Natural Energy Public Library - Design to Reality

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In late 1988, the Nelson City Council (New Zealand) purchased a second hand car sales yard to turn into a public library. A performance-oriented specification permitted a natural energy design approach to be taken. Within the constraints of a tight budget, a low-energy design was developed based on extensive daylight modelling and computer thermal simulation. The library was opened in February 1990 and two years of monitoring have been completed.

Daylight measurements have confirmed the accuracy of the original artificial sky measurements but have also highlighted inadequacies in the treatment of clear sunny sky conditions. Most significantly, they have identified an inherent problem in all building performance predictions based on historical weather data: it is difficult for any designer used to absolute performance data from energy consuming equipment to comprehend the stochastic data that results from use of climate dependent energy sources.

The heating energy use measurements have confirmed the general reliability of the SUNCODE computer program used in the performance analysis. However, it has also highlighted some significant differences between prediction and reality. The "cool-down" test results, for example, could not be precisely replicated by the program even after adjustment for the as-built construction and for the actual weather conditions.

The cooling season temperatures in this daylit, naturally ventilated building were of particular concern in the design stages. Measurement has confirmed that, in this climate, natural ventilation can maintain internal temperatures within the comfort zone for an acceptable proportion of the working year.

Introduction

During the 1980's the New Zealand government supported a large number of investigations into energy use in non-domestic buildings. Although this data collection has resulted in a significant information resource, there has been little attempt to build low-energy, solar non-domestic buildings.

This paper reports the performance monitoring of the first non-domestic building which has attempted to build on the lessons of this extensive research base - a new public library for Nelson city. The design process was constrained by the economics of the feasibility of solar heating, daylighting and natural ventilation of a deep plan building on a less than ideal, urban site in a provincial town.

Apart from a number of "atrium" interiors (Shum 1990) solar energy is not consciously used in non-domestic building design in New Zealand. Non-domestic building energy performance has been intensively studied in a number of sector-wide (Baird et alia, 1984; Baird, Donn, & Pool, 1982; Isaacs & Donn, 1987) and detailed studies (Donn & Pool, 1984; Bruhns & Baird, 1988; Baird & Pool, 1987). These investigations showed that the area energy use index for non-domestic buildings ranges from 300 MJ m^{-2} to 1000 MJ m^{-2} (7.7 kWh ft^{-2} to 25.8 kWh ft^{-2}), and with heating and cooling comprising 20% to 50% of the total energy use but only 6% to 30% of the total cost. Lighting, provided by expensive electricity, can be up to 80% of the energy running costs.

These results point to the importance of daylighting as a substitute for electricity. Despite these results, confirmed by case studies from many reports published in other countries (e.g. Databuild, 1989) few, if any, New Zealand non-domestic buildings employ daylighting or other solar techniques to reduce energy use.

Nelson is a small provincial city (latitude 41° 16' S, longitude 173° 15' E) in the north of the South Island. The climate is relatively benign (2400 -base 18°C- degree days) as the region is spared many of the storms that characterise areas near the Cook Strait between the North and South Islands. It is the sunniest region in New

Zealand - averaging 2418 hours of bright sunshine a year and 16 MJ m^{-2} day^{-1} (0.41 kWh ft^{-2} day^{-1}) solar radiation. Summer temperatures over 30°C (86°F) are not uncommon, with 36°C (97°F) the highest reported. Winter temperatures can be cool, with a record low of -7°C (19°F) (de Lisle & Kerr 1965).

Structure of the Paper

This paper reports the results of two years of monitoring during which the authors were able to compare the performance of the building to the performance expected from the design process. This comparison was in terms of both its energy use and the internal conditions delivered. In the following sections, the lighting performance and the thermal performance for heating and cooling are examined. The lighting is provided by clerestory and high-level perimeter windows, plus a regular array of fluorescent lights switched according to the predicted daylight distribution. The thermal performance for heating depends mainly on the thermal integrity of the building envelope and the effectiveness of the heating control systems. For cooling, the performance is a complex combination of shading, opening windows, and people.

The most significant message identified in the whole research and development programme, from design to occupancy and monitoring, is an inherent problem in all building performance predictions based on historical weather data: it is difficult for any designer used to absolute performance data from energy consuming equipment to comprehend the stochastic data that results from use of climate dependent energy sources. It is even more difficult to communicate these concepts to a client. Those who are inexperienced in computer thermal modelling expect that a computer will be able to "predict" actual energy consumption. The designer or investor wants energy to be as neatly handled as the finance package. They find it difficult to cope with the idea that the model may be an accurate indication of the likely physical behaviour under ideal conditions, but not a precise prediction of energy consumption under actual conditions. They look for certainty, when the tools can only provide guidance.

Lighting Simulation

Daylight measurements have confirmed the accuracy of the original artificial sky measurements but have also highlighted the expected inadequacies in treatment of daylight in a climate where the sky is clear more than 50% of the time.

Lighting Electricity

The original design brief established desired lighting levels of "400 lux at 750 mm above floor level" (37 footcandle at 30 inches). Trials in the School of Architecture mirror box (4 m x 4 m x 2.4 m - 13.1 ft x 13.1 ft x 7.9 ft) artificial sky documented the 'daylight factor' for a physical model of the building. A specific 'daylight factor' cannot predict a specific internal lighting level unless the external daylight level is known. All that could be "predicted" was a probability of daylight exceeding certain design values on average throughout the year. It was noted that daylight would provide more than 400 lux (37 footcandle) for an average of 2.2 hours of the working day throughout the year for 70% of the public areas of the library (>2% daylight factor). Daylight at this level provides more than 400 lux for an average of 6.7 hours of the 8 am-5 pm working day, for 25% of the public areas (>5% daylight factor). Had the budget allowed the placement of more skylights or clerestory windows then these daylight factors could have been exceeded. These options were discussed and rejected for cost reasons.

Comparison of the daylight factor plan taken from the design model, and actual measurements taken on 27 July 1990 show that the expected daylight levels were not achieved. The actual measurements show that 400 lux is exceeded for an average of 2.2 hours per day over 60% rather than 70% of the public areas of the library. Within the margin of error for measuring the areas, the daylight factors near the perimeter of the building are very similar in the model and in the actual building.

There are several complicating factors that made the lighting system work less effectively than originally expected. For most of these, the costs of modification to bring expectation and reality into line are expected to be high. The main areas of difference, and possible actions (*identified in italics*) are:

(1) the presence of dark coloured louvres, blinds and other reflecting surfaces near window openings and the use of windows smaller than originally modeled meant daylight levels inside do not reach the levels expected - *no change economically feasible*;

(2) the fluorescent lighting levels reach 600 lux (56 footcandle) on average without daylight assistance, thus the area under the lights (especially the emergency lights that are on continuously) can appear much brighter and more cheerful than the areas lit to the daylight target - *perhaps switch tubes individually, but rewiring not cheap*;

(3) the fluorescent luminaires do not switch their tubes individually, so cannot be used to supplement daylight. For example if the daylight level is 402 lux then that is "sufficient", but if it is 350 lux then the lights are all on and the level is boosted to 950 lux (88 footcandle) - *Modifications possible, but rewiring is not expected to be cheap*;

(4) the lighting circuits are zoned to provide only 4 switches to control all the public areas, and the zones, while relating closely to expected daylight distribution, do not form an intuitive operation for library staff - *Modifications are possible through running additional cables from the switch board to the lighting control panel and adding contactors to the switch board.*

Although the lighting electricity use is above that expected, it is very small in comparison to the heating electricity use. Some savings are possible from the US$620 annual lighting electricity cost, but effort should firstly be directed at the heating electricity use. If we compare the actual energy use of 30 GJ (8.3 MWh) for lighting with the 74 GJ (20.6 MWh) expected if the lights are on continuously for the time that the library is open, then it would appear there is already a significant reduction in lighting energy use due to daylighting.

Heating Energy Use Simulation

The heating energy use measurements have confirmed the general reliability of the SUNCODE-PC computer program (Wheeling et al 1985) used in the performance analysis. Its predictions accurately reflect the behaviour of the Nelson Library. However, these predictions are not precise measures of actual performance. Some significant differences were observed between prediction and reality. The "cool-down" test results, for example, could not be precisely replicated by the program even after adjustment for the as-built construction and for the actual weather conditions.

Unoccupied Monitoring

The model validation test is based on the SERI Class B testing (see for example Swisher 1985), following the approach of Tucker (1987). The purpose of unoccupied monitoring is to enable a comparison of the actual thermal characteristics with those used in the initial computer modelling. The results are used to calculate the heat loss coefficient, thermal decay time constant and thermal capacity.

The library is a very large open space fitted with electric heating and ceiling fans, permitting energy consumption to be monitored and the air temperature to be maintained evenly throughout the main floor.

Unoccupied monitoring was carried out from 27 July to 31 July 1990. The steady state test ran from 7:00 pm 28 July to 8:00 am 29 July. The cool-down test was carried out from midnight 30 July to 7:00 am 31 July. Throughout the tests the weather remained fine with minimum wind.

The intention of the SUNCODE-PC modelling was to model realistically the building's overall energy consumption in relationship to the climate. As far as it is possible to make comparisons between the various SUNCODE-PC summary parameters describing the thermal performance, the physical measurements confirm the original assumptions in the design model.

As a final check, the base SUNCODE model was rerun to simulate the tests that had been performed. Weather files for Nelson were created which followed the climate during the testing period. The results, and the external temperature conditions are illustrated in Figure 1.

Figure 1 shows the SUNCODE model predicted a much sharper response to the outside temperatures than measured. The small fluctuations in the graph of the test measurements are due to the testing equipment recording only in 1 degree Celsius increments. Following this run, the SUNCODE model was adjusted to reflect the actual infiltration measurements.

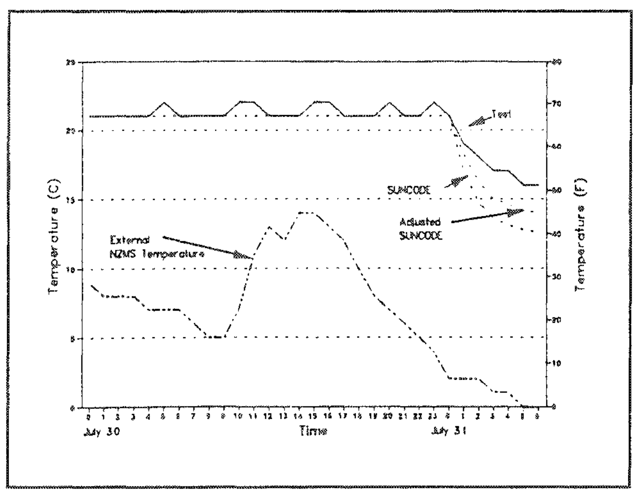

Figure 1. Cooldown Test Temperatures

In the base model, an infiltration (air leakage) rate of 1 air change per hour was used (assuming all windows closed) but this may have been too high based on the later infiltration measurements. The effect of reducing the infiltration from 1 ACH to 0.1 ACH is to increase the temperatures during the cool down period. However it does not bring the rate of temperature decay into line with that actually measured.

The rate of fall in the internal temperature is a combination of heat loss and heat gain from the building heat storage. A standard deduction from this data would be that the real building has a higher heat capacity than modelled. Alternatively it may be lower real heat loss, which would agree with the conclusions in the following sections.

From this data it can be inferred that the building envelope affords greater protection to the inside spaces than was initially assumed. The building is thus less responsive to external conditions, and the internal climate is far more stable than anticipated. This conclusion is consistent with the temperatures measured in February 1990, when the building remained cooler than predicted.

Manually Recorded Temperatures

At approximately 9 am each work morning, library staff recorded the present, the minimum and the maximum temperatures from a min-max thermometer, as well as the three electric meter readings.

The range of internal temperatures by month (from library staff recording) is shown in Figure 2, while Figure 3 gives the external range (at the nearest meteorological station) for the 1990/91 year. 1990 was a cool year, with minimum external temperatures close to or below zero from April through October. The internal daytime temperatures (9 am and maximum) remained within acceptable limits. The monthly average 9 am internal temperature was above 18°C (64°F) for the 1990 winter (May to October), and above 16°C (61°F) for the 1991 winter months (April to July 1991). The minimum internal temperature occurred when the library was unoccupied and unheated, and although it had an impact on the overall energy use of the building through the reduction in stored heat, it did not affect users as they were not present.

Internal temperature distributions for the Children's Desk are given in Figure 4, and the same analysis of the nearest meteorological station external temperature data is given in Figure 5. The left hand curves are the minimum temperatures, the middle thicker line the 9 am temperature and the right hand curves are the maximum temperatures. The curves are calculated by counting the number of readings in 1°C intervals, calculating the percentage in each group, and summing. Thus below any given point, the curve represents the proportion of readings that were below the given temperature, and above, the proportion above that temperature.

The greater the horizontal separation, the greater the temperature fluctuation - as can be seen for the external climate. Summer temperatures inside remained stable, while winter temperatures varied, particularly with the effect of overnight cooling (minimum temperature) and late afternoon sun (maximum temperature). In less than 10% of the days on which temperatures were taken was the 9 am temperature less than 14°C (57°F).

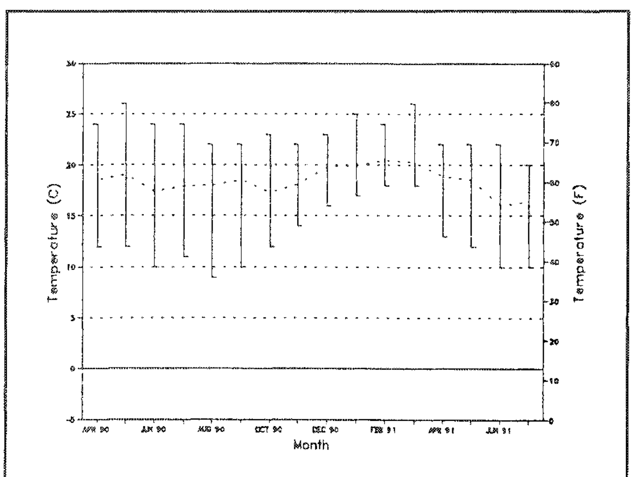

Figure 2. Internal Temperature Range by Month

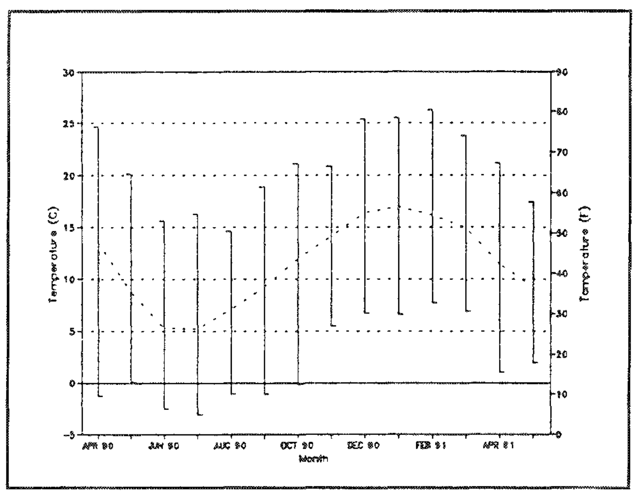

Figure 3. External Temperature Range by Month

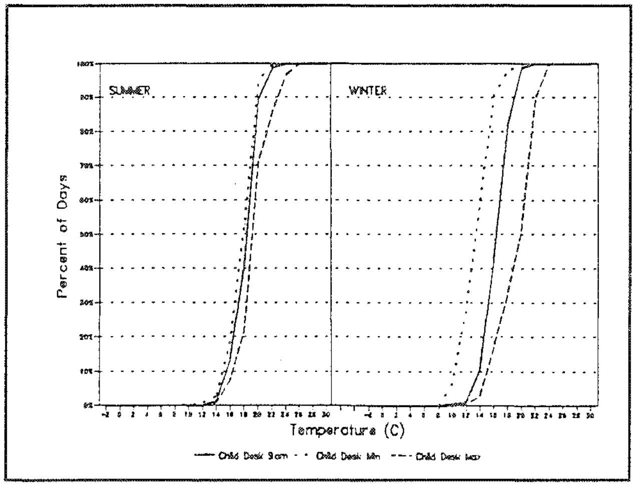

Figure 4. *Children's Desk Temperature Distribution*

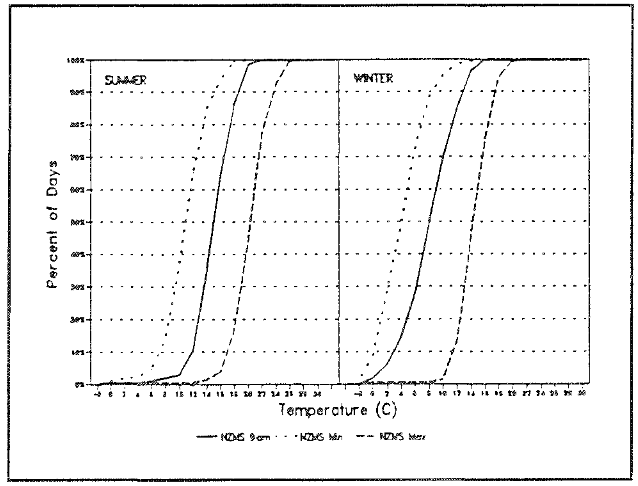

Figure 5. *NZMS External Temperature Distribution*

The recordings from the heating system sensors provide information on the temperature range not only during occupation but also after hours. Figure 6 provides the maximum, average 9 am and minimum temperatures for working days (i.e. Monday through Saturday inclusive) for the time periods: midnight to 8:30 am; 8:45 am to 5:45 pm (day time working hours); and 6 pm to 11:45 pm for the months of April, May and June 1991. These temperatures have been extracted from the control records with corrections applied, but a maximum accuracy of no more than $\pm$ 1°C would be expected.

It can be seen that during the occupied hours (the central region of the graph) the temperatures are within the normally accepted comfort range for library activities (ASHRAE, 1989). Only in May 1991 during day time working hours did the minimum temperature drop below 15°C (59°F).

The 00:00 (midnight) to 8:15 am time period had a wider range with the minimum temperatures likely to be in the dead of the night and the maximum temperatures just before official opening hour. These results demonstrate that library temperatures are now under reasonable control.

For comparison with other buildings of similar use, common practice is to calculate an index to normalise for size - most often the Area Energy Use Index (AEUI) (Baird et alia 1984). The AEUI for the library when it is operated correctly during 1991 was a low 180 MJ m^{-2} (4.6 kWh ft^{-2}).

The conclusion reached from regression analyses relating heating energy use and climate is that at most 24% of the variation in heating energy use in the library can be said to be related to the variation in external climate.

None of the heating control system sensors are monitoring external temperature. In addition, the heating peak power and energy use largely occurs in the first three hours of operation and is not (apparently) related to external temperature extremes. These observations, and the conclusions of the last paragraph, suggest that controls that made the energy use more responsive to the variations in external climate could reduce the energy use. Then the programmable controller could be used as an optimiser rather than as a complicated timeclock as at present.

Figure 7 compares the actual energy use in 1990 and 1991 with that produced by the SUNCODE modelling program. The high energy use in 1990 shows clearly, with a noticeable fall between July and August 1990 when the improvements to the control system were implemented. The 1991 consumption is lower, but still higher than the SUNCODE model suggested.

The main difference between the actual and modeled energy use is due to heating, where the actual 1991 consumption of 318 GJ is about 60% more than the adjusted model of 190 GJ. This again suggests that there are possibly still further energy savings achievable.

Cooling System Simulation

The most important aspect of the whole SUNCODE calculation process was not the heating energy simulation, but the cooling energy requirement and the calculation of the likely behaviour of the building on hot days if it were naturally ventilated. The client was convinced of the

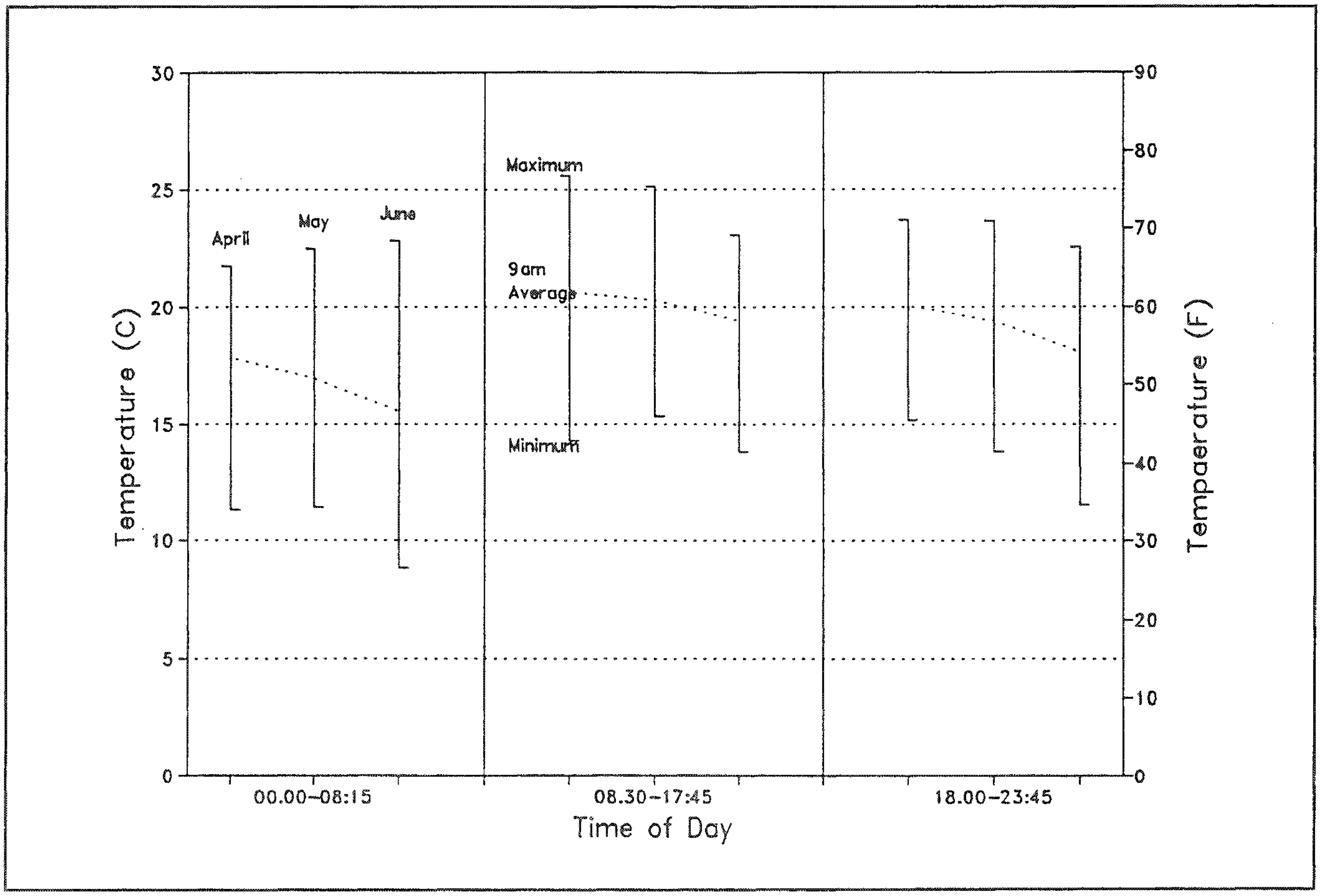

Figure 6. Temperature Range by Time of Day for April-June 1991

potential of natural ventilation only after extensive discussion of graphs of the SUNCODE calculations of each alternative building design's internal temperatures on hot summer days. Eventually, the client's decision came down to "If it is 28°C to 32°C (82°F to 90°F) inside on the few days a year it is 26°C to 30°C (79°F to 86°F) outside, then we will choose openable windows for cooling because of the air quality and quantity control this gives us at other times". Discussion of these possibilities with the client and the architect at an appropriately early phase in the design process allowed the capital savings from the budgeted cooling system to be put towards the extra cost of the roof-top clerestories, and the small central courtyard which acts as a lightwell.

Much discussion at this early design stage centred on the likely quality of air reaching the noses of people in the centre of this deep plan building, in amongst the book stacks. For this reason the cross flow ventilation from the ceiling level windows plus floor level vents at the perimeter and the clerestories was supplemented by the installation of large diameter, slow moving fans suspended from the ceiling.

Measurement of the performance of the building has confirmed that, in the Nelson climate, natural ventilation can maintain internal temperatures within the comfort zone for an acceptable proportion of the working year.

Fresh Air Provision

Although many assumptions can be made about the provision of fresh air in naturally ventilated buildings, measurement of it has, in the past been very difficult and expensive. Computer based tracer gas systems are available in New Zealand, but have high set-up costs and require regular attention during the measurement period. It was decided to use a low cost, passive measurement system.

In 1982, Brookhaven National Laboratory developed a perfluorocarbon tracer (PFT) technology based on passive

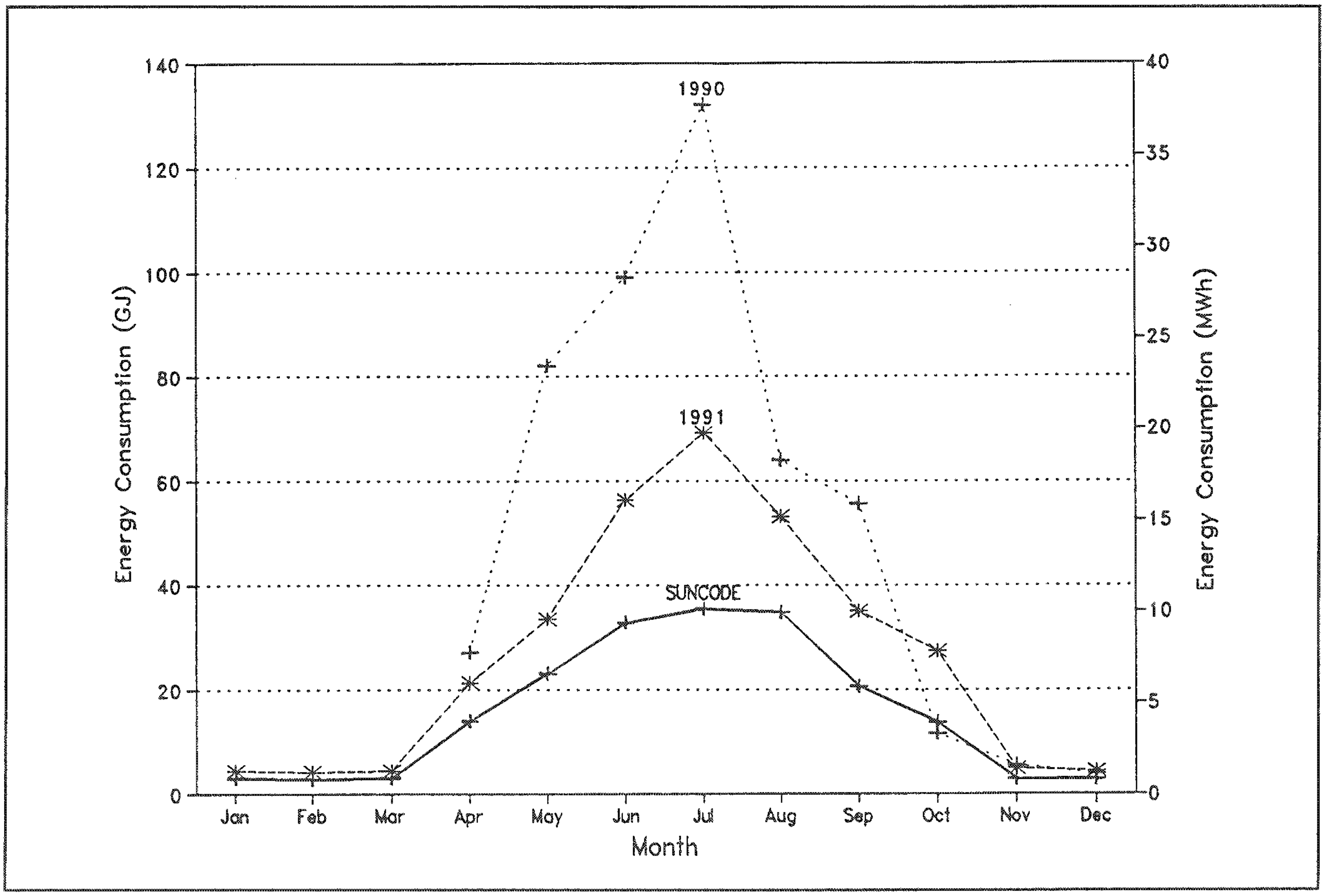

Figure 7. SUNCODE Model and 1990 & 1991 Actual Energy Use

emitters and receivers (Dietz et alia 1983). In 1986 NAHB National Research Centre began offering an Air Infiltration Measurement Service (AIMS) based on the tracer method primarily for monitoring airflows in homes (Song & Fan 1989). Although the various components of the system are expensive, in use the cost is low as all equipment is returned after measurements are completed.

The twenty three AIM receivers were installed in summer between 13:25 and 14:15 on 11 February 1991, and removed between 12:30 and 13:00 on 23 February 1991. The receivers were analysed at the NAHB laboratory and the analysis certificate records the date of analysis as 19 March 1991.

The measured air exchange rate of 1.8 air changes per hour (ACH) is an average over the 286 hours from 11 to 23 February, the height of summer in Nelson. The library was open for 103 of these hours (36%). Assuming the infiltration is insignificant during hours when the library is closed, the average air exchange during these summer days would be of the order of 5 ACH during opening hours. The windows and vents had been sized to permit at least 5 ACH when necessary for cooling ventilation, as a result of the SUNCODE calculations of the maximum likely indoor temperatures on hot summer days. It is noteworthy that the building is maintaining levels of comfort during the cooling season which the users are very happy with, and that it is apparently using 5 ACH to achieve this.

Conclusions

The results of the monitoring have shown that in the New Zealand climate the coupling of energy modelling with design work can result in an energy efficient building. Even so, if the energy systems are not commissioned and operated correctly, an energy efficient building can easily turn into an energy wasteful building.

The result of this work, demonstrated by the monitoring reported here, has been to provide a comfortable, spacious building. People report that they are comfortable, contented and working in an environment they wish to be in, even though the internal conditions are not constant. The principal conclusions arising from the analyses presented above can be categorised under three headings: Temperatures, Daylighting, Heating Energy.

Temperatures

The provision of detailed, performance oriented specifications permitted the designers to take an innovative approach to the design of this building. Although such specifications can still be used to force particular solutions, they were also tempered with an acceptance of trade-offs. In exchange for a small number of summer days with high internal temperatures, a naturally ventilated building was possible. The requirement that the heating system should allow for a winter working temperature of 20°C (68°F) when there is an outside minimum temperature of 5°C (41°F) has been achieved.

During the coldest week of the year (10 June 1990 to 16 June 1990), the temperature at the Children's Desk averaged 15°C (59°F) at 9 am when the outside temperature averaged 2°C (36°F). The target inside-outside temperature difference of 15°C (59°F) has not quite been reached at this worst time of the day. For the rest of the library, and for the rest of the day at the Children's Desk, the target difference is maintained. We expect the Children's Desk area could be brought up to a more acceptable temperature at 9 am if the heating system were more responsive to external temperatures and not operating merely as a time-clock, or if extra local heaters were installed in this area.

Daylighting

The library receives a good supply of daylight throughout the floor area, as suggested by the modelling. Although the levels of illumination have almost met the specification in all places, a major influence on the use of electric light appears to be the effect of the large amount of vertical glazing in the exterior walls. The light levels visible through this glass are very high on all surfaces. As a consequence, users turn on the lights near the centre of the building because they judge their local light as comparatively low and hence inadequate. This aspect of the energy design has not worked as well as would have been hoped but the overall feeling of light and of openness, a design intention of the architect, has been achieved. The view to the outside over the book-stacks from almost anywhere in the public areas of this deep plan building supports this "feeling".

Heating Energy

The building has achieved considerable savings in electricity use as well as in the reduced capital costs through not requiring either a new substation or air conditioning. Although the first year of operation had a high energy use, this is attributable to the fact that the heating control system was still in the process of commissioning. This initial period of high use does serve as an indication of how much energy might be used in a building if it is not operated correctly. The well operated building (1991) shows a 60% saving for heating energy used compared to 1990.

Now that the heating control system has been commissioned, there are still opportunities for further savings through improved understanding of the operation of the library and use of the controller. In particular the poor relationship between internal temperatures, external temperatures and energy use suggests that the heating system controller's optimum start-stop feature would be of benefit.

Investment Economics

The capital cost savings made in this building by using natural energy and natural ventilation are about US$37,000. These more than paid for the energy efficient features and the additional design work required. The energy modelling work cost US$10,000 while the additional design and quantity surveying work was estimated at US$2,500.

Operating cost savings have been estimated based on an alternate system with air conditioning provided by unit heat pumps (COP 1:3) for 5 zones at a capital cost of US$5,500 per zone and a design life of 5 years. They would use 53,000 kWh per year cooling energy and a 1.5 kW fan for air distribution. The approximate annual operating cost of US$8,360. For heating, there would be net savings of US$3,740 from the use of the heat pump in place of direct electric heating, for a total annual saving of US$4,620. The major part of these savings come from reduction of capital and maintenance costs, as the added cooling energy costs are almost equal to the savings in heating energy due to the benefits of the heat pump.

Replication

The range of energy options available in Nelson is limited - electricity, LPG or coal. The purpose of this final section is to draw conclusions that have wider significance for low-energy buildings in other parts of New Zealand.

If the building had been built in a city with natural gas, this would have been the choice for the heating fuel. The result would have been to highlight the higher cost lighting electricity relative to the heating energy. A comparison that does not consider any differences in capital cost, regular maintenance costs or supply charges is made in the following graphs.

The total electrical energy use in the Nelson library over the year once the initial commissioning work had been completed was 318 GJ. Figure 8 shows the components of the energy use, the cost of energy and the total expenditure. An energy use efficiency of 100% has been assumed for heating - whether by night store or radiant ceiling panels. This gives a total annual energy cost of US$6,210.

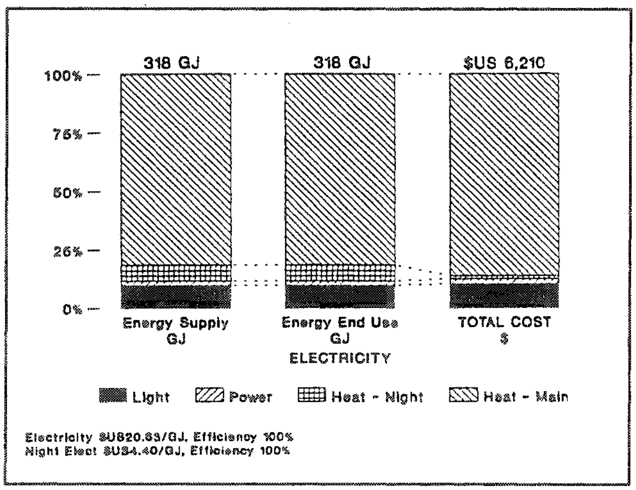

Figure 8. Energy Breakdown - All Electric

Figure 9 takes the heating energy use shown in Figure 8, assumes efficiency of 70% for a flued gas heater and calculates the total annual energy cost of US$2,530 based on a gas price of US$4.40/GJ.

It can be seen that in a building of this type in a city with an alternative lower cost heating fuel, the electrical energy use for lighting would be far more important as a proportion of the total expenditure.

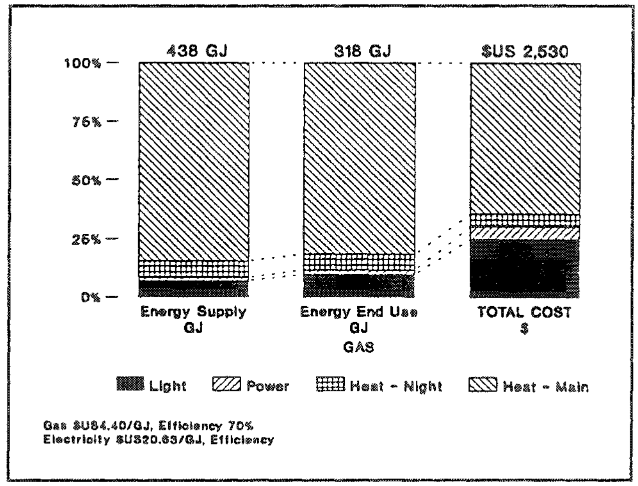

Figure 9. Energy Breakdown - Gas Heating

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