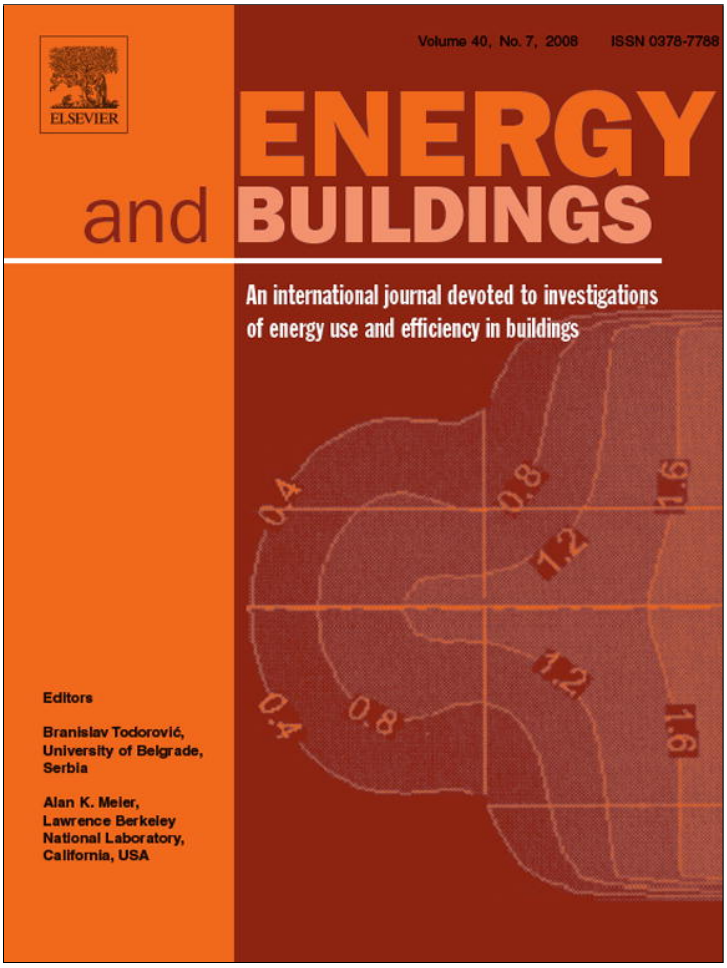
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The efficacy of an energy efficient upgrade program in New Zealand

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Abstract

This paper details the physical effects of a government sponsored, residential energy efficiency upgrade program in New Zealand, with data gathered from 100 houses located in Dunedin. House energy use and thermal indoor environment were monitored over a 2-year period. Houses were found to be 0.4 °C warmer (annual average increase) after the upgrade with a 0.6 °C increase recorded over the winter months, after being corrected for energy consumption and weather conditions. A small, but statistically insignificant, reduction in energy consumption was also found. In absolute terms, indoor temperatures were found to be very low and did not come close to WHO recommendations. The data showed occupants could be exposed to indoor temperatures below 12 °C for nearly half of the 24 h day during the three winter months. The findings were quite surprising as the upgrade program had the goal of making houses warmer and healthier by reducing heat loss through improved thermal insulation. Householders, however, provided very little heating to living areas and even less to bedrooms thus contributing to the less than desirable indoor thermal environment.

Keywords: Energy efficiency; Retrofit programmes; Indoor temperatures; Energy consumption; Low income

1. Introduction

The present paper details a study undertaken by the University of Otago (Energy Studies Group) to measure the efficacy of a New Zealand government sponsored energy efficiency housing retrofit program. The study included the monitoring of 100 state houses in Dunedin (Otago, South Island) for temperature and energy consumption over a 2-year time span, with the aim of identifying improvements in comfort and reductions in energy use after the upgrades.

An IEA report suggested that: ‘‘By 1995 New Zealand had the lowest space heating intensity (measured as energy per square meter per degree day) of all the countries studied, even including Japan, and was about half of Australian levels’’. Residential energy use in New Zealand for 1995 was around 17 GJ/capita/annum compared to around 35 GJ/capita/annum in Australia, 30 GJ/capita/annum in Europe and 54 GJ/capita/annum in the US [1]. The low values for New Zealand residential energy use reflect unusually low levels of space heating. These findings are unusual as New Zealand has had historically some of the cheapest electricity of all of the OECD countries. According to Ministry of Economic Development, however, the energy consumption for the residential sector in New Zealand is likely to increase [2]. In 2005 the residential energy sector in New Zealand accounted for about 13% of the total energy consumed [3] in the country with an average of 12,150 kW h/year/dwelling.

New Zealand has a cool temperate climate, lying between 34 and 46° south. The South Island is significantly cooler than the North Island with Dunedin having some 2580 heating degree days (base of 18 °C) compared to Auckland in the north which has 1150 heating degree days (base 18 °C). About 80% of housing stock in New Zealand was built before energy efficiency regulations with regard to insulation came into effect in 1977–1978 [4].

Public housing in New Zealand was built to a high standard according to the prevailing regulations but with no insulation. New Zealand houses have larger floor areas than the average among OECD countries [5]. Also newer houses are larger than older ones [6] and are moving to lower occupancy levels [7]. Houses that have a larger building envelope area and/or poor levels of insulation require more energy to achieve minimum levels of thermal comfort. To compensate perhaps for the larger house sizes, people in New Zealand tend not to heat the entire house. Consequently houses in New Zealand are relatively poor in terms of thermal comfort [8,9]. In terms of the future, new

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housing is not going to change the situation significantly due to low building turnover rates and it is likely that approximately 70% of the 2030 housing stock already exists [10].

1.1. International studies

Many international studies reveal that there are health impacts associated with cold housing [11,12]. Houses that are cold are also likely to be damp leading to mould and fungal growth; together these are known to cause respiratory problems for the occupants [13]. Damp and mould is an endemic problem in many homes in New Zealand, compounded by low levels of heating and often poor ventilation [14]. Low indoor temperatures moist air and then cyclic heating followed by cooling further increases the risk of condensation [15]. This situation is known to lead to high levels of seasonal mortality and respiratory diseases such as asthma [16,17].

The financial inability to heat the home to an adequate temperature results in thermal discomfort and health risks, a condition which has been defined in the UK as fuel poverty [18,19]. A study on ''Poverty and Comfort'' by the Building Research Association of New Zealand (BRANZ) suggested that ''*energy is a significant cost item for low income households*'' and that ''*our houses are not achieving conditions which promote or even support good health*'' [20]. A more recent study suggested that between 10% and 14% of the population of New Zealand is currently living under fuel poverty conditions, with the percentage in the lower south island much higher [21]. Wilkinson et al have shown that in the UK there was a gradient of risk with the age of the houses; the older the houses the greater the risk of death in winter [22].

Thus far the existing research is not controversial; cold homes are unhealthy. What is happening in recent times is that all governments, including the New Zealand government, are under pressure to address the anthropogenic global warming problem by tackling energy consumption on the demand side. One relatively easy way to reduce fossil fuel usage is thought to be by improving residential housing insulation levels, as this measure can both reduce energy consumption and improve health by increasing indoor temperatures. But if homes are not already adequately heated, the outcomes are usually at the expense of each other, that is, higher temperatures mean more energy consumption or reduced energy savings.

Because the turnover of housing stock is quite low this demand side problem is often tackled by retrofitting existing housing with various energy efficient upgrade packages. The importance of retrofitting was recently pointed out at a Sustainable Buildings workshop held in 2006, organized jointly by the OECD and the IEA, the report resulting from the workshop suggested that: ''*since existing buildings account for a large proportion of the total stock, upgrading the energy efficiency of existing buildings has become an urgent task*'', and that a ''*Cost-benefit analysis tools, quantifying environmental gains are expected to assist decisions of owners for appropriate renovation*'' [23]. Internationally several energy efficient retrofitting programs have been designed and implemented aiming to both alleviate fuel poverty and to provide higher levels of comfort, while simultaneously reducing energy use and CO_2 emissions.

The environmental health of the planet is now receiving a high priority and so achieving energy reductions and consequent CO_2 emission reductions are often paramount, especially in selling the upgrade project. According to the New Zealand Ministry of Social Development in 2003 [24]: ''*The Energy Efficiency Retrofit Programme has provided the largest reduction in HNZC's environmental footprint over the last two years. Based on EECA estimates, HNZC retrofits completed to date will save tenants (collectively) approximately $1.0m per year*'' and *"reduce CO_2 emitted into the atmosphere by approximately 60,000 tonnes"*.

The efficacy of the upgrade programs, however, has been found to be somewhat controversial as they can be expensive and can often produce ambiguous outcomes (see below). This has been particularly true in terms of levels of energy reduction, where for instance, Milne and Boardman found in the UK that ''*In most cases of domestic energy efficiency retrofits, there are varying degrees of differences between the predicted energy savings, based on the calculated heat loss reduction, and the actual energy savings achieved in practice*'' [25]. In general the findings of several studies have suggested that lower levels of energy reduction than expected occur due to a trade-off between taking the savings as thermal comfort rather than decreasing their energy consumption [26,25].

Other authors suggest that the simplicity of the model assumptions used to estimate the assumed benefits might not be accurate due to not having taken into account all the variables, with high levels of errors used for the model calculations. In addition the well documented 'rebound effect' [27,28] needs to be taken into account whereby, according to Hass et al: ''*... Increases in energy efficiency will lead to cheaper prices for service provided and to a substantial increase in service and energy demand. This increase will outweigh the conservation effect to a large extent and, hence, make conservation programs useless*''. In their study of retrofitting residential homes in Austria, Hass et al concluded that ''*Standards with respect to building codes are very important tools to increase the thermal quality of new buildings" and "due to prevailing low energy prices, a triggering tool, which may be rebates or loans, has to be implemented to increasing the efficiency of the building stock*'' [29]. Another study, this time in the UK, by Bell and Lowe, found that a 40% greater fuel consumption was recorded above the predicted level in centrally heated dwellings because of the householders preference towards the continued use of existing (and inefficient) individual gas fire appliances in tandem with a new (efficient) gas central heating system [30]. Many people recognise that retrofit programs might provide benefits other than reducing energy consumption, especially if designed for low income householders. In a cost-benefit study, Clinch and Healy suggested that improving energy efficiency in housing will not necessarily result in reduction in energy use [19].

There is, however, some evidence, particularly for smaller upgrade projects, that residential housing energy retrofit programs are successful in reducing energy consumption. One study in the UK (York) monitored four houses that had been retrofitted, and found reduced energy consumption after the upgrade [30].

A study exploring energy savings options for the Danish residential sector by Tommerup et al. also found that: "a profitable savings potential of energy used for space heating of about 80% is identified over 45 years within the residential building stock if the energy performance are upgraded when buildings are renovated" [31]. They achieved 61 kW h savings per annum but with substantially higher initial costs leading to a long payback time of 30 years. Another study that retrofitted 10 houses, in the colder regions of the United States, found that additional ceiling and wall insulation was quite cost effective with actual energy savings ranging from 12% to 21% [32].

A Swedish study by Erlandsson and Levin, comparing the environmental impact of retrofitting existing housing against the construction of new buildings on a national scale, concluded that retrofitting was a positive option [33]. Another Swedish study by Gustafsson concluded that the optimal level of extra insulation on existing buildings depends on the optimal heating systems with a high degree of interdependence. Significantly they suggested that it is essential that the two variables, insulation and degree of space heating should be optimized simultaneously [34].

A study undertaken in Belgium by Verbeeck and Hens suggested a hierarchy of energy saving measures for retrofitted dwellings which involved roof and floor insulation as priorities followed by thermally better performing glazing and a more efficient heating system [35].

On the other hand some studies have suggested that retrofit programs may not be attractive in terms of simple payback times. A study undertaken by Guler et al. exploring options for the Canadian residential sector concluded that the energy savings potential of retrofit upgrades in Canada was small (0–8% of the total energy consumption for the Canada residential sector), their findings suggested that upgrading the heating system alone would provide the largest energy savings potential followed by basement insulation upgrades, ceiling insulation upgrades and thermostat upgrades. Long simple payback times were calculated leading to the conclusion that "*It can not be realistically expected that any household could consider energy efficiency upgrades with payback periods 20 years or longer to be feasible*" [36].

Several studies, which monitored retrofit programs to analyse energy consumption reduction and temperature increases, found that householders might benefit from a higher percentage of energy reduction and lower percentage of thermal benefit. A study by Skumatz evaluating a USA utility energy-conservation programme found that 75% of the benefits of the programme were given by reduction in energy consumption while the remaining 25% was given to improvement of thermal comfort [37]. These results, agreed with a study by The Energy Saving Trust in the UK which found similar percentages [38]. The results were also consistent with a UK study by Milne and Boardman which monitored retrofitted low income households. The study by Milne and Boardman found that "*at a temperature of 16.5 °C, 30% of the potential energy saving were taken as an increase in comfort temperature*" [25]. Furthermore, a study, involving different economic sectors in the UK, suggested that the amount of energy reduction and temperature increase depended upon the level of income of the householders, in this study, the authors concluded that in low income homes the benefits would be divided into 40% of energy savings and 60% improvement in thermal comfort, while over all economic sectors the division would be 70% energy savings and 30% improvement in thermal comfort [39]. This result is consistent with another study by Conniffe and Scott [40] and an Irish study by Sheldrick which similarly concluded that low income households realise almost all of the benefits of improving energy efficiency as improved comfort. These researchers found that after a retrofit program was implemented "*fuel bills fell by only 2.7% which suggested that the comfort benefits of the programme were substantial*" [41].

A Swedish study by Wall, comparing residential housing modelling with measurements (in this case of new passive solar designed houses) also found that energy consumption was around 25% higher than expected. The difference between the calculation and the measurements was found to be mainly due to higher indoor temperatures, higher household electricity use and a lower solar fraction for the solar collector than predicted [42].

The largest residential upgrade project undertaken in the UK has been the Warm Front (WF) project which encourages retrofitting of existing dwellings to reduce negative effects of people living in cold homes. After monitoring houses over two winters, several papers have been published analysing the impact of the program. One study resulting from this work, Hong et al. concluded that "*... the potential improvement in energy efficiency from the installation of draught stripping, insulation and gas central heating system was not observed*" and that "*there appears to have been no reduction in fuel consumption as a result of the WF measures, even after taking into account the increased temperature in the post intervention properties*" [43].

The "Warm Front" program is part of 'The UK Fuel Poverty Strategy' [44] which aims to reduce fuel poverty by providing grants for insulation and space heating systems to low income householders. Results by Oreszczyn et al. for the same WF project suggested that there had been an increase of 1.6 °C in temperatures for living rooms and 2.8 °C for bedrooms after houses were fully upgraded, and central heating was installed, although only 0.7 °C a temperature increase was recorded for the living area in houses which had only the insulation installed [45]. In terms of energy reduction, the Hong study found that the projected potential energy reduction saving of 61% predicted by their model was not found even after normalizing by area and heating degree days. The decrease in energy consumption found by Hong et al. was found to be between only 10–17% due to insulation and 0% due installation of an efficient central space heating system. They suggested that the difference between the modelling and the monitoring could be due to the rebound effect, errors in calculation or due to the simplicity of the model (assumption on air tightness, % of area insulated, efficiency of the heating system) [43].

As can be seen above the conclusions regarding the efficacy of retrofitting programs throughout the world are not generally consistent but trend towards lower energy savings than expected and relatively small temperature increases, unless the retrofit had been accompanied by a full central heating installation.

1.2. New Zealand regulations and previous studies

The New Zealand government like, most others is under pressure to both improve the nation's health and to reduce its greenhouse gas emissions. The policy commitment has been expressed implicitly through the New Zealand Housing Strategy [46], the National Energy Efficiency and Conservation Strategy [47] and the ''Warm Homes Project'' [48], administrated by the Energy Efficiency Conservation Authority (EECA), all of which intend to improve the energy efficiency of New Zealand houses through tangible programs. Examples of such programs include the 'Energy Wise Home Grants' and 'Housing New Zealand Corporation's Energy Efficiency Retrofit Programme'. The main goal of these programs is to reduce heat losses by installing insulation on top of the ceiling and under the floor and also by reducing air infiltration. The present paper is an investigation of the efficacy of the Housing New Zealand Housing Corporation (HNZC) energy efficiency retrofit program as applied to low income state houses.

Two previous studies have investigated temperatures and thermal comfort in New Zealand homes. The earliest study undertaken during 1971–1972 by the New Zealand Department of Statistics looked at household electricity consumption and thermal comfort. Surveying some 200 homes across the nation they found that: ''*the mean temperature levels in the kitchens, lounges and main bedrooms of insulated houses were not significantly higher or lower than the mean temperature levels in the corresponding rooms of un-insulated houses*'' [49].

In terms of energy use, the 1971–1972 report suggested that while in theory the insulation should lead to a 30–35% reduction in electricity used for home heating, in practice this saving was not achieved, possibly due to the insulated houses having a greater installed capacity of electric heating, although inexplicably this increase should have been reflected in higher indoor temperatures. The measured results were for electricity consumption for space heating only; comparing insulated houses with non insulated ones, they showed no statistically significant reduction in energy use for this study with a sample of 200 houses across the country. The study found that the national (sample average) indoor temperatures during winter were 15.8 °C for living rooms and 14.4 °C for bedrooms for non insulated houses. Corresponding temperatures recorded for houses located in the south of the South Island were 13.6 °C for living rooms and 12.6 °C for bedrooms (for non insulated houses). The measured, non-statistically significant, average temperature increase after upgrades was 0.5 °C for both rooms.

A recent national study undertaken by BRANZ reported that houses built after the 1978 insulation standards were introduced were, on average, 1.0 °C warmer than houses built before the regulations came into force. The national (sample average) pre-1978 annual average indoor temperature was found to be 17.6 °C and post-1978 was 18.6 °C. The primary difference between this data and the 1972 report data was that the BRANZ results were for houses which were fully insulated (walls and ceiling) and not just ceiling insulated as for the earlier work. In addition the post-1978 houses were much more likely to have had aluminium window frames installed, which from our present work have been shown to have considerably improved reduction in air ingress than the earlier used wooden framed windows.

The HEEP study also found that ''when insulation levels of houses are increased, expected technical savings are not achieved, as occupants tend to use some of these savings ('take-back') in order to increase the temperature within the house. As temperature levels in New Zealand houses appear to be low compared to other countries, increases in temperatures may have benefits other than energy savings, such as improvements to health'' [50]. Thus, newer homes are warmer during winter than older houses presumably due to the presence of insulation. Significantly they found only a small difference in energy use and thermal comfort as a function of income levels across the country.

These previous studies have shown, winter indoor temperatures in New Zealand homes are below WHO recommendations regardless of the location and the household's income levels. One of the reasons for this finding was reported to be that little energy was used for space heating. In fact if the electricity consumption data per household for New Zealand is analysed since 1974 it shows almost no increase over a 31-year period. (7.66 MW h average consumption for 1974 compared to 8.15 MW h in 2005) [51]. For the same period of time the commercial usage (per user) grew by a factor of three. While other fuel sources have certainly been increasing, especially natural gas usage in the north island, the stagnation in electricity usage is difficult to explain in view of the growth of electrical appliances. The other reason for the low temperatures was of course poorly insulated homes.

1.3. The energy efficiency retrofit program by HNZC

The New Zealand national Energy Efficiency Retrofit Program implemented by the HNZC aims to increase insulation levels on all pre-1978 houses across the country in a 10–12 year program, investing about 4 million NZ $ per year. The program started in 2001 and involved installing ceiling insulation (polyester blankets), under floor insulation (aluminium foil below suspended floors), hot water cylinder insulation and draught stoppers. HNZC owns some 65,000 rental houses nationwide and it is expected that by 2012 some 45,000 of these will have been upgraded.

1.4. The study area

The study area for the present paper was located in the south of New Zealand including Dunedin city (population 120,000) which has an annual average temperature of 11 °C, and 2580 heating degree days (base 18 °C). The coldest months are June to August with mean temperatures of 7 °C while the warmest months are January and February when mean temperatures are

Fig. 1. Typical state houses in southern regions of New Zealand.

of around 15 °C. Thus, while space heating is essential during winter months, air conditioning has not been considered necessary in the region. Dunedin has one of the oldest housing stocks in the country with almost 30% of houses built before 1930s [52]. People living in the area also generally have lower levels of income compared with the rest of the country [53], consequently there are higher percentages of people living in fuel poverty conditions (between 26% and 32% for Dunedin city) 21. In addition many of the houses have poor solar access during winter months due to the hilly topography.

HNZC owns approximately 3260 houses in this southern area, including those in Dunedin city. Construction of the houses fell into roughly three categories as can be seen in Fig. 1: weatherboard, brick veneer, and masonry veneer houses all built between 1940s and 1970s. The main structural and material differences between these categories are significant in terms of thermal comfort. Houses were originally built with no insulation and all had single glazed windows with mostly wood frames that were quite leaky after 50 years of weathering. No doors were insulated and weather proofing in terms of air ingress retardation measures were virtually non existent. Unfortunately housing in New Zealand is still a long way (still) from northern European standards.

1.5. Methodology, sample selection and data collection

The current project, which was funded by the Foundation for Research Science and Technology (FRST), monitored houses from the second year of the upgrade program over a period of 2 years, measuring energy consumption and indoor thermal environment. From a total of 200 houses being upgraded in Dunedin in that timeframe, 100 houses were selected to be monitored, these being grouped into two Samples, A and B as shown in Table 1. Due to the need to match the study to the timeline of the actual upgrading process, the comparisons were made in two steps. An initial comparison was made between the two samples of houses during the years 2002–2003 (with the same weather conditions but different houses and occupants). Then a second comparison was made with the same houses, before (2002–2003) and after (2003–2004) they were upgraded (i.e. with same houses and occupants but over consecutive years with different weather conditions).

Houses in Sample A were split into two groups with 22 (D1–D22) houses being monitored in detail. The equipment for these houses was installed in December 2002 and included: electricity meters with a pulse output, pulse counting energy data-loggers for measurement of household electricity consumption as a function of time (20 min intervals), HoBo temperature/relative humidity data-loggers in living rooms (1 h intervals) (HoBo Temperature and Relative Humidity model H08-003-02), and HoBo temperature data-loggers in bedrooms (HoBo Temperature).

The remaining houses in Sample A (D23–D50) together with all houses in Sample B (D51–D100) had basic monitoring equipment installed including ‘iButton’ temperature data-loggers in living rooms and bedrooms recording at 1 h intervals (iButton Temperature monitors by Dallas Instruments) and hour meters on the thermostat circuit to measure electricity use for hot water.

The main household electricity supply meter was read at each visit during the study and, with permission of the householders, additional historic data was collected from the relevant electricity retailer. Electricity consumption for space heating was estimated by looking at the seasonal component of the total consumption, taking into account the seasonal variability of electricity consumption for hot water heating. Information on ‘other’ energy consumption for space heating, that is non-electricity consumption (solid fuel and LPG), was collected from the households during each two monthly site visit.

Air tightness was measured by using “blower door” measurements for a selection of 30 houses (Infiltec E-3 Blower Door, DM4 Dual Digital Micro-manometer). Ambient temperature was collected from the local meteorological station. All temperature data-loggers were calibrated against a traceable standard RT200 platinum resistance thermometer before being deployed in the field and again checked after final retrieval from the homes. Electricity meters were calibrated and installed by the local certified electricity metering company.

Table 1
Sample selection

Sample	Houses denomination	Date of upgrade	Year of program	No. of houses
A	D1–D50	February 2003–June 2004	2002–2003	50
B	D51–D100	October 2003–February 2004	2003–2004	50

1.6. Results of the socio-economic survey

A form based survey was undertaken in order to collect data on household energy use, comfort conditions and socio-demographic characteristics, together with information about the physical characteristics of each house. Results of the survey found that 45% of houses were weatherboard (1940–1950), 47% were brick (1940–1950) and 8% were masonry veneer (1970–1978). The mean floor area was 90 ± 15 m^2 and window to wall ratio was 22.5 ± 15%. 80% of houses had the living room facing north (including N/NE/NW). In terms of income levels, the sample average was found to be 60% lower than the average income for the same region. Electricity was the first choice for a space heating fuel with an average of NZ $120 ± 40 per month for winter bills (June to August) and NZ $80 ± 40 for summer (December to February).

In terms of other fuel usage for space heating, 40% of houses used wood with a yearly consumption ranging from 0 to 7.8 m^3 (the sample average was 1 m^3/year with a standard deviation of 200%). Thirty-nine percentage of houses used coal with annual usage ranging from 0 to 3250 kg (the sample average was 420 kg/year with a standard deviation of 200%). Nineteen percentage of houses reported using LPG heaters with LPG usage ranging from 0 to 470 kg (sample average of 27 kg/year with a standard deviation of 300%). In terms of space heating appliances, 63% of living rooms had open fires (with half of these being sealed) and 29% had retrofitted multi-fuel burners. Bedrooms were heated only by portable electric resistance heaters. All houses had electric hot water cylinders with more than half being of an older and less efficient type. The sample hot water temperature average was 61 ± 8 °C and the shower flow rate was 5.6 ± 2 l/min. Half of the occupants agreed that before the upgrade, houses did not feel comfortable in terms of temperature level or degree of dampness during winter. In addition 80% reported unwanted air ingress problems.

In terms of sample homogeneity, the samples were considered to have similar characteristics, allowing a reasonably fair level of comparison. The most distinct difference in the project sample to a national or regional cohort was in terms of the age of the occupants. In the survey sample, 41% of the occupants were over 50 years of age compared with 22% of occupants over 50 years old for Dunedin city.

1.7. Ambient conditions

Ambient weather data for Dunedin city consisted of hourly averages for air dry-bulb temperatures, wet-bulb temperatures, relative humidity, global solar radiation, wind direction, and mean wind speed.

While daily temperatures from year to year over the study period showed the usual seasonal variation, it was observed that the monthly mean temperatures were generally similar for the same months over the three consecutive calendar years covering the two year investigation. Daily mean solar radiation values during the summer months, varied between a high of 30 MJ/m^2/day to a low of 6 MJ/m^2/day. Monthly averages for solar radiation levels for 2002, 2003 and 2004 were also similar for the same months during the winter months with a little more variation over the summer. In winter the mean solar radiation was less changeable and averaged at about 5 MJ/m^2/day. A comparison of Heating Degree Days (HDD) was done, there was a small increase in the total HDD through the years with 2004 being somewhat cooler than the previous two years (past 30 years average: 2545 HDD; 2002: 2574 HDD; 2003: 2655 HDD; and 2004: 2852 HDD).

1.8. Indoor temperatures

The sample average (100 houses) recorded for indoor temperatures was 14.9 °C for living areas and 13.4 °C for bedrooms when averaged over the two years 2003 and 2004. During the winter months from June to August the actual temperatures for the sample (100 houses) were lower, averaging for those months 13.9 ± 0.4 °C for the living rooms and 10.6 ± 0.3 °C for bedrooms.

The histograms shown in Fig. 2 show data collected from all 100 houses participating in the study for living rooms and bedrooms for the winter months (June to August). It can be seen that occurrences of temperatures above 18 °C were very rare, not reaching even 3% during this winter period.

Indoor temperatures in the living rooms during 'awake-hours' (AH) and in bedrooms during 'sleep-hours' (SH) were calculated to represent a more realistic 'exposure' of the occupants to indoor temperatures. AH are defined as the period between 8am and 11pm and SH are from 11pm to 8am. Occupants were found to be exposed to indoor temperatures of

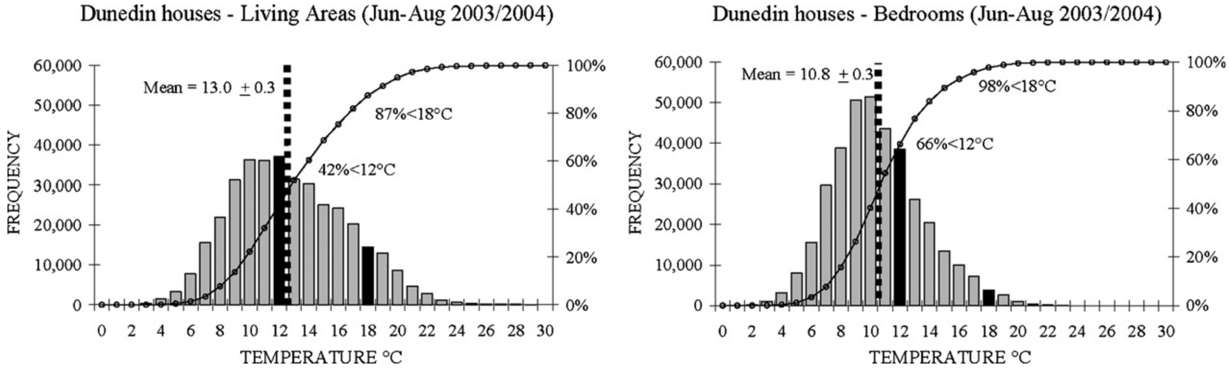

Fig. 2. Hourly temperature frequency profiles for June–August 2003 and 2004.

less than 12 °C, for nearly half (48%) of any 24 h day during the three winter months. These percentages were calculated assuming that the occupants were in the living rooms during AH and in the bedrooms during SH and thus would be an overestimate if they were actually in a public heated place, but an underestimate if they were outdoors exposed to ambient. The socio economic survey gave us data to suggest that the daytime occupancy was between 65% and 70% of the total number of household members and that the night time occupancy was close to 100% of the total number of occupants.

In addition, the actual minimum indoor temperatures recorded for each house (for the upgraded Sample B homes only) was also analysed. Bedrooms recorded an average minimum temperature (the individual household minimum temperatures averaged over the sample of 50 houses), during SH for the winter months (June to August) of 5.0 °C for 2003 and 5.3 °C for 2004. Living areas during AH fared little better, recording a sample average (50 houses) minimum temperature of 5.3 °C in 2003 and 5.4 °C in 2004. The above analysis suggests that the upgrade program had little impact in improving these very low minimum temperatures and that during winter months, people were exposed to very low indoor temperatures. Individual minimum indoor temperatures for homes ranged from between 1 and 10 °C during the winter months.

Temperature differences between the older and the newer homes were one of the most significant findings in the study and are a clear indication of the thermal improvement presented in the later vintage houses. Later vintage houses (post-1970s) with brick cladding and aluminium window frames presented significantly higher annual average indoor temperatures (17.4 ± 0.6 °C for living rooms and 14.2 ± 1.0 °C for bedrooms) than the earlier built brick and weatherboard homes (14.6 ± 0.2 °C for living rooms and 13.4 ± 0.2 °C for bedrooms).

1.9. The efficacy of the upgrade

In order to identify improvements after the upgrade, the net temperature variations were compared. Here the net temperature variations are defined as the differences between the indoor and ambient temperatures with positive indicating warmer than ambient and negative indicating cooler than ambient. In addition because 2004 (2852 HDD) was somewhat colder than 2003 (2654 HDD), a simple linear normalisation was used based on the HDD. The final values are reported as normalised net temperature differences (NTD).

The average ambient temperature recorded over the three winter months (June to August) during 2003 was 7.3 °C, for the same winter period in 2004 it was 6.6 °C. The actual indoor temperatures, averaged across both samples, for the winter of 2003 was 12.8 °C for living rooms and 10.5 °C for bedrooms. Actual indoor temperatures, averaged across the sample, for the winter of 2004 were 12.6 °C for the living rooms and 10.4 °C for the bedrooms. The NTD improvement after the upgrade for both living areas and bedrooms, during winter months, was found to be 0.6 ± 0.2 °C.

Our first comparison looked at both samples with the same weather conditions (2003) but different houses and occupants (upgraded houses in Sample A and non-upgraded houses in Sample B).

The results showed that Sample A was warmer than Sample B by 0.3 ± 0.2 °C in the living rooms and 0.4 ± 0.2 °C in the bedrooms when both samples were upgraded. This temperature difference was presumed to be due to both the structural and behavioural differences between the two samples. Using these values to correct the observed temperature differences during the first winter when Sample A was upgraded and Sample B was not upgraded we found a consistent increase in temperatures of 0.6 ± 0.2 °C in both the living rooms and the bedrooms due to the upgrade. Similarly for the full year, the results of the first comparison showed that the annual average improvement in indoor temperatures for both the living area and the bedrooms was 0.4 ± 0.2 °C.

The second comparison was made between the same houses over 2003 and 2004 (before and after upgrade). Results again showed an increase of 0.6 ± 0.2 °C for both the living rooms and the bedrooms during winter months (June to August). The annual average improvement in indoor temperatures for both living rooms and bedrooms was again found to be 0.4 ± 0.2 °C.

The consistency between the two comparison methods was thus good and we are confident that we found an increase of 0.4 ± 0.2 °C in annual average indoor temperature (averaged over the sample) after the houses were upgraded. The temperature improvement during the winter months from June to August was found to be 50% higher at 0.6 ± 0.2 °C. These small temperature improvements are consistent with the international results reported earlier 44, the 1972 survey 50 and the BRANZ HEEP findings 9. Occupants were found to be exposed to absolute indoor temperatures considerably below the WHO recommended minimum of 16 °C.

When the temperature records were analysed over a 24 h period the larger NTDs found in the living rooms were found to occur mostly after the space heating had been turned off and the family had (presumably) gone to bed. The 24 h profile for one of the samples is shown in Fig. 3. In 2003 that is before insulation, the cooling is seen to occur at a faster rate than during the following year that is after the upgrade.

1.10. Relative humidity

The measured data showed that there was a 6 ± 1% reduction in averaged annual relative humidity of the living rooms after the insulation upgrade. This measured reduction, using HoBo humidity sensors, was entirely consistent with the 0.4 °C annual average increase in temperature observed.

1.11. Air infiltration

The average infiltration for a sub sample (30) of our survey houses was found to be 0.82 ACH/h with the majority of houses between 0.6 and 1.0 ACH/h. Tests were done at a 50 Pa pressure difference (multiplier 1/14). Fig. 4 shows a histogram of the measurements obtained.

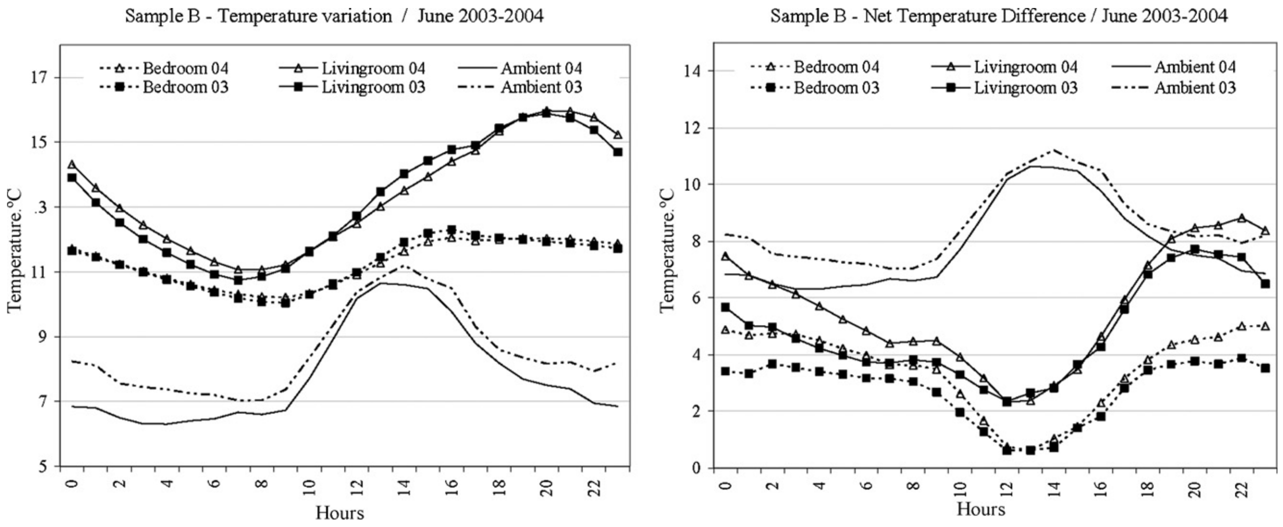

Fig. 3. 24 h temperature profiles for houses in Sample B for June 2003 and June 2004.

2. Results: Energy consumption

While we are very confident in the temperature improvements found after the upgrades, the changes in energy use was more problematic due to the fact that large changes in self reported usage of 'other fuels' (mainly wood and bottled LPG) tended to swamp the more accurately monitored changes in electricity usage. In terms of the total amount of energy provided by other fuel usage for space heating, the total energy produced by each appliance was converted into kW h using the respective calorific values for the different fuel used and the average efficiency values of the appliances as defined in the New Zealand Energy Data File [54]. As the reported use of these 'other fuels' was considerably less reliable (because it was occupant reported rather than measured) than the measured electricity use, the variation in the two fuel types are reported separately. As for the temperature data, the energy use data was corrected due to the difference in the HDD over the monitoring period. The total sample (100 houses) average energy consumption per annum for the monitoring period was found to be 8690 kW h comprised of 22% for other fuels (1960 ± 430 kW h) and 78% for Electricity (6730 ± 80 kW h).

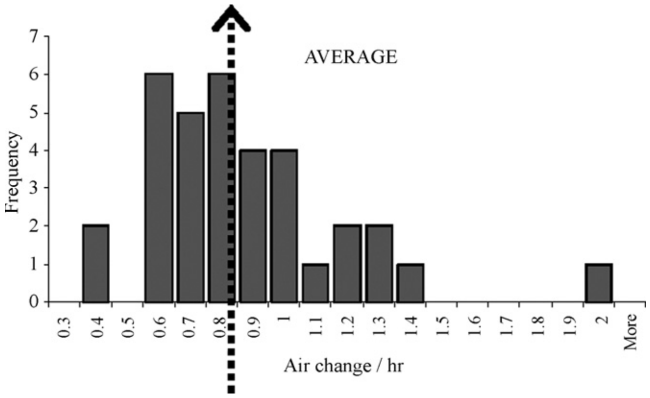

Fig. 4. Histogram showing results of blower door tests.

For houses in Sample A, the historically obtained household annual mean electricity consumption was 7500 ± 60 kW h during 2002 before the houses were upgraded. The measured household annual mean electricity consumption from July 2003 to June 2004 was 6850 ± 110 kW h after the insulation upgrades. After considering the HDD differences between the 2 years, there was a reduction of 13% in electricity consumption for the whole year after houses were upgraded. There was, however, an increase in 'other fuels' energy used for space heating, after the houses in Sample A were upgraded in 2003, which tended to balance out the electricity savings, making the total energy, used for space heating over both consecutive winters (2003–2004) almost the same.

For houses in Sample B, the annual sample averaged electricity consumption per household was 6660 ± 110 kW h in 2003 before upgrading and 6310 ± 110 kW h in 2004, after houses were upgraded. After considering HDD differences, the electricity consumption was found to increase slightly by 7%.

It was concluded that there was a statistically significant reduction of around 10 ± 3% of household electricity consumption for the whole year after the upgrade process. This electricity consumption reduction would represent 7 ± 2% reduction of the total household energy consumption (i.e. including other fuels). Both our results and the BRANZ HEEP survey have shown that space heating energy in the residential sector use is around 1/3 of the total energy consumption [55], this percentage would mean that the upgrade would produce a reduction of 21 ± 6% of the energy used for space heating alone. Because of the large errors involved (standard deviations in the sample mean of up to 200%) in the estimation of 'other fuels' usage, however, the changes in total energy use recorded after the upgrades were not considered statistically significant.

Energy consumption for water heating was found to account for, on average, around 35% of the total year electricity consumption for the study houses. This percentage is in good agreement with other studies 9. There was no reduction in hot water energy consumption after the upgrade due to the fact that

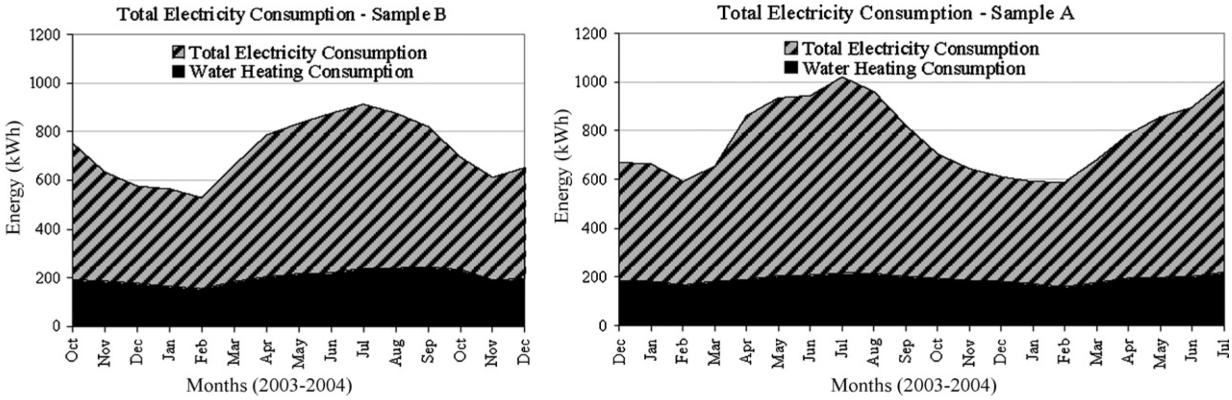

Fig. 5. Electricity consumption for Sample A and Sample B during the monitoring period.

only 2% of the cylinders were insulated during the upgrade process because of the lack of space around the cylinders. Fig. 5 shows the electricity used during the monitoring period for both samples of houses. As it can be seen, there is an increase in energy use during winter months. The lower segment of the graph shows electricity consumption for water heating.

2.1. *The occupants opinions*

Views of the occupants, elicited during the formal socio-economic survey, of the upgraded houses in Dunedin showed that 25% were delighted with the upgrade, saying the house was ‘‘*much warmer than before*’’, 17% said it was ‘‘*warmer*’’, 18% indicated only ‘‘*slightly warmer*’’*,* and 40% expressed the feeling that there was ‘‘*not much difference in thermal comfort*’’. Most occupants expressed the opinion that their ‘other fuel’ usage had slightly reduced after the insulation upgrade. The householder perceptions reflected the relatively low level of increase in measured indoor temperatures. Increasing the ceiling temperature would have increased the mean radiant temperature somewhat and this could have been responsible for some of the reported increase in comfort.

3. Conclusions and discussion

Our measured data have shown that low indoor temperatures exist in public housing in southern New Zealand for most of the year, but particularly in winter, whether or not the houses had the standard upgrade package. This result is consistent with previous studies [9,49]. It can thus be suggested that improving indoor temperatures by increased housing insulation and appropriate heating is still a critical issue in southern New Zealand. The conclusion from the temperature measurements suggest that deleterious health effects are likely to result from such poor thermal comfort, especially for occupants in the over 65 years age group [14].

The bottom line from our results showed a small increase of 0.4 °C in annual average indoor temperatures after a relatively modest upgrade package and no significant improvement in indoor temperatures observed since at least the 1972 survey. Our study is in agreement with both previous studies in New Zealand that indoor temperatures lower than 16 °C are likely to predominate during winter months in low income homes located in the south of the South Island of the country and that houses located in this area recorded highest indoor temperatures in the living areas. The 1972 survey recorded living area temperatures of 13.6 °C for the three winter months in good agreement with our study which recorded 13.9 ± 0.4 °C for similar fabric houses. The BRANZ HEEP study recorded 14.7 ± 0.5 °C but this study included mostly houses built after the insulation regulations came into force in 1978–1979.

It is clear that improving insulation at the levels used by HNZC energy efficiency package has not improved indoor temperatures in the southern part of the South Island in New Zealand to levels that would be considered healthy. It is also likely that the insulation level may decrease in the future as the foil insulation used under floor deteriorates when it accumulates dirt and loses it low emissivity. Even higher levels of insulation applied to the post 1978 building standards suggested only a 1.0 °C rise in winter average indoor temperatures [9]. We would thus agree with Gustafsson that increasing insulation without tackling the lack of space heating is not a good idea [34]. Also the suggestion of Verbeeck and Hens recommending a hierarchy of energy saving measures including insulating all the building fabric and instituting cost efficient space heating is thought to have some merit [35].

Computer thermal modelling was undertaken with results published in a previous report [56]. The modelling together with the actual measurements suggested that if no indoor temperature increase was achieved after the upgrade, then a reduction of between 6% and 10% in total household energy consumption for Dunedin houses participating in the research might have been expected. An energy saving for a 10% reduction in total electricity use is equivalent to around 870 kW h per year, valued at NZ $156 (at $0.18/kW h) and save 160 kg of CO_2 (using the 2004 figures for electricity generation and average CO_2 emissions in NZ of 0.185 kg CO_2 per kW h). The savings would equate to a simple payback time of 10 years, as the initial cost of the upgrade package was around $1600 (2004 NZ $). This is not quite as long as the 20 years found for Canadian study by Guler et al. but suggests that serious economic analysis is needed before proceeding with any upgrade project [36]. In addition, in view of the current findings, the savings suggested by HNZC [24] may be

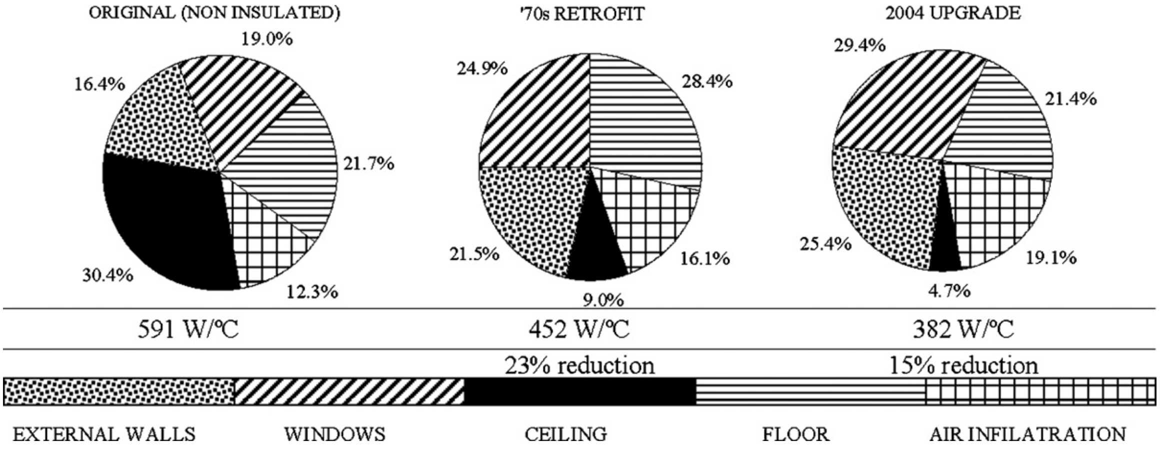

Fig. 6. Comparison of heat losses through the different components of the building envelope for a typical state house: original vs. 70s retrofit vs. 2004 upgrade package.

optimistic after accounting only for the real energy reductions after the upgrade. According to our results householders choose to benefit from the upgrade as 25% energy reduction, while the remaining 75% was taking by an increase in indoor temperatures. This result is in good agreement with international studies exploring low income householders behaviour and their response to energy efficiency programs [25,40,41].

In order to better understand the efficacy of retrofit upgrades, a typical State house was modelled by using standard thermal resistances for each material in the building fabric at each stage of the upgrade. Three historical progressions of upgrading were identified and analysed as shown in Fig. 6. The first graph shows an estimate of how the building would have performed as originally built in 1950s with no insulation at all. The second graph shows the house as retrofitted in 1970s (with R2.2 'insulfluf' installed in the ceiling) and the third graph shows the house in 2004 after the current upgrade undertaken by the HNZC energy efficiency program but with the 'insulfluf' deteriorating to R1.3. As can be seen there was a considerable reduction in heat loss through the ceiling after the first upgrade in 1970s with around 90% of heat loss occurring through building components other than the ceiling after the upgrade.

As might be expected, insulating the ceiling again in 2004 only offered a small improvement over the earlier upgrade reducing the percentage loss through the ceiling to 5% from the 10% after 1970s upgrade. Improving the floor had an impact of further reducing 8% of the overall heat losses, but there is some uncertainly over the long term efficacy of foil insulation [57]. Un-insulated walls and the single glazed wooden frame windows accounted for more than 60% of the remaining fabric losses, while air infiltration is estimated to represent a further 19%. In terms of the total heat loss, there was a possible reduction of 23% after the first 1970s retrofit but only a further 15% after the current upgrade. Clearly there are limits to improving the thermal performance of the building by retrofitting to the ceiling and floor.

In terms of total energy used, the measured values of around 8700 kW h per annum per household or 4100 kW h/person/annum (15 GJ/person/annum), are very low by world standards [1]. If space heating accounts for around one third of the total energy in the residential sector then only around 2900 kW h are currently being used for space heating (our survey results looking at the seasonal component of the total energy use gave 2970 kW h). Computer calculations [21], however, suggest that to maintain an indoor environment compatible with the UK fuel poverty definitions [18] around 14,500 kW h/household per annum would be needed in Dunedin. That means that occupants in the study group would have to increase their space heating energy use by around 500% to get to the UK defined thermal comfort regime (21 °C in living areas 18 °C in bedrooms). The solution to future proof housing in the public sector in New Zealand will in all likelihood need a combination of more intensive fabric upgrades with wall insulation and improved glazing as well as incorporating improved space heating.

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