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CRADA Final Report
for CRADA Number ORNL94-321

Moving Advanced Desiccant Materials into Mainstream Non-CFC Cooling Products

J. R. Sand
G. Grossman
C. K. Rice
P. D. Fairchild

(Principal Investigator)
Oak Ridge National Laboratory

Irwin L. Gross

Engelhard/ICC
(Fresh Air Solutions by Engelhard/ICC)

Prepared by the
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
managed by
Lockheed Martin Energy Research Corp.
for the
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Energy Division

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ABSTRACT

Desiccant air-conditioning systems can be used as alternatives for conventional air-conditioning equipment in any commercial or residential building. Recent breakthroughs in desiccant materials technology and the creation of new markets by Indoor Air Quality issues make desiccant-based air-conditioning equipment practical for many space-conditioning applications. Barriers to broad acceptance of this technology are (1) a perception of inefficiency from earlier research on desiccant space-conditioning systems; (2) lack of suitable "metrics" to comparatively evaluate desiccant-based system performance against conventional systems; and (3) absence of computerized algorithms that allow convenient incorporation of desiccant modules in heating, ventilating, and air-conditioning simulation programs used by evaluation and application engineers.

The purpose of this Cooperative Research and Development Agreement (CRADA) between Lockheed Martin Energy Research Corporation (Contractor) and Engelhard/ICC was to develop the enabling technologies that permit the widespread field application and successful commercial development of non-chlorofluorocarbon comfort conditioning systems based on advanced desiccant materials and desiccant air-conditioning methodologies.

As a result of this work, a flexible computer simulation model that allows construction and simulation of a composite, desiccant air-conditioning system from its basic components was developed and shared with the CRADA partner. Marketing studies were performed that identified target applications/markets for desiccant-based products. A draft test standard for regenerated desiccant systems was written, which can serve as the basis for product rating and certification standards. Also, a highly instrumented desiccant dehumidification test bed was built and installed at Oak Ridge National Laboratory, which can be used to verify results seen in field test site units, assess schemes for rating the performance of desiccant-based systems, and map the performance of systems in response to variations in fundamental design parameters and specifications.

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ACRONYMS

AC	air conditioning
ANSI	American National Standards Institute
ARI	Air-Conditioning and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BOCA	Building Officials and Code Administrators International
CRADA	Cooperative Research and Development Agreement
DB	dry bulb temperature
DBAC	desiccant-based air conditioning
ETS	Engelhard Titanium Silicate
HP	horsepower
HPDM	heat pump design model
HVAC	heating, ventilation, and air conditioning
IAQ	indoor air quality
ICBO	International Conference of Building Officials
MCWB	mean coincident wet bulb temperature
NTUs	number of transfer units
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
RBAC	refrigerant-based air conditioning
Rh or RH	relative humidity
SBCCI	Southern Building Code Congress International
SHRs	sensible heat ratios
TXV	thermostatic expansion valve
WB	wet bulb temperature

EXECUTIVE SUMMARY

Desiccant dehumidification technology is emerging as a technically viable alternative for comfort conditioning in many commercial and institutional buildings. Attempts to improve the indoor air quality of buildings has resulted in increasingly stringent guidelines for occupant outdoor air ventilation rates. Additionally, revised building heating, ventilating, and air-conditioning (HVAC) design criteria based on regional peak dew point data highlight the importance of the latent (moisture removal) building load relative to the sensible (temperature) building load. Desiccant-based air-conditioning equipment is ideally suited to efficient dehumidification of building ventilation air, and when used in combination with conventional, vapor compression, air-conditioning systems, indoor temperature and humidity can be controlled independently.

At present, there is no HVAC industry-accepted basis for adequately comparing the moisture removal efficiency of a desiccant system to that of vapor compression equipment. With the introduction of American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 62, ventilation rates are increased by a factor of 4 (from 5 to 20 ft^3/min per occupant) for most occupancy classifications. Under humid outdoor conditions, conventional electric vapor compression cooling systems will not be able to remove the moisture without first cooling the air below an acceptable comfort level and then reheating. This method would result in excessive energy requirements and higher utility demand charges. Utilizing desiccant systems to pretreat the air and remove moisture upstream of the conventional cooling system would enable conventional vapor compression systems to meet the new operating requirements without incurring severe energy penalties. The method of test resulting from this work is needed to compare the savings from using a desiccant system in conjunction with a conventional vapor compression system and to evaluate the moisture removal efficiency of the two systems.

Recent indoor air quality studies have shown that bioaerosols are a primary link to building-related illness, infections, toxic syndromes, and hypersensitivity diseases. By reducing these airborne microorganisms through the application of desiccant-based technology, outside air requirements may be reduced for some types of buildings, thus reducing energy requirements to condition the air.

The purpose of this Cooperative Research and Development Agreement (CRADA) with Engelhard/ICC is to develop the enabling technologies that permit widespread field application and successful commercial development of desiccant dehumidification systems for comfort conditioning

1. STATEMENT OF THE OBJECTIVES

Specific objectives anticipated as a result of Oak Ridge National Laboratory's (ORNL's) participation in this research and development work are

- characterization and verification of desiccant material, component, and system performance;
- development of practical laboratory and analytical methods for assessing desiccant system performance, which can be used in comparisons with conventional and alternative systems;
- identification of target applications and markets where desiccant technology has distinct, inherent advantages and is cost competitive with conventional systems; and
- establishment of the energy and environmental benefits of desiccant-based air-conditioning systems.

Air-conditioning equipment based on gas-fired, thermally activated technologies (absorption equipment and regenerated desiccant technologies) help alleviate the peak electrical demand experienced by power companies in the summer months.

A U.S.-based manufacturing, sales, and service industry is growing up around the application of desiccant products in *niche* markets. The industry requires these system simulation tools, advanced desiccant materials, and enabling technologies for sustained growth and expansion into broader based markets.

2. BENEFITS TO THE DEPARTMENT OF ENERGY (DOE) MISSION

This work supports DOE's goals of fostering energy efficiency and improving environmental quality in the building equipment area. Desiccant-based products appear to have a broad application potential for makeup air treatment in large buildings with a significant, associated energy saving benefit. Successful development and utilization of this technology has several advantages over chlorofluorocarbon (CFC)- or hydrofluorocarbon (HCFC)-based vapor compression equipment:

- Electric energy use and demand can be lowered with associated reductions in carbon dioxide emissions.
- Indoor air quality (IAQ) can be significantly improved.
- Use of fluorocarbon refrigerants can be reduced.
- New desiccant material advances and systems development can generate new U.S. products and export opportunities, which can foster creation of new jobs.

3. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

3.1 MARKET EVALUATION

3.1.1 Market Segments for Regenerated Desiccant Products and Target Markets

The unique potential of desiccant-based air conditioning (DBAC) has been documented in numerous places, most comprehensively in studies published by the National Renewable Energy Laboratory and ORNL.[*,†] A summary of advantages include

- significant potential for energy savings,
- reduction or elimination of ozone-depleting refrigerants,
- improved indoor air quality, and
- better control of humidity.

As with any technology, the market potential of DBAC is determined both by its capabilities and its pricing. A marketing report must integrate those two components into a structure that will allow trade-offs and the rationale behind those product choices to be understood. The DBAC systems are hybrids of traditional (fans, coils, air-handling boxes) and nontraditional components (desiccant and heat exchanger wheels). Because these components will ultimately become parts in systems, which also include air handling, refrigeration, and heating components, an accurate evaluation must be based on the size of that component market and the price of those components. This

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[*] A. Peseran, T. Penney, and A. Czanderna, "Desiccant Cooling: State-of-the-Art Assessment," NREL/TP-254-4147, October 1992, National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401-3393.

† John Fischer, "Active Desiccant Based Preconditioning Market Analysis and Product Development," ORNL/SUB-94-SV044/1, June 1999, Prepared by SEMCO for Oak Ridge National Laboratory, Oak Ridge, TN 37831-6070.

entails (1) an estimate of the size of the overall commercial market, (2) calculation of the value of DBAC in that market, (3) calculation of the price/performance points necessary to deliver the benefits of DBAC competitively with the refrigeration-based market standard, and (4) estimation of the portion of the overall market that can be served by DBAC components.

3.1.2 Currently Served Markets

Desiccant-based equipment has had a solid industrial market for decades. It is only within the past 5 years that the capability to handle latent load has been moved into the commercial marketplace. That advance has been through the targeting of specific market segments where the competitive performance advantages of DBAC systems are particularly significant. These specifically targeted markets and their estimated size in annual dollars are listed in Table 1.

Table 1. Estimated U.S. markets for desiccant air-conditioning products

	Segment size ($ million)		
Market	Low	High	Midpoint
Restaurants	80	100	90
Hotel/lodging	100	200	150
Health care	35	70	50
Supermarkets/convenience stores	50	100	75
Schools	200	400	300
Movie theaters	20	40	30
Midpoint total			695

Collectively, the size of HVAC sales in these segments is estimated to be between $485 million and $910 million annually in the United States. Each segment, except for schools, has a group of high-profile national and regional accounts, who for the most part are centralized in their buying decisions. Working directly with the accounts' headquarters will be critical to achieving broad-based trial and acceptance of DBAC on an accelerated basis.

3.1.2.1 Restaurants

Restaurants present a good application for desiccant systems for three primary reasons. First, they tend to possess low sensible heat ratios (SHRs). This low SHR is due to the high infiltration of outside air from the frequently opened doors, the dense occupation at peak times, and the latent load produced from food preparation. Second, most restaurant owners will naturally be very concerned with customer comfort, as repeat sales and large bills per visit are crucial keys to success in this market, especially in full service restaurants. A third factor favoring desiccants in restaurants is ventilation. With most restaurants exhausting out of kitchens, negative pressurization ensues, adding to the latent load, and generally straining HVAC systems. Additionally, restaurants have to contend with the ventilation problems of excessive food odor and cigarette smoke. ASHRAE 62-89 calls for dining rooms to provide 20 ft^3/min per person.

3.1.2.2 Hotels/lodging

Hotels constitute an appropriate market for desiccant systems because they have very high ventilation requirements due to their 24-h/d, 7-d/week operation, as well as their necessary attentiveness to customer comfort. Latent loads can be particularly high due to the moisture generated from bathrooms as well as the infiltration that results from bathroom exhaust fans' creating negative inside pressure. The problem is exacerbated by the fact that sensible demand is often not great, which causes system cycling, allowing moisture buildup, especially when fan coil units are still blowing in outside air (which is untreated). For newly constructed hotels held by code to ASHRAE 62-1989, the outdoor air requirement is 30 ft^3/min per room in bedrooms and 20 ft^3/min per capita in conference rooms.

There are three primary modes by which hotels introduce ventilation air to guestrooms. The most central and most easily controlled is through the building's duct system as part of the air handler supplying the rest of the hotel area. A cruder method is through the transfer of air from the corridors using positive pressurization. This is prohibited by code in some areas. The third method is through room units, most commonly through-the-wall fan coil units. These machines provide ventilation air, but are usually oversized (creating cycling in subpeak conditions) and lack a low enough SHR in most climates to remove sufficient latent load. When Engelhard/ICC systems, for example, are employed, providing makeup air through ductwork or from corridors, fan coil unit dampers can be shut; this allows these room units to operate exclusively on recirculated air and treat only sensible heat, which is much more efficient.

Market Dynamics: A 1988 survey by the American Hotel and Motel Association indicated that mold and mildew cost the industry $68 million annually in damage repairs and lost revenues. Seventy-six percent of respondents to the survey reported financial losses due to mold, mildew, and musty odors. Seventy percent of guests complained of stale smells, rust, and discolored wall coverings in their rooms. Excess moisture in building materials allows omnipresent fungal spores to grow. Besides destroying materials, mold and mildew emit aerosols, accounting for the often-reported musty odors and sometimes even generating allergic reactions. By keeping indoor air below 60% relative humidity (RH), moisture absorption by building materials is largely prevented, precluding the growth of mold and mildew. Positive pressure must be maintained to prevent infiltration of moisture from outside air.

There are 45,000 hotels and more than three million hotel rooms in the United States Seventy-five percent of the rooms belong to the top 25 hotel chains. Data from the Census Bureau (September 1995 year-to-date Construction Report) indicate that Texas, Florida, Georgia, and North Carolina rank among the top five states in new hotel construction. These areas are among the most humid in the United States. Overall, the estimated amount spent on HVAC equipment in the hotel segment is $120 million annually.

3.1.2.3 Hospitals/nursing homes

There are several factors that make hospitals and nursing homes very good applications for desiccant systems. First is the high requirements put forth in ASHRAE 62-89: 25 ft^3/min/person in patient rooms and 30 ft^3/min/person in operating rooms. This is particularly challenging for hospitals and nursing homes from an operating cost perspective, since near-capacity occupation occurs for 24 h/d, 365 d/year.

In addition to this requirement, hospitals are very concerned with nosocomial (institutionally acquired) infection caused by airborne microorganisms. An estimated 2 million infections are acquired in U.S. hospitals yearly. This concern may cause hospitals to exceed the ASHRAE cubic feet per minute standards and/or to put extra care into maintaining lower RH, since microbial proliferation is most pronounced at RHs exceeding 60%. Indeed, 62-1989 states that "Relative humidity in habitable spaces preferably should be maintained between 30% and 60% to minimize growth of allergenic or pathogenic organisms." ASHRAE 62-89 also makes the claim that if "relative humidity in occupied spaces and low velocity ducts and plenums exceeds 70%, fungal contamination can occur." The humidity remediation challenge that ensues with high quantities of outside air is especially pronounced in operating rooms, where low RHs, which are often required by local codes, need to be achieved with dry bulb temperatures that are generally in the mid-60s.

A recent study published in the *New England Journal of Medicine* examined the effect of cold room temperatures during surgery on a patient's postoperative recovery. A patient's body temperature often cools down during surgery to about 94.5°F. The study states, "Being cold inhibits the body's defenses against germs. It decreases blood flow to the skin, lowering the supply of oxygen, which is necessary to fight infection. Cold also interferes with blood clotting; warm patients bleed less."

The study conducted by Daniel Sessler, an anesthesiologist at the University of California at San Francisco, studied 200 patients having surgery either in the typical chilly way or by being kept warm (with the assistance of blankets). He says, "Six percent of the warmed patients developed wound infections during their recovery, compared with 19 percent of those who had gotten cold. The warmed patients also healed faster."

Regarding microbial control, there is another potential benefit of DBAC systems. Although the causal mechanism has not been identified, desiccant systems have consistently been shown to directly reduce bacterial and fungal levels of the air passing through them. The 1992 *ASHRAE Handbook* (22.7) states:

> In addition to preventing the growth of mold, mildew, and bacteria through keeping buildings dry, desiccant systems are used to supplement filters to remove bacteria from the air itself... The utility of certain liquid and solid desiccants in such systems stems from their ability to either kill microorganisms, or to avoid sustaining their growth.

Market Dynamics: Hospitals are also good targets for DBAC because they tend to be energy-conscious and more life-cycle than first-cost driven. There are approximately 6,700 hospitals in the United States, of which 4,800 have at least 100 beds. There are approximately 3,500 nursing homes in the United States, containing about 400,000 beds. With people living longer, elder care facilities are expected to be a long-term growth market. The projected construction expenditure on health care facilities in the United States for 1995 is $2.1 billion. The states spending the most on construction in 1995 are Illinois, Texas, Florida, Louisiana, and Pennsylvania. The estimated size of the HVAC market in health care is $75 million.

While most health care facilities are independently owned and operated, there are several companies managing multiple sites. These organizations offer the best path to repeat sales in the health care segment.

3.1.2.4 Supermarkets/convenience stores

Supermarkets represent the most accepted application of desiccant air conditioning. The typical scenario involves targeted distribution of a mixture of makeup and recirculated air to the frozen and refrigerated food aisles of the store. There are several key benefits. First, the low humidities allow the food to avoid sweating and frosting, which extends product life. Secondly, product appearance is enhanced due to this lack of sweating and frosting, both on the food and on the cases. A third benefit to the store is that these aisles are kept at warmer, more comfortable temperatures, which encourages more buying, especially in the summer when conventionally dehumidified stores regularly chill scantily clad customers. The final major benefit to supermarkets is the energy savings that accrue through avoiding dehumidification and reheat by conventional equipment. Not only is this mechanical handling of the latent load expensive, per se, but the frequency of the defrost cycles, due to higher dew points in comparison with stores using desiccants, introduces another substantial cost increase.

Targeted distribution by desiccant systems fits well with conventional rooftops that can provide the sensible cooling required by other sections of the store. Regeneration through rack waste heat is another potential synergy. One big obstacle in supermarkets is the high first-cost sensitivity of owners. Margins are very slim in the industry, and thus cash flows can present a problem.

Market Dynamics: There are 31,000 supermarkets in the United States; 13,000 are independent, and 18,000 are chain-owned. Total grocery sales from this group are close to $300 billion. Additionally, there are 52,000 other grocery stores and 71,000 convenience stores in the country.

3.1.2.5 Schools

Schools represent an excellent and growing application for DBAC systems. IAQ, as an issue, is perhaps emotionally strongest in the school segment because children are involved. Children's immune systems are not yet conditioned for harsher environments, and thus are more affected by air pollution than adults. The school segment is most at risk of IAQ lawsuits because (1) children are involved (high propensity to get sick, and parents feel extra concerned for their children's health and safety); and (2) schools are predominately public facilities. Fifteen thousand schools with 7.9 million students reported having some IAQ problem. Another 6,000 schools with an additional 3.7 million students reported having ventilation problems.

Schools have high latent loads due to the frequency with which doors are opened and density of room occupation. People in a densely filled environment emit a lot of body heat. ASHRAE 62-89 requires 15 ft^3/min/person of outside air, a 200% increase over ASHRAE 62-81. Classrooms have a high occupancy rate, as much as 30 people per classroom, necessitating 450 ft^3/mins of outside air brought into the room.

Market Dynamics: Approximately 65 million students attend primary and secondary schools in the United States. There are more than 14,800 school districts/buying units broken down as follows: public (9,000+), private (2,200), and universities (3,640). Of the space in new high schools and elementary schools, 82% and 87%, respectively, are air conditioned.

In 1993, more than $63 billion was spent on facility and building upgrade and modifications. Schools built in the 1960s and 1970s have an average life of 20 to 30 years. Years of deferred maintenance, flawed designs, and cheap construction have led to general building deterioration. Unfortunately, many districts that are in the greatest need for improvements to their HVAC systems are the ones that can financially least afford to make the upgrades. Many districts in cities like New York, Chicago, and New Orleans go without air conditioning all together. Schools in these districts suffer major structural damage, often caused by neglect, overcrowding, and delayed maintenance and repair.

Three demographic trends suggest the need for better indoor air management systems: (1) the greatest growth pressures on school districts with most acute heat and humidity problems. The domestic population is migrating and growing the most in the Southeast (Florida, Carolinas, Georgia) and south central (Texas). For example, Dade County, Florida (the nation's fourth largest school district) has experienced a 44% growth in the past 10 years and expects the growth rate to continue for the next 10 years. (2) The next baby boom: U.S. school age population is expected to increase by 19% over the next 10 years and 33% between now and 2030. This will require more and bigger schools to be built to meet the demand. (3) Year-round schedules are being instituted by many districts as a way of easing overcrowding. This will place a greater demand on the school's HVAC system to meet higher sensible and latent loads. At the same time, schools will lose downtime for maintenance and upgrading facilities and HVAC systems.

3.1.2.6 Movie theaters

Theater owners have a difficult time creating a comfortable environment for their patrons, especially in warm humid areas. People in a densely filled theater emit a lot of body heat. At the same time, because the people are rather sedentary, they are much more susceptible to cool clammy conditions than in other indoor environments. The absence of heat generated by lighting fixtures, to offset the cool conditions generated by the air conditioning, further exacerbate the patron's comfort levels.

The above scenario makes theaters a good niche opportunity for desiccant systems. DBAC is able to address the issue of dehumidification without having to significantly cool the air, creating a more comfortable environment for the theater attendee. Theaters will experience the residual benefit of increased revenue from ticket sales, as patrons are more likely to go to the theater, and from sales of high margin concessions at the theater. A desiccant system, such as Engelhard/ICC's Desert Cool handles fresh, even humid outside air without compromising on efficiency the way refrigeration-based equipment does.

Market Dynamics: Despite the growth of cable TV and the home video market, people still go to the movies. U.S. attendance at movie theaters exceeded 1.2 billion people in 1993. At the same time, attendance has remained healthy; the number of theaters keeps increasing. In 1993, there were approximately 6,000 theater locations containing almost 25,000 screens. The number of screens has risen 25% in a mere 7 years.

The theater category is the smallest in terms of air-conditioning equipment sales of the targeted applications. The size of the air-conditioning equipment sales is estimated at $30 million annually. While there are hundreds of small independent theater operators, the growth in the industry is being driven by large chains. In 1993, the top 15 chains accounted for 57% of all U.S. indoor theater screens. It is these chains that are most likely to set up the large multiplex entertainment complexes.

3.1.3 Market Potential

As Table 2 indicates, the worldwide market for commercial air conditioning in 1991 was $7.8 billion. This includes buildings served currently by a wide variety of air-conditioning systems, including chillers, packaged rooftop equipment, split systems, and various types of air-handling systems. Desiccant and heat exchanger wheels, when packaged correctly, can be integrated with the full range of air-handling systems to displace refrigeration tons from chillers and compressors in a wide variety of equipment. The present mix of products from DBAC manufacturers only addresses a portion of that market.

Desiccant systems are best suited to dealing with the latent (moisture removal) portion of the building air-conditioning load. An estimate of the size of that latent load percentage is shown in Fig. 1.

Using this logic, the size of the market for desiccant and heat exchanger wheels (independent of the energy recovery market) amounts to 25–40% of the refrigeration market described above, or 16.5% of the total commercial market. Latent air-conditioning market estimates are given in Table 3. Units that incorporate wheels into packaged and air-handling equipment and integrate them with refrigeration components would have a much larger market.

Table 2. World commercial air-conditioning market

	1991 Market ($ million)					
	North America	Japan	Australia/ Asia	Europe	Latin America	Total
Commercial applied	$770	$1,038	$588	$1,865	$88	$4,349
Commercial unitary	$1,327	$1,263	$325	$545	$84	$3,544
Total	$2,097	$2,301	$913	$2,410	$172	$7,893

Source: DRI/McGraw Hill.

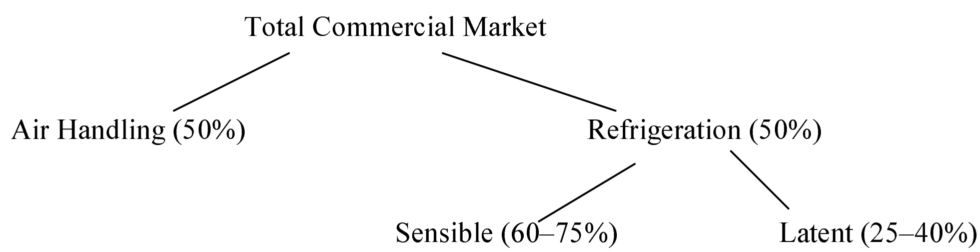

Fig. 1. Assumptions used in calculating latent market.

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Table 3. Latent portion of commercial air-conditioning market ($ million)

	North America	Japan	Australia/Asia	Europe	Latin America	Total
Commercial applied	$127	$171	$97	$308	$15	$718
Commercial unitary	$219	$208	$54	$90	$14	$585
Total	$346	$379	$151	$398	$29	$1,303

3.1.4 Current Market Drivers

The existence of DBAC-based equipment alone is likely to provide a reason for end users to consider supplementing their air-conditioning equipment with desiccant-based equipment. There are several drivers, which are forcing end users to look for different approaches. Those drivers are indoor air quality (and its regulation) and humidity. Figure 2 illustrates the impact that recent changes to the ventilation code and recent improvements in the understanding of effects that humidity loads have on building loads. Essentially, in the case of restaurants, the recent changes have nearly tripled the latent load per square foot of store area. This combined impact has forced users to reevaluate their systems at a time when DBAC equipment is just beginning to become commercial.

3.1.4.1 Indoor air quality

ASHRAE Standard 62-1989, "Ventilation for Acceptable Indoor Air Quality," has a number of requirements and recommendations with which the HVAC industry is struggling to comply. The primary prescription outlined is to increase the amount of ventilation (fresh) air delivered to occupied spaces (Table 4). Refrigeration-based cooling has a difficult time efficiently handling the high latent loads in fresh air over a large part of the country, especially with packaged equipment. That latent load, if not adequately treated, creates conditions where mold and mildew flourish.

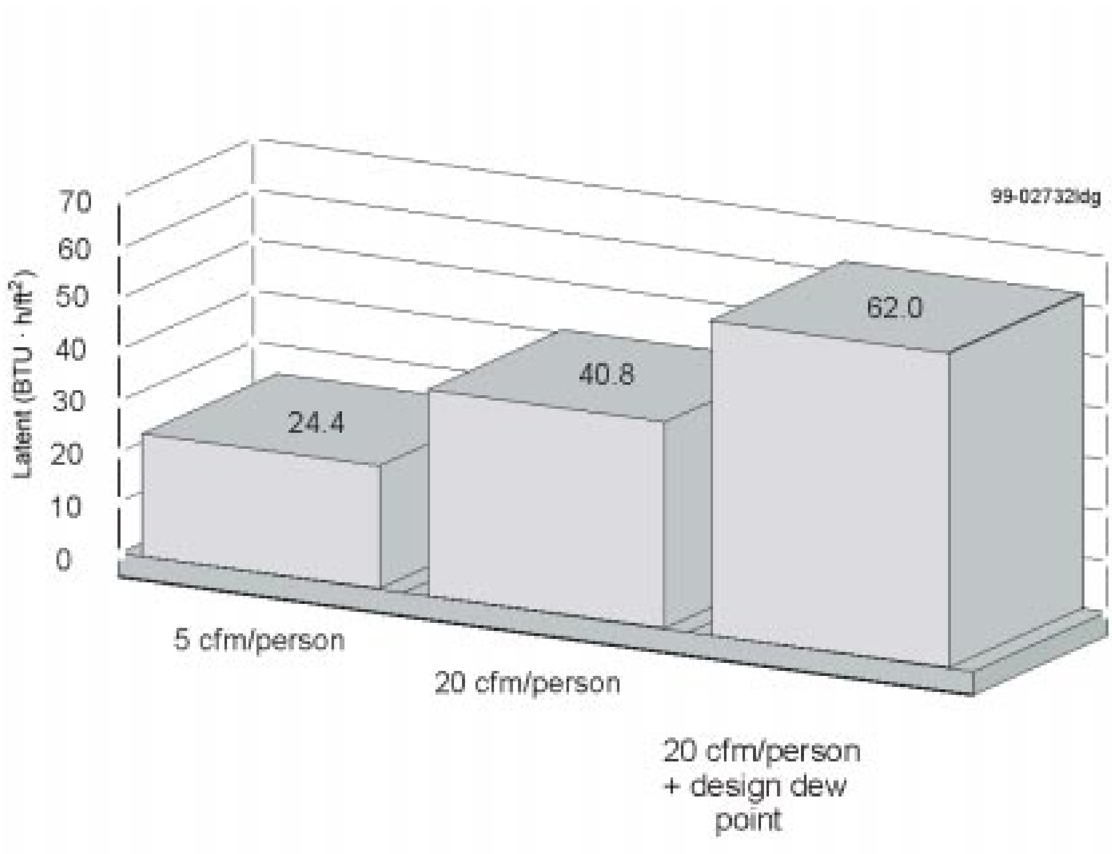

Fig. 2. Restaurant latent loads.

Major requirements and recommendations of ASHRAE Standard 62-1989 affecting ventilation and humidity can be summarized as follows:

1. Acceptable air quality is to be achieved by providing ventilation air of the specified quality and quantity to the space. The specified quantity averages nearly 20 ft^3/min/person (see Table 4), compared with an average of 5 ft^3/min/person in the previous standard.
2. Humidity can support the growth of pathogenic or allergenic organisms such as fungi, mycotoxins, and dust mites. RH in habitable spaces should range between 30% and 60%. RH above 70% in spaces, ducts, or plenums can allow fungal contamination to occur.

Table 4. Comparative ventilation standards

Application (commercial facility)	New ASHRAE 62-1989 (ft^3/min/person)	Old ASHRAE 62-1981 (ft^3/min/person)
Health care (patient)	25	7
Food (dining rooms)	20	7
Food (fast food/cafeteria)	20	7
Food (kitchen)	15	10
Hotel (conference room)	20	7
Hotel (bedroom)	30	15
Theaters (auditorium)	15	7
Theaters (lobby)	20	7

3.1.4.2 Regulatory environment

The ASHRAE Standard is important in that the bodies responsible for regulating such things have adopted its recommendations. As shown in Table 5, there are three major building codes in the United States. The International Conference of Building Officials (ICBO) publishes the Uniform Building Code (U.B.C.); the Southern Code Building Congress International (SBCCI) publishes the Standard Building Code (S.B.C.); and the Building Officials and Code Administrators International (BOCA) authors the National Building Code (N.B.C.).

Table 5. U.S. code jurisdiction

Code	Primary territory covered	Level of adoption of ASHRAE 62-89
BOCA	Northeast	Adopted the outdoor air ft^3/min ventilation standards from Table 2 of ASHRAE 62-89 in their 1993 N.B.C.
SBCCI	Southeast United States	Adopted 62-89 fully (1991 S.B.C.)
ICBO	Western/Central United States	Included 62-89 as a nonbinding appendix

3.1.4.3 Regulatory direction regarding IAQ

ASHRAE Standard 62-89 is being revised, and it seems that the new version will be tighter and more forceful regarding RH, will designate clearer liability for IAQ problems, and may be applicable to more than just new commercial construction.

There is pending IAQ regulation from the Occupational Safety and Health Administration (OSHA) that would institute a mandatory written IAQ compliance program for all businesses. As the regulations have been proposed, RH readings above 60% in required routine inspections would mandate that maintenance and/or additions be performed on the building's HVAC system. Federal regulations preempt any local dictates; the OSHA rules, if adopted, would not be subject to any local modifications in the way that the building codes are. Though no immediate action is expected from this effort, it does indicate a regulatory direction that should not be ignored.

3.1.4.4 Humidity control

In the 1997 *Fundamentals Handbook*, ASHRAE published the 1%, 2.5%, and 5% occurrences of extreme dew point temperatures and mean coincident dry-bulb temperatures. This study relied on data from the U.S. Weather Service and chose absolute humidity levels across the United States up to 25% higher than the design humidity levels supported by ASHRAE previous to that time. As this new information becomes available, engineers will need to design HVAC systems with a higher standard, reflecting air-conditioning loads calculated with lower SHRs. This design change requirement moves the entire HVAC playing field toward desiccant-based products.

3.1.4.5 Actual building loads

There is growing understanding in the HVAC world that humidity loads are of greater significance than current load calculation methodologies take into consideration. The ASHRAE 1%, 2.5%, and 5% design dew point data mentioned above reviewed hourly weather data over 30 years for 143 cities in the United States. and Canada. Absolute humidity levels were calculated in the same manner as ASHRAE has been calculating design bulb temperatures for many years.

These data show that the actual air-conditioning loads to which buildings are exposed are far higher in humidity than would be estimated using standard dry bulb/mean coincident wet bulb (DB/MCWB) methodology, and they have peak humidities and peak temperatures at different times of the day.

From these data, it is clear that humidity is far more than an incidental component of air-conditioning loads throughout much of the world. In fact, humidity is often as important as heat in the sizing and design of mechanical systems.

In both cities shown in Table 6, as well as most other cities sampled, the absolute ventilation load is higher at the design humidity point than at the design temperature point. This high load, at an SHR that is often below 0.20, is a very difficult load for refrigeration-based equipment to handle.

Table 6. Sample U.S. ventilation loads

Peak ventilation loads	Design temperature method (DB/MCWB)	Design humidity method (DB/MCWB)
Baltimore		
Total, Btu·h /1000 ft^3/min	40,080	45,360
Sensible	59%	19%
Latent	41%	81%
Oklahoma City		
Total, Btu·h/1000 ft^3/min	44,480	49,720
Sensible	61%	15%
Latent	39%	85%

When ventilation loads are applied to buildings, it is clear that they have a dramatic influence not only on the size of the building load, but also on its makeup. What is most striking is at the design dry bulb, the sensible load only makes up 63% of the total load. Of that total load, 50% is generated by people and ventilation. Because of that makeup, it is extremely difficult for 75 tons of conventional packaged rooftop air-conditioning equipment to handle what is nominally a 75-ton load.

Design point, by definition, occurs less than 250 h/year. What about the rest of the year? Compiling U.S. Air Force weather bin data into monthly hours of dehumidification and cooling shows patterns that are often disregarded by standard load analyses. In most cities, the number of hours in which ambient conditions impose a humidity load on a conditioned space is twice as high as the number of "cooling hours."

Not only do peak sensible and latent loads deviate depending on the calculation method utilized, they also tend to peak at different times of the day. Figure 3, from a typical summer day in Florida, clearly illustrates how weather affects the air-conditioning load in a space.

Daily temperature and humidity cycles affect buildings in a predictable way. Figure 3, from a sample building in Florida, shows highly variable sensible loads, peaking in the late afternoon. The latent load, on the other hand, remains consistent throughout the operating day. This combination leads to a building SHR that varies between approximately 0.48 and 0.6.

Active humidity control equipment, sized to handle the consistent latent load, can allow conventional cooling equipment to be sized and operated efficiently to match the sensible load.

3.2 PRICE/VALUE EVALUATION

The metrics of DBAC are somewhat different than those of refrigeration-based air conditioning (RBAC) and must be understood to accurately value the equipment. While the IAQ and comfort benefits described above are meaningful in the marketplace, their value is difficult to quantify. For that reason, we will take them out of the equation here in order to develop competitive price points.

It is quite clear that the HVAC market places a limited value on operating cost reductions at the expense of first cost premiums.[*,†] Therefore, an analysis of the market potential of DBAC should target first cost competitiveness rather than operating cost reductions. Separate control of

*D. Houghton and D. Hibberd, "Packaged Rooftop Air Conditioners: A Buyer's Guide for 5.4 to 20 Ton Units," E Source TU-93-1, 1993, E Source Inc., Boulder, CO, USA.

†J. Gregerson and K. L. George, "Guide to Efficient Unitary Equipment," E Source TU-95-5, 1995, E Source Inc., Boulder, CO, USA.

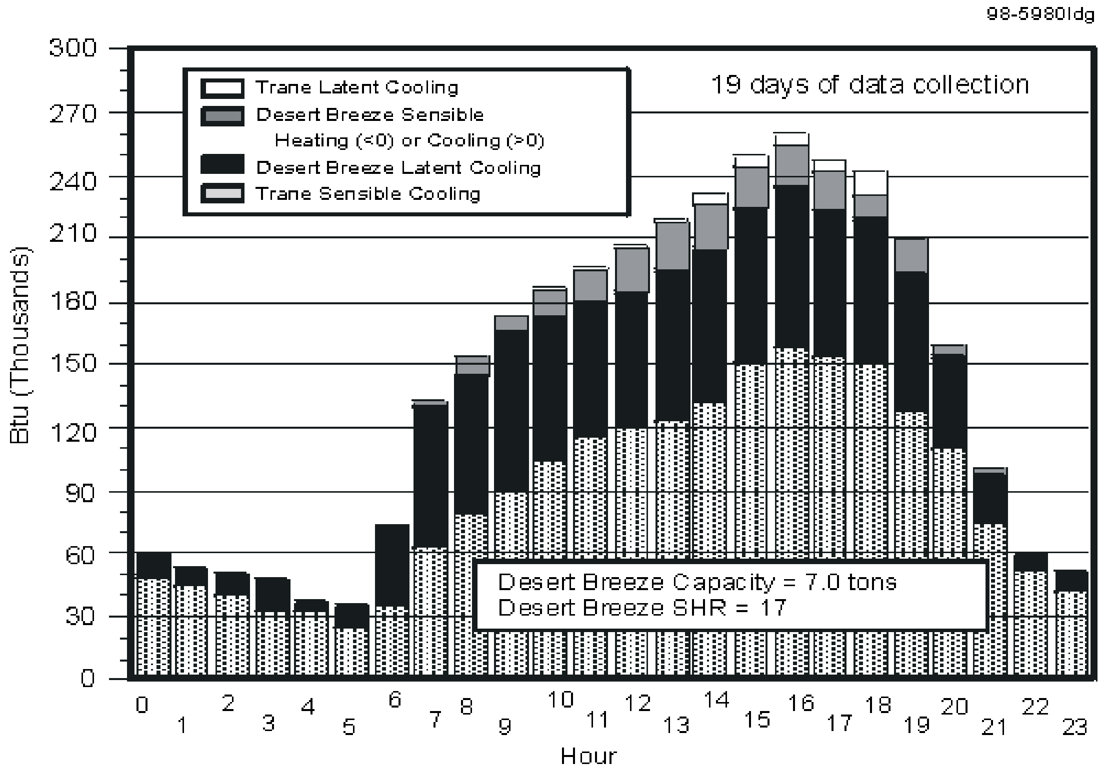

Fig. 3. Average hourly sensible and latent loads—2000 ft^3/min *Desert Breeze* and 20-ton Trane unit—Pensacola, Florida, July 1996.

temperature and humidity has some clear and objectively quantifiable impacts that must be considered in evaluating price targets for these desiccant-based systems. A major opportunity to institute active humidity control in a cost-effective way lies in correct sizing of equipment for a building. Equipment sizing rules of thumb based on the capabilities and limitations of conventional refrigeration-based equipment have been used for a long time. Those rules of thumb work, in many cases, by oversizing the sensible cooling portion of the equipment to compensate for any shortcomings in the dehumidification portion. The sum total usually delivers adequate comfort for most of the year, although at a lower temperature and higher humidity than the original design set points.

A mechanical system can deliver the conditions specified in the original design when both the sensible cooling and dehumidification components are adequately sized. By sizing the active humidity control system for the dehumidification load and then sizing the conventional equipment for the internal sensible cooling load, a designer can eliminate the "overcooling" often associated with trying to manage humidity with a refrigerant-based system only.

3.3 SINGLE-BLOW TESTING

ORNL modified the design of its heat exchanger coil testing loop to accommodate desiccant wheel sections supplied by the Engelhard/ICC CRADA partner. These modifications made it possible to perform "single-blow" testing of Engelhard/ICC's proprietary titanium silicate desiccant material loaded on their Mylar® honeycomb substrate. In a single-blow test, a stationary-mounted section of the desiccant wheel is subjected to two sequential "single blows" of preconditioned air

(Cohen et al., 1989).* The first airstream fully regenerates the desiccant on the test section by subjecting it to high dry bulb temperatures until the temperature and humidity levels of air passing through the test section are unchanged. During the second phase of the test (the process phase), moist, relatively cool air is blown through the desiccant test section while transient conditions of air passing through the sample are monitored. The desiccation process removes moisture from the air while heat is released during the sorption process, so air emerges from the test section drier and warmer than when it entered. The outlet conditions of air exiting the static test section were recorded and used in the evaluation process.

These results were used for comparison with designed and established operating conditions for the desiccant wheel used in this dehumidification system:

- Moisture sorbed, on the whole, increases with desiccant regeneration temperatures.
- Moisture sorbed from the process airstream increases with decreasing wheel revolutions per hour.
- Moisture sorbed decreases with increasing air face velocity.
- Moisture sorbed increases with desiccant loading on the wheel.
- Moisture sorbed increases with increasing wheel thickness.

Engelhard/ICC determined the size, shape, wheel depth, and degree of desiccant loading based on their analysis of a performance versus cost formula for their product. These single-blow test results confirmed that the operating conditions established by Engelhard/ICC for the wheel were optimal for product performance. In these tests with the Engelhard/ICC sample, regeneration outlet humidities and temperatures were seen to take an increasingly larger portion of the wheel's surface exposed to regeneration conditions to totally desorb for increasing wheel speeds with the same face velocities. A faster rate of absorption was seen for increasing face velocity and increasing process/regeneration switching rate (rotation rate) of the Engelhard/ICC unit. This implies that an increased wheel angle is required for full absorption at the same face velocity.

3.4 COMPUTER MODELING/SIMULATION

Initial efforts at creating a simulation tool consisted of a system-specific mathematical model of a desiccant air conditioner, where desiccant and heat exchange wheels were simulated using proprietary correlations provided by Engelhard/ICC and literature data. Single-blow tests provided some data for the simulation. Engelhard/ICC manufactured a unit and started developing a computerized simulation program for a hybrid system with reject heat from the conventional compression system employed to regenerate the desiccant.

A "business sensitive" methodology for mathematically modeling the heat and mass transfer effectiveness of a desiccant wheel operating with given rotational speeds and air face velocities was discussed and analyzed in conjunction with the CRADA partner. Correlations for heat and mass number of transfer units (NTUs) were developed for rotating heat exchangers and desiccant wheels using empirical equations provided by Engelhard/ICC and published literature data. These correlations were used for both the heat exchanger and desiccant wheels in Engelhard/ICC's products. Mathematical models for the desiccant wheel and rotating heat exchanger were written into a Fortran® code. Additional Fortran® code required to perform psychrometric correlations was added to the desiccant system model being developed for Engelhard/ICC.

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*B. M. Cohen, S. R. Wysk, and R. B. Slosberg, "Advanced desiccant cooling system development desiccant wheel sample performance testing," GRI Report No. 89/0036.1, 1989.

3.4.1 Analytical Modeling Work on Engelhard/ICC *Desert Breeze* (Hybrid-Desiccant/ Vapor Compression) Units

In the equipment-specific modeling effort directed at the *Desert Breeze* product, analytical support was provided by ORNL to assist Dr. Eileen Chant, a subcontractor to Engelhard/ICC, in her development of a model for this unit. This hybrid-desiccant/vapor compression unit uses the rejected heat from the condensers of the vapor compression section to regenerate the desiccant wheel. Because of ORNL's experience in modeling vapor compression heat pumps, we were asked to develop an improved simulation of the performance of the vapor compression portions of the *Desert Breeze* units.

Each *Desert Breeze* unit employs two air-conditioning units that are separate, parallel, refrigeration circuits with evaporating and condensing coils arranged in series. We were asked to model the combined performance of these two units with our DOE/ORNL Heat Pump Design Model (HPDM) and to parametrically map their performance over the ranges of expected inlet air temperatures, moisture content, and flow rates seen by the evaporators and condensers.

We worked with Dr. Chant to make appropriate assumptions to simplify the number of parametric mappings needed for input to the *Desert Breeze*-specific model. Based on this collaboration, two types of performance analyses were planned.

First, design calculations were needed to predict the required regeneration airflow at design conditions to obtain 140^{o}F regeneration air entering the desiccant wheel. The required regeneration airflows, as well as capacity and electric power consumption, were to be predicted as a function of reasonable design values for evaporator inlet air temperature, RH, and flow rates for fixed-design condenser inlet air temperatures. The second type of calculations were for off-design process-side conditions. In these cases, the condenser airflow rate and inlet temperatures were to be held fixed at design values, and the regeneration temperatures entering the desiccant wheel, and, again, capacity and power consumption, were to be calculated for variations in process air conditions and possibly flow rates about design values.

We also interacted with Dr. Chant, ICC engineers, and compressor and thermostatic expansion value (TXV) suppliers to assemble sufficient component data as required by the DOE/ORNL model. To this end, we obtained compressor maps of the 15 models used which differ in size, voltage, or hertz to cover the 3.5-, 5-, and 7-ton sizes, 50- and 60-Hz operation, and 200- to 400-V range. There are three possible blower motor sizes for the process and regeneration air streams. While we have collected data for all sizes, our initial model validation and parametrics were to focus on the 5-ton unit, with 5-hp blowers and compressor. We obtained data sets from Dr. Chant on this unit from tests conducted at Engelhard/ICC.

The coil circulating schematics and geometries were obtained for all the coils used in the three sizes produced. The condensers have cross-counterflow desuperheater configurations with merged subcooling regions and two-to-one merging from desuperheating to condensing regions. The DOE/ORNL model was modified to handle such circuit mergings in the condenser. Changes were also made to handle the cross-counterflow desuperheater arrangement. Further modifications were made to a separate version of the HPDM condenser routine to find the required airflow rate to maintain the desired 140^{o}F-regeneration air temperature for design analysis.

Once the design and off-design models were validated/calibrated against Engelhard/ICC test data, we planned to use them to generate a series of parametric performance tables for implementation into Dr. Chant's design/simulation program.

However, before proceeding further, the labor-intensive, single-purpose nature of this approach was reevaluated relative to a more general approach that could prove more flexible and thereby more beneficial in the longer view. It was concluded, as a result of this investigation, that Engelhard/ICC would benefit more, in the long term, from representing such equipment components directly within a system model in a modular reconfigurable fashion. With such a model, the interactions between the vapor-compression stages and between design and off-design operation would not have to be precomputed for each configuration. This more direct integrated approach, once implemented, will allow a variety of arrangements to be evaluated for each proposed target application at both design and off-design conditions.

Since system-specific models are quite restricted and cannot be readily modified to model other systems, we recommended that component modules be developed that are capable of representing the vapor-compression-cycle portions of *Desert Breeze* type units. This would include air-to-refrigerant evaporators and condensers and map-based compressor models. The heat exchanger models should be capable of representing the design and off-design performance of the desuperheater sections with an accuracy comparable to the DOE/ORNL HPDM. Such modules would be coupled to the desiccant cycle model developed at ORNL to predict performance for various types of hybrid systems. Data collected for the present *Desert Breeze* design could be used to validate the design and off-design predictions of such a model.

3.4.2 Desiccant Cycle Model

ORNL and the industrial partner agreed to give a high priority to developing a more versatile modeling tool of modular structure that enables simulation of systems under varying configurations and desiccant materials. ORNL had done this before in the computer code ABSIM, which can be used to simulate absorption systems in varying cycle configurations and with different working fluids. This simulation tool has gained wide acceptance in the absorption community. An input interface of the model was developed to allow the user to specify heat and mass transfer performance in several ways (in terms of NTU), or effectiveness, or deviation from equilibrium, etc. This makes the model more versatile in accepting different methods of describing component performance. The overall structure of the desiccant cycle model program and elements of its flow diagram have been established as shown in Fig. 4.

Models described in the literature were found to be overly simplistic based on assumptions that are not always satisfied, such as the Lewis analogy equating heat and mass NTUs for a desiccant wheel. A more fundamental approach was taken in this new model based on governing physical equations required to simulate each component; for example, satisfying energy balances and water mass balances. The overall structure of the model was formulated. Simulation algorithms for desiccant components were developed. The more fundamental approach made the numerical task more difficult, so a mathematical solver was incorporated in the code, as demonstrated previously with complex absorption systems. Properties of desiccant materials were compiled and transformed into a form compatible with the property database. In this program, the components and properties are linked together by a main program according to user's specifications to form the complete system as shown in Fig. 4.

A different approach was adopted for the simulation of the desiccant wheel. Instead of following the time-dependent changes in temperature and humidity of a desiccant particle as it turns with the wheel, the process and regeneration parts of the wheel housing are treated as two control volumes, with the rotating desiccant flowing into and out of them, as does the air. This "Eulerian" (vs "Lagrangian") approach makes it possible to consider the desiccant wheel as a flow system operating in steady state, similar to conventional heat pumps. This greatly simplifies the simulation while maintaining its fundamental physical accuracy.

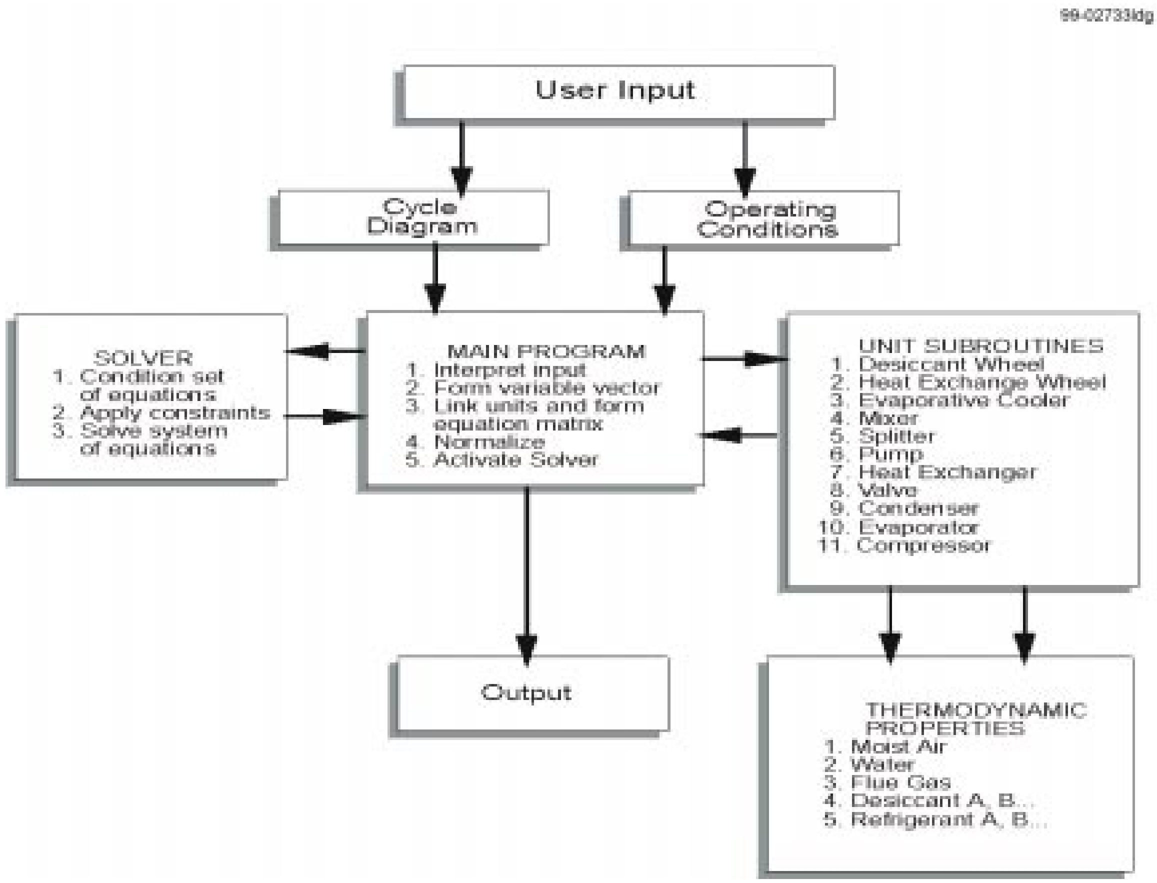

Fig. 4. Outline of desiccant cycle model.

A great deal of effort has concentrated on the development of simulation algorithms for the desiccant components such as desiccant wheel, heat exchange wheel, and evaporative cooler. Properties of working substances, particularly of desiccant materials, were compiled and transformed into a form compatible with the property database. These included literature data as well as proprietary materials of interest to our CRADA partner, such as Engelhard Titanium Silicate (ETS).

A graphical interface was added to the code, which makes the simulation task quite user-friendly. It allows the user to compose the cycle diagram on the computer screen, input the data interactively, and view the results of the simulation superimposed on the cycle diagram. A detailed output is also produced in the form of a table showing the temperature, flow rate, concentration, and enthalpy of the working substance at each state point, and the heat duty and transfer characteristics of each component.

The model developed under this project makes it possible to evaluate system performance with different design alternatives, compare different desiccant-based systems to each other, and predict performance under varying ambient and other operating conditions. The computer simulation model may also lead to development of desiccant application marketing software, which would allow architect and engineering firms or building owners to compare various desiccant components and alternative systems with conventional vapor compression equipment or to combine/integrate desiccant technology, where advantageous, into “hybrid” systems that better satisfy health, comfort, economic, and energy efficiency needs.

3.5 SYSTEM RATING AND CERTIFICATION STANDARD DEVELOPMENT

ORNL initiated contact and participated in the relevant ASHRAE and Air Conditioning and Refrigeration Institute (ARI) technical committees and product groups to stay current with the effort to develop rating and certification standards for desiccant system components.

3.6 SYSTEM PERFORMANCE MAPPING AND VERIFICATION

An Engelhard/ICC DC030 Desert/Cool© system was installed in the ORNL Building Equipment Technology engineering laboratory for testing over a range of different ambient conditions. Instrumentation, including humidity sensors, gas and water flow meters, differential pressure transducers, air flow meters, and temperature sensors were being installed to measure and monitor the performance of the system while varying operating parameters such as wheel speed, air flow rate, and desiccant material being used (Fig. 5). Initial tests of the unit were performed at the ARI standard 95°F air-conditioning ambient rating conditions to determine if this system met the dehumidification capacity specifications given in the accompanying product literature. These tests were performed with the unit functioning in the *ventilation mode*, where the unit conditions the 95°F dry bulb/85°F wet bulb air before it is introduced to the building and uses this outside air for regeneration of the desiccant (ETL 1995).* In large part due to these laboratory tests at ORNL and results from similar Engelhard/ICC units installed at field test sites, desiccant wheels in most of the field installations of Engelhard/ICC* *Desert Air* units were replaced with more heavily loaded wheels to increase their dehumidification capacity. Field data indicated that the field units were unable to meet dehumidification capacities claimed in their product performance publications, and laboratory tests confirmed this discrepancy.

Extensive modifications of the ORNL desiccant system test installation were made in cooperation with and using engineering calculations provided by our CRADA research partner. More powerful variable speed fan motors were installed, which boosted airflow rates from 2,200 ft^3/min up to 3,500 ft^3/min. The original desiccant wheel shipped with the unit was replaced with one prepared and supplied by the CRADA partner, which had 50% higher desiccant loading to increase dehumidification capacity. Boilers and heating coils on the regeneration side of the unit were replaced with equipment that will allow wheel regeneration temperatures up to 230°F to 250°F even with increased airflow rates. Additionally, variable speed motors were installed to allow control of the desiccant and heat exchanger wheel rotation rates. These modifications put ORNL in a unique position to experimentally study the parametric effects of process variables on the performance of a thermally regenerated desiccant unit for design optimization and evaluation of system modulation strategies.

Experimental results from these parametric studies are also to be used for future, computer-model verification work.

4. INVENTIONS

None.

*ETL, "Laboratory testing the Engelhard/ICC Desiccant Unit at ETL" Report, December 1995, CDH Energy Group, P.O. Box 641, Cazenovia, NY 13035.

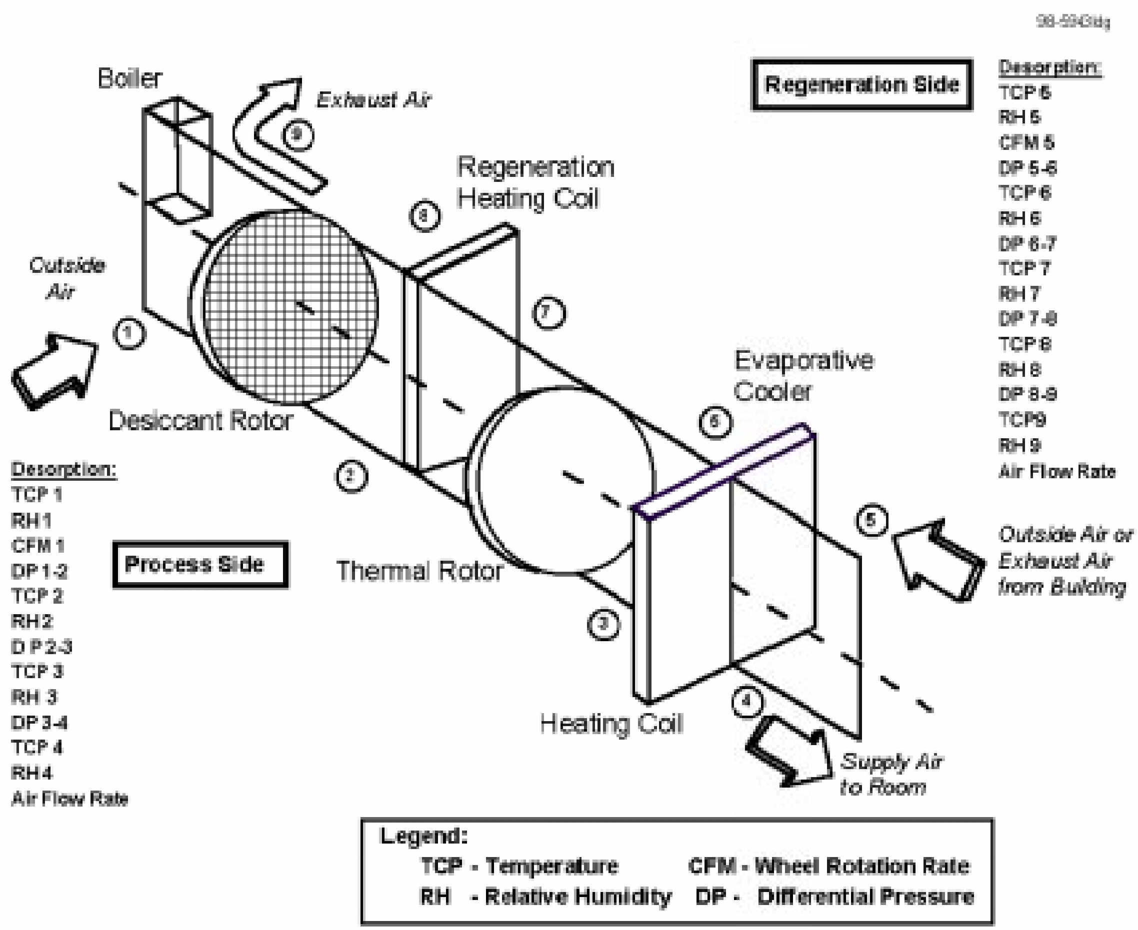

Fig. 5. ORNL desiccant cooling system schematic.

5. COMMERCIALIZATION POSSIBILITIES

Recent parametric performance testing on the laboratory breadboard unit may suggest static design changes to optimize system performance and/or control strategies that can be used for efficient capacity modulation.

6. PLANS FOR FUTURE COLLABORATION

A new CRADA is being prepared with Fresh Air Solutions by Engelhard/ICC (formerly Engelhard/ICC) to extend this collaboration. The goals of this new CRADA will be to (1) continue development of computerized modeling algorithms for desiccant systems through comparisons with laboratory and field performance data, (2) evaluate the performance impact of different product configurations suggested by the Participant through modeled and experimentally measured system testing, and (3) develop the draft method of test currently under consideration for desiccant systems into an ASHRAE/ARI/ANSI equipment standard.

7. CONCLUSIONS

A computer simulation model that allows selection and assembly of a number of basic system components (heat exchangers, desiccant wheels, evaporative coolers, etc.) to make a desiccant-based dehumidification system has been developed and reviewed with our CRADA partner. The model makes it possible to simulate a variety of desiccant-based cycles in flexible and modular form and connect them thermally to refrigerant-based cycles. To the best of our knowledge, no other model of this kind exists.

Marketing studies have identified HVAC market segments that can benefit most and are most likely to require desiccant-based air-conditioning products. These studies have also indicated product performance capabilities and approximate equipment costs that are needed for a successful commercial product.

A highly instrumented desiccant dehumidification system has been installed in the ORNL Buildings Technology Engineering test laboratory. This in-house system is being used to support and verify results seen with field units, characterize and map performance characteristics of current commercial products, test and assess ideas for desiccant product rating and performance standards, and perform parametric studies to evaluate design options and unit modulation strategies.

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