#3028

H3028

MOISTURE TRANSFER CHARACTERISTICS OF HEAT RECOVERY VENTILATION SYSTEMS EMPLOYING ROTARY HEAT WHEELS - WINTER AND SUMMER CONDITIONS

L. C. Hoagland - Airxchange, Inc.

ABSTRACT

Increasing airtightness of new energy-efficient housing has led to serious problems with excessive indoor moisture in winter as well as with other "trapped" indoor air contaminants. Heat recovery ventilation systems are being used increasingly as an effective means to solve these indoor pollution problems by introducing fresh outdoor air without the full penalty of the associated heating and cooling costs. Heat recovery via a rotary heat exchanger is shown to be an ideal solution for both winter and summer conditions.

Under winter conditions, the rotary heat exchanger rejects an adequate, but not excessive, amount of moisture from the indoor environment. By comparison, ventilation systems employing stationary heat exchangers reject excessive amounts of moisture at low outdoor temperatures and often require extra humidification to maintain indoor comfort.

Under summer conditions where air conditioning systems are employed to maintain indoor comfort, airtight construction and heat recovery ventilation equipment is also beneficial. Here indoor moisture releases are removed by the air conditioning equipment. However, to reduce both energy consumption and required air conditioner capacity, it is important that the heat recovery ventilator be capable of exchanging moisture as well as sensible heat between indoor and outdoor air in order to exclude the outdoor moisture load. Rotary heat exchangers containing a coating of desiccant material on the heat transfer matrix are capable of meeting this need, but stationary heat exchangers, in general, are not.

Analytical results corroborated by extensive test data are presented showing both the winter moisture rejection characteristics and summer outdoor moisture exclusion characteristics of a typical rotary heat exchanger system designed for residential use.

INTRODUCTION

The recent trend toward increasing air tightness in construction of new energy-efficient residential housing has led to excessive indoor humidity levels during cold weather, causing both visible moisture problems (condensation, mold growth, etc.) and structural damage.[1] Heat recovery ventilation systems are being used increasingly in tight houses to help improve indoor air quality including moisture rejection.[2] The two basic types of air-to-air heat exchangers used in these residential ventilation systems are rotary regenerators and stationary (fixed plate) recuperators.

Nearly all stationary heat exchangers are constructed of non-permeable materials that do not allow transfer of moisture between the exhaust and fresh airstreams. Consequently, all of the moisture contained in the exhaust air is rejected from the house. Because cold outdoor air is very dry compared with indoor air, the result is a substantial reduction in indoor humidity levels. When outdoor temperatures drop below about -5°C (23°F) the condensate which forms inside the heat exchanger freezes and progressively blocks the exhaust air passages.[3] Periodic defrosting action is required to maintain the heat exchanger operational. This required defrosting action complicates the system and causes reductions in both heat recovery efficiency and ventilation airflow during the time required to clear the ice.[3]

In contrast, the rotary type heat exchanger allows for some moisture transfer between exhaust air and fresh airstreams through either condensation and re-evaporation or absorption and desorption within the heat exchange matrix as the heat wheel rotates between exhaust and fresh airstreams. Only part of the moisture content of the entering exhaust air is transferred; a substantial portion also is rejected outdoors.

Due to the continuous re-evaporation of condensate from the exhaust stream back into the dry fresh airstream, the rotary type heat exchanger does not become blocked with ice and needs no defrosting until the outdoor temperature drops to about 5 - 10°F. Only at outdoor temperatures below about 5°F or at unusually high indoor humidity levels does the rotary exchanger require frost protection means.

Because rotary heat exchangers transfer some of the moisture between airstreams, some people have claimed that they are not as desirable for use in tight houses as the stationary type which rejects more moisture from the indoor atmosphere. This discussion attempts to dispell that misconception by presenting test results on moisture removal for rotary heat exchangers and by showing that the combination of this moisture removal characteristic plus a small amount of natural ventilation provides a relatively ideal moisture removal characteristic for most homes.

MOISTURE REJECTION BY HEAT RECOVERY VENTILATION - WINTER CONDITIONS

A heat recovery ventilation system consists of two fans, a heat exchanger and a suitable ducting system.

One fan exhausts stale air from the dwelling, the other fan draws in an equal amount of fresh outdoor air and the heat exchanger recovers heat from the exhaust airstream and transfers it to the fresh airstream. The two basic types of heat exchangers employed in these systems are rotary regenerators and stationary (fixed plate) recuperators. The rotary regenerator consists of a rotating disc or drum type heat transfer matrix which passes alternately through the exhaust airstream and the fresh airstream as they flow in counterflow fashion through the assembly. (Figure 1). The stationary recuperator may be one of several types such as cross-flow, counterflow, multi-pass cross-flow, etc., but most stationary exchangers* are characterized by the fact that the two airstreams are totally separated by the heat transfer surface (plates, tubes, etc.) so that there is no moisture exchange between airstreams. (c.f. cross-flow exchanger shown in Figure 2.)

Ventilation Rates - Most authorities addressing the compromise between improved energy efficiency and acceptable indoor air quality currently agree that an air change rate in the range of 1/2 to 3/4 air changes per hour (ACH) is required for acceptable air quality. Whereas much lower air change rates are technically possible and are certainly desirable to reduce energy costs, a minimum of 1/2 ACH appears to be required to maintain a healthy indoor environment. Even higher ventilation levels are beneficial in many instances. To provide a basis for a meaningful discussion of moisture transfer via ventilation systems, we shall examine the important case of an average size single family home with 1600 ft^2 of floor area and 1/2 ACH of forced mechanical ventilation. The interior volume is 1600 x 7½ = 12,000 ft^3 so 1/2 ACH requires a ventilation rate of 6000 ft^3/hr or 100 cubic ft per minute (CFM).

In a previous paper [4] the author compared the winter moisture removal rates in homes equipped with mechanical ventilation systems having either

a) stationary heat exchangers, or
b) rotary heat exchangers.

Some of those results are repeated here, whereas details of the analysis can be found in the original paper.

Stationary Heat Exchanger Systems - The ideal stationary (or "fixed plate") heat exchanger provides total separation of the exhaust and fresh air streams so that all moisture contained in the indoor air being exhausted is rejected outdoors, either as water vapor in the discharged airstream or as liquid condensate. Thus the rate of moisture removal from this type ventilation system is simply equal to the air mass flow rate multiplied by the difference between the humidity ratio of indoor air and outdoor air. The moisture removal curves of Figure 3 were constructed by applying this principle to a 100 CFM ventilation airflow for a typical single family house. The moisture removal rate is expressed as gallons/day and is shown as a function of outdoor air temperature and indoor relative humidity (R.H.) for a fixed indoor temperature of 70^oF and fixed outdoor R.H. of 80%**. Notice from Figure 3 that the moisture removal rate increases steadily as outdoor temperature is reduced and as indoor R.H. increases.

It is estimated that the average family of four releases three gallons per day of water into the home (ASHRAE[5]). From Figure 3 it is apparent that at 3 gallons per day water removal, the resulting indoor humidity levels are reasonable when outdoor temperature is about 30^oF or above. However, indoor humidity levels drop too low when outdoor temperatures go below about 15-20^oF (15% to 20% R.H.). To maintain indoor comfort under these low outdoor temperature conditions (30% R.H. or greater) it becomes necessary to operate an indoor humidifier which results in increased energy costs. This example serves to illustrate that straight mechanical ventilation at 1/2 ACH without any moisture exchange between fresh air and exhaust streams produces excessively dry indoor conditions at low outdoor temperatures (below about 20^oF.)

Rotary Heat Exchanger Systems - In the rotary heat exchanger where both exhaust air and fresh airstreams pass through the same heat transfer matrix, some of the moisture contained in the airstream being exhausted may be condensed or absorbed in the matrix and re-evaporated or desorbed into the fresh incoming airstream. In the desiccant coated rotary heat exchanger (total enthalpy type) some moisture transfer occurs under all operating conditions. However, in the "sensible" type rotary heat exchanger (no - desiccant coating) this moisture exchange occurs only at lower outdoor temperatures when the cold face of the heat exchanger is below the indoor dew point. Moisture transfer of this type is often desirable because cold outdoor air in winter is very dry and the mechanical ventilation introduced by a heat recovery ventilator can cause an excessive loss of interior moisture, thereby necessitating the use of a humidifier to maintain comfortable indoor humidity levels. Since a substantial amount of heat must be added to the water evaporated in a humidifier, this imposes a significant additional heating load on the home heating system.

---

*This discussion of stationary heat exchangers does not apply to those made with porous materials (e.g. treated paper) separating the two airstreams.

**The effect of outdoor relative humidity is quite small. To simplify this presentation, all results are for 80% R.H. outdoors, a value believed to represent average conditions in most of the U.S.A.

The author's previous paper[4] contains an analysis of a typical sensible rotary heat exchanger and includes a family of curves showing the moisture removal characteristics of a sensible rotary heat wheel having a 75% heat recovery effectiveness. These results are supported by extensive test data on the Airxchange, Inc. sensible rotary heat exchanger as illustrated by three "typical" test data points in Figure 4. Figure 4 shows a reprint of these results from that work,* illustrated for a 100 CFM ventilation system.

To facilitate comparison with stationary heat exchanger performance, as discussed above, the moisture removal curves from Figure 3 are shown also on Figure 4 as the faint dashed lines. Both types of heat exchangers have the same moisture removal performance at the higher outdoor temperatures where no condensation occurs within the heat exchanger. However, as outdoor temperature is reduced to the point where condensation begins at the heat exchanger cold face, the moisture removal rate for the sensible rotary type exchanger begins to fall below that of the stationary type exchanger. At a given indoor relative humidity, the moisture removal rate from the rotary exchanger is nearly constant over a wide range of outdoor temperatures.

Its moisture removal rate reaches a peak at about 15^oF to 25^oF (depending upon indoor R.H.) and begins a gradual decline as outdoor temperature drops. However, at temperature in the range of $+5^oF$ to $+15^oF$ the moisture removal rates curves exhibit a sharp change in slope and begin a gradual increase as outdoor temperature drops further. This change in slope occurs at the point where the frost control preheater is activated as explained briefly in the following discussion on freezing.

The important point illustrated by Figure 4 is: the winter moisture removal rate of the sensible rotary heat exchanger providing the required 1/2 ACH of ventilation is nearly constant over a wide range of outdoor temperatures and very closely matches the estimated moisture generation rate for the average family of 4 at comfortable indoor humidity levels.

Total Enthalpy Heat Wheel Systems - Desiccant coated heat wheels (often characterized as "total enthalpy" exchangers because they transfer both sensible and latent heat and moisture) are frequently desired for use under summer conditions since the exclusion of outdoor humidity is important for reducing the air conditioning load. Therefore, it is of interest to examine the winter moisture rejection characteristic of the desiccant coated heat wheel in comparison with the sensible type heat wheel because many building occupants will not want to change heat wheels from winter to summer.

Consider a typical desiccant coated rotary regenerator having an enthalpy effectiveness of 75%. It has been found that the process line for a typical exchanger of this type forms a straight line on a psychrometric chart.[10,11] The moisture rejection characteristics easily can be determined from the following relationships

$$h_3 - h_4 = 0.75\ (h_3 - h_1)$$

$$w_3 - w_4 = 0.75\ (w_3 - w_1)$$

where h = air stream enthalpy
w = air stream humidity ratio

subscripts
1 = outdoor air
3 = indoor air (exhaust)
4 = exhaust air leaving exchanger

Application of these relations to a 100 CFM heat recovery ventilator in a manner similar to that described by the author for the sensible heat wheel[4] results in a family of moisture rejection characteristic curves as shown in Figure 5. The excellent agreement with laboratory test results is illustrated by including a small sampling of data points for the case of 40% indoor relative humidity.

The phantom lines in Figure 5 show the moisture removal characteristics of the sensible rotary heat wheel (from Figure 4) to facilitate comparison with the total enthalpy type. The total enthalpy rotary exchanger has only slightly less moisture removal capability at low outdoor temperatures but it falls further below the sensible heat wheel moisture rejection at the more mild outdoor temperatures in the range of 20^oF-50^oF. The 75% effective total enthalpy heat wheel as illustrated will probably meet the moisture rejection needs of most dwellings, especially when considered in combination with a small amount of natural ventilation as described below, following the discussion of heat exchanger freezing.

---

*As modified for a preheat frost control strategy

FREEZING OF CONDENSATE IN HEAT EXCHANGERS

At low outdoor temperatures, condensate forms in both rotary and stationary type heat exchangers. When the cold face heat exchanger surface temperature goes below the freezing point, the condensate begins freezing and cannot be drained away. It progressively blocks the flow passages and reduces airflow. In most stationary heat exchangers this freeze up phenomenon occurs whenever outdoor temperature drops below about 20°F - 25°F [3] (depending on heat exchanger efficiency). Those heat exchangers that are intended for use in cold climates incorporate either defrost systems to melt the ice and drain away condensate periodically or preheaters to prevent the inlet air from going below about 20°F - 25°F. Both of these freeze protection strategies result in a significant loss in seasonal efficiency in cold climates.

In the rotary exchanger the continuous re-evaporation of condensate (or frost) into the dry fresh air stream provides a mechanism for avoiding freeze up problems until substantially lower outdoor temperatures are reached. A typical 75% efficient rotary heat exchanger does not begin to build frost until the outdoor temperature drops to about 0°F at 20% indoor R.H. or +10°F at 40% indoor R.H.[4,6]

Various strategies to avoid freeze up may be employed in rotary heat exchangers also. However, one of the most attractive strategies at present is to preheat the inlet air up to the frost threshold temperature for the given indoor humidity conditions prevailing. For most climatic regions, the number of hours per year where preheating is required is very limited, resulting in a rather small annual energy penalty. As an example, Table 1 shows the number of hours per year with outdoor temperatures below 5°F in several northern U.S. cities and the total electric energy in Killowatt hours required to heat 100 CFM of ventilating air up to 5°F during those hours. The moisture rejection analysis results presented in Figure 4 as discussed above are based on this frost avoidance strategy. At outdoor temperatures ranging from 0° at 20% R.H. to 15°F at 60% R.H., the use of preheating was assumed whenever lower outdoor temperatures were encountered. This results in slightly increased moisture rejection capacity as outdoor temperatures drop below the frost up threshold as illustrated in Figure 4. Laboratory research and field observation of low temperature heat exchanger operation is continuing and new results and experience on this subject will be reported in the future.

TOTAL MOISTURE REMOVAL - NATURAL AND MECHANICAL VENTILATION COMBINED

The foregoing discussion has presented the moisture removal characteristics of mechanical ventilation systems incorporating rotary heat exchangers and a comparison with stationary (non-permeable) heat exchangers or ventilation without heat exchange. When these systems are installed in homes, the moisture removal which they provide always is supplemented by a certain amount of additional natural infiltration of outdoor air through cracks and leaks in the structure and by opening of doors and windows. Although modern energy-efficient home construction practice has reduced natural infiltration to relatively low levels, the amount of infiltration remaining is still capable of significant winter moisture removal and should be included in any final assessment of overall moisture removal mechanisms.

A typical value for the natural infiltration in a modern "tight" house is about 0.15 air changes per hour (ACH). Some of the most tightly constructed houses built in recent years have natural infiltration rates of about 0.1 ACH.[13] Manufactured homes built to the current HUD standard have natural infiltration rates averaging about 0.2 ACH.[1] A reasonable example case for combined natural and forced ventilation would then be 0.15 ACH natural with 0.5 ACH mechanical ventilation. It is of interest then to compare an average 1600 ft^2 house with 0.15 ACH natural infiltration plus 0.5 ACH mechanical ventilation via 1) a stationary type heat exchanger system (or straight mechanical ventilation without heat exchange) vs 2) rotary heat exchangers.

Figure 3 illustrated the moisture removal with 1/2 ACH mechanical ventilation through a stationary heat exchanger. This is equivalent to 1/2 ACH of natural infiltration; thus 0.15 ACH natural would provide three tenths of this amount of moisture removal. Combining the 1/2 ACH mechanical ventilation through a stationary heat exchanger system (Figure 3) with 0.15 natural infiltration results in the total moisture removal characteristic shown by the dashed lines in Figure 6.

Similarly, by adding the 0.15 ACH natural infiltration moisture figures to those of Figure 4, the solid lines of Figure 6 are obtained representing the combination of 0.15 ACH natural and 0.5 ACH mechanical ventilation via the sensible rotary heat exchanger. In a similar manner the characteristics are obtained for the desiccant type rotary exchanger as shown by the dot-dash lines on Figure 6.

Remembering that a dwelling for the average family of four must reject about three to four gallons of water daily, it is clear from the three sets of curves in Figure 6 (and from Table 2 which is derived from Figure 6)* that the rotary exchangers have the more favorable moisture rejection characteristics. For example,

---

*Table 2 helps to illustrate some of the points discussed above by tabulating from Figure 6 the resultant indoor relative humidity levels versus outdoor temperature for the cases of 3 gals/day and 4 gals/day moisture removal for 1) a stationary heat exchanger 2) a sensible rotary heat exchanger, and 3) a desiccant rotary heat exchanger.

it shows that the moisture removal rate for a given indoor humidity level is nearly constant over a broad range of outdoor temperatures from 25°F to -20°F. Furthermore, 3-4 gallons per day water removal can be achieved with indoor relative humidity in the 25-30% range below 25°F outdoor temperatures and at somewhat greater indoor R.H. at outdoor temperatures above 25°F. These indoor R.H. values are within the comfort zone and should eliminate other moisture problems such as condensation staining, mold growth and dust mites experienced in many tight houses recently.

Although use of the desiccant type rotary exchanger will result in higher indoor relative humidity in the outdoor temperature range of 20-50°F, this resultant indoor humidity appears to be acceptable and will not cause condensation on a typical double glazed window.[12]

By contrast, the curves in Figure 6 for the stationary type heat exchanger show that a 3-4 gallons per day water removal requirement will lead to excessively low indoor relative humidity at the lower outdoor temperatures (e.g. 12-16% @ -20°F increasing to only 25% @ +20°F. Humidification will be required to maintain comfort.

Another point is worth noting here. Although the above example assumed that the natural infiltration was a constant 0.15 ACH over the entire outdoor temperature range, it is well known that the magnitude of natural infiltration is a function of the indoor to outdoor temperature difference.[9] Thus, at the lowest outdoor temperatures, the natural infiltration contribution to moisture removal is likely to be greater than indicated in this example relative to its magnitude at the higher outdoor temperatures. This makes the combination of a low level of natural infiltration plus 1/2 ACH mechanical ventilation through a rotary exchanger even more favorable to the moisture removal needs of the average home.

SUMMER MOISTURE REJECTION WITH TOTAL ENTHALPY ROTARY EXCHANGERS

In the summer when air conditioning systems are employed to maintain indoor comfort levels, air tight construction and heat recovery ventilation equipment are beneficial also. Air conditioning equipment is used to reduce both the air temperature and moisture content for maintenance of indoor comfort. In most areas of the United States where air conditioning is popular, the removal of moisture is a very important part of the air conditioning equipment function. In hot and humid areas such as the southeast and south central United States, it is not unusual for 2/3 of the total air conditioning load for ventilating air to be devoted to the moisture removal function.

The recent trend toward air tight home construction also can contribute significantly toward reducing air conditioning loads because most of the summer moisture removal load results from infiltration of humid outdoor air. When controlled mechanical ventilation is used to provide acceptable air quality, it becomes advantageous to use a heat and moisture exchange device to reduce both the temperature and moisture content of the ventilation air introduced into the dwelling. Rotary heat exchangers containing a desiccant material within the heat exchange matrix can provide both of these functions thereby contributing significantly to reducing the air conditioning load while providing the benefits of fresh air. In contrast, stationary heat exchangers, in general,* do not provide moisture transfer and therefore are unable to contribute to reduction of the latent load which is often the largest fraction of the total A/C load.

As an example of the beneficial moisture transfer characteristics of a desiccant type rotary heat regenerator, consider again the case of a home that requires 100 CFM of mechanical ventilation to maintain indoor air quality. If this ventilation air were introduced to the home without the benefit of either heat or moisture exchange with the exhaust air, then moisture would be introduced into the home at the rate shown by the upper curve in Figure 7. The dew point of outdoor air is the independent variable for this graph and is, of course, related to outdoor temperature and humidity as shown in Figure 8. Further appreciation of the magnitude of the moisture gain can be obtained by examining the resulting addition to the air conditioning load and the daily cost of A/C operation to handle this additional load. The results of analysis for these factors is shown on Figure 7 by including two additional vertical scales showing tons of A/C required to remove the added moisture and the daily cost of electricity (@ 8¢/KWH) to supply this A/C load. All assumptions required for the calculations are listed on Figure 7.

---

*Although most stationary or "fixed plate" type heat exchangers do not allow moisture exchange between airstreams, the Mitsibushi "Lossnay" exchangers are constructed with permeable separating plates and do allow for some moisture transfer.

Examination of this curve for summer moisture introduction thru ventilation shows that the rate of moisture influx is very substantial - up to 16 gallons per day at the maximum dew point of 79°F and 8 - 10 gallons per day at a 70°F dew point which is frequently encountered throughout a wide area of the U.S.

A "total enthalpy" type rotary heat exchanger containing a desiccant coating can reduce this moisture load substantially. It is not unusual for these units to have heat and moisture exchange efficiencies in the 70-90% range. A typical unit with 75% heat and moisture exchange efficiency will exclude three quarters of the load shown in Figure 7 resulting in the net moisture and A/C load as illustrated by the lower curve. Here the moisture load for 100 CFM ventilation is reduced to 2 gallons/day at a 70°F outdoor dew point or 4 gallons/day at the highest recorded dewpoint of 79°F. Air conditioning cost savings are significant also; e.g. 50¢/day at 67°F outdoor dewpoint which occurs often in many U.S. cities and up to $1.00/day at 76°F dewpoint which occurs more rarely.

CONCLUSIONS

The analytical results presented here for moisture removal characteristics of 100 CFM heat recovery ventilation systems employing rotary heat exchangers (both sensible and total enthalpy types) are corroborated by test results on the Airxchange rotary heat wheels having about 75% thermal effectiveness. They can be scaled to any other airflow rate and should apply approximately to other rotary exchangers having similar thermal effectiveness.

The following are some of the more significant conclusions derived from the moisture transfer results discussed above.

1. Straight mechanical ventilation at 100 CFM without any moisture exchange between fresh air and exhaust streams (e.g. without heat recovery or via a stationary heat exchanger) produces excessively dry indoor conditions in the average home at low outdoor temperatures (below about 20°F). Figure 3

2. The winter moisture removal rate of the sensible rotary heat exchanger is nearly constant over a wide range of outdoor temperatures and at 100 CFM airflow it closely matches the estimated moisture generation rate for the average family of 4 at comfortable indoor humidity levels. Figure 4

3. Although the desiccant type rotary heat exchanger removes less moisture from the home than the sensible type rotary exchanger, (especially at milder outdoor temperatures), it still has adequate winter moisture removal capability for many tight home situations. In the more severe cases it may be advisable to change heat wheels twice a year using the sensible type in winter and the desiccant type in summer.

4. Since even the tightest houses provided with balanced mechanical ventilation still have some natural infiltration, it is important to include that effect in any assessment of total indoor moisture rejection capability. The results presented for the case of 0.15 ACH natural infiltration combined with 0.5 ACH of heat recovery mechanical ventilation show that the rotary type exchangers have an ideal moisture rejection characteristic; a nearly constant 3-4 gallons per day moisture removal at R.H. levels within the comfort zone, over a wide range of outdoor temperatures. This removal rate nearly matches the estimated moisture generation rate for the average family of 4. Figure 6, Table 2

5. Airtight construction and heat/moisture recovery ventilation is also beneficial under summer conditions where air conditioning is employed to reduce indoor temperature and humidity levels. In most air conditioning climates, moisture transfer capability in the heat exchanger is very important and the desiccant coated total enthalpy type heat wheel is almost essential for heat recovery equipment serving this market. (Figure 7) Heat exchangers that are not capable of excluding outdoor moisture will have very limited application to air conditioned dwellings.

Most of the above conclusions are based on a 1600 ft^2 house occupied by an average family of 4 releasing 3 - 4 gallons of water per day into the indoor air. Obviously, there are many situations involving either greater or lesser moisture loads where the above conclusions may not be entirely accurate. However, the moisture rejection characteristics presented in Figures 3 thru 6 should be useful to engineer the ventilation system to the special needs of any particular dwelling.

REFERENCES

1. Zieman, M.L., and Waldman J.D., 1984, "Moisture Problems in Mobile Homes" Final Report on HUD contract No. H-10992, RADCO, Inc., Carson, CA.

2. Offerman, F.J. et al, 1982, "Residential Air Leakage and Indoor Air Quality in Rochester, NY", Report No. LBL-13100-UC-95d, prepared for U.S. DOE, Lawrence Berkeley Laboratory, Berkeley, CA.

3. Fisk, W.J., et al, 1983, "Freezing in Residential Air-to-Air Heat Exchangers: An Experimental Study Report No. LBL-16783, UC-38, prepared for U.S. DOE by Lawrence Berkeley Laboratory, Berkeley, CA.

4. Hoagland, L.C., 1985, "Moisture Removal Characteristics of Heat Recovery Ventilation Systems Utilizing a Sensible Rotary Heat Exchanger & Comparison with Stationary Heat Exchanger Systems", Moisture and Humidity - 85 - ISA, Special publication for conference in Washington, D.C., April, 1985.

5. ASHRAE Handbook - 1977 Fundamentals Ch. 20, Pg. 20.1, ASHRAE, NY, NY.

6. Ruth, D.W., Fisher, D.R. & Gawley, H.N., 1975, "Investigation of Frosting in Rotary Air-to-Air Heat Exchangers", ASHRAE Transactions, 81 Part 2.

7. Shaw, C.Y., 1981, "A Correlation Between Air Infiltration and Air Tightness for Houses in a Developed Residential Area", ASHRAE Paper No. 2655.

8. Shurcliff, W.A., 1982, "Air-to-Air Heat Exchangers for Houses", Brick House Publishing Co., Andover, MA.

9. ASHRAE Handbook - 1977 Fundamentals, Ch. 21 Ventilation, pp. 21.1 - 21.6, ASHRAE, NY, NY.

10. Airxchange, Inc., Hingham, MA, Technical Note 115, Performance of Desicccant Coated Heat Wheels in Rotary Type Heat Recovery Ventilators, October, 1985.

11. Cargocaire, Inc., Amesbury, MA technical literature on SENEX rotary heat exchangers.

12. ASHRAE Handbook - 1977 Fundamentals, Ch. 20, Pg. 20.8, Figure 4 for U = 0.55, ASHRAE, NY, NY.

13. New York State Energy Research & Development Authority, "Indoor Air Quality, Infiltration and Ventilation in Residential Buildings," NYSERDA Report 85-10, March 85. (Section 4 - Air Exchange Results and Discussion pp. 4-32 - 4-48.)

TABLE 1

FROST CONTROL PREHEATER FOR ROTARY HEAT EXCHANGERS -
ANNUAL ENERGY REQUIREMENTS TO PREHEAT 100 CFM OF OUTDOOR AIR TO +5°F
IN VARIOUS NORTHERN U.S. CITIES

Climatic Region	Energy Required To Preheat 100 CFM to +5°F KWH/Yr	No. Hours/Year Preheater Operates	Maximum Preheat Watts
Boston, MA	2	13	500
Burlington, VT	61	280	1110
Chicago, IL	16	96	650
Duluth, MN	258	773	1275
Fargo, ND	318	922	1275
Minneapolis, MN	99	421	950
Missoula, MT	48	181	950
Spokane, WA	11	60	800

TABLE 2

INDOOR RELATIVE HUMIDITY RESULTING FROM 3-4 GALLONS
PER DAY WATER RELEASE INTO A 1600 FT^2 HOME

- 0.15 ACH Natural Ventilation
- 0.5 ACH Mechanical Ventilation Thru Heat Exchanger A, B, & C

Outdoor Temp. -°F	A. Stationary HX 3GPD/4GPD	B. Sensible Rotary HX 3GPD/4GPD	C. Desiccant Rotary HX 3GPD/4GPD
-20 F	12% R.H./16%	18% R.H./28%	26% R.H./33%
-10	13½/17	21/30	27/35
0	15/19	23/33	29/36
+10	18/22	24/36	31/39
20	22/26	27/38	35/43
30	28/32	32/44	41/50
40	37/42	41/53	51/59

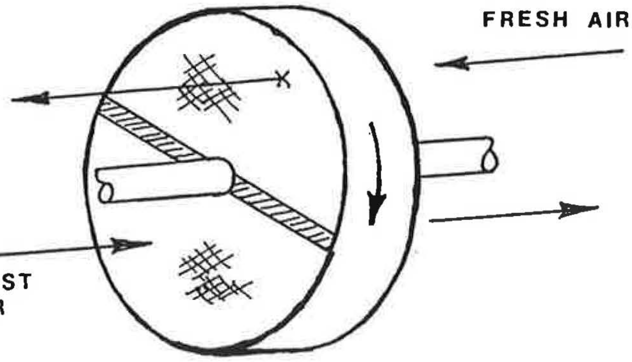

FIGURE 1 ROTARY HEAT EXCHANGER

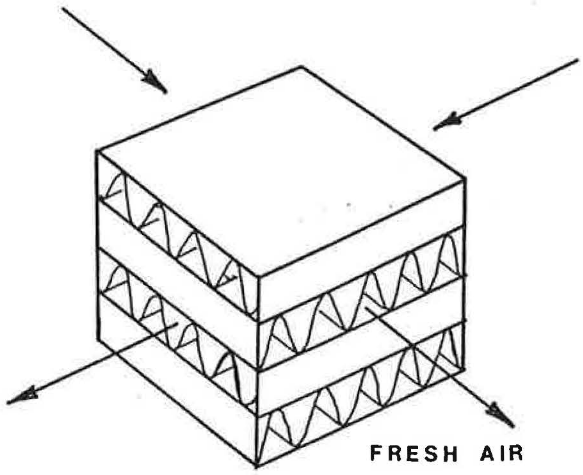

FIGURE 2 STATIONARY HEAT EXCHANGER
CROSS FLOW TYPE

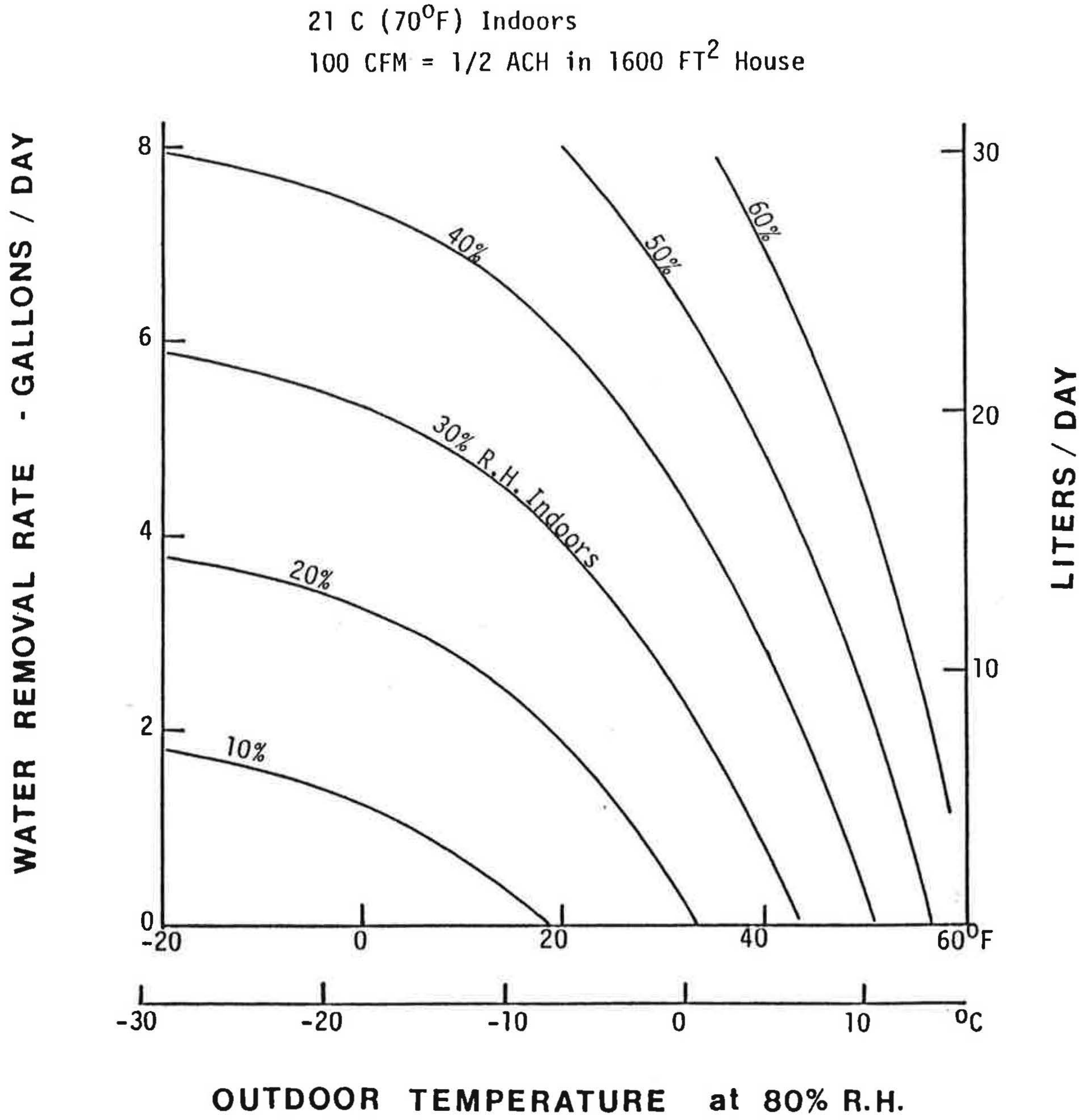

FIGURE 3 WINTER MOISTURE REMOVAL RATES FOR 100 CFM STATIONARY HEAT EXCHANGER – OR VENTILATION w/o HEAT EXCHANGE

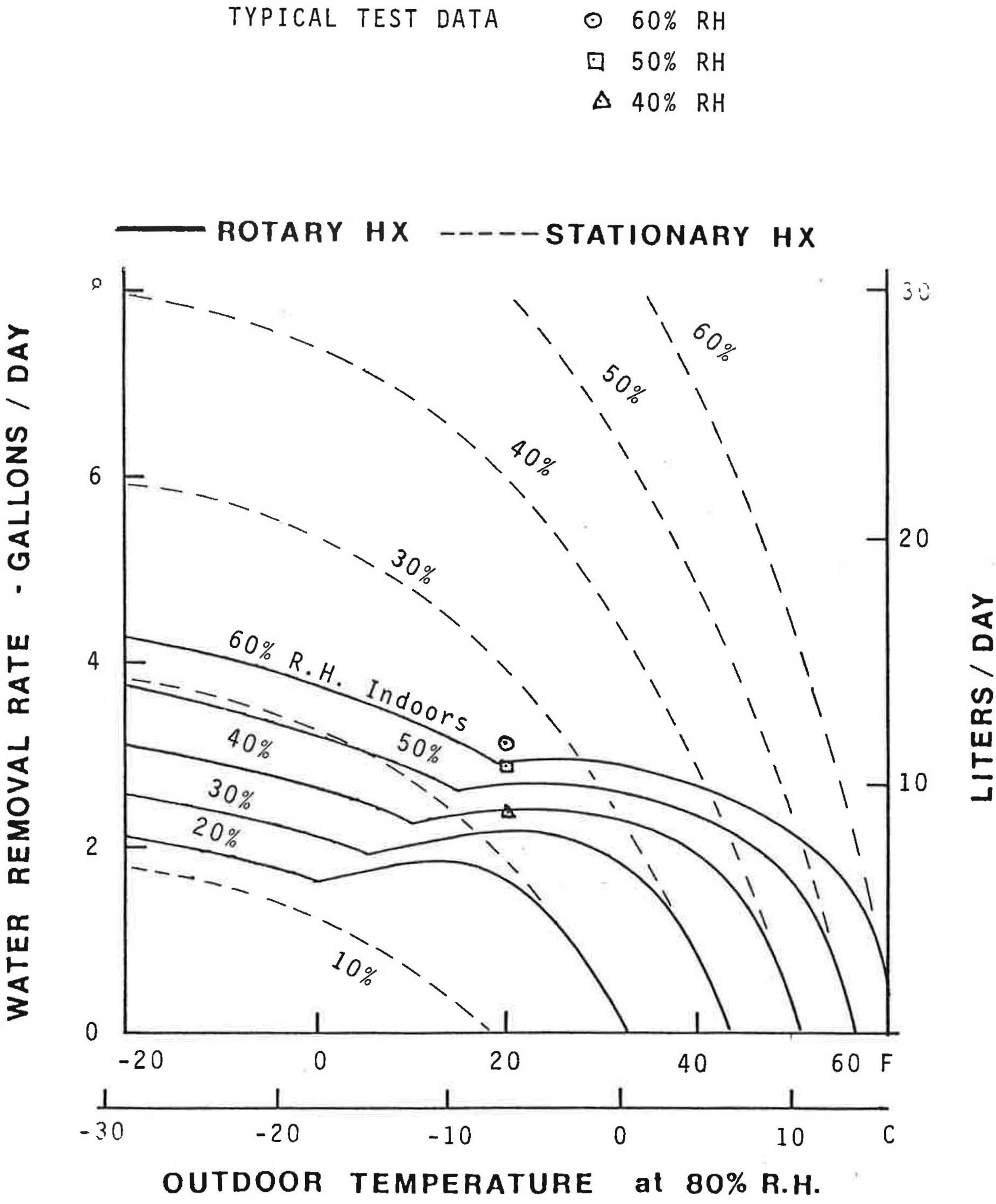

FIGURE 4 WINTER MOISTURE REMOVAL RATES FOR 100 CFM SENSIBLE ROTARY HEAT EXCHANGER

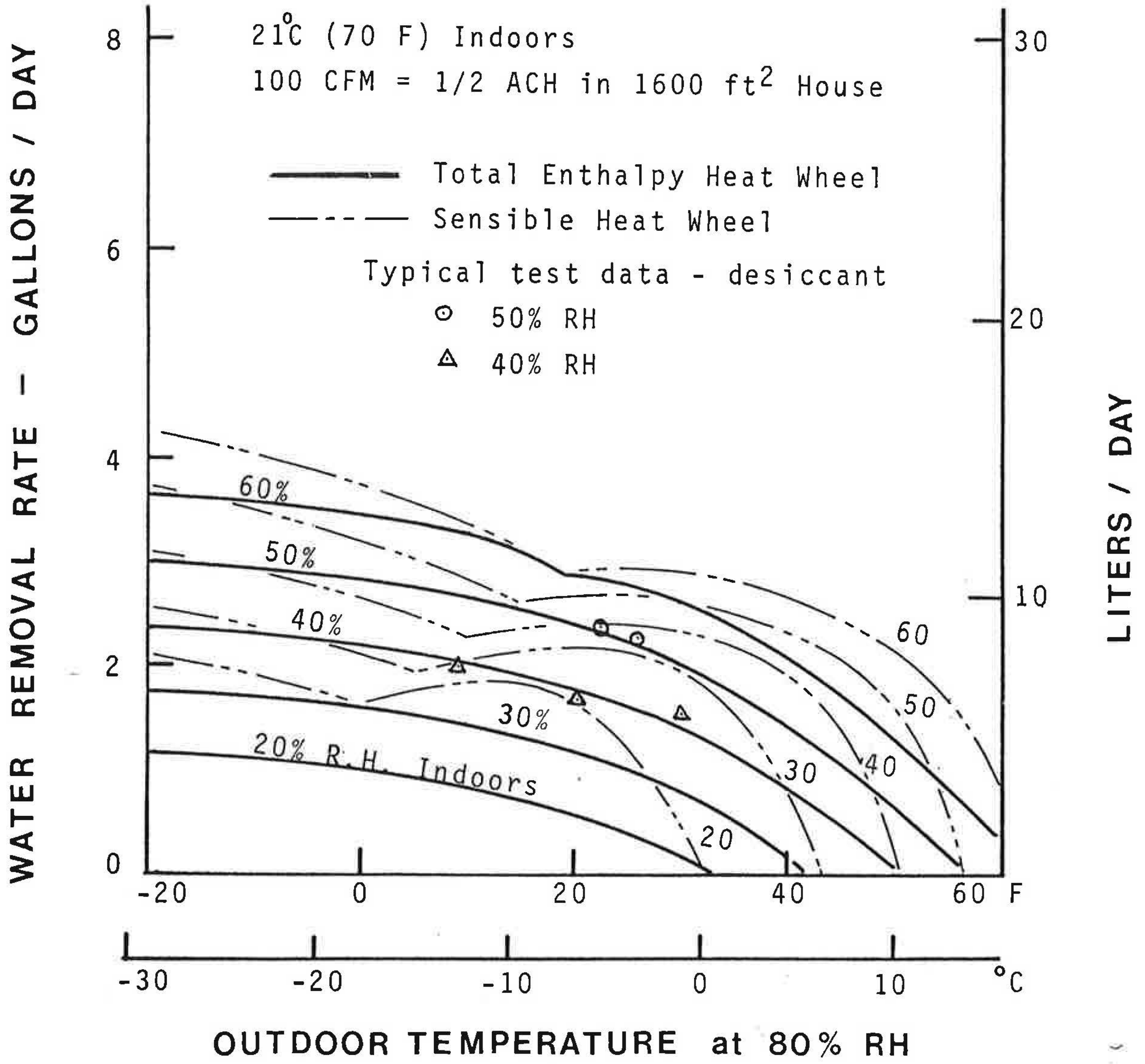

FIGURE 5 WINTER MOISTURE REMOVAL RATES FOR 100 CFM ROTARY HEAT EXCHANGER - TOTAL ENTHALPY & SENSIBLE TYPES COMPARED

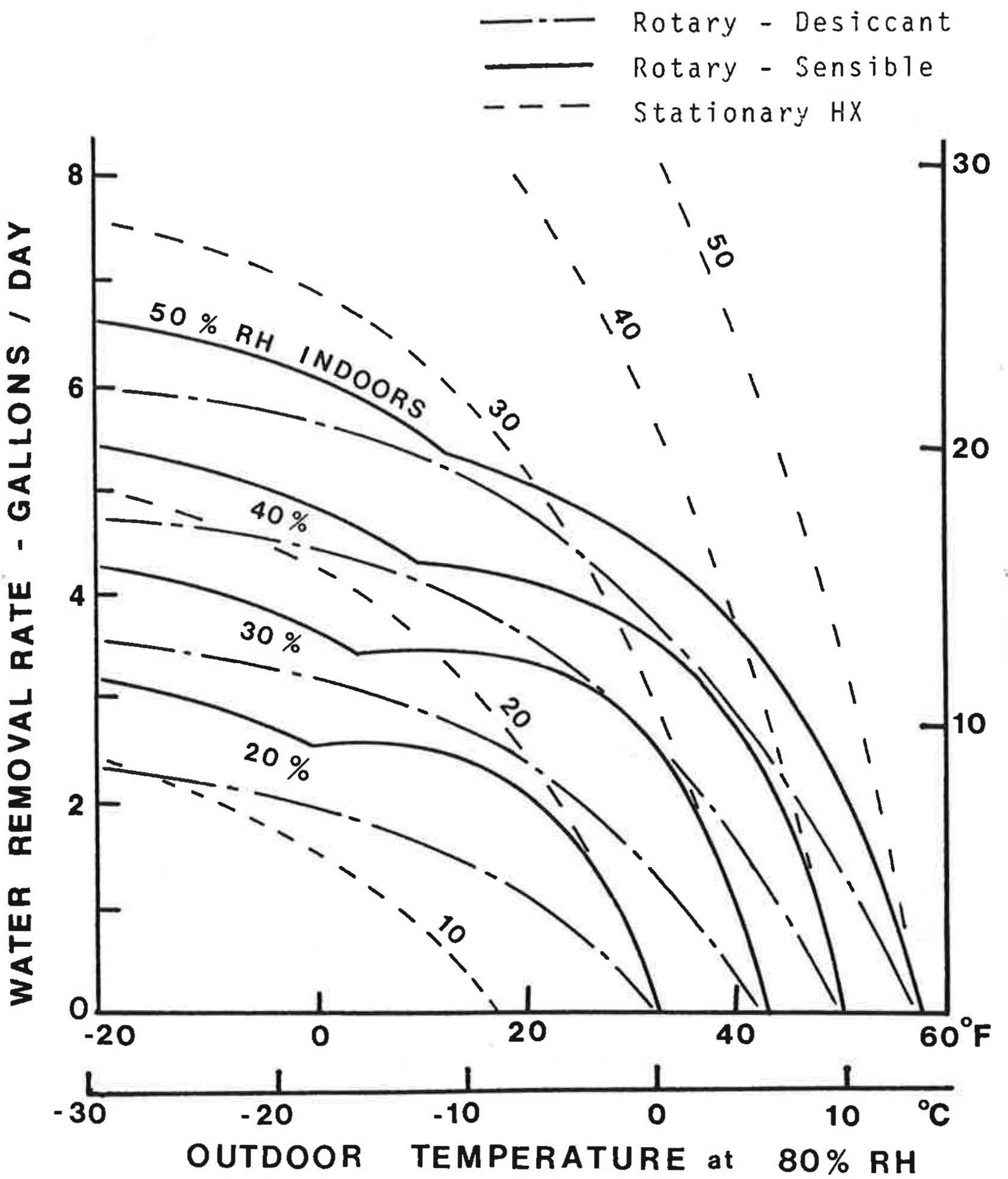

FIGURE 6 WATER REMOVAL PERFORMANCE OF A 1600 FT^2 HOME WITH 0.15 ACH NATURAL INFILTRATION AND 1/2 ACH MECHANICAL HEAT RECOVERY VENTILATION

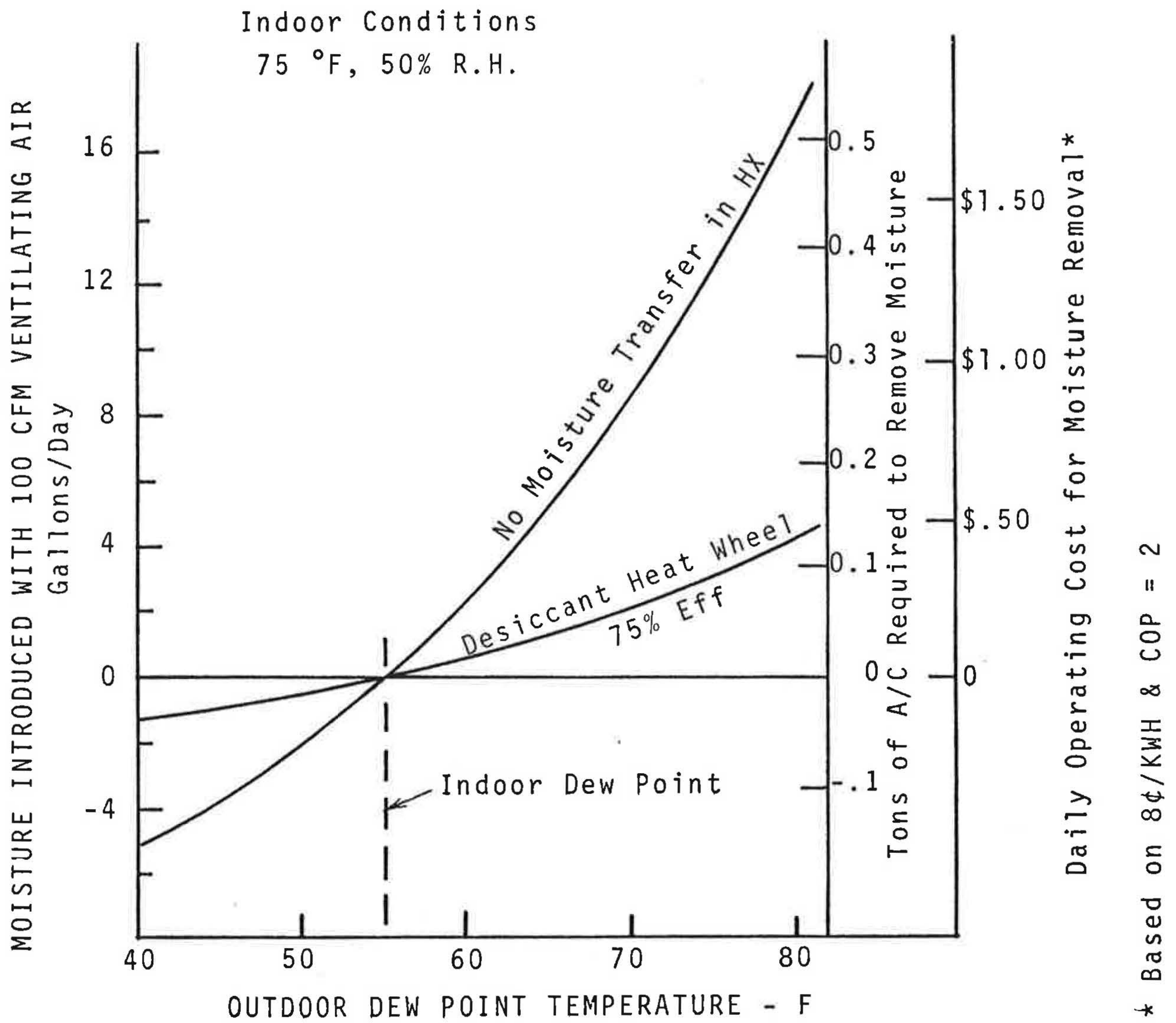

FIGURE 7 SUMMER CONDITIONS - MOISTURE INTRODUCED WITH 100 CFM VENTILATION AIR & REMOVAL COST

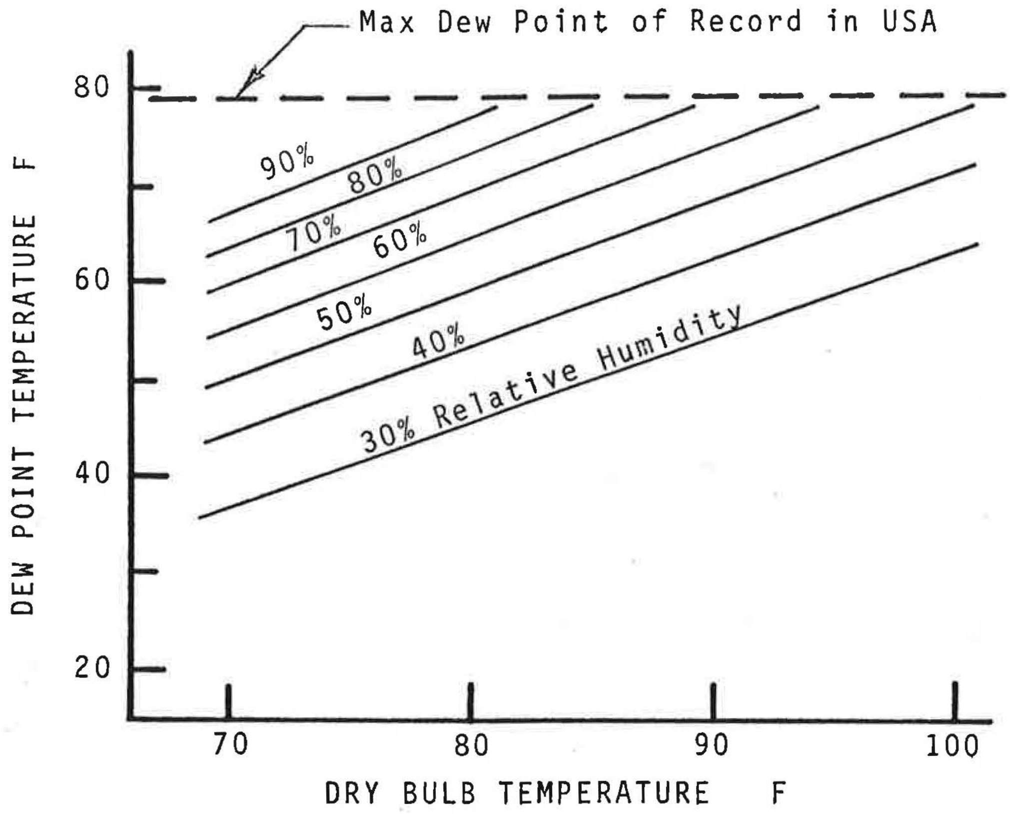

FIGURE 8 DEW POINT TEMPERATURE VS DRY BULB TEMP AND RELATIVE HUMIDITY