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Promising Advances in Desiccant Cooling

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Advances in Open-Cycle Solid Desiccant Cooling

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ABSTRACT

Of the solar cooling options available open cycle solid desiccant cooling looks very promising. A brief review of the experimental and analytical efforts to date shows that within the last 10 years thermal performance has doubled. Research centers have been developed to explore new materials an geometry options and to improve and validate mathematical models that can be used by design engineers to develop new product lines. Typical results from the Solar Energy Research Institute's (SERI) Desiccant Cooling Research Program are shown. Innovative ideas for new cycles and spinoff benefits provide incentives to continue research in this promising field.

INTRODUCTION

One function of buildings is to maintain comfortable temperatures and humidity. Reducing the nonrenewable energy required to achieve this is a major national goal. In summer, infiltration, ventilation, solar gains, building envelope conduction and internal heat and moisture generation by the occupants and equipment raise the temperature and humidity of the conditioned space. Better equipment, building design and insulation, sealing and ventilation systems can reduce but not eliminate five of these heat loads. The heat and moisture generated by occupants depend on building function and cannot be significantly altered [1]. A cooling system with reduced energy consumption, especially one using renewable energy that can be nationally marketed and retrofitted to existing building stock, is an extremely attractive alternative to the consumer and utility and the industry that supplies and installs the product.

Conventional vapor compression systems using electricity have reached their limits after sixty years of research and development. The cost of electricity increases at a rate depending on supply and demand. New cooling systems using renewable energy sources directly are being developed when the economics show a favorable rate of return. This paper focuses on cooling options using the renewable energy sources available nationally, which are direct solar and a type of indirect solar, the energy of the unsaturated atmosphere.

These energy sources impose constraints on the candidate systems. Closed cooling systems in which the refrigerant does not contact the atmosphere can not use the energy of the unsaturated atmosphere. Open systems evaporating water into the atmosphere as a refrigerant use this energy source and use less direct solar energy; e.g., the simple evaporative cooler requires energy only to move the water and air. Closed systems may be combined with open systems to take advantage of this. The performance of open systems is reduced in humid areas unless dehumidification is used. A solar collector will deliver more heat at low temperatures because heat losses are less [2,3]. These facts lead us to choose open cycles using dehumidification with low temperature heat as promising options for a national renewable energy cooling system.

A nationally marketed and retrofitted system ideally needs to be compact and have low cost and maintenance with high performance and reliability. High performance may be achieved if the system approaches the limits set by the second law of thermodynamics. This requires that all heat transfer should be across small temperature differences and all mass transfers across small concentration differences. Of commercial dehumidifiers only the adiabatic regenerative dehumidifier does this.

The design of regenerative dehumidifiers is complicated by the mass transfer resistance and poor mechanical and manufacturing properties of available desiccants. New materials, geometries, and manufacturing techniques are capable of reducing size, cost, and maintenance while increasing the performance and reliability of regenerative dehumidifiers. An improved adiabatic regenerative dehumidifier will facilitate national marketing and retrofitting of desiccant open cooling systems.

Open-cycle desiccant systems using adiabatic regenerative dehumidifiers have been referred to as adiabatic desiccant open cooling (ADOC) systems. The Solar Energy Research Institute (SERI) for the Department of Energy's (DOE) Active Heat and Cooling Program has been pursuing basic research and development in the area of solid desiccant solar cooling as one alternative. This paper briefly describes the development of this technology to its current state and work currently in progress at SERI and elsewhere. The likely future trends and opportunities, however, are of greatest interest and are consistent with DOE's long-term goals for renewable energy cooling. Near-term applications for conservation are presented to show how desiccant cooling is practical now, and spinoffs to other technologies are imminent.

A SHORT HISTORY OF THE TECHNOLOGY

The simple evaporative cooler is the oldest open-cycle cooling system. During the 1930s, it was developed to the form that is still widely marketed today [4]. The small amount of energy it consumes for fans and pumps can be reduced considerably by applying modern knowledge of heat and mass transfer and fluid mechanics [5]. Simple evaporative coolers only cool down to the wet bulb temperature, which limits their effective use to the hot dry areas of the Southwest.

Indirect and regenerative evaporative coolers were developed as an improvement to these simple evaporative coolers of the 1930s [4]. Later, however, they did not compete economically with conventional vapor compression or simple evaporative coolers. The large size of the metal plate heat exchangers was an important disadvantage. More compact and economical heat exchangers for these coolers have been developed and marketed [5,6,7] with further improvements possible [8,9,10]. Indirect and regenerative evaporative coolers cool down to the dew point temperature, which, being less than the wet bulb temperature, gives them a broader climatic range than the simple evaporative coolers. This range does not extend to humid climates.

Pennington [11] solved the problem of limited climatic range of open cooling systems. He saturated a rotary heat exchanger matrix with a desiccant solution making an adiabatic regenerative dehumidifier. He coupled this dehumidifier with a heat source to a double regenerative evaporative cooler (Fig. 1). Pennington's cycle is now routinely referred to as the ventilation cycle. Pennington gave a

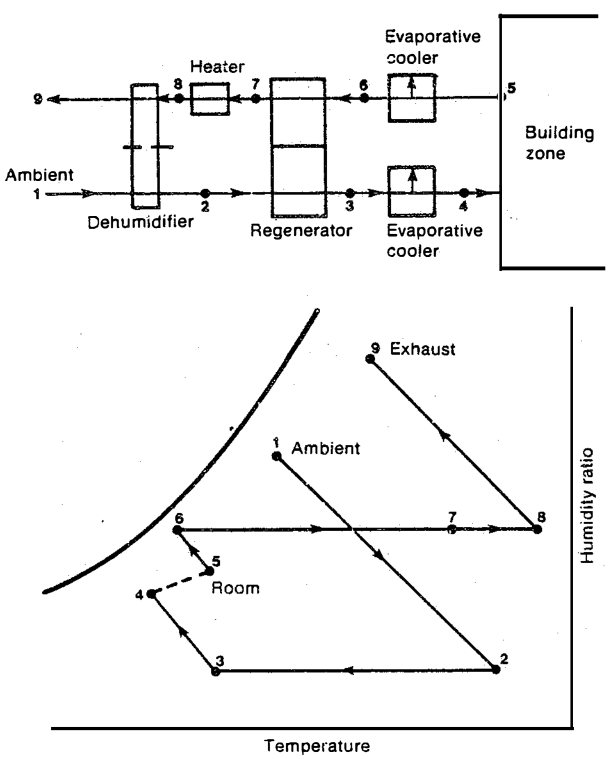

Fig. 1. Schematic and Psychrometric Chart for Pennington's Cycle

sound description of the phenomena in a regenerative dehumidifier but did not give the performance of his prototype. He discovered that rotating the regenerative dehumidifier at a reasonably high speed would make it transfer the total heat or enthalpy to the incoming fresh air stream during winter heating.

Munters [12] improved Pennington's regenerative dehumidifier by introducing parallel passages. Regenerative dehumidifiers for drying conditioned spaces are commercially available from a number of suppliers [13]. Total heat or enthalpy regenerators for building exhaust air to fresh air energy recovery are also available [13].

The Institute of Gas Technology (IGT) recognized the potential of the ventilation, or Pennington, cycle for gas-fired air conditioning and built a number of prototypes in the 1960s [14]. Solar energy prototypes were built in the late 1970s by IGT [15], AiResearch Manufacturing Company [16] and Exxon Research and Engineering Company [17]. By 1981 thermal coefficients of performance (COP) (ratio of cooling energy delivered to heat energy supplied) over 0.5 had been achieved experimentally at ARI standard test conditions.

The early IGT effort was hampered by the lack of a satisfactory analytical method for predicting the performance of regenerative dehumidifiers. The available methods [18,19,20] could only predict performance at rotational speeds so low that the whole matrix was in equilibrium with the entering airstream at the end of both dehumidification and regeneration periods.

Dunkle [21], in response to a request from the Australian mining industry, had independently of Pennington [11] developed a proposal for an ADOC cycle. A compact, spirally wound, parallel-plate heat exchanger was developed [5]. Johnston [22] used the results of tests on packed beds of silica gel beads to predict the performance of Dunkle's cycle. The predictions were disappointingly low, and Dunkle's group realized that the regenerative dehumidifier needed to be understood before ADOC cycles could be improved.

Banks, working in Dunkle's laboratory, initiated the development of a comprehensive theory of combined heat and mass transfer in regenerative dehumidifiers and related devices in 1967. He introduced combined potentials, analogous to temperature, and combined specific capacity ratios, analogous to specific heat ratios, in terms of which combined heat and mass transfer can be described [23]. These quantities can be calculated from the vapor pressure isotherms, the specific heat of the matrix, and the thermodynamic properties of moist air. Maclaine-cross and Banks [24] used combined potentials and specific capacity ratios in predicting the performance of the regenerative dehumidifier and enthalpy regenerator. This analogy theory makes the many phenomena of regenerative dehumidifiers understandable and has subsequently been simplified for rapid calculation by Jurinak [25].

Nelson et al. [26] applied the analogy theory of regenerative dehumidifiers to predicting the performance of ADOC cycles. They proposed a regenerative dehumidifier with a matrix consisting of thin parallel plates of silica gel separated by uniform air passages. Their predicted performance was much better than previously measured for ADOC cycle performance.

Maclaine-cross [27] included the effect of a Lewis number other than unity in the analogy theory and found good agreement with an accurate finite difference solution of the partial differential equations. This finite difference algorithm was based on detailed numerical analysis and extrapolation to zero grid size using three carefully chosen grid sizes. His program, MOSHMX, [27] has been widely used by subsequent investigators.

Jurinak and Mitchell [28] used MOSHMX to study the effect of isotherm shape, maximum water content, heat of adsorption, regenerative matrix thermal capacitance, matrix moisture diffusivity, and adsorption hysteresis on dehumidifier performance. They found that the best performance was obtained with a type 1 vapor pressure isotherm shape, characteristic of microporous silica gel desiccant. They concluded that commercially available microporous silica gels were attractive materials for dehumidifier construction.

Jurinak [25] also studied the effect of matrix properties on the ventilation cycle performance. Adding heat capacity to a desiccant regenerative dehumidifier matrix increases COP and, hence, reduces energy consumption slightly. However, it reduces specific capacity greatly, which increases capital costs. Minimum life cycle cost requires a minimum desiccant matrix heat capacity. Jurinak and Mitchell [29] recently used MOSHMX to predict the optimum purge rate for a regenerative dehumidifier. For operating conditions typical of the ventilation cycle the predicted benefit of purge was small.

Effective Lewis numbers measured on packed beds of silica gel spheres have been between 3 and 30, indicating excessive mass transfer resistance [30, 31]. Mass transfer resistance of silica gel has been investigated at UCLA [32,33]. SERI has fabricated and tested parallel plate matrices of desiccant-coated polyester films [34]. The smaller particle size used by SERI greatly reduces the mass transfer resistance, and the dehumidifier approximates the Nelson et al. [26] proposal previously discussed.

A thermal COP of 1.1 was predicted at standard test conditions for ventilation cycles using this dehumidifier [35,36]. This makes a gas-fired ventilation cycle competitive in energy consumption with electric vapor compression [36,37]. However, higher COP and reduced capital costs are necessary for a solar energy cooling system to compete with conventional alternatives. The application of ADOC cycle components to energy conservation in building cooling has been proposed and investigated. Some applications are currently commercial, and others are so promising they deserve mention. By encouraging the manufacture and improvement of ADOC cycle components, the applications in the following two paragraphs are contributing to the development of a national renewable energy cooling system.

Vapor compression systems dehumidify inefficiently, and adiabatic regenerative dehumidifiers dehumidify more efficiently. Combining the two into a hybrid cycle with the condenser providing most of the regeneration heat (Fig. 2) gives substantial overall energy conservation [38,39,40,41]. For supermarkets with open refrigerated cabinets hybrid cycles are economical today using commercially available dehumidifiers [42].

Fresh air introduced into office buildings adds substantially to the cooling loads. The enthalpy load may be reduced or cooling may be extracted by using an evaporative cooler in the exhaust air stream before a rotary heat exchanger exchanging with the fresh air [9,10] (Fig. 3). The rotary heat exchanger will work as an enthalpy exchanger [43,44] whenever the outside air is humid. When the outside air is dry, the evaporative cooler and heat exchanger work together as a regenerative evaporative cooler, substantially reducing energy consumption.

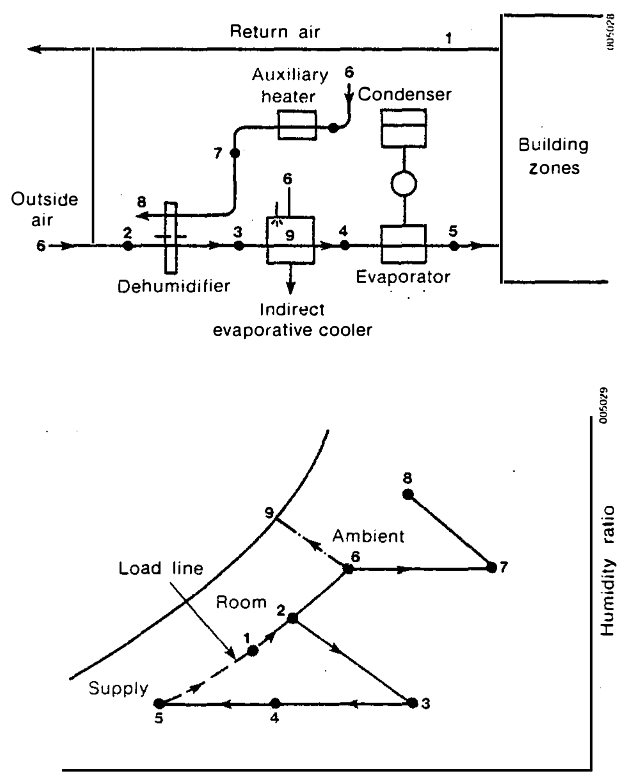

Fig. 2. **Schematic and Psychrometric Chart for Hybrid Desiccant Cooling Cycle**

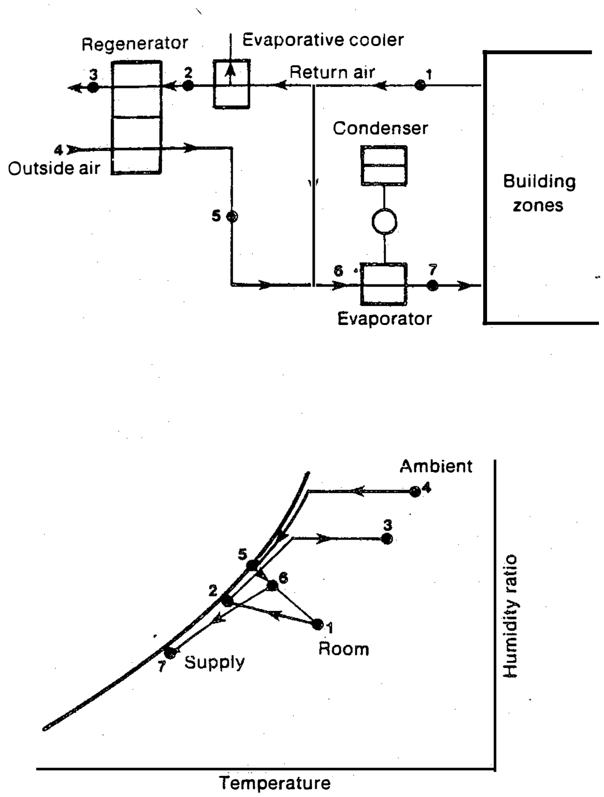

Fig. 3. Schematic and Psychrometric Chart for Hybrid Exhaust Air Regenerative Evaporative Cooling Cycle

Recent theoretical research into advanced ADOC cycles has shown the possibility of substantially higher thermal COPs. Maclaine-cross and Banks [8] proposed a regenerative evaporative cooler that minimized the temperature differences across which heat was transferred and the concentration differences across which moisture was transferred. The second law of thermodynamics would lead one to expect improved performance, and the predicted performance was substantially better than less thermodynamically ideal regenerative evaporative coolers. Lavan et al. [45] calculated the thermal COP for a thermodynamically reversible ventilation cycle at standard test conditions as 4.66. Maclaine-cross [46] has proposed an ideal ADOC cycle requiring no thermal energy (i.e. infinite COP) at standard test conditions.

Reduction of collector cost improves the economics of a renewable energy cooling system in a similar fashion to increasing thermal COP. Solar collector costs will be reduced by economies of scale as solar heating expands. Recent research [47,48] into collector materials, manufacturing methods and concepts has shown considerable promise of reducing costs further.

A renewable energy cooling system can follow various development paths. Fundamental work on solid desiccant dehumidifiers shows immediate promise for advanced ADOC cycles unexplored to date.

THE CURRENT NATIONAL EFFORT ON DESICCANT COOLING

Several organizations (private, utility and federal sectors) have been working on various desiccant cooling, integrated HVAC options (Fig.

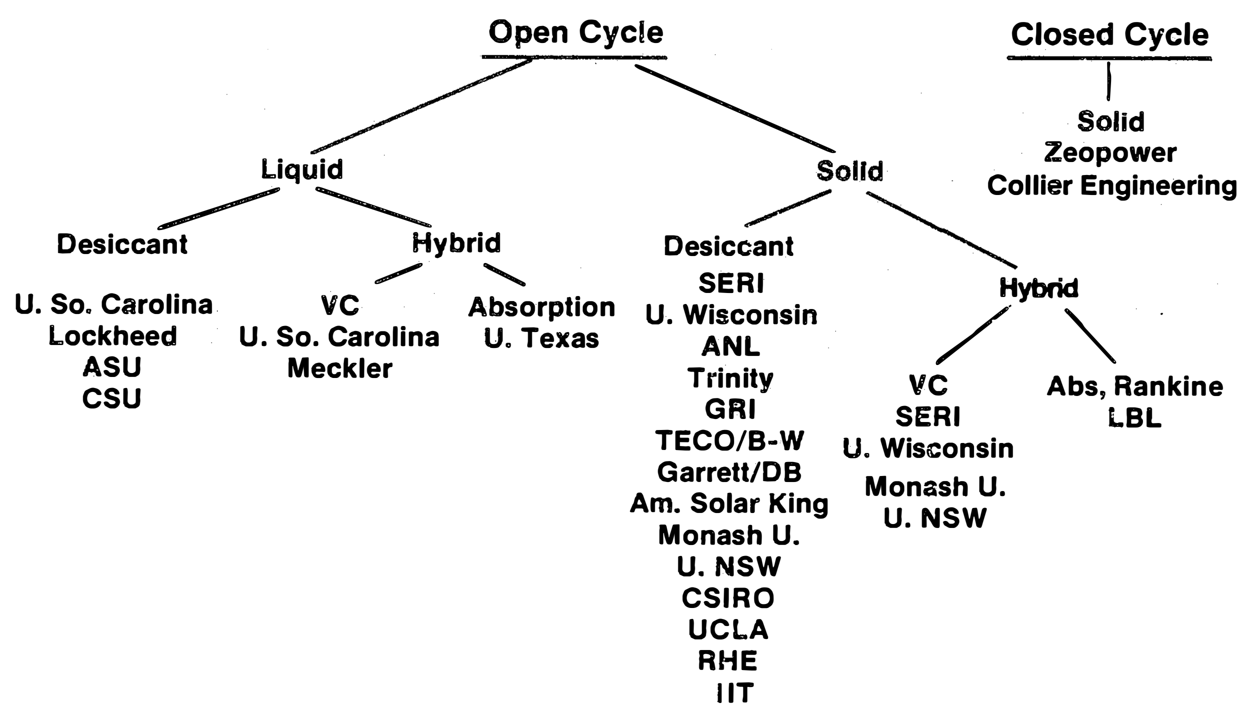

Fig. 4. Organizations Contributing to Desiccant Cooling Research

4). Each organization has its own development strategy, depending upon its product line, principal interest, or long-term mission statement. It is beyond the scope of this paper to be comprehensive and knowledgeable about all of the research activities in the field of desiccants; however, we do briefly mention the publicly available larger efforts with special attention to the work funded by the Department of Energy.

The Gas Research Institute (GRI) is conducting one of the larger gas-fired cooling research efforts. GRI's strategy [49] for cooling systems is to develop cost-effective, gas-fired and recovered-heat-driven adsorption and absorption equipment for a range of sizes and applications within the residential and commercial markets. GRI's desiccant dehumidification/cooling program includes both near- and mid-term projects. All hardware development projects currently involve HVAC manufacturers on a cost-shared basis. GRI feels integrated dehumidification/chiller systems that separate latent and sensible load control show good potential for the near term, especially when cost optimized systems are packaged using existing or readily modified technology. These systems are being developed first for supermarkets, which are an ideal early market application because of the high latent-sensible load ratio. The technology will then be extended to the broader commercial market in the 20- to 100-ton size range.

GRI is also looking into the technical and economic feasibility of combining desiccant dehumidification with passive and other sensible cooling techniques for residential buildings. Advanced desiccant cooling technology, based on the early work by Exxon Corporation, is being developed for residential and light commercial applications in the 2- to 20-ton size range. Two parallel development projects are in place, each involving a major HVAC manufacturer, for designing and fabricating laboratory prototype units. Aside from these larger hardware projects, GRI has funded SERI to investigate the use of enhanced geometries to promote the rate of mass transfer [50]. This work just started in February 1985.

American Solar King Corporation, committed to near-term commercialization of a solar regenerated desiccant cooling system, has introduced the first residential solar desiccant cooling unit, which is intended to directly compete [51] with electric vapor compression units. The Solar King desiccant system, called the Sunaire, is packaged with eight, 4x8 collectors and a storage tank with backup heating devices. The company thinks it can meet its target cost of $10,000 with an annual sale of 10,000 units, which is estimated to be only 0.7% of the market penetration for air conditioning. Field testing at eight sites, mostly in the southern part of the United States, has given Solar King confidence in the systems mechanical reliability. Solar King places a high priority on reliability for their system, which has been designed to be cost-effective on a life cycle basis. This was only achieved after careful engineering tradeoffs without compromising the mechanical integrity of the system.

The Federal Government in the last few years has restructured its role to only fund long-term, high risk research and development that will not be pursued by the private sector under normal incentives. Hence, the current DOE solar desiccant cooling projects are limited to developing high performance, low cost desiccants and other system component materials; researching heat and mass transfer phenomena in absorbent and adsorbent geometries; and analyzing advanced desiccant cooling system concepts as a mechanism for quantifying the impact of material and component progress. A conscious effort is being made to leave engineering development to the private sector, which is investing their own resources to commercialize the technology.

A fundamental research aim in materials and sorption kinetics is to develop predictive analytical models and improve them by validation with experimental data. In some cases, accurately measuring properties for existing desiccant materials in the range applicable for cooling can provide quantitative data to industry that is immediately beneficial.

SERI has the federally funded national lead in solar regenerated solid desiccant cooling research. A five-year plan with associated long-term technical and programmatic goals consistent with this current philosophy has been developed by Zangrando [52]. Researchers at SERI have focused primarily on material and heat and mass transfer issues. The Argonne National Laboratory (ANL) is concentrating on advanced material options. The University of Wisconsin is supporting both ANL and SERI through systems analysis activities. The Florida Solar Energy Center (FSEC) has recently started looking at novel cooling concepts. Professor Lavan at Illinois Institute of Technology (IIT) is investigating cooling concepts with regard to second law thermodynamic analysis [45]. Each element of this integrated national team effort is discussed later. A simplified flowchart of current experimental and analytical activities (Fig. 5) shows this interaction.

CURRENT MATERIALS RESEARCH ACTIVITIES

The cost-effective deployment of many new renewable energy conversion technologies is currently limited by the durability and life cycle cost of the materials used. Research on desiccant materials and degradation studies of their sorption performance are greatly needed. Fundamental materials research includes efforts to understand and quantify the degradation processes of common desiccants and to provide new material options for improving the sorption kinetics and, thus, the mass transfer in solid desiccant geometries. The ideal goal is to identify a cost-effective material with optimal performance in the temperature range unique to a solar regenerated desiccant dehumidifier. The

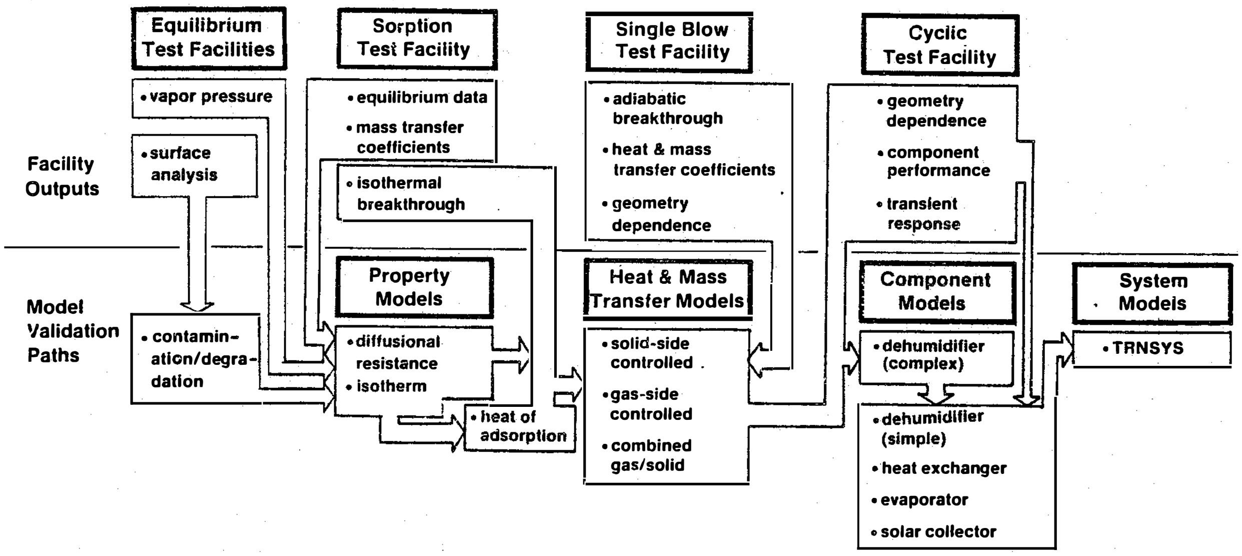

Fig. 5. Research and Development Activities Under the Solar Desiccant Cooling Program

important parameters for the solid desiccant material would include the sorption capacity, the heat of sorption, the rate of sorption at or near the desiccant bed temperature, the rate of vapor evolution at an elevated temperature, and the cyclic repeatability of the sorption amount and rates.

From sorption isotherms the binding energy can be determined and used to calculate the rate of desorption from the surface. The rate of diffusion through the porous material can be calculated and in principle, the rate of evolution from the solid can be determined and compared with experimental results. Although considerable sorption data are available in the literature for candidate desiccant adsorbent materials, these data have not been analytically scrutinized to determine what maximum rates of water vapor evolution are possible at very low driving potentials. Recently, GRI let a contract to Collier at ENERSCOPE, Inc. to study the effect of adsorption isotherm shape on cooling system performance. The results of this work are specifically aimed at developing a new desiccant material for use in gas-fired cooling machines.

We know that sorption rates will be reduced by pore volume diffusion and intraparticle diffusion in various geometries. Recent papers by Pesaran and others have attempted to validate analytical models of this process from experiments on solid desiccants. Previous work has focused on conventional volumetric and scanning electron microscopic (SEM) techniques to provide a limited understanding of the fundamental sorption processes. To understand the molecular processes for water-solid adsorbent desiccant systems, Czanderna at SERI is combining the use of a quartz crystal microbalance [53], infrared and surface spectroscopies to correlate rates and amount sorbed with the chemical bonds formed (related to the heats of adsorption), and surface composition (effects of chemical modification). Any changes in the amount sorbed and rate of sorption should result from a change in the bonding at the surface (infrared).

The experimental data are not sufficiently available for assessing the potential of polymeric materials designed and used as desiccants. The objectives of this research have been developed from the obvious unexplored opportunities for providing scientific understanding and information about candidate water-desiccant materials and rationale for modifications of the adsorbents that might be necessary.

Researchers at SERI, collaborating with Argonne National Laboratory (ANL), are assessing the use of desiccants in candidate devices. They are concerned with the form of the desiccant materials; quantification of performance of fundamental geometries with desiccants attached, including total desiccant geometries, vapor flows, and heat and mass exchange characteristics in these geometries; sorption hysteresis; and desiccant material contamination/degradation effects. Recent quantitative results (Fig. 6) show how the materials capacity changes with time using field samples of silica gel regenerated by gas and electric sources. Specifically, the ANL work is concerned with securing isotherms for water on nonconventional desiccants, such as manganese oxides; analyzing for surface area and

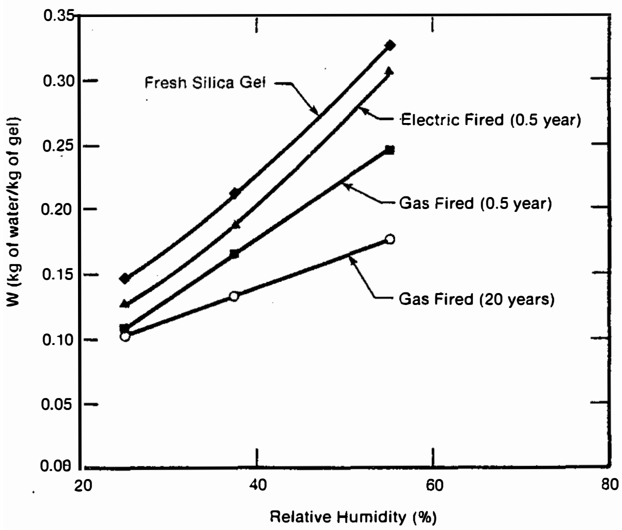

Fig. 6. Degradation of Silica Gel Vapor Pressure Isotherms

pore size distribution; separating interparticle and intraparticle diffusion processes; and studying new material combinations with a low heat of adsorption and less diffusional resistance.

Regular density silica gel is the preferred desiccant for solar application by universities and industry, yet there is considerable scatter (±15%) in the equilibrium isotherm data published in the literature. The SERI sorption test facility (Fig. 7) was used by Pesaran and Zangrando [54] and Zangrando and Pesaran [55] to quantify and refine the equilibrium properties of regular density silica gel, molecular sieve, and one form of manganese dioxide under temperature and humidity conditions typical of those occurring in solar desiccant cooling system operations. Typical results from that work are shown in Fig. 8.

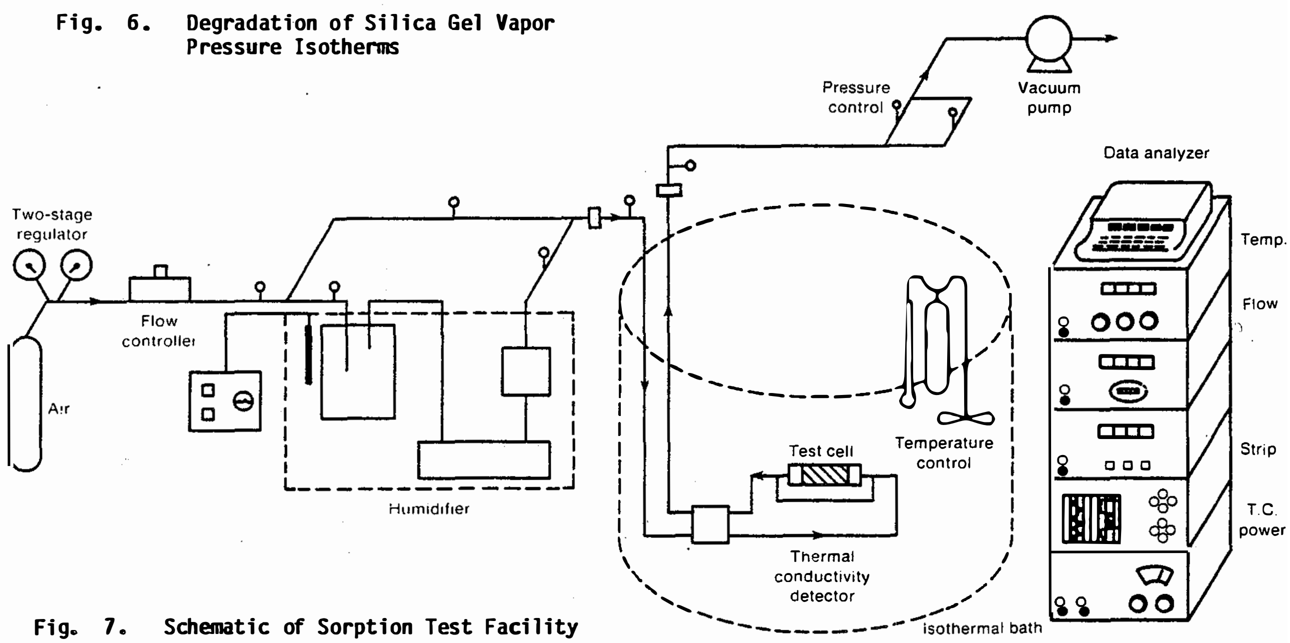

Fig. 7. Schematic of Sorption Test Facility

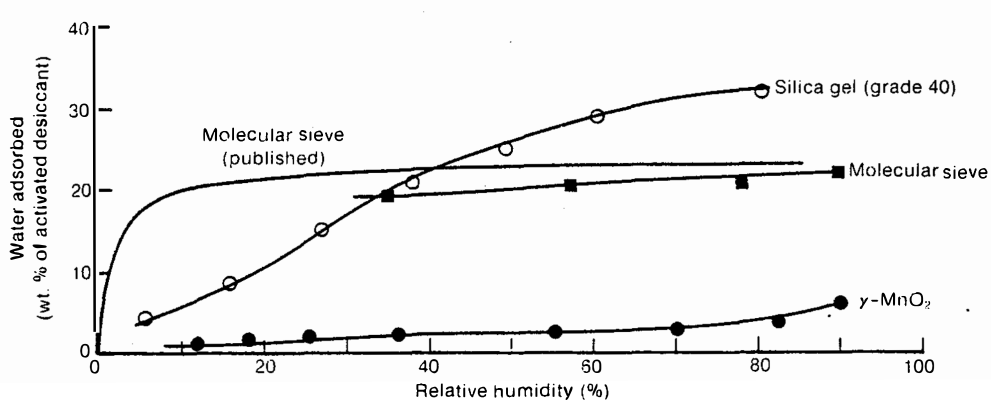

Fig. 8. Typical Adiabatic Breakthrough Data Results from Sorption Test Facility

HEAT AND MASS TRANSFER RESEARCH

The SERI sorption test facility was also used to generate mass transfer rate data under isothermal conditions for a packed bed geometry and a single channel of parallel passage configuration [54]. The mass transfer rate data were obtained by monitoring the outlet water vapor concentration as a function of time after a step change in the inlet water vapor concentration to the desiccant. This set-up provided initial isothermal data for comparison with mass transfer models of simple geometries. This flow of information from a facility output to a model validation path is shown on Fig. 5.

Another facility at SERI, called the single blow test facility (see Fig. 9), provides heat and mass transfer rate data under adiabatic conditions, which are more realistic of practical dehumidifier operations in a static (nonrotating) mode. The first geometry considered for commercial desiccant dehumidifiers was a packed bed. Kutscher and Barlow [31] found that the packed bed provided low heat-transfer-to-pressure-drop ratios (St/f = 0.05) and was economically unattractive for use in solar desiccant cooling applications. Further testing by Barlow and Schlepp [34] indicated that the parallel passage geometry generated a larger heat-transfer-to-pressure-drop ratio (St/f = 0.49). Typical experimental results from a parallel passage geometry in a single blow operation is shown in Fig. 10.

Since performance is not the only relevant parameter for a cost-effective desiccant system, other configurations, such as honeycombs, air-side enhanced geometries, solid desiccant impregnated surfaces, extrudable polymeric geometries, etc., are all providing incentives to various industrial suppliers, which further enhances the opportunity for near-term industrial marketability. These configurations are being tested in the single-blow test facility to investigate their performance under conditions typical of solar air conditioning.

These trade-offs (between cost, performance, and reliability) are best answered by the private sector who then complete the engineering design and product development for satisfactory residential and commercial applications. The basic analytical tools developed and validated by the research groups can be used by industry to encourage critical technical review of new options extrapolating to other physically similar geometries and processes.

Van Leersum and Close [30] showed that the dynamic rotating behavior of desiccants in the adsorption/desorption cycle can significantly affect the performance of a dehumidifier. Figure 11 shows the relationship between the simultaneous heat and mass transfer processes in an actual dehumidifier geometry. The diffusion resistance must be accurately measured to predict the dehumidifier performance. To characterize this dynamic behavior SERI constructed a cyclic test facility (see Fig. 12) [56] to characterize the performance of desiccants on geometries in cyclic operation at conditions typical of those that would occur in a solar regenerated desiccant cooling system.

Unvalidated analytical dehumidifier models predict optimum ventilation cycle performance for a flow ratio (regeneration to process air flow rate) near 0.8. Testing is currently being performed for a range of 0.6 - 1.0 for parametric study and to verifiy this prediction. Rotation speed can have a 10% to 15% effect on performance. SERI's present test matrix calls for a wide range of speeds. Low speeds will allow us to check the equilibrium properties used in the math model, while high speeds will allow us to check the effective Lewis number (importance of solid-side diffusional resistance to gas-side mass transfer).

In the recirculation cycle process inlet conditions are cooler and somewhat drier than in the ventilation cycle. The regeneration humidity ratio is significantly higher, which is typical. Model predictions of optimum flow ratios near 0.6 show the effect of these changes. Purging the hot, wet wave of air from the dehumidifier can have a 8% to 12% effect on performance. A range of purge angles will be tested and the model predictions verified.

The typical examples cited, although concentrating on steady-state results, will be taken so as to produce useful transient data.

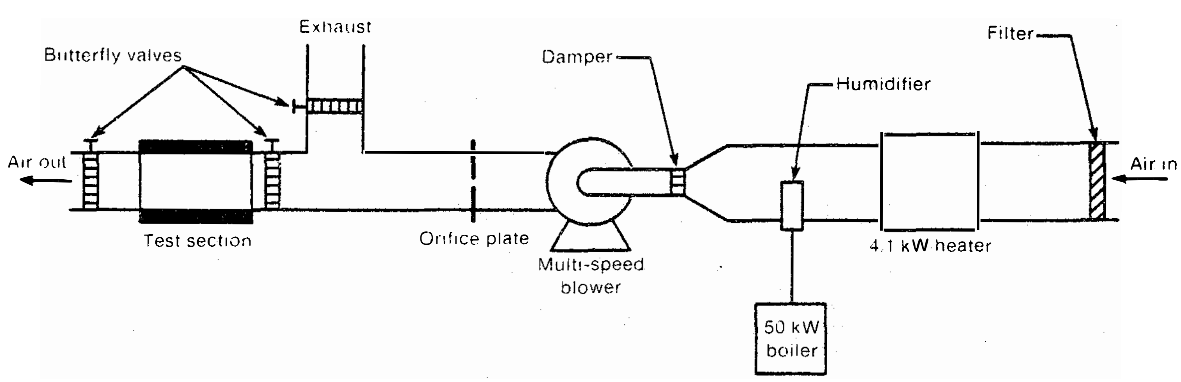

Fig. 9. Schematic of Single Blow Test Facility

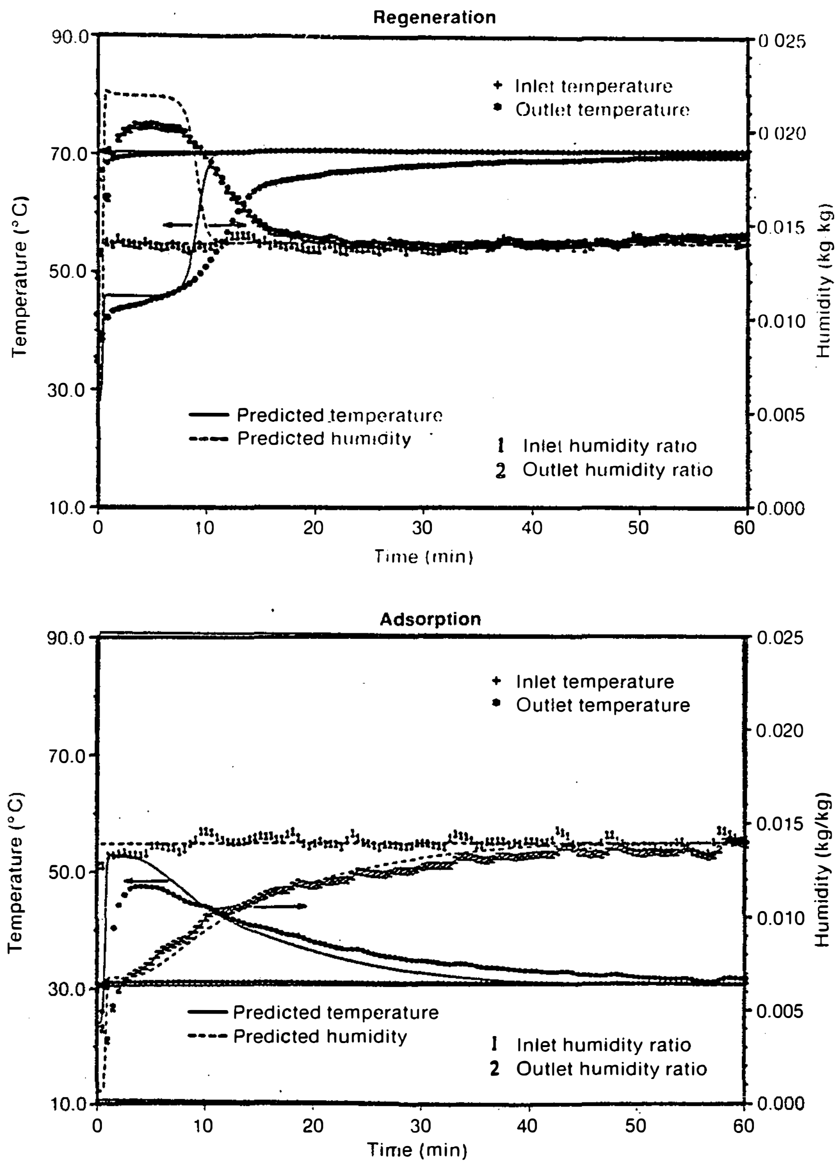

Fig. 10. Typical Results from Single-Blow Test Facility

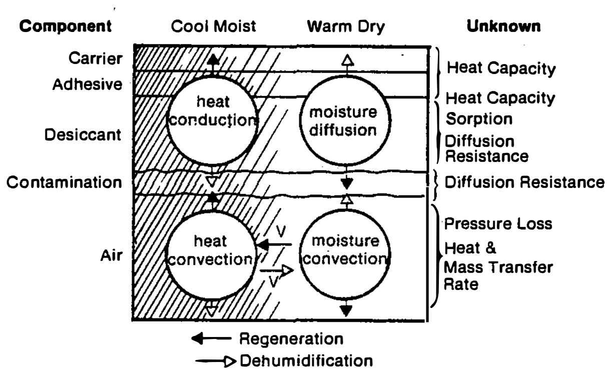

Fig. 11. Combined Heat and Mass Transfer Processes in a Dehumidifier

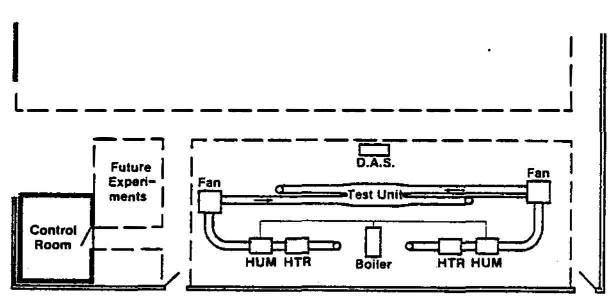

Fig. 12. Schematic of Cyclic Test Facility

Figure 13 shows data taken on a typical dehumidifier geometry. Notice how there is a direct relationship between the rotational speed and transient response. Steady-state values are reached after fifty (50) minutes of testing on this particular device.

Validation of steady-state models is of first importance because of its usefulness in system simulations, numerical investigations of design variation, and in providing feedback to materials and transfer coefficient research. However, accurate transient models are important to more accurately determine "real" system performance and in developing efficient system control strategies. Once again, validated theoretical models are intended to provide industry with tools to design desiccant dehumidifiers with improved confidence.

SYSTEMS ANALYSIS ACTIVITIES

As shown in Fig. 6, all of the experimental data is reduced in a form suitable to validate property, heat and mass transfer, and component and system models. It is at the system modeling level that fundamental research directions can be parametrically analyzed.

The University of Wisconsin has utilized the general system analysis computer code, TRANSYS, to provide more credible estimates of the impact on performance by changing various material, component, and system parameters. To the degree of uncertainty by which we can model the physical processes in a desiccant cooling system, this type of analysis can set performance goals for the material and components that reduce the gap between conventional technologies and the alternatives. For example, the payoff to develop a new material with a certain isotherm shape can be assessed with respect to overall system performance, size reduction, parasitic power requirements, and so on. These tradeoffs can show where the greatest sensitivities are, and hence, define new challenges for the research community. Without this feedback the payoff would be unclear and it would be hard to defend research opportunities.

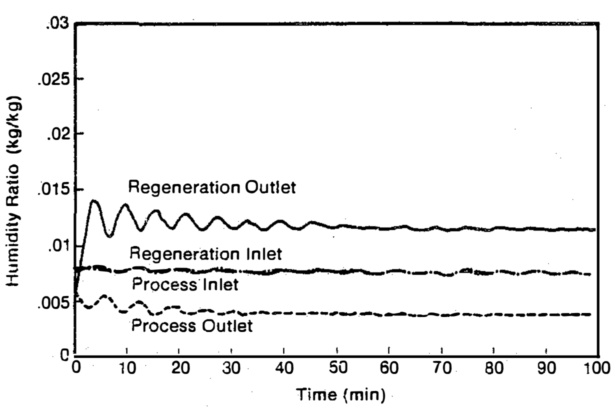

Fig. 13. Preliminary Results from Cyclic Test Facility

Systems analysis efforts also provide the opportunity to look at creative ideas, such as hybrid (dehumidification coupled to vapor compression) cooling options or entirely new concepts.

The Florida Solar Energy Center (FSEC) [57] under funding from DOE is investigating a novel cooling concept (Fig. 14) that couples a desiccant dehumidification technique with a night-sky cooling concept. Night-sky cooling works efficiently where buildings can radiate daytime generated heat to the night sky. To do this, the temperature difference between the building surface (usually the roof) and the clear, deep night sky must be as great as possible. This is a cooling technique that works well in the southwest, where air temperatures and solar heat loads are high during the day and where the night sky is very clear and cold.

In places like Florida nighttime air is quite humid, and the sky temperature is generally much closer to that of the buildings roof surface. Researchers at FSEC state that the humid air acts as a blanket between the roof surface and night sky, preventing the roof from radiating heat efficiently to deep space. To overcome the effects of humidity and small temperature differences the roof surface temperature would have to be raised to achieve significant cooling potential.

FSEC's concept uses a desiccant material to adsorb moisture from the air to drive up the temperature of a metal roof radiator. Conceptually, they feel a building would be designed structurally with well-insulated concrete block walls with internal cores as the cooling ducts. During the day, the massive walls would store internally generated heat and moisture from the building. At night air would be forced through the ducts carrying the stored heat and moisture to the roof plenum (attic). Within this space, a thin bed of silica gel would adsorb this moisture from the humid air. During the day, the roof would transfer solar radiation to the room plenum and dry the silica gel for the next night's cycle of adsorption. The moisture from the silica gel would be carried away by an

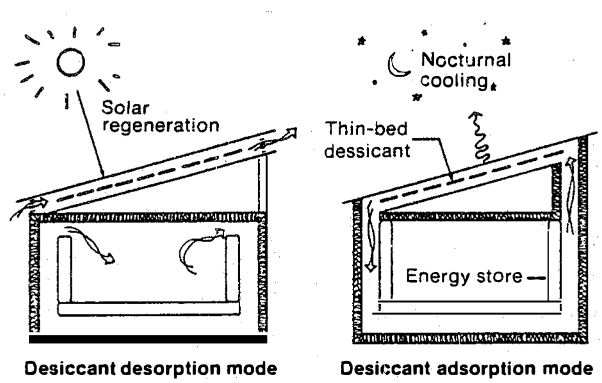

Fig. 14. A Novel Cooling System Proposed by FSEC

air current between the metal roof and the desiccant bed. A radiant barrier under the silica bed would prevent radiant heat from crossing the attic and penetrating into the building itself. FSEC is analyzing this concept to see if the system is technically feasible.

PROJECTIONS FOR THE FUTURE

There are several promising outlooks for desiccant cooling applications in the future. GRI development projects are expected to yield 5- to 20-ton gas regenerated desiccant cooling systems with thermal COPs at an ARI design condition of over 1.1. On a seasonal basis thermal COPs of 2.0 or higher will be achieved by use of the evaporative cooling feature at less humid, off-design conditions. An EER of 35 or higher (0.34 kW/ton) for electric parasitic power requirements of fans, pumps, and wheel motors is projected.

GRI's cooling system package is projected to be larger than the equivalent capacity electric vapor compression units. The installed costs of these systems are also projected to be higher than the electric vapor compression alternative, but if the project goals are met, it should provide attractive payback periods of under three years, depending on climate and local energy prices.

The first gas regenerated desiccant cooling systems introduced to the marketplace will be light commercial units of 5 to 10 tons. These should be commercially available June 1988. Field tests of several prototypes will be carried out during the summer of 1986.

The substantial progress over the past 20 years in developing adiabatic desiccant open cooling (ADOC) cycles, as reviewed in this paper, can be measured by the increases in thermal COP with the time shown in Fig. 15. The state of the art is a thermal COP of 1.0 at ARI standard test conditions.

SERI's planned research in materials and component heat and mass transfer will raise the thermal COP to 1.3 by 1990 while enabling manufacturers to reduce costs and increase market penetration (Table 1) [52]. After 1990, emphasis will shift from the dehumidifier to other components and from the classical ventilation cycle to new cycles currently the subject of academic debate [45,46]. This will enable the target [52] of a thermal COP over 2.0 to be achieved for an ADOC cycle by the year 2000. The ratio of gas to solar collector cost is expected to have increased to a level at which more than half the thermal energy will be solar.

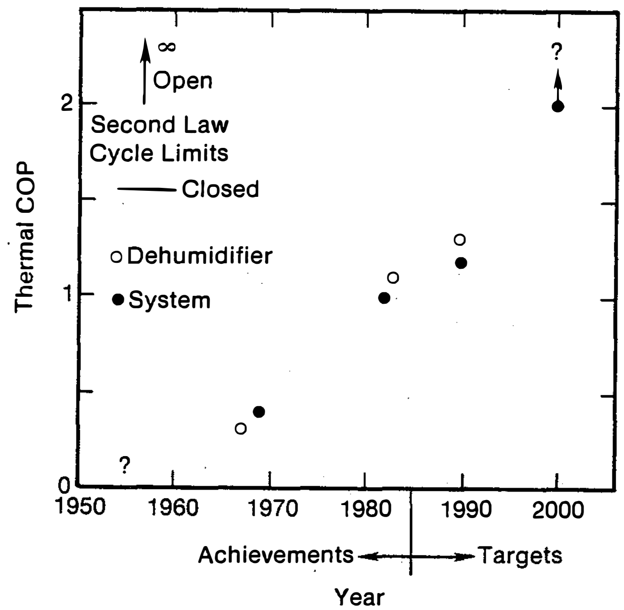

Fig. 15. Progress in ADOC Cycle Thermal Coefficient of Performance at ARI Conditions

CONCLUSIONS

The feasibility of a solar desiccant cooling system is here today. Many choices and compromises must be made to arrive at an acceptable system design. One design team may be excited by a new material breakthrough, while another team could be satisfied with existing materials but interested in increasing mass transfer to reduce dehumidifier size. Others, whose product line may be evaporative coolers, could be inspired by a promising new cycle using their product and would use existing technology to accomplish the dehumidification. With these conflicting requirements SERI's facilities are generic to most of these concerns. The research is performed on a logical path with experimental data providing input to validate math models intended for industry to use as engineering design tools.

Research goals based on an objective analysis of the material, component, and system's ideal limits provide the rational behind DOE's Cooling Program. As technology transfers are made from the basic research community to industry, further market penetration by renewables is imminent. Going from a research stage to a product line involves risk. The private sector knows that both the industrial and residential consumer will ultimately make their decision based primarily upon the cost-effectiveness of the product or system. Successful businesses know when to take this risk.

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Table 1 Technology Status - Solid Desiccant Cooling

Component/System		Current Status	5-Year Goals	Long Term Goals
Dehumidifier	Coefficient* of Performance	1.1	1.3	2.0–3.0**
	Cost	$1,200-$1,800/Ton	$1,000/Ton (projected)	$500/Ton (projected)
	Life	10 Years	10 Years	15 Years
System	Coefficient* of Performance	1.0	1.2	2.0**
	Cost	$3,500/Ton (estimate)	$2,000/Ton (projected)	$1,500/Ton (projected)
	Life	10 Years	10 Years	15 Years

*At ARI Standard Conditions.

**Maclaine-Cross, I.L. (1985)—The higher COP applies to large (commercial) systems.

Electron, Anthony Fraioli of Argonne National Laboratory, Jim Coellner of American Solar King, Kennard Bowlen of Cargocaire, Al Czanderna, Larry Flowers, Ahmad Pesaran, Kenneth Schultz, and Federica Zangrando from the SERI Desiccant Research Team. The preparation of the manuscript and typing was patiently and meticulously handled by Ms. Deborah Chroniak.

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