MACRO- ENCAPSULATION OF PCM

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MACRO-ENCAPSULATION OF HEAT STORAGE
PHASE-CHANGE MATERIALS
for Use in Residential Buildings

Sixth Quarterly Progress Report

December 29, 1977 - March 29, 1978

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FOREWORD

The work described in this report is an extension of a basic effort already performed under contract NSF-C906. The general objectives are: 1) to assess the technical and economic feasibility of encapsulated phase change materials (PCM's) for storing heat in residential solar energy systems, and 2) to develop and evaluate such encapsulated phase change materials.

The project involves three tasks:

Task 1 - Materials selection, including a limited literature search, selection of candidate phase change materials, and selection and characterization of encapsulating materials.

Task 2 - Procurement of phase-change and encapsulating materials, encapsulation studies, and testing of the encapsulated materials.

Task 3 - Preliminary design and economic evaluation of a residence-sized heat storage sub-system.

Task 1 has been completed, and Task 2 efforts are in progress.

I. ENCAPSULATED PCM'S

A variety of containers was examined and the results reported earlier under this program.¹ The final selection of phase change material (PCM) - encapsulant pairs was based primarily on: (1) container-PCM material compatibility studies, (2) container-PCM costs, (3) PCM fusion temperatures, and (4) a need to cover a wide spectrum of container types to determine durability under repeated freeze-thaw conditions. In many cases, a PCM has more than one potential encapsulant type, hence, the selected PCM-encapsulant pair tested (see Table I) may not reflect the optimum combination.

TABLE I

Selection of PCM-Encapsulant Pairs

<u>Phase Change Material</u>	<u>Fusion Temp (°C)</u>	<u>Encapsulant</u>
CaCl ₂ ·6H ₂ O	27	High Density Polyethylene Bottle (HDPE)
Mg(NO ₃) ₂ ·6H ₂ O/NH ₄ NO ₃ Eutectic	50	R-2 Retort Film
Stearic Acid + Palmitic Acid	60	Sulfonated HDPE Bottle
Mg(NO ₃) ₂ ·6H ₂ O	89	Drawn Steel Aerosol Can

Several series of complete freeze-thaw cycles have been run using the above PCM-encapsulant pairs (see Table II). The heating/cooling modes were performed using forced air when cycled in the storage unit and free convection when cycled in an oven. In some cases, PCM-encapsulant combinations were cycled other than those shown in Table I.

¹ORO/5217-1.

²ORO/5217-2, Jan.-Mar., 1977.

TABLE II: TENTATIVE RESULTS FOR ENCAPSULANT LIFETIME STUDY

Phase Change Material	Encapsulant		Testing Device	No. of Cycles (Approx.)	Tested	No. of Containers w/Stress	
	Type	Size (liters)				Cracks	Leaks
<u>CaCl₂•6H₂O</u>							
	HDPE Bottle (Monsanto)	0.47	Storage Unit	70	129	71	0
	" " "	0.47	Oven	150	6	6	0
	" " (Dow)	1.00	"	150	6	6	0
	High/Low Density (50/50) PE Bottle with Bellows (Falcon)	0.95	"	130	1	0	0
	LDPE Bottle	1.00	"	130	1	0	0
	Polypropylene	0.35	"	40	3	-	0
	Steel Aerosol Can						
	Seamless (Drawn)	0.58	"	130	1	0	0
	Seamed (Soldered)	0.58	"	130	1	0	0
	Steel Paint Can	3.79	"	20	2	0	0
<u>Mg(NO₃)₂•6H₂O/NH₄NO₃ Eutectic</u>							
	R-2 Retort Film (3.85 mils)						
	Vertical Pouch (3-Seam)	0.24	"	50	3	-	3
	Horizontal " "	0.24	"	100	3	-	0
	R-2 Retort Film (4.15 mils)						
	Horizontal Pouch						
	4 Seams	0.66	"	80	3	-	3
	3 Seams	0.75	"	180	3	1	0
<u>Stearic Acid + Palmitic Acid</u>							
	Sulfonated HDPE	0.36	"	50	8	8	4
<u>Mg(NO₃)₂•6H₂O</u>							
	Steel Aerosol Can	0.36	"	50	8	8	4
	Seamless (Drawn)	0.53	Storage Unit	20	128	-	51
	"	0.53	Oven	150	3	-	3
	Seamed (Welded)	0.56	"	10	1	-	1
	Seamed (Soldered)	0.56	"	10	1	-	1

A. CaCl₂·6H₂O - Two sizes of sealed HDPE bottles (0.47 and 1.00 liter) filled about 90% with liquid CaCl₂·6H₂O were cycled 150 times in an oven. Also, 129 HDPE bottles (0.47 liter) were cycled nearly 70 times in the thermal energy storage unit. The results were similar in both cases with visible signs of stress cracks developing along the top edge shoulder of the bottles. Over half of the bottles in the storage unit developed stress cracks. The most severe cases occurred near the air inlet of the storage unit where the temperature changes are the most rapid. Even though all the bottles in the oven developed cracks by 150 cycles, there were no air or liquid CaCl₂·6H₂O leaks detected in the tests using the oven or storage unit. Stress cracks are due to the contraction/expansion of the bottle with a 10% volume variation upon changing phase.

To overcome the problem of stress crack formation, we are investigating the possibility of using a flexible, low density polyethylene (LDPE) bottle, or a polyethylene bottle (50/50 blend of high/low density) with bellows (3/8" deep). The latter was designed for storage of photographic chemicals (Falcon® air-evac®). The bellows are located about 1/2" apart along the full 7" length of the bottle. However, during phase change only the top 2-3 bellows are involved in the expansion/contraction of the bottle. This is especially appealing, since a bottle design with only a few bellows near the top would not significantly increase the container cost, while greatly increasing container life. After 130 cycles, both bottle types show no signs of stress cracks. However, further investigation is needed because the moisture loss rate through LDPE is five times as great as the rate through HDPE.

Polypropylene bottles and various types of steel cans have also given promising results thus far with $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$.

B. $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O} / \text{NH}_4\text{NO}_3$ Eutectic - R-2 retort film, commercially used for storing and cooking foodstuffs, has been used to encapsulate $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O} / \text{NH}_4\text{NO}_3$ eutectic. This film, available from Continental Can Company, is a laminate of 3 mils polyethylene, .35 mils aluminum foil and .5 mils Dupont Mylar brand polyester. Six 3-seam pouches (.24 liter, about 1 3/4" x 11" x 3/4") were made using a Vertrod® impulse heat sealer (Model 20P - 1/8" wide seal). The film was folded lengthwise and sealed on the remaining three sides, thus containing the PCM. Three pouches were suspended vertically and three were laid horizontally on a metal support. After 50 cycles all three suspended pouches had ruptured at the seam intersection at the lower corner of the pouch. It is believed that the weight of the PCM along with some isolated expansion of the PCM during initial melting created excessive stress on the seam. However, the horizontally laid pouches lasted over 100 cycles. The volume reduction of the material causes the pouch to suck in at the top surface along its entire length. This widely distributed depression of the film was not symmetric in that different size dimples form along the length of the pouch. Fortunately, these dimples appear in different sizes and locations at the top surface with each freezing cycle, thus helping to extend the life of the film.

A second R-2 retort film (3.3 mils polyethylene, .35 mils foil and .5 mils polyester) was used to fabricate larger pouches (about 2 3/4" x 17 3/4" x 1"). Three 4-seam (.66 liter) and 3-seam (.75 liter) pouches each were prepared and laid horizontally on a metal support. After 80 cycles the 4-seam pouches had ruptured at the center of one lengthwise seam.

However, the 3-seam pouches were still intact after 180 cycles, with one pouch just starting to show signs of stress at the center of its lengthwise seam. Both pouch types form dimples as observed previously, and even though there was less PCM contained in the 4-seam pouch (both pouches filled to the same % capacity), it is not known why the lifetimes differed so greatly. It is believed that these pouch lifetimes will depend primarily on the size of the pouch, the % filled with PCM, and the quality and width of the seal. Preparations are currently underway to evaluate 75 of these 3-seam pouches in the thermal storage unit. Metal racks will be used to support the pouches horizontally, with air blown past them in a vertical flow pattern.

C. Stearic Acid - Palmitic Acid - The inside surfaces of eight round-shouldered HDPE bottles (.36 liter) were sulfonated in an effort to provide extra chemical resistance to the PCM mixture of stearic and palmitic acid. By 50 cycles, all of the bottles developed stress cracks, with half of them actually leaking liquid PCM. This PCM upon cooling freezes differently from the $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ in that it doesn't form a pocket in the top center of the solid PCM. Rather, the entire mixture shrinks uniformly, pulling itself away from the inside wall of the container. Unless a container is used which will shrink or collapse with this material, poor heat transfer will result from this dead air space. Other than the different freezing characteristic, this PCM-container combination gave results similar to the $\text{CaCl}_2 \cdot \text{H}_2\text{O}$ -HDPE combination. It is suspected that leaks result much faster once the initial stress crack forms and the unsulfonated material under the sulfonated surface is exposed.

D. Mg(NO₃)₂·6H₂O - Various types of steel aerosol cans have been cycled both in the storage unit and oven. In nearly all cases, the can develops hair-line stress cracks at various locations. However, the type of can used (drawn, welded and soldered) usually determines the location of the stress cracks. Cracks developed: (1) on the top edge shoulder just below the dome for drawn seamless cans, (2) on the seam for welded seamed cans and (3) on the dome for soldered seamed cans. It is suspected that in all cases the cracks develop where the steel can had been worked or heat treated the most. Also, there may be variations in stress crack location with procedural changes in can fabrication or different batches of the same type can.

E. Encapsulant Lifetime Improvement - Tentative results for the encapsulant lifetime study indicate that more problems with PCM encapsulation were encountered than expected. For CaCl₂·6H₂O, a polyethylene bottle with a few bellows near the top appears to be the most promising from the standpoint of durability and economic considerations. Steel aerosol cans appear acceptable at least for durability reasons. More work is needed to determine if a polypropylene bottle is a suitable substitute.

For Mg(NO₃)₂·6H₂O/NH₄NO₃ eutectic, the 3-seam horizontally laid film packages give acceptable results. More work is needed to identify a suitable container for Mg(NO₃)₂·6H₂O.

For the stearic acid mixture, the best remaining option seems to be encapsulation in glass bottles. We will consider this, along with the option of replacing stearic acid with an alternate PCM.

II. HEAT STORAGE TEST PROCEDURE - $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$

ASHRAE¹ (94-77) standards for testing thermal storage units were followed. The detailed procedure was modified slightly from that reported earlier² for testing $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ as a heat storage medium, in that the "maximum charge temperature" and "minimum charge temperature" were redefined to compensate for much higher heat loss rates at the higher operating temperatures involved.

The inlet air temperature was step-changed (Figure 1) between 71.5°C and 106.5°C to bracket the melting point of $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$. The "maximum charge temperature" was set at 94.83°C , one third the interval from the melting point to the maximum inlet temperature. (In the case of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, half the interval was used.) The "minimum charge temperature" was set at 77.33°C , one third the interval from the minimum inlet temperature to the melting point. (For $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, half the interval was chosen.) The temperature difference between maximum and minimum charge temperatures was maintained at 17.5°C , the same as for $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$.

The reason for these modifications of procedure is because of the difficulty, or even impossibility for the case of the lowest air flow rate, of the outlet air temperature reaching midway between the inlet and fusion temperature during charging. This is due to excessive heat losses through the walls of the storage unit.

¹American Society of Heating, Refrigeration and Air Conditioning Engineers.

²ORO/5217-5.

Figure 1

LATENT HEAT TYPE THERMAL STORAGE UNIT

III. HEAT STORAGE TEST RESULTS - $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$

The thermal energy storage unit is shown in Figure 2. One inch of extra insulation (four inches total) was added to the sides and bottom of the storage unit. Two more inches (five inches) were added to the top of the unit and also on the nine foot long outlet air duct from the storage unit to the temperature sensors. Steel aerosol cans (128 cans-.53 liter/can) were filled with liquid $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ to 95% of their capacity. The cans were sealed after the PCM froze and were placed in the storage unit in an equilateral triangular pitch arrangement. Thermocouples were placed in nine cans located at various positions (1-9) in the storage unit so that temperature-time profiles for individual cans of $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ could be observed. The storage unit was sealed and cycled for 9 complete freeze/thaw cycles before any data were taken.

For a typical charge cycle (Figure 3), the temperature time profiles are nearly identical to that observed for $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, except that the test times are longer for $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ for equivalent air flow rates. This is primarily due to larger heat loss rates through the walls of the storage unit, thereby decreasing the energy available for storage as well as decreasing the energy currently stored in the PCM. All of the PCM melted, except for a small portion of a few cans at position 9. Since these temperatures are for the material which is last to freeze (thermocouple location is at the center of the bottle), the charge capacity isn't significantly decreased. For the discharge profiles (Figure 4), however, there are a number of cans which aren't completely discharged (frozen), thereby decreasing the discharge capacity somewhat. Although the apparent decrease is also exaggerated by thermocouple location, the unit appears not to have discharged to the extent

Figure 2

Magnesium Nitrate Hexahydrate Storage Medium,
Air - Heat Transfer Fluid, Thermal Energy Storage Unit

Containers .066M Dia .157 HT Bottles
Walls .20 mm Tin Plated Steel

Layout .019M Spacing Equilateral Triangular Pitch
Minimum Possible Void Fraction .45
Bottle positions with thermocouples ① → ⑨

Figure 3

Charge Cycle: Magnesium Nitrate Hexahydrate
in Steel Aerosol Cans

Figure 4

Discharge Cycle: Magnesium Nitrate Hexahydrate
in Steel Aerosol Cans

that it had charged. Note that the order of melting is reversed for the cans at positions 6 and 7. This is due to the presence of the bend in the air flow path of the storage unit, causing either short-circuiting or a difference in the air heat transfer coefficients. Also note that there is very little supercooling of $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ ($1-2^\circ\text{C}$) due to the presence of additives which provide adequate nucleation.

A total of eight pairs of charge/discharge cycles (Runs 10-15, 19, 20) were done at four air flow rates (52-86 CFM). Profiles of the outlet air temperature vs. time were generated, according to the test procedures stated earlier, for the charge (Figure 5) and discharge (Figure 6) cycles.

The charging (discharging) profiles for the outlet temperature are only shown for the duration of the test, even though steady-state was achieved before initiating a step change for the next successive cycle. The shaded areas between the outlet and inlet air temperatures (shown only for 86 CFM in each case) was manually integrated and used to determine each charge (discharge) capacity. For the discharge profile, there is a significant spread in the initial outlet air temperatures. This is due to the variation of heat loss with air flow rate and results in different steady-state outlet air temperatures prior to the step change in the inlet air stream temperature. The temperature profiles for the lowest air flow rate for both charging and discharging are most similar to the nearly ideal latent heat type storage unit (Figure 1). This is attributed to the longer times available for better temperature equilibrium between the PCM and the passing air.

OUTLET AIR TEMPERATURE vs TIME

OUTLET AIR TEMPERATURE vs TIME

Figure 6

$\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ - Discharge Cycle

Air Flow Rate - CFM $\left(\frac{\text{Ft}^3}{\text{Min}}\right)$

Discharge Time - τ_d (Hr)

The reduced data with energy balance results for all runs are shown by Table I. The runs of similar air flow rates have been grouped. Each column heading, except the last, has subcolumns 1 and 2, representing the charge and discharge cycles, respectively.

The charge (discharge) test times are shown as a function of the air flow rates through the storage unit (Figure 7). As mentioned earlier, the dominating heat losses from the storage unit to the surroundings work against charging, thus causing the prolonged charge times (13-28 hrs), especially at the lower air flow rates. The discharge times are controlled primarily by two opposing factors. Heat loss tends to decrease discharge times since it contributes to discharging the unit. Solid crystal buildup of $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ on the inside surface of the cans tends to impede heat transfer from the molten cores to the air, causing an increase in discharge times. It will be shown later that the effect of crystal buildup is slightly dominating. However, larger diameter cans would greatly augment this effect and result in a significantly increased discharge time and decreased storage capacity.

Measured pressure drops across the storage unit are compared with theoretical values derived for air flow through a staggered arrangement of tube banks (Figure 8). A density difference for the different temperature air streams, charging and discharging, is reflected in the two theoretical curves shown. Measured values fall just above the respective theoretical curves because the pressure drop relationship does not account for the added pressure drop due to the bends in the air flow path through the storage unit. In designing

TABLE I: TEST RESULTS ON MAGNESIUM NITRATE HEXAHYDRATE ENCAPSULATED IN STEEL AEROSOL CANS

Run	Air Flow Rate (CFM)		Test Time (τ -Hr)		Storage Unit Pressure Drop (ΔP -in. H ₂ O)		Energy Loss Through Insulation (KJ)		Energy Recovered (Delivered) By Air Stream		Energy Balance (KJ)		%Dev
	1	2	1	2	1	2	1	2	DC		CC (Q _{in} -loss)	DC* (Q _{out} +loss)	
									(Q _{in})	(Q _{out})			
19	86	86	12.8	8.1	.67	.75	10,653	5,639	32,544	16,054	21,891	21,693	
20	86	85	12.8	8.1	.68	.76	11,160	5,706	32,692	15,878	21,532	21,584	
					Average		10,907	5,673	32,618	15,966	21,712	21,639	+0.3
10	74	73	15.9	9.1	.49	.55	12,216	5,675	34,707	15,227	22,491	20,902	
11	74	73	15.3	9.2	.49	.56	12,059	6,144	33,702	16,169	21,643	22,313	
					Average		12,138	5,910	34,205	15,698	22,067	21,608	+2.1
12	61	61	21.6	10.4	.33	.40	17,042	7,208	38,762	14,881	21,720	22,089	
13	61	60	21.6	10.4	.34	.38	18,246	7,078	39,409	14,334	21,163	21,412	
					Average		17,644	7,143	39,086	14,608	21,442	21,751	-1.4
14	52	51	28.2	11.6	.24	.30	22,065	7,518	43,514	13,823	21,449	21,341	
15	52	52	28.3	11.5	.26	.30	22,206	7,667	43,967	13,595	21,761	21,262	
					Average		22,136	7,593	43,741	13,709	21,605	21,302	+1.4

1 = Charge

2 = Discharge

DC* = Corrected Discharge Capacity

$$\% \text{ Dev} = \frac{(Q_{in}-loss)-(Q_{out}+loss)}{(Q_{in}-loss)} \times 100$$

CHARGE (DISCHARGE) TIME vs AIR FLOW RATE

Figure 7

STORAGE UNIT PRESSURE DROP vs AIR FLOW RATE

Figure 8

a residential storage unit, typically one will select an air flow rate corresponding to the maximum allowable pressure drop, thus giving the shortest possible charge (discharge) times.

The heat loss during charging increases from about 10,900 KJ at 86 CFM to about 22,100 KJ at 52 CFM. The heat loss during discharging ranges from about 1/2 to 1/3 (5,700 KJ and 7,600 KJ) the heat losses during charging for equivalent air flow rates. The net increase in heat loss during charging with decreasing air flow rate is reflected by the increasing test times shown in Figure 7. Of course, the lower heat losses during discharging are simply a result of the lower temperature driving force ($\bar{T}_{\text{unit}} - T_{\text{amb}}$) during the shorter test times. Using the integrated values of the temperature/time profiles for the charging (discharging) curves (Figures 5 and 6), the amount of energy delivered (Q_{in}) and recovered (Q_{out}) by the air stream were determined. The amount of energy stored in the PCM (charge capacity) is equal to the energy delivered to storage less the losses incurred ($Q_{\text{in}} - \text{loss}$). Since the discharge capacity is defined as the recovered energy by the air stream (Q_{out}), we call that energy plus the losses ($Q_{\text{out}} + \text{loss}$) the corrected discharge capacity. Also a % deviation, defined as the percent difference between the charge and corrected discharge capacities is reported. Actually, these two values need not balance since the temperature spans defined by the testing procedure do not perfectly coincide. However, they should be close and will indicate any trends with air flow rate. The deviation oscillates about $\pm 1.4\%$.

Two bar graphs are shown in Figures 9 and 10 illustrating the transfer of energy during charging and discharging, respectively, versus air flow rate for the cases of $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$

M Of KJ

Figure 9

Figure 10

Loss

Total Energy Transferred To (From) Storage Unit

(m.p. 89°C) and $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ (m.p. 27°C) PCM's. The total height of each bar in Figure 9 represents the total energy delivered to the storage unit at a given air flow rate. This would be the energy delivered by a solar collector in actual practice. The shaded area of each bar represents the amount of the delivered energy which is lost. The remainder is the energy which is stored in the PCM. It can be seen for the case of $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ that the stored energy is fairly constant at about 22,000 KJ while the energy lost to the surroundings accounts for 33-51% of the total amount of energy delivered for storage. The case of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ shows losses that account for only 15-22% of the delivered energy while the stored energy is fairly constant at about 23,000 KJ. This clearly illustrates the heat loss problems incurred with higher-melting PCM's when using air as the heat transfer fluid. The slightly higher average of stored energy for $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ is due to the higher heat of fusion, even though less PCM was used than for the $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ case. Figure 10 is the same type of bar graph except that the total height of the bars represent the amount of energy stored in the PCM prior to discharging (corrected discharge capacity). Note that this stored energy prior to discharge differs from the stored energy after charging since the temperature spans defined by the test procedure do not coincide. The shaded area still represents the loss, this time during discharging. The remaining energy represents the energy recovered from the PCM by the air stream alone. The amount of energy recovered by the air stream is nearly 100% for $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, but only 64-74% (26-36% loss) for the $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$. It must be pointed out that the heat loss values for both cases are larger than that expected for a storage unit of optimum design containing the same amount of PCM. For these cases, there is a void fraction of about 0.7,

compared with a minimum possible void fraction of about 0.5 (32% more surface area than needed for the given container arrangement). Of course, when scaling up to a higher capacity unit, the % loss value will be even less due to the smaller surface to volume ratio. For the higher melting PCM's, a liquid heat transfer medium should provide less heat loss to the surroundings than air, due to a higher heat capacity and lower convective heat transfer coefficient. The importance of adequate insulation is obvious.

Theoretical charge and discharge capacities (TCC and TDC) were calculated for the storage unit. Pertinent information and results are listed in Table II. The temperature range of the storage unit during the test was estimated using the minimum and maximum cutoff temperatures.

The theoretical and measured capacities for $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ were plotted against the air flow rate (Figure 11). Also, the losses were added to the measured discharge capacity and plotted as the corrected discharge capacity. Due to the large losses incurred, it was difficult to determine any trend of the charge and discharge capacities with air flow rate. However, the charge and corrected discharge capacities were divided by the respective theoretical capacities (% capacity) and plotted vs. air flow rate (Figure 12). For the air flow rates used, the storage unit was able to charge and discharge an average of 97.6% and 95.1%, respectively, of its theoretical capacities. These values may be shifted up or down depending on the assigned maximum and minimum outlet air temperatures for terminating each test cycle. However, the difference between the percent capacity for charge and discharge is consistent with the observations of the temperature-time profiles for individual cans in the

TABLE II

Theoretical Charge and Discharge Capacities

Mg(NO ₃) ₂ •6H ₂ O		
Fusion Temp., °C	89	
Heat of Fusion, Cal/g	38	
Specific Heat, Cal/g °C	0.60 (liquid)	
	0.44 (solid)	
Total Weight, Kg	100	
Steel (Storage Unit Structure)		
Specific Heat, Cal/g °C	0.10	
Total Weight, Kg	125	
	<u>Charging</u>	<u>Discharging</u>
Temperature Range, °C (Est.)		
High	94.83	about 102.00
Low	about 70.00	77.33
Theoretical Capacity, KJ ¹	22,231	22,676
	(TCC)	(TDC)

¹Not including specific heat of steel aerosol cans
(<.3% of theoretical capacities).

Figure 11

CAPACITY (ENERGY) vs AIR FLOW RATE

Figure 12

% CAPACITY (ENERGY) vs AIR FLOW RATE

storage unit. At all the air flow rates, the unit was not discharged to the extent that it had charged by the end of the respective test times.

The maximum and minimum heat rates for each cycle were determined for $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (Table III). The maximum heat rate for charging (discharging) occurs immediately following the step change, where the difference between the inlet and outlet temperatures is at a maximum. The minimum heat rate occurs at the end of each test cycle. This value is often used as the design rate for this size storage unit. These maximum and minimum heat rates are plotted as a function of flow rate (Figure 13). The actual operation of a storage unit would most likely have a heat rate midway between the maximum and minimum values, corresponding to a temperature near the fusion temperature.

A hypothetical plot (Figure 14) was made of the storage capacity in hours vs. air flow rate for this particular unit when charging (discharging) constantly at these maximum and minimum heat rate values. It is interesting to note that because of the excessive heat loss for $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, the actual charge profile corresponds closest to hypothetical at its minimum heat rate, while the actual discharge profile corresponds closest to hypothetical at its maximum heat rate.

TABLE III: CHARGING AND DISCHARGING HEAT RATE

Run	Air Mass Flow Rate (m-KG/Hr)		Heat Capacity (C_{tf} -KJ/KG °C)		Heat Rate (q-KJ/Hr)				Capacity (Hr)			
					1		2		At. Max. Heat Rate		At. Min. Heat Rate	
					Max.	Min.	Max.	Min.	CC/q		CC/q	
	1	2	1	2					1	2	1	2
19	130	146	1.038	1.020	5195	1575	3961	868	4.2	5.5	13.9	25.0
20	131	143	1.041	1.023	5250	1591	3891	853	4.1	5.5	13.5	25.3
			Average		5223	1583	3926	861	4.2	5.5	13.7	25.2
10	112	122	1.038	1.021	4476	1357	3313	726	5.0	6.3	16.6	28.8
11	111	125	1.038	1.022	4436	1345	3398	745	4.9	6.6	16.1	30.0
			Average		4456	1351	3356	736	5.0	6.5	16.4	29.4
12	90	104	1.037	1.019	3593	1089	2819	618	6.0	7.8	19.9	35.7
13	92	100	1.036	1.019	3670	1112	2711	594	5.8	7.9	19.0	36.0
			Average		3632	1001	2765	606	5.9	7.9	19.5	35.9
14	77	86	1.038	1.020	3077	931	2333	511	7.0	9.1	23.0	41.8
15	77	89	1.038	1.020	3077	931	2415	529	7.1	8.8	23.4	40.2
			Average		3077	931	2374	520	7.1	9.0	23.2	41.0

1 = Charge

2 = Discharge

DC* - Corrected Discharge Capacity

	T_{in}	T_{out}^o	T_{out}^f	ΔT	ΔT^o	ΔT^f
Charging (°C)	106.5	~68.0	94.83	$T_{in} - T_{out}$	38.5	11.67
Discharging (°C)	71.5	~98.1	77.33	$T_{out} - T_{in}$	26.6	5.83

Figure 13

HEAT RATE vs AIR FLOW RATE

Figure 14

CAPACITY (TIME) vs AIR FLOW RATE

Nomenclature

C_{tf}	=	specific heat of transfer fluid - $\frac{\text{CAL}}{\text{G}^\circ\text{C}}$
CC	=	charge capacity of thermal storage unit - KJ
DC	=	discharge capacity of thermal storage unit - KJ
L	=	heat loss rate - $\frac{\text{KJ}}{\text{HR}^\circ\text{C}}$
$\dot{m}$	=	mass flow rate of transfer fluid - $\frac{\text{KG}}{\text{HR}}$
ΔP	=	pressure differential across storage unit - in. H ₂ O
q	=	heat rate - $\frac{\text{KJ}}{\text{HR}}$
Q	=	total heat - KJ
Q_{in}	=	total heat delivered to storage unit through transfer fluid - KJ
Q_{out}	=	total heat delivered by storage unit through transfer fluid - KJ
$\bar{T}_a$	=	average ambient temperature - $^\circ\text{C}$
T_{in}	=	temperature of transfer fluid entering storage unit - $^\circ\text{C}$
T_{out}	=	temperature of transfer fluid leaving storage unit - $^\circ\text{C}$
$\bar{T}_{unit}$	=	average temperature of storage unit $(\frac{T_{in} + T_{out}}{2})$ - $^\circ\text{C}$
ΔT	=	temperature difference of inlet and outlet $ T_{in} - T_{out} $ - $^\circ\text{C}$
τ	=	test time (hr)
τ_c	=	charging test time (hr)
τ_d	=	discharging test time (hr)

IV. UTILIZATION ACTIVITY

Contacts with American Air Filter Co. have developed an interest in a demonstration of PCM storage, using $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, with a tempered-water multiple heat pump system. Several sites, both new construction and retrofit, are being considered.

Charles Tilford of Suntek, Inc. and Ralph Beckman, Architect visited our facilities to discuss applications for encapsulated $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ and potential demonstration projects.

V. PLANS

1. Initiate testing of $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O} / \text{NH}_4\text{NO}_3$ eutectic, encapsulated in plastic film pouches, in the storage test device.
2. Continue cycling tests on PCM-encapsulant candidates.
3. Choose between stearic acid/glass bottles or an alternate PCM/encapsulant pair for the final series in the storage test device.
4. Update computer model to fit magnesium nitrate hexahydrate results.
5. Update economic analysis of thermal storage unit design.
6. Evaluate storage unit designs in total solar systems using TRNSYS.

VI. CONCLUSIONS

Life test cycling of PCM/encapsulant combinations has shown more severe container degradation than expected:

- 1) High density polyethylene bottles containing $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ show cracks at points of high stress. This can be cured by using a bottle of lower density polyethylene, or a bottle with bellows construction.
- 2) Plastic/aluminum composite film pouches containing $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O} / \text{NH}_4\text{NO}_3$ eutectic fail if hung vertically. If supported horizontally they seem satisfactory, but the type and quality of seams is important.
- 3) Sulfonated polyethylene bottles containing stearic acid mixture show severe cracking.
- 4) Steel aerosol cans containing $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ fail by stress corrosion cracking. Inhibition is being studied.

Testing has been completed on $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ encapsulated in steel aerosol cans. Measurements were complicated by high heat losses experienced at temperatures up to 107°C . Nevertheless, good values were gotten for charge and discharge capacities, and a good energy balance was obtained. Measured capacities were 93-99% (ave. 96%) of theory.

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