HIGH HUMIDITY STORAGE OF VEGETABLES AND FRUITS[1]

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This paper reviews some of our work over the last 25 years in the area of vegetable and fruit storage at very high relative humidity (RH) levels. During this time, recommended levels of RH for the storage of most fruits and vegetables have increased (2). This has occurred, partly as a result of the work reviewed here and partly because recent developments in design and construction of storages (3-6,13,16) and in the use of plastic packaging have resulted in higher humidities being maintained for many stored commodities without adverse effects (2). The recommended levels are mostly, however, still below saturation (100% RH) (15). One of the reasons for this is the widely held conviction that such high levels of RH encourage and accelerate decay. The work reviewed here shows that this conviction is not valid for many vegetables and for apples.

Five aspects of the work dealing with vegetables and apples are discussed in some detail: 1) methods for studying the effect of RH on quality and decay, 2) results demonstrating the effect of RH, 3) host-parasite relationships during high humidity storage, 4) interrelations between temp, RH and moisture loss during storage and the factors affecting these variables, 5) commercial application of high humidity storage.

Methodology of high humidity storage tests

In addition to the measurement and control of RH and temp, other factors that could influence the results of the test (in terms of moisture loss, decay, and quality) were taken into account. These included pre-storage conditions, the relation between RH, temp and vapor pressure dificit, and moisture absorption by storage containers. The effect of RH under controlled atmosphere conditions was also tested for some commodities.

Pre-storage factors considered included pre-harvest conditions and treatment, cultivar, injuries during harvest, and post-harvest handling. These are known to affect decay and quality losses during storage. Great care was therefore taken to select cultivars suitable for storage, growers known for the quality of their produce and growing areas where the particular produce is stored commercially. Where at all possible, produce was harvested by hand and transported carefully to the laboratory and cooled to about the storage temp on the day of harvest.

Since produce moisture loss during storage is a direct function of water vapor pressure deficit (VPD) and hence of temp as well as RH, temporal and spatial temp variations had to be kept to a minimum. Increasing the temp of saturated air at 0°C by 1°C, for example, causes a water VPD of about 45 pascals (Pa), reducing the RH from 100 to 93%. A 1°C change at 10°, however, causes a water vapor deficit of about 85 Pa with about the same RH (94%). Since moisture loss is approximately proportional to VPD in that range of RH (7,10,22), the rate of moisture loss at 11°C will be almost double that at 1°C, although the RH is slightly higher. Therefore storage life would be almost halved. This illustrates the importance of temperature control in both testing and storage.

To obviate the effect of moisture absorption by the wooden boxes in which produce was stored (1), they were sprayed with water until saturated. The boxes (1 bushel, 35.2 liters) weighed about 4 kg dry and absorbed up to 2 kg of moisture. This amount of moisture, if removed from the produce during storage, could have causes moisture losses of 10 to 20%. Changes in weight of the produce and the boxes were always determined separately in these tests.

RH measurements

Measurements of RH were made with a specially designed (by the second author) multiple junction wet- and dry-bulb thermocouple instrument accurate to better than 1% RH in the range 75-100%. In practice, constantly occurring minor variations in RH made it more convenient to estimate long term average RH from correlation with weight loss. For commodities with a relatively high transpiration coefficient, for example, 0 to 0.7% weight loss per month at 0°C meant an RH of 98-100%, while weight losses of over 1.5% per month indicated an RH of less than 95%.

Decay loss and quality changes

All small scale tests and some of the large scale tests involved comparisons between storage at 98-100% RH and storage at one or more lower levels of humidity (90-95% mostly, 75-85% in a few instances). In each comparision, the produce at different humidities was the same cultivar from the same grower, treated the same during and after harvest and the storage temp was the same (within ± 0.3°C). Most comparisons were made at 0-1°, but some were made at higher temp (up to 7°). At 98-100% RH, the effects of modified atmospheres (1-10% O_2, 5-11% CO_2), repeated surface condensation, storage of more than one kind of produce in the same container and rate of air change were also studied. Detailed results for these comparisons, as well as details on the equipment used, and of the method evaluation of the produce during storage are presented in previous papers (8,9,17-20,24-29).

Typical results of small scale storage tests are presented in Table 1 for carrots, parsnips and rutabagas and in Table 2 for cabbage. Losses in quality and weight were substantially less at the higher humidity for all products. Carrots, parsnips and, to a lesser extent, rutabagas, became soft and shrivelled and the outside cabbage leaves turned yellow and wilted at 90-95% RH, but not at 98-100%. Losses from decay in cabbage and carrots were also noticeably less at the higher humidity level.

Similar results were obtained with most of the other commodities tested. (2,8,9,13,17-20,24-29). In all cases there were noticeable differences in moisture loss due to RH with consequent differ-

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Table 1. Effect of relative humidity and temperature on moisture loss and decay of carrots, parsnips and rutabagas stored in air.[z]

Commodity	Cultivar	Storage temp, (°C)	Storage time (mo.)	Weight loss due to dessication, % per 30 days: Relative humidity 90-95%	98-100%	Weight loss due to decay, (%): Relative humidity 90-95%	98-100%
Carrots	Gold Pack	0-1	8	1.6	0.3	30	15
		3.5-4.5	8	2.1	0.4	50	15
	Special Long Type Nantes	0-1	8	1.1	0.1	30	10
		3.5-4.5	8	–	0.8	–	10
Parsnips	Hollow Crown	0-1	9	0.8	0.2	2	2
		3.5-4.5	9	2.1	0.4	20	15
Rutabagas	Laurentian	0-1	9	0.9	0.1	2	2
		3.5-4.5	9	2.1	0.1	10	10

[z]Results are averages from 2-4 tests (different growing locations) in one crop year for parsnips and rutabagas and in up to 3 crop years for carrots; variability in decay was generally less than ±5%.

Table 2. Effect of relative humidity and temperature on color change and trimming loss of Penn State Ballhead green cabbage, stored in air for up to 7 months (averages of results from 2-6 tests).

Storage temp (°C)	Storage time until a noticeable change in color occurred, months		Trimming loss, % of pre-storage (storage in months)	
	RH		RH	
	90-95%	98-100%	90-95%	98-100%
0-1	2-4	3-5	35(7)	25(7)
3.5-4.5	2-3	3-4	35(5)	30(5)
7-8	1-2	1-2	20(3)	15(3)

ences in crispness, turgidity and color (for green vegetables). For Brussels sprouts, celery, Chinese cabbage and leeks, decay was less at 98-100% than at lower levels of RH, similar to the results obtained with cabbage and carrots. For cauliflower and potatoes, as for parsnips and rutabagas, decay was not appreciably affected by humidity in the range tested. For onions, on the other hand, decay (usually in the form of neckrot) tended to be higher at the higher humidity level. Results of large-scale tests and observations in commercial storages confirmed the conclusions of small-scale tests.

Most observations on apples were obtained from pilot scale tests or full scale commercial operation using the MacIntosh cultivar stored in air and in controlled atmosphere. Weight loss was lower at 98-100% RH (0-0.2% per month) than at 90-95% RH (0.4-6% per month), and no difference in rate of decay due to RH was noted.

Of the other factors studied, modified atmospheres at 98-100% increased the storage life of green vegetables further. Green cabbage and celery, for example, could be stored up to one month longer in 1-3% oxygen and 5% carbon dioxide than in air at the same high level of humidity. Benefits were a better retention of the green color and reduced decay. Modified atmospheres reduced the storage life of carrots, however, by increasing decay. Rate of air change (up to 300 changes per day) generally did not affect decay, color or quality, while repeated surface condensation during storage tended to be beneficial rather than detrimental.

The effects of RH and temp on the storage life of vegetables studied in this laboratory are summarized in Table 3. Storage life has

Table 3. Effect of relative humidity and temperature on estimated storage life of vegetables stored in air.

Vegetables	Cultivars tested	Storage temp, (°C)	RH, (%)	Storage life,[z] weeks	Main factor(s) limiting storage life
Brussells sprouts	Jade Cross	0 to 1	90-95	6-8	Wilting[y,x], decay, yellowing
			98-100	10-12	Decay
Cabbage	Penn State	0 to 1	90-95	14-22	Decay, wilting, yellowing
	Ballhead		98-100	18-26	Decay, yellowing
	Storage Green	3.5 to 4.5	90-95	10-14	Decay, wilting, yellowing
	Houston Evergreen		98-100	12-16	Decay, internal growth, rooting
		7 to 8	90-95	8-12	Internal growth, rooting
			98-100	8-12	Internal growth, rooting
Carrots	Special Long	0 to 1	90-95	15-30	Decay and softening
	Type Nantes		98-100	30-40	Decay, rooting and sprouting[w]
	Royal Dutch Nantes	2 to 3	98-100	30-40	Decay, rotting and sprouting[w]
	Royal Chantenay	3.5 to 4.5	90-95	15-30	Decay and softening
	Gold Pack		98-100	20-40	Decay, rooting and sprouting[w]
		7 to 8	98-100	20-40	Decay, rooting and sprouting[w]
Cauliflower	Imperial 1006	0 to 1	90-95	3-4	Brown spots on heads
	Super Junior		98-100	3-4	Brown spots on heads
	Self-blanche				
Celery	Utah 15	0 to 1	90-95	8-10	Wilting, yellowing, decay
	Utah 52-70		98-100	10-12	Decay, yellowing
	Merveilleux	0 to 1	98-100	4-5	Decay
Chinese cabbage	Michihli	0 to 1	90-95	8-12	Wilting, yellowing, decay
			98-100	10-14	Decay
Leeks	Unik	−1 to −1.3	98-100	14-18	Decay
	Elephant	0 to 1	90-95	7-9	Decay and wilting
			98-100	9-11	Decay
Onions	Autumn Spice	0 to 1	75-80	35-40	Softening due to drying
	(maleic hydrazide		98-100	30-40	Decay
	treated against	4 to 5	75-80	35-40	Softening due to drying
	sprouting)		98-100	30-40	Decay
Parsnips	Hollow Crown	0 to 1	90-95	20-30	Shrivelling, decay
	(maleic hydrazide		98-100	>35	Decay
	treated)				
		3.5 to 4.5	90-95	15-25	Shrivelling, decay
			98-100	⩾35	Decay
Potatoes	Kennebec	4 to 5	85-90	⩾35	Softening, decay, sprouting[w]
	Katahdin		98-100	⩾35	Decay, sprouting[w]
	Sebago	7 to 8	85-90	⩾35	Softening, decay, sprouting[w]
			98-100	⩾35	Decay, sprouting[w]
		9 to 10	98-100	30-35	Decay, sprouting[w]
Rutabagas	Laurentian	0 to 1	90-95	⩾35	Softening, decay, sprouting[w]
			98-100	>35	Decay, sprouting[w]
		3.5 to 4.5	90-95	⩾35	Softening, decay, sprouting[w]
			98-100	⩾35	Sprouting[w], decay

[z]A loss of 20-30% of prestorage wt as a result of trimming and culling necessitated by yellowing, shrivelling, wilting, softening, and decay alone or in combination, was assumed to end the useful storage period.

[y]Weight losses generally amounted to 0 to 0.5%/30 days at 98-100% RH and 0.7-2.0%/30 days at the lower humidity levels.

[x]A total moisture loss of 5-6% causes the first noticeable softening or wilting of root crops and solid cabbage heads, while a total moisture loss of over 8% makes them virtually unsaleable. With leafy vegetables, a weight loss of 3 to 4% becomes noticeable (outside leaves wilted) and requires trimming.

[w]Depending on the use of sprout inhibitor.

been defined as the period during which the loss of produce caused by culling and trimming necessitated by weight loss (wilting and shrivelling), yellowing, rooting, sprouting and decay did not exceed 20-30%. This criterion was based on the following considerations:

1) Once losses reach this level, the rate of deterioration usually increases rapidly.
2) For up to 20-30% trimming losses, vegetables such as cabbage, celery, Chinese cabbage, and leeks retain an identity closely related to the freshly harvested product.
3) The labor and handling cost of trimming and discarding more than 20-30% of the produce is likely to be prohibitive.

The range of storage life given in each case includes variability due to cultivar, storage season and growing area. Factors responsible for limiting storage life are listed (in order of importance) in each instance. It should also be pointed out that the quality of produce stored at the higher level of humidity was usually better at the end of the indicated storage life than that stored at the lower humidity, because of the greater cripness and firmness resulting from reduced moisture loss. As Table 3 shows, 98-100% RH resulted in a longer storage life than 90-95% RH for most vegetables. As already indicated, for cabbage, carrots and leeks the main reason for the longer storage life at high RH was reduced decay. For Brussels sprouts, celery, Chinese cabbage, parsnips, potatoes and rutabages, loss of moisture and associated loss of quality were the main factors limiting storage life at the lower humidity although decay was also often less at the higher RH. The storage lives given for 90-95% RH are in good agreement, for the most part, with data given by Lutz and Hardenburg (15) for comparable conditions.

Host-parasite relationships during high humidity storage

The unexpected decrease in decay at 98-100% RH as compared to 90-95% for many vegetables indicated a need to understand some of the underlying host-parasite relationships. With carrots as host, it was found that *Botrytis cinerea* was the most important pathogen, followed by *Sclerotinia sclerotiorum.*

Of the 4 aspects of host-parasite relationships studied (periderm thickness, fungistatic properties of the tissue, survival of pathogens (21) and pectolytic enzyme production by the pathogens (30)) only the enzyme production was affected by RH in a way parallel to the effect of RH on decay. It was found that substantially more enzymes were produced on the surface of carrots stored at 90-95% than on those stored at 98-100% RH (Table 4). Results also indicated that this higher enzyme production was caused by a lesser availability of nutrients at the lower humidity level. It was noted that at 98-100% RH, molds grew luxuriantly on the surface of many root vegetables without causing decay or other damage. It was also found that pectolytic enzymes, when present on the surface of carrots, are deactivated more rapidly during storage at 98-100% than at 90-95%. Since these enzymes play an important role in the penetration of the pathogen into the host, the difference in enzyme production at different RH is probably a major factor in the effect of RH on decay.

Factors affecting temperature, RH, and moisture loss

Special temperature variation and moisture loss in storages for fresh fruits and vegetables depend on a number of related factors including heat of respiration, coefficient of moisture transpiration, velocity of air movement through the stored produce, RH of the air entering the stack of stored produce, density of loading and size of storage room, as well as stacking arrangement, type of packaging (moisture absorption, resistance to air movement, thermal resistance) and precooling procedure. Because these factors vary among storage rooms and storage years, it is difficult to obtain enough comparable data under commercial conditions for analysis of the relations between these factors and their effects on the 2 variables of great concern in fresh fruit and vegetable storage, spatial temp variation and rate of moisture loss. A comprehensive mathematical analysis was therefore made to evaluate the effects of the basic factors affecting spatial temp variation and moisture loss in fresh fruit and vegetable storages (11,14). In this analysis, values used for heat of respiration, coefficient of moisture transpiration, air velocity and initial RH were based on experimental measurements made by us.

From this analysis, ti may be noted:

a) An increase in air velocity lowers the rate of moisture loss (Fig. 1) as well as the temperature gradient, under many conditions.

b) For commodities with a high coefficient of transpiration, RH of the air entering the load has little effect on moisture loss, except where the air stream enters the load. There, the effect of low RH is severe, and as drying proceeds the "drying front" will advance.

Table 4. Effect of RH on pectolytic activity present on the surface of naturally inoculated unwashed carrots stored at 0-1°C for 40 weeks and on inoculated washed carrots stored at 20°C for 2-3 weeks.

Storage temp (°C)	Storage time (wk)	Pectolytic activity (arbitrary units) Relative humidity 90-95%	98-100%
0-1	40	0.6	<0.1
20	2-3	0.5	0.3

c) For commodities with a high coefficient of transpiration, RH of the air entering the load has little effect on RH in the bulk of the load where the level approaches saturation (Fig. 2). This being the case, presumed harmful effects of high RH may be over-rated.

d) RH is strongly affected by coefficient of transpiration, but is relatively independent of heat of respiration, air velocity and initial RH.

e) Heat of respiration strongly affects temp gradient (Fig.3) and moisture loss. This may explain part of the beneficial effect of controlled atmosphere storage. Since heat leakage into the storage space through the walls will have an effect similar to increasing the heat of respiration, this explains part of the advantage of the jacket system of room construction.

Commercial application of high humidity storage

Many storages are now being designed, built and operated to maintain high levels of RH. In Canada, 11 commercial jacketed storages for

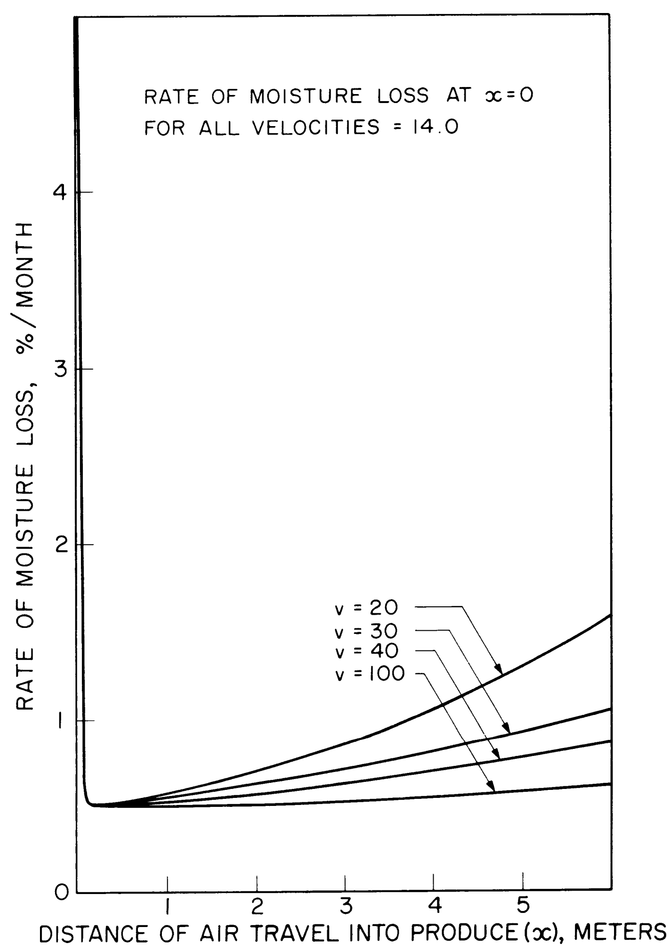

Fig. 1. Effect of air velocity (V, m/hr) on rate of moisture loss of stored produce (RH = 95%, temp = 0°C, at $x = 0$; for other boundary conditions see (11,14)).

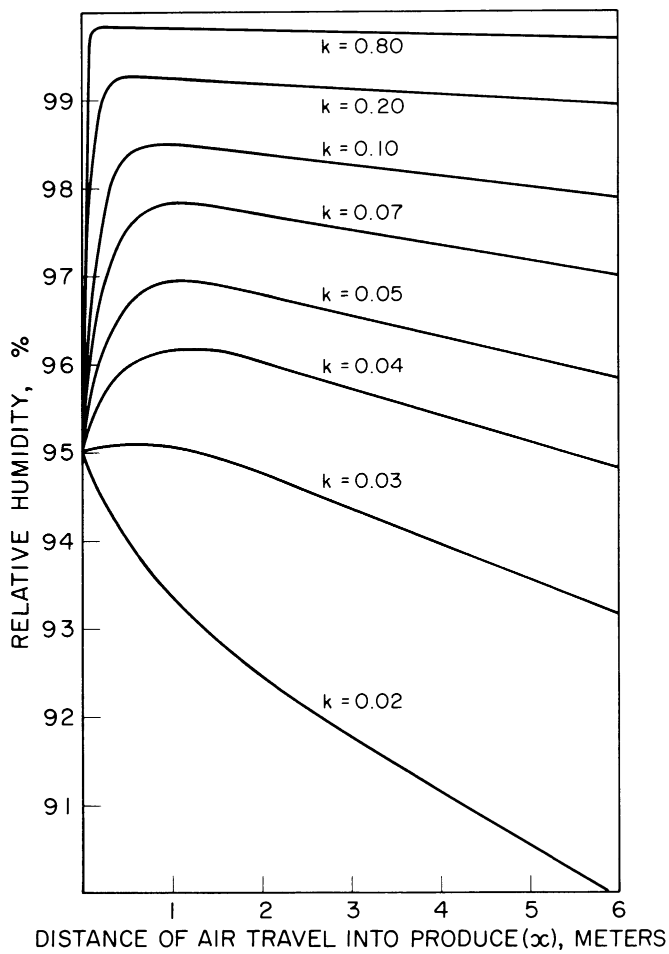

Fig. 2. Effect of transpiration coefficient (k, g/ hr. kg (g/m^3) on relative humidity variation in stored produce (RH = 95%, temp = 0°C, at x = 0; for other boundary conditions see 11,14)).

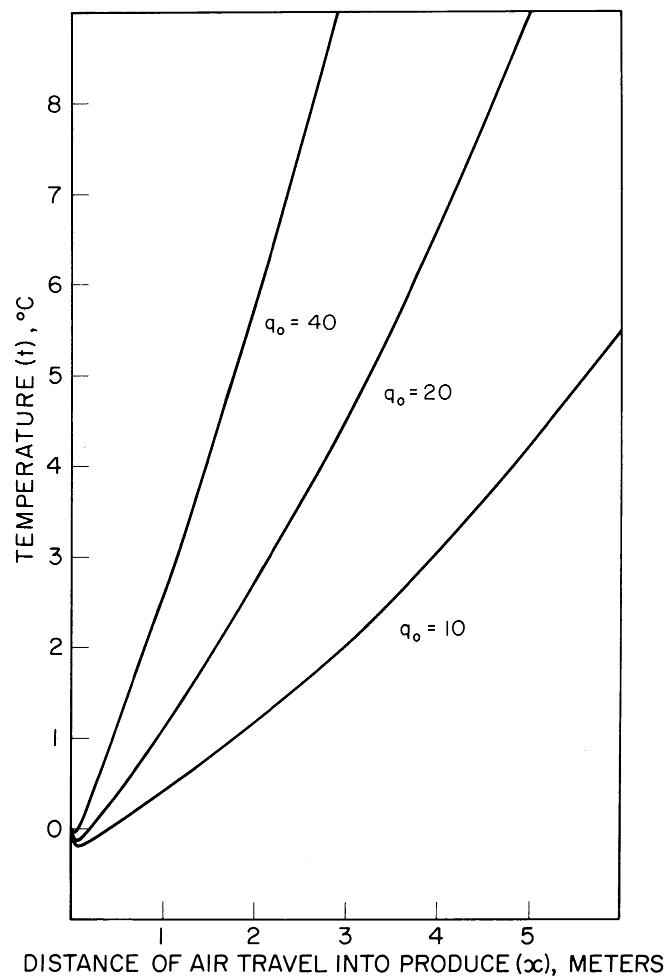

Fig. 3. Effect of heat of respiration (q_o, cal/kg. hr) on temp variation in stored produce (RH = 95%, temp = 0°C, at x = 0; for other boundary conditions see (11,14)).

vegetables are now in operation. These have a combined capacity of over 10,000 tons, and maintain 97-100% RH. They have so far been used mainly for carrots, cabbage and rutabagas (4,13). In addition, similar jacketed storages have been in use for controlled atmosphere storage of apples in Canada for many years (3). Several storages of another type, capable of maintaining up to 97% RH (5,16) are also in operation in Canada for the storage of cabbage, carrots and rutabagas, and similar storages are operating in the U.S. (16). Storage and handling of vegetables in plastic packaging, often resulting in humidity levels approaching saturation, has found widespread use to reduce weight loss and to improve quality for many vegetables without an appreciable increase in decay (2).

Temperature measurements in commercial jacketed storages have shown that temperature gradients during high humidity storage can be kept within acceptable limits, provided a reasonably open stacking arrangement is used, allowing access of room air to all sides of pallet boxes. Internal air circulation reduces temperature gradients and reduces rates of moisture loss further. Open construction of pallet boxes and an open stacking arrangement are necessary for fast precooling as well (12).

Conclusions

Results of extensive small and large scale laboratory tests and of commercial experience have shown that:

1. Decay of Brussels sprouts, cabbage, carrots, cauliflower, celery, Chinese cabbage, leeks, parsnips, potatoes and rutabagas, as well as of apples, during refrigerated storage at 98-100% RH was less than or about equal to that during storage at lower humidity levels.
2. Weight losses during storage at 98-100% RH were substantially less than during storage at lower humidities, particularly for those vegetables with a high coefficient of transpiration.
3. The reduced weight loss at the higher humidity level results in firmer, crisper and higher quality vegetables, and, in the case of leafy vegetables, substantially fresher color.
4. Optimum storage conditions for these vegetables therefore include an RH of 98-100%, as close to saturation as possible, such as can be obtained in jacketed rooms.
5. Temp gradient in vegetables during high humidity storage can readily be maintained within acceptable limits.
6. The reduced decay at 98-100% RH as compared to 90-95% for carrots and possibly several other vegetables is at least in part caused by a lower production of pectolytic enzymes by the pathogenic micro-organisms at the higher humidity level.

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