PROCEEDINGS OF THE 18th

IECEC '83

INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE

VOLUME

5

OF 5 VOLUMES

ENERGY CONSERVATION
LATE PAPERS
INDEX

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"Energy for the Marketplace"

SHERATON-TWIN TOWERS
ORLANDO, FLORIDA
AUGUST 21-26, 1983

Participating Societies

SAE The Engineering Resource For Advancing Mobility

Intersociety Energy Conversion Engineering Conference

PURPOSE:

To reduce the overlapping and duplicative effort of the sponsoring societies in the field of advanced or non-conventional energy conversion. This conference is concerned with the engineering and application aspects of non-conventional energy conversion systems and devices as opposed to the details that are presented at various specialist conferences. Papers are screened for technical competence, clarity and brevity.

ORGANIZATION:

A standing IECEC Steering Committee consisting of two members from each society coordinates all conference activities. Each year a society (this year AIChE) sponsors the conference. Session Organizers are appointed by the General Chairman and the Program Chairman. Session Organizers invite abstracts and receive abstracts from a general solicitation through the Program Chairman. Within limits set by the General and the Program Chairman the Session Organizers are responsible for the content of their sessions and appoint appropriate Session Chairmen.

SPONSORING SOCIETIES:

American Institute of Chemical Engineers
(1976 Conference)

American Nuclear Society
(1977 Conference, Washington, D.C.)

Society of Automotive Engineers
(1978 Conference, San Diego, CA)

American Chemical Society
(1979 Conference, Boston, MA)

American Institute of Aeronautics and Astronautics
(1980 Conference, Seattle, WA)

American Society of Mechanical Engineers
(1981 Conference)

Institute of Electrical and Electronic Engineers
(1982 Conference)

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Message from the General Chairman

Today throughout the world, there has been a de-emphasis in energy conversion projects simply to satisfy government requirements, and a realization that energy conversion must make sense in the marketplace. We as engineers, must consider how our projects are eventually going to be used, and how they will be eventually incorporated into products that people will buy and use.

For the last 18 years, the Intersociety Energy Conversion Engineering Conference (IECEC) has been a marketplace for ideas for potential products. Here, gathered together in one meeting, are the latest reports on technologies of diverse natures which will eventually compete for the marketplace. If your product is electricity for instance, you can evaluate the state of technology of several different types of heat engines, such as Stirling, Brayton Cycle, Rankine Cycle to operate different types of electric generators. You can see how photovoltaics, thermonics, and thermoelectric, MHD, and possibly other methods are doing in the direct conversion area. You can determine how wind energy, tidal energy, ocean thermal energy might fit into your needs. Possibly a new type of energy conversion will be discussed which you have never heard of before. As a marketplace for ideas, the Intersociety Energy Conversion Engineering Conference is ideal.

The utility of having one meeting for all use-related energy conversion technologies was recognized by the major engineering societies and related professional societies back in 1966. The result is the organization of the IECEC, to eliminate duplication of separately sponsored meetings. Each year, one of the sponsoring societies takes its turn to supervise and run this Conference. This year, the society is AIChE. The continuity of this Conference is provided by a Steering Committee composed of two representatives of each of the societies. The intent of the IECEC is to avoid subjects that are appropriate for established conferences on conventional power systems. It also intends to compliment all the specialist conferences that are meetings of experts in a limited area of energy conversion.

Orlando is an attractive vacation spot, and the meeting is scheduled before school starts. Therefore, we have not scheduled any late afternoon or evening activities at the conference, so that you may attend many of the internationally known attractions with your family or associates.

Since this meeting fulfills world-wide needs to learn how to do more with less by means of improved energy conversion, it has grown into an important international meeting. Particularly, we have important contributions from Europe and Japan in many technical areas. This year, the Japan Society of Mechanical Engineers is becoming one of the co-operating societies who help sponsor the IECEC. These co-operating societies do not take turns sponsoring one of the meetings, but do support the meetings with publicity to their members and do receive the privilege of registering at a reduced rate. However, whether you are a member of a sponsoring group or not, I am glad you were able to attend and partake of this meeting. If you are here as a specialist, we hope you will be interested to some degree in the whole field in energy conversion.

W. R. Martini
General Chairman

Message from the Program Chairman

This year's conference is the 18th in the series. Reflection on the changing national energy interests and priorities reveals that the energy conversion field has evolved from one of strong orientation toward military and aerospace applications to one of greater breadth that recognizes a wide spectrum of terrestrial and private-sector requirements. This shift has brought with it greater concern for the economics of the marketplace. Hence this year's theme "Energy for the Marketplace."

Superimposed on the shift discussed above is the present federal policy of emphasis on longer-range R&D, coupled with a de-emphasis of government-funded demonstration and commercialization projects. These added constraints have placed new and difficult challenges before the energy conversion engineering field. It is in this new atmosphere of difficult financial and policy constraints that we present the 18th IECEC.

The program in this Proceedings shows the areas of current interest, many of which lie in the private sector. I think that the spectrum of topics represents a healthy balance among the technical fields, and among the potential markets. Some of them are in healthy competition; others complement one another. Frank McLarnon and I hope that you find this program interesting and informative. Thank you for joining us for a successful 18th IECEC.

Elton J. Cairns
Technical Program Chairman

Table of Contents

VOLUME V—ENERGY CONSERVATION

Energy Efficient Buildings

Energy I—Building Energy Systems I: Envelope Systems and Retrofit Studies

Organizer and Chairman: J. J. Hirsch, *Lawrence Berkeley Laboratory, Berkeley, CA*
Co-Chairman: J. M. Calm, *EPRI, Palo Alto, CA*

Energy II—Building Energy Systems IV: Performance Calculations

Organizer and Chairman: J. J. Hirsch, *Lawrence Berkeley Laboratory, Berkeley, CA*
Co-Chairman: W. L. Carroll, *Lawrence Berkeley Laboratory, Berkeley, CA*

839326

IDENTIFICATION OF OPTIMAL STRATEGIES FOR BUILDING RETROFIT WITH UNKNOWN FUTURE ENERGY COSTS

Philippe CONSTANT

LABORATOIRE DE PHYSIQUE DU BATIMENT
UNIVERSITE DE LIEGE (BELGIUM)

ABSTRACT

In the selection of the best alternative solution to reduce energy consumption in building we are confronted with at least two basic questions which can be stated as follows :

- how to choose the most cost-effective project ?
- how to make a consistent choice even when the future of energy escalation rates is unknown ?

This paper shows that the computation of the marginal cost-effectiveness of any project against each other is a suitable solution to the first question.
Concerning the second point, application of decision making analysis provides an attractive solution assuming that if it is impossible to know the exact values of future energy escalation rates it is at least possible to define an internal in which those values should be located.
In this paper an original approach to assist the decision process is presented. Basic theory of decision making analysis is briefly summarized and then applied to the selection of the best project from a set of eight feasible solutions.

INTRODUCTION

After evaluating the technical feasibility of different retrofitting measures we usually try to select the most cost-effective solution from the set of alternatives.

When there is only one (or no) project meeting the cost-effectiveness criteria the task is very easy. (Un)fortunately, several projects are usually cost-effective and the point is therefore to choose between either efficient but expensive solutions either cheaper but also less effective solutions.

In this paper, we propose the computation of not only the cost-effectiveness of a project with regards to the present conditions (i.e. no retrofitting) but also to compare the cost-effectiveness of any project to all other projects to make sure that any incremental investment is desirable.

Another problem when trying to identify the best project is due to the low level of knowledge available about future energy prices which are known to have a major impact in the significance of the results.

In this paper, we will set the decision process as it is in fact, that is to say that the decision maker knows neither the future energy escalation rates, neither the probabilities of occurence of those rates. We will only assume that the decision maker is able to define an interval in which those values should be likely located.

A brief description of concepts related to economics and decision analysis will precede a case study devoted to the selection of the best candidate from a set of eight feasible retrofit measures.

1. ECONOMIC EVALUATION

1.1. Cost-effectiveness conditions

Let us suppose that we have computed the energy savings obtained by a set of mutually exclusive solutions and we want to select the best measure.

Necessary condition of cost-effectiveness

The first step in that study is to compute the cost-effectiveness of all measures against the reference case to make sure that it is worthy retrofitting the building. This economic comparison with the reference has to be done on a total cost analysis including :

- initial cost;
- replacement cost;
- maintenance cost;
- energy cost.

If we choose the internal rate of return |3| to evaluate the cost-effectiveness of projects we have to solve equation 1 for each project :

$$AEC_o - AEC_j = 0 \qquad . \qquad (1)\ *$$

for j = 1, 2, 3, ... m
with AEC_j = annual equivalent cost of project j
AEC_o = annual equivalent cost of reference case.
The discount rate satisfying equation 1 is said to be the internal rate of return of project j against the reference. The comparison of this rate with the minimum attractive rate of return (MARR) set by the decision maker leads to the determination of the cost-effectiveness of project j :

(2)
$ROR_{j-o} > MARR$, project j is acceptable

$ROR_{j-o} < MARR$, project j is rejected

Condition 2 is a necessary but insufficient condition to verify cost-effectiveness of mutually exclusive solutions.

Sufficient condition of cost-effectiveness

If no project or only one project meets the cost-effectiveness criteria, the study is over because we may conclude that either no retrofit measure or only one retrofit measure is desirable and therefore the best strategy has been identified.

In the usual case with more then one cost-effective project, a further step has to be taken since we cannot select the best candidate from the set of cost-effective alternative solutions.

To get this information we have to compute the marginal cost-effectiveness of any project compared to the others :

$$AEC_j - AEC_k = 0 \quad (3) *$$

for j = 0, 1, 2, ... m-1 and k = 1, 2, ... m

The necessary and sufficient condition for cost-effectiveness reads :

(4)
$ROR_{k-j} > MARR$, project k is cost-effective

$ROR_{k-j} < MARR$, project k is rejected

1.2. Energy escalation rates

Although it may be impossible to predict future energy prices, it is usually possible to identify a set of probable energy escalation rates.

When applying equations 1 and 3 to n different energy escalation rates we may verify the cost-effectiveness of the m projects under different conditions corresponding to n states of nature.

Equations 1 and 3 yield results for each state of nature that can be represented as follows :

STATE OF NATURE i :

```
 Project k                       Pro l
|_________|_______________|_______|______|MARR(%)
0        Ai              Bi      Ci   100
```

Figure 1.

This shows that with the state of nature i, project K is the best project for any MARR between 0 and A_i, project l is the best project for any MARR between B_i and C_i, ...

By applying those equations n times corresponding to n states of nature we obtain figure 2 :

STATE OF NATURE 1:

```
|_______|_______|______|______________|MARR(%)
0      A1      B1     C1...          100
```

STATE OF NATURE 2:

```
|_____|_______|______|______________|
0    A2      B2     C2...          100
```

STATE OF NATURE n-1 :

```
|____|_______|_______|________________|
0   An-1    Bn-1    Cn-1...          100
```

STATE OF NATURE n :

```
|____|_______|_______|________________|
0   An      Bn      Cn               100
```

Figure 2.

At this point, if we assume that the n states of nature are a suitable picture of future, we may identifiy zones of optimal projects without even making a single assumption on the probabilities of states of nature :

> ANY PROJECT IS OPTIMAL IF LOCATED IN ZONES COMMON TO EVERY STATE OF NATURE, THAT IS TO SAY THAT ANY PROJECTS IS OPTIMAL IF LOCATED IN ZONES COMMON TO STATES OF NATURE CORRESPONDING TO MINIMUM AND MAXIMUM ENERGY ESCALATION RATES.

SYNTHESIS

```
|______|_|_______|_|________|__________|
0      A A'      B B'       C         100
```

FIGURE 3

Figure 3 shows the zones common to the all states of nature :

- OA, A'B, B'C, ... are totally defined zones in which we are able to identify optimal projects;
- AA', BB', ... are undefined zones in which we ignore the solution.

Only an additional information given either by the decision maker either by the probabilities of states of nature will allow the complete solution of the problem.

2. DECISION MAKING ANALYSIS

To fill the uncertainty gaps between the certainty zones, different ways are available depending on the amount of information we assume to have about the probabilities of states of nature.

Three different approaches to decision making are usually identified |2| :

- the decision maker has no information about the probabilities of the states of nature. This situation is referred to as decision making under uncertainty;
- the decision maker is assumed to know the probabilities of states of nature. This decision is termed decision making under conditions of risk;

* Equations 1 and 3 may have multiple roots. Reference |3| indicates a convenient way to obtain the real internal rate of return by introducing an auxiliary rate of return when the project is in overrecovering mode.

- the decision maker does not have enough information to specify the probabilities but can rank the probabilities of states of nature in which the alternative strategies would have to operate. The decision maker is therefore able to state for n states that $P_1 > P_2 > ... > P_n$ (P_i = probability of occurence of state of nature i).

Because it seems totally impossible to predict accurately future energy costs on a middle-term period (10-20 years), we will consider that the decision maker is only able to specify a likeable range of escalation rates; this situation is therefore related to the decision making under uncertainty.

2.1. Decision making under uncertainty

In this case the decision maker is said to have no information at all on the probabilities of states of nature and therefore assumes that all probabilities are set equal (Laplace case) :

$$P_1 = P_2 = ... P_{j-1} = P_n = 1/n$$

This situation is often referred to as "insufficient reason" and corresponds to the maximum level of uncertainty (maximum level of entropy).

Even in such a situation the decision process may be defined as a trade-off between expected values and variance :

- the expected value of strategy (S) under n different states of nature is defined in this case |2| as the mean outcome of strategy (S) :

$$U(S) = 1/n \ \Sigma X_j = \overline{X} \quad (5)$$

where X_j = outcomes of strategy (S) given state j
$\overline{X}$ = mean outcome of strategy (S)
n = number of states of nature

- the variance of strategy S under n different states of nature is defined |2|

$$VAR\ (S) = 1/n \ \Sigma (X_j - X)^2 \quad (6)$$

If we assume that expected values and variance are traded-off against each other linearly, we may define a simple characteristic index of any strategy :

$$I = X + b\sigma \quad (7)$$

where b = risk aversion coefficient
$\sigma = (VAR)^{1/2}$ = standard deviation

Equation (7) assumes a linear relationship between expected value and standard deviation but the decision maker is obviously free to trade-off in another way.

Application of those equations in the range of internal rates of return corresponding to the undefined zones will extend the identification of the optimal solution to the full range of minimum attractive rates.

3. A CASE STUDY

3.1. Technical and economic data

To illustrate the practical use of the previous procedure we will apply it to the selection of the best alternative solution for retrofitting a multi-family building located in Belgium.

The yearly energy consumption of this building for heating the space and the domestic hot water is 2 899 GJ |6|. The site and the Belgian climate could be briefly summarized as follows :

- SITE :

  - latitude : 50° 32' NORTH
  - longitude : 5° 30' EAST
  - altitude : 150 m

- ANNUAL AVERAGES :

  - prevailing wind direction : S W
  - average wind speed : 4.3 $m.s^{-1}$
  - global radiation on horizontal plane : 3 456 $MJ.m^{-2}$
  - diffuse proportion : 63 %
  - degree days : 1 956° C days (base temp. 15/15° C)
  - average maximum temperature (july) : 21.8 °C
  - average minimum temperature (january) : 1.8° C

Eight different proposals (P_1 to P_8) were made in order to reduce the energy consumption. (P1 is the cheapest one, P8 the most expensive).

- PO is the reference case, i.e. no energy conservation measure
- P1 is called "light retrofit". Conservation measures are limited to :
  - burner remplacement;
  - air infiltration reduction;
  - aluminium sheet behind radiator;
- P2 produces the domestic hot water (DHW) by an air-water heat pump ;
- P3 is the addition of P1 and P2;
- P4 consists in the installation of a new boiler using natural gas instead of oil;
- P5 is called "medium retrofit". In addition to light retrofit measures , this project includes an optimizer with external temperature probes and insulation on breast-walls ;
- P6 produces DHW by a night electricity heater;
- P7 produces DHW by solar energy (100 m^2 of single pane solar panels);
- P8 is called "heavy retrofit", insulation on the boiler and on pipes crossing unheated space is added to the conservation measures of the medium retrofit project.

PROJECT	INITIAL INVESTMENT COST	MAINTEN. (BF)*	ENERGY CONSUMPTION (BF/year) ELECTR. (KWH)	OIL (GJ)	GAS (GJ)
0	0	5 000	5 606	2 899	0
1	218 720	5 000	5 606	2 364	0
2	250 000	7 500	32 070	2 400	0
3	468 720	7 500	32 070	1 905	0
4	550 000	- 14 000	5 606	0	2 424
5	575 720	5 000	5 606	1 931	0
6	660 000	7 500	37 718	2 400	0
7	770 000	12 500	7 606	2 736	0
8	805 720	5 000	5 606	1 747	0

TABLE 1 : ECONOMIC DATA

(*) : U.S. DOLLAR = 50 BF

The computation of the life cycle cost is conducted with the following assumptions :

	OIL	GAS	ELECTR. DAY	ELECTR. NIGHT
COST	470BF/GJ	342BF/GJ	4.65BF/KWH	2.67BF/KWH

TABLE 2 : ENERGY COST

3.2. Cost-effectiveness computation

The first step in such an analysis is to verify that there is at least one project meeting the cost-effectiveness criteria. This is made by application of equation 1 yielding the internal rate of return of each project against the reference case.

Table 3 gives the results of such a computation in three extreme scenarios of energy escalation rates.

PROJECT	OIL 0 GAS 20 ELECTRIC. 20	20 20 0	20 0 20
1	> 100	> 100	> 100
2	0	72.4	92.9
3	0	> 100	> 100
4	0	> 100	> 100
5	78.7	> 100	> 100
6	0	34.5	48.8
7	0	28	29.3
8	66.8	> 100	> 100

TABLE 3 : INTERNAL RATES OF RETURN

Those figures shows that energy conservation measures were highly advisable but still do not allow the selection of the best alternative solution from the set of feasible projects.

3.3. Marginal cost-effectiveness

To proceed further with the selection of the best solution we need to know the marginal cost-effectiveness of any project against the others.

The decision whether to select a particular alternative rests on the determination of the economic desirability of the additional increment of investment required by one alternative over the others.
The increment is desirable if it yields a prospective rate of return greater that the minimum attractive rate of return |3|.

Equation 3 completes table 3 by computing the desirability of projects not only in regard to reference case but also with respect to the other alternatives.

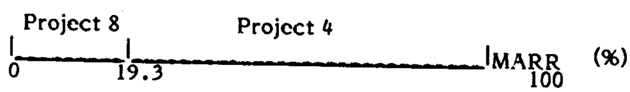
Table 4 gives the computation results with 20 % oil and gas annual increase, 0 % electricity annual increase.

	0	1	2	3	4	5	6	7
1	>100	0	0	0	0	0	0	0
2	92.9	0	0	0	0	0	0	0
3	>100	84.9	>100	0	0	0	0	0
4	>100	>100	>100	>100	0	0	0	0
5	>100	88.2	>100	18.2	0	0	0	0
6	48.8	0	0	0	0	0	0	0
7	29.3	0	0	0	0	0	0	0
8	>100	79.1	>100	73.5	19.3	64.9	100	100

TABLE 4 : MARGINAL RATES OF RETURN

The fourth column shows that project 4 against project 3 has a rate of return higher then 100 % and that project 5 has a rate of return of 18.2 % against project 2.

As said before, information contained in table 4 may be summarized in a "decision making line". This line states that for any MARR below 19.3 %, project 8 is the best candidate and for any MARR higher then 19.3 %, project 4 is the most desirable alternative.



3.4. Energy escalation rates

At this point of the analysis, we are able to verify the cost-effectiveness of alternative solutions and to identify the best project according to our value of the minimum attractive rate of return. But it is still necessary to solve the question related to the predicition of future energy prices.

Let us suppose f.i. that the decision maker thinks it likely that oil and gas escalation rates will be in the range of 0 to 20 % (i.e. - 8 to 12 % in real terms with 8 % inflation rate). The certainty zones are obtained by identification of project zones common to the two extreme scenarios of energy escalation rates. Computation of the decision lines related to those extreme cases yields :

```
ENERGY
RATES

OIL      ELECT.              DECISION LINES
GAS      (%)

                          P4        P1        P0
0        20         |_________|_____|_________|MARR(%)
                              91.8  114.8     200

                               P4          P1 P0
20       10         |____________________|__|__|
                                       127.5 157.7 200

                          P4                  P0
WITH CERTAINTY      |_________|_______________|___|
                              91.8           157.7 200
```

The certainty zones show that project P4 optimal for any MARR between 0 and 91.8 % while P0 is optimal for any MARR in the range of 157.7 to 200 %. This gap |91.8, 157.7| should be filled.

3.5. Decision making under uncertainty

As explained previously, each project in such an analysis can be characterized of a single index presented in equation (7). Two values set the limits of the risk aversion coefficient :

$(b)_{MIN} = -0.013$ corresponds to the most pessimistic behaviour. This value is the maximum risk aversion coefficient verifying the certainty zone limits.

$(b)_{MAX} = 0$ corresponds to a very optimistic behaviour still in good agreement with the certainty zone limits.

Any value of the risk aversion coefficient located in the range - 0.013 to zero is an acceptable risk measurement for the decision maker. A strong risk aversion behaviour (b = - 0.013) is represented below and the corresponding decision making outcome can be stated as follows :

if 0 < MARR < 91.3 %, natural gas boiler (P4) is the best project
91.5 < MARR < 109.5 %, light retrofit (P1) is the optimal project
MARR > 109.5 %, doing nothing is the best solution.

```
          P4              P1               P0
_|______________|___________|________________| ( MARR)
 0             91.5        109.5            200
```

Without knowledge on energy escalation rate probability value or probability ranking it is therefore possible to identify the optimal alternatives if the range of likely energy escalation rates is defined.

4. CONCLUSIONS

The main objective of this paper was obviously not the identification of a single retrofitting strategy but rather to build up a general methodology for decision making :

- in a first step we showed that it was always possible to select the best candidate from a set of mutually exclusive solutions by applying the concept of marginal rate of return.

- in a second step we proved that the very poor knowledge available about the future doesn't yield an unsolvable problem outside the domain of rational decision making.

It is furthermore important to note that this approach, even when concerned with uncertainty, doesn't require the stipulation of any artificial rate of return before the cost-effectiveness evaluation is carried out, preserving therefore all the advantages of ROR cost analysis.

Finally this approach is believed to be suitable not only for retrofit analysis but also for a wide range of decisions occuring at different stages of the building design process.

4. AKNOWLEDGEMENTS

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839327

THERMAL PERFORMANCE OF INSULATED WALL SYSTEMS WITH METAL STUDS

Bakhtier Farouk and Donald C. Larson

Drexel University, Philadelphia, Pennsylvania.

ABSTRACT

An experimental and numerical investigation of the thermal performance of metal-stud wall systems is reported. The thermal performance was measured with a temperature controlled test plate. The method provides reliable thermal resistance values for building envelope components which are inhomogeneous and can be employed in the field to monitor the long-term thermal integrity of envelope components. A comprehensive computer code (HEATING V) was then used to assess the validity of the experimental scheme and to perform parametric studies with different configurations and geometries of the envelope system.

INTRODUCTION

Inhomogeneous and nonuniform building envelope components are quite common. These include, for example, insulated metal-stud wall systems and sprayed-on foam roof systems. Energy use in buildings can be introduced by improving the thermal performance of the building envelope. Thermal resistances of the building envelope components have been found to vary depending on their configuration, thickness, etc. In order to assess the performance of the building envelope, increased emphasis must be placed upon in-situ or field evaluations. Laboratory testing of the thermal performance of building subsystems is necessary but such testing cannot replace thermal evaluations of the complete buildings, in particular, when long-term performance data are required. In the field a building is subject to many environmental stresses and periodic thermal testing is required to determine whether the initial performance of the envelope is maintained over the life of the building. An experimental and numerical investigation of the thermal performance of an insulated wall system with metal studs is reported here. The thermal resitance is measured with a temperature-controlled test plate to which heat flow sensors and thermocouples are attached. Temperatures and heat flows are measured after equilibrium is achieved. The measurements can be made without disturbing the structure of the envelope systems by using test plate temperatures approximating outside ambient temperatures. The temperature controlled test plate brings the outside surface temperature of an insulation system to an approximately uniform temperature and therefore the boundary conditions at the outer surface of the inhomogeneous wall system will be different from the field conditions.

The experimental measurements do not provide, however, insight into the physical mechanisms which cause higher or lower resistance values to the inhomogeneous systems studied. To assess the validity of the experimental measurements, the thermal measurements of the insulation systems were also analyzed numerically using a multi-region two-dimensional heat conduction model. The inhomogeneous composition of the wall systems and the thermal boundary conditions imposed for the test plate measurements were efficiently simulated in the model. A comprehensive computer code (HEATING V) was used to obtain the thermal resistance values. Parametric studies are made with different configuration and boundary conditions of the envelope systems. Temperature and heat flow lines were obtained within the solution domains and the region of the thermal short-circuits were identified.

EXPERIMENTS

The field testing approach described here employs heat flow sensors semipermanently attached to a temperature-comtrolled test plate. The test plate is portable and is used to make periodic thermal resistance measurements on building envelope components. The plate is placed against the outside of the building (or on the inside of a basement wall), is heated or cooled to an equilibrium temperature either above or below the inner surface temperature, and the inside and outside surface tmperatures and the heat flow are measured. Generally the test plate is heated in the summer and cooled in the winter so that the measurements may be made without disturbing the structure of the building component. The test plate is small enough to be portable, but is large enough to assess the heat transfer through a building component over a reasonably large area. When the insulation system is laterally inhomogeneous, the test plate is moved from one location to another to obtain an average thermal resistance and to ensure that representative areas of the insulation system are sampled.

The test plate provides constant temperature boundary conditions on the puter surface of the building component, but the conditions on the inside are not subject to the same controls. In practice, however, the inside air temperature is sufficiently stable so that a reliable value for the thermal resistance is obtained. Except for this lack of control of the inside surface temperature, the test plate method is similar to the laboratory scale ASTM Test for Steady-State Thermal Transmission Properties by means of the Heat Flow Meter (C518-76). Such laboratory tests, however, employ relatively small homogeneous specimens whereas a field test method must be applicable to real envelope structures where one-dimensional heat flow cannot be assured.

The application of the test plate method to an insulated wall is constructed with steel studs which provide thermal short circuits. Such non-uniform insulation systems are quite common so that it is important that a field test method make meaningful measurements on such systems. The primary experimental device is a 1.22m square 0.95cm thick aluminum test plate which is shown in cross-section in Figure 1. Three heat flow sensors spaced 30.5cm apart are attached at the bottom of the plate with heat sink compound. Two sheets of an elastomeric membrane of 1.14mm ethylene propylene diene monomer (EPDM) serves as a guard for the heat flow sensors. The heat flow sensor and the thermocouple leads are protected by the outer EPDM cover and are terminated at a connector at the edge of the plate. The top of the test plate is fitted with copper tubes and headers for the heat transfer fluid. A uniform fluid temperature (or if desired, a controlled variable temperature) is provided by a programmable thermostatically-controlled bath and circulator. Fluid temperatures ranging from -20 C to 40 C are used which correspond to the range of external envelope temperatures experienced in this area. The calibration procedure for the test plate is similar to that employed in an ASTM heat flow meter test (C518) and is described in [1].

The test plate was used to determine the thermal resistance of the insulated wall which is shown in Figure 2. The wall has vertical galvanized steel studs, with a 40.6cm separation, 8.9cm of aluminum foil faced fiberglass blanket insulation and 1.3cm gypsum board sheathing.

NUMERICAL ANALYSIS

A two-dimensional numerical model was applied to calculate the thermal resistance values of the insulated wall system shown in Figure 2. The inhomogeneous wall system precludes any analytical approach to obtain the temperature distribution and hence the calculation of the thermal resistance values. The metal studs and aluminum foil on the top of the fiberglass insulation introduces difficulties for the analysis.

With no internal generation and steady-state conditions, the governing equation for the wall system is given by

$$\Delta \cdot (k \nabla T) = 0 \qquad (1)$$

where k is the thermal conductivity. For the wall system studied, the thermal conductivity varied widely from one region to another. The above equation was solved numerically for a symmetry region of the wall system (metal stud being at the center) along with specified boundary conditions. The boundary-conditions were specified such that they conformed to the test plate measurements.

A comprehensive computer code (HEATING V) developed at the Oak Ridge National Laboratory was efficiently used to obtain the numerical solutions. The physical problem is approximated by a system of nodes each associated with a small volume. The system of equations describing the temperature distribution is derived by performing a heat balance about each node.

For a steady-state heat conduction problem, the heat balance equation for node i reduces to

$$\sum_{m=1}^{M_i} k_{\alpha m}(T_{\alpha m} - T_i) = 0 \qquad (2)$$

where M_i is the number of neighboring nodes. The value of M_i depends on the spatial dimensions of the problem being considered. α_m is the m^{th} neighbor of the i^{th} node. By choosing the increments between lattice lines small enough, the solution to the system of equations yields a practical approximation to the appropriate differential equation.

If there are I nodal points in the solution domain, there will be a system of I equations with I unknowns. An iterative technique is used by HEATING V to solve the system of equations. A relaxation factor is used to over or underrelax the iterative procedure. An extrapolation procedure, commonly used to increase the rate of convergence in an iterative solution to a system of equations viz. the "Aitken δ^2 extrapolation procedure", is also used [2].

HEATING V possesses a variety of boundary conditions to enable the user to model the physical problem as accurately as possible. The configuration of the problem is first approximated by dividing it into regions, depending on the shape, material structure, indentations, cutouts and other deviations from the general geometry. According to the rules governing region division for HEATING V, the problem geometry (Figure 3) was divided into 9 rectangular divisions. Regions 1 and 8 are the gypsum board sheathing, regions 3, 6 and 9 represent the metal stud, region 2 is the aluminum foil while regions 4, 5 and 7 are the fiberglass insulation. HEATING V is designed so that simultaneously, one may consider surface-to-surface heat transfer across a region as well as conduction through the region. Due to the symmetry, zero gradient boundary conditions are considered for the vertical boundaries. To simulate the test plate measurements, a constant temperature boundary condition is considered for the lower boundary and a convective heat transfer coefficient is specified for the upper boundary. The dimensions of the divided regions can be approximated from Figure 3 (drawn in scale)

For surface to surface boundary conditions the leakage term is calculated as follows

$$[k_{\alpha m}\ (T_{\alpha m} - T_i)] = k_b (T_b - Ti) \qquad (3)$$

where k_b is the effective conductance from surface node i to the opposing surface node b and T_b is the temperature of the opposing surface node b [2].

RESULTS AND DISCUSSION

The experimental measurements are first described. The thermal resistance of the insulated wall was measured at three locations and the results are given in Table 1. The test plate was oriented with the heat flow sensors horizontal so that the three sensors are aligned perpendicular to the metal studs. The resistance values at each location were calculated from three-hour averages of the temperatures and heat flows. The minimum center-to-center heat flow sensor to stud flange separations are also given on the table. In test location #3 heat flow sensor #2 was almost directly over the stud flange while heat flow sensor #1 was midway between the studs. The heat flow recorded by sensor #2 was 4.6 times greater than the heat flow recorded by sensor #1. The thermal resistance had a minimum value at this location. In test location #2 none of the heat flow sensors were closer than 41mm from the stud flange and in this location the measured thermal resistance was highest. The average value of the measured thermal resistance was 1.17 m^2 K/W (6.62 ft^2h-F/Btu.)

The experimental thermal resistance of the wall is much lower than the value calculated by assuming one-dimensional heat flow. If we use values of R_I = 1.94 m^2K/W (11 ft^2hF/Btu) for the fiberglass blanket insulation, R_s = 2.26 X 10^{-3} m^2K/W (0.0128 ft^2hF/Btu) for the steel stud (k = 45 W/mK) and R_w = 7.93 X 10^{-3} m^2K/W (0.45 ft^2 hF/Btu) for the wall board and assume one-dimensional heat flow, the wall resistance would be given by

$$1/R_T = A_I/(2R_w + R_I) + A_s/(2R_w + R_s) \qquad (4)$$

where A_I and A_s are the fractional cross-sectional areas of the insulation and stud respectively. The stud wudth and spacing were measured to be o.51 and 406mm respectively and R_T was found to be equal to 2.07 m^2K/W (11.7ft^2hF/Btu). The value is close to the value obtained by summing the insulation and wall board resistance and is of course unrealistic in that it neglects the transverse heat flow in the flange of the stud as well as in the wallboard.

To provide insight into the physical mechanisms which cause the experimental resistance to be 43% lower than the value calculated assuming one-dimensional heat flow, the two-dimensional numerical model was applied for the insulation problem considered.

Figure 4 shows the calculated surface temperature distribution for the wall system subject to a convective boundary condition. The surface temperature peaks sharply near the metal studs which induces lateral heat transfer and in effect, a thermal short-circuiting. The heat transfer coefficient at the surface was set equal to 8.1 W/m^2K (1.42 Btu/hr ft^2F) and the ambient temperature was set to 0 C (32 F), while the other surface temperature was kept constant at 21.1 C (70 F). The thermal conductivity values of gypsum board and the fiberglass insulation were equal to 0.16 W/mK (1.11 Btu-in/hft^2F) and 0.25 W/mK (.363 Btu-in /hft^2F) respectively. † For reference purpose the location of the metal stud is also shown in Figure 4.

Figure 5 gives the steady state temperature profiles for the wall system along three vertical sections at 10.16cm, 20.32cm and 30.48cm (4, 8 and 12 in) from the left end of the 40.6cm (16 in) long symmetry unit considered. The temperature profiles at 10.16cm (4 in) and 30.48cm (12 in) almost overlap but the one at 20.32cm (8 in) is significantly different. The near isothermal region at the midsection is due to the metal stud and the effect of two-dimensional heat transfer is quite evident. This also explains the nonuniformities of the experimental measurements of the resistance values. Figure 6 shows the isotherms for the solution domain. The thermal short circuiting is seen to be significant even of the metal stud is very thin. An average thermal resistance value (wall to wall) for the wall system was calculated once the temperature distribution was obtained. The heat flux distribution q(x) at the exposed surface was first calculated. The thermal resistance of the wall was then found from

$$R = \frac{\int_x (T_i - T(x))\, dx}{\int_x q(x)\, dx} \qquad (5)$$

where T_i is the specified surface temperature at the lower section and T(x) is the surface temperature distribution at the exposed wall. The thermal resistance value obtained from the calculation agreed well with the mean resistance value obtained from the experiements. For the particular case where the surface heat transfer coefficient was set to equal to 8.1 W/m^2k (1.42 Btu/hr ft^2 F) the average value of the measured thermal resistance was 1.22 m^2K/W (6.96 ft^2h-F/Btu) without the .0036cm (.0014 in) aluminum foil (region 2 in Figure 3). Computations were also carried out with the aluminum foil which resulted in a slightly decreased value of the thermal resistance.

† 3.5 in. (8.89cm) insulation was considered to fill the 4 in. (10.16cm) cavity.

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TABLE 1 -- Wall Test Results

Test Location	Upper Temperature (C)	Lower Temperature (C)	Heat Flow (W/m^2)				Heat Flow Sensor to Stud Distance (mm)			Thermal Resistance m^2K/W (ft^2 hF/Btu)
			Q_1	Q_2	Q_3	$\bar{Q}$	d_1	d_2	d_3	
1	49.9	25.4	8.0	12.6	41.6	20.8	89	117	16	1.18 (6.69)
2	49.2	25.4	7.8	24.8	25.1	19.2	159	41	64	1.24 (7.04)
3	53.2	26.3	9.9	45.3	19.9	25.0	197	3	102	1.08 (6.11)

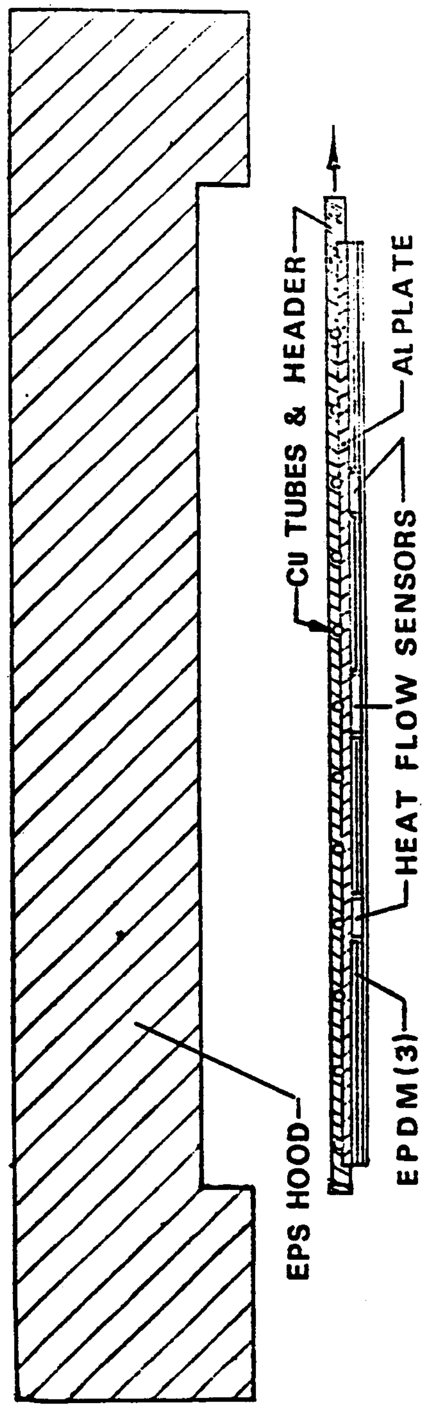

FIGURE 1
TEST PLATE CONFIGURATION

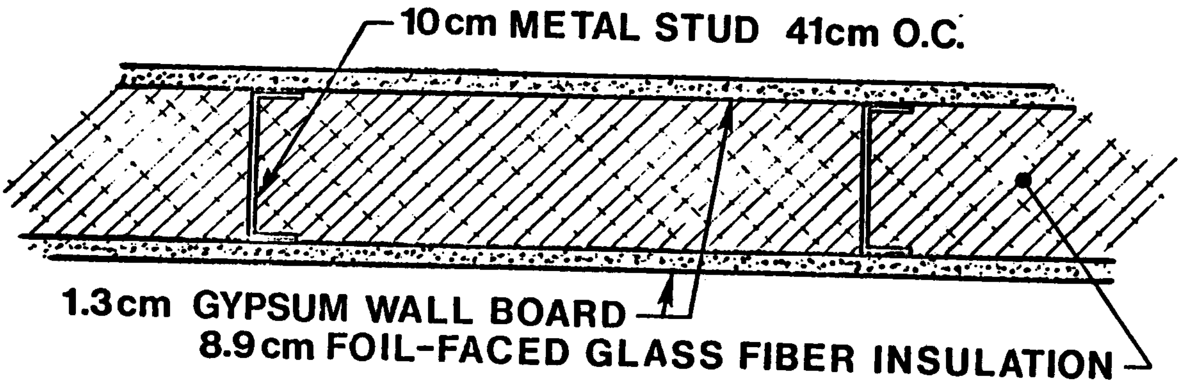

FIGURE 2

CROSS-SECTION OF THE INSULATED WALL

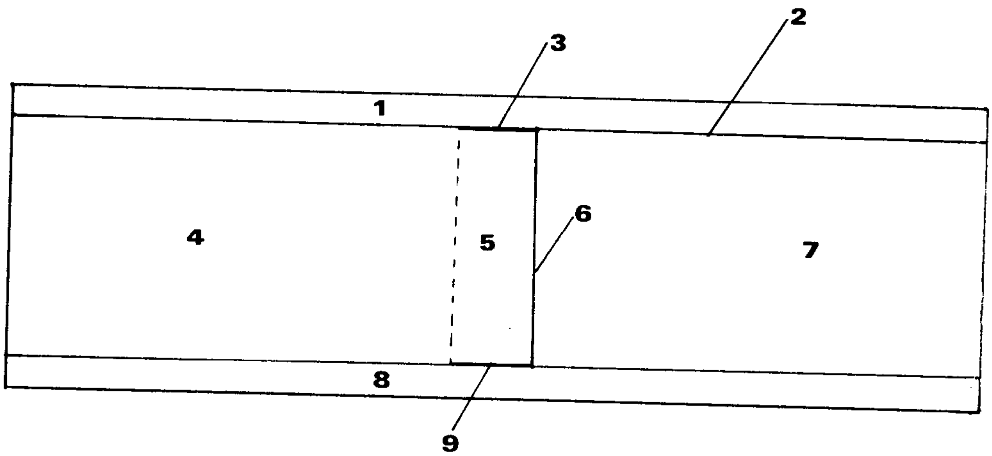

FIGURE 3

REGION DESCRIPTION FOR TWO-DIMENSIONAL RECTANGULAR MODEL OF THE INSULATED WALL