EFFECTS OF INDOOR RELATIVE HUMIDITY ON REFRIGERATED DISPLAY CASE PERFORMANCE

Ronald H. Howell, Professor
Luis Rosario, Graduate Student
Antonio Bula, Graduate Student
Department of Mechanical Engineering
University of South Florida
Tampa, Florida, USA

ABSTRACT

Refrigerated display cases are normally rated at a store environment of 24^0C (75^0F) and a relative humidity of 55%. If the store can be maintained at lower relative humidities, significant quantities of compressor energy, defrost energy and anti-condensation heater energy can be saved.

In this study a model was developed for a 4650 m^2 (50,000 ft^2) food store with a typical mix and quantity of refrigerated display cases. Moisture balances were done for a typical day in a typical store for each month of the year yielding a twenty-four hour variation in the store relative humidity.

Using these calculated hourly values of relative humidity for a 24 hour typical day, the store relative humidity distribution was calculated for a full year of store operation in Tampa, Florida. Savings of 10% in annual display case operating costs were found for changes of 5 percent in the store relative humidity for the Tampa, Florida region. The total store energy bill (display cases, air-conditioning and lights) would be reduced by 4.7% for this 5% change in relative humidity. These are significant cost savings for a supermarket.

INTRODUCTION

When a refrigerated display case operates in the supermarket environment, it exchanges heat and moisture with this environment. The moisture exchange between the display case and the store environment is the most troublesome because it causes the energy requirements for maintaining a satisfactory temperature within the display case to be high, detracts from the aesthetic display of refrigerated products, and deters the proper protection of the product. However, maintenance of a low relative humidity in the store environment requires an air-conditioning system with satisfactory performance characteristics and results in a higher first cost and a higher operating cost. But, the cost of operating the display cases will be lower due to less latent load on the refrigeration coil, fewer defrosts to be required, and less anti-sweat heater operation. Higher store relative humidity will result in lower operating cost of the HVAC equipment but will also result in more condensation on the display case walls and product and more frost on the refrigerator evaporator coils.

A research project sponsored by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) studied this problem and resulted in a final report (Ref. 1) and two technical papers (Refs. 2 and 3). In these references a procedure was developed that evaluates the effects of relative humidity on the energy performance of refrigerated display cases. In the technical papers a simplified set of procedures for evaluating the effects of store's relative humidity on refrigerated display case energy requirements, anti-sweat heater energy, defrost energy requirements, and store air-conditioning energy requirements are developed.

ENERGY SAVINGS PROCEDURES

Several procedures were developed by Howell and Adams (Ref. 1) which evaluated the effect of store relative humidity on display case energy requirements. These energy requirements were divided into three components: energy required by the case refrigeration, energy required by the case anti-sweat heaters, and energy required for case defrost. All three of these components and only these components of the display case loads will be affected by the store or ambient relative humidity. Each of these refrigerated display case loads were evaluated on a percent change basis (compared to operation at 55% RH) and are given by the following equations.

$$TP = QRH/Q \quad (1)$$
$$AP = ASWRH/ASW \quad (2)$$
$$DP = DFRH/DF \quad (3)$$

where

TP = percent change in display case energy requirement when operated at a relative humidity other that 55%.
AP = percent change in display case anti-sweat heater load when operated at a relative humidity other than 55%.
DP = percent change in display case defrost energy requirements when operated at a relative humidity other than 55%.
ASW = anti-sweat heater energy requirement for the display case at the design value of relative humidity of 55%.
ASWRH = anti-sweat heater energy requirement for the display case at a given relative humidity.
DF = defrost energy requirement for the display case at the design value of relative humidity of 55%.
DFRH = defrost energy requirement for the display case at a given relative humidity.
Q = display case refrigeration energy requirement at the design value of relative humidity of 55%.
QRH = display case refrigeration energy requirement at a given relative humidity

Values for TP and DP were evaluated by Howell (Ref. 2) for the situation when the store temperature was kept at 24^0C (75^0F) and are summarized in Tables 1 and 2. These numbers were generated for a wide variation in types of display cases as well as a full variation of case geometries and operating parameters. Details of these geometries and parameters are given in References 1, 2 and 3. Values for AP are given in Table 3 and were also developed and described in References 1, 2 and 3.

TABLE 1 Load Change Factors for Case Refrigeration Energy (TP) and Case Defrost Energy (DP) at Various Relative Humidities and at 24^0C (75^0F) for Multi-Shelf Vertical Cases.

RH	DP	TP	DP	TP
	Multi-shelf Meat		Multi-shelf Dairy	
30	0.417	0.733	0.259	0.647
35	0.532	0.786	0.406	0.717
40	0.648	0.839	0.553	0.788
45	0.766	0.893	0.703	0.858
50	0.882	0.947	0.851	0.929
55	1.000	1.000	1.000	1.000
60	1.118	1.054	1.149	1.071
65	1.235	1.108	1.299	1.142
	Multi-Shelf Deli		Glass Door-Ice Cream	
30	0.321	0.683	0.527	0.825
35	0.455	0.746	0.620	0.859
40	0.590	0.809	0.715	0.895
45	0.727	0.873	0.812	0.929
50	0.862	0.936	0.905	0.964
55	1.000	1.000	1.000	1.000
60	1.137	1.063	1.095	1.035
65	1.273	1.127	1.191	1.070
	Glass Door Frozen Food		Multi-shelf Frozen Food	
30	0.519	0.814	0.534	0.829
35	0.614	0.851	0.626	0.862
40	0.710	0.888	0.719	0.897
45	0.807	0.925	0.813	0.931
50	0.903	0.962	0.906	0.965
55	1.000	1.000	1.000	1.000
60	1.096	1.037	1.094	1.035
65	1.193	1.074	1.188	1.069
	Multi Shelf Produce			
30	0.290	0.646		
35	0.430	0.715		
40	0.571	0.785		
45	0.715	0.856		
50	0.856	0.927		
55	1.000	1.000		
60	1.143	1.070		
65	1.286	1.141		

TABLE 2 Load Change Factors for Case Refrigeration Energy (TP) and Case Defrost Energy (DP) at Various Relative Humidities and at 24^{0}C (75^{0}F) for Single Shelf Horizontal Cases.

RH	DP	TP	DP	TP

	Single-Shelf Meat		Single-Shelf Frozen Food	
31	0.465	0.799	0.553	0.853
34	0.536	0.826	0.612	0.872
38	0.609	0.853	0.673	0.892
41	0.684	0.881	0.736	0.912
44	0.760	0.910	0.799	0.933
48	0.838	0.939	0.865	0.955
51	0.918	0.968	0.931	0.978
55	1.000	1.000	1.000	1.000
58	1.083	1.031	1.069	1.021
62	1.169	1.064	1.141	1.044
	Single-Shelf Ice Cream		Single-Shelf Produce	
31	0.558	0.865	0.363	0.774
34	0.617	0.881	0.448	0.803
38	0.678	0.900	0.535	0.834
41	0.739	0.919	0.624	0.866
44	0.802	0.939	0.715	0.897
48	0.867	0.958	0.807	0.929
51	0.932	0.979	0.902	0.965
55	1.000	1.000	1.000	1.000
58	1.068	1.022	1.099	1.035
62	1.139	1.044	1.201	1.070

TABLE 3 Load Change Factors (AP) for Anti-Sweat Energy Requirements for All Display Cases at a 24^{0}C (75^{0}F) Ambient.

	Display Case Temperature			
Store Relative Humidity, %	5^{0}C (41^{0}F)	3^{0}C (37^{0}F)	-2^{0}C (29^{0}F)	-22^{0}C (-7^{0}F)
65	1.28	1.23	1.16	1.07
60	1.15	1.12	1.09	1.04
55	1.0	1.0	1.0	1.0
50	0.84	0.87	0.91	0.96
45	0.67	0.73	0.81	0.91
40	0.48	0.58	0.70	0.86
35	0.27	0.41	0.57	0.81

STORE MODEL

A model was developed for a typical supermarket which was based on data prepared by the Food Marketing Institute Energy Committee. The layout for this typical supermarket is given in Figure 1. The store description is as follows:

store floor area: 3716 m^2 (40,000 ft^2)
conditioned space: 2787 m^2 (30,000 ft^2)
Air Supply rate: 14.16 m^3/s (30,000 cfm)
Outside ventilation air: 1.84 m^3/s (3900 cfm)

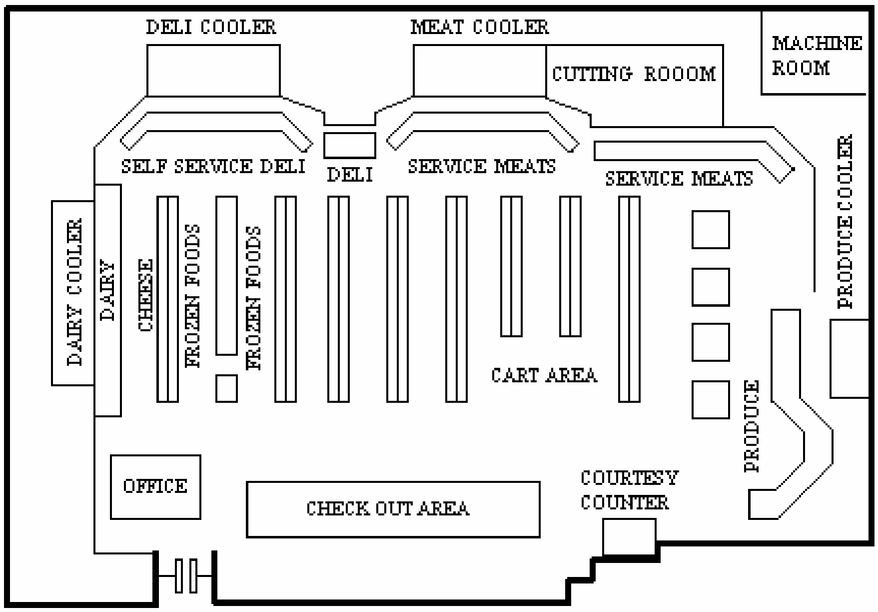

Figure 1 Layout of Typical Supermarket

Hours of Operation: 24 hours/day
People in Store: 180 maximum. 92W (315 Btuh) sensible and 75W (255 Btuh) latent
See Schedule in Figure 2
Indoor Conditions: 24^0C (75^0F), 55% relative humidity
Supply Air Conditions: 13^0C (55^0F), 95% relative humidity
Installed Refrigerated Case Capacity:
- medium temperature single shelf [73m(240 ft)] [42 kW (12 tons)]
- medium temperature multi-shelf [73m(240 ft)] [105 kW (30 tons)]
- low temperature reach-in [91m (300 ft)] [53 kW (15 tons)]

Location: Tampa, Florida. See Figures 3 and 4 for outside conditions for a typical January and August day.

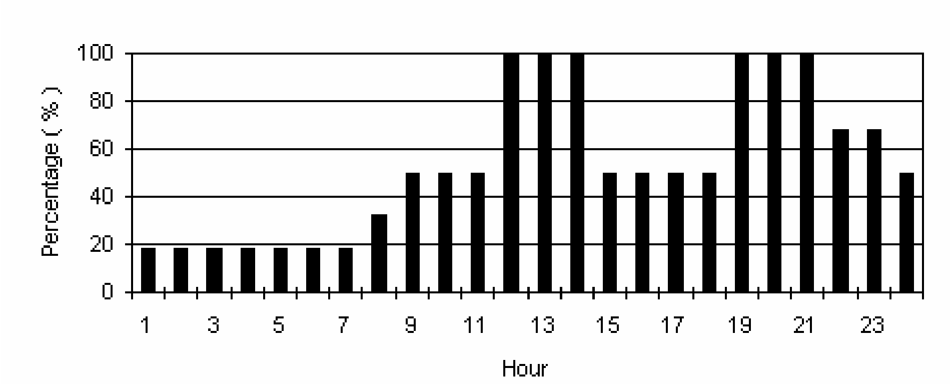

Figure 2 Schedule of People Occupancy in Supermarket

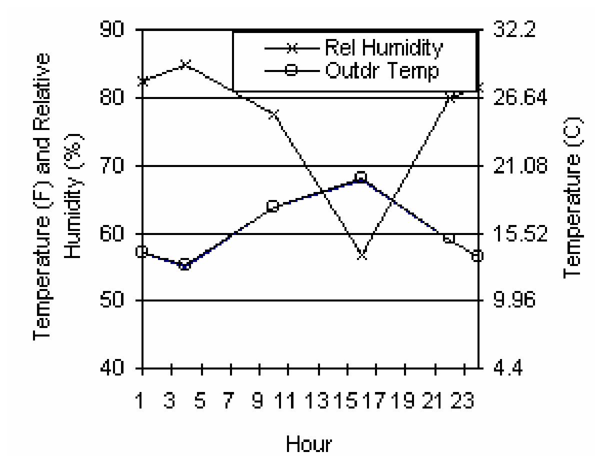

Figure 3 Typical January Daily Outdoor Temperature and Relative Humidity for Tampa Florida.

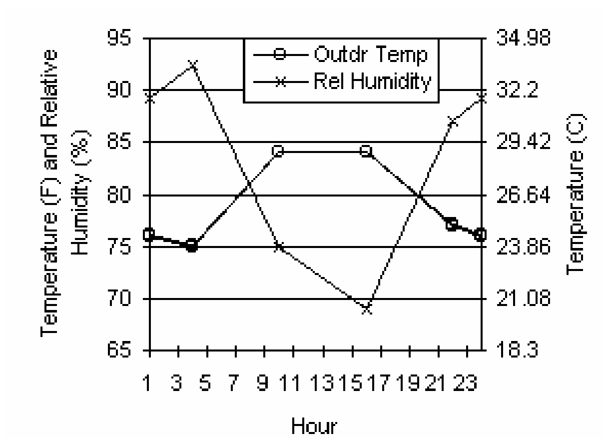

Figure 4 Typical August Daily Outdoor Temperature and Relative Humidity for Tampa, Florida

An hourly moisture balance was performed on the supermarket for a typical 24 hour day in the months of January, April, August and October. Assuming that the months preceding and following each of the above months has the same average weather, an annual effect can be obtained from these four months of weather data. The moisture balance, in terms of the latent energy balance is

$$QL_{space} + QL_{infil} = QL_{people} + QL_{produce} + QL_{Meat\ pr} + QL_{bakery} - QL_{display\ case} \quad (4)$$

which states that the net moisture loss due to the building envelope and the operation of the air-conditioning equipment is balanced by the net production of moisture within the supermarket. The terms in Eqn. (4) are calculated from the following equations (Ref. 1)

$$QL_{space} = 4840 x CFM_{space} x (W_{space} - W_{supply}) \quad (9)$$

$$QL_{infil} = 4840 x CFM_{infil} x (W_{space} - W_{outside}) \quad (10)$$

$$QL_{people} = 255 x NP \quad (11)$$

$$QL_{produce} = 1400 \text{ Btu/hr (constant for 24 hours)} \quad (12)$$

$$QL_{Meat\ pr} = 1400 \text{ Btu/hr (from 5 am to 10 am)} \quad (13)$$

$$QL_{bakery} = 12000 \text{ Btu/hr (from 5 am to 10 pm)} \quad (14)$$

$$QL_{display\ case} = \begin{bmatrix} 17{,}280 \text{ Btu/hr-med-temp single shelf} \\ 68{,}400 \text{ Btu/hr-med-temp multi-shelf} \\ 34{,}200 \text{ Btu/hr-low-temp reach-in} \end{bmatrix} \quad (15)$$

These values were obtained by using a latent load for each type of case (12% for single-shelf, 19% for multi-shelf and the reach-ins) based on their performance with store relative humidity maintained at 55%. At lower store relative humidities these numbers will be lower and will affect the simulated store relative humidity. This effect is assumed to be secondary for this calculation, however more precise calculations could be done but it would add severe complexity to the calculation.

where,

CFM_{infil} = $[44.5 \text{ x } NP - 0.095 \text{ x } NP^2 + 10^{-4} NP^3]\ \Delta P_{building}$

NP = number of people in the store

CFM_{space} = 30,000 cfm

W = humidity ratio

Typical illustrations for the supermarket display cases are given in Figures 5 and 6. Figure 5 is an illustration (Ref. 4) of a single shelf horizontal display refrigerator and

Figure 6 (Ref. 4) is a multiple shelf vertical display refrigerator.

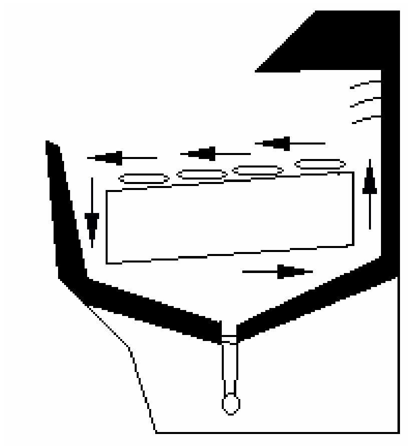

Figure 5 Single Shelf Horizontal Display Refrigerator (Ref. 4)

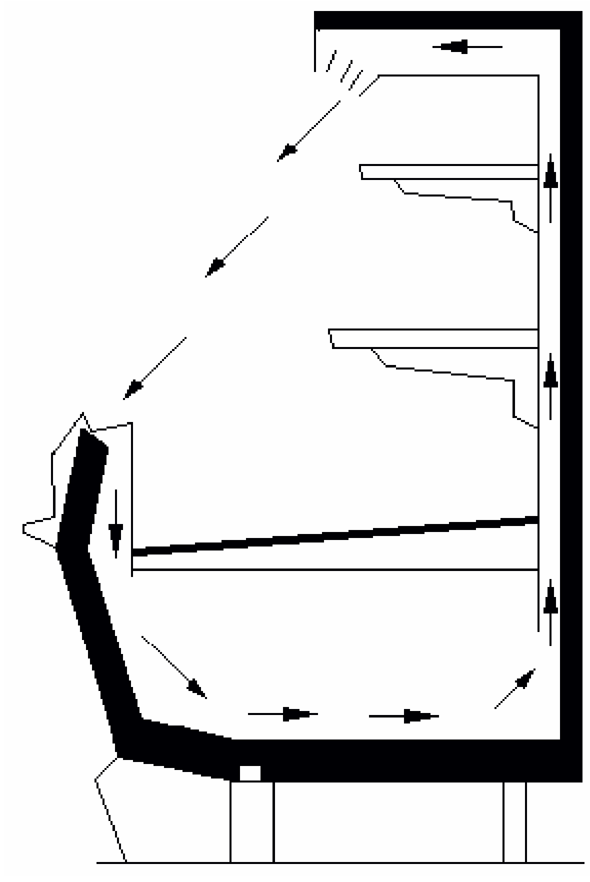

Figure 6 Multiple Shelf Vertical Display Refrigerator (Ref. 4)

Steady state simulations were carried out on an hourly basis for the typical day in each of the four months: January, April, August and October. This hourly moisture balance resulted in a relative humidity profile for the typical day inside of the store. This was done assuming that the store temperature was maintained at 24^{0}C (75^{0}F). The weather data for these four months was obtained from References 5 and 1 and as an example the months of January and August are illustrated in Figures 3 and 4 respectively.

SIMULATION RESULTS

The results from the above simulations were run for the typical twenty-four hour day for the months of January, April, August and October. For brevity only the plots for January and August are shown here. Figure 7 is an hourly plot of relative

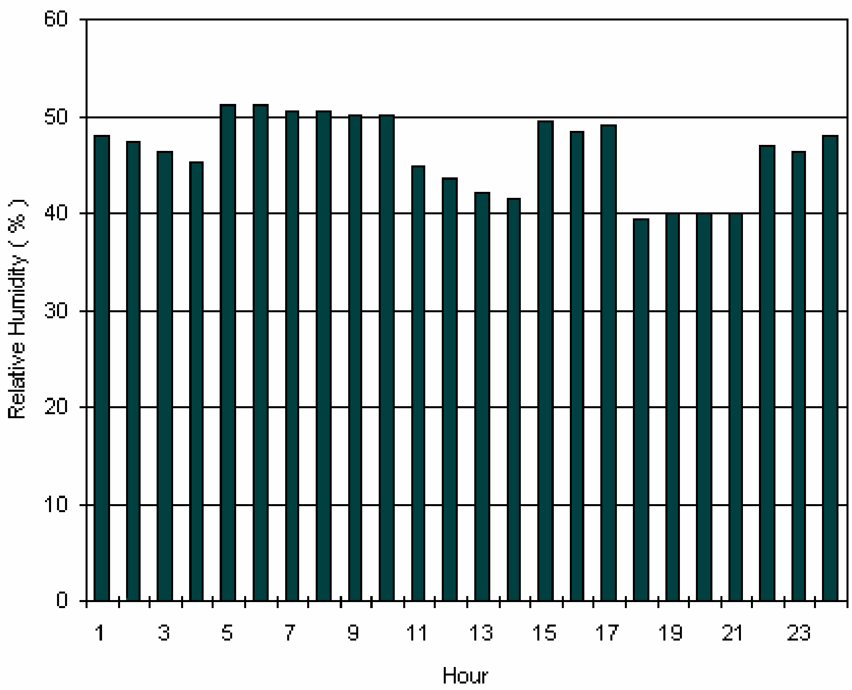

Figure 7 Hourly Relative Humidity for Model Store for January for Tampa, Florida

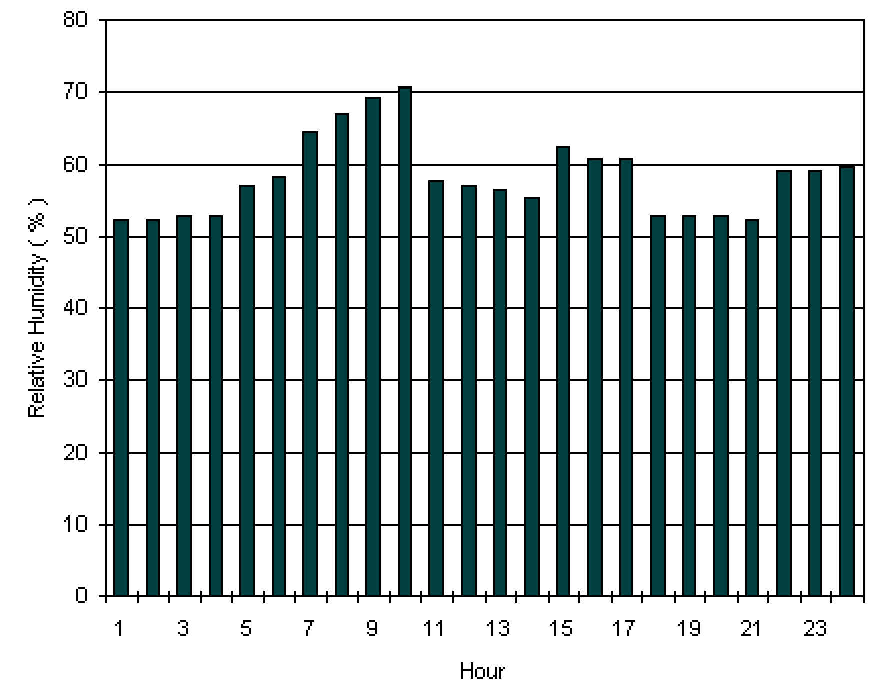

Figure 8 Hourly Relative Humidity for Model Store for August for Tampa, Florida

humidity for January and Figure 8 is an hourly plot of relative humidity for August. The hourly values for the four months simulated have been averaged separately and are presented in Table 4. In Table 4 the months of July and September were taken to be identical to August since the weather in Tampa, Florida is very consistent during the summer months. The months of February and March were determined from a linear relationship between January and April. May and June were linearly determined from the April and July values while those

TABLE 4 Average Relative Humidity Inside the Model Store at 24^{0}C (75^{0}F) for Each Month for Tampa, Florida

Month	Average Relative Humidity Inside Store, %
January	46.3
February	47.2
March	48.0
April	48.6
May	52.0
June	55.0

July	58.2
August	58.2
September	58.2
October	47.9
November	47.5
December	46.8

for November and December were the linear results between October and January.

The results given in Table 4 are strongly dependent on many of the assumptions made for the model store. However, these values appear to be typical for a supermarket with air-conditioning located in a climate such as Tampa Florida. Expected variation would be between 45% and 60% relative humidity. These values should be more representative of what is expected in a supermarket rather than using a design store relative humidity of 55%. From these results changes in display case refrigeration energy can be estimated for increases or decreases in store relative humidity brought about by changes in the operation of the stores air-conditioning system.

DISPLAY CASE ENERGY CONSUMPTION CHANGES

In order to evaluate the savings in energy in the operation of the display cases it is necessary to establish a base energy consumption for the refrigeration energy, defrost energy and anti-sweat heater energy. The establishment of these values is given in Table 5. The 73m (240 ft) of medium temperature single shelf units were assumed to use 600 Btu/hr per foot and have an energy efficiency ratio (EER) of 8 Btu/Wh. The 73m (240 ft) of medium temperature multiple shelf units used 1500 Btu/hr per foot and had an EER of 7. The 91m (300 ft) of low temperature reach-in cases used 600 Btu/hr per foot and had an EER of 6. These assumptions allowed the calculation of the kW demand and the kWh per month given in Table 5 for the three display cases.

TABLE 5 Display Case Energy for Simulated Store for 55% Store Relative Humidity

CASE TYPE	ft (m)	CASE TEMP ^{0}F (^{0}C)	Btu/hr· ft	Btu/hr (kW)	EER Btu/Wh	kW	kWh/Month
Medium Temp Single Shelf	240 (73)	37 (3)	600	144,000 (42)	8	18	11,664
Medium Temp Multiple Shelf	240 (73)	37 (3)	1500	360,000 (105)	7	51.4	37,008
Low Temp Reach In	300 (91)	29 (-2)	600	180,000 (53)	6	30	19,440
TOTAL	780 (237)	--	--	--	--	99.4	68,112

Defrosts	2 to 4 per day,	16,667 kWh/month
Anti-sweat Heaters	23.4 kW	16,850 kWh/month

The number of defrosts varied from 2 to 4 per day and consumed 16,667 kWh per month and the total anti-sweat heater load was 23.4 kW which consumed 16,850 kWh per month. These values are shown in the bottom of Table 5. The approximate values for these load estimates were obtained from Howell and Adams (Ref. 1). They are taken at the rated store relative humidity of 55%. The annual energy load for the refrigeration, defrost and anti-sweat heaters is about 1,219,500 kWh. Normally, this load is about 70% of the supermarkets total annual energy consumption.

In order to evaluate savings in display case energy with reductions in ambient store relative humidity it is necessary to determine TP, DP and AP. These three modifiers can then be used with the energy loads given in Table 5 to estimate energy requirements at other store relative humidities.

The average relative humidity in the model supermarket was determined from the data presented in Table 4. The twelve months were averaged (assuming each month had the same number of days) yielding an **annual average store relative humidity of 51.2%**. Again, this appears to be a reasonable number for the Tampa, Florida climate. Since display cases are rated at 55% ambient relative humidity the actual annual energy requirement for the display cases in this model store would be less than 1.22 million kWh as previously estimated.

In order to determine how much less the energy bill would be for these display cases the three "energy modifiers" were determined. These were done using the data in Tables 1, 2 and 3. Values for TP, DP and AP were found for store relative humidities of 51.2%, 45%, 40%, and 35%. The values for TP, DP and AP are 1.0 for 55% RH. The values for these three energy modifiers are given in Table 6 for the three types of installed display cases

TABLE 6 Display Case Energy Modifiers for Various Store Relative Humidities

CASE TYPE	Average Annual Store Relative Humidity = 51.2%			Average Annual Store Relative Humidity = 45%		
	TP	DP	AP	TP	DP	AP
Medium Temp Single Shelf	0.951	0.895	0.901	0.87	0.727	0.73
Medium Temp Multiple Shelf	0.946	0.887	0.901	0.858	0.703	0.73
Low Temp Reach-In	0.968	0.918	0.93	0.915	0.765	0.81
	Average Annual Store Relative Humidity = 40%			Average Annual Store Relative Humidity = 35%		
	TP	DP	AP	TP	DP	AP
Medium Temp Single Shelf	0.809	0.59	0.58	0.746	0.455	0.41

Medium Temp Multiple Shelf	0.788	0.553	0.58	0.717	0.406	0.41
Low Temp Reach In	0.878	0.675	0.70	0.83	0.54	0.57

From the display case energy requirements at 55% relative humidity given in Table 5 and the TP, DP and AP factors summarized in Table 6, annual energy requirements at 51.2%, 45%, 40% and 35% store relative humidities were determined. These results are given in Table 7. The separate loads as well as the total display case loads are given so that these may be compared to actual situations.

TABLE 7 Display Case Annual Energy Requirements at Various Store Relative Humidities

	55% RH	51.2% RH	45% RH	40% RH	35% RH
REFRIGERATION, kWh	817,340	779,040	716,260	660,250	609,120
DEFROSTS, kWh	200,000	180,000	146,330	121,200	93,400
ANTI SWEAT, kWh	202,200	184,470	153,900	126,740	95,500
TOTAL, kWh	1,219,540	1,143,510	1,016,490	908,190	798,020

In Table 8 the percent savings in energy for the various components as well as the total display case energy savings are given for the various store relative humidities. The changes in energy requirements are nearly linear in this range of relative humidity. These results show that

For a 5% reduction in store relative humidity:

The refrigeration load is reduced 7%.,
The defrost load is reduced 14%,
The anti-sweat heater load is reduced 15%, and
The TOTAL display case load is reduced 10%.

DISPLAY CASE AND AIR-CONDITIONING ENERGY CHANGES

It is necessary now for the designer or store operator to determine the percent increase in air-conditioning energy required to reduce the store relative humidity by 5%. Will this increased cost be less than the cost savings of the 10% reduction in display case energy? If so, it is then economically justifiable to lower the store relative humidity.

For the simulated model store previously described it was estimated (Ref. 3) that the annual air-conditioning (AC) energy requirement needed to maintain the store at 24^{0}C (75^{0}F) and 55% relative humidity (RH) was 478,600 kWh using an AC unit with an energy efficiency ratio of 9.5 Btu/watt-hr (2.812 watts cooling/watts power). If the store relative humidity was lowered to 45% RH the same AC unit would require 499,600 kWh and if lowered to 35% RH the store AC unit would require 516,600 kWh. Also, in order to evaluate reasonable percent changes in energy for the total supermarket, a value for the annual energy required by lights and appliances was needed and this was evaluated as 300,00 kWh. Table 9 compares changes in energy requirements for each component of the store electric bill at different relative humidities.

TABLE 8 Percent Changes in Energy for Various Store Relative Humidities

Relative Humidity, %	55	51.2	45	40	35
TOTAL DISPLAY CASE ENERGY, kWh	1,219,540	1,143,510	1,016,490	908,190	798,020
Percent Change Compared to Base Case at 51.2% RH	+6.65	0	-11.1	-20.6	-30.2
Defrost Energy, kWh	2000,000	180,000	146,330	121,200	93,460
Percent Change Compared to Base Case at 51.2% RH	+11.1	0	-18.7	-32.7	-48.1
Anti-sweat Energy, kWh	202,200	184,470	153,900	126,740	95,500
Percent Change Compared to Base Case at 51.2% RH	+9.61	0	-6.6	-31.3	-48.2
Refrigeration Energy kWh	817,340	779,040	716,260	660,250	609,120
Percent Change Compared to Base Case at 51.2% RH	+4.9	0	-8.05	-15.2	-21.8

TABLE 9 Changes in Total Store Energy Requirements at Various Relative Humidities

Relative Humidity (RH), %	55	51.2	45	40
Total Display Case Annual Energy, kWh	1,219,500	1,143,500	1,016,500	908,200
Air-Conditioning Annual Energy, kWh	478,600	491,600	499,600	508,100
Lights and Appliances, Annual Energy, kWh	300,000	300,000	300,000	300,000
TOTAL STORE ANNUAL ENERGY, kWh	1,998,100	1,935,100	1,816,100	1,716,300
Savings Realized by Changing from 55% RH, kWh	--	62,980	182,000	281,800
Savings in kWh for Each 1% Reduction in RH, kWh	--	16,570	18,200	18,800
Percent Savings in Total Store Energy by Changing from 55% RH, %	--	3.1	9.1	14.1
Percent Savings in Total Store Energy for each 1% Change in RH	--	0.81	0.91	0.94

From Table 9 it can be seen that for a 5% reduction in store relative humidity there is about a 4.7% reduction in the total store annual energy. For each 1% reduction in store relative humidity, there is an approximate savings in annual store energy of about 18,000 kWh.

CONCLUSIONS

Moisture balances on supermarkets are necessary and can be done in order to assess the effect of reduced store relative humidity on display case energy requirements. For the simulated model store described here and located in a warm and humid climate such as Tampa, Florida the annual average supermarket relative humidity was 51.2% and ranged between 45% and 60% during the model year. It was also shown that for a 5% reduction in store relative humidity that the

Display case refrigeration load was reduced by	7%
Air-conditioning load was increased by	2%
TOTAL STORE ENERGY LOAD WAS REDUCED BY	**4.7%**

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