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# Impact of Desiccant Degradation on Desiccant Cooling System Performance

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# Impact of Desiccant Degradation on Desiccant Cooling System Performance

by

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## ABSTRACT

The performance of open-cycle desiccant cooling systems depends on several factors, some of which can change beyond manufacturers' specifications. For example, the desiccant sorption process may degrade with time on exposure to airborne contaminants and thermal cycling. Desiccant degradation can reduce the performance of a dehumidifier and thus the performance of desiccant cooling systems. Using computer simulations and recent experimental data on silica gel, the impact of degradation was evaluated. Hypothetical degradations of desiccants with Type 1 moderate isotherms were also simulated. Depending on the degree and type of desiccant degradation, the decrease in thermal coefficient of performance (COP) and cooling capacity of the system was 10% to 35%. The 35% loss in system performance occurs when desiccant degradation is considered worst case. The simulations showed that the COP, and to a lesser degree the cooling capacity of these degraded systems, could be improved by increasing the rotational speed of the dehumidifier. It is shown that easy engineering solutions might be available for some types of degradations.

## KEY WORDS

Adsorption, air conditioning, air cooling, contamination, dehumidification, desiccant, tobacco smoke, silica gel.

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## INTRODUCTION

Use of open-cycle desiccant cooling systems thermally regenerated with natural gas, solar energy, or other thermal sources is on the rise for air-conditioning purposes. In a typical desiccant cooling system, a desiccant dehumidifier removes the moisture (latent load) from the process air. Then the air is cooled to the desired conditions by a set of regenerative evaporative coolers or by vapor compression coolers. The desiccant material in a dehumidifier adsorbs (or absorbs) moisture from the process air to be dried. Later, the desiccant material is regenerated with hot air (generated by a thermal source) to drive the moisture from the desiccant for the next adsorption cycle. A desiccant may co-sorb pollutants from the air in addition to water vapor. Although the co-sorption may remove pollutants from the air stream and improve the indoor air quality (Hines et al. 1990), it may adversely affect the desiccant and reduce its useful life.

The service life of desiccant dehumidifiers for broad air-conditioning cooling applications is a concern of manufacturers and end-users. The service life of a dehumidifier depends mainly on the life of the desiccant material inside it. The useful life of a desiccant material depends on the process and magnitude of degradation, which can be caused by hydrothermal cycling or exposure to contaminants or both. Contamination and degradation may change the sorption properties of the desiccant, e.g., adsorption isotherm shape and magnitude, heat of adsorption, and moisture diffusion rate. Because these properties affect the performance of a desiccant cooling system (Collier 1989 and Collier et al. 1990), it is important to quantify the impact of desiccant degradation on system performance. The impact can be determined by experiments in the field and laboratory, computer system simulations, or combinations. The computer simulation provides a cost-effective approach for evaluating many desiccant degradation scenarios under a variety of operating conditions. However, without realistic desiccant degradation data, the simulation results can be meaningless.

In this study, we have used recently obtained degradation data on silica gel samples (Pesaran and Dresler 1990) in a system model (Collier 1989) to evaluate the impact of these silica gel degradations on system performance. Based on the observations from these recent experiments on desiccant degradation, hypothetical degradation scenarios are proposed for Type 1 moderate isotherm desiccants. They are then used in the system model to evaluate the impact of Type 1 moderate desiccant degradation. Note that desiccants with Type 1 moderate isotherm are considered the desired or optimum materials for desiccant cooling applications (Collier et al. 1990). These results can provide end-users with a perspective on desiccant degradation. An engineer may also use the results to design systems that are less susceptible to system performance degradation.

## EXPERIMENTAL DATA ON DESICCANT DEGRADATION

Recently, an experimental study has been conducted at the Solar Energy Research Institute (SERI) to obtain data on degradation of desiccants exposed to airborne contaminants and thermal cycling under controlled conditions (Pesaran and Dresler 1990). In this study, 200 samples of six different desiccants were exposed to either humid ambient air or humid contaminated air in a test facility. All the desiccant samples were cycled between warm and hot air streams to simulate the operation of a desiccant dehumidifier rotating (or switching) between warm adsorption and hot regeneration air streams.

Based on the recommendations of a desiccant contamination workshop, cigarette smoke, a mixture of gaseous and particulate contaminants, was studied as the first contaminant. The smoke concentration in a space depends strongly on the type of space, ventilation rates, and the smoking patterns of the occupants. All of these vary widely resulting in a hard-to-define smoke concentration level in a typical space. According to Wadden and Schiff (1983), the case of 5-425m$^3$ homes with 1 to 3 air change per hour and 7 to 35 cigarettes burned per hour represents the expected range of concentration in a smoking residence. The concentration of the "total particulate matter" of smoke in this case is 1.1 to 3.0 mg/m$^3$. We have selected twice the upper bound of this range as the highest concentration of "total particulate matter" of smoke to estimate the frequency of burning cigarettes in the test facility. We have injected smoke produced by burning 6 cigarettes per hour in a test cell with air flow rate of 20 cfm.

The desiccant samples were run in the test facility 24 hours a day for a number of months. Assuming that a dehumidifier works 8 hours a day for 6 months in a year and contaminant concentrations in the facility and in the field are the same, one month of testing in the facility is equivalent to six months of field testing. Taking into account the higher concentration of the contaminants in the test facility, one month of testing in the facility may be equivalent to 1 to 2 years of field experiment.

After 0.5, 1, 2, or 4 months from the start of the experiment, appropriate desiccant samples were removed from the facility and their sorption capacities were measured. Of the desiccants tested (silica gel, microbead silica gel, molecular sieve, activated alumina, activated carbon, and lithium chloride matrix), only typical results from silica gel will be presented in this paper. Pesaran and Dresler (1990) provide a detailed description of the results of the above study.

Figure 1 provides typical results of sorption capacity of silica gel (Davison, Grade 40) samples measured at 30.5°C (Pesaran and Dresler 1990). The figure shows capacities of a virgin sample, a sample thermally cycled for 0.5 month with ambient air, and a sample thermally cycled for 4 months with contaminated air. The capacity of the 0.5-month ambient sample is 5% to 20% lower than the capacity of the virgin sample. The 4-month contaminated silica gel sample has 30% to 70% lower moisture capacity than virgin sample. Pesaran and Dresler (1990) also observed that most of the capacity loss occurred in the first month of testing and that for microporous materials the capacity loss is larger at lower relative humidities. The data in Figure 1 were used in a computer model to obtain system performance degradations (see next section).

## SYSTEM ANALYSIS

This section presents the results of computer simulations to evaluate the impact of desiccant degradation on the performance of a ventilation desiccant cooling system under American

Refrigeration Institute (ARI) design conditions (see Table 1).

## Modeling

The system model used for this study was developed by Collier (1989). Collier's code simulates performances of a rotary dehumidifier, a heat exchanger, and an evaporative cooler for evaluation of desiccant cooling system performance. The dehumidifier model in Collier's code is principally based on the combination of the pseudo-steady-state model of Barlow (1982) and the finite-difference algorithm of Maclaine-cross (1974). Collier's code was validated with experimental data (Collier et al. 1989).

Table 1 summarizes the characteristics and conditions of the baseline system that is modeled. The physical dimensions of the studied dehumidifier are similar those of a dehumidifier tested at SERI. The rotational speed of the dehumidifier affects the outlet air temperature and humidity from the dehumidifier and therefore affects the performance of a cooling system. For a given desiccant, dehumidifier design, and operating conditions, the performance can be optimized by selecting an optimum rotational speed. The optimum rotational speed will be discussed later. It should be noted that the rotational speed is inversely proportional to cycle time between adsorption and regeneration processes. This cycle time can be applied to solid dehumidifiers with any configuration: rotating wheel, rotating drum, dual beds with switched air streams, or dual beds with switched beds.

Two types of desiccants were used for simulations: microporous silica gel with experimental degradation data and a desiccant with Type 1 moderate isotherm with hypothetical degradation scenarios. Simulations were conducted with and without staged regeneration for dehumidifier. Staged regeneration has been shown to be effective in improving the performance of the cooling system (Collier 1989 and Collier et al. 1990). In staged regeneration, the regeneration process consists of two stages. In the first stage, the air exiting from the warm side of the sensible heat exchanger is used for regeneration of the desiccant without adding external heat. In the second stage, the remainder of the air exiting the heat exchanger is used with additional external heat to regenerate the desiccant.

When a desiccant degrades, both the magnitude and the shape of its isotherm may change. According to Collier et al. (1990), the shape is the more important factor in changing the performance of the dehumidifier and the system. For all simulations in this paper, we assumed that the heat of the adsorption (as a function of moisture adsorbed) was the same for the virgin and degraded desiccants. Because the heat of adsorption has second-order effects on performance results (Collier 1989), the assumption about the heat of adsorption is expected to have minor effects on the results. The performance of desiccant cooling systems is usually defined in terms of two performance parameters: cooling capacity and thermal coefficient of performance (COP). The cooling capacity (CC) is defined as the amount of cooling (in terms of kJ or Ton) delivered by the system divided by the amount of air passing through the system (in terms of kg or scfm). The thermal COP is defined as the amount of cooling delivered by the system divided by the thermal energy input for regeneration of the desiccant dehumidifier. Here, we have assumed that the system pressure drop is independent of the type of desiccant or effects of degradations. Therefore, the electrical energy consumption was fixed for the specified air flow rate.

## Results Using Silica Gel and Without Staged Regeneration

The following silica gels were simulated: virgin silica gel (Davison, Grade 40), the silica gel exposed to the ambient air for 0.5 month, and the silica gel exposed to the contaminated air for 4 months. The 0.5-month ambient sample represents a "weakly degraded" silica gel and the 4-month smoked sample represents a "strongly degraded" silica gel. The experimental data for each desiccant were fit with a fifth-order polynomial for model simulations.

Figure 2 compares the results of the system simulations for the virgin and degraded silica gels and nominal parameters given in Table 1. The comparisons are made on a relative basis. The thermal COP and cooling capacity of the baseline system using the virgin silica gel were used to normalize the performance parameters. For the system with virgin silica gel, the COP is 0.80 and the cooling capacity is 18.4 kJ/kg at an optimum dehumidifier rotational speed of 12 rev/hr. This optimum value was obtained with the best combination of the highest COP and CC. Note that the maximum COP and maximum CC may not occur at the same rotational speed. From Figure 2, it can be observed that if the rotational speed of the dehumidifier wheel is kept constant at 12 rev/hr, the "weakly degraded" silica gel shows a decrease of about 11% in COP or CC, and the "strongly degraded" silica gel shows a decrease of about 28%. As expected, the performance degradation of the cooling system with "strongly degraded" silica gel is higher than with the "weakly degraded" silica gel.

It can be seen from Figure 2 that if the rotational speed of the dehumidifier is increased as the desiccant degrades, some of the loss in the thermal COP and cooling capacity can be recovered. This recovery is mostly in the COP. For example, if the rotational speed of the dehumidifier with "strongly degraded" silica gel is increased to 15 rev/ hr, the decrease in COP from baseline will be only 13%, which is lower than the 26% with 10 rev/hr. At 15 rev/hr the decrease in CC is 28%, very close to the 29% decrease with 10 rev/hr. An increase to 20 rev/hr for the "strongly degraded" desiccant will improve the COP to only a 7% decrease from the baseline COP; however, the CC will decrease to 31% (2% higher than with 10 rev/hr). This trend can be observed for other cases: increasing rotational speed decreases the loss in the COP from the baseline COP but may slightly increase the loss in CC.

We also investigated the effects of higher resistance to moisture diffusion in silica gel particles because of contamination and using a sensible heat exchanger with lower effectiveness. When the outer surfaces of a desiccant are affected by a contamination layer, the rate of moisture penetration to the desiccant decreased and affected the mass exchange process in the dehumidifier. The Lewis number or Le (the ratio of moisture-transfer resistance to heat-transfer resistance) is expected to increase as a result of contamination. A 200% increase in moisture diffusion resistance in silica gel particles (Le = 3) increases performance losses by another 3% to 9%.

The impact of the change in heat exchanger effectiveness was also studied. If a heat exchanger with effectiveness of 0.87 is used, the losses in the COP and CC are 2% higher for the "weakly degraded" desiccant and about 7% to 10% lower for the "strongly degraded" desiccant than in the baseline system with a 0.93 heat exchanger effectiveness. Further parametric study with silica gel without any staged regeneration is discussed by Pesaran (1990).

## Results Using Silica Gel and With Staged Regeneration

The performance of the ventilation cooling system as specified in Table 1 was simulated with staged regeneration at 95°C. The fraction of area for staged regeneration was 0.3 (i.e., external heat for regeneration was added in 30% of the area for regeneration process). The total air flow rate for the two regeneration zones was kept as 0.2 kg/s with only 30% heated to 95°C. The effects of moisture resistance and sensible heat exchanger effectiveness were also investigated.

Figure 3 compares the results of the system simulations for the virgin and degraded silica gels with staged regeneration. Figure 3 shows the normalized performance parameters with respect to the COP or CC of the system using virgin silica gel. The system with virgin silica gel and staged regeneration has a COP of 1.05 and a cooling capacity of 13.2 at an optimum dehumidifier rotational speed of 3 rev/hr. It should be noted that operating the same system at staged regeneration mode has changed the optimum rotational speed of the dehumidifier, increased the thermal COP (by 33%), and decreased the cooling capacity (by 33%) consistent with the trends of the parametric study of Collier et al. (1990). Figure 3 also presents the impact of increased moisture resistance in silica gel particles because of contamination or fouling. As in the case without staged regeneration, we assumed a 200% increase in moisture resistance or a Le number of 3. The following can be concluded if the rotational speed of the dehumidifier is kept fixed at 3 rev/hr for all silica gels:

- The "weakly degraded" silica gel shows a decrease of about 7% in COP or CC for Le of 1 and 16% and 13% decrease in COP and CC, respectively, for Le of 3.
- The "strongly degraded" silica gel shows a decrease of about 43% and 39% in COP and CC, respectively, for Le of 1 and a decrease of about 45% and 41% in COP and CC, respectively, for Le of 3.

As expected, the performance degradation of the cooling system with "strongly degraded" silica gel is higher than with "weakly degraded" silica gel. The increase in moisture resistance (increase of Le) has a larger adverse impact on performance for the "weakly degraded" than for "strongly degraded" silica gel. The performance degradation with staged regeneration using the "weakly degraded" silica gel is lower than with the case without staged regeneration. However, the performance degradation of the system with "strongly degraded" silica gel and with staged regeneration is higher than the system without staged regeneration.

Another observation from Figure 3 is that if the rotational speed of the dehumidifier is increased for "strongly degraded" silica gel, some of the loss in the thermal COP and cooling capacity can be recovered. For example, if the rotational speed of the dehumidifier with "strongly degraded" silica gel and Le = 1 is increased to 7.5 rev/hr, the decrease in COP from virgin baseline will be only 12%, which is lower than the 43% with 3 rev/hr, and the decrease in CC from virgin baseline will be 21%, which is lower than the 39% with 3 rev/hr. The same trend can be seen with Le = 3. No improvement in performance can be obtained for the "weakly degraded" silica gel by increasing the dehumidifier rotational speed.

Figure 4 compares the results of simulation with heat exchanger effectivenesses ($E_{hx}$) of 0.93 and 0.87 for virgin and degraded silica gels. It is a well known fact that desiccant cooling system performance decreases when heat exchanger effectiveness decreases. Using virgin silica gel, the COP and CC of a system with $E_{hx}$ of 0.87 are 0.74 and 10.1 kJ/kg, respectively. This COP is about 29% lower, and the CC is about 23% lower, than those of the system using virgin silica gel and $E_{hx}$ = 0.93. Our purpose here is to show the effects of desiccant degradation for systems with different heat exchanger effectivenesses, so the performance parameters on Figure 4 are normalized with respect to the performance parameters of virgin silica gel. On Figure 4, the COPs and CCs for the simulations with $E_{hx}$ = 0.93 are normalized with COP and CC of the system with virgin silica gel and $E_{hx}$ = 0.93 (i.e. COP = 1.05 and CC = 13.2 kJ/kg). The COPs and CCs for the simulations with $E_{hx}$ = 0.87 are normalized with COP and CC of the system with virgin silica gel and $E_{hx}$ = 0.87 (i.e. COP = 0.74 and CC = 10.1 kJ/kg). The following can be observed at the fixed rotational speed of 3 rev/hr:

- For the "weakly degraded" silica gel, the decrease in COP and CC is about 8% with $E_{hx}$ = 0.87 (similar to 7% decrease with $E_{hx}$ = 0.93).

- For the "strongly degraded" silica gel, the decrease in COP and CC is about 44% with $E_{hx}$ = 0.87 (slightly higher than 39% to 43% with $E_{hx}$ = 0.93).

Another observation from Figure 4 is that at other dehumidifier rotational speeds, the performance of the system with $E_{hx}$ = 0.87 is lower than that of the system with $E_{hx}$ = 0.93. This is particularly the case for the "strongly degraded" silica gel when the rotational speed is increased to 7.5 rev/hr to recover some of the degraded performance. The shape of the curves for "strongly degraded" silica gel is different than the shape of the virgin and "weakly degraded" silica gels. This is attributed to the change in the shape of the "strongly degraded" isotherm.

## Results Using Type 1 Moderate Isotherm Desiccant and Without Staged Regeneration

A Type 1 moderate isotherm with maximum moisture capacity of 0.4 kg water/ kg desiccant (shown on Figure 5) was simulated as the capacity for virgin Type 1 desiccant. Two hypothetical degradation scenarios were assumed: *linear loss* -- a fixed 40% loss at every relative humidity and *nonlinear loss* -- a varying loss which decreases with increase of relative humidity (loss factor = 0.6 - 0.4 * RH). These scenarios assume combined hydrothermal and smoke contamination degradations. The varying loss was hypothesized based on the observation of desiccant contamination experimental results (Pesaran and Dresler 1990) that loss in capacity because of contamination was higher at lower relative humidities. Figure 5 illustrates these two degradation scenarios.

The virgin and degraded Type 1 moderate desiccants in the baseline cooling system were first simulated without staged regeneration. The thermal COP and cooling capacity of the system with virgin desiccant was 0.7 and 21.6 kJ/kg-air at the optimum speed of 3.75 rev/hr. At this rotational speed the system with "linear loss" desiccant showed negligible loss in performance: less than 3% in COP and less than 4% in CC. The system with "nonlinear loss" desiccant showed about 10% loss in COP and CC. Upon increasing the rotational speed, loss in COP was recovered almost completely and the loss in CC was decreased to less than 3%. The effects of increased Le number and decreased heat exchanger effectiveness are under investigation.

## Results Using Type 1 Moderate Isotherm Desiccant and With Staged Regeneration

The virgin and degraded Type 1 moderate desiccants in the baseline cooling system were also simulated with staged regeneration. Figure 6 presents the results. The thermal COP and cooling capacity of the system with virgin Type 1 moderate desiccant and staged regeneration were 1.0 and 18.1 kJ/ kg-air at the optimum speed of 3 rev/hr. The performance parameters on Figure 6 are normalized with these COP and cooling capacity. Note that Type 1 moderate desiccant and staged regeneration provides the best combination of COP and cooling capacity among the four cases simulated.

It can be seen from Figure 6 that for the "linear loss" Type 1 moderate desiccant, the COP and CC have decreased by 12% and 9%, respectively, and for the "nonlinear loss" desiccant the COP and CC have decreased by about 5%. These were for fixed rotational speed of 3 rev/hr. Upon increasing the rotational speed to 5 rev/hr, loss in COP can be recovered almost completely and the loss in CC can be decreased to less than 3%. The effects of increased Le number and decreased heat exchanger effectiveness are under investigation. One interesting observation from Figure 6 is that the "nonlinear loss" desiccant performs better than the "linear loss" desiccant. This is because of the shape of the isotherms hypothesized for the "nonlinear loss" desiccant. The results of other isotherm shapes may be different. Actual degradation data need to be obtained for Type 1 moderate desiccants, after such materials are successfully manufactured, to determine the system performance degradations.

## CONCLUDING REMARKS

Using recent experimental data on degradation of silica gel, and a computer simulations, the impact of desiccant degradation was evaluated for a ventilation cycle. It was found that the loss in the thermal COP and cooling capacity depend on the degree of degradation and the type of regeneration. The degradation in performance was largest with "strongly degraded" silica gel and staged regeneration. A desiccant with Type 1 moderate isotherm was also simulated with two hypothetical degradation scenarios. With these degradations, Type 1 moderate isotherm desiccant showed a maximum of 12% loss in capacity. Actual degradation data on Type 1 moderate desiccant should be obtained. When realistic data on the degradation of desiccants are obtained and the impact of the degradation on system performance is quantified, the strategies to combat desiccant degradation will be evaluated. Among these strategies are:

- Filtering -- the pollutants are removed before entering the dehumidifier by some filter medium. This increases the pressure drop, decreases the cooling capacity due to air side pressure drop, and also adds to the initial cost.
- Replacing -- the degraded desiccant dehumidifier is replaced with a new one. This increases cost.
- Cleaning -- the degraded desiccant dehumidifier is removed, cleaned and installed back. This increases the maintenance cost.
- Deep regeneration -- occasionally the desiccant dehumidifier is regenerated at high regeneration temperatures to burn off contaminants. This will add cost and may adversely affect the desiccant performance.
- Adjusting operation -- the operating conditions of the cooling system (such as regeneration temperature and rotational speed of the dehumidifier) are adjusted during the course of operation.

Further investigation is required prior to drawing final conclusion on these strategies. However, the results of this study indicate that increasing the rotational speed of the dehumidifier can reduce the adverse affects of desiccant degradation. The magnitude of improvement depends on type of desiccant, type of degradation and method of regeneration. Future work should focus on obtaining experimental data on degradation of new desiccants, performing system calculations to obtain the impact of desiccant degradation upon a variety of operating and design conditions, and evaluating strategies to combat desiccant degradation.

## ACKNOWLEDGMENTS

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## NOMENCLATURE

| | |
|---|---|
| ARI | American Refrigeration Institute |
| CC | cooling capacity (kW/kg-air/s or kJ/kg) |
| COP | coefficient of performance |
| $E_{hx}$ | heat exchanger effectiveness |
| RH | relative humidity |
| Le | Lewis number |
| $Ntu_h$ | number of heat transfer units |
| cfm | cubic feet per minute |
| W | equilibrium moisture capacity |

## TABLE 1
## Baseline System Parameters and Conditions

| | |
|---|---|
| **Dehumidifier** | Matrix Density: 157 kg desiccant/$m^3$<br>Matrix Heat Capacity: 1960 kJ/kg K<br>Total Frontal Area: 0.49 $m^2$<br>Matrix Depth: 0.2 m<br>Passage Hydraulic Diameter: 2.3 mm<br>Total Transfer Area: 95 $m^2$<br>Adsorption or Regeneration Air Flow Rate: 0.2 kg/s<br>Adsorption/Regeneration: balanced flow and balanced area<br>Number of Heat Transfer Units ($Ntu_h$): 22.5<br>Process Lewis Number (Le): 1 |
| **Desiccants** | One of these desiccants:<br>- Virgin silica gel (Davison, Grade 40)<br>- Type 1 moderate isotherm desiccant with separation factor of 0.1 |
| **Regeneration** | 95°C air temperature |
| **Outdoor Conditions** | ARI rating point (1 atm., 35°C, and 0.014 kg moisture/kg air) |
| **Indoor Conditions** | ARI rating point (1 atm., 26.7°C, and 0.011 kg moisture/kg air) |
| **Sensible Heat Exchanger** | Effectiveness of 0.93 |
| **Evaporative Coolers** | Effectiveness of 0.95 |

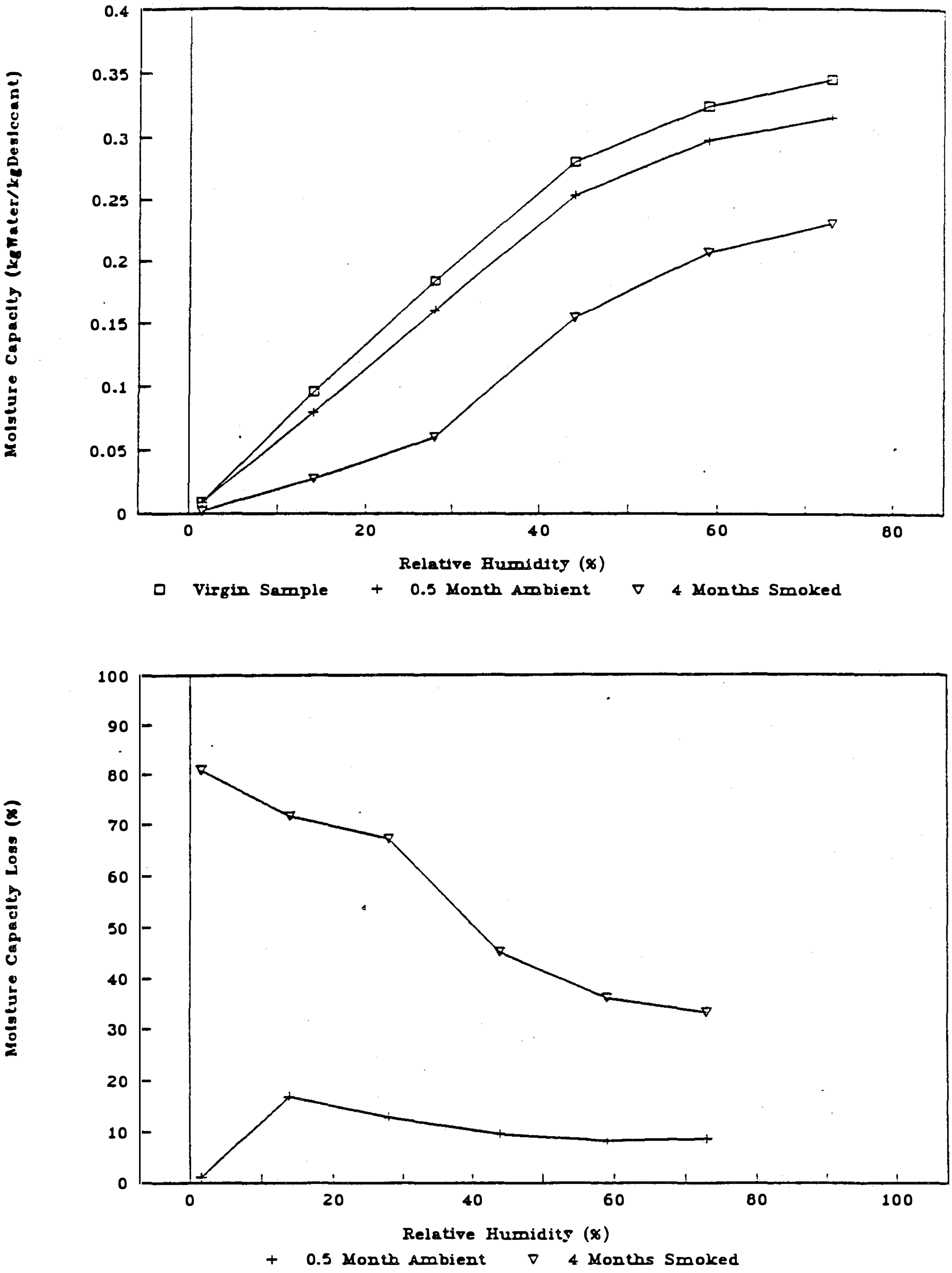


**Figure 1** Experimental Data on Moisture Capacity of Virgin and Degraded Silica Gel Samples at 30.5°C (from Pesaran and Dresler 1990)

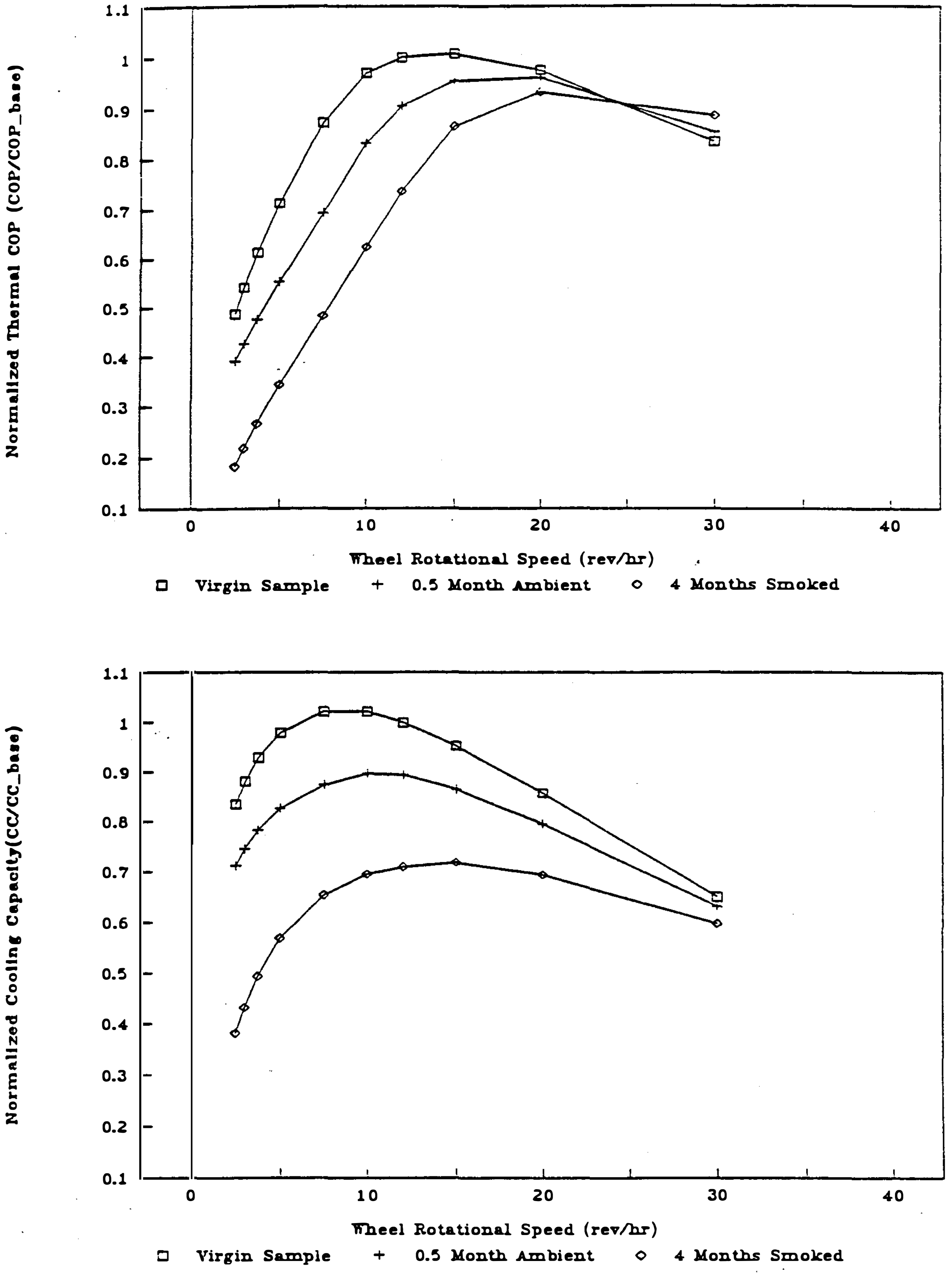


**Figure 2** Impact of Silica Gel Degradation on a Ventilation Desiccant Cooling System without Staged Regeneration ($Ntu_h = 22.5$, $Le = 1$, $E_{hx} = 0.93$)

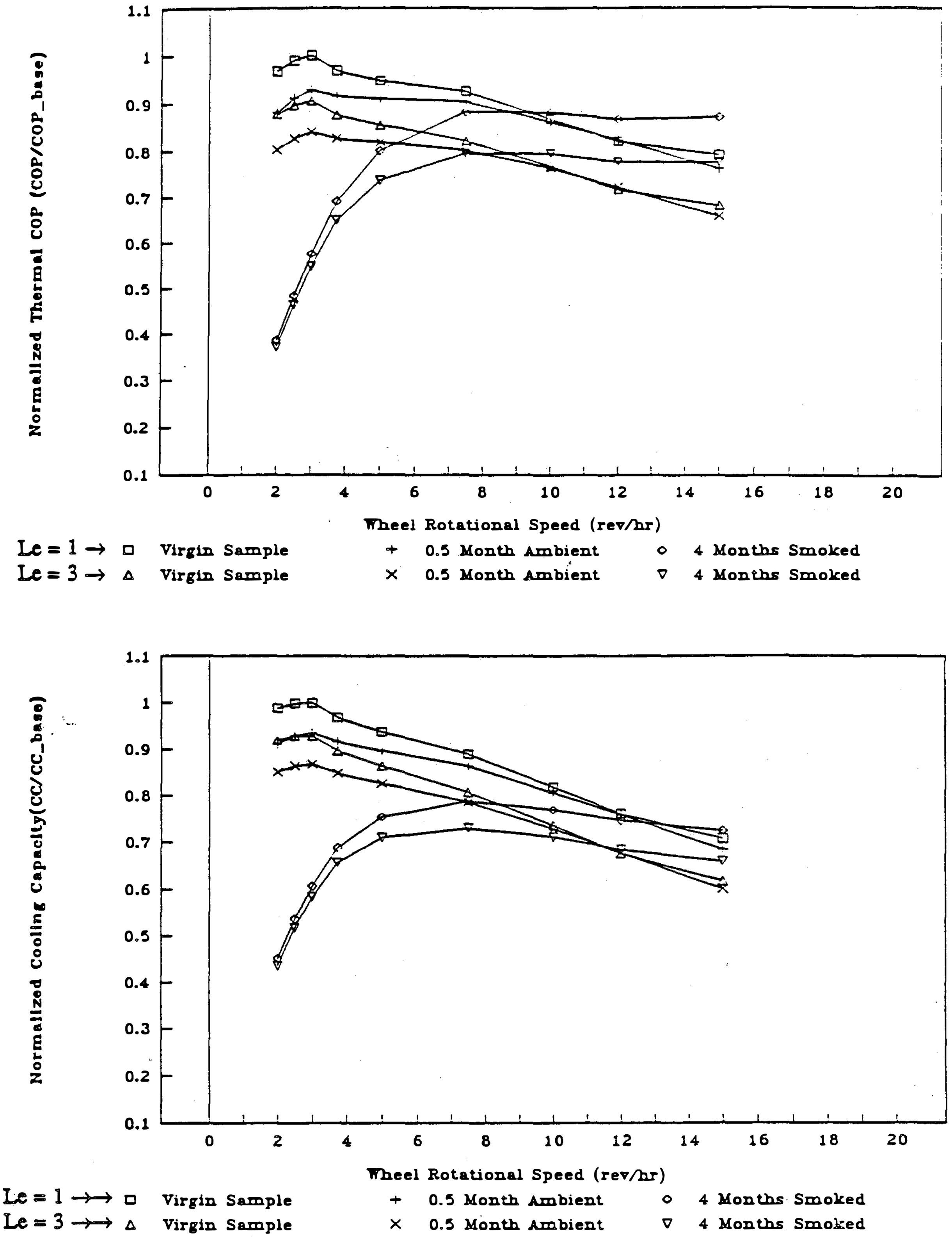


**Figure 3** Impact of Silica Gel Degradation on a Ventilation Desiccant Cooling System with Staged Regeneration ($Ntu_h = 22.5$, $Le = 1$ or $3$, $E_{hx} = 0.93$)

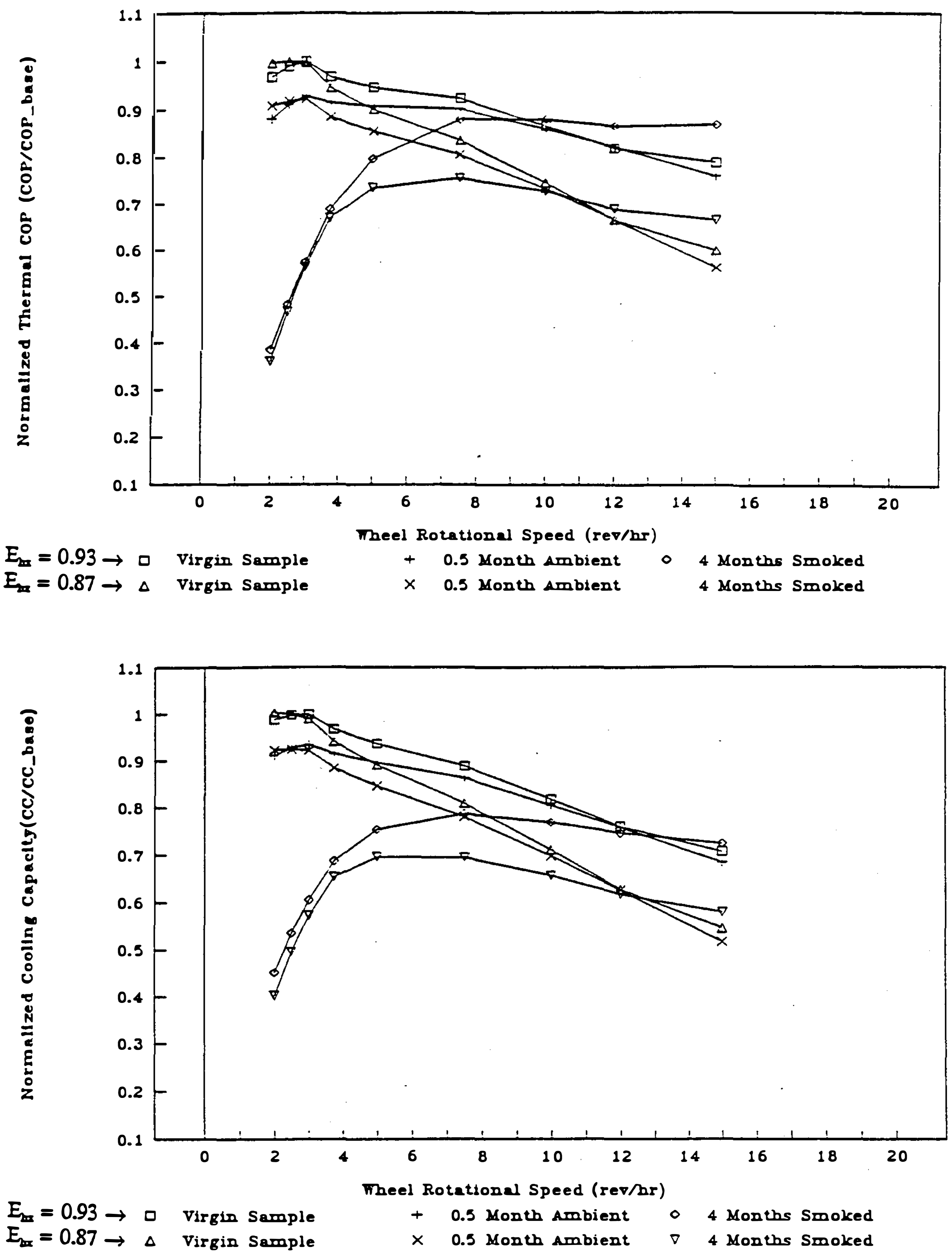


**Figure 4** Impact of Silica Gel Degradation on a Ventilation Desiccant Cooling System with Staged Regeneration ($Ntu_h$ = 22.5, Le = 1, $E_{hx}$ = 0.93 or 0.87)

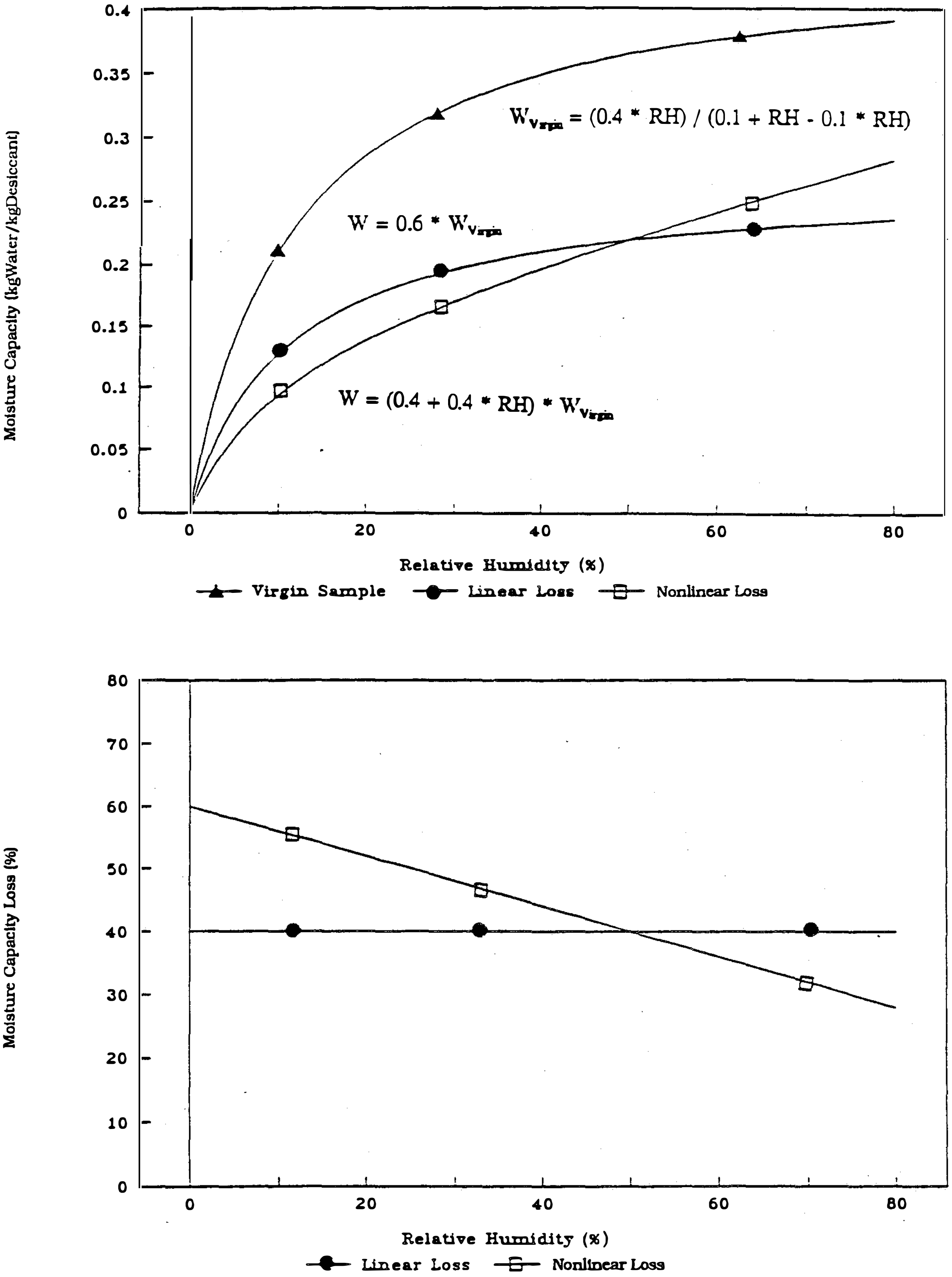
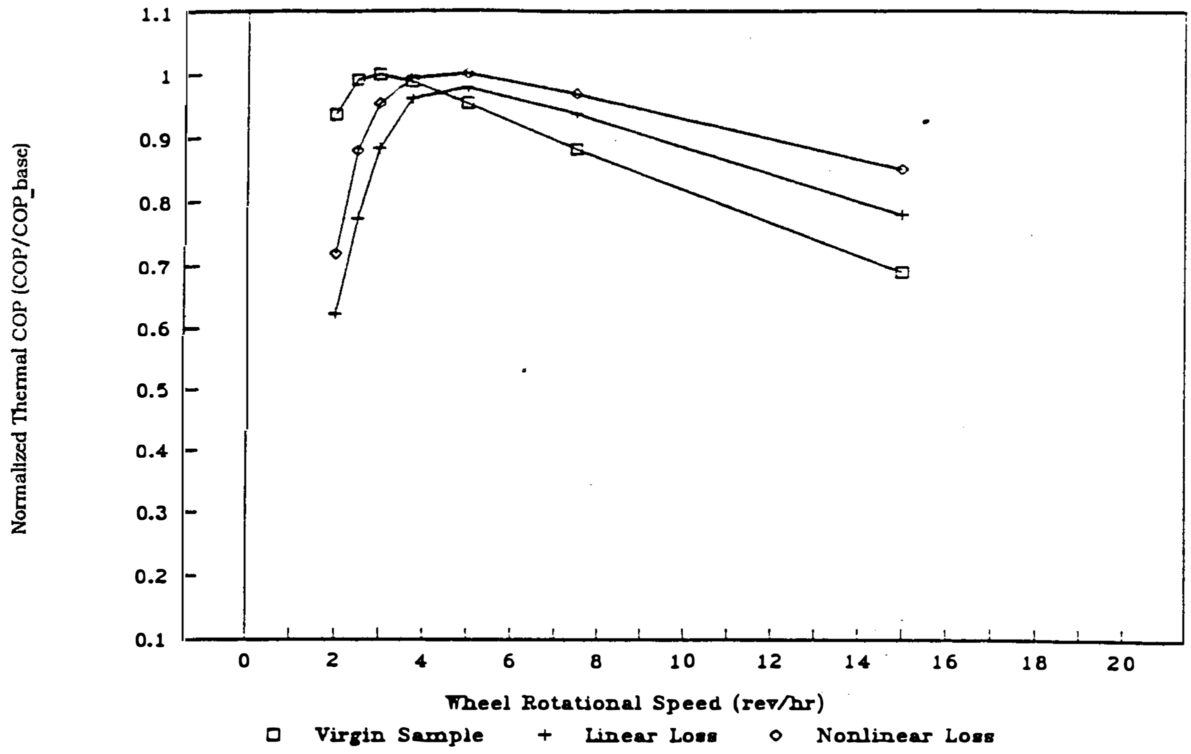


**Figure 5** Moisture Capacity of a Type 1 Moderate Isotherm: Virgin and with Two Hypothetical Degradation Scenarios



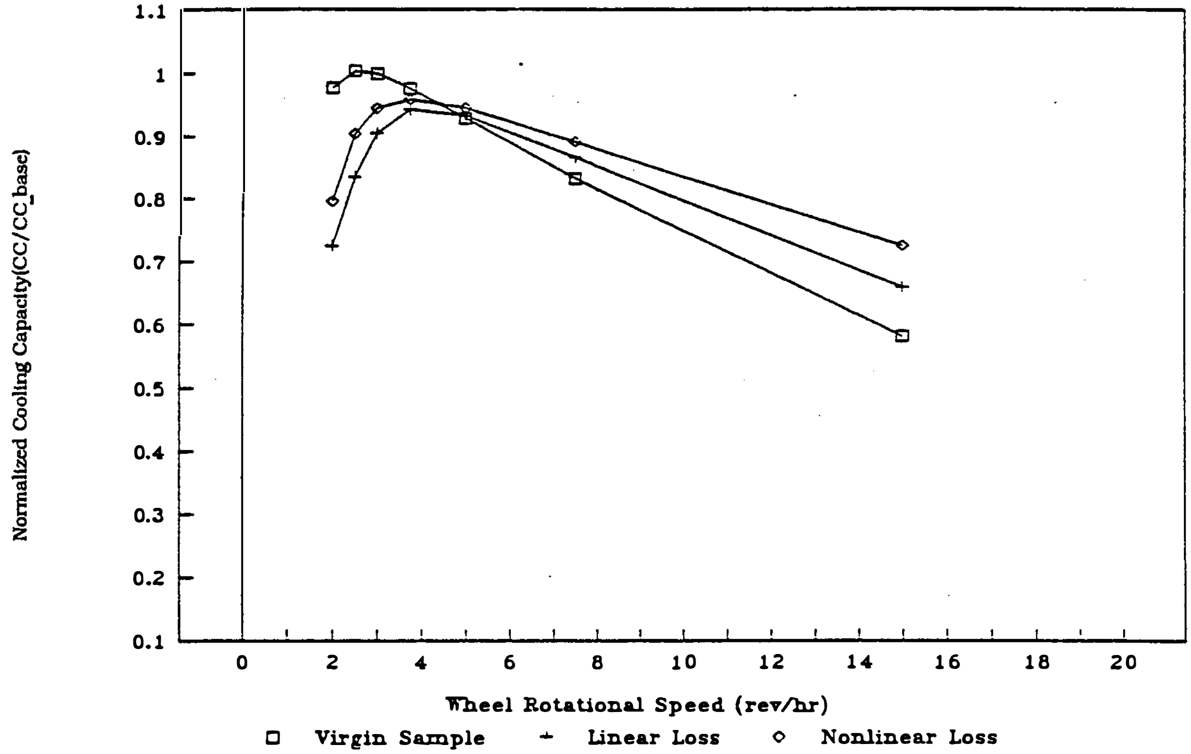


**Figure 6** **Impact of Type 1 Moderate Desiccant Degradation on a Ventilation Desiccant Cooling System with Staged Regeneration ($Ntu_h$ = 22.5, Le = 1, $E_{hx}$ = 0.93)**