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Recovery of Water from Atmospheric Air in Arid Climates

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Abstract

The possibility of using hydrated salts supported on carrier beds for extracting water from cool night air and solar energy for recovering the moisture for use as drinking water is dealt with. Equipment for obtaining sorption data in the laboratory is described. The rate of water adsorption by salts from air is a linear function of relative humidity, the amount adsorbed depending on the partial pressure of water exerted by the hydrated salt or by the aqueous salt that results on exposure to the moist air. To assure maximum adsorption it is important to select salts whose saturated aqueous solution exhibits minimal aqueous tension. Hydrated salts supported on carriers, composed of as widely different materials as porous glass, sand, and fibrous board, all release water equally well on heating, despite their large differences in physical makeup.

INTRODUCTION

There are many regions in the world where drinking water is scarce. Since in some arid lands the relative humidity increases substantially as the air cools during the night, it occurred to us to evaluate hydrated salts for collecting moisture from air.

The purpose of this paper is to present moisture adsorption data on various substrate/desiccant systems that were subjected to controlled humidities at room temperature, and to suggest a possible collector

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system for recovering water from the atmosphere in an arid environment.

A search of the literature revealed no published studies that deal with the problem of collecting drinking water from humid air. However, LeGuelennec (*1*) has described a novel apparatus which utilizes a series of slowly revolving thin disks and air blown from a blower to evaporate water from saline water, and then condenses the moisture-laden air by means of a condenser into drinking water.

EXPERIMENTAL SECTION

Materials

The salts used as adsorbents were reagent grade LiCl, $CaCl_2 \cdot 2H_2O$, $MgCl_2 \cdot 6H_2O$, and $NaC_2H_3O_2 \cdot 3H_2O$. The salts were supported on various carriers such as 1) microporous glass plates with surface areas of about 150 m^2/g, 2) a fibrous board as shown in Fig. 1, and 3) coarse and fine sand, with particles ranging from ~160 to 700 μm and ~5 to 65 μm, respectively.

Preparation of Specimens

The porous glass plates (2.54 × 2.54 × 0.2 cm) were immersed in hot, saturated salt solutions containing the salts and amounts of solvent shown in Table 1. The impregnating solutions were at their respective boiling points to assure maximum loading of the porous glass with the salts. After impregnating for 6 h, the plates were dipped in hot distilled water (~95°C) for 15 s to remove excess salt from their external surfaces.

TABLE 1
Impregnating Solutions

Salt (g)	Distilled water (mL)
25.5 LiCl	20
91.8 $MgCl_2 \cdot 6H_2O$	10
120.0 $NaC_2H_3O_2 \cdot 3H_2O$	20

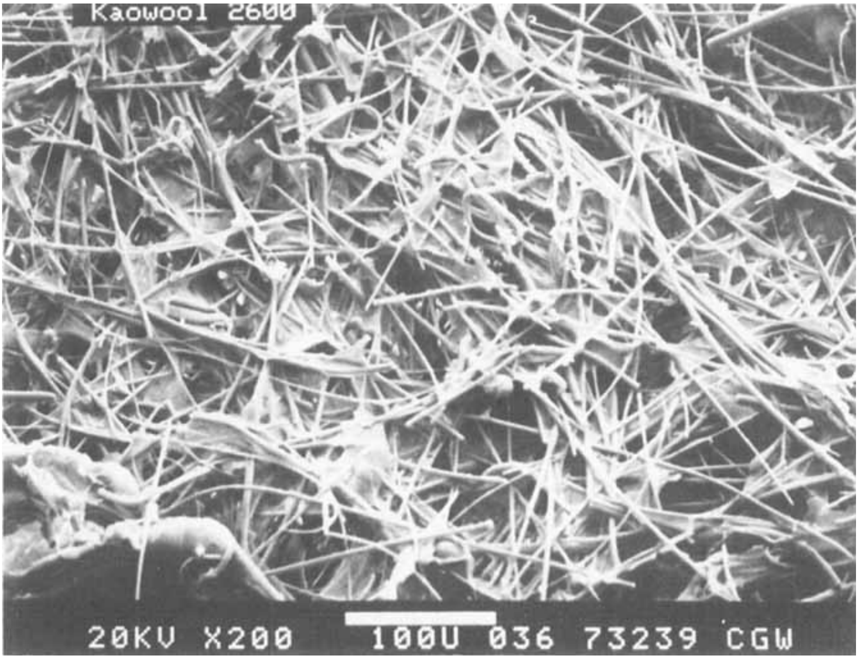

FIG. 1. Scanning electron micrograph of fibrous board.

The plates were then immediately placed in an electric oven for activation.

Sections cut from the fibrous board were impregnated in solutions composed of distilled water and $MgCl_2 \cdot 6H_2O$ or $CaCl_2 \cdot 2H_2O$. The molarity of the solutions ranged from about 1 to 7.5 *M*. After 15 min immersion at ~22°C, the specimens were plotted with filter paper to remove excess salt solution and then dried in an oven.

The sand specimens were prepared by adding fixed amounts of salt solutions containing $MgCl_2 \cdot 6H_2O$ or $CaCl_2 \cdot 2H_2O$ to sand contained in small aluminum trays. Some of the sand/desiccant mixtures were pulverized, after baking at 120°C, in a mortar with a pestle and then subjected to humid air either in the trays or in small glass baskets.

Moisture Adsorption Measurements

Some of the above specimens were first activated in an electric oven at

~120°C, using small glass baskets as containers. The baskets with plates were transferred hot in 250 mL Erlenmeyer flasks containing Drierite as desiccant. This was accomplished by suspending the basket to the balance through a small hole in a glass cover on the flask. The rim of the flask and cover were ground to make a seal, and the hole was closed with a glass cap with a ground rim except during the short time of weighing.

After determining the weights of the activated specimens, the glass baskets with contents were transferred into similar 250 mL Erlenmeyer flasks, each containing 50 mL sulfuric acid of appropriate concentration to give the desired relative humidity. The specimens, suspended over the acid, were then weighed periodically as described above.

All measurements were made in duplicate, the values obtained being averaged prior to plotting.

RESULTS AND DISCUSSION

Water Adsorption by Microporous Glass/Salt Systems

The amounts of water adsorbed by porous glass containing LiCl, $MgCl_2 \cdot 6H_2O$, or $NaC_2H_3O_2 \cdot 3H_2O$ at relative humidities of 10, 20, and 50% are summarized in Table 2. The units in the table are given in gallons

TABLE 2

Water Adsorbed by Porous Glass/Desiccant Systems at 50, 20, and 10% Relative Humidity, gallons/acre

Salt	50%	20%	10%	Time (h)
LiCl	623	424	245	24
$MgCl_2$	466	273	157	"
$NaC_2H_3O_2$	242	53	37	"
LiCl	366	240	146	10
$MgCl_2$	288	162	96	"
$NaC_2H_3O_2$	129	32	27	"
LiCl	224	139	80	5
$MgCl_2$	191	101	60	"
$NaC_2H_3O_2$	80	25	20	"

TABLE 3
Aqueous Tensions of Saturated Aqueous Salt Solutions (2)

Salt phase	Aqueous tension, mmHg	Temperature, °C
$LiCl \cdot H_2O$	2.63	25
$MgCl_2 \cdot 6H_2O$	7.8	25
$NaC_2H_3O_2 \cdot 3H_2O$	13.3	20

per acre rather than in g/cm^2 surface area exposed to the humid atmosphere. The data show that the water adsorption is greatest for plates impregnated with lithium chloride and lowest for plates impregnated with sodium acetate, with magnesium chloride in between. This can be explained in terms of the partial pressure of water exerted by the hydrated salt, or by the aqueous salt solutions that result on exposure to the moist atmosphere. Based on aqueous tension in Table 3, the order of water recovery for the above salts is Li-, Mg-, and Na-salts. This is in agreement with the order observed in the study. Data for untreated porous glass included in Table 4 indicate that the porous glass itself is responsible for a large portion of the total water adsorbed by the salt-laden specimens prepared by impregnation in 4.4 *M* salt solutions.

TABLE 4
Water Adsorbed by Porous Glass Impregnated with 4.4 *M* Salt Solutions and Activated at 116°C, gallons/h

Salt	50% rh	20% rh	10% rh	Time, h
None	171	113	85	24
LiCl	411	239	156	"
$MgCl_2$	378	247	169	"
$NaC_2H_3O_2$	247	96	58	"
None	159	103	69	10
LiCl	310	171	101	"
$MgCl_2$	285	169	99	"
$NaC_2H_3O_2$	169	65	38	"
None	134	76	48	5
LiCl	211	108	63	"
$MgCl_2$	194	101	58	"
$NaC_2H_3O_2$	108	40	26	"

TABLE 5
Water Adsorbed by Fibrous Board, gallons/h

50% rh	20% rh	10% rh	Time, h
1772	981	557	24
981	514	278	10
567	319	173	5

Water Adsorption by Fibrous Board/Salt System

Adsorption data for fibrous specimens loaded with 4.4 *M* $MgCl_2 \cdot 6H_2O$ or $CaCl_2 \cdot 2H_2O$ solutions are summarized in Table 5. The fibrous material has a solution pickup of 450% compared to 26% for porous glass, based on dry weight of carrier. This accounts for the fact that the amount of water collected by the activated fibrous specimens that had been impregnated in the magnesium chloride solution is dramatically greater than that for the $MgCl_2$-loaded porous glass specimens in Table 4.

Figure 2 summarizes the moisture adsorption data for $MgCl_2$-loaded fibrous specimens subjected to 10, 20, and 50% rh. It shows that the amount of water adsorbed depends on the relative humidity, with higher humidity favoring greater adsorption, as expected. The graphs show that the slopes of the lines change as X, the abcissa, changes. This suggests that the relationship of moisture adsorption with time is related to the most general equation of the second order:

$$Ax_2 + By^2 + Cx + Dy + Exy + F = 0$$

Water Adsorption by Salt-Loaded Sand

The above studies lead one to conclude that 1) moisture gettering by carrier/desiccant systems depends on the ability to support large amounts of desiccant per unit volume of carrier, and 2) highly porous carriers are needed to maximize moisture adsorption. Unfortunately, the carriers that enable one to achieve maximum water pickup are probably too expensive for desiccant-based water recovery systems considered for arid regions. Since sand is generally plentiful, it was felt that this naturally occurring material deserves to be evaluated as a carrier.

Preliminary studies were made with sand/desiccant mixtures contained in aluminum weighing trays, approximately 2⅜″ and 2″ in diameter at top and bottom, respectively. Adsorption tests carried out

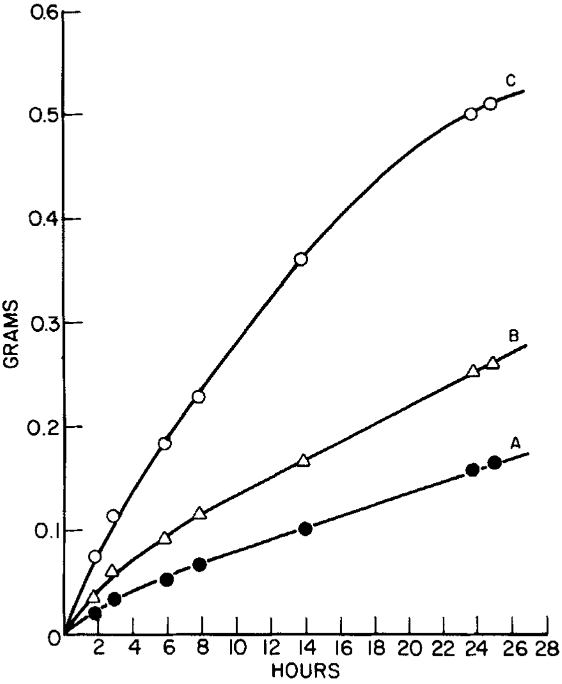

FIG. 2. Adsorption of water by fibrous board specimens at (A) 10, (B) 20, and (C) 50% rh. The specimens were loaded with 4.4 *M* $MgCl_2 \cdot 6H_2O$ solution prior to activation at 114°C.

with fine and coarse sands loaded with equal amounts of 4.4 *M* $MgCl_2 \cdot 6H_2O$ solution showed that the adsorption of moisture is independent of particle size. This is illustrated in Fig. 3. Furthermore, the sand/desiccant systems were found to be comparable in performance to that of high surface area material such as porous glass, as illustrated in Table 6.

Additional tests with calcium chloride or magnesium chloride showed

TABLE 6
Water Adsorbed at 44% rh by Carriers Loaded with 4.4 *M* $MgCl_2 \cdot 6H_2O$

Carrier	Water, g/in.^{2}
Fine sand	0.104
Coarse sand	0.101
Porous glass	0.104

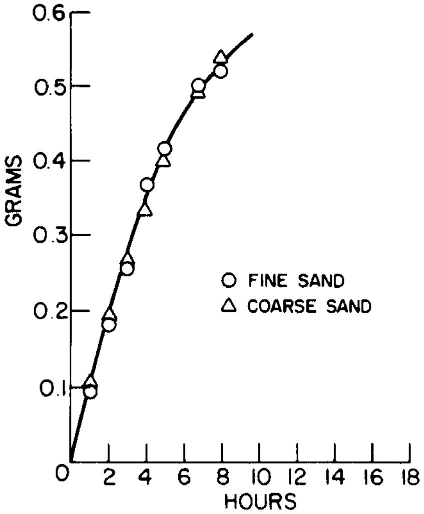

FIG. 3. Water adsorption at 44% rh by coarse and fine sand loaded with equal amounts of 4.4 *M* $MgCl_2 \cdot 6H_2O$ solution prior to activation at 115°C. External surface area was 3.98 in.^{2}.

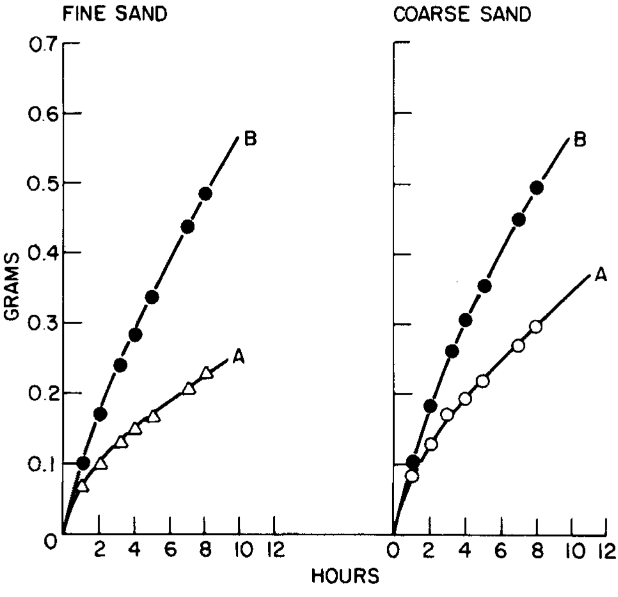

FIG. 4. Water adsorption of sand/$CaCl_2 \cdot 2H_2O$ mixtures at 40.5% rh. (A) Mixture not pulverized, (B) mixture pulverized. External surface area was 4 in.^{2}.

that the moisture gettering ability of these two desiccants is about the same. This is not surprising since the two compounds have similar aqueous vapor tensions as shown in Table 7.

Figures 4 and 5 show that the method used in incorporating desiccants in fine and coarse sand greatly influences their adsorption characteristics. Comparison of Curves A and B in these figures show that the adsorption and desorption of water is dramatically increased by subjecting the predried sand/desiccant mixtures to a pulverization treatment. It is hypothesized that the pulverization treatment assures not only more uniform distribution of the desiccant in the carrier but also produces a more open structure for ingress and egress of water vapor.

The role of increasing the concentration of desiccant in carriers

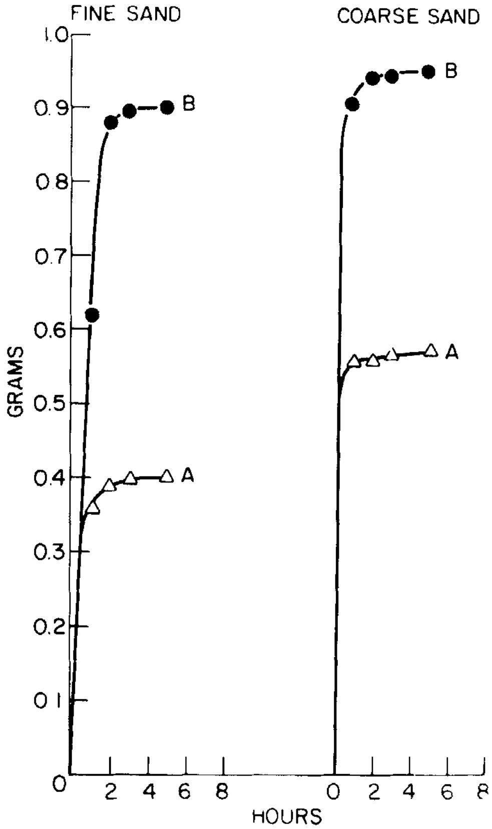

FIG. 5. Water removal at 115°C from sand/$CaCl_2 \cdot 2H_2O$ mixtures shown in Fig. 4.

TABLE 7
Aqueous Tension (2)

Compound	Temperature,°C	Relative humidity, %	Aqueous tension, mmHg
$MgCl_2 \cdot 6H_2O$	26	33	7.8
$CaCl_2 \cdot 2H_2O$	24.5	31	7.15

composed of fine and coarse sand is illustrated in Fig. 6. Figure 7 shows that desiccant by itself is less effective as a moisture getter than when admixed with sand. Furthermore, the rate of removal of moisture from a pure desiccant is also considerably less than when it is supported on a carrier. The slower rate of desorption of pure desiccant is assumed due to compaction of salt crystals, preventing ready passage of moisture from the interior of the crystalline body.

To obtain some insight into how depth of carrier bed affects moisture adsorption, it was decided to measure adsorption rates of carrier/

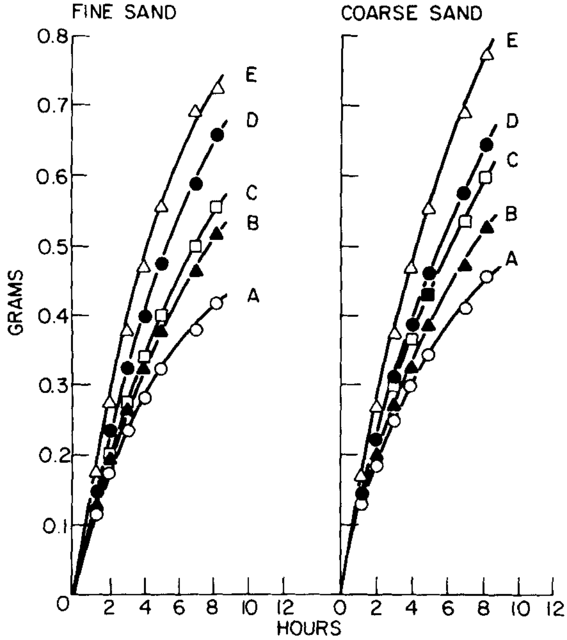

FIG. 6. Water adsorption at 41.5% rh by fine and coarse sand loaded with (A) 1.62, (B) 3.24, (C) 5.51, (D) 6.47, and (E) 11.03 g $CaCl_2 \cdot 2H_2O$.

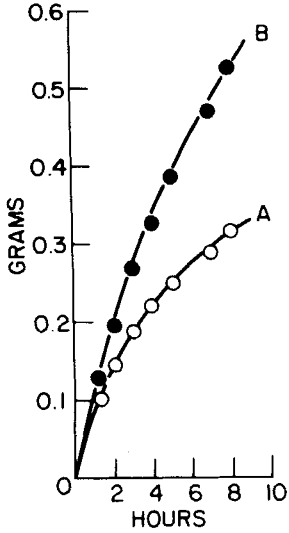

FIG. 7. Water sorption of 3.23 g $CaCl_2 \cdot 2H_2O$ (A) unsupported and (B) supported on sand.

desiccant mixtures having constant composition as a function of depth of bed. Data for pulverized and untreated mixtures are shown graphically in Fig. 8. The linear relationship between moisture adsorption, expressed in grams, and amount of sand suggest that the adsorption efficiency does not diminish with depth of bed, which in this study ranged from ~3 to

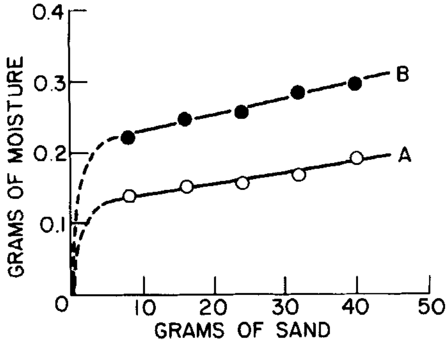

FIG. 8. Moisture adsorption by (A) untreated and (B) pulverized sand/$CaCl_2 \cdot 2H_2O$ mixtures as a function of depth of bed expressed in terms of grams of sand. Exposure time was 5 h at 42% rh.

~14 mm for untreated mixtures and to somewhat greater depths for the pulverized mixtures.

Figure 9 shows a plot of the amount of moisture adsorbed by constant sand/desiccant mixture as a function of relative humidities. The mixture was prepared by admixing 4.4 *M* $CaCl_2 \cdot 2H_2O$ solution with 25 g coarse sand and intermittently baking until the salts contained in 33 mL of solution had been incorporated. After final baking to dryness, the mixture was deagglomerated and poured into glass baskets, 0.883″ in diameter and 0.5″ high, and activated at 116°C. The relationship between water adsorption and relative humidity is essentially linear and can be expressed by

$$q = \frac{h}{m} + a \tag{1}$$

where q = quantity of water adsorbed per unit time
h = relative humidity in percent

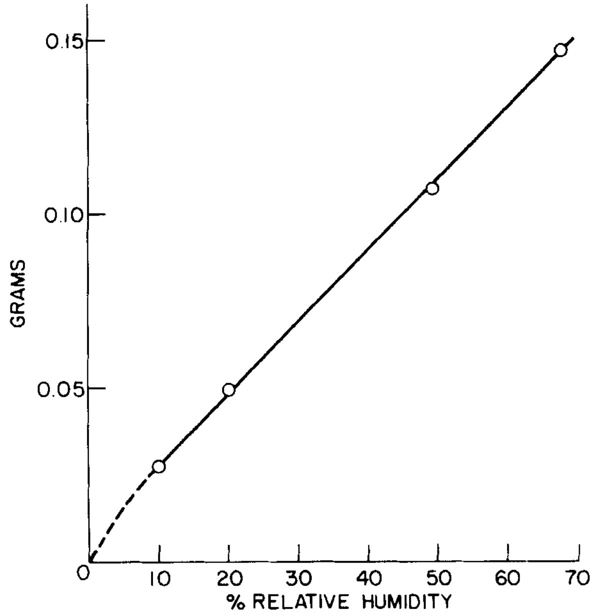

FIG. 9. Water adsorption of pulverized sand/$CaCl_2 \cdot 2H_2O$ mixtures as a function of relative humidity at 25°C. Surface area was 0.88 in.^{2}. Adsorption time was 5 h.

m = slope of the line
a = intercept at y axis

The relationship in Eq. (1) is not unexpected since desiccants adsorb water from moist air at rates depending upon the vapor pressure of water in the moist air with respect to that over the desiccant. The intercept of the line in Fig. 9, if drawn in, probably represents the amount of moisture that was adsorbed during the transfer of the specimens from the Drierite-containing Erlenmeyer flask to that containing the desired relative humidity.

Summary of Adsorption Data

The water adsorption data for carriers composed of porous glass, coarse sand, and fibrous board are summarized in Table 8. The higher water adsorption values in the second column under porous glass are due to the fact that lithium chloride has a lower aqueous tension than magnesium chloride. The aqueous tension of the latter and that of calcium chloride are essentially the same, permitting one to intercompare the performance of the carrier/desiccant systems that contain these salts.

The superior performance of the $MgCl_2$-loaded fibrous carrier is attributed to the open fibrous structure shown in Fig. 1 which increases the surface area of the desiccant exposed to the humid atmosphere.

Moisture Collector System

In practice the equipment might consist of a bed of desiccant/carrier, a

TABLE 8
Amount of Water Adsorbed in 5 h by Desiccants on Various Carriers, gallons/acre

Relative humidity, %	Porous glass		Coarse sand	Fibrous board
10	60	80	79	173
20	101	139	157	319
50	191	224	323	567
68	—	—	428	—
Desiccant	$MgCl_2$	LiCl	$CaCl_2$	$MgCl_2$
Aqueous tension (mmHg at 25°C)	7.8	2.63	7.2	7.8

flat glass cover, a horizontal metal tube for condensing the water vapor, a trough for collecting the water, and a water storage tank buried deep under the earth. A schematic drawing illustrating these essential parts is shown in Fig. 10.

The cover would be open during the night to allow moisture to be adsorbed from the air, and closed during the day to permit the radiant energy of the sun to expel the water of hydration that had been collected during the night. The resulting water vapor would then be condensed on the tubular condenser and drained by gravity from the trough into an underground storage tank. Part of the water in the tank (cooled by the surrounding earth) would serve as cooling water for condensing the moisture-laden air inside the solar heated collector.

To maximize the adsorption of the radiant energy that falls on the moisture-containing bed, it may be desirable to blacken the metal that supports the desiccant/carrier bed. The condenser, on the other hand, would have to be properly shielded from the sun to assure satisfactory condensation of the water vapor produced over the solar-heated hydrated bed.

The moisture collector system must be properly gasketed to minimize loss of moisture during the solar heating cycle. The percent of adsorbed water that is evolved in 2 h of heating of various desiccant/carrier systems is shown in Table 9. It should be noted that carriers composed of as widely different materials as porous glass, sand, and fibrous board all release water equally well.

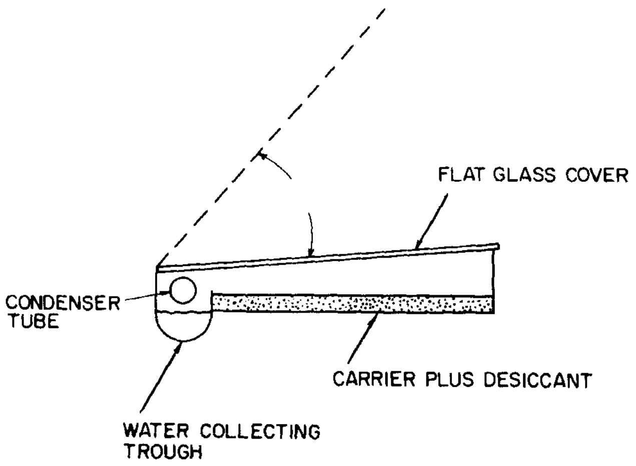

FIG. 10. Schematic drawing of water recovery system.

TABLE 9
Water Evolved on Heating

Carrier	Desiccant	Temperature, °C	Time, h	Water release, %
Porous glass[a]	Magnesium chloride	110	2	79.8
Sand[b]	Calcium chloride	116	2	81.4
Fibrous board[c]	Magnesium chloride	115	2	81.9

[a] ~50 Å pore size and ~150 m^2/g surface area.
[b] ~160 to 700 micron particles.
[c] ~2 to 5 micron diameter refractory fibers.

Cost of Water

According to a recent study by Arthur D. Little, Inc. (*3*), the cost of 1000 gallons of water prepared by multistage flash evaporation and by reverse osmosis is $5.50 and $5.60, respectively. Extraction of water from the air, based on sand as carrier, has been estimated to be about $0.035/gallon, or at least six times more than water obtained from the sea or brackish waters by evaporation or reverse osmosis.

It is possible that the cost of water from the air could be lowered by 1) circulating the humid air over the desiccant bed to increase the rate of moisture adsorption, 2) making small additions of a highly deliquescent salt such as lithium chloride to calcium chloride, or 3) by further increasing the surface area of the desiccant/carrier exposed to the air.

CONCLUSIONS

The rate of water adsorption from air by activated hydrated salts is a linear function of relative humidity, the amount adsorbed depending on the partial pressure of water exerted by the hydrated salt or by the aqueous salt solution that results on exposure to the moist air. To assure maximum water adsorption it is important to select salts whose saturated aqueous salt solutions exhibit minimal aqueous tension.

Inexpensive particulate carriers such as sand compare favorably with high surface area carriers in ability to getter water from humid atmospheres, provided the sand/desiccant mixtures are pulverized prior to use. Desiccant by itself is less effective as a moisture getter than when supported on a carrier.

Ordinary sand outperforms high surface area porous glass as support for desiccants, but not desiccants supported on fibrous board. Carriers composed of as widely different materials as porous glass, sand, and fibrous board all release water equally well on heating, despite their large differences in physical makeup.

The cost of water extracted from air using calcium chloride as moisture getter and solar energy for recovering the moisture is expected to be about 3.5 cents per gallon.

Acknowledgments

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