INNOVATIVE HVAC CYCLES FOR SEVERE PART LOAD CONDITIONS IN THE HUMID CLIMATE

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ABSTRACT

This paper reports observations by the authors made in the course of performing field surveys and detailed analyses of approximately three hundred U. S. Navy buildings located in a humid climate. In the course of this work humidity related problems were found in many of the buildings.

Face & bypass control is suggested as one of the best methods of achieving passive humidity control under common difficult part load conditions. However, some conditions cannot be handled without additional measures. This paper explores techniques, other than reheat, as means for improving space comfort conditions under the worst conditions.

It is shown that pre-cooling or desiccant dehumidification of ventilation air can offer substantially improved performance, especially in conjunction with varying the ventilation air quantity as a percentage of supply air.

INTRODUCTION

During the summers of 1983, 1984, 1985, and 1986 Engineering Sciences, Inc. personnel per-

Naval Station, Subic Bay, Republic of the Philippines. The primary purpose of these studies was to identify deficiencies in the air conditioning systems which affect their ability to provide the required comfort conditions in an energy efficient manner.

The ESI staff performed extensive field tests and analyses on the buildings, their air conditioning equipment and its controls. Deficiencies (in design and/or condition) which cause them to fail to perform their desired function in an efficient manner were identified. Recommendations were then made to correct these problems and supporting calculations performed to assess the economic attractiveness of each investment.

Unfortunately many problems were observed and most were related to the very high humidity of these climates (e.g., 97.5 percent design conditions are 88/80 (°F/°F) for Okinawa). In short, the fundamental observation is that the comfort conditioning systems simply do not work. Many of the buildings observed have space relative humidities over 70 percent.

Very little hard, quantitative information is available for designers of HVAC systems in the humid climate. Consequently, a number of myths exist about the relative performance of different types of systems. The authors have conducted research over the last several years to understand the failings of the systems being designed, and hopefully provide design guidance for future systems. Earlier papers [1], [2], and [3], discuss the performance of the most commonly found air conditioning systems and their capacity control methods under normal operations at various part loads, and during the morning start-up period after an overnight shutdown. The results are briefly summarized below.

This paper continues the search for further improvements in humidity control by assessing the benefits of (a) reduced infiltration (via improved building envelope tightness or increased ventilation), and of (b) pretreating the ventilation air (via precooling or desiccant drying).

PERFORMANCE CRITERIA FOR EFFECTIVE AIR CONDITIONING IN THE HUMID CLIMATE

The two most important criteria which must be met for successful air conditioning designs in

control capability; that is, they must maintain good room humidity levels under all loads. To do this the coil sensible heat ratio (CSHR) must follow room sensible heat ratio (RSHR) at likely part load conditions.

2. They must deliver supply air temperatures at part loads sufficiently close to the room dew point to prevent condensation on diffusers.

In order to assess the performance of various capacity control methods in meeting these criteria, the authors developed a series of coil/room simulation computer routines which can be used to predict the psychrometric conditions that result when an air conditioning system adjusts its capacity in response to changes in interior, skin, and outside air loads [3]. The results have been corroborated in the field, and thus confidence has been gained in their use.

Unfortunately the RSHR tends to drop at the most probable part load conditions in humid climates while the CSHR tends to rise for the more commonly used methods of capacity control. It is this fundamental mismatch of sensible heat ratios that causes most of the problems. Consider, for example, a chilled water air handling unit with a coil, a modulating chilled water valve, and a room thermostat with a 4°F proportional band. As the valve closes and less water flows, the coil begins to warm up. The latent cooling falls off much faster than the sensible cooling (i.e., CSHR increases rapidly). The result is that room humidity ratio will increase dramatically under the more probable part load conditions. On the other hand, modulating capacity by varying air flow through the coil and keeping chilled water flow constant has quite different results. Sensible cooling actually falls faster than latent cooling, which is desirable. VAV and face & bypass systems both give these results. VAV, however, fails to meet the criterion for avoiding condensation at diffusers due to very cold supply air temperatures at part loads. Face & bypass avoids this shortcoming and meets both performance criteria quite well. Figures 1 and 2 compare the performance of a chilled water valve vs. face & bypass control under various loads (in a building designed for 78°F, 60 percent Rh). For a full performance comparison of capacity control methods see a previous paper by the authors, "Passive Humidity Control: A Comparison Of Air-Conditioning Capacity Control Methods For The Humid Climate." [3] Although there are other innovative capacity control methods that may ultimately prove superior to face & bypass, of the presently used methods it gives the best performance of any modulating type system and thus is a good choice for illustrating the infiltration/ventilation questions addressed hereafter. Therefore, the remainder of our discussion will assume a chilled water air handling unit with face & bypass dampers modulated proportionally by a space thermostat.

Notice from Figure 2 that, even with the much preferred face & bypass control, there are difficult part load conditions that cannot be handled successfully (room humidity ratios are clearly out of the comfort range). Can the situation be improved passively, that is, without reheat?

DIFFICULT PART LOADS

The air conditioning system experiences difficulties when the RSHR drops, that is, when the latent loads increase or the sensible loads are reduced. Unfortunately, this is almost always what happens under part load conditions which is where the system operates most of the time. Suppose that the system has been designed to satisfy the load when the ambient is 88/80 (°F/°F). There will, of course, be a solar load included in the design calculations. A part load condition frequently encountered is that of a rainy day during the design month (typically 81°F/79°F). The latent load due to ventilation and infiltration air is unchanged but the sensible load has reduced 60 percent. The solar load (all sensible) is reduced to zero. The internal sensible and latent loads are unchanged. The net result of all of this is that the sensible heat ratio required of the coil drops drastically.

In Figure 3 three common outside air conditions in Okinawa are shown. Point 1 is the design day condition. Point 2 would be typical for a cloudy day. Point 3 would be typical for a cloudy, rainy day. However, any of these conditions could occur with or without the sun. Assume a one-story 10,000 sq. ft. office building, well constructed and relatively tight (3/4 air change per hour infiltration with no building pressurization), roof U = 0.05, wall U = 0.10 with 25 percent single pane glass, 100 people, 1.5 watts/sq. ft. lights, ventilation = 10 cfm/person, exhaust = 5 cfm/person, 13,000 cfm supply air. Also assume the air conditioning system is properly sized for 76°F, 50 percent Rh indoor conditions on a 88/80 (°F/°F) day, and properly operated. (Note: equipment oversizing and improper operation exacerbate humidity control problems [3]). Points 1a, 2a, and 3a are the resulting room conditions when our face & bypass system operates, with the dry bulb thermostat set on 76°F, to condition the space with the three above mentioned outside air conditions on a sunny day. Points 1b, 2b, and 3b result when the sensible heat ratio is reduced due to loss of solar load. Without the sun the space becomes considerably more humid. Note the space is cooler since the sensible load is reduced. Overall the space is less comfortable. Point 3b (Point 3 is the most difficult ambient condition) is marginally in the comfort zone on a cloudy day.

THE EFFECT OF BUILDING ENVELOPE TIGHTNESS

The most pernicious load is that due to infiltration. In some cases it may be 100 percent latent. Furthermore, it is introduced directly into the conditioned space. Empirical research into infiltration rates in buildings indicate that they vary greatly. Certainly, many of the existing buildings in Okinawa have rates more than double that assumed for the building above. The importance of building envelope tightness is illustrated in Figure 4. The points for the tight building of Figure 3 are repeated as groups A and B for the solar and no solar load conditions respectively. Points in groups C and D are for a loose building (1.5 air change per hour with no building pressurization) for the solar and no solar load conditions respectively. Note how comfort is lost in the loose building when the sensible load is lost. The point resulting from ambient condition 3 is quite unsatisfactory. Even in a tight building, ambient condition 3 is difficult. This is a very common load condition in the humid climate. The remainder of this paper will explore measures for handling this condition.

THE EFFECT OF PRE-COOLING VENTILATION AIR

Although much better than chilled water valve control, face & bypass control difficulties occur when sensible load is severely reduced and the dry bulb thermostat modulates to bypass substantial air around the wild coil. The bypassed air includes proportional fractions of return air and incoming moist ventilation air. One might expect improved performance if the ventilation air were pre-cooled prior to mixing with return air. This would require a separate cooling coil in the outside air duct. The psychrometric process is shown exaggerated in Figure 5. Figure 6 illustrates the improvement in both the tight and loose building for the difficult 81/79 (°F/°F) ambient condition with no solar load. The tight building is now comfortable under the worst conditions. The loose building, though improved, is still significantly too humid for comfort. The high infiltration load is the culprit.

THE EFFECT OF DRYING VENTILATION AIR WITH DESICCANTS

Improvements in desiccant dehumidification technology [4], including the reduction of temperature level of the heat required for regeneration of the desiccant, have increased its competitiveness as a cooling option. Drying the ventilation air prior to mixing with return air has several benefits. More moisture can be removed from the ventilation air than by normal vapor compression refrigeration. Secondly, in buildings with reasonably low infiltration and internal latent loads, moisture removal in the ventilation air may be all the latent cooling that is required, allowing the main cooling coils to be sensible cooling only. This allows smaller refrigeration systems operating at higher evaporator temperatures, and thus higher COP's. It could allow the use of terminal fan coil units, supplied with dry primary air, which otherwise are not suitable for the humid climate [5].

The system schematic would be the same as shown in Figure 5, but with the pre-cooling coil replaced by a desiccant dehumidifier. Figure 7 illustrates the process psychrometrically, exaggerated for clarity. Figure 8 demonstrates the performance improvement.

THE EFFECT OF INCREASING VENTILATION TO REDUCE INFILTRATION

Calculating expected infiltration rates in a building is difficult though much work is being done in this area. Calculating changes in a known infiltration rate due to changes in building pressurization (i.e., changes in ventilation and relief rates) is somewhat easier. When this research began the authors found little in the literature to address this issue and subsequently developed a first level approximation [6]. Air flow through a barrier is related by the following:

$$Q = k(P_2 - P_1)^n \qquad \text{(Eq. 1)}$$

where:

Q	Flow
$P_2 - P_1$	Pressure difference across the barrier
k	Constant describing the tightness of the barrier
n	Exponent appropriate for the nature of the openings

Previous analysis for typical cracks in buildings (and typical wind velocities) suggest that the flow is turbulent and $n = 0.5$ is a good approximation. (Note that this is not true for large openings in buildings, such as open doors or windows, where $n = 1.0$ is a better approximation). Using this relationship one can develop expressions for mass balances in a building which relate infiltration, exfiltration, ventilation and relief. In so doing one finds there are three distinct regimes possible:

A. The building is so heavily positively pressurized that air is exfiltrating at both the leeward and windward walls.

B. Air is infiltrating in the windward wall and exfiltrating out the leeward wall. (Note: the building may have either a positive or negative pressure).

C. The building is so heavily negatively pressurized that air is infiltrating at both the windward and leeward walls.

The mathematical assumptions are only valid for Case B, but fortunately it covers a rather large region and certainly includes the majority of cases of practical interest. Case B applies whenever $-1.4 < (V-R)/I_o < +1.4$. If one assumes the value of k in Equation 1 above is constant as well as such contributions to P_2-P_1 as wind speed and stack effect (i.e., only ventilation and relief are varied), relationships result which can be approximated by the following straight line equations:

$$I = I_o - 0.35\,(V-R) \qquad \text{(Eq. 2)}$$

for a building in which relief exceeds ventilation and the space is negatively pressurized, and

$$I = I_o - 0.71\,(V-R) \qquad \text{(Eq. 3)}$$

for a building in which ventilation exceeds relief and the space is positively pressurized

where:

I	Actual Infiltration
I_o	Infiltration rate with no pressurization due to ventilation and relief (i.e., $I = I_o$ when $V = R$)
V	Ventilation
R	Relief (exhaust)

The implications are obvious and expected; when one increases ventilation by a certain amount, one does not get a corresponding one-for-one decrease in infiltration. Conversely, when one reduces ventilation a certain amount (a common energy saving tactic), infiltration increases somewhat due to reduced positive or increased negative pressurization in the space, but not one-for-one.

With this digression we now return to the question of the effect of varying ventilation and infiltration on comfort conditions. Simulations were run changing the ventilation, for both the tight and loose building, while keeping relief constant; in one case doubling ventilation from 1000 cfm (in the assumed building) to 2000, and in the second, eliminating ventilation altogether (0 cfm). In all cases the new infiltration rates were calculated using Equations 2 and 3. The results show negligible difference in room conditions. This implies that when ventilation is increased; for example to reduce infiltration, the benefits to the RSHR line are nearly equally offset by the resultant increased total outside air that must be dehumidified (V+I). At least with the face & bypass system, there appears to be no comfort penalty when one reduces ventilation rates to save energy.

Next consider increasing ventilation to reduce infiltration if the ventilation air is pre-cooled or dehumidified with a desiccant. Intuitively this would seem to have merit since the RSHR improvements are gained without an increase in moisture reaching the face & bypass coil. The results are shown in Figure 9 for the loose building and Figure 10 for a tight building. It appears that substantial improvements in comfort are achieved by combining a pre-treatment of ventilation air (pre-cooling or desiccant drying) with an upward adjustment in the amount of ventilation air. Even in the loose building under the worst part load conditions, the space can be conditioned into the ASHRAE comfort zone. In a tighter, better constructed building, the effects are much more dramatic and ideal comfort conditions are achievable under all circumstances with only moderate increases in ventilation air. An increase in ventilation air is not without an energy penalty; however, it in no way compares to the large amounts of extra energy required by an active humidity control system using reheat. While not a panacea, pre-treatment of ventilation air combined with adjustments in ventilation quantities, is a good way to improve indoor humidity in the humid climate even under the most difficult of conditions.

CONCLUSIONS

1. Many HVAC systems do not work in the humid climate, primarily because the most commonly used capacity control systems are fundamentally inadequate for handling the difficult part load conditions which occur a majority of the time.

2. Some capacity control systems have good performance in meeting the two most important criteria: they exhibit good passive humidity control (i.e., they maintain control of space relative humidity without reheat); and they supply air sufficiently close in temperature to the room dewpoint such that condensation on diffusers does not occur. The face & bypass system is one of the best modulating type systems in these regards. Chilled water valve modulation is the worst, and should never be used in the humid climate. However, even the best common systems have problems with the worst part load conditions.

3. Part load conditions are the most difficult when latent load increases and sensible load decreases. Unfortunately this is what usually occurs in a humid climate. Infiltration is the agent which introduces the majority of the moisture. Its severity is obviously dependent on ambient conditions, and design day conditions are much better than off-design conditions because the sensible portion of load is greatest on the hottest days. Over half the sensible load is typically solar, and cloudy days result in significant decreases in room sensible heat ratios.

4. The tightness of the building envelope has a dramatic effect on the ability to maintain control of space humidity. Buildings should be made as tight as feasible.

5. Changes in ventilation quantities affect building pressurization and thus affect infiltration rates, but not one-for-one. In existing buildings with face & bypass systems, ventilation may be decreased in order to save energy, with no comfort penalty. Increases in ventilation rates to reduce infiltration do not succeed in improving space conditions.

6. Pre-cooling of ventilation air improves control of relative humidity, particularly when ventilation percentages of total supply air increase.

7. Desiccant drying of ventilation air is an improvement over pre-cooling in terms of comfort. Although this type of system is more complex and costly, it opens up several opportunities for using energy wisely. Waste heat from cogeneration or solar collectors can drive the dessicant cycle, improving comfort while improving overall cooling system COP at the same time. If ventilation percentages of total supply air are increased, passive humidity control is possible under the most difficult conditions.

8. There are many unanswered questions which need further research in order to develop quantitative design information for the practicing engineer. Tasks suggested by the work done to this point are:

    a. More extensive field testing must be to corroborate results predicted analytically.

    b. This paper addresses the psychrometric ramifications of pre-cooling and desiccant drying of ventilation air to quantify the benefits. The pre-cooled air and dryed air conditions used for the analyses were those easily achievable by cooling coils and dehumidification systems. However, no attempt is made here to address the practical options for designing these systems. Questions such as where to locate the coil, how to integrate it into the cooling system, how to control it, etc. must be addressed. Many questions remain about the economics of the desiccant dehumidification systems in various situations.

c. Many innovative approaches to passive humidity control are still unresearched. One system which appears to offer significant improvements over the face & bypass system with wild coil is the combination face & bypass/variable air volume system, which does a better job of conditioning the ventilation air and handles perturbations to the control system (e.g., changes in thermostat setpoint) better. Ideas such as this, with combinations of ventilation precooling or drying must be considered.

ACKNOWLEDGEMENTS

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REFERENCES

1. Todd, Tom R., "Energy Conservation Experiences with HVAC Systems in the High Humidity Climate, A Case History", Second Annual Symposium on Improving Building Energy Efficiency in Hot and Humid Climates, College Station, Texas, 1985.

2. Todd, Tom R., "Start-up of Air Conditioning Systems after Periods of Shutdown (Humidity Considerations)", Third Annual Symposium on Improving Building Energy Efficiency in Hot and Humid Climates, Arlington, Texas, 1986.

3. Todd, T., Pate, M., "Passive Humidity Control: A Comparison of Air Conditioning Capacity Control Methods for the Humid Climate," ASHRAE Far East Conference, Singapore, September, 1987.

4. Meckler, Gershon, "Energy-Integrated HVAC Systems Use Nonrefrigerated Cooling Techniques," ASHRAE Technical Data Bulletin (a collection of papers from the ASHRAE winter meeting, January 1986.)

5. Spielvogel, Lawrence G., "Air Conditioned Buildings in Humid Climates, Guidelines for Design, Operation and Maintenance", ARMM Consultants, Gloucester, New Jersey, April 1980.

6. Todd, Tom R., "Air Conditioning Tune-up and Alternate Energy Survey," Camp S.D. Butler, Okinawa, Japan, Appendix C part 5 of unpublished Final Report for Pacific Division of the Naval Facility Engineering Command, U. S. Navy, April 1985.

7. American Society of Heating, Refrigerating, and Air Conditioning Engineers, ASHRAE Handbook: Fundamentals, Atlanta, GA 1985.

CHW VALVE CONTROL CONDITIONS

1. DESIGN DAY
2. TROUBLE PLC WITH 80/78
3. TROUBLE PLC WITH 75/69
4. TROUBLE PLC WITH 70/65

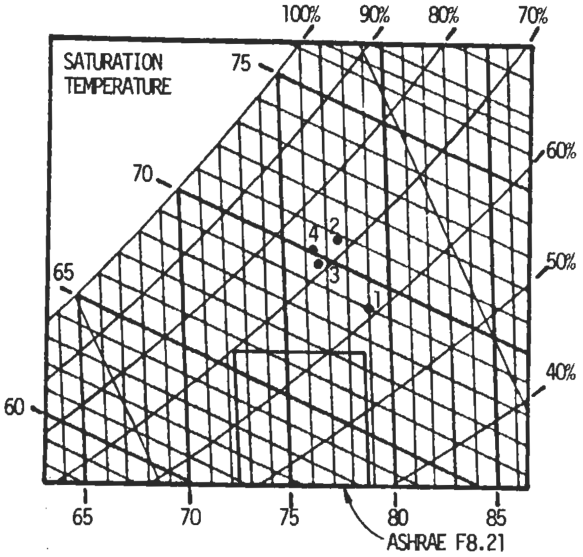

FIGURE 1

CHW VALVE UNDER VARIOUS LOADS

DAMPER CONTROL CONDITIONS

1. DESIGN DAY
2. TROUBLE PLC WITH 80/78
3. TROUBLE PLC WITH 75/69
4. TROUBLE PLC WITH 70/65

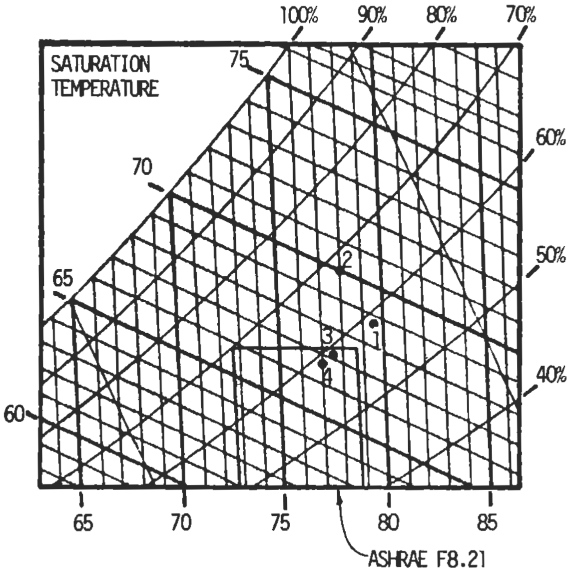

FIGURE 2

F/B CONTROL UNDER VARIOUS LOADS

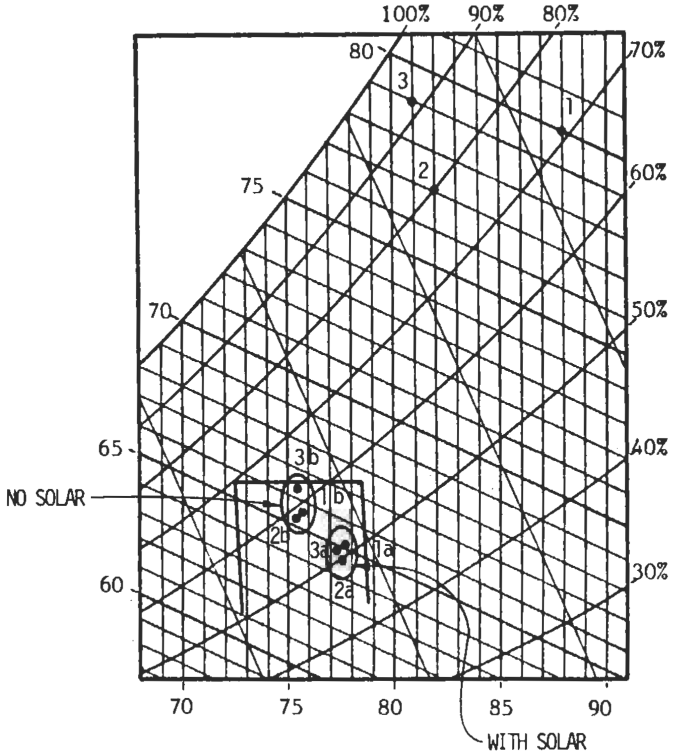

FIGURE 3

THE EFFECT OF REDUCED SENSIBLE LOADS

GROUP	CONDITION
A	TIGHT, SOLAR
B	TIGHT, NO SOLAR
C	LOOSE, SOLAR
D	LOOSE, NO SOLAR

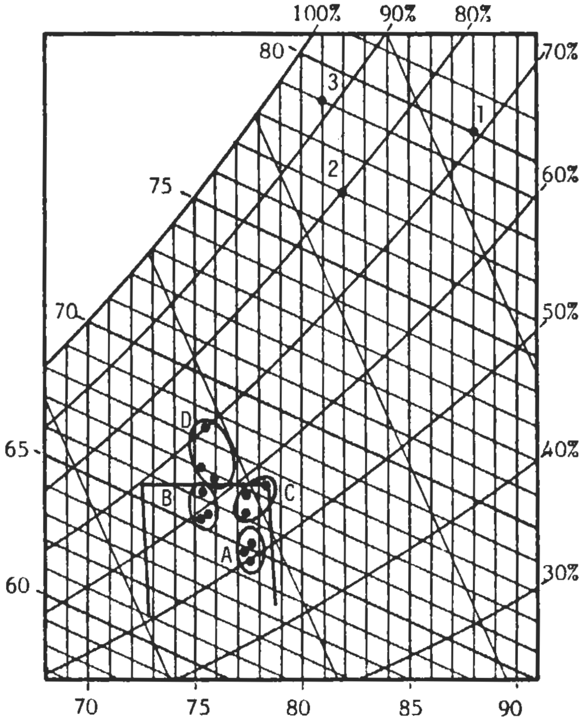

FIGURE 4

THE EFFECT OF BUILDING ENVELOPE TIGHTNESS

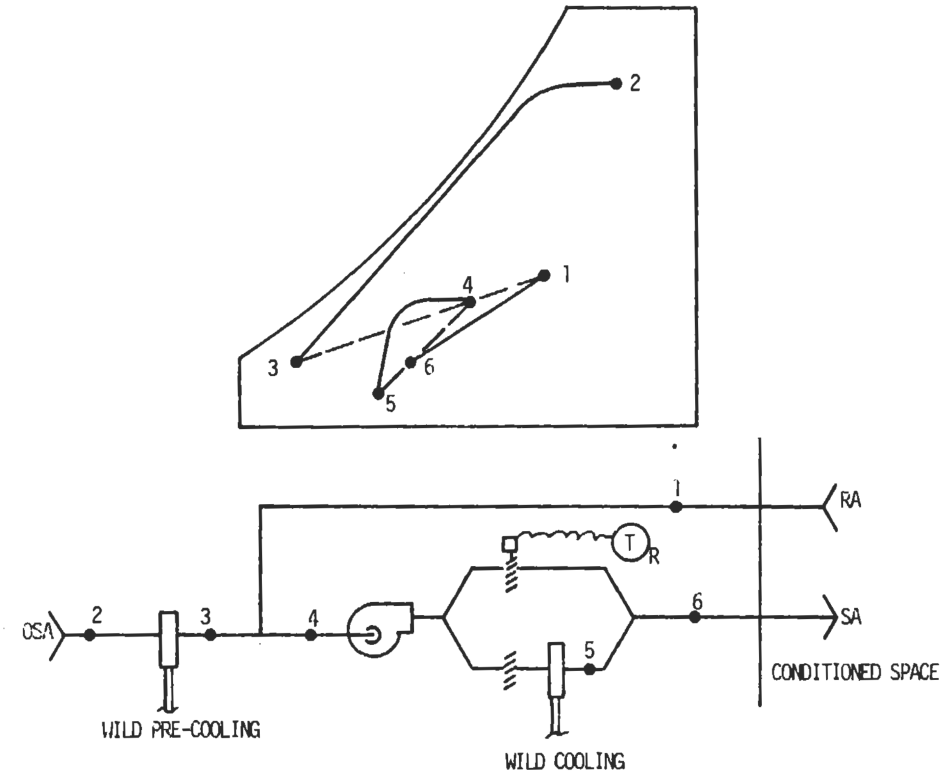

FIGURE 5

PSYCHROMETRIC PROCESS FOR PRE-COOLING VENTILATION AIR WITH A FACE & BYPASS SYSTEM

POINT	CONDITION
1	OSA
2	LOOSE, PLAIN VENTILATION
3	LOOSE, PRE-COOLED VENTILATION
4	TIGHT, PLAIN VENTILATION
5	TIGHT, PRE-COOLED VENTILATION

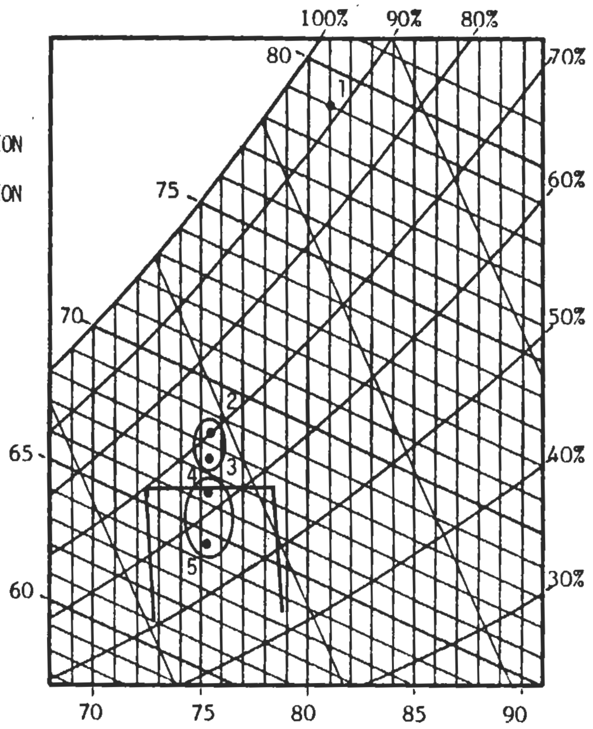

FIGURE 6

THE EFFECT OF PRE-COOLING VENTILATION AIR

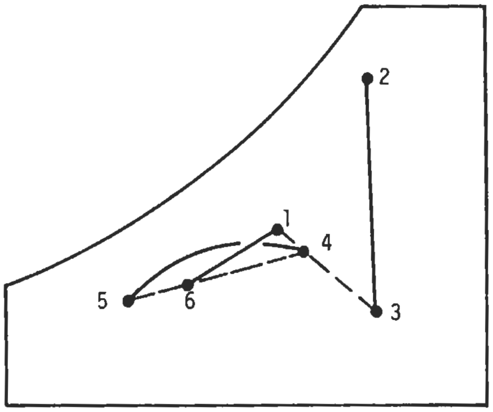

FIGURE 7

PSYCHROMETRIC PROCESS FOR

DESICCANT DEHUMIDIFICATION OF

VENTILATION AIR WITH A FACE & BYPASS SYSTEM

POINT	CONDITION
1	OSA
2	LOOSE, PLAIN VENTILATION
3	LOOSE, PRE-COOLED VENTILATION
4	LOOSE, DESICCANT DEHUMID. VENTILATION
5	TIGHT, PLAIN VENTILATION
6	TIGHT, PRE-COOLED VENTILATION
7	TIGHT, DESICCANT DEHUMID. VENTILATION

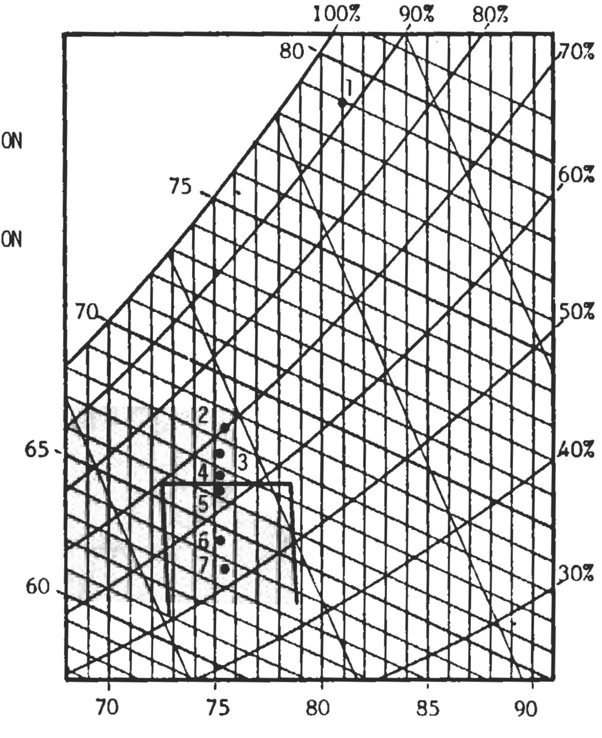

FIGURE 8

THE EFFECT OF DRYING

VENTILATION AIR WITH DESICCANTS

POINT	CONDITION
1	OSA
2	PLAIN VENTILATION (1000 CFM)
3	PRE-COOLED VENTILATION (2000 CFM)
4	DESICCANT DEHUMID. VENTILATION (2000 CFM)

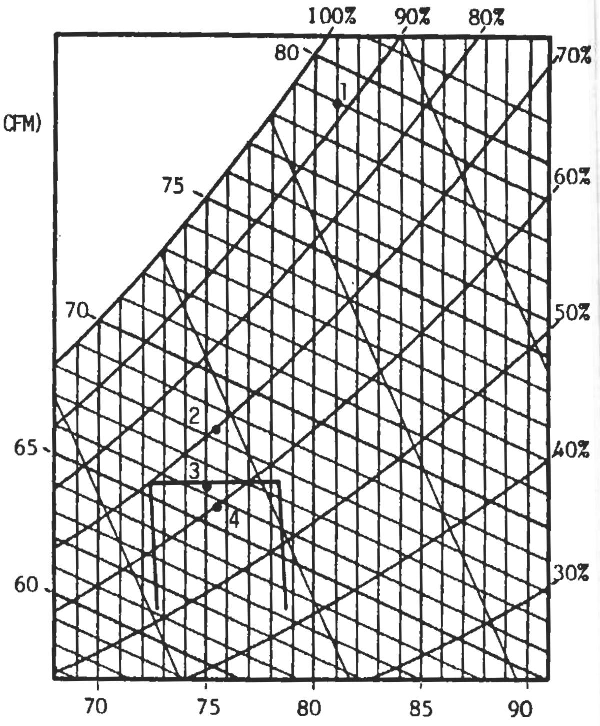

FIGURE 9

THE EFFECT OF INCREASING PRE-TREATED VENTILATION AIR TO REDUCE INFILTRATION IN A LOOSE BUILDING

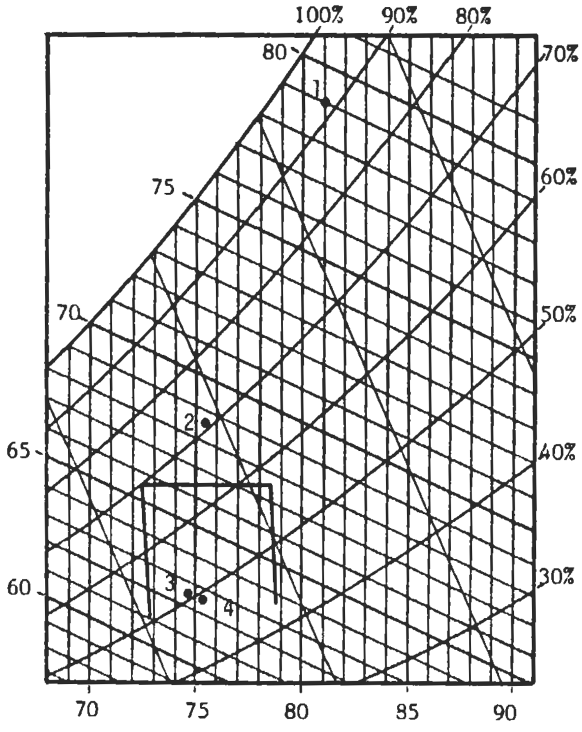

FIGURE 10

THE EFFECT OF INCREASING PRE-TREATED VENTILATION AIR TO REDUCE INFILTRATION IN A TIGHT BUILDING

POINT	CONDITION
1	OSA
2	PLAIN VENTILATION (1000 CFM)
3	PRE-COOLED VENTILATION (2000 CFM)
4	DESICCANT DEHUMID. VENTILATION (2000 CFM)