MOISTURE CONDENSATION ABOVE INSULATED SUSPENDED

CEILINGS - EXPERIMENTAL RESULTS

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ABSTRACT

One of the common methods of reinsulating above the heated and cooled space of a commercial building is to apply insulation above the grid suspended ceiling. However, there is concern that during the heating season, moisture condensation problems may occur in the cool space (i.e., the plenum) between the roof and the insulated suspended ceiling. For this reason, an experimental program to determine humidity within a plenum above an insulated suspended ceiling as a function of plenum temperature and indoor relative humidity was undertaken.

A test chamber was designed and constructed to simulate a cold plenum space and a warm, humidified interior living space. Three ceiling systems were evaluated:

1. 5/8-inch, PVC film-faced, glass fiber ceiling board with 6-inch thick glass fiber batts on top and one recessed lighting fixture in place.

2. 5/8-inch, PVC film-faced, glass fiber ceiling boards with 6-inch thick glass fiber batts on top.

3. 3-inch thick, PVC film-faced, glass fiber ceiling panels.

During the tests, the temperature in the warm space below the suspended ceiling was held at approximately 70 F while the relative humidity was incrementally increased to a level in excess of 60%. Temperatures in the plenum were lowered to a minimum value of 5 F. Water vapor moved through the ceiling panels at the rate allowed by the commercial materials and installation. The low vapor permeance of an actual built-up-roof system was simulated with a heavy plastic sheet.

The results of the experimental work demonstrated that the simplified model currently used for predicting moisture concentrations in plenum spaces is not accurate. In addition, the experimental results and subsequent moisture migration calculations demonstrated that moisture condensation is not likely to be a problem above the insulated suspended ceilings investigated.

INTRODUCTION

In recent years, a common method of insulating commercial buildings above the heated and cooled living space has been to place insulation over the grid suspended ceiling. Most buildings insulated in this way are single-story, flat-roofed structures with standard suspended ceilings. The technique is frequently practiced on single-story office buildings or retail stores using insulation of two general types:

1. Glass fiber batts that are laid on top of an existing or a new suspended ceiling board

2. Thick glass fiber ceiling panels that have considerable insulating value.

A cross-section of a typical commercial roof-plenum-ceiling section is illustrated in Figure 1. This method of insulating at the ceiling line is considerably less expensive and

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easier than applying insulation along the roof, accounting for its popularity.

There has been some conjecture, both public (1) and private, that insulating a building in this manner will lead to moisture condensation problems in the area between the ceiling and the roof, known as the plenum. To date, there have been no experimental or published case studies to document moisture and temperature conditions around insulated suspended ceilings in commercial buildings. Nevertheless, calculations, based on the assumptions of moisture equilibrium between the plenum and the heated space below, steady-state, one-dimensional heat transfer, and perfect thermal and vapor mixing suggest that moisture condensation problems should be commonplace among buildings in northern locations.

In order to clarify the issue, a laboratory experimental program was undertaken to determine the moisture variation across an insulated ceiling as a function of plenum temperature and indoor relative humidity. The objectives were twofold: 1) to determine whether a simplified model for predicting moisture condensation in plenum air is accurate, and 2) to determine under what conditions, if any, noticeable moisture condensation might occur in the plenum.

STATE-OF-THE-ART-ANALYSIS

There is an existing simplified model for predicting the occurance of condensation in a plenum such as that illustrated in Figure 1. That model is based on the following assumptions:

- Steady state, one-dimensional heat transfer
- A plenum space that is vapor sealed from the outdoor environment
- A ceiling with a finite, non-zero vapor permeance
- A vapor pressure equilibrium, across the ceiling, up to condensation in the plneum
- Perfect thermal and vapor mixing in the plenum
- Uniform condensation in the plenum air after the relative humidity reaches 100 percent. There is no provision for condensation occurring on surfaces.

Using steady state heat transfer principles, the plenum temperature can be calculated by the following equation:

$$T_{pl} = \frac{\dfrac{T_o}{R_{ir} + R_{roof} + R_{or}} + \dfrac{T_i}{R_{ic} + R_{ceil} + R_{oc}}}{\dfrac{1}{R_{ir} + R_{roof} + R_{or}} + \dfrac{1}{R_{ic} + R_{ceil} + R_{oc}}} \quad (1)$$

where:

T_{pl} = plenum dry bulb temperature

T_o = outdoor dry bulb temperature

T_i = indoor dry bulb temperature

R_{ceil} = insulated ceiling thermal resistance

R_{roof} = insulated roof thermal resistance

R_{ic} = air film thermal resistance below the ceiling (2)

R_{oc} = air film thermal resistance above the ceiling (2)

R_{ir} = air film thermal resistance below the roof (2)

R_{or} = air film thermal resistance above the roof (2)

Knowing the indoor, or warm side, temperature and relative humidity, one can use a psychrometric chart (Figure 2), to determine whether or not 100 percent relative humidity is reached in the plenum at the plenum temperature. As an example application of this simplified model, suppose a building interior is maintained at 70 F and 30 percent relative humidity with an outdoor temperature of 30 F. If the built-up roof is assumed to have an R-value of 6, the ceiling an R-value of 22, and the appropriate ASHRAE film coefficients (2) are applied, the plenum temperature will be 39 F. The psychrometric chart shows that the warm side vapor pressure at 70 F and 30 percent relative humidity is about 0.23 inches of mercury. Assuming an equal vapor pressure across the ceiling, the relative humidity in the plenum space at the calculated plenum temperature of 39 F is 90 percent. One would not expect condensation to occur under these conditions because the plenum relative humidity is below 100 percent. However, suppose the outdoor temperature drops to -10 F and indoor conditions remain the same. The new plenum temperature will be 8 F, according to the equation. At this temperature, the maximum vapor pressure that can be maintained in the plenum, at 100 percent relative humidity, is approximately 0.06 inches of mercury. The conclusion then would be that condensation would be occurring and that a vapor pressure difference of 0.17 inches of mercury would be maintained across the ceiling.

Figure 3 shows a series of curves of plenum relative humidity as a function of plenum temperature and indoor relative at a constant indoor temperature of 70 F. These curves have been plotted using the simplified model. They clearly show that, if the model is accurate, 100 percent relative humidity will be reached in plenums above insulated suspended ceilings in many buildings located in a northern climatic zone. Hence, condensation would occur above the insulated suspended ceilings in most of these buildings. Again, it should be emphasized that this model assumes steady state, one-dimensional heat transfer, a vapor sealed roof-plenum, and perfect thermal and vapor mixing in the plenum.

DESCRIPTION OF TEST APPARATUS

Figure 4 depicts the test chamber used in the laboratory experiment designed to measure plenum relative humidity and test this model. Design requirements for this chamber included:

- Maintaining a "living space" environment below the roof section at 70 F and between 20 and 65 percent relative humidity
- Providing a temperature capability above the roof section that would give a plenum temperature as low as 5 F
- Providing for negligible water vapor movement from (a) the "living space" through the sidewalls and floor, (b) the "living space" into the space above the roof section, and (c) outside into the space above the roof section
- Providing for installation and removal of the ceiling-roof sections with a closure design that would provide a positive seal against water vapor movement into the space above the roof section
- Providing instrumentation and power control systems that allow for essentially unmanned operation with only periodic monitoring

The test chamber had overall outside dimensions of approximately 16 ft x 11 ft x 11 ft. It consisted of an upper and a lower section which were separated by the roof test specimen. The lower section contained a reinforced shelf 5 ft from the floor that supported the roof section; thus, the "living space" height was 5 ft. The floor, sidewalls, and shelf support were all covered with a 6 mil thick polyethylene sheet vapor barrier on the inside surfaces. The floor and sidewalls were insulated with R-11 glass fiber batts. A small refrigerator unit in the "living space" provided temperature and relative humidity control. The upper section of the test chamber was removable and provided a support structure for the refrigeration and ducting systems that supplied refrigerated air to the space above the roof section. The test chamber upper section contained a 200 cfm air handler and a 3 HP water-cooled condensing unit and associated hardware. The upper section was clamped to the lower section with an angle iron through-bolt system utilizing a closed-cell sponge rubber gasket that was 1/2 inch thick by 3-1/2 inches wide between the 2- by 4- plates. This gasket extended around the perimeter of the upper and lower sections.

TEST SPECIMEN DESCRIPTION

Tests were performed on three different ceiling-plenum-roof configurations, as illustrated in Figures 5 a, b, and c. Each ceiling specimen measured 7.0 by 10.8 ft providing for 76 sq ft of test area. The specimens were constructed on a standard 2 by 4 ft suspended ceiling gridwork. Each specimen had a roof R-value of 4. Specifications for the three ceiling configurations were:

1. A 6-inch thick, R-19 unfaced glass fiber batt placed on 5/8-inch, PVC film-faced, R-3 glass fiber ceiling board, with a standard 2- by 4- ft recessed fluorescent lighting fixture installed.

2. A 6-inch thick, R-19 unfaced glass fiber batt placed on 5/8-inch, PVC film-faced, R-3 glass fiber ceiling board.

3. A 3-inch thick, PVC film-faced, R-12 glass fiber ceiling board.

The recessed fluorescent lighting fixture was installed in Specimen 1 to determine its effect on water vapor transport and not its thermal effect to the plenum.

To enhance the one-dimensional heat transfer assumption, the sides of each test specimen were highly insulated to minimize the heat transfer across those surfaces. Ideally, these specimens would simulate an interior section of a large roof area.

TEST CONDITIONS

In an attempt to test the applicability of the existing model and to determine under what conditions moisture would be a problem, a series of tests were developed. The experimental design was based upon controlling plenum temperature, indoor temperature, and inside relative humidity then measuring the resultant plenum relative humidity. Each test ran for 24 hours. At the end of each test period, the indoor relative humidity was changed and the plenum relative humidity was measured again. In all cases, temperatures and the relative humidites reached steady state within 6 to 8 hours after changes were made in the control variables. Temperatures were measured with thermocouples while a direct measurement of moisture content in the plenum air space was made using both Thunder Scientific PC2000 relative humidity probes and a Gulton Industries 3133 Temperature-Relative Humidity Recorder.

TEST RESULTS

The test results showing measured values of indoor temperature, indoor relative humidity, plenum temperature, and plenum relative humidity are listed in Table 1. The indoor temperature was held at approximately 70 F while plenum temperature was allowed to go as low as 5 F. The indoor relative humidity for all the tests was between 28 and 64 percent. This is somewhat high for indoors especially during the winter months in a commercial building located in a northern area. Field measurements have shown that more typical values would be in the ranges of 15 to 25 percent.

For test number 9, where the indoor relative humidity was 53 percent and the plenum temperature was 5 F, plenum relative humidity only reached 79 percent. The simplified model would predict a plenum relative humidity of 100 percent. Note that the 79 percent was the highest plenum relative humidity recorded during the tests. On two occasions, ceiling boards were removed at the end of a series of tests (test number 5 and test number 14) and test personnel inspected the plenum for condensation. Condensation was not found in either case.

DISCUSSION OF RESULTS

All measured values of plenum relative humidity were less than 100 percent, as shown in Table 1, whereas the simplified model predicted a value of 100 percent in all cases, indicating that condensation should be occurring.

It appears that the measured data do not follow the simplified model for predicting the plenum relative humidity and, hence, the plenum vapor pressure. In addition, these measurements show that a vapor pressure difference, rather than a vapor pressure equilibrium, was being maintained across the ceiling panels during the tests. One can only hypothesize why this occurred even though the plenum relative humidity was less than 100 percent. One explanation is that condensation did, in fact, occur in the plenum during these tests, but at such a low rate that it was not detectable. In addition, since condensation tends to be a surface phenomenon, it would necessarily have occurred in local cold spots such as on the outer plenum surface area. The fact that relative humidity was always less than 100 percent can possibly be explained by considering the limited capability of cold air to hold moisture. If a small amount of localized cold surface condensation did occur, it could have easily depleted the plenum air of enough moisture to keep the value of the plenum R.H. below 100 percent.

To explain this further, examine test number 14: for T_i equal to 70.0 F and for RH_i equal to 50 percent, the indoor vapor pressure would equal 0.38 inches of mercury (from Figure 2). For T_{pl} equal to 14.6 F and RH_{pl} equal to 66 percent, the plenum vapor pressure would equal 0.06 inches of mercury (from Figure 2). For the ceiling used in test number 9, the installed vapor permeance rating was 1.4 Perm (determined by previous tests unrelated to this program). Assuming that condensation was occurring, the calculated condensation rate based on these data is only 2.4 fluid ounces of water per 100 sq ft of ceiling per day. Since 50 percent is an unrealistically high value for relative humidity in a typical commercial building during the middle of winter in a northern zone, this indoor vapor pressure of 0.38 inches of mercury would represent an upper limit. Therefore, if condensation was occurring in an actual building, it would be at a considerably lesser rate than 2.4 fluid ounces per 100 sq ft per day. These calculations, coupled with measured data, demonstrate that moisture condensation above ceilings of this type may not be a problem.

CONCLUSIONS

In summary, insulated suspended ceilings have been tested in the laboratory for moisture condensation and conformance to a simplified model. This simplified model does not accurately predict the values of plenum relative humidity. The reason for this is probably that several of the original assumptions are in error. Specifically, it is suspected (1) that there is not perfect vapor mixing in the plenum and (2) that condensation, if it occurs, forms on cold surfaces and not simply in air that has reached 100% relative humidity. The presence of a recessed fluorescent lighting fixture had no noticeable effect on vapor transport. In addition, calculations based on the moisture permeance rating of the installed ceiling panels and measured conditions across it reveal that, even under severe conditions of low plenum temperature and high indoor relative humidity, moisture condensation, if it occurred, would not likely be a problem above ceilings of the type tested.

RECOMMENDATIONS

It should be emphasized that the laboratory experimental testing program described in this report was only a first step in evaluating moisture condensation potential above insulated suspended ceilings. Further testing should be performed. As a second step, a data list or a graph of typical moisture concentrations in commercial buildings as a function of outdoor temperature needs to be developed from field measurements. Third, tests should be performed on ceiling systems that have higher vapor permeances than the PVC film-faced, glass fiber ceiling panels tested during this work.

REFERENCES

1. Misselhorn, Donald J., "Some Problems with Insulation Over Suspended Ceilings," ASHRAE Journal, Vol. 21, No. 3, March, 1979.

2. ASHRAE Handbook & Product Directory: 1977 Fundamentals, 1978.

TABLE 1

EXPERIMENTAL TEMPERATURE AND PERCENT RELATIVE HUMIDITY DATA

Test number	Ceiling configuration	T_i, F	RH_i, %	T_{pl}, F	RH_{pl}, %
1	6" batts, lamp	65.3	33	23.6	55
2	6" batts, lamp	72.4	33	30.2	55
3	6" batts, lamp	70.7	53	18.0	68
4	6" batts, lamp	68.3	64	19.1	72
5	6" batts, lamp	73.7	40.	21.2	69
6	6" batts, lamp	66.8	47	17.3	72
7	6" batts, lamp	71.6	47	41.3	80
8	6" batts, lamp	67.7	64	39.5	79
9	6" batts, no lamp	63.5	53	5.0	79
10	6" batts, no lamp	76.7	28	10.0	76
11	6" batts, no lamp	78.9	28	18.0	74
12	3" ceiling board, no lamp	69.0	32	12.4	62
13	3" ceiling board, no lamp	70.6	38	14.0	63
14	3" ceiling board, no lamp	70.0	50	14.6	66

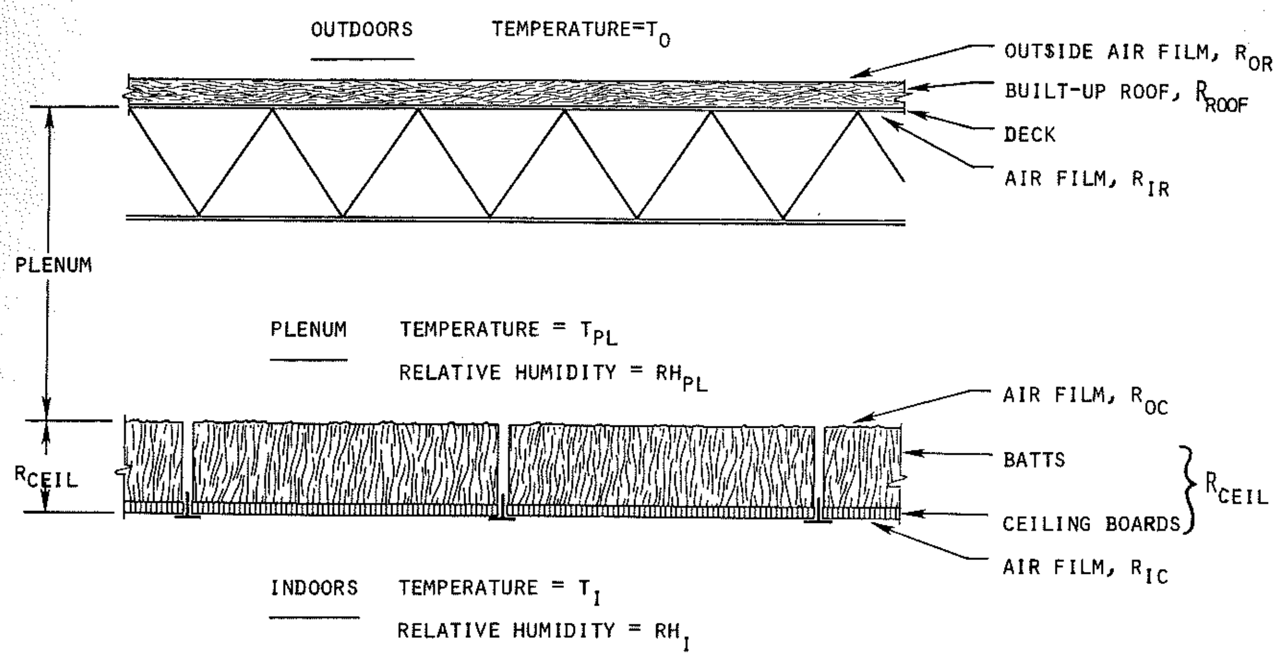


Fig. 1 Cross section of typical insulated suspended ceiling-plenum-roof section

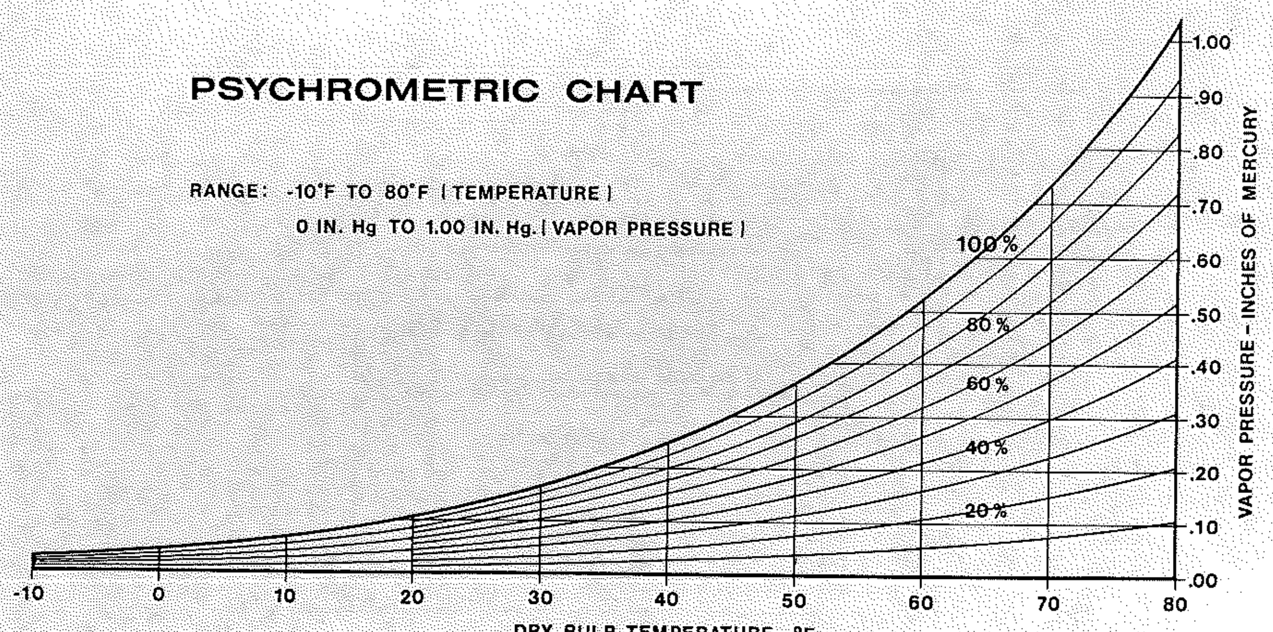


Fig. 2

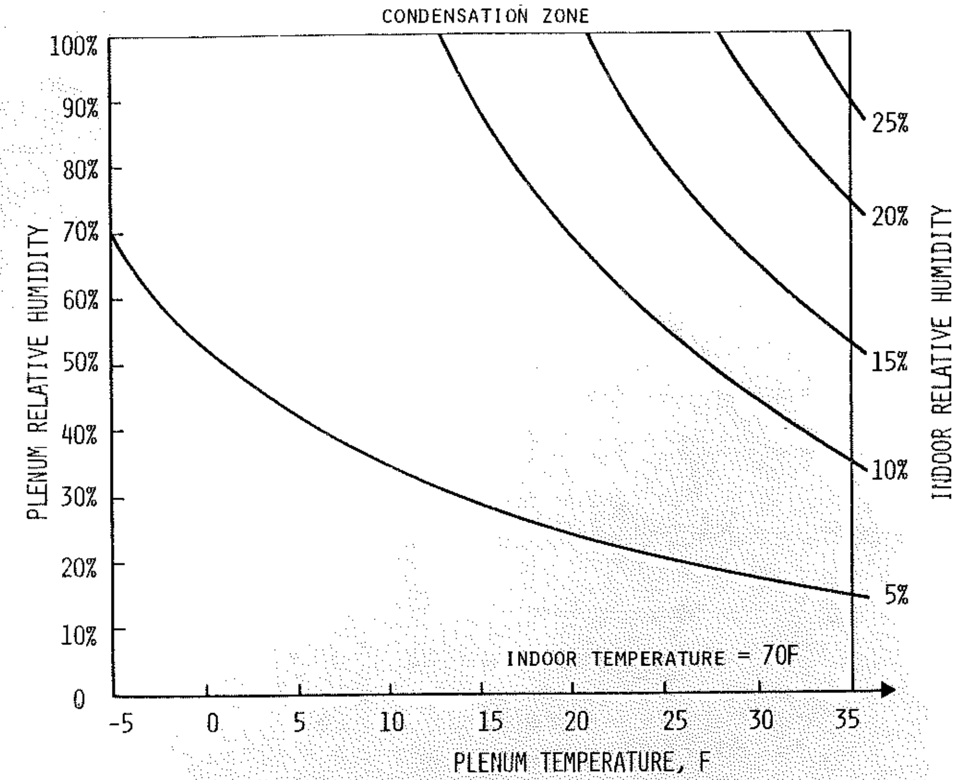


Fig. 3 Simplified model for plenum moisture concentration: plenum relative humidity as a function of plenum temperature for different values of indoor relative humidity

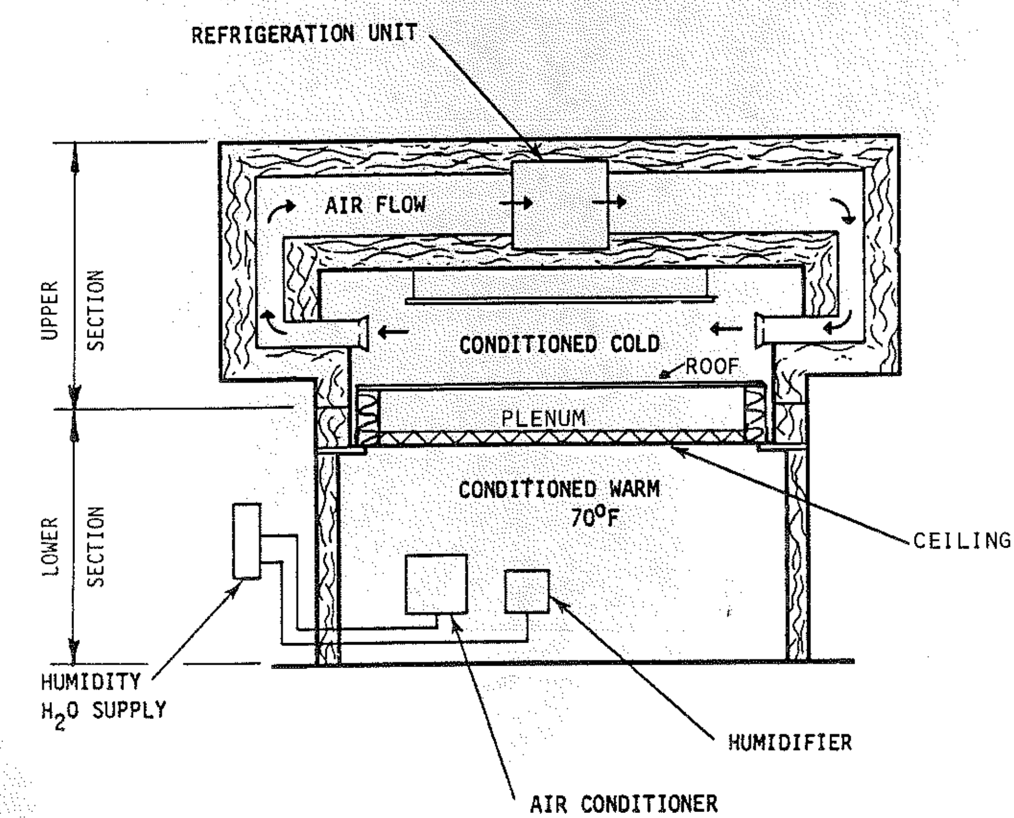
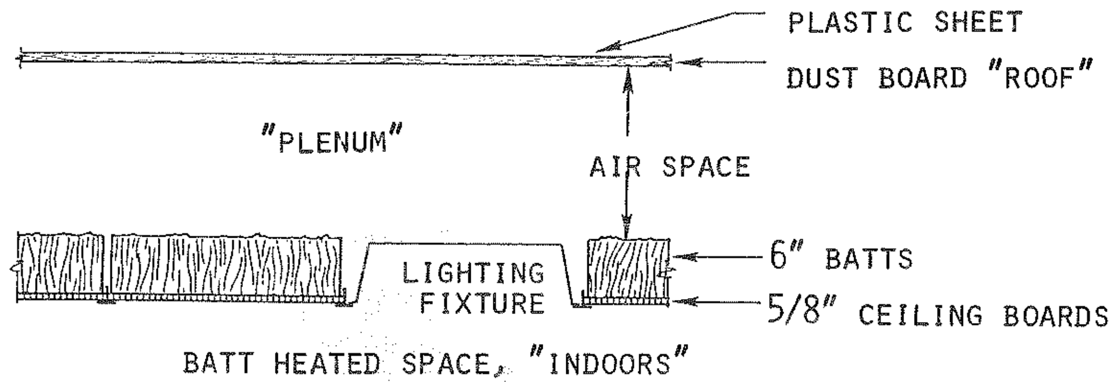
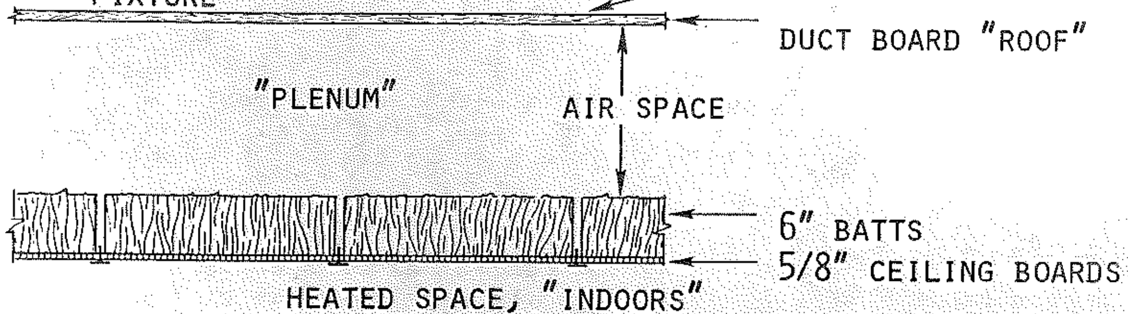


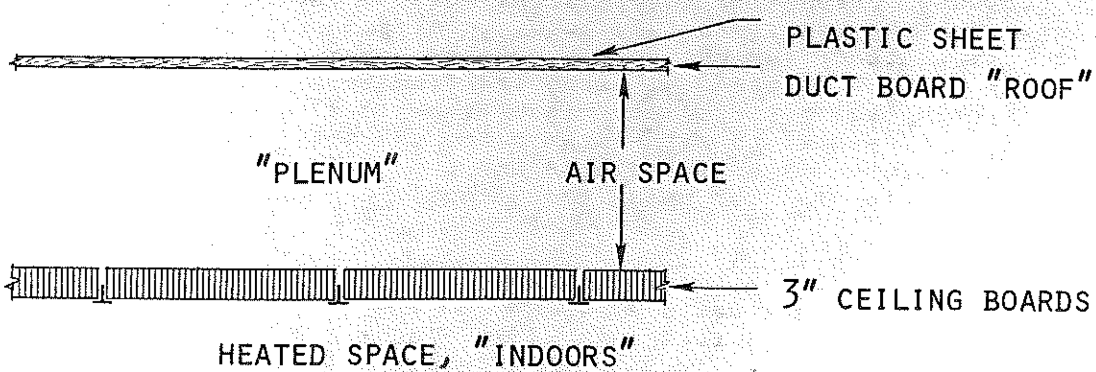
Fig. 4 Test chamber schematic



A. CEILING-CROSS SECTION FOR TESTS 1-8 PER TABLE 1:
6-INCH FIBERGLASS BATTS ON 5/8-INCH FIBERGLASS CEILING BOARDS AND A SINGLE RECESSED LIGHTING FIXTURE



B. CEILING CROSS-SECTION FOR TESTS 9-11 PER TABLE 1:
6-INCH FIBERGLASS BATTS ON 5/8-INCH FIBERGLASS CEILING BOARDS



C. CEILING CROSS-SECTION FOR TESTS 12-14 PER TABLE 1:
3-INCH FIBERGLASS CEILING BOARDS

Fig. 5 The three ceiling-plenum-roof configurations