AUXILIARY COOLING LOADS IN PASSIVELY COOLED BUILDINGS: AN EXPERIMENTAL RESEARCH STUDY

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ABSTRACT

Currently accepted methods of passive cooling offset only sensible building loads. In the warm, humid southeastern gulf coast climates the latent building load can comprise 35% of the building load in the typical residence. As the sensible load on residences in these climates is reduced or offset by passive cooling techniques, this latent cooling load percentage increases rapidly. In such residences the auxiliary cooling load cannot be effectively met by conventional cooling equipment.

The Florida Solar Energy Center (FSEC) is examining the auxiliary cooling requirements of residences in warm, humid climates. The study addresses both the thermal and moisture response of buildings. A total of eight wall systems, three frame wall types and five concrete block wall types are under test at the FSEC Passive Cooling Laboratory (PCL) in Cape Canaveral.

Moisture studies involve examination of the absorption and desorption rates of building materials and furnishings and the development of improved moisture migration modelling techniques for inclusion in building energy analysis programs. TARP (Thermal Analysis Research Program), developed at NBS by George Walton, and FLOAD, by FCHART Software, have been chosen as the analysis programs with which cooling alternatives are examined.

BACKGROUND

FSEC has chosen to use a combination of analytical and experimental studies to examine cooling loads in hot, humid climates. Most experimental studies are conducted in the FSEC PCL. The PCL is a reconfigurable building of residential scale in which various passive cooling and energy conservation building techniques can be experimentally evaluated under closely controlled but full-scale conditions.

The PCL is capable of the precise production of both sensible and latent energy. Any reasonable interior condition can be produced. Both the drybulb and dewpoint temperatures can be separately controlled and maintained by computer. The latent and sensible energy required to produce and maintain those conditions can be precisely monitored. Figure 1 shows a test cell load-measurement schematic illustrating the load and measurement systems.

The strategy employed for most tests consists of side-by-side testing (Figure 2) in which the performance of one component or test space is compared with another. One component is usually "standard" throughout the test period. This serves as a control for the evaluation of the less standard or "experimental" component. Reference 1 contains more detailed information on the PCL.

Current testing comprises two test cells located on the west side of the PCL. Both cells are equipped as shown in Figure 1 for moisture and thermal testing. One cell (cell D) contains wood frame exterior wall systems while the other (cell E) contains concrete block exterior wall systems. In all, eight different wall systems are under test -- three wood frame systems and five concrete block systems (1).

Analytical studies at FSEC are conducted using a variety of software. Detailed analysis of thermal and mass transfer problems are conducted with either finite difference or finite element programs which have been developed in-house to meet the specific needs of the work (2). In addition, two building energy analysis programs are being used for parametric building analysis. A large-scale conduction transfer function code called TARP (Thermal Analysis Research Program) (3) is being used for detailed analysis and a microcomputer based bin-method program called FLOAD (4) is being used for other studies.

Neither of these building energy analysis codes comes equipped to correctly analyze moisture.

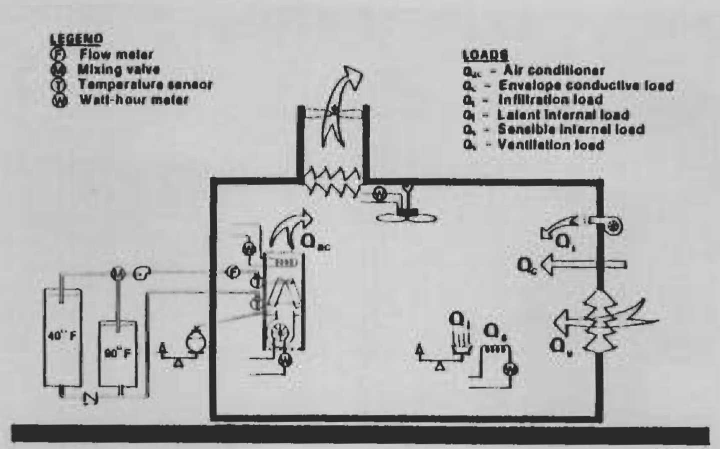


Figure 1. Passive Cooling Laboratory (PCL) Measurement, loads and Energy Balance Schematic.

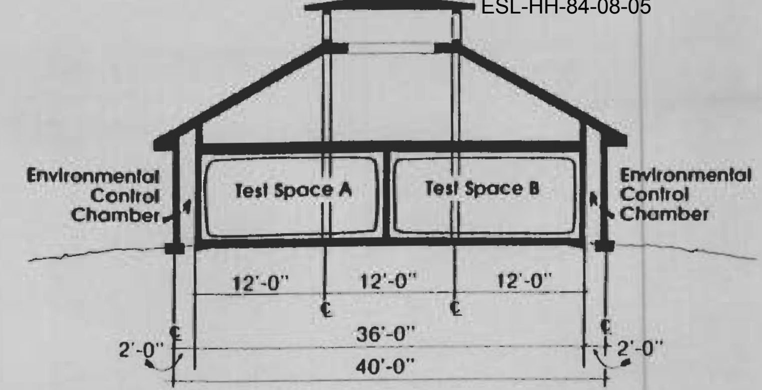
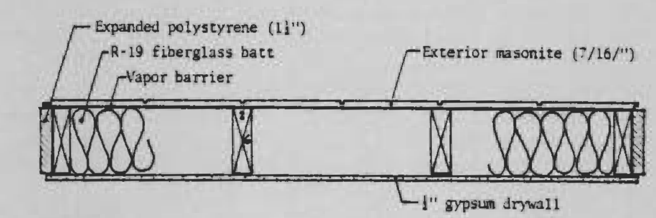
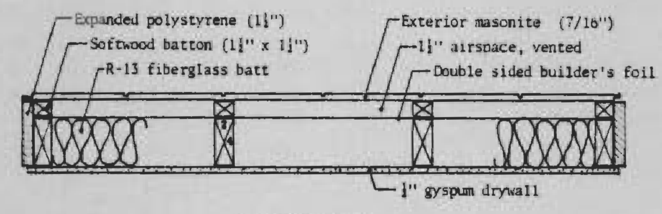


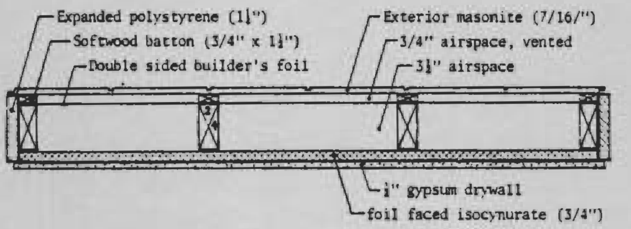
Figure 2. Section thru PCL Showing Environmental Control Chambers and Side-by-Side Testing Strategy.



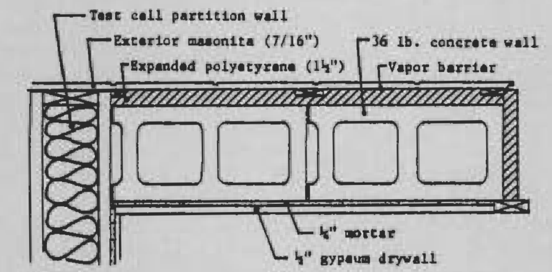
D.1. 2 x 6 INSULATED WALL



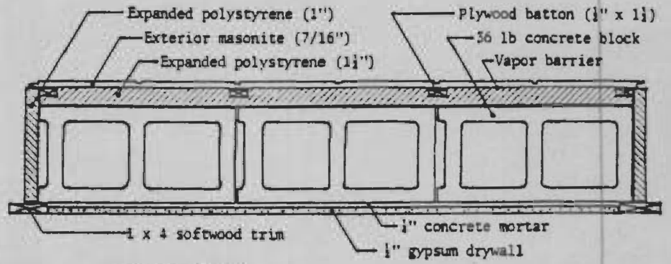
D.2. 2 x 4 INSULATED RADIANT BARRIER SKIN



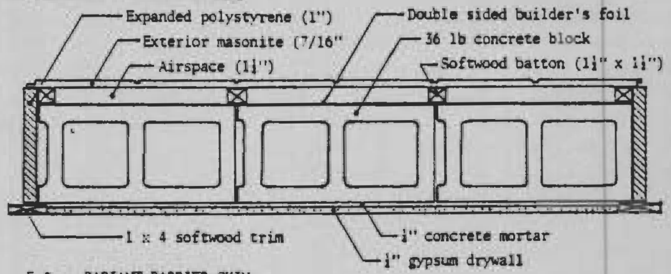
D.3. 2 x 4 INSULATED MULTIPLE RADIANT BARRIER WALL



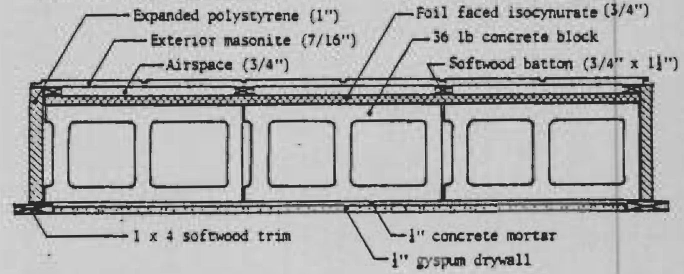
E.1. EXTERIOR INSULATION (COUPLED)



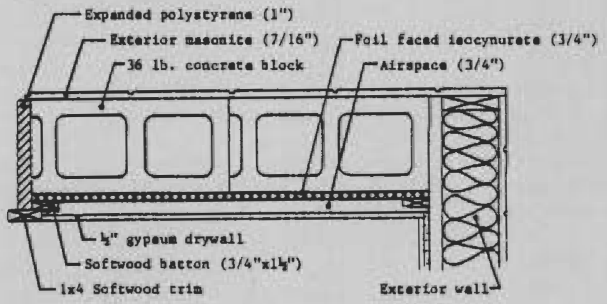
E.2 EXTERIOR INSULATION



E.3 RADIANT BARRIER SKIN



E.4 INSULATED RADIANT BARRIER SKIN



E.5. INTERIOR INSULATED RADIANT BARRIER

Figure 3. Plan View of Eight Wall Systems Under Test in FSEC PCL.

Therefore, a major effort is underway at FSEC to develop moisture migration algorithms for inclusion in TARP, and the FSEC version of TARP now has detailed moisture modelling capabilities. For certain materials (mostly newer synthetics), however, there is little or no moisture property data and absorption, diffusion and desorption parameters are not yet well established.

SELECTED RESULTS

EXTERIOR WALL TESTS

Eight exterior wall systems have been under test in the PCL since September 1983. Five of these wall systems are equipped with radiant barrier systems. A radiant barrier system comprises an airspace with one or more of its boundaries functioning as a radiant barrier (low emissivity surface). For the PCL tests, aluminum foil is used as the radiant barrier surface. Two of the radiant barrier systems are applied to wood frame walls and three are applied to concrete block walls. For the block wall systems, two radiant barriers are located at the exterior boundary of the wall and one is located at the interior boundary of the wall. Figure 3 shows a plan view of each wall system.

Measurements

Extensive measurements are taken for each wall system. At a minimum, the surface boundary temperatures of each material in the composite section are taken. For concrete block systems the air core temperature is also measured with a radiation shielded probe. In addition, flux measurements are taken at the interior surface boundary of each wall system. Complete exterior meterological data also are taken, including solar insolation measurements on a vertical plane parallel to the external surface of the wall systems.

All measurements are taken at a 15-second scan interval, then averaged and recorded to nine-track tape at 15-minute recording intervals. A concerted effort is made to use only the finest quality probes and data acquisition systems, and all sensitive measurement instruments are calibrated against NBS traceable reference standards on a regular basis. Heat flux meters are calibrated by independent testing laboratories at temperatures ($\simeq 80^{\circ}F$) and fluxes ($\simeq 2$ Btu/ft^2 · hr) likely to be experienced in testing. Conductivity correction factors that account for differences between meter and mounting material conductivities are applied to their outputs (5).

Analysis

Data analysis takes many forms; the ultimate objective of each form is to provide simplified results that may be applied in the field. Since R-values are most often used in the field, an attempt is made here to transpose the peak seasonal performance characteristics of radiant barrier systems to their apparent R-values. For the purpose of in-situ testing and analysis, only peak conditions during which heat flow is primarily undirectional may be used for such an analysis.

The general form of the equations used in the analysis is derived from the steady-state heat flow equation

$$R_a = \Sigma\Delta T / \Sigma Q \quad \text{..........................(1)}$$

where
R_a = Apparent R-value
$\Sigma\Delta T$ = Sum of the measured temperature differentials across the composite
ΣQ = Sum of the measured heat fluxes at the interior surface boundary

It is important to note that the summations in Eq. 1 must be continuous and cover a period of time sufficiently long to mask the time constant of the wall system (6).

Three weather periods were chosen for the analysis. One was a summer condition and two were winter conditions. During the summer condition and one of the winter conditions the exterior radiant barrier systems were vented with ambient air. During the remaining winter condition vents were sealed to evaluate unvented radiant barrier systems.

Because of variations in wall construction from wall system to wall system the ΔT term in Eq. 1 varied dramatically from wall system to wall system. Therefore, apparent resistances were normalized to a standard wall construction. A base-case construction was chosen for each test cell and the walls containing radiant barrier systems were compared to it. For the wood frame test cell, wall D.1 was chosen as the base. For the concrete block test cell, wall E.1 was used as the base for wall E.5, and E.2 was used as the base for walls E.3 and E.4 (see Figure 3).

The calculated base-case composite ASHRAE R-values were then used with measured heat fluxes to determine the normalized resistance of the radiant barrier wall systems with respect to the non-radiant barrier base-case walls.

Results

Table 1 gives the results of wall test analysis. Although D.2 and E.3 have essentially the same reflective vented airspaces their summertime R-values are radically different, R-9.7 and R-5.7 respectively. This is probably due to the base resistance of the remainder of the wall section. The effect of a radiant barrier is to nearly eliminate the sol-air effect. Thus, radiant barrier R-values tend to be higher for walls with high levels of ordinary insulation. It also illustrates the fact that reflective airspaces reflect heat, so they cannot be well characterized by an R-value although R-value for a vented 3/4" wall is 5.3 (wall E.4) as opposed to 5.7 for the 1 1/2" wall (E.3). The sealed radiant barrier wall (E.5) has an R of 4.9 but it is on the inside of the wall.

The performance of vented radiant barriers is poor in winter. D.2 yielded an R of 0.2 while the double radiant barrier in D.3 had 5.7. In D.3 the outside reflective airspace was vented and the inner reflective airspace was kept sealed for all tests. The outer vented radiant barrier showed no real value in wall D.2. The sealed radiant barrier R-value appears to be similar for D.3 and E.5 at R-5.7 in winter. Wall E.3 approaches the same value when its exterior vents are sealed in winter. The vented radiant barriers in E.3 and E.4 performed better in summer but worse in winter than did E.5.

Because of warm weather, the closed-vent data set was collected for only two days. Closing the vents did improve performance. The better R-value for the

Table 1
Vented and Sealed Radiant Barrier Wall Data

	---FRAME WALLS---			---------MASS WALLS ---------				
	D.1	D.2	D.3	E.1	E.2	E.3	E.4	E.5
FLUX RATIO BASE		D.1	D.1			E.2	E.2	E.1
	A) SUMMER VENTS OPEN (Except E.5)							
Test days = Sept. 17-20, 1983								
Average high=88.0 - Average low=75.8	Av. Cell Temp.= n/a			Av. Cell Temp.=77.1				
Heat flux into space, Btu	115	106	111	205	191	197	124	137
ASHRAE R-value w/o refl. space (s)	20.4	12.4	6.66	8.4	8.4	2.4	7.7	7.7
Flux ratio wrt basecase		0.93	0.96			1.03	0.65	0.67
R-value of overall wall	20.4	22.0	21.2	8.4	8.4	8.2	12.9	12.6
R-value of reflective space (s)		9.7	14.5			5.7	5.3	4.9
	B) WINTER VENTS OPEN (Except E.5)							
Test Days = Jan. 10-12, 1984								
Average high=72.7 - Average low=66.4	Av. Cell Temp.=72.4			Av. cell Temp.=72.1				
Heat flux out, Btu	132	216	200	315	346	562	289	198
ASHRE R-value w/o refl. space (s)	20.3	12.3	6.5	8.3	8.3	2.3	7.6	7.6
Flux ratio wrt basecase		1.63	1.66			1.62	0.84	0.63
R-value of whole wall wrt basecase	20.3	12.5	12.2	8.3	8.3	5.1	10.1	13.3
R-value of reflective space (s)		0.2	5.7			2.8	2.4	5.7
	C) WINTER VENTS CLOSED							
Test Days = Feb. 7-8, 1984								
Average high=62.9 - Average low=43.5	Av. Cell Temp.=71.2			Av. Cell Temp.=70.4				
Heat flux out, Btu	59	96	98	126	124	239	113	86
ASHRAE R-value w/o refl. space (s)	20.3	12.3	6.5	8.3	8.3	2.3	7.6	7.6
Flux ratio wrt basecase		1.36	1.55			1.15	0.80	0.60
R-value of whole wall wrt basecase	20.3	15.0	13.1	8.3	8.3	7.2	10.4	13.9
R-value of reflective space (s)		2.7	6.5			4.9	2.8	6.3

reflective space in E.3 compared to that in E.4 is apparently due to the base resistance of the remainder of the wall, the same phenomenon which apparently caused the differences between D.2 and E.3 and D.3 and E.4 in summer, but applied in the opposite direction. For summertime, if the R-value for the interior reflective airspace of wall E.5 (4.9) is added to the ASHRAE R-value for solid parts of wall D.3, the resultant R-value for the exterior vented radiant barrier airspace in D.3 becomes 9.7, identical to that of wall D.2. This same procedure can be applied to wall D.3 for each of the three cases (winter open and winter closed), producing net R-values for the exterior radiant barrier airspace that are very close to those given in wall D.2.

Three observations stand out:

- o The performance of vented exterior radiant barrier systems is poor in the winter season for all wall types but is particularly poor for frame wall systems.
- o The performance of exterior radiant barrier systems in summer appears to be related to the base wall resistance and type. Frame walls appear to benefit more from exterior radiant barriers than do mass walls.
- o The performance of interior radiant barrier systems does not appear to be very strongly dependent on either season or wall type.

MOISTURE STUDIES

As sensible cooling loads are decreased, the latent load on buildings takes on increasing importance. Cooling load analysis of a typical Florida residence located in various Florida climates is indicative of the problems that are faced in such climates. Figure 4 graphically depicts a breakdown of cooling loads of a typical frame wall residence located in three Florida cities.

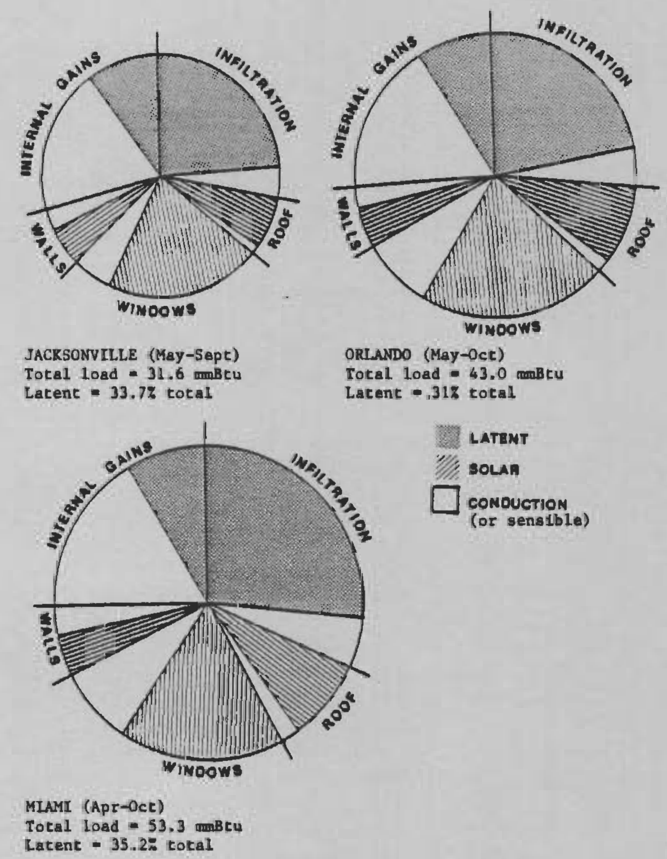
Certain key points become apparent in examining the results. First and very important, internal loads and infiltration account for more than 50% of the total load. More than half of this is a moisture load. Neither of these loads can be greatly reduced through building design. The infiltration load may be reduced from .75 ACH to .5 ACH but internal gains probably cannot be reduced without serious life-style changes.

Therefore, in terms of building design and heat gain prevention, we may only affect 50% of the total load. Large savings in externally driven sensible loads can probably be obtained through strategic window shading and radiant barrier strategies. Overall, we can reduce these external loads by half.

Another serious cooling problem is caused by the high moisture loads in such climates. Each of the three climates produces a moisture load greater than 30% of the total load. However, as sensible loads are reduced through improved building practices, the load structure changes dramatically because moisture loads cannot be simultaneously reduced by currently available techniques. If the externally driven loads (solar and conduction) in the residences analyzed are reduced by half, the moisture load becomes greater than 40% of the total load.

Additional FSEC studies (7) have examined this problem with respect to air-conditioner performance. They show surprising results. As the load structure on the building changes, commercially available vapor compression mechanical units become ineffective in dealing with moisture loads. Figures 5 and 6 illustrate the effect of such changes. Three residence types and two mechanical unit efficiencies are compared in figure 5. The house types are given as: CON-conventional, LOW-low energy use, and PAS-very energy efficient. Mechanical systems are given as TAC-typical (SEER 8.0) and HAC-high efficiency (SEER 11.0). The lines ploted are for interior balance point air conditions reached assuming steady-state machine performance characteristics. Two major observations may be drawn from Figure 5.

- As air-conditoner efficiency increases, the ability to remove moisture decreases.
- As the thermal protection of the building envelope improves, the indoor balance point relative humidity rises.



JACKSONVILLE (May-Sept)
Total load = 31.6 mmBtu
Latent = 33.7% total

ORLANDO (May-Oct)
Total load = 43.0 mmBtu
Latent = 31% total

MIAMI (Apr-Oct)
Total load = 53.3 mmBtu
Latent = 35.2% total

Figure 4. Cooling Season Load Structures for a Typical 1500 sq.ft. Frame Residence Located in Three Florida Cities.

Figure 6 illustrates the rather severe problems faced by very energy efficient residences where balance point conditions may remain above 70% relative humidity. This level is unacceptable in residences because of the potential for mold and mildew growth (8). Alternative latent cooling systems will be required for such residences.

This problem is compounded even further when passive cooling techniques are introduced. Current research indicates that passive cooling techniques are capable of statisfying most of the sensible building load. If carried to the extreme, night sky radiation roof pond systems located in Florida can condense moisture on the ceiling plane and rain on the building interior (9). Other techniques such as night only ventilation may introduce more moisture load than their sensible cooling potential warrants. Investigation of this problem is difficult because current building energy analysis techniques model moisture transport in an extremely rudimentary fashion at best.

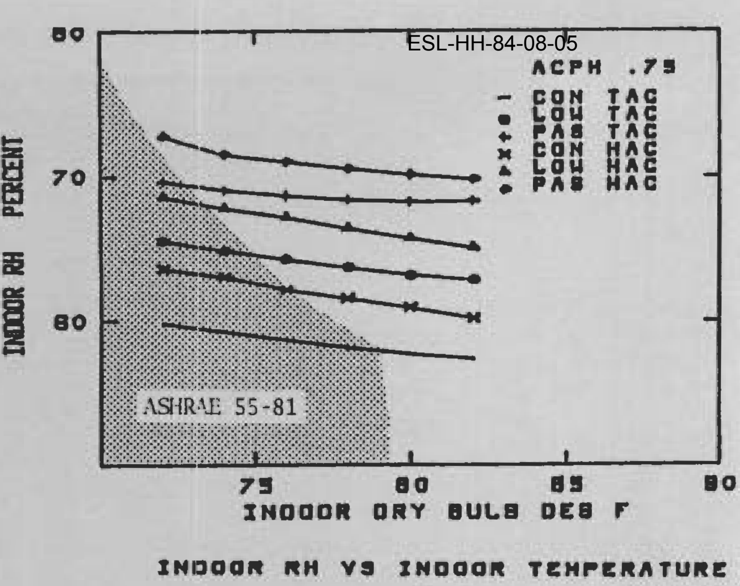


Figure 5. Interior Balance Point Relative Humidities Reached by Six Building/Air Conditioner Combinations in Miami, FL for Various Thermostat Settings.

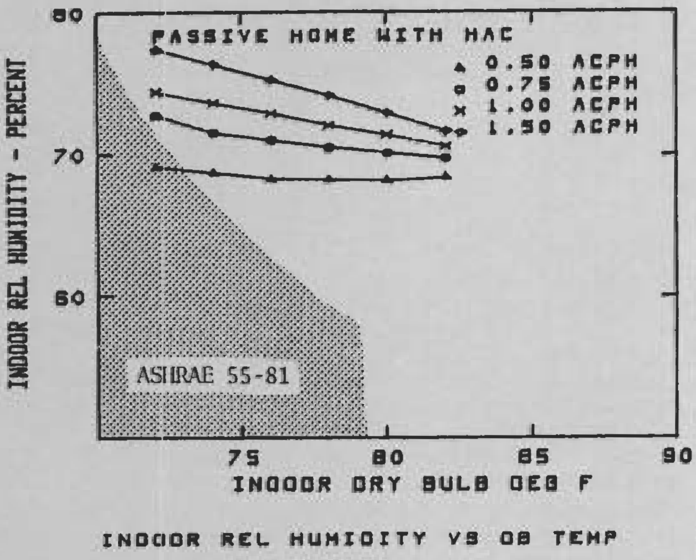


Figure 6. Interior Balance Point Relative Humidities Reached by Very Energy Efficient House with High Efficiency Air Conditioner in Miami, FL for Various Thermostat Settings and Infiltration Rates.

Moisture Modelling

Analyzing moisture in buildings is a complex problem. Current practice in building energy analysis models assumes that all changes in zone humidity are reflected in the zone air conditions. In reality building components and furnishings may absorb and desorb large amounts of moisture. In addition, mechanical system performance characteristics, particularly the sensible heat fraction (SHR), are quite sensitive to the zone humidity.

FSEC has developed a detailed moisture modelling program that is capable of accounting for the migration, absorption, and desorption of moisture in real buildings. The model has been well validated against available experimental moisture data for specific materials (2) and compared against measured conditions in full-scale attics with good results. Figure 7 gives the results of FSEC's MADAM (Moisture Absorption Desorption Analysis Model) program and measurements taken by Cleary (10). The agreement is excellent. This is primarily due to the detailed capability of the MADAM model. A correlation between external wind speed was used in the model to obtain an internal surface convection coefficient (on which moisture surface transfer is highly dependent). Without this correlation agreement is not as good.

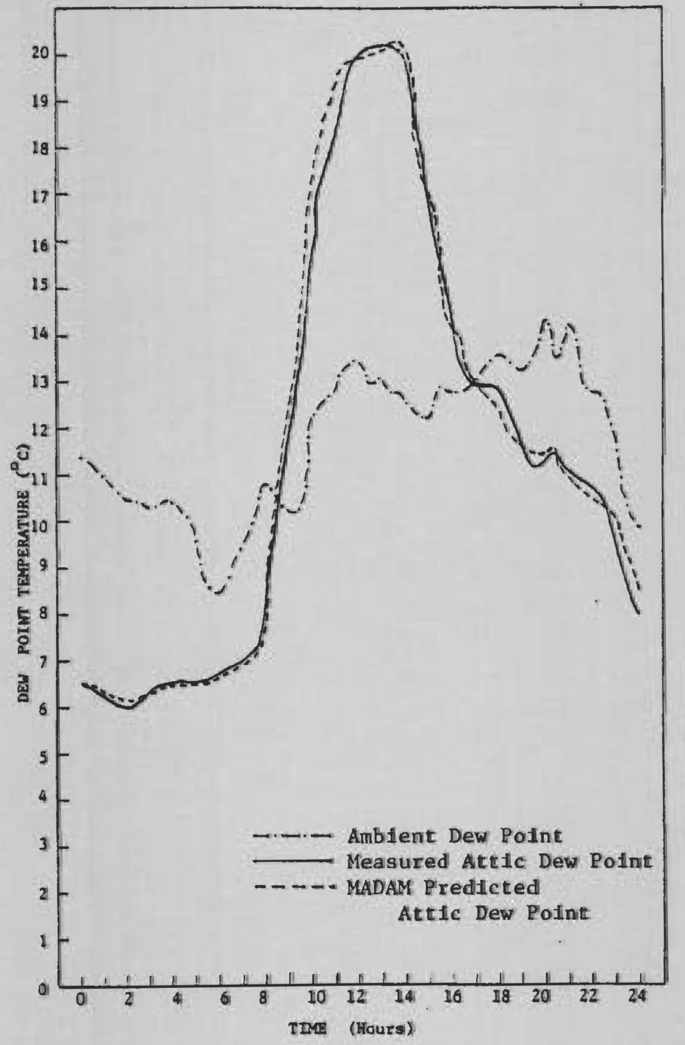


Figure 7. Comparison of MADAM Computer Code Prediction with Measured Attic Data from Full-Scale Residence Located in Oroville, CA for March 20, 1984.

MADAM is an extremely detailed finite element model. Its accuracy and detail have allowed us to incorporate more simplified but accurate modeling techniques in TARP using material moisture parameters that are developed through MADAM analysis.

Design day TARP runs for Orlando, Florida, have been made with the FSEC moisture algorithm in place. The analysis technique utilized a hypothetical mechanical system capable of maintaining zone moisture conditions at 60% RH. The mechanical system was run with a 30-minute "on" cycle during each hour. Results from the run are shown in Figure 8. The solid line in the figure gives the instantaneous moisture load on the space assuming no moisture absorption and desorption. The dashed line gives the load assuming the same mechanical system and with moisture asorption and desorption by the building materials (drywall in this case). The dots given in the figure show the mechanical system SHF required to maintain these conditions.

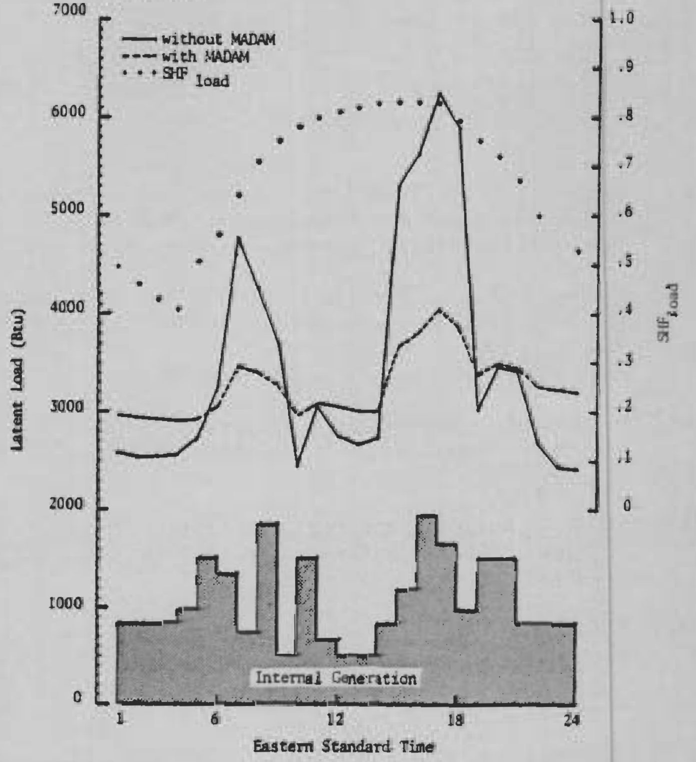


Figure 8. TARP Analysis of Latent Load Predictions with and without Absorption Desorption Model.

It is quite interesting to note that a significant difference exists between the loads when absorption and desorption are modelled. This is especially true for the peak condition. It is also interesting to note the large SHF variance that is required to maintain this 60% RH. The results are given for the final day of a 5-day run at design conditions (db high = 93°F, db low = 77°F, coincident wb = 76°F, clearness = .95). The daily moisture loads on the building are still unequal by a small amount at the end of this period, indicating that the moisture time constant of a building may be rather large as compared to the thermal time constant.

CONCLUSIONS

FSEC has concluded from its studies that moisture problems in buildings located in hot, humid climates are quite significant. The inclusion of moisture algorithms in TARP has shown material absorption and desorption to be a very significant effect that is not currently considered in building energy analysis codes.

Very energy efficient and passively cooled structures may suffer unacceptable moisture problems without enhanced dehumidification capabilities. Certain passive cooling strategies (night venting) may pay a moisture penalty that exceeds the thermal cooling benefit in very humid climates. In order to understand and evaluate these problems it is important that moisture research continue and that building energy analysis codes correctly analyze moisture effects.

ACKNOWLEDGMENTS

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