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ENERGY EFFICIENCY IN CHINESE APARTMENT BUILDINGS: PARAMETRIC RUNS WITH THE DOE.2 COMPUTER PROGRAM

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DISCLAIMER

This is the second of two papers presented by A. H. Rosenfeld at the First U.S.-China Conference on Energy, Resources and Environment, Beijing, China, November 7-12, 1982. Paper I ("Technology for Energy-Efficient Buildings," LBL 15182, EEB 82-2) is in the Proceedings; this paper was completed after the Proceedings deadline.

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ENERGY EFFICIENCY IN CHINESE APARTMENT BUILDINGS:

Parametric Runs with the DOE.2 Computer Program.

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ABSTRACT: Using a typical-design uninsulated Beijing apartment building as a base case, we have used the DOE.2 energy analysis program to study the cost-effectiveness of more energy-efficient building design. Two measures have attractive simple payback times: reduced infiltration (one to two years payback) and insulation of the north wall (six years). The cost of conserved coal for the insulation measure is 1.3 Yuan/GJ, which is less than half the international price of coal. This insulation adds only 0.6% to the first cost of the building, yet, combined with more attention to infiltration, it reduces annual heat load from 230 MJ/m^2 to 130. The first cost of these two measures is probably offset by downsizing the heating plant. In Shanghai, reduced infiltration and insulation are justified not on the basis of saving fuel, but because they make the dwellings much more comfortable.

KEY WORDS: Apartment Building, Conservation, Cost of Conserved Coal, Energy Analysis, Energy Efficiency, Glazing, Infiltration, Insulation, Least Cost, Life-Cycle Cost.

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CONTENTS

I. INTRODUCTION, by A. H. Rosenfeld

This paper is the second of a pair. I was invited to speak on "Technology for Energy-Efficient Buildings" at the First U.S.-China Conference on Energy, Resources and Environment, to be held in Beijing, November, 1982. Accordingly, I submitted "Paper I" [Rosenfeld, 1982], recommending that Chinese apartment buildings should have more insulation, and better coupling to their thermal mass, and that Chinese office buildings should modify their window design to improve daylighting.

In Paper I, the recommendations about insulation were based on hand calculations and on U.S. prices for insulation. The results looked so interesting that the four present authors decided to obtain Beijing and Shanghai weather tapes for our DOE.2 computer program (for building energy analysis), make a series of parametric runs, and gather prices from colleagues in China. The result is this Paper II.

Methodology. We have made eight parametric runs for each city, starting with the typical-design "Base Case" described in Section II. We tried more insulation, double glazing, and decreased infiltration.

DOE.2 gives us "load" and "fuel" savings. "Load" is defined as the heat that must be delivered by the heating system. "Fuel" is the Load divided by the efficiency of the heating system (which we assume is 70%), and we assume that the fuel is coal.

Once we know the first cost of each measure, and the annual coal savings, we calculate two economic criteria (defined in Section VII):

1. Simple Payback Time, and
2. Cost of Conserved Coal

We also note the decrease in peak hourly load achieved by each measure. This decrease permits downsizing the heating system, and perhaps saves more then the first cost of the measure.

II. A TYPICAL DESIGN THREE-APARTMENT "MIDDLE" UNIT

Computer simulations were done for a "typical design" low-rise residential building representative of current Chinese construction. The building is four stories high, with load-bearing walls and prefabricated hollow-core concrete slab floors. (see Figure 1) For the sake of simplicity, only a middle floor unit with three apartments and a stair well has been simulated. The assumption is made that there are neither heat losses or gains through party walls, floor, or ceiling. For roof or end units, the total heating loads would be larger, but the energy savings per m^2 from wall and window conservation measures would remain essentially the same.

The dimensions of the three-apartment middle unit are 17.1m by 8.4m, with floor-to-floor height of 2.8m. The total floor area is 143.6 m^2, with 66.1 m^2 of exterior walls, 174 m^2 of interior walls, and 24.1 m^2 of windows. For all computer runs the floors were modeled as 18 cm thick hollow-core concrete panels topped with 2 cm of cement. The ceilings

	North wall	South wall
Wall area	36.0 m²	30.1 m²
Windows	11.9	12.2
Doors	0	5.5
Base case wall construction	37cm brick R-0.70	24cm brick R-0.53 (°C m²/W)

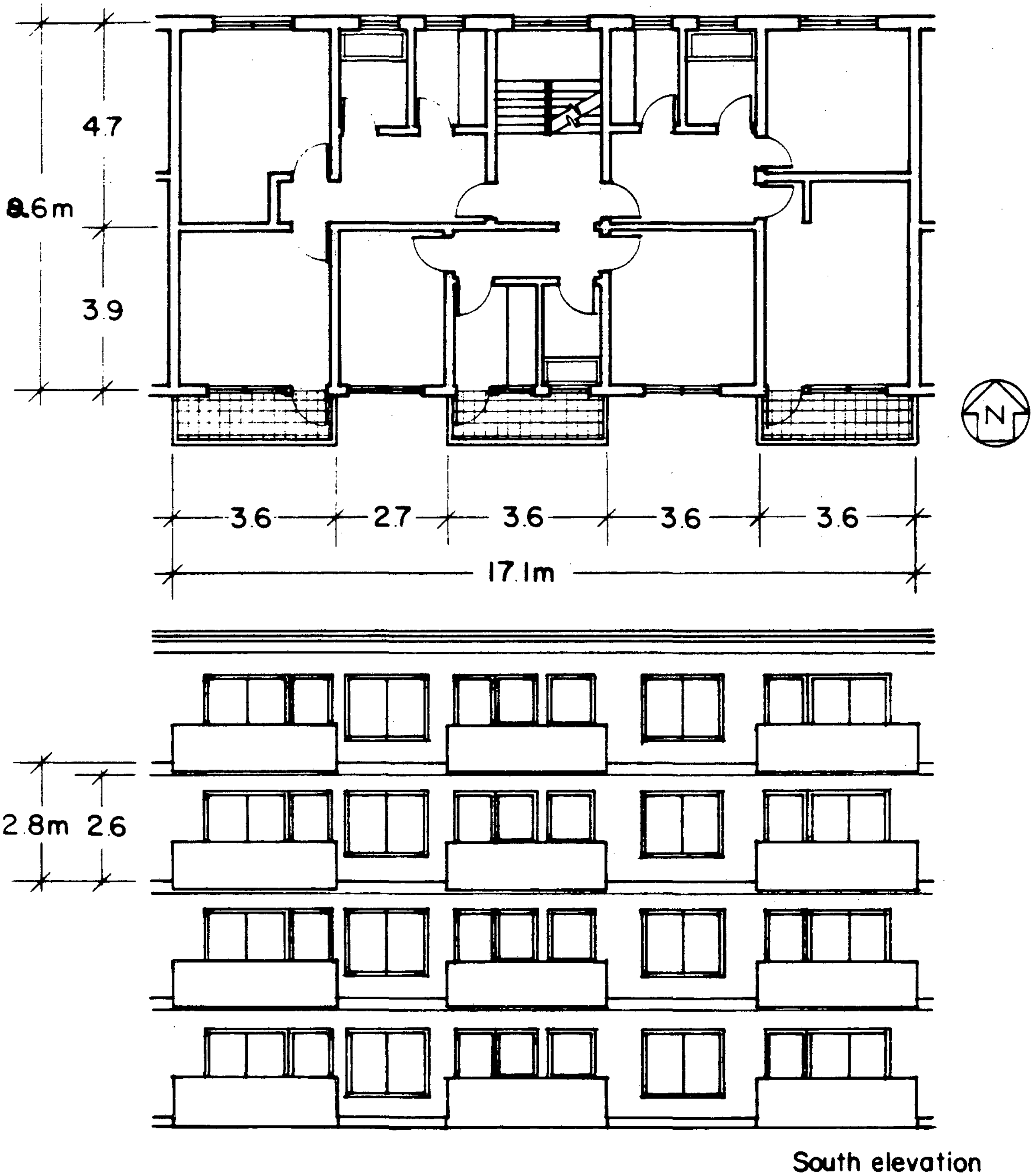

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Fig. 1. Typical Design for Three-Apartment Middle Unit. For the base case, the north wall (37-cm brick) has a conductance $k = 1.42\ W/m^2K$. When a 7.5-cm cavity, filled with expanded perlite, is introduced between the same 37 cm of bricks, k drops to $0.45\ W/m^2K$.

were modeled as identical to floors, except with 2 cm of plaster instead of cement. Interior walls were assumed to consist of 24 cm thick brick with 2 cm plaster on both sides. For exterior walls and windows, various different constructions were simulated. The base case building has 37 cm brick with 2 cm plaster for the north wall, 24 cm brick with 2 cm plaster for the south wall, and single-glazed windows. Other exterior wall types simulated are insulated cavity walls and insulated concrete sandwich panels. Double-glazed windows were also simulated.

There are large differences between Chinese and American residential buildings in terms of their form, choice of building materials, housing density, and user operations. The three-apartment unit is assumed to have an occupancy of 12, i.e., a density of 1 person/12 m^2, which is more than three times that of U.S. single family homes.[1] For internal loads, we have taken into account people, plus cooking and lights (assumed to be 10 W/m^2 for 5 hours each evening). [See App. C, Note 1] Solar gains through windows are computed hourly from weather data.

Infiltration

Air infiltration is an important factor in determining building energy use, but we have been unable to find data on infiltration rates of Chinese apartments. For U.S. residential stock, the distribution of infiltration rates peaks between 0.2 to 1.0 ach (air changes per hour), with new homes averaging 0.7 ach. However, it would be dangerous to extend these values to China due to differences in building materials and construction practices. In the absence of reliable data, we have simulated the three- apartment middle unit using two infiltration rates - "leaky" averaging at 1.0 ach, and "tight" averaging at 0.5 ach.

III. THE DOE.2 COMPUTER PROGRAM

In 1979, the U.S. Congress passed a law [42 USC 6831-6840] calling for the development of mandatory Building Energy Performance Standards (BEPS). BEPS in turn created the need for a reliable (but quick) public-domain computer program capable of calculating the optimum thermal design for many types of buildings in many climate zones in the U.S. Funded by the U.S. Department of Energy (DOE), Rosenfeld, at LBL, led a consortium of National Laboratories in writing, documenting, and verifying this program, now called DOE.2. DOE.2 now also runs in many other countries and is just being installed in Beijing.

In 1980, the Reagan Administration canceled the plans for a mandatory BEPS, but DOE.2 is still widely used to design buildings, and retrofit them, and make studies such as this one. We believe that DOE.2 can also be used effectively to calculate energy-use ratings for buildings.

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[1] We have chosen to use the design density for Chinese residential buildings rather than the actual housing density, which is closer to 1 person/4 m^2. The design density reflects conditions in newly occupied apartments, and will become more standard as cities gradually overcome their housing shortage in the future.

DOE.2 is driven by an hourly weather tape and by schedules for occupancy and equipment use. (We ordered the Beijing and Shanghai weather tapes from NOAA, the U.S. National Oceanic and Atmospheric Administration.) DOE.2 calculates hourly thermal loads and internal gains. If heating or cooling is required it then simulates HVAC (Heating, Ventilating, and Air Conditioning) systems which supply or extract heat.

For the present study, we made two sets of runs. For Beijing, we assumed heating to 18°C. For Shanghai, we "floated" the building through the year without any heating. We assume no cooling whatsoever. We recognize that 18°C is warmer than most Chinese keep their apartments today, but we assume that in 25-50 years this will be a normal thermostat setting.

For a recent overview of American computer programs for building energy simulation, see [Miller '82] and for a typical recent application, see [Choi '82]. DOE.2 has an accuracy [prediction--measurement] of about ± 10%. [Wagner '82]

IV. HEATING SIMULATION

We assumed that heat is supplied (through radiators) by hot water, heated by coal, with a system efficiency of 70%. We American building scientists are unfamiliar with coal boilers, and when we got to Beijing we found that the empirical efficiency is only about 40%, calculated as follows:

We were told by many Chinese, and read in China Daily, that Beijing apartments use 20 kg of standard coal per m^2 of floor area. At 7000 kCal/kg (=29,000 kJ/kg), this corresponds to 84 GJ per 3-apartment middle unit. But our Base Case load calculation (Table I, line 1) is 33.76 GJ, so the empirical system efficiency is 34/84 = 40%. this is consistent with our information from Professor Feng Jun-Kai of the Mechanical Engineering Department, Qinghua University, that hand-stoked boilers average 50% efficient, even though a modern chain-grid boiler can attain 80%.

If we correct our calculations to a 40% efficiency, then our coal savings must be increased by 7/4, and the cost of conserved coal and the payback times must be decreased by 4/7, i.e., all our recommended conservation measures are 1.75 times more attractive.

On sunny spring and fall days, solar gains may exceed conductive losses, and then DOE.2 permits the apartment temperature to "float" up as far as 26°C so as to store solar heat for comfort after sunset. At 26°C it opens the windows.

For convenience in simulation we treat the three apartments as one thermal zone of uniform temperature. For calculating total energy use for the three apartments, we believe this one-zone approximation is good to within ten percent. But during the summer (or all year in Shanghai) our calculated floating temperatures are only averages. In practice it would take open doors, fans, or "thermodeck" to keep temperatures uniform between the north and south apartments.

V. CONSERVATION OPTIONS AND COSTS

For this simple study, which emphasizes saving coal in the winter and no air conditioning, we consider only three options: a) insulation, b) double glazing, and c) reducing infiltration.

The costs of these options were estimated by one of us (T., D.) based on considerable correspondence with colleagues in China.

A.1) Insulating the North Wall with Expanded Perlite

We noted that Beijing apartment buildings are generally built with brick bearing walls 24 cm thick on the south, but 37 cm thick on the north to avoid problems with condensation. This makes it logical for the first conservation measure to be modifying the construction of the north wall into a cavity wall, with an inner bearing wall of common brick 24 cm thick, a 7.5 cm cavity to be filled with insulation (which we have chosen to be expanded perlite), and finally an outer wall of facing brick 13 cm thick. For mechanical rigidity, the inner and outer brick walls would be connected with some inexpensive steel hooks, bridging the cavity. Swedish experience with rock-wool insulation in similar cavity walls shows that a vapor barrier is unnecessary. [Adamson '82]

The only costs for this conservation measure would be that of the insulation material (i.e.,expanded perlite). We have estimated the cost of adding perlite to be 3.4 Yuan per m^2 of wall, plus an additional 1.6 Yuan for the additional labor, resulting in a total cost of 5 Yuan per m^2 of north wall. (See Section VI for more discussion on the price of perlite). [2] Since the north wall area for the three-apartment unit is 36.0 m^2, the total cost for this conservation measure is 180 Yuan.

In App. D, we discuss how we chose 7.5 cm as our insulation thickness and how this compares with recommendations by other authors. [Li '82]

A.2) Adding a Cavity and a Brick Facing Wall to the South Wall

Since the south wall of typical Beijing apartments is only one brick-length thick, adding insulation would require the addition of a second thin wall outside of the main wall, resulting in a construction identical to that of the proposed north wall. [See App. C, Note 3]

The total cost for this conservation measure would be substantially greater than that for insulating the north wall, since it entails the cost of a second wall. Based on a cost for brick of 65 Yuan per 1000, the material cost for the additional wall would be 4.50 Yuan per m^2. Assuming that labor would double this cost, we arrived at a cost of 9

[2] Because of insufficient information about labor costs in China, our methodology has been to double the cost of materials. Since there are no extra material costs for building a cavity into the north wall, we have assumed 1.6 Yuan per m^2 for extra labor, including mortaring in the steel hooks.

Yuan per m^2 of new wall. Added to the insulation costs of 4 Yuan per m^2 calculated earlier, the cost for this conservation measure is 13 Yuan per m^2 of wall. Since there is 30.1 m^2 of south wall for the three-apartment unit, the total cost would be 391 Yuan.

A.3) Double Glazing

This conservation measure entails changing all windows except the one in the stairwell from single-pane glass to thermopane. We were informed that the extra cost for thermopane is 22.5 Yuan more per m^2 of glass, hence, the total cost for double-glazing would be 21.6 m^2 of window x 22.5 Yuan/m^2 = 486 Yuan.

A.4) Reducing Infiltration

Chinese building scientists tell us that there is poor quality control in window factories, with the result that there are usually cracks between the window and the frame, with the further result that the air infiltration rates in Beijing run around 1 air change per hour (ach). This could be reduced to 1/2 ach without any significant decrease in indoor air quality, partly by better quality control during manufacture, and partly be a design change to include a flexible gasket to improve the seal.

Steel windows now cost about 40 Yuan each, i.e., 500 Yuan for our 3-apartment unit. Our colleagues estimate that it might cost 5-10% more to manufacture tighter windows and save the 1/2 ach. This option would then cost at most 50 Yuan, but would save 30% of the coal needed--making better windows far the most attractive conservation option on our list.

Note, however, that the cost of better windows is so hard for us to estimate that we have not made it the first option on our Table I or Fig. 2. Instead, we have calculated two entire Tables and Curves, one for 1 ach, and one for 1/2 ach.

VI. UNCERTAINTIES IN PRICE--PERLITE AND COAL

A. Perlite

Worldwide, the most popular mineral-based, relatively cheap insulators are mineral wool, expanded perlite and aerated concrete. We had no price for mineral wool, and aerated concrete calls for more of a change in building construction that we considered desirable; so we chose perlite, which is well known, but unreasonably expensive. We regret that we were not able to inform ourselves about cellulose or even corn husks.

One of our group, Metin Lokmanhekim, is consulting with the Kuwait Institute for Scientific Research, helping to introduce perlite-filled concrete building blocks into Kuwait. In the process of ordering perlite plants, we have become familiar with perlite costs. In Kuwait, even using imported raw material and expanding it locally, the cost at the plant will be about \$10/m^3 (20 Yuan per m^3). For China we were told 100 Yuan/m^3 (including a 30% management cost), which is 5 times our Kuwait cost. This must be because perlite is used only rarely, so for this study we have simply adopted 50 Yuan/m^3 as a compromise. We need to fill a cavity 7.5 cm thick, so this amounts to 4 Yuan/m^2. We have rounded this up to 5 to take care of the cost of pouring it into the cavity.

After we got to China, our colleague, Mo Yong Fen tracked down the following discouraging sequence of 1980 prices for lightweight loose perlite:

		Yuan/m^3
1.	From the factory in NE China	17
2.	From the warehouse in Beijing	25
3.	Delivered to the building site	40
4.	Delivered, stored till needed	75
5.	Line 4, with 33% management fee	100

And the prices above do not include the cost of pouring the perlite into the cavity. We were told that for concrete ceiling slabs, the cost of delivery and storage on site adds only 20% to the warehouse price--why does it add 200% for insulation? We believe that the mini-table above shows that our guess of 50 Yuan/m^3 is reasonable or even conservative.

B. Coal

Chinese coal in Beijing costs 0.8 to 1.5 Yuan/GJ (20-40 Yuan/tonne). These prices were set shortly after Liberation and have not been revised, even though China can now sell coal to Japan for about 100 Yuan/tonne, i.e., 3.6 Yuan/GJ. We assume that over the 50-year lifetime of buildings being built today, Chinese coal prices will be tied to world prices and will no longer be a reason to subsidize inefficient buildings.

We have discovered an indication that already, in Beijing, heat is worth more than the official price of coal. The Beijing power plant supplies hot water for district heating, but charges 3.6 Yuan/GJ. Since there is a market for this heat, we presume there must be a shortage of the cheap coal.

So, in this study, we either avoid the issue (by quoting instead a cost of <u>conserved</u> coal) or when we quote "simple payback times," we value coal at its wholesale price, as delivered to U.S. power plants. In April, 1982, this price was $1.56/GJ or about equal to 3 Yuan/GJ, and is presumably what coal is worth delivered to a Chinese district heating plant; this should be cheaper than the cost for coal delivered to an apartment building.

VII. ECONOMIC CRITERIA--THE COST OF CONSERVED COAL

In Section VIII we shall present our results in Tables I and II. Here we want to explain how we calculate columns D, E, and F.

- Annual Coal Cost (Col. D) assumes a heating system efficiency of 70% and an international cost of coal of \$1.65/MBtu. Then an exchange rate of \$1 = 2.0 Yuan leads to 3.13 Yuan/GJ.

  From the host of economic criteria which can be calculated from the cost of a measure (Δ Yuan) divided by its annual energy savings (Δ E), we have chosen the simplest--SPT (Simple Payback Time), and one that is more general and allows us to compare investments in efficiency with investments in new coal supply--this measure is "Cost of Conserved Coal"--CCC.

- SPT (Simple Payback Time--Col. E). This is simply the cost of the measure (Col. C) divided by the annual savings in the cost of coal (Col. D). It is equal to the true payback time only in the limit that the time is short, or the interest rate is low, and that annual maintenance costs are small. If SPT is less than about ten years, the measure should be attractive.

- CCC (Cost of Conserved Coal--Col. F). We like this measure because it is independent of the price of coal and depends mainly on Δ Yuan and Δ E. Each planner can then have his own idea of the value of coal, averaged over the useful life of the building. If the CCC is less than the price of coal, then the measure is attractive. The American equivalents (Cost of conserved fuel, Cost of conserved electricity) are now widely used by American energy planners [Rosenfeld '81; Meier '82].

We work in constant ("real") 1982 Yuan (assuming no inflation). Unfortunately, we are unfamiliar with Chinese economic policy, so we have to assume a real interest rate i and a lifetime t for the conservation measures. We take i = 6%/year, and t = 30 years.

We can then calculate the annual "cost of capital" or "capital recovery rate--CRR."

$$CRR = \frac{i}{1 - \left(\frac{1}{1+i}\right)^t} = 7\,\tfrac{1}{4}\%/\text{year} \quad (1)$$

We can now annualize the investment in a conservation measure, by assuming that we borrowed the money Δ Yuan, and pay it back over 30 years.

$$\text{Annual cost of investment} = CRR \times \Delta\ \text{Yuan} = 7\,\tfrac{1}{4}\% \times \Delta\ \text{Yuan} \quad (2)$$

Before we divide this by the annual energy savings, we must remember that we are trying to calculate the cost of conserved coal. To get from energy to coal we must divide by 0.7, which is the assumed efficiency of the heating system.

$$\text{Annual coal savings} = \Delta E/0.7 \tag{3}$$

The cost of conserved coal is then the ratio of annual expressions (2) and (3):

$$CCC = \frac{\text{Cost of Investment}}{\text{Saved GJ of Coal}} = \frac{.0724\,\Delta\ \text{Yuan}}{\Delta\ E/0.7}$$
$$= .05\ \frac{\Delta\ \text{Yuan}}{\Delta\ E}\left(\frac{\text{Yuan}}{\text{GJ}}\right) \tag{4}$$

We repeat: the calculation of CCC has nothing to do with the price of coal, PC. If CCC is less than PC, we should invest in conservation. If CCC is more expensive than PC, we should burn coal and expand production to cover growth. Of course, PC should be the "societal" price, including externalities like polluted cities, acid rain, and the greenhouse effect.

VIII. RESULTS

The results of our runs and of our economic calculations are presented in Tables I (for Beijing) and II (for Shanghai) and are plotted in Fig. 2.

A. Beijing (3043 heating degree days, base 18^{o}C; 1078 HDD, base 8^{o}C)

We have ordered the measures starting with the shortest payback time, which is the same as the cheapest cost of conserved coal. For both high- and low-infiltration, we see that the first two conservation measures are very attractive, but that it does not pay to add to the south wall a cavity and another facing brick wall.

Note the striking overall decrease in annual heating load, from 35 GJ for the Base Case (and 1 ach) down to 10 GJ for the insulated, double-glazed, airtight case (with 1/2 ach). This decrease should produce a spectacular improvement in Beijing's winter air quality (and presumably public health).

In App. A, we even give the decrease in peak heating load: heating systems can be downsized from 0.228 to 0.105 MJ/(hr-m^2). As discussed in Section IX, this potential downsizing may save enough money to pay for the insulation, double glazing, and decreased infiltration.

Fig. 3: Individual Gains and Losses

Figure 3 is for the reader who is interested in building science as well as economics We re-display the same Beijing data as already plotted in Fig. 2, but now separated into individual gains and losses.

In building energy analysis it is conventional to call heat gains "positive" and to plot them upwards. Losses (offset by the heating system) are then "negative" and plotted downwards. We see the simulated

TABLE I. COSTS AND ENERGY SAVINGS OF CONSERVATION MEASURES FOR THREE-APARTMENT MIDDLE UNIT (143 M^2) IN BEIJING

<values in brackets are the differences between successive computer runs, "δ ">

A. Wall Construction	B. Annual Heating Load (GJ)	C. Cost of Individual Measures (Yuan, =Y)	D. Annual Coal Costs (Yuan, =Y)	E. Simple Payback Time (years)	F. Cost of Conserved Coal (Yuan/GJ)
High Infiltration (1.0 ach) (Highly Recommended ↓)					
Standard Brick	33.76	Y 3,000*	Y 151.00	-	-
δ =	<-6.72>	<+180>	<-30.06>	6	1.34
Insulate North Cavity Wall	27.04	180	120.94		
δ =	<-9.86>	<+486>	<-44.10>	11	2.45
Add Double-Glazing	17.19	666	76.89		
δ =	<-4.72>	<+391>	<-21.11>	19	4.14
Insulate South Cavity Wall	12.47	1057	55.78		
Low Infiltration (0.5 ach) <+ 50 Y ? > (Highly Recommended ↓)					
Standard Brick	24.93	Y 3,000*	Y 111.51	-	-
δ =	<-6.41>	<+180>	<-28.67>	6	1.40
Insulate North Cavity Wall	18.52	180	82.84		
δ =	<-8.94>	<+486>	<-39.99>	12	2.71
Add Double-Glazing	9.58	666	42.85		
δ =	<-3.92>	<+391>	<-17.53>	22	4.99
Insulate South Cavity	5.66	1057	25.32		

Notes for Tables I and II :

Column Headings

C. * For the standard brick base case 3,000 Yuan refers to the proportional cost of a central heating system assigned to the three-apartment unit.

For north cavity wall, outer 13 cm brick is simply moved outwards for a 7.5 cm cavity to be filled with perlite; assume 7.5 cm of loose perlite costs 4.00Y/m^2 of wall.

For double-glazing, assume thermopane costs Y22.5/m^2 of window more than single-pane glass.

For south cavity wall, assume same perlite costs as for north wall, and a 13 cm thick brick wall costing Y4.50/m^2 for materials and Y4.50/m^2 for labor.

D. Assume heating system efficiency of 70% and international cost of coal at $1.65/MBtu = 3.13Y/GJ. [1$ = 2.0Y]

E = <Col C>/<Col D>

F = 0.05 x <Col C>/<Col B>; this should be compared with the price of coal, which is about 3.13 Yuan/GJ (see text).

TABLE II. COSTS AND ENERGY SAVINGS FOR CONSERVATION MEASURES FOR THREE-APARTMENT MIDDLE UNIT (143 M^2) IN SHANGHAI

<values in brackets are the differences between successive computer runs, " δ ">

A. Wall Construction	B. Annual Heating Load (GJ)	C. Cost of Individual Measures (Yuan, = Y)	D. Annual Coal Costs (Yuan, = Y)	E. Simple Payback Time (years)	F. Cost of Conserved Coal (Yuan/GJ)
High Infiltration (1.0 ach)					
Standard Brick	13.42	Y 3,000 *	Y 60.02	-	-
	δ = <-3.28>	<+180>	<-14.67>	12	2.74
Insulate North Cavity Wall	10.14	180	45.35		
	δ = <-4.79>	<+486>	<-21.42>	23	5.07
Add Double-Glazing	5.35	666	23.93		
	δ = <-2.04>	<+391>	<- 9.12>	43	9.58
Insulate South Cavity Wall	3.31	1057	14.80		
Low Infiltration (0.5 ach) <+ 50 Y ? >					
Standard Brick	9.26	Y 3,000 *	Y 41.42	-	-
	δ = <-2.89>	<+180>	<-12.93>	14	3.11
Insulate North Cavity Wall	6.37	180	28.49		
	δ = <-3.94>	<+486>	<-17.62>	28	6.17
Add Double-Glazing	2.43	666	10.87		
	δ = <-1.38>	<+391>	<- 6.17>	63	14.17
Insulate South Cavity Wall	1.05	1057	4.70		

(see notes for Table I)

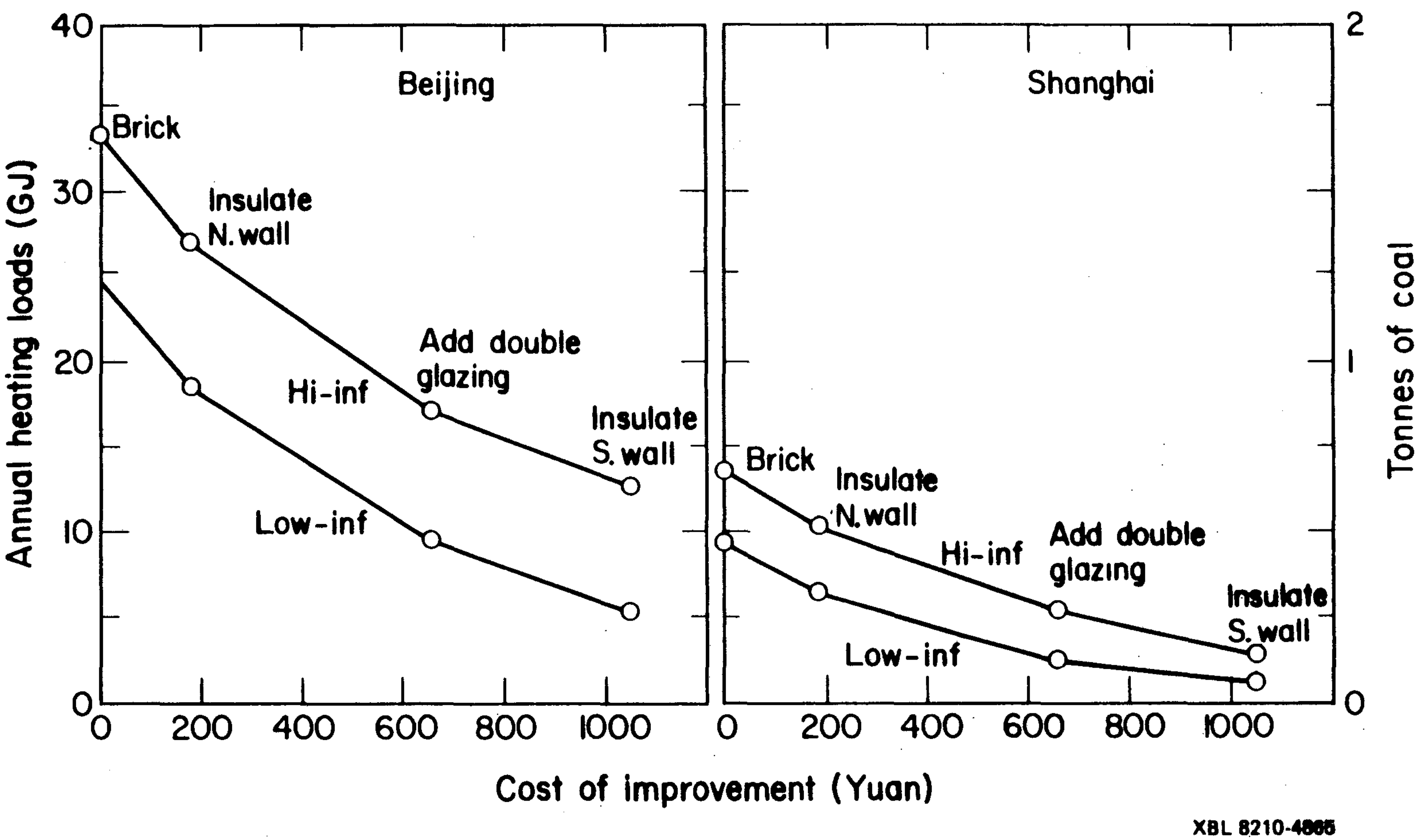

Fig. 2. Annual heating load decreases as a series of conservation measures is applied to a three-apartment middle unit in Beijing and Shanghai. We estimate that the cost of improving window and door seals so as to reduce infiltration from 1 "ach" (top curve) to ½ (lower curve) costs roughly 50 Yuan, compared with 200 Yuan for insulating the north wall.

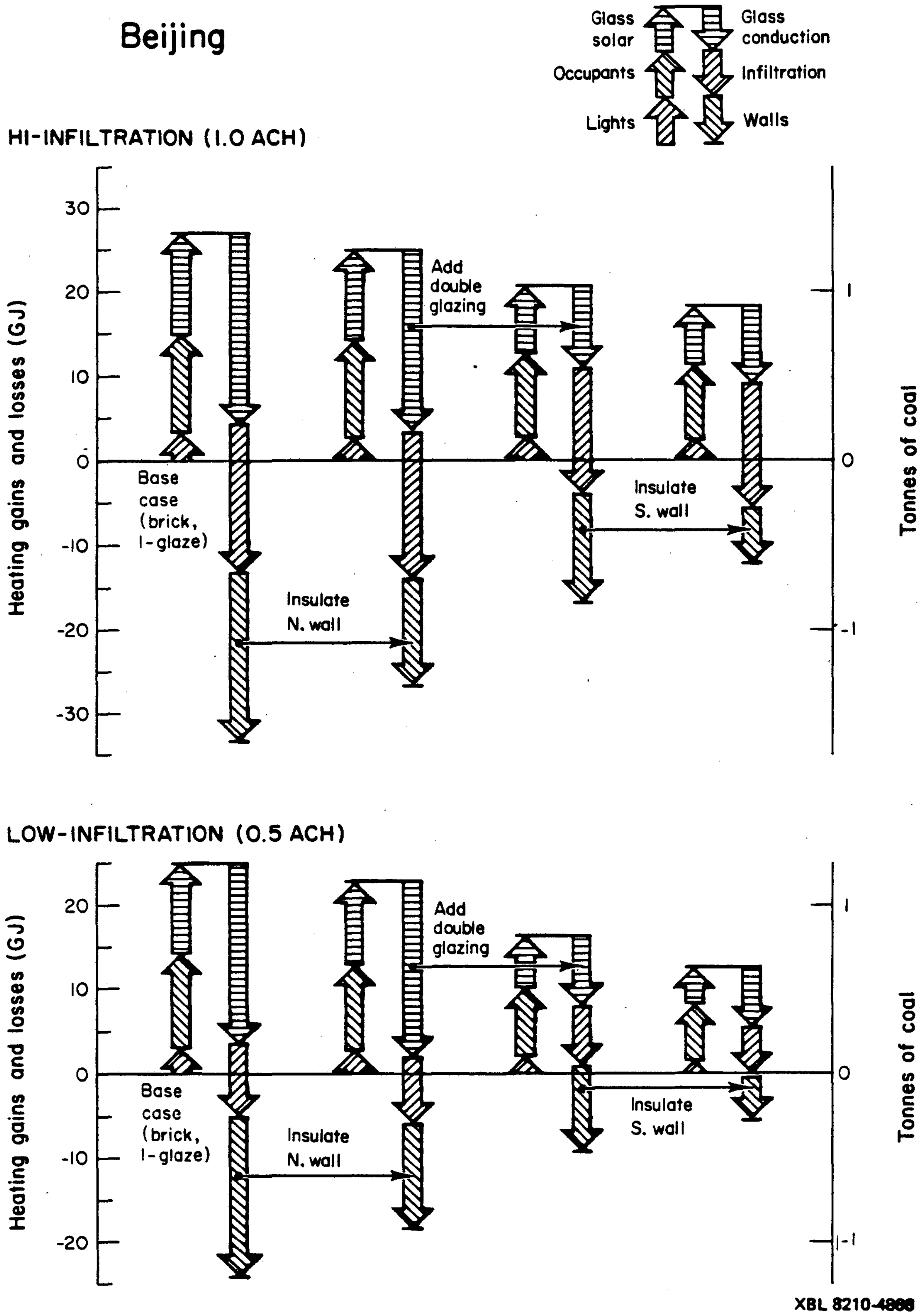

Fig. 3. Individual annual heating gains and losses for the sequence of designs in Fig. 2, for Beijing.

gains (lights, occupants, and solar gains through the windows) and losses (from conduction through the windows and walls, and from infiltration). For the base case, we note that the windows are net losers, but almost break even if double glazed. (Double-glazed south windows are actually net gainers, but the north ones, of course, still lose.)

For the base case we also note that the three sources of loss are about equal (windows, walls, and infiltration). As we make modifications, we reduce the losses first from the windows and then from the walls, and as we tighten the buildings we reduce the infiltration. The result is that by the time we get to Measure 6, the three losses are again about equal, but each has been reduced to one third.

The reader who is new to this science may be surprised that as the building is improved, the <u>gains</u> decrease too, although, of course, not as fast as the losses. This is because the heating season decreases as the building is tightened. Said more precisely: in adding up the hourly values, we count the gains only if they are useful because heat is needed during that hour; hence, as the building improves and heating hours decrease, so do the gains.

- In <u>App. B</u> we again present gains and losses, this time for each month of the year. There we can easily note the decrease in the heating season.

- Results of Other Options--See App. A

  We have made DOE.2 runs for other options--notably for sandwich panel walls, but we have not yet determined the increase in first cost. These results are presented in App. A, along with peak heating loads for each option.

  There is, of course, far more information available in a DOE.2 run than we have been able to discuss. Microfiche versions of the output are available from the authors.

B. <u>Shanghai (1887 heating degree days, base 18°C; or 568 HDD, base 10°C)</u>

We are aware that only special residential buildings in Shanghai have heating systems, so that the main point in the computer runs is to calculate the floating temperatures within the building. However, since we have set up the runs, we thought it mildly interesting to present Table II, the Shanghai equivalent of Table I for Beijing.

We see that it is still attractive to design an insulated north wall (provided that the planned construction is to be 37 cm thick, which we have been informed is the case for better quality buildings). Double glazing will be attractive as soon as real coal prices rise 20%, but building a cavity wall in place of a 24 cm south brick wall is ridiculous. We also see that infiltration losses are important even for a mild climate like Shanghai, and that reducing infiltration by 0.5 ach through tighter construction can save 40% of the heating load.

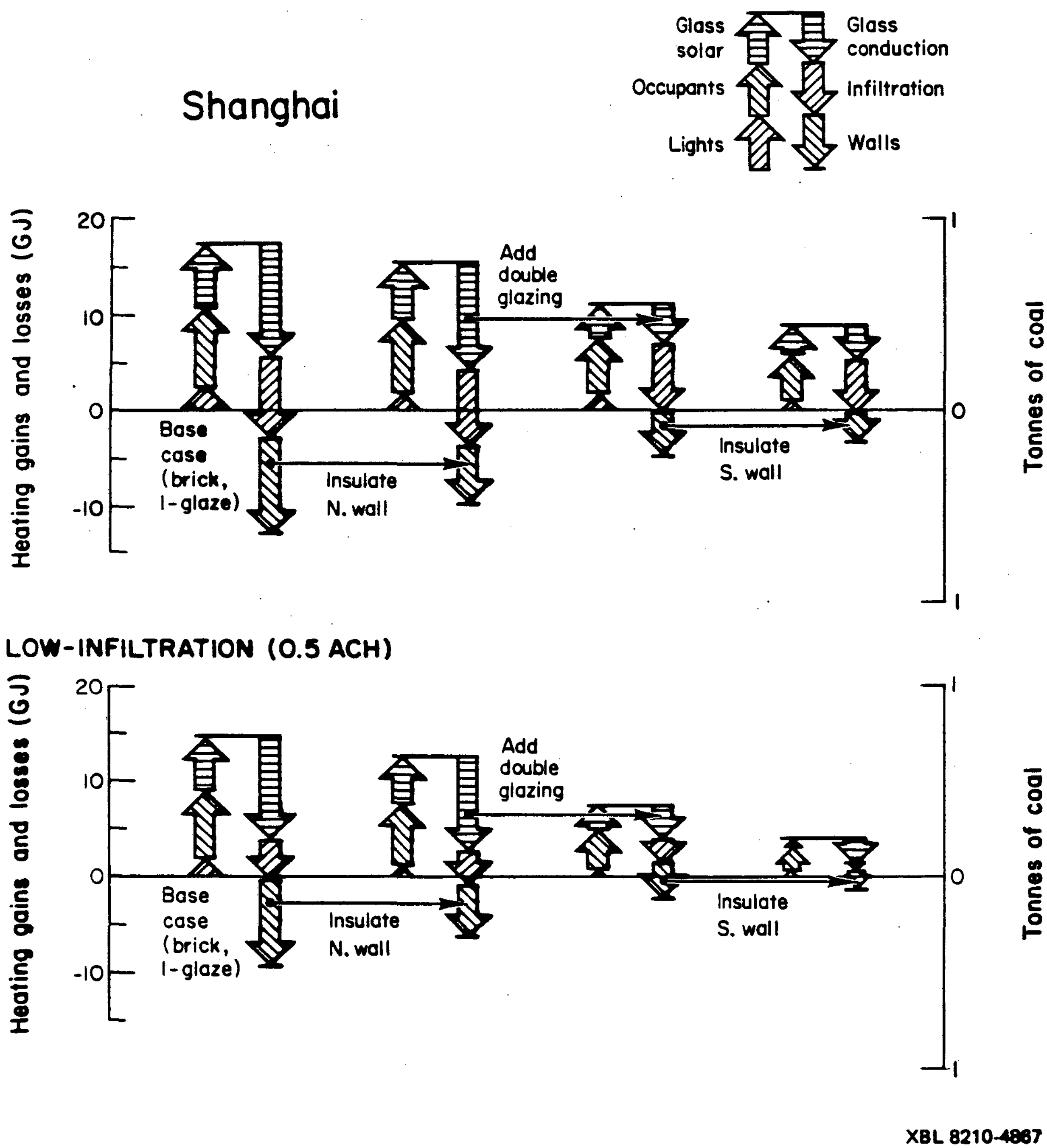

Fig. 4. Individual annual heating gains and losses for the sequence of designs in Fig. 2, for Shanghai.

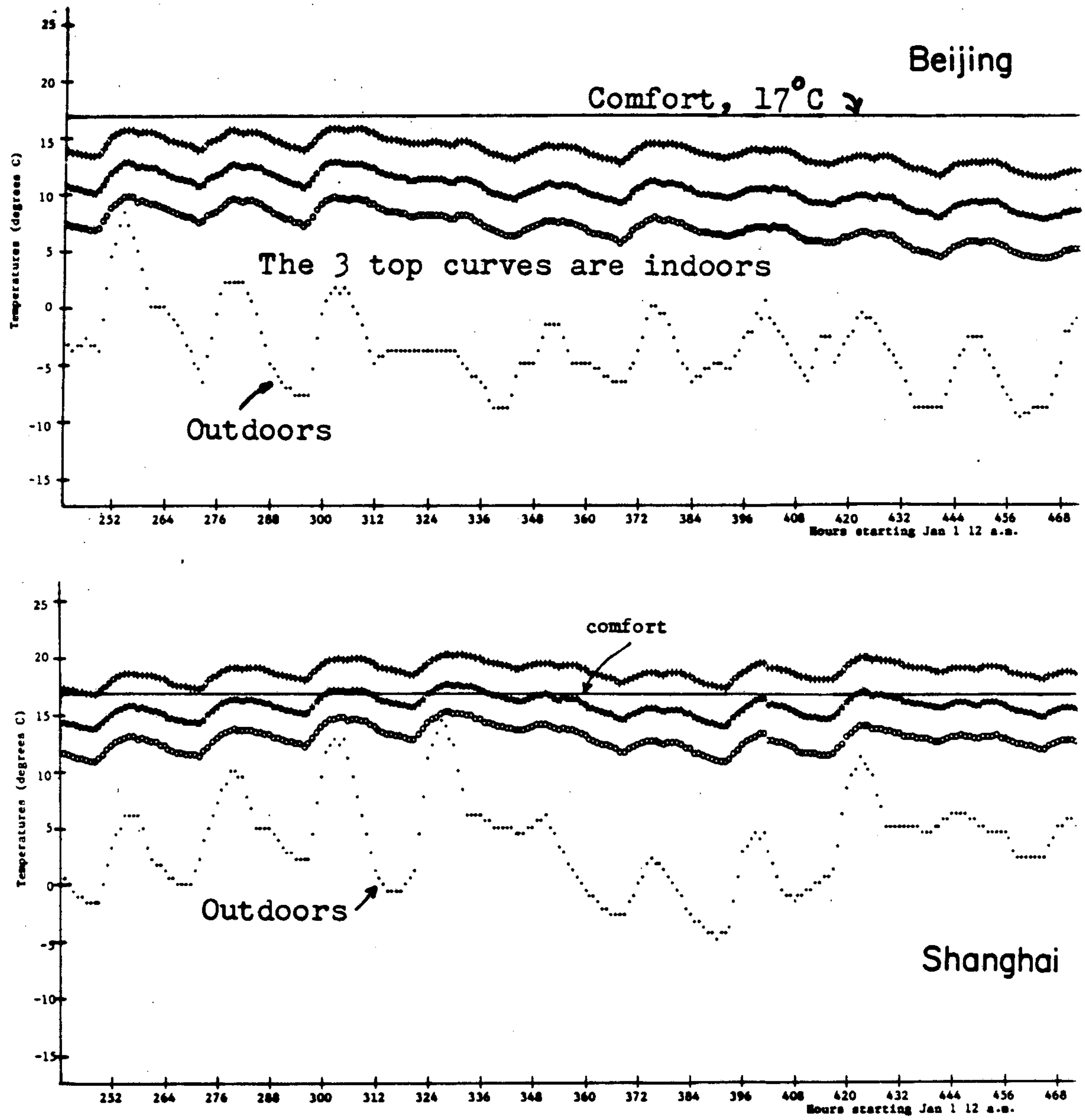

Fig. 5. Floating winter indoor temperatures in Beijing and Shanghai (Jan. 10–Jan. 20). The lowest indoor line is the base case brick building; the next (3° higher) is the recommended case with insulated north wall and reduced infiltration; the top (6° above the base case) is the best case with added double glazing. On the average, the base case "floats" 10° above ambient temperatures in Beijing and 8° in Shanghai due to high internal loads and solar gains. When conservation measures are added, this difference between floating and ambient temperatures becomes even more dramatic. Notice that for Shanghai the best case floating temperatures are well within the comfort zone.

C. "Floating" Temperatures (i.e., without any mechanical heating)

For buildings without mechanical heating systems, the goal of conservation measures would be to capture enough of the free heat (from solar gain, people, cooking, and lights) to raise indoor temperatures to the comfort range, which is generally defined in the U.S. as 17-18°C. This can be achieved fairly easily in Shanghai, but is much more difficult in colder climates like Beijing.

Figure 5 shows floating indoor temperatures in January for Beijing and Shanghai apartments with base case construction, recommended case with insulated north walls, and best case with double glazing added. Notice (Table III) that in Beijing each conservation step increases indoor floating temperature by 3.3 degrees, while in cloudier Shanghai the increase is 2.8 degrees. However, because of milder outdoor conditions, the absolute floating temperatures are higher for Shanghai, averaging 18°C for the best case construction, well within the comfort range. For Beijing, even the best case construction would still require some mechanical heating, although the heating season would be shorter and the system could be downsized.

TABLE III. FLOATING TEMPERATURES IN BEIJING AND SHANGHAI FOR APARTMENTS WITH DIFFERENT CONSERVATION MEASURES

	Beijing	Shanghai
ΔT Free (Base Case - Outside T)[See Fig. 5]	10°C	8.3°C
ΔT Free (Recommended Case - Outside T)	13.3°	11.1°
ΔT Free (Best Case - Outside T)	16.6°	13.9°
T Balance with T Thermostat = 18°C (For Base Case)	8°	10°
Heating Degree Days at T Balance (8°C for Beijing, 10°C for Shanghai)	1078	568

IX. OFFSETTING FIRST COSTS--DOWNSIZING THE HEATING SYSTEM

We have recommended two options for Beijing based on a simple comparison between their costs and the savings in coal. Compared to the entire building, the cost for these conservation measures is very small, representing only 2% of the cost of construction (see Table IV). In addition, there will be substantial savings from reducing the heating system which have not been included in our economic analysis. Appendix A shows that the recommended conservation measures will lower peak heating loads by 32%, or if infiltration is also reduced, by 54%. We believe that the savings available by downsizing the 3,000 Yuan heating plant will offset most, if not all, of the 700 Yuan cost of the recommended conservation measures. Specifically, we estimate that half the cost of the plant is boilers and radiators, adding to 1500 Yuan. If we downsize them to 1/2, we should save 750 Yuan, which offsets the conservation measures.

TABLE IV. COMPARISION OF COST OF CONSERVATION MEASURES WITH FIRST COSTS OF CONSTRUCTION AND HEATING SYSTEMS FOR TYPICAL THREE-APARTMENT MIDDLE UNIT IN CHINA

	Yuan	Percent
Total Construction	30,000	100 %
Heating Plant Only	3,000	10 %
Tighter Windows	50 (?) *	0.2 % *
Insulate North Cavity Wall	180 *	0.6 % *
Add Double Glazing	486 *	1.6 % *
Insulate South Cavity Wall	391	1.3 %

* = recommended

For milder climates, the costs for conservation can be weighed against the possibility of eliminating mechanical heating. With good passive solar design, better insulation, and infiltration reduction, it may be possible to eliminate mechanical heating completely for many cities that currently require them. Careful research, however, would be necessary to determine these locations and the level of conservation required to achieve this goal.

X. CONCLUSIONS

We now conclude by comparing our result with the cost of conserved coal (CCC, Eq. 4) and also directly with the capital investment needed to supply an annual tonne of coal.

For our 3-apartment unit in Beijing, Table I showed that it should cost 180 Yuan to insulate the north wall, and we estimate 100 Yuan more to reduce infiltration, adding to 280 Yuan. These two "best" measures should save 15 GJ of delivered heat, equivalent to 2/3 tonne of coal, delivered to the building site.

The CCC (Eq. 4) is then:

$$CCC = 0.05 \times \frac{\Delta \text{ Yuan}}{\Delta \text{ E}} = 0.05 \, \frac{280}{15} = 1 \, \frac{\text{Yuan}}{\text{GJ}} \tag{5}$$

We have earlier compared this with the World Price of Coal, PC:

$$PC = 3.13 \text{ Yuan/GJ} \tag{6}$$

It is then clear that we should recommend investment in the conservation measures, rather than in new coal supply.

To strengthen this argument, we now restate it in an even more direct, and (we hope) compelling way. There are uncertainties about our estimate of a capital recovery rate, because it has to compare first cost with a stream of annual savings. Some may be concerned that the increased first cost will place a heavy burden on the present Chinese economy (although Table III shows that we have increased the first cost of the building by, at most, 1%). To address these uncertainties, we now compare strictly the first cost for conservation with the first costs for increasing coal production.

We have just said that our two most strongly recommended conservation investments add to 280 Yuan and save 2/3 annual tonne of coal. We restate this as CCAT (Cost to Conserve an Annual Tonne).

$$CCAT = \frac{280 \text{ Yuan}}{2/3 \text{ Annual Tonne}} = \frac{420 \text{ Yuan}}{\text{Annual Tonne}} \tag{7}$$

Now, what investment in coal mines and infrastructure is needed to produce and transport an annual tonne?

We quote John Walsh with a JPL estimate that the capital cost for doubling U.S. coal production (mines, roads, railroads, etc.) as $275 or 550 Yuan per annual tonne. Because of the abundance of coal and labor, Walsh estimates that the capital costs for China would be 20% smaller, or 440 Yuan per annual tonne. We put this in the notation of Eq. (7) by writing CSAT (Cost to Supply an Annual Tonne):

$$CSAT = \frac{440 \text{ Yuan}}{\text{Annual Tonne}} \tag{8}$$

By comparing equations (7) and (8) we then come to a simple, compelling conclusion: our conservation options pay for themselves in first cost alone. When we add on the savings from down-sizing heating systems, the long-term savings in energy use, and the decrease in pollution and land destruction due to mining, it should be clear that society benefits far more from conservation than from increased coal production. These arguments would be even more credible if better data were available for Beijing apartments: coal use, boiler efficiency, and infiltration.

XI. ACKNOWLEDGEMENTS

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APPENDIX A. PEAK HEATING LOADS AND ADDITIONAL OPTIONS.

TABLE A-1. DOE-2 HEATING LOADS FOR THREE-APARTMENT MIDDLE UNIT (143 M^2) IN BEIJING

Wall Construction	Number of Glazings	Infiltration Rate (ach)	Annual Heating Load (GJ)	Peak Heating Load (MJ/hr x m^2)
Standard Brick	1	1.0 ach	33.76	0.228 (100%)
Insulated North Cavity Wall	1	1.0 ach	27.04	0.205 (89%)
Insulated North Cavity Wall	2	1.0 ach	17.19	0.156 (68%)
Insulated North & South Cavity Wall	1	1.0 ach	21.99	0.182
Insulated North & South Cavity Wall	2	1.0 ach	12.47	0.131
Sandwich Panel with 3" insul	1	1.0 ach	23.21	0.188
Sandwich Panel with 4" insul	1	1.0 ach	21.33	0.181
Standard Brick	1	0.5 ach	24.93	0.177 (78%)
Insulated North Cavity Wall	1	0.5 ach	18.52	0.155 (68%)
Insulated North Cavity Wall	2	0.5 ach	9.58	0.105 (46%)
Insulated North & South Cavity Wall	1	0.5 ach	13.80	0.132
Insulated North & South Cavity Wall	2	0.5 ach	5.66	0.081

TABLE A-2. DOE-2 HEATING LOADS FOR THREE-APARTMENT MIDDLE UNIT (143 M^2) IN SHANGHAI

Wall Construction	Number of Glazings	Infiltration Rate (ach)	Annual Heating Load (GJ)	Peak Heating Load ($MJ/hr-m^2$)
Standard Brick	1	1.0 ach	13.42	0.133
Insulated North Cavity Wall	1	1.0 ach	10.14	0.116
Insulated North Cavity Wall	2	1.0 ach	5.35	0.086
Insulated North & South Cavity Wall	1	1.0 ach	7.66	0.099
Insulated North & South Cavity Wall	2	1.0 ach	3.31	0.068
Standard Brick	1	0.5 ach	9.26	0.109
Insulated North Cavity Wall	1	0.5 ach	6.37	0.093
Insulated North Cavity Wall	2	0.5 ach	2.43	0.061
Insulated North & South Cavity Wall	1	0.5 ach	4.24	0.075
Insulated North & South Cavity Wall	2	0.5 ach	1.05	0.043

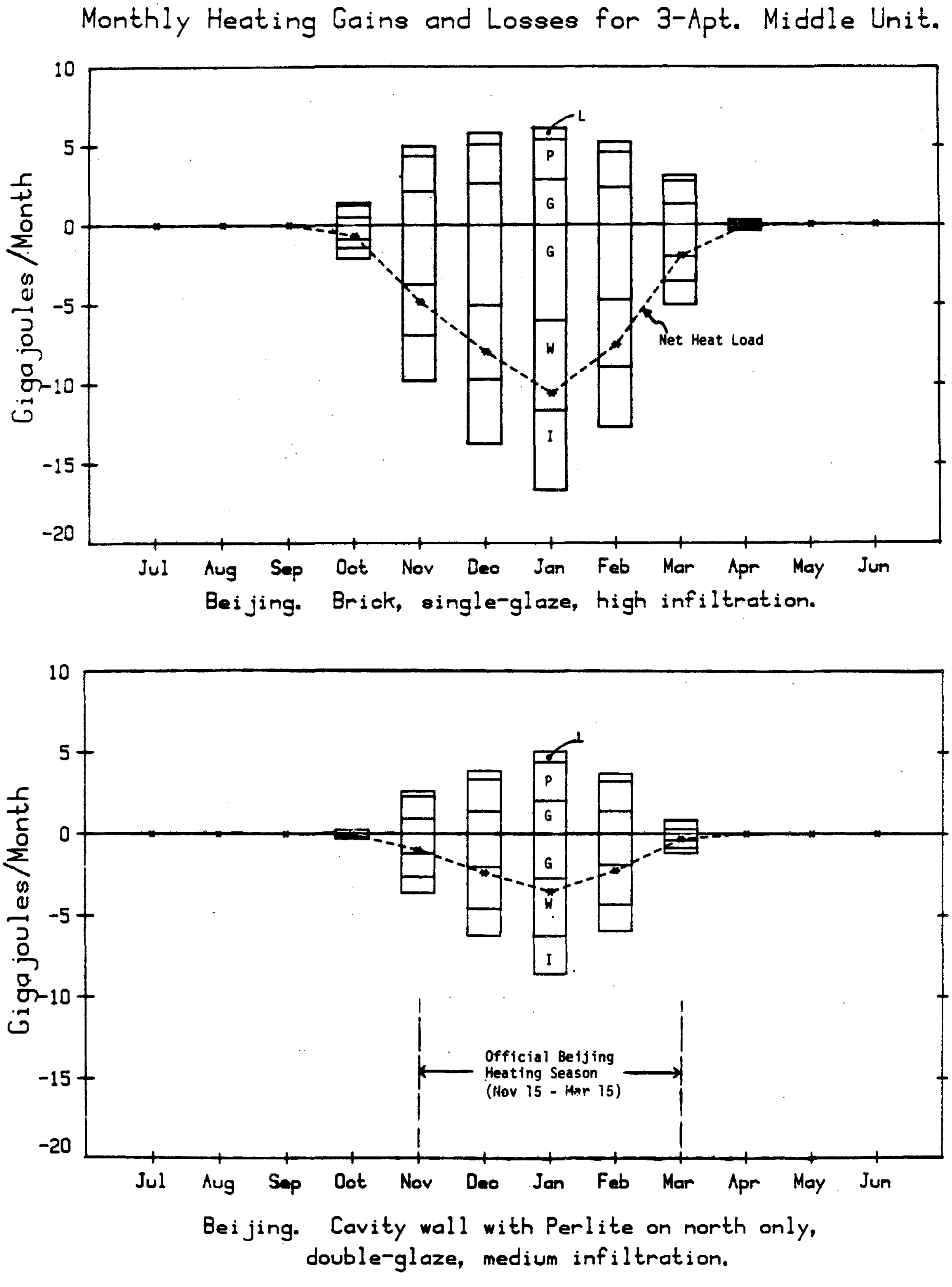

Fig. B.1. Monthly heating gains and losses for three-apartment middle unit in Beijing with different constructions. Heating gains and losses for each month are shown from top to bottom: L = lights, P = people, G = glass solar gain, G = glass conduction loss, W = walls, and I = infiltration. * = net heating loss for the month. These are the same calculations as plotted in Fig. 3, except that the entire heating season has been separated month by month; note the shortening of the heating season as the thermal design is improved.

APPENDIX D. ESTIMATE OF OPTIMUM INSULATION THICKNESS

There is a well-known formula (D4) for the optimum thickness, X, of insulation. For the reader who does not immediately recognize it, we derive it here, mainly to define the notation.

At first neglect the brick wall, which is equivalent to 3.8 cm of perlite. We shall subtract the 3.8 cm in Eq. D5. Assume a north wall, so we can neglect a correction for solair temperature.

Per m^2 of facade, the total annual cost, $\dot{C}$ (which we want to minimize) is the sum of insulation cost + coal cost, i.e.,

$$\dot{C} = \dot{C}_{in} + \dot{C}_c \tag{D1}$$

where $\dot{C}_{in}$ = annualized cost of insulation

= C (insulation) x CRR

[CRR = Capital Recover Rate

= 0.0725/year, see text, Eq. (1)]

$$\text{So,} \quad \dot{C}_{in} = C_{in}\left(\frac{\text{Yuan}}{m^3}\right) X \times \text{CRR}$$

where C_{in} = cost of a cubic meter of insulation,

and X = insulation thickness in meters.

The annual coal cost, at a system efficiency $\eta = 0.7$, is given by:

$$\dot{C}_c = \frac{\lambda}{X} \times \text{HDD} \times \frac{86{,}400 \text{ sec.}}{\text{day}} \times \frac{C_c}{0.7} \times \frac{10^{-9}\text{GJ}}{\text{J}} \tag{D2}$$

where λ = conductivity of perlite = .055 $W(mK)^{-1}$

HDD = Heating Degree Days in Beijing

= 1078 HDD base 8°C, where the 8°C "balance" temperature comes from T (thermostat) = 18°C, and ΔT (free) = 10°C [See text, Section VIII C, Table III and Fig. 5.].

C_c = 2.66 Yuan/GJ, see Section VI.

Equation D1 is then of the form:

$$\dot{C} = AX + \frac{B}{X} \tag{D3}$$

and its minimum occurs when $\frac{d\dot{C}}{dX} = 0$, i.e.,

APPENDIX C. MINOR CORRECTIONS TO BE MADE TO A FUTURE SET OF PARAMETRIC RUNS

After three weeks in China in November, 1982, we are able to suggest several minor improvements to our assumptions which should be made before anybody makes a new set of runs.

We are confident they will not change the thrust of our conclusions, so we have not redone the DOE.2 runs--but we list them here.

1. Internal Loads.

a) Cooking. 15 kg of propane (600 GJ) appears to last 30-40 days. At 5 hours/day, this corresponds to 20-25 W/m^2 of floor.

b) Lighting. A typical apartment, with fluorescent lamps, uses approximately 30 W/room, = 30 x 9 = 270 W/unit = 2 W/m^2.

A glance at Figs. 3 and 4 shows that doubling our assumed $10W/m^2$ has no significance for the heat gains.

2. Our runs turn on the heat whenever it is needed, whereas in Beijing the official heating season is only four months, November 15 to March 15. We should change the thermostat schedule accordingly.

3. The optimum thickness of insulation could be reduced from 7.5 cm of perlite to 5 cm, as discussed in App. D; or a series of parametric runs could be made, varying X(opt) above and below 5 cm to look for the exact optimum.

4. We assumed a constant boiler efficiency of 0.7. This should be reduced to some more reasonable value, perhaps 0.4. as discussed in Sect. IV.

$$A - \frac{B}{X^2} = 0,$$

so, $$X(opt) = \sqrt{\frac{B}{A}}$$

i.e., $$X(opt) = \sqrt{\frac{\lambda \times HDD \times 86.4 \times 10^{-6} \times C_c/\eta}{C_{in} \times CRR}}$$

and inserting numerical values below D2.

$$X(opt) = \sqrt{\frac{.055 \times 1078 \times 86.4 \times 10^{-6} \times 2.66\frac{Y}{GJ} \times \frac{1}{0.7}}{34\frac{Y}{mJ} \times .0725}} \quad (D4)$$

$$= 8.9 \text{ cm} = 5.1 \text{ cm} + 3.8 \text{ cm equivalent of brick wall.} \quad (D5)$$

Instead of the optimum 5.1 cm we actually used 7.5 cm in our runs. We freely admit that this was just a guess, based on an assumed higher balance temperature and consequently higher value of HDD, namely 1740. We are frankly not accustomed to the large ΔT (free) associated with Beijing's high density of occupants and sunny winter days.

In App. C we have suggested that a final set of runs could reduce the perlite thickness from 7.5 to 5 cm.

Finally, we cite the recommendation of Li, Zhao, and Zhang of Qinghua University [Li '82]. They assume prices and an interest rate similar to ours, but a much lower thermostat temperature, $12^{\circ}C$, for which they quote the Beijing heating degree-days as 1642 DD. They should, but do not, correct for ΔT (free). They recommend 24 cm.

If in Eq. D5, we replace 1078 HDD by 1642 HDD, X(opt) becomes 11 cm, which is 7 cm of perlite plus the 37 cm brick wall. We find this to be encouraging agreement.

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