GL013608

A response to the proposal of an energy effectiveness factor, Ee

By JAMES M. CALM, PE, Energy and Environmental Systems Div., Argonne National Laboratory, Argonne, Ill.

In the August 1976 issue of ***Heating/Piping/Air Conditioning***, an energy effectiveness factor, *Ee*, was proposed as an evaluation function permitting comparison of alternate integrated conversion systems*. This article represents a response to that proposal and is based on work sponsored by the Office of Energy Conservation of the Energy Research and Development Administration (ERDA). We shall define a coefficient of performance for integrated energy systems, discuss some problems associated with the *Ee* concept, and compare the *Ee* and *COP* approaches.

A.‡ The accepted practice in performance evaluation is to compare the useful outputs or products to the energy inputs required to obtain them. Both the conversion efficiency, η, and the coefficient of performance, *COP*, as well as its dimensional form, the energy efficiency ratio *EER*, follow this form. The *COP* differs from η in that "free" source input energy such as heat from the ambient air is not included as an energy input for heating. For the cooling *COP*, the useful output is

---

*Coad, William J., "Energy Effectiveness Factor," *Heating/Piping/Air Conditioning*, August 1976, pp. 35-38.

‡Editor's note: *This discussion is arbitrarily divided into Sections A through M as designated by boldface letters, as is Mr. Coad's rebuttal. Cross reference to like lettered sections in the two articles will make it easier to follow the criticism and rebuttal on specific points.*

COP vs. Ee

A rebuttal to the suggested use of a COP value in lieu of Ee

By WILLIAM J. COAD, PE, Vice President, Charles J. R. McClure & Associates, St. Louis, Mo.

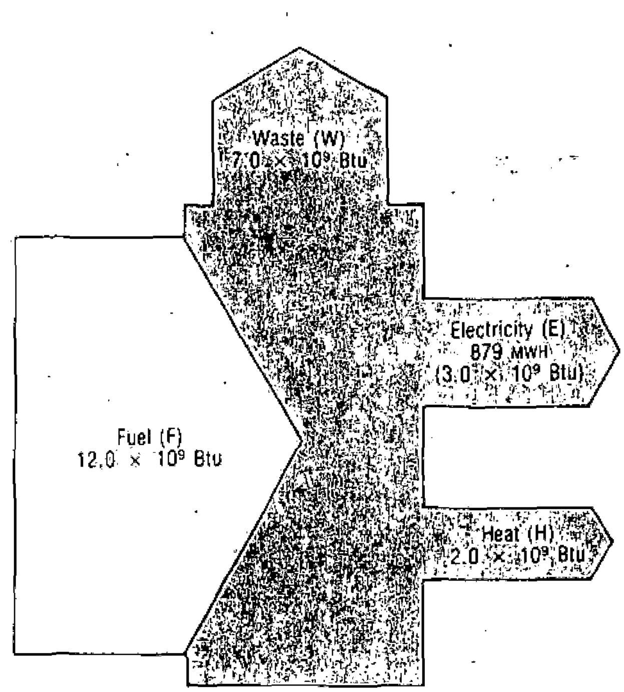
This discussion is presented as a rebuttal to Mr. Calm's critique, in which he proposes a newly defined term of coefficient of performance to be applied in lieu of our previously proposed *Ee*. (To distinguish his **COP**, we shall present it in boldface when using it as he has defined it.)

A. Let us first consider the introductory argument concerning the term of combined plant efficiency, η, where:

$$\eta = (E + H)/F$$

Although there is no question that electricity is a higher quality form of energy than heat, the two are interchangeable in the degrading direction. That is, electricity can be used or degraded to heat, producing the direct thermal conversion of 3413 Btu per KWH. This is done intentionally in many energy community systems, but where it is unintentional, the first law will ultimately create the cascading effect. As the electricity is converted to use for lighting, it is converted to heat; as it is converted to power use, the mechanical energy from the motor shaft is eventually found in the form of heat (generally resulting from friction, either molecular or boundary); and in transmission systems or power conversions, all losses and inefficiencies ultimately convert to heat. Thus, it is totally valid to add the two forms as proposed in the above equation.

B. The first "problem" cited by Mr. Calm, together with its examples, demonstrates precisely the pitfall



1 First law balance diagram for total energy system A.

the cooling produced or heat removed, and the energy input is considered to be only the work or energy required to provide the cooling. Thus, while η is based on the first law of thermodynamics, *COP* is not, because "free" energy sources or sinks such as ambient air heat are not included in the calculations.

A simple extension of this approach to integrated energy systems would be:

$\eta = (E + H)/F$

where

E = electric energy input, KWH × 3413 Btu per KWH
H = heating energy output, Btu
F = fuel energy input, Btu

B. Two problems arise with this approach. The first is that because electric energy and heating energy are produced by thermodynamically irreversible processes and are not in the same energy form, their thermal values or qualities are not equal. Because of this, a comparison of systems based on η ratios is limited to systems for which the ratio *E/H* is the same. A simple illustration of this is given by comparison of Figs. 1 and 2, both of which are integrated heating and cooling systems with the aggregate inputs and outputs shown for a one-year period. For these illustrations, the efficiencies would be:

$\eta_A = (3 + 2)/12 = 0.42$

s. COP vs. Ee

that the concept of energy effectiveness factor was intended to prevent. The arguments are:

- The characteristics of combined plants are such that it would be very difficult to obtain the some quantitative value of combined efficiency with the different "mixes" of product shown.
- Assuming these options were available, two cases are implied by the example.

CASE 1. Assume the community has a need for 3 GB thermal units and 2 GB electric units (power and lighting). The plant, however, achieves the optimum combined efficiency when producing the mix of 2 GB thermal units and 3 GB electric units. Under these conditions, the plant can be operated at maximum combined efficiency and the 1 GB electric energy converted to thermal energy at the point of use. (This technique has been used extensively to optimize combined efficiencies in such plants for some years.)

CASE 2. The optional methods imply that the needs of the energy community served by System A are 3 GB electrical (assumed power and light) and 2 GB thermal. Under the premises stated — *i.e.*, optimally electricity could be converted at a time integrated thermal efficiency of 0.3 and heat at a time integrated thermal efficiency of 0.6 — the fuel required to serve the community would be 13.3×10^9 Btu. Using the *Ee* concept, this would reveal:

$Ee = (3 + 2)/13.3 = 0.37$

Since this is less than the combined plant quotient of 0.42, the *Ee* evaluation reveals that the best method of serving this load is with the combined plant.

Contrarily, with the System B product mix requirement, the *Ee* for the alternative method of serving the community is:

$Ee = (3 + 2)/11.7 = 0.427$

Since this is greater than the *Ee* for the combined plant (0.42), the preferred method for serving a community with *this* mix is the proposed alternative.

C. These two cases reveal the validity of the *Ee* concept when applied to alternative methods of serving a given community "mix." Concerning the closing statement of the first "problem," the logic escapes me. The time integrated combined efficiency (numerically identical to *Ee*) has served precisely the function intended: it has served as an evaluation function to show that combined plants with the indentical *Ee* are not the preferred method of serving *all* energy community product mix requirements!

D. The statement of the second suggested "problem" apparently reveals an oversight in the reading of the original article. The denominator term, *F*, was specifically defined as follows: "The input fuel energy, *F*, is expressed as the high heat value of the depletable energy resource (fossil or nuclear fuel) consumed by the plant (or community) annually. Since this energy flow is

Coefficient of performance

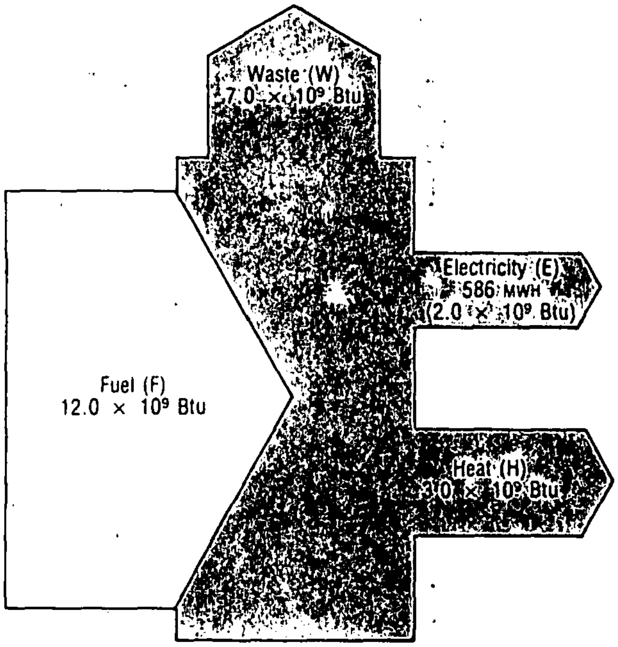
$\eta_B = (2 + 3)/12 = 0.42$

where η_A and η_B are the efficiencies of Systems A and B (Figs. 1 and 2), respectively. Thus, both systems have identical fuel efficiencies and fuel inputs. If these integrated systems are compared to nonintegrated systems using typically encountered seasonal efficiency values of $\eta_E = 0.3$ for electricity and $\eta_H = 0.6$ for heating, the fuel requirements for Systems A and B, F_A and F_B, to produce the same outputs would be:

$$F_A = (E/\eta_E) + (H/\eta_H)$$
$$= (3 \times 10^9/0.3) + (2 \times 10^9/0.6)$$
$$= 13.3 \times 10^9 \text{ Btu}$$
$$F_B = (E/\eta_E) + (H/\eta_H)$$
$$\doteq (2 \times 10^9/0.3) + (3 \times 10^9/0.6)$$
$$= 11.7 \times 10^9 \text{ Btu}$$

C. It should be obvious that in these examples integrated System A (Fig. 1) is more advantageous than the nonintegrated system in terms of fuel resource requirements. This is not true for System B (Fig. 2), even though its fuel input and efficiency are identical to those of System A (Fig. 1). Thus, it can be seen that efficiency, η, may not be used to compare systems with different product mixes.

D. The second problem with using η for integrated systems is that if part or all of the heating output were in the same direction as the product flow f, [then] $f = F$."



2 First law balance diagram for total energy system B.

s. COP vs. Ee

Energy effectiveness factor

Thus, F was specifically defined so as not to include so-called free energy. As an example, looking at Mr. Calm's first example, if a solar collection/utilization system reduced the input fuel energy to 8 GB, the *Ee* would increase from 0.42 to 0.625! This is a truly valid way to recognize the value of utilizing solar energy! Contrarily, if the auxiliary power requirements of collecting, converting, and storing solar energy resulted in an increase in the fuel input, the *Ee* would decrease, revealing that the solar energy collected was counterproductive to resource conservation.

E. Mr. Calm's proposal simply to numerically add the output energy products, divide by the fuel input, and define the quotient as COP is worthy of some rebuttal.

First, from the standpoint of semantics and customary engineering terminology, *COP* has classically been rigorously defined as the ratio of refrigeration system external energy input from the low temperature sink to the high grade energy input required to create the energy flow motivation from the low to the high (reject) temperature. To simply introduce a totally different meaning for the same expression is not valid in keeping with the fundamental tradition of physics as a science of exact definition.

Second, it is not valid mathematically to add the cooling energy to the higher grade forms as was done in the second **COP** equation, to wit:

$$\text{COP} = (E + H + C)/F$$

This situation is different from Mr. Calm's opening discussion of the time integrated thermal efficiency equation: cooling energy is *not* convertible to heating or electrical, and electrical and heating are not *directly* convertible to cooling as is electrical to heat. The Clausius statement of the second law of thermodynamics expresses this phenomenon quite clearly: "No machine whose working fluid undergoes a cycle can absorb heat from one system, reject heat to another at a higher temperature and produce no other effect." Thus, either the heat energy, H, or the electrical energy, E, can be converted to the cooling form, C, *only* through a second law process in which the E or the H is the " other effect." Herein lies the absolute requirement to include the classical *COP* term, defined as the refrigeration effect divided by the external energy input:

$$COP = C/E \text{ or } H$$
$$E \text{ or } H = C/COP$$

In commercially available air conditioning refrigeration machinery, compression machinery (powered by relatively high grade energy in the form of electricity or produced by a collection process from a "free" source, such as a solar collection or heat pump system, rather than by a fuel conversion process, η would count the "free" source energy input with the fuel input in the denominator.

E. This objection is easily circumvented by using a *COP* for which F would not include the "free" energy:

$$COP = (E - H)/F$$

If the integrated system were also to include cooling, the performance measure would require that the cooling be treated as a product, even though it is a thermal system input. Thus, the *COP* could be calculated as:

$$COP = (E + H + C)/F$$

where

C = cooling energy input, Btu

Note that E and H were defined as energy outputs, while C is as an energy input, even though all are system products.

For Fig. 3, the *COP* would be:

$$COP = (3.413 + 3 + 0.6)/11.38$$
$$= 0.62$$

F. Before proceeding further, three observations are in order. First, the earlier cited restriction of this *COP* value to comparisons of systems with the same product ratios would still apply because of the differences in the thermal qualities of the products. Second, the *COP* suggested here, as any *COP*, is not a first law based measure but rather a simple ratio of useful products to work input required to obtain the products. And third, the *COP* may be calculated for any time period desired (*e.g.*, peak cooling hour, peak heating day, transition month, annual operation, etc.), provided that the same period is used for the fuel measurement as for the aggregation of each of the products.

G. The energy effectiveness factor, *Ee*, proposed in the August 1976 issue of HPAC, differs from the above *COP* only in its treatment of the cooling component. In the *Ee* proposal, cooling is noted as a first law thermal *input*, even though it is a system product *output*. To resolve this phenomenon, the *Ee* proposal suggests that the product value of the cooling, c, be computed as the cooling required divided by the *COP* of community refrigeration system(s), $(COP)_s$. The proposal further suggests that the $(COP)_s$ be set at the values established in ASHRAE Standard 90-75. The energy effectiveness factor was thus presented as:*

$$Ee = (e + h + c)/f$$

where

$e = E$ = annual electric energy output, KWH ×

---

*The *Ee* as presented in the August 1976 article showed the *Ee* numerator as the product rather than the sum of the outputs. This typographical error was subsequently corrected in the October issue.

vs. COP vs. Ee

prime mover shaft power) has a range of *COP* of approximately 2.20 to 4.71 depending on the machinery and the auxiliary devices included in the calculation. For thermally motivated machinery, the range is approximately 0.5 to 1.0.

With this fundamental concept in mind, the key philosophy of the development of the originally proposed energy effectiveness factor was to retain all scientific and mathematical integrity and redefine the outputs of the integrated plant in terms that were consistent — products. The "values" of those products were then summed and divided by the input product, achieving a quotient based on defensible techniques, *with no restrictions*. The method by its very nature is a comparative evaluation parameter. Thus, it is applicable to 1) evaluating comparative methods (including alternative integrated plant designs) of serving the same energy community; 2) evaluating the value of the integrated plant approach for one energy community as compared to another; or 3) comparing the actual performance achieved to the performance anticipated in planning.

F. Following his third **COP** equation, Mr. Calm states, first, that there are restrictions to the use of the proposed **COP** concept. *Such restrictions do not apply to the* Ee *concept.*

His second observation is that "the *COP* suggested here, as any *COP*, is not a first law based measure but rather a simple ratio of useful products." However, the technique of adding energy outputs and inputs mathematics in the proposed numerator confused the value of the products; herein lies the invalidity. If a unit of refrigeration were required by the community and the central plant provided for this in the form of chilled water, the numerator term would be unity. If, however, the central plant provided, say, electric power that could provide the same unit of refrigeration at a *COP* of 2, the numerator term would be 0.5, a more realistic term insofar as the comparative *value* of that product is concerned.

Regarding the third observation, the time period concept presented is applicable to *any* evaluation function. Inclusion of any specific time period simply converts a power function to an energy function (thus, the difference between classical thermal efficiency versus time integrated thermal efficiency).

G. In the *Ee* concept, it *was* recognized that "cooling energy," from a first law balance concept, *enters* the plant. This recognition is fundamental and cannot be ignored; it is a simple law of physics. First law balance can and legitimately should be performed on *any* energy conversion system including straight degradation (fuel to heat or electricity to heat), power conversion (fuel or heat to shaft or electricity), or refrigeration (shaft or heat to move energy from a low level to a high level). This phenomenon cannot be legitimately ignored. The classical definition of *COP* does not ignore the first law

Coefficient of performance

3413 Btu per KWH
$h = H$ = annual heat energy output, Btu
C = annual cooling energy input, Btu
$c = C/(COP)_s$
$f = F$ = annual fuel energy input, Btu

The product diagram for the system of Fig. 3 is shown in Fig. 4, for which the energy effectiveness factor as calculated in the *Ee* proposal is:‡

$$c = C/(COP)_s = (0.6 \times 10^9)/1.8 = 0.33 \times 10^9$$

$$Ee = (3.413 + 3 + 0.33)/11.38 = 0.59$$

H. There are several problems associated with the proposed *Ee* using the ASHRAE Standard 90-75 values for $(COP)_s$.

I. First, the 90-75 *COP* values are minimum rather than typical. Tables 6.2, 6.4, and 6.5 of 90-75 provide that the *COP* values will be increased beginning in 1980, so it is apparent that the *COP* values are conservative for the present. An *Ee* comparison of alternative integrated systems using $(COP)_s$ to nonintegrated systems with typical *COP* ratings would, therefore, provide an unsupported advantage to the integrated systems.

J. Second, an application of the *Ee* for a community would require distinction between the various cooling system sizes, types, and input energy sources rather than the use of a single value for $(COP)_s$. For example, the $(COP)_s$ for cooling systems over 65,000 Btuh would be 2.0 rather than 1.8; heat operated cooling equipment would use 0.4 if direct fired and 0.65 if indirect fired. The conversion of *C* to its product value *c* would therefore become a sizable analysis for a large community.

Third, the 90-75 *COP* values are for prescribed rating conditions given in Tables 6.1 and 6.3 of the Standard. The *Ee* would therefore be limited to application at those conditions, but they are not applicable to annual operation for which *Ee* was suggested.

K. Fourth, the *Ee* was presented as an evaluation function consistent with the first law viewpoint. As such, heating in the integrated system, if provided by a solar collection or heat pump cycle rather than by energy conversion, would require a product value adjustment similar to cooling to be consistent.

L. Finally, even if appropriate $(COP)_s$ values were used and a product value were calculated for the heating output when warranted, the *Ee* would still be limited to comparisons of systems with the same product mix ratios. Demonstration of this comparison limitation is

---

‡Fig. 4 is Fig. 4b of the August 1976 *HPAC* article, with a minor correction for *c*:
$c = C/(COP)_s = 0.6/1.8 = 0.33$

COP vs. Ee v

Energy effectiveness factor

or suggest the *addition* of positive values and negative values; it simply expresses as a quotient the ratio of an absolute value of a low level thermal product power obtained to a motivating thermal product power input. Similarly, the classical definition of thermal efficiency (also for a "second law" process; *i.e.*, heat engine) expressed as a quotient the ratio of a thermal product power output to a thermal product power input.

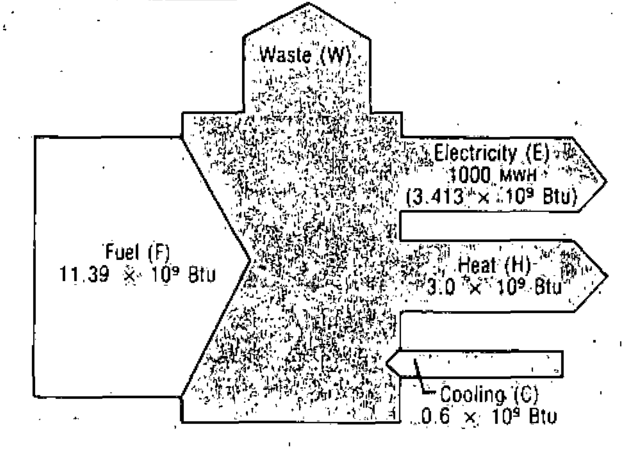
It is when an attempt is made to sum cycle input *energy* and cycle output *energy* that the "product" value must be clearly identified. The original article simply attempted to point out this significance and stated that *the analyst applying the concept must recognize it and apply a product value conversion, the refrigeration cycle* COP, *to legitimatize the evaluation*.

H. The original article stated ". . . the numerical value of $(COP)_s$ must be fixed at a level commercially available in community systems." The suggestion that $(COP)_s$ be set at the values in ASHRAE Standard 90-75 was simply that — a suggestion. These values are in no way related to the *concept* of *Ee*. The quoted statement should stand on its own regarding the concept.

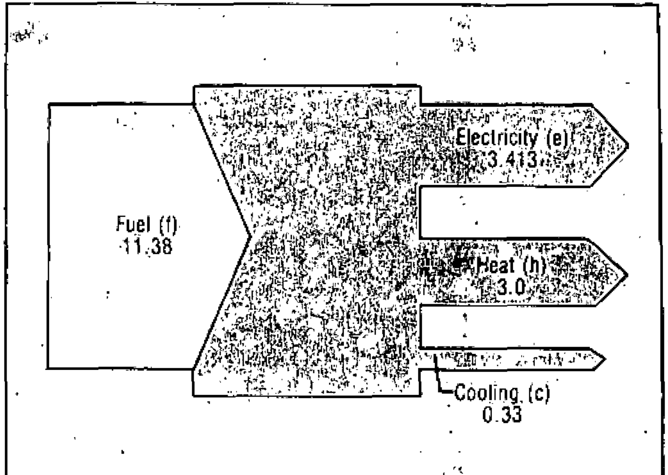
I. In the first of his four points of discussion, Mr. Calm states that "an *Ee* comparison of alternative integrated systems using $(COP)_s$ to nonintegrated systems with typical *COP* ratings would, therefore, provide an unsupported advantage to the integrated system." This should be discussed. If, indeed, the *COP* values of the cooling systems utilized in a community are low ("typical *COP* ratings"), other things being equal, more fuel is consumed to provide a given unit of cooling, resulting in a lower *Ee*! Thus, from the standpoint of energy utilization effectiveness, the low *COP* apparatus pays the price. If, on the other hand, one integrated plant is being compared to the anticipated or predicted performance, the numerical value of $(COP)_s$ is irrelevant, as long as it is consistent.

J. Regarding the second and third points, to obtain the most valid evaluation, the mix of community refrigeration unit sizes that would be employed if converted within the community should be understood and mathematically averaged if the 90-75 values are being used. It is true that the annual or seasonal refrigeration *COP* (energy base) will not likely be equal to the rated *COP* (power base). Unfortunately, reliable data on the energy related *COP* are not available, and corrections for this must be judgment factor inputs on the part of the analyst. (ASHRAE is currently organizing a standards panel to draft Standard 103.1—P, "Methods of Testing for Cooling Seasonal Efficiency of Unitary Air Conditioners and Heat Pumps.")

K. The fourth point is inconsistent with the *Ee* thesis. Earlier comments regarding solar energy should adequately address this point.



3 First law balance diagram for electric, heating, and cooling system.



4 Product diagram for electric, heating, and cooling system (Fig. 3).

identical to the earlier illustration for the η comparisons using Systems A and B of Figs. 1 and 2. (Assuming that the heat produced in Systems A and B was provided by energy conversion rather than by a heat pump or other "free" energy source, the *Ee* values for these systems would be equal to the η and *COP* values.)

M. Given this constraint, it is not clear that the *Ee* offers any advantage over the integrated system *COP* suggested earlier. Whereas the *Ee* calculation entails considerably more effort and is subject to challenge of the values used for $(COP)_s$, the simpler evaluation function would appear to be the preferred choice.

COP vs. Ee

L. Earlier statements regarding example Systems A and B should adequately clarify the final critique.

M. The proposed **COP** evaluation appears to be somewhat lacking in philosophical concept and difficult to defend mathematically and conceptually. The numerical or quantitative values obtained are identical to those utilizing the energy effectiveness factor, *Ee*, with an assumed $(COP)_s$ of unity! This "simpler" function pays for its simplicity in use limitations. The originally proposed *Ee* function can be reduced to the simpler form in those cases where such reduction is justified, but it can also be utilized in its less "simple" format by competent analysts when the simplifying limitations are not justified.

In the original article we stated — and this is a fundamental requirement — "the boundaries of the system being evaluated must be carefully defined . . . . In converting from the first law concept to the product concept, *the boundaries must be held fixed.*" This boundary concept is a germane rule of any comparative engineering analysis!

Consider, for example, any energy community with electric and cooling requirements of 4 GB each, served by a combined plant having a fuel input of 20 GB. Mr. Calm's proposed **COP** would have a value of:

COP = (4 + 4)/20 = 0.4

If the same community needs were provided for with unitary cooling apparatus at 1.76 KW per ton (*COP* = 2), the energy requirements from the electric generating plant would be a total of 6 GB. At a conversion efficiency of 33 percent, the input fuel would be 18 units, and the proposed **COP** would be:

COP = 6/18 = 0.33

Thus, we would have a higher **COP** for the option that consumed more fuel energy! Herein lies the fallacy.

An analysis utilizing the energy effectiveness factor concept would assign to the cooling product of the integrated plant a value of:

$c = C/(COP)_s = 4/2 = 2$

Then,

$Ee = (4 + 2)/20$

$Ee = 0.3$

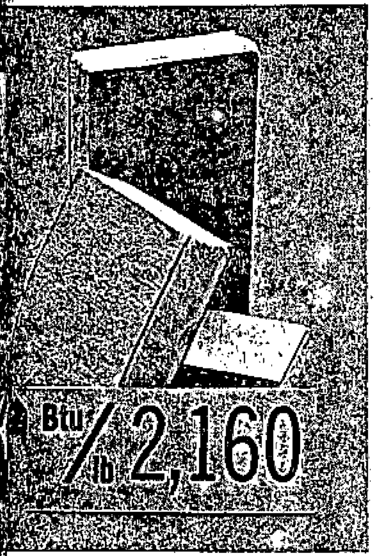
This, being lower than the 0.33 for the optional choice, is consistent with the phenomenon that the central plant is a less effective way of providing for this community.

In summary, considering the *Ee* concept of the thesis and the **COP** concept of the antithesis, a synthesis appears to be a specific definition of **COP** that would serve to validate both its logic and use: *When the comparative analysis is such that the quantities and forms of energy products crossing the boundary between the community and the energy plant(s) are fixed, the* $(COP)_s$ *of the energy effectiveness factor can be set at unity and the resulting evaluation function defined as coefficient of performance* **(COP).**

he energy intensity of uilding materials

re energy is consumed by the construction of a
lding than will be used in many years of operation.

OBERT A. KEGEL, PE,
President, Hevac Engineering Inc.,
ivision of K.C.M. Engineers,
ling, Illinois



Americans have lived in a very affluent society for many generations. We have learned to enjoy and take for granted an overabundance of energy, food, water, and natural resources. We consume a prodigious amount of commodities during the course of our everyday life. It is part of human nature to be free in spending, in consuming, and; I'm afraid, in misusing such vital commodities as energy. Nations who do not possess these necessities in such abundance have learned (as we have not) to conserve, ration, and use wisely.

Now for the first time in contemporary history, we are beginning to experience shortages in some areas, namely energy. We recognize some inequitable distribution, allocation problems caused in some cases by the overinvolvement of some government systems, and deliberate tampering with the free market system. These, however, contrary to the ultra-conservative critics of the "establishment" are not the only causes. Other factors include: the prodigious appetite of the American consumer, a tendency to misuse material wealth, and recalcitrance to ration personal expenditure of energy. In short, we are all to blame for the current energy problem!

Those of us who consider ourselves to be realists are convinced that an energy crisis exists—not only exists, but is getting worse. If the problem continues, it will be a real deterent to the policy of continued economic growth. There are those who do have problems admitting that there is a crisis and that the super abundant life enjoyed by the privileged of the world (citizens of the United States and Canada) is threatened. These people wear rose colored glasses.

I am not saying that the "sky is falling in" or that we should revert to a pre-automobile existence—not at all! Depending upon the source of the data, there is still adequate sources of fossil fuel—coal, oil, and natural gas. But the questions must be asked: How adequate? and at What cost? The answers depend upon the depth of research performed. It is beyond the scope of this article to argue the point; however, the fact does remain that there is a limited amount. There was only a given amount created in the beginning, and additional fossil fuels are not being generated, created, or manufactured. In short, we will run out. Contrary to the rather simplistic and naive attitude of most people toward subjects such as energy or the national debt, it is our responsibility to concern ourselves with the future, as well as the present.

Certainly, the federal government in part recognizes potential problems in the area of energy; note, for example, project independence. Whether we can achieve the goal of becoming independent—even by 1985—is questionable. Half of 1975 is gone, and no significant legislation has been passed or programs formulated.

This is, however, not to say that

all forms of fossil fuel will be depleted tomorrow if we do not conserve today. One does not die from eating one fish contaminated with mercury; however, if it is part of a steady diet, you may become very ill.

In short, we have the responsibility to recognize the problem exists, thoroughly define it, and collectively solve it. Each of us contributed to the problem; each of us must contribute to the solution.

Energy intensity

A great deal has been said, is yet to be said, and should be said about the operation and design of all types of buildings from the standpoint of how much glass, insulation, and lighting should be installed; what type of mechanical system to use; and various ways to save energy; etc. In this article, I would like to take a different and new approach to this topic—energy consumed by new construction.

Energy consumed by new construction is over and above that used to heat, light, cool, and ventilate a new building. The materials that a building is constructed of and the equipment used to construct it require considerable quantities of energy during manufacturing assembly and in transportation to the construction site. Construction itself is a consumer of very significant quantities of energy.

Life-cycle costs

A brief review of economics serves as a foundation for this argument. Those readers who are economists of some type and/or who are in positions of responsibility in your respective occupations need to be acquainted with the concept of life-cycle costs. Very simply stated, life-cycle accounting is a complete accounting of all expenses incurred with a particular investment over its useful life. For example, in a particular building, an initial investment cost of $40 per sq ft may be realized. The building operating costs, including heating, ventilating, cooling, lighting, and electricity; and maintenance cost for cleaning, repairing, and replacement; plus usury costs are incurred each month and year for the entire life of the building. Assume the building has a useful life of 40 years. In that time, it may be necessary to replace a boiler or an air conditioning unit. In that event, the replacement cost must be considered in the total life-cycle cost analysis.

All actual costs and all projected costs should be compared in the same time frame since with the elapse of time, money would earn interest if invested. Future investments can be accounted for by considering the amount of money that would accrue from interest if it had been deposited at an interest bearing rate and withdrawn at a future time to meet interim expenses.

Alternative building systems can be compared by this type of analysis. In true life-cycle considerations, it is within the realm of reason to additionally consider the total use of energy in a given project. This is in addition to both first and owning costs.

Other than the monthly utility charge, regardless of what fuel the building uses, the evaluation of energy expenses has to date been less tangible. Now, however, it is and should be a very real and vital part of the total analysis. A building design should not only be more advantageous from a life-cycle—dollar consideration—standpoint, but it should also be advantageous from a total life-cycle energy viewpoint.

Other energy expenses

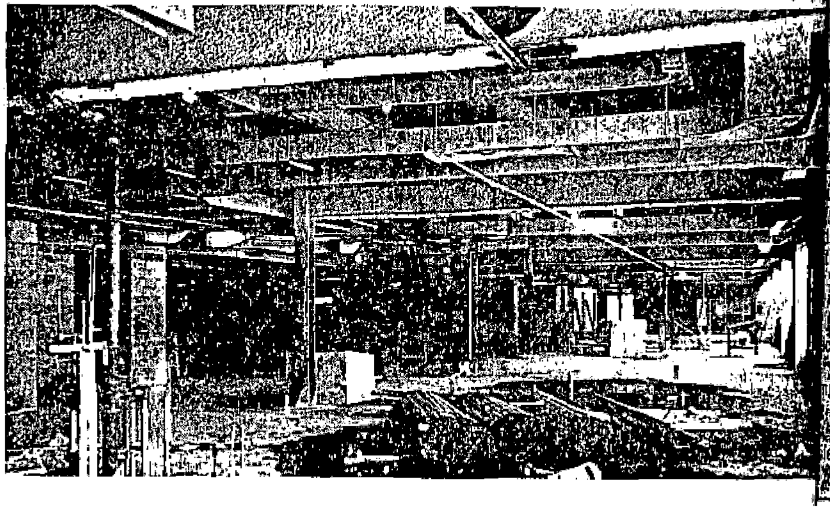
Consider that a building is composed of tremendous quantities of
steel, aluminum, copper, glass, i
sulation, dry wall, vinyl tile, ca
peting, ceiling tile, asbestos ti
concrete etc. Consider that it r
quires approximately 27,500,00
Btu to fabricate one ton of ste
And, this includes only the he
required to convert from raw o
limestone, and coke to steel ing
plus rolling to some structu
shape. It does not include all t
energy necessary for mining, pro
essing, transportation, etc., to t
mill.

Similarly, it requires appro
mately 82,000,000 Btu to fabrica
one ton of aluminum. Other bui
ing components, such as those li
ed previously, have equally i
pressive energy requirements. T
concept is occasionally referred
as the *energy intensity* of a m
terial. Table 1 lists some of th
data.

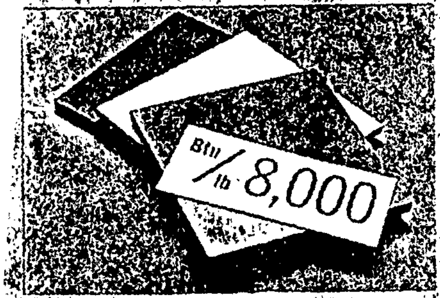
In addition to the energy co
sumed to properly heat, cool, a
light a given space and the ene
used to fabricate the various m
terials, there is a considerable
ergy expense incurred in erect
the materials—digging foundatio
pouring concrete, putting steel
place, hoisting wall panels, pour
floors; installing interior partitio
door frames, windows, glass, c
peting; and assembling a wh
host of other building compone
as the labors of the engineer, ar
tect, and contractor become rea

There are three major ene
components:

- Energy required to fabri
materials and equipment.
- Energy required to erect
terials and equipment.
- Energy required to heat, li



Typical construction scene at analyzed college.



—Energy intensiveness of typical materials:

	To fabricate	
	Btu per lb	Btu per unit
n	41,000	
materials	1,500	
	413	
blocks 8 by 16 in.)		15,200 per block
	40,000	
	2,160	
	12,600	
ion		
(1 in., 3 lb. density)		51,400 per sq ft
(2 in.)		7,700 per ft
lding (board)		2,040 per sq ft
	4,134	
ng		6,945 per sq ft
	13,800	
ile	8,000	

studies have been initiated by among others the Federal Energy istration to verify this type of data. At the time this research onducted, much of this information was "classified" by the re- ve manufacturer. Some of those consulted in obtaining this data sted here: 1) Aluminum Association of America, 2) American Co., 3). Anaconda American Brass Co., 4) G.D.F. Corp., 5) Bacon, 6) Gold Bond Corp., 7) Pittsburgh Plate Glass Indus- Inc., 8) Portland Cement Association, 9) Republic Steel Corp., S. Gypsum, 11) University of Illinois, Dept. of Forestry.

2—Summary of building materials and equipment to construct the example building.

al	Total weight, tons	Weight, lb per sq ft
um	39.5	0.18
materials	200	0.93
te	30,375	141
e blocks	14,040	65
	109	0.50
	2,157	10
	94.7	0.44
tion	27.5	0.1
	17.5	0.1
ng fixtures	100	0.46
	1,080	5
	3,518	16.3
ile	21.5	0.1
	51,779.7	240.1

3—Summary of energy used to fabricate the rials and equipment used to construct xample building.

al	Total Btu, × 10⁶	Btu per sq ft
um	3,198	7,400
materials	600	1,390
te	25,057	58,000
te blocks	3,862	8,940
	8,720	30,190
	1,492	3,450
	2,484	5,750
ion	9,814	22,720
	145	340
ng fixtures	3,971	9,190
	1,000	2,320
	139,901	323,840
e	1,150	2,660
	201,394	476,190

Table 4—Energy expended on construction.

Activity	Btu × 10⁶	Btu per sq ft
1) Clearing of site	7,840	18,148
2) Compaction of materials	200	463
3) Crane operation	1,526	3,532
4) Design energy	2,000	4,630
5) Excavation of footings, etc.	1,045	2,419
6) Fill (backfill)	627	1,452
7) Gasoline powered compressors, etc.	100	231
8) Helicopters to set equipment in place	4,689	10,854
9) Labor travelling to job site	17,500	40,509
10) Material delivery	7,560	17,500
11) Off-site fabrication	10,000	23,100
12) Plumbing and heating pipe assembly	160	370
13) Roofing	50	115
14) Seeding and planting	100	231
15) Temporary electric power	4,643	10,748
16) Temporary heat	30,600	70,833
Total	88,640	205,135

Table 5—Summary of energy expended for building operation. Design conditions are: summer: 78 F with 65 percent RH inside and 94 F with 78 percent RH outside; winter: 72 F inside and −10 F outside.

Loads	Energy, Btu
Heating	
• Building transmission load	3,650,000
• Building ventilation load	17,264,000
Total	20,914,000
Cooling	20,975,000
Lighting and miscellaneous power	2.88 watts per sq ft
Summary	
Heating	
• Day	21,272,934,000
• Night	8,898,709,000
Cooling (Btu's consumed within the building)	6,410,673,000
Lighting and electricity (Btu's consumed within the building)	10,828,728,000
Annual total	47,411,044,000
Total energy per square foot per year	109,748

Table 6—Summary of energy consumed by all three major components of project.

Energy consumed	Base building, Btu	Btu per sq ft per yr
Building materials and equipment	201,394,000,000	466,190
Construction energy	88,640,000,000	205,135
Total	290,034,000,000	671,325
Operating energy, annual	47,411,044,000	109,748

cool, ventilate, and other miscellaneous uses for electricity (operating energy).

The first two, of course, are expended prior to moving into a building, and the latter encompasses operating energy used after the building is occupied.

These energy components may be looked at as analogous to life-cycle analysis. The exception is that the energy that will be spent in terms of Btu's—not dollars—does not earn money at the present, as invested dollars reserved for future expenditures would earn interest. Therefore, a usury multiplication factor cannot be used as it can with money. In fact, on a monetary basis, the cost of energy will rise with time. We have seen the last days of so-called inexpensive energy in the United States.

To illustrate this concept, we have analyzed a typical project now under construction. It will be used as a community college. The building will have 432,000 sq ft, three stories, a steel structure, and glass and architectural steel walls. It is located in Chicago. The entire building has been discected from the standpoints of equipment and materials used, energy consumed for construction, and energy used for operation. Although this building is an institutional structure, a designer may apply the same thought processes in analyzing the energy intensity of any type of building.

During this analysis, you will see that the buildings you are acquainted with, whether they are used for learning, working, playing, health, or living, used more energy before they were occupied than will be used for a considerable time after startup. In fact, for this example, construction consumed six years' worth of operating energy.

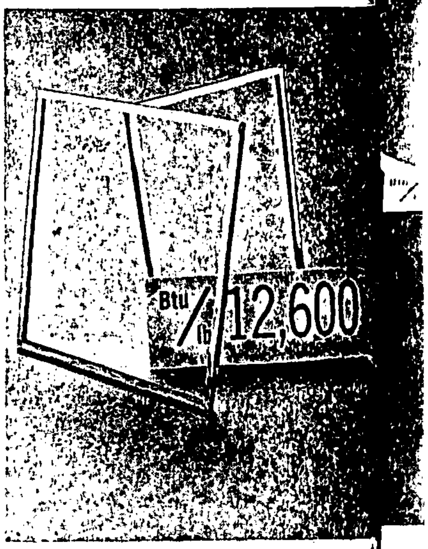
It is very interesting (and something the designer should be aware of) to note the total weight of material and equipment of a building (see Table 2). This particular building has approximately 39.5 tons of aluminum, 30,375 tons of concrete, 3518 tons of steel. Table 2 summarizes the various components and shows both total quantity as well as equivalent weight in pounds per square foot of the total building. The total weight is 51,779 tons.

Mechanical designers may be interested that the steel alone in mechanical equipment, pipes, hangers etc, weighs 185 tons. There are 207 tons of steel for plumbing pipes, valves, and accessories; 300 tons of sheet metal and fans; and 24 tons of steel in electrical equipment. This is exclusive of copper, aluminum in the mechanical and electrical equipment and steel in the plumbing fixtures. Electrical switch gear alone has 36 tons of copper. There are 6319 light fixtures; each has copper, plastic, and steel components. Although we think of most insulation as being relatively lightweight, the pipe, duct, and building insulation combined weighs 27.5 tons.

After determining various weights, the values listed in Table 1 can be used to translate weight into energy used in fabrication of the various materials and equipment. Table 3 shows the totals for these calculations. Remember, these values cover only the manufacture of the material and assembly of equipment, or shipping plus fabrication. Nothing is included for the energy expended in mining and transporting the material to the mills or factories.

Like the data on weight, this information has been itemized on the basis of total energy required to fabricate as well as on a Btu per square foot basis. The numbers expressed in this manner are rather impressive—aren't they. Did you ever think that to construct this type of building 476,190 Btu per sq ft of energy is expended for materials and equipment. The buildings you are familiar with now, regardless of construction, would be equally impressive when presented in this way.

Now that the amount of energy consumed by materials and equipment has been determined, let's set this part aside for a moment and define the other component of the energy expended before operation commences—the energy required to erect materials and equipment.



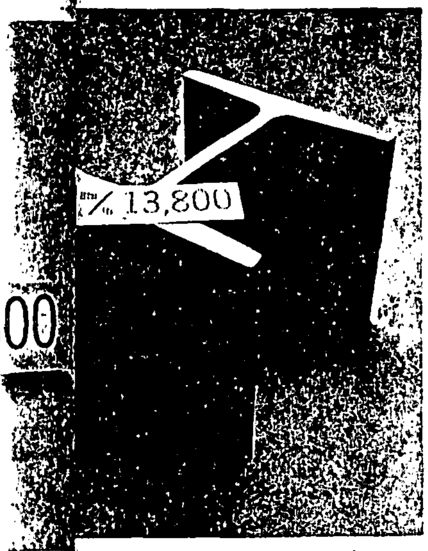
Refer to Table 4 and visualize t normal construction activities, su as site clearing, excavation, form concrete, backfilling, etc., just name a few. These have been liste in a generalized form in Table 4. I cluded are such items as the gasoli used by the designers in commuti to their offices as well as to the jo site for observation (Item 4). Item includes the expenses of constructi labor traveling to the jobsite. Ite 11 includes an estimate of the e ergy required for off-site fabric tion. In this case, it is primarily f architectural steel. Other items li ed are self-explanatory.

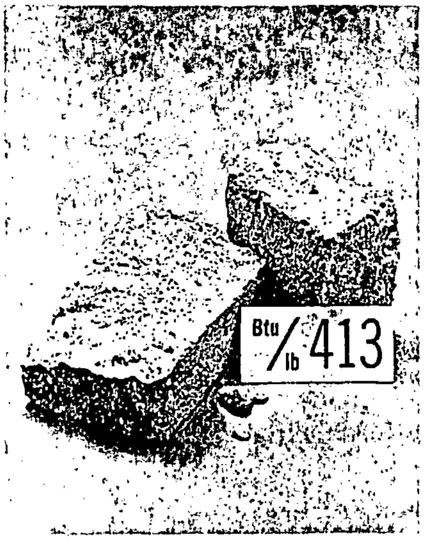
It is interesting to note that he copters were used to set certa equipment in place. In this ca two different sizes were used; o has a greater capacity and is us to handle central equipment.

Total energy expended for t effort is 86,640 × 10^6 Btu; or t equivalent of 205,135 Btu per sq for the project.

Operating energy

Having determined the ener expended for materials and equi ment and to construct the proje the energy required to operate t building can be calculated. The d sign engineer's calculated heati ventilating, and cooling loads p connected lighting and miscella ous power loads are itemized Table 5. The building is occupi 85 hours per week. This is som what greater than for a grade high school, but it is not unus





higher education institution.
entilation load may seem high,
t the time of construction,
codes dictated very high ven-
n quantities.*

le 5 reflects the total annual
y requirement. This was deter-
via normal calculations
RAE procedures). (The writer
re of the opinion that a com-
analysis would be somewhat
complete and more accurate
ell.) The result is that the
ng will require 109,748 Btu
sq ft per year to provide
C, electricity, and a total en-
nent. This works out to be
1× 10^6 Btu per year.

results of all three of the
y consuming components are
d in Table 6.

time the building can oper-
efore exceeding the energy
med prior to occupancy in
xample is 6.12 years:

71,325/109,740) = 6.12

er buildings, of course, would
different pay-back periods.
oint is, however, that every-
requires energy, especially in
nstruction industry. The de-
, mechanical engineer, and
ect should all be cognizant of
ergy required to produce cer-
materials, to fabricate equip-
and to erect materials, etc.

y intensive materials

s evident from looking at a list of materials that some require more Btu per pound or per square foot to fabricate than others. These are the so-called energy intensive materials. Glass, aluminum, and steel, for example, are higher in energy intensity than drywall or paint. Frequently, a designer (particularly where the eventual operation of a building is affected) has a choice of using various materials that have a bearing on the total energy, life-cycle accountability of building. For example, steel can be used in lieu of aluminum, or wood can be substituted for either of these. The design of a building may be optimized based on the materials selected by the designer and the total energy required to construct it decreased. Indeed, operating energy may be decreased in addition.

It is not fair to simply look at materials on the basis of energy intensiveness but rather what is being gained from the investment of energy required to produce the material.

It is interesting to consider in relation to life-cycle concepts, the pay-back period in terms of energy of a particular material. For example, consider insulation. Insulation has a rather high energy intensity—a high ration of Btu per pound to fabricate. However, in spite of the rather large quantity of insulation used in our example building, it really does not weigh very much per square foot. It actually has a very high payback rate!

Consider another example. To fabricate a 1 sq ft sheet of ⅛ in. glass requires 19,500 Btu (heating only). The U-value for single glazing is 1.13 Btu per sq ft, F; and for double glazing, it is 0.64 Btu per sq ft, F. The difference is 0.49 Btu per sq ft, F. If we assume an inside design temperature of 72 F, and an average outside temperature of 35 F (typical of northern Illinois), the time required to recover 19,650 Btu through the investment in a second sheet of glass is (space heating only):

19,650/0.49(72—35) = 1084 hr

A typical heating season in the Chicago area is usually put at about 5500 operating hours. At this rate, the second sheet of glass would pay for itself in terms of energy in less than 0.2 years. Certainly, this is a wise investment of energy. Remember, this is on the basis of heating only. If cooling were to be considered also, it would be even less.

Other examples comparing materials to Btu saved per Btu invested per year are: glass fiber building insulation, 20:1; duct insulation, 15:1; pipe insulation, 47:1; and glass (by above example), 5:1. Similarly, a designer should investigate other examples.

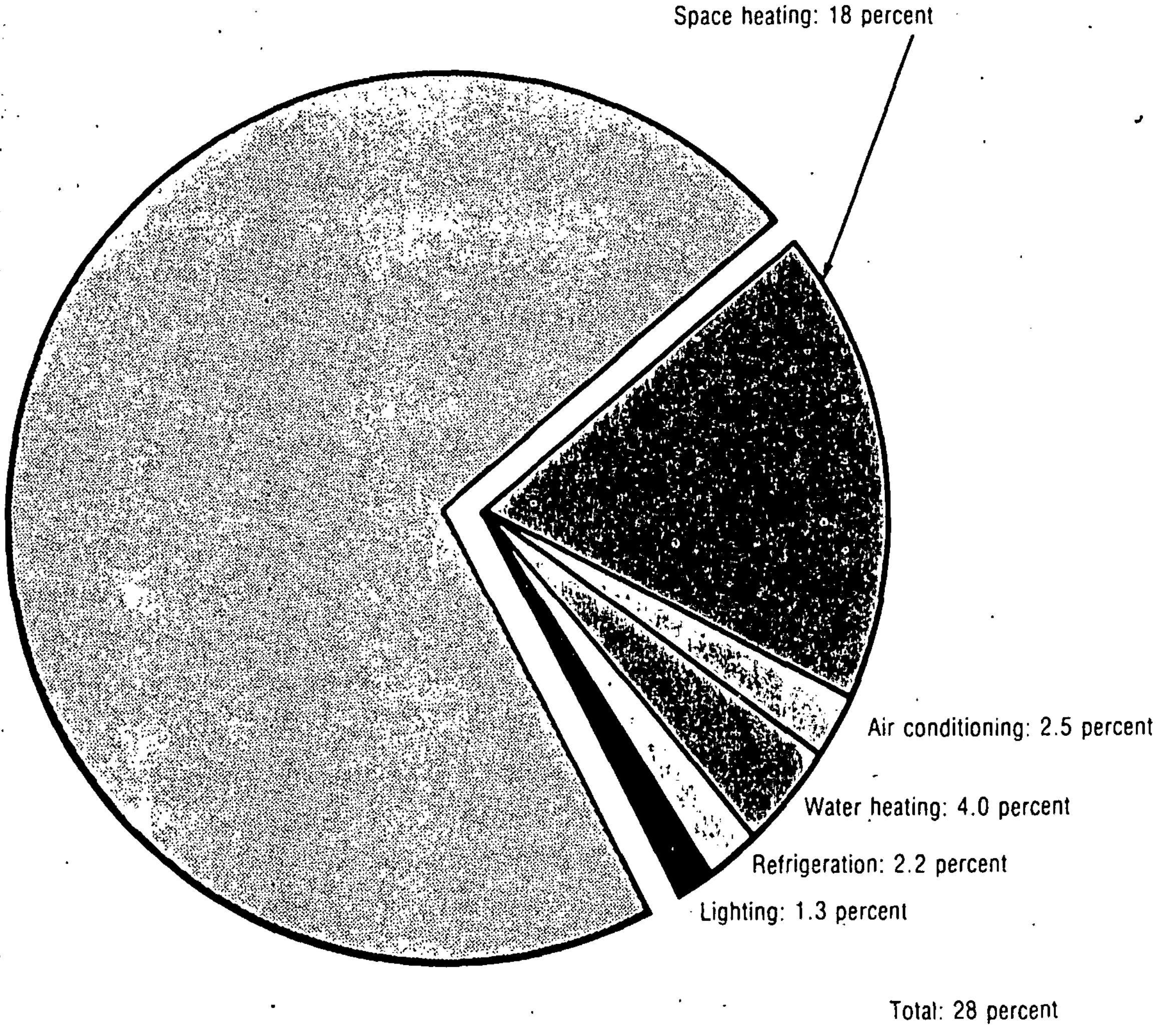
Energy optimization, or energy consciousness, and its uses in our environment are quite evident in these examples. Each of us in our everyday lives should be conscious and aware of the energy required to support our way of life as it exists today and should be in the future. I am not proposing that Americans discontinue their way of life, only that we conserve energy to provide for future generations.

Those of us who read this magazine are in a position to be aware of each Btu a building requires. It is our responsibility to use each Btu as wisely, as conscientiously, and as carefully as possible. Then, we can provide for continued growth of the economy.

The building is used by the City Colleges of Chicago and is owned by the Capital Development Board, State of Illinois, with whom Mr. Kegel worked during this project. The architect was Dubin Dubin Black & Moutoussamy; the mechanical engineer was Environmental Systems Design, Inc.

---

*"Proven Ways to Save Energy in
ional Buildings," HPAC, May
p. 54.



1 Estimated percentage of total energy consumption in U.S. allocated to space heating and closely related systems.

Universal acceptance of the standards may come in several different ways. The attention being given to the critical energy situation is making the government and the public more aware of some of the possible improvements. This situation should cause the heating and air conditioning industries to undergo a self-examination of their position. Proper specifications, codes, and ordinances should make it easier for manufacturers to justify more efficient equipment and for the architects and engineers to convince the owners to select the proper structure and the most economical system for minimum energy consumption.

Undoubtedly, some government legislation will be necessary to outlaw certain wasteful practices and procedures and to establish a national energy conservation policy. Caution must be exercised in this regard. It is desirable to first validate the effectiveness of certain conservation practices before recommendations are enacted into law and become mandatory.

Normally, the building construction as well as the type of system chosen will be governed by economic justification unless there are laws to the contrary. Taxing and banking influences must help to provide the necessary motivation and support. Also, in the final analysis, the actual amount of energy conservation realized will depend to a large degree on the extent and nature of the procedure actually implemented by the building owner and the operator.

The forthcoming series of articles will be concerned with possible improvements in building construction, equipment, design and application practices for the maximum conservation of energy by heating and air conditioning systems. It is hoped that these articles will aid the consulting engineer and contractor, particularly, to keep abreast of the progress and developments in this field and to take a more active part in promoting efficient use of energy to the general public. The first of the series will deal with architectural aspects.

FUEL CONSUMPTION IN RESIDENTIAL HEATING AT VARIOUS THERMOSTAT SETTINGS

During the winter of 1973 the energy crisis reached each and every American home as the gas and oil shortage changed the life style of the energy consumer. The public responded eagerly in conserving gasoline by lowering highway speed limits and through car pooling. To conserve fuel oil, homeowners were requested to lower the thermostat settings to 68F during the day and to 64F or 60F at night. The public was advised that such adjustments are not only healthy but will also save money. The slogan, "My limit is 68" was created. In this study we focus on heat losses based on the indoor-outdoor temperature difference and investigate the effect of varied thermostat settings on fuel consumption.

R. MICHAEL P. ZABINSKI

ARRY LOVERME

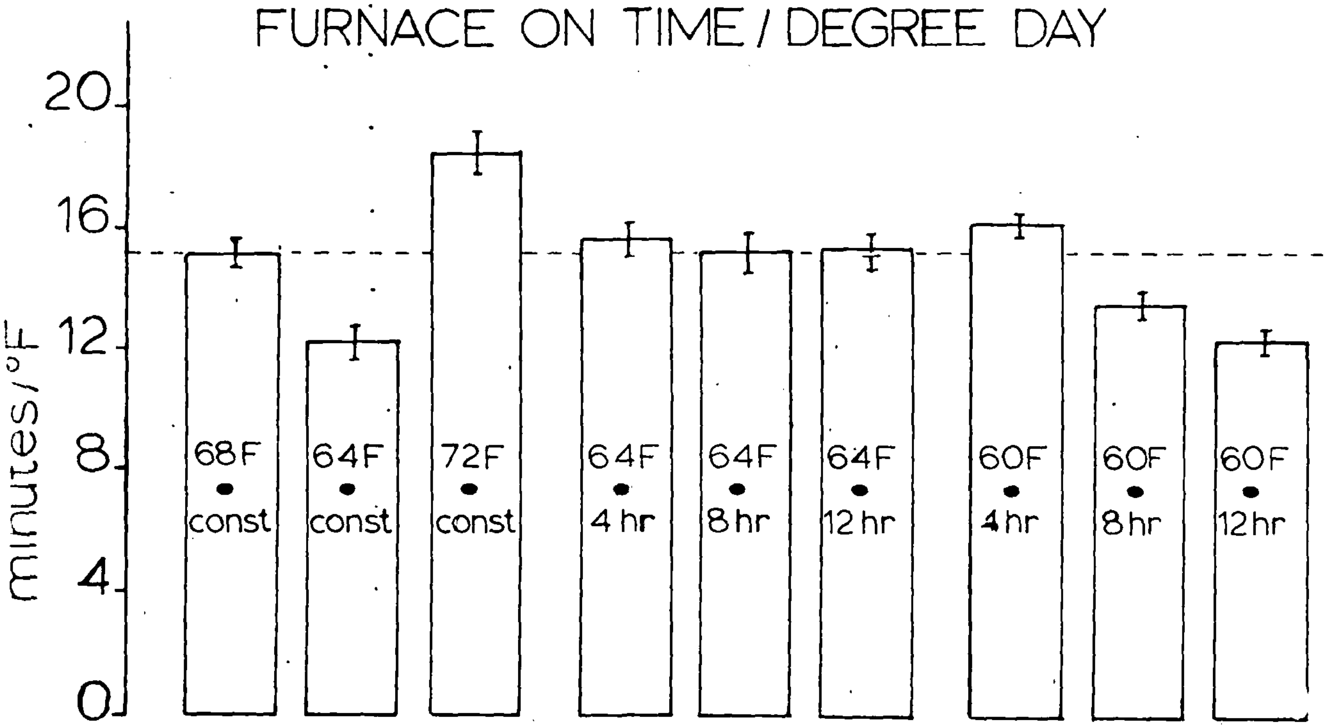
It is certainly well known that heat losses in a home are primarily dependent upon the indoor-outdoor temperature difference, as well as other factors such as the direction and intensity of the wind, and the amount of sunshine[1]. Two important questions immediately arise: Does lowering the temperature overnight necessarily save fuel, and what are the optimum thermostat settings? Assuming a reference temperature in the home of 68F we consider:

- The extent of the thermostat temperature lowering;
- The length of time over which the temperature is reduced. We determine the relative fuel consumption in two baseboard heated, oil fired, single family dwellings.

MATERIALS AND METHODS

The study was performed in two single family dwellings: House I, a 1800 square-foot, split-level located in Orange, CT, and House II, a 2000 square-foot, two-story home located in Easton, CT. Fuel consumption was monitored by an electric clock wired across the furnace motor. Each test day started at 6 p. m. and continued for 24 hours. The furnace on-time which represents fuel consumption as the nozzle injects fuel at a constant flow rate into the combustion chamber was recorded for the entire heating period (December, 1973 to May, 1974). Each of the following thermostat settings was investigated during at least five days by monitoring the daily furnace on-time:

- 1–68F constant (reference temperature)
- 2–72F constant
- 3–64F constant



. 1: House I—Fuel consumption for various thermostat settings. Fuel consumption is defined as furnace on-time per 24 hours, degree day (min./F). Standard errors of the mean are shown

---

r. M.P. Zabinski is Associate Professor of Physics and Engiering, Fairfield University, Fairfield, CT, and Larry LoVerme an undergraduate student, Fairfield University. This study was nded by a Fairfield University research grant.

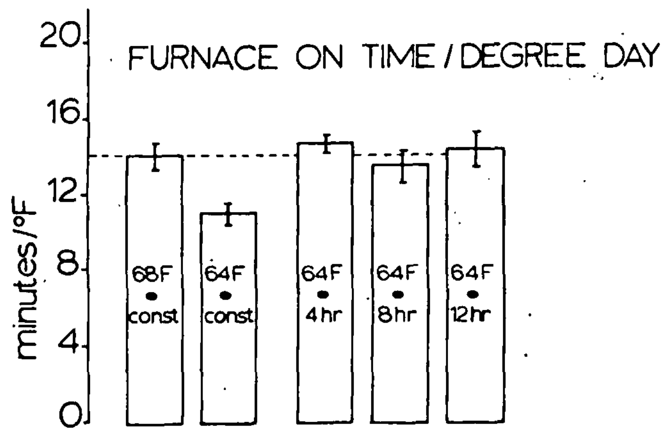


Fig. 2: House II—Fuel consumption for various thermostat settings. Fuel consumption is defined as furnace on-time per 24 hours, per degree day (min./F). Standard errors of the mean are shown

- 4–64F–4 hours; 64F, 6 p. m. to 10 p. m., remainder of 24 hour period at 68F
- 5–64F–8 hours; 64F, 10 p. m. to 6 a. m., remainder of 24 hour period at 68F
- 6–64F–12 hours; 64F, 6 p. m. to 6 a. m., remainder of 24 hour period at 68F
- 7–repeat (4), (5), (6) at 60F.

Thermostat adjustments were performed at the specified times. For example, the 64F–4-hour test (item 4 above) started at 6 p. m. as the thermostat was lowered from 68F to 64F; four hours later at 10 p. m., the thermostat setting was raised to 68F and left unchanged until the end of the test, the next day at 6 p. m. This test was then repeated several times not necessarily on successive days.

RESULTS

Degree Days

The degree day is widely used as a means of comparing the efficiency of fuel consumption of one period with another for the same house[2]. Since periods to be compared may not have the same weather conditions (degree days), the comparison can be made only after the fuel consumption data has been normalized by computing daily fuel consumption per degree day. The resulting unit value eliminates the outdoor temperature as a variable. It does not, however, account for such variables as wind speed, relative humidity, and barometric pressure.

Degree days are conventionally calculated from the daily high and low temperatures where degree day equals the difference between 65F and the average formed by the high and low temperatures. Since the high and low temperatures are not necessarily accurate reflections of the day's temperature history, and since it is important to use accurate degree day values to normalize the data, daily degree day data for this study was calculated from hourly temperature readings taken at the Bridgeport, Connecticut Municipal Airport, National Weather Service. The airport is located within 15 miles of the two houses tested. The 24 temperature readings were averaged for each day and subtracted from 65 to compute degree days. The degree day data computed on this basis was found to deviate on the average by 1.5F per day from the degree day data computed by the conventional method.

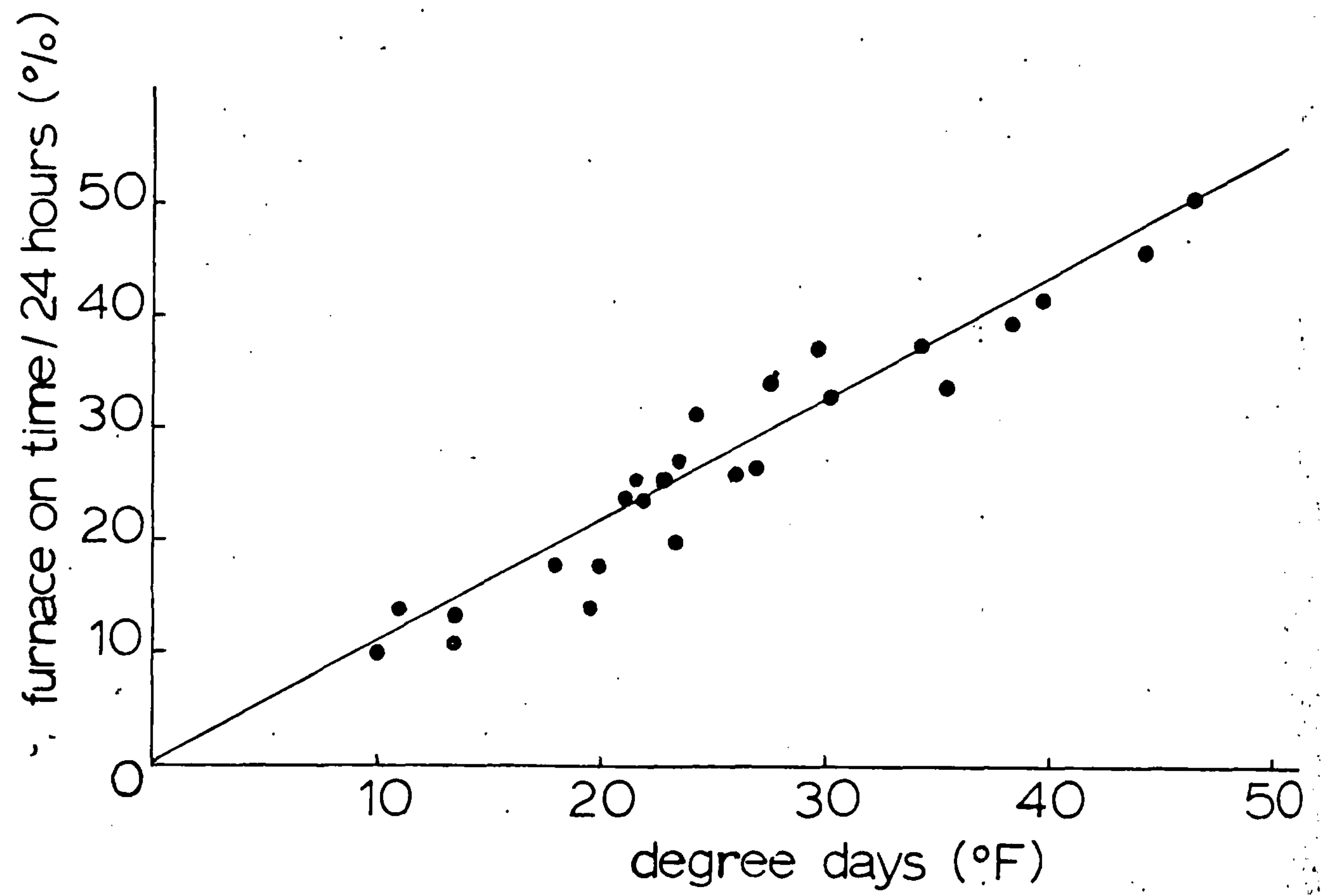


Fig. 3: Relation between the operating time of the burner in a 24 hour period and degree days. Closed circles are experimental points takn in House I at thermostat setting 64F — 12 hours. Least square line shows fuel consumption approximately proportional to degree days

Table 1

	HOUSE I				HOUSE II			
Thermostat setting	Fuel Consumption min/DD	% RFC(*)	No. of test days	Standard error of the mean	Fuel Consumption min/DD	% RFC(*)	No. of test days	Standard error of the mean
72F constant	18.32	−21.4	4	.70				
68F constant	15.09	0	22	.31	13.91	0	7	.59
64F constant	11.98	+20.6	5	.56	10.93	21.4	5	.64
64F — 4 hours(**)	15.49	−2.7	9	.60	14.6	−4.9	9	.50
64F — 8 hours	15.09	0	13	.50	13.47	+3.1	6	.80
64F — 12 hours	15.18	−0.6	25	.41	14.34	−3.0	8	.92
60F — 4 hours	16.00	−6.0	6	.14				
60F — 8 hours	13.55	+10.2	9	.52				
60F — 12 hours	12.62	+16.4	11	.43				

(*)with respect to 68F constant, for example for 72 constant, thermostat setting: $\% \text{ RFC} = \frac{15.09-18.32}{15.09} \times 100 = -21.4\%$

(**)remainder of 24 hour period at 68F

Table 2—t Tests

	HOUSE I				HOUSE II			
68F constant vs.	t	d.f.	P	Statistically Significant	t	d.f.	P	Statistically Significant
72F constant	4.08	24	<.001	yes				
64F constant	4.39	25	<.001	yes	2.3	11	<.05	yes
64F — 4 hours	.64	29	>.5	no	.89	14	>.5	no
64F — 8 hours	.01	33	>.5	no	.45	11	>.5	no
64F — 12 hours	.16	45	>.5	no	.38	13	>.5	no
60F — 4 hours	2.1	26	<.05	yes				
60F — 8 hours	2.61	31	<.02	yes				
60F — 12 hours	4.62	26	<.001	yes				

The climatological summary for Bridgeport, CT is as follows:

Average Temperature for January 1973

Daily Maximum	Daily Minimum	Monthly
38.0	22.8	30.4
36.8	21.6	29.2

Fuel Consumption

The degree day data along with the daily furnace on-times were used to compute the fuel consumption in minutes per degree day. The fuel was used for space heating as well as domestic hot water with the latter considered fixed and not variable. Figs. 1 and 2 illustrate the fuel consumption for Houses I and II respectively. Due to thermostat limitations it was not possible to reduce the temperature to 60F in House II. A constant temperature test at 72F was also omitted for House II. Standard errors of the mean are shown. As expected the fuel consumption is largest for a constant house temperature of 72F and least at a constant temperature of 64F. All other thermostat settings result in intermediate fuel consumptions. Table 1 summarizes the numerical data for Houses I and II. The variability of the computed fuel consumptions is fairly small as indicated by the standard errors of the mean. These variations can be attributed to the aforementioned variables not included in the analysis as well as variations in household activities resulting, for example, in open doors and windows. The consistency of the data is further demonstrated by Figure 3 in which fuel consumption (minutes/degree day) is plotted against degree days for the case of 64F–12 hours in House I. A least square regression analysis of the data yields a high degree of correlation ($r = .96$). Observe that fuel consumption is approximately proportional to degree days[3].

Relative Fuel Consumption

We define per cent relative fuel consumption (RFC) for a given thermostat setting X as

$$\text{RFC} = \frac{\text{fuel consumption at 68 F — fuel consumption at X}}{\text{fuel consumption at 68F}} \times 100$$

For example, House I at 72F constant:

$$\text{RFC} = \frac{15.09 - 18.32}{15.09} \times 100 = -21.4\%$$

We note that RFC=0 for 69F constant. Similarly, a positive RFC value implies fuel savings while a negative RFC represents fuel losses when compared with the reference temperature setting of 68F constant.

Figs. 4 and 5 show relative fuel consumption for Houses I and II respectively. The results of Houses I and II are consistent. A constant temperature of 72F yields a relative fuel consumption of slightly more than −20% in House I, or approximately 5% per degree. Equivalently, for 64F constant temperature the total fuel savings are approximately 20% (RFC<0) in both houses. Intermediate settings result in smaller fuel savings and losses.

Statistical analyses for significance in differences were made on the basis of pair comparisons using the student test (Table 2).

DISCUSSION

This study investigated the effect of various thermostat settings on fuel consumption in two single family dwellings with oil fired, hot water, baseboard heating systems. Fuel consumption was monitored by an electric clock and the data normalized by calculating the furnace on-time per degree day. Several thermostat settings were checked and the following major conclusions are drawn:

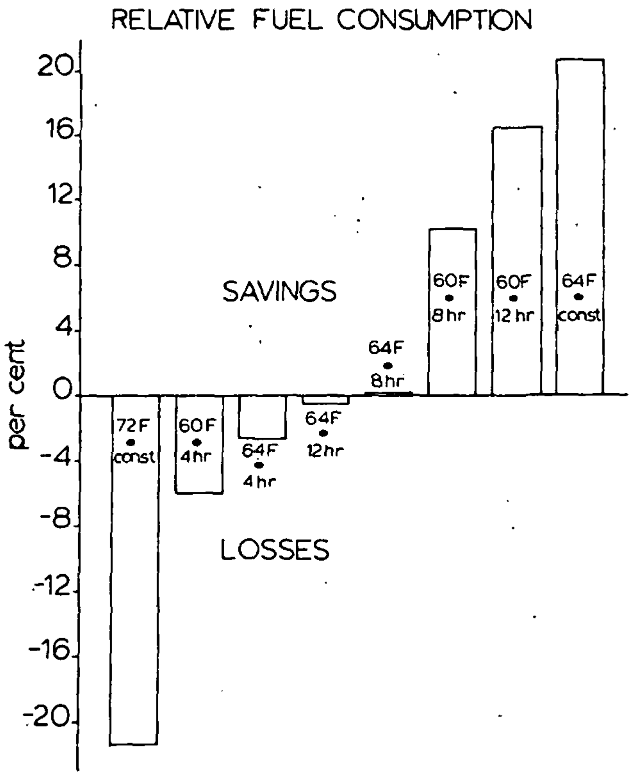


Fig. 4: House I—Per cent relative fuel consumption (RFC) for several thermostat settings. Positive values indicate fuel savings and negative values indicate losses with respect to 68F constant house temperature

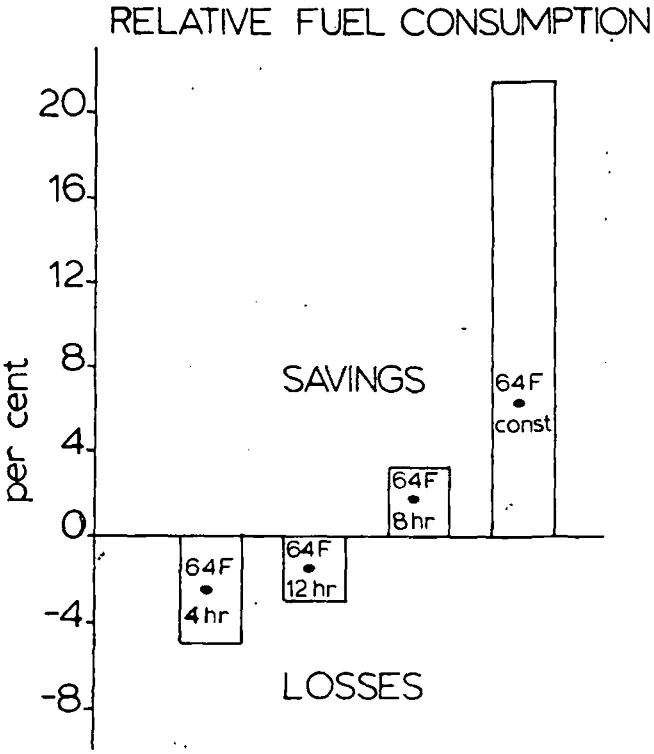


Fig. 5: House II—Per cent relative fuel consumption (RFC) for several thermostat settings. Positive values indicate fuel savings and negative values indicate losses with respect to 68F constant house temperature

1. The two houses tested differed in their location, style, and construction, yet the furnace on-times, the normalized fuel consumptions, and the relative fuel consumptions were in good agreement.

2. Lowering the house temperature for a short period of time—4 hours or less—results in no fuel savings when compared with a constant 68F setting. The t test shows no statistically significant difference ($P > .5$) in the data for 68F constant and 64F–4 hours (see Table 2 for Houses I and II). In fact our data shows a small loss in fuel for such short periods of temperature reduction. The losses become more significant as the temperature is lowered further down to 60F for 4 hours ($P < .05$), since inefficiencies introduced on reheating are more severe.

3. Short term adjustments of the thermostat are generally wasteful.

4. Lowering the temperature to 64F for a period of 8 to 12 hours results in no significant fuel savings or losses ($P > .5$, Table 2) and any physical discomfort experienced in the process is in vain.

5. Lowering the temperature to 60F for 8 to 12 hours results in considerable fuel savings of approximately 10% and 16% respectively (Table 1). The t tests confirmed the significance of the data ($P < .02$, Table 2).

6. Maintaining the house temperature at a constant 64F results in a 20% fuel savings or approximately 5% per degree below 68F. This saving must, however, be weighed against the physical discomfort experienced at this low house temperature.

7. The difference in data between 72F and 68F is statistically significant ($P < .001$), Table 2. The motto "68 is healthy for you, your wallet, and your country" is substantiated by a better than 20% fuel saving.

The results reported herein are characteristic of the two houses studied and the local Connecticut climatological conditions. However, the general trends, and overall conclusions are certainly applicable in geographic areas experiencing similar winters. Five to six thousand degree days and 25 to 35 inches of snowfall describe a typical Connecticut winter[4]. In warmer regions the percent fuel saving realized by similar thermostat settings will be much larger. However, the actual quantities of heating fuel saved would be much greater in cold areas than in warm regions because far more fuel is needed in such areas to heat buildings. The close agreement in the results for the two houses studied reinforces the validity of the method of testing and analysis. □

REFERENCES

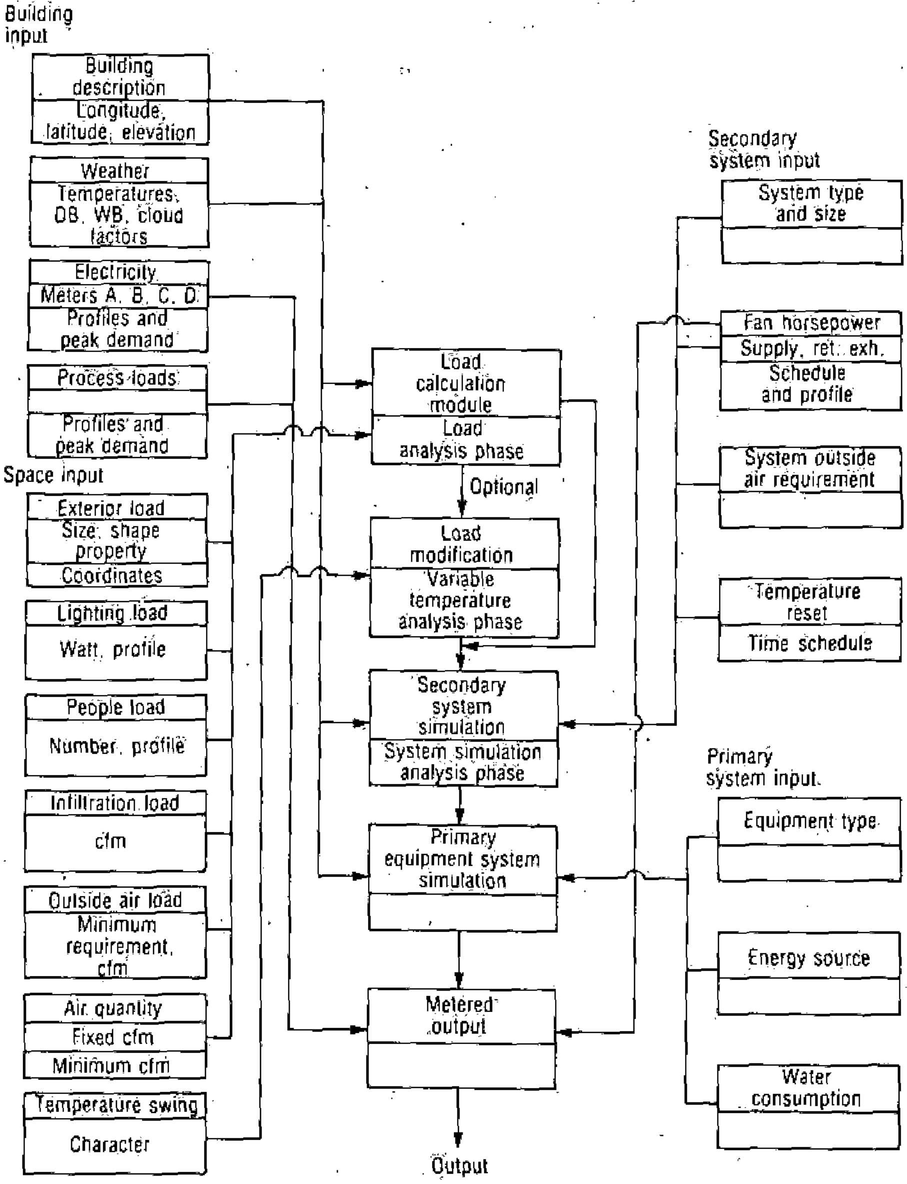
(1) Harris, W.S., Summary cooperative research on hydroni heating and cooling, University of Illinois, Urbana, Illinois 61801
(2) Estimating Fuel Energy Consumption for Space Heating 1966 Guide and Data Book, Ch. 16, American Society of Heating, Refrigerating and Air Conditioning Engineers.
(3) Colborne, W.G., Performance of Intermittently-Fired Oi Furnaces, ASHRAE Transactions, Vol. 63, 1957, p. 427.
(4) Local climatological data, Bridgeport, Connecticut, U.S Department of Commerce, National Oceanic and Atmospheri Administration Environmental Data Service, 1972.

Predicting building energy requirements

The computer dilemma

By J. MARX AYRES, PE, President,
Ayres & Hayakawa Energy Management,
Los Angeles, Calif.

Analysis of alternate energy conservation strategies for designing new buildings and retrofitting existing ones requires accurate calculations of monthly energy loads that must be passed through appropriate utility rate schedules to obtain annual energy costs. Methodologies for calculating thermal performance of buildings and their energy requirements have developed rapidly in recent years.[1] Use of the computer as a design tool has increased and has, in fact, become necessary due to the complex and lengthy computat procedures required for analys building energy usage. The succ ful implementation of ASH Standard 90-75, *Energy Conse tion in New Building Design,* quires the development of a c prehensive yet simple calcul procedure for estimating the a energy requirements of buildin



1 Simplified flow chart for an energy simulation computer program.

Energy calculations

The thermal performance o building and its energy consump depend on a great many fac other than the weather, but vari methods have been developed in past, such as the simplistic deg day method and the conventi bin method, which use weather to proportion the peak design lo to obtain monthly, daily, and ho loads[3]. These approximate pro dures, when verified against ac operating experience, meet needs of some engineers, but are unable to include in t analysis all of the essential eleme of energy calculations.

It is now generally accepted the only rational way to calcul energy requirements is to emp computers to conduct hour-by-h calculations of all building lo over a full year of weather d Thermal loads consist of heat tra fer through the building skin due air temperature differentials solar loads; the outside air int duced into the building; and internal loads due to people, ligh and equipment. HVAC systems spond to these dynamic loads try to maintain temperatures d tated by system controls a equipment. To analyze the perf mance of these systems and th energy consuming compone they must be mathematically m

---

[1] *Superscript numerals refer to referenc end of article.*

or simulated, and their hourly energy requirements calculated. These loads must then be integrated with other non-HVAC loads (such as base electric, cooking, domestic hot water, process, etc.) to arrive at monthly total building demand and consumption loads.

The computer dilemma

The implementation of any national energy conservation standard for building design requires the widespread use of computers to conduct hour-by-hour peak load and annual energy calculations. For example, Section 10 of Standard 90-75 requires detailed and comprehensive calculations based on 8760 hours of operation of the building and its service system. The ASHRAE literature references for implementation of Section 10 are booklets of computer algorithms. Although there are several sophisticated computer programs available based on the dynamic simulation of hourly building performance, they are very complex and proprietary, and this discourages their use in the average engineering office. As an illustration of the complexity of the problem, a simplified flowchart for an energy simulation program now under development by the Automated Procedures for Engineering Consultants (APEC) is shown in Fig. 1.[4]

Most engineering offices that design building service systems have less than 15 employees, and only about half that number are involved in HVAC design work. The owners of the firms are usually the key designers, and they are under constant pressure to get work in and out of the office to stay in business. It is no wonder then, that ASHRAE is always being asked by its membership to *simplify* design procedures and offer ready made, easy to use technical solutions. For load calculations, engineers want a simplified design manual that is easier to read and use than the ASHRAE Handbook. They hesitate to use computer programs for energy calculations. They do not understand the procedures involved, and they fear the higher cost associated with the initial usage of computer programs.

Even in large, multidisciplined offices, where structural and civil engineers routinely use computers, the mechanical and electrical engineers remain skeptical and must be pushed into using them. The most successful computer programs are extensively documented and written so the design engineer can make step-by-step verifications with hand calculations to assure technical correctness. The older, experienced engineers are ex-

Table 1—Analysis of existing buildings.

Building name	Location	City	Occupancy	No. of floors	Facade, % glass	Units or rooms	Area, sq ft
Century Park Apts	Century City	Los Angeles	Apartments	20	31	6	4830
Hyatt Regency	Boardway Plaza	Los Angeles	Hotel	21	41	26	6100
Holiday Inn	Bel Air	Los Angeles	Hotel	16	32	16	3840
Richard Henry Dana	Golden Gateway	San Francisco	Apartments	22	32	16	8700

Occupied typical floor

	Supply air, cfm		Exhaust air, cfm		Outside air, cfm		
		per sq ft		per sq ft		per sq ft	Remarks
Century Park Apts	5800	1.2	1810	0.37	2090	0.34	HVAC
Hyatt Regency	6840	1.1	1580	0.26	1690	0.28	HVAC
Holiday Inn	4500	1.2	1200	0.31	1440	0.37	HVAC
Richard Henry Dana	—	—	2760	0.32	—	—	Heating only; no outside makeup air to rooms.

Corridor typical floor

		Supply air, cfm		Outside air, cfm		
	Area, sq ft		per sq ft		per sq ft	Remarks
Century Park Apts.	650	600	0.90	100	0.15	HVAC
Hyatt Regency	1470	800	0.55	800	0.55	HVAC
Holiday Inn	1650	640	0.40	640	0.40	HVAC
Richard Henry Dana	1650	1200	0.85	1200	0.85	Heating only; no outside makeup air to rooms.

Table 2—Model building criteria

Item	Circular	Rectangular	Remarks
Number of floors	20	20	All typical
Orientation, long sides	—	E/W	Separate runs Los Angeles N/S, NE/SW, NW/SE
Diameter, ft	91.5	—	—
Length × width, ft	—	274 × 66	—
Typical floor area, sq ft	6,560	18,084	—
Total area, gross sq ft	131,200	361,680	—
Floor-to-floor, ft	10	10	—
Facade, percent glass	30 and 60	30 and 60	Single, draped, solar conductance equals 0.50
Curtain wall, U-factor	0.17	0.17	End walls, U = 0.50
Rooms, units per floor	16	38	—
People per room or unit	2	1	450 MBtuh per person
Lights, watts per sq ft	1.0	1.0	—
Outside air, cfm per sq ft	0.36	0.36	—
Base electric, KW per room	1.76	1.76	—
Process, MBtuh per room	11.6	11.6	Domestic hot water

Table 3—Peak load design conditions (ASHRAE Handbook of Fundamentals, 1972).

Item	San Diego	Riverside	Los Angeles	Bakersfield	San Francisco
Airport	SD	March Air Force Base	LA	BF	SF
Latitude, degree-minutes	32-4	33-5	34-0	35-2	37-4
Elevation, ft	19	1511	99	495	8
Summer outdoors:					
Dry bulb, F	86	99	86	103	83
Wet bulb, F	71	72	69	72	65
Dew point, F	64	59	61	56	55
Winter outdoors:					
Dry bulb, F	38	26	36	26	32
Summer indoors:					
Dry bulb, F	75	75	75	75	75
Relative humidity, percent	50	50	50	50	50
Winter indoors, F	75	75	75	75	75

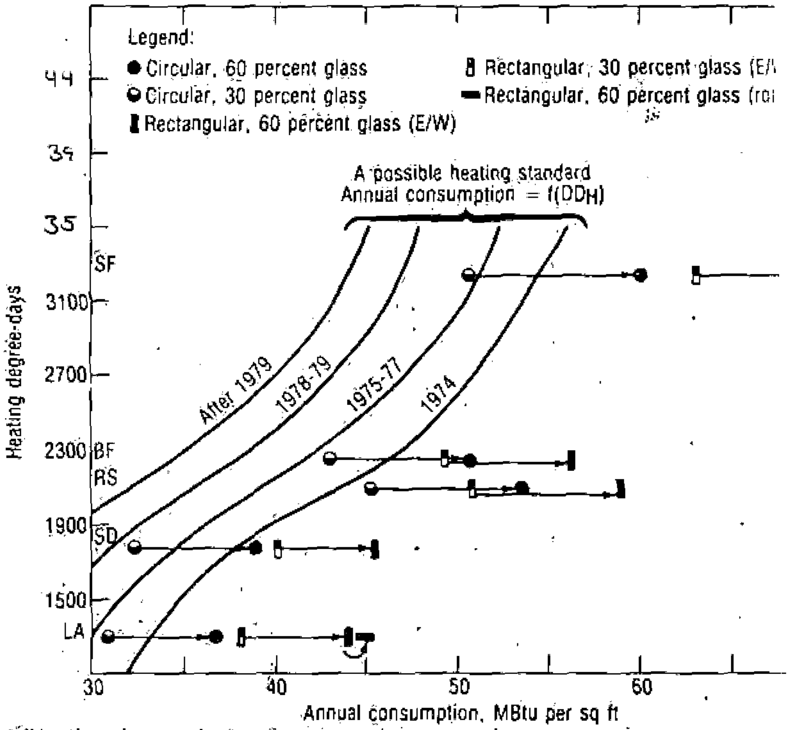
tremely skeptical of computerized procedures and prefer to rely on judgments and time tested short cuts; while younger engineers often look on the computer as the only way to go, even though they are costly to implement and the methodologies in the black-box may be worthless.

Practical HVAC and energy calculation software must be designed for routine use in the production mode, and it must be continually supported, maintained, and updated.

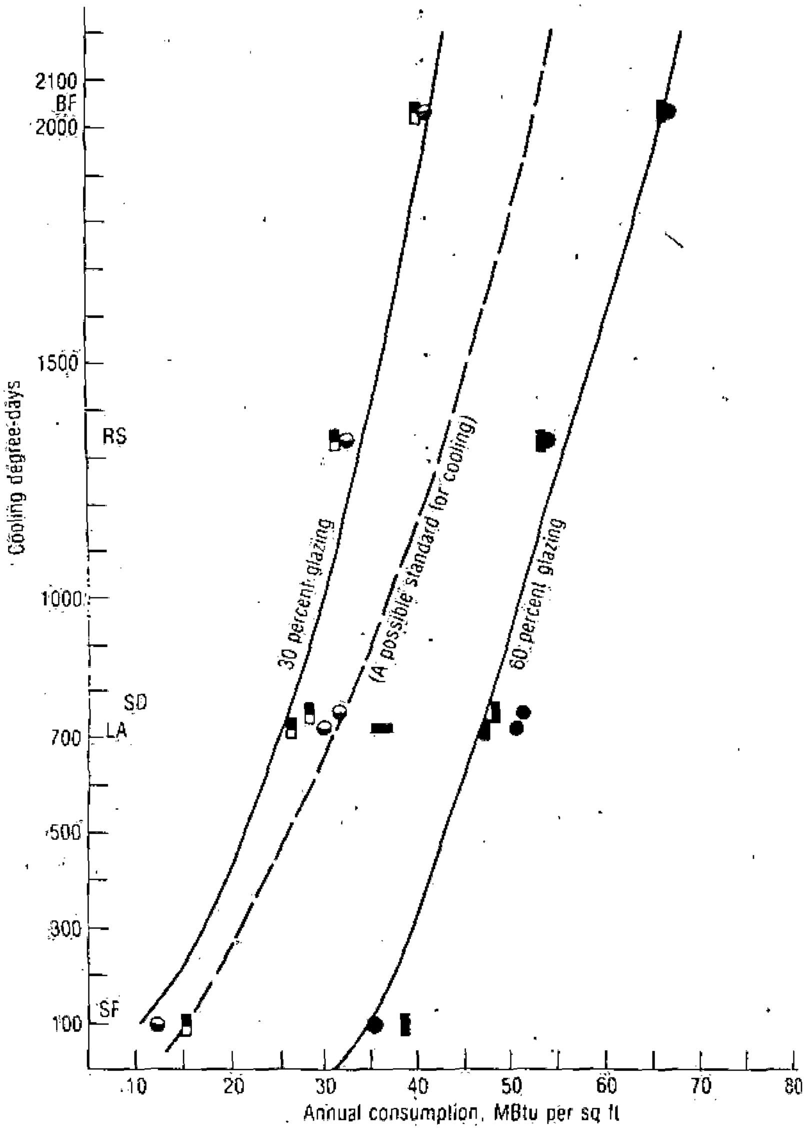
The computer, like any other tool in an engineering office, must enhance productivity and provide an economic return on investment. The question, of course, is to clearly establish how it will be used and what the costs will be. Everyone who has worked with computers will admit that the tip of the iceberg represents what the computer salesman says your costs will be, and the base of the iceberg represents the large hidden costs that you actually will incur. Regardless of these difficulties, it is technically feasible to maintain the accuracy of computer energy calculations and to establish mechanisms that transfer this new technology to the HVAC design engineer in private practice and his counterparts within government agencies.

Impact of weather

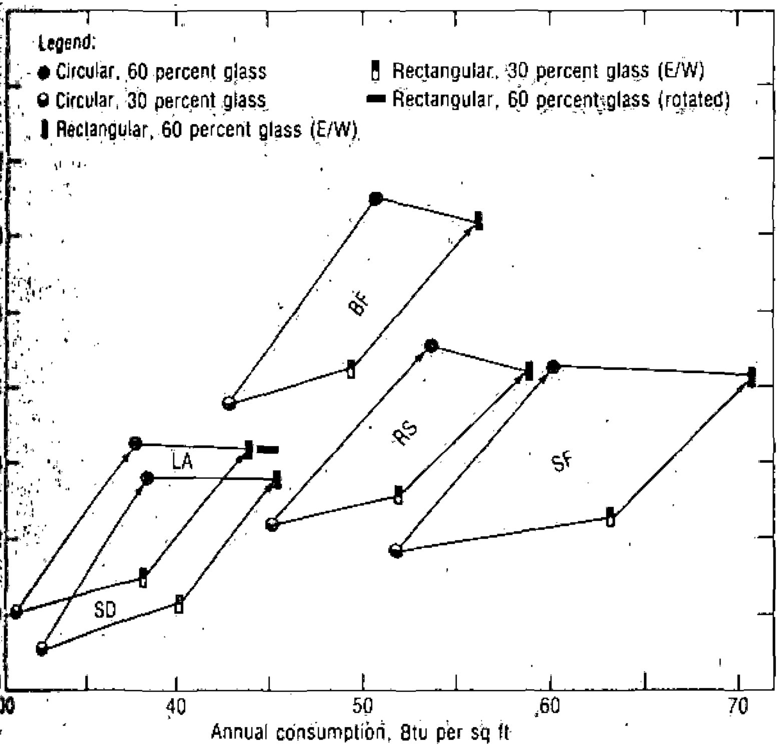
The impact and structure of weather data for computerized energy calculations has been under discussion for years in ASHRAE between TC 4.2 (Technical Committee on Weather) and the TGER (Task Group on Energy Requirements), now TC 4.7 (Energy Calculations). Meteorologists are unable to establish procedures for the selection of a "typical" year of weather to drive the building model. In 1974, a compromise was reached — for purposes of comparative energy calculations — to use a so-called test year based on a procedure developed by the TGER. This procedure was released by the Society in 1975 under the name of Test Reference Year (TRY) Weather. In the meantime, all types of typical year weather programs are in use by owners of proprietary energy calcu-



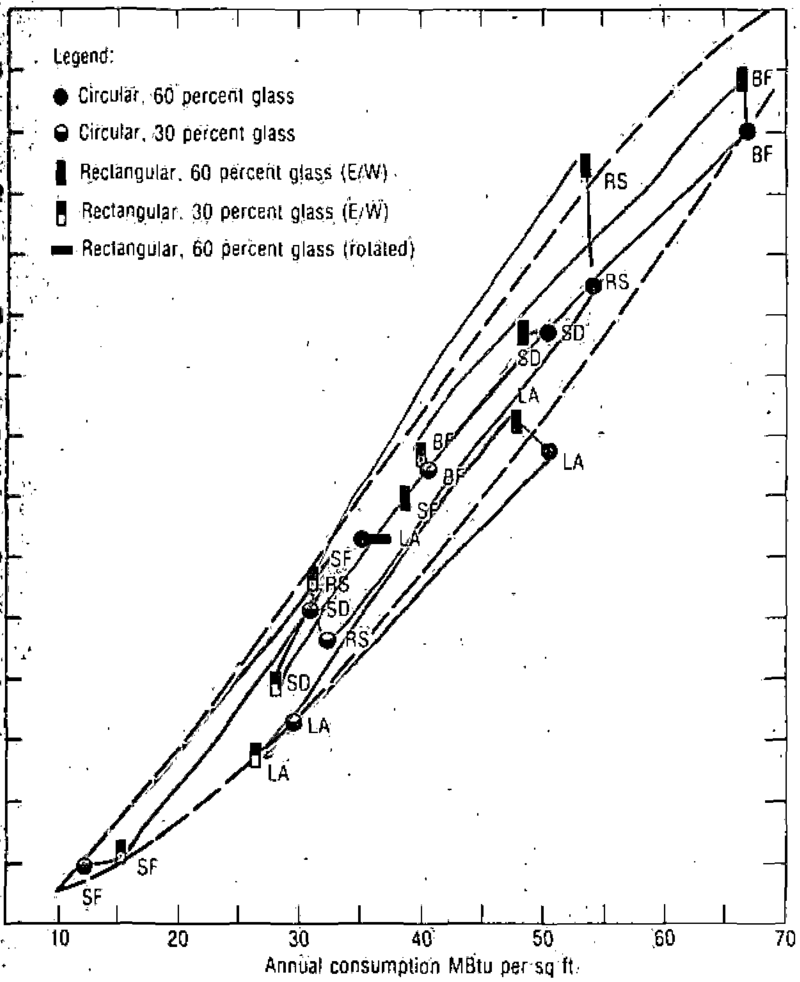
2 Heating degree-days versus annual consumption.



4 Cooling degree-day versus annual cooling requirements.



7 Heating peak load versus annual consumption.



8 Cooling peak load versus annual consumption.

lation programs. They range from well defined analyses of 10 years of data to the selection of any year that approaches the published average heating degree-day for a specific location.

The need for 8760 (365 days per year × 24 hr per day) sequential hourly building calculations has been studied in an effort to reduce computer computational time costs. The fact that 8760 calculations are made using supposedly accurate weather data certainly does not in itself make the energy calculations correct. On the other hand, most of the experience to date has been with processing hourly data for a full year, and a rational methodology for the selection of typical days for each month or group of months to reduce these calculations has not been developed.

The importance of the weather certainly varies with building construction, use and type of proposed energy consuming systems. In buildings with low thermal resistance envelopes and/or that require large quantities of outside air, the weather will play a dominant role; whereas in buildings with large internal loads, minimum outside air requirements, and well insulated envelopes, the weather will play only a minimal role.

The impact of weather on energy requirements for high rise residential buildings was examined in a recent study[5] for the State of California in its effort to develop energy budgets modified by degree-day locations. The study tried to establish a correlation of energy consumption with outside dry bulb and/or peak loads. If this could be accomplished, it was assumed that a governmental plan checker could verify a hand calculated peak load submitted by the HVAC design engineer (or read a drawing to obtain the size of the installed equipment) and then refer to curves for the appropriate degree-day location to obtain the annual energy requirements.

Four existing high rise residential buildings (Table 1) were analyzed to establish the typical rectangular and circular building models listed in Table 2. The peak thermal loads for the models were hand calculated