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Thermal performance of two technically similar super-insulated residences located at 61°N and 41°N latitude

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Abstract

Two super-insulated contemporary residences constructed in 1992 in different climatic regions had the same designer, followed the recommendations of the Alaska Craftsman Home Program and have identical envelope details. One located on a mountainside in Anchorage, AK, has a 180 m² floor area and 6100 °C heating degree-day winters while the other with 128 m² is in Lebanon, CT, with 3400 °C degree-days.

The walls are 29 cm thick ($R=7.2$ m² K/W) and insulation in the roof is 61 cm thick ($R=13.2$). Wall construction minimizes thermal bridging and includes a vapor barrier and a polyester fabric air barrier. The Alaskan residence has floor heating while the Connecticut house has baseboard heating, supplied from gas and oil-fired boilers respectively. Both houses have mechanical ventilation with heat recovery and substantial window areas on the south sides for solar heating assistance.

The energy consumption normalized for area and weather differences is about 30% less for the Alaskan house. About half of this difference is due to a less-efficient boiler, a quarter to the proportionately smaller roof and the remainder to increased air leakage of a fireplace and additional entrances of the Connecticut house. The Alaskan residence won the 1992 Governor's Award for Excellence in Energy Efficient Design.

Keywords: Thermal performance; Insulation; Energy-efficient design

1. Introduction

In cold climates, energy efficiency is an important building design consideration because the *potential for energy consumption is so large*. Furthermore, in cold climates, pleasing and comfortable interior conditions are important because *occupancy time is so large*. When it is unpleasant and dark outside during the long winter it need not also be unpleasant inside. Fortunately energy efficiency achieved through increased thermal insulation better isolates the inside from the outside weather and improves comfort as well as energy efficiency in comparison to conventional construction.

Conventional American wood-frame construction is with vertical 5 cm × 10 cm studs 41 cm apart covered with 1.3 cm plasterboard on the inside and 1.6 cm plywood and siding on the outside. The wall cavity is filled with fiberglass to give the wall a total thermal resistance (R) of about 2.3 m² K/W. Similarly conventional upper ceiling and flat roof construction is with 5 cm × 15 cm ceiling rafters 41 cm apart with fiberglass between, with 1.9 cm plywood and roofing on top and 1.3 cm plasterboard below to give a total thermal resistance of about 3.5 m² K/W. A structure with a substantial increase in insulation above conventional is deemed super-insulated.

This paper is about two such super-insulated houses constructed in 1992 at two different geographic regions of the United States. One (Figs. 1 and 2) is located on a mountainside in Anchorage, Alaska, has a floor area of 180² and experiences long winters (6131 °C degree-days with 18 °C base); the other (Fig. 3) is taller but a little smaller with 128 m² of effective floor area and is located on a lake in Lebanon, CT, where the climate is milder (3394 °C degree-days). The winter/summer outside design temperatures in Anchorage and

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Fig. 1. North and west sides of the Alaskan residence.

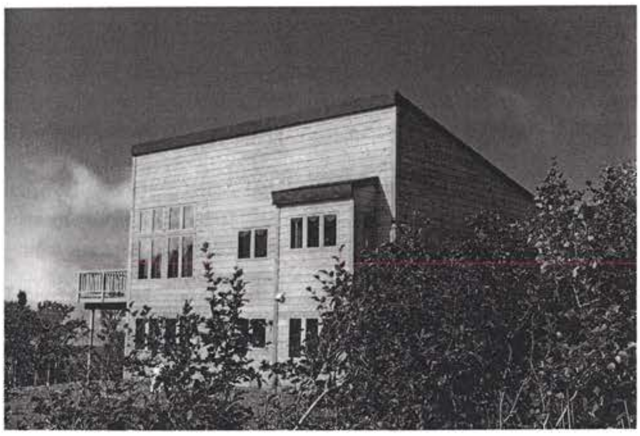

Fig. 2. South and east-facing sides of the Alaskan residence.

Fig. 3. Connecticut residence's south and east-facing sides.

Lebanon are −31/22 and −16/32 °C [11]. Both locations are coastal with Anchorage (61°10′N) situated on the Cook Inlet of the Pacific Ocean and Lebanon (41°33′N) being 30 km inland from the Atlantic Ocean.

2. Architectural design

Both homes had the same designer, Hans Berglund, and design objectives of livability for a small family (Figs. 4 and 5), beauty, healthy comfortable interior, fuel economy and ease of construction. To achieve the latter two objectives, both houses closely followed the recommendations of the Alaska Craftsman Home Program [2,3] and in that regard the structures are nearly identical technically in terms of the thermal envelope details, mechanical ventilation with heat recovery, and hydronic heating. The Alaska Craftsman Home Program promotes various practical and tested techniques to

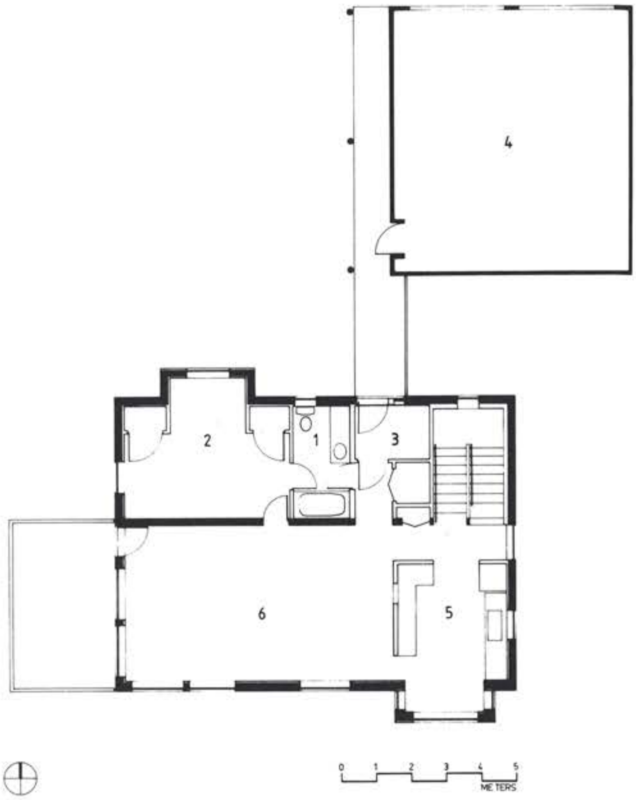

Fig. 4. Plan of Alaskan residence's main or second floor.

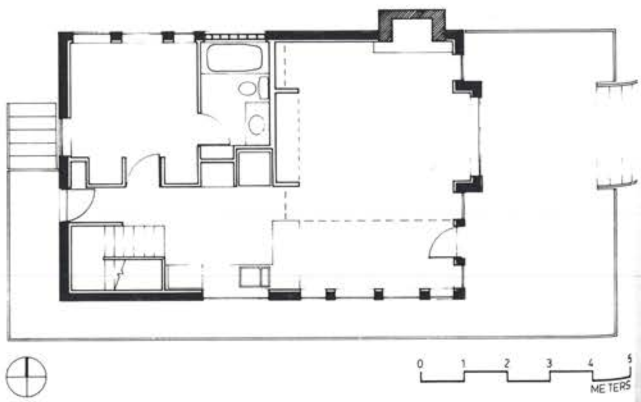

Fig. 5. Plan of Connecticut residence's main or first floor.

increase thermal resistance and reduce energy consumption.

The Anchorage house was built on a large unrestricted lot (1.9 ha) on the southern edge of the city. In contrast, the Lebanon house was a complete rebuilding of an existing single-level lake cottage (Red Cedar Lake) on a very small (0.09 ha) and restricted lot. Because of its small lot, the zoning restrictions would not permit any enlargement of the cottage's footprint of 56 m^2. Thus, to achieve the livable floor area desired, the Lebanon house was built tall, up to the permitted height of 10.7 m, and narrow. This resulted in larger wall envelope areas relative to the roof (Table 1) which partially impacted the low-energy and energy-efficiency objectives but resulted in beautiful views of the lake, particularly from the third floor.

The thermal resistance of a building can be increased primarily by increasing the thickness of wall and roof. One way to increase wall thickness and insulation is to increase the thickness of the structural wood members and put them further apart. This also reduces thermal bridging. But there is a limit to wall stud separation as windows, doors and corners need framing support. In the construction of these houses, the structural supports were increased 50% to 5 cm×15 cm over conventional 5 cm×10 cm elements and then extra insulation was added to both sides of the structural wall (Fig. 6). Outside of the studs, 1.6-cm-thick plywood sheathing was nailed on to give structural resistance to twisting from wind and seismic events. Foam insulation (2.5-cm-thick tongue and groove) was attached to the plywood with glue and nails and covered with a polyester fabric air barrier. The caulked foam insulation is to waterproof and increase the air impermeability of the envelope. Furthermore, its insulation reduces thermal bridging to the outside and the likelihood of condensation occurring in the structural elements of the wall. Cedar siding was nailed on the outside with a 0.6 cm airspace between siding and air barrier to ventilate the back side of the siding. The inside of the structural wall was covered with a 0.2 mm polyethylene vapor barrier. Then horizontal 5 cm ×7.6 cm strapping was attached to support the 1.3 cm gypsum-board inside wall surface. This inside wall cavity, in addition to providing 7.6 cm for fiberglass insulation, is a space for running wires and pipes in the outside walls without puncturing the vapor barrier. The thermal resistance (R) of this wall construction is calculated to be 7.2 m^2 K/W [1].

Because the Alaskan (AK) house is built into a mountainside, its first floor is partially below grade on three sides. Structurally the below-grade walls are of cement blocks tied together with reinforcing bars (Anchorage is a class 1 seismic zone). The blocks are covered with 5 cm of foam insulation (Fig. 7). Above grade to the next floor the foam is covered with plywood, foam, air barrier and siding. The inside surface has 5 cm×10 cm wood nailer strips 41 cm apart covered with 1.3 cm gypsum board with the cavity filled with fiberglass or foam board. Below the cement floor there is 5-cm-thick rigid foam insulation. The insulation thickness is increased to 10 cm near (1.2 m) edges of slab. The below grade part of the Connecticut (CT) house (Fig. 8) is a 1.07-m-high crawl space with non-reinforced cement block walls insulated with 2.5 cm and 5 cm foam on outside and inside. Any exterior foam that extends above grade in both structures is covered with stucco.

The floors and roofs (both have flat or low-pitched roofs) are supported by wood trusses (Figs. 7 and 8) that provide space in the roof for 61 cm of fiberglass insulation and a ventilated airspace between the in-

Table 1
Physical characteristics of the houses

Characteristic	Anchorage, Alaska	Lebanon, Connecticut
Footprint area (A) (m^2)	96.6	55.7
Length; width; height (h) (m)	11.4; 8.2; 7.6	9.1; 7; 10.6
Area per floor (m^2)	88.9; 91.3	53.7; 38.9; 18.3
Wall areas (m^2) (% glass)		
north	69.7 (3.4)	72.5 (7.4)
east	64.6 (4.6)	60.4 (21)
south	69.7 (18.7)	72.5 (13.3)
west	64.6 (16.6)	60.4 (11.7)
% glass of vertical walls	11.3	13.1
Total surface area (TSA) (m^2)	492.5	383.1
Exterior envelope area (EA) (m^2)	395.9	327.4
Volume (m^3)	667	452
Surface/volume	0.74	0.85
Slenderness $h/(A^{1/2})$	0.77	1.42
Roof area/EA	0.24	0.18
Heating system	Floor, gas, hot water	Baseboard, oil, hot water

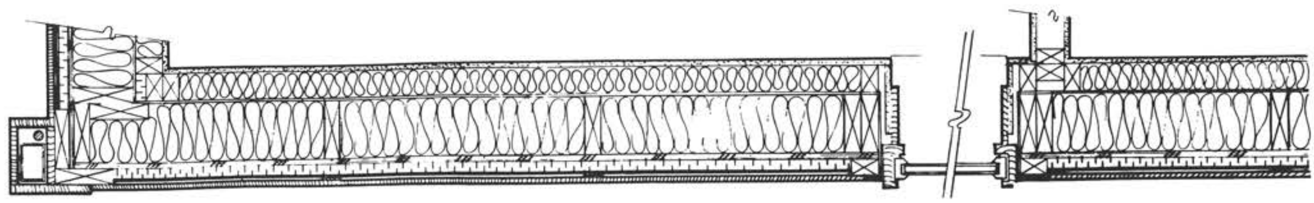

Fig. 6. Plan detail of wall.

sulation and the roof (60 cm^2 net vent area per m^2 of roof). A continuous vapor barrier and plasterboard is attached to the underside of the trusses. The thermal resistance of this roof construction is calculated to be 13.2 m^2 K/W [1]. The cavities of all of the interior walls and floors are insulated for heating zone isolation and to reduce sound transmission.

Both residences have substantial window area (Table 1) on the sunny sides for light and passive solar heating assistance. The east side of the Alaskan house faces the mountain which effectively blocks the low rising winter sun. Windows on other sides are typically small and located high on the outside walls. The windows are of the awning, casement or fixed type with wooden frames. They have two layers of glass, a reflective interior film, a sealed argon-filled space between ($R=0.8$ m^2 K/W (entire window)) and are clad on the outside with vinyl (CT) or aluminum (AK). Further, the cladding has a 6-cm-wide flange for nailing and weathersealing the window to the wall. Deciduous trees shade the Connecticut house from summer solar heating. The Alaskan house is at the tree line and experiences no solar shading other than from the mountain. There are no solar obstructions to the west and southwest but the mountains effectively block the low rising winter sun to the east and much of the south. An open interior design using high ceilings (up to 3.4 m in the kitchen and living room areas of the Alaskan house (Fig. 7) and up to 5.5 m in the living room of the Connecticut house (Fig. 8)), glass block and partial height partition walls give a feeling of spaciousness and help to distribute light throughout the living areas.

3. Mechanical systems

Each house is heated with circulated hot water from gas (AK) and oil (CT)-fired boilers. Gas was not available at the Connecticut site. Boiler selection was based on the heat loss estimates at design conditions of 10.7 kW and 9.4 kW for Alaska and Connecticut (measured 7.6 kW at $T_o=-17$ °C on 16 Jan. 1994). The boilers installed were the smallest available from the respective manufacturers with energy output capacities of 15.5 kW and 20.8 kW. Both boilers have fan-induced draft systems that exhaust directly to the outside at boiler level without a traditional passive chimney to the roof. However, a fireplace for occasional use in the Coı necticut house has a chimney to the roof.

The Alaskan residence has floor heating laid in tw heat control zones (1st and 2nd floor) consisting plastic tubing buried in 2.5 cm lightweight gyp-cret The Connecticut house has baseboard heating with zones (3rd floor, 2nd floor and two on 1st floor). Tl baseboard elements are set back into the wall at tl floor (Fig. 8) to maximize the usable floor space. Bo homes have an additional zone to heat domestic h water in an insulated aquastat-controlled 151-liter tan

The tight construction of both residences necessitat mechanical ventilation for fresh-air requirements durir the heating season. Air-to-air heat exchangers in bo reduce the energy cost of continuous forced ventilatic with outside air (about 0.3 ach). The effectiveness the heat exchangers are about 0.78 (AK) and 0. (CT). Air is exhausted to the heat exchanger from tl kitchen and two bathrooms. Fresh air is supplied fro the heat exchanger to the two-story-high living roo of the Connecticut house and to the living, family ar bedrooms of the Alaskan house.

4. Energy consumption

The energy used to heat the two houses during tl 1992–93 winter (1 Sept. to 31 Aug.) is listed in Tat 2 together with other energy-related items. The me surements are for as-used conditions. The occupar of both houses are working couples. The Alaskan hou typically kept the thermostat at 20 °C during the da when occupied and lowered it to 16 °C at night ar when unoccupied. The Connecticut house kept tl thermostat at 21 °C during the days and lowered it 18 °C at night and to 15 °C when unoccupied. Sor construction work continued until January in bo houses and may have affected energy use. Fuel heati values of 39 972 kJ/m^3 for gas and 38 600 kJ/l for were used to convert fuel to energy consumption.

For comparison purposes, the energy consumpti numbers in Table 2 are also normalized for degre days (*DD*), floor area (*FA*), total surface area (*TS* (includes basement floor), envelope area (*EA*) withc basement floor), and volume. All of the normaliz energy consumption values show the Alaskan house using less energy than the Connecticut house.

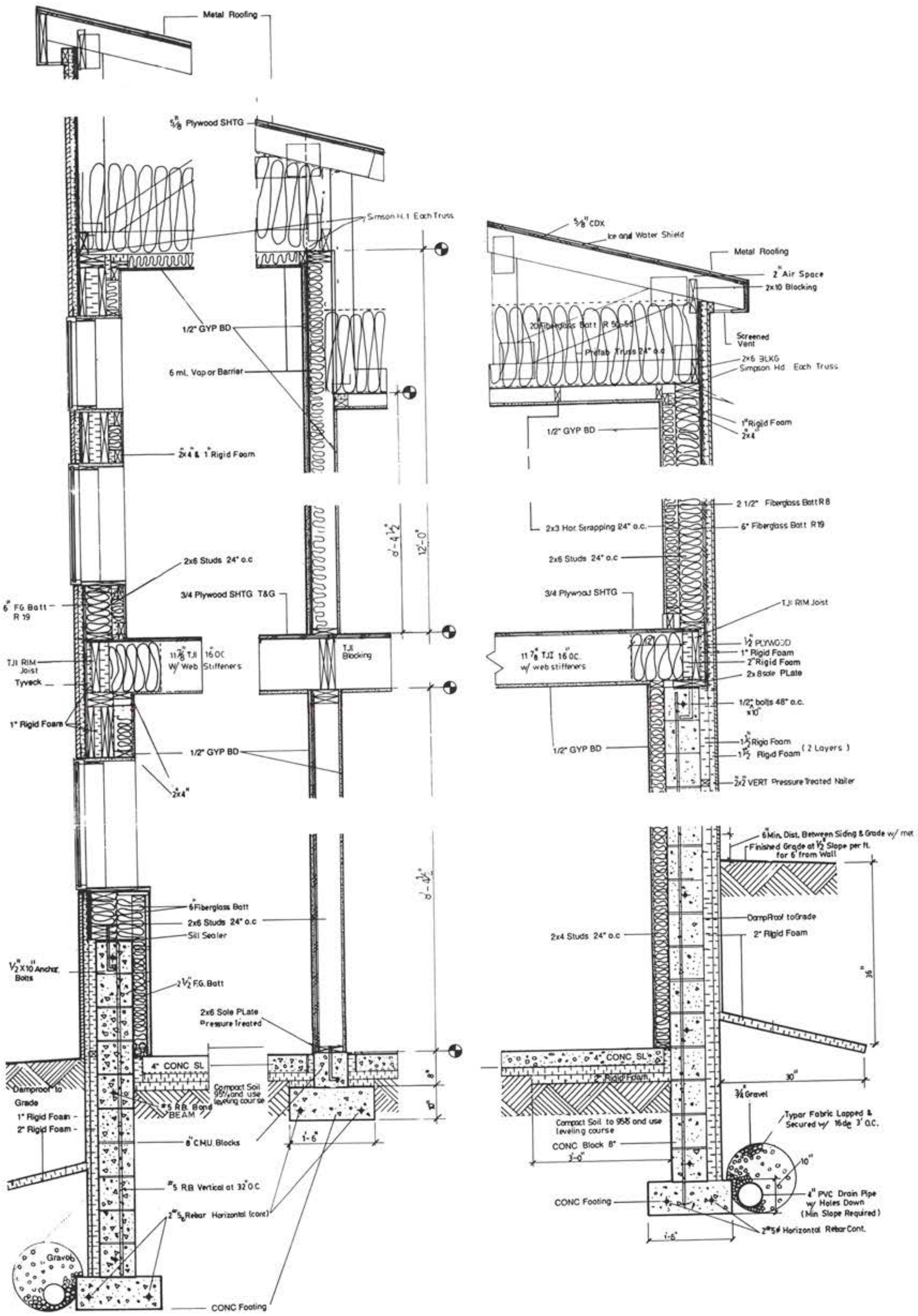

Fig. 7. Section elevation of building envelope details for the Alaskan house.

The daily measured heat consumption for each house as a function of outside conditions is plotted in Fig. 9. The data represent measurements made on 20 days during the fall 1993 and one-day near-design conditions in Jan. 1994 for the Connecticut house, and daily monthly averages for the Alaskan house from September 1992 through March 1994. The outside mean daily temperatures are the average of daily maximum and minimum

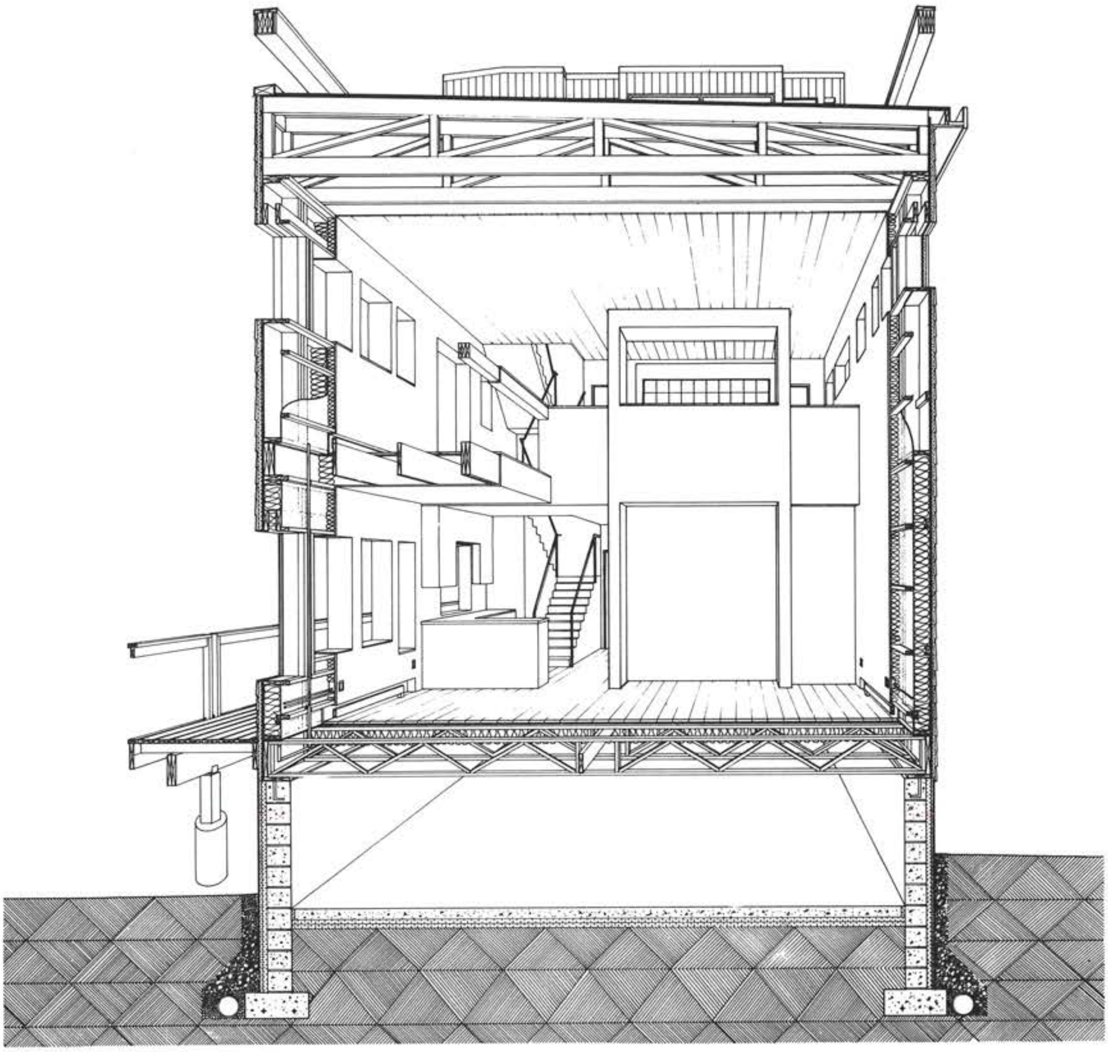

Fig. 8. Cutaway view of Connecticut house showing construction details.

Table 2
Energy consumption for 1992–93 winter

Characteristic	Anchorage, Alaska	Lebanon, Connecticut
Fuel	Gas	Oil
Boiler efficiency	0.88	0.76
1992–93 fuel consumption	2280 m^3	1631 liters
Cost US$	470	366
Electric power cost US$	450	226
Degree-days °C	6130	3394
Occupants	2	2
1992–93 energy input (MJ/yr)	90075	62973
Effective floor area (m^2) (*FA*)	180	128
Energy/yr/*FA* (MJ/yr m^2)	505.7	492.2
Energy/*DD* (MJ/K)	14.7	18.6
Energy/*FA*/*DD* (kJ/m^2 K)	82.5	144.9
Energy/*DD*/*TSA* (kJ/m^2 K)	30.2	48.4
Energy/*DD*/*EA* (kJ/m^2 K)	37.1	56.7
Energy/*DD*/volume (kJ/m^3 K)	22.3	41.0

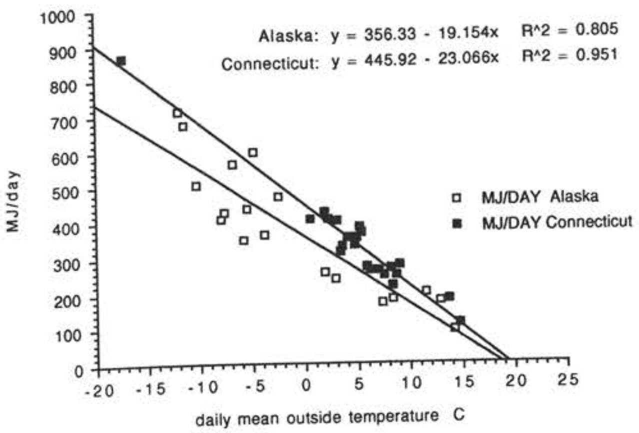

Fig. 9. Relationships between daily measured heat consumption and average outside temperatures for the two houses.

temperatures measured locally in the shade. During this measurement period, the Connecticut house had a constant indoor temperature of 21 °C. The Alaska house used the outside temperatures measured at Anchorage Airport but lowered 2.06 °C for the 323 m higher altitude of the house [1].

From Fig. 9, the balance point or average daily outside temperature below which fuel is used for heating is about 18.6 °C and 19.3 °C for the AK and CT residences.

Another way to compare energy consumption is with the overall specific energy consumption (*SEC*) of the two residences calculated as

$$SEC = Q/(\text{day} \times EA \times (T_i - T_o) \times 24) \qquad (1)$$

which normalizes the daily average heat energy by envelope area (*EA*) and average inside temperature (T_i). Evaluated from the regression lines of Fig. 9 for an outside temperature (T_o) of −10 °C, the *SEC* values are 0.8475 and 1.14 W/(m^2 K) for the Alaskan and Connecticut houses. These *SEC* values are in terms of fuel heat input and include boiler inefficiencies and ventilation heat loss effects. The calculation assumed constant indoor temperatures (T_i) of 18.9 °C and 21 °C for the AK and CT houses. The resulting *SEC* values indicate, as did the normalized energy consumption parameters of Table 2, that the Alaskan home is the more thermally efficient of the two. From the ratio of *SEC* values (1.14/0.85 = 1.34), the Alaskan house is about 34% more energy-efficient by this measure.

The solar effect on heat consumption is substantial. As an illustration, after a constant (14-hour) controlled inside temperature of 21 °C when outside conditions were clear, still and −21 °C winter (7 Feb., Lebanon), solar radiation an hour after sunrise decreased measured oil consumption by 46% from the pre-sunrise rate of 0.85 l/h (9.3 kW) at the same outside conditions. The Connecticut daily energy consumption data of Fig. 9 does not show a solar effect. Cloudy and sunny weather with the same daily mean outside temperature had nearly the same daily energy consumption. Presumably during clear sunny weather, the night temperatures are correspondingly colder than during cloudy conditions, and at least for the Connecticut house the solar gain during the day is compensated with a loss at night.

5. Comfort

In addition to low fuel consumption, the thick insulation and tight construction of these residences isolates their interior environment from outside conditions and enhances thermal comfort at both the 61° and 41°N latitude climate locations. The temperature deviation of inside surfaces of outside walls from room temperature is small, reducing discomfort from thermal non-uniformities and drafts.

In the Alaskan house, thermal non-uniformities of the occupied space are further minimized by its hydronic floor heating system. Measured air temperatures at steady state in the occupied zone were very uniform and independent of location and height (Fig. 10) [4]. The measurement locations were: (A) in the corner of the living room 0.6 m from south and east windows; (B) in the center of the living room; (C) in the living room 0.6 from an interior partition wall; (D) in the kitchen; and (E) in the center of the bedroom. The greatest non-uniformity in air temperature was at the 0.1 m height at locations A and C, where presumably air cooled by the outside walls and windows falls to the floor and moves toward the center of the room.

The design challenge in applying floor heating systems in cold climates is to provide sufficient heat for comfort without over elevating the floor temperature and causing foot discomfort. Fortunately, due to the low energy requirements of this house, the floor temperature required for comfort at design conditions (−31 °C, heat loss = 54 W/m^2 of floor area) is <27 °C. Foot discomfort generally occurs at temperature >29 °C [5]. The floors are carpeted except for the tiled kitchen and bathrooms. At outside conditions of −17 °C the quasi-steady floor temperatures of carpeted areas measured 23 °C with the tiled surfaces a little warmer. The occupants' thermal sensations for their feet and whole body were always very similar. No perception of draft was noted.

Because of the persistent cold weather of Anchorage winters, the heating load is relatively stable and the system's long time constant of approximately three hours has not been a disadvantage. Furthermore, the floor heating system provides maximum usable floor space, is silent and invisible to the occupants, and the warm floor is great for playing children. The occupants and guests have commented that the warm tile floor of the bathroom was a particularly pleasant aspect of the floor heating system on cold winter mornings.

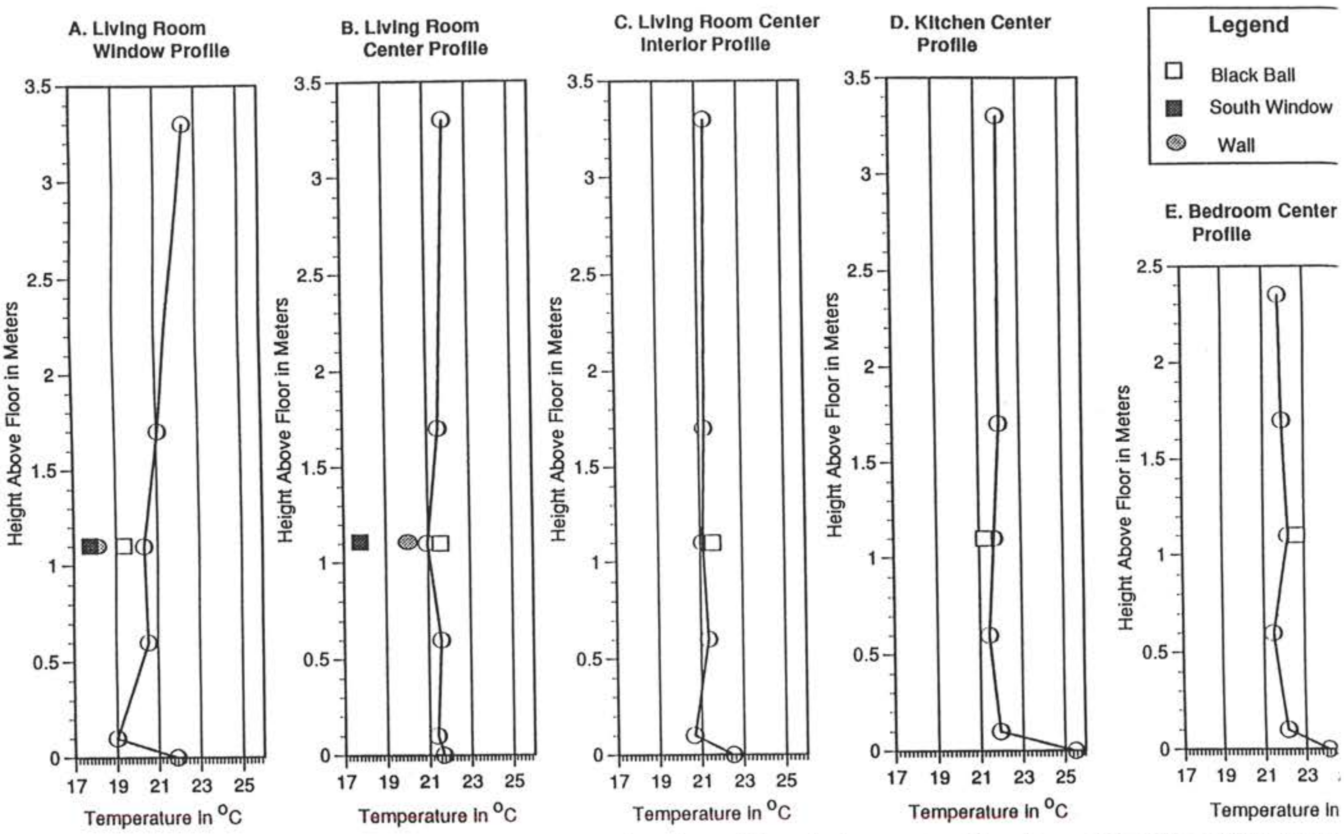

Fig. 10. Temperatures measured in the Alaskan house at quasi-steady conditions in the evening with a thermostat setting of 21.1 °C wh outside temperature was −5 °C.

In contrast, the house at 41°N latitude has hydronic baseboard heating and the air temperatures are less uniform. Typical air temperature profiles measured in the center of the living room and on the 3rd floor are plotted in Fig. 11 for weather conditions similar to those of Fig. 10 [6]. Such profiles with cool temperatures near the floor and warmer more uniform ones above are characteristic of baseboard heating [7]. As in the Alaskan house, no draft or foot discomfort was reported during comfort studies of this residence.

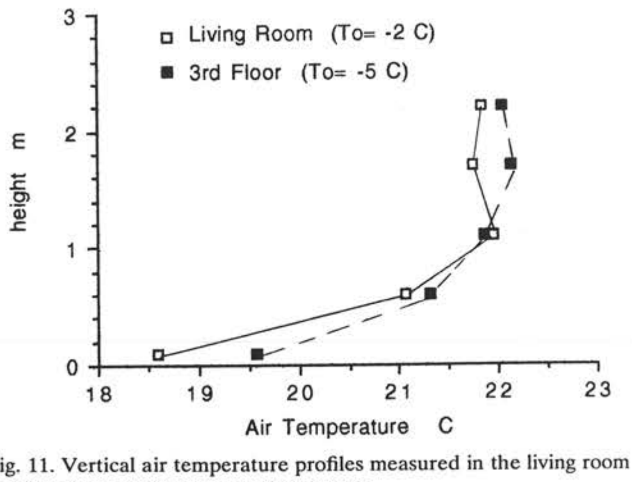

Fig. 11. Vertical air temperature profiles measured in the living room and 3rd floor of the Connecticut house.

The super insulation also provides considerable the mal security. As an illustration, during an October 19 ice storm the Anchorage house was without power an heat for 60 hours. Though the cold continued outsic (−2 °C), the inside temperature dropped to only °C during the period. The Alaskan house has no firepla for auxiliary heat in such situations.

In addition, the super insulation of the shell ai insulation in partition walls installed for thermal pu poses also help to acoustically isolate the inside fro the outside and reduce sound transmission from win rain, sleet, etc.

Interior views of the two houses (Figs. 12 and 1 show finishing treatments and that low-energy ai energy-efficient houses can be attractive and pleasa on the inside.

6. Discussion

The Alaskan mountainside site is subjected to high average winds and less daily sunlight in its more northe location. Thus, at first, it is surprising that it shou consistently measure as more energy-efficient than t CT house with nearly identical thermal envelope deta But on further considering Tables 1 and 2, the ene performance differences are not surprising. The (

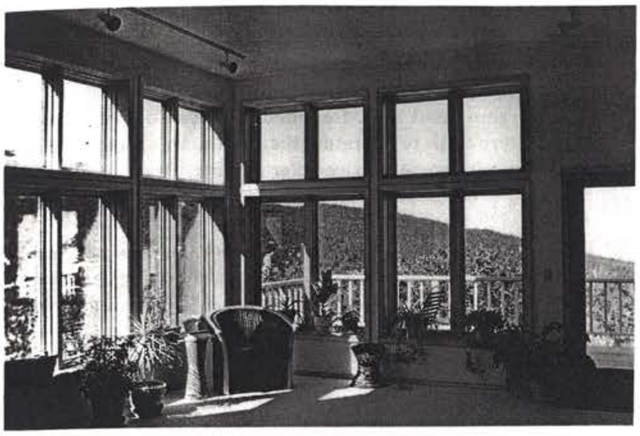

Fig. 12. Living room of the Alaskan house overlooking the valley.

Fig. 13. Dining area of the Connecticut house overlooking the lake.

house is tall and narrow with a 2% higher fraction of glass. The Alaskan house is low with a wider structure built partly into the hillside. The CT house has a recreational fireplace while the Alaskan house does not. Also, the conventional non-condensing oil boiler of the Connecticut house is less efficient than the condensing gas boiler.

In calculating the effect of these design differences, the lower boiler efficiency accounts for about half (53%) of the increased specific energy consumption of the Connecticut house. The roofs of both houses have the same high thermal resistance ($R = 13.2$ m^2 K/W). However, the roof of the Alaskan house is 24% of the total above-ground outside surface area while the roof of the Connecticut house is only 18% of the outside area. This difference in roof wall proportions accounts for about one fourth (23%) of the *SEC* difference. The remaining 24% is likely due to greater air leakage in the Connecticut house. A blower door test of the Alaskan house quantified the air leakage with a 50 Pa pressure difference to be 0.9 air changes per hour, but to date the Connecticut house has not been similarly tested. It is reasoned therefore that infiltration would be greater for the Connecticut house due to its fireplace, proportionately more windows, a greater stack effect from its increased height and its seven doors to the outside in contrast to three for the Alaskan house. Furthermore, the Alaskan house has an 'Arctic entrance' designed to reduce heat loss from the main doorway to the outside. It consists of the outside door, a subheated room for changing jackets and boots and an inside door to the residence. In the Connecticut house, the additional outside doors to balconies on the 2nd and 3rd floors and to the crawl-space basement, the fireplace and additional window area are appropriate and interesting for this lakeside setting, but these features do increase its energy consumption. In comparison to other low-energy houses being built for cold climates, the houses of this study have approximately the same wall and roof insulation as recent low-energy Finnish houses [8] and the measured airtightness of the Alaskan house appears better.

In Sept. 1992, the Alaskan residence won the 1992 Governor's Award for Excellence in Energy Efficient Design [9]. The award corroborates the overall high thermal quality of both homes, the better energy efficiency of the Alaskan residence and the construction practices advocated by the Alaska Craftsman Home Program.

7. Conclusions

The housing designs of this study, based on the Alaska Craftsman Home Program, work in both Alaska and southern New England and are desirable at both locations for long-term energy, comfort and thermal security reasons. Construction details and measured energy consumption of the two houses are very similar. The taller Connecticut house with fireplace, more doors and a less-efficient boiler has a slightly higher energy consumption normalized for degree-days and area. Super insulation equally increased the construction cost of both homes by about 6% (7900 US$ for CT). Eliminating the 2.5 cm layer of foam insulation from the exterior would reduce the increased construction cost by 30% (3000 US$ for CT) while only reducing the thermal resistance of the wall by 12% ($R = 0.9$). or the foam could be replaced with less expensive fibrous material.

The extra costs of a super-insulated home can be recovered faster through energy savings in the 61°N latitude location than in the 41°N one, but it is worthwhile in both, as it would also be in a southern climate for reducing air-conditioning. A conventional US home would consume about 60% or more energy than the ones described here. Thus the payback would be about 282 and 220 US$/yr for the Alaskan and Connecticut houses. However, the weather, heat loss and comfort levels would remain relatively constant with passing years while the cost of fuel would likely rise making the super-insulated house an attractive long-term choice.

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