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BUILDING ENVELOPE THERMAL ANOMALY ANALYSIS

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EXECUTIVE SUMMARY

A detailed study has been made of building energy thermal anomalies (BETA's) in a large modern office building using computer simulation, on-site inspections, and infrared thermography. The goal was to better understand the heat and moisture flow through these "bridges", develop the beginnings of a classification scheme, and establish techniques for assessing the potential for retrofit or initial design modifications.

In terms of presently available analytical techniques, a one-dimensional equivalent of the bridge and its affected area can be created from a steady-state computer simulation. This equivalent, combined with a degree day model, yields good estimates of the bridge behavior in buildings employing heating only. With heating and cooling, the equivalent must be used with an hour-by-hour simulation.

A classification scheme based on the one-dimensional equivalent is proposed which should make it possible to create a catalog of basic bridge types that can be used to estimate their effects without requiring a complete hour-by-hour simulation of each building. The classification relates both energy loss and moisture condensation potential to the bridge configuration and the building envelope. The potential for moisture condensation on interior surfaces near a BETA was found to be as significant as the energy loss and this factor needs to be considered in assessing the complete detrimental effects of a bridge. With such a catalog, building designers and analysts would be able to determine and estimate the advantages or disadvantages of modifying the building envelope to reduce the impact of a thermal bridge.

I. INTRODUCTION

At this point in the understanding of building energy thermal anomalies (BETA's) there are a number of unanswered questions of considerable importance. First of all, one seeks some method of incorporating these thermal anomalies into building energy use simulations. A thermal anomaly, also referred to hereafter as a thermal bridge, is defined as a penetration by any heat conductive material through a buildings thermal insulation system. A detailed model of each bridge cannot easily be run as part of a building hour-by-hour simulation by the architectural design industry because of data input and computing time constraints. On the other hand, simple models are insufficient for the multi-dimensional nature of the heat flow in the region of bridges. An easily applied methodology for analysis is thus one important long term goal of the BETA program.

Secondly, we need to develop a catalog of thermal anomaly types based on some criteria such as structural configuration or difference in the heat flow between the anomaly and the surrounding structure. An important result of such a classification scheme is the ability of a design firm to identify from this scheme the bridges within a building that can be economically redesigned to prevent excessive impact on the energy use of the building. Additionally, even though a particular bridge may have an economic solution it is important that the designer determine the frequency of occurrence of that bridge to be certain that the investigation towards a design change is warranted. In other words, unique thermal bridges that occur in limited numbers may not be practical to redesign if the magnitude of the energy savings will not compensate for the architects design time.

Finally, we need to set down some procedures by which the detrimental effects of anomalies may be negated either through retrofit activities or modification of new building construction methods. Such procedures are dependent on economic as well as engineering considerations. For example, a thermal bridge which increases the envelope heat loss by 5% may be worth fixing in a building

where envelope losses constitute 50% of the total building energy use but not in one where envelope losses are only 30% of the total. Such differences are possible between identical buildings with different use patterns, internal loads, climatic conditions or HVAC systems. Therefore, the economics attributable to retrofitting a bridge is a complex calculation and cannot be generalized simply based upon typical wall or roof configurations. In addition, we must consider effects of moisture damage due to bridges because of local cold areas at the bridges where moisture may condense. The problem, therefore, is more than simply identifying thermal bridges in various structures.

At present, we simply do not have enough information to answer these questions, nor is there a clear methodology for organizing the assault on the unknowns. We need to study thermal bridges in more buildings, obviously, but we need to do this intelligently to avoid spending excessive efforts in non-productive areas.

In the final analysis, what we need (simply stated) is a method by which a designer can identify thermal anomalies in a given building, evaluate their impact on the energy use of the building, and assess economic solutions to those bridges that have major operating cost impact.

To this end, we have carefully examined the thermal performance of a number of thermal bridges in a typical modern office building using very detailed numerical models of the bridges coupled with hour-by-hour simulations of its energy use. This has been augmented by on-site examinations of the structure and infrared thermography.

The overall methodology of the study was as follows:

1. Select a typical modern office building.

2. Model the building energy use with a detailed hour-by-hour simulation (DOE-2) verified against actual utility bills.

3. Identify potential thermal bridges by examination of construction drawings. Verify the existence of these bridges by site visits and confirm them as sources of heat loss by infrared thermography.

4. Model the heat transfer characteristics of the thermal bridges with a detailed finite difference simulation program (HEATING 6).

5. Determine the effects of these bridges on the energy use of the building by altering and re-running the DOE-2 hour-by-hour simulation.

6. Develop some possible "fixes" of the bridges and evaluate their impact with the computer programs.

Using this approach, we were able to judge the true impact of various thermal anomalies on the economics of building operation, which is the key factor in determining whether or not to expend money to modify the building design. The study also pointed out some interesting facts about how modern office buildings operate, some types of analyses that do not work well and others that appear reasonable for certain types of bridges.

While the total number of thermal anomalies that have been subjected to analysis is still small, we are beginning to see some general characteristics and types. The path towards a classification system now appears somewhat clearer and we shall direct further attention to this topic later in this report.

II. BUILDING DESCRIPTION

The structure used as the base for this study is an office building of typical modern construction located in Northern Virginia. The east side of the building is open to the Potomac River and the other sides face buildings of similar height. The building consists of two main sections:

1. The north section. A 5-story unit of 85,385 square feet containing offices.

2. The south section. A 2-story unit of 22,742 conditioned square feet housing a studio, board room, and supporting offices.

The two sections are linked by a 2-story lobby/entrance of 2600 square feet. Attached to the lobby are a 1686 square foot kitchen/cafeteria and a 713 square foot conference room.

The entire building sits over a partially enclosed parking garage. The floor over this garage is reinforced concrete with 2 inches of rigid insulation with an R-value of 10.2 HR-SF-°F/BTU.

The exterior walls are concrete curtain walls with batt insulation giving an R-value of 14 HR-SF-°F/BTU. The roof consists of built up roofing with rigid insulation giving an R-value of 18.2 HR-SF-°F/BTU.

There are basically 3 types of interior partitions:

1. Concrete block with 12 inches of acoustic insulation around the sound studio (R - 23)
2. Concrete block with tile, stone, or plaster finish (R = 1.5 - 2.5)

3. Gypsum board sandwich with batt insulation (R = 12).

The building houses approximately 390 occupants and operates from 8 A.M. to 5 P.M., 5 days per week.

Glazing is mostly double pane aluminum frame with a solar tint. The total wall and glass areas are as shown in Table 1 below.

Table 1: Model Building Wall and Glass Areas

	South Section	North Section + Penthouse	Lobby
Gross Wall SF	9499	40890	1898
Door SF	48	276	72
Glazing SF	1746	16872	1560
Net Wall SF	8005	23742	266
Roof SF	12334	18375	520
% Glass	18	41	82
SF Floor Over Garage	12858	13474	2384

The activities housed in the various sections are as follows:

South Section:

Floor 1 = audio/visual studio and support areas

Floor 2 = offices and conference rooms

North Section:

Floor 1 = print shop and storages

Floors 2 - 5 = offices

Penthouse = mechanical equipment

The north section has a central core housing rest rooms, elevators and mechanical equipment for each floor with office space occupying the perimeter.

III. ENERGY USE

The annual energy use for the building was analyzed using the DOE-2 computer program. In order to obtain reasonable agreement between the model and actual utility bills, considerable care was taken in assembling the input information. Repeated site visits were made to verify occupancy and equipment schedules, discussions with occupants were conducted, and several runs were made to eliminate errors. In addition, a separate simulation was run with an in-house computer program to further verify the results of the DOE-2 run.

Weather conditions for the study were taken from 1984 NOAA data for Washington National Airport. The annual energy use comparison between the DOE-2 simulation and actual utility bills is shown in Figure (1). The average weather conditions used for the DOE-2 simulation are shown in Figures (2), (3), and (4).

The agreement between actual energy use and the DOE-2 simulation for the year is within 9% which is well within the range of similar studies. Yuill [18] achieved a similar agreement using BLAST to study the energy use in two large office buildings. Diamond [7] performing part of the DOE-2 verification project found agreements between 2% and 24% for the total energy use of seven test buildings. Similar results have been reported by Copeland [6]. Once one adjusts the model for obvious discrepancies, eliminating the remaining difference proves to be impractical. Yuill [18] and Copeland [6] discuss this issue in some detail. In the present study, the following factors were felt to be contributory to the 9% difference:

1. The variable scheduling of outdoor lighting (parking lots, etc) which is part of the utility bill and difficult to predict.

2. Differences in the billing period by the utility company (which does not match monthly beginnings.) Establishing the exact day of meter reading within a few days is not usually possible (a situation encountered by the above cited references as well).

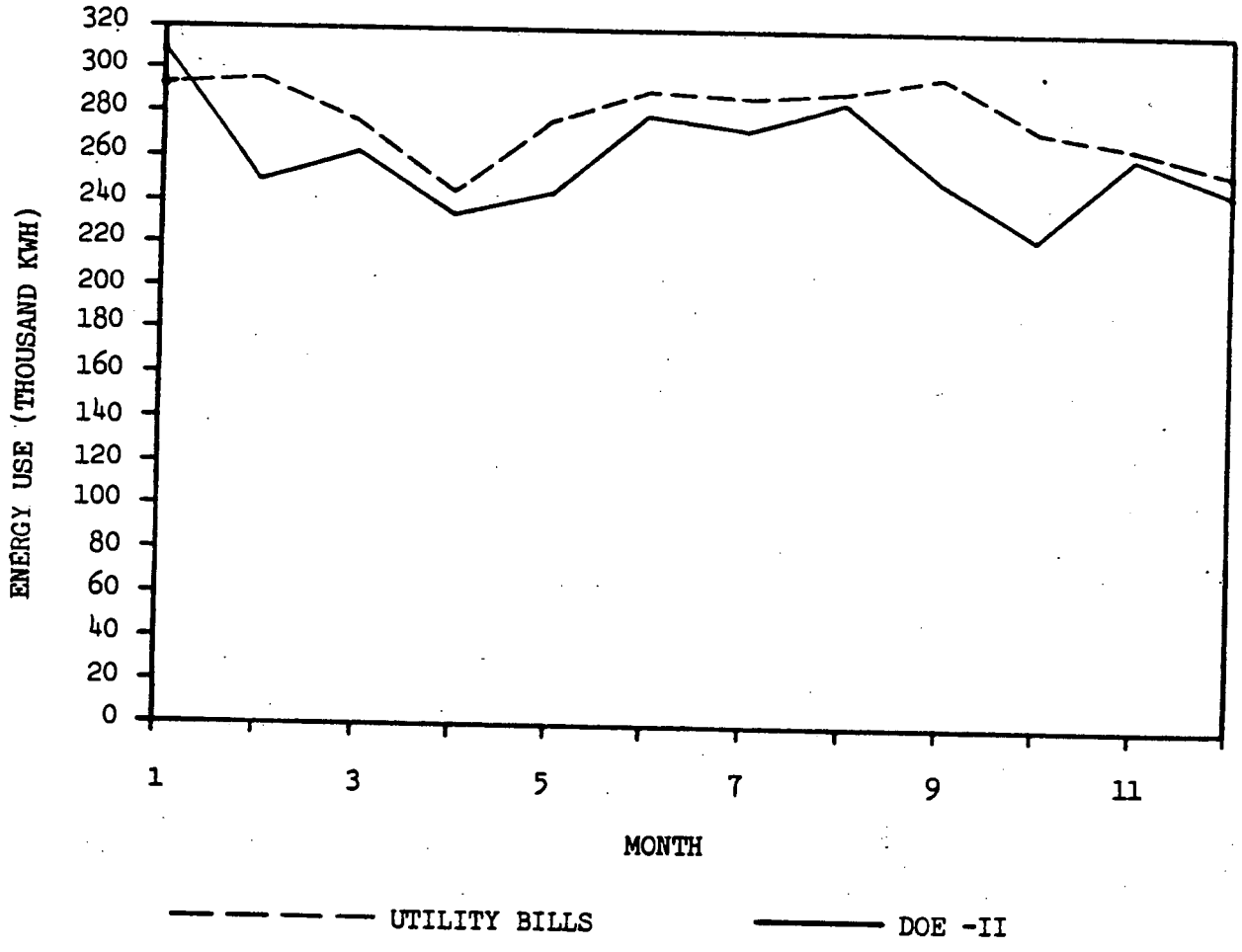


Fig. 1.) Comparison of Energy Use with the Utility Bills and the DOE-2 Program

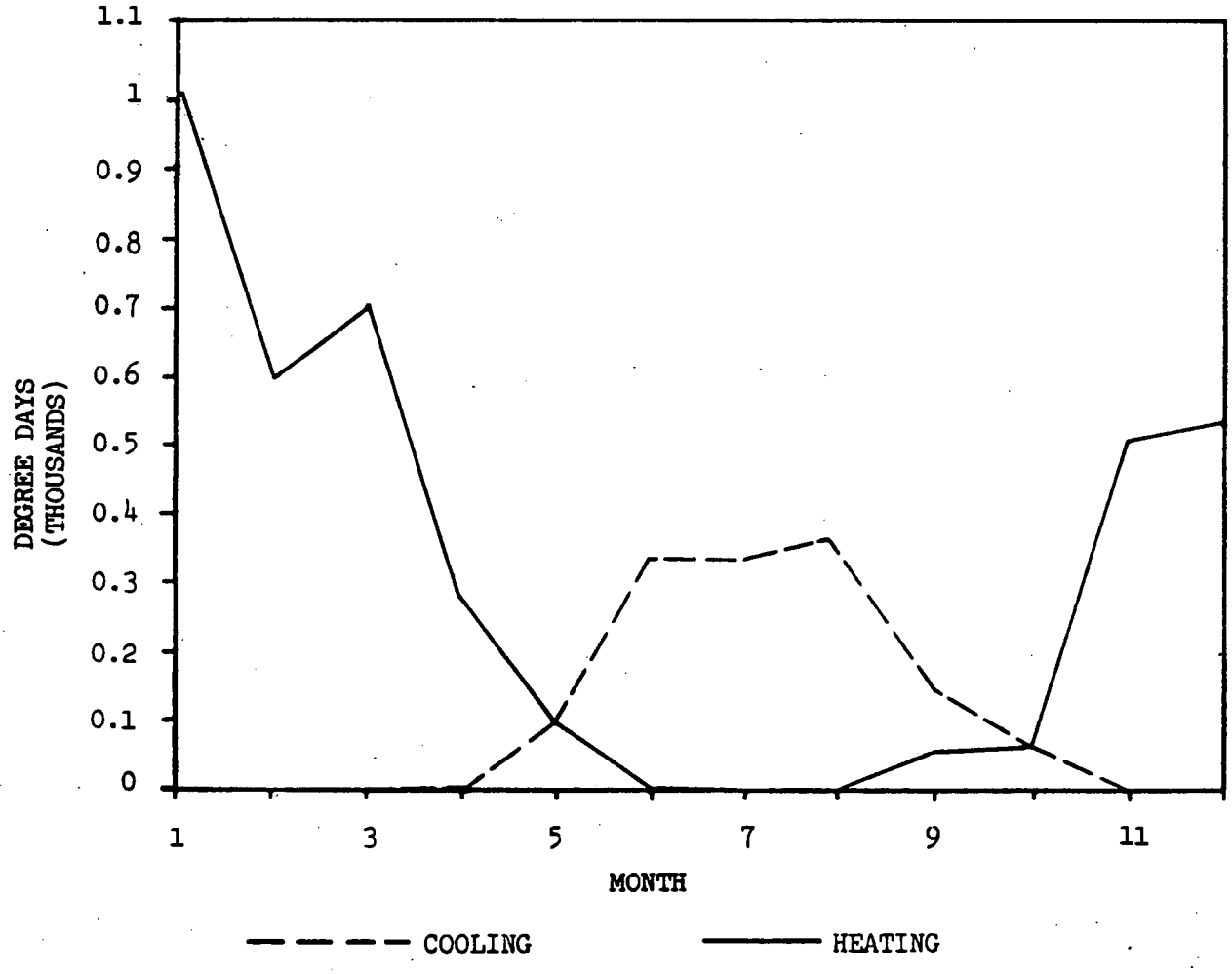


Fig. 2.) Heating and Cooling Degree Days (1984 Wash. Nat. Airport)

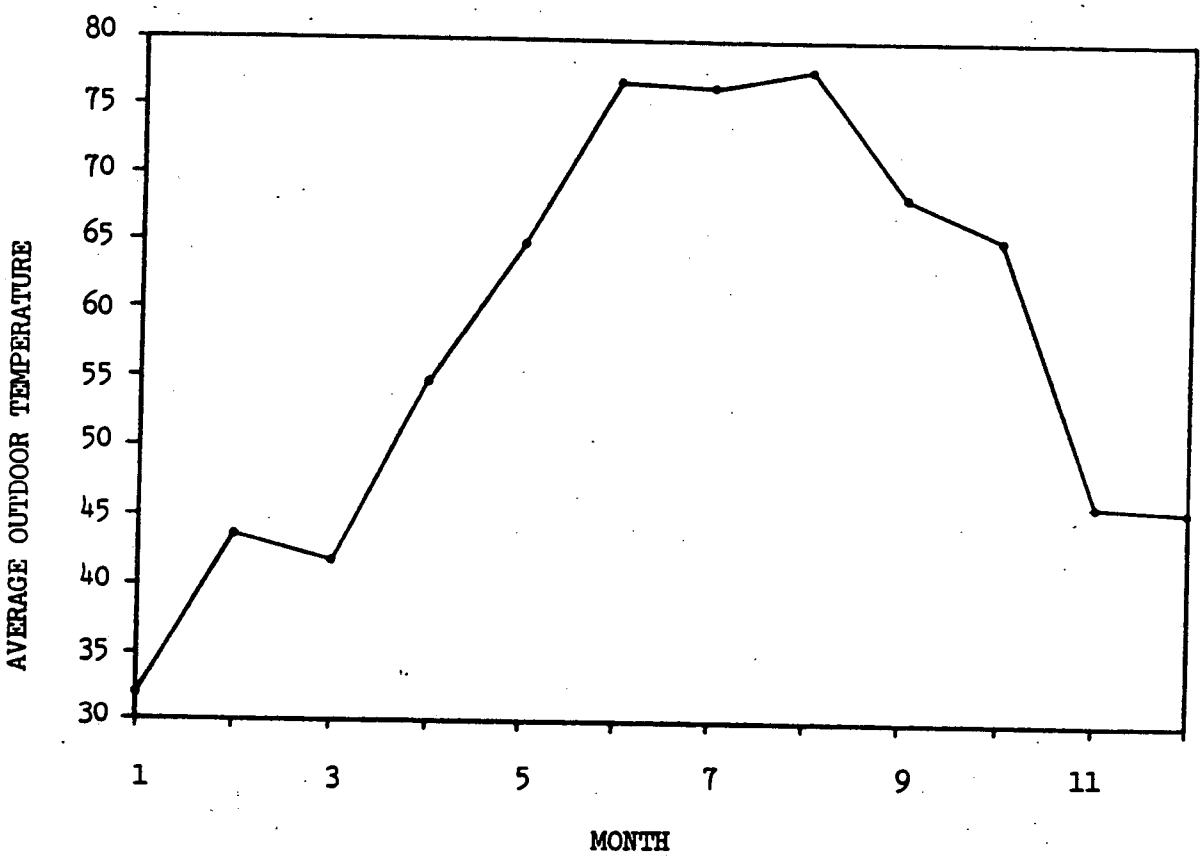


Fig. 3.) Average Outdoor Temperature (1984 Wash. Nat. Airport)

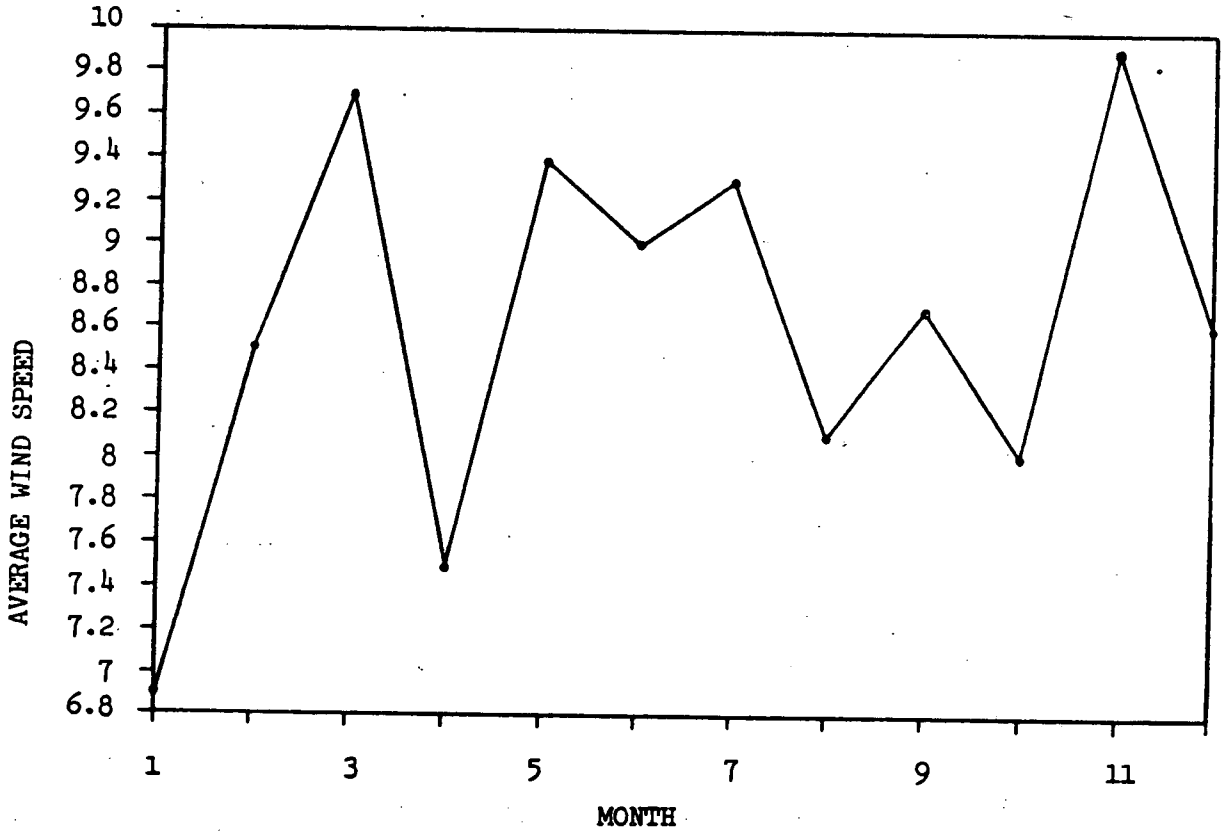


Fig. 4.) Average Wind Speed (1984 Wash. Nat. Airport)

3. Variable scheduling of the audio-visual studio. This facility consumes considerable energy when in use with associated high internal loads. The use varies dramatically from month-to-month, and there is no record of how many lights, etc. were employed by various users.

4. Since NOAA no longer provides actual solar insolation data for many locations, approximations based on cloud cover must be introduced. This obviously has a considerable impact on monthly loads.

5. The thermal bridges throughout the building that were modeled into the DOE-2 program as idealized building envelope configurations will also create differences between the DOE-2 simulation and the actual utility bills.

There are, of course, many small errors associated with the selection of envelope material properties and convection coefficients. Bauman [1] among others, has pointed out many differences between actual convection coefficients and ASHRAE recommended values. All of these factors contribute to the final accuracy of the simulation. In view of this, the overall model of the building provides a credible base upon which to study the effects of changes to the envelope.

IV. BRIDGES IDENTIFIED

A number of thermal bridges were identified within the model building by examining architectural design drawings. After this initial identification, it was necessary to verify the existence of the suspected thermal anomalies by field inspection. Verification was made possible by the use of infrared thermography.

At this point, knowing the existence of thermal bridges and having architectural details of these bridges, decisions had to be made as to which thermal bridge would be analyzed in detail. A total of seven were chosen based upon the following criteria: simplicity of geometry for computer simulation, number of occurances within the model building, and repeated use of similar design details within the architectural community.

Figures (5) through (11) illustrate the geometries of these bridges and give the undisturbed R-value of the wall or roof in which the bridge resides. This R-value includes air film resistances of 0.17 HR-SF-°F/BTU and 0.60 HR-SF-°F/BTU on the inside and outside surfaces, respectively. Note that on Figures 5, 6, and 7 that there are two R-values shown. Due to the fact that roof insulation thickness varies to accommodate roof drainage, the R-value across the roof also varies. The "R = 24.65 (In Neighborhood of Bridge)" relates to 6 inch thick roof insulation, which happens to be the actual insulation thickness in the areas where the bridges shown in Figures 5, 6, and 7 occur. Conversely, the "R = 19.05 (Average Over Total Undisturbed Roof)" relates to an average insulation thickness across the roof.

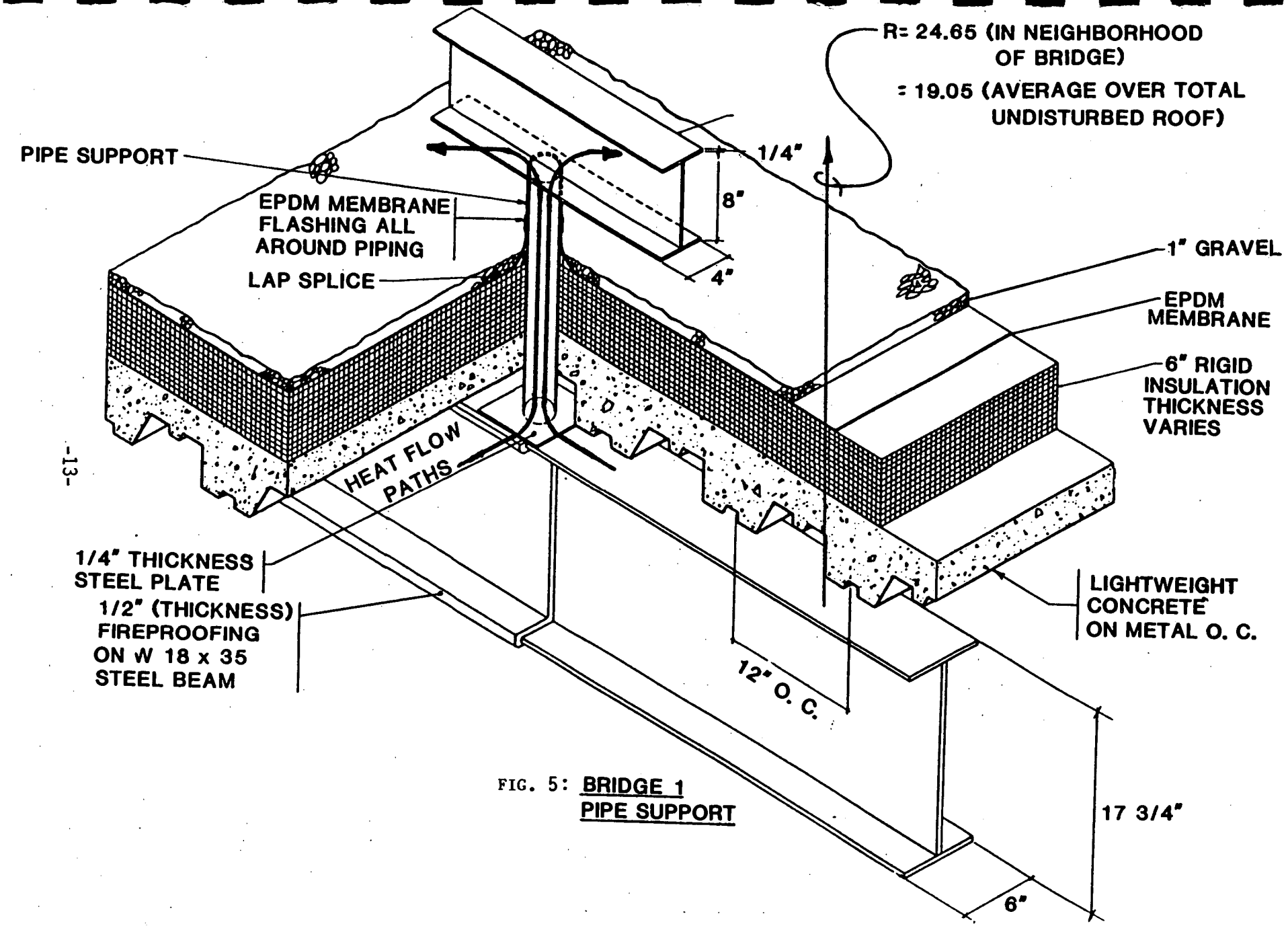


FIG. 5: BRIDGE 1 PIPE SUPPORT

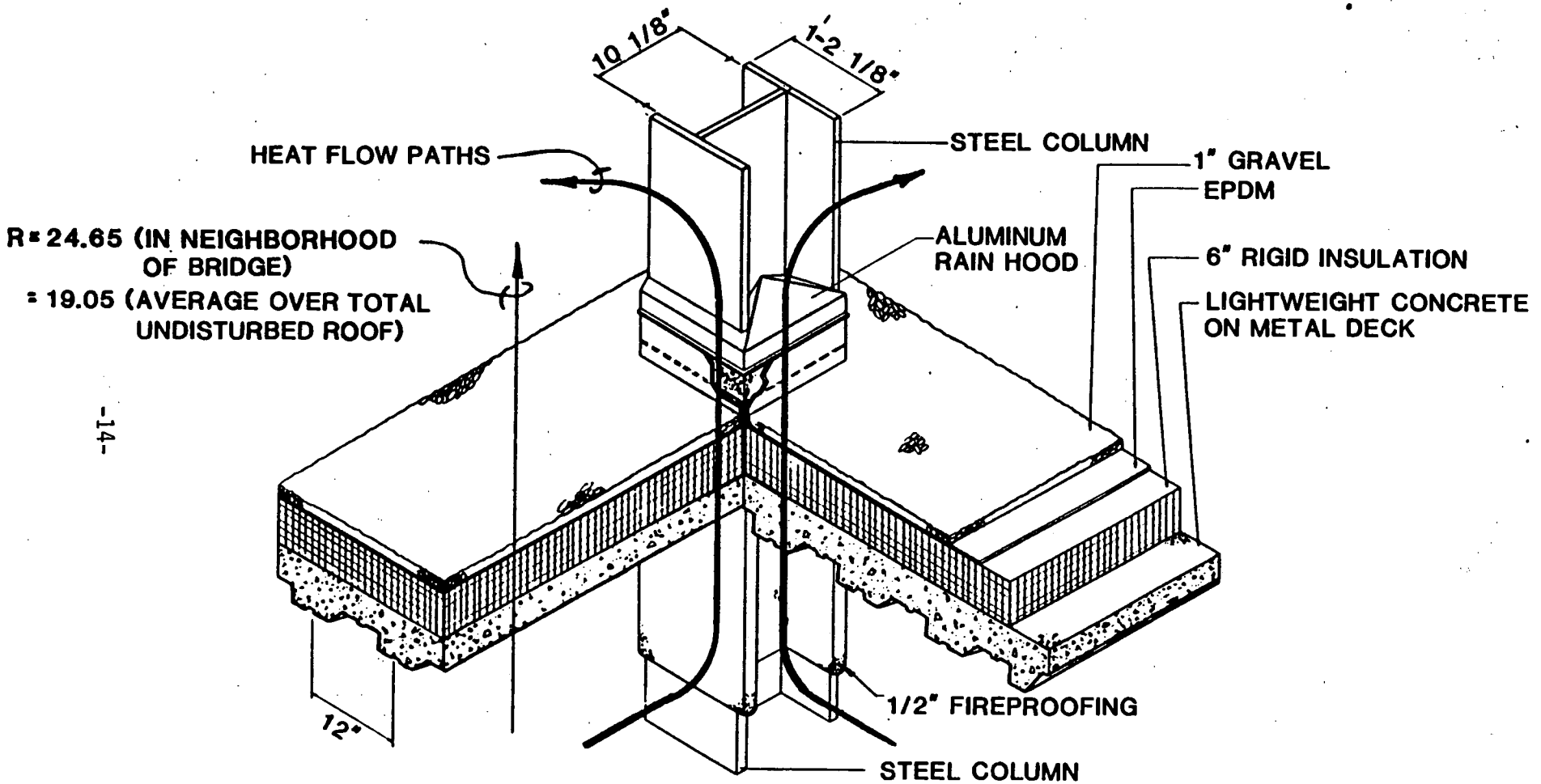


FIG. 6: BRIDGE 2, STEEL COLUMN PENETRATION

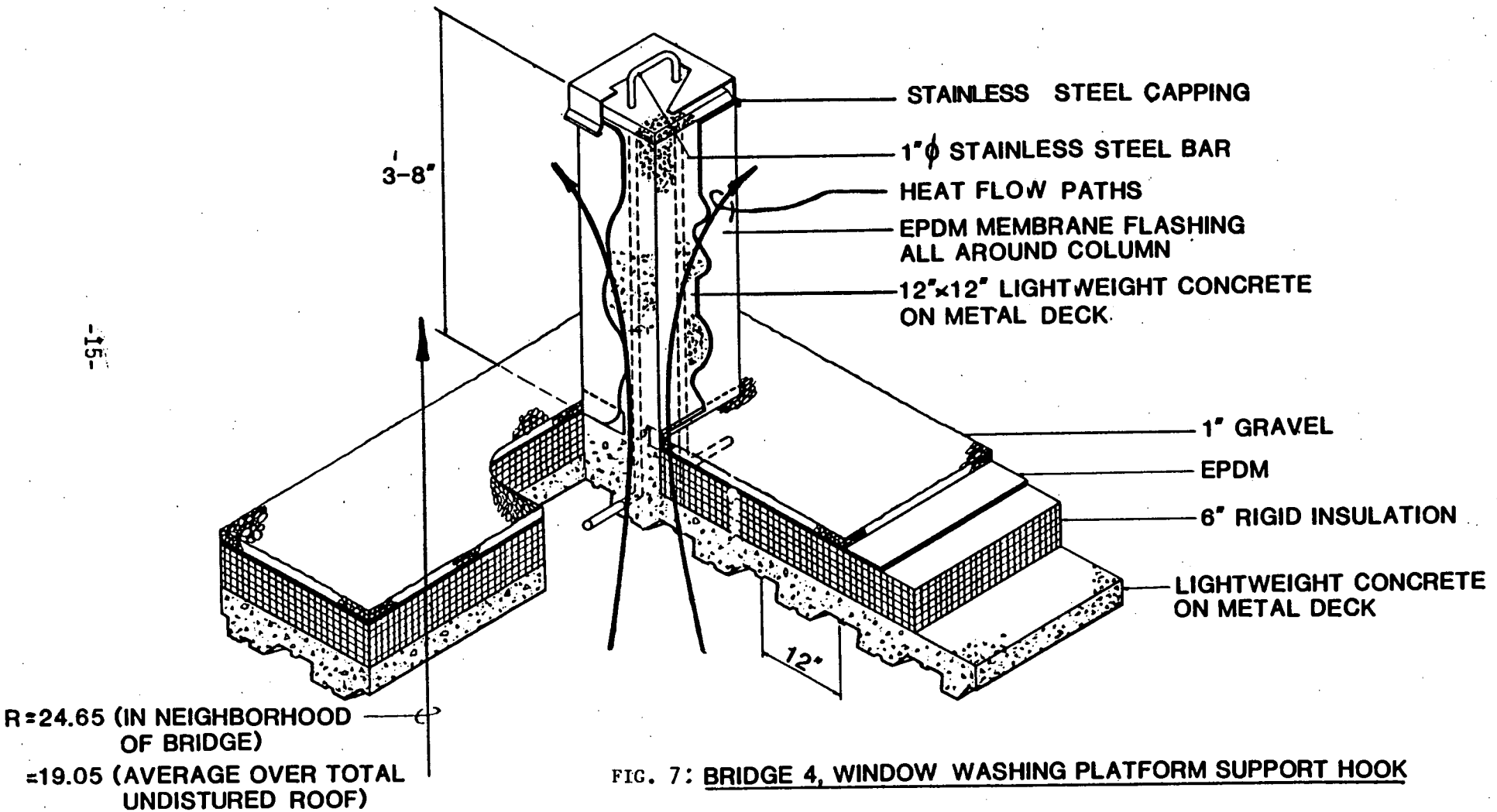


FIG. 7: BRIDGE 4, WINDOW WASHING PLATFORM SUPPORT HOOK

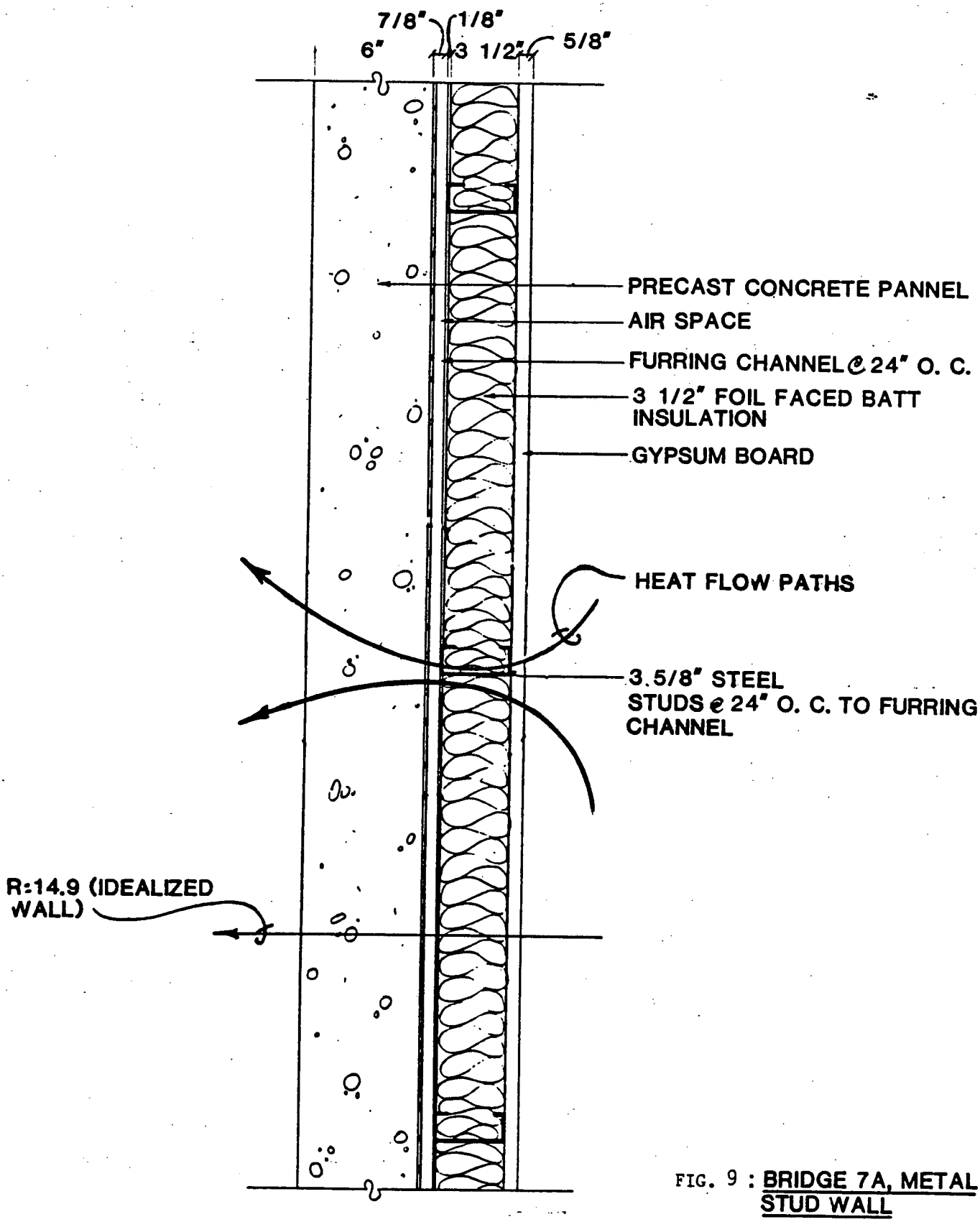


FIG. 9 : BRIDGE 7A, METAL STUD WALL

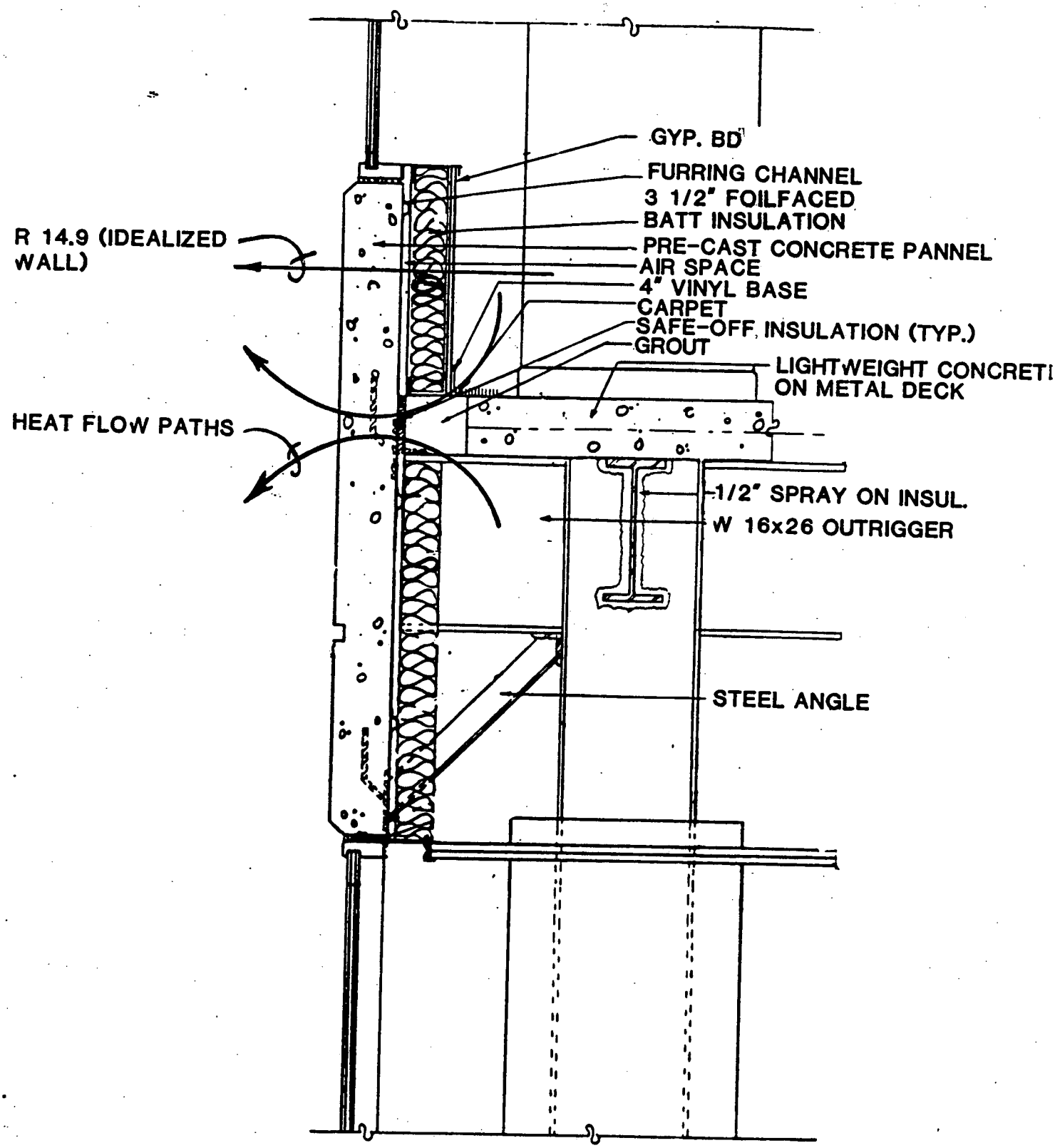


FIG. 10: BRIDGE 7B, 2- DIMINSIONAL FLOOR PENETRATION

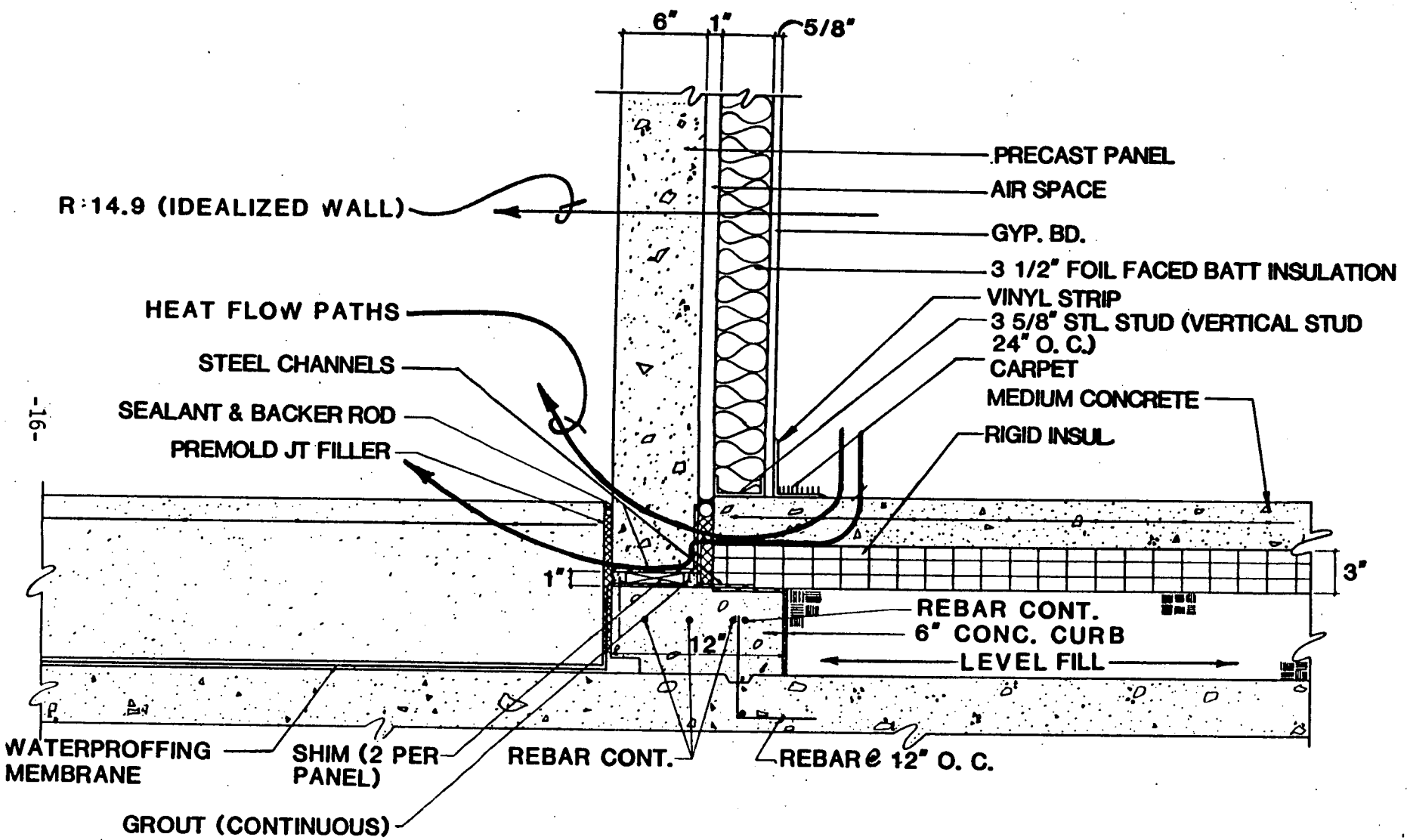


FIG. 8 : BRIDGE 5, FLOOR SLAB PERIMETER

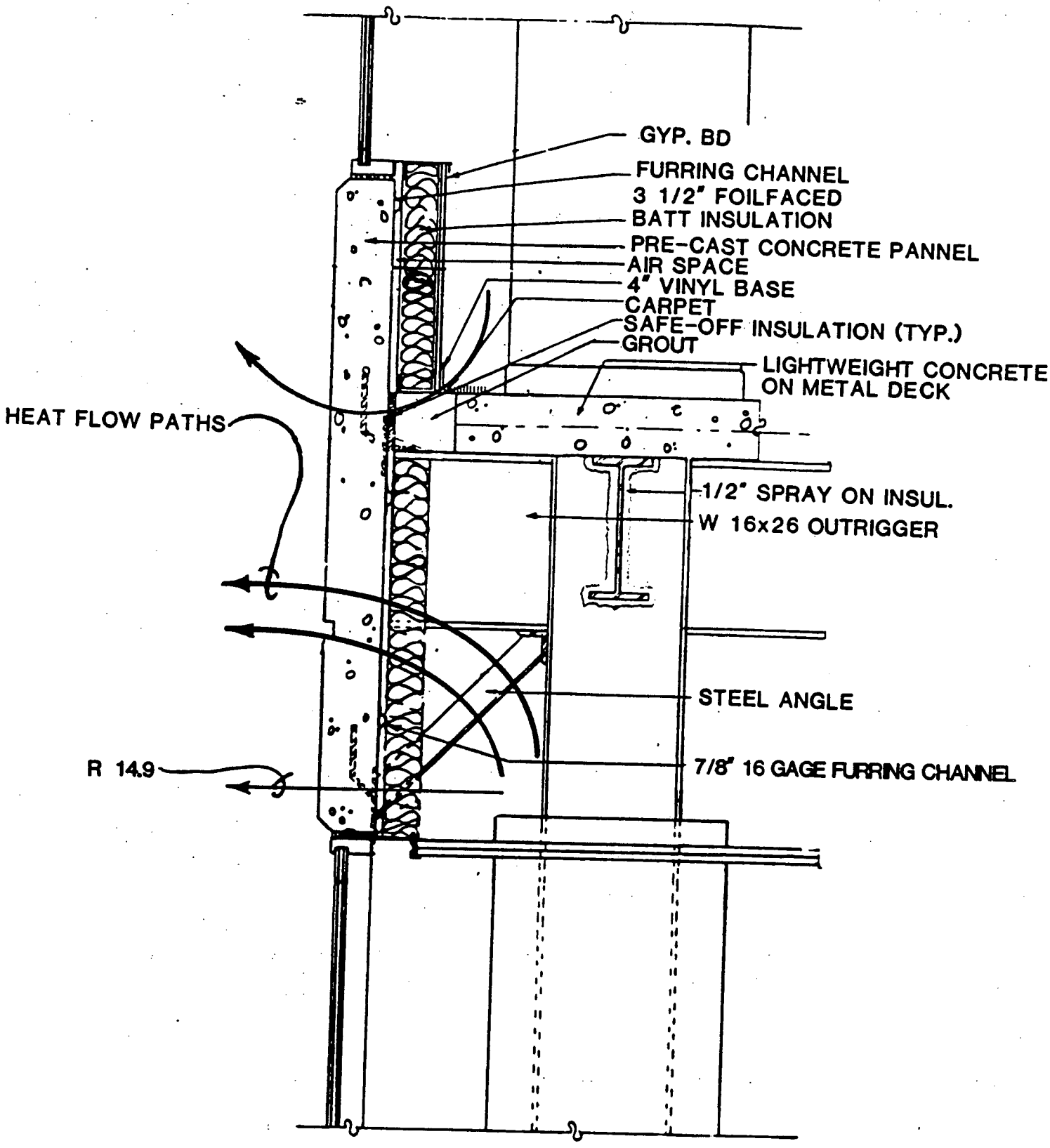


FIG. 11: BRIDGE 7C, FLOOR PENETRATION PLUS EXTERIOR WALL SUPPORT BEAM PENETRATION

V. ANALYSIS OF BRIDGES

Since most hour-by-hour simulation programs employ some form of response factors or transfer function coefficients for transient analysis of the envelope, this form of model would be the most convenient for studying thermal bridges. Current transfer function models such as those used in DOE-2 [10] are, however, restricted to one-dimensional heat flows. Thermal bridges are highly two or three dimensional because of the large differences in thermal conductivities within them. Attempts to generate response coefficients by working backwards from heat flows computed by finite difference modeling were unsuccessful. Similar difficulties were encountered by Pederson [13] who used experimentally determined heat flows.

The difficulties are due to the one-dimensional restriction in current transfer funtion computer algorithms. A more recent scheme that shows promise has been proposed by Ceylan [3,4]. This method generates response coefficients directly from a finite difference or finite element model and has been applied successfully to several two-dimensional problems [3]. The difference in methodology between this new technique and previous ones is basically as follows.

Traditional transfer function methods are based on an exact solution to the transient heat conduction equation by Laplace transforms. The scheme was originally applied to building envelopes by Mackey [11], generalized by Choudhry [5] and others, and computerized by Stephenson [14]. Transfer function or "response coefficients" are hourly descretizations of the exact Laplace transform solution. This method is also used for transient DC electric circuit problems. While it is applicable to multi-dimensional heat flow problems as well, its use has been restricted to one-dimensional situations because of the large computing times required.

Ceylan's method begins instead with a finite difference or finite element solution of the heat conduction equation. The claim is that this avoids the need to solve a large Eigenvalue problem and thus reduces computer time. At present, Ceylan's method appears to be the only one available for multi-dimensional heat conduction problems. This technique clearly warrants further investigation.

In the present study, the development of new response coefficent methods was beyond the project scope. We thus used a finite difference computer program (HEATING 6) to study the steady-state heat flow through the bridges and the surrounding wall or roof. The two-dimensional effects of the bridge influence heat flows for several feet around the bridge site. This coupled with the large temperature gradients resulted in quite dense finite difference meshes, several thousand nodes in some cases.

From this finite difference model, we were able to determine an equivalent steady-state thermal resistance for each bridge and an affected area. The effected area is that region of the envelope including the bridge in which the heat flow is two or three dimensional. By replacing this effected area by an equivalent one-dimensional slab, we were able to treat a wall or roof with a bridge as two parallel one-dimensional heat flow paths. This technique gives the correct heat flow for steady state conditions. An exact transient model for use in DOE-2 could not, of course, be created. Instead, we replaced the bridges with their steady-state equivalent and used the existing envelope thermal capacitance. By this method we were able to approximate the effect of each bridge on the total building energy use.

VI. BRIDGE HEAT LOSS RESULTS

For each bridge, the percent change in heat flow was determined relative to the original envelope for:

1. The portion of the envelope incorporating the bridge
2. The total building envelope
3. The total building load

The corresponding percent change in energy use by the building then depends on the particular HVAC system and the climatic conditions. The percent change in energy use times the energy cost in the locality then gives the financial cost of the bridge. For the building studied here, total annual energy costs are \$224,000 with an annual energy use of 3.38×10^6 KWH. The amount of this energy use attributable to heating and cooling loads (not counting lights and equipment) is 47%, therefore, a 1% change in building load saves \$1053.

Table (2) illustrates energy costs for the building studied attributable to each bridge. These costs are, of course, specific to this building and its particular climate and operating procedure. The same bridges may have different effects elsewhere.

A method of quantifying each bridge that is independent of the local climate and the building in which it resides is of more general value. One such method shown in Table (2) is the "temperature depression method". We define the temperature depression as:

$$\text{TEMPERATURE DEPRESSION} = \frac{\text{INSIDE WALL SURFACE TEMPERATURE} - \text{OUTSIDE AMBIENT TEMPERATURE}}{\text{INSIDE AIR TEMPERATURE} - \text{OUTSIDE AMBIENT TEMPERATURE}}$$

and the DEPRESSION RATIO as

$$\text{TEMPERATURE DEPRESSION RATIO} = \frac{\text{TEMPERATURE DEPRESSION AT COLDEST POINT ON INSIDE SURFACE OF BRIDGE}}{\text{TEMPERATURE DEPRESSION OF UNDISTURBED ENVELOPE}}$$

Table 2: Bridge Heat Loss Results

Bridge	Number of Occurances In This Building	% Changes in Total Building Energy Use Due To The Bridge	Annual Cost Per Occurance $	Annual Cost Due To All Occurances $	Temperature Depression Ratio
1	6	0.00246	0.43	2.6	0.08/0.97
2	3	0.0126	4.43	13.3	0.73/0.97
3	21	0.0117	0.58	12.3	0.82/0.97
5	Continous Around Perimeter	0.245	0.37/ft*	257.9	0.57/0.96
7A	Continous Over All Walls	1.01	0.04/ft^2**	1063.5	0.78/0.96
7B	Continous Around Perimeter	0.48	0.33/ft**	505.4	0.73/0.96
7C		0.048		50.5	0.72/0.96

** ft^2 of Wall

* Linear ft of Perimeter

The temperature depression is a useful way of assessing the effect of the bridge on moisture condensation. With it, one may determine the outside air temperature at which moisture will begin to condense on interior surfaces. For example, one may construct a graph such as Figure (12) by setting the inside surface temperature equal to the dew point of the inside air.

From this graph we can see, for example, that bridge 5 with a temperature depression of 0.57 may create moisture problems and thus warrant remedial efforts even though it is not the most significant bridge from an energy standpoint.

The temperature depression ratio, computed from a steady-state finite difference model of the bridge and its immediate surroundings is a relatively easy parameter to determine and is of value to the building analyst. Quantifying the energy aspects of bridges, however, is more difficult.

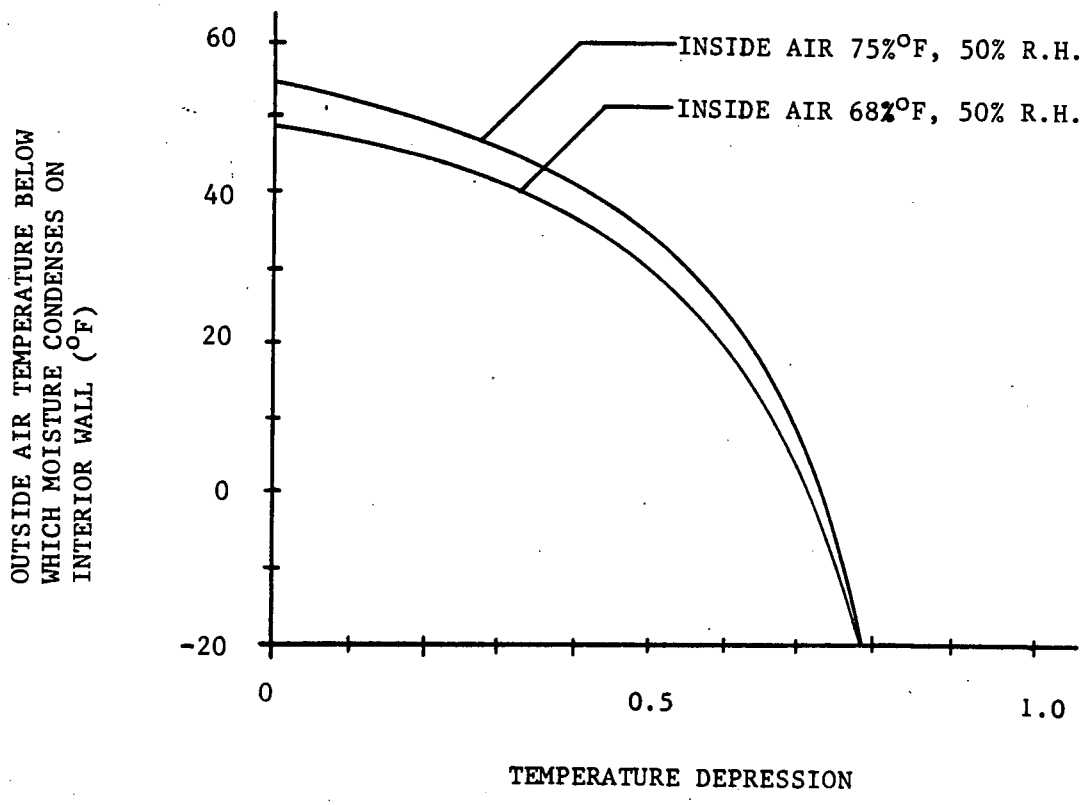


FIG. 12: Moisture Condensation Temperature

VII. Simple Bridge Models

A. Bridge Heat Loss

One of the objectives of this study is to investigate the possibility of using simplified bridge models to assess the negative effects of bridges without running time consuming hour-by-hour computer simulations. Ultimately, these simple models might be used to develop a bridge catalog system that would, in turn, be used by the architectural design community to determine what design details need to be updated to eliminate thermal bridges.

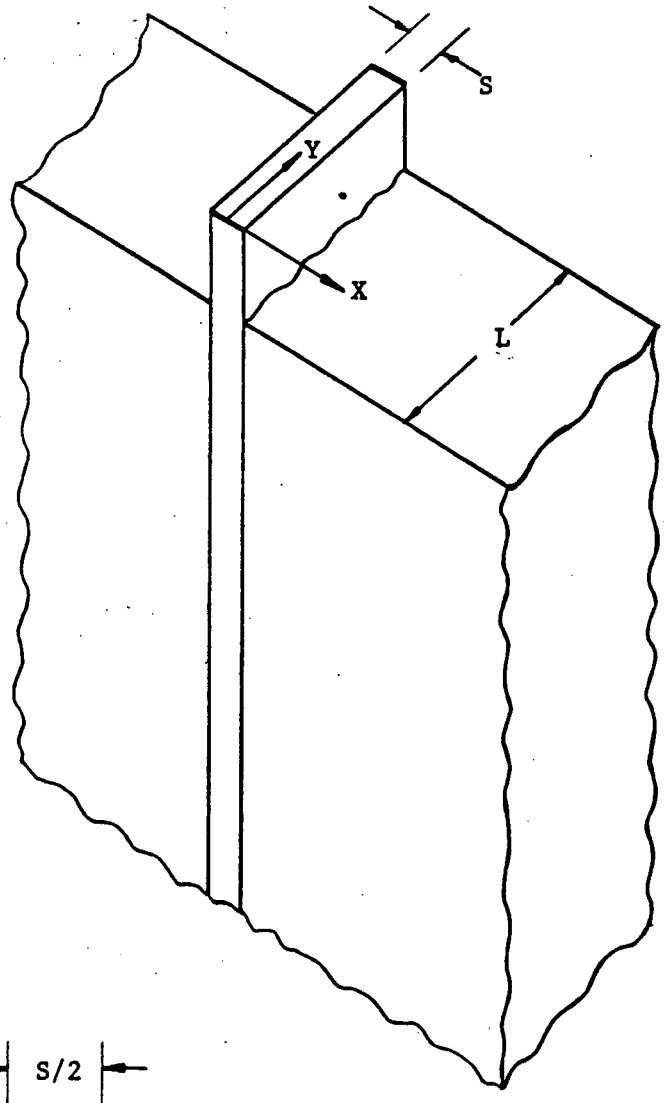
In order to better understand the energy behavior of thermal bridges and to begin the development of some simpler ways to predict their effect, a number of smaller studies were performed. In the first, we examine the steady state heat flow through a simple two-dimensional bridge/wall combination.

Consider the simplest bridge consisting of a long slab of high thermal conductivity and width S penetrating a homogeneous wall of thickness L as shown in Figure (13). The outside and inside air temperatures and convection coefficients are T_o, T_i and h_o, h_i respectively. We may model this configuration as a two-dimensional heat conduction problem as shown in the figure to determine the internal temperatures and surface heat fluxes by a finite difference computer simulation. For illustrative purposes, we consider a steel penetration of a masonry wall with

bridge	undisturbed wall
p_b = 490 lbm/ft^3	p = 70 lbm/ft^3
c_b = 0.12 Btu/lbm-^{o}f	c = 0.2 Btu/lbm-^{o}F
K_b = 28 Btu/hr-ft-^{o}F	K = 0.60 Btu/hr-ft-^{o}F
S = 2 inches	L = 8 inches

and select standard convection coefficients of

h_o = 4.5 Btu/hr-ft^2-^{o}F h_i = 1.5 Btu/hr-ft^2-^{o}F



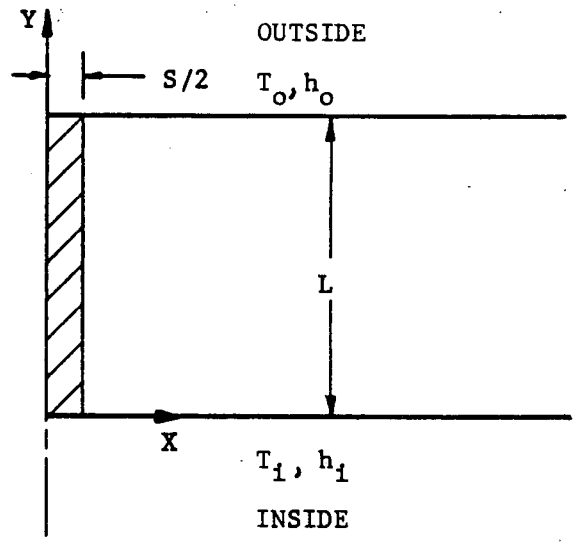


FIG.13: Simple Two-Dimensional Bridge

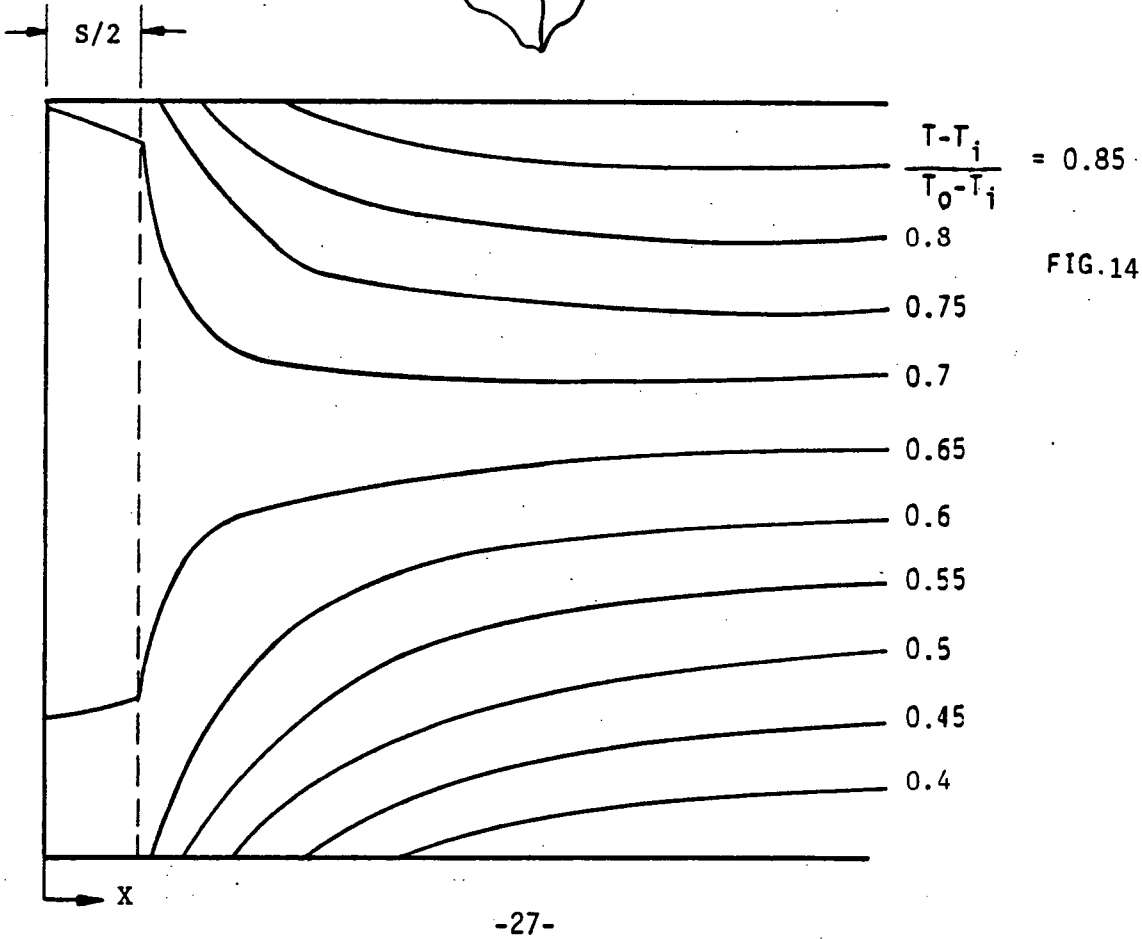


FIG.14: Isotherms in the Region Near The Bridge

FIG. 15: Local Heat Flux on the Inside and Outside of the Wall vs Distance From Bridge Center for Steady State Conditions

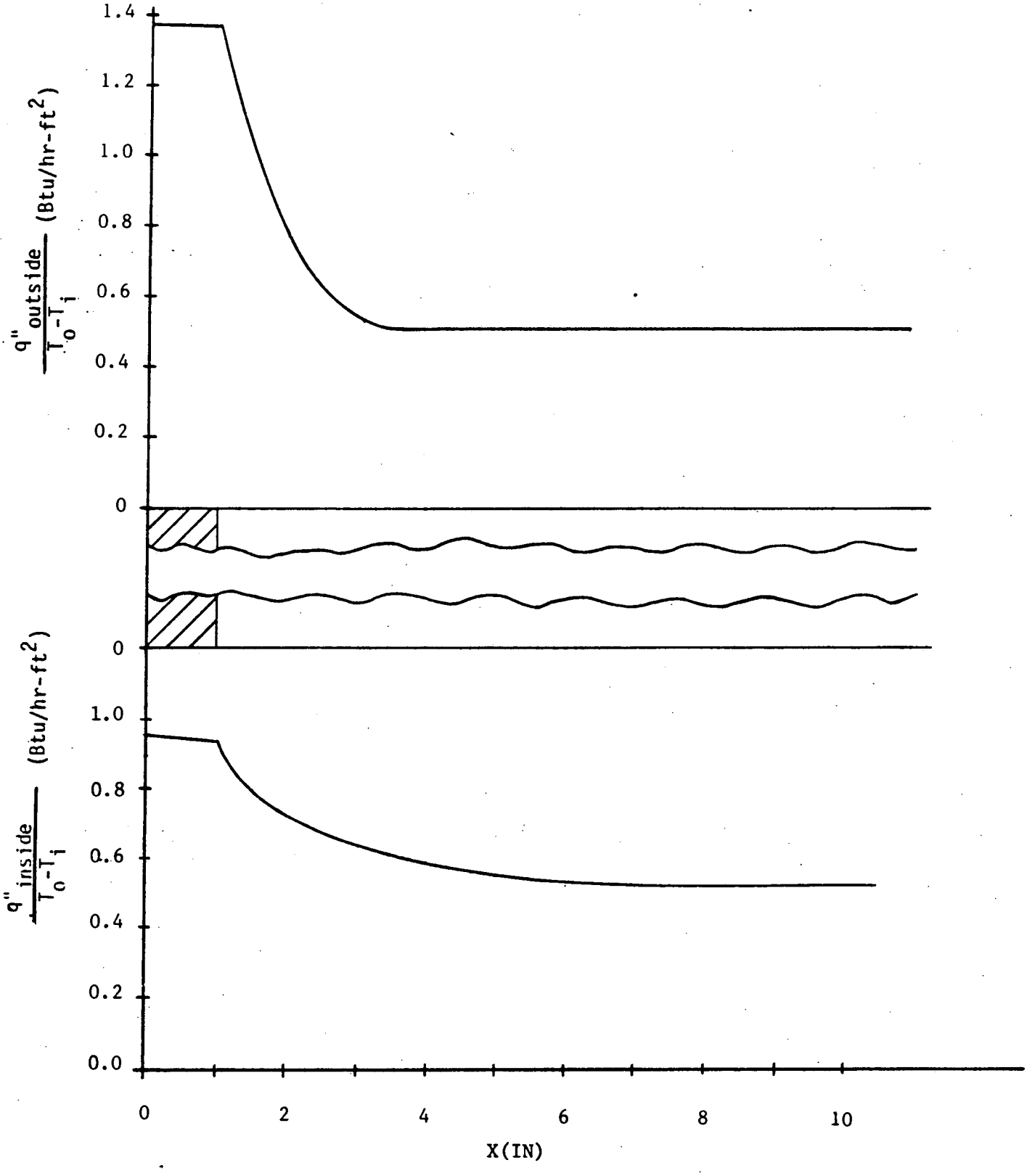


Figure (14) shows the isotherms in the neighborhood of the bridge and Figure (15) shows the local surface heat flux $q''/(T_o-T_i)$ on the outside and inside of the wall under steady state conditions.

The temperature and heat flux gradients are quite steep in the neighborhood of the bridge and degenerate to those for the undisturbed wall as x increases. The finite difference model requires several hundred nodes to achieve sufficient accuracy.

If we select an x-location far from the bridge where the isotherms are almost parallel, then we may replace the bridge/wall combination with two parallel heat flow paths, one through the equivalent slab for the bridge and affected region of the wall and the other as the remainder of the wall. The steady state heat flow can then be determined by simply replacing the bridge and the affected region of the wall by an equivalent thermal resistance.

If q" is the local heat flux per unit area from the inside surface to the inside air, then the total heat flow up to any location x_e will be

$$q' = \int_0^{x_e} q''dx \tag{1}$$

and the effective thermal resistance of the wall up to this location, R_e can be determined by

$$\frac{(T_o - T_i)\, x_e}{1/h_o + R_e + 1/h_i} = \int_0^{x_e} q''dx \tag{2}$$

A rational method for selecting x_e is to find that x-location where the local heat flux on the inside surface is within 1% of that for the undisturbed wall. We thus seek x where

$$\frac{q'' - q''_o}{q''_o} = 0.01$$

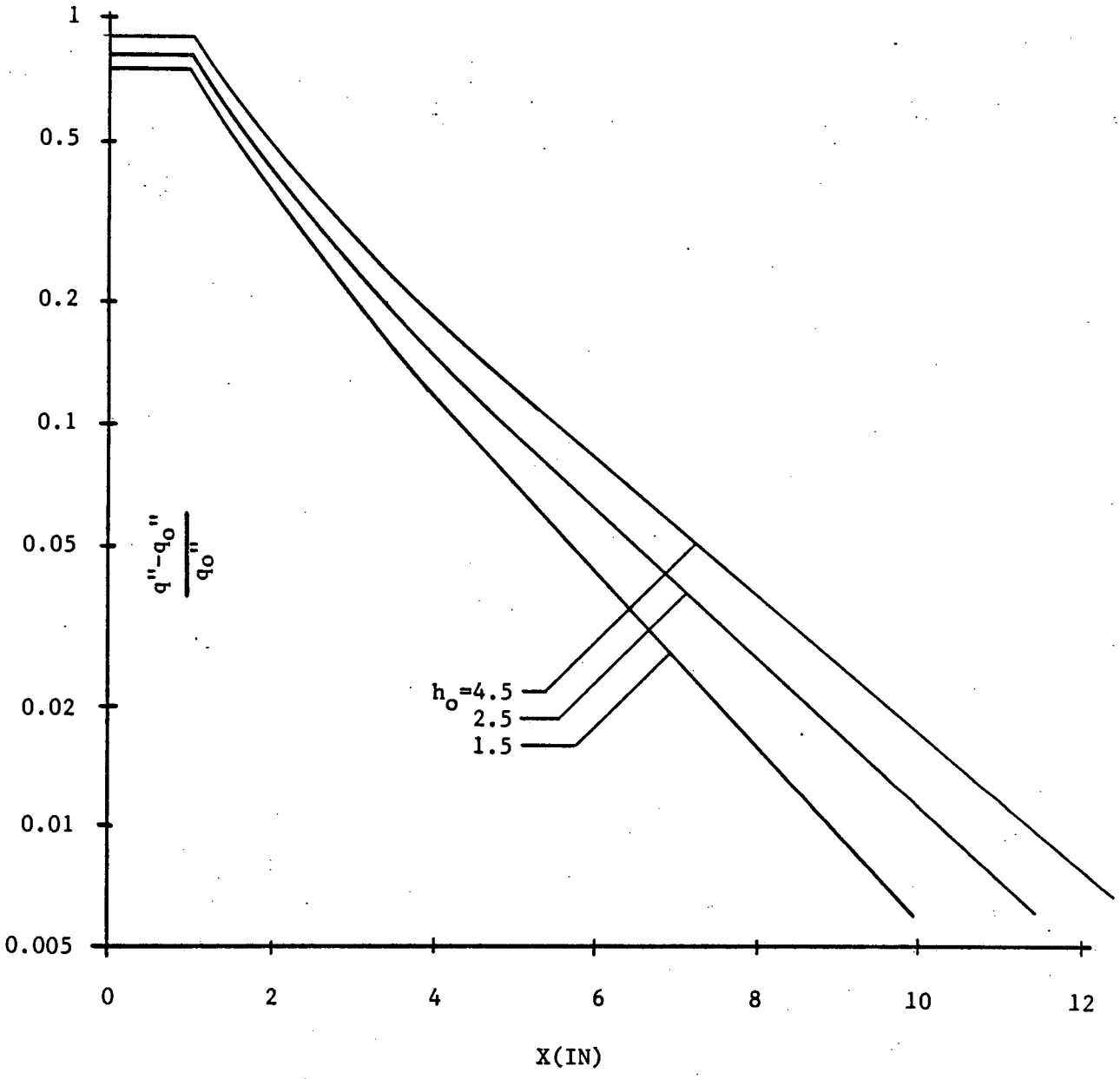


FIG. 16: Relative Heat Flux vs Distance from Bridge Center for Several Values of h_o

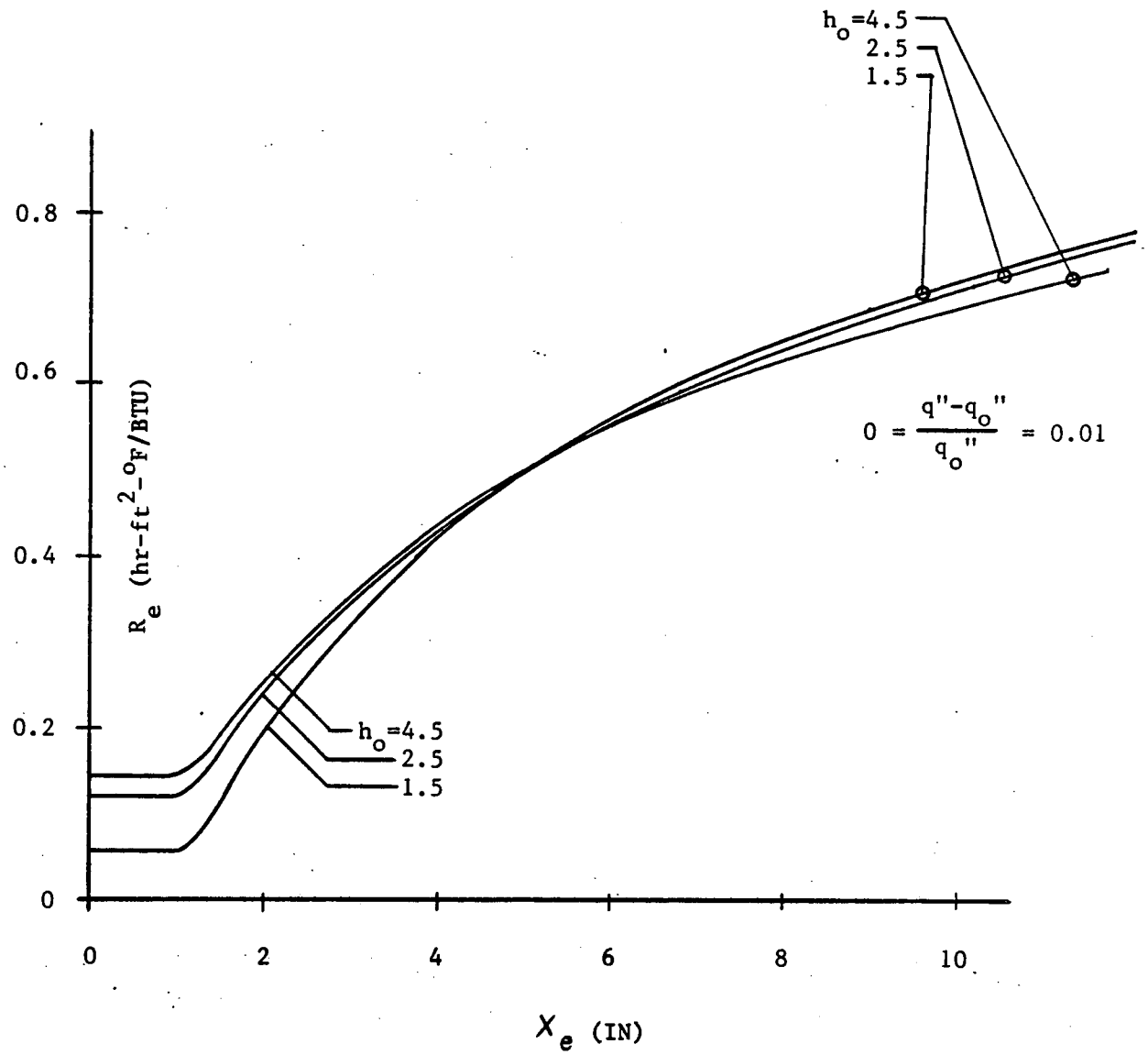


FIG. 17: Equivalent "R" Value for Bridge and Affected Region of Wall

q_o'' being the heat flux for the undisturbed wall

$$q_o'' = \frac{(T_o - T_i)}{1/h_o + L/K + 1/hi}$$

Figure (16) shows a plot of the above function vs x for the case studied and Figure (17) gives the corresponding effective thermal resistance for the bridge. The effects of h_o on the results increases as the contribution of h_o to the overall thermal resistance of the wall increases. We thus see more effect at smaller values of h_o. Even so, if we consistantly take R_e at the x_e where the local heat flux is within 1% of that for the undisturbed wall, the variation in R_e with h_o is small enough to neglect. This technique, then, is a reasonable method for modeling this example bridge with a simple equivalent wall. When the undisturbed wall "R" value is higher, the method is even more accurate. This is the basic method used to model the steady state behavior of the bridges in the building studied. Each is replaced by an equivalent effected area and "R" value.

Consider next, the same example wall/bridge combination under transient conditions. If we replace the bridge and its associated affected region of the wall with an equivalent one-dimensional wall, we would first of all have to use the equivalent thermal resistance R_e for this one-dimensional wall in order to assure equivalence of total integrated heat flow. We would then have to decide upon an effective thermal capacitance

$$C = pcL \tag{5}$$

so that the transient heat flow from the equivalent wall to the inside air matches the total heat flow from the bridge and its affected region of the wall. The simplest approach is to use our R_e in combination with the thermal capacitance of the undisturbed wall. If the total thermal mass of the bridge is small relative to the total thermal mass of the affected portion of the wall, this approximation may be unacceptable.

To illustrate the nature of this problem, consider our simple example. Suppose we separate the structure into an effective one-dimensional wall occupying a width x_e = 11.4 inches (corresponding to the point where the local heat flux is within 1% of that for the undisturbed wall under steady state conditions) in parallel with the rest of the undisturbed wall. From Figure (17) then, we would require an effective thermal resistance of R_e = 0.72 hr - ft^2 - °F/Btu.

Figure (18) illustrates the heat flux from the inside of the wall in response to a sinusoidal variation in the outside temperature for h_o = 4.5. Two of the curves are for the undisturbed wall and a wall consisting of bridge material alone. The third curve shows the response of a one-dimensional wall having a thermal resistance of 0.72 and a thermal capacitance equal to that of the undisturbed wall. The fourth curve is the integrated heat flux

$$q'' = \frac{1}{x_e}\int_0^{xe} h_i\,(T_{surf} - T_i)dx \qquad (6)$$

over the inside surface of the bridge and the affected region of the wall. This curve is from a finite difference simulation of the actual two-dimensional configuration subjected to the same outside temperature variation. The outside temperature variation in all cases is

$$T_o = T_{oa} + T_{om}\sin(2\pi t/24) \qquad (7)$$

Since the one-dimensional equivalent wall has the same R as the bridge plus the affected wall region (R_e), the total average heat flux is in agreement with the actual integrated heat flux over the 24 hour cycle. The phase lag and amplitude, however, are not in exact agreement. It is possible, of course, to find an effective thermal capacitance, C_e, for the one-dimensional model which brings it into exact agreement with the actual behavior of the bridge plus affected region. For this example, using C_e = 17 (or almost twice that for the undisturbed wall) gives excellent agreement.

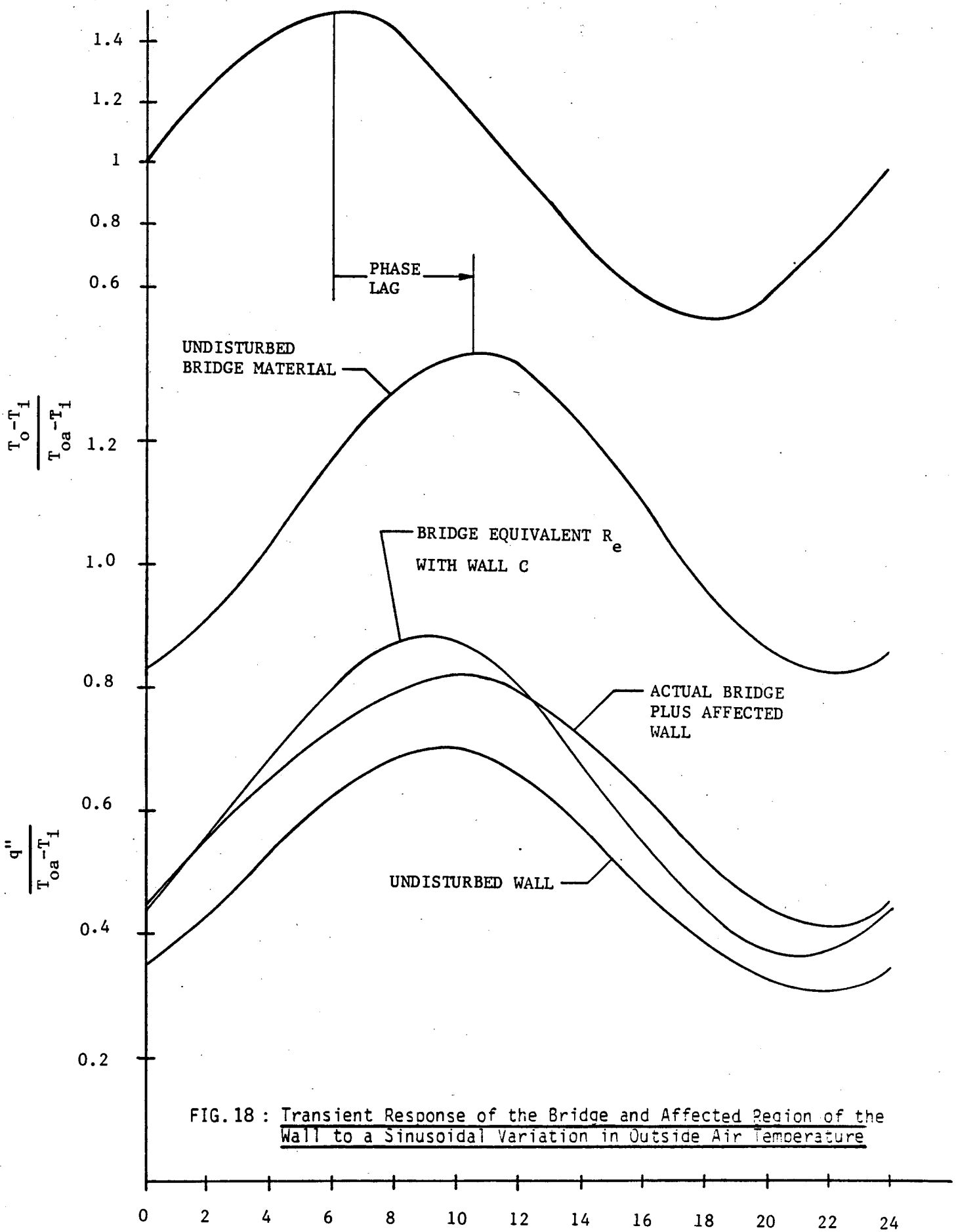


FIG. 18 : Transient Response of the Bridge and Affected Region of the Wall to a Sinusoidal Variation in Outside Air Temperature

As this example shows, a multi-dimensional bridge structure can be replaced by an equivalent one-dimensional wall in parallel with the undisturbed wall by simply creating an effective R and C as long as the temperature variation imposed is a simple sinusoid. This a reasonable first approximation for heat flow estimates but is not sufficient for detailed studies.

When the imposed temperature fluctations are more complex, we need more than two equivalent constants to model the transient response, ie., we need a set of response coefficients which, as previously discussed, are difficult to determine.

In the present studies of bridges, an effective "R" value was created for each bridge but the thermal capacitance was taken as that for the undisturbed wall. In the building studied, the thermal mass of the bridges was not as great relative to that of the undisturbed wall as in the simple example studied here. For this reason, less error was involved in this approximation. Clearly this aspect of the problem requires further work but the computational effort is considerable and beyond the scope of the present study. The simple model was examined as an aid to our understanding of the phenomena.

B. Bridge Heat Loss Impact on Building Systems

Consider next the dynamic behavior of a bridge/wall combination and the building heating and cooling system. If the inside and outside air temperatures are specified funtions of time and vary periodically over any specified cycle, then the total integrated heat flow through the structure will equal the overall heat transfer coefficient times and the integrated average temperature difference. A change in the thermal resisitance of the wall would then lead to a corresponding change in the total averaged heat flow through the wall.

Let A_o and R_o be the original area and thermal resistance of a wall into which a bridge of effective resistance R_e and area A_e is inserted. The heat flow through the original wall will then be

$$\frac{q_o}{\int (T_o - T_i)dt} = \frac{A_o}{1/h_o + R_o + 1/h_i} = U_o A_o \qquad (8)$$

while through the wall plus bridge, the heat flow will be

$$\frac{q}{\int (T_o - T_i)dt} = \frac{A_o - A_e}{1/h_o + R_o + 1/h_i} + \frac{A_e}{1/h_o + R_e + 1/h_i} = U_o(A_o - A_e) + U_e A_e \qquad (9)$$

The percent increase in heat flow due to the inclusion of the bridge is then

$$P = \frac{q - q_o}{q_o} \times 100 = \frac{U_o(A_o - A_e) + U_e A_e - U_o A_o}{U_o A_o} \times 100 = \frac{A_e}{A_o}\left(\frac{U_e}{U_o} - 1\right) \times 100 \qquad (10)$$

If we know the total amount of heating or cooling load for an element of the building without a bridge, then the change due to the addition of a bridge into this element would be given by the above equation.

In principle then, if one has the total contribution to the building heating and cooling loads of the conduction heat flow through any element of the envelope, the change due to a thermal bridge in that element may be estimated from equation (10) without the need for a complete hour-by-hour simulation of the building with the bridge included.

This idea was tested by running the DOE II program with each of the bridges inserted. The change in heating and cooling load by conduction through the element of the envelope in which the bridge was inserted was compared with the prediction of equation (10). Table (3) shows the characteristics of the original envelope along with the equivalent overall thermal resistance of the bridge and affected areas (using $h_o = 4.5$, $h_i = 1.5$). Table (4) shows the comparison of the actual change in load with that predicted by equation (10)

Table 3: Bridge Affected Areas and Equivalent Thermal Resistance

Bridge	Area of Affected envelope A_o (ft^2)	Undisturbed $1/U_o$(hr-ft^2-^oF/Btu)	Bridge effective area* A_e (ft^2)	Bridge Effective $1/U_e$(hr-ft^2-^oF/Btu)
1	19375	19.05	96	14.4
2	19375	19.05	48	4.41
3	19375	19.05	336	13.25
5	9987	14.90	1404	6.01
7a	26232	14.90	26232	10.14
7b	26232	14.90	6030	7.6
7c	26232	14.90	450	6.71

*Bridge A_e times the number of occurances of this bridge

Table 4: Comparison of Predicted Change in Total Conduction Load Through Envelope Elements with DOE II Simulation

Bridge	Percent Change in Annual Conducton Load			
		DOE II Simulation		
	Equation (10)	Heating	Cooling	Total
1	0.16	0.1936	0.666	0.212
2	0.82	0.992	3.416	1.090
3	0.76	0.919	3.166	1.010
5	20.80	17.360	-6.636	18.46
7a	46.94	55.60	-25.50	49.10
7b	22.08	26.50	-13.2	25.20
7c	2.09	2.7	-1.2	2.6

The simple method shows reasonable agreement with the increase in heating load but fails for the cooling load. We shall discuss this shortly but let us first consider the extension of the simple method to the total building load.

The region in which a bridge resides will, in general, be only one portion of the total envelope. If "f" represents the fraction of the total envelope conduction load attributable to the portion of the envelope in which the bridge is inserted,

$$f = \frac{q_o}{q_{total}}$$

then the estimated % change in the total envelope conduction load due to the bridge will be

$$\text{\% change in total envelope load due to bridge at } A_o = P_e = fP = \frac{q - q_o}{q_{total\ conduction}} \times 100 \qquad (11)$$

Furthermore, if "f_e" represents the fraction of the total building load attributable to envelope conduction loads,

$$f_e = \frac{q_{total\ conduction}}{q_{building}}$$

then the estimated % change in the total building load due to the bridge will be

$$\text{\% change in total envelope load due to bridge at } A_o = P_{total} = f_e P_e = \frac{q - q_o}{q_{building}} \times 100 \qquad (12)$$

Table (5) shows the fraction of the total envelope conduction load attributable to that portion of the envelope in which each bridge resides, f, for each bridge. These are smaller than the simple area ratios because they are ratios of conduction heat flow through all walls, roofs, floors, and glazing of the entire building.

Table 5: "f" Value Associated With Each Bridge

Bridge	for heating	for cooling	for total load
1,2,3	0.07064	0.01685	0.06263
5	0.0503	0.0188	0.0456
7a,7b,7c	0.1032	0.0867	0.1007

Using the "f" values, the associated predicted changes in the total building annual envelope conduction load were compared with those from the DOE II simulations. The results are shown in Table (6). Once again, the simple method fails to predict the annual changes in cooling load.

Table 6: Comparison of Predicted and DOE II Simulation Total Annual Change in Envelope Loads Due to Bridges

Percent Change in Total Envelope Conduction Load

	Heating Load		Cooling Load		Total Load	
Bridge	equation (11)	DOE II	equation (11)	DOE II	equation (11)	DOE II
1	0.0113	0.0164	0.0027	0.0032	0.0100	0.0144
2	0.0579	0.0840	0.0139	0.0165	0.0514	0.0740
3	0.0537	0.0780	0.0128	0.0153	0.0476	0.0680
5	1.046	0.9343	0.391	-1.030	0.948	0.650
7a	4.844	5.140	4.070	-1.420	4.727	4.170
7b	2.279	2.500	1.914	-0.630	2.223	2.040
7c	0.216	0.250	0.182	-0.077	0.211	0.204

To compare equation (12) with DOE-2 simulation results, the f_e values were determined from the base DOE II run as follows:

	Heating MBtu/yr	Cooling MBtu/yr	Total MBtu/yr
Total envelope conduction (walls, roof, floor, glass)	144.922	253.549	1703.471
Total building load	2287.543	2692.094	5583.637
f_e = conduction/total	0.50213	0.09404	0.30508

Table (7) shows the comparison between equation (12) and the actual changes in total building load due to each bridge.

Table 7: Comparison of Predicted and DOE II Simulation Increase in Total Annual Building Load Due to Bridges

	Heating Load		Cooling Load		Total Load	
Bridge	equation (12)	DOE II	equation (12)	DOE II	equation (12)	DOE II
1	0.0057	0.0049	0.00025	0.00035	0.00305	0.00246
2	0.0291	0.0250	0.00131	0.0018	0.0157	0.0126
3	0.0270	0.0230	0.0012	0.0017	0.0145	0.0117
5	0.525	0.487	0.037	0.019	0.289	0.245
7a	2.432	2.630	0.383	-0.550	1.442	1.010
7b	1.114	1.250	0.180	-0.260	0.678	0.480
7c	0.1085	0.111	0.017	-0.022	0.0644	0.048

The simple model is thus accurate for predicting changes in the building heating load but fails for the cooling load. While it might appear that the method is acceptable for the total load as well, the figures in Table (7) are misleading. Because the envelope conduction load is a much smaller percent of the total building load for cooling than it is for heating, the failure of the simple method for cooling load does not influence the total load as much as the heating load.

As we move from the bridge in its surrounding envelope element up to the total building, the number of factors influencing the load increases and so does the number of conditions that violate the simple assumptions upon which the simple model is based. While the effect of a decrease in the envelope thermal resistance is to always increase the heating load, the cooling load may either increase or decrease depending on the operation of the building. This situation was encountered by Copeland [6].

> "Even simple architectural changes performed by computer simulation can yield unexpected results, e.g., when the addition of insulation to the roof of a one-story structure was modeled. Contrary to what one might expect, this insulation actually increased total energy consumption. This was due to the greater cooling load resulting from slower dissipation of internal loads."

The dynamics of building operation, the effects of internal loads and internal heat storage, and other factors make our first simple model inadequate for the prediction of changes in cooling load due to bridges. The model, therefore, will also fail when cooling loads make up a significant portion of the total load.

C. Alternative Modeling Methods

To gain additional knowledge about the interaction of bridges and building dynamics without involving a considerable amount of DOE II runs, a simpler model of a building was created and analyzed. Figure (19) shows the simple structure created. This building consists of one envelope element containing a bridge with glazing, internal loads, infiltration, and mass. The wall, bridge, and the internal mass were divided into nodes for finite difference simulation and a 24 hour analysis run for various conditions. The program runs on a personal computer and is listed in the appendix.

The user may specify two levels of sensible and radiant internal loads and two levels of infiltration, starting at two different times during the day as shown in Figure (20).

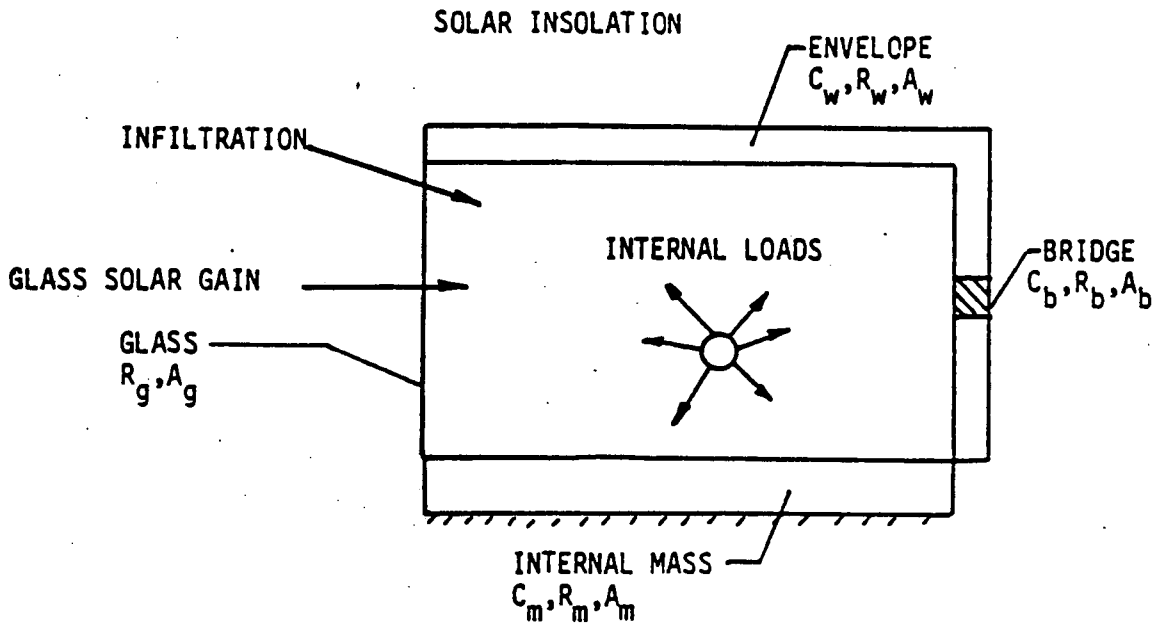


FIG. 19 : Simple Building Model for Studying Building Dynamics

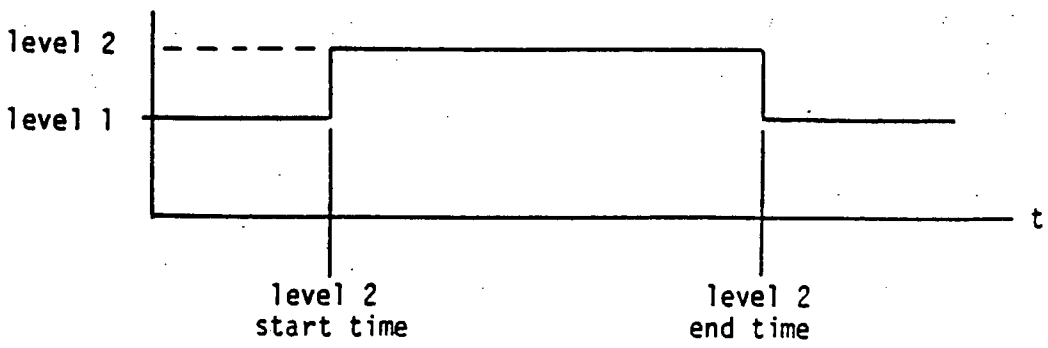


FIG. 20: Load Schedules

Thermostat setting for heating and cooling during unoccupied and occupied periods as well as HVAC system maximum heating and cooling capacity are also specified.

Solar insolation and solar gain through the glass is specified by the peak value and the hour when this peak occurs. A sine function is then used to determine values on either side of the peak hour.

Outdoor air temperature is modeled as

$$T_o = T_{oa} + T_{om} \sin \frac{2\pi(t-9)}{24} \tag{13}$$

with T_{oa} and T_{om} specified by the user. This produces a minimum at t=3 hours and a maximum at t=15 hours.

The model assumes that all solar radiation through the glass strikes the interior mass while the internal radiant load is distributed uniformly over all interior surfaces. At any instant, the heat required for the HVAC system is

+ convection from inside air to walls
+ convection from inside air to interior mass
+ convection from inside air to bridge
+ convection from inside air to glass
+ infiltration loss
- internal sensible load

which will be a cooling load if negative and a heating load if positive.

The individual elements of this summation make up the various elements of the heating or cooling load. Each is summed by the program over the 24 hour period to compute the total contribution of each to the total load.

During unoccupied periods with thermostat setback, if the interior temperature is within the upper and lower limits of setback, the heating or cooling load is set to zero and the interior air temperature allowed to float. Similarly, if the required heating or cooling load exceeds the maximum capacity of the HVAC system, the system input is set at the maximum and the resulting air temperature computed from the heat balance.

At each time increment, the individual contributions to the load are accounted for in one category as total load elements. If the HVAC system input at this time is zero, the individual contributions are not accounted for as net load elements. We thus have two accounting systems, one that sums up total heat flows within the building, and a second which only sums the heat flows when the HVAC system is "on".

While this model is lacking in several details and combines the walls and roof as one single homogenous envelope element, it is sufficiently accurate to illustrate the effects of a thermal bridge under dynamic building operation. In this respect, then, it is a valuable tool for increasing our understanding of these effects.

To illustrate what such a simple model is capable of and to explain some of the phenomenon we observe in the DOE II results, we consider a simple building with the following characteristics:

Wall:	area	A_w = 1.4 ft^2 per ft^2 of conditioned floor area
		R_w = 15 Hr-ft^2-^oF/Btu
		C_w = 12 Btu/ft^2-^oF
Glass:	area	A_g = 0.4 ft^2 per ft^2 of conditioned floor area
		R_g = 1.5 hr-ft^2-^oF/Btu
Bridge:	area	A_b = 0.1 ft^2 per ft^2 of conditioned floor area
		R_b = 4.0 hr-ft^2-^oF/Btu
		Cb = 20 Btu/ft^2-^oF

Internal mass:

area $A_m = 1.5\ ft^2$ per ft^2 of conditioned floor area

$R_m = 10\ hr\text{-}ft^2\text{-}^oF$

$C_m = 6\ Btu/ft^2\text{-}^oF$

The internal loads and infiltration schedule per ft^2 of conditioned floor area for this example are shown in Figure (21).

The entire program is set up in terms of heat flows per unit area of conditioned floor space which makes total building size unimportant and specification of areas, infiltration rates, and internal loads easier.

We shall now begin with some simple thermostat schedulings and observe the influences of increasing complexity. For each schedule the 24 hour analysis was run for:

a. a day when the total load is heating
b. a day when the total load is cooling
c. a day when the load is mixed heating and cooling

We begin with a total heating condition where the ambient air is at $T_{oa} = 20°F$ with a $\pm$ 10°F variation over the day, no solar loads, and a constant inside air temperature of 75°F. Table (8) shows the computer output of the resulting loads and Figure (22) illustrates the load variation over the day for the base run with no bridge. The simulation was then repeated with the bridge included. The results of this are shown in Table (9).

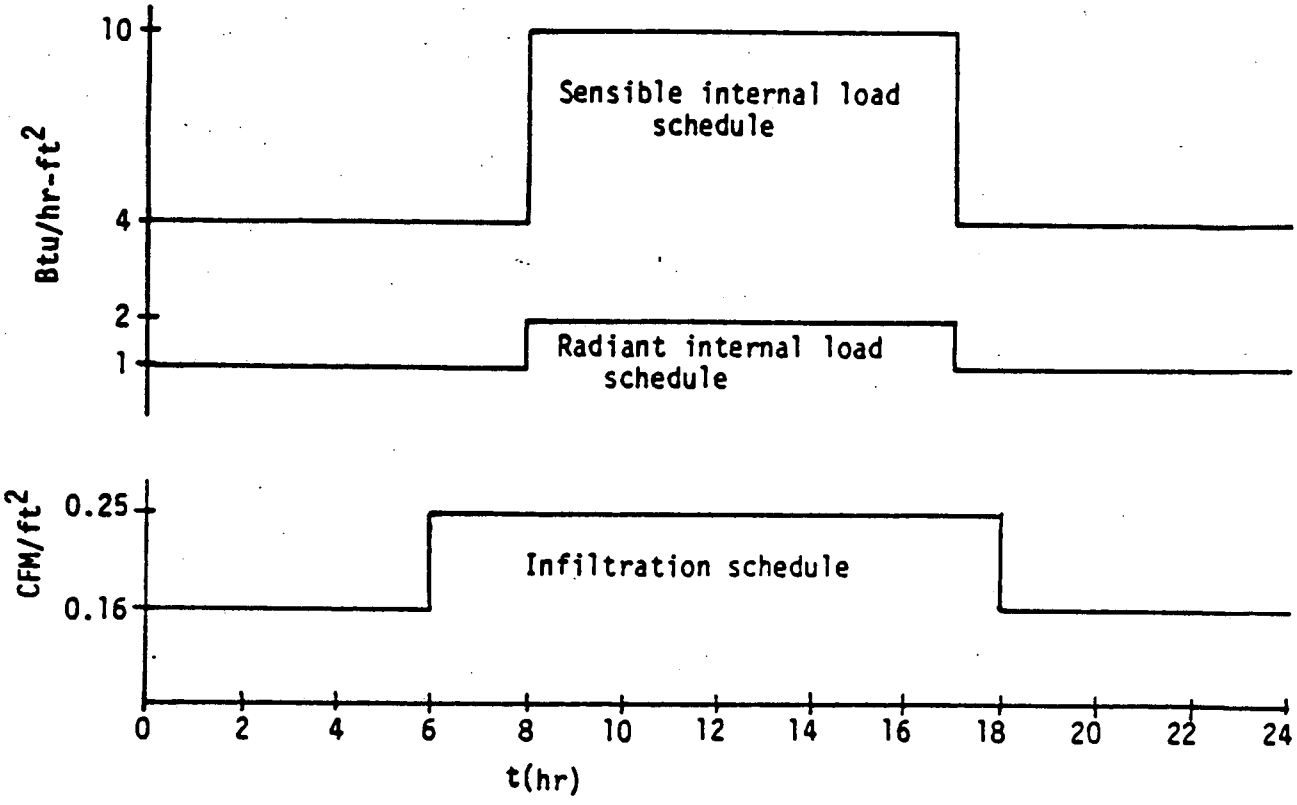


FIG. 21: Schedules for Example Building

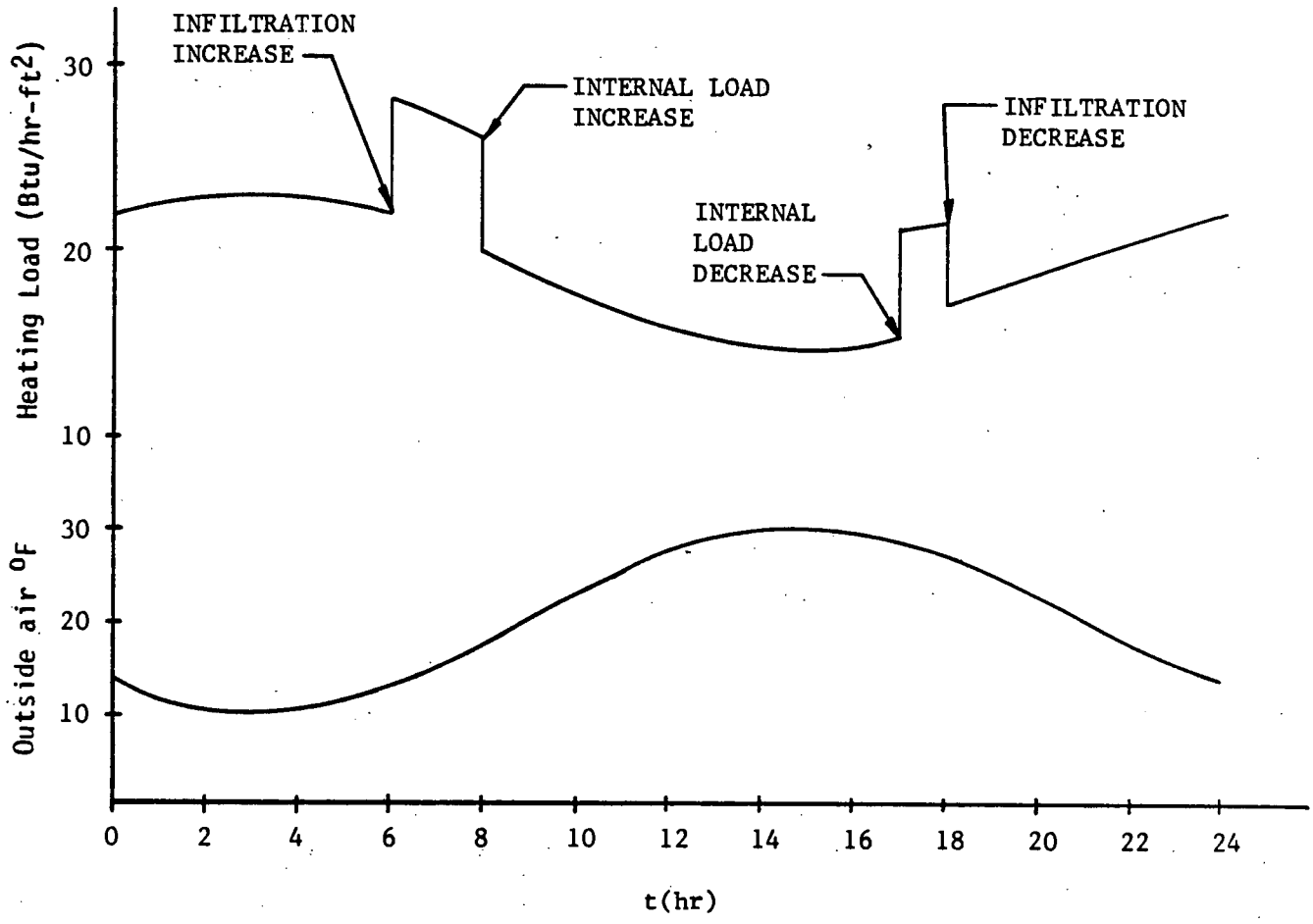


FIG.22 : Hourly Load Variation, Base Run Heating, No Bridge

Table 8: Simulation Results for Base Run, Heating With No Bridge

LOAD SUMMARY

	Total heat flows in	Total heat flows out	Net heat flows in	Net heat flows out
from walls	0.00	120.97	0.00	120.97
from interior mass	1.87	0.00	1.87	0.00
glass conduction	0.00	218.15	0.00	218.15
infiltration	0.00	286.46	0.00	286.46
glass radiation	0.00		0.00	
internal sensible	149.40		149.40	
internal radiant	32.90		32.90	

Net heating load = 474.3097 Hours heating = 24.00006
Net cooling load = 0 Hours cooling = 0

element	R	C	Area/sq.ft-floor
walls	15.000	12.00	1.400
internal mass	10.000	6.00	1.500
glass	1.500		0.400
bridge	4.000	20.00	0.000

Infiltration cfm/sq.ft-flr	0to6.0= 0.16,	6.0to18.0= 0.25,	18.0to24= 0.16
Thermostat set (heating)	0to6.0= 75.00,	6.0to18.0= 75.00,	18.0to24= 75.00
Thermostat set (cooling)	0to6.0= 75.00,	6.0to18.0= 75.00,	18.0to24= 75.00
Internal load (sensible)	0to8.0= 4.00,	8.0to17.0= 10.00,	17.0to24= 4.00
Internal load (radiant)	0to8.0= 1.00,	8.0to17.0= 2.00,	17.0to24= 1.00
Solar insolation peak	0.00 Btu/hr-sq.ft at 0.00 hours		
Glass solar load peak	0.00 BTu/hr-sq.ft at 0.00 hours		

Table 9: Simulation of Heating With Bridge

LOAD SUMMARY

	Total heat flows in	Total heat flows out	Net heat flows in	Net heat flows out
from walls	0.00	140.69	0.00	140.69
from interior mass	1.87	0.00	1.87	0.00
glass conduction	0.00	218.15	0.00	218.15
infiltration	0.00	286.46	0.00	286.46
glass radiation	0.00		0.00	
internal sensible	149.40		149.40	
internal radiant	32.90		32.90	

Net heating load = 494.0344 Hours heating = 24.00006
Net cooling load = 0 Hours cooling = 0

Even though the load varies considerably over the 24 hour period, the simple method for predicting the effect of the bridge under these conditions is valid.

Undisturbed $A_o = 1.4$ $\quad 1/U_o = 1/4.5 + 15 + 1/1.5 = 15.89$

Bridge $A_e = 0.1$ $\quad 1/U_e = 1/4.5 + 4 + 1/1.5 = 4.89$

Predicted percent increase in heat load of wall

$$P = \frac{A_e}{A_o}\left(\frac{U_e}{U_o} - 1\right) = \frac{0.1}{1.4}\left(\frac{15.89}{4.89} - 1\right)x100 = 16.07\%$$

From simulation:

$$P = \frac{140.69 - 120.97}{120.97} x100 = 16.3\%$$

From base run,

$$f = \frac{\text{wall conduction load}}{\text{total envelope load}} = \frac{120.97}{120.97 + 218.15} = 0.3567$$

Predicted percent increase in envelope heat load

$$P_e = fP = 0.3567(16.07) = 5.73\%$$

From simulation:

$$P_e = \frac{(140.69 + 218.15) - (120.97 + 218.15)}{120.97 + 218.15} X\ 100 = 5.82\%$$

From base run,

$$f_e = \frac{\text{envelope conduction load}}{\text{total load}} = \frac{120.97 + 218.15}{474.31} = 0.715$$

Predicted percent increase in total load

$$P_t = f_e P_e = 0.715(5.73) = 4.1\%$$

From simulation:

$$P_t = \frac{494.03 - 474.31}{474.31} x\ 100 = 4.16\%$$

We now take the opposite case with outdoor air temperature and solar radiation such that the load is always cooling. The Results of the simulation for the base case with no bridge is shown in Table (10) and with the bridge in Table (11). Figure (23) shows the ambient conditions and the hourly load profile.

Table 10: Simulation Results for Base Run, Cooling With No Bridge

LOAD SUMMARY

	Total heat flows in	Total heat flows out	Net heat flows in	Net heat flows out
from walls	53.86	0.00	53.86	0.00
from interior mass	32.42	0.00	34.42	0.00
glass conduction	46.06	3.00	46.06	3.00
infiltration	64.57	3.66	64.57	3.66
glass radiation	244.44		244.44	
internal sensible	149.40		149.40	
internal radiant	32.90		32.90	

Net heating load = 0 Hours heating = 0
Net cooling load = 339.6485 Hours cooling = 24.00006

Table 11: Simulation Results for Cooling With Bridge

LOAD SUMMARY

	Total heat flows in	Total heat flows out	Net heat flows in	Net heat flows out
from walls	62.23	0.00	62.23	0.00
from interior mass	32.42	0.00	32.42	0.00
glass conduction	46.06	3.00	46.06	3.00
infiltration	64.57	3.66	64.57	3.66
glass radiation	244.44		244.44	
internal sensible	149.40		149.40	
internal radiant	32.90		32.90	

Net heating load = 0 Hours heating = 0
Net cooling load = 348.0261 Hours cooling = 24.00006

Once again the simple model predicts the changes in load due to the bridge quite well.

Next we consider the intermediate case in which there is both heating and cooling load requirements during the day. Figure (24) shows the ambient conditions and load variation during the day for this case. The simulation output with and without the bridge is shown in Tables (12) and (13).

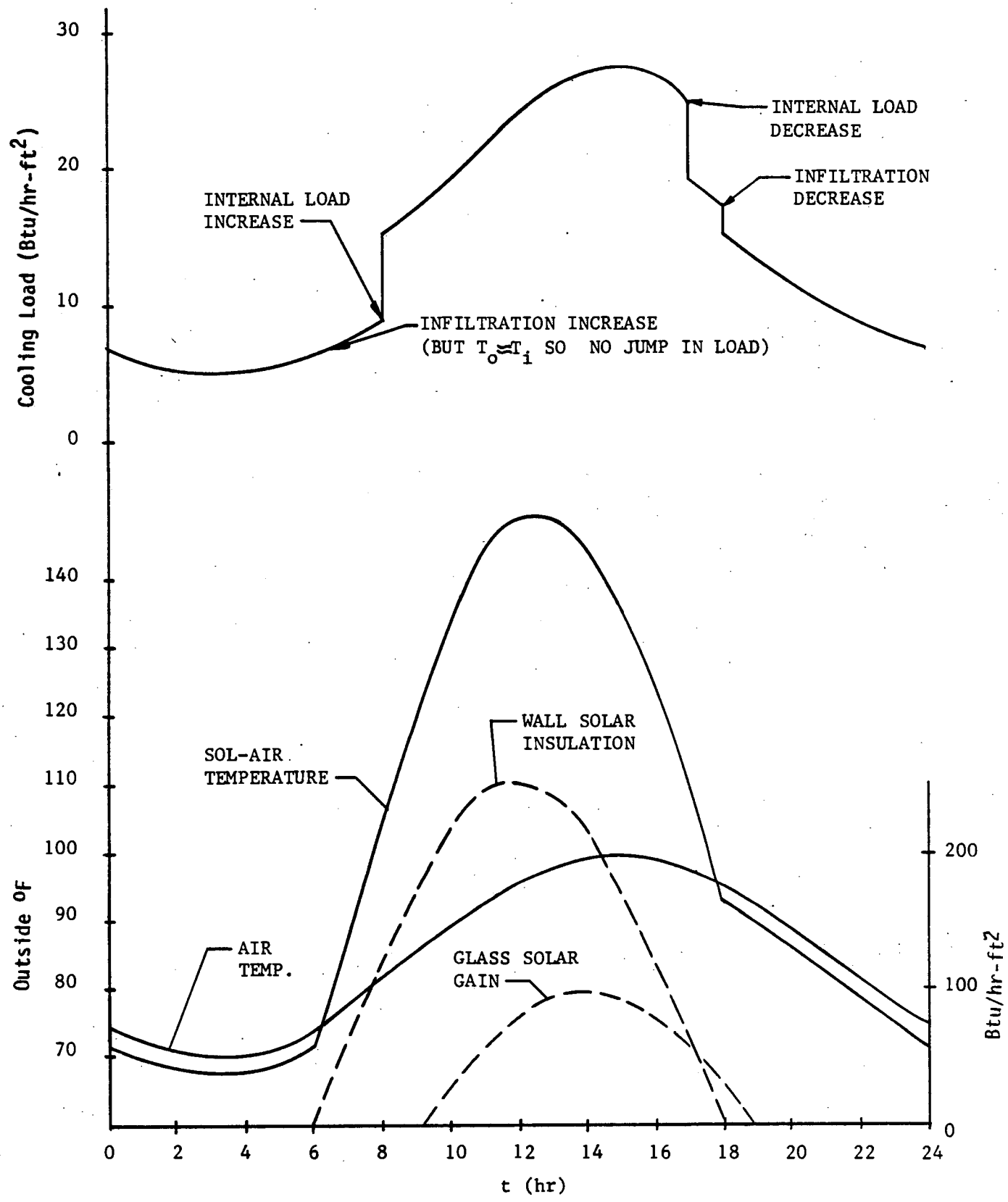


FIG. 23: Hourly Load Variation, Base Run, Cooling With No Bridge

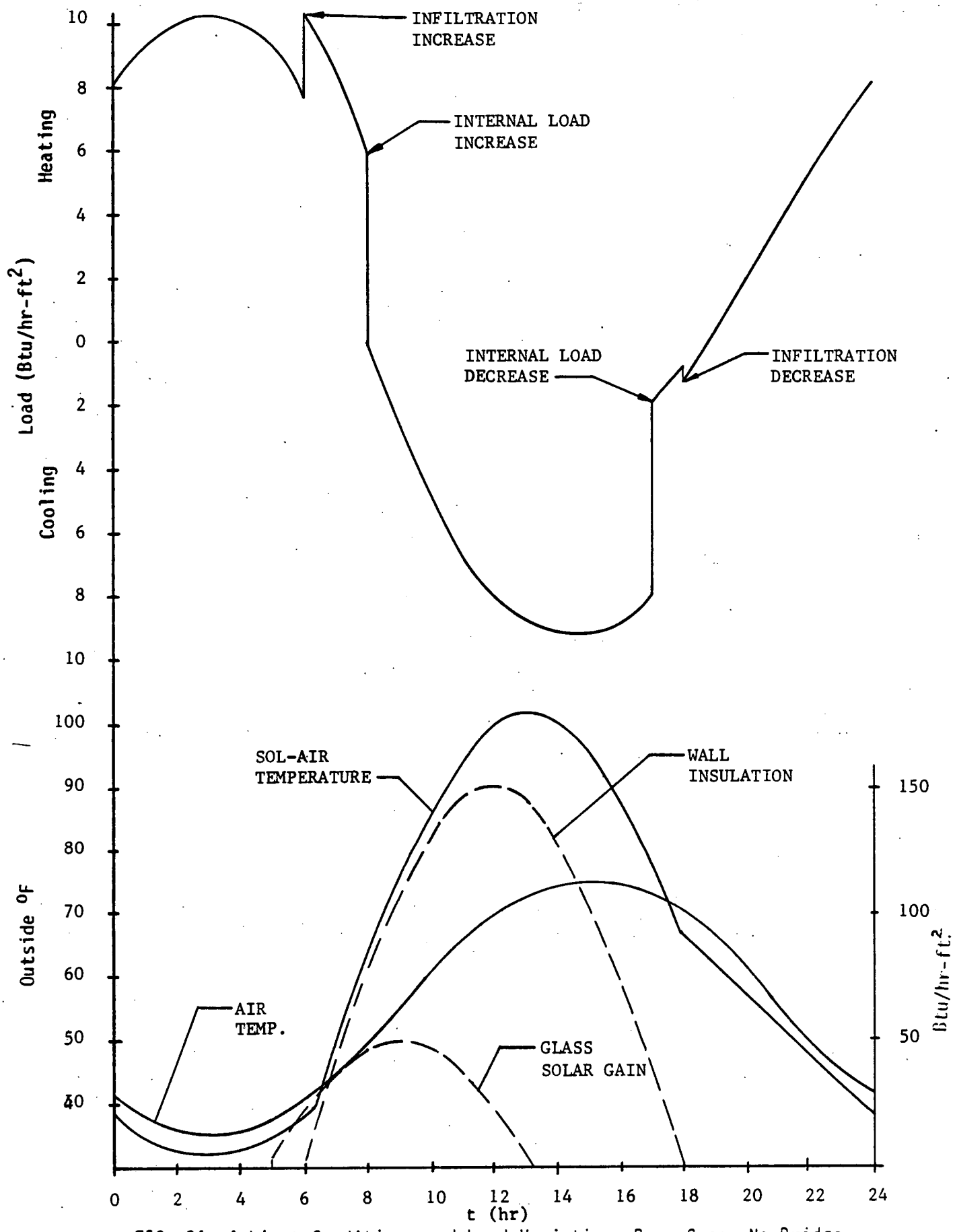


FIG. 24: Ambient Conditions and Load Variation, Base Case, No Bridge

Table 12: Simulation Results for Base Case, Both Heating and Cooling, No Bridge

LOAD SUMMARY

	Total heat flows in	Total heat flows out	Net heat flows in	Net heat flows out
from walls	0.00	24.54	0.00	24.54
from interior mass	15.68	0.00	15.68	0.00
glass conduction	0.29	77.79	0.29	77.79
infiltration	0.00	95.58	0.00	95.58
glass radiation	110.51		110.51	
internal sensible	149.40		149.40	
internal radiant	32.90		32.90	

Net heating load = 96.41057 Hours heating = 13.20001
Net cooling load = 63.87921 Hours cooling = 10.80001

Table 13: Simulation Results for Heating and Cooling With Bridge

LOAD SUMMARY

	Total heat flows in	Total heat flows out	Net heat flows in	Net heat flows out
from walls	0.00	28.76	0.00	28.76
from interior mass	15.68	0.00	15.68	0.00
glass conduction	0.29	77.79	0.29	77.79
infiltration	0.00	95.58	0.00	95.58
glass radiation	110.51		110.51	
internal sensible	149.40		149.40	
internal radiant	32.90		32.90	

Net heating load = 97.80454 Hours heating = 13.80001
Net cooling load = 61.05095 Hours cooling = 10.7

Here we observe that the bridge results in an increase in the net heating load but a decrease in the net cooling load. The simple method for predicting the effect of the bridge fails for this case as illustrated in Table (14).

Table 14: Comparison of Simple Method for Predicting Effect of Bridge With Simulation Results for Three Cases

		Heating only	Cooling only	Both heating and cooling heat	cool	total
Wall P	predicted	16.07	16.07	16.07	16.07	16.07
	actual	16.3	15.54	17.2	0.0	17.2
f		0.3567	0.539	0.24	0.0	0.24
Envelope P_e	predicted	5.73	8.66	3.85	0.0	3.84
	actual	5.82	8.38	4.12	0.0	4.11
f_e		0.715	0.294	1.06	0.004	0.638
Load P_t	predicted	4.10	2.55	4.09	0.0	2.45
	actual	4.16	2.47	1.44	-4.43	-0.89

As a second example, the simulation was run with the thermostat settings shown in Figure (26) which allow night setback of the HVAC system.

A comparison of the simple model with the simulation is given in Table (15)

Table 15: Simple Model vs Simulation for Night Setback Operation

With Heating Only (T_{oa} = 20°F)			With Cooling Only (T_{oa} = 85°F)		
	Predicted	Simulation		Predicted	Simulation
P	16.07	11.9	P	16.07	9.38
Pe	7.21	5.8	P_e	9.47	5.55
P_t	5.09	4.1	P_t	2.76	1.87

The simple model assumes that the integrated average temperature difference over the 24 hour period is the same with the bridge as without it. If either the interior air temperature or the number of hours over which heating or cooling is required change, then this assumption is violated. The simple model is thus only correct when the interior air temperature is fixed throughout the entire period and only heating or only cooling is required over the entire period. In all other situations, the simple model will overpredict the effect of the bridge on the building total energy consumption. This conclusion can be extended from a single day to the annual energy consumption

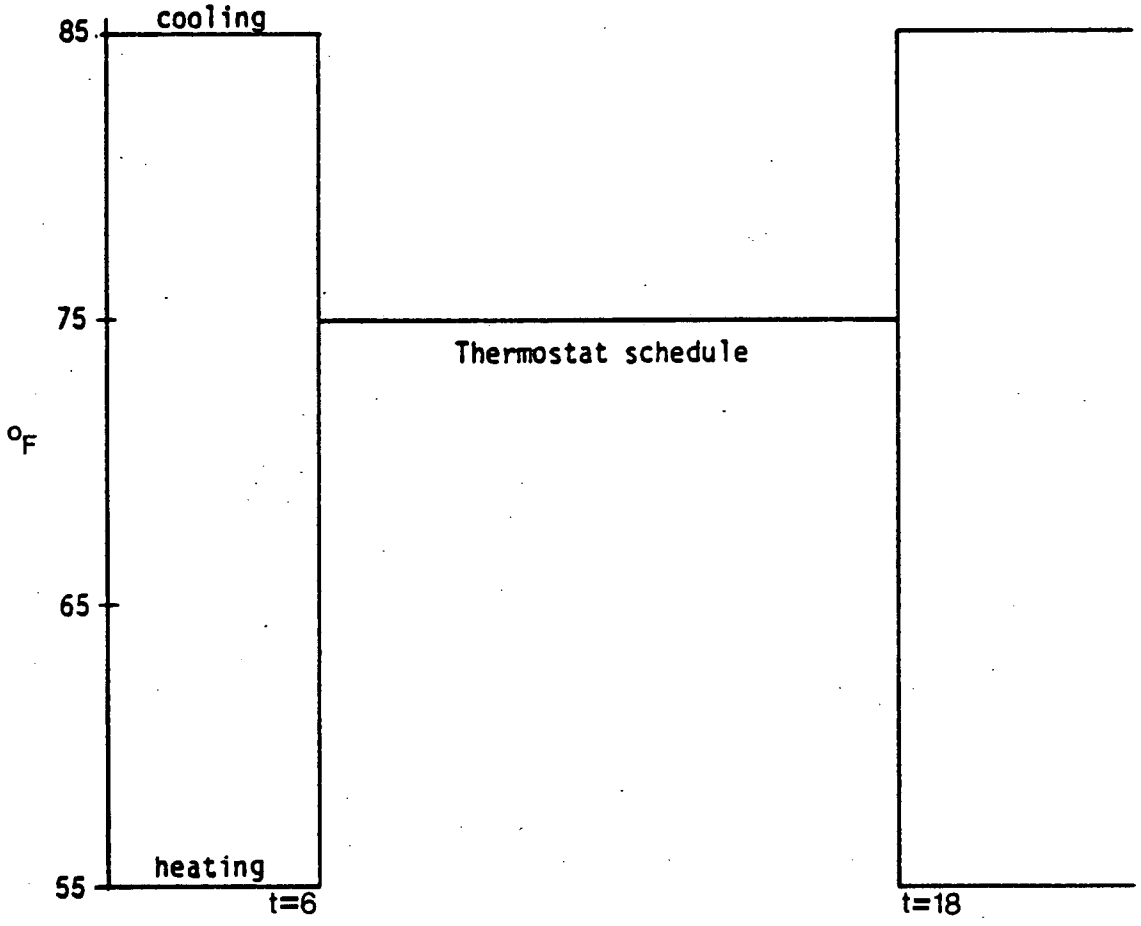


FIG. 26 : Thermostat Schedule with Night Setback

in general by noting that the simple model overpredicts the bridge effect in the majority of cases in Table (7). In order to work, any simple model must be able to anticipate what will happen to the building envelope and the building HVAC system when a bridge is inserted based on what happen without the bridge and the properties of the bridge itself. While the changes in the local envelope can be estimated simply, their effect on the HVAC system operation is more involved.

Simple computer models such as the one use above, are useful tools for aiding in the understanding of problems such as this without the obscuring clutter associated with real buildings.

VIII. RECOMENDATION FOR CATEGORIZING BRIDGES

At this point it appears possible to supply building designers and analysts with simple parameters that convey the effects of bridges on building energy use and their moisture damage potential. Creation of these parameters requires at the minimum a steady - state numerical simulation of the bridge and a portion of its surroundings. Use of the parameters requires:

1. For moisture damage potential; a knowledge of the building interior air state and the frequency of cold outside ambient conditions as well as the location of the bridge and succeptibility of nearby materials to moisture damage.

2. For energy penalties; some form of hour-by-hour model of the building into which one may insert the equivalent R-value and affected area because, as we have shown, simple ratios of R-values is only approximate. At best, simple ratios over predict the effect of the bridge. Because of this, however, it is possible to eliminate insignificant bridges. If a simple ratio shows that a bridge is not worth fixing, then an hour-by-hour simulation will show that it is even less so.

A catalog of bridges, then, should include the following items:

1. A description of the bridge.

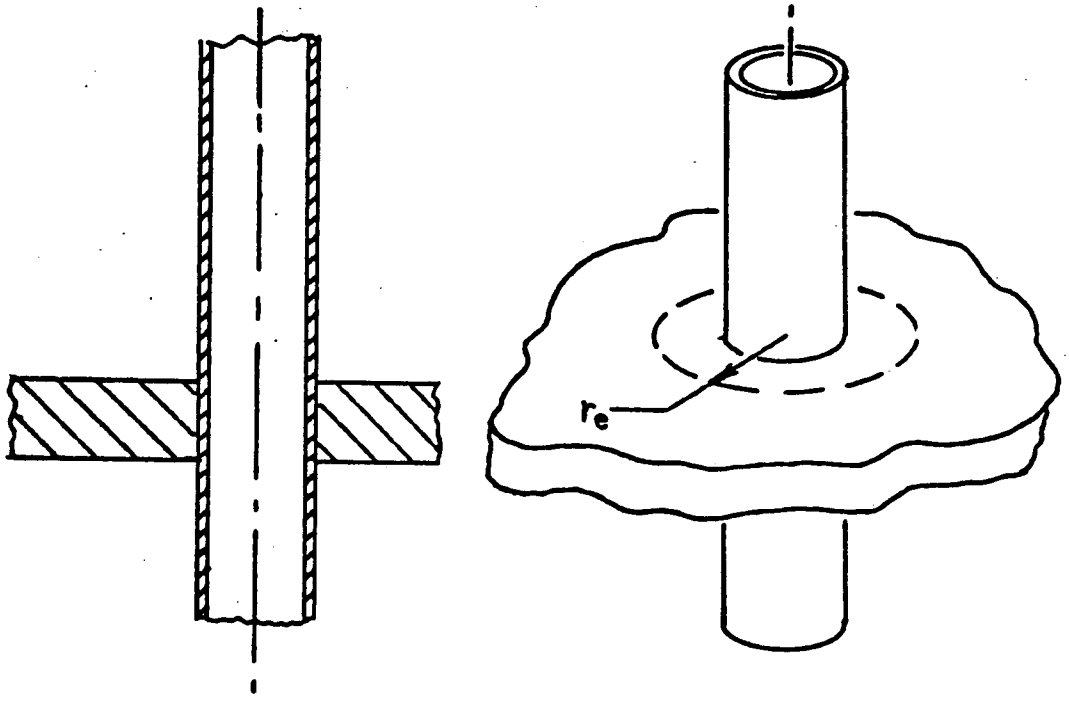
2. Types of buildings in which it typically occurs (masonry, frame, curtain wall, old or new construction) along with typical numbers of occurrance.

3. Equivalent R-value affected area, and temperature depression ratio when inserted in several types of envelopes.

4. Typical energy penalties per occurance in several types of buildings and climates.

5. Typical retrofit or initial design schemes that reduce the impact along with their construction/renovation costs.

The basic items in such a catalog might be tabulated in a manner similar to that shown in Figure (27).



Nominal pipe dia.	Undisturbed wall R	Radius of Equivalent wall, r_e	Equivalent wall R	Temperature depression ratio

FIG.27 : Possible Format for Bridge Catalog Entry

In order to use such a catalog for heating loads, one would proceed as follows:

If

A_e = Affected Area

R_e = Equivalent "R" Value

R_o = Undisturbed Wall "R" Value

h_i = Inside Film Coefficient

h_o = Outside Film Coefficient

Then the steady-state heat loss through the bridge affected area is

$$Q_e = \frac{A_e\,[T_i - T_o]}{1/h_i + R_e + 1/h_o}$$

While the heat flow with no bridge is

$$Q_o = \frac{A_e\,[T_i - T_o]}{1/h_i + R_o + 1/h_o}$$

The difference being

$$Q_e - Q_o = A_e\,[T_i - T_o]\left(\frac{1}{1/h_i + R_e + 1/h_o} - \frac{1}{1/h_i + R_o + 1/h_o}\right).$$

$$= A_e[T_i - T_o]\Delta U$$

From this one may estimate the additional heating energy lost through a wall due to the presence of the bridge using degree days (HDD).

$$\Delta\dot{E} = A_e[24][\Delta U][HDD]$$

Table 16: Comparison of Predicted Heating Load Loss By Degree Days with DOE-2 for Bridges Studied

			----------MBtu----------		
Bridge	$A_e(ft^2)$	ΔU	$\Delta \dot{E}$	DOE-2	EQ .10
1	96	0.017	0.157	0.198	0.164
2	48	0.1743	0.803	1.02	0.843
3	336	0.023	0.742	0.941	0.778
5	1404	0.0993	13.38	12.66	15.17
7a	26232	0.0315	79.32	83.2	70.24
7b	6030	0.0645	37.34	39.65	33.04
7c	450	0.082	3.54	4.04	3.13

Using 4000 heating degree days, Table (16) illustrates that this method is reasonable. With such an estimate, a designer can proceed to estimate the energy costs associated with each bridge.

Several modifications of the bridges by design changes were examined to determine the value of an investing effort to reduce the energy loss. These modifications are illustrated in Figures (28) through (31).

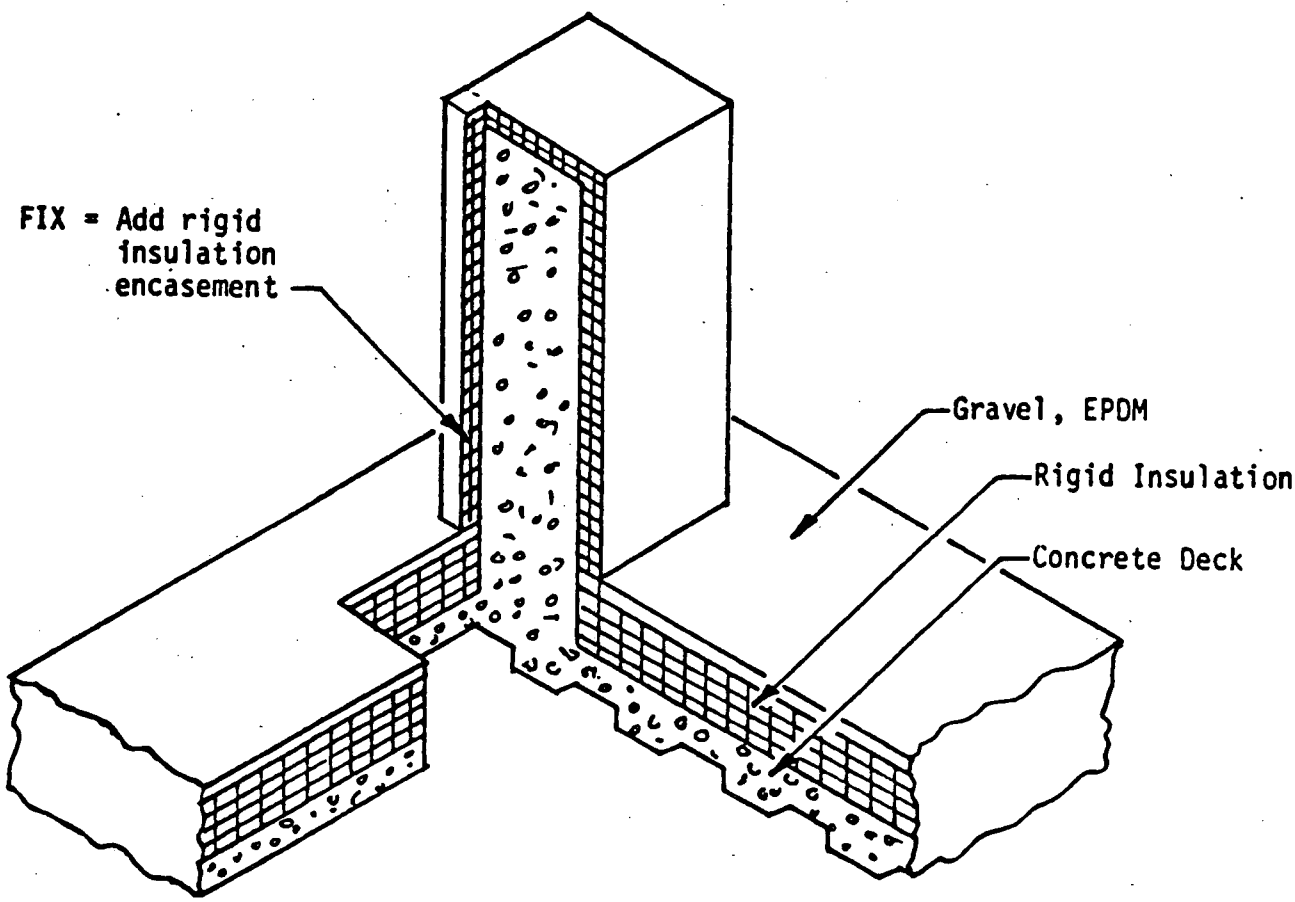


FIG. 28: "Fix" for Bridge 3

	1/U (hr-ft^2-^{o}F/Btu)	Temperature depression ratio
Original bridge	13.3	0.82/0.97
With 1" rigid insulation	15.8	0.88/0.97
With 2" rigid insulation	16.6	0.88/0.97
undisturbed roof	19.0	0.97/0.97

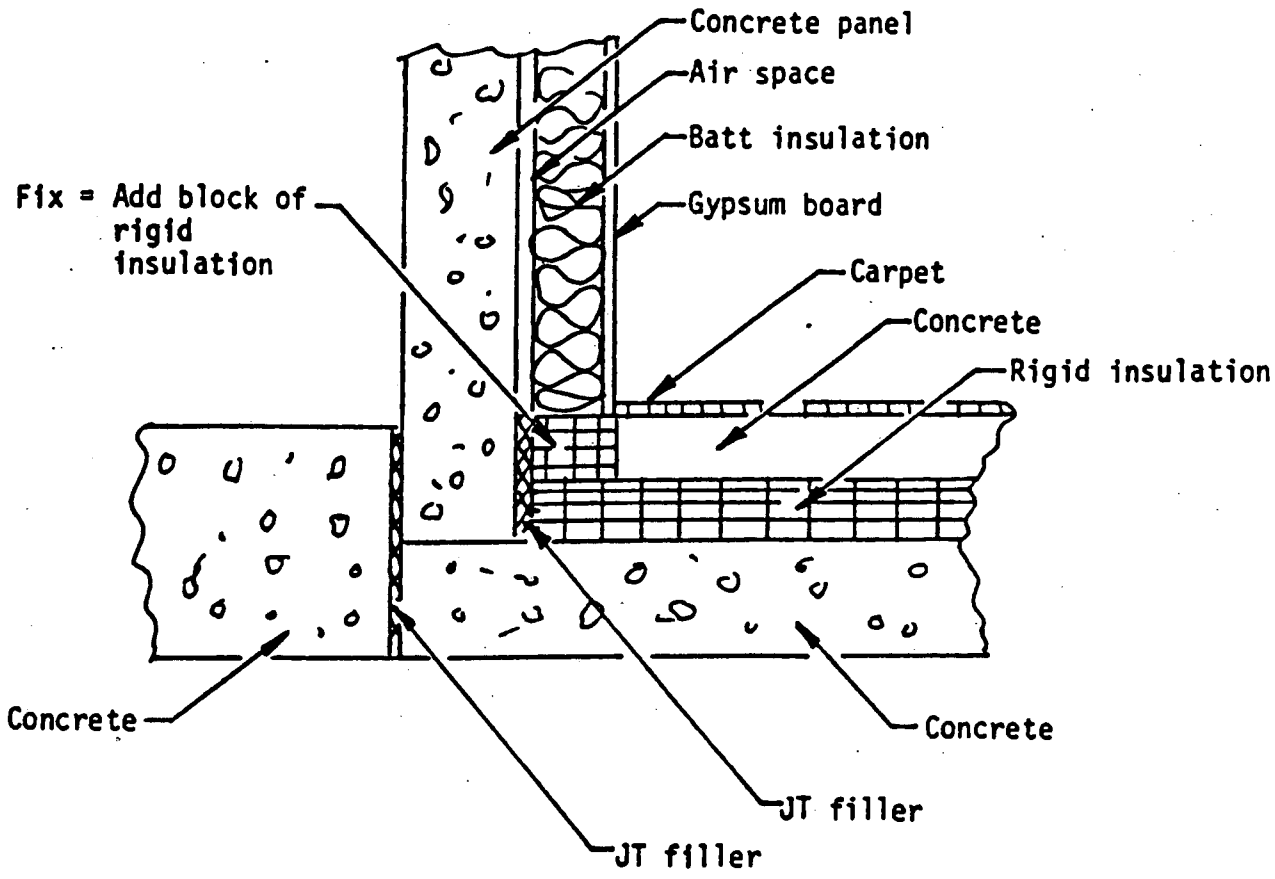


FIG. 29: "Fix" for Bridge 5

	1/U (hr-ft^2-^{o}F/Btu)	Temperature depression ratio
Original bridge	6.0	0.57/0.96
With fix	9.0	0.85/0.96
Undisturbed wall	14.9	0.96/0.96

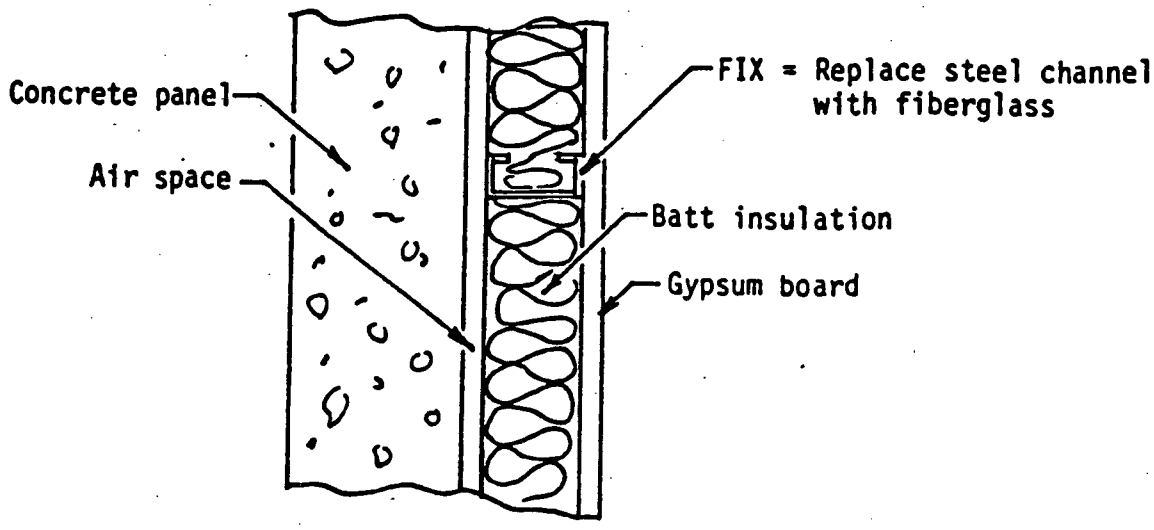


FIG. 30: "Fix" for Bridge 7a

	1/U (hr-ft^2-^{o}F/Btu)	Temperature depression ratio
Original bridge	10.1	0.78/0.96
With fix	11.0	0.83/0.96
Undisturbed wall	14.9	0.96/0.96

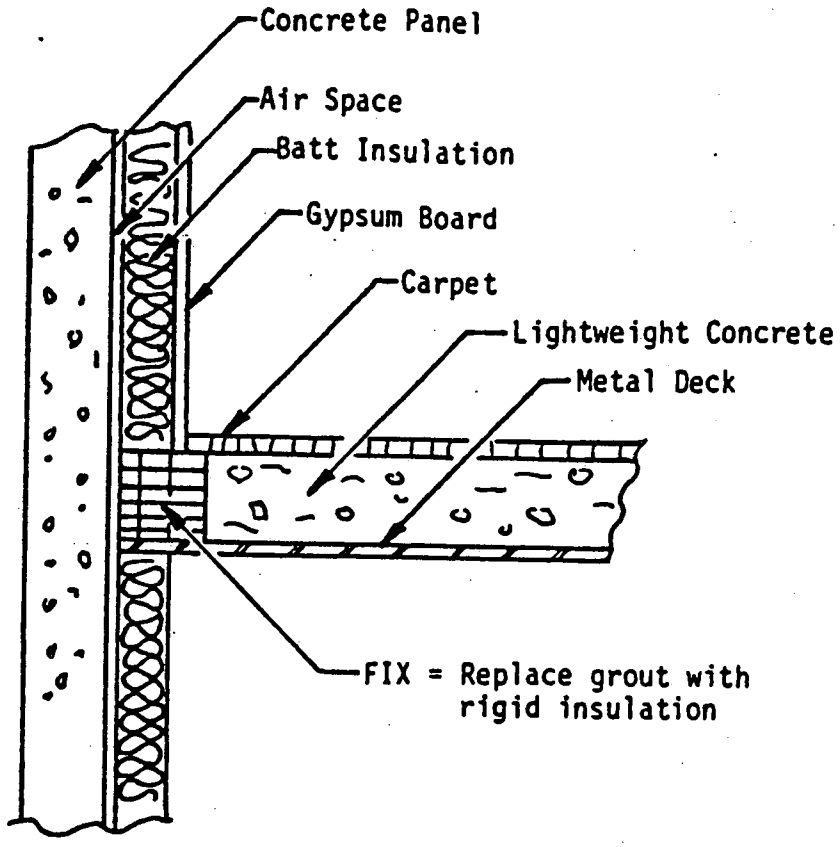


FIG. 31 : "Fix" for Bridge 7b

	1/U (hr-ft^2-^{o}F/Btu)	Temperature depression ratio
Original bridge without steel deck	7.6	0.73/0.96
with fix	14.6	0.95/0.96
Original bridge with steel deck	7.1	0.74/0.96
with fix	11.3	0.86/0.96
Undisturbed wall	14.9	0.96/0.96

As can be seen from Figures (28) through (31) the heat flow and temperature depression are two separate items. It is possible for a corrective measure to alter the heat flow paths enough to substantially reduce condensation potential even though total heat loss is not reduced significantly.

The decision to modify the design of an identified thermal bridge has to be made based upon the energy loss related to that bridge along with the condensation potential related to that bridge. By the method previously discussed the energy benefits of modifying that bridge can be determined, however, it is much more complicated to affix costs related to moisture damage. As can be seen in Table (17) the energy cost associated with the bridges is quite small, therefore, the decision to modify a bridge needs to be based on both moisture damage maintenance costs and energy benefits weighted against the modification cost.

Table 17: Dollar Energy Savings by Retrofits, Model Building

	Annual $ savings per occurrence	Total annual $ savings
3 with 1" added insulation	0.24	1.44
3 with 2" added insulation	0.30	1.80
5	0.18/ft*	122.85
7a	0.007/ft^2**	189.30
7b without deck	0.23/ft*	349.58
7b with deck	0.19/ft*	288.08

* linear ft of perimeter

** ft^2 of wall

IX. CONCLUSIONS

In this study we have done an in-depth investigation of a number of thermal bridges in a real building. A methodology of analysis was developed in which the bridge and its affected region of the envelope are replaced by an equivalent one-dimensional wall. This equivalent wall is then used in an hour-by-hour simulation of the building. A simple bridge was examined in detail to illustrate the method of selecting the location of the division between the bridge equivalent wall and the rest of the envelope based on the local heat flux on the inside surface. When one is far enough from the bridge so that the local heat flux is with 1%, or less, of the heat flux for the undisturbed wall, then the bridge can be effectively isolated and treated as a separate heat flow path. The effective thermal resistance of the equivalent wall can then be determined from a steady-state finite difference simulation.

In this study, the effective thermal capacitance of the equivalent wall was taken as that of the undisturbed wall because thermal response factors for multi-dimensional problems cannot be determined with existing algorithms. One identified need is thus to develop this capacity.

Using the equivalent wall, the effect of the bridges identified on the energy consumption of the building was determined and the value of modifications to the bridges to reduce their impact was examined.

In many cases, the bridge resulted in a decrease in cooling energy because it allowed additional energy to escape at night on mild days of the year. With night setback of the HVAC system, this reduces the amount of energy required to "Pull down" the next morning. On days when both heating and cooling are required, the increased energy use due to the bridge is much less than one might expect based on a steady-state analysis. Over the year, then, many bridges are not as detrimental as they first appear.

These complexities related to the dynamic behavior of the building cannot be modeled accurately without running an hour-by-hour simulation of the building with and without a bridge. A simpler dynamic model of a building was created and run for a number of cases to verify this conclusion and to better understand why simple bridge heat loss models are inadequate.

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