VACUUM INSULATING WINDOW R & D: AN UPDATE

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ABSTRACT

Windows are the face of a building. They provide the communication between the occupants and the outside world. Daylight, ventilation and view are highly valued and the occasional excess heat gain or loss, drafts, condensation and glare are tolerated because windows make a building habitable. However, as much as 5% of the total U.S. national energy budget can be attributed to building fenestration and consequently, the U.S. Department of Energy conducts research to improve the energy efficiency of windows.

One of these research projects at the Solar Energy Research Institute (SERI) is evaluating the practical feasibility of an evacuated, insulating window glazing with a center-of-glass thermal resistance of about R=16 (F ft^2 hr/Btu) and a solar heat gain factor of more than 0.8. The basic design is similar to a conventional, sealed insulating glass unit with a low-emissivity coating. The increased thermal resistance is achieved by evacuating the very narrow (0.02 inch) permanently sealed space between the panes. Very small, nearly invisible, glass spheres spaced about one inch apart in the evacuated gap support the window against collapse under atmospheric pressure.

This paper focuses on analyses which were conducted to determine the probable energy performance of a vacuum insulating window in northern U.S. climates. It compares the heating energy requirements for residential buildings with conventional, double glazed windows to the same buildings with a variety of high performance windows including the vacuum window. Three different types of building were considered; conventional light weight construction, super-insulated construction and passive solar heated buildings. The vacuum window was predicted to provide net useful energy gain over the heating season even when used on the north side of all three building types in locations such as Boise, Idaho or Portland, Oregon. The net energy savings over conventional sealed insulating glass windows was predicted to be about 60 kBtu/year for each square foot of window.

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INTRODUCTION

A vacuum insulating window design and fabrication process have been invented at SERI (Benson and Tracy, 1987). Engineering design analyses suggest that this window will have a thermal resistance of about R=16 F ft^2 hour/Btu (thermal conductance of 0.35 watt/m^2 K) at the center of the glass area and will have an area-averaged thermal resistance greater than R=10 depending on the design of the window frame.

The new window achieves its large thermal resistance from a combination of design elements. The principle barrier to heat flow is a narrow evacuated space (about 0.02 inches) between the two glass panes (Figure 1). It is proposed that this evacuated space be permanently sealed by laser welding the perimeter in a vacuum chamber at an elevated temperature. Radiative heat transfer across the evacuated gap is reduced by use of one or two transparent, low-emissivity coatings on the interior glass surfaces. Internal mechanical supports are required to prevent the atmospheric pressure from collapsing the evacuated structure. This support is provided by a regular array of glass spheres (0.02 inch diameter) distributed between the glass sheets. These spheres are virtually invisible. A small quantity of a reactive metal is placed in the vacuum gap during assembly in order to trap any gases evolved from the internal surfaces after sealing and to insure the very high vacuum (less than 10^{-5} torr, < 0.0013 Pa) that is required.

A new method has been used to predict the heating energy use of residential buildings which incorporate high performance windows such as the vacuum window. This method predicts that the use of a vacuum insulating window will save about 60 kBtu of heating energy per square foot of window area per year when compared to conventional insulating windows in climates typical of the northern tier of states in the U.S.

Impact of Energy-Efficient Windows on Building Energy Use

Seasonal Performance of Advanced Glazings. A variety of energy-efficient glazings are available with thermal performance superior to typical double glazing. The superior insulating values are achieved with the use of low-e coatings, additional interpane spaces (created by additional glass panes or plastic films that could have low-e or antireflecting coatings), and/or low-conductance fill gases. Several of these measures involve a reduction in solar transmittance and hence a trade-off between improved R-value versus reduced solar heat gains. On the other hand, the solar transmittance of windows can be increased by use of low-iron glass and/or antireflectance coatings.

Glazing characteristics such as the overall heat-transfer coefficient and shading coefficient are often available from the manufacturer or can be calculated (Arasteh, et al, 1986). Based on such values, performance at winter or summer design conditions can be determined. Heating season performance can be estimated from glazing characteristics in a manner analogous to calculations for solar collectors (Harrison and Barakat, 1983), but this approach requires an assumption of heating season length and does not account for the degree of thermal storage in the building. Hourly simulations can be used to include these aspects of building performance (Rubin and Selkowitz, 1981), and correlation methods based on hourly simulations have been developed. However, these simulations have been limited to a few typical glazing types such as single, double, or triple glazing (with or without night insulation) (Balcomb, et al, 1984). In this paper, a simple method has been used to extend the well known Solar Load Ratio (SLR) calculations to nonstandard glazing types.

Analytical Approach. Glazings can be characterized in terms of overall heat-transfer coefficient (U) and shading coefficient (SC). For a given area (A), heat loss is proportional to UA. The SC, as defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), is the ratio of the solar heat gain through the glazing (including the fraction of solar radiation absorbed in the glazing that is subsequently transferred into the room) to the solar heat gain through single glazing. The SC can be thought of as an effective transmittance relative to standard single glazing.

The method described in this paper is based on the following premises for passive solar heated buildings:

- a change in the UA of the glazing is indistinguishable from an equivalent change in the overall building UA
- a change in the SC of the glazing is indistinguishable from an equivalent change in the window area or the transmitted solar gains.

Hence, nonstandard glazing types can be analyzed with the monthly SLR method or with the annual load collector ratio (LCR) method by using modified building and climate parameters to account for differences from standard glazing properties. The necessary modifications are given in this paper to use this approach with the fast solar load ratio (FSLR) method developed by Wray (Wray, et al, 1983).

This approach depends on the additional assumption that glazing performance can be adequately based on U and SC. The validity of using constant Us and SCs to estimate seasonal glazing performance has been confirmed by comparison with detailed hourly calculations (Harrison and Barakat, 1983). To account for variation in solar transmittance at off-normal incidence angles, SCs could be based on average incident angle transmittances. Some effects are not accounted for in this approach (or in some hourly simulations such as DOE-2 and SERIRES): 1) effects of infrared coupling between the inner surface of the glazing and other building interior surfaces and 2) effects of mean radiant temperature and occupant comfort; however, these effects on energy usage are known to be small.

The FSLR Method. The following relationships are used in the FSLR method:

$$Q_{aux} = Q_L(1 - SHF_Y) \tag{1}$$

$$Q_L = (BLC + G \cdot A_s)DD_Y \tag{2}$$

$$SHF_Y = (1 - e^{-SLR_m}) (1 - a\ e^{-SLR_m^*}) \tag{3}$$

$$SLR_m^* = [F \cdot (VT_s/DD)_m \cdot \alpha]/(LCR + G) , \tag{4}$$

where

U = thermal conductance per unit area = 1/R (Btu/°F hr ft^2)

Q_{aux} = auxiliary heating (Btu/yr)

Q_L = building heating load (Btu/yr)

SHF_Y = annual solar heating fraction

BLC = building load coefficient (Btu/°F day), not including $U*A_s$

G = effective glazing conductance (Btu/°F day ft^2)

A_s = south glazing area (ft^2)

DD_Y = annual heating degree-days (°F day), based on the balance point temperature T_b

a = location-dependent correlation factor

SLR_m^* = scaled solar load ratio for the month with minimum SHF

F = system-dependent scale factor

$(VT_s/DD)_m$ = ratio of monthly solar radiation transmitted through vertical south glazing to monthly degree-days (Btu/ft^2 °F day), for month with minimum SHF

α = effective solar absorptance

LCR = load collector ratio (BLC/A_s).

The parameters a, F, G, and α were determined from hourly simulations and are tabulated (Wray, et. al., 1983).

Modified Parameters. To extend the FSLR method for additional glazing types, modified input parameters are used to account for the new glazing properties U' and SC' (where U and SC are properties of the reference glazing type; i.e., double glazing). Four modified parameters are to be used in Equations 2 through 4:

$$G' = G - 24(U - U') \tag{5}$$

$$(VT_s/DD_m)'' = (VT_s/DD_m)' (SC'/SC) \tag{6}$$

$$DD_Y' = DD_Y \text{ based on } T_b' \tag{7}$$

$$a' = \text{the correlation factor "a" based on } T_b' \,, \tag{8}$$

where

$$(VT_s/DD_m)' = (VT_s/DD_m) \text{ based on } T_b'. \tag{9}$$

Values for DD_y', a', and $(VT_s/DD_m)'$ can be determined from tabulated FSLR data by interpolation based on the modified balance point temperature:

$$T_b' = T_{set} - \frac{Q_{int} + VT_n A_n SC'}{BLC + G'A_s - 24(U - U')A_n} \,, \tag{10}$$

where

Q_{int} = internal heat gains from appliances, people, etc. (Btu/day)

T_{set} = thermostat heating set point (°F)

VT_n = monthly solar radiation transmitted through vertical north glazing (Btu/ft^2 month)

A_n = north glazing area (ft^2).

Glazing, Climate, and Building Data. Glazing characteristics are shown in Table I. U-values and SCs shown in the first and second data columns are for standard soda-lime double glazing with an air gap. The U-values shown in the third data column are for the same window with a krypton gas fill. The SCs shown in the fourth data column are for low-iron glass. In all cases, the gaps between panes are assumed to be 0.5 in.

Climate characteristics for Portland and Boise are extracted from tabulated FSLR data (Wray, et al, 1983)

Building characteristics include T_{set} = 70°F, Q_{int} = 50,000 Btu/day, and A_n = 50 ft^2. The conventional BLC value of 10,800 Btu/°F day is representative of a residential building of approximately 1500 ft^2. The passive solar BLC is 8400 Btu/°F day and the superinsulated BLC is 6000 Btu/°F day. The passive solar south glazing area is 200 ft^2. The conventional and superinsulated south glazing areas are 50 ft^2. The passive solar value of F corresponds to a recommended level of storage mass (6 ft^2 of 4-in.-thick concrete per ft^2 of south glazing). The conventional and superinsulated values of F correspond to the mass of drywall and lightweight building materials relative to 50 ft^2 of south glazing.

Results and Discussion. Glazing performance is shown in terms of:

- net useful flux (per ft^2 of glazing) calculated as the difference in auxiliary energy use with and without the glazing (indicates the absolute energy value of glazing)
- net energy savings (per ft^2 of glazing) calculated as the difference in net useful flux for the particular glazing versus double glazing (indicates the incremental energy value versus conventional double glazing).

Figure 2 shows net useful flux per ft^2 of glazing in two northern U.S. cities, Portland, Oregon and Boise, Idaho. For north glazing (Figure 2a), net useful flux is essentially identical regardless of building type. For south glazing, the trends in net useful flux are similar for all building types (i.e., the curves are approximately parallel) and the levels of net useful flux depend on building type.

Figure 3 shows net energy savings (relative to double glazing). For south glazings in Portland (Figure 3a), net energy savings are lower in the passive solar building (by less than 10%) compared to the conventional building. Net energy savings in the superinsulated building compared to the conventional building are slightly higher for glazings with low-e films and slightly lower for glazings with antireflectance films. For north glazings in Portland (Figure 3b), net energy savings are insensitive to building type, except that savings are slightly lower for the passive solar building. For south glazings in Boise (Figure 3c), net energy savings show a complex dependence on building type and glazing type. For north glazings in Boise (Figure 3d), net energy savings are approximately 15% lower in the passive solar building than in the other building types.

Figure 4 shows the effects of low-iron glass and low-conductance gas fill, singularly and together, in the conventional building in Portland, the conventional building in Boise, and the passive solar building in Boise. In Portland, the results for the solar building (not shown) are essentially identical to the conventional building results. In all cases, the savings for the combination approximately equal the sum of the savings for low-iron glass and the savings for gas fill separately. For north glazings, most of the savings are due to the gas fill. For south glazings in the conventional building in Portland and the passive solar building in Boise, the savings owing to low-iron glass and the savings owing to gas fill are approximately equal. For south glazings in the conventional building in Boise, the savings are greater than in other building types and climates, and savings due to low-iron glass are greater than savings due to gas fill. The increase in savings is especially large for the second glazing type; i.e., with low-e coating on the glass.

DISCUSSION

Parametric variations of glazing types in typical residential buildings can be analyzed easily with SLR methods by using modified building parameters to account for differences from standard glazing properties.

For glazings with suspended plastic films and low-e or, in some cases, antireflectance coatings, net energy savings (relative to double glazing) are 15 to 48 $kBtu/ft^2$ yr, depending on building type and glazing orientation. Further savings of approximately 10 to 20 $kBtu/ft^2$ yr are possible, particularly for south glazings, with the use of low-iron glass and a low-conductance gas fill. Predicted savings for an evacuated glazing are 51 to 67 $kBtu/ft^2$ yr, superior to all other glazing types analyzed and approximately 3 to 5 times better than other glazing types that do not incorporate suspended plastic films. Table II summarizes comparisons for conventional buildings.

Net energy savings (relative to double glazing) for south glazing in Boise are lower than for north glazing in Boise or either orientation in Portland. Net energy savings for south glazing in Boise are more sensitive to building type, and the pattern of energy savings among glazing types is different.

At present, the costs of delivered energy is on the order of $10 per million Btus and the predicted energy savings for a vacuum window would be worth only about $0.6 per square foot each year. If a vacuum window were made for $5 per square foot more than a conventional insulating window, its installed cost would be about $15 per square foot more than a conventional window and its simple payback period would be 25 years. Other high performance windows with similarly long and longer energy paybacks are presently enjoying market success and so we must recognize that whether a vacuum insulating window can become a practical reality depends upon other benefits perceived by the market in addition to energy savings.

The other potential benefits of a vacuum window include: greater comfort through the prevention of drafts and reduced radiative body heat losses near the window; greater architectural freedom to locate windows wherever and in whatever size is desired without sacrificing comfort and energy efficiency; and others such as the prevention of water condensation on the inside pane and the light-weight, thin-section designs which may make them suitable as operable windows.

CONCLUSIONS

Preliminary applications analyses using a simple building performance prediction method suggest that vacuum insulating windows could find very beneficial application in the climates typical of the northern U.S. Energy savings of 50 to 70 $kBtu/ft^2$ window area per year could be expected from the use of vacuum windows in place of conventional double-pane windows in representative areas such as Portland, Oregon and Boise, Idaho.

The acceptance of a vacuum insulating window glazing by the residential building industry will depend critically upon the production costs. Other advantages of the vacuum window glazing may favor its acceptance. Advantages such as its light weight and thin section, reduced convective drafts and condensation, good view quality and the design freedom its use allows architects in orienting windows for maximum aesthetic impact.

Ongoing laboratory research at SERI is aimed at testing the feasibility of a potentially high-speed, low-cost fabrication process which may allow more economical production of the vacuum window. Facilities have recently been completed in which small scale, evacuated test windows up to about three feet square will be made by vacuum laser sealing. Major U.S. glass and window manufacturers have expressed interest in the design concept and have expressed willingness to test prototypical samples.

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Table I. Glazing characteristics.

Glazing Type	U	SC	U^k	SC^l
1.‡ g-g	0.50	0.88	0.46	0.94
2. g-eg	0.34	0.77	0.27	0.82
3. g-e-g	0.24	0.67	0.20	0.71
4. g-e-e-g	0.15	0.60	0.11	0.63
5. g-a-g	0.34	0.85	0.30	0.91
6. g-a-a-g	0.26	0.82	0.23	0.88
7. g-v-eg*	0.10	0.82	--	--

U-value units are Btu/h ft^2 °F; to convert to W/m^2 K, multiply by 5.68.

g = soda-lime glass (1/8 in. thick)

e = low-e coating on glass or plastic film with low-e coating on inside surface (e = 0.15)

a = plastic film with antireflectance coatings on both surfaces

v = vacuum

l = low-iron glass (1/8 in. thick)

k = krypton gas fill in place of air

* estimated characteristics for vacuum glazing (with borosilicate glass)

‡ numbers 1 through 7 refer to labeled points on the horizontal axes of Figures 2, 3, and 4.

Table II. Summary of predicted net annual energy savings vs. standard double glazing in a conventional building (kBtu/ft^2 yr).

Glazing Type	Portland		Boise	
	South Glazing	North Glazing	South Glazing	North Glazing
1. g-g	--	--	--	--
2. g-eg	16	19	12	23
3. g-e-g	25	30	16	37
4. g-e-e-g	32	39	20	48
5. g-a-g	23	24	24	28
6. g-a-a-g	31	33	32	38
7. g*-v-eg*	56	58	60	67

g = soda-lime glass (1/8 in. thick)

e = low-e coating on glass or plastic film with low-e coating on inside surface (e = 0.15)

a = plastic film with antireflectance coatings on both surfaces

v = vacuum

l = low-iron glass (1/8 in. thick)

* estimated characteristics for vacuum glazing (with borosilicate glass).

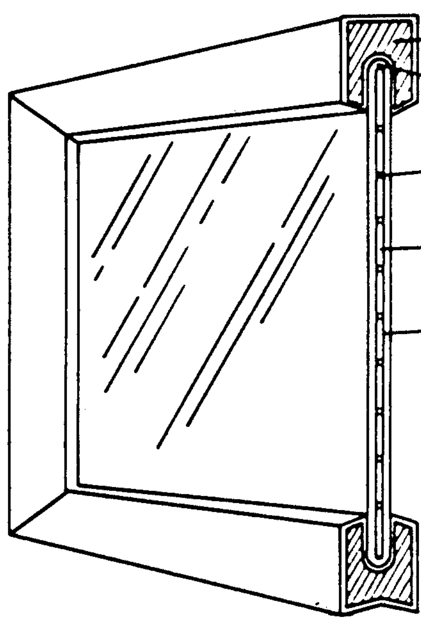

Figure 1. Schematic diagram of the evacuated window glazing design.

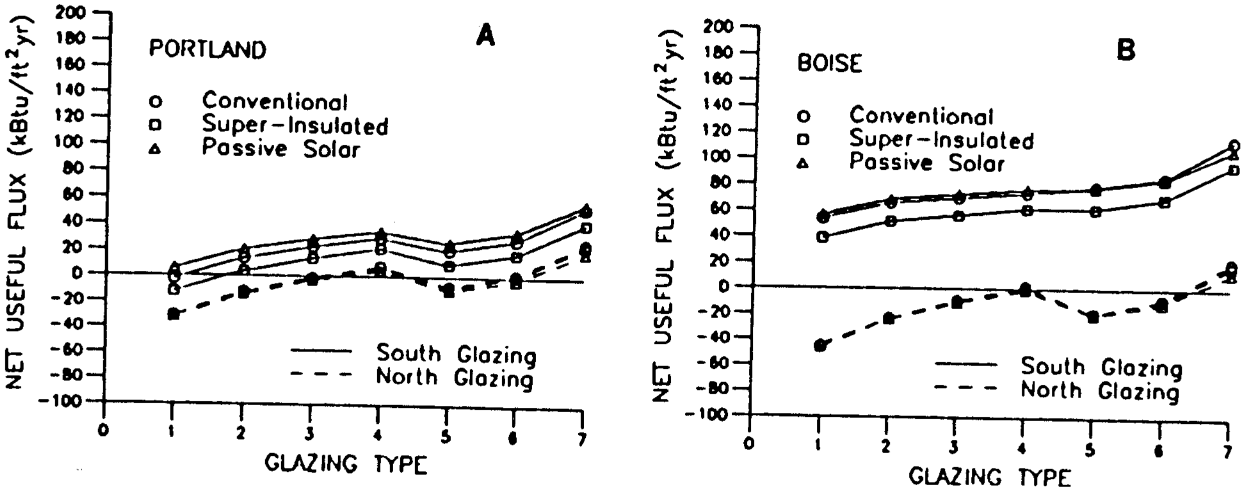

Figure 2. Net useful solar heat flux through different types of glazing (Table II) for three building types.

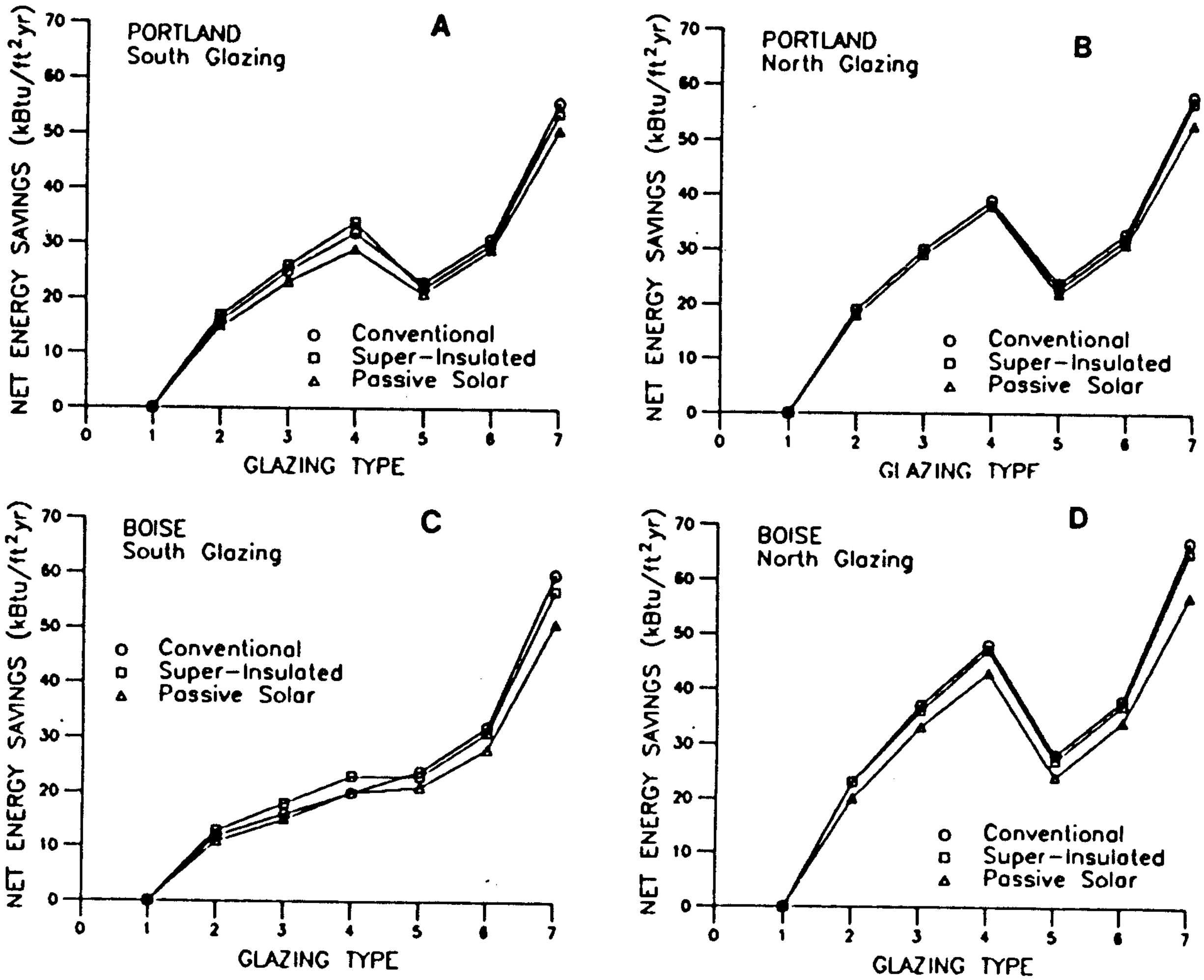

Figure 3. Net reduction in heating energy use (relative to conventional double glazing) for three building types.

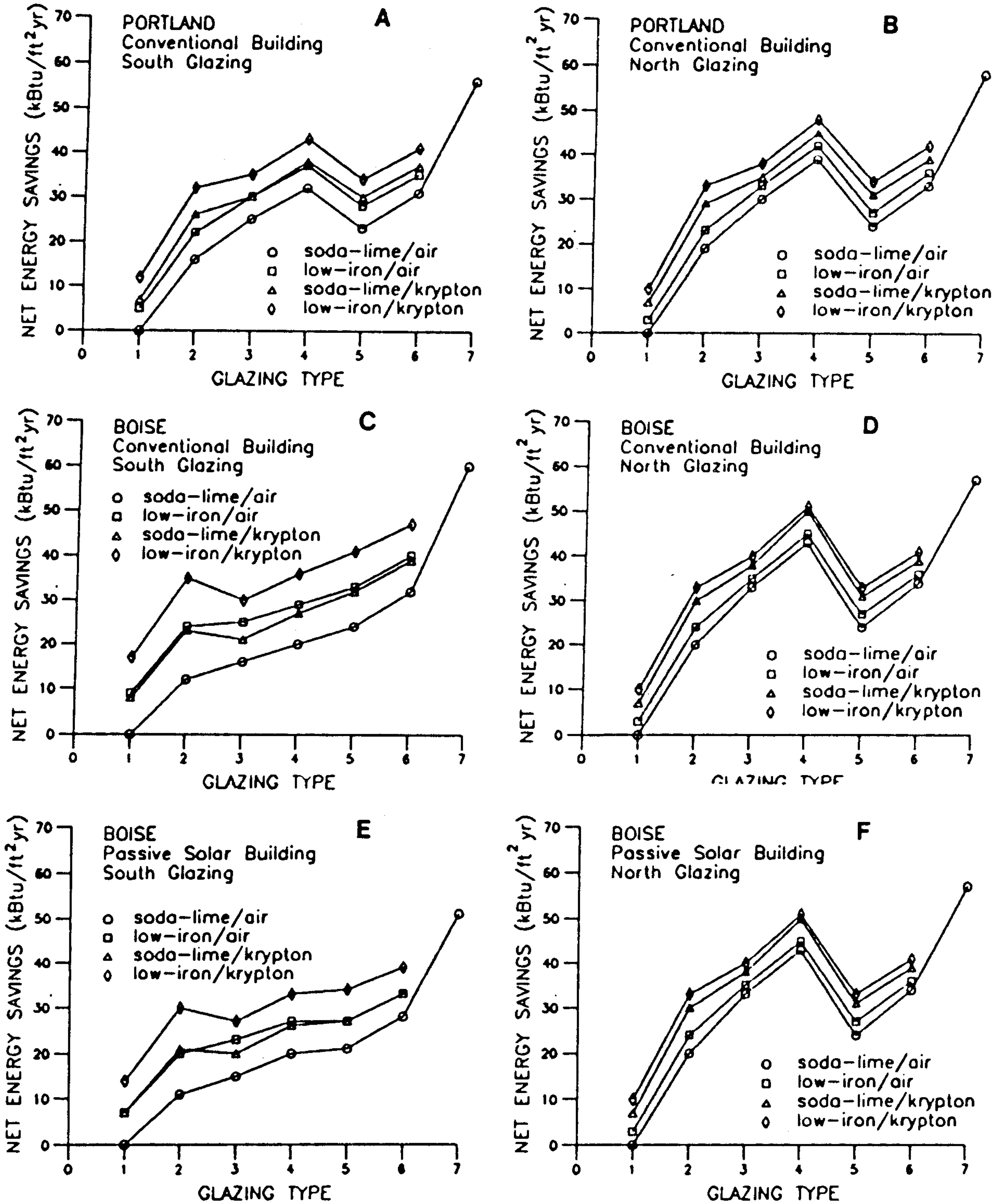

Figure 4. Net reduction in heating energy use (relative to conventional double glazing) for different types of glazings (Table II) used in south or north-facing conventional or passive solar heated residential buildings.