Session III No. 4

CIRA Economic Optimization Methodology

R.C. Sonderegger *ASHRAE Associate Member*
P.G. Cleary
J.Y. Garnier *ASHRAE Associate Member*
J.D. Dixon

ABSTRACT

CIRA is a user-friendly, microcomputer-based energy analysis and retrofitting tool for residential buildings. Aside from a monthly analysis of heating, cooling, and appliance use, CIRA can develop a list of retrofits ordered by decreasing savings-to-cost ratio for any house and any climate specified by the user. The list is terminated when no retrofits with a positive economic return remain or when a preset budget is reached, whichever comes first. This paper presents the approaches used in CIRA to deal with a number of well known problems inherent in economic optimization of buildings, such as (1) interactions among retrofits, (2) handling of mutually exclusive retrofits, (3) decreasing marginal returns as more retrofits are installed, and (4) constraints on computer time and memory for a full-scale optimization.

INTRODUCTION

A microcomputer-based package of programs has recently been developed, that performs residential building energy analysis and determines economically optimal mixes of discrete energy-saving measures (retrofits) for a given building and for a chosen dollar budget. The program package is called "Computerized Instrumented Residential Audit" (CIRA).[1] The catalog of retrofits used by CIRA approaches 100 items; it includes envelope performance retrofits (such as increased insulation and air leakage reduction), HVAC modifications (such as replacement burners and duct sealing), appliance improvements (such as water-heater blankets and efficient refrigerators), and other miscellaneous retrofits (such as clock thermostats). From the catalog the program chooses those retrofits that are applicable to the building under consideration and ranks them by decreasing savings-to-cost ratio. This ratio is defined for each retrofit as the incremental life-cycle savings (energy savings minus future maintenance and replacement costs) divided by the incremental first cost.

As is well known, space heating or cooling energy savings associated with any given retrofit depend on which other retrofits have already been installed. To reduce the potentially large number of yearly energy consumption calculations to be carried out during optimization, a scheme has been developed based on partial derivatives of yearly energy consumption.

In the energy calculation model used by CIRA, each retrofit is described by a change in one or more of the following: (1) the building load coefficient, (2) the internal gains, (3) the furnace or air conditioner efficiency, or (4) the heating or cooling distribution losses. Every time annual heating and cooling energy consumptions are evaluated, CIRA also calculates their partial derivatives with respect to (1) and (2). The energy saving from each retrofit can be estimated for changes in (1) or (2) as the product of the partial

R.C. Sonderegger, P.G. Cleary, J.Y. Garnier, J.D. Dixon, Energy Performance of Buildings Group, Energy and Environment Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720 USA

derivatives and the change in (1) or (2). For changes in (3) and (4), analytical expressions are used to estimate the energy savings.

During optimization, retrofits are chosen in order of individual savings-to-cost ratio until the annual energy consumption has been reduced by an estimated 25%. At this stage, the chosen retrofits are "installed" in the house by making the cumulative changes in (1), (2), (3) and (4) above permanent; the energy consumptions and derivatives are recalculated, and the estimated savings from the installed retrofits are adjusted so that the sum of the savings is correct. This process of chosing, installing, and adjusting is repeated until either the dollar limit is reached or no more retrofits exist with savings-to-cost ratios greater than one. In this paper, this process is described in detail and illustrated using a sample house.

ENERGY AND COST CALCULATIONS

Yearly Energy Calculations

Monthly energy calculations are done for five main uses: space heating, space cooling, domestic water heating, electricity, and fossil-fuel use for other appliances. The last three energy calculations are relatively straightforward and depend on the program users' inputs regarding the stock of appliances, the number of occupants, and so forth.

Space heating and space cooling consumption is calculated using monthly, variable-base degree-days and degree-nights for both heating and cooling seasons. The base temperatures used in calculating the degree-days and degree-nights are derived from thermostat settings, solar and internal gains, infrared radiation losses to the sky, and the thermal performance of the building envelope. Thermostat setbacks are handled by using the concept of effective thermal mass of the house. Performance variations of HVAC equipment with changes of part load and ambient conditions are taken into account. Degree-days and degree-nights for different reference temperatures are evaluated by using a site-specific empirical correlation with monthly average daily and nightly outdoor temperatures. Space heating and cooling predictions using this method have been shown to approximate the results from the DOE-2.1 building simulation program[2] within $\pm 10\%$. Preliminary comparisons with measured energy consumption data from 42 houses have shown a comparable correspondence between measured and predicted yearly heating and appliance energy consumption, with higher discrepancies for month-by-month consumptions.[3]

Calculation of Energy Savings of Individual Retrofits

As discussed in Ref 1, CIRA calculates the energy consumption of a house as a function of many parameters, such as thermal resistance, leakage area, thermal mass, spatial distribution of thermal resistance and leakage area, furnace efficiency, and distribution losses. For a given house, these parameters may each have up to four different values, for the periods: heating day, heating night, cooling day, and cooling night.

The CIRA retrofit database stores information on how each of these parameters is altered by a retrofit. More than one parameter may be changed--e.g., adding a storm window in winter will decrease the building load coefficient by increasing the thermal resistance of the window and decreasing its air leakage, but it also decreases the internal gains by reducing solar gain. The actual database entry for this retrofit (in Reverse Polish Notation) reads:

A12={D12¦.92+¦} : A13={D13!.6*} : A09={D09!.88*} (1)

where

¦ is the symbol for the "invert" operation
! is the symbol for the "enter" operation
A12/D12 are the new and old U-values, respectively
A13/D13 are the new and old specific leakage areas
A09/D09 are the new and old winter solar gain factors

The above instruction thus reads: "add R-0.92 (in British units) to the window system being retrofitted; reduce its leakage area by 40%; reduce its winter solar gain factor by 12%." The program then translates these instructions into corresponding changes of the building parameters that determine annual energy consumption and recalculates the latter. This structure allows the addition of almost any retrofit to the database used for the optimization.

It is necessary to retain the specific effect on the building structure, as opposed to global values such as "percent savings," because the energy savings actually achieved by each retrofit will depend on local weather conditions, on the economic assumptions, and on the thermal characteristics of the house--or on what retrofits have been previously installed. A shortcut to increase the speed of calculation will be presented in a later section.

<u>Dollar Savings and Costs</u>

For each retrofit, the energy saving calculated by CIRA is converted into a gross lifetime dollar saving by multiplying by the price of energy and reducing to present value.

$$S = \sum_{f=1}^{4} (-\Delta E_f) * P_f * \sum_{n=1}^{N} \left(\frac{1+e_f}{1+d}\right)^n \tag{2}$$

<u>where</u>

- ΔE_f are changes in yearly consumption for each fuel caused by the retrofit (GJ/yr or MBtu/yr)
- f is an index denoting fuel type
- P_f are fuel prices ($/GJ or $/MBtu)
- e_f are real fuel price escalation rates (fractional)
- d is the real discount rate (fractional)

The time horizon, escalation rate, price of energy, and discount rate are all input by the user; they are not fixed by the program.

The maintenance costs are given as a percentage replacement after a number of years, e.g., 100% after 3 years for plastic storms. (The costs and the maintenance schedules of all retrofits are stored in an external database and can easily be changed by the user to suit local conditions.) If the lifetime of a retrofit is short, more than one replacement may be needed. For example, for a ten year horizon and plastic storms, the storms would have to be replaced after three, six, and nine years, so the maintenance cost would be:

$$M = IC * \frac{PR}{100} * \sum_{n=3,6,9} \left(\frac{1+m}{1+d}\right)^n \tag{3}$$

<u>where</u>

- IC is the initial cost for the retrofit ($)
- M is the present value of maintenance expenditures over the life of the retrofit being considered ($)
- m is the real escalation rate of maintenance costs (fractional)
- d is the real discount rate (fractional)
- PR is the percent replacement of the retrofit necessary at periodic intervals (%)

Real escalation rates are yearly cost increases corrected for general inflation. For instance, real and nominal maintenance escalation rates are related by the expression:

$$m = \frac{m' - i}{1 + i} \tag{4}$$

where

m is the real maintenance escalation rate (fractional)
m' is the nominal maintenance escalation rate (fractional)
i is the inflation rate (fractional)

For the purposes of the printout, Fig. 1, the maintenance cost is annualized to:

$$AM = M \Bigg/ \sum_{n=1}^{n=N} \left(\frac{1 + m}{1 + d}\right)^n \tag{5}$$

where

AM is the annualized maintenance cost ($)
N is the economic horizon (years)

AM is therefore the amount in constant dollars that would have to be paid into a fund every year, increasing 100*m% per annum, to pay for all maintenance over the lifetime of the retrofit. The initial cost of a retrofit is calculated from data in the retrofit library as:

$$IC = C_f + (C_m * Q) \tag{6}$$

where

IC is the initial cost ($)
C_f is the fixed cost ($)
C_m is the marginal cost per "quantity" of retrofit ($/Q)
Q is the quantity of retrofit (square foot, linear foot, ea., etc.)

The total lifetime dollar savings (LS) from a retrofit is the sum of the dollar savings minus the sum of the maintenance costs--i.e., S - M as defined above. The savings-to-cost ratio (SCR) is defined as

$$SCR = \frac{S - M}{IC} \tag{7}$$

As discussed in the next sections, retrofits are ranked in decreasing order of SCR, and retrofits with an SCR of less than one are removed from the list. This optimization criterion is somewhat biased in favor of low-cost measures. Another possible optimization criterion could have been net life-cycle savings --the quantity (S-M-IC)--but that, in turn, favors expensive retrofits. A review and discussion of the different economic optimization strategies can be found in an NBS pamphlet.[4]

ECONOMIC OPTIMIZATION

Principle of the Optimization Procedure

After the energy consumption of the original house has been evaluated, the retrofitting process begins. First, CIRA scans a disk library of several hundred retrofit options. The entries contain costs (per square foot, per linear foot, or per unit) and figures of merit (typically: added thermal resistance, decreased solar or internal gains, decreased leakage area, and improved efficiency). Those retrofits that physically cannot apply to the building are not considered, for instance, cavity insulation for solid masonry walls or sliding storms for casement widows. For each retrofit, initial and maintenance costs are calculated, the latter including a periodic allowance for partial replacement where appropriate. The next step is to rate each retrofit by the energy savings it would cause if taken alone. These are converted to dollar savings and reduced to net present value. From these items the savings-to-cost ratios are calculated. The retrofits are sorted by this ratio, and the retrofit with the highest savings-to-cost ratio is chosen, then removed from the list of retrofits and installed in the house. Finally, the new energy consumption of the house is recalculated.

Now the process starts anew. Each remaining retrofit is re-rated (for the altered house) by calculating a new savings-to-cost ratio. These retrofits are sorted and the best one chosen and installed. The second installed retrofit naturally has a lower savings-to-cost ratio than the first, and this trend continues as more retrofits are chosen. The loop of rating, sorting, installing, and recalculating energy consumption continues until there are no more cost-effective retrofits. The list of retrofits is then printed out, together with relevant economic parameters. A sample output for a limited library of retrofits is shown in Fig. 1. At the top is some summary information about the house and the economic assumptions--prominent by its omission is the economic horizon, in this case 20 years. The fuel costs chosen represent the national averages for residences for April, 1982.[5] The rest of the printout shows the list of retrofits ordered by decreasing SCR. The "Name and Location" column refers to components of the house, such as windows and walls, and to their user-chosen names, such as "west" windows or "north" walls. The remaining four columns are self-explanatory.

Discussion of a Sample Retrofit of the Hastings Ranch House

The sample house used throughout this paper is an uninsulated ranch house in Washington, D.C., weather, built according to the "Hastings Ranch House" specifications.[6]

The optimization begins with a rating of all applicable retrofits in the library. Fig. 2 is a graphical illustration of the results of this initial rating process. Each retrofit is represented by an arrow. The horizontal coordinate of each arrow represents the initial cost,and the vertical axis represents life-cycle savings of a retrofit, taken by itself without considering any interactions yet. In this example, all arrows have slopes greater than one, that is, they all would be cost-effective taken by themselves. Not surprisingly, the first retrofit chosen for the sample house in these weather conditions is to reset the water heater thermostat to 120°F (49 °C). This has a nominal cost of 50 cents, and saves $687 over the twenty-year period under consideration, including maintenance costs and after reducing to present value. Its savings-to-cost ratio is 1373 (the printout in Fig. 1 shows 999.9 for any savings-to-cost ratio greater or equal to 1000). The water heater thermostat reset was chosen because it is steepest, which is a graphical way of stating that its savings-to-cost ratio is greatest. In Fig. 3 this initial retrofit is shown as a small, almost vertical arrow in the lower left hand corner.

The next most cost-effective retrofit is an automatic night setback thermostat. This retrofit costs $120 and results in a lifetime saving of $3427, for a savings-to-cost ratio of 28.6. Next is the installation of 6 inches of loose fiberglass in the attic, at a cost of $695 for a savings of $12,853 and a savings-to-cost ratio of 18.5.

The noticeable kink in the curve in Fig. 3 at this point reflects the quantum jump in savings-to-cost ratio going from the initial high-payoff retrofits to the more expensive window retrofits. Normally there would be many intervening retrofits to make a smooth curve; the abrupt change here is an unintentional consequence of the small size of the sample of retrofits chosen to illustrate the optimization.

Continuing with the retrofits, after an insulating blanket on the water heater comes double glazing for the north, east, and west windows, at a cost of $504, a saving of $2048, and savings-to-cost ratio of 4.1. The very next retrofit is to "remove" this double glazing and install triple glazing instead. This retrofit costs an additional $216 (the difference between triple glazing at $936 and double glazing at $720) and saves an additional $786, for an incremental savings-to-cost ratio of 3.7.

The optimal mix of retrofits often depends on the constraint placed on the initial budget or investment. As the budget increases, it may become cost-effective to upgrade a retrofit on a particular component with a more expensive but mutually exclusive retrofit with higher savings. In our example, a budget of $1350 (the sum of all costs thus far) calls for double glazing on all but the south windows. After increasing the budget to $1566, the most cost-effective retrofit for this house is triple glazing on the same windows. Referring to Fig. 2, the incremental retrofit from double to triple glazing would be represented by an arrow (not shown) connecting the tips of arrows #6 and #7, which represent double and triple glazing, respectively. Here, this incremental retrofit was chosen because its savings-to-cost ratio was higher than any of its competitors at this stage of retrofit.

A similar removal of an earlier retrofit occurs with attic insulation, where it is found that going from 6 inches of fiberglass to 9 inches has a savings-to-cost ratio of 1.2, after installation on other components of several intervening retrofits with higher cost-effectiveness. For each installed retrofit, CIRA remembers how to "undo" its cost to the homeowner and its effect on one or more building parameters, using a string of instructions similar to the one shown in Eq 1. Instructions on how to undo any retrofit must be retained in case a competing retrofit, presently not chosen because of inferior cost-effectiveness, will be chosen later at a higher level of cumulative investment for lack of better alternatives.

The next most cost-effective retrofit is double glazing of the south windows. Again, this retrofit and all its competitors are magnified in Fig. 4. with the same scale (but not the same origin) as Fig. 2. Notice that many of the retrofits in Fig. 2 are still present, but the arrows representing them are considerably shallower. The cause is a general decrease in marginal return on conservation investment. The intervening retrofits have made double glazing on the south windows and all other remaining retrofits comparatively less cost-effective. Double glazing, #8, was chosen at this point for lack of better alternatives. The gradual decrease of the savings-to-cost ratio of any individual retrofit as the retrofitting process advances is an expression of the well-known diminishing marginal energy savings of retrofits in buildings: "more insulation saves progressively less."

A more extreme example is the 85% efficient gas furnace. Throughout the retrofitting process, it was considered cost-effective, but always less so than other retrofits. When its turn finally came after all other retrofits had been installed, its SCR was found barely shy of one and was thus excluded and not plotted (although the printout in Fig. 1 shows this retrofit anyway).

Another related phenomenon can be observed in Fig. 3 in which the progressive flattening of the curve represents the diminishing marginal energy savings with increasing total investment in energy conservation, a familiar phenomenon in macroeconomics.[7]

It is interesting to observe how retrofitting the south windows with double glass was not found cost-effective until the windows on all other orientations had already been triple glazed. For this house, the south windows are shaded with overhangs. Thus, the cooling savings realized from reduced summer solar gain due to multiple glazing is scarcely utilized and reduces the cost-effectiveness of double-glazing the south windows. Of course, multiple glazing is not generally used to reduce solar gain. Outdoor or even indoor shading--not included in the reduced catalog of this sample retrofit optimization--would likely be more effective.

The retrofitting process is terminated after the regenerative gas furnace. Taken as a whole, the optimal package of retrofits costs $6206 and saves $27,897 over 20 years, including maintenance and reduced to present value. The cumulative savings-to-cost ratio is therefore 4.50. Expressed another way, this is equivalent to a discounted payback of about 5 years or an internal rate of return of over 20%.

Fig. 5 shows how the consumptions of the different fuels used in this sample house vary through this same retrofitting sequence. As expected, the general trend is downward. Note, however, the slight increases in heating consumption when a more energy-efficient refrigerator (#12) is installed at a

$1734 investment level. This reflects the decrease in "free heat" in the living space following an appliance retrofit. Conversely, cooling consumption benefits from such retrofits.

In Fig. 6 the same sequence of retrofits is represented by the total yearly operating cost to run this sample house, using the different fuel prices input by the CIRA user. The periodic retrofit maintenance costs are not included in this operating cost. Here, the inverse negative of the slope of the curve at any point represents the marginal simple payback of the retrofits. For example, if only retrofits with a simple payback of 3 years or less were to be considered in this sample house, then only retrofits on a section of curve steeper than the slope minus one-third would have to be considered. In this case, this would leave only the two water heater retrofits, the clock thermostat and the 6-inch attic insulation.

Implementation of the Optimization Procedure in CIRA

In principle, the procedure outlined above requires the recalculation of annual energy consumption each time a single retrofit is rated. Under such a procedure, a complete retrofit selection process (in which 200 or more retrofits, including the same retrofit for different components, are considered) could require several thousand calculations of annual energy use. This would take an unacceptable length of time. To speed up the process, CIRA rates the retrofits by an estimate of the savings based on partial derivatives of annual energy consumption and selects retrofits not individually but a batch at a time. After each batch, it recalculates annual energy consumption and corrects the estimates.

Partial Derivatives

As discussed in an earlier section, CIRA calculates the energy consumption of a house as a function of many parameters. However, only four of these are varied by most common retrofits. They are:

1. B (Btu/hr ^{o}F or W/^{o}C): Building load coefficient, (including infiltration losses)

2. I (Btu/hr or W): Internal gains, (including solar gain and sky radiation losses)

3. F (fractional): Rated heating or cooling efficiency

4. D (fractional): Distribution losses

For a given house, these parameters may each have up to four different values for the periods heating day, heating night, cooling day, and cooling night. Since the effect of a retrofit on each of these four parameters is known, rather than recalculating the exact change in energy for each retrofit, we can estimate this change from the sensitivity of annual energy use to these four parameters. For B and I, this sensitivity is described by two partial derivatives for heating and two for cooling. To estimate the partial derivatives with respect to building load coefficient, CIRA decreases the latter by 10% and recalculates the annual heating and cooling energy use. The change in heating energy use divided by the change in building load coefficient approximates the partial derivative of heating energy use with respect to load coefficient, with all other parameters held constant.

$$\left.\frac{d\ E_h}{d\ B_h}\right| \simeq \frac{E_h(B) - E_h(0.9 * B)}{0.1 * B} = X_h \tag{8}$$

where

E_h is energy use for heating (MBtu/yr or GJ/yr)
B_h is building Load Coefficient for heating (Btu/hr·^{o}F or W/^{o}C)
B is value of B_h of house to be retrofit (Btu/hr·^{o}F or W/^{o}C)

$E_h(B)$ is energy use of house with B_h equal to B (MBtu/yr or GJ/yr)

$E_h(0.9*B)$ is energy use of house with B_h decreased 10% (MBtu/yr or GJ/yr)

For the internal gain derivatives, CIRA subtracts 200 Btu/hr (58.6 W) from the internal gain and recalculates heating and cooling energy use.

$$\left.\frac{d\ E_h}{d\ I_h}\right| = \frac{E_h(I) - E_h(I - 200)}{200} = Y_h \tag{9}$$

where

E_h = energy use for heating (MBtu/yr or GJ/yr)
I_h = internal gains for heating (Btu/hr or W)
I = value of I_h of house to be retrofitted (Btu/hr or W)
$E_h(I)$ = energy use of house with I_h equal to I (MBtu/yr or GJ/yr)
$E_h(I-200)$ = energy use of house with I_h decreased by 200 (Btu/hr or W)

For the energy savings from HVAC equipment efficiency increases and HVAC distribution loss reductions, CIRA uses the fact that energy use is inversely proportional to rated efficiency and distribution efficiency (the latter defined as one minus distribution losses):

$$\frac{E_2}{E_1} = \frac{F_1 * (1-D_1)}{F_2 * (1-D_2)} \tag{10}$$

where

F_1 = HVAC efficiency at condition 1
F_2 = HVAC efficiency at condition 2
D_1 = distribution efficiency at conditon 1
D_2 = distribution efficiency at conditon 2
E_1 = energy use at F_1 and D_1
E_2 = energy use at F_2 and D_2

To rate a retrofit by the total energy use change it causes in heating and cooling, CIRA simply adds the contributions in the four main parameters:

$$\Delta E_h = (X_h * \quad \Delta B_h) + (Y_h * \Delta I_h) - E_h * (\frac{\Delta F_h}{F_h} - \frac{\Delta D_h}{1-D_h}) \tag{11}$$

and

$$\Delta E_c = (X_c * \quad \Delta B_c) + (Y_c * \Delta I_c) - E_c * (\frac{\Delta F_c}{F_c} - \frac{\Delta D_c}{1-D_c}) \tag{12}$$

The first two terms in Eqs 11 and 12 are the products of the partial derivatives and changes in B and I, as described above. The last terms are an estimate of the change in annual energy consumption caused by changes in rated efficiency and distribution losses, based on the relation in Eq 10 above.

Grouping of Retrofits in Batches

The second strategy used by CIRA to speed up the optimization process is to choose retrofits in small batches instead of one by one. There are two main conditions on the composition of a batch of retrofits: a batch may not contain more than one retrofit for each component and may not reduce the estimated energy consumption of the house by more than 25%. The first condition prevents such events as the simultaneous installation of double glazing and insulating shades on a single window. Clearly, the installation of the first retrofit would greatly diminish the savings from the second. This is called a collision of retrofits. The second condition is required because the derivatives vary as the building load coefficient and the internal gains vary. A 25% change in energy consumption is the range over which the variation in the derivatives has been found to be acceptable.

After a batch of retrofits is installed on the house, a complete recalculation of annual energy consumption is carried out. The results of this calculation are used to adjust the savings apportioned to each retrofit that affects space heating and cooling. The adjustment factor so calculated has been found to normally lie between 1.05 and 0.95. The saving from each space heating or cooling retrofit is adjusted so that the total saving is correct.

For example, the retrofits chosen could be a a new furnace, a new refrigerator, a water heater blanket for an electric water heater, and an insulating panel for a window. Taken individually, they might be estimated to save exactly 25%. However, when they are installed together, they might save 23%. The refrigerator and water heater do not interact with each other, so the sum of the electric savings they gave individually is the saving they give when installed together. However, savings from the furnace and the insulating panel are affected by the presence of the refrigerator and the blanket, so they are adjusted downward to get the correct total. The complete process is illustrated in Fig. 7. It represents the space heating and cooling energy consumption estimates for each retrofit as a dotted line and the corresponding corrected values as a continuous curve for each fuel type identical to the curves in Fig. 5. An asterisk indicates the exact energy calculated for the house with all the retrofits installed that have been chosen so far. No adjustments of the energy estimates are needed for water heating and electricity, as discussed earlier.

The optimization begins with separately estimating the energy savings for all retrofits and sorting them by decreasing SCR. The winner in the first batch of retrofits is the water heater thermostat setback. The next batch is the automatic clock night setback. It is alone (not included with the previous or following retrofits) because of the strong effect of thermostat setbacks on the partial derivatives. After each of these two batches have been installed, CIRA recalculates the exact yearly energy space heating and cooling energy consumptions and corrects the initial estimates. The result is plotted as the continuous curve for the first two retrofits.

The next batch of retrofits is limited to the 6 inches of attic insulation, because this, alone, decreases the space conditioning consumption by one third. Again, compare the initial estimate indicated by the third asterisk with the exact recalculation. The process continues with wrapping the water heater, double glazing the non-south windows as the winners in the next batch, then recalculating the exact energy consumptions, and so on.

CONCLUSIONS

Optimizing a mix of retrofits on a building is a tedious process. It may be compared to the textbook case of ranking investments by return on investment. Each retrofit, then, is viewed as an investment in energy savings and the monetary savings realized over the years to come constitute the return. However, the analogy is incomplete at best, because the returns on retrofit investments are a moving target. With each retrofit that the "investor" acquires, the returns on all remaining retrofits change, in general downward.

The yearly energy consumption of a building is neither a linear nor a simple function of the building parameters, let alone of the retrofits affecting these parameters. Furthermore, for individual retrofits the parameters affecting energy are rarely monotonic functions of cost. A good example is the multitude of window shades commercially available, some cheap and others expensive, in which there is often little correlation between cost and R-value or shading coefficient or any reasonable combination thereof. Therefore, unless radical assumptions are made on the cost structure of retrofits and unless the energy calculations are considerably simplified, the elegant analytical techniques of optimization under constraints are difficult to apply.[8]

It is partly because of these difficulties that the numerical, tedious approach to retrofit optimization was taken in CIRA. The program evaluates the actual energy savings of every possible retrofit several times as the house under consideration progresses from the original state to advanced weatherization. The strategy used by CIRA to find the mix of retrofits with the largest net life-cycle savings is essentially that used by a blind person to find the highest point of a hill: follow the line of steepest ascent. That is, keep rerating retrofits and implement those with the highest savings-to-cost ratio until the available budget is used up or the remaining retrofits point down. This pragmatic method is simple but effective. Rating retrofits by estimated savings and installing retrofits in batches enables the method to also be efficient for microcomputer applications.

REFERENCES

1. R.C. Sonderegger, J.Y. Garnier and J. D. Dixon, Computerized, Instrumented, Residential Audit, (Berkeley, CA: Lawrence Berkeley Laboratory, Publication 425 Revised, April 1982).

2. See, for example, DOE-2 Reference Manual (Version 2.1A), (Berkeley, CA: Lawrence Berkeley Laboratory [LBL-8706 Rev. 2] May 1981).

3. Unpublished results of work conducted by Energy Performance of Buildings Group, Lawrence Berkeley Laboratory (Summer 1982).

4. U.S., National Bureau of Standards Simplified Energy Design Economics by H.E. Marshall and R.T. Ruegg (Washington D.C.: National Bureau of Standards Special Publication 544, 1980).

5. U.S., Department of Energy, Monthly Energy Review EIA-0035(August 1982), pp. 89-90.

6. U.S., National Bureau of Standards, Three Proposed Typical House Designs for Energy Conservation Research by S.R. Hastings (Washington D.C.: National Bureau of Standards, 1977 [NBSIR 77-1309]).

7. See, for example, Chapter 11 on Investment Demand in W.H. Branson, Macroeconomic Theory and Policy (New York: Harper & Row, 1972).

8. See J.D. Balcomb, "Optimum Mix of Solar and Conservation," Proceedings of the 1980 Annual Meeting of the American Section of the International Solar Energy Society (Newark: American Section of the International Solar Energy Society, 1981), p. 1202.

CIRA--------COMPUTERIZED INSTRUMENTED RESIDENTIAL AUDIT--------CIRA

'ASHRAE-TEST' house in WASH-DC at 14 feet.

Spent: $4205.50 Limit: $10000.00

Real DISCOUNT rate (%): 3.00 Real MAINT ESC rate (%): 0.00

	Heating	Cooling	Water	Electric
Type of EQUIPMENT	Gas Furnace	Central AC	Gas	-na-
Fuel PRICES ($/MBtu)	5.30	20.50	5.30	20.50
Real ESCALATION rate (%)	3.00	3.00	3.00	3.00

	Retrofit DESCRIPTION	NAME & LOCATION	Initial COST	1st Year SAVINGS	Annualized MAINTENANCE	Net SAVGS to COST R
1	Set water htr. thermostat to 120 F	Smith APPLIANC	$0.50	$34.41	$0.09	999.9
2	AUTO. 5 F Htg. & Clg. NIGHT SETBACK	ASHRAE-TEST GENERAL	$120.00	$174.68	$4.47	28.6
3	Install 6 inches of loose fiberglass	Insulated ROOF/CEI	$695.00	$648.24	$7.50	18.5
4	Install R-6 water htr. blanket	Smith APPLIANC	$30.00	$13.93	$2.62	8.0
5	DOUBLE glaze	North WINDOWS	$168.00	$34.14	$0.00	4.1
6	DOUBLE glaze	East WINDOWS	$168.00	$34.14	$0.00	4.1
7	DOUBLE glaze	West WINDOWS	$168.00	$34.14	$0.00	4.1
8	*TRIPLE glaze	North WINDOWS	$72.00	$15.41	$0.00	3.7
9	*TRIPLE glaze	East WINDOWS	$72.00	$15.41	$0.00	3.7
10	*TRIPLE glaze	West WINDOWS	$72.00	$15.41	$0.00	3.7
11	DOUBLE glaze	South WINDOWS	$168.00	$29.14	$0.00	3.5
12	Buy new EFFICIENT REFRIGERATOR	Smith APPLIANC	$700.00	$106.92	$0.00	3.1
13	*TRIPLE glaze	South WINDOWS	$72.00	$8.85	$0.00	2.4
14	INSULATE with 3.5" blown-in cellulose	North WALLS	$440.00	$45.76	$0.00	2.1
15	INSULATE with 3.5" blown-in cellulose	South WALLS	$440.00	$38.64	$0.00	1.8
16	INSULATE with 3.5" blown-in cellulose	West WALLS	$260.00	$22.02	$0.00	1.7
17	INSULATE with 3.5" blown-in cellulose	East WALLS	$260.00	$22.02	$0.00	1.7
18	*Install 9 inches of loose fiberglass	Insulated ROOF/CEI	$300.00	$21.73	$3.24	1.2

* - This replaces a previous retrofit on this component. Savings and costs are in addition to those of the replaced retrofit.

CIRA--------COMPUTERIZED INSTRUMENTED RESIDENTIAL AUDIT--------CIRA

Figure 1. An illustrative retrofit package for a Hastings ranch house in Washington, DC, weather. These retrofits appear in all the following figures, with the same identifying numbers throughout. A reduced retrofit database was employed; the selection of retrofits is not typical.

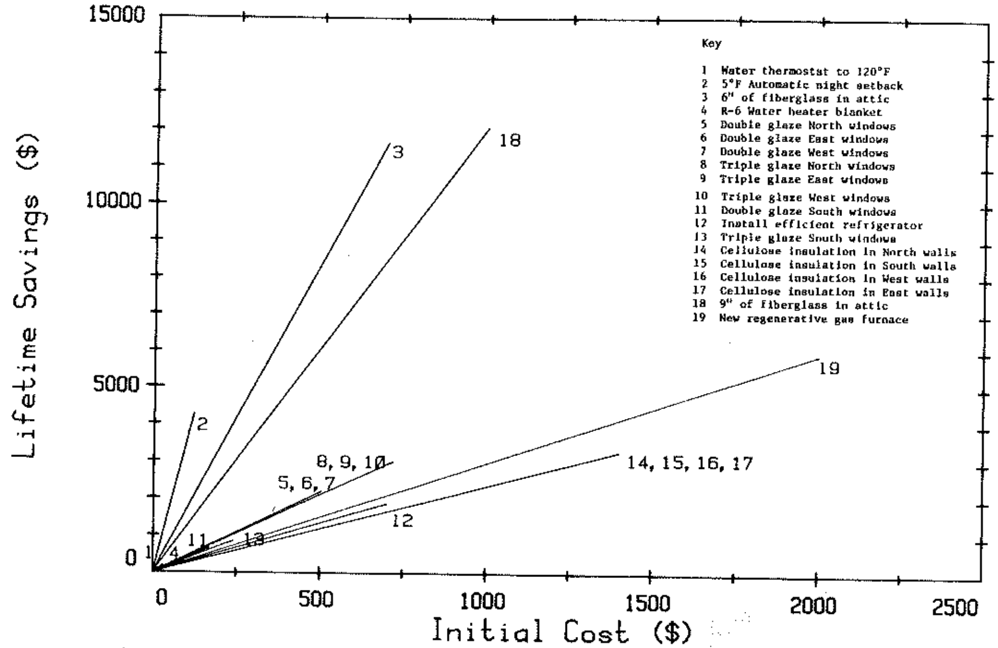

Figure 2. Savings and costs for all the retrofits in the reduced database as if they were to be installed individually in the Hastings ranch house in Washington, DC, weather. Energy costs and escalation rates assumed for this CIRA run are given in Fig. 1.

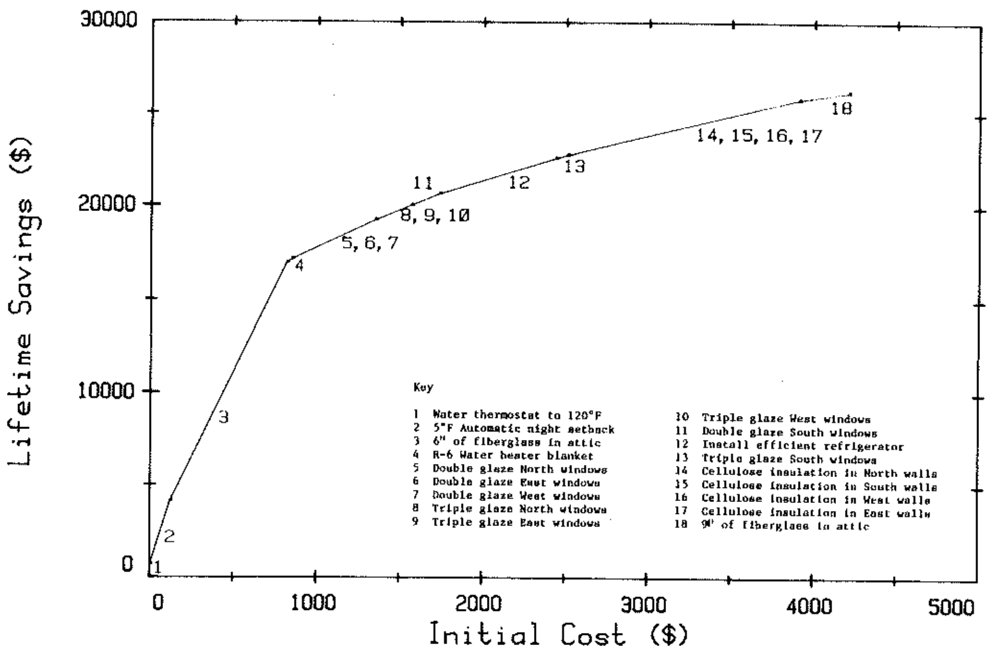

Figure 3. Cumulative lifetime savings from the illustrative retrofit package of retrofits for the Hastings ranch house in Washington, DC, weather. Energy costs and escalation rates assumed for this CIRA run are given in Fig. 1.

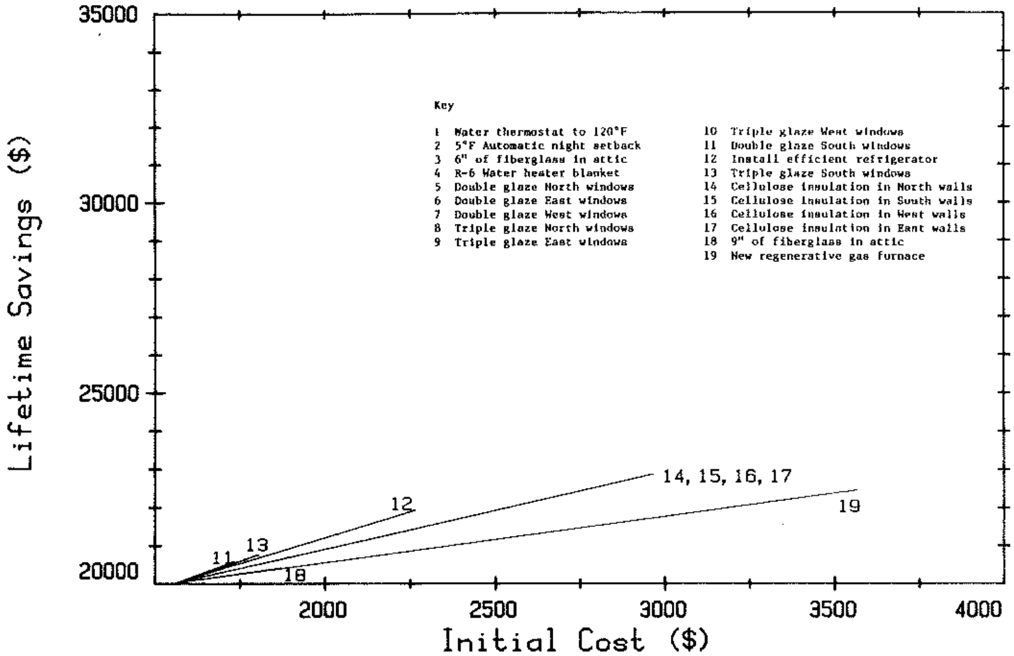

Figure 4. Savings and costs for the retrofits remaining in the database after $1566 has been invested, as if they were individually installed on the Hastings ranch house with the $1566 worth of retrofits in place.

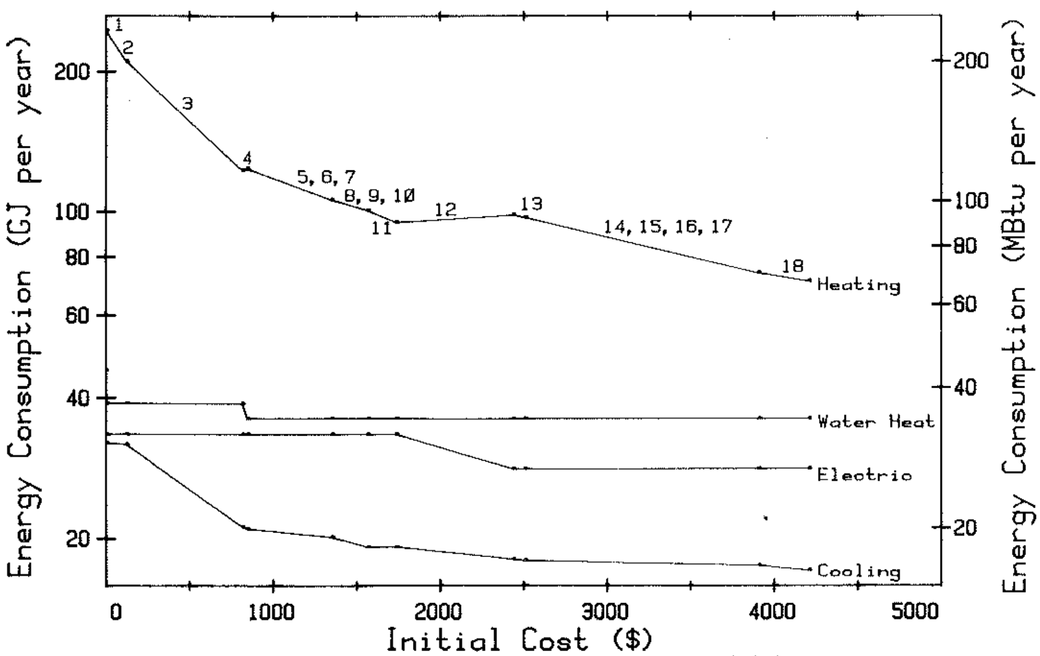

Figure 5. Energy consumptions by end use as functions of initial cost as the installation of retrofits proceeds in optimal order in this CIRA run. Note that the scale is logarithmic. MBtu are millions of British thermal units. For key, see Fig. 1.

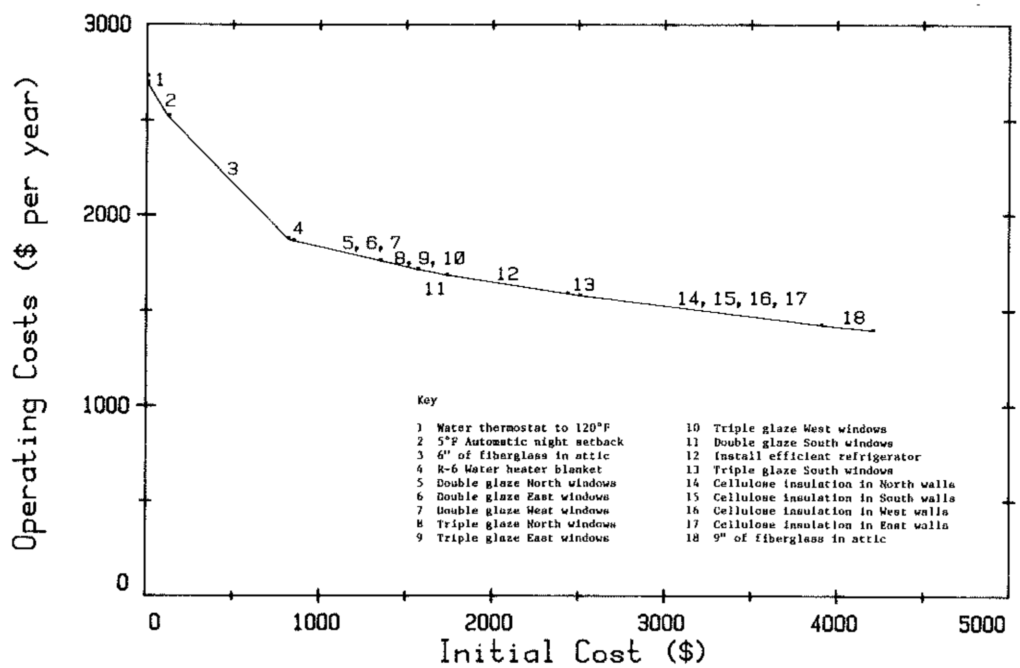

Figure 6. Operating costs for the Hastings ranch house as a function of initial cost as the installation of retrofits proceeds in optimal order in this CIRA run. Energy costs and escalation rates are given in Fig. 1.

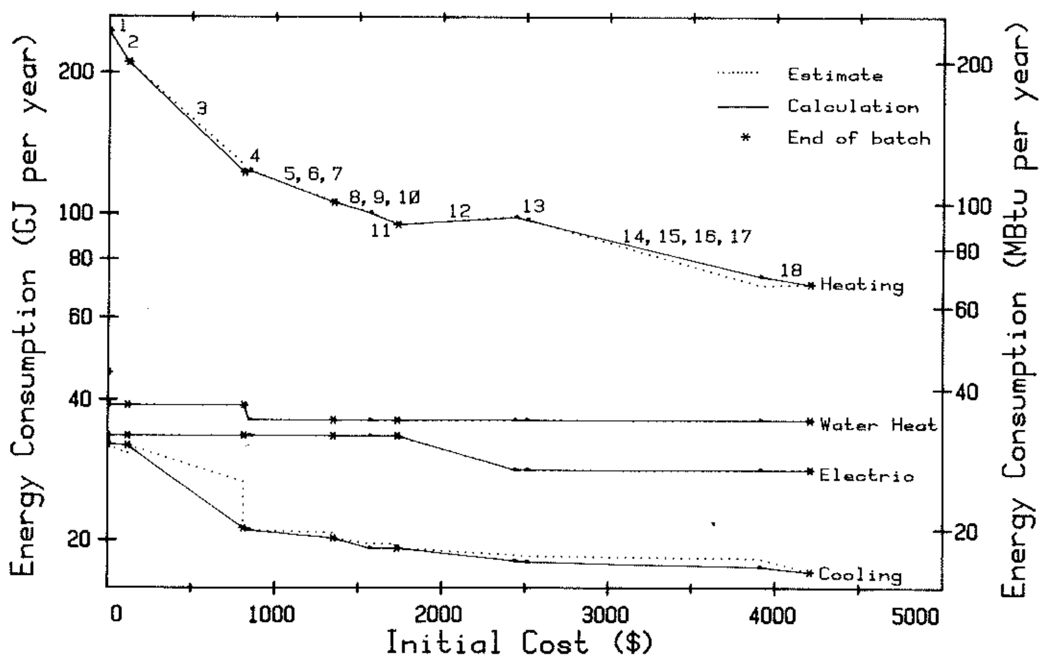

Figure 7. Energy consumptions by end use as functions of initial cost as the installation of retrofits proceeds in optimal order in this CIRA run. Both the estimated energy reductions (calculated with partial derivatives) and the exact calculations are shown. Note that the scale is logarithmic. MBtu are millions of British thermal units. For key, see Fig. 1.

Discussion

N. Sharabianlou, Energy Specialist, California Energy Comm., Sacramento: How does CIRA account for the effect of thermal mass? Does it account for interior thermal mass as well as exterior mass?

R.C. Sonderegger: Thermal mass is accounted for two ways. One, if there is a change in thermostat setting between day and night, CIRA calculates the amount of heat released ar absorbed by the effective thermal mass of the building and adds or subtracts it as appropriate to the previously calculated stead-state load. Two, storage of direct-gain solar radiation through windows is accounted for by a solar storage factor dependent of building mass and outside temperature that partitions the solar gain experienced over a 24-hour period between the day and the night periods.

Sharabianlou: Can CIRA be applicable for nonresidential buildings? If so, what modifications should be made?

Sonderegger: At present, CIRA can be used for any single-zone building, as far as the engineering algorithms are concerned. However, part of the questions and part of the retrofit catalog are specifically geared for residential applications. These retrofits and these questions would have to be altered to handle other types of buildings. We are in the process of extending CIRA to small commercial buildings.

Sharabianlou: What type of HVAC systems can be handled by CIRA? If seasonal performance factors are used for these systems, how are they derived and what are their limitations?

Sonderegger: The HVAC system that CIRA knows about are: gas furnace, gas boiler, oil furnace, oil boiler, heat pump, unit gas heater, electric furnace, electric baseboard, stove, wood-burning equipment, central air-conditioning, room air-conditioning, evaporative cooler. The distribution systems available are forced air, steam, water, gravity air, in room. Location and degree of insulation of the forced air ducts or water or steam pipes are used to calculate distribution losses, which in turn are used when calcualting seasonal efficiencies. Other information used for seasonal performance evaluation is: rated efficiencies or COP, total and/or sensible capacity, part-load performance curves derived from data from Brookhaven Natl. Lab. and the National Bureal of Standards, and variation in total and sensible cooling capacity and COP for cooling systems using correlations derived from manufacturer's specifications. The limitation of this approach is mainly that it is strictly accurate only for the exact equipment for which the performance curves were derived.

R.L. Smorada, Resch. Chemist, DuPont Christina Lab., Wilmington, DE: Please comment on the LBL model for air infiltration.

Sonderegger: The residential infiltration model developed at LBL uses the concept of effective leakage area, along with builidng and site parameters to make infiltration predictions from available weather data. The leakage area is either measured using a blower door, or estimated by adding individual component leakage ares from walls, windows, doors, vents, ceiling, etc. Default values are provided by CIRA to assist the user based on measured component leakage areas or theoretical calculations.

Other building parameters of importance are the grade-to-ceiling height and the relative distribuition leakage area among walls, ceiling, and floor. Again, the CIRA defaults provide helpful guidance to the non-technical user.

Site parameters are the terrain class and the shielding class. There are five terrain classes, from open flat terrain to a built-up city. There are five similar shielding classes, but they affect the immediate vicinity of the house, while terrain classes refer to the surrounding to within about a ten-mile radius.

The model is the result of carefully applied approximations to a set of basic fluid dynamic equiations. The approximations have been extensively validated, as well as the overall predictive performance of the model. An early version of the LBL model is part of the 1981 edition of the ASHRAE Handbook of Fundamentals. For more information, cunsult the following artical:

M.H. Sherman, D.T. Grimsrud, "The Measurement of Infiltration using Fan Pressurization and Weather Data," Lawrence Berkeley Lab. Report, LBL-10852, EEB-epb-80-11, in the Proceedings of the First International Air Infiltration Centre Conference, London, EEB-epb-81-9, 1980.

K. Pater, Staff Engr., Argonne (IL) Lab.: Besides DOE-2, have you compared it with any other program?

How does it credit lighting and kitchen equipment?

R.C. Sonderegger: No, we have only compared it to DOE-2.1. However, we have also compared CIRA predictions for monthly overall energy use to actual utility bills from seven gas heated houses in Walnut Creek, California, with an average discrepancy of approximately $\pm$ 20%. We have also compared yearly predictions to those same houses, to 14 Midway, Washington (of which some before and after extensive retrofits), and to a solar house in Syracuse, N.Y. For those yearly predictions, the average discrepancy was much less than 10% with the largest one 13%.

Lighting and kitchen equipment are credited through a question, "Lighting and other internal gains", with a default value set at 1,000 Btu/hr. Special appliances, such as refrigerator, water heater, clothes washer and dryer and cooking range are determined separately.

J.A. Kremers, Prof. of Architecture, Kent (OH) State Univ.: How does the program handle the variable of length of building life?

R.C. Sonderegger: This parameter is entered by the user when responding to the question "Economic Horizon. . ." It is used in all present value calculations.

R.M. Ward, Proj. Dir., TRA, Seattle, WA: Can program also give payback period?

R.C. Sonderegger: Yes, to be more specific, it gives the discounted paybback period for every measure recommended. This discounted payback period is defined as the period over which a measure would exactly pay for itself, assuming that energy savings escalate each year at the proper fuel escalation rate and that the initial investment appreciates at the discount rate.

E. Dahan, Product Mgr., W. R. Grace, Cambridge, MA" What parameters are accounted for in the weather file input? Are latent and sensible heat loads calculated?

How is air infiltration accounted for? Does the effective leakage area get input?

R. C. Sonderegger: The parameters contained in each weather file are: monthly specific air infiltration caused by wind, monthly specific air infiltration caused by buoyancy, monthly average outside temperatures for day and night (defined by 8 A.M. amd 8 P.M.).

Four triplets of coefficients (one triplet each for heating day, heating night, cooling day, cooling night) that correlate variable-base degree-days with monthly average wet-bulb temperatures. 12 quintuplets of coefficients for total solar flux, used to compute the total solar flux on a vertical surface of any azimuth during the computation 12 monthly average horizontal solar fluxes. 12 monthly average diffuse solar fluxes.

Both sensible and latent cooling loads are calculated, but only sensible heating loads are calculated. Air infiltration is accounted for using the LBL infiltration model, as described in the answer to the inquiry by Mr. Smorada. The effective leakage area is input either based on blower door measurements or with the assistance of CIRA, which asks for types of windows, number of wall penetrations, etc., and then suggests appropriate leakage areas for each envelope component.