COMPUTER-AIDED ENERGY SAVINGS REDESIGN OF THE EXTERIOR ENVELOPE OF AN APARTMENT BUILDING

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ABSTRACT

A finite difference thermal analyzer was used to predict energy savings affected by redesign of the exterior envelope of a Denver hi-rise apartment building. The redesigned building utilized passive solar features that will save 40% of the energy required for the original building and can increase the comfort level during the hot summer months.

The thermal modeling technique is described in detail for three building configurations. The passive solar elements investigated included building orientations, thermal mass of wall and size and shading of windows. Monthly energy requirements for each configuration are presented in tabular form.

INTRODUCTION

The authors were involved in challenging thermal trade-off study which was part of Phase II Development of Energy Performance Standards for the Design of New Buildings, sponsored by HUD/DOE and administrated by the A.I.A. Research Corporation of Washington, DC. In brief, each of the selected 165 architect-engineer teams were asked to completely redesign an existing building in accordance with available energy conservation techniques and to determine how much energy could be saved. In our case, we were asked to redesign a 200 unit, 13 story hi-rise apartment building near downtown Denver, Colorado. The only constraints imposed on the study was that any modification must conform to the Denver Building Code and the HUD Minimum Property Standards for Multifamily Housing. The architect team member was allowed to consider almost any design to find a building configuration with the best energy savings potential.

Preliminay calculations indicated a passive solar approach would be the most effective. A new building envelope was developed which incorporated features such as southern (SE or SW) exposure of all living and bedrooms, some increase in window areas, elimination of glass areas to the north, increasing the mass of the building walls to the south and west, and providing proper shading.

The Rocky Mountain Region is blessed with abundant solar energy, which if properly used can reduce the depletable energy requirements of almost any building. Because of the many variables (weather, sun, building envelope, orientation, wall construction, etc.) influencing the energy balance and

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energy consumption, a computer-based analysis was selected.

A finite difference computer program called MITAS (developed for aerospace applications originally) was used to perform the energy analysis, rather than a conventional response factor computer program. The authors have used the MITAS program for several years to perform energy analyses on a variety of buildings. Three different apartment configurations were modeled in the computer simulation. Heating and cooling requirements for each apartment configurarion were calculated for each hour for the entire year. Each of the apartment configurations is shown with its corresponding computer model. Results are listed in tabular form.

DISCUSSION

Figure 1 shows the building as built in 1975. It is an "L" shaped design with 9 stories on one wing and 13 on the other wing. Floors and ceilings are solid prestressed concrete. Exterior walls consist of 1 inch stucco on the outside, 3 ½ inch metal studs with R-11 insulation between the studs, and ½ inch gypsum board on the inside. Window areas extend horizontally over the full length of the building. Heating is provided by a central hot water system, with each unit individually controlled. The apartment units are not cooled. However, common areas on the first floor, such as lobby, offices and meeting rooms are cooled by refrigerated air conditioning systems. The building is ventilated and partially cooled by pressurizing the central corridors with cooled outside air.

The guidelines for redesign set down by the A.I.A. Research Corporation were very liberal. The architect-engineer teams could consider any concept, provided it used current state-of-art building construction methods, did not change the functional scope of the building and conformed to local building codes, zoning laws, and HUD Minimum Property Standards. Concepts more costly than the original design could be considered and were limited only by professional judgement. Cooling was not considered since the original building did not have cooling. The cooling loads were calculated in this study and are included here for information only. Some cooling might be provided by opening the operable windows. The exact amount of cooling from opening windows is difficult to model since each resident might use different criteria for opening windows.

The first concept that was considered changed the orientation of the building so that the apartments faced either east or west, instead of northeast and southwest. Window areas were reduced and the thermal mass of the wall on the west side was increased. The heavier wall consisted of 1 inch of stucco on the outside, 1½ inch of Styrofoam insulation, 8 inch cinder block filled with sand and ½ inch gypsum board in the inside.

The other concept that was considered was called the sawtooth design and is shown in figures 2 and 3. This concept is a complete redesign of the building to obtain southeast or southwest window exposures for all apartments and no windows on the north. Figure 4 shows a cross section through the living room including the exterior shading devices employed. The exterior walls facing northwest and southwest were changed from lightweight frame walls to medium weight cinder block walls, the same as the west walls of the first concept mentioned above. Walls on the northeast and southeast remained the same as the original design. Window areas were reduced and an overhang was provided to reduce summer solar heat gain.

All the design changes mentioned above are made using sound engineering judgement. The team members thought that these changes should reduce the energy consumpion of the building. However, verification of the efficacy of the changes and the magnitude of the energy savings requires more than pure judgement. One sure way of determining the energy savings is to make the changes and measure the results. This method is costly and time consuming. Another method is to use a computer simulation that predicts energy transfer through the various building elements. There are many computer programs available that are designed to predict energy consumption of a building. The better computer programs use transfer functions or finite difference methods to predict energy transfer in the building elements. We chose to use the finite difference approach because of prior experience with this type of thermal analysis and the belief that if is more flexible and controllable in the hands of an experienced user.

The particular finite difference thermal analyzer that was chosen is called MITAS. This program has been used for more than 15 years in the aerospace industry to predict thermal performance of aircraft and spacecraft.

COMPUTER MODEL DETAILS

Three apartment configurations were selected for detailed analysis ie. original design, straight wall concept and the sawtooth concept. Since the only change between each configuration was wall orientation and configuration, is was decided to model only the walls, floor and windows of a representative apartment. Air infiltration was not included in the model because it would be approximately the same for all concepts and might mask the effects of the other changes. A detailed discussion of each model is presented below.

Original Design

Figure 5 shows the orientation, configuration and node diagram for the original design. The node diagram represents one apartment on one side of the building. A similar node configuration was used for the other side of the building. The wall is represented by two nodes, one for the stucco and one for the framewall. Each of these nodes was assigned the appropriate thermal mass to simulate the actual wall. The stucco wall was connected to the variable external air temperature with a variable conductor to simulate wind induced convection. A variable energy quantity was impressed upon the outside of the stucco node to simulate solar radiation. The other side of the stucco node was connected to the framewall with a conductor that simulates the conduction in the wall.

The constant temperature internal air boundary node was connected to the framewall with a conductor to simulate the natural convection at the internal wall of the apartment. The 8 inch thick concrete floor of the apartment is simulated with a node of the appropriate thermal capacitance. Another vaiable energy quantity was impressed on the floor node to simulate solar energy transmitted through the windows onto the floor. The model is completed by a window node connected to the internal air and the external air. Hourly values for solar radiation incident on the external wall and internal floor, outside air temperature, and external surface forced convection were supplied by a program that used actual hourly Denver weather data and ASHRAE methods to generate solar radiation. Heating and cooling requirements for the apartment were obtained by measuring the amount of energy required to maintain the internal air node at a constant 74 degrees F.

A transient solution with the variable weather and solar boundary conditions was performed with an implicit backward differencing subroutine in the MITAS program. Detailed hourly temperature and heat flux results from the MITAS transient solution were written on a magnetic tape so that the solution could be examined for any time frame in the year.

Straight Wall Concept

The straight wall concept is very similar to the original design except for facing direction of the walls, the size of the walls and windows and the mass of the walls on the west side. The node diagram for the east side is essentially the same as the original design. Figure 6 indicates the node diagram for the west side. The solar boundary conditions for the straight wall design are different than the original design because the walls face a different direction(east and west rather than northeast and southwest). The same transient thermal solution was used as that for the original design.

Sawtooth Wall Concept

Figure 7 shows the configuration and node diagram used to simulate the sawtooth wall concept. The model for the sawtooth concept is more complex than for the other concepts because of the additional wall and more complex wall configuration.

The node diagram for the northeast and southeast walls is similar to that for the original design. For the northwest and southwest walls one side of the stucco wall is connected to the external air by a conductor that is dependant on the direction and velocity of the wind. The other side of the stucco is connected to the outer surface fo the cinder block by a conductor that accounts for the resistance of the Styrofoam insulation. The outer surface of the cinder block is connected to the inner surface of the cinder block and the dry wall by a conductor that accounts for the resistance of the of the cinder block and the dry wall. Then the inner surface of the dry wall is connected to the internal air by a conductor that simulates the natural convection. The conctete floor is connected to the internal air by a natural convection conductor. The concrete floor and external surface of the wall have variable energy quantities impressed on then to simulate incident solar radiation. The same methods as described for the original concept were used to provide variable external air temperature and solar radiation boundary conditions. The transient thermal solution method used on the original design was also used for the sawtooth design concept.

RESULTS

All three concepts were run simultaniously and detailed output was recorded on magnetic tape. A seperate program was used to interrogate the magnetic tape to extract the summarized results shown in Table 1. The table is divided into two parts, one for heating and one for cooling. The cooling loads are shown only for information because they were a by product of the analysis. For each of the three concepts the calculated heating and cooling loads for a typical apartment on each side of the building are shown in Table 1.

For the heating season the straight wall concept will save 18% of the energy required for the original design and the sawtooth concept will save 40%. If the buildings were cooled the straight wall concept would save 35% and the sawtooth concept would save 38% of the energy required for the original design. These are based on an inside temperature of 74 degrees F.

The increase in construction cost due to the stepped perimeter design and heavier wall construction has been estimated to amount to 6½ %. This increase in cost was well within the guidelines imposed by A.I.A. Research Corporation.

CONCLUSIONS

All of the energy savings realized by the two alternate designs can be attributed to passive solar features. The straight wall concept eliminated the northeast window and wall exposure, which significantly reduced the heating energy required for the east facing apartment. Even though the west facing apartment experienced an increase in heating energy, the total for both apartments was less than for the original design. The lightweight east wall permitted better utilization of the morning solar energy when the outside temperature was low.

Additional energy savings were realized with the sawtooth concept, even though the wall area is thirty percent greater than the straight wall concept. Most of this savings is due to the increased solar gain through the southeast and southwest facing windows.

The cooling energy requirements would have been significantly lower for the straight wall and sawtooth concepts. Part of the reduction is due to the summer shading provided by the overhang above the windows. The cooling energy requirements are based on a 74 degrees F inside temperature. This is somewhat lower than is customary today. It is possible that if the internal temperature was set at 80 degrees F that the cooling requirements would become insignificant.

Building energy systems, including all types of passive building features, can be simulated accurately with finite difference thermal analyzers. Yet, very few analysts use finite difference analyzers. This is probably because these programs do not include equipment simulation subroutines necessary for building energy thermal analysis. Special heating and cooling system subroutines were assembled for this study. These subroutines are not complicated and can be constructed by anyone familar with FORTRAN programming. There is a need for someone with the proper funding to assemble the various equipment simulation subroutines for use in finite difference thermal analyzers. If this were done, more analysts would use this flexible, powerful and accurate method to simulate building energy systems.

REFERENCE

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2. Pedreyra, D. "Finite Difference Computer Evaluation of a Passive/Hybrid Solar Heated House", Proceedings of The 1978 Annual Meeting of The American Section of The International Solar Energy Society, August 1978.

ACKNOWLEDGMENT

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TABLE 1. TYPICAL APARTMENT UNIT HEATING AND COOLING LOAD SUMMARY
MBTU/MONTH

SEASON	MONTHS	ORIGINAL N.EAST	ORIGINAL S.WEST	ORIGINAL TOTAL	CONCEPT 1 (STRAIGHT) EAST	CONCEPT 1 (STRAIGHT) WEST	CONCEPT 1 (STRAIGHT) TOTAL	CONCEPT 2 (SAWTOOTH) EAST	CONCEPT 2 (SAWTOOTH) WEST	CONCEPT 2 (SAWTOOTH) TOTAL
HEATING	OCT	620	-972	-352	-143	240	97	-323	-182	-505
	NOV	1,843	478	2,321	735	1,172	1,907	572	803	1,375
	DEC	2,396	1,058	3,454	1,103	1,591	2,694	942	1,210	2,152
	JAN	2,684	1,136	3,820	1,180	1,822	3,002	970	1,383	2,353
	FEB	2,270	972	3,242	1,009	1,481	2,490	879	1,151	2,030
	MAR	1,540	300	1,840	492	993	1,485	430	725	1,155
	TOTAL 6 MONTHS	11,353	2,972	14,325	4,376	7,299	11,675	3,470	5,090	8,560
COOLING	JUN	-1,995	-2,031	-4,026	-1,363	-1,225	-2,588	-1,191	-1,167	-2,358
	JUL	-2,875	-2,779	-5,654	-1,936	-1,779	-3,715	-1,798	-1,716	-3,514
	AUG	-1,882	-2,280	-4,162	-1,443	-1,215	-2,658	-1,389	-1,285	-2,674
	TOTAL 3 MONTHS	-6,752	-7,090	-13,842	-4,742	-4,219	-8,961	-4,378	-4,168	-8,546

(-) VALUES INDICATE COOLING LOAD

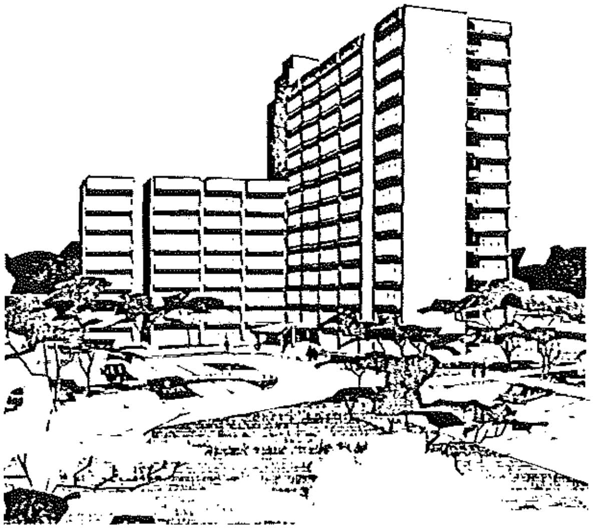

FIGURE 1. 13-STORY HI-RISE APARTMENT BUILDING

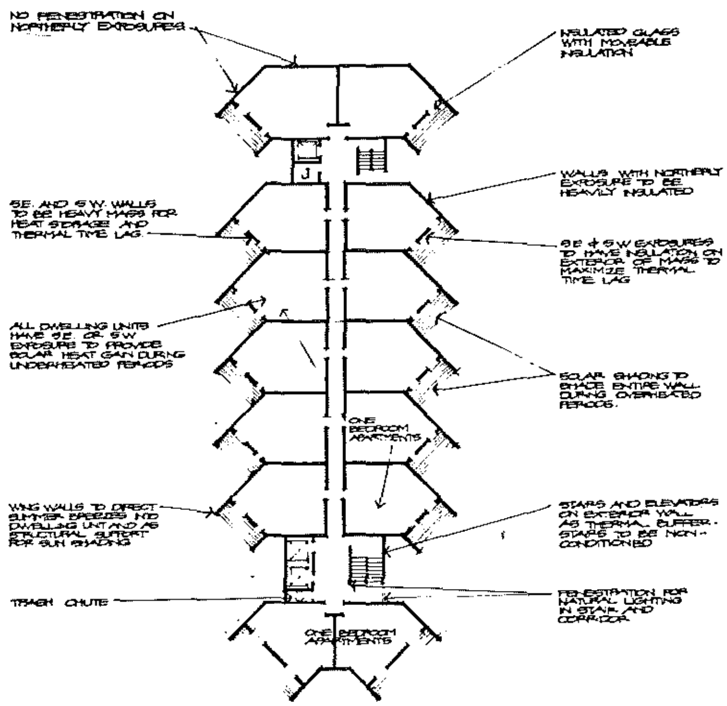

FIGURE 2. TYPICAL FLOOR PLAN OF REDESIGN

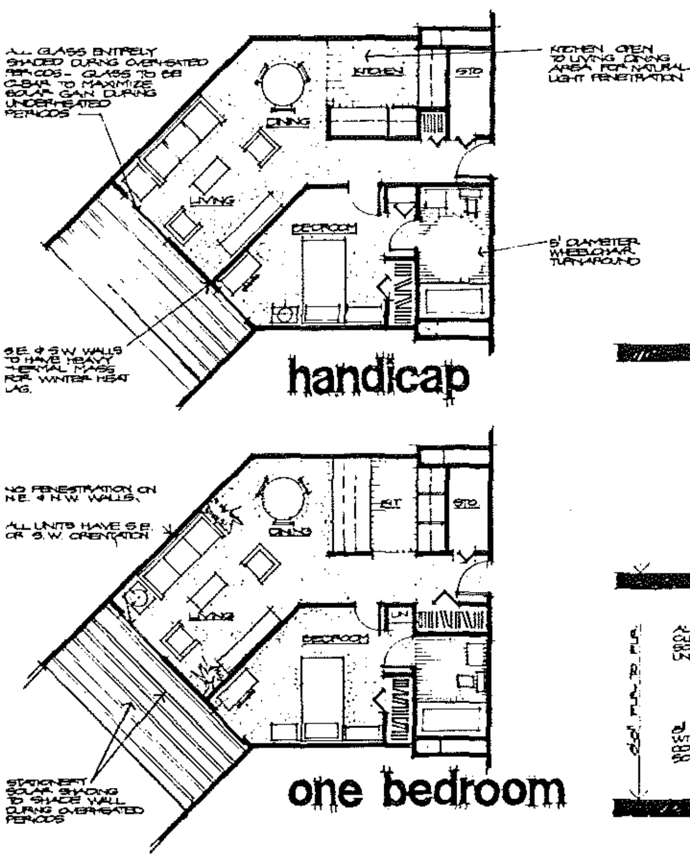

FIGURE 3. DETAIL UNIT PLAN

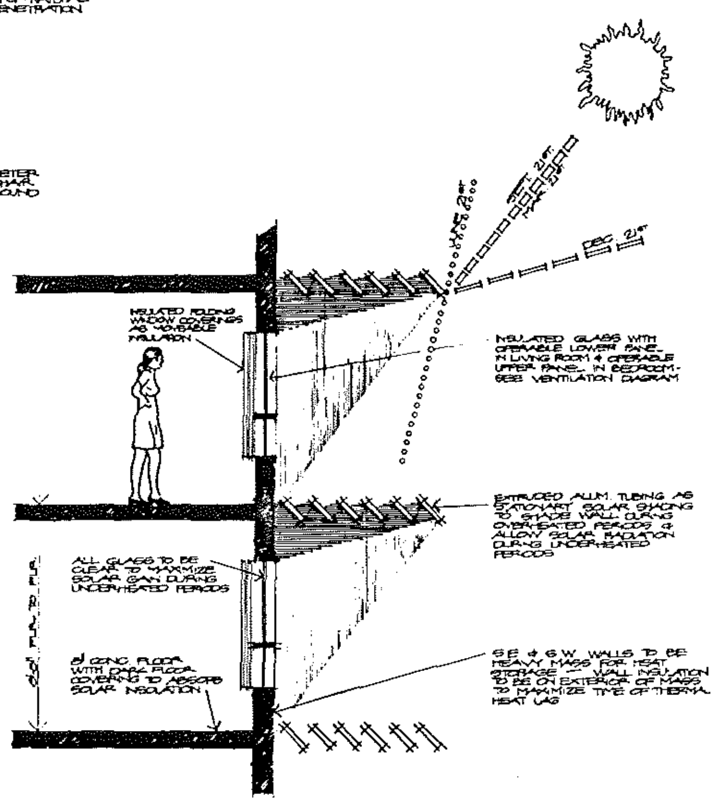

FIGURE 4. SECTION THROUGH LIVING ROOM

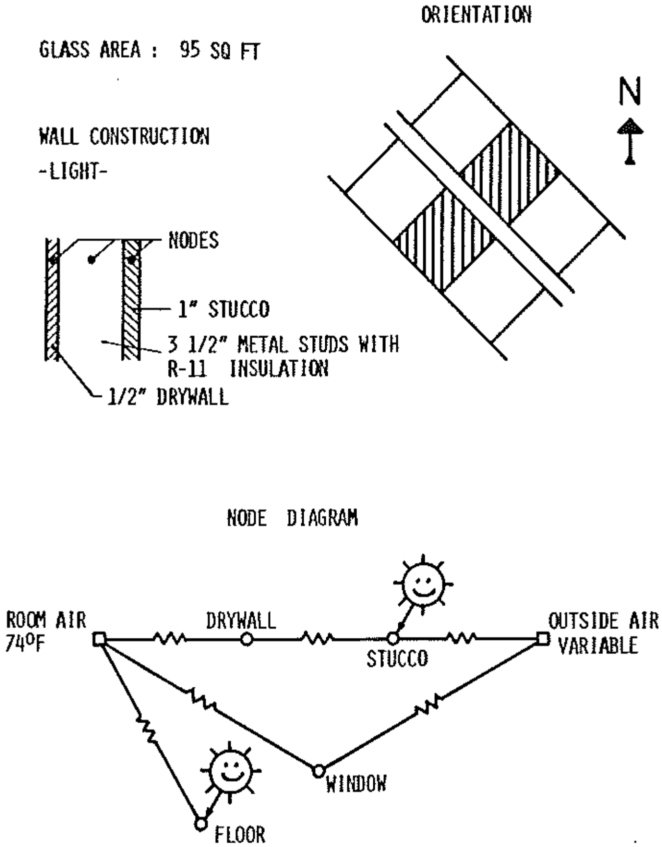

FIGURE 5. ORIGINAL DESIGN CONFIGURATION AND NODE DIAGRAM

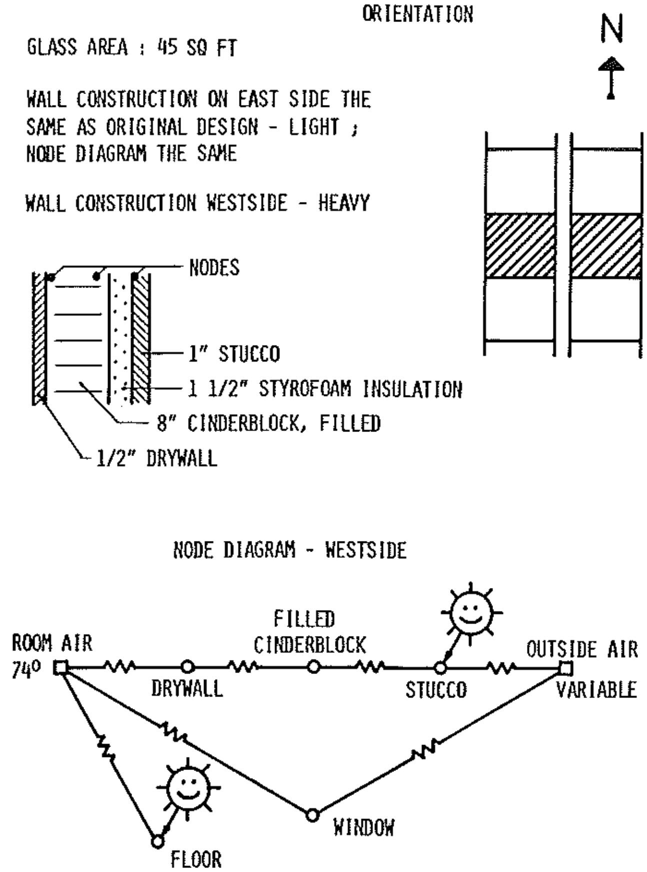

FIGURE 6. STRAIGHT WALL CONCEPT CONFIGURATION AND NODE DIAGRAM

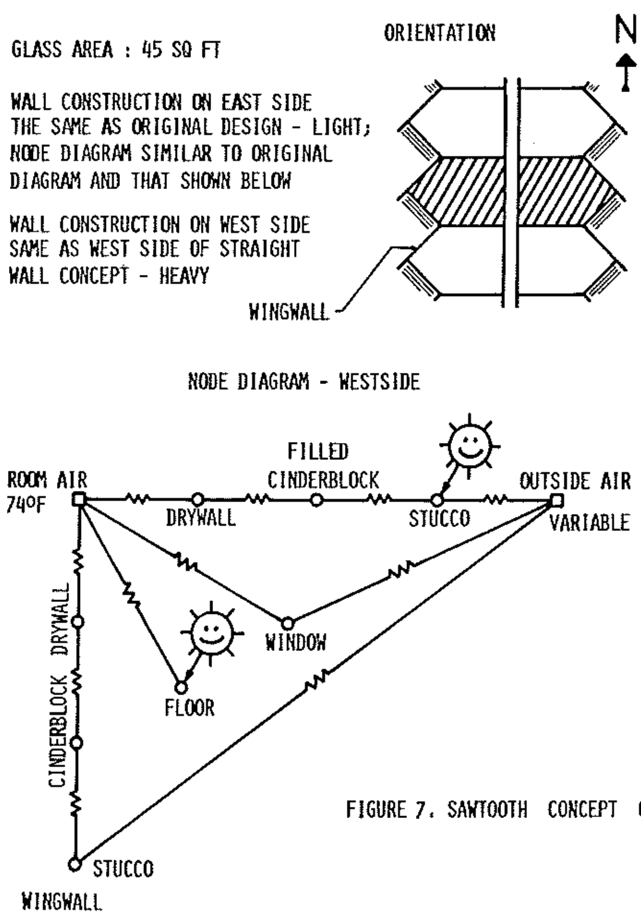

FIGURE 7. SAWTOOTH CONCEPT CONFIGURATION AND NODE DIAGRAM

Session I - Questions and/or Comments

Twenty and McQueen

a. Sherwood R. Peters, Lawrence Berkeley Laboratory

Q: The usefulness of the paper would be greatly enhanced by including the governing equations and the listing of the coding of the computer model.

A: All equations needed for the analysis of system performance are included in Figures 1 through 4 along with system schematic drawings. The coding of the model for the calculator was and is felt to be proprietary property of Energy Management and Control Corporation. The purpose of the paper was to present the theory of development of the programs and to provide such information as to allow the reader to develop similar programs.

Hans

a. Sherwood R. Peters, Lawrence Berkeley Laboratory

Q: Attempts to simplify the calculation of energy budget analysis is a highly desirable thing. The concept of solar acceptance factor appear to be a useful concept. My understanding is that it is to be a function of the temperature difference, the energy received and the thermal mass. It would appear to me necessary to have some way of relating the ability of the energy received to meet the load. There are two reasons why this situation may occur. In a relative mild climate there may be a large number of degree days that are relative close to the balance point of 65°. Large solar gains may not be able to be fully utilized, requiring a large part of the gain to be dumped. On the other hand in very severe climates there may be few days in that condition. Most of the degree days may be a large distance from the balance point, hence little likelihood that energy in those months would have to be dumped. The above comments all assume that the balance point is really 65°. To make this approach useful it is necessary to have good understanding of what the delta T is, that is to say the delta T from the balance point to some average T ambient. It also appears necessary to have some understanding of the distribution of energy received with respect to the size and time history of the load. If indeed these are factors being included, it appears that approach proposed should be quite useful.

A: Problems of modeling the effects of actual heating load distribution are inherent in all simplified design methods based on the degree-day concept and load averaging. Adding the considerations of solar gain distribution to those of heating load distribution increases this complexity still further. The ASHRAE Modified Degree-Day Procedure permits some correction of the error resulting from load averaging. It is intended that the proposed Variable Temperature Design method would permit similar compensation for climatic effects that are not quantified by comulative degree-day numbers. The alternative presently available reference of outdoor design temperatures, however, also does not seem to represent a useful reference point for these purposes. Consequently, this phase of the proposal still needs further development. The comparative heating load calculations discussed in this paper show that at sufficiently large indoor-outdoor temperature differentials the streamlined procedure based on load averaging can yield acceptably accurate heating load estimates, but the boundaries of such conditions have remained uninvestigated. The temperature dependency of the solar acceptance factor is recognized by keying it to a reference temperature condition (SAFn°F). This reference temperature may be the average indoor-outdoor temperature differential for the period under consideration, assuming the indoor temperature in turn to be referenced to a standardized room condition (such as 5°F$\pm$ daytime temperature swings about a 65°F reference level). Variations in SAF values between mid-winter and spring or fall months resulting from such temperature references should be consistent with variations in actual design conditions reflected by more detailed energy balance analysis.

b. Robert O. Smith, Robert O. Smith & Associates

Q: How do you estimate the amount of solar gain likely to be actually used in the building? (The remainder must be rejected or stored.)

A: Heat received and stored for later recovery is part of the useful solar heat gain. Rejection of solar heat by reflectance is modeled by adjustments to a number of design coefficients. Reflectance from glass is accounted for in the selection of an appropriate glass transmittance coefficient T. Reflectance from variable sun control devices (such as curtains and venetian blinds) is modeled by adjustments to the energy management factor EMF. Reflectance from interior room surfaces is one of the variables considered in the determination of the solar acceptance factor SAF. Rejection of solar heat through an increased indoor-outdoor temperature differential during the daylight hours is a function of the starting temperature and room temperature rise for that period. Starting temperature effects are recognized by adjustments to energy management factor EMF. Room temperature rise is a function of certain design and construction features (distribution of sunlight and building thermal mass effects). The basic solar acceptance factor (SAF) value is intended to be keyed to a standardized room temperature profile (such as a $5^{o}F\pm$ variation about a $65^{o}F$ reference level, or $60^{o}F$ to $70^{o}F$ temperature swing). Although control of overheating beyond that target level may not be automatic, such excess heat is no longer considered part of the useful solar heat gain. The recognizable solar heat credit, therefore, is estimated on the basis of an SAF value for a well designed house with sufficient thermal mass is estimated at 0.95 (with a 5-percent allowance for interior reflectance losses), the pro-rated value for a similar structure with insufficient thermal mass may be only 0.67.

Dexter

a. Mervin W. Dizenfeld, P.E., U. S. Department of HUD

Q: Since mass is more important for cooling, and insulation for heating, where would be the ideal location for insulation in relation to mass in mild climates and in severe heating climates?

A: Walls with insulation inside the thermal mass perform somewhat different from walls with insulation outside the mass. For maximum energy savings, the insulation placement should be determined not by climate but by the hours which the building is conditioned. If the building is conditioned 24 hours per day, the insulation should generally be placed outside the mass. The mass is then adjacent to the conditioned space and helps to stabilize loads by storing heat or coolth* within the conditioned space. However, buildings conditioned less than 24 hours per day should generally have insulation near the inside wall surface with any mass outside the insulation. This is because energy savings due to night temperature setback are greatest if the space temperature is quite responsive. The temperature thermostat is set back and rises quickly in the morning when the termostat is set up to the daytime value. Buildings with insulation near the inside wall surface are more responsive than buildings with thermal mass at the inside surface. Thus, the ideal position for insulation is generally at the inside surface of walls of buildings which are intermittently conditioned.

*From Yellott, J. "International and Historical Perspective", DOE Third National Passive Solar Heating and Cooling Conference, San Jose, 1979.

b. F. Heller, Toronto Board of Education

Q: For servere climates such as southern part of Canada where is the best possible location off the mass wall (a) on outside of wall, (b) close to interior condition, or (c) between insulation barriers?

A: See above.

c. Robert H. Loreaux, Solarcrete Corporation

Q: Is mass considered external or internal to insulation? What difference may that make? Is mass factor not conditioned by type of material and/or specific heat rather than simply weight?

A: The results presented here are really a mixed bag. Some of the walls have inside insulation and some outside. The specific walls used in the study of mass are presented in Table 6, Chapter 25, ASHRAE Handbook of Fundamentals, 1977. The insulation study used walls 36-39 of 1977 ASHRAE Chapter 25 Table 27. As discussed in answer to questions 1 & 2 above, walls do perform somewhat differently with different insulation locations. Optimal location is determined by the hours the building is occupied.

The effects of mass on wall performance do depend on specific heat as well as weight. The specific heat of most walls is in the range of 0.20-0.25 Btu/lb-F, and is not under the control of the designer. However, wall weight can be selected by the designer. For this reason I have presented some results here in terms of weight rather than thermal mass.

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a. William Rudoy, University of Pittsburgh

Q: What were the internal gains from people, lights, and appliances? Did you consider radiation interchange between exterior surfaces and the internal partitions, floors and ceilings?

A: Internal gains from people, lights and appliances were not included in the simulation. They were excluded because the purpose of the study was to determine relative effects of certain architectural changes and the reduction in heating requirements as a result of the internal heat gains would have made no difference in the study results. Radiation exchange between the various internal surfaces were not included in the simulation. The added complexity of radiation modeling could have been included but was not because its inclusion would have made no difference in the study results.

b. R. I. Hussli, Reynolds Metals

Q: Were operable windows used in the apartment building? If so, was natural ventilation considered in the analysis?

A: Yes, operable windows were used in the apartment building. Natural ventilation was not included in the analysis because of the difficulty of accurately modeling the human element that determines which windows are open and how far they are opened. Furthermore the primary purpose of the study was to determine savings in heating energy and windows are not normally open during the heating season.