank
- Appliances incl. HRV and Exterior Receptacles (derived)

HRV Total Run Time
- Demand Time
- Defrost Time
- Low Speed Time (derived)

Range Hood Fan Total Run Time

Mains Water
- Hot Water



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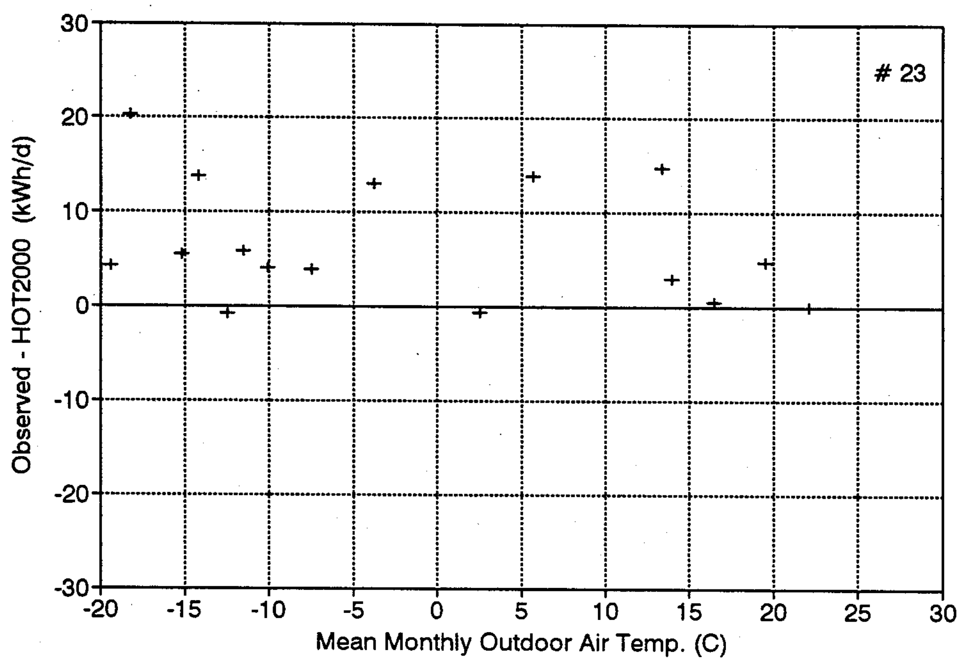

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Figure A.23(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
(ii) Model Performance Signature

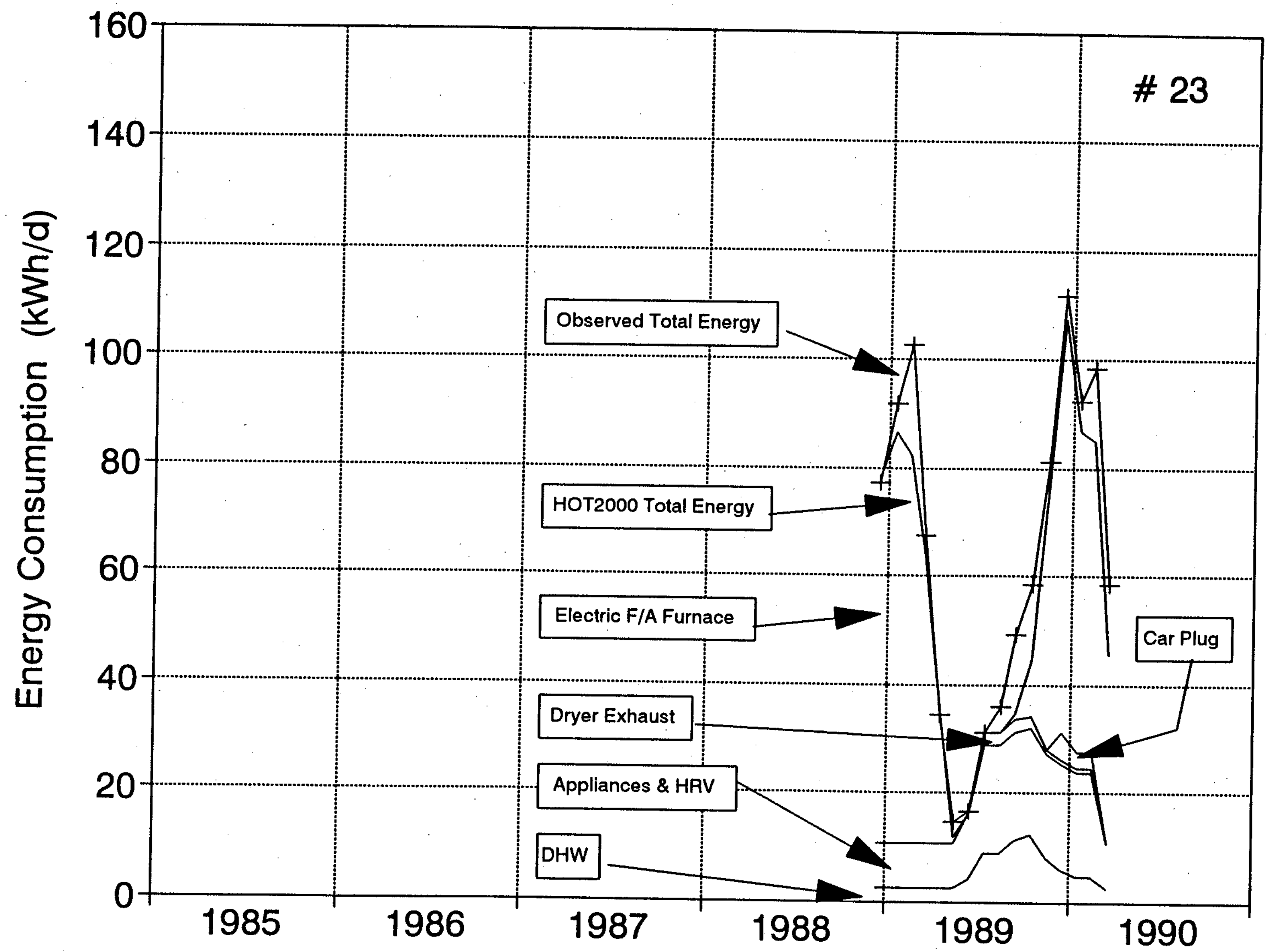
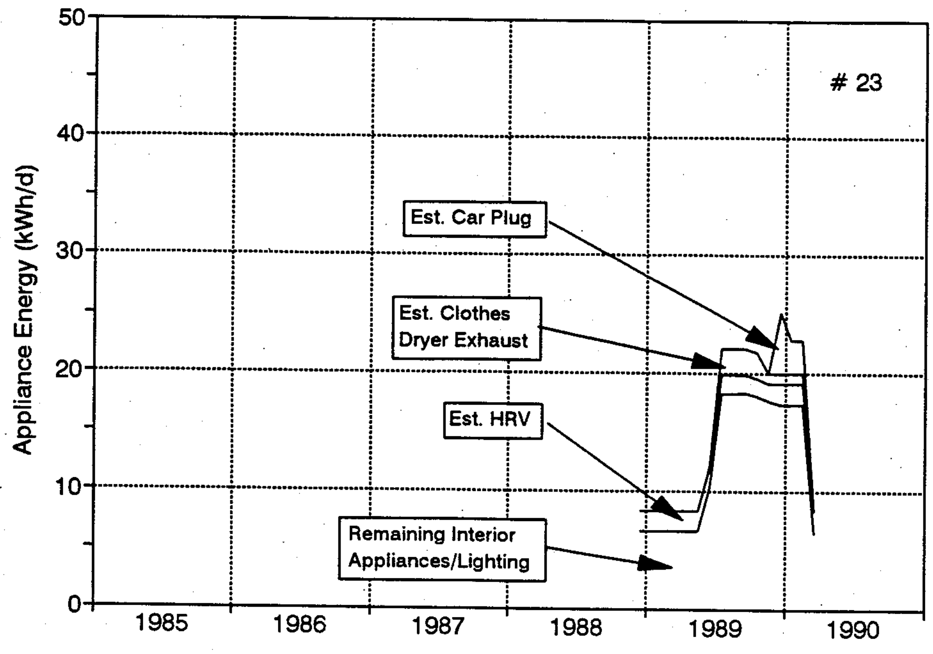


Figure A.23(a) Energy Profile



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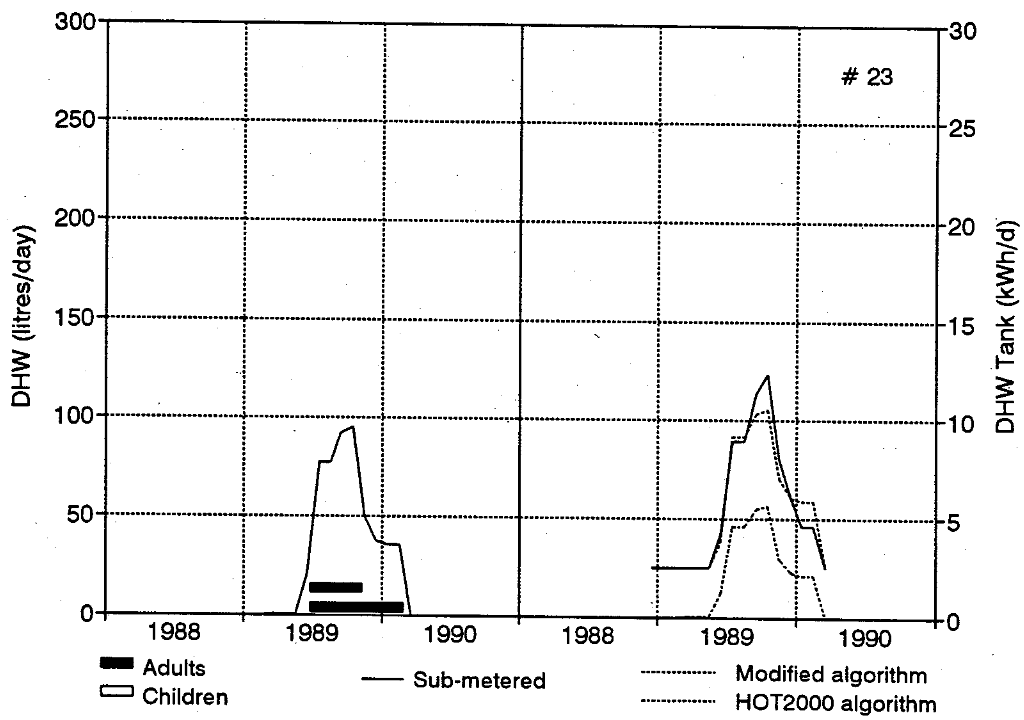


(ii)

Figure A.23(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Hot Water Usage and Number of Occupants

A.24 House # 24

A.24.1 Thumbnail Sketch

Type:	one-storey wood frame over full basement
Footprint:	98 square metres
Heated Volume:	461 cubic metres
Construction:	conventional, with 6 mil poly air/vapour barrier
Ceiling:	R 7.0 (blown-in cellulose) glass fibre batts over vaulted ceiling portion
Main Walls:	R 4.7 (glass fibre, batts plus semi-rigid sheathing)
Basement Walls:	R 3.5 (glass fibre batts, interior)
Basement Floor:	R 1.2 (glass fibre semi-rigid sheathing below slab)
Windows:	wood-framed, quad-glazed (two suspended films) units, also vinyl-framed tripane units with two low-e coatings and argon gas fill
Heating system:	electric baseboard heaters and radiant ceiling panels
Ventilation system:	HRV (low-capacity, single crossflow, dedicated ducts, plus supplemental bathroom exhaust fan
DHW system:	electric tank

A.24.2 Energy Sub-Metering Schedule

- Main Electric
  - Space Heating (derived)
    - Basement Baseboard Heaters
    - Main Floor Resistance Heaters (baseboards or ceiling panels)
  - Domestic Hot Water Tank
  - Appliances incl. HRV and Exterior Receptacles (derived)

- HRV Total Run Time
  - Demand Time
  - Defrost Time
  - Low Speed Time (derived)

- Bathroom Fan Total Run Time

- Mains Water
  - Hot Water

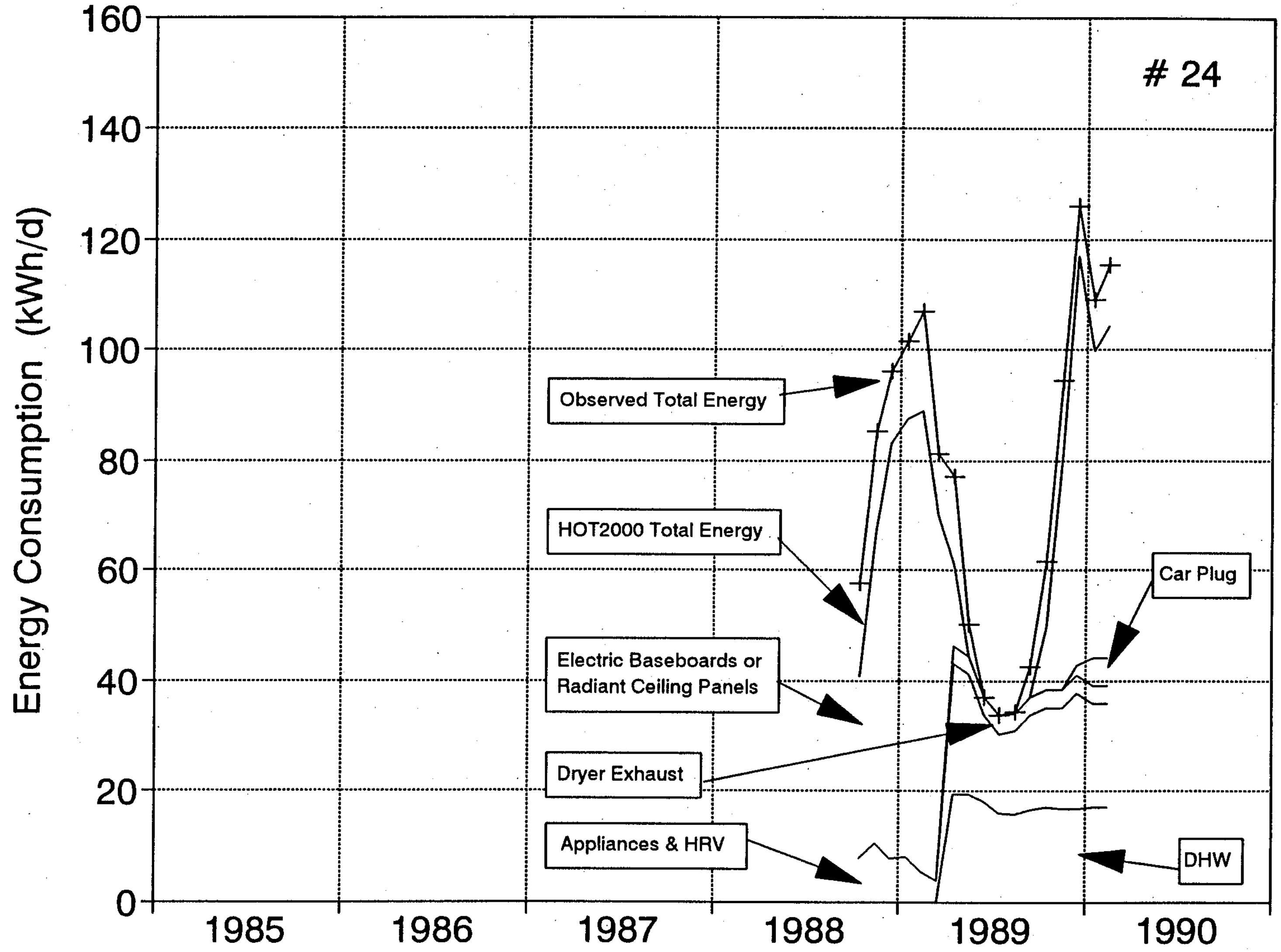
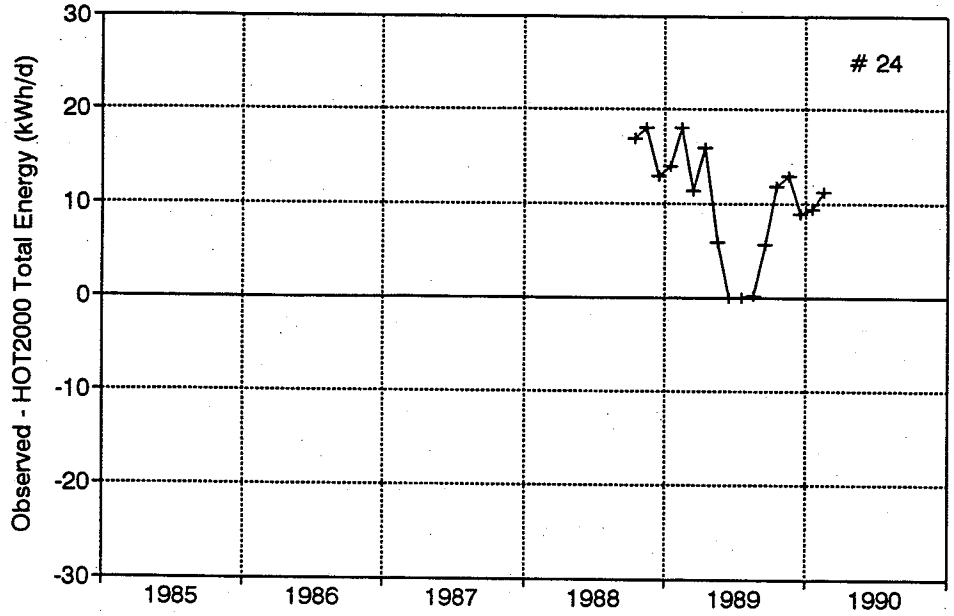


Figure A.24(a) Energy Profile



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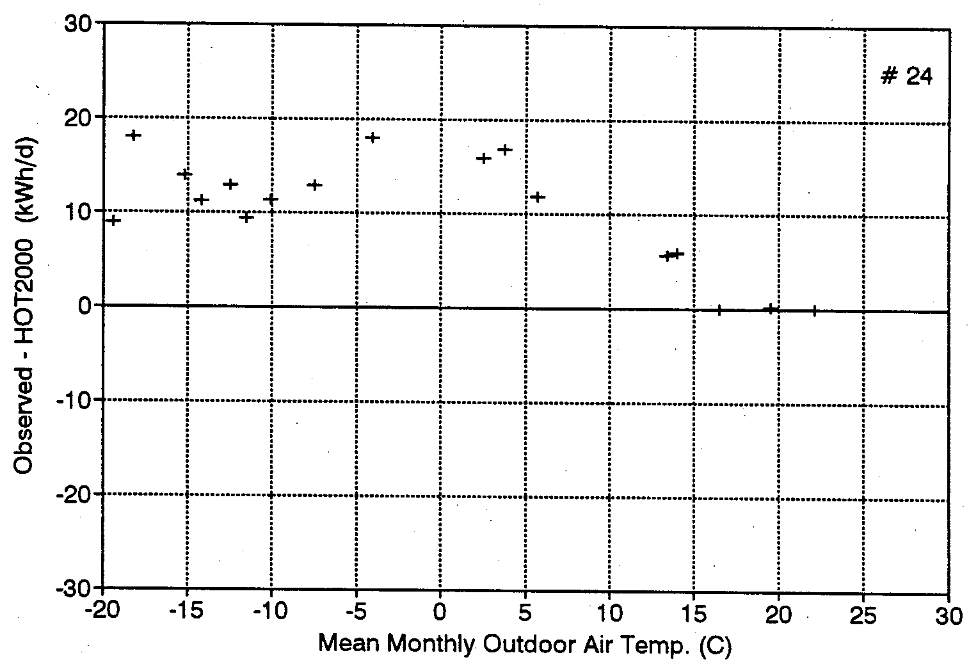

(ii)

Figure A.24(b) Energy Model Performance
(i) Difference Between Monthly Observations and Predictions
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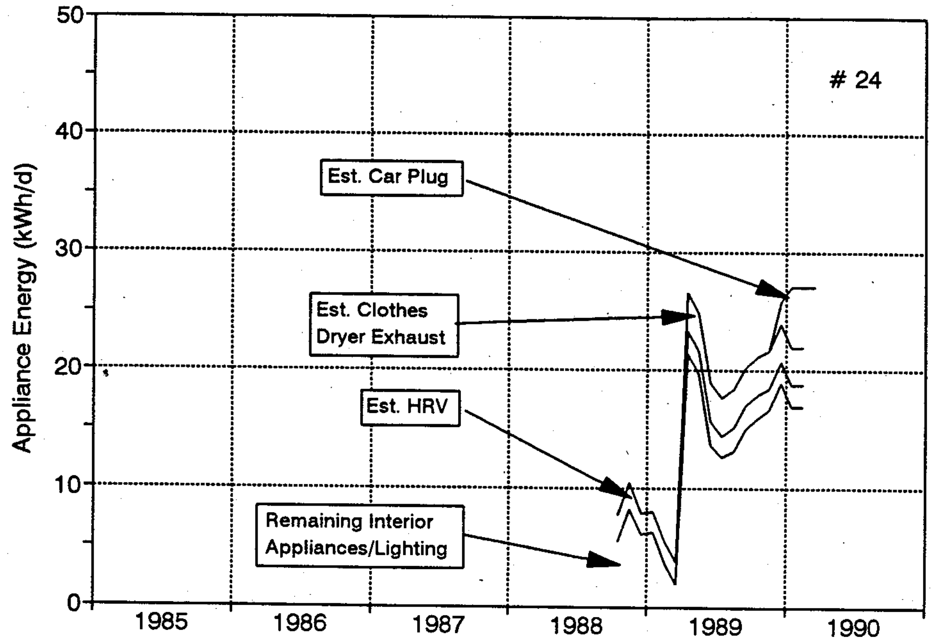

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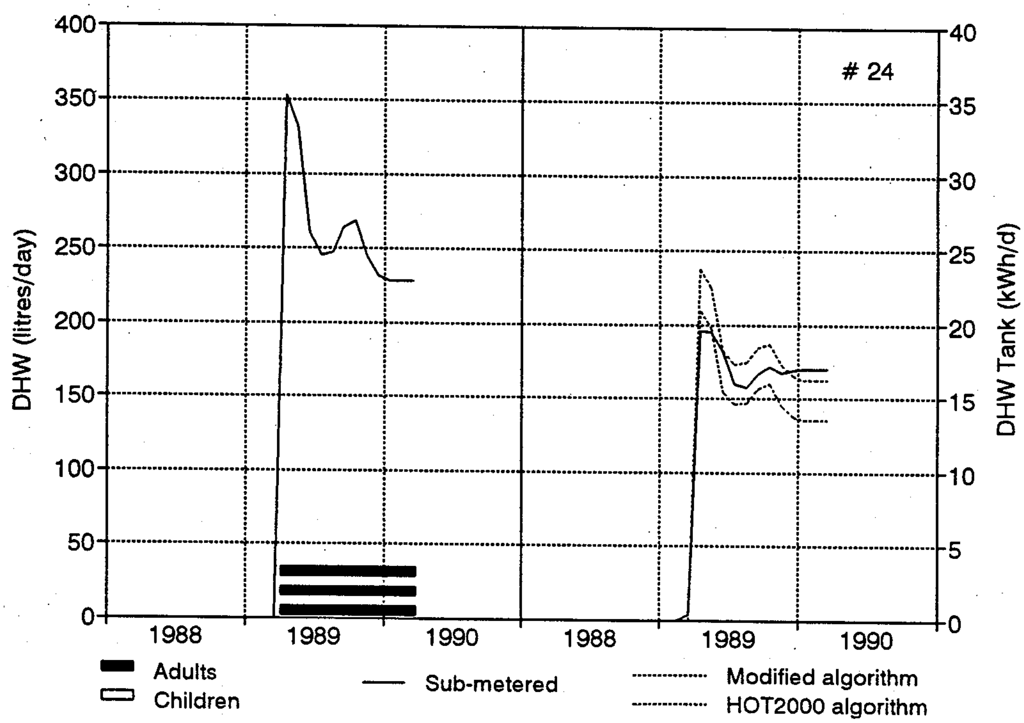


(ii)

Figure A.24(c) Occupancy Factors
(i) Breakdown of Observed Non-Heating Energy
(ii) Hot Water Usage and Number of Occupants

APPENDIX B

REPORT ON HOURLY MONITORING OF HOUSE #24

A COMPARISON OF CEILING PANEL AND BASEBOARD HEATING SYSTEMS UNDER UNOCCUPIED CONDITIONS

UNIES Ltd.

A COMPARISON OF CEILING PANEL AND BASEBOARD HEATING SYSTEMS UNDER UNOCCUPIED CONDITIONS

B.0 SUMMARY

Flip-flop operation of a dual heating system in a new unoccupied Winnipeg R-2000 bungalow over the 1988/89 heating season together with continuous monitoring of temperatures, forced ventilation rates, and energy consumption was used to assess the differences between the conventional electric baseboard heating method and a system of heating via low-density electric heating panels located above the ceiling surface. The observed differences in performance were found to be modest. In particular, at a constant wall-mounted thermostat setting and ventilation rate, average house air temperature was slightly lower (less than one degree) with the ceiling panel system in operation. At the same time, head-to-ankle temperature gradient on the main floor level was approximately 0.5 degree, a reduction from the typical one degree gradient measured with the baseboard heaters in operation. De-weatherized electricity consumption rates were found to be higher in the case of the ceiling panel system, the difference amounting to an average of about 3 percent at 0°C and 7 percent at -40°C over the four-month winter monitoring interval. These results project to about 4.6 percent greater electricity consumption for the ceiling panels in comparison to the baseboard heaters over the period October 1 to April 30 under long-term normal Winnipeg temperature conditions.

B.1 INTRODUCTION

One of the Flair Energy Demo experimental houses (House #24) constructed in Winnipeg in early 1988 has a dual heating system. The house is a 100 square metre bungalow on full concrete basement, built to R-2000 energy standards, with the following other notable features: a mixture of triple- and quadruple-glazed so-called "superwindows"; a dedicated, ducted ventilation system with heat recovery, utilizing high-sidewall supply-air registers and baseboard-level return-air registers.

The dual heating system comprises a single conventional baseboard electric resistance heating system in the basement along with a conventional baseboard electric resistance heating system on the main living level plus a set of electric heater panels mounted above the ceiling drywall of the living level, between the ceiling framing members. In the basement, each of the four baseboard heaters responds in accordance to its own unit-mounted thermostat. On the main level, three heating circuits are used, each one servicing a single zone with parallel panel and baseboard systems. Room temperatures are individually controllable from wall-mounted thermostats, of which there are six, two to a zone. A ganged knife switch controls all three zones, such that the entire main level of the bungalow is heated either with the baseboard system or the panel system.

A continuous data acquisition system (Sciemetric Instruments Inc., Model 161) interfaced to a personal computer (MS-DOS compatible) and controlled by a software package (Sciemetric Instruments Inc., MAXIMON PLUS) has been used to record energy consumption rates and interior environment data (temperatures, relative humidity, air flow rates) over most of the 1988-89 heating season. Figure B.1 indicates the locations of the relevant monitored variables. For all but the last part of the monitoring period, the house was unoccupied, allowing a high degree of control over temperature settings and ventilation rates and, in particular, facilitating a comparison of operation with each heating system.

B.2 THE MONITORED PERIOD

A summary of the general operating environment of the house over the 1988-89 heating season is shown in Figures B.2 and B.3. By October 1, 1988, construction, finishing, and decorating activities were virtually complete. Commissioning of mechanical systems took place in late August 1988, and included balancing of the ventilation supply and return flows. The heating system was activated for the first time on October 4, 1988. Water use was negligible throughout the monitoring period, and the water heater was not energized until late March 1989.

From October 4 to November 26, thermostat settings were uncontrolled, but remained near 21°C. Mechanical ventilation was continuous at the demand level (approx. 49 l/s, or 0.40 ach). The flow values calculated from DCV readings do not show a balanced condition in Figure B.3 until about the end of October. The gradual movement away from the higher supply and lower return air flows toward balanced flow is interpreted to be the response of the Environmental Control Technology Inc. (ECT) Model LPTB-003-c-1 differential pressure sensors (no adjustments to air flows were made between August 1988 and the end of the monitoring period).

From November 26, 1988 to March 31, 1989, all six main floor thermostats were maintained at settings of 20°C, and the balanced ventilation rate was held at the low speed level (approx. 35 l/s, or 0.28 ach). Space heating was toggled between the ceiling and baseboard sources at intervals ranging from a week to a month. Water use remained negligible, and the water heater remained empty. The house was entered infrequently and no major disruptions to house operation occurred within this period.

Occupancy began on April 1, 1989 with the owners having full control of thermostat and ventilation settings and water usage.

Southern exposure and a lack of interior shading prior to occupancy allowed the house to derive a significant portion of its heating energy requirements from the sun, such that the electrical heating systems dominated only in the December-March period. Differences between the effects of operation with each of the two systems therefore could be expected to be most detectable for that interval. With thermostat settings and air flows held virtually constant during the period, differences in measured variables may be considered to result primarily from the two heating systems and the forcing outdoor environment.

B.3 INTERIOR TEMPERATURE DISTRIBUTIONS

Figures B.4, B.5, and B.6 illustrate the effects on the "average" air temperature in the house, taken as the temperature of the blended house air in the return (exhaust) air system just before it entered the HRV, and on the temperatures (shielded thermocouples) next to the walls in the living room and main bedroom which have south and north exposure, respectively. Compared to baseboard heating, operation of the ceiling panels was accompanied by slightly lower average temperatures, a more prominent difference being observable in the exhaust air temperature than in the individual near-wall temperatures. The former difference was typically approaching one degree Celsius, while the latter was in the order of 0.5°C. In the figures, these differences are superimposed on a further discernible variation which parallels the major ups and downs of measured outdoor temperature.

When the panels were in use, ceiling drywall surface temperature below the panels was elevated by about 3 to 5 degrees, as illustrated in Figure B.7. In this figure, and in Figure B.8, the vertical temperature differentials in the living room and bedroom are shown, indicating that vertical stratification was smaller when the overhead heating panels were being used, and, further, that the vertical temperature differentials were greater for both systems when the outdoor driving temperatures were lower. The typical one degree Celsius difference between head height and ankle height with the baseboards operating was replaced by a difference of about 0.5°C when the ceiling panels were the source of heat.

Figures B.9 and B.10 further exemplify the effect of the two heating systems on the balance between surface and air temperatures in the living space. The blended return air temperature at the HRV was close to the head-height temperature at the wall for both monitored rooms. In general, the ceiling panel system appears to have reduced temperature variation by keeping the air and near-floor temperatures closer together. This would be consistent with a radiative transfer of energy to the lower parts of the room from a ceiling being maintained at an elevated temperature. It should be noted that any such radiation could also have affected the action of the house's thermostats.

In Figures B.4(a) to B.10(a), the clarity of the observations is reduced by the effect of mid-day solar gain. On sunny days, the requirement for heating was reduced dramatically for several hours and normal stratification was disrupted by the sun's heating of the lower portions of the south-facing rooms of the house. The continuous mechanical circulation of air served to partially distribute the solar gain to the other parts of the house. The companion Figures B.4(b) to B.10(b) summarize the temperature effects for a daily twelve-hour period during which the sun remained below the horizon.

Figures B.11, B.12, B.13, and B.14 indicate in more detail the typical effects of the two heating systems on the interior environment. Shown are four different days when the outdoor driving forces were similar. In the figures, the zigzag nature of air temperatures is due to an interaction between the hourly averaging of data and the approximate 45 minute return period of the HRV's defrost cycle. Four times every three hours, average interior air temperatures were temporarily elevated by the recycling of interior air in place of outdoor supply air.

In summary, vertical stratification was reduced when the ceiling panels were providing the heating, temperatures near the floor being maintained closer to the average temperature of the air in the house. It is conceivable that occupant response could be influenced by differences of the magnitude observed in the figures (i.e., up to about one degree Celsius), and, as a result of the choice of thermostat settings, heating energy usage rates could also be affected.

B.4 ENERGY CONSUMPTION

For the period November 26, 1988 to March 31, 1989, operating temperatures and air flows in the bungalow were maintained at constant settings, while the source of heat on the main floor was alternated between the ceiling panels and the perimeter baseboards. During this period, approximately 48 percent of the electricity consumed in the house was provided to the basement baseboard heaters, 45 percent was expended through the dual heating system on the main floor, and approximately 7 percent, or about an average of a continuous 300 W, was used by the HRV and a few light bulbs. The only energy supplied to the water heater during this time was that used during a brief late March 1989 test of the unit, prior to first occupancy. Figures B.15 and B.16 show the hourly expenditures of electricity in the house over the four-month winter period.

Because of the strong degree of control over house operation which was effected during the monitoring period, all fluctuations appearing in Figures B.15 and B.16 may be considered to be due only to the reaction of the house and its energy systems to the forcing environment. Outdoor temperature is the major influence on heating load during mid-winter in the geographical vicinity of the test house, with a very high correlation between temperature and residential heating energy usage being typical. For the intervals of baseboard and ceiling panel heating in the monitored house, daily heating energy vs. temperature relationships are shown in Figures B.17 and B.18. The figures indicate that for the same daily average outdoor temperature, the ceiling panel system in the test house would have used more electricity than the baseboard heating system to maintain an identical thermostat setting.

To determine whether exterior environmental influences other than temperature (e.g., incident solar radiation) may have had a non-uniform effect on energy requirements during the alternating trials, comparisons were also made for different subsets of the five monitored intervals with baseboards operating and the six with ceiling panels operating. Regression outcomes varied slightly among the combinations examined, as expected, but consistently indicated greater consumption for the ceiling panels in the range of sub-freezing temperatures.

In Figures B.19 and B.20, the regression results for the full four-month period are summarized. The latter figure indicates that all other energy consumption patterns in the house (i.e., primarily the heating done by the basement baseboard units) other than those of the dual heating system were insignificantly affected by the flip-flop operation. It may therefore be assumed that the basement heating system contributed to space heating in the same way for both of the main floor heating systems.

The difference in power requirements shown in Figure B.19 is about 7.0 percent at -40°C, 5.9 percent at -20°C, and 3.1 percent at 0°C. The regression lines cross at 7.3°C. For a heating season with long-term normal Winnipeg temperatures from October 1 to April 30, the additional energy used by the ceiling panel system would be approximately 4.6 percent, compared to that estimated for the companion baseboard heating system.

B.5 DISCUSSION

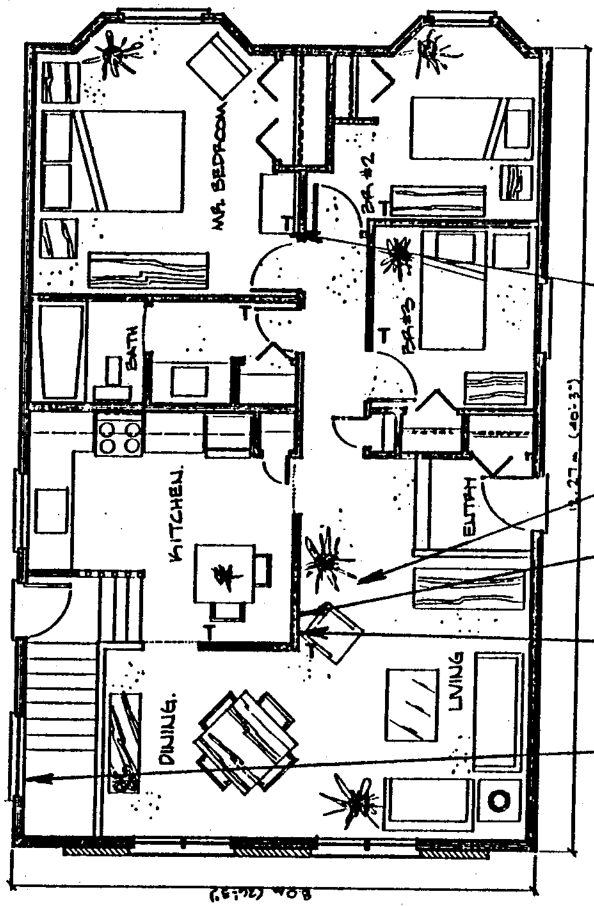
Back losses from the ceiling panels are a possible contributor to the greater electricity consumption observed with that system. The quantitative difference in performance observed should not, however, be taken directly as a measure of the difference in seasonal efficiency between the two systems. Interior temperature settings were maintained constant during the test period, but the interior environment, including surface temperatures, which resulted from heating system operation was somewhat different in the two cases. It is conceivable that the increased uniformity in temperatures which was shown to accompany operation of the ceiling panel heating system could also affect an occupant's choice of thermostat settings.

A study of the effects of a hydronic radiant floor heating system done at the Alberta Home Heating Research Facility (Dale and Ackerman, 1989) provides an interesting complement to the results reported herein. A slightly lower energy consumption observed for the comparison electric forced air heating system was thought to be due to a combination of (a) higher losses from the basement floor which operated at a 3 to 5 °C temperature premium when the panels were drawing and (b) higher losses from the ceiling which was also maintained at an elevated temperature during panel operation.

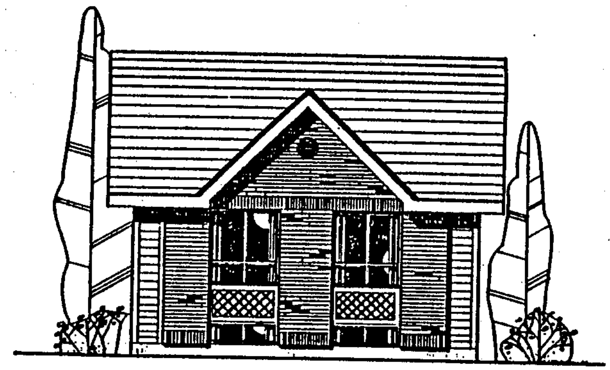
Vertical temperature distributions were concluded in the Alberta study to be sufficiently similar for the two systems that occupant behaviour was not expected to be affected differently. With respect to this result, it was noted that temperature profiles in the Alberta experiment may have been influenced by the fact that interior circulation of air was mechanically induced by the forced air furnace when it was running and was uncontrolled when the floor panels were providing the heat.

B.6 REFERENCE

Dale, J. D., and M. Y. Ackerman, "A Comparison of Radiant Floor and Forced Air Heating", 15th Annual Conference of the Solar Energy Society of Canada, Penticton, British Columbia, June 1989.



(note: house was unfurnished during heating system trials)



TBh, TBl	central partition wall, NW bedroom, 1.8 m and 0.15 m above floor, shielded
TLp	ceiling in living room, near central partition, below heating panel
TLv	supply air arriving in living room, central partition wall high sidewall vent, 2.3 m above floor
TLh, TLl	central partition wall, living room, 1.8 m and 0.15 m above floor, shielded
TLw	interior surface of west-facing dining room window, no overhang
Tam	located at ventilation air inlet grille (outdoor temperature)
Tsa	supply air leaving the HRV
Txa	exhaust air entering the HRV
T	thermostat

Figure B.1 Key to Monitored Points: Dual Heating System Comparison, House 24, Winnipeg

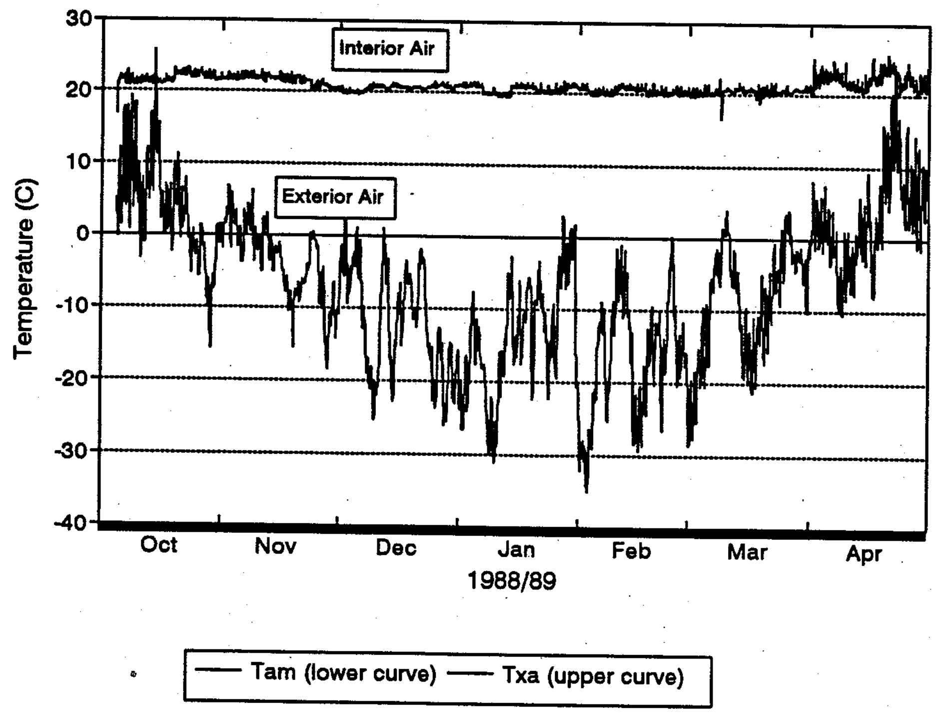


Figure B.2 Hourly Air Temperatures, House #24

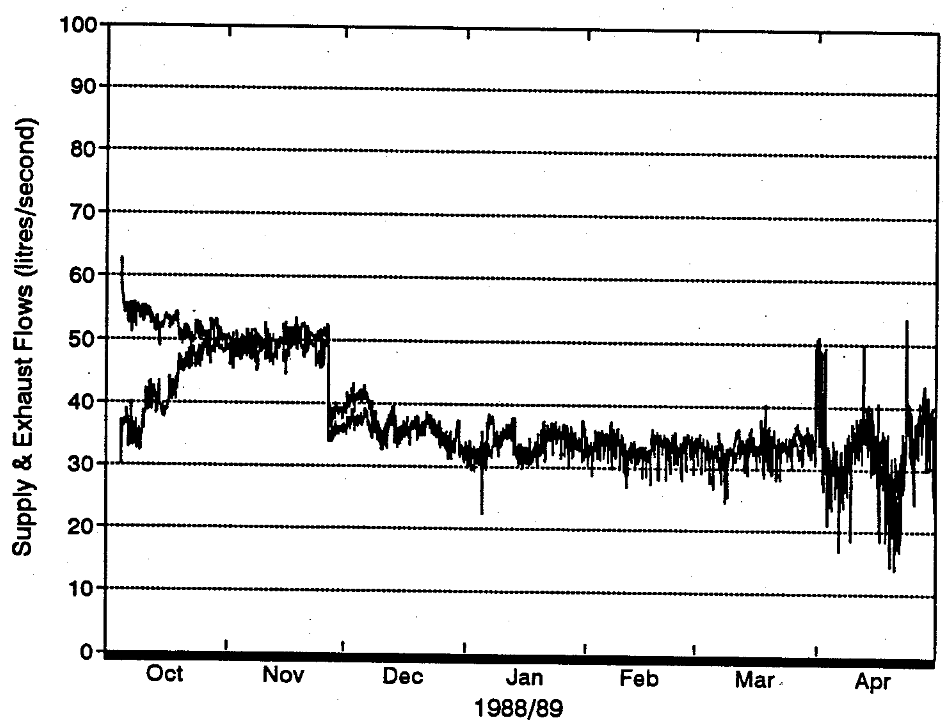
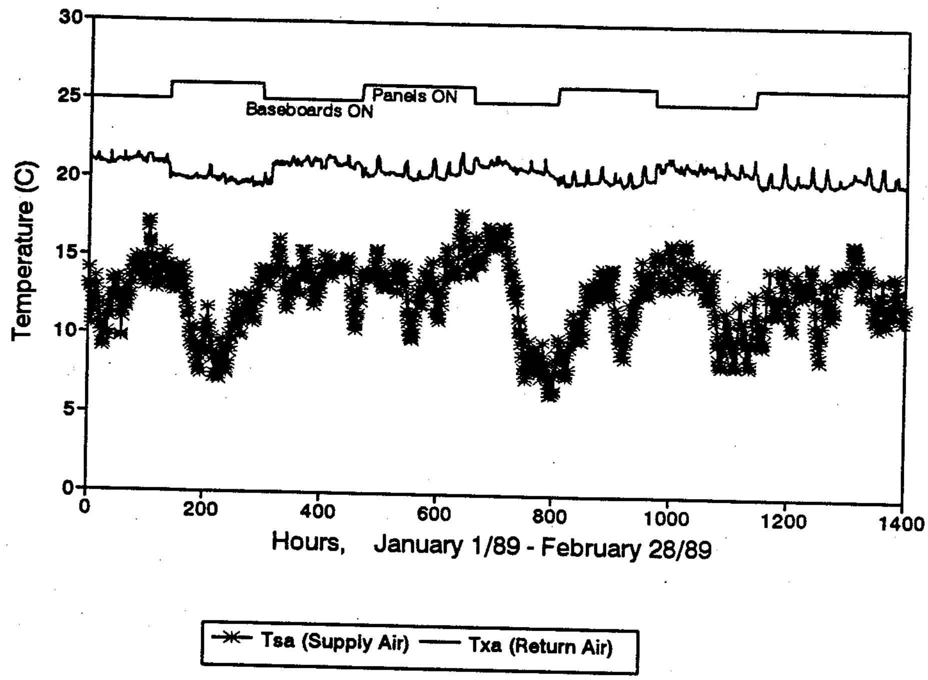
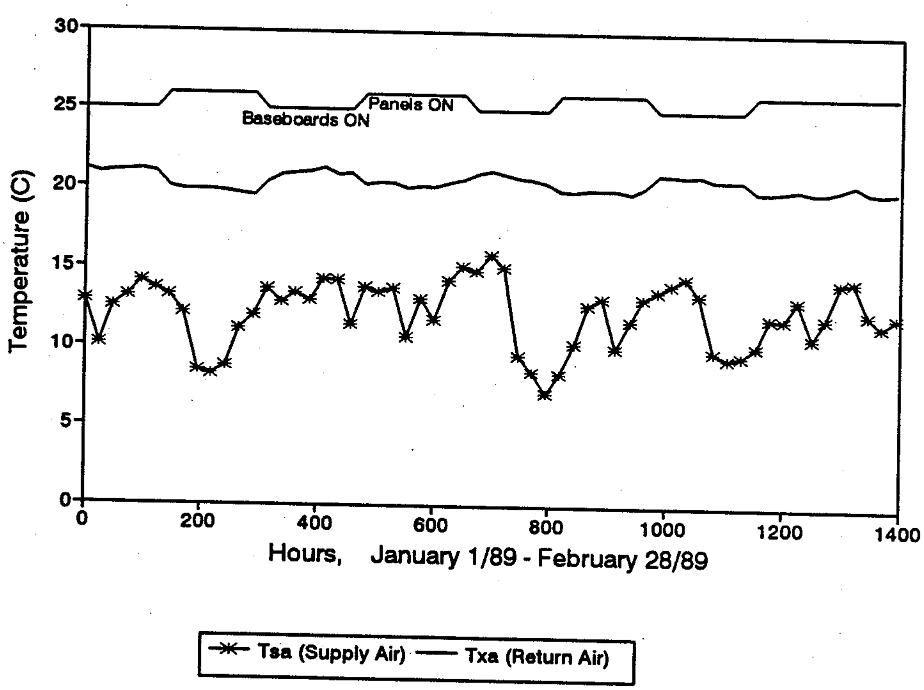


Figure B.3 Hourly Ventilation Rates, House #24



(a)



(b)

Figure B.4 Ventilation System Air Temperatures, House #24
(a) Hourly; (b) Average Between 19:00 and 07:00.

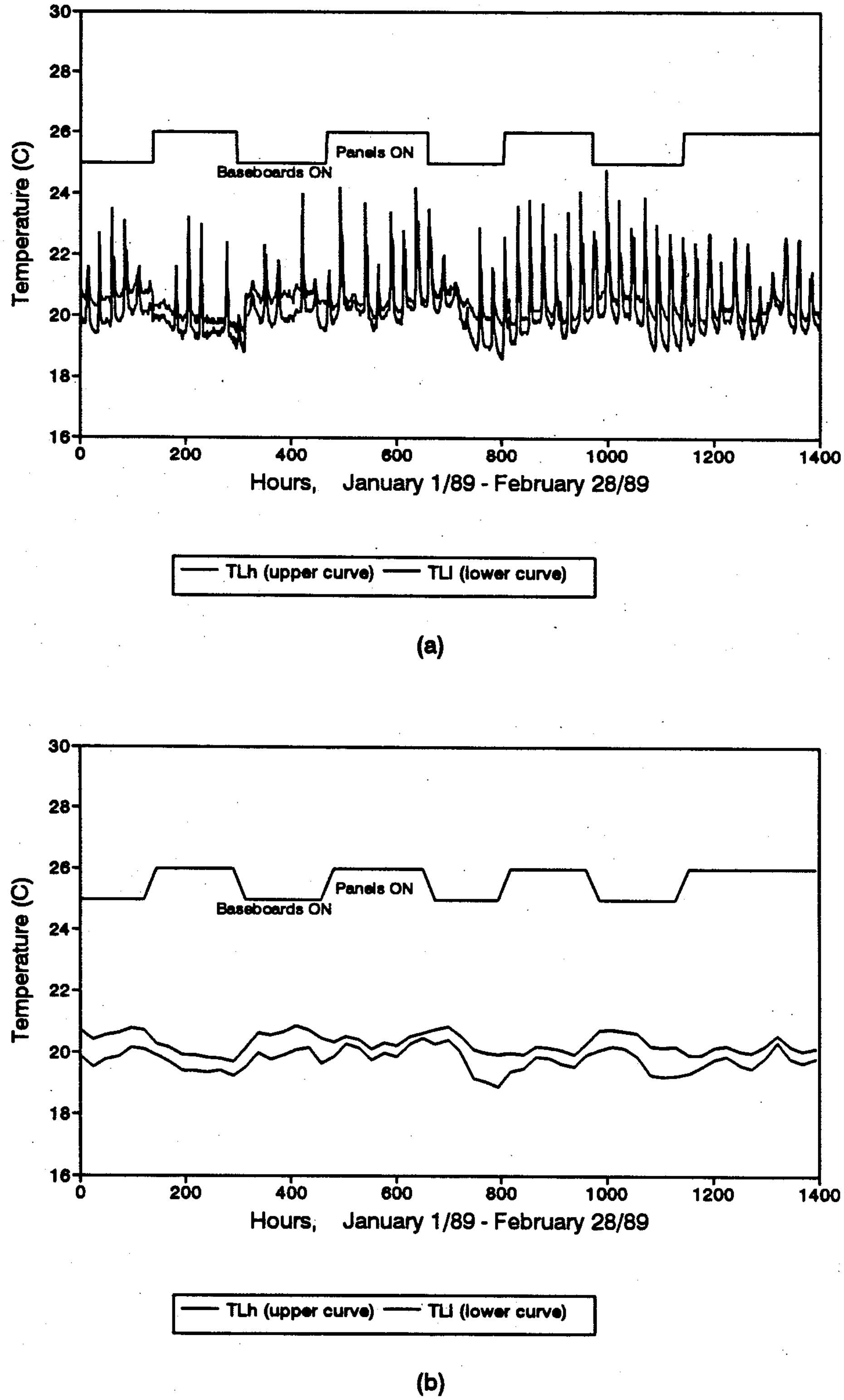
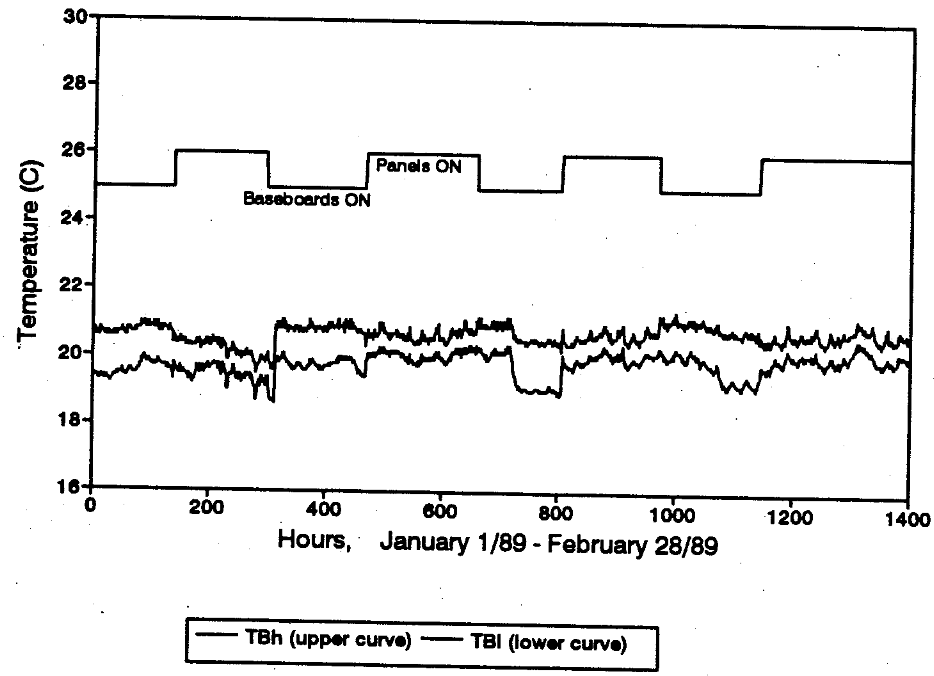
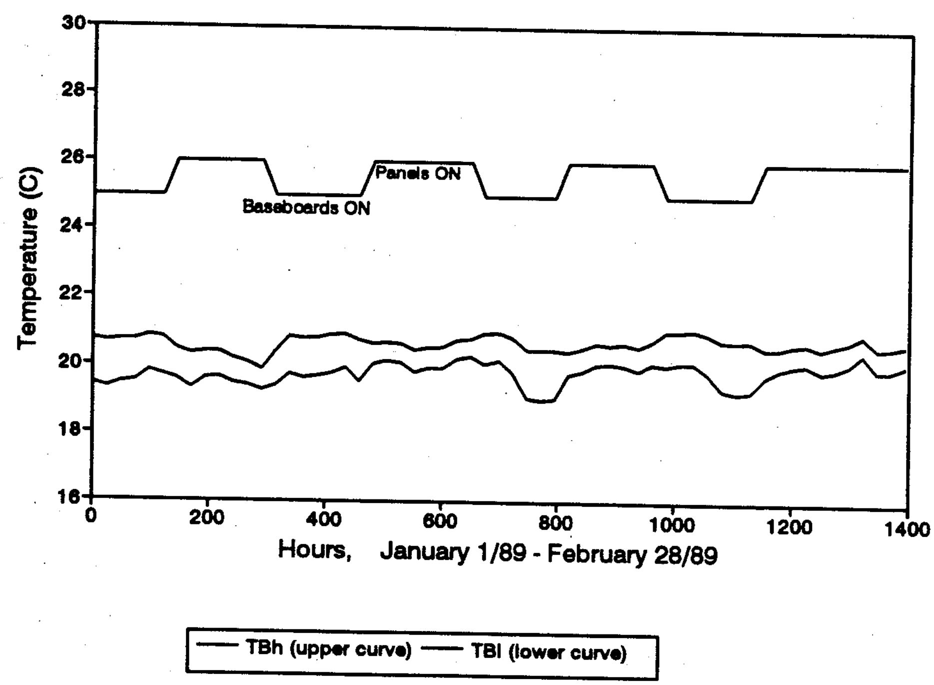


Figure B.5 Living Room Temperatures, 1.8 and 0.15 m Above Floor: (a) Hourly; (b) Average Between 19:00 and 07:00.

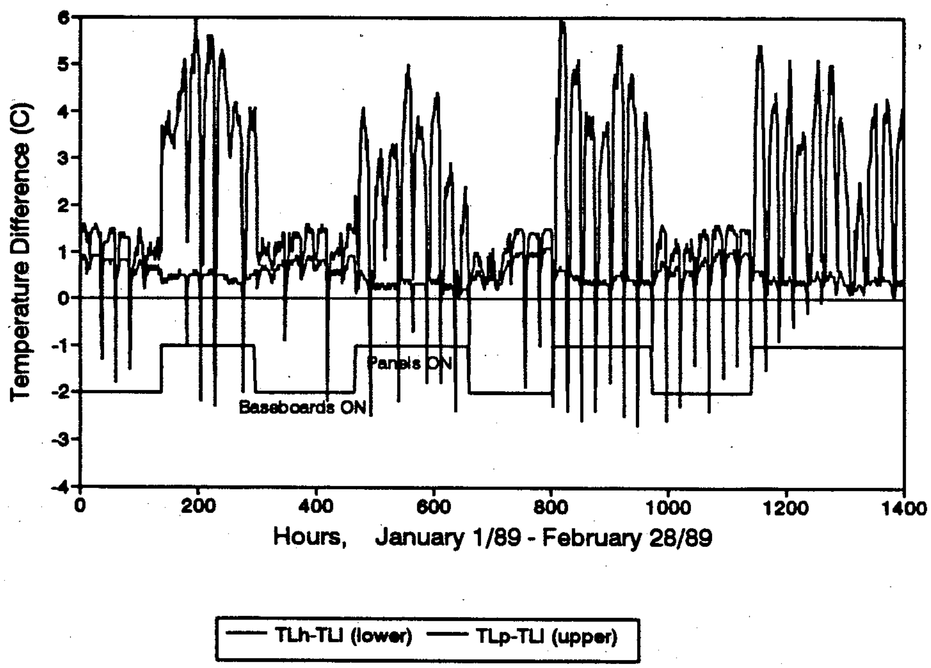


(a)

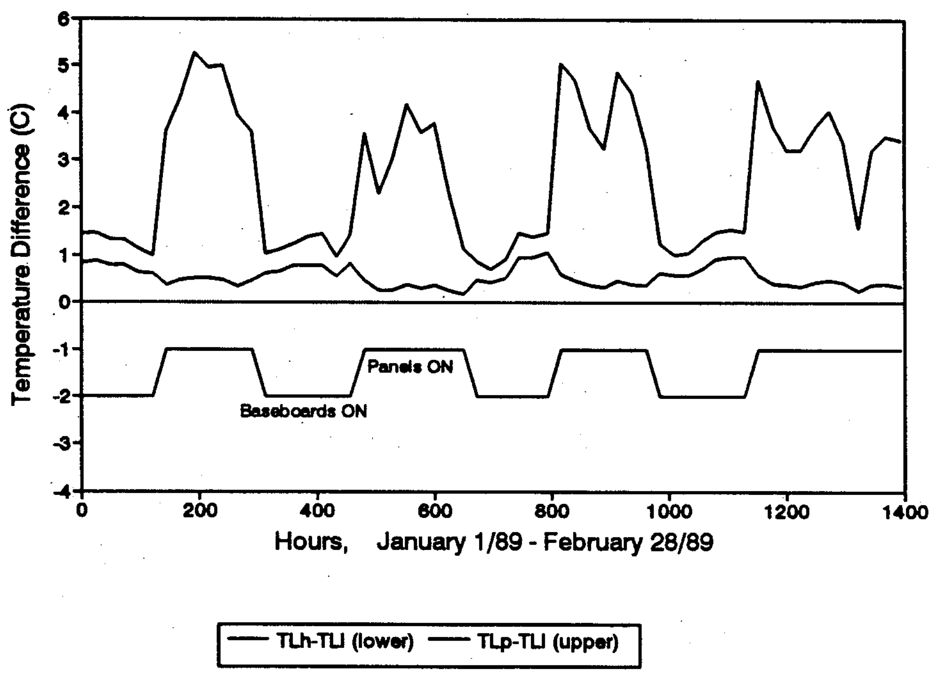


(b)

Figure B.6 NW Bedroom Temperatures, 1.8 and 0.15 m Above Floor: (a) Hourly; (b) Average Between 19:00 and 07:00.

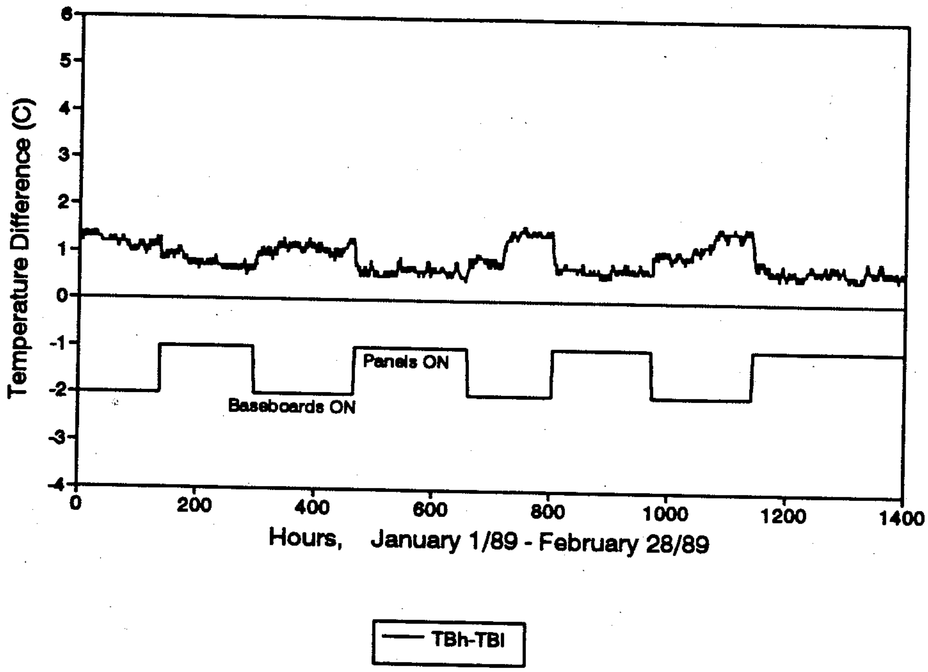


(a)

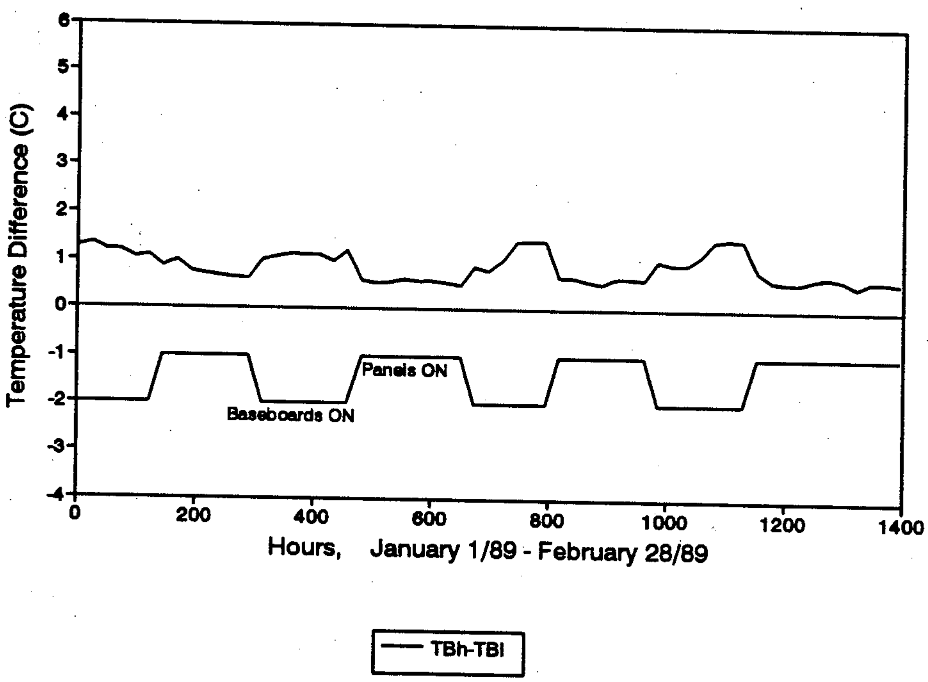


(b)

Figure B.7 Living Room Temperature Stratification:
(a) Hourly; (b) Average Between 19:00 and 07:00.

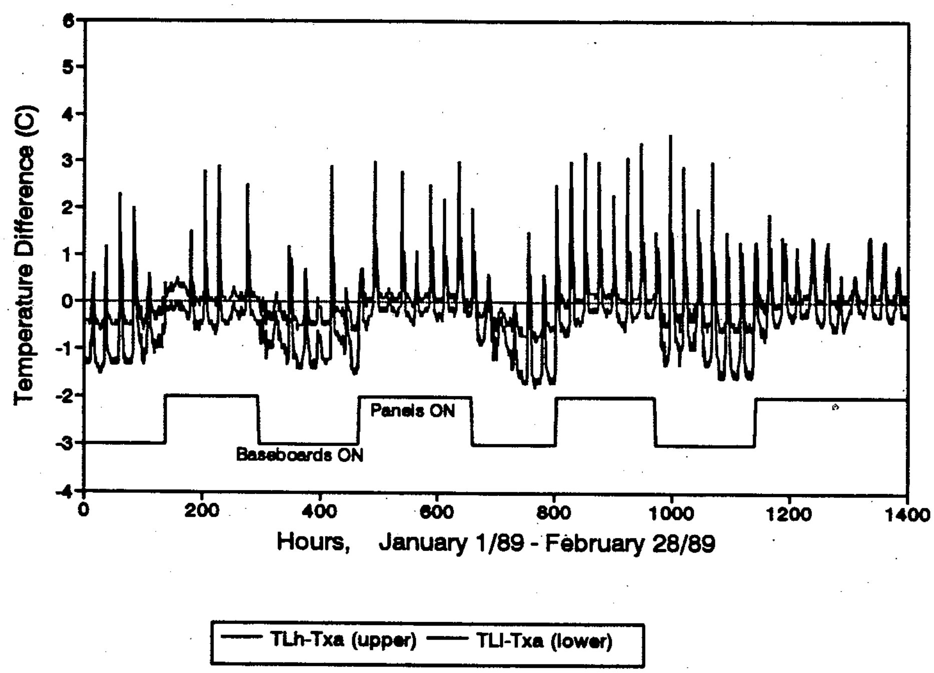


(a)

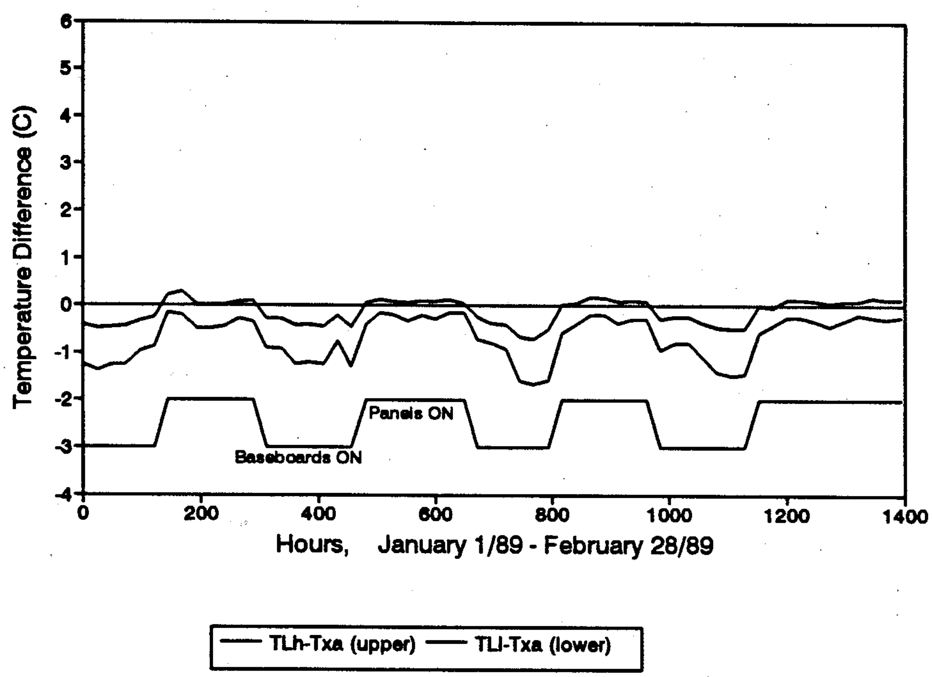


(b)

Figure B.8 NW Bedroom Temperature Stratification:
(a) Hourly; (b) Average Between 19:00 and 07:00.

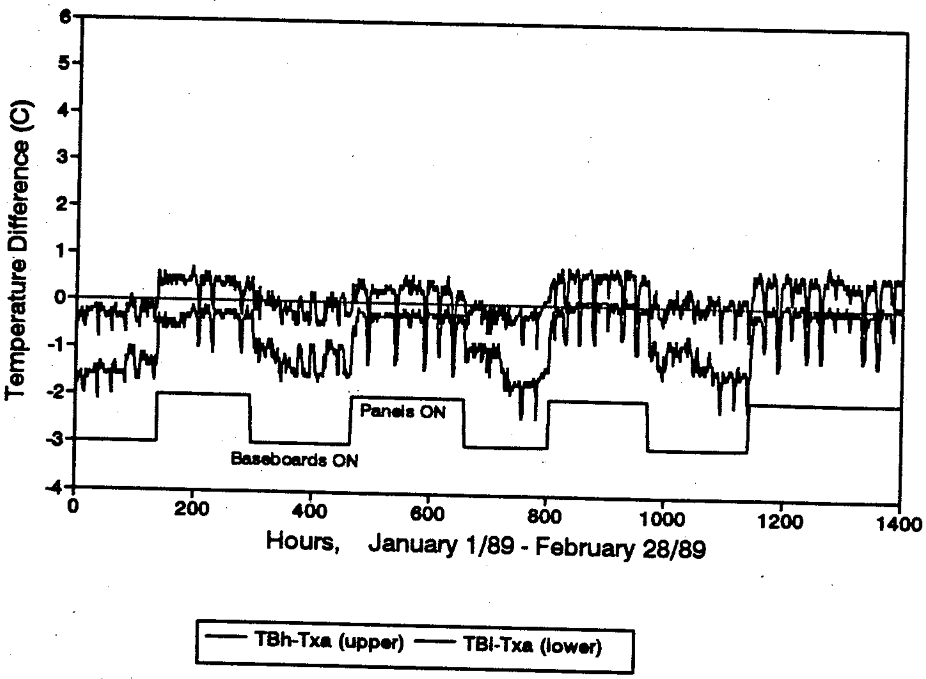


(a)

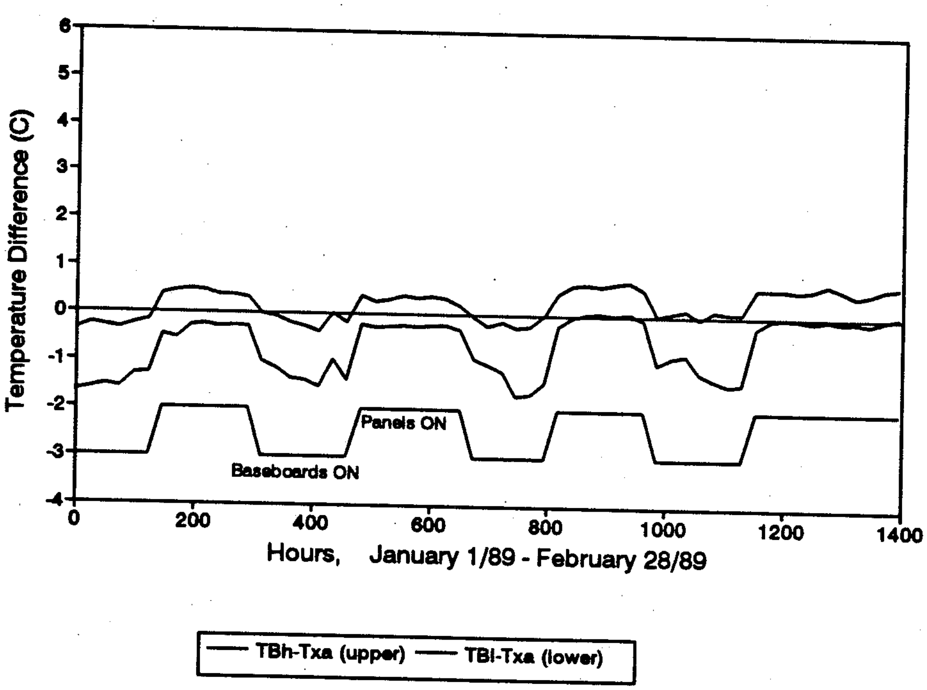


(b)

Figure B.9 Living Room Temperature Balance:
(a) Hourly; (b) Average Between 19:00 and 07:00.



(a)



(b)

Figure B.10 NW Bedroom Temperature Balance:
(a) Hourly; (b) Average Between 19:00 and 07:00.

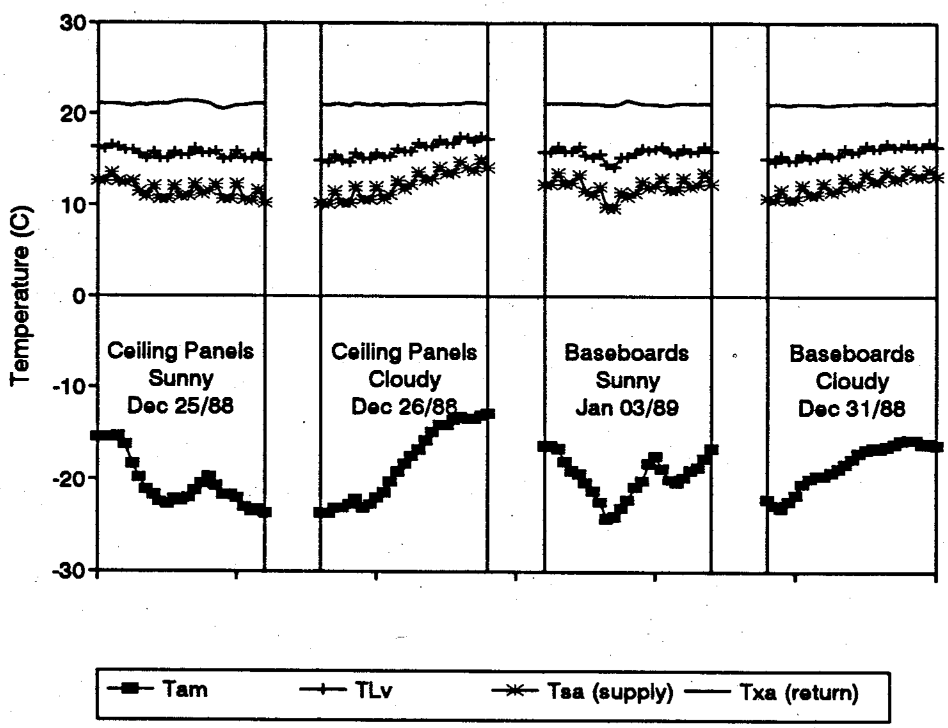


Figure B.11 Hourly Operating Air Temperatures on Four Typical Days

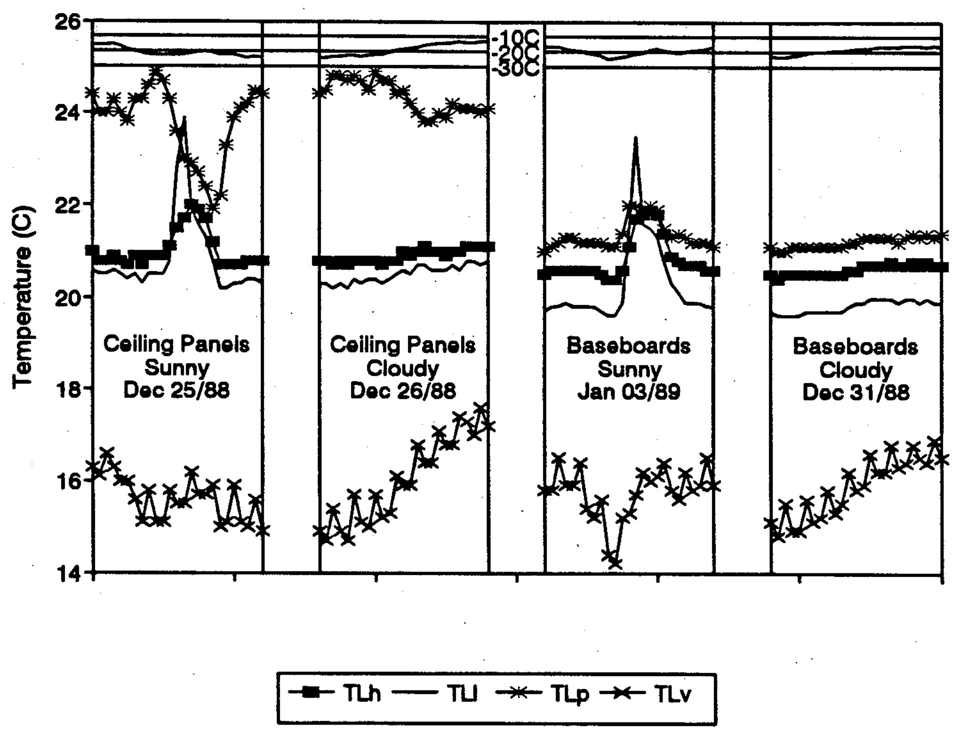


Figure B.12 Hourly Living Room Conditions on Four Typical Days

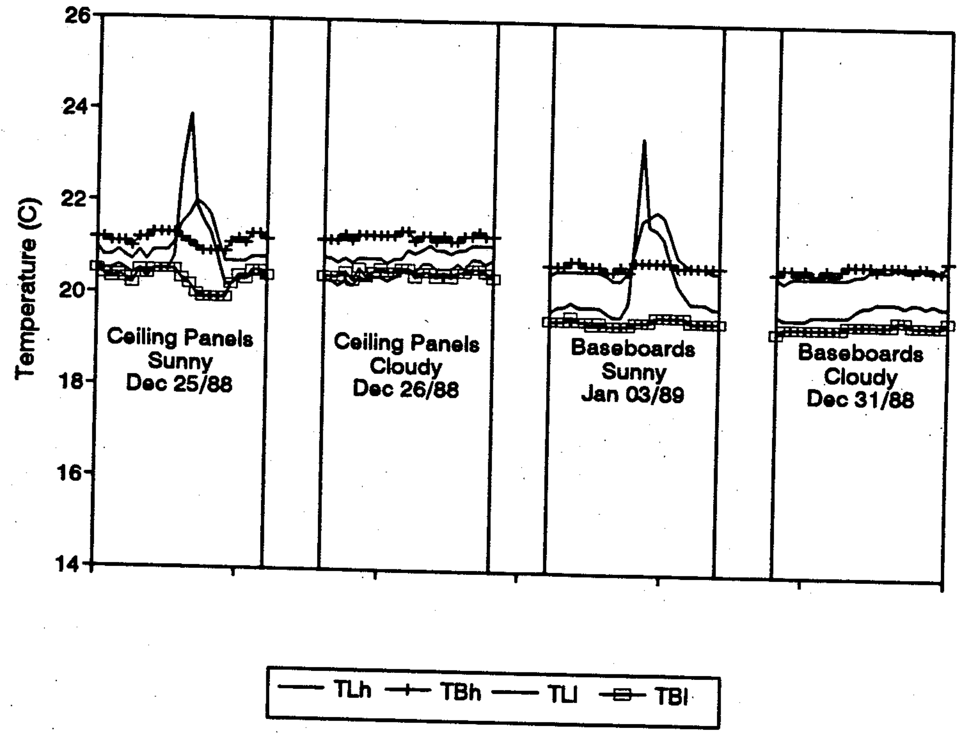


Figure B.13 Hourly Room Temperatures on Four Typical Days

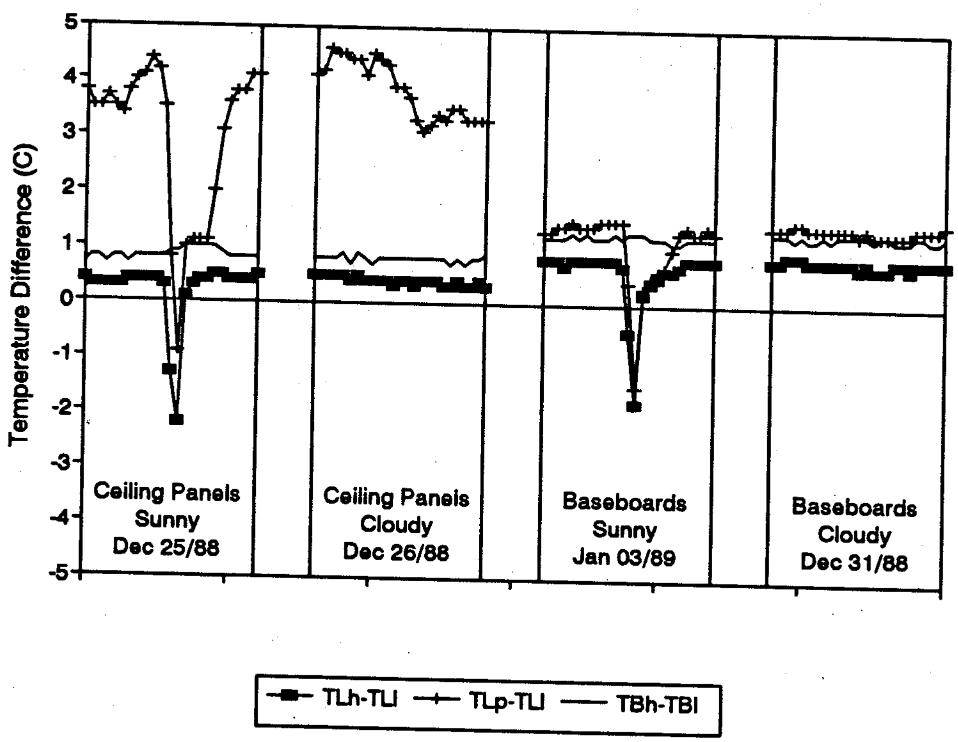


Figure B.14 Room Temperature Stratification on Four Typical Days

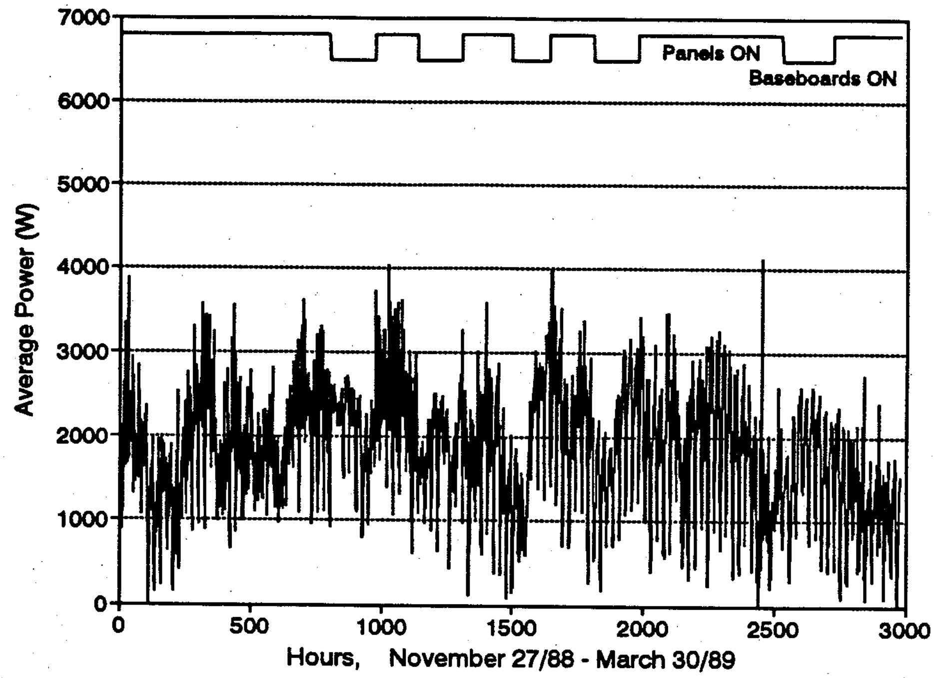


Figure B.15 Hourly Mean Power Usage by Main Floor Heaters Only

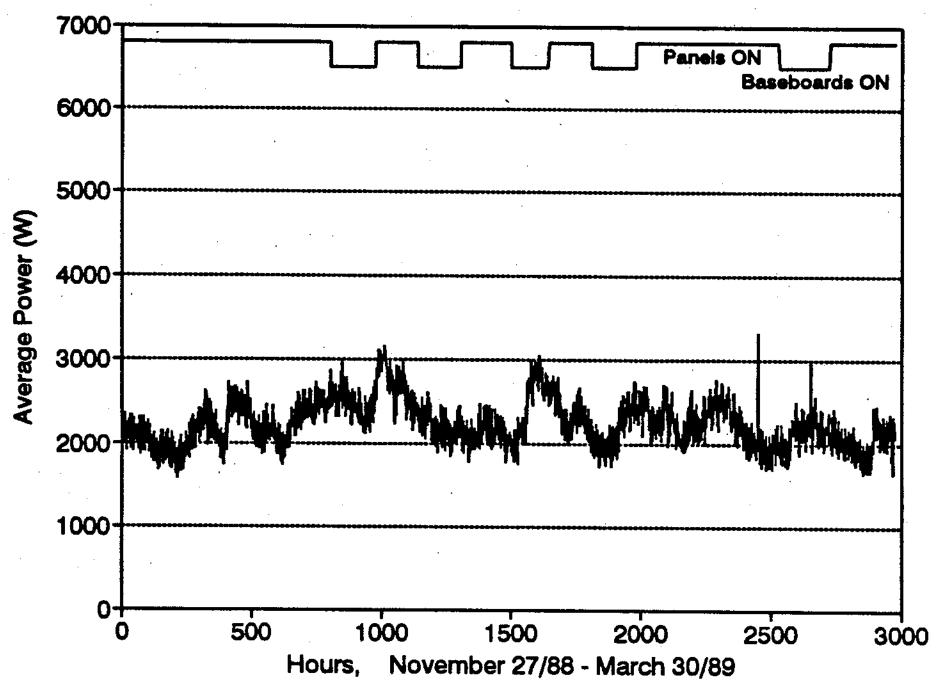


Figure B.16 All Power Usage Other Than by Main Floor Heaters

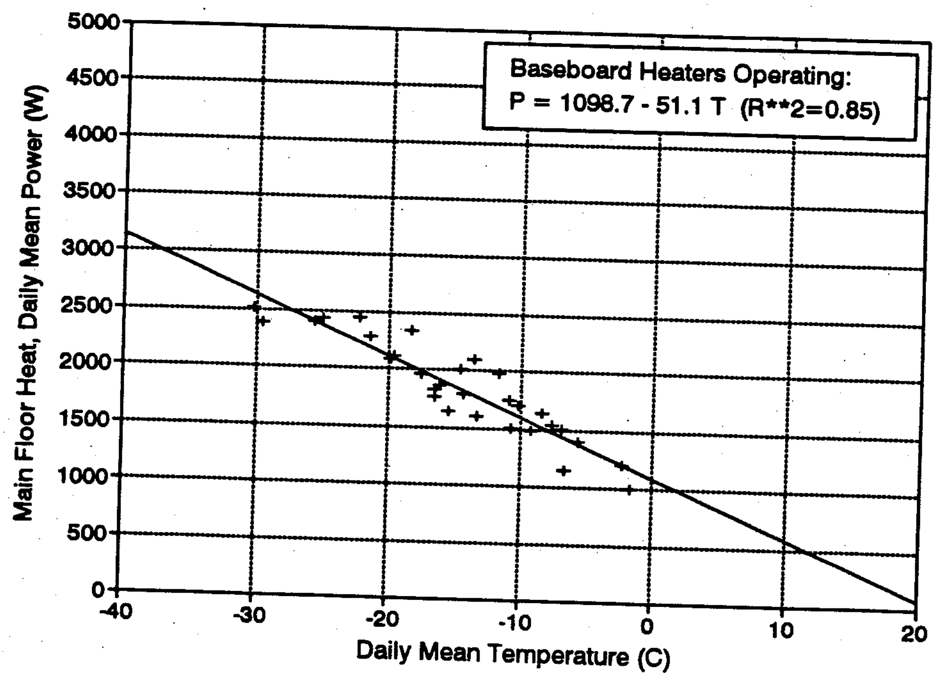


Figure B.17 Power/Temperature Correlation: Baseboard Heaters

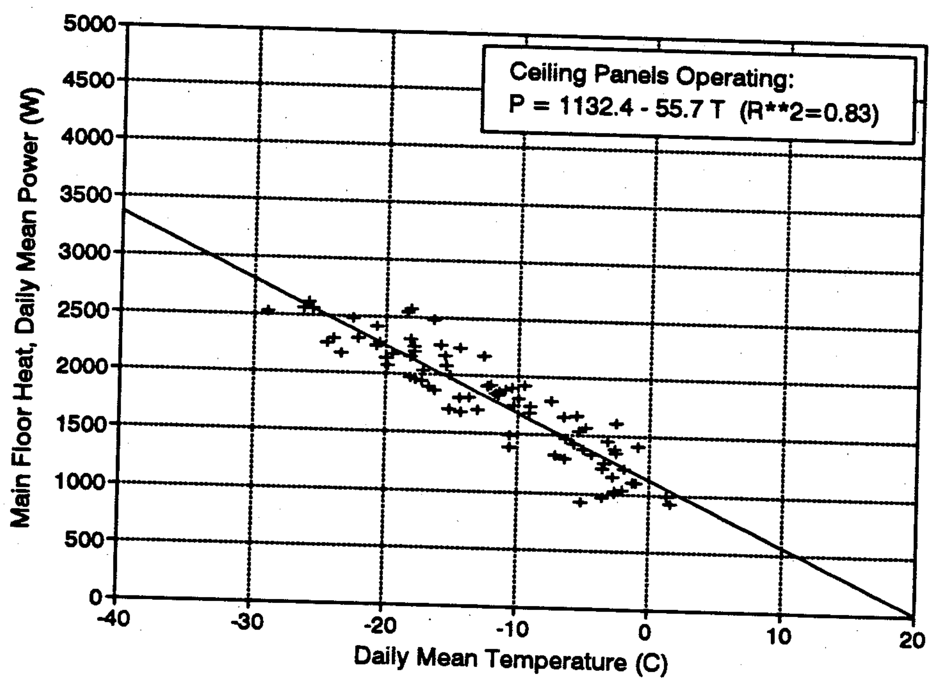


Figure B.18 Power/Temperature Correlation: Ceiling Panels

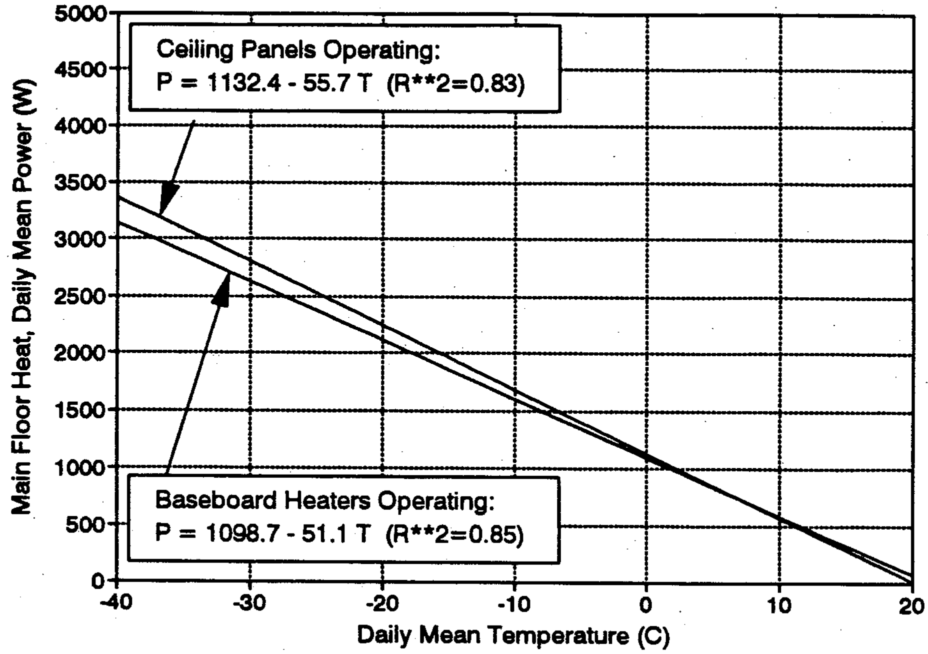


Figure B.19 Correlation Summary: Main Floor Heaters

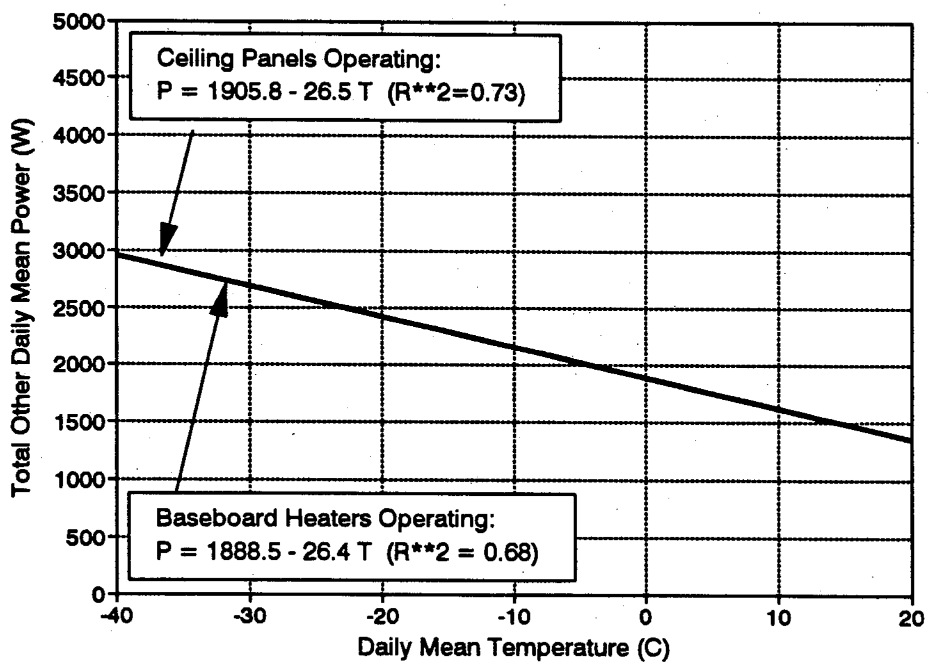


Figure B.20 Correlation Summary: All Other Power Usage