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OVERVIEW OF DEVELOPING PROGRAMS IN SOLAR DESICCANT COOLING FOR RESIDENTIAL BUILDINGS

TO BE PRESENTED AT THE
ANNUAL MEETING OF THE AMERICAN
SOCIETY OF HEATING, REFRIGERATING,
AND AIR-CONDITIONING ENGINEERS

DETROIT, MICHIGAN

JUNE 24-28, 1979

Solar Energy Research Institute

1536 Cole Boulevard
Golden, Colorado 80401

A Division of Midwest Research Institute

Prepared for the
U.S. Department of Energy
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DISCLAIMER

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ABSTRACT

This paper provides an overview of the ongoing work in desiccant cooling under the national solar heating and cooling research program. Open cycle adsorption and absorption systems are examined. The different dehumidifier bed configurations are the distinguishing features of these systems. The basic operating principles of each dehumidifier concept are explained along with some discussion of their comparative features. Performance predictions developed by SERI for a solar desiccant solar system employing an axial-flow desiccant wheel dehumidifier are presented. In terms of life-cycle cost and displaced fossil-fuel energy, the results indicate that it should be beneficial to use solar desiccant coolers in residential applications. Although no prototype testing of any of these concepts is currently underway, test results are expected and will be reported within one year.

INTRODUCTION

Several air-conditioning configurations involving different physical, chemical, and electrical processes can be used to produce cooling effects adequate for residential buildings. These systems are summarized in Table 1.

TABLE 1

POTENTIAL AIR-CONDITIONING PROCESSES

Process Type	Open Cycle	Closed Cycle
Mechanical compression	Air cycle	Rankine cycle Brayton Stirling
Absorption	Desiccant	Absorption
Adsorption	Desiccant	Adsorption
Electronic transport	Thermionic emission	Peltier effect

The processes can be implemented in open or closed cycles. The closed cycle involves two separate process loops coupled by heat exchangers, with one loop for the refrigeration process and the other for the transfer of heat from the load. The open cycle eliminates the interfacing heat exchanger by combining the process and heat transfer loops.

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Contractors for the U.S. Department of Energy (DOE) are performing research and development work on solar cooling systems involving desiccation processes. In the open cycle adsorption processes, three contractors are developing solar cooling systems with different dehumidifier bed concepts. These projects are in various stages of completion, ranging from basic research and analysis to cooling system development and commercialization studies. Several other organizations have studied the open cycle absorption process, with proposed differences in the systems mainly in the method of regenerating the desiccant material. DOE has given the Solar Energy Research Institute (SERI) program management responsibilities for national solar cooling programs using desiccant processes, and SERI is continuing its own research program in desiccant cooling.

OPEN CYCLE ADSORPTION PROCESSES

The open cycle adsorption desiccant processes in Table 1, when coupled to a solar energy supply system, represent a potentially attractive alternative to conventional air-conditioning systems. Most existing refrigeration and air-conditioning equipment operates on a closed mechanical compression cycle, specifically the Rankine vapor compression cycle. The major advantages of a solar desiccant cooler based on a recyclable air desiccation process include:

- It uses inexpensive materials and has potentially low manufacturing cost.
- It usually uses air and inert inorganic materials and thus may not present corrosion or environmental problems.
- It can tolerate air leakage and be serviced easily.
- It can tolerate a wide range in solar input and still generate a useable output.

Most of the research and development work on the adsorption process for solar cooling applications has focused on the desiccant cycle. The early work was done in Australia (Commonwealth Scientific and Industrial Research Organization) and the United States (Institute of Gas Technology) on systems using two open process air streams thermally coupled through rotary regenerators. The building air stream was dried in a desiccant bed, cooled in a regenerative heat exchanger, and refrigerated by evaporative cooling. The air dryer was reactivated by an outside air stream that was solar heated to supply the desorption energy. In both cases, the desiccant bed operated in an adiabatic process.

Although many desiccant materials can adsorb water vapor from air, attention has focused on molecular sieve and silica gel. The equilibrium adsorption curves for molecular sieve and silica gel are given in Fig. 1 [1]. Molecular sieve has better adsorption characteristics at low relative humidities or at high temperatures. Thus, dehumidifiers using molecular sieves can operate successfully in the adiabatic mode where both the dehumidified air and the desiccant bed are at high temperatures. Molecular sieves, however, require relatively high regeneration temperatures (150°C) for desorbing which for solar energy applications means using high performance collectors or a solar system combined with an auxiliary heat source.

Silica gel, on the other hand, can be desorbed at relatively low temperatures. Fig. 1 shows that the equilibrium water capacity of silica gel is very small at relatively low temperatures (80°C), which allows silica gel dehumidifiers to utilize simple flat-plate collectors for regeneration. However, silica gel also has good adsorption capacity only at low temperatures, and its adsorption capacity decreases rapidly as the bed temperature increases. The performance of a silica gel bed is improved if the adsorbent is maintained at a low temperature during dehumidification by removal of the heat of adsorption.

Desiccant System Alternatives

The major, unique component in all desiccant cooling systems is the dryer bed, which removes moisture from the air being processed in the system. If this step can be accomplished without a substantial fraction of the heat of condensation remaining in the process stream, all of the cooling in the cycle is completed. The subsequent isoenthalpic evaporative process simply converts latent capacity into sensible cooling.

The various ongoing projects in desiccant cooling can be described in terms of the approach they take to the dryer bed design. Four concepts are depicted in Figs. 2 to 5 and are compared in Table 2.

TABLE 2

DEHUMIDIFIER BED CONCEPTS

Approach	Fig.	Material	Advantages	Concerns
Rotary axial flow	2	molecular sieve	compact design; prototype model exists	requires gas boost; large auxiliary power; large air duct system
Rotary radial outflow	3	silica gel	reduced auxiliary power; low temperature reactivation	silica gel without cross cooling; large air duct system
Cross-cooled fixed bed	4	silica gel	low temperature reactivation; compact size	added auxiliary power in cooling; large air duct system
Liquid spray	5	lithium chloride	minimum auxiliary power; potential for simple collectors	mass transfer rates; loss or contamination of the desiccant

Rotary Axial Flow Systems. The Institute of Gas Technology (IGT) is developing a solar desiccant cooling system that employs a molecular sieve dehumidifier wheel and a natural-gas-fired burner to supplement the delivered solar energy. Other components include evaporative coolers and a rotary regenerative heat exchanger between the process and reactivation streams. A substantial amount of development work has been done on this concept, culminating in field tests of prototype systems [2]. The performance of these prototypes indicated that reliable cooling is possible but that further development work is necessary to reduce thermal and auxiliary power requirements.

The major component of the system is the desiccant wheel, which converts warm, moist air to dry air. Rather than employing stationary beds and switching air streams as in a cross-cooled dehumidifier, the desiccant wheel keeps the process and reactivation air streams stationary and moves the desiccant bed alternately between the two streams. The desiccant wheel is constructed from a special composite paper containing asbestos fibers and molecular sieve. Part of the current work effort is seeking a replacement material for the asbestos matrix.

As shown in Fig. 2a [3], a rotary desiccant wheel is divided by a partition into two balanced-flow segments, one for moisture removal and the other for the passage of the high temperature (approximately 125°C) reactivation air stream. These two streams flow in opposite directions. Fig. 2a shows the simplest desiccant wheel configuration.

Fig. 2b [3] shows two design improvements currently in development: a purge section and a two-stage reactivation temperature.

As the desiccant wheel crosses the transition from the reactivation zone to the process zone, the desiccant material is hot and dry. Thus, little or no dehumidification occurs in the first portion of the process zone (10° to 15°) until the desiccant is cooled sufficiently. The purge zone removes heat from the initial process section of the wheel for recycle to the reactivation stream. The net result is a lower primary energy requirement for the reactivation stream and lower average process stream humidity and temperature.

The two-stage reactivation temperature scheme can result in a significantly drier process stream at the expense of a slightly higher process stream temperature. The portion of the wheel moving from the process side to the reactivation side is wet and warm. Thus, the reactivation stream temperature in the first part of the reactivation zone need not be as severe as in the later stages of reactivation when the wheel is relatively hot and dry.

These design modifications have the potential to significantly improve the capacity and efficiency of the state-of-the-art axial flow wheels. In addition, two-speed fan operation should reduce auxiliary power requirements by reducing the part-load power draw.

Prototypes employing axial-flow, desiccant wheel dehumidifiers have been field-tested. The current program includes the laboratory testing of a desiccant cooler with improved design features resulting from the ongoing development effort. Test results should be available in the Fall of 1979.

Rotary Radial Outflow System. AiResearch Manufacturing Company is developing a solar desiccant cooler featuring a rotary radial outflow configuration with a granular silica gel dryer bed and a regenerator. The design is configured to reduce auxiliary power requirements of the dryer and heat exchanger components by increasing their face area and reducing the airflow length.

Figs. 3a and b [4] illustrate the air conditioner schematic (with projected performance parameters) and the dehumidifier arrangement. The desiccant bed and the regenerator are two counter-rotating concentric drums. The desiccant material is granular silica gel and the regenerator matrix is a fine screen of galvanized steel.

A top view of the dehumidifier along the axis of rotation is shown in Fig. 3b. The solar heater is located between the dryer and regenerator. Warm, humid air from the residence is directed to the adsorbing side of the rotary dryer. Water is adsorbed from the air stream, which is heated in the process. The air is then cooled in the rotary regenerator. The specific humidity of this air stream is sufficiently low that its dry-bulb temperature can be lowered by adiabatic humidification to levels adequate for sensible cooling while retaining reasonable latent cooling capacity.

Ambient outside air is used to regenerate the sorbent bed and cool the rotary regenerator. First, the outside stream is humidified adiabatically and circulated through the rotary regenerator. About one-half of the stream is then exhausted from the dehumidifier without flowing through the dryer. The remainder is heated in a fixed-boundary heat exchanger by solar thermal energy and passed through the dryer to desorb the desiccant.

A minor amount of air directly from the ambient stream is circulated through the hot portion of the sorbent bed as it rotates from the desorbing zone to the adsorbing zone. In this way, the bed is cooled to a temperature level at which it can adsorb moisture from the return air from the residence. The preconditioning air flow is then used to preheat the bed prior to desorption, thus reducing the solar thermal energy necessary for this purpose.

This program will include the laboratory testing of a dehumidifier bed and a 5.4 kW prototype cooling system. The tests are scheduled for completion in the Fall of 1979.

Cross-Cooled Fixed Bed System

The Illinois Institute of Technology (IIT) is developing a solar desiccant cooling system that uses silica gel in a cross-cooled dehumidifier. The present system consists of a cross-cooled dehumidifier constructed of paper-like sheets of silica gel in a Teflon matrix. This concept is represented schematically in Fig. 4 [5]

The cooling system consists of two cross-cooled dehumidifiers of equal size in conjunction with evaporative coolers. One dehumidifier removes moisture from the process air while the other is being regenerated with solar energy. The process air leaving the cross-cooled dehumidifier in the dehumidification mode is dry and only moderately warm. Cooling is achieved by evaporation of water. In the adsorbing cycle, the air from the conditioned space is passed through the process channels of the dehumidifier, with the cross-cooling accomplished either by ambient air or by room air. In the desorbing cycle, the saturated bed is regenerated by hot air from flat-plate solar collectors. A rock-bed storage system is provided for storing the excess collected energy. There is also the possibility of storing excess cooling capacity in rock-bed storage.

The system can operate in a recirculating or ventilating mode. In the recirculating mode, the air from the room is passed through the process channels, which are lined with silica gel sheets, to achieve the required dehumidification. The process stream leaving the dehumidifier is sprayed with water before it enters the conditioning space. The cross-cooling stream is evaporatively cooled ambient air. In the ventilating mode, ambient air is passed through the process channels and evaporatively cooled room air is passed through the cross-cooling channels.

Much of the current work on this concept is still basic research and development, including development of mathematical analysis methods and testing of silica gel sheets and small models of the isothermal dehumidifier bed. However, a 2.7 kW prototype cooling system will be built and tested under the current program.

Liquid Desiccant (Absorption Process) Systems

A solar cooling concept which is gaining interest is the continuous open cycle absorption cooler. This concept, initially developed over 40 years ago, has received recent attention from researchers in the U.S.S.R. [6, 7]. The absorption cycle is similar to its closed cycle counterpart except that the weak absorbent solution regenerates by losing refrigerant to the earth's atmosphere instead of being recovered in the condenser. Cooling is accomplished by evaporating refrigerant from an external source in the evaporator rather than by obtaining refrigerant from the condenser. Thus the condenser is eliminated in the open cycle; however, an external source of refrigerant must be available. Whenever the refrigerant is water, the open cycle becomes very feasible.

A schematic diagram of an open cycle absorption cooling system similar to that built and operated by Russian investigators is shown in Fig. 5 [8]. The weak absorbent solution is heated and then concentrated in the solar collector, which is open to the atmosphere. The strong regenerated solution leaves the collector and passes through a liquid column in which pressure is reduced from atmospheric levels. The strong solution then passes through a regenerative heat exchanger and then to the absorber, where the strong solution absorbs water from the evaporator, maintaining the reduced pressure required by the evaporator. The heat of absorption for the water-absorber solution is removed by heat transfer to a cooling tower loop. In the evaporator, water from an external source is evaporated at reduced pressure with the energy supplied by heat from the cooled space. The resulting weak solution is pumped from the absorber back to atmospheric pressure through the regenerative heat exchanger and to the collector, completing the cycle. The vacuum pump shown is necessary to deaerate the solution after it has been exposed to the atmosphere.

An important aspect of the open cycle refrigeration system in Fig. 5 is the unique relationship between collector performance and system performance. The useful energy output of both the collector and the cooling system is the evaporation of water. For every pound of water evaporated in the collector, one pound of water can be evaporated in the evaporator and absorbed in the absorber. Thus, the water evaporation rate from the collector determines cooling system performance.

A major advantage of this system as compared to a conventional closed cycle absorption system is the simplicity of the collector. The solar collector for the open cycle can be simply a tilted, flat, blackened surface over which absorbent solution flows as a fluid film. No glazings, fluid flow channels, selective surfaces, etc., are required. The solution is heated by contact with the solar-energy-absorbing roof. Its temperature is raised to a point at which the solution water vapor pressure exceeds that of the atmosphere, at which time an energy and mass transfer process begins.

Other system configurations for an open cycle absorption cooler are possible. One possibility is a mass transfer of water vapor from the dilute solution using a closed air-heating collector with some gas/liquid contacting device such as a packed bed. The packed bed is supplied with solar-heated air which drives off the refrigerant vapor. This concept could broaden the application of the open cycle system to more humid locations and eliminates a problem inherent in the open collector design, namely, foreign particles and rain entering the system.

SERI is evaluating the open cycle absorption process to determine its potential for solar cooling and to establish research priorities for reaching that potential. Although some research and development work has been done, much more effort is required to develop a viable residential or commercial cooling system.

PERFORMANCE PREDICTIONS

During the past several months, SERI has begun developing computer models for use in evaluating the performance of the various desiccant cooling systems. SERI has studied a solar desiccant cooling system employing an early version of an axial flow desiccant wheel similar to that shown in Fig. 2a. The study evaluated residential solar cooling potential to identify optimum cooler/collector system sizes, climatic conditions, and economic parameters. The steady-state performance of the desiccant cooling system was analyzed, and a dynamic analysis was performed for five U.S. cities using hourly weather data to determine seasonal solar desiccant cooler performance. Typical results presented here illustrate potential desiccant cooler performance.

Figs. 6 and 7 [9] show the steady-state performance of a nominal 9.0-kW-capacity solar desiccant cooler. These plots illustrate the effect of ambient humidity and regeneration temperature on cooler capacity and the coefficient of performance (COP). Increasing ambient humidity tends to decrease the desiccant cooler capacity and COP, as shown in Fig. 6. However, the desiccant cooler shows the most sensitivity to regeneration temperature. Fig. 7 shows that the cooler capacity varies greatly with regeneration temperature and that the system COP peaks around 75 to 80°C. The design capacity (9.0 kW) requires about an 85°C regeneration stream.

The annual performance of the solar desiccant cooler is the determining factor in whether the cooler can be applied beneficially to residential cooling. Maximum cost-effectiveness occurs when a system is sized for solar heating and cooling is added as a complementary summertime use of the collected energy. Thus, the chiller must be sized to operate efficiently with the available collector area, and the load must be reasonably consistent with the resulting capacity. The sunny parts of the middle United States generally meet these constraints. Of the five cities studied by SERI, Washington, D.C. represents the best climate for solar desiccant coolers. For a solar desiccant cooler in Washington, D.C. with an electrically-driven vapor compression cooler as backup, a desiccant cooler of 4.5 kW capacity could be driven from 35 m^2 of solar collectors. The annual desiccant cooler COP would range from 0.5 to 0.6, and the energy efficiency ratio (EER) could be in the range from 13 to 18 (EER is defined here as the seasonal cooling capacity delivered divided by the total electrical energy input).

These results, in terms of cost and displaced fossil fuel in Fig. 8, show that it should be beneficial to use solar desiccant coolers combined with solar space heaters in residential applications. Fig. 8 shows cost/benefit (defined as the life-cycle cost of the solar system divided by the life-cycle cost of a conventional system) and percent fossil fuel energy displaced for solar space heating/vapor compression cooling and solar space heating/solar desiccant cooling systems. Adding a solar desiccant cooler to a solar space heater increases the system cost effectiveness (the solar system is cost effective when cost/benefit is less than or equal to 1.0). In addition, fossil fuel energy is conserved by employing solar desiccant cooling in place of conventional vapor compression systems.

According to evaluations made by the DOE cooling contractors, the potential exists for even more efficient systems with designs of the type described in the first part of this paper. It is not yet clear which design can achieve the most cost-effective air conditioning system. The promise of an efficient solar desiccant cooler that can conserve fossil fuel and compete effectively with conventional air conditioning methods continues to be pursued aggressively and supported by a test and analysis program.

CONCLUSIONS

An advanced solar desiccant cooling system with a COP in the range from 0.6 to 0.8 can be achieved with solar collector output temperatures of about 70°C to 85°C. When integrated with a collector system, this combination may be able to achieve a higher cooling capacity per unit of input solar energy than alternative solar cooling techniques. It may also be capable of significantly exceeding the EER of conventional air conditioning sources and result in the displacement of large amounts of fossil energy from building cooling applications. To realize this potential, however, several difficult engineering problems must be solved. These include:

ADVANCED SYSTEM DEVELOPMENT

- Reduction of auxiliary power requirements from present levels by
  - development of lower pressure-loss dehumidifier bed design and
  - increased air system efficiencies.
- Improve the system cost effectiveness by
  - reduction of both the total equipment cost and the cost or amount of adsorbent material used and
  - development of a more cost-effective regenerative heat exchanger with high heat transfer effectiveness.

IMPROVED APPLICATIONS ANALYSIS

- Development of optimized system control strategy and hardware.
- Identification of preferred system configurations, applications, and backup energy strategy.

The present program addresses all of these problem areas. Within one year, enough system test data will be available to assess preferred dehumidifier bed designs and the potential for approaching predicted system performance. Once the achievable system hardware performance is defined, the resulting economics and fossil fuel energy displacement will determine the extent to which the technology can penetrate the residential air conditioning market.

REFERENCES

1. Lavan, Z. et al., "Development of a Solar Desiccant Dehumidifier," Illinois Institute of Technology, undated.

2. Staats, William R. et al., Field Testing of Solar-MEC Systems - Final Report, Institute of Gas Technology, July 1977.

3. Wurm, Jaroslov et al., Solar-MEC Development Program - Project 9103 Third Quarter Progress Report, Institute of Gas Technology, Report No. COO-4495-13, December 1978.

4. AiResearch Manufacturing Company of California. Technical Progress Report - Development of a Solar Desiccant Humidifier, Report No. 78-14957-1, March 31, 1978

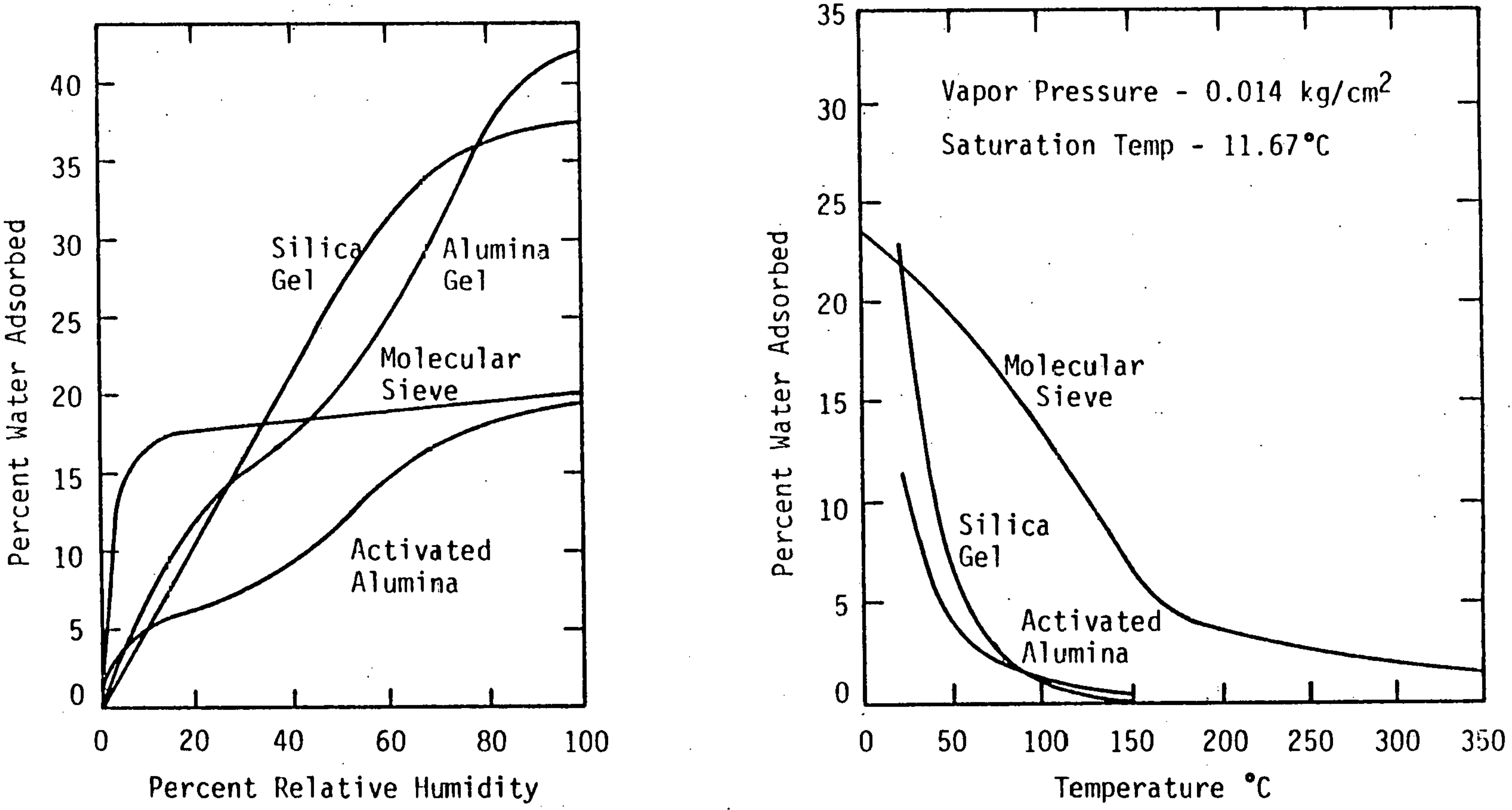
5. Illinois Institute of Technology, First Semi-Annual Progress Report on Development of a Solar Desiccant Dehumidifier," June 10, 1978.

6. Kakabaev, A. and Khandurdyev, A., "Absorption Solar Refrigeration Unit with Open Regeneration of Solution," Geliotekhnika, Vol. 5, No. 4, pp 69-72, 1969.

7. Baum, V. A. and Kakabaev, K. and Klyshchayeva, O., "Technico-Economic Characteristics of Solar Units for Cooling Buildings," Third Soviet-American Seminar on General Aspects of Solar Energy Technology, 1977, (Unpublished).

8. Collier, R. K., The Analysis and Simulation of an Open Cycle Absorption Refrigeration System, Los Alamos Scientific Laboratory, Report No. LA-UR-78-1729, undated.

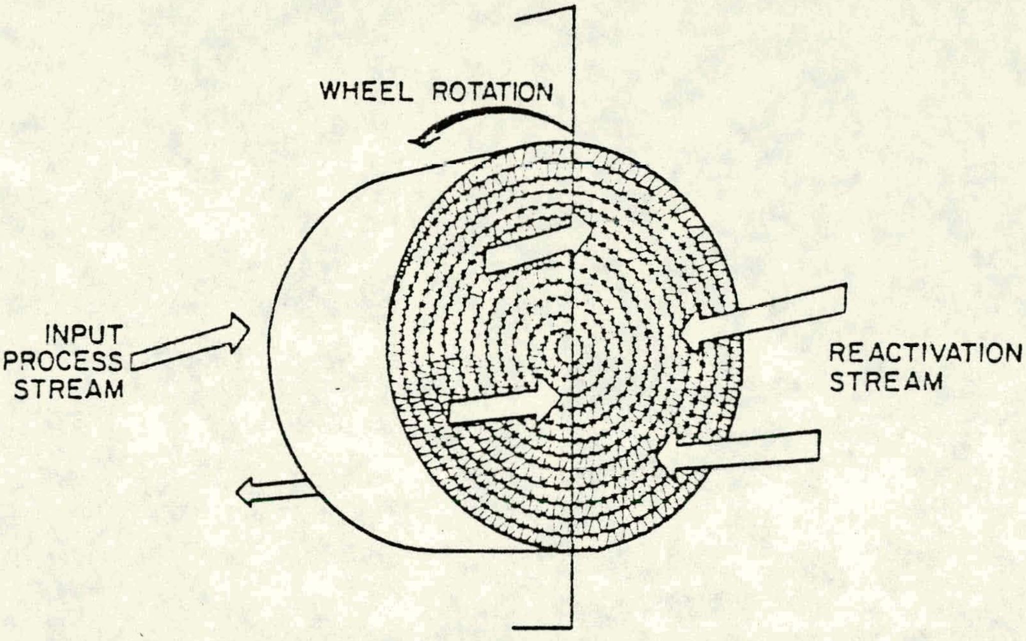
9. Shelpuk, Benjamin C., Hooker, Douglas W., Jorgensen, Gary J., and Bingham, Carl E., Seasonal Performance Simulations and Economic Analyses of Solar Heating and Disc-Type Desiccant Cooling Systems, Solar Energy Research Institute, Report No. SERI/TR-34-090 (to be published).



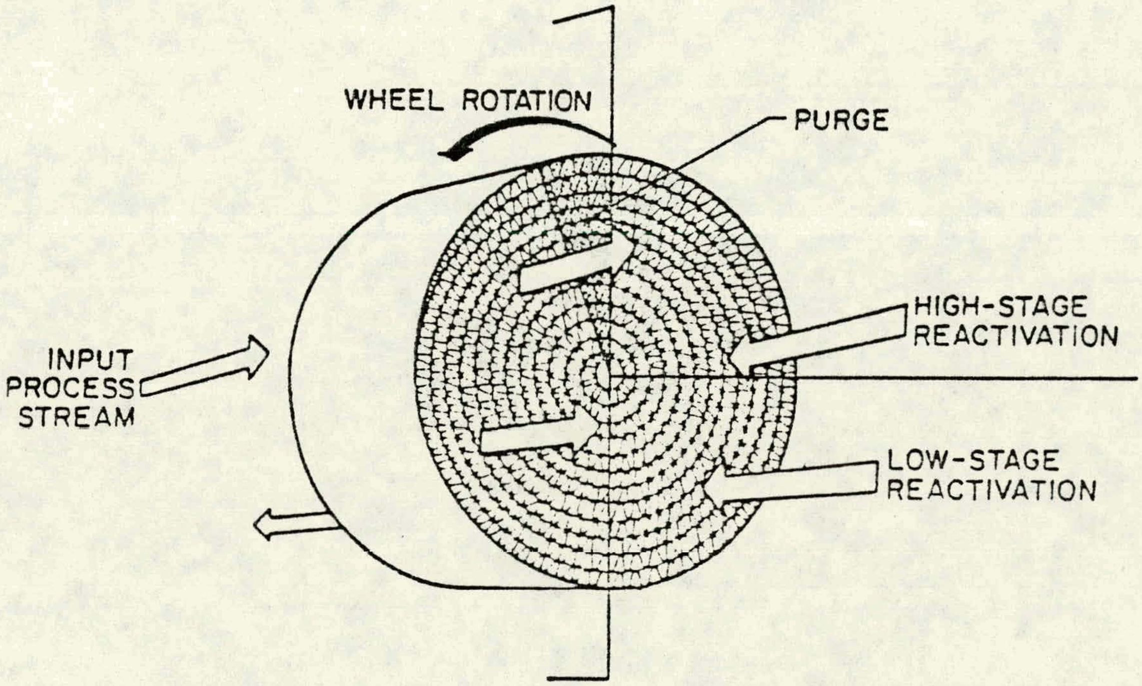
a) Adsorption vs Relative Humidity

b) Adsorption vs Temperature

Figure 1. DESICCANT/WATER-VAPOR EQUILIBRIUM CURVES [1]

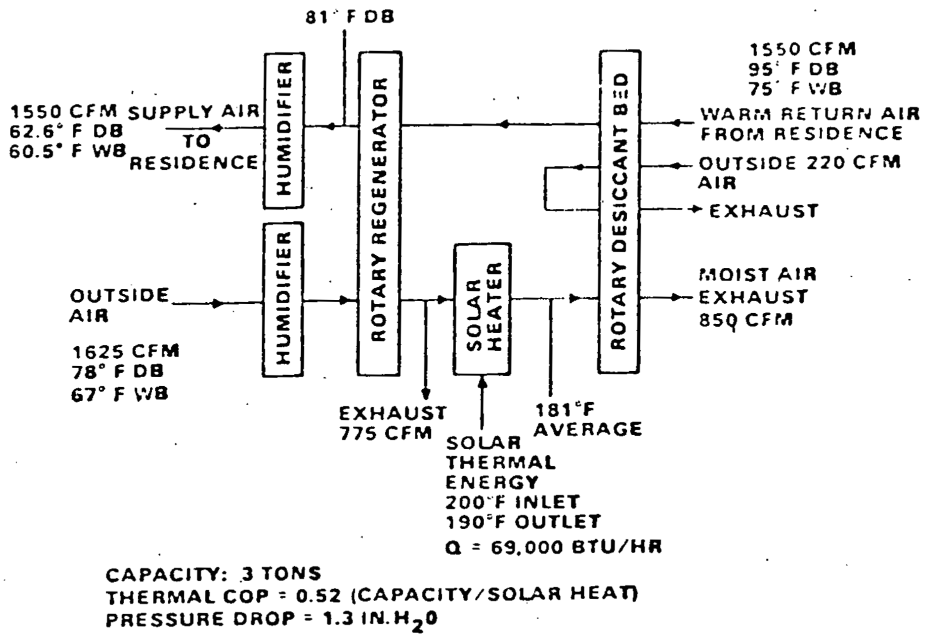


[a] Basic Desiccant Wheel

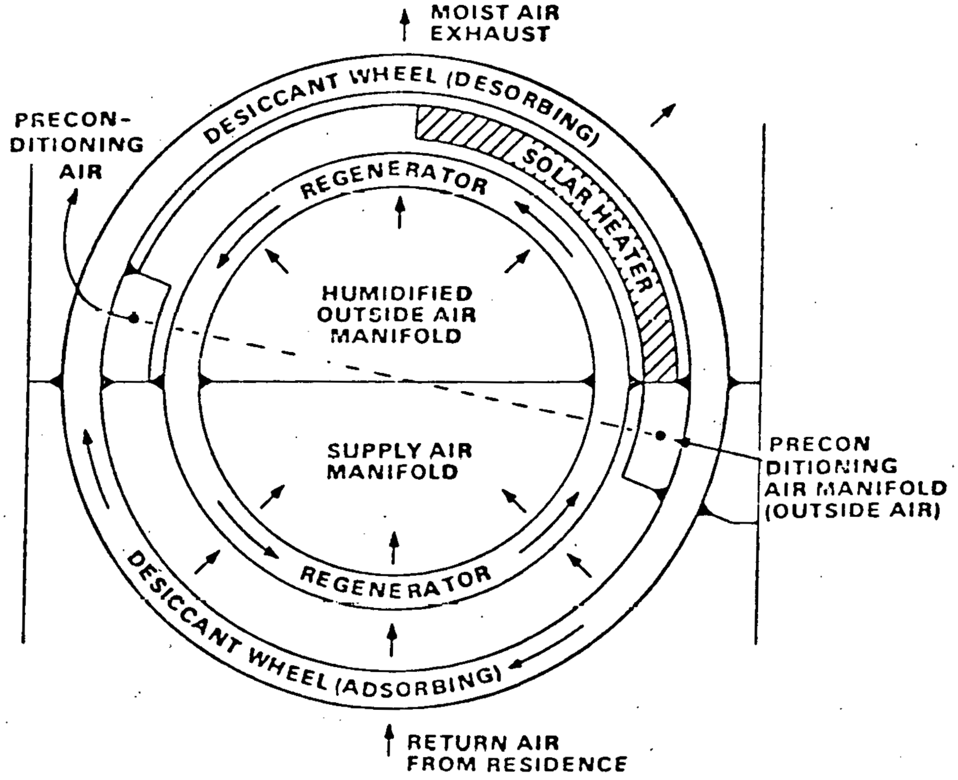


[b] Improved Desiccant Wheel

Figure 2. ROTARY AXIAL FLOW DEHUMIDIFIER [2]



(a) Schematic of Air-Conditioner Employing Rotary Bed Dehumidifier [4]



(b) Rotary Bed Dehumidifier Arrangement [4]

Figure 3. ROTARY RADIAL OUTFLOW SYSTEM [4]

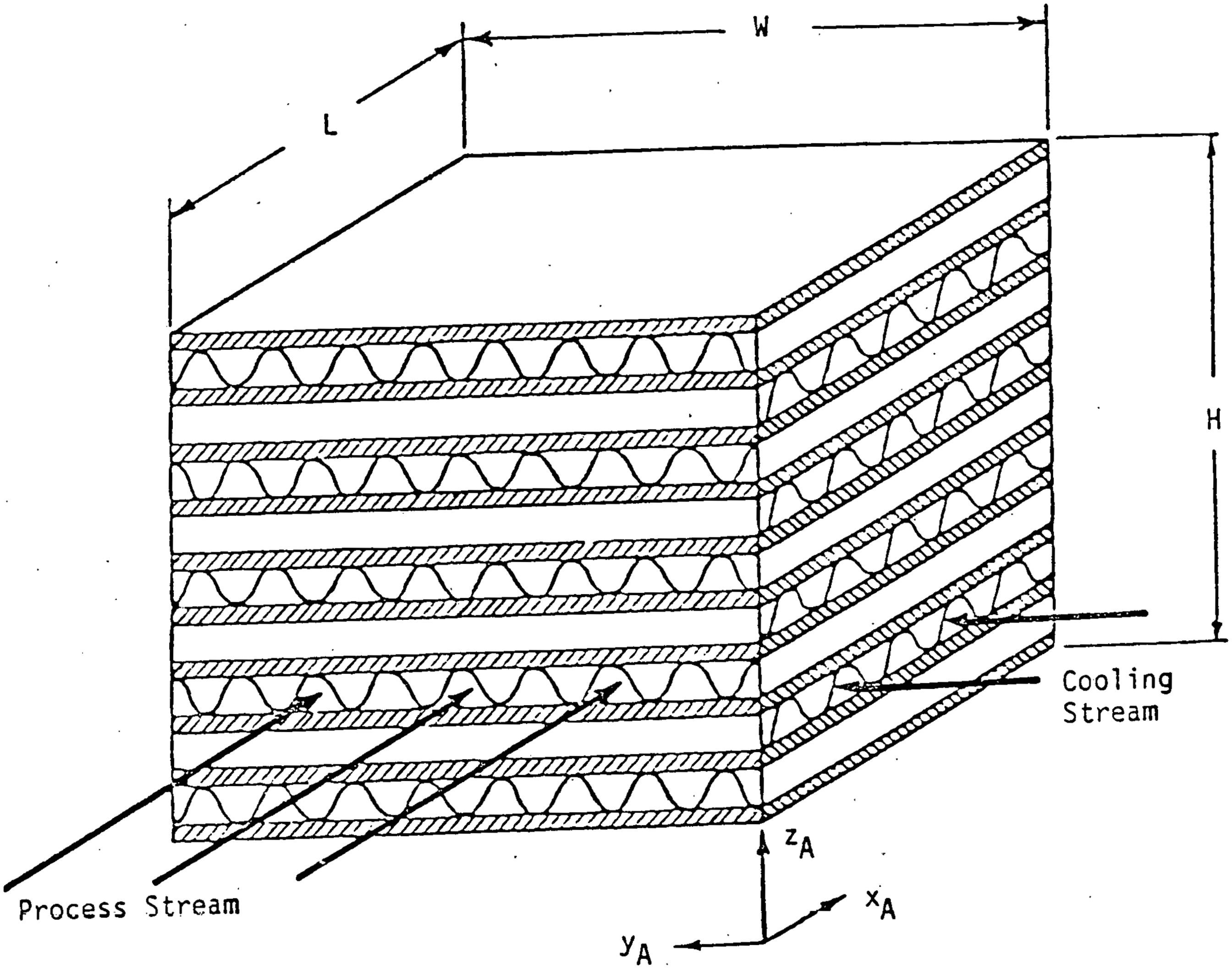


Figure 4. SCHEMATIC OF CROSS-COOLED DEHUMIDIFIER [5]

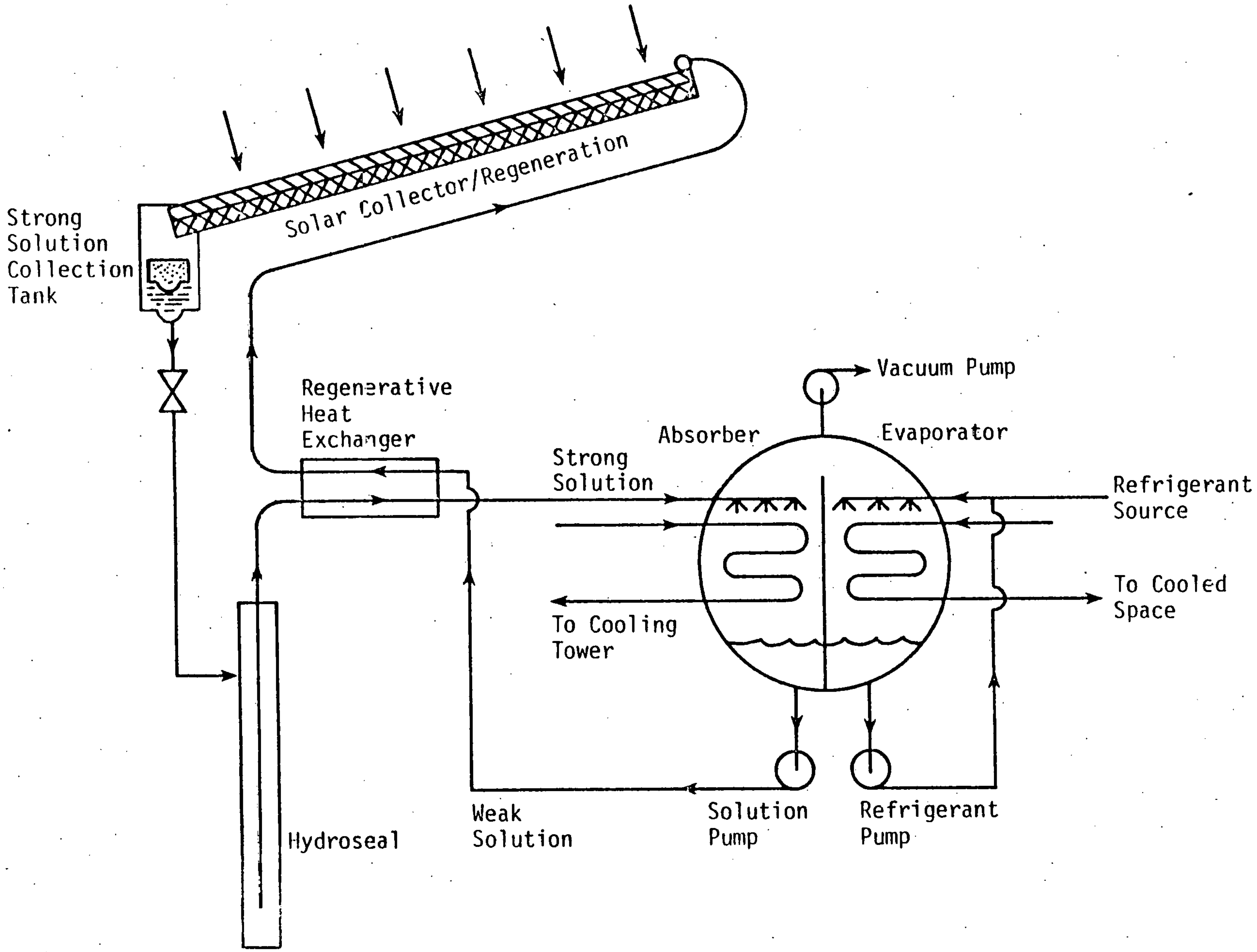


Figure 5. OPEN CYCLE ABSORPTION COOLING SYSTEM [8]

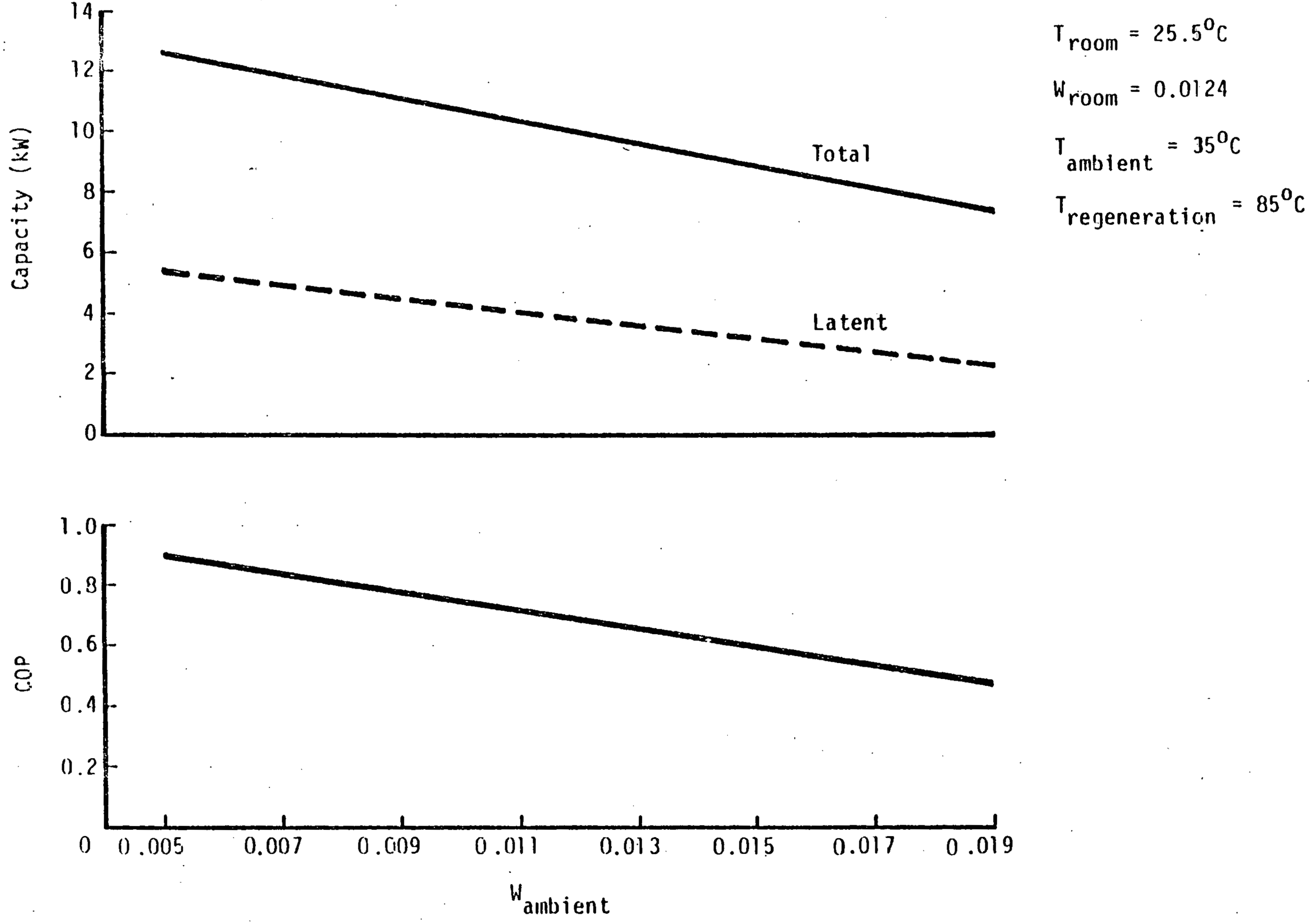


Figure 6. STEADY-STATE SENSITIVITY TO AMBIENT HUMIDITY [9]

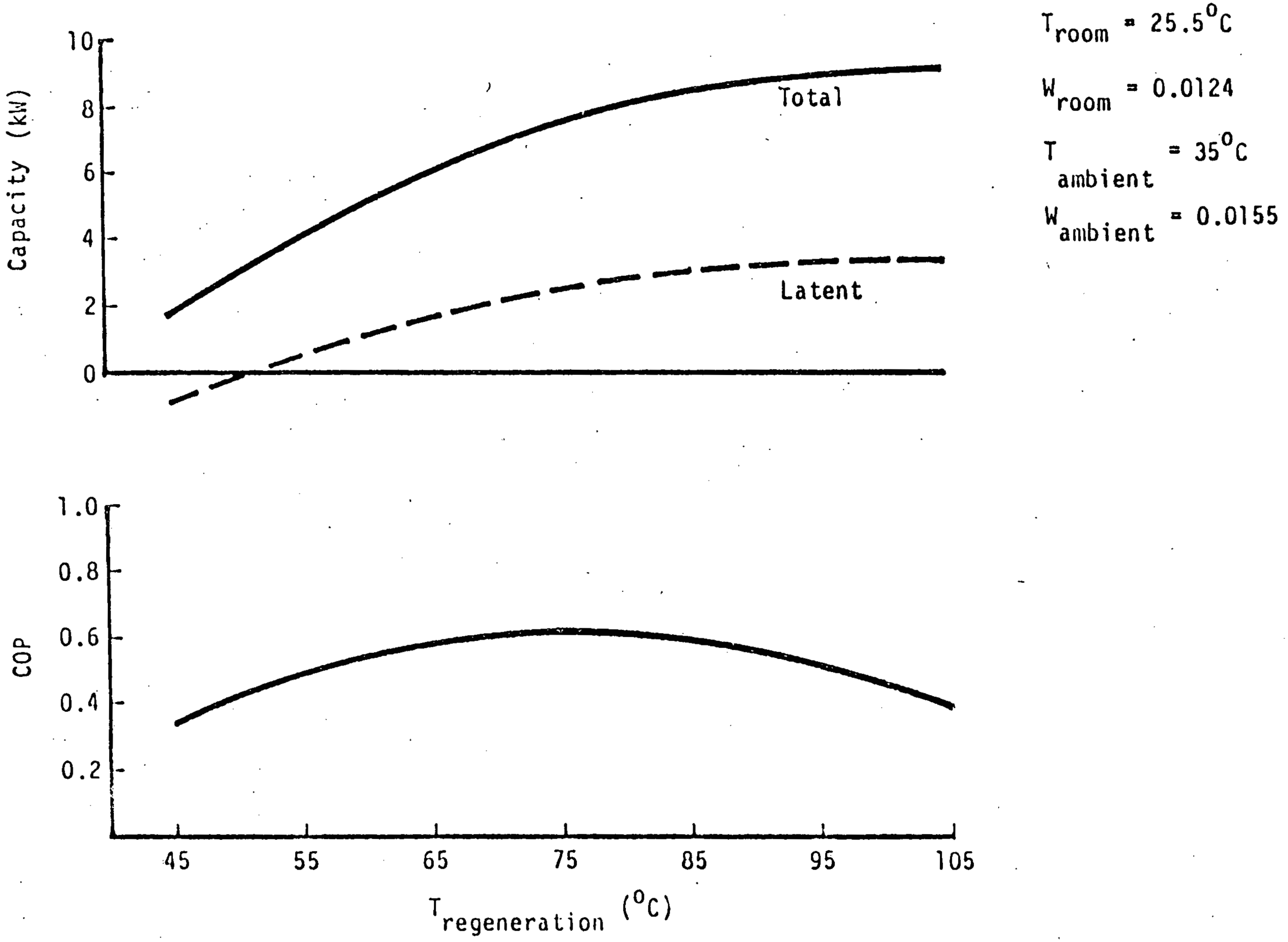


Figure 7. STEADY-STATE SENSITIVITY TO REGENERATION TEMPERATURE [9]

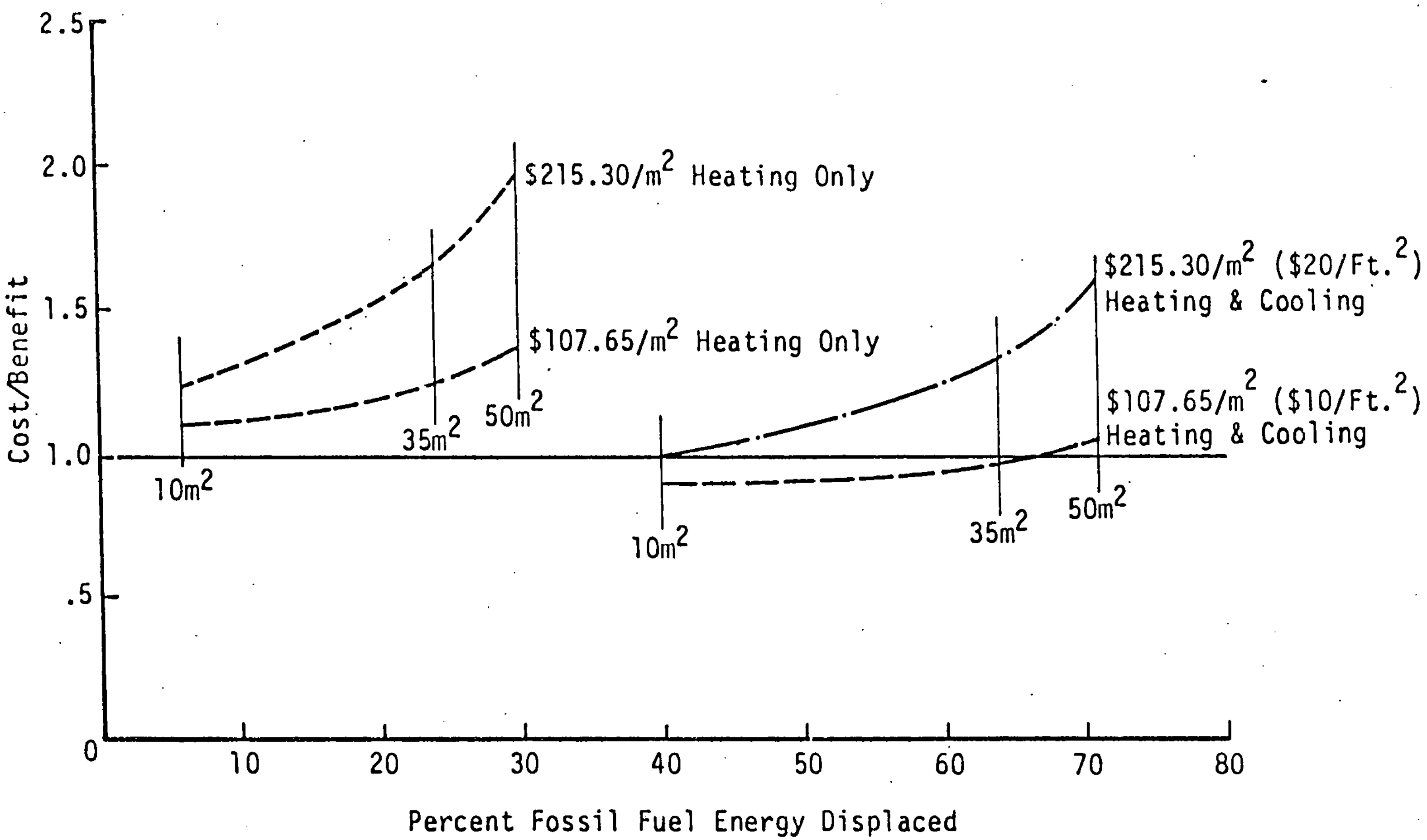


Figure 8. COST/BENEFIT VERSUS FOSSIL FUEL ENERGY DISPLACED, WASHINGTON, D.C., 4.5 kW DESICCANT COOLER WITH AUXILIARY, 1985 BASE YEAR [9]

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