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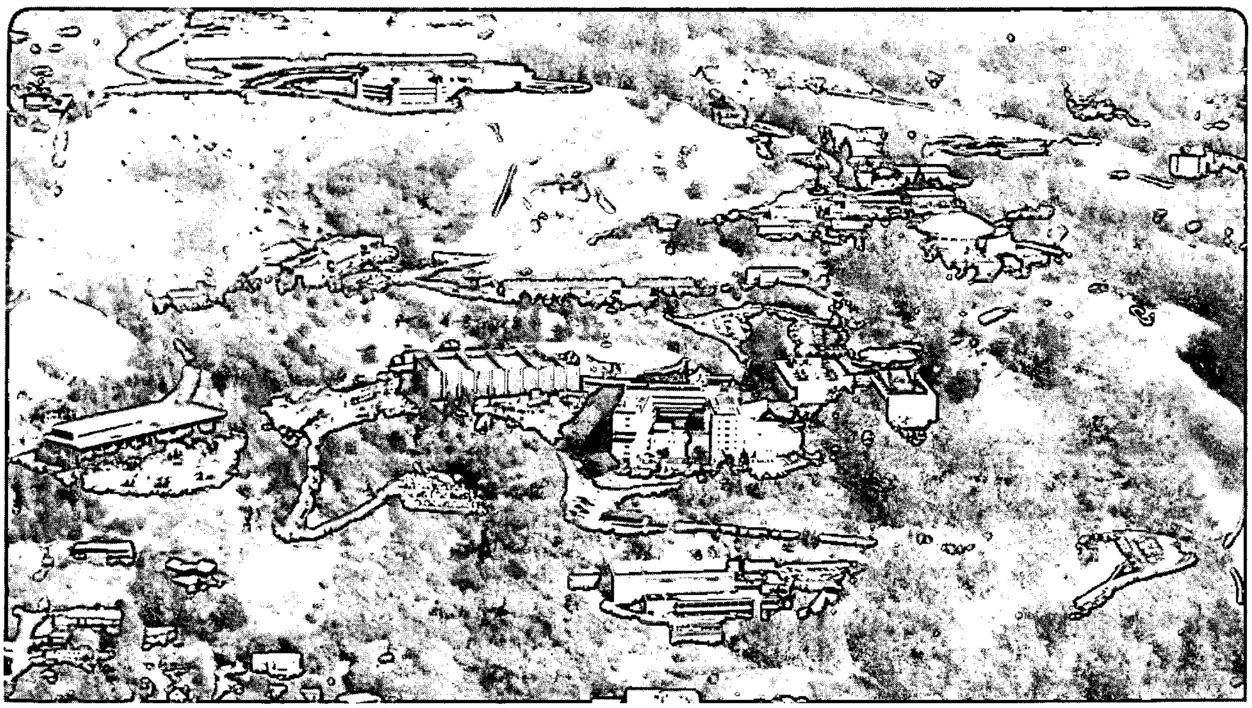

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ENGINEERING NOTE

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M. A. Green	MECHANICAL ENGINEERING	Berkeley	27 May 1982

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TITLE

A COMPARISON OF THERMAL MODELING METHODS FOR BUILDINGS

This engineering note compares four methods of thermal modeling buildings using scale models. This note will demonstrate how well the scaling method developed by Richardson and Berman works[1] The case chosen to compare thermal modeling is an extreme one which should demonstrate the weaknesses of all of the methods of scale modeling. The methods of thermal modeling were all looked at for one-sixth scale models. These modeling methods are as follows:

1) A straight scaling of all dimensions of a building. The materials used are the same as in the full-scale structure. The modeling time day (called the circadian period) is 24 hours. The modeling gas is air.

2) All dimensions in the structure are scaled except for wall thickness. The model wall thickness is the same as the full-scale structure. The wall materials used are the same as the full-scale structure. The circadian period is 24 hours. The modeling gas is air.

3) This method is the same as 2 except the model is housed in a chamber containing air at 21.2 atmospheres.

4) The Richardson-Berman method where the walls approach being fully scaled. The modeling is done in a Xenon-Argon atmosphere with a circadian period of 6.39 hours. This method is supposed to model all aspects of the building thermal dynamics.

The advantages of the Richardson-Berman modeling method become clear when a comparison is made between the methods given in this report. (There may be other methods of modeling which have not been studied by this author.) The characteristics of a passive solar structure are also clearly evident from the modeling methods given here.

1. The Full-Scale Passive Solar Structure to be Modeled

The structure chosen to demonstrate the various modeling methods is a passive solar structure similar to the one described in *Reference 2.* This structure, which has a cross-section shown in Figure 1, is typical

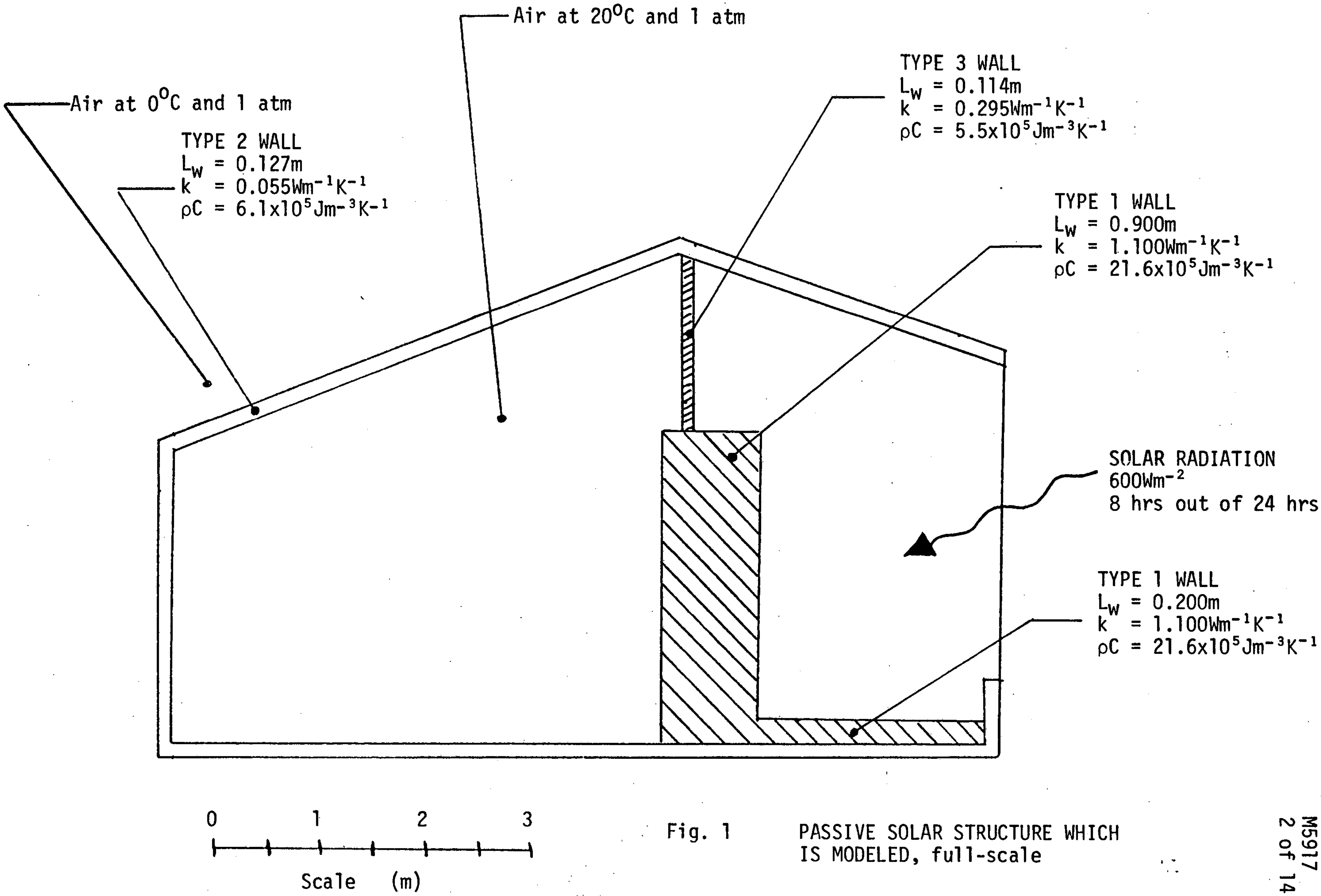


Fig. 1 PASSIVE SOLAR STRUCTURE WHICH IS MODELED, full-scale

of what might be used in a passive solar system. The structure is divided into two parts. The first part is a solar greenhouse which collects solar energy and stores it in the walls and floor. The second part is a room which could be considered to be the living space. The structure shown in Figure 1 is 8m wide, 5m high and 15m long. It is assumed that solar flux enters through the window at the right. It is assumed there is no infiltration into the structure and that there are no heaters within the passive solar structure.

The structure has three types of walls (called Wall Number 1 through Wall #3). Wall Number 1 is made from heavy concrete. This wall type forms part of the dividing structure between the two rooms and is assumed to be 0.9m thick. This wall type is also the floor of the solar greenhouse section of the house. (The floor is assumed to be 0.2m thick.) Wall Number 1 type is characterized by high specific heat per unit volume and high thermal conductivity. Wall Number 2 is the main insulating and weather wall for the structure. (The word *wall* can be applied to the floor and ceiling of the structure.) This wall is an R-14 wall and is characterized by a low thermal conductivity and low specific heat per unit volume. Wall Number 3 is a typical interior wall for a west coast home. This wall has an intermediate thermal conductivity and a low specific heat per unit volume. The characteristics of the three wall types are as follows:

WALL #1: Heavy concrete wall
- ρ = 2250 kg m^{-3}
- ρC = 2.16 x $10^6 Jm^{-3}K^{-1}$
- k = 1.10 $Wm^{-1}K^{-1}$
- L_W = 0.2m and 0.9m

WALL #2: West coast R-14 wall 5 inches thick
- ρ = 430 kg m^{-3}
- ρC = 0.60 x $10^6 Jm^{-3}K^{-1}$
- k = 0.055 $Wm^{-1}K^{-1}$
- L_W = 0.127m

WALL #3: Inside dividing R-3 wall 4.5 inches thick
- ρ = 450 kg m^{-3}
- ρC = 0.55 x $10^5 Jm^{-3}K^{-1}$
- k = 0.295 $Wm^{-1}K^{-1}$
- L_W = 0.114m

The passive solar structure is assumed to be in air at 1 atm. The nominal inside temperature of the structure is 20°C. The nominal temperature outside the structure is 0°C. The windows on the right side of the structure (see Figure 1) are assumed to have an area of

48.75m^2 (3.35 x 14.55m). The solar flux is assumed to be 600 Wm^{-2} over 8 hours of a 24-hour day.

The parameters of the full-scale structure are given in TABLE 1. The useful parameters to look at are 1) the ratio of wall thermal capacity to internal gas thermal capacity, 2) the heat storage time constant which is given in circadian periods(model days), and 3) the ratio of heat entering the model from the sun over the ratio of heat being transferred out through the outside walls from 20^o to 0^{o}C (or the appropriate model temperature). The heat storage time constant is defined as the time in circadian periods the solar flux needs to heat up the walls of the structure 20^{o}C (assuming no heat leaks out). An effective passive solar system has a heat storage time constant and a ratio of heat flux in to heat flux out which is greater than one. This means the structure absorbs more heat than it emits and the structure is capable of storing more than one day's (one circadian period) worth of radiative input.

One measure of the effectiveness of the thermal model method is to compare the three parameters given above. This is done for the four modeling methods in TABLE 1. The other measure of model effectiveness is how the model reproduces internal dimensions and how convective cells perform in the model. From TABLE 1, it is clear that the gas is not an important heat sink for the model. However, at least half the heat transfer inside the model is through natural thermal convection. The shape of the model inside also affects its radiative heat transfer inside. Each of the four modeling methods will be compared to the full-scale structure.

2. Scale Model Method 1

This method of scaling the structure is to scale all dimension down a factor of six. The materials in the walls are the same as in the full-scale structure. The scale model structure is in an air atmosphere at 0^{o}C with the inside to be kept at 20^{o}C. This method does a good job of showing an architect what the building or structure looks like. The client is impressed but as a thermal model this method is a complete bust.

When one looksat TABLE 1, one finds that the ratio of wall thermal capacity to gas thermal capacity is the same as for the full-scale structure (a slight plus). When one looks at the heat storage time constant and the ratio of heat in to heat out, one can see that this method of modeling does not produce an effective passive solar system. The reasons are simple. The volume, hence the mass, of the building goes down faster than the surface area. Therefore, the heat storage time constant is one sixth of the full-scale structure when the scale model is at one-

TABLE 1. VARIOUS PARAMETERS FOR THE FULL-SCALE PASSIVE SOLAR STRUCTURE AND THE VARIOUS SIXTH-SCALE MODEL METHODS

PARAMETERS	FULL-SCALE STRUCTURE	ONE-SIXTH SCALE MODELS			
		Method 1	Method 2	Method 3	Method 4##
Total volume of structure (m^3)	502.5	2.340	3.415	3.415	2.604
Outside area of structure (m^2)	423.3	11.805	15.438	15.438	12.727
Total volume to total area ratio	1.187	0.198	0.221	0.221	0.205
Total volume of the walls (m^3)	96.8	0.451	2.839	2.839	0.932
Internal gas volume (m^3)	405.7	1.889	0.576	0.576	1.672
Type of atmosphere	air	air	air	air	Xe-Ar#
Pressure of stmosphere (atm)	1.00	1.00	1.00	21.17	4.31
Ratio of wall thermal capacity to internal gas thermal capacity	266	266	5630	266	261
Length of circadian period (hr)	24	24	24	24	6.39
Length of solar radiation period (hr)	8	8	8	8	2.13
Radiation heat flux rate (Wm^{-2})	600	600	600	600	2701
Window area (m^2)	48.75	1.360	1.360	1.360	1.360
Circadian period heat flux In (J)	8.42x10^8	2.35x10^7	2.35x10^7	2.35x10^7	2.81x10^7
Circadian period heat flux Out (J)	2.96x10^8	5.34x10^7**	0.98x10^7**	0.98x10^7**	1.06x10^7
Heat storage time constant (C.P.)*	3.15	0.53	3.23	3.23	3.17
Ratio of heat In to heat Out	2.76	0.46**	2.40**	2.40**	2.65

\# 91.6% Xenon and 8.4% Argon

* C.P. is defined as circadian periods (model days)

** Convective heat transfer on the inside and outside of Wall Type 2 is not considered

This is the only method which models convective heat transfer

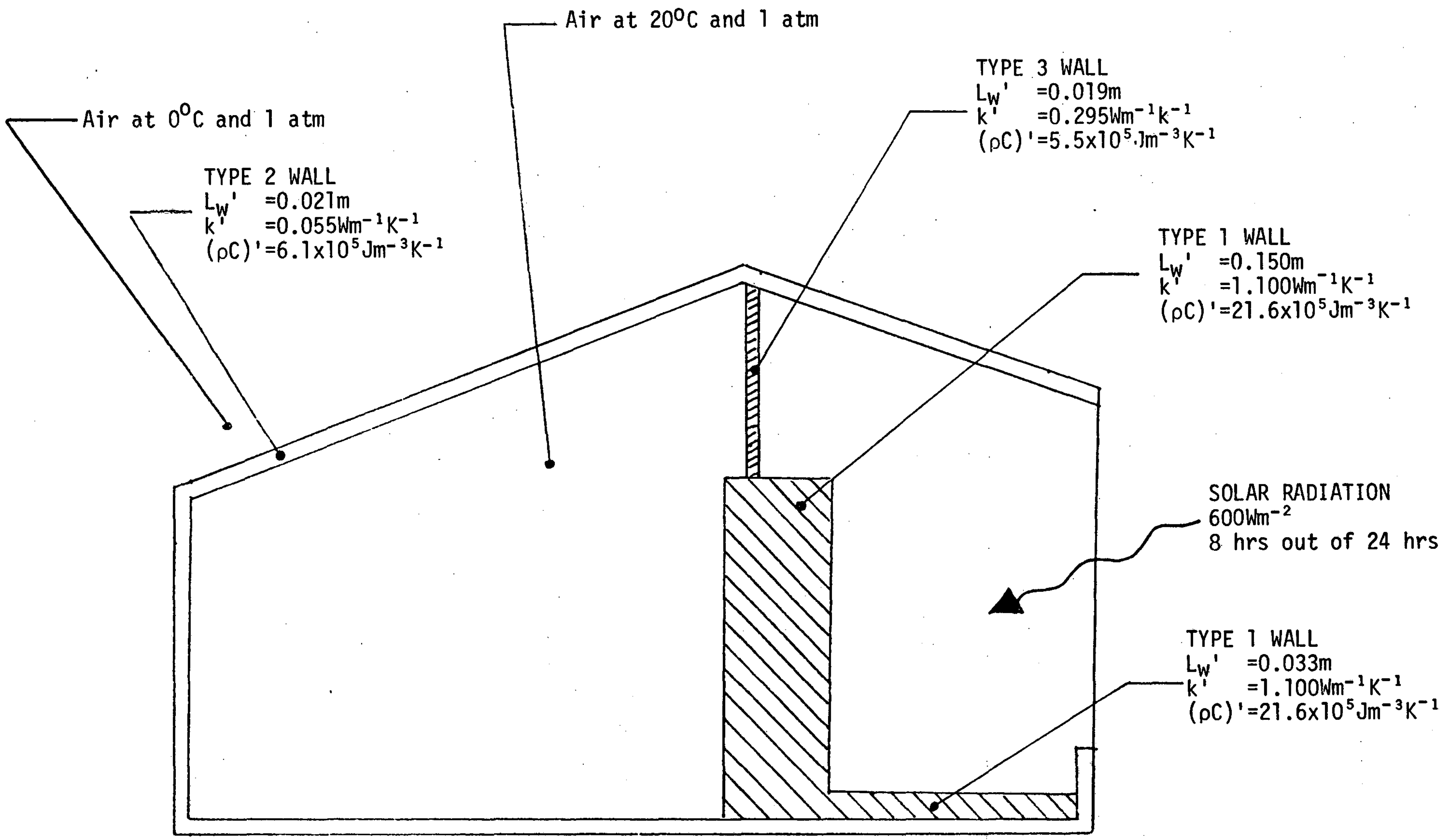


Fig. 2 TYPE 1 MODEL OF A PASSIVE SOLAR STRUCTURE, 1/6th Scale

sixth scale. Heat is transported out of the model faster than it is put in because the conductive heat transfer per unit wall area is six times higher in the one-sixth scale model than it is in the full-scale structure. Thus the ratio of heat out to heat in is reduced by a factor of six. (Note: if convective heat transfer on the inner and outer wall boundaries is considered, the ratio of heat in to heat out would be less than 6 times lower.)

The beautiful architect's model does not model convective heat transfer at all well. A full-scale structure is likely to have fully developed turbulent natural convection. The model probably has laminar natural convection. The pattern of air flow inside the model is altered despite the fact that the internal dimensions are scaled. The conclusion that one reaches about Method 1 is that it does not model heat transport in the full-scale passive solar structure.

3. Scale Model Methods 2 and 3

The Method 1 modeling method did not create an effective passive solar structure. The obvious solution to the problem is to make all walls in the model the same material and thickness as the full-scale structure. This does two things: 1) the ratio of wall volume to window area and total area is about the same as in the full-scale structure; 2) the wall thickness is increased so that conductive heat transfer is the same per unit area in the model as it is in the structure.

When one does a one-dimensional analysis, one can see that the major time constants of the model passive solar structure would be the same as for the full-scale structure. (The same solar heat flux and the same circadian cycle are assumed.) Figures 3 and 4 illustrate that the space inside the Type 2 walls was kept the same as in model Method 1 (see Figure 1). This improves the modeling somewhat, but still major three-dimensional problems remain.

From TABLE 1, one can see that both Method 2 and Method 3 yield effective passive solar structures. The heat storage time constants and ratios of heat in to heat out are close to those calculated for the full-scale structure. Method 2 shows that the air plays no role in heat storage. Increasing the pressure in the model to 21.17 atm in Method 3 increases the air heat capacity and it improves the convective heat transfer in the model. Method 3 is a slight improvement over Method 2 but what a price is paid. Method B requires a 22-atm test chamber.

Neither Method 2 or 3 models convective heat transfer at all well. Method 3 is better than Method 2 but that is kind of like saying apples are better than oranges to someone who just plain dislikes

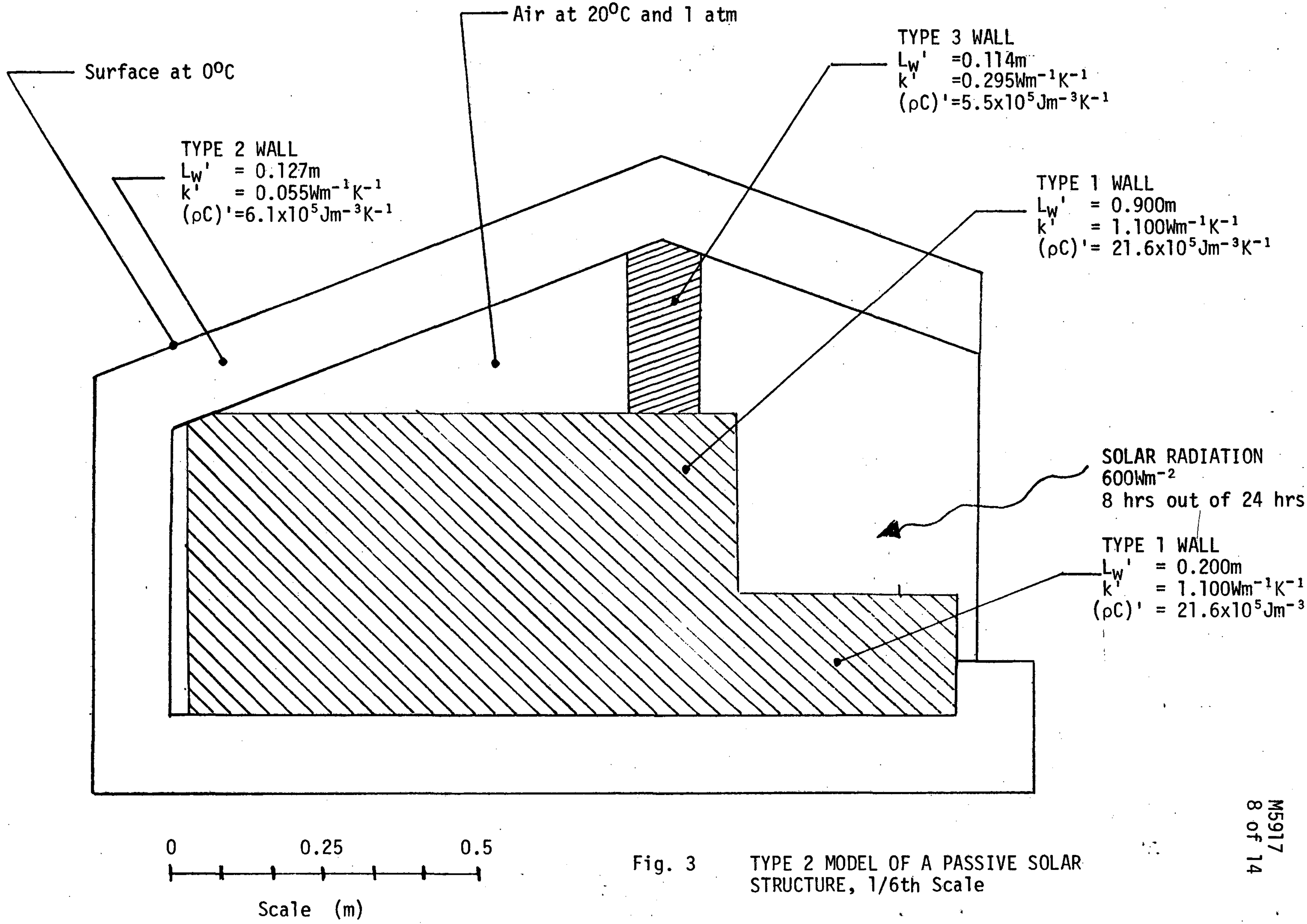
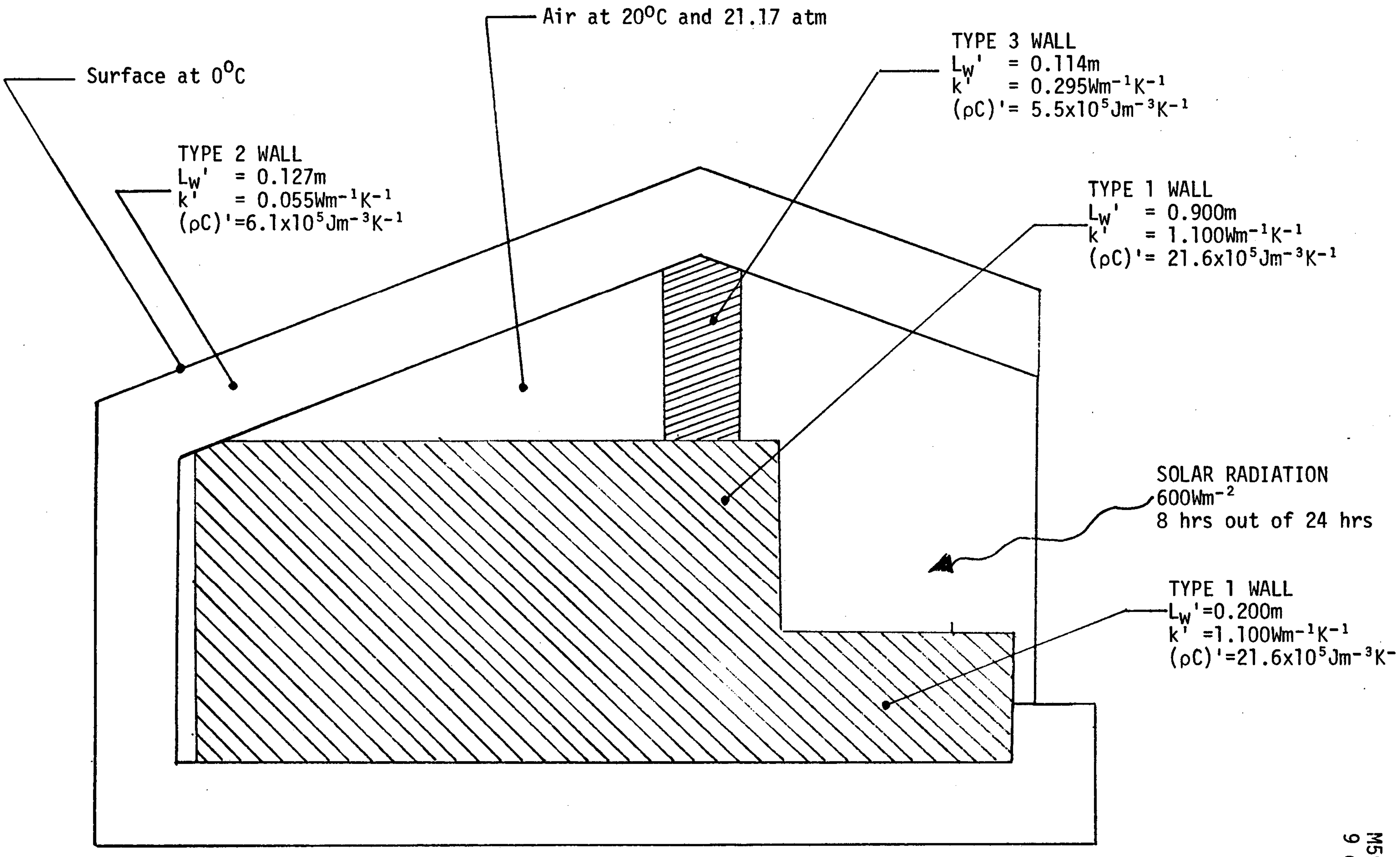


Fig. 3 TYPE 2 MODEL OF A PASSIVE SOLAR STRUCTURE, 1/6th Scale



0 0.25 0.5

Scale (m)

Fig. 4 TYPE 3 MODEL OF A PASSIVE SOLAR STRUCTURE, 1/6th scale

fruit. The inside of the model building bears no resemblance to the inside of the full-scale structure. The solar green house volume has been reduced considerably but the volume of the living space has been reduced to non-existence. It is clear from Figures 3 and 4 that convective air flows in neither case at all resemble those in the full-scale structure. Free convection in the Method 2 model is still laminar. Free convection in the Method 3 model becomes borderline turbulent, but the Gr. number not the same in the Method 3 model as in the full-scale model (even if the relative inside dimensions were the same).

Method 2 or 3 may be a useful scaling method for passive solar systems with one large room with the energy storage element built into one wall and the floor. The scaling factor should not be too large. Even under the best of conditions, Method 2 or 3 does not scale convective heat transfer well. From a thermal modeling standpoint, both Methods 2 and 3 are better than Method 1. In either case, the architect will not be pleased with the result.

4. Scale Model Method 4, the Richardson-Berman Method

The Richardson-Berman method of modeling is described in *References 1* and *2*. This method involves doing the modeling in a dense gas[3] at somewhat elevated temperature. The walls are made from different materials than the materials used in the full-scale structure. The Richardson-Berman method comes very close to modeling everything in a fully scaled way. The powerful advantage the Richardson-Berman method has is that all forms of heat transfer are modeled simultaneously. The circadian period for the model is shorter than 24 hours. This period is set by the modeling method. The method given here can model a week in real structure time in less than two days.

Since the structure and the Method 4 model of the structure are essentially the same as the sample given in *Reference 2*, I refer the reader to the reference for the step-by-step way the model parameters were set. The three wall types in the full-scale structure are modeled by walls with the following characteristics:

WALL #1: copper and hard rubber (for heavy concrete)

ℓ_W = 0.3060

k' = 0.547 $Wm^{-1}K^{-1}$

$(\rho C)'$ = 30.5 x 10^5 $Jm^{-3}K^{-1}$

L_W' = 0.275m and 0.061m

WALL #2: NEMA G-10 + styrofoam (for the R-14 wall)
ℓ_w = 0.3708
k' = 0.033 $Wm^{-1}K^{-1}$
$(\rho C)'$ = 7.0×10^5 $Jm^{-3}K^{-1}$
L_w' = 0.047m

WALL #3: NEMA G-10 + styrofoam (for the R-3 wall)
ℓ_w = 0.1314
k' = 0.063 $Wm^{-1}K^{-1}$
$(\rho C)'$ = 18.1×10^5 $Jm^{-3}K^{-1}$
L_w' = 0.015m

One notices that the scaling factor for the wall thickness ℓ_w is not equal to the scaling factor for the entire model ℓ_f (a one-sixth scale model has $\ell_f = 0.167$). The first two wall types are thicker than a truly scaled wall. The third type is thinner. In this case the Richardson-Berman method does not yield a perfect model but one will see that this method is much better than any of the other methods.

The model is put into a dense atmosphere which is not air. The gas must fit the model walls.[2,4] The gas chosen in this case is a mixture of 91.6 per cent Xenon and 8.4 per cent Argon at a pressure of 4.31 atm. The temperature within the room is elevated from 20°C to 71.3°C. The temperature outside the model is 15.8°C instead of 0°C.)

Figure 5 shows that there is a change in shape and space but not a serious one. TABLE 1 shows that the heat capacity ratio, heat storage time constant, and ratio of heat in to out is very close to that calculated for the full-scale structure. The differences in these parameters can be attributed to the fact that the walls are not perfectly scaled. From Figure 5, one can see that the thermal model even looks like the full-scale structure and it is an effective passive solar system. The radiative flux is increased from 600 Wm^{-2} for 8 hours out of 24 hours to 2701 Wm^{-2} for 2.13 hours out of a circadian period of 6.39 hours.

The real advantage of Method 4 is the way it handles convective heat transfer. Convective heat transfer rate (compared to other heat transfer rates) matches those found in the full-scale structure. The only problem is the change in shape caused by the fact that the wall thickness does not scale in exactly the same way as the gross dimensions scale. The sample case chosen for this Note is an extreme one. If a single-wall type is used, perfect scaling can be obtained, but since three types of wall must be matched to one another and the gas, the scaling of wall thickness is not perfect. A different choice of materials in the model walls will improve the scaling somewhat. Despite the

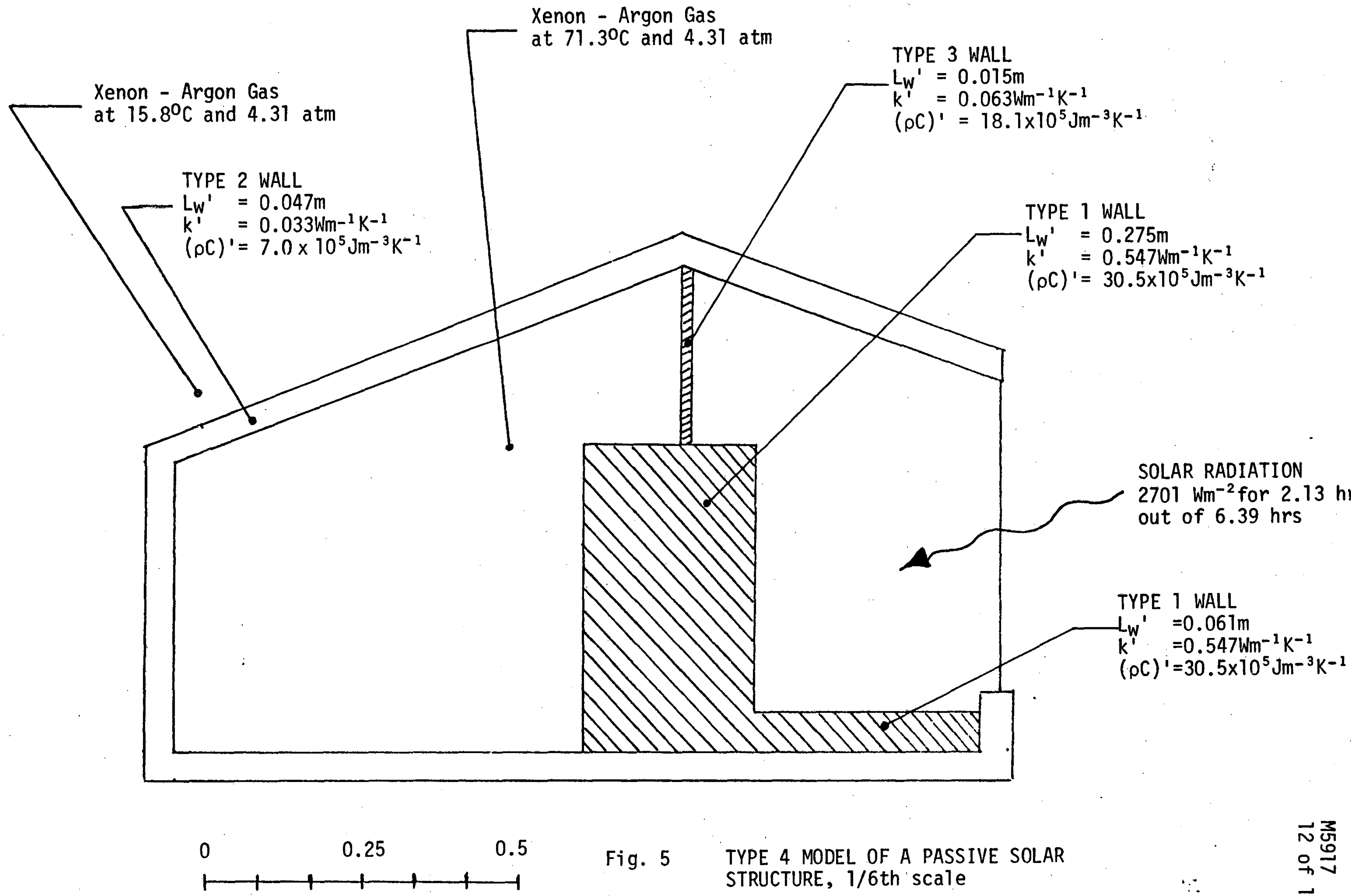


Fig. 5 TYPE 4 MODEL OF A PASSIVE SOLAR STRUCTURE, 1/6th scale

imperfect scaling, the Richardson-Berman method can be used to model a passive solar structure with reasonable accuracy.

5. Concluding Comments

This report shows that direct scaling of a passive solar structure does not work in terms of thermal modeling that structure. As a thermal model Method 1 must be rejected because the model has virtually none of the characteristics of a passive solar structure. Methods 2 and 3 where the wall thickness and materials are the same as the full-scale structure do retain the basic characteristics of a passive solar structure. Radiation heat transfer vs. conductive heat transfer are well modeled in a one-dimensional sense using Methods 2 and 3. There are major difficulties with model Methods 2 and 3 which concern three-dimensionality and convective heat transfer modeling. The modeling of small passive solar structures using Methods 2 and 3 is not attractive.

Method 4, the Richardson-Berman method, is potentially the only method which can successfully combine the three modes of heat transfer. Models which have more than one wall type will not be perfect models. Some three-dimensionality problems remain. Even in extreme cases such as the one present here, the total heat transfer and convective behavior can be modeled in a three-dimensional structure. The results of such three-dimensional modeling should be better than computer calculations on a three-dimensional model. The results of our doghouse experiment,[5] we hope, will confirm this contention.

ACKNOWLEDGEMENT

Sam Berman suggested the usefulness of comparing a couple approaches in modeling. I thank him for his suggestions.

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UNIVERSITY OF CALIFORNIA
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