A METHODOLOGY FOR THE EVALUATION OF THERMAL PERFORMANCE OF WINDOWS BASED UPON LIFE-CYCLE COST

by

Timothy D. Butler

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APPROVED:

Benjamin H. Evans, Chairman

Harold S. Hill

Donald W. Barnes, Jr.

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c1

TABLE OF CONTENTS

Page

Chapter

LIST OF TABLES

Table Page

LIST OF FIGURES

Chapter I

INTRODUCTION

Available energy, inexpensive in the past, is becoming increasingly scarce and expensive. Projections of national energy consumption established by the U. S. Geological Survey indicate that domestic reserves of both natural gas and petroleum will be exhausted by the year 2000.(1) The shortage of natural gas experienced by the eastern half of the United States during the first few months of 1977 further dramatized the fact that fossil fuels are fast disappearing. The economic law of supply and demand is forcing the cost of energy to increment at an ever-accelerating rate. As a result of the rapid increase in the cost of energy there has emerged a new public awareness of the necessity for efficient energy utilization. Considering that 18% of the total energy demand of the United States is used for space heating of buildings, future architectural design should be more responsive to the increasing cost of energy.(2) This is in sharp contrast to present trends in

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(1) Patrick Binns, "State Legislative Incentives for Solar Energy Implementation," Industrialization Forum, Vol. 7, No. 2-3 (1976) p. 3.

(2) NBS Technical Options for Energy Conservation in Buildings ,Institute for Applied Technology, NBS Technical Note 789, (July 1973) p. 25.

architectural design as typified by the World Trade Center in New York which consumes enough electricity to power a city having a population of 100,000 residents.(3) The architectural profession is in a unique position to have a major impact upon decreasing the rate of national energy consumption. It has been estimated that, "The decisions made by architects and engineers can reduce energy expenditures in our buildings by 50 percent with no penalty to the quality of life in our buildings."(4) This is equivalent to a decrease in total national energy consumption of more than 10% when all buildings are included.

Review of Literature

Historically, windows have a special role in architecture. With the development of electric lighting this role of the window as a tool for creating space lost its prominent position. The availability of inexpensive energy seemed to hasten the end of the dependence upon windows for light. With the advent of the energy crisis of

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(3) Robert G. Ramsey,"Energy, Environment, Management and Systems," Industrialization Forum, Vol. 7, No. 2-3 (1976) p. 27.

(4) Richard G. Stein, "Architecture and Energy," Architectural Forum ,Vol. 139, No. 1 (July-August 1973) p. 53.

the 1970's the window began to regain the lost position it once enjoyed.

In addition to admitting daylight, which helps to conserve electric energy, the windows role in collecting solar energy has also been recognized. This has resulted in a transformation of the interior built environment into a low temperature solar collector. Such technology is far from new. To quote J. W. Griffith, former President of the Illuminating Engineering Society, "Utilization of solar energy as . . . . heat through windows is one of the oldest and most common uses of a natural resource."(5)

In recent years, the use of windows has been restrained because of the mistaken belief that they were energy losers. For example, studies conducted by Anson, Kennedy and Spencer in Melbourne, Australia indicate that the life-cycle cost (the amortized equivalent of running and maintenance costs plus the initial cost) of the building may be decreased by the reduction of heat gain associated with the windows.(6) This approach fails to recognize solar heat gain in the winter in the design analysis of window sizes,

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(5) J. W. Griffith, "Resource Optimization Calls for Analysis Based on Life-Cycle Cost," Professional Engineer, Vol. 45, No. 6 (June 1975) p. 40.

(6) M. Anson,"Effect of Envelope Design on Cost Performance of Office Buildings," National Bureau of Standards Special Publication 361, Vol. 1 (March 1972) pp. 395-406.

orientation and glazing material which can be quite substantial and can result in substantial energy savings.(7) Even though windows may be energy losers in the winter when the sun is not shining (or on north facing walls) the total annual effect of properly used windows can often be a net annual increase of heat from the sun. "Proper design of the total effect of windows can conserve nonreplaceable energy in most buildings."(8) Research sponsored by the American Physical Society shows that "A substantial amount of beneficial heat can be gained from solar transmission through architectural windows."(9) Furthermore, their research shows that when these windows were evaluated by life-cycle costing models, in a manner similiar to that utilized by the Anson study, "The incremental capital costs necessary to make some windows better in conserving net energy than insulated walls are not high."(10)

While a number of analytical models have been developed to determine the heat gain through the building envelope or to establish the life-cycle cost of the building wall

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(7) Peter Bruberry, "Conserving Energy in Buildings," The Architects Journel, Vol. 11 (September 1974) p. 626.

(8) J. W. Griffith, "Resource Optimization Calls for Analysis Based on Life-Cycle Cost," Professional Engineer , Vol. 45, No. 6 (June 1975) p. 40.

(9) S. M. Berman, et al, Energy Conservation and Window Systems (National Physical Society, 1975), p. 47.

(10) Ibid.

components, no comprehensive model of sophistication exists which combines these aspects of heat gain and cost. For example, the system for determining heat gain developed by the National Bureau of Standards, and referred to as National Bureau of Standards Load Determination (NBSLD), was referred to as the most extensive system of its type at the Energy Research and Development Administration (ERDA) Conference and Workshop on Passive Solar Heating in May 1976. Yet this system, while it takes into account shading fins and overhangs, fails to include items such as the area of a window that is shaded from direct solar radiation by the window frame itself.(11)

Economic models, such as the life-cycle cost model published by the Brick Institute of America, have their limitations.(12) While this model interrelates climatic analysis, energy consumption and initial cost of building envelope components it fails to include any comprehensive heat gain calculations. There is neither a simulation of insolation nor allowance for shading factors. This error becomes apparent when one considers the cost-benefit ratio of a shading device consisting of a horizontal louver. This

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(11) Institute for Applied Technology, NBSLD, The Computer Program for Heating and Cooling Loads in Buildings, (Washington: U. S. Government Printing Office, 1976) pp. 29a-45a.

(12) Brick Institute of America, "Ultimate Cost of Building Walls," (January 1972) pp. 10-15.

type of shading device would place the window in shadow during the summer months when the altitude of the sun is high, but would allow penetration of direct insolation during the winter months. Another important aspect which this model fails to consider is orientation which, if used advantageously, can result in an infinite cost-benefit ratio "since the layouts which give economy in energy can also satisfy the other planning requirements."(13)

Since it is clear that windows can contribute to the conservation of energy when properly used (and when properly evaluated) what is needed is a model by which the heat gain associated with the thermal performance of windows can be determined with respect to its impact upon the life-cycle energy consumption cost of the building. Through the utilization of such a model each window assembly could be tailored to the specific latitude and orientation influencing the selection of alternative glazing types.

Scope of Study

The study to be undertaken will lead to the development of a static life-cycle cost model, which if implemented as a computer simulation could be used in the selection of fenestration glazing material. The model is to be based

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(13) Peter Burberry, "Conserving Energy in Buildings," The Architects Journal Vol. 11 (September 1974) p. 626.

upon thermal characteristics of the glazing material in relation to the building space heating requirements. Potential effect of shading devices will not be included. Evaluation will be made only between alternative fenestration materials, where all other building design characteristics (size and number of fenestration openings, wall composition, wall orientation, mechanical equipment, etc.) will be held constant. Selection of alternative glazing materials will be based upon optimum life-cycle cost. A case study will be conducted to evaluate two alternative glazing materials for the purpose of testing equations used in the static life-cycle cost model.

Chapter II

SOLAR HEAT GAIN THROUGH WINDOWS

Heat gain entering a building from the exterior environment is composed of a number of components including 1) heat conducted through solid wall components and glazed wall openings, 2) re-radiation of heat absorbed by solid wall components and glazed wall openings, 3) infiltration of warm air (during summer months) through solid wall components and around fenestrations, and 4) solar radiation transmitted through glazed wall openings. Of these components which constitute heat gain, direct solar radiation through glazed surfaces often constitutes the major proportion of the total heat gain which enters a building.(14) Since insolation through windows can exert such an impact upon the thermal quantity of an interior environment, insolation should be considered in the design of a building. Heat gain attributed to insolation can influence many basic design decisions, including the following: A) the quantity and type of glass used, B) whether the glass used should be shaded, C) the orientation of the glass, anD d) the selection of the building heating

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(14) Y. Y. Yuvshinov, "Method for Determining Total Heat Gain from Direct Solar Radiation Entering Structure," <u>Geliotekhnika</u>, Vol. 9, No. 4 (1973) p. 113.

and cooling systems.(15)

Solar heat gain through glass consists of the summation of a) radiation transmitted through the glass, which is modified by the angle at which the solar beam strikes the glass surface, and b) the absorption factor of the glass, a portion of which is re-radiated to the interior.(16) Before this heat gain can be determined, however, it is first necessary to establish the amount and direction of solar energy impinging upon the glass.(17)

Nature of Insolation

The amount of insolation upon any surface is a function of 1) the intensity of the solar beam which impinges upon the surface, 2) the angle of incidence of that beam, 3) the amount of diffuse radiation from the sky incident upon that surface, and 4) the radiation reflected from the ground and other adjacent surfaces.

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(15) Ibid.

(16) P. Petherbridge, "Transmission Characteristics of Window Glasses and Sun Controls," Sunlight in Buildings, R. G. Hopkinson (Rotterdam: Bouwcentrum International, 1967) pp. 187-190.

(17) A. G. Loudon, "The Interpretation of Solar Radiation Measurements for Building Problems," Sunlight in Buildings, R. G. Hopkinson (Rotterdam: Bouwcentrum International, 1967) p. 111.

Direct Radiation. The intensity of the solar beam is dependent upon a number of astronomical and climatic variables which include, 1) the declination of the earth, defined as the angle between the solar beam and the equitorial plane, 2) the altitude of the sun, which is the angle between the solar beam and the horizon and dependent upon the declination, latitude and time, and 3) the pollution, water vapor and dust content of the atmosphere.(18) These variables act to modify the solar constant (the intensity of solar radiation beyond the atmosphere measured normal to the solar beam) as follows: As the earth revolves about the sun its declination changes. This is due to the tilt of the earth relative to the earth's orbital plane (a plane which touches all of the points made by the earth as it revolves about the sun). This tilt (which equals 23.45 degrees) causes the changing seasons and determines the distance the solar beam must travel through the atmosphere. For example, from September 21 to March 22 the rays of the sun are normal to the earth's surface at some point in the southern hemisphere. This causes the angle of attack of the sun's rays in the northern hemisphere to have a lower angle of incidence into the atmosphere. Therefore, those rays must travel a greater distance through

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(18) J. I. Yellot, "Calculation of Solar Heat Gain Through Single Glass," Solar Energy, Vol. 7, No. 4 (1963) p. 173.

the atmosphere, resulting in greater absorption and dispersion of radiation, decreased radiation striking the earth at that latitude, decreased temperature of the atmosphere, and the occurrence of the seasons of autumn and winter in the northern hemisphere. (Figure 1)

Solar altitude (as earlier stated) is a function of the declination, the time, expressed as the hour angle, and the latitude. Solar altitude may be expressed by the following equation:

SIN ALTITUDE = (COS LATITUDE x COS DECLINATION x COS (HOUR ANGLE) + SIN LATITUDE x SIN DECLINATION)

Subsequent equations in this document are expressed in *APL* notation. *APL*, (the acronym for A Programming Language) is a means for describing processes of manipulating either alphabetic or numeric data. *APL* notation will be used because of its ability to describe mathematical operations with less ambiguity than conventional algebraic notation. While *APL* notation is algebraic in origin some operators will be unfamiliar to the reader. Explanations of these operators can be found in Appendix A. The *APL* equivalent to the above alegbraic equation is given below.

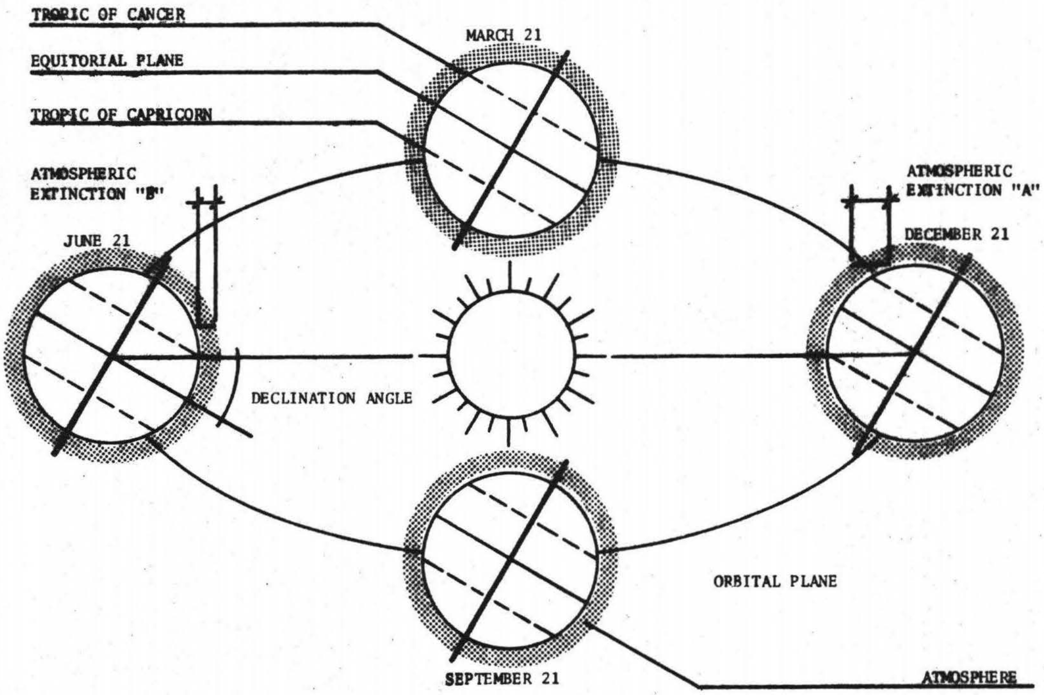

Fig. 1. Seasonal Angle of Incidence.

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(19) J. L. Threlkeld, Thermal Environmental Engineering (Englewood Cliffs: Printice-Hall, Inc., 1962) p. 313

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ALTITUDE ←  ARCSIN (((COS  LATITUDE) ×  (COS DECLINATION)  ×
(COS HA)) + (SIN LATITUDE) × (SIN DECLINATION)))
2                                                      (EQ. 1)
```

where,

```
SIN X = 1 ○ X × ○ ÷ 180
ARCSIN X = (¯1 ○ X ) × ( 180 ÷ ○1 )
COS X = 2 ○ X × ○ ÷ 180
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and where; *HA* is the hour angle in degrees between the solar beam and the location of the sun at 12:00 (solar noon); *ALTITUDE* equals the angle in degrees between the solar beam and the horizon for the hour being considered; *DECLINATION* equals the declination of the earth for the day under consideration in degrees, and *LATITUDE* is the latitude of the location under consideration expressed in degrees. (Figure 2)

As the solar beam passes through the atmosphere it is scattered, and otherwise dimenished through absorption, by pollutants, dust and water vapor. That radiation which has been scattered will eventually reach the surface of the earth as diffuse radiation. The intensity of the solar beam reaching the earth is dimenished by a factor known as the atmospheric extinction coefficient. This factor is a result of the length of the solar path through the air mass and is

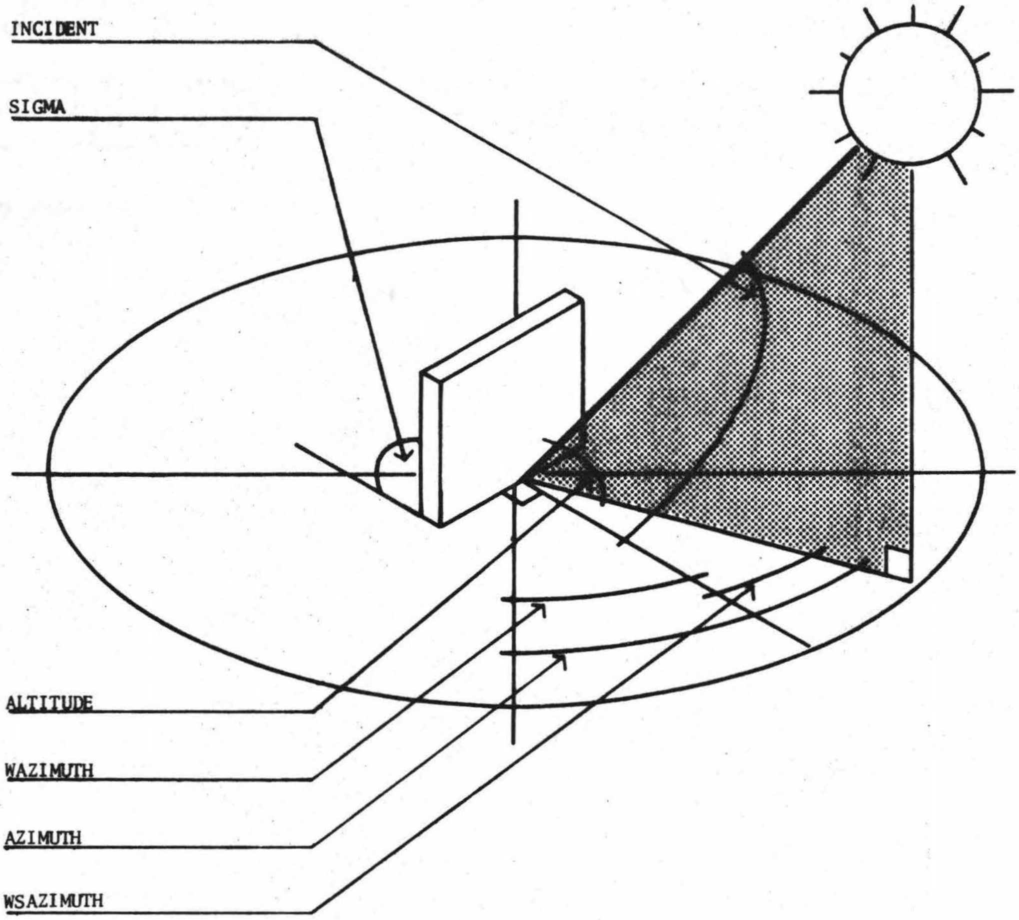

Fig. 2. Solar Angle Definitions.

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(20) <u>American Society of Heating, Refrigerating and Air Conditioning Engineers, Guide and Data Book, 1972</u>. p. 393.

expressed as a ratio of the actual distance of the solar path to the minimum possible distance of the solar path at sea level. (Figure 3)

Since the intensity of the solar beam is measured normal to its path it is necessary to multiply the value of the incident radiation by the cosine of its angle of incidence into the atmosphere and a line normal to the earth's surface. This cosine correction is necessary to determine the intensity of the radiation perpendicular to the surface (the vertical component of the radiation). Therefore, given the atmospheric extinction coefficient and the apparent radiation, (the intensity normal to the solar beam at the earth's surface) the direct solar radiation striking normal to the earth's surface expressed in BTU per hour per square foot (*DIRECT*) can be calculated from the following equation:

$$\mathit{DIRECT} \leftarrow \mathit{APPARENT} \div * \,(\ \mathit{EXTINCTION} \div \mathit{SIN\ ALTITUDE}\ )$$

(*EQ*. 2)

where; *APPARENT* equals the apparent radiation in BTU per (hour) (square foot), and *EXTINCTION* equals the atmospheric extinction coefficient.(21) While mathematical relationships

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(21) American Society of Heating, Refrigerating and Air Conditioning Engineers, Guide and Data Book, 1972, pp. 386-394.

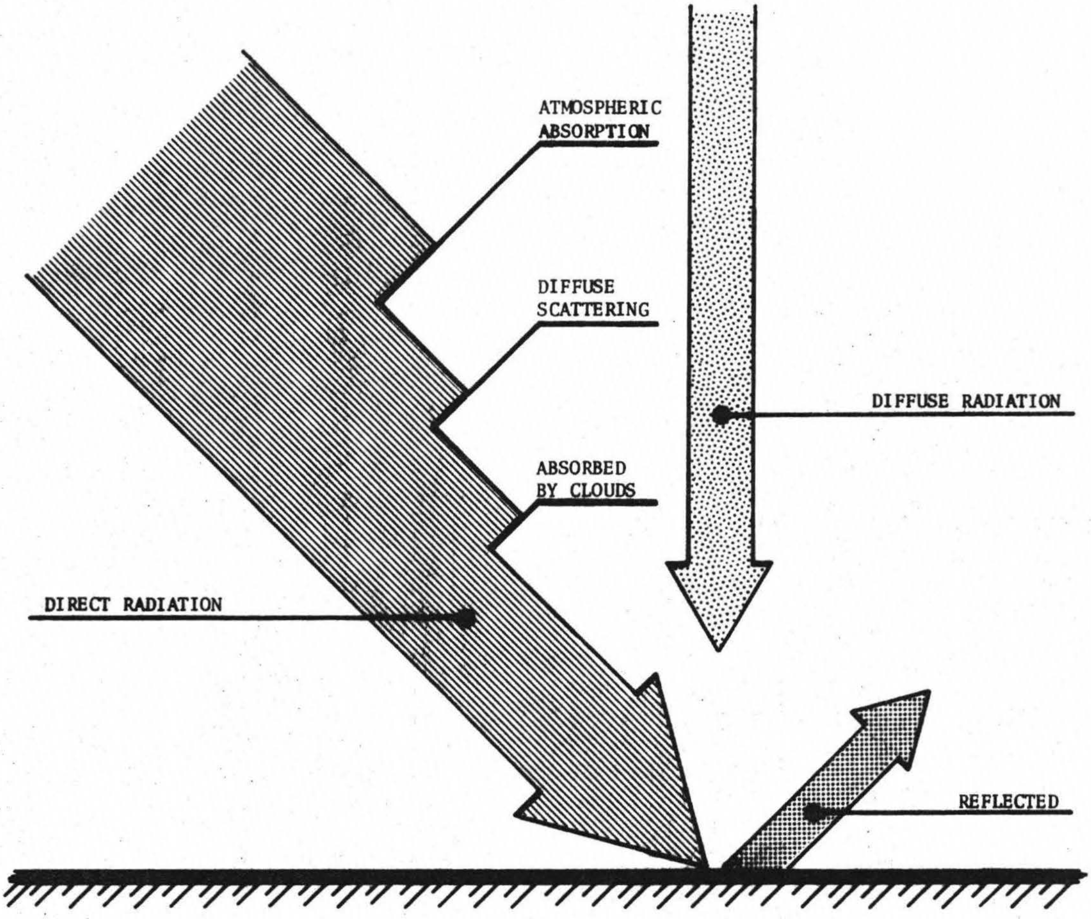

Fig. 3. Distribution of Incoming Radiation.

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(22) Rudolph Geiger, The Climate Near the Ground (Cambridge: Harvard University Press, 1975) p. 346.

can be determined among direct radiation, diffuse radiation, apparent radiation and extinction resulting from air mass, these relationships are generally regarded as theoretical. Insufficient data exists to allow the determination of values of insolation on a totally theoretical basis. It is for this reason that design data for heat transfer calculations is usually based upon empirical forumlae consisting of "statistical summaries of observed radiation."(23)

__Calculation of Cloudy Day Radiation__. Calculation techniques discussed thus far have dealt with only the amount of radiation on horizontal surfaces for cloudless conditions. It is necessary to modify these cloudless conditions by a correction factor to establish conditions for a cloudy sky. Kimura and Stephenson have developed a comprehensive method for modifying the quantity of incident solar radiation with respect to the cloud cover data and cloud type. It is this methodology which has been incorporated into the National of Standards Load Determination (NBSLD) computer program for calculating heating and cooling loads in

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(23) R. J. Cole, "The Longwave Radiative Environment Around Buildings," __Building and Environment__, Vol. 11 (1976) p. 5.

buildings.(24) Although this technique, which was developed from the analysis of Canadian weather data, is probably the most advanced available, the technique is based upon data which is generally not obtainable from the National Weather Service. An alternative method to that developed by Kimura and Stephenson utilizes only the percent possible sunshine (*PPS*), which is available from any weather station. This method, proposed by Sigmund Fritz and based upon earlier work by Angstrom, suggests that a correction factor for radiation on horizontal surfaces can be determined by the equation

$$PPSCORRECT \leftarrow .35 + .61 \times PPS \qquad (EQ.\ 3)$$

where percent possible sunshine (*PPS*) is calculated by the equation

$$PPS \leftarrow (CLOUDLESS \div POSSIBLE) \times 100 \qquad (EQ.\ 4)$$

where; *CLOUDLESS* equals the number of hours of radiation received per day during cloudless conditions; and *POSSIBLE*

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(24) Institute for Applied Technology, NBSLD, The Computer Program for Heating and Cooling Loads in Buildings, (Washington: U. S. Government Printing Office, 1976) p. 15a.

equals the number of hours of radiation which could be received per day. Additional research by D. W. Barnes while at N. C. State University suggests that the coefficients used in the Fritz equation (*EQ.* 3) should equal unity.(25) Based upon these combined research efforts the cloud cover correction factor can be calculated by

$$PPSCORRECT \leftarrow .35 + .65 \times (PPS \div 100)$$

(*EQ.* 5)

As was demonstrated, through the use of cosine correction, insolation is subject to application of vector addition. It is therefore possible to utilize those same principles to determine the isolation upon any surface at any angle from the horizontal and at any orientation.

<u>Angle of Incidence of Solar Beam</u>. In order to determine the amount of insolation impinging upon surfaces other than horizontal it is necessary to determine the azimuth of the sun at the point under consideration. The solar azimuth, defined as the angular distance in the horizontal plane

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(25) Sigmund Fritz, "Average Solar Radiation in the United States," <u>Heating and Ventilating</u>, Vol. 46 (July, 1949) p. 61; see also, Donald W. Barnes, "A Method for Estimating Total Solar Radiation for Average Conditions" (unpublished working paper, North Carolina State University at Raleigh, 1974) p. 2.

between the north-south axis and the location of the sun, in degrees, can be determined by the following equation:

$$\mathit{AZIMUTH} \leftarrow \mathit{ARCSIN}\ (((\mathit{COS}\ \mathit{DECLINATION}) \times \mathit{SIN}\ \mathit{HA}\ ) \div \mathit{COS}\ \mathit{LATITUDE}\ )$$

(*EQ.* 6)

This equation can also be used to determine the angle of attack for vertical surfaces facing due south. For vertical surfaces which have wall azimuths (defined as the angle between the north-south axis and a line normal to the surface of the wall) other than zero degrees it is necessary to determine the location of the surface under consideration relative to the position of the sun. This location, (described by the wall-solar azimuth) equals the angle, in the horizontal plane, between the location of the sun and a line normal to the surface of the wall. (Refer to Fig. 2.) The wall-solar azimuth for walls which have a heading less than 180 degrees can be numerically determined by the equation

$$\mathit{WSAZIMUTH} \leftarrow \mathit{AZIMUTH} + \mathit{WAZIMUTH}$$

(*EQ.* 7*A*)

during the morning hours, and

$$\mathit{WSAZIMUTH} \leftarrow \mathit{AZIMUTH} - \mathit{WAZIMUTH} \qquad (\mathit{EQ}.\ 7\mathit{B})$$

during the afternoon hours, where *WSAZIMUTH* equals the wall-solar azimuth; *AZIMUTH* equals the solar azimuth in degrees, and *WAZIMUTH* equals the wall azimuth in degrees. For walls which have a heading greater than 180 degrees the equations are reversed such that

$$\mathit{WSAZIMUTH} \leftarrow \mathit{AZIMUTH} - \mathit{WAZIMUTH} \qquad (\mathit{EQ}.\ 8\mathit{A})$$

during the morning hours, and

$$\mathit{WSAZIMUTH} \leftarrow \mathit{AZIMUTH} + \mathit{WAZIMUTH} \qquad (\mathit{EQ}.\ 8\mathit{B})$$

during the afternoon hours.(26)

Given the wall-solar azimuth and the solar altitude it is now possible to deterine the angle of incidence from the equation

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(26) *American Society of Heating, Refrigerating and Air Conditioning Engineers, Guide and Data Book, 1972*, p. 393.

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INCIDENT ← ARCCOS ((COS WSAZIMUTH) × COS ALTITUDE)
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(*EQ*. 9)

where,

```
ARCCOS X = (¯2 ○ X) × (180 ÷ ○1)
```

For surfaces which are inclined, *EQ*. 9 must be expanded to include the inclination angle (*SIGMA*) where *SIGMA* is the angle between horizontal and the surface, and expressed in degrees. Therefore, *INCIDENT* may be redefined such that

```
INCIDENT ← ARCCOS (((COS ALTITUDE) × (COS WSAZIMUTH) × (SIN
SIGMA)) + (SIN ALTITUDE) × (COS SIGMA))
```

(*EQ*. 10)

Applying this value to *EQ*. 2, along with a cloud cover correction factor, it is now possible to determine the intensity of direct radiation upon any surface in BTU per hour per square foot (*ALLDIRECT*) from

```
ALLDIRECT ← PPSCORRECT × DIRECT × COS INCIDENT
```

(*EQ*. 11)

This value may be applied to any glazed fenestration, at any angle and orientation, for the determination of solar heat gain attributed to direct radiation through windows.(27)

Diffuse Radiation. Research conducted by Stephenson indicates that diffuse radiation incident upon horizontal surfaces can be deduced from the ratio of total observed radiation from the sky vault to the incident radiation normal to the path of the incident ray. It can also be concluded from Stephenson's research that this ratio (*CRATIO*) is directly proportional to the atmospheric extinction coefficient. This is a result of the proportionality between the scattering of the incident ray to the length of the solar path through the air mass. Based upon Stephenson's findings it is possible to determine the quantity of diffuse radiation falling upon horizontal surfaces (*DIFFUSE*) expressed in BTU per hour per square foot.(28) This may be expressed by

DIFFUSE ← *CRATIO* × *DIRECT*

Research conducted by Threlkeld substantiates Stephenson's findings and advances the premise to include a methodology which can be used to determine the amount of diffuse solar

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(27) D. G. Stephenson, "Equations for Solar Heat Gain Through Windows," Solar Energy, Vol. 9, No. 2 (1965) p. 85.

(28) Ibid, p. 82.

radiation falling upon any surface.(29) Assuming that diffuse radiation is effected equally by a cloudy condition as is direct radiation, a cloud cover correction factor may also be included. Using Threlkeld's equation the diffuse radiation which falls upon any surface can be determined from

$$\mathit{DIFFUSE} \leftarrow \mathit{DIRECT} \times \mathit{CRATIO} \times \mathit{CORRECTION} \times \mathit{PPSCORRECT} \qquad (\mathit{EQ}.\ 12)$$

where,

$$\mathit{CORRECTION} \leftarrow .45$$

when,

$$\mathit{COS\ INCIDENT} < {}^{-}0.02$$

or,

$$\mathit{CORRECTION} \leftarrow (0.55 + 0.437 \times \mathit{COS\ INCIDENT}) + (0.313\ \mathit{COS2\ INCIDENT})$$

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(29) J. L. Threlkeld, "Solar Irradiation of Surfaces on Clear Days," Transactions, American Society of Heating and Air Conditioning Engineers, Vol. 64 (1958) p. 45.

when,

```
COS INCIDENT > ¯0.02
```

and where,

```
COS2 X = (2 ○ X × ○ ÷ 180) * 2
```

A terse *APL* expression for this conditional equation is as follows:

```
DIFFUSE ← DIRECT ×  CRATIO × PPSCORRECT × (( 0.55  + 0.437 ×
COS2 INCIDENT)) 0.45 [ 1 + ¯0.02 ≥ COS INCIDENT ]
                                                      (EQ. 12A)
```

This equation may be applied to any glazed surface, at any angle and orientation, for the determination of solar heat gain attributed to diffuse solar radiation.

<u>Reflected</u> <u>Radiation</u>. Radiation reflected upon glazed surfaces from other buildings, the ground, etc., can account for a sizeable thermal load upon the building, but insufficient data exists to properly analyze this component with respect to building design. For example, the albedo (average percentage reflection) for urban areas ranges from 15 to 25 percent, increasing exponentially for horizontal

surfaces as the elevation of the sun decreases, but the complexities of calculating the effect upon the thermal load of adjacent buildings has not been adequately developed.(30) Presently, most techniques which take into account reflected radiation utilize only an average value for the reflected component which neglects the directional aspect of the radiation. While it may be appropriate to use such techniques for the calculation of radiation at a point on horizontal surfaces (i. e., the ground or roof) this is not well suited for the determination of radiation incident upon vertical surfaces since there is no allowance for the directional component of the radiation from the ground to the window.(31)

The amount of insolation falling upon either inclined or vertical glazed surfaces, as previously stated, is equal to the summation of, 1) the intensity of the solar beam (corrected for its angle of incidence), 2) the amount of diffuse radiation from the sky incident upon the surface, and 3) the reflected radiation from the ground and adjacent surfaces. Therefore, based upon the equations previously described, and neglecting the reflected radiation component,

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(30) Rudolph Geiger, The Climate Near the Ground (Cambridge: Harvard University Press, 1975) pp. 14-17.

(31) P. S. Scanes, "Climatic Design Data for use in Thermal Calculation of Buildings--Estimated Clear Sky Solar Radiation versus Measured Solar Radiation," Building Science, Vol. 9 (1974) p. 221-223.

$$TOTALRADIATION \leftarrow ALLDIRECT + DIFFUSE$$

(*EQ.* 13)

where; *TOTALRADIATION* equals the total radiation falling upon any surface expressed in BTU per hour per square foot.

Principles of Heat Transfer

Heat transfer between thermodynamic systems (a region defined as a point of reference for the analysis of energy flows) may occur through the means of conduction, convection, or radiation.(32) Whatever the means of transfer, thermal energy can neither be created nor destroyed. This "conservation of energy" can be stated algebraically as "(ENERGY IN) - (ENERGY OUT) = (CHANGE IN ENERGY STORED)" and is generally referred to as the first law of thermodynamics.(33)

Conduction. Based upon the first law of thermodynamics, conduction may be defined as the flow of energy in the form of heat aross system boundaries, and is a result of a change in temperature between the two systems as the heat tries to

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(32) J. L. Threlkeld, Thermal Environmental Engineering (Englewood Cliffs: Printice-Hall, 1962) p. 21.

(33) W. C. Reynolds, Energy from Man to Nature (New York: McGraw-Hill, 1974) p. 7.

flow to a cooler region.(34) This flow from hot to cold is an attempt by the energy to achieve a state of entropy, which may be defined as a measure of the kinetic energy within a thermodynamic system distributed such that it is unavailable for conversion into work. Entropy, characterized as a randomness of a thermodynamic system, is inversely proportional to the ability of a thermodynamic system to do useful work. This state of disorder is commonly referred to as the second law of thermodynamics.(35)

Conduction in BTU per hour can be quantified by the "heat-conduction-rate equation," or Fourier's law, and is defined as

$$\mathit{CONDUCTION} \leftarrow (\mathit{CONDUCTIVITY} \times \mathit{AREA} \times (\mathit{TEMP}1 - \mathit{TEMP}2)) \div \mathit{DISTANCE} \qquad (\mathit{EQ}.\ 14)$$

where *CONDUCTIVITY* equals thermal conductivity of the material under consideration expressed in BTU per (hour) (square foot) (degree Fahrenheit), *AREA* equals the area in square feet of the material under investigation normal to

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(34) J. L. Threlkeld, Thermal Environmental Engineering (Englewood Cliffs: Printice-Hall, Inc., 1962) p. 21.

(35) Charles Kittle, Thermal Physics (New York: John H. Wiley & Sons, Inc., 1969) pp. 46-47.

the direction of heat flow, *TEMP*1 − *TEMP*2 equals the difference in degrees Fahrenheit between the surfaces, and; *DISTANCE* equals the distance between the surfaces in feet.(36)

Convection. The transmission of thermal energy can be accomplished via convection through a liquid or a gas. Convective heat transfer occurs by first increasing the internal energy (the summation of the kinetic energy within molecular particles) of the convective medium (referred to as a "working fluid") and then transmitting the change in internal energy through the working fluid via conduction. In this energy transfer the working fluid becomes a "fluid transport of internal energy."

Convective heat transfer (*CONVECTION*) in BTU per hour can be calculated from the following equation:

$$CONVECTION \leftarrow CONVECTIVITY \times AREA \times (TEMP1 - TEMP2) \qquad (EQ.\ 15)$$

where; *CONVECTIVITY* equals the convective heat transfer coefficient expressed in BTU per (hour) (square foot) (degree Fahrenheit), *AREA* equals the cross-sectional area in

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(36) W. C. Reynolds, Energy from Nature to Man, (New York: McGraw-Hill, 1974) p. 77.

square feet of the convective medium (working fluid) normal to the direction of heat flow, and (*TEMP*1 − *TEMP*2) equals the difference in degrees Fahrenheit between points in the convective medium.(37)

<u>Radiation</u>. Radiation is the transfer of thermal energy between two bodies by electromagnetic waves passing through low density gases, liquids or other separating media. This thermal transfer is a result of a temperature differential between the two bodies.(38)

The amount of radiation transmitted from an object in BTU per hour (*RADIATION*) can be determined from the equation

$$RADIATION \leftarrow EMISSIVITY \times SBCONSTANT \times AREA \times (TEMP1*4 - TEMP2*4) \qquad (EQ.\ 16)$$

where *EMISSIVITY* equals the radiative property of the surface per unit of time, (expressed as the ratio of the amount of heat radiated by the material per unit time to the amount of heat radiated by a blackbody (an idealized body which emits the maximum amount of radiation which it can

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(37) Ibid., pp. 77-79.

(38) J. L. Threlkeld, <u>Thermal Environmental Engineering</u> (Englewood Cliffs: Printice-Hall, Inc., 1962) p. 23.

absorb) of equal configuration and surface area per unit of time) *SBCONSTANT* equals the Stephan-Boltzmann constant (based upon the Stephan-Boltzmann Law which states that "the temperature dependence of the radiant energy density equals its absolute temperature raised to the fourth power") and equal to 1.72 E ¯9 BTU per (hour) (square foot) (degree Rankine), *AREA* equals the surface area of the radiative body in square feet, *TEMP*1 equals the temperature of the radiative body in degrees Rankine, and *TEMP*2 equals the temperature of the surround, to which the radiation is emitted, in degrees Rankine.(39)

Heat Transfer Through Glazing

The discussion thus far has described 1) a means for determining incident radiation upon glazing and 2) basic information necessary to understand the thermodynamic principles of heat transfer between materials. With this base of information it is now possible to examine the intricacies specifically associated with heat transfer through glazing.

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(39) Charles Kittle, Thermal Physics (New York: John H. Wiley & Sons, Inc., 1969) p. 258; see also W. C. Reynolds, Energy from Nature to Man (New York: McGraw-Hill, 1974) p. 82.

Solar Heat Gain Through Single Glazing. Whenever direct solar radiation strikes a surface of an glazed opening one portion of the solar beam is reflected by the glass, one portion of the radiation is absorbed by the glass, and still another portion of the radiation is allowed to pass directly through the glass. These properties of the glazing are a result of 1) the composition of the glass, 2) the surface treatment (or finish) of the glass (e. g. vacuum deposition) and 3) the angle of incidence which the solar beam strikes the surface. The solar-optical properties of glass (transmission, absorption, and reflection) are determined for each glass sample by empirical methods using a TRA-Scope (a type of modified pyrheliometer) and the sun at solar noon. Studies using a TRA-Scope have shown that the summation of 1) radiation reflected from the sample, 2) radiation transmitted through the sample, and 3) radiation absorbed by the sample equals the incident solar radiation striking the glass sample. Therefore, the properties of the glass can be described as a ratio of the quantity of radiation reflected, transmitted, or absorbed to the quantity of radiation striking the surface of the glass for a given angle of incidence. Hence, the coefficients of absorption, transmission and reflection must equal unity. Therefore, given the amount of solar radiation which strikes the surface of the glass, (*ALLDIRECT*) and the solar-optical properties of the glass for the given angle of incidence where $\mathit{TRANSMISSIVITY}$ equals the coefficient of transmission; $\mathit{ABSORPTIVITY}$ equals the coefficient of absorption, and $\mathit{REFLECTIVITY}$ equals the coefficient of reflection, then

$$\mathit{REFLECTED} \leftarrow \mathit{REFLECTIVITY} \times \mathit{ALLDIRECT}$$

(*EQ*. 17)

$$\mathit{ABSORBED} \leftarrow \mathit{ABSORPTIVITY} \times \mathit{ALLDIRECT}$$

(*EQ*. 18)

$$\mathit{TRANSMITTED} \leftarrow \mathit{TRANSMISSIVITY} \times \mathit{ALLDIRECT}$$

(*EQ*. 19)

where $\mathit{REFLECTED}$ equals the amount of radiation reflected by the glass in BTU per hour per square foot; $\mathit{ABSORBED}$ equals the amount of radiation absorbed by the glass in BTU per hour per square foot, and $\mathit{TRANSMITTED}$ equals the amount of radiation transmitted through the glass in BTU per hour per square foot. Table 1 provides an indication of the solar-optical properties for generic types of glass where the angle of incidence equals 30 degrees.(40)

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(40) J. I. Yellot, "Calculation of Solar Heat Gain Through Single Glass," Solar Energy, Vol. 7, No. 4 (1963) p. 167.

Table 1. Solar-Optical Properties for Selected Glass Types. (Incident angle equals 30 degrees.)

Glass Type	Transmissivity	Absorptivity	Reflectivity
<u>Clear</u>			
Common glass	0.87	0.05	0.08
Borosilicate Plate	0.86	0.07	0.07
Soda-Lime Plate	0.76	0.19	0.07
<u>Heat-Absorbing</u>			
Gray Plate	0.44	0.51	0.05
Bronze Plate	0.47	0.48	0.05
<u>Selective-Reflecting</u>			
SRG-38:33	0.33	0.53	0.14
SRG-24:28	0.28	0.53	0.19
SRG-35:26	0.26	0.56	0.18
<u>Laminated Reflecting</u>			
"Gold"	0.38	0.34	0.24
"Infra-red"	0.12	0.38	0.50
"Silver"	0.05	0.33	0.63

NOTE: All glass types are nominally 1/4 inch thick. Ratios for Selective-Reflecting glass refer to Visible Transmittance : Solar Transmittance. Values given are for average spectral transmittance between the wavelengths of 0.3 and 2.0 microns.

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(41) Ibid., p. 173.

While the determination of solar radiation reflected by, or transmitted through, glazing is dependent only upon the solar-optical properties of the glazing material, the portion of the absorbed insolation re-radiated to the interior of the building is affected by a number of variables. These variables include, 1) the convective heat transfer coefficient for the inner and outer surfaces of the glass, 2) the heat transfer coefficient of the glass, and 3) the inner and outer temperatures of the glass. This problem is further complicated since the heat from solar radiation absorbed within the glass can also be re-radiated to the exterior environment. Applying the first law of thermodynamics to this system produces the algebraic equation

$$(ALLDIRECT \times ABSORPTIVITY) = ((HEATIN + HEATOUT) + (HEATSTOR2 - HEATSTOR1)) \qquad (EQ.\ 20)$$

where *HEATIN* equals the heat transmitted to the interior by convection and radiation; *HEATOUT* equals the heat transmitted to the exterior by convection and radiation, and (*HEATSTOR2* - *HEATSTOR1*) equals the change in the amount of heat stored within the glass.(Figure 4) Assuming that the condition is steady state, (the heat transfer acts continuously) then the amount of energy stored equals zero.(42)

In order to determine the amount of heat transfered to the building interior by conduction and re-radiation, the interior temperature of the glass surface must first be calculated (refer to equations 15 and 16). Studies conducted by John Yellot of the Solar Energy Laboratory at Arizona State University have shown that the inner temperature of the glass can be determined theoretically by applying the first law of thermodynamics assuming that 1) the heat transfer to the interior is steady state, and 2) there is no temperature differential across the glazing.

Applying these constraints to *EQ*. 20, Yellot concluded that the heat gain contribution by re-radiation and convection resulting from the absorption of direct radiation (*RADCONVECT*) can be determined by the equation

$$RADCONVECT \leftarrow U \times ((ABSORBED \div RADCONOUT) + (TEMPOUT - TEMPIN))$$

(*EQ*. 21)

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(42) J. I. Yellot, "Calculation of Solar Heat Gain Through Single Glass," Solar Energy, Vol. 7, No. 4 (1963) p. 167.

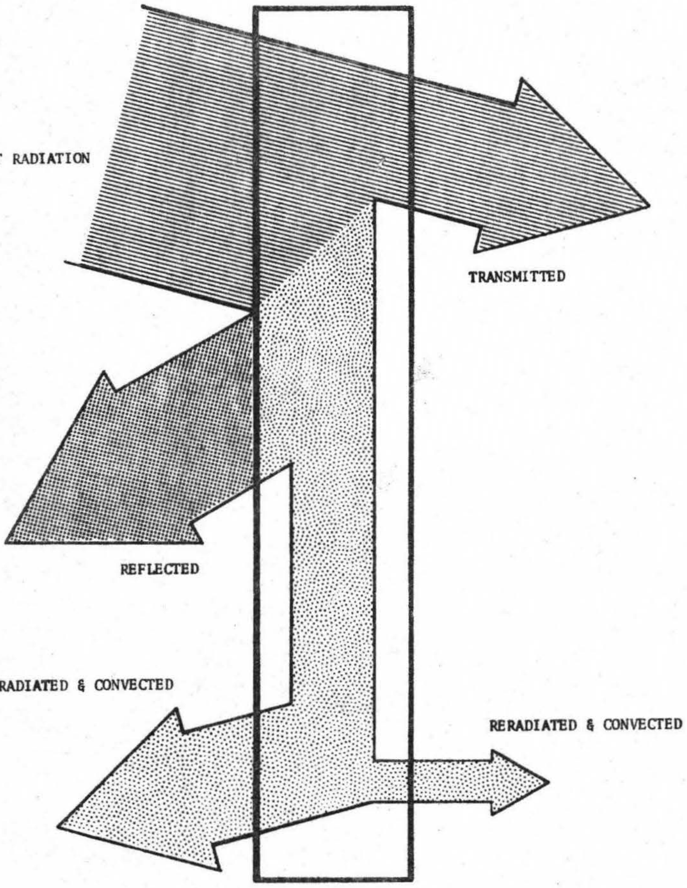

Fig. 4. Single Glass Heat Balance.

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(43) J. R. Waters, "Solar Heat Gain Through Unshaded Glass," <u>Sunlight in Buildings</u>, R. G. Hopkinson (Rotterdam: Bouwcentrum International, 1967) p. 170.

where; *RADCONOUT* is the combined coefficient of radiative and convective heat transfer for the surface of the glass expressed in BTU per (hour) (degree Fahrenheit); *TEMPOUT* equals the temperature, in degrees Fahrenheit, of the exterior environment; *TEMPIN* equals the air temperature, in degrees Fahrenheit, of the interior environment; and *U* equals the combined heat transfer coefficient for the glass and air films, expressed in BTU per degree Fahrenheit. Before *EQ*. 21 can be calculated, a number of intermediate values must be either selected from tables, or calculated from other equations. Specifically, the values to be ascertained consist of the following: 1) the combined coefficient of radiative and convective heat transfer of the glass (*RADCONOUT*); 2) the average temperature of the glass in degrees Fahrenheit (*MEANGLASSTEMP*); 3) the emissivity of the glass (*EMISSIVITY*); 4) the combined coefficient of radiative and convective heat transfer for the inner surface of the glass expressed in BTU per (hour) (degree Fahrenheit); and 5) the combined heat transfer coefficient for the glass and air films (*U*).

RADCONOUT, the combined coefficient of heat transfer for the outer surface of the glass, is based upon equations for forced convection and equations for radiation to a "black" environment. *RADCONOUT* is a function of the outside air film's thermal resistance, which in turn is a result of the wind speed blowing across the glass.

RADCONOUT is generally not affected by the orientation of building in relation to the direction of the wind. The value generally accepted for heat gain calculation for buildings is equal to 4.0 BTU per degree Fahrenheit. This value is acceptable for wind speeds from 4 to 8 miles per hour.

The average temperature of glass, in degrees Fahrenheit (*MEANGLASSTEMP*), can be calculated by the equation

$$\mathit{MEANGLASSTEMP} \leftarrow ((\mathit{TEMPIN} + \mathit{TEMPOUT}) + (\mathit{EMISSIVITY} \times \mathit{ALLDIRECT}) \div \mathit{RADCONOUT}) \div 2$$

(*EQ.* 21.1)

where, *EMISSIVITY* is equal to the absorptivity of the glass. This phenomenon is generally referred to as Kirchoff's Law.

RADCONIN is the combined coefficient of heat transfer for the inner surface of the glass expressed in BTU per (hour) (degree Fahrenheit). *RADCONIN* is calculated by the equation

$$\mathit{RADCONIN} \leftarrow (0.27 \times ((\mathit{MEANGLASSTEMP} - \mathit{TEMPIN}) * 0.25)) + (\mathit{EMISSIVITY} \times (((0.17123 \times (((460 + \mathit{MEANGLASSTEMP}) \div 100) * 4)) - (0.17123 \times (((460 + \mathit{TEMPIN}) \div 100) * 4))) \div (\mathit{MEANGLASSTEMP} - \mathit{TEMPIN})))$$

(*EQ.* 21.2)

where the expression used to produce the terms

$$0.17123 \times (((460 + TEMPIN) \div 100) * 4)$$

and,

$$0.17123 \times (((460 + TEMPIN) \div 100) * 4)$$

is the Stephan-Boltzmann equation to determine the radiative power of a blackbody.

U equals the combined heat transfer coefficient of the glass and air films expressed in BTU per degree Fahrenheit. Since the thermal resistance offered by the glass is negligible (in comparison to the inner and outer air surface films) *U* is calculated by the equation

$$U \leftarrow (RADCONIN \times RADCONOUT) \div (RADCONIN + RADCONOUT)$$

(*EQ.* 21.3)

By first calculating these intermediate values it is possible to determine the heat gain comtribution by re-radiation and convection resulting from the absorption of direction radiation (*RADCONVECT*) from *EQ.* 21.(44) Therefore,

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(44) J. I. Yellot, "Calculation of Solar Heat Gain Through Single Glass," Solar Energy, Vol. 7, No. 4 (1963) p. 170.

given the amount of heat transfer resulting from the thermal absorptivity of the glass (convection and re-radiation) the total rate of heat transfer from direct radiation passing through single glazing can be determined from

$$\mathit{DIRECTGAIN} \leftarrow \mathit{TRANSMITTED} + \mathit{RADCONVECT}$$

(*EQ.* 22)

Additional research by Yellot has shown that the heat gain contribution by re-radiation and convection of absorbed diffuse radiation ($\mathit{DIFRADCON}$) can be determined by using *EQ.* 21, with the exception that $\mathit{ABSORBED}$ has been replaced by the constant $\mathit{DIFABSORB}$, which is equal to

$$\mathit{DIFABSORB} \leftarrow \mathit{ABSORPTIVITY60} \times \mathit{DIFFUSE}$$

(*EQ.* 23)

where $\mathit{ABSORBTIVITY60}$ equals the coefficient of absorption for glass when the angle of incidence is equal to sixty degrees. Substituting $\mathit{DIFABSORB}$ for $\mathit{ABSORBED}$ in *EQ.* 21 the following equation is obtained:

$$\mathit{DIFRADCON} \leftarrow U \times ((\mathit{DIFABSORB} \div \mathit{RADCONOUT}) + (\mathit{TEMPOUT} - \mathit{TEMPIN}))$$

(*EQ.* 24)

Combining the thermal contribution by diffuse radiation (*DIFRADCON*) to *EQ.* 22 provides

$$TOTALGAIN \leftarrow DIRECTGAIN + DIFRADCON \qquad (EQ.\ 25)$$

where *TOTALGAIN* is equal to the total heat gain through single glazing from diffuse and direct radiation components and expressed in BTU per square foot of glass.(45)

<u>Solar Heat Gain Through Double Glazing</u>. The process for calculating solar heat gain through double glazing is similiar to that used for single glazing, with the exception that it is necessary to determine the rate of heat transfer by convection and radiation across the air space separating the two planes of glass.(46) (Figure 5)

<u>Air space heat transfer coefficients</u>. The rate of heat flow by convection and radiation across an air space is dependent upon 1) the temperature difference across the air space (which in turn is dependent upon the surrounding air

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(45) Ibid., p. 168.

(46) J. R. Waters, "Solar Heat Gain Through Unshaded Glass," <u>Sunlight in Buildings</u>, R. G. Hopkinson (Rotterdam: Boucentrum International, 1967) p. 173.

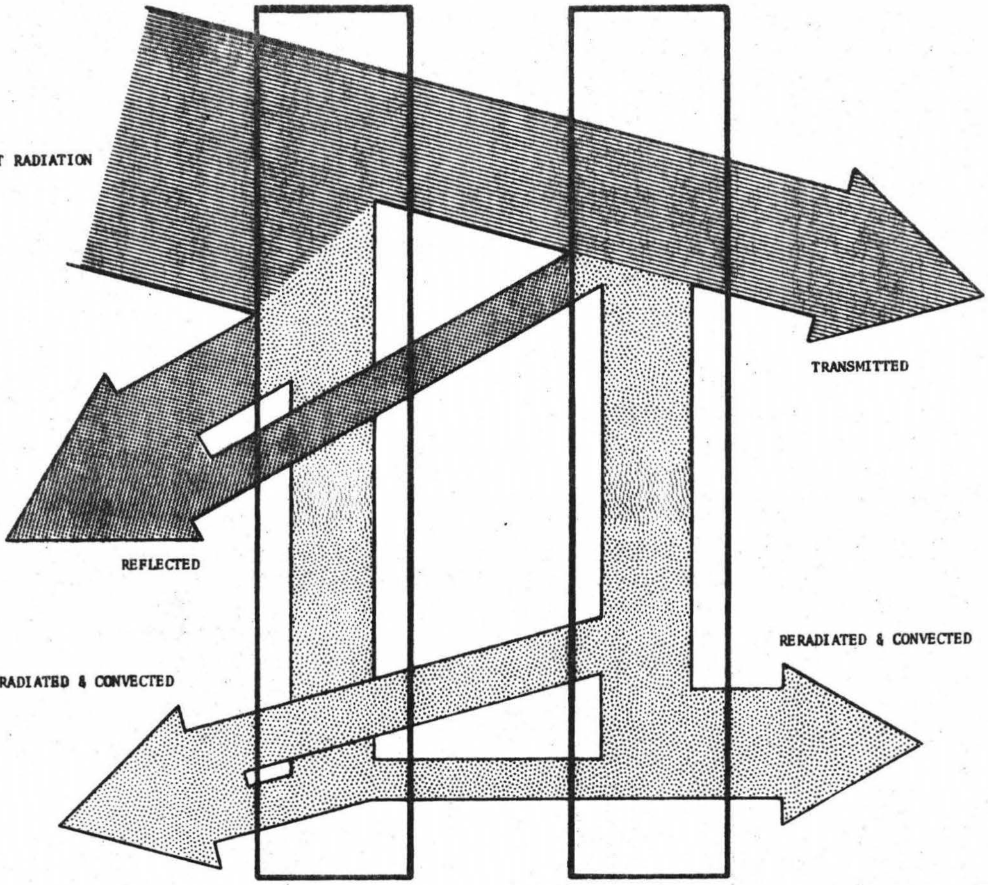

Fig. 5. Double Glass Heat Balance.

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(47) Ibid.

temperatures), 2) the convective heat transfer coefficient of the inner surfaces facing the enclosed building space, and 3) the emissivities of the surfaces facing the air space. (Refer to equations 15 and 16.)(48) The combined heat transfer coefficient for convection and radiation between glazed surfaces (*INTERCONSTANT*) is given in Table 2. It is important to note that these values apply only for double glazed units which have a reflective coating. For insulating glass without a reflective coating the value of *INTERCONSTANT* equals 1.3 BTU per (hour) (square foot) (degree Fahrenheit).

In order to utlize Table 2 it is first necessary to calculate the mean air space temperature for double glazing, the air temperature difference and the effective emissivity for the airspace. The mean air space temperature in degrees Fahrenheit (*MEANGLASSTEMP*) is determined by the equation

$$\mathit{MEANGLASSTEMP} \leftarrow (\mathit{TEMPIN} + \mathit{TEMPOUT} + (\mathit{ABSORPTIVITY} \times \mathit{ALLDIRECT}) \div \mathit{RADCONOUT}) \div 2 \qquad (\mathit{EQ}.\ 26)$$

The temperature difference of the surrounding air in degrees

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(48) F. W. Hutchinson, "Convective Resistances of Air Spaces Located in Walls, Floor, or Ceiling," Air Conditioning, Heating, and Ventilating, (February, 1963) p. 57.

Fahrenheit (*TEMPDIFF*) is calculated by

$$\mathit{TEMPDIFF} \leftarrow \mathit{TEMPOUT} - \mathit{TEMPIN} \qquad (\mathit{EQ}.\ 27)$$

As in the case for single glazing these equations apply only when the temperature gradient across each plane of glass composing the double glass assembly equals zero.(49) The combined effective emissivity for the air space (*EEMISSIVITY*) is calculated by using the equation

$$\mathit{EEMISSIVITY} \leftarrow \div\ ((\ \div\ \mathit{EMIS}2)\ +\ \div\ \mathit{EMIS}1)\ -1 \qquad (\mathit{EQ}.\ 28)$$

where *EMIS*1 and *EMIS*2 are the emissivities for the inner and outer surfaces facing the air space.(50) Since Kirchoff's Law states that the emissivity of a glass surface is equal to its absorptivity, *EQ*. 28 may be altered such that

$$\mathit{EEMISSIVITY} \leftarrow \div\ ((\ \div\ \mathit{ABSORPTIVITY})\ +\ (\div\ \mathit{ABSORPTIVITY}2)\ -\ 1) \qquad (\mathit{EQ}.\ 29)$$

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(49) J. I. Yellot, "Calculation of Solar Heat Gain Through Single Glass," Solar Energy, Vol. 7, No. 4 (1963) p. 170.

(50) American Society of Heating, Refrigerating and Air Conditioning Engineers, Guide and Data Book, 1972, p. 396.

where *ABSORBTIVITY* and *ABSORBTIVITY2* are values obtained from Table 1 for the absorption coefficients for the two air space surfaces.(51) Using these values for the mean air space temperature, the air temperature difference, and the effective emissivity of the air space, the proper coefficient of heat transfer for the appropriate air space thickness can be selected from Table 2.

Heat transfer rate calculations. As direct radiation strikes a double glazed surface the transmission of heat through the first layer of glass is identical to the heat transfer calculated for a single piece of glass. Therefore, it is only necessary to expand equations 21 and 22 to account for the effect of the second layer of glass and the air space contained by the double glass assembly upon the heat flow through the first layer of glazing. If the inner layer of glass is isolated as a thermodynamic system, its inward heat flows consists of 1) the radiation transmitted through the outer layer of glass and, 2) the re-radiated portion of the absorbed thermal component of the outer layer of glass. This re-radiated component is in turn modified by a) the combined heat transfer component across the air space (*INTERCONSTANT*), b) the external coefficient of convective

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(51) J. L. Threlkeld, Thermal Environmental Engineering (Englewood Heights: Printice-Hall, Inc., 1962) p. 25.

Table 2. Air Space Heat Transfer Coefficients (*INTERCONSTANT*) expressed in BTU per (hour) (square foot) (degree Fahrenheit).

Air Space Thickness Equals 0.500 inches.

Mean Air Space Temperature Degrees F.	Air Temp. Diff. F deg.	Effective Emissivity (*EEMISIVITY*)				
		0.050	0.100	0.200	0.400	0.820
10	30	0.409	0.444	0.516	0.658	0.957
	50	0.430	0.465	0.536	0.679	0.979
	70	0.449	0.484	0.556	0.699	0.999
	90	0.467	0.503	0.574	0.717	1.019
30	30	0.422	0.462	0.543	0.704	1.043
	50	0.440	0.480	0.561	0.723	1.062
	70	0.457	0.498	0.579	0.741	1.081
	90	0.473	0.514	0.595	0.758	1.099
50	30	0.435	0.481	0.572	0.754	1.136
	50	0.451	0.497	0.588	0.770	1.153
	70	0.467	0.512	0.603	0.786	1.169
	90	0.481	0.527	0.618	0.801	1.186
90	30	0.467	0.524	0.628	0.866	1.345
	50	0.479	0.536	0.650	0.879	1.358
	70	0.491	0.548	0.663	0.891	1.372
	90	0.503	0.560	0.675	0.904	1.386
110	30	0.486	0.549	0.676	0.930	1.463
	50	0.496	0.560	0.687	0.941	1.475
	70	0.507	0.571	0.698	0.953	1.487
	90	0.517	0.581	0.709	0.964	1.500

Table 2. (continued) Air Space Heat Transfer Coefficients (*INTERCONSTANT*) expressed in BTU per (hour) (square foot) (degree Fahrenheit).

<u>Air Space Thickness equals 0.375 inches</u>.

Mean Air Space Temperature Degrees F.	Air Temp. Diff. F deg.	Effective Emissivity (*EEMISIVITY*)				
		0.050	0.100	0.200	0.400	0.820
10	30	0.508	0.544	0.615	0.757	1.056
	50	0.520	0.556	0.627	0.770	1.069
	70	0.533	0.568	0.640	0.783	1.083
	90	0.545	0.581	0.652	0.796	1.097
30	30	0.528	0.568	0.649	0.810	1.149
	50	0.538	0.578	0.659	0.821	1.160
	70	0.549	0.598	0.670	0.832	1.172
	90	0.559	0.600	0.681	0.844	1.185
50	30	0.548	0.594	0.685	0.866	1.248
	50	0.556	0.602	0.693	0.875	1.257
	70	0.565	0.611	0.702	0.855	1.268
	90	0.574	0.620	0.712	0.895	1.279
90	30	0.592	0.649	0.763	0.991	1.470
	50	0.597	0.654	0.768	0.997	1.476
	70	0.603	0.661	0.775	1.004	1.484
	90	0.610	0.668	0.782	1.012	1.494
110	30	0.618	0.681	0.808	1.062	1.595
	50	0.621	0.685	0.812	1.066	1.600
	70	0.627	0.690	0.817	1.072	1.607
	90	0.632	0.696	0.824	1.079	1.615

Table 2. (continued) Air Space Heat Transfer Coefficients (*INTERCONSTANT*) expressed in BTU per (hour) (square foot) (degree Fahrenheit).

<u>Air Space Thickness equals 0.250 inches.</u>

Mean Air Space Temperature Degrees F.	Air Temp. Diff. F deg.	Effective Emissivity (*EEMISIVITY*)				
		0.050	0.100	0.200	0.400	0.820
10	10	0.731	0.767	0.838	0.980	1.279
	50	0.733	0.769	0.840	0.983	1.282
	90	0.742	0.778	0.850	0.993	1.294
30	10	0.762	0.802	0.883	1.044	1.383
	50	0.784	0.804	0.885	1.047	1.386
	90	0.770	0.811	0.892	1.054	1.396
50	10	0.791	0.836	0.927	1.109	1.491
	50	0.794	0.839	0.931	1.113	1.495
	90	0.798	0.844	0.935	1.119	1.503
90	10	0.849	0.904	1.020	1.248	1.727
	50	0.858	0.915	1.029	1.257	1.737
	90	0.859	0.917	1.031	1.261	1.742
110	10	0.881	0.945	1.072	1.325	1.858
	50	0.894	0.958	1.085	1.339	1.873
	90	0.895	0.959	1.086	1.341	1.878

Table 2. (continued) Air Space Heat Transfer Coefficients (*INTERCONSTANT*) expressed in BTU per (hour) (square foot) (degree Fahrenheit).

Air Space Thickness equals 0.188 inches.

Mean Air Space Temperature Degrees F.	Air Temp. Diff. F deg.	Effective Emissivity (*EEMISIVITY*)				
		0.050	0.100	0.200	0.400	0.820
10	10	0.948	0.984	1.005	1.197	1.146
	50	0.961	0.997	1.068	1.211	1.510
	90	0.962	0.998	1.069	1.213	1.514
30	10	0.982	1.022	1.103	1.264	1.602
	50	1.002	1.042	1.123	1.285	1.624
	90	1.002	1.042	1.124	1.286	1.627
50	10	1.012	1.057	1.148	1.330	1.712
	50	1.041	1.087	1.178	1.360	1.742
	90	1.041	1.087	1.178	1.361	1.746
90	10	1.070	1.127	1.241	1.469	1.948
	50	1.122	1.179	1.293	1.522	2.001
	90	1.123	1.180	1.295	1.524	2.006
110	10	1.101	1.165	1.292	1.545	2.078
	50	1.167	1.230	1.358	1.612	2.146
	90	1.169	1.233	1.360	1.616	2.152

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(52) American Society of Heating, Refrigerating and Air Conditioning Engineers, Guide and Data Book, 1972, p. 396.

and radiative heat transfer, and c) the heat transfer coefficient (U value) for the inner layer of glass. Combining these factors with the result of the re-radiation of the outer layer of glass produces the following equation for determining the rate of convective heat transfer through double glazing ($\mathit{RADCONVECT2}$):

$$\mathit{RADCONVECT2} \leftarrow \mathit{RADCONVECT} + U \times \mathit{ABSORPTIVITY2} \times \mathit{TRANSMISSIVITY} \times (\div \mathit{RADCONOUT}) + \mathit{INTERCONSTANT} \qquad (\mathit{EQ}.\ 30)$$

where $\mathit{ABSORPTIVITY2}$ is the coefficient of absorption for the inner layer of glass, and $\mathit{TRANSMISSIVITY}$ is the coefficient of transmission for the outer layer of glass. Assuming that the outer and inner layers of glass are identical *EQ*. 30 can be stated as

$$\mathit{RADCONVECT2} \leftarrow U \times (\mathit{ABSORPTIVITY} \times \mathit{ALLDIRECT} \div \mathit{RADCONOUT}) + ((\mathit{ABSORPTIVITY2} \times \mathit{TRANSMISSIVITY} \times \mathit{ALLDIRECT}) \times ((\div \mathit{RADCONOUT}) + \div \mathit{INTERCONSTANT})) + (\mathit{TEMPOUT} - \mathit{TEMPIN}) \qquad (\mathit{EQ}.\ 31)$$

Heat gain from direct transmission through double glazing is dependent upon the transmissivities of both layers of glass as the outer layer acts as a filter decreasing the amount of radiation impinging upon the inner layer of glass. The solar heat gain contribution by direct transmission through double glazing (*DIRECT2*) is given by the equation

$$DIRECT2 \leftarrow ALLDIRECT \times TRANSMISSIVITY \times TRANSMISSIVITY2$$

(*EQ.* 32)

where *TRANSMISSIVITY* and *TRANSMISSIVITY2* are the coefficients of transmission for the outer and inner layers of glass, respectively.(53) Based upon equations 31 and 32, the total heat transfer from direct radiation through double glazing (*DIRECTGAIN2*) in BTU per (hour) (square foot) is given by the equation

$$DIRECTGAIN2 \leftarrow DIRECT2 + RADCONVECT2$$

(*EQ.* 33)

The preceding material has described a number of similiarities between the calculation techniques for the determination of the direct solar heat gain component for single and double glazing.

If an equitable comparison of thermal performance is to be made of single glazing relative to double glazing (one objective of this paper), it is important to compare only

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(53) Ibid., p. 395.

thermal qualities which can be determined for both conditions. Hence, comparison of thermal performance between alternative glazing types is limited only to direct radiation. However, there is no basis for the assumption that the diffuse solar heat gain component for double glazing can be calculated in a similiar manner to that used for single glazing. Research conducted thus far has failed to provide a satisfactory technique for calculating the diffuse solar heat gain component through double glazing.

Solar Control Devices.

A great amount of research has been conducted in an effort to determine the effect of external shading devices upon windows and window systems. The inclusion of a discussion of their calculated effect is beyond the scope of this paper, (limited to a selection methodology for alternative glazing types). However, a discussion of shading devices included within the glazing itself is appropriate and necessary.

Considerable research has been undertaken in the Soviet Union to determine the effects of a shading device placed between the layers of double glazing. In this research, Ershov, Gul'karov, and Tsipenyuk, have attempted to establish the heat flow rate for a window assembly containing an internal shading device by mathematical modeling based upon the first law of thermodynamics. Unlike research conducted by individuals such as Stephenson, Barnes, or Yellot, the research by Ersov, et. al. is yet to be substantiated by empirical study. For this reason, the methodlogy developed by this Soviet team of researchers must be viewed as a yet untested methodology.(54)

Chapter 2 has sought to provide a background of information on the determinants and modifiers of solar radiation, and the calculation techniques necessary to determine the rate of heat transfer through alternative types of window glazing. With this information it is possible to determine the heat load contribution by alternative types of windows upon the interior building environment.

It is possible, therefore, to determine the rate of heat transfer through alternative window glazing. The value of this process to the designer is to provide a basis for the evaluation of alternative glazing materials which will make possible 1) energy conservative building design, and 2) reduced building operating costs which can be evaluated over the anticipated life of the building.

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(54) A. V. Ershov, "Calculation of Heat Transfer by Convection and Long-Wave Thermal Radiation from a Window with a Screen-Type Sunshield," Gelioteckhnika, Vol. 7, No. 2 (1971) p. 57.

Chapter III

LIFE-CYCLE COSTING

Economic analyscan be is a very powerful design tool because 1) it provides an objective basis for the evaluation of alternative design solutions, 2) allows unlike items to be compared, and 3) provides a common set of units for otherwise irreconcilable units, such as degrees Fahrenheit, decibels, and footlamberts.(55) In economic analysis only one goal exists--cost optimization. Applied to the design process this usually consists of developing a number of alternative design solutions and applying the "life-cycle cost concept."

Life-cycle cost analysis is a technique which considers all relevant costs over the life of each alternative design. This is accomplished by performing the following steps: 1) Identify relavant cost items for each alternative. Such items may include the initial cost, annual maintenance costs, replacement costs (as in the case of building subsystems), running costs (heating, lighting, taxes, and insurance) and the salvage value for each alternative. 2)

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(55) Peter Manning, "Lighting in Relation to Other Components of the Total Environment," _Transactions of the Illuminating Engineering Society of Great Britain_, No. 3 (1968) p. 159.

Forecast the amount of each of these costs and when they will occur during the expected life of each design solution. 3) Discount (or amortize) these costs to their present value.(56)

Discounting of these cash flows is accomplished through the use of interest rate factors in accordance with the investor's opportunity rate, where the opportunity rate is equal to the percentage which an individual, corporation, or other enterprise will accept as the lowest rate of return on an investment. (This is not to be confused with the interest rate which is charged a borrower. When utilizing life-cycle cost techniques, the cost for borrowing money, as it is in the case of depreciation, is charged as an annual cost.) The opportunity rate for larger corporations is generally 10% or greater since the firm can invest in federal bonds, which is a low-risk investment paying ten percent interest; hence the minimum opportunity rate might be considered as 10%. The firm has the option to invest in itself (in the form of capital expansion or increased operating capital), or to invest outside the corporation through the purchase of stocks or bonds in other

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(56) A. J. Dell'Isola, "Inside Value Engineering: An Expert's View," Actual Specifying Engineer (April 1973) p. 82, see also, Rosalie T. Ruegg, Solar Heating and Cooling in Buildings: Methods of Economic Evaluation, Institute for Applied Technology, NBS Report No. NBSIR 75-712 (July 1975) p. 4.

organizations. Either of which may provide an investment rate higher than 10%.(57) 4) Now compare the various alternative designs based on their life-cycle cost.

Four basic concepts remain paramount whenever an economic analysis, and particularly a life-cycle cost analysis is undertaken:

1) Any economic analysis used to compare or contrast design alternatives is a relative analysis. To avoid the misleading tendency of building clients to think only in terms of real or immediate dollar values, LCC provides an opportunity for comparison of alternative design solutions on an economic basis. However, the bases used for this comparison cannot be considered as absolute--over a period of yeats the parameters may change. The comparative figures are only simulations used to provide some immediate indicators.(58)

2) In the development of any life-cycle cost analysis only those quantities which are not common to alternative designs need to be included in the model. Since the models are evaluated for their relative ultimate cost differences, constants may be omitted. For example, if two alternatives

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(57) J. W. Griffith, and B. J. Keely, Life-Cycle Cost-Benefit Analysis (K-G Associates, 1976) p. 1B-8.

(58) D. P. Hayworth, "The Principles of Life-Cycle Costing," Industrialization Forum, Vol. 6, No. 3-4 (1975) p. 14.

are to be compared in which a) the maintenance costs for the two alternatives (on an annual basis) would be identical and b) the life-cycles for the two alternatives are of equal duration, then maintenance costs need not be made a factor to be included in the economic model.(59)

3) The life-cycle cost process must be utilized in a consistent manner for all alternatives analyzed. Each alternative must consist of the same variables to be analyzed--only the values may change. For example--if the annual maintenance costs for one alternatives is known, but there is insufficient information available on the annual maintenance costs for the other, then it is not accurate to include the known maintenance costs for the one alternative and omit any maintenance costs for the other.(60)

4) In developing life-cycle cost models, inflation is generally not included as a factor. The decision to ignore inflation is based upon the assumption that as the buying power of a dollar decreases over time, there will also be more dollars on hand with which to make purchases. (This can be likened to an annual wage increase to compensate for the annual increase in the cost of living.) While this

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(59) J. W. Griffith, and B. J. Keely, Life-Cycle Cost-Benefit Analysis (K-G Associates, 1976) p. 1B-5.

(60) D. P. Hayworth, "The Principles of Life-Cycle Costing," Industrialization Forum, Vol. 6, No. 3-4 (1975) p. 14.

assumption about inflation has not proven to be entirely true, life-cycle cost models based upon this assumption are satisfactory for relative cost analyses.(61)

Compound Interest Factors

In the development of mathematical models to represent anticipated cash flow over a given period of time (or over the life of a design alternative) it is necessary to use one or more of six basic interest rate formulas to evaluate these costs. These interest rate formulas are used to calculate compound interest factors, which when multiplied by a sum (or sums) of money will act to move the value of that sum backward or forward in time. This conversion of worth is performed so that alternative cash flow systems may be compared with other cost alternatives on an equivalent basis. These six compound interest factors (and their corresponding interest rate formulas to be discussed in this section) consist of the following: 1) single compound amount factor (*SCA*), 2) single present worth factor (*SPW*), 3) uniform compound amount factor (*UCA*), 4) uniform sinking fund factor (*USF*), 5) uniform capital recovery factor (*UCR*), and 6) uniform present worth factor (*UPW*). Graphic examples of the use of these compound interest

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(61) J. W. Griffith, and B. J. Keely, Life-Cycle Cost-Benefit Analysis (K-G Associates, 1976) p. 18-8.

factors and their use is illustrated in figure 6.(62) In addition, the following notation will be used throughout this chapter: *OPRATE* equals the interest rate per period earned from holding an asset; *PRESENT* equals the present value in dollars of an asset; *FUTURE* equals the future, or terminal value of an asset in dollars; *YEARS* equals the number of time periods for which the investment lasts, and *ANNUAL* equals the value of an annuity (series of equal annual payments).

Single Compound Amount Factor. The single compound amount factor (*SCA*) is used to convert the single present value of an asset in dollars (*PRESENT*) to the future worth (*FUTURE*) when given the number of years into the future the value is to be determined, and the annual opportunity rate of the investor. The interest rate formula used to perform this operation is derived as follows. (Although interest periods could be more frequent than annual, as in the case of continuous compounding, the relative difference between annual and continuous compounding is so small that for most practical applications annual compounding can be used.)

If a sum of money (*PRESENT*) is invested at a given

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(62) Paul T. Norton, Handbook of Industrial Engineering and Management, ed. W. G. Ireson and E. L. Grant (Englewood Cliffs: Printice-Hall Inc., 1971) p. 127.

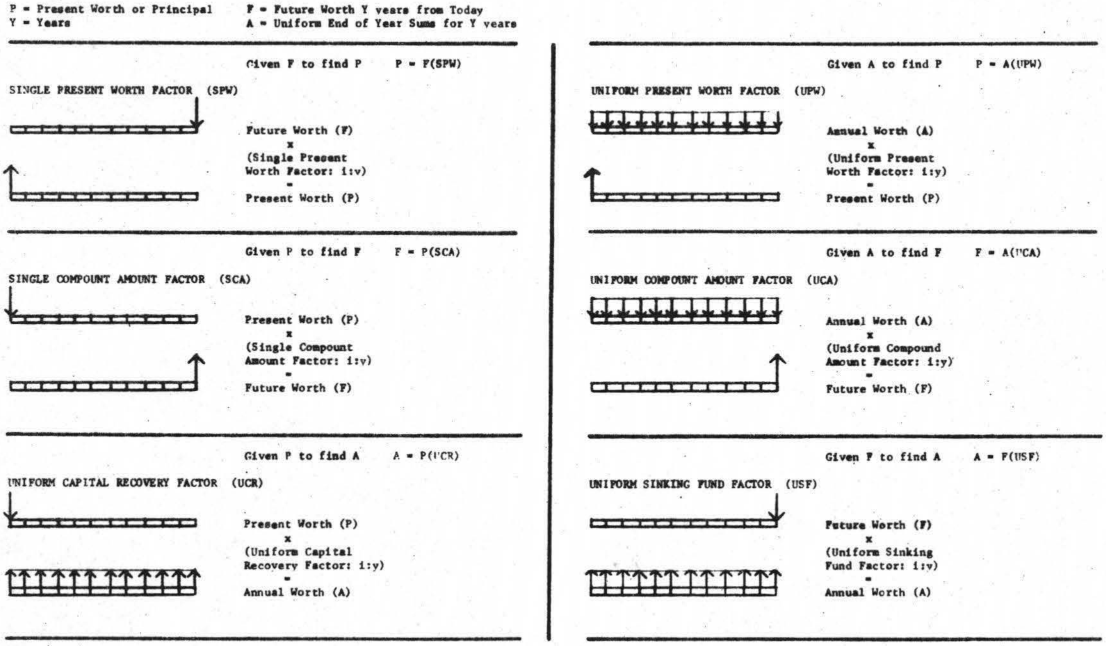

Fig. 6. Graphic Examples of Compound Interest Factors.

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(63) J. W. Griffith, and B. J. Keely, <u>Life-Cycle Cost-Benefit Analysis</u> (K-G Associates, 1976) p. ii.

opportunity rate per annum (*OPRATE*), then the amount of money earned from the simple interest one year (*YEARS*) hence is equal to

$$PRESENT \times OPRATE \times YEARS$$

and the total asset is equal to

$$PRESENT + (PRESENT \times OPRATE \times YEARS)$$

Since the opportunity rate is calculated on a per annum basis this equation may be re-arranged to become

$$PRESENT \times (1 + OPRATE)$$

If this sum of money is maintained in the same investment for an additional interest period, then the total asset at the end of the second interest period (since the interest earned on the previous period has been compounded) is equal to

$$PRESENT \times (1 + OPRATE) \times (1 + OPRATE)$$

which can be re-arranged as

$$PRESENT \times (1 + OPRATE) * 2$$

Likewise, the total amount of money controlled at the end of the third interest period is

$$\mathit{PRESENT} \times (1 + \mathit{OPRATE}) \times (1 + \mathit{OPRATE}) \times (1 + \mathit{OPRATE})$$

which can be re-arranged as

$$\mathit{PRESENT} \times (1 + \mathit{OPRATE}) * 3$$

If the number of periods generated is replaced by the term *YEARS*, then the generalized form of the equation used to determine the total sum of money at the end of *YEARS* interest periods, and at a given opportunity rate, (*FUTURE*) is

$$\mathit{FUTURE} \leftarrow \mathit{PRESENT} \times (1 + \mathit{OPRATE}) * \mathit{YEARS}$$

(*EQ*. 33)

The term $(1 + \mathit{OPRATE}) * \mathit{YEARS}$ is commonly referred to as the single compound amount factor (*SCA*) such that

$$\mathit{SCA} \leftarrow (1 + \mathit{OPRATE}) * \mathit{YEARS}$$

(*EQ*. 34)

and,

FUTURE ← *PRESENT* × *SCA*

(*EQ*. 35)

where, *SCA* is the single compound amount factor for the opportunity rate and interest periods under investigation.(64) Henceforth, the following notation will be used to express information regarding opportunity rate and number of interest periods:

YEARS SCA OPRATE

Compound interest factors will therefore be treated as dyadic functions. (Refer to Appendix A for a discussion of dyadic functions.) Equation 35 can be restated as

FUTURE ← *PRESENT* × (*YEARS SCA INTEREST*)

(*EQ*. 36)

Single Present Worth Factor. The single present worth factor (*SPW*) is used to determine the present worth of a single future value. This function, therefore, is used to perform the converse operation of the single compound amount

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(64) Roy Pilcher, Principles of Construction Management (Maidenhead: McGraw-Hill Book Co., Ltd., 1976) pp. 20-21.

factor. As such, the equation used to determine the single present worth factor is the reciprocal of the interest rate formula used to determine the single compound amount factor. The single present worth factor (*SPW*) is given by the following equation:

$$SPW \leftarrow \div\ (1 + OPRATE)\ YEARS \qquad (EQ.\ 37)$$

such that,

$$PRESENT \leftarrow FUTURE \times (YEARS\ SPW\ OPRATE) \qquad (EQ.\ 38)$$

Through the use of *EQ.* 38 the sum of money *FUTURE* is amoritized to its equivalent value at an earlier date.(65)

Uniform Compound Amount Factor. The uniform compound amount factor (*UCA*) is used to determine the future worth of an annuity (a series of equal payments, each of which is made at the end of equal periods). For the purposes of most life-cycle cost models, as stated earlier, this results in a

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(65) J. C. Francis, *Investments: Analysis and Management* (New York: McGraw-Hill Book Co., 1972) p. 225.

series of uniform annual payments (ANNUAL) over YEARS years and with an opportunity rate of OPRATE. The derivation of the formula necessary to calculate this future worth consists of the following:

The first payment of an annuity will receive no interest for the first year since it is made at the end of the first interest period. It will, however, earn in successive years

$$\mathit{ANNUAL} \times \mathit{OPRATE} \times (\mathit{YEARS} - 1)$$

and its total end of year value will be

$$\mathit{ANNUAL} \times (1 + \mathit{OPRATE}) * (\mathit{YEARS} - 1)$$

Additional payments will be made at the end of successive years such that the compound amount of the second year's payment is

$$\mathit{ANNUAL} \times (1 + \mathit{OPRATE}) * (\mathit{YEARS} - 2)$$

The compound amount of the third year's payment is

$$\mathit{ANNUAL} \times (1 + \mathit{OPRATE}) * (\mathit{YEARS} - 3)$$

and so on until the final payment is made which earns no interest. Summing these amounts results in the future worth of the annuity, or

$$\mathit{FUTURE} \leftarrow (\mathit{ANNUAL} \times ((1 + \mathit{OPRATE}) * (\mathit{YEARS} - 1))) + (\mathit{ANNUAL} \times ((1 + \mathit{OPRATE}) * (\mathit{YEARS} - 2))) + (\mathit{ANNUAL} \times ((1 + \mathit{OPRATE}) * (\mathit{YEARS} - 3)))$$

which can be re-arranged to become

$$\mathit{FUTURE} \leftarrow \mathit{ANNUAL} \times (1 + (1 + \mathit{OPRATE}) + ((1 + \mathit{OPRATE}) * 2) + ((1 + \mathit{OPRATE}) * 3))$$

Multiplying both sides of the equation by (1 - *OPRATE*) and solving for *FUTURE* yields the generalized expression

$$\mathit{FUTURE} \leftarrow \mathit{ANNUAL} \times (((1 + \mathit{OPRATE}) * \mathit{YEARS}) - 1) \div \mathit{OPRATE}$$

(*EQ*. 39)

The uniform compound amount factor is calculated by the expression

$$\mathit{UCA} \leftarrow (((1 + \mathit{OPRATE}) * \mathit{YEARS}) - 1) \div \mathit{OPRATE}$$

(*EQ*. 40)

such that

FUTURE ← *ANNUAL* × (*YEARS UCA OPRATE*)

(*EQ*. 41)

where *UCA* is the uniform compound amount factor for the opportunity rate and interest periods under consideration.(66)

Uniform Sinking Fund Factor. The uniform sinking fund factor (*USF*) is used to determine the annuity necessary when the future worth, opportunity rate, and number of interest periods (*YEARS*) are known. In terms of its performance, the uniform sinking fund factor, and its corresponding interest rate equation, operate conversely to the uniform compound amount factor. Just as in the situation involving the single present worth factor, the interest rate equation for the uniform sinking fund factor is the reciprocal of its converse--the uniform compound amount factor.(67) Taking the reciprocal of *EQ*. 39 provides the following term:

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(66) Roy Pilcher, Principles of Construction Management (Maidenhead: McGraw-Hill Book Co., Ltd., 1976) p. 22.

(67) J. W. Griffith, and B. J. Keely, Life-Cycle Cost-Benefit Analysis (K-G Associates, 1976) p. 2B-6.

$$\mathit{ANNUAL} \leftarrow \mathit{FUTURE} \times (\mathit{YEARS} \div ((1 + \mathit{OPRATE}) * \mathit{YEARS}) - 1)$$

(*EQ*. 42)

Therefore, the uniform sinking fund factor (*USF*) is given by the expression

$$\mathit{USF} \leftarrow (\mathit{YEARS} \div ((1 + \mathit{OPRATE}) * \mathit{YEARS}) - 1)$$

(*EQ*. 43)

such that

$$\mathit{ANNUAL} \leftarrow \mathit{FUTURE} \times (\mathit{YEARS}\ \mathit{USF}\ \mathit{OPRATE})$$

(*EQ*. 44)

Uniform Capital Recovery Factor. The uniform capital recovery factor (*UCR*) is used to determine the amount of an annuity when given its present value, opportunity rate, and number of annual payments. It can be thought of as a means for determining the amount of each annual payment to be made for a sum of money invested today. The uniform capital recovery factor is identical to the uniform sinking fund factor (used to determine the annuity of a future worth) with the exception that the future worth has been translated to become a single present worth. The derivation of the interest rate equation is given below.

The interest rate equation used to calculate the uniform sinking fund factor (*EQ.* 42) is

$$\mathit{ANNUAL} \leftarrow \mathit{FUTURE} \times (\mathit{YEARS} \div ((1 + \mathit{OPRATE}) \ast \mathit{YEARS}) - 1$$

Setting *FUTURE* equal to the future value of the single compound amount factor (*EQ.* 34) will translate, by equivalence, *FUTURE* to *PRESENT* and produce the equation for the uniform capital recovey factor.(68)

$$\mathit{ANNUAL} \leftarrow \mathit{PRESENT} \times (\mathit{OPRATE} \times ((1 + \mathit{OPRATE}) \ast \mathit{YEARS})) \div (((1 + \mathit{OPRATE}) \ast \mathit{YEARS}) - 1)$$

(*EQ.* 45)

From the above equation the uniform capital recovery factor is given by the term

$$\mathit{UCR} \leftarrow (\mathit{OPRATE} \times ((1 + \mathit{OPRATE}) \ast \mathit{YEARS})) \div (((1 + \mathit{OPRATE}) \ast \mathit{YEARS}) \ast \mathit{YEARS} - 1)$$

(*EQ.* 46)

such that

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(68) W. J. Fabrycky, G. J. Thuesen, H. G. Thuesen, <u>Engineering Economy</u> (4th ed. Printice-Hall, Inc., 1971) p. 60.

$$\mathit{ANNUAL} \leftarrow \mathit{PRESENT} \times (\mathit{YEARS}\ \mathit{UCR}\ \mathit{OPRATE}) \qquad (\mathit{EQ}.\ 47)$$

Uniform Present Worth Factor. The uniform present worth factor (*UPW*) is used to determine the present value of an annuity when given the amount and number of payments com the annuity, and the opportunity rate of the cost center. The uniform present worht factor, acts as the converse to the uniform capital recovery factor and is algebraically its reciprocal. Therefore, the reciprocal of *EQ*. 46 results in the formula required to calculate the uniform present worth factor (*UPW*).(69)

$$\mathit{UPW} \leftarrow (((1 + \mathit{OPRATE}) * \mathit{YEARS}) - 1) \div (\mathit{OPRATE} \times ((1 + \mathit{OPRATE}) * \mathit{YEARS})) \qquad (\mathit{EQ}.\ 48)$$

such that

$$\mathit{PRESENT} \leftarrow \mathit{ANNUAL} \times (\mathit{YEARS}\ \mathit{UPW}\ \mathit{OPRATE}) \qquad (\mathit{EQ}.\ 49)$$

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(69) Ibid.

Economic Analysis of Alternatives

Alternative design solutions can be compared by using one or more of the following approaches: 1) present value or ultimate cost models, 2) annual cost models, 3) break-even analysis, and 4) rate of return on investment analysis. All of these techniques are valid methods for analyzing investment decisions to determine which of the investments (or design alternatives) should be selected.

Present Worth Models. The present worth model is one method for analyzing alternative cash flow systems, which results in the reduction of all forecast costs and revenues to one single cost expressed in present dollars. This cost is commonly referred to as the ultimate cost. Calculation of the ultimate cost is accomplished by using one or more of the six compound interest factors discussed earlier to discount each cost back to its equivalent present worth. Revenues are discounted to present worth and deducted from the discounted costs as a credit. In calculating present worth equivalency a number of concepts should be considered. These concepts are discussed in the following paragraphs.

Discounting factors can be combined to convert future costs to present worth. For example, if a cash flow model consists of an annuity of $100 from years 8 to 15 then the single present worth factor would be used in connection with the uniform present worth factor. If the opportunity rate for this example is 10%, then the equation used to calculate the solution would be

$(8\ SPW\ .10) \times 100 \times ((15 + 8)\ UPW\ .10)$

The uniform present worth factor has been used to discount the annuity back to the eighth year and then the single present worth factor was used to discount this single value back to the present value.

When utilizing present worth models the lives of the alternatives should be equal if the two models are to be reduced to equivalency. For example, if two models are analyzed where model "A" has an expected life of 15 years, and model "B" has an expected life of 20 years, then to calculate the ultimate cost for each of the models and compare them as equivalent is a grave error. When comparing present worth models which have different life spans the models are expanded to become equivalent by selecting, for analysis purposes, a time period which is a common multiple of the alternatives under consideration. In the above example a convenient time span to be used would be 60 years. Model "A", with a life span of 15 years, would be calculated as though it were implemented 4 times (initially and then 3 renewals), and model "B" as though it were implemented 3 times. Discounting these modified models to present value results in equivalent conditions which can then be compared and the alternative with the lowest ultimate cost chosen.(70)

Annual Cost Models. The annual cost model is a method of economic analysis which reduces all forecast costs and revenues attached to each design alternative to a uniform annual cost. Annual cost models are developed in the following manner: 1) All costs, for each alternative, are discounted to present value. Revenues are discounted to present value and deducted from the discounted costs as a credit. This is calculated in an equivalent manner to a present worth model, with the exception that discounting for each alternative is done independently. It is not necessary to establish equivalent life spans for the alternatives analyzed, as in the development of the present worth model. 2) Once the ultimate cost has been determined for each alternative, the ultimate cost is converted to an annual cost by use of the uniform capital recovery factor. Therefore, the annual cost for each alternative is determined by the equation

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(70) J. W. Griffith, and B. J. Keely, Life-Cycle Cost-Benefit Analysis (K-G Associates, 1976) p. 4B.

PRESENT × (*YEARS UCR OPRATE*)

(*EQ*. 50)

where; *YEARS* is equal to the anticipated life span for the alternative; *OPRATE* is equal to the opportunity rate for the investor; and *PRESENT* is equal to the ultimate cost determined for each alternative. Once the annual cost has been determined for each alternative, comparisons can be made, and the alternative with the lowest annual cost chosen.(71)

Using annual cost models as a means of evaluating alternatives is, at times, preferred to using present worth models. For example, it is generally easier to communicate annual cost differences to clients who have little knowledge of life-cycle costing techniques than it is to explain a present worth model which has been expanded to achieve equivalent life spans.(72)

<u>Break-even Analysis</u>. Break-even analysis (also referred to as payback method) is another method which can be used to select between alternative investment strategies. Break-even equations are used to determine the number of years

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(71) Ibid., p. 3B-1.

(72) Ibid., p. 4B-4.

required to return the original investment in addition to the opportunity rate of the investment.(73) Although break-even analysis is easily calculated, it can lead to incorrect conclusions. One major weakness of break-even analysis is that the method fails to take into account benefits which accrue after the date when break-even conditions occur.(74)

The equation used to determine break-even condition is based upon use of the single compound amount factor (used to determine the future worth of a present value) and the uniform sinking fund factor (used to determine the annuity required of a future worth). If the interest rate equations of these two compound interest factors are graphed as a function of time they will intersect at a point which constitutes the break-even condition. Therefore, the equation necessary to determine the point where the break-even condition exists is determined by setting the interest rate equation used to calculate the single compound amount factor (*EQ.* 34) equal to the interest rate equation used to calculate the uniform sinking fund factor (*EQ.* 43) and solving for *YEARS*. The result of this algebraic transformation is the following equation:

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(73) E. F. Brigham and J. F. Weston, Managerial Finance (Hinsdale: The Dryden Press, 1975) p. 264.

(74) Rosalie T. Ruegg, Solar Heating and Cooling in Buildings: Methods of Economic Evaluation, Insititute for Applied Technology, NBS Report No. NBSIR 75-712 (July 1975) p. 24.

$$BEYEARS \leftarrow (\circledast(SAVINGS \div (OPRATE \times INITCOST)) \div (SAVINGS \div (OPRATE \times INITCOST - 1))) \div (\circledast(1 + OPRATE)) \qquad (EQ.\ 51)$$

where; *BEYEARS* equals the number of years necessary to pay off the difference between the initial costs of the alternative investment strategies (*INITCOST*); and *SAVINGS* equals the operational difference between the two investment strategies.(75)

Rate of Return Analysis. Rate of return analysis is a method for evaluating alternative investments based upon the opportunity rate which would be generated by each design solution under investigation. Rate of return analysis is developed in the following manner: 1) Determine all costs and revenues for each alternative and develop a cash flow model equation in the same manner as for a present worth model. Compound interest factors are to be left in their symbolic form (e. g. *SPW*, *UCA*, etc.). 2) Set the cash flow equation equal to zero. 3) Solve for the interest rate factors using various opportunity rates. (This is a trial-and-error procedure.(76) The alternative which would produce

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(75) Robert A. Hess, "Beat Energy Waste in Existing Schools," Air Conditioning & Refrigeration Business (May 1974) p. 58.

the greatest opportunity rate is selected as the optimum strategy.

Rate of return analysis, just as break-even analysis, has its limitation. Although the principles involved for determining the rate of return are based upon solid concepts (and generally provides the correct solution) it is limited by the complexity involved in solving the cash flow equations. Some of which may be indeterminant in nature.

Because of the specific limitations of both break-even and rate of return analysis models, either the present worth model or the annual cost model should be utilized in the analysis of alternative economic decisions which effect the built environment.(77)

It is possible, therefore, to evaluate alternative designs on the basis of life-cycle cost. This process provides the opportunity, for objective analysis of alternative designs which include either 1) a number of variables or, 2) variables which, otherwise, would be impossible to correlate in the decision-making process.

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(76) C. A. Bogert, and others, Methods of Building Cost Analysis (Building Research Institute, Inc., 1962) pp. 9-10.

(77) Rosalie T. Ruegg, Solar Heating and Cooling in Buildings: Methods of Economic Evaluation, Institute for Applied Technology, NBS Report No. NBSIR 75-712 (July 1975) p. 24.

Chapter IV

ENERGY-COST CALCULATION OF HEATING SYSTEMS

The amount of energy consumed by a heating system is dependent upon 1) the demand for heat from the building space, 2) the operating characteristics of heating system used (e. g., hot water, forced air), and 3) the efficiency of the heat source. Of these characteristics, the amount of heat required for conditioning the space is the most responsive to architectural design decisions. Specifically, decisions made with respect to the selection of alternative glazing materials can greatly effect the amount of energy which must be supplied by the building's heating system.

Calculation of Augmentation Energy

Heat gain from solar radiation transmitted through glazed wall openings can substantially reduce the amount of energy required for seasonal building space heating. This reduction of required energy is attributed to the contribution of solar heat gains acting as a credit toward the amount of energy consumed by the HVAC system to offset building heat losses. Since solar heat gains can supply much (if not all) of the building's space heating requirement during mild weather, the building's heating system acts only to suppliment these natural heat gains.(78)

Therefore, the cost of energy required to offset building heat losses can be determined as a function of the amount of purchased energy necessary to augment the building heat gains. The quantification of this required additional energy (referred to as augmentation energy) acts in accordance with the first law of thermodynamics. (Refer to Chapter 2.)(79) Hence, the calculation of augmentation energy (and its attached cost) is based upon the tradeoff condition which exists between the energy associated with heat gain, and the additional energy provided to offset the building's total heat loss. Applying the first law of thermodynamics to this tradeoff condition provides the steady-state heat balance equation for the building. This equation can be written as follows:

$$\mathit{AUGMENTATION} \leftarrow \mathit{LOSSTOTAL} - \mathit{GAINTOTAL}$$

(*EQ.* 52)

where; *GAINTOTAL* equals the summation of building heat gains (e. g., heat conducted through solid wall components and glazed wall openings, re-radiation of heat absorbed by solid

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(78) C. C. Thomas, "How Heat Gains Affect Fuel Bills," Air Conditioning, Heating and Ventilating (November, 1963) p. 61.

(79) Metlin Lokmanhekim and Gershon Meckler, "Integrating Life-Cycle Cost Analysis Into a Total Energy Analysis," Specifying Engineer, (January 1977) p. 71.

wall components and glazed wall openings, infiltration of warm air through solid wall components and around fenestration, and solar radiation transmitted through glazed wall openings) expressed in BTU per hour; *LOSSTOTAL* equals the summation of building heat losses (e. g., conduction of heat leaving the building through solid wall and roof components and glazed wall openings, and the infiltration of air around fenestration openings and solid components) expressed in BTU per hour; and *AUGMENTATION* equals the amount of energy to be supplied in BTU per hour. If the sources of heat gain attributed to solar radiation glazed wall openings are substituted into *EQ.* 52, the equation used to determine the building's augmentation energy can be written as

$$\mathit{AUGMENTATION} \leftarrow \mathit{LOSSTOTAL} - \mathit{SUBGAIN} + (\mathit{FEET} \times (\mathit{TRANSMITTED} + \mathit{RADCONVECT})) \qquad (\mathit{EQ}.\ 53)$$

for single glazing, and

$$\mathit{AUGMENTATION} \leftarrow \mathit{LOSSTOTAL} - \mathit{SUBGAIN} + (\mathit{FEET} \times (\mathit{DIRECT2} + \mathit{RADCONVECT2})) \qquad (\mathit{EQ}.\ 54)$$

for double glazing. In the preceding equations *FEET* equals the number of square feet of glazing material; and *SUBGAIN* equals the summation of all other building heat gain components, with the exception of those involving solar heat gain through glazed fenestration.(80)

Flow System Energetics of Heating Systems

Centralized mechanical systems used for building space heating operate upon a principle of transportation and dispersal of thermal energy. Heating systems which are characterized by this principle include the following: 1) forced air systems, 2) hot water, 3) radiant, and 4) steam. All make use of a medium to transport the thermal energy. This medium, either air, water or steam, is called a working fluid. Working fluids have certain physical properties including 1) density, 2) specific volume, 3) enthalpy, and 4) specific heat. The density (*DENSITY*) of a working fluid in pounds per cubic foot, and in the liquid state of matter can be determined by the equation

$$DENSITY \leftarrow MASS \div VOLUME \qquad (EQ.\ 55)$$

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(80) R. R. Avezov, and others, "Influence of Solar Installation Orientation on Its Efficiency," Geliotekhnika, Vol. 9, No. 3 (1973) p. 67.

where; *MASS* equals the weight of the fluid in pounds mass; and *VOLUME* equals the volume of the liquid in cubic feet. For fluids in a gaseous state of matter, the density in pounds per cubic foot is given by the "ideal gas equation"

$$\mathit{DENSITY} \leftarrow (\mathit{PRESSURE} \times 144) \div (\mathit{GASCONSTANT} \times (460 + \mathit{TEMPGAS}))$$

(*EQ*. 56)

where; *PRESSURE* equals the atmospheric pressure exerted upon the gas in pounds per square inch; *TEMPGAS* equals the temperature of the gas in degrees Fahrenheit; and *GASCONSTANT* is a physical constant of the gas expressed in (foot) (pounds force) per (pounds mass) (degree Rankine). (For air *GASCONSTANT* equals 53.3.) The specific volume of a fluid is the fluid's volume per unit of mass. This equals the reciprocal of the fluid's density.(81) Therefore, the specific volume for a fluid expressed in cubic feet per pound mass (*SPECVOL*) is given by the equation

$$\mathit{SPECVOL} \leftarrow \div\ \mathit{DENSITY}$$

(*EQ*. 57)

The enthalpy of a fluid (also referred to as heat content)

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(81) W. C. Reynolds, Energy from Nature to Man, (New York: McGraw-Hill, Inc., 1974) pp. 102-103.

is equal to the amount of heat in the fluid per unit of mass. For mechanical systems this is generally expressed in the units BTU per pound mass. The change in enthalpy ($\mathit{\Delta ENTHALPY}$) can be related to the specific heat of a fluid by the equation

$$\mathit{\Delta ENTHALPY} \leftarrow \mathit{SPECHEAT} \times \mathit{\Delta TEMP} \qquad (\mathit{EQ}.\ 58)$$

where; $\mathit{\Delta TEMP}$ equals the change in temperature of the fluid in degrees Fahrenheit; and $\mathit{SPECHEAT}$ is the specific heat of a fluid at constant pressure and expressed in BTU per (pound mass) (degree Rankine). Specific heat, by definition, equals the amount of heat necessary to raise one pound of fluid one degree Rankine. Specific heat is a physical property of a fluid. The values of specific heat at constant pressure, and moderate temperatures, for air, water, and steam (the most common working fluids for heating systems) equal 0.24, 1.0, and 0.446 respectively.(82) Based upon these concepts of fluid flow energetics, energy consumption can be determined for alternative heating systems.

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(82) Ibid., pp. 111-112.

__Hot Water and Steam Systems.__ Heating systems which recirculate their working fluids (e. g., hot water or steam) transport only that amount of energy required to offset the net heat loss (*AUGMENTATION*) plus an additional quantity of energy which is lost as a function of the system efficiency. Therefore, the total amount of energy, in the form of fuel, consumed by the system in BTU per hour (*ENERGY*) equals

$$\mathit{ENERGY} \leftarrow \mathit{AUGMENTATION} \div \mathit{EFFICIENCY}$$

(*EQ.* 59)

where; *EFFICIENCY* equals the efficiency of the system represented as a fraction. This equation (*EQ.* 59) is valid for hot water, steam and forced air systems operating in the steady-state condition. Hot water and steam systems would require additional energy to heat the water contained by the boiler at the time the boiler was fired. The amount of energy in BTU per hour for the initial firing of the boiler (*FIRING*) is given by the equation

$$\mathit{FIRING} \leftarrow (\mathit{BOILERVOLUME} \times \mathit{DENSITY} \times \mathit{SPECHEATVOL} \times (\mathit{SUPPLYTEMP} - \mathit{AMBIENT})) \div \mathit{EFFICIENCY}$$

(*EQ.* 60)

where; *BOILERVOLUME* equals the amount of fluid contained by the boiler in cubic feet; *SPECHEATVOL* equals the specific heat of the working fluid at constant volume expressed in BTU per (pound mass) (degree Rankine); *SUPPLYTEMP* equals the temperature of the heated fluid in degrees Rankine when it leaves the boiler; and *AMBIENT* equals the temperature of the fluid in the boiler prior to the time of firing.(83) In practice, energy calculations for recirculating working fluid systems are made for only the steady state condition.

Forced Air Systems. The process for calculating energy consumption for forced air systems is similiar to recirculating working fluid systems, with the exception that for forced air systems it is necessary in addition to determine the amount of energy required to warm air drawn into the mechanical system from the external environment. This external source of fresh air is warmed to the supply air temperature (*SUPPLYTEMP*) and discharged into the building to be used for ventilation purposes. The amount of energy in BTU per hour required to warm this external source of air (*VENTWARM*) is given by the equation

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(83) Walter P. Bishop and Dimitri Jelovcich, "Estimating Fuel Oil Consumption," Air Conditioning, Heating and Ventilating (July, 1963) pp. 57-58.

$$\mathit{VENTWARM} \leftarrow ((\mathit{AIRFLOW} \times 60) \times \mathit{DENSITY} \times \mathit{SPECHEAT} \times (\mathit{SUPPLYTEMP} - \mathit{TEMPOUT})) \div \mathit{EFFICIENCY}$$

(EQ. 61)

where; $\mathit{AIRFLOW}$ equals the amount of air drawn into the system from the exterior environment in cubic feet per minute; $\mathit{DENSITY}$ equals the density of the air in pounds per cubic foot; $\mathit{SPECHEAT}$ equals the specific heat at constant pressure for air expressed in BTU per (pound mass) (degree Rankine). For air the value of $\mathit{SPECHEAT}$ equals 0.24 BTU per (pound mass) (degree Rankine). $\mathit{SUPPLYTEMP}$ equals the supply temperature of the air in degrees Fahrenheit; and $\mathit{TEMPOUT}$ equals the outdoor air temperature.

Forced air systems, just as recirculating working fluid systems, consume the amount of energy necessary to compensate for the net heat loss plus the energy lost as a function of system efficiency (ENERGY).(84) Hence, the total amount of energy consumed by a forced air heating system in BTU per hour ($\mathit{TOTALENERGY}$) equals

$$\mathit{TOTALENERGY} \leftarrow \mathit{ENERGY} + \mathit{VENTWARM}$$

(EQ. 62)

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(84) Ibid., p. 85.

Calculation of Energy Cost. The process for calculating the cost of energy required by the system to meet the demand is a very simple process involving a minimum number of variables. These variables consist of 1) the amount of energy required by the mechanical system (*ENERGY* or *TOTALENERGY* depending upon the type of system), and 2) the physical constants of the fuel used including, a) the heat of combustion of the fuel in BTU per pound mass, (*COMBUSTHEAT*); b) the weight per unit volume of the fuel (*WTVOL*); and c) the purchase price of the fuel per unit volume (*FUELCOST*) expressed in dollars.(85) After this information has been obtained the cost of the energy used by the heating system in dollars per kilowatt-hour (*KWCOST*) can be calculated by the equation

$$KWCOST \leftarrow (FUELCOST \div WTVOL \times COMBUSTHEAT))) \times 3413 \qquad (EQ.\ 63)$$

Refer to Table 3 for a listing of selected fuels, their physical properties and costs.) With this information, the cost of energy necessary for building space heating (*HEATCOST*) can be determined by the equations

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(85) W. C. Reynolds, *Energy from Nature to Man*, (New York: McGraw-Hill, Inc., 1974) p. 165.

Table 3. Costs of Alternative Fuels.

FUEL	COST/ UNIT	QUANTITY	TAX/ UNIT	ACTUAL COST/ UNIT
Fuel Oil	.478/ gal.	constant	4%	.460/ gal.
Propane	.437/ gal.	minimum qty.	4%	.420/ gal.
	.520/ gal.	amt < 500 gal.	4%	.500/ gal.
	.780 gal.	amt > 500 gal.	4%	.750/ gal.
Natural Gas	1.75/ 1000c.f.	amt < 1000 c.f.	N/A	N/A
	1.50/ 1000c.f.	1000<amt<3000c.f.	N/A	N/A
	1.20/ 1000c.f.	3000<amt<50,000	N/A	N/A
	0.90/ 1000c.f.	amt>50,000c.f.	N/A	N/A
Coal	67.50/ ton	constant	4%	64.90/ ton
Electricity	.0292/ kwhr.	average	N/A	.0292/ kwhr.

$$\mathit{HEATCOST} \leftarrow (\mathit{TOTALENERGY} \div 3413) \times \mathit{KWCOST} \qquad (\mathit{EQ}.\ 64\mathit{A})$$

Table 3. Costs of Alternative Fuels. (Continued)

FUEL	CONVERT	HEAT VALUE (ENERGY/LB.)	HEAT VALUE/ UNIT	NET COST/ KWHR	GROSS COST/ KWHR
Fuel Oil	6.3 lb./ gal.	18,000 BTU/ lb.	113400 BTU/gal	.0138	.0143
Propane	4.24 lb./ gal.	21,625 BTU/ lb.	91690 BTU/gal	.0156	.0162
	4.24 lb./ gal.	21,625 BTU/ lb.	91690 BTU/gal	.0186	.0193
	4.24 lb./ gal.	21,625 BTU/ lb.	91690 BTU/gal	.0279	.0290
Nat'l Gas	.041 lb./ cu. ft.	24,000 BTU/ lb.	984 BTU/gal	.0060	.0060
	.041 lb./ cu. ft.	24,000 BTU/ lb.	984 BTU/gal	.0052	.0052
	.041 lb./ cu. ft.	24,000 BTU/ lb.	984 BTU/gal	.0041	.0041
	.041 lb./ cu. ft.	24,000 BTU/ lb.	984 BTU/gal	.0032	.0032
Coal	2000 lb./ ton	12,000 BTU/ lb.	24000000 BTU/gal	.0092	.0096
Electricity	N/A	N/A	N/A	.0292	.0292

NOTES: Prices obtained from a survey of retail suppliers in Southwest Virginia, with the exception of electric utility prices obtained from Va. S.C.C. Tariff No. 7. Survey prices apply only for time periods prior to 11 May 1977. or unit prices based upon quantity.

for forced air heating systems, or

$$HEATCOST \leftarrow (ENERGY \div 3413) \times KWCOST \tag{EQ. 64B}$$

for hot water and steam heating systems.

The preceding equations have provided a methodology to calculate the amount of energy, and its cost, necessary for seasonal building space heating. Using these equations, the designer has a basis for calculating the cost of energy as a tradeoff condition for the analysis of heat gain through window glazing. This information can be used as an input for life-cycle cost analysis of alternative window glazing.

Chapter V

MODEL DEVELOPMENT

In life-cycle cost analysis, assumptions are frequently made because of a lack of dependable (or absolute data. For example, throughout the development of the preceding equations the heat transfer condition was considered as in a steady state. Such assumptions do not negate the value of a life-cycle cost model as long as those assumptions are understood and can be placed in proper perspective. Often, a number of factors can be omitted thus simplifying the task of the analyst.

Assumptions of Life-Cycle Cost Model

The life-cycle cost model presented in the paper is based upon a number of assumptions made to facilitate its development. 1) All design decisions will be held constant, with the exception of those involving alternative glazing materials. 2) Initial and maintenance costs for heating equipment and distribution systems will not be included in the cash flow model. Since the size of the heating plant is determined by the maximum heat loss of the building, it is assumed that glazing details will not change the size of the heating plant needed. 3) Maintenance costs for the glazing will be assumed identical regardless of glazing type since the quantity of glazed area will be held constant. Also, since the regions of unsupported glass are equal, the probability of replacement due to breakage, and its attached cost, is approximately equal. 4) Energy costs for air handling equipment will be treated as a identical for alternative systems. Air circulation will be assumed to be continuous to prevent heat build-up insided glazed areas. 5) The quantity of diffuse radiation passing through double glazing will be assumed to equal the quantity of diffuse radiation passing through single glazing. This assumption is based on the absence of an appropriate methodology for calculating transmission of diffuse radiation through double glazing. 6) Only heat gains which are used to offset building heat losses will be considered. Excessive heat gains are usually counteracted by some form of cooling system, a discussion of which is beyond the scope of this paper.

Life-Cycle Cost Model

The following life-cycle cost model provides a rational method which can facilitate the selection of alternative glazing materials for building fenestration. Selection is to be made upon economic optimization of alternatives. The model consists of the following three parts: 1) climatic and operational data, 2) heat gain calculation through either single or double glazing, and 3) life-cycle energy cost calculation. The model presented in the following pages is in a tabular form, and can only be used for the evaluation of glazing for a specific hour. A case study using this model is provided in Appendix C.

Part A: Climatic and Operational Data

latitude of the site, in degrees, where investigation is to be made

LATITUDE = ____________

day of year for which calculation is to be made

DATE = ____________

solar time for which calculation is to be made

TIME = ____________

hour angle for solar time in degrees

HA = ____________

declination of the earth in degrees

DECLINATION = ____________

temperature of exterior environment in degrees Fahrenheit

TEMPOUT = ____________

temperature of interior environment in degrees Fahrenheit

TEMPIN = ____________

wind speed striking glazed surfaces in miles per hour

MPH = ____________

calculate solar altitude in degrees from *EQ*. 1

ALTITUDE = ____________

enter azimuth of the glazed region (in degrees) under investigation

WAZIMUTH = ____________

enter tilt angle (in degrees) of the surface under investigation

SIGMA = ____________

enter percent possible sunshine from statistical references for day and time under investigation

PPS = ____________

calculate from *EQ*. 5 the correction factor for percent possible sunshine

PPSCORRECT = ____________

calculate solar azimuth in degrees from *EQ*. 6

AZIMUTH = ____________

calculate wall-solar azimuth in degrees from either *EQ*. 8, or *EQ*. 9 depending upon time of day and wall azimuth

WSAZIMUTH = ____________

from statistical references enter direct radiation normal to the earth's surface in BTU per (hour) (square foot)

DIRECT = ____________

from *EQ.* 10, calculate the angle of incidence in degrees solar beam strikes glazing

INCIDENT = ___________

calculate from *EQ.* 11, the quantity of direct solar radiation striking glazed surface in BTU per (hour) (square foot)

ALLDIRECT = ___________

entry the total building heat loss, in BTU per hour, for the day and hour for which calculation is to be made

LOSSTOTAL = ___________

enter the number of square feet of glazing material under analysis (all glazed fenestration under investigation must have the same orientation)

FEET = ___________

enter the total building heat gain from components other than the glazed fenestration under study

SUBGAIN = ___________

enter whether heating system is a recirculating working fluid system (RWFS) or a forced air system (FAS)

SYSTEM = ___________

enter the air pressure of the outdoor air in pounds per square foot

PRESSURE = ___________

calculate the density of the working fluid using *EQ.* 55 for RWFS or *EQ.* 56 for FAS given, for FAS, *TEMPGAS* equals *TEMPOUT*

DENSITY = ___________

enter the efficiency rating for the heating system

EFFICIENCY = ___________

if heat is provided by a forced air syftem (FAS) enter the amount of air drawn into the system from the exterior environment in cubic feet per minute

AIRFLOW = ___________

if heat is provided by a forced air system enter the specific heat at constant pressure for air in BTU per (pounds mass) (degree Rankine)

SPECVOL = ___________

if heat is provided by a forced air system enter the supply air temperature in degrees Fahrenheit

SUPPLYTEMP = ___________

enter type of fuel used by heating system

FUELTYPE = ___________

calculate cost of fuel per KWH from *EQ.* 63, or select from Table 3

KWCOST = ___________

enter opportunity rate per interest period for cost center

OPRATE = ____________

enter number of interest periods per year

PERIODS = ____________

enter interest period in life of building analysis represents

YEARS = ____________

enter anticipated number of interest periods in life of building

LIFE = ____________

Part B: Heat Gain Calculation Through Single Glazing

from Table 1 select the solar-optical properties for the alternative glass type under investigation

TRANSMISSIVITY = ___________

ABSORPTIVITY = ___________

REFLECTIVITY = ___________

calculate the quantity of radiation reflected by the glass in BTU per (hour) (square foot) from *EQ*. 17.

REFLECTED = ___________

calculate the quantity of radiation absorbed by the glass in BTU per (hour) (square foot) from *EQ*. 18.

ABSORBED = ___________

calculate the quantity of radiation transmitted through the glass in BTU per (hour) (square foot) from *EQ*. 19.

TRANSMITTED = ___________

given that *ABSORPTIVITY* equals *EMISSIVITY*, and *RADCONOUT* equals 4.0 BTU per degree Fahrenheit, calculate the average temperature of the glass in degrees Fahrenheit from *EQ*. 21.1.

MEANGLASSTEMP = ___________

calculate the combined coefficient of heat transfer from the inner surface of the glass in BTU per (hour) (degree Fahrenheit) from *EQ.* 21.2.

RADCONIN = ___________

calculate the combined heat transfer coefficient for the glass and air films in BTU per degree Fahrenheit from *EQ.* 21.3.

U = ___________

from *EQ.* 21, calculate the heat gain contribution from the re-radiation and convection of direct radiation absorbed by the glass in BTU per (hour) (square foot)

RADCONVECT = ___________

calculate the total rate of heat transfer from direct radiation passing through glass in BTU per (hour) (square foot) from *EQ.* 22.

DIRECTGAIN = ___________

calculate the required building augmentation energy in BTU per hour from *EQ.* 53

AUGMENTATION = ___________

Part C: Heat Gain Calculation Through Double Glazing

from Table 1 select the solar-optical properties for the exterior layer of glass in the double glass assembly

TRANSMISSIVITY = ___________

ABSORPTIVITY = ___________

REFLECTIVITY = ___________

from Table 1 select the solar-optical properties for the interior layer of glass in the double glass assembly

TRANSMISSIVITY2 = ___________

ABSORPTIVITY2 = ___________

REFLECTIVITY2 = ___________

calculate the quantity of radiation absorbed by outer layer of glass in BTU per (hour) (square foot) from *EQ.* 18

ABSORBED = ___________

from manufacturer's specifications enter the air space thickness for the double glass assembly in inches

AIRSPACE = ___________

given that *RADCONOUT* equals 4.0 BTU per degree Fahrenheit, calculate the mean glass air space temperature in degrees Fahrenheit from *EQ.* 26

MEANGLASSTEMP = ___________

calculate the temperature difference of the surrounding air in degrees Fahrenheit from *EQ.* 27

TEMPDIFF = ___________

calculate the effective air space emissivity from *EQ.* 29.

EEMISSIVITY = ___________

select the appropriate heat transfer coefficient for convection and radiation in BTU per (hour) (square foot) (degree Fahrenheit) from Table 2

INTERCONSTANT = ___________

given that the emissivity (*EMISSIVITY*) for a double glazed assembly equals its effective emissivity (*EEMISSIVITY*) calculate the combined coefficient of heat transfer for the inner surface of the assembly in BTU per (hour) (degree Fahrenheit) from *EQ.* 21.2

RADCONIN = ___________

given that *RADCONOUT* equals 4.0 BTU per degree Fahrenheit, calculate the combined heat transfer coefficient for the glass and air films in BTU per degree Fahrenheit from *EQ.* 21.3

U = ____________

calculate the rete of convective heat transfer through the outer layer of a double glazed assembly in BTU per (hour) (square foot) from *EQ.* 21 given *RADCONOUT* equals 4.0 BTU per degree Fahrenheit

RADCONVECT = ____________

calculate the rate of convective heat transfer through double glazing in BTU per (hour) (square foot) from *EQ.* 30

RADCONVECT2 = ____________

calculate the rate of direct transmission of radiation through double glazing in BTU per (hour) (square foot) from *EQ.* 32

DIRECT2 = ____________

calculate the total rate of heat transfer from direct radiation through double glazing in BTU per (hour) (square foot) from *EQ.* 33

DIRECTGAIN = ____________

calculate the required building augmentation energy in BTU per hour from *EQ.* 54

AUGMENTATION = ____________

Part D: Life-cycle Energy Cost Calculation

calculate the amount of energy consumed by the heating system in BTU per hour using *EQ.* 59 for RWFS, or *EQ.* 59, *EQ.* 61, and *EQ.* 62 for FAS

ENERGY = ____________

VENTWARM = ____________

TOTALENERGY = ____________

calculate cost of heating in dollars, from *EQ.* 64*A* for FAS, or *EQ.* 64*B* for RWFS

HEATCOST = ____________

enter initial cost of glass analyzed in this study in dollars

GLASSCOST = ____________

calculate the single present worth factor for this analysis from *EQ.* 37

SPW = ____________

calculate the present worth of *HEATCOST* from *EQ.* 38, given *FUTURE* equals *HEATCOST*

PRESENT = ____________

sum *PRESENT* and *GLASSCOST* to produce life-cycle cost for this static analysis

LCC = ____________

Chapter VI

CONCLUSIONS OF THE STUDY

Based upon the case study contained in Appendix C the life-cycle cost model presented in this paper can facilitate the optimum selection of alternative glazing materials for building fenestration. The method established presents a rational means to evaluate energy costs associated with heat gain through windows during the heating season of the year. The method represents a step forward in knowledge which, based upon the review of literature, had prevously not been investigated. As presented, the method is based on a static condition--allowing the calculation of energy for a specified hour and day of the year. Computer simulation of the method would be necessary to obtain costs for more than a few hours of the year. Such a computer simulation would require the following: 1) Hourly insolation, temperature, and wind velocity data for the locale where the design is to be implemented. 2) Calculation made on an hourly basis. Periods when the total heat gain for the building exceeded heat loss would be used to calculate exergy expended for cooling. 3) Energy costs would be discounted to present worth to determine the cost of energy as a present value. Presentation of the equations in APL notation allows rapid implementation of the model. Discounting would be performed on an hourly basis using formulas presented in chapter 2.

Implementation of a computer simulation as outlined, and based upon the methodology would allow the design professional 1) capability to specify fenestration based upon thermal performance, 2) means to promote energy conservation vital to national need, and 3) ability to make design decisions which will provide his client with a minimum life-cycle cost on his investment.

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APPENDIX A: COMMON APL OPERATORS AND USE

Kenneth E. Iverson, while at Harvard University, developed a means of describing processes of manipulating either alphabetic or numeric data. His original published work entitled, A Programming Language, became the basis for the development of a new computer programming language simply titled APL. APL, as originally developed by International Business Machine (IBM), is presently recognized as the most powerful computer programming language to date. The power of APL stems from its ability to allow a computer to perform mathematical operations on two sets data without looping through a sequence of operations. This capability is commonly referred to as parallel processing.

APL can be used to perform operations on the following types of mathematical arguments: 1) scalar quantities, defined as a single value, such as 9.2 or 18, 2) vectors, defined as a group of numbers with only one dimension, as in a line, such as 8 13.1 ¯0.14 or, 3) arrays, defined as a group of numbers with more than one dimension, such as a matrix. The normal order of operations for APL is from right to left (Polish notation), an example of which is

3 × 4 + 2

yields

18

but may be overridden by use of parenthesis. For example,

(3 × 4) + 2

yields

14

The arrangement between arguments and operators (built in functions such as subtraction or matrix divide) can be in either the dyadic form, which requires one operator and two mathematical arguments, or the monadic form, which requires the operator and only one mathematical argument. The dyadic form consists of the following arrangement:

LEFT ARGUMENT operator RIGHT ARGUMENT

an example of which is

5 × 2.3 ¯7

where 5 is the left argument (a scalar) and 2.3 ¯7 is the right argument (a vector). Because of the parallel processing feature of APL the solution to the problem

5 × 2.3 ¯7

is

11.5 ¯35

The monadic form consists of the following arrangement of operators and arguments

LEFT ARGUMENT operator

an example of which is

÷2

which yields a result of

.5

its inverse. Operators may have either a monadic usage, a dyadic usage, or both. In cases where an operator has both forms, its name, as well as its operation, will vary dependent upon its usage. The following partial listing provides the differences of common APL operators dependent upon whether the monadic or dyadic form is used.(86)

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(86) Leonard Gilman, and A. J. Rose, APL: An Interactive Approach, (New York: John H. Wiley & Sons, Inc., 1974) p. vii.

APL Operators

Symbol	Monadic or Dyadic	Name	Operation
<	D	less than	returns 1 if left argument less than right argument, zero if not
≤	D	less than or equal	returns 1 if left argument is less than or equal to right argument, zero if not
=	D	equal	returns 1 if left and right arguments are equal, zero if not equal
≥	D	gtr. than or eq.	returns 1 if left argument is greater than, or equal to right argument, zero if not
>	D	greater than	returns 1 if left argument is greater than right argument, zero if not
∨	D	logical OR	returns 1 if either or both arguments equal 1, zero if both arguments equal zero
∧	D	logical AND	returns 1 if both left and right arguments equal 1, zero if either or both arguments equal zero
⍱	D	logical NOR	returns 1 if both arguments equal zero, zero if either or both arguments equal 1
⍲	D	logical NAND	returns 0 if both arguments equal 1, and 1 if either or both arguments equal zero

Symbol	Monadic or Dyadic	Name	Operation
−	M	arith. negation	returns negative value of right argument
−	D	subtraction	returns difference of left and right arguments
+	M	identity	returns right argument
+	D	addition	returns sum of left and right arguments
÷	M	reciprocal	returns the reciprocal of right argument
÷	D	division	returns quotient of left and right arguments
×	M	signum	returns positive 1 if right argument is greater than zero, and negitive 1 if right argument is less than zero
×	D	multiplication	returns product of left and right arguments
?	M	roll	returns a random integer greater than 1 and less than the right argument
?	D	deal	produces number of random integers specified by left argument with values between 1 and the right argument such that there is no integer repeated
∊	D	membership	for each element of the left argument (a vector) returns a 1 if the element is contained in the right argument, 0 if not

Symbol	Monadic or Dyadic	Name	Operation
ρ	M	shape	returns the length of a vector, or dimension of an array
ρ	D	reshape	returns a vector, or array, having a shape specified by the left argument and composed of the elements in the right argument
~	M	logical negation	returns 1 if right argument equals zero, and 0 if right argument equals 1
↑	D	take	if left argument is positive, N↑A returns first N elements of vector A, if left argument is negative returns last N elements of vector A
↓	D	drop	if left argument is positive N↓A returns with first N elements of vector A removed, if left argument is negative returns last N elements of vector A
ι	M	index generator	returns a vector of consecutive integers from 1 to the value of the right argument, inclusive
ι	D	index of	returns subscript of left argument where its value first occurred in the vector composing right argument
○	M	pi times	returns product of Pi and right argument

Symbol	Monadic or Dyadic	Name	Operation
○	D	circle functions	returns function of right argument (in radians) based upon value of left argument left arg. — F(x) 1 — sin x ¯1 — arcsin x 2 — cos x ¯2 — arccos x 3 — tan x ¯3 — arctan x
⌽	M	reversal	returns the vector specified in the right argument in reverse order
⌽	D	rotate	returns right argument rotated the number of elements specified by left argument
⍉	M	transpose	returns the matrix specified in the right argument such that the rows and columns are reversed
*	M	exponential	returns e raised to right argument
*	D	power	returns left argument raised to the right argument
⍟	M	natural logarithm	returns the LOG base e of right argument
⍟	D	log to a base	returns the logarithm of the right argument whose base is the left argument
⌈	M	ceiling	returns the least integer greater than or equal to the right argument

Symbol	Monadic or Dyadic	Name	Operation
⌈	D	maximum	returns the greater of the right and left arguments
⌊	M	floor	returns the greatest integer less than or equal to right argument
⌊	D	minimum	returns the lesser of the right and left arguments
⍋	M	grade up	returns a vector of indices which will sort right argument into ascending order
⍒	M	grade down	returns a vector of indices which will sort right argument into descending order
!	M	factorial	returns factorial of right argument
[ ]	D	index	returns a vector composed from the elements of the left argument as specified by the subscripts within the brackets
⍎	M	execute	returns the value of an expression entered as character data
|	M	absolute value	returns absolute value of right argument
|	D	residue	returns remainder resulting from division of left operand by right argument
,	D	catenate	returns left and right arguments together as a vector (or array)

Symbol	Monadic or Dyadic	Name	Operation
,	M	ravel	converts an array into a vector
⌹	M	matrix inverse	returns the inverse of the matrix entered as the right argument
/	M	reduction	performs the operation specified as the left argument on the elements composing the right argument (a vector or array)
\	M	scan	performs the operation specified as the left argument on the elements composing the right argument, from left to right, and returns the results as a vector
←	D	assignment	stores the argument on the right as the variable named on the left
→	M	branch	equivalent to command "go to"
()		parenthesis	alters order of operations to perform operations contained within parenthesis first

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(87) Mark Arnold, "What is APL," *Byte*, No. 15 (November 1976) pp. 20-24, 123-126.

APPENDIX B: TABLE OF NOMENCLATURE

ABSORBED = quantity of direct radiation absorbed by the glass
UNITS: BTU per (hour) (square foot)

ABSORPTIVITY = coefficient of solar-optical absorption by glass; for double glazing--the coefficient of absorption for the outer layer of glass.
UNITS: no dimension

ABSORPTIVITY2 = for double glazing--the coefficient of absorption for the inner layer of glass
UNITS: no dimension

ABSORPTIVITY60 = coefficient of absorption for glass when the angle of incidence equals 60 degrees
UNITS: no dimension

AIRFLOW = amount of air drawn into the heating system from the exterior environment
UNITS: cubic feet per minute

ALLDIRECT = intensity of direct solar radiation upon any surface
UNITS: BTU per (hour) (square foot)

ALTITUDE = angular distance of the sun above the horizon
UNITS: degrees

AMBIENT = temperature of the fluid contained by a boiler prior to firing
UNITS: degrees Fahrenheit

APPARENT = apparent solar radiation at air mass equal to 0
UNITS: BTU per (hour) (square foot)

AREA = surface area of either a material normal to the direction of heat flow or of a radiative body
UNITS: square feet

AUGMENTATION = amount of energy to be supplied by the mechanical system necessary to suppliment the natural heat gains
UNITS: BTU per hour

AUGMENTATION = amount of thermal energy to be supplied to the building heating system
UNITS: BTU per hour

AZIMUTH = solar azimuth angle
UNITS: degrees $def *BEYEARS* = point in time when economic break-even conditions exist for a given investment
UNITS: years

BOILERVOLUME = amount of fluid contained by a boiler
UNITS: cubic feet

CLOUDLESS = period of time radiation is received during cloudless conditions
UNITS: hours per day

COMBUSTHEAT = heating value of a fuel
UNITS: BTU per pound mass

CONDUCTION = rate of conductive heat transfer
UNITS: BTU per hour

CONDUCTIVITY = thermal conductivity of a given material
UNITS: BTU per (hour) (square foot) (degree Fahrenheit)

CONVECTION = rate of convective heat transfer
UNITS: BTU per hour

CONVECTIVITY = convective heat transfer coefficient
UNITS: BTU per (hour) (square foot) (degree Fahrenheit)

CORRECTION = Threlkeld's correction factor for diffuse radiation
UNITS: no dimension

CRATIO = ratio between total observed radiation from the sky vault to the incident radiation normal to the path of the incident solar beam
UNITS: no dimension

DECLINATION = angular distance between the earth's orbital plane and the solar beam
UNITS: degrees

DENSITY = density of the heating system working fluid
UNITS: pounds per cubic foot

DIFABSORB = quantity of diffuse radiation absorbed by glass
UNITS: BTU per (hour) (square foot)

DIFFUSE = diffuse solar radiation upon any surface
UNITS: BTU per (hour) (square foot)

DIFRADCON = heat gain contribution by re-radiation and convection of absorbed diffuse radiation
UNITS: BTU per (hour) (square foot)

DIRECT = direct solar radiation normal to the surface of the earth
UNITS: BTU per (hour) (square foot)

DIRECT2 = heat transfer of direct radiation through double glazing
UNITS: BTU per (hour) (square foot)

DIRECTGAIN = rate of heat transfer of direct and diffuse radiation through single glazing
UNITS: BTU per (hour) (square foot)

DIRECTGAIN2 = for double glazing--the rate of heat transfer of direct and diffuse radiation through double glazing
UNITS: BTU per (hour) (square foot)

DISTANCE = distance between exterior surfaces of a material measured along the path of the heat flow
UNITS: feet

EFFICIENCY = efficiency of the heating system
UNITS: ratio

EEMISSIVITY = for double glazing--the combined effective emissivity for the air space
UNITS: no dimension

EMISSIVITY = radiative property of a surface expressed as a ratio
UNITS: no dimension

EMIS1 = for double glazing--the emissivity of the inner surface of the outer layer of glass
UNITS: no dimension

EMIS2 = for double glazing--the emissivity of the outer surface of the inner layer of glass
UNITS: no dimension

ENERGY = amount of fuel consumed by a mechanical system for the heating of its recirculated working fluid
UNITS: BTU per hour

EXTINCTION = atmospheric extinction coefficient
UNITS: no dimension

FEET = number of square feet of glazing material
UNITS: square feet

FUELCOST = purchase price of fuel per unit volume
UNITS: dollars per unit volume

FUTURE = future, or terminal, value of an asset
UNITS: dollars

GAINTOTAL = summation of building heat gains
UNITS: BTU per hour

GASCONSTANT = physical gas constant
UNITS: (foot) (pounds force) per (pounds mass) (degree Rankine)

HA = solar hour angle
UNITS: degrees

HEATIN = heat transmitted by the glass to the interior by convection and radiation
UNITS: BTU per (hour) (square foot)

HEATOUT = heat transmitted by the glass to the exterior by convection and radiation
UNITS: BTU per (hour) (square foot)

INCIDENT = angle of incidence of the solar beam and a line normal to the surface under investigation
UNITS: degrees

INITCOST = the difference between the initial costs of alternative investment strategies
UNITS: dollars

INTERCONSTANT = for double glazing--the air space heat transfer coefficient
UNITS: BTU per (hour) (square foot) (degree Fahrenheit)

KWCOST = cost of fuel used by heating system
UNITS: dollars per kilowatt-hour

LATITUDE = latitude of the site under consideration
UNITS: degrees

MASS = weight of the heating system working fluid
UNITS: pounds mass

MEANGLASSTEMP = for double glazing--the mean air space temperature for single glazing--the average glass temperature
UNITS: degrees Fahrenheit

OPRATE = interest rate per period earned from holding an asset
UNITS: no dimension

POSSIBLE = maximum possible period of time solar radiation can be received
UNITS: hours per day

PPS = percent possible sunshine
UNITS: percentage

PPSCORRECT = cloud cover correction factor
UNITS: no dimension

PRESENT = present value of an asset
UNITS: dollars

PRESSURE = atmospheric pressure exerted upon the heating system working fluid
UNITS: pounds per square inch

RADCONIN = combined coefficient of radiative and convective heat transfer for the inner surface of the glass
UNITS: BTU per (hour) (degree Fahrenheit)

RADCONOUT = combined coefficient of radiative and convective heat transfer for the outer surface of the glass
UNITS: BTU per (hour) (degree Fahrenheit)

RADCONVECT = heat gain contribution from single glass by re-radiation and convection of absorbed direct radiation
UNITS: BTU per (hour) (square foot)

RADCONVECT2 = heat gain contribution from double glass by re-radiation and convection of absorbed direct radiation
UNITS: BTU per (hour) (square foot)

RADIATION = rate of radiated heat transmitted by an object (Stephan-Boltzmann Law)
UNITS: BTU per hour

REFLECTED = rate of radiation reflected by glass
UNITS: BTU per (hour) (square foot)

REFLECTIVITY = coefficient of solar-optical reflection by single glazing; for double glazing--the coefficient of solar-optical reflection for the outer layer of glazing
UNITS: no dimension

SAVINGS = difference in operating costs between two investment strategies
UNITS: dollars

SBCONSTANT = Stephan-Boltzmann constant
UNITS: BTU per (hour) (square foot) (degree Rankine)

SCA = single compound amount factor
UNITS: no dimension

SIGMA = tilt angle from horizontal of a surface under investigation
UNITS: degrees

SPECHEAT = specific heat of a working fluid at constant pressure
UNITS: BTU per (pound mass) (degree Rankine)

SPECHEATVOL = specific heat of a working at constant volume
UNITS: BTU per (pound mass) (degree Rankine)

SPECVOL = specific volume of a fluid
UNITS: cubic feet per pounds mass

SPW = single present worth factor
UNITS: no dimension

SUBGAIN = summation of all building heat gain components, minus solar heat gain components
UNITS: BTU per hour

SUPPLYTEMP = temperature of the working fluid when it leaves the boiler or heat exchanger
UNITS: degrees Fahrenheit

TEMPDIFF = the temperature difference between interior and exterior air separated by a plane of glass
UNITS: degrees Fahrenheit

TEMPGAS = temperature of a gas
UNITS: degrees Fahrenheit

TEMPIN = temperature of the inside environment
UNITS: degrees Fahrenheit

TEMPOUT = temperature of the outdoor environment
UNITS: degrees Fahrenheit

TOTALENERGY = total amount of energy consumed by a forced air heating system
UNITS: BTU per hour

TOTALGAIN = total heat gain through single glazing from diffuse and direct radiation
UNITS: BTU per (hour) (square foot)

TOTALRADIATION = total radiation falling upon any surface
UNITS: BTU per (hour) (square foot)

TRANSMISSIVITY = coefficient of solar-optical transmission through single glass; for double glazing--the coefficient of solar transmission through the outer layer of glass
UNITS: no dimension

TRANSMISSIVITY2 = for double glazing--the coefficient of solar transmission for the inner layer of glass
UNITS: no dimension

TRANSMITTED = rate of radiation transmitted through single glazing
UNITS: BTU per (hour) (square foot)

U = combined heat transfer coefficient for glass and air films
UNITS: BTU per (hour) (square foot) (degree Fahrenheit)

UCA = uniform compound amount factor
UNITS: no dimension

UCR = uniform capital recovery factor
UNITS: no dimension

UPW = uniform present worth factor
UNITS: no dimension

USF = uniform sinking fund factor
UNITS: no dimension

VENTWARM = amount of energy required to warm external source of air drawn into warm air heating system
UNITS: BTU per hour

VOLUME = quantity of heating system working fluid
UNITS: cubic feet

WAZIMUTH = wall azimuth angle
UNITS: degrees

WSAZIMUTH = wall-solar azimuth angle
UNITS: degrees

WTVOL = weight per unit volume of fuel
UNITS: pounds per gallon, or pounds per cubic foot

YEARS = number of time periods which an investment lasts
UNITS: years

ΔENTHALPY = change in enthalpy of a working fluid
UNITS: BTU per pound mass

ΔTEMP = change in temperature of a working fluid
UNITS: degrees Fahrenheit

APPENDIX C: CASE STUDY

Analyze two alternative window assemblies to be used on a building located in Greensboro, N. C. (latitude equals 36.07 degrees) for December 21 at 10:00 solar time during the first year in the life of the building. The glazing material proposed in alternative 1 is Pittsburgh Plate Glass (PPG) 1/2" Solargray19 glass with coefficients of transmission, absorption, and reflection equal to 0.24, 0.71, and 0.05 respectively. The cost of the installed assembly equals $8.16 per square foot. The glazing material proposed in alternative 2 is PPG metal edge Twindow insulating glass composed of 1/8" Graylite31 glass, with coefficients of transmission, absorption, and reflection of 0.56, 0.38, and, 0.06 respectively, and an inner light of 1/8" clear glass, with coefficients of transmission, absorption, and reflection of 0.85, 0.07, and 0.08 respectively. The two lights in the combined assembly are separated by a 1/4" air space. The cost of the installed assembly equals $9.40 per square foot. The orientation of the 4200 square feet of vertical fenestration glazing material is due south. The building has a calculated heat loss of 240,000 BTU per hour. total heat gain from sources other than the glazed assemblies to be analyzed equals 30,000 BTU per hour. The building is to be heated by an oil fired forced air system, and is to be maintained at 70 degrees Fahrenheit. The supply air temperature (heat temperature) equals 180 degrees Fahrenheit. Cost of fuel oil for the heating system equals 47.8 cents per gallon. Ten thousand cubic feet per minute of outside air is to be used for ventilation. The outside air temperature is 28 degrees Fahrenheit with a 6 mph wind blowing. Percent possible sunshine equals 78%. The overall heating efficiency for the heating system is assumed to be 70%. The opportunity rate for the analysis equals equals 12% per annum, compounded daily. Anticipated life of the building is assumed to be 40 years. Determine which type of glazing material should be used based upon a present worth model.

<u>Part A:</u> <u>Climatic and Operational Data</u>

latitude of the site, in degrees, where investigation is to be made

LATITUDE = 36.07

day of year for which calculation is to be made

DATE = 355

solar time for which calculation is to be made

TIME = 10:00

hour angle for solar time in degrees

HA = 30.00

declination of the earth in degrees

DECLINATION = -23.45

temperature of exterior environment in degrees Fahrenheit

TEMPOUT = 28.00

temperature of interior environment in degrees Fahrenheit

TEMPIN = 70.00

wind speed striking glazed surfaces in miles per hour

MPH = 6.00

calculate solar altitude in degrees from *EQ.* 1

ALTITUDE = 24.07

enter azimuth of the glazed region (in degrees) under investigation

WAZIMUTH = 0.00

enter tilt angle (in degrees) of the surface under investigation

SIGMA = 90.00

enter percent possible sunshine from statistical references for day and time under investigation

PPS = 78.00

calculate from *EQ.* 5 the correction factor for percent possible sunshine

PPSCORRECT = 0.88

calculate solar azimuth in degrees from *EQ.* 6

AZIMUTH = 34.57

calculate wall-solar azimuth in degrees from either *EQ.* 8, or *EQ.* 9 depending upon time of day and wall azimuth

WSAZIMUTH = 34.57

from statistical references enter direct radiation normal to the earth's surface in BTU per (hour) (square foot)

DIRECT = 274.00

from *EQ.* 10, calculate the angle of incidence in degrees solar beam strikes glazing

INCIDENT = 41.71

calculate from *EQ.* 11, the quantity of direct solar radiation striking glazed surface in BTU per (hour) (square foot)

ALLDIRECT = 179.97

entry the total building heat loss, in BTU per hour, for the day and hour for which calculation is to be made

LOSSTOTAL = 240,000.00

enter the number of square feet of glazing material under analysis (all glazed fenestration under investigation must have the same orientation)

FEET = 4200.00

enter the total building heat gain from components other than the glazed fenestration under study

SUBGAIN = 30,000.00

enter whether heating system is a recirculating working fluid system (RWFS) or a forced air system (FAS)

SYSTEM = FAS

enter the air pressure of the outdoor air in pounds per square inch

PRESSURE = 14.70

calculate the density of the working fluid in pounds per cubic foot using *EQ.* 55 for RWFS or *EQ.* 56 for FAS given, for FAS, *TEMPGAS* equals *TEMPOUT*

DENSITY = 0.081

enter the efficiency rating for the heating system

EFFICIENCY = .70

if heat is provided by a forced air system (FAS) enter the amount of air drawn into the system from the exterior environment in cubic feet per minute

AIRFLOW = 10,000.00

if heat is provided by a forced air system enter the specific heat at constant pressure for air in BTU per (pound mass) (degree Rankene)

SPECVOL = 0.24

if heat is provided by a forced air system enter the supply temperature in degrees Fahrenheit

SUPPLYTEMP = 180.00

enter type of fuel used by heating system

FUELTYPE = OIL

calculate cost of fuel per KWH from *EQ.* 63, or select from Table 3

KWCOST = .0143

enter opportunity rate per interest period for cost center

OPRATE = 0.00033

enter number of interest periods per year

PERIODS = 360

enter interest period in life of building analysis represents

YEARS = 355

enter anticipated number of interest periods in life of building

LIFE = 14,400

Part B: Heat Gain Calculation Through Single Glazing

(Alternative 1)

from Table 1 select the solar-optical properties for the alternative glass type under investigation

TRANSMISSIVITY	=	0.24
ABSORPTIVITY	=	0.71
REFLECTIVITY	=	0.05

calculate the quantity of radiation reflected by the glass in BTU per (hour) (square foot) from *EQ.* 17.

REFLECTED	=	9.00

calculate the quantity of radiation absorbed by the glass in BTU per (hour) (square foot) from *EQ.* 18.

ABSORBED	=	127.78

calculate the quantity of radiation transmitted through the glass in BTU per (hour) (square foot) from *EQ.* 19.

TRANSMITTED	=	43.19

given that *ABSORPTIVITY* equals *EMISSIVITY*, and *RADCONOUT* equals 4.0 BTU per degree Fahrenheit, calculate the average temperature of the glass in degrees Fahrenheit from *EQ.* 21.1.

MEANGLASSTEMP = 64.97

calculate the combined coefficient of heat transfer from the inner surface of the glass in BTU per (hour) (degree Fahrenheit) from *EQ.* 21.2.

RADCONIN = 1.13

calculate the combined heat transfer coefficient for the glass and air films in BTU per degree Fahrenheit from *EQ.* 21.3.

U = 0.88

from *EQ.* 21, calculate the heat gain contribution from the re-radiation and convection of direct radiation absorbed by the glass in BTU per (hour) (square foot)

RADCONVECT = -8.85

calculate the total rate of heat transfer from direct radiation passing through glass in BTU per (hour) (square foot) from *EQ.* 22.

DIRECTGAIN = 34.34

calculate the required building augmentation in BTU per hour from *EQ.* 53

AUGMENTATION = 65,772.00

Part D: Life-cycle Energy Cost Calculation

(Alternative 1)

calculate the amount of energy consumed by the heating system in BTU per hour using *EQ.* 59 for RWFS, or *EQ.* 59, *EQ.* 61, and *EQ.* 62 for FAS

ENERGY = 93,960.00

VENTWARM = 2,532,714.

TOTALENERGY = 2,626,714.

calculate cost of heating in dollars, from *EQ.* *64A* for FAS, or *EQ.* *64B* for RWFS

HEATCOST = 11.00

enter initial cost of glass analyzed in this study in dollars

GLASSCOST = 34,272.00

calculate the single present worth factor for this analysis from *EQ.* 37

SPW = 0.88

calculate the present worth of *HEATCOST* from *EQ.* 38, given *FUTURE* equals *HEATCOST*

PRESENT = 9.68

sum *PRESENT* and *GLASSCOST* to produce life-cycle cost for this static analysis

$LCC = 34{,}281.68$

Part C: Heat Gain Calculation Through Double Glazing

(Alternative 2)

from Table 1 select the solar-optical properties for the exterior layer of glass in the double glass assembly

TRANSMISSIVITY = 0.56

ABSORPTIVITY = 0.38

REFLECTIVITY = 0.06

from Table 1 select the solar-optical properties for the interior layer of glass in the double glass assembly

TRANSMISSIVITY2 = 0.85

ABSORPTIVITY2 = 0.07

REFLECTIVITY2 = 0.08

calculate the quantity of radiation absorbed by outer layer of glass in BTU per (hour) (square foot) from *EQ.* 18

ABSORBED = 68.39

from manufacturer's specifications enter the air space thickness for the double glass assembly in inches

AIRSPACE = 0.25

given that *RADCONOUT* equals 4.0 BTU per degree Fahrenheit, calculate the mean glass air space temperature in degrees Fahrenheit from *EQ.* 26

MEANGLASSTEMP = 57.57

calculate the temperature difference of the surrounding air in degrees Fahrenheit from *EQ.* 27

TEMPDIFF = 42.00

calculate the effective air space emissivity from *EQ.* 29.

EEMISSIVITY = 0.063

select the appropriate heat transfer coefficient for convection and radiation in BTU per (hour) (square foot) (degree Fahrenheit) from Table 2

INTERCONSTANT = 1.30

given that the emissivity (*EMISSIVITY*) for a double glazed assembly equals its effective emissivity (*EEMISSIVITY*) calculate the combined coefficient of heat transfer for the inner surface of the assembly in BTU per (hour) (degree Fahrenheit) from *EQ.* 21.2

RADCONIN = 0.57

given that *RADCONOUT* equals 4.0 BTU per degree Fahrenheit, calculate the combined heat transfer coefficient for the glass and air films in BTU per degree Fahrenheit from *EQ.* 21.3

U = 0.50

calculate the rate of convective heat transfer through the outer layer of a double glazed assembly in BTU per (hour) (square foot) from *EQ.* 21

RADCONVECT = -12.45

calculate the rate of convective heat transfer through double glazing in BTU per (hour) (square foot) from *EQ.* 30

RADCONVECT2 = -12.42

calculate the rate of direct transmission of radiation through double glazing in BTU per (hour) (square foot) from *EQ.* 32

DIRECT2 = 85.66

calculate the total rate of heat transfer from direct radiation through double glazing in BTU per (hour) (square foot) from *EQ.* 33

DIRECTGAIN = 73.25

calculate the required building augmentation in BTU per hour from *EQ.* 54

AUGMENTATION = -97,650.00

Part D: Life-cycle Energy Cost Calculation

(Alternative 2)

calculate the amount of energy consumed by the heating system in BTU per hour using *EQ.* 59 for RWFS, or *EQ.* 59, *EQ.* 61, and *EQ.* 62 for FAS

ENERGY = 0.00

VENTWARM = 0.00

TOTALENERGY = 0.00

calculate cost of heating in dollars, from *EQ.* *64A* for FAS, or *EQ.* *64B* for RWFS

HEATCOST = 0.00

enter initial cost of glass analyzed in this study

GLASSCOST = 39,480.00

calculate the single present worth factor for this analysis from *EQ.* 37

SPW = 0.88

calculate the present worth of *HEATCOST* from *EQ.* 38, given *FUTURE* equals *HEATCOST*

PRESENT = 0.00

sum *PRESENT* and *GLASSCOST* to produce life-cycle cost for this static analysis

LCC = 39,480.00

Summary of Results

Alternative 1

```
required building  augmentation energy  in BTU
per hour

                              AUGMENTATION      =  65,772.00

amount of energy consumed by heating system in
BTU per hour

                              TOTALENERGY       = 2,626,714.

cost of heating in dollars

                              HEATCOST          =      11.00

initial cost of glass

                              GLASSCOST         =  34,272.00

present worth of cost of heating in dollars

                              PRESENT           =       9.68

life-cycle cost in dollars

                              LCC               =  34,281.68
```

<u>Alternative 2</u>

required building augmentation energy in BTU per hour

AUGMENTATION = -97,650.00

amount of energy consumed by heating system in BTU per hour

TOTALENERGY = 0.00

cost of heating in dollars

HEATCOST = 0.00

initial cost of glass

GLASSCOST = 39,480.00

present worth of cost of heating in dollars

PRESENT = 0.00

life-cycle cost in dollars

LCC = 39,480.00

Results of Case Study

On the basis of the analysis conducted between the two alternative glazing materials alternative 2 (the metal edge Twindow) is more satisfactory on the basis of the space heating costs for the location, time, and date specified (*HEATCOST*). This analysis for alternative 2 is inconclusive even for this particular hour of the year since the additional 97,650.00 BTU of solar heat gain (*AUGMENTATION*) would have to be removed from the building at additional cost. (Costs of energy in this paper deal only with space heating.)

Based solely upon a life-cycle cost analysis, (*LCC*) for this hour of the year alternative 1 is more satisfactory, primarily because of its lower initial cost (*GLASSCOST*). A climatic simulation would be necessary to allow a total analysis between these two alternatives.

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A METHODOLOGY FOR THE EVALUATION OF THERMAL PERFORMANCE OF WINDOWS BASED UPON LIFE-CYCLE COST

by

Timothy D. Butler

(ABSTRACT)

The purpose of the research described herein was to establish the algorithms necessary to perform life-cycle cost analyses of the solar heat gain through building windows as a function of the ability of the glazing to allow the penetration and utilization within the interior built environment of available sensible radiation from the natural environment. The life-cycle cost model allows evaluations which will influence the glazing selection in response to seasonal changes in insolation and the net energy effect of orientation.

The research consisted of two phases. The first included a search of the literature on energy related studies and resulted in a compilation of algorithms necessary to determine heat gain through windows, equations required to determine energy cost, and equations necessary to perform life-cycle costing. The second phase of the research was a synthesis process to resolve interfacing problems between unlike calculation systems and units of measure which were encountered. This was accomplished through basic inductive processes familiar to life-cycle

costing/value engineering techniques. This resulted in a schematic model to correlate the heat gain calculation with the energy cost calculation to determine the life-cycle cost for the window assembly.

The research built upon existing processes to develop a more comprehensive technique for the analysis of window systems to aid in meeting economic performance specifications during the winter heating months.