
Commissioning Twin Houses for Assessing the Performance of Energy-Conserving Technologies

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ABSTRACT

In 1998, twin houses were built at the Canadian Centre for Housing Technology in Ottawa to assess the energy performance of new and innovative energy-efficient materials and components for houses. The two research houses are identical energy-efficient houses, typical of tract-built models available on the local housing market. They also feature identical simulated occupancies based on home-automation technologies and are monitored for energy performance and thermal comfort. The simulated occupancy controls turn major appliances, lighting, and equipment on and off. The houses were commissioned in the winter and spring of 1999 and benchmarked in the next heating season. This paper records the energy features of the houses and commissioning results. With the benefit of detailed monitoring of energy systems in both houses, many of the anomalies in component operation and controls were found and fixed. These anomalies could easily go undetected in regular houses.

INTRODUCTION

The concept of side-by-side testing of whole house performance is not new. Four side-by-side houses were built in the suburbs of Ottawa in 1977 (Quirouette 1978) and monitored extensively for a number of years (Brown 1980). The energy efficiency measures being assessed in that project were initially built into the houses. The project assessed the total impact of design packages involving many different energy upgrades in each house. This is in contrast to the current facility, which was designed to assess individual technologies separately. As well, the original houses were initially unoccupied and later occupied by different families—both situations being problematic for realistic assessments of the technology packages. Later, two pairs of identical U.K. and Swedish prefab houses were built in the U.K. (Rayment et al. 1993, 1997). Initially, these were initially identical and featured automated controls based on laboratory control techniques to regulate energy usage inside the houses. Although these houses were successful in assessing individual energy-conserving measures, these houses were not typical of North

American style houses (e.g., only 84 m² liveable area and no basement) and operated in the moderate U.K. climate.

In 1998, twin houses were built at the Canadian Centre for Housing Technology to assess the energy performance of new and innovative energy-efficient materials and components for houses in the Canadian context. The two research houses—the *reference house* and the *test house*—were built to a design submitted by a local builder for the project. The houses are typical in construction, appearance, and layout of tract-built houses available on the local housing market. They are identical and are built to the R-2000 standard—Canada's benchmark for energy-efficient house design. They have approximately 210 m² of liveable area and feature a full basement and a two-car garage.

The research houses also feature standard sets of major appliances typically found in North American homes. A system based on home automation technology simulates human activity by operating appliances, lighting, and other equipment according to an identical schedule in both houses. The simulated occupancy system is also used to monitor energy performance.

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TABLE 1
Selected Characteristics of the Houses

Component	Characteristic
Construction standard	R-2000
Stories	2
Liveable area	210 m ²
Basement	Poured concrete, full basement.
Garage	Two-car, recessed into the floor plan; isolated control room in the garage
Attic	RSI 8.6
Walls	RSI 3.5
Rim joists	RSI 3.5
Exposed floor over the garage	RSI 4.4 with heated/cooled plenum air space between insulation and subfloor.
Basement walls	RSI 3.5 in a framed wall. No vapor barrier.
Basement floor	Concrete slab, no insulation
Windows	Low-e, insulated spacer, argon filled, with argon concentration measured to 95%.
Window area	South facing: 16.2 m ² Total: 35.0 m ²
Air barrier system	Exterior, taped fiberboard sheathing with laminated weather resistant barrier. Taped penetrations, including windows.
Airtightness	Reference 1.07 ach @ 50 Pa; Test House 0.97 ach @ 50 Pa
Heat recovery ventilator	High efficiency (84% nominal)
Furnace	Condensing gas @ 91% efficiency (as measured)
Hot water heater	Conventional, induced draft @ 67% efficiency (as measured).
Air conditioning	High efficiency - SEER 12 (nominal)

This paper describes the commissioning process of the twin research houses, highlighting the main elements that were found to be different from a thermal performance point of view and needing correction. Performance benchmark characteristics were developed against which energy-saving devices could be rated in side-by-side comparisons.

Description of the Test and Reference Houses

The two houses were built side by side in the fall of 1998. The same trades built the houses by stages in sequence from one house to the other (e.g., footings were poured in one house, then the next, then basement walls, etc.). The houses were never more than two weeks apart in the construction process at any point in time. Construction was stopped at the pre-drywall stage for 2 ½ weeks to allow the installation of over

TABLE 2
List of Meters Installed in Each House

Electric Meters		Gas Meters	
1	Heat recovery ventilator	1	Furnace
2	Furnace	2	Hot water heater
3	Dishwasher		
4	Clothes washer	Water Meters	
5	Refrigerator	1	Main (entire house)
6	Air conditioner	2	Second floor
7	Dryer	3	DHW
8	Stove	4	Kitchen sink
9	Main panel	5	Dishwasher
10	Lights & receptacles		
11	Control room		
12	Exterior lights		
13	Brown plates (Monitoring)		
14	DHW power vent fan (added)		

250 sensors in each house. Twenty-one electric, gas, and water flow meters were also installed. The houses were completed in January 1999. We refer to one house as the *reference house*, which is intended to remain unchanged through the various experiments at the facility. The second house is referred to as the *test house*, in which different energy-efficient technologies are assessed. The technologies are always installed in such a way that the test house can be returned to the original configuration, which we refer to as the *benchmark configuration*. Table 1 lists selected characteristics of the two houses, and Table 2 lists the meters installed.

The *reference house* is a typical two-story wood-frame house, with 210 m² of liveable area, set on a cast-in-place concrete basement, with style and finish representative of current houses available on the local housing market. The house is built to meet the R-2000 Standard with a package that includes tight, well-insulated assemblies, low-e argon-filled sealed glazing units. It has a high-efficiency sealed combustion condensing gas furnace, a power-vented conventional hot water heater, and a heat recovery ventilator. The furnace, water heater, and gas fireplace are all vented through the wall, eliminating the need for chimneys. The house has an airtightness characteristic of 1.07 ach @ 50 Pa—well below the R-2000 requirement of 1.5 ach @ 50 Pa. The monitoring and control room is located in an isolated room built in the garage with special conduits leading to each floor to run wiring. The conduits were sealed on completion of the wiring. The *test house* was notionally identical to the *reference house*, but this had to be verified through the commissioning process. For example, its airtightness characteristic was 0.97 ach @ 50 Pa—10% lower than the reference house. We needed to



Figure 1 Twin research houses.

determine how this and a whole host of other factors would affect the overall thermal performance of each of the houses.

After a first round of commissioning and benchmarking, the test house was modified to incorporate several heating systems by incorporating a split plenum with dampers in the forced air distribution system. The benchmark was unchanged by this adaptation, as verified in subsequent weeks of benchmarking. A network of piping and valves was also developed to accommodate several water heaters. The houses are shown in Figure 1.

Data Collection

Four sets of data were collected during the test period. These were:

1. The main data set of approximately 250 sensors (mostly temperatures and RH) collected to keep track of operating conditions inside and out. Data were saved on an hourly basis, and a selected set was saved every 5 minutes.
2. Utility meter readings (2 gas meters, 14 electric meters, and 5 water flow meters—data stored hourly (see Table 2).
3. Weather data from a weather station situated about 350 m north and west of the houses (hourly).
4. Detailed heating equipment performance indicators were monitored separately by our research partners (not reported here).

Simulated Occupancy Controls

The houses are equipped with sophisticated home-automation technologies, which operate lighting, plumbing, and major appliances (stove, washer, dryer, and dishwasher). Generating the equivalent amount of heat with lamps simulates heat release associated with occupant presence and the operation of small appliances. The system features a combination of off-the-shelf home automation control modules and some unique custom adaptations by the consultant. For instance, the available clothes washer featured conventional

mechanical dial settings and timers, which had to be adapted for electronic controls. This proved to be the most troublesome unit to debug completely because of this uneasy marriage of old and new technologies. In contrast, the dishwasher had electronic controls in which simple pulses could be used to activate and reset. This system of simulated occupancy was designed to be identical and synchronized in both houses. A target of 20 kWh per day of electricity consumption was set, which corresponds to an accepted standard used for modeling energy systems in houses (Swinton and Sander 1992). As is explained below, the target was overshoot by a considerable margin, and some adjustments were made. The simulated occupancy schedule is in Table 3.

ANALYSIS APPROACH

The analytical approach commonly used in side-by-side monitoring consists of comparing the energy performance of one building against the other for selected time intervals over a selected period of time. The time interval is typically one day, as used in the BRE Test Houses in the U.K. (Rayment 1998), and in Oakland for side-by-side office testing (Lee et al. 1998). Each day is considered to be a separate experiment in which an identical sequence of events occurs both within the house (using the simulated occupancy) and outdoors (weather). The results are reported on a graph of daily results, on which the consumption of one house is plotted against the other. Through varying exterior conditions, a plot is developed of these daily experimental results over time, and a statistical relation is found between the operating characteristics of each house. An example of such a graph is shown in Figure 2, which is discussed later in the paper. Although the technique is deceptively simple, a number of key factors require careful consideration:

- The houses cannot simply be assumed to be identical, and calibration is essential. The assessment of innovative technologies requires a characteristic benchmark line—a performance characteristic relating the test house performance in its benchmark configuration to the reference house performance, for all cases. The technology that is assessed in the test house is, therefore, not compared directly to that of the reference; rather, it is compared to the performance of what the benchmark equipment would be in the same house under the same conditions. The distinction is important if the houses turn out not to be perfectly identical, as was the case for the hot water consumption discussed below. The development of benchmark characteristics allows for slight differences between the houses, without affecting the accuracy of the assessment of a technology.
- The period chosen for analysis (e.g., 24 hours) and the time of day chosen for start and end of the 24-hour period have an influence on the scatter of the result. For example, plots prepared of the same data on a morning-to-morning basis had different scatter than plots produced on an afternoon-to-afternoon basis. Time lag in

TABLE 3
Simulated Occupancy Schedule

Overnight			
Electric & Gas	Water Utility	Time	Duration
Master bedroom humans		0:00	6 h 45 min
Bedroom 2 humans		0:00	6 h 45 min
Morning			
Electric & Gas	Water Utility	Time	Duration
Hall thermostat		6:30	16 h 30 min @ 21°C
2 nd floor lights		6:45	60.0 min
	1. Master bedroom shower	6:50	10.2 min
Family room/Kitchen humans		7:00	60.0 min
Kitchen products 1		7:00	10.2 min
Main floor lights		7:00	60.0 min
Kitchen fan		7:30	10.2 min
Kitchen stove and oven		7:30	20.0
Living room blinds		7:30	Open
	2. Kitchen tap	7:45	3.0 min
Afternoon			
Electric & Gas	Water Utility	Time	Duration
Kitchen fan		12:00	15.0 min
Kitchen stove and oven		12:00	15.0 min
Family room/Kitchen humans		12:00	30.0 min
Kitchen products 1		12:00	10.2 min
Main floor lights		12:00	15.0 min
	3. Kitchen tap	12:30	3.0 min
Evening			
Electric & Gas	Water Utility	Time	Duration
Basement lights		16:30	45.0 min
	4 and 5. Clothes washer	17:00	45.0 min
Outside lights		17:00	7 h
Kitchen fan		17:30	3.6 min
Kitchen stove and oven		17:30	30.0 min
Family room/Kitchen humans		17:30	2 h 30 min
Kitchen products		17:30	10.2 min
Main floor lights		17:30	2 h 30 min
Dining room products		18:00	2 h
2 nd floor lights		18:00	2 h
	6. Kitchen tap	18:30	6.0 min
	7. Dishwasher	19:00	40.0 min

TABLE 3 (Continued)
Simulated Occupancy Schedule

Dryer		19:00	25.2 min
Living room humans		19:00	2 h
	8. Main bathroom bath	20:00	4.8 min
Bedroom 2 humans		21:00	3 h (continued next day)
	9. Master bedroom	22:30	15.0 min
Master bedroom humans		23:00	1 h (continued next day)
Hall thermostat		23:00	7 h 30 min @ 21°C
Continuous (not controlled by simulated occupancy)			
Living room blinds		0:00	Horizontal position
HRV fans		0:00	24 h
Furnace fan		0:00	24 h
Standby load (basement)		0:00	24 h
Refrigerator		0:00	Cycles on its own controls
Outside lights		photocell	hours of darkness

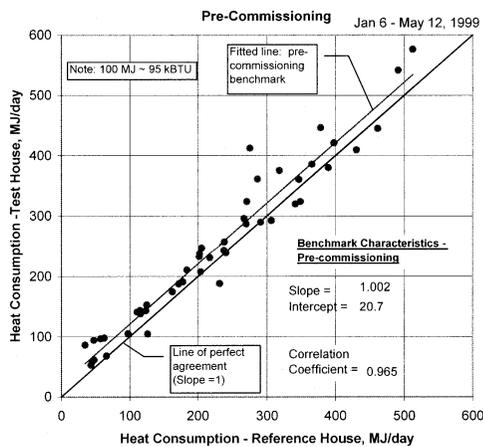


Figure 2 Precommissioning benchmark data for space heating and statistically fitted line.

the building's energy system, the cyclic nature of heating system operation, as well as the scheduled events during the day, all can carry the effects caused by events in one 24-hour period to show up in the next. These effects are not necessarily synchronized between the houses. Meter accuracy and consumption have an effect on the scatter as well. A 24-hour midnight-to-midnight analysis was shown to minimize these effects. This period of analysis could be revisited for assessing systems that would involve thermal mass, where lag effects might require longer periods of analysis.

- Meter resolution also needs to be considered when setting the period of analysis. For instance, our electric meters were originally specified with a resolution of one

kilowatt-hour. This was sufficient for analysis of overall house consumption, but for the analysis of daily consumption of smaller appliances, such as the dishwasher (with the drying cycle turned off), the truncation error of the meter was the same order of magnitude as the consumption. As a result, the minimum period of analysis for consumption comparisons of individual appliances was found to be at least a week. A plan for the replacement of all electrical meters with units that are accurate to the third of a watt-hour was underway at time of writing. This will allow hourly comparisons of consumption, which are needed for identifying and debugging anomalies more quickly.

MONITORING AND COMMISSIONING

The first winter of operation started in January 1999 and continued until the heating season ran out in early May. During this period, the houses were finalized, debugged, and commissioned. The key objective of the commissioning exercise was to ensure that all of the operating characteristics of the houses were understood and characterized for all operating conditions. As a result, when performing experiments involving other technologies, all resulting differences between house performance could be confidently attributed to performance of the technology and not to some undocumented anomaly in facility performance. This proved to be a daunting task. The following is a discussion of the anomalies and resulting changes.

- Although the high-efficiency furnaces appeared to be identical, one air circulation fan motor consumed 30% less energy than the other. Not having an independent

benchmark to determine which one was defective, and after prolonged debugging attempts by the contractor, both motors were replaced and rewired, eliminating the difference. It turned out that the fan motor consuming 30% more had been correctly installed and wired in the first place—it was delivering full power, but the other was not. A check of fan motor speed settings and air-flow rates through the system probably would have uncovered and solved the problem more quickly. Such an installation problem would likely go undetected by homeowners under similar circumstances. Policing the entry of visitors and coordinating researchers in the houses was a problem.

- Initial tours of the completed houses resulted in people continually breaking visiting rules by flicking light switches and pressing control buttons. The worst such example was a heat recovery ventilator (HRV) control setting that was changed from its original position resulting in far more high-speed cycling in one house than the other. This resulted in the large scatter of data shown in Figure 2. Resetting these controls and carefully balancing and monitoring HRV performance was the single largest factor in eliminating scatter in performance between the houses.
- Monitoring the indoor air quality just after final closing of the houses was a priority. As a result, the equipment used for this process was allowed to be placed within the reference house (unlike other monitoring equipment in the isolated control room in the garage). Unfortunately, the resulting imbalance in total house heating consumption was only detected later, once the analysis technique was put in place. This effect is clearly shown by the 20.7 MJ/day offset in Figure 2. The test house required more heating due to the absence of the approximately 275 W of internal gains associated with the temporary IAQ monitoring equipment in the reference house. The preliminary slope of the line in Figure 2 hinted at the near perfect match of the houses, confirmed in the next heating season when most of the anomalies were found and resolved.
- It can be seen in Figure 2 that as commissioning progressed into the spring of 1999, toward the lower end of the consumption curve in Figure 2, the scatter was reduced considerably.

Eventually, actual tours in the houses were stopped altogether, except under very special circumstances. Virtual tours from the neighboring information center, using computer links, were set up to satisfy that demand.

- Temperatures at the interior surface of windows appeared to be anomalous on cold, sunny days. Figure 3 shows such a profile on a day that started with a low of -20°C . The interior surface temperature reached above 45°C . This was originally believed to be mea-

surement error of the thermocouples placed on the window surface with a small bead of white cement compound, due to a different balance of the radiative components of heat transfer at the bead. However, independent measurements with an IR-based sensing device were within 1°C of all thermocouple measurements. Local shading of the thermocouple bead only reduced apparent surface temperatures by 1°C . The interior surfaces of the south-facing windows were very hot to the touch. These high temperatures are apparently associated with the high-performance characteristics of the window, possibly caused by a postulated high absorptance of the low-e coating on Surface 3 of the sealed unit. These window properties need to be characterized in more detail. The same windows in occupied south-facing offices nearby are associated with high levels of discomfort from overheating, due to the relatively large size of these windows. This was an unresolved issue at time of writing.

- The furnace fans, once they were set to operate at the same power consumption, were initially run continuously at high speed for better air distribution and mixing. This resulted in consumption rates of 500 W continuous, or 12 kWh per day on average, effectively blowing the targeted power budget of 20 kWh per day by a large margin (see Figure 4). These fans were subsequently reset to operate at low speed on a continuous basis and only kick into high speed during furnace (or air conditioner) operation. This reduced furnace fan consumption to approximately 8.6 kWh/day. A higher-efficiency motor in one of the technologies, which was investigated later, consumed only 7.2 kWh/day, while delivering slightly more airflow. ECM technologies would presumably do even better.
- The draw of hot water over a thermocouple in the hot water line downstream of the water heater results in the

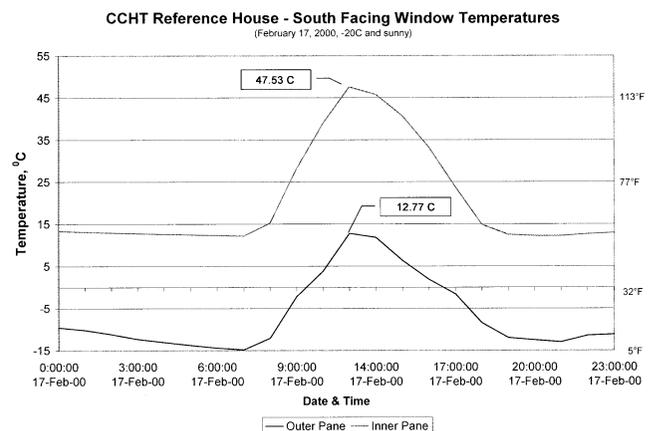


Figure 3 Sunny day profile of interior and exterior glazing surface temperatures.

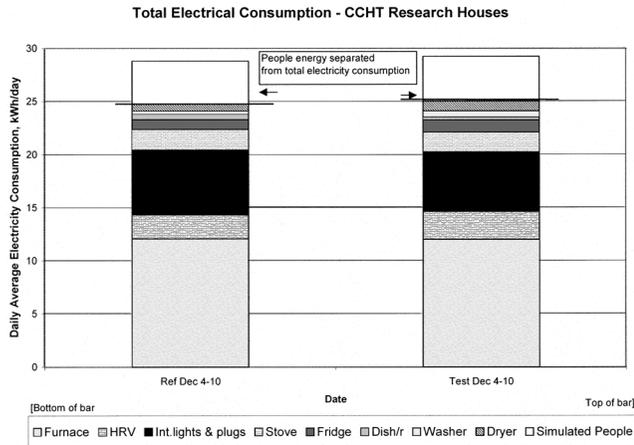


Figure 4 Comparison of average daily electricity consumption of both houses measured over one week. (The heat release from people, simulated with lamps, is recorded separately but added here to show total internal heat gain.)

temperature profile recorded in Figure 5. The spikes were used as a standard characteristic of the simulated occupancy’s water using devices in operation, which was used to verify proper operation of each hot water using device. Typical total daily consumption of hot water was measured to be 268 L/day on average in the reference house and 279 L/day in the test house. The difference was the result of small cumulative differences in each device and was, therefore, difficult to correct because the flow rates were determined by tap settings that could only be set in approximately the same position in each house. Appliance settings were also fixed and did not provide opportunity for fine-tuning. This difference was accepted and accounted for in the benchmarking. The differences did not bias the comparisons, but just positioned the benchmark with an offset (see Figure 6).

- Not having actual occupants posed a heightened need for review of all monitored characteristics on a very regular basis during commissioning:
 - solenoid operation of the shower failed to turn off on one occasion, resulting in an 8-hour shower, with high humidity throughout the house.
 - On one occasion, the stove was inadvertently left on by the simulated occupancy for 12 h overnight and only turned off at its scheduled time in the morning. This event went undetected for several days. Later, comparison of daily stove consumption in both houses confirmed that the problem was with the stove in the reference house, but this did not give the full picture

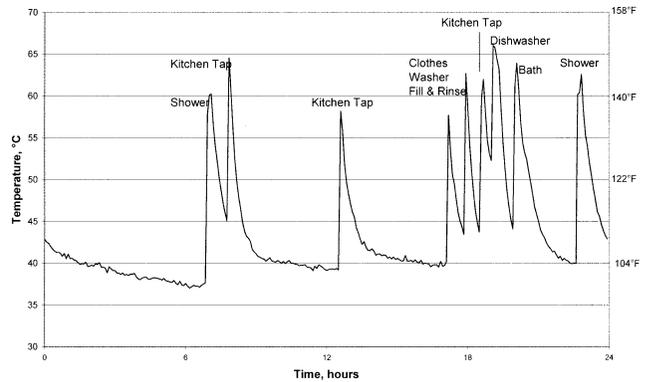


Figure 5 A thermocouple placed in the hot water line downstream of the water heater records pipe water temperature rise and drop, as water using devices are turned on and off.

Benchmark of Gas Consumption for Hot Water Heating

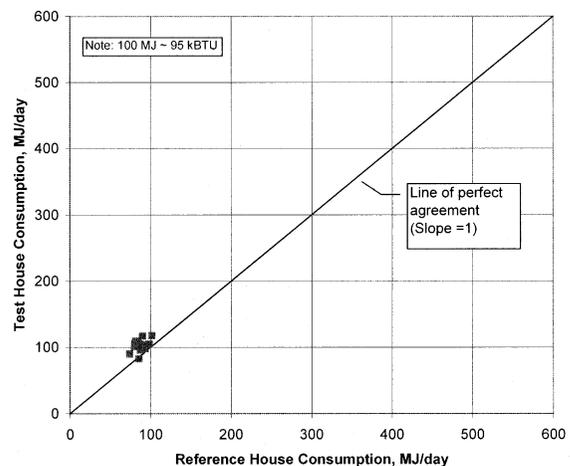


Figure 6 Benchmark data for domestic water heating (shown on a scale consistent with the space heating graphs for comparison).

of what had happened. Detailed review of temperature measurements in the kitchen area showed that the area over the stove had been much warmer than other areas of the house, and these data helped isolate the exact start and stop time of the event. Review of our logs revealed that a manual change of automation system clocks for daylight saving time in spring was not properly coordinated with the simulated occupancy schedule. This resulted in the elimination of the hour in which the stove is normally turned off.

- Two thermostats were installed in each house—a regular electronic thermostat and one that is programmable through the simulated occupancy system. In the early stages, the controlled thermostat of the simulated occupancy system was used. The control system was not completely debugged at that stage. On one occasion, the simulated occupancy controller froze, and the thermostat was stuck in the on position. The indoor temperature reached 38°C (100°F) before the problem was noticed. The electronic thermostat was used until the entire simulated occupancy system was debugged.

As a result of these and many other commissioning experiences, operating procedures and checklists were refined and adhered to, which resulted in a much higher level of confidence in the results.

Benchmarking

The objective of benchmarking was to account for any remaining post-commissioning differences between the houses and record these statistically to give a point of reference for any future technology assessments. Benchmarking the houses occurred over the period from November 1999 to the end of January 2000. Figure 6 shows the results for hot water heating, with slight scatter and an offset. The test house consumed about 18% more energy for hot water heating than the reference house. The higher consumption of the test house is related to a number of cumulative factors that are difficult to control. Slightly greater hot water draws were noted in the test house as discussed above, and there was poor control over actual water heater temperatures in each house. The built-in temperature controls of the water heater are not meant for fine-

tuning. Nevertheless, this offset became part of the benchmarked condition and, therefore, would not affect future comparisons, which will take this offset into account. It was also important to remember that the documented difference in hot water consumption also plays a role in the space heating system, which was benchmarked concurrently. Refining the hot water situation would necessitate re-benchmarking the space heating as well, which is undesirable to do given time and resource constraints and the satisfactory result described below.

Benchmarking the space heating consumption, theoretically the more challenging exercise, turned out to be simpler in that the results confirmed that the objective of the design was met—virtually overall identical thermal performance, on a statistical basis. Figure 7 shows the benchmarking of the test house against the reference over the same period. It is noted that whereas each day's result is not necessarily a perfect match, statistically, this is a near-perfect result, with the slope being measured only 0.7% lower than a perfect fit with a slope of 1. We interpret this result as follows: small differences associated with daily comparisons appear to be random and cancel out, given a large enough sample of points. As well, the house airtightness and hot water consumption were both documented to be slightly different, so it is important to note that the excellent space heating correlation is the result of the net cancellation of many small differences in the house's total energy system.

Experience in interpreting results of subsequent assessments with this facility suggests that approximately two to three weeks of data (14 to 21 data points) are sufficient to give a good statistical estimate of performance, provided that the weather patterns in that period are sufficiently variable so as to develop data points distributed over a substantial portion of the range shown in these figures. A strategy of alternating technologies from week to week was adopted to ensure that each technology was operated in different conditions throughout the heating season.

Finally, the benchmark line needed for assessing heating systems that supply both space heating and hot water is calculated by finding the total of the benchmark result for hot water heating and that for space heating, resulting in the characteristic shown in Figure 8. That benchmark of total gas consumption was checked later in the heating season, after several weeks of experiments, and it essentially remained intact as shown by the data points, which mostly touch the previously derived benchmark line.

Figure 9 illustrates how the facility and analysis procedures are used to assess the performance of two technologies against the benchmark. On days where data points for a given technology fall above the benchmark line, that technology consumes more than the benchmark configuration and vice versa. The fact that the characteristic performance lines of the technologies cross the benchmark line turned out to be due

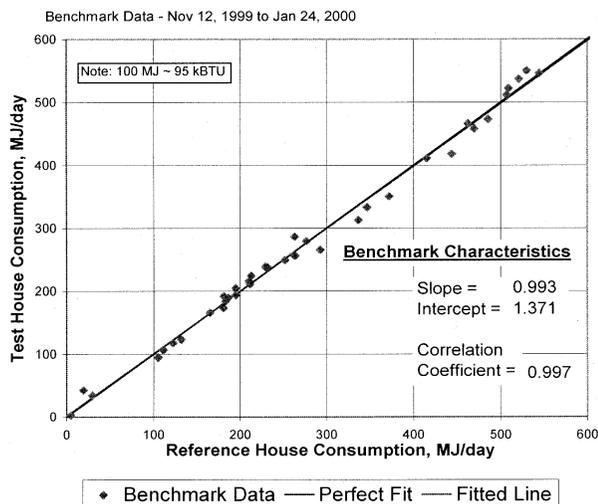


Figure 7 Post-commissioning benchmark data for space heating and statistically fitted line.

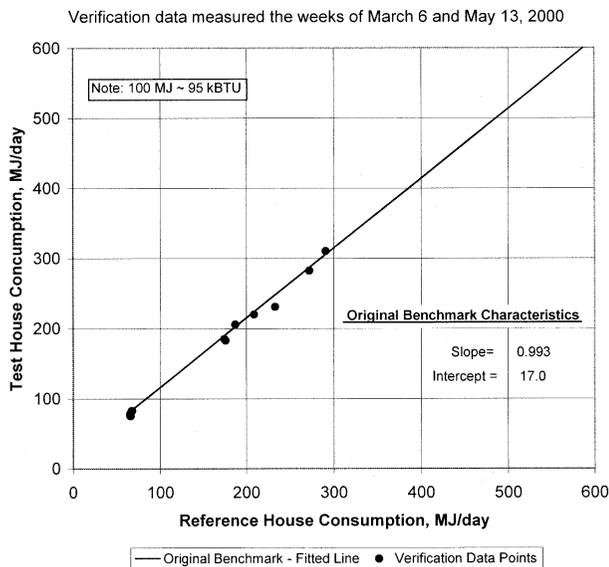


Figure 8 Verification of benchmark of total gas consumption (space and water heating combined) during assessment of technologies.

more to the moving target offered by the benchmark than due to changes in performance of the technology. The explanation is as follows: the benchmark for space heating is based on high-efficiency condensing technology (e.g., 91%). The benchmark for water heating is based on conventional technology (e.g., 67%), as specified in Table 1. At any given point during the heating season, the overall combined efficiency of the benchmark heating equipment is a combination of the two efficiencies, in proportion to the relative size of space heating load to hot water heating load. Once this was realized, it became clear that the technologies used for space and water heating should be as close as possible in efficiency to present a relatively fixed efficiency target for combined heating equipment technologies.

The strong statistical linear fit of these performance lines suggests that the characteristic could be used to assess overall seasonal performance comparisons, based on approximately three weeks of testing for each technology.

CONCLUSIONS

In 1998, twin houses were built at the Canadian Centre for Housing Technology in Ottawa to assess the energy performance of new and innovative energy-efficient materials and components for houses. This paper describes the energy features of the houses, commissioning, and benchmarking results. With the benefit of detailed monitoring of energy systems in both houses, many of the anomalies in component operation and controls were rectified. Close monitoring and supervision of the operation of the houses was shown to be a necessary element of gaining full control over their operation.

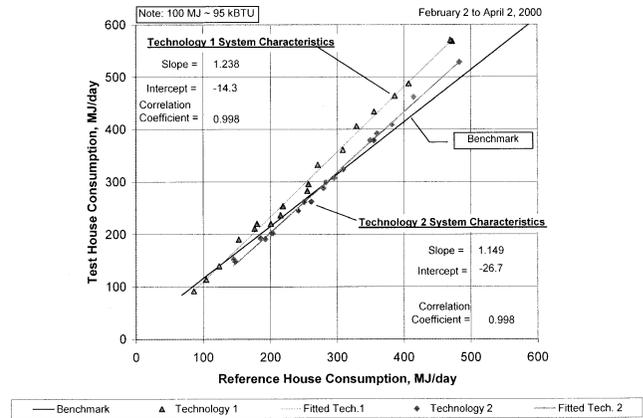


Figure 9 Example of assessment of two technologies using the benchmark for total gas consumption as a reference.

Once commissioned, the houses were shown to perform in a near-identical fashion. Remaining differences were benchmarked in a detailed fashion to ensure that the performance characteristics attributed to new technologies by this facility would be solely attributable to the technology and not to unaccounted anomalies in the operation of the facility. The resulting facility was shown to be capable of delineating performance differences with a high level of accuracy. A two-to three-week monitoring period for each technology was found to be sufficient for performance comparison purposes.

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