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Thermal Energy Storage Technical Progress Report April 1992–March 1993

M. Olszewski

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THERMAL ENERGY STORAGE TECHNICAL PROGRESS REPORT APRIL 1992 - MARCH 1993

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THERMAL ENERGY STORAGE TECHNICAL PROGRESS REPORT
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ABSTRACT

The Department of Energy (DOE) is supporting development of thermal energy storage (TES) as a means of efficiently coupling energy supplies to variable heating or cooling demands. Uses of TES include electrical demand-side management in buildings and industry, extending the utilization of renewable energy resources such as solar, and recovery of waste heat from periodic industrial processes. Technical progress to develop TES for specific diurnal and industrial applications under the Oak Ridge National Laboratory's TES program from April 1992 to March 1993 is reported and covers research in the areas of low temperature sorption, thermal energy storage water heater, latent heat storage wallboard and latent/sensible heat regenerator technology development.

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1. PROGRAM OVERVIEW

Thermal energy storage consists of a range of technologies that allow an energy supply to be coupled to a heating or cooling demand. Acting as a buffer, TES facilitates the use of a time-varying energy resource to meet a constant or variable demand for heat or cool. Alternatively, TES is used to store available energy as sensible or latent heat in a material to meet an energy demand occurring at a later time. There are several advantages afforded by the use of TES including: (1) reduced sizes for heating and cooling systems in buildings, (2) load management of electricity used for heating and cooling, (3) waste heat utilization, and (4) renewable energy use.

In the case of buildings, heating and cooling systems are sized to maintain occupant comfort on design days during summer and winter. Design days are defined such that the probability of experiencing actual weather and load conditions worse than design day conditions is very small. Therefore, typical heating and cooling systems are oversized and consequently underutilized for most of the time so that they operate either cyclically or at reduced capacity. A TES system coupled to downsized heating/cooling plants allow them to be operated continuously so that they can meet a thermal demand that is much larger than the installed capacity. The overall result is a smaller and less costly heating/cooling system that operates most of the time at its most efficient rating. This feature can also be used when a building is expanded; TES increases the duty cycle of the existing space conditioning system so that the larger peak thermal load can be met with no increase in installed capacity.

A second benefit of TES in buildings is that it provides flexibility in scheduling heating and cooling system operation. That is, the TES system can respond to the space conditioning demands of the building, and the heating/cooling system can be operated independently or on a fixed schedule. In the case of electric chillers, heat pumps or resistance heating systems, this TES feature can be an advantage to a customer interested in avoiding on-peak electric costs as well as to the electrical utility interested in shifting load from certain times of the day. Due to rapid electric load growth caused by commercial building air conditioning, utilities are providing an opportunity for cool TES in the form of cash incentives, TES feasibility studies and rate schedules that encourage implementation of thermal storage.

Industrial applications for TES include processes in which waste heat generation is noncoincident with a heating demand. By storing heat that is otherwise wasted in flue gas, a TES system permits this energy to be reused in processes such as drying or preheating. The result is an overall reduction in energy requirements of industry and a reduction in thermal emissions from individual plants.

Solar energy used for space heating or cooling usually requires a TES system to extend the solar resource to nighttime periods. Conventional solar TES systems consisting of masonry or stored water are based on sensible heat in which the energy stored is directly proportional to the change in temperature of the storage material. These materials located on the interior of a building can overheat the occupied space unless relatively large TES masses are used. Depending on climate and the cost of fuel, these systems can be uneconomic and are particularly unsuited for retrofit applications. Advanced TES systems use the latent heat of solid-liquid or solid-solid transformations in phase change materials (PCMs). These transformations are energetic and occur over a relatively small temperature range—an advantage for a TES system that is charged or discharged by room air.

The DOE TES program has continued research to develop and support commercialization of TES technologies for each of these application areas. The cycling frequency for TES systems aimed at solar applications, and demand reduction during electrical off-peak periods is diurnal, whereas the cycling frequency for industrial applications of TES is less restrictive. For these reasons, TES research is arranged into the two broad areas: diurnal TES and industrial TES.

1.1 DIURNAL TES PROGRAM

The diurnal TES program is aimed at the development of TES materials and systems for specific applications. A principal project within the diurnal program is the development of a chill storage system that can be used to provide off-peak refrigeration in the -40°C (°F) to -7°C (20°F) range. All refrigerated warehouses, food processing and many chemical processing plants require refrigeration in this temperature range, most of which is electrically driven. A chill TES system permits the compressor load to be removed from the on-peak period and cooling is provided either continuously or on a schedule and at a rate that is controlled by the process or storage conditions. Under contract to Martin Marietta Energy Systems, Inc., the Rocky Research Company is working to develop a chill TES system based on sorption of ammonia by a salt to produce an ammoniated complex compound.[1] During the charging process, a compressor draws ammonia from a complex compound inside a reactor; the ammonia is condensed and stored in a refrigerant receiver. At the end of the charging process, most of the ammonia in the system resides in the receiver leaving the salt in the reactor with a low ammonia concentration. During the discharging process, the ammonia in the receiver evaporates with heat from the cooling load and returns to recombine with the salt in the reactor. Ammonia movement in the discharge process occurs without compressor operation due to the pressure difference between the receiver and reactor. During the charging process, the compressor drives ammonia vapor from the reactor to the condenser/receiver subsystem. The fact that the chill TES system uses ammonia is a key advantage since ammonia is a refrigerant of choice in many industrial cooling systems. Details of recent technical results in this project are described in Section 2.1.

A second major program initiative is the development of an advanced TES water heater to provide residential hot water with off-peak electricity. In order to successfully shift domestic hot water heating to an off-peak use of electricity, sufficient thermal capacity must be included in the water storage system such that the on-peak demands for hot water can be met from storage. Current water heaters store 60 or less gallons of water at about 60°C. To accomplish the peak shifting objective would require an equivalent thermal storage of at least twice that amount (i.e. 120 gallons of water at 60°C). Conventional means to accomplish this would be to double the water storage size by purchasing a larger tank or using multiple units. This alternative has not been favored by consumers because the amount of floor space dedicated to the water heating system becomes too large. The approach taken in this program element is to double the thermal storage capacity of the water heater using either latent or sensible TES. Thus the increase in thermal capacity is accomplished without increasing the physical dimensions of the unit. Under contract to Martin Marietta Energy Systems, Inc., the University of Florida is developing three concepts through the prototype stage. This work is described in Section 2.2.

A third major initiative is the development of building materials with enhanced heat capacity. Although early techniques for using containerized PCMs in buildings have been examined, commercialization of these concepts have foundered due to the added expense of engineering them into standard structures, or in the case of latent heat storage in some PCMs, stability problems. A promising approach to resolve both of these issues is the incorporation of congruently melting PCMs into conventional building materials. Using the building material itself to hold the PCM eliminates the need for a separate container, and using congruently melting PCMs improves the effective lifetime of the concept. An approach being examined by the University of Dayton Research Institute (UDRI) uses a paraffin PCM contained in the matrix of standard gypsum wallboard. Prior work has shown[2] that once the PCM is inside the wallboard, it is effectively contained (even when melted) by surface forces between the PCM and the large area provided by the needles of gypsum in the core of the wallboard. This work also identified a paraffin blend that melts and freezes at approximately 22°C (72°F), which is in the room temperature range, and also identified and tested an immersion method for incorporating the PCM into the wallboard. Wallboard manufacturers have not shown as much interest in the immersion process for the PCM wallboard as a method whereby the PCM could be added to the wet wallboard mix during manufacture. Therefore, efforts were focused on examining methods for preparing the PCM as a dry powder that could be added as proposed. This work showed that the paraffin PCM could be added to certain finely divided silica to produce a dry powder even at temperatures above the melting point of the PCM. The dry powder is about 60 - 80 wt. % PCM. Further details of this work are presented in Section 2.3.

1.2 INDUSTRIAL TES

Industrial TES consists of technologies used to capture available waste heat for reuse in an industrial process. For several years, the industrial TES program has continued development of a composite TES material that, as pellets, could be used in a packed bed regenerator. The material, a composite consisting of a ceramic matrix suffused with a eutectic, was carried through laboratory development by the Institute of Gas Technology in prior years.[3] Later analytical studies on the predicted performance of a packed bed of composite material were conducted by Mississippi State University (MSU). During the reporting period, MSU completed fabrication of a packed bed test facility and initiated testing of sensible heat media to confirm the validity of their computer model. This work is described in Section 3.1.

2. TECHNICAL PROGRAM - DIURNAL THERMAL ENERGY STORAGE

2.1 DEVELOPMENT OF COMPLEX-COMPOUND CHILL STORAGE SYSTEM

Coordinative complex compounds (a solid metal salt bonded to gaseous refrigerant) are ideal reaction media for heat, cool, or chill storage systems. The multitude of salt and refrigerant combinations make thermal storage possible at temperatures from approximately -50°C to 300°C. Storage is possible by either transferring refrigerant between two complex compounds or using one complex compound to draw refrigerant from a reservoir.

Previous work at Rocky Research had focused on three options for implementing complex compounds in a thermal storage system: a pumpable complex compound slurry system, use of a carrier liquid for refrigerant transport to the complex compound, and solid bed reactors. The results from these investigations showed the simplest and most cost effective method to be a solid bed reactor directly coupled to the refrigeration system's receiver. Manufacturers also expressed a preference for this type of design.

A practical embodiment of the direct-coupled compressor- charged system is shown in Figure 2.1.1. During the charging process, the compressor is active and ammonia gas leaves the complex compound reactor. Compressor discharge superheat is used to maintain the complex compound temperature at approximately 35°C. During the discharge process, the compressor does not operate and the adsorption of ammonia into the complex compound maintains suction on the low pressure receiver. Refrigeration continues via the circulation of liquid refrigerant from the low pressure receiver to the load. The complex compound temperature is maintained by means of the evaporative condenser or cooling tower.

Work during this reporting period focused on confirming the performance of larger scale reactors with salts chosen for the application described above. The work was directed at obtaining sufficient design data such that the design for a full-scale system could be completed.

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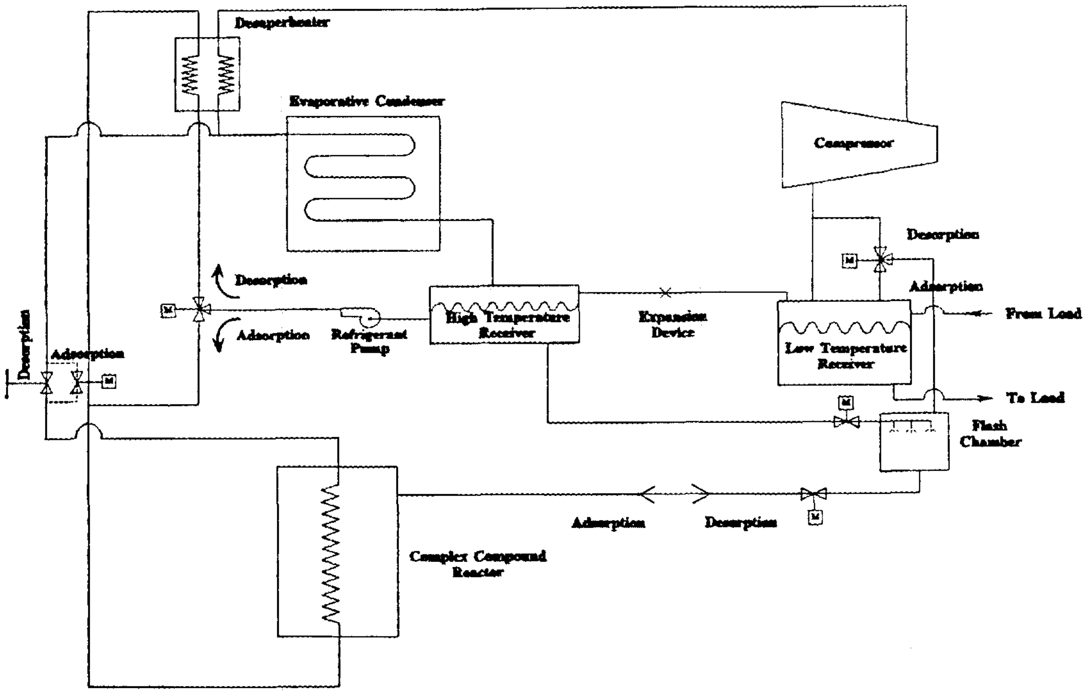

Fig. 2.1.1. Integration of Thermal Storage Module with Existing Refrigeration System.

2.1.1 LABORATORY EVALUATION OF ECONOMICALLY PROMISING DESIGNS

The emphasis of this task was the optimization of the solid-bed heat exchanger for thermal energy storage. The optimization criteria was based on a figure-of-merit that is a function of both the ammonia storage capacity and reactor cost. A step-by-step breakdown of efforts leading to the selection of the "optimal" heat/mass exchange system for the solid-bed storage reactor follows, along with an additional task of evaluating the effect of system compressor oil on the complex compound reactor core.

2.1.1.1. Testing of Single Core Reactor Modules

Laboratory testing of single core reactor modules was accomplished using small capacity test stands shown in Figure 2.1.2. These stations consist of a ligand column with a level scale, a reactor vessel, temperature baths, pressure regulators, and instrumentation to measure ammonia pressure, ammonia temperature, and complex compound temperature.

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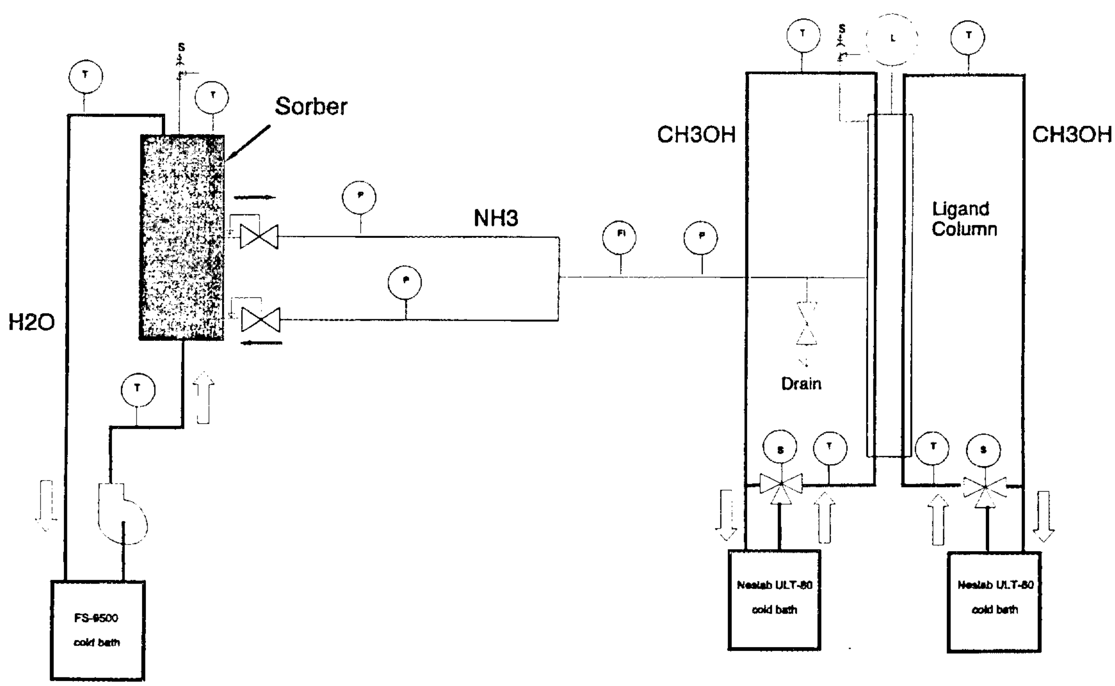

Fig. 2.1.2. Small Scale TES Test Apparatus.

For testing, the complex compound is loaded into a reactor vessel and a continuous supply of 35°C water is circulated through the reactor core. During an adsorption test, a heat transfer fluid is circulated through the ligand column to establish an ammonia pressure that is higher than the salt's vapor pressure. The delivery pressure is then controlled by a regulator. For a desorption test, the ligand column pressure is lowered to below that of the complex compound, allowing ammonia to flow from the compound back to the ligand column.

An adsorption period of 4 hours was established as the baseline for system comparison. Adsorption conditions used for most of the tests were an ammonia pressure of 1.334 bar (corresponding to -18°F evaporation) and a salt temperature of 95°F, which is conservative. Test desorption times, while changed for a few tests, were typically run for 3 hours. For most of the tests, the desorption process was completed in less time, but was allowed to proceed for 3 hours. Desorption test conditions were nominally chosen to be 95°F salt temperature and 0.617 bar (-45 °F) ammonia pressure. In an operating system, desorptions would not typically be done this way since either a mechanical compressor or a high temperature thermal source would be used that would allow condensation of the ammonia to occur at cooling tower temperatures. However, small, oil-free mechanical compressors for the type of volumetric flow rates required for the apparatus were not on the market.

Results for the most significant of these tests is shown on Figure 2.1.3. The tests included a range of normalized heat transfer parameters from 0.67 to 2.0 as well as normalized loading parameter from 0.89 to 1.11. The figure shows only a subset of the total runs. Both the ammonia uptake and the figure of merit are shown as a function of the normalized heat transfer, mass transfer and loading parameters.

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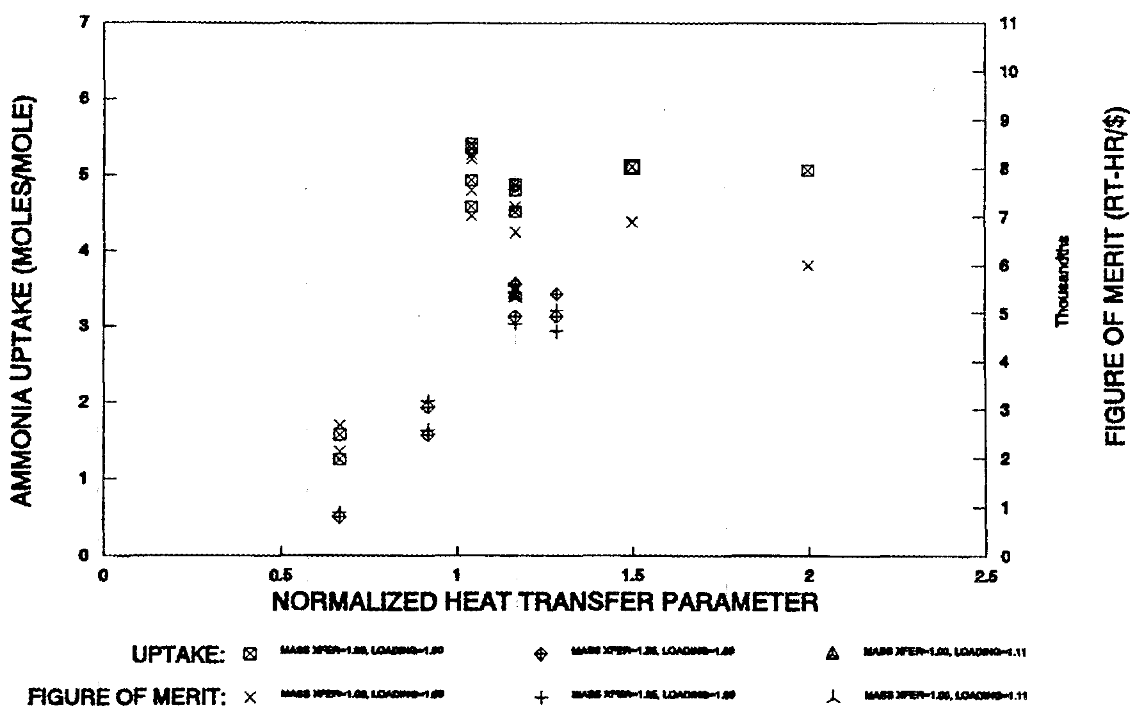

Fig. 2.1.3. Ammonia Uptake and Figure of Merit for Small Scale Reactor Tests.

The figure of merit is based on the refrigeration effect associated with the ammonia uptake and the idealized costs for the reactor components. Included in these costs are the salt cost (quote from manufacturer), aluminum material cost ($1.00/lbm including a

25% metal working markup), the steel material cost ($0.35/lbm including a 25% metal working markup) and an associated vessel cost component ($7.21/cu.ft. vessel @ 250 psi ASME). The figure of merit has units of ton-hr of cooling per dollar. Note that the inverse of the figure of merit is not the cost per ton-hr for a chill storage reactor because the figure of merit value does not include specific, design-related costs.

As Figure 2.1.3 indicates, the pattern with a 1.0 diffusion parameter and a 1.0 loading parameter had the best figure of merit and the highest ammonia uptake. According to the data taken, the figure of merit for this design is highest in the heat transfer parameter range of 1.04 to 1.17.

Tests were typically run for three or four cycles to determine the operating mole range under the specified adsorption/desorption time periods. These results were used as the basis for the selection of larger cores for testing in the larger size, multiple core test apparatus.

2.1.1.2. Design and Construction of Multiple Core Test Apparatus

A "large capacity" test apparatus, capable of testing packaged multiple reactor core modules with a loading of up to 500 grams of salt, was designed and built. The test apparatus was similar to the small scale test stand with the exception that two parallel ligand columns were needed because of the larger ammonia uptake. The 6-inch reactor vessel was designed to be capable of accommodating three multiple reactor core modules with their salt retainers. As with the smaller test apparatus, constant temperature baths are used to provide the proper salt and ligand conditions.

In the large reactor vessel, the packaged modules can be arranged with parallel manifolding to ensure even temperature distribution. A salt retainer/distributor is placed between each of the multiple module cores.

2.1.1.3 Testing of Multiple Module Reactor Cores

Testing of the single module reactor cores indicated that the highest figure of merit performance was for a diffusion parameter of 1.0 with a heat transfer parameter of 1.04

to 1.17. Using these results, iterations were made using Rocky Research's single/multiple module equivalence software to size a multiple module core with similar heat and mass transfer characteristics for subsequent testing. This reduced the number of multiple module types that needed to be tested.

Testing of the single and multiple module reactors was done in the large capacity test apparatus with most absorption tests being performed at the identical 6°C approach conditions as the single module tests. These cores were tested without a retainer that would impair the flow of ammonia by adding pressure drop. The packaged arrangement had multiple module cores with incorporated salt retainers. In addition, a sheet of non-permeable neoprene was used to enclose the whole bundle. The neoprene ensured that the only path of ammonia to the core was through the end of the retainer sheet. This represents the worst case scenario. The cores were circuited in parallel to allow an even distribution of heat transfer fluid to each module.

The results of these tests are shown on Figure 2.1.4 which is a representation of the four hour adsorption ammonia uptake as a function of the normalized heat transfer parameter. The figure shows the uptake for a 1.0 diffusion parameter single module pattern, two multiple module reactor cores and three packaged multiple module cores as well as a large reactor tested at Standard Refrigeration (a description of this test is provided in the next section). The results showed a tendency towards better packaged module performance with larger diffusion parameters. This is inconsistent with mass transfer theory since higher diffusion parameters would require longer diffusion path lengths, thereby reducing mass transfer. These results are better explained by the inconsistencies in the loading of the packaged cores. An exact comparison between the cores requires that the salt stay evenly loaded when ammoniated and that the retainer stay intact. Neither of these is the case in a real test. The salt tends to expand and can fracture the retainer. Fracturing the retainer allows for easier diffusion to the salt but also allows the salt to lose contact with the reactor core, hurting performance. These loading inconsistencies from test to test are probably the reason that the high diffusion parameter pattern performed the best of the three cores tested.

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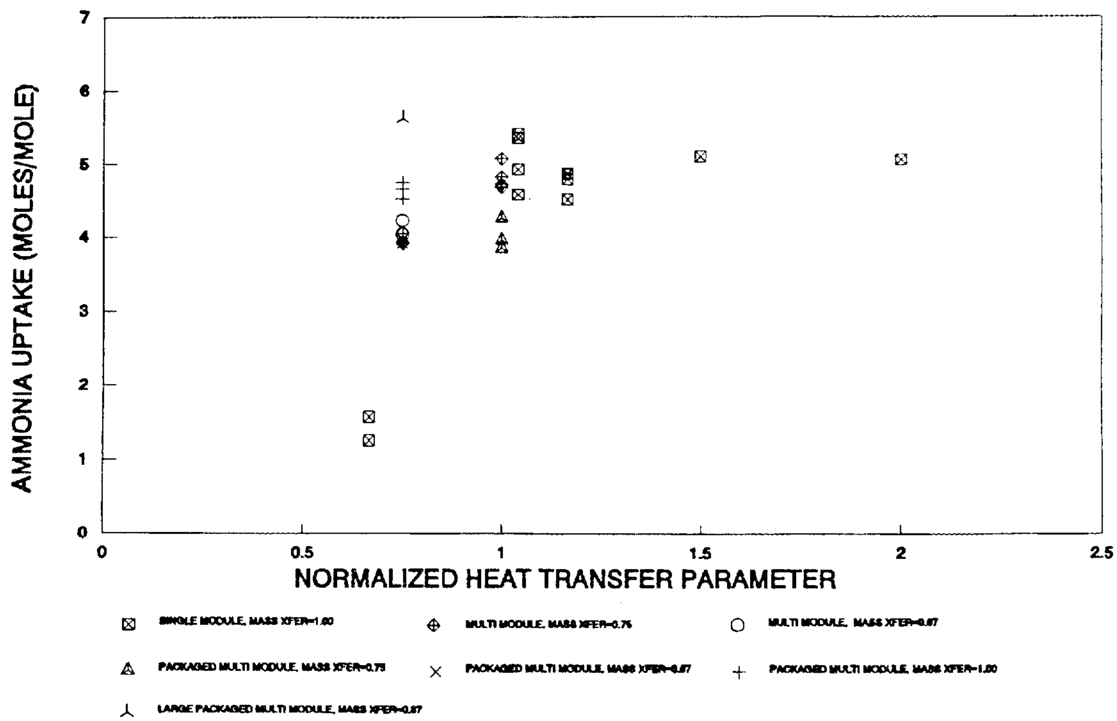

Fig. 2.1.4. Test Results Showing Ammonia Uptake With Various Reactor Modules.

Packaged multiple module reactor test performance was in the 3.9 to 4.7 moles/mole uptake range, which is slightly lower than desired. The tests were performed with the same pressure and temperature conditions as the small scale tests.

2.1.1.4. Testing of Large Scale Reactors

Near the conclusion of testing, an opportunity arose to test a large reactor with a packaged multiple module core that corresponded to those being tested in the laboratory. Adsorption testing of this reactor was done at Standard Refrigeration for a unit that was built for a different application. The reactor had a 0.87 normalized mass transfer parameter multiple module pattern and 128 lbm of the complex compound CC180-1580. The test run at Standard showed excellent performance when compared to tests of a corresponding geometry in the laboratory. Because of test conditions, it was only possible to keep the approach pressure within a range of values. However, this range was always below the minimum approach of 0.356 bar (6°K), which was the worst test condition for the corresponding laboratory test. The final uptake of 77.4 lbm of ammonia for a salt loading of 128 lbm corresponds to a value of 5.64 moles of ammonia per mole of salt. Along with the 0.87 normalized diffusion core pattern, this reactor used the same retainers as the laboratory tests, but performed much better. This is probably due to a number of factors that resulted in better ammonia contact with the salt.

It can be assumed that the performance demonstrated at Standard with a reactor that is two orders of magnitude larger in size than the laboratory reactors is more representative of the final TES reactor. For this reason, as well as the fact that laboratory testing has shown this pattern to have comparatively good performance, the 0.87 diffusion parameter pattern has been chosen as the reactor design for the large sized TES units. It should be noted that the 5.64 mole uptake is represents excellent performance when compared to other tests. This is shown on Figure 2.1.4, which compares the uptake of a number of different reactor cores, all with a normalized loading factor of 1.00.

2.1.1.5. Cyclic testing with compressor oil saturated ammonia vapor.

The long-term ability of complex compounds to adsorb and desorb over many cycles is an important issue for thermal storage systems which must cycle once per day over a life of many years. Verification of cycle life over thousands of cycles has been proven in earlier work. However, in an industrial application such as thermal storage, the ammonia will be exposed to compressor oil. Any effect that this may have on system performance must be substantiated.

During this phase of the project, cyclic stability testing was done to determine the effect of compressor oil-laden ammonia vapor on reactor performance. This was done using an apparatus that forced the ammonia to pass through a column of compressor oil during adsorption. This "bubbling" through the compressor oil exposed the ammonia to a large amount of oil previous to its adsorption into the complex compound.

The tests were run for 1723 cycles, and represent over 4 1/2 years of thermal storage operation. Cycling for these tests was done at higher than nominal ammonia approach pressures in order to allow a large number of adsorption/desorption cycles to take place in a short time. The calibration tests, were done at the expected thermal energy storage conditions. After 1723 cycles there was no degradation in the ammonia uptake of the complex compound. The testing ended when the failure of a pressure control valve resulted in the contamination of the salt.

2.1.2 DEVELOPMENT OF ECONOMICALLY VIABLE REACTOR DESIGNS

In earlier phases of the project and during the early part of Phase IV of the project, Standard Refrigeration had been the designated manufacturing partner for the project. In Phase IV it became apparent that another manufacturer, Baltimore Air Coil, would be better suited to the construction of large, industrial-sized reactors. Baltimore Air Coil has agreed to be the manufacturing partner for the manufacture and testing of an industrial size unit in the next phase of the project.

The ultimate objective of this task is the design and economic evaluation of a reactor of a practical size for industrial thermal energy storage. Rocky Research took the lead in performing these tasks, but with significant aid from both Standard Refrigeration and Baltimore Air Coil.

2.1.2.1. Engineering Design - Reactor Heat Exchangers

The design "type" for the final reactor was evaluated early in this task. Three different reactor designs were considered: a single module with a small diameter low cost shell, a packaged single module, and a packaged multiple module. A computer model laid out the reactor core geometries and performed calculations of total mass, subcomponent mass, vessel volume utilization, free volume, heat capacity, and total material costs for the design. Real subcomponent costs were used.

The first comparisons were made between the low cost shell (PVC plastic) with a single module design and the packaged large shell (steel) single module design. The packaged design was considered for 16", 20", and 24" vessel diameters. Results showed that while the costs of the reactor modules themselves were very close to each other, the additional ammonia manifolding required for the PVC design would make its cost prohibitive.

Comparisons between the packaged single and multiple module reactor designs were then made for a 24" diameter vessel. The results showed a 25% better vessel volume utilization and an estimated 30% reduction in material costs for the packaged multiple module design. The packaged multiple module design had a resulting mass ratio of heat exchanger metal to complex compound of 5.1 to 5.2 while the packaged single module reactor had a ratio of 5.8 to 6.3. Therefore, for reasons of cost, vessel volume and reduced mass, the packaged multiple module design was chosen. This design was presented to Standard Refrigeration for their consideration. Standard was supportive of the design and, because of it, has changed the design of their complex compound product from a packaged single module to a packaged multiple module design.

2.1.2.2. Costing of Complex Compound Reactors

The costing effort required the use of computer model along with volume pricing information on reactor subcomponent and labor costs. The acquisition of cost information for subcomponents was made more difficult because many manufacturers could not or would not offer high volume quotes. For this reason, it is believed that a large manufacturer should be better able to negotiate with these same subcomponent producers when a market is established, resulting in a lower reactor manufacturing cost. Therefore, the estimates presented here should be considered to be "worst case".

Subcomponent costs were obtained for tubing, heat transfer surface, spacer materials, salt, vessel material and tube sheets for all the possible designs being considered. Two sources were used for the vessel and tube sheet cost estimation formula and resulted in almost identical estimates. A major HVAC manufacturer supplied heat transfer surface cost information that was used to derive a model for costing other sizes as needed. Consideration was made for the labor costs to manufacture the product assuming non-automated manufacturing of 100's of units per year. The labor costs were broken up based on a 25 step manufacturing process. The cost spreadsheet assigns a labor time period associated to each assembly step. Labor costs are assumed to be $ 25.00/hr, fully marked up.

2.1.2.3. Preliminary Analysis of Allowable System Cost

An economic analysis to determine the acceptable equipment cost on a per ton hour basis was performed for an industrial food processing plant application in three different utility areas. The three areas selected were Chicago, New York City, and Southern California. The economic model was based on an energy cost difference between off-peak and on-peak rates, an avoided capacity credit of $260/ton for a -20°F compressor, a cooling efficiency of 2.06 kW/ton, and a charging efficiency of 2.41 kW/ton. No credit is taken for any utility first cost incentive package offered for load shifting equipment, although most utilities would offer such an incentive. The following costs are used for the utilities indicated:

	Rate	Seasonally Adjusted Demand ($/kW)	Energy On-Peak ($/kWh)	Energy Off-Peak ($/kWh)
Chicago	Comm Ed 6L	$13.29	$0.05961	$0.02784
New York	Con Ed Schd 4	$9.61	$0.07842	$0.04773
Southern CA	SoCal Ed TOU-8	$8.17	$0.10798	$0.05053

The resulting payback as a function of TES discharge period and installed cost are shown on Figure 2.1.5 for Chicago. New York and Southern California were also evaluated with similar results. In all cities, the TES discharge period is a significant contributor to the overall economics of the system because of the avoided capacity credit for a conventional compressor that is accrued by use of the system.

For a total installed cost of $382.81 per ton-hr, including all markups, all of the utility areas showed a payback in 2 ½ to 3 ½ years, based on a three hour discharge period.

Use of the peak demand reduction capability can be directed by the utility or it can be based on the plant's production schedule. For instance if product is being loaded into

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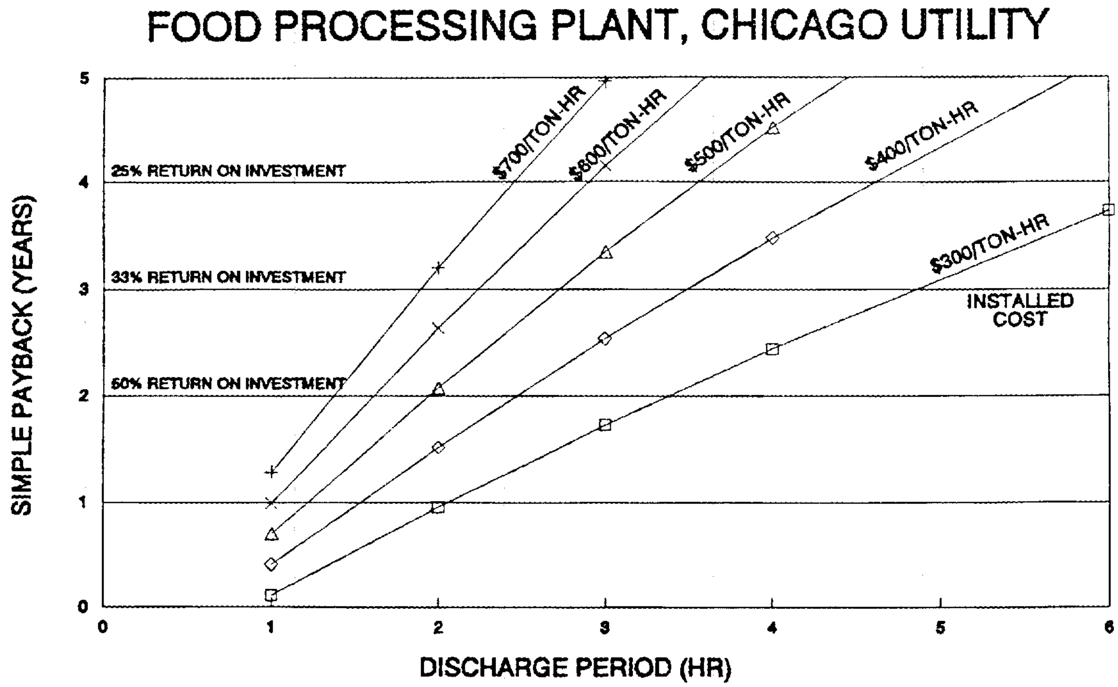

Fig. 2.1.5. Thermal Storage System Economics.

the refrigerated area to be cooled, the plant's cooling capacity can be increased by discharging the complex compound during this period, thus reducing this peak demand.

Peak clipping of the demand refrigeration load is also possible. Because the discharged or partially charged reactors are activated by simply opening a valve between them and the low temperature receiver and providing a cooling fluid flow, with proper control (either predictive or set point oriented) the reactors can be used to eliminate the peak demand above a given datum. This may allow smaller sized, shorter discharge units to be used with less than a 2 years payback (for a 2 hour total discharge).

2.1.2.4. Design of a Complex Compound Reactor

A 50 ton-hr reactor was designed using the same core pattern as large scale multiple module reactor. The reactor is a 36" diameter cylinder with an overall length of 227 inches. The vessel contains 2269 lbs. of complex compound forming salt. The ammonia and cooling sides of the reactor are designed to withstand at least 250 psi. Ammonia and cooling fluid connections are Schedule 40, 6" steel tubing with standard 250 lb. flanges. The calculated capacity of the design is 52.2 ton-hr with an estimated weight for the fully loaded reactor of about 12,500 lbs. Total manufactured cost is estimated to be $10,508 per vessel. Table 2.1.1 summarizes manufactured cost and weight estimates on a total, ton-hr, and salt mass basis.

The reactor contains a packaged multiple module core with a length of 188 inches. A number of different cores were selected to allow the best utilization of the internal volume of the cylinder while reducing the inventory required by the manufacturer. The present design allows for utilization of 57.7% of the internal volume of the vessel. Large tube sheets at each end support the core with additional longitudinal support provided by dual function interior supports. A sleeve surrounds the core to aid in salt retention.

Figure 2.1.6 shows an external view of the entire reactor with the ammonia inlet at the top and cooling water ports on both sides. Design drawings of the reactor assembly and subassemblies have been produced and were sent to the manufacturing partner, Baltimore Air Coil for their review. The installed cost for the system can be expected to be related to the manufacturer's cost by a multiplier in the range of 1.75 to 2.30 for this type of industrial equipment. A Rocky Research refrigeration consultant has indicated that an experienced design/build contractor should have a multiplier of 65%. A major manufacturer is expected to require a profit margin of approximately 15% for this equipment. This results in a total multiplier of 1.90. This means that the installed cost for the equipment is $382.81 per ton-hr ($201.48 X 1.90) for the equipment.

2.1.2.5. Design Review - Complex Compound Reactor

Rocky Research distributed design drawings of the 50 ton-hr reactor assembly and subassemblies to the manufacturing partner, Baltimore Air Coil for their review and design recommendations.

As the result of their analysis, Baltimore Air Coil suggested several design improvements. BAC engineers offered detailed recommendations on many subassembly components

Table 2.1.1

50 TON-HR THERMAL ENERGY STORAGE REACTOR DESIGNS

	Shell Diameter (in)	Length (ft)	Salt Mass (lb)	Total Mass (lb)	Number of Tubes	Salt Volume Utilization	LB Salt/ TON-HR
Design	36.00	15.667	2268.6	10845	762	0.577	43.5

TOTAL COSTS

	Core	Salt	Spacer	Shell	Tube Sheets	Total Matls	Labor	Total
Total Cost	$3,891.6	$3,291.7	$619.8	$1546.6	$689.1	$10,039	$468.7	$10,508
Costs per TON-HR	$74.62	$63.12	$11.88	$29.66	$13.21	$192.49	$8.99	$201.48
Costs per Pound of Salt	$1.715	$1.451	$0.273	$0.682	$0.304	$4.425	$0.207	$4.632

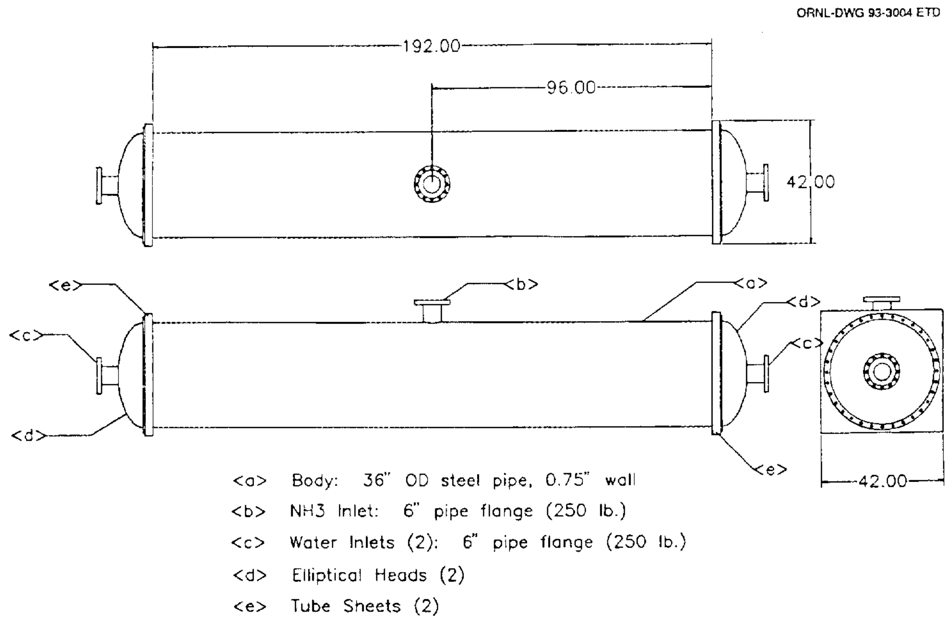

Fig. 2.1.6. Exterior View of Fifty Ton-hr Thermal Storage Reactor Module.

including the vessel, tube sheet, water box, and vessel stands. All of these design changes will result in a reactor cost reduction. Concerns were voiced over corrosion within the carbon steel tubing if it is to be used in contact with aerated cooling tower water. However, if ammonia is used as the heat transfer medium, as shown in Figure 3, this will not be an issue. For exposure to water, possible solutions for the corrosion issue include constructing the tubes of a material other than carbon steel, coating the inside of the tubes, or treating the cooling water.

Although similar but smaller reactors have been manufactured by Standard Refrigeration, BAC expressed concern over whether the existing manufacturing methods could be applied to a reactor of this size. Having witnessed the assembly of a similar, but smaller reactor vessel, they expressed some reservations about the assembly procedure from a manpower and quality control perspective. Rocky Research engineers who supervised the reactor assembly stated that modifications in the assembly process have greatly simplified it from the procedure witnessed, since the unit built at that time was the very first using the packaged multiple reactor core. Standard Refrigeration is now producing these reactors as a product.

2.2 THERMAL STORAGE WATER HEATER DEVELOPMENT

Electric water heaters are the second largest consumers of residential electricity. Nationally they consume 17 billion kWh/y and represent a demand of 26 GW. Thus any effective strategy to reduce utility peaking problems must address this demand as an element of the overall strategy.

Approximately 3 million units are sold annually with almost 2.6 million of those units having a storage capacity of 30 to 55 gallons. This water storage capacity does not afford sufficient storage capability to reduce peak load requirements by shifting water heating to an off-peak activity. To achieve the load shifting objective would require additional water storage capacity that could only be accomplished by adding extra water tanks, and this would require additional floor space within the residence. Thus the objective of this development activity is to develop a water heater that has double the thermal capacity of a conventional water heater but occupies the same volume.

Three concepts are being explored. The first uses a bed of high density polyethylene pellets (HDPE) whose internal structure has undergone crosslinking. The crosslinking step allows the pellets to store significant amounts of energy in a phase transition and maintain the structural integrity of the pellet. Thus the form stable PCM can be used in a packed bed arrangement. The second concept uses a more conventional arrangement of PCM, bulk encapsulation of a PCM that undergoes a solid/liquid phase transition. The third design uses a sensible heat concept and stores the required amount of energy via large temperature changes in the storage medium. The following sections describe the development activities accomplished for each of the concepts during the reporting period.

2.2.1 HDPE PELLET BED CONCEPT

High density polyethylene (HDPE) pellets, trade name ALATHON M6210, were purchased from Occidental Chemical Corporation. These pellets were crosslinked by Nutron Products using a radiation dose of 10mRad. Physical properties of the crosslinked HDPE pellets were then determined. The pellets were tested to determine the transition temperature, heat of transition, increase in volume, and swelling in solvent. On average, the transition temperature was found to be 126°C. The heat of transition was measured by DSC (differential scanning calorimeter) at a heating rate of 2°C/min. It was found to be about 180 kJ/kg during heating and 165 kJ/kg during cooling. It has been reported that there is a 5-6% increase in volume when HDPE changes phase. However, in a mixture with propylene glycol the total volume change is higher. In a closed container the total increase in the volume was found to be about 15% when heated well above the transition temperature of the HDPE pellets, for a mixture of 65.7% pellets and 34.3% propylene glycol. Swelling tests were also conducted to determine the amount of crosslinking. They showed a satisfactory level of crosslinking. The heat transfer coefficient for the pellets when used in a packed bed were also determined. This information was needed to design a storage water using a packed bed of the HDPE pellets on the TES component. The overall heat transfer coefficient for HDPE pellets in a heat transfer oil (propylene glycol) was determined in a double pipe heat exchanger, and was found to be in the range of 100 to 180 w/m^2K for different flow rates.

An experimental set up for testing an HDPE pellet bed storage unit was designed and fabricated. This unit was used to determine the thermal performance of the concept. It consisted of a steel tank that contained a mixture of HDPE pellets and propylene glycol, as shown in Figure 2.2.1. A screen was placed close to the bottom of the tank. In this configuration the electric elements heat the propylene glycol. This in turn heats the HDPE pellets by conduction and convection. Heat was recovered by passing the cold water through a finned copper coil in the tank. About 74.4 kg (163.7 lbs) of crosslinked HDPE pellets along with 56.6 liters (14.95 gal) of 100% propylene glycol was charged in the insulated storage tank. The tank was equipped with several thermocouples, a flow meter, etc., to monitor the system.

Several discharging tests of this unit were conducted with flow rates of 1, 1.5, 2, 2.5, and 3 gpm. In these tests the mixture of HDPE and propylene glycol was heated to a temperature of 140°C. Thus the amount of thermal energy stored in the temperature interval of 60 to 140°C is 11.65 kWh. Table 2.2.1 reports the amount of heat that was recovered during the discharging period for different water flow rates. The total amount of thermal energy extracted during these runs varies between 7.3 to 9.15 kWh. In these

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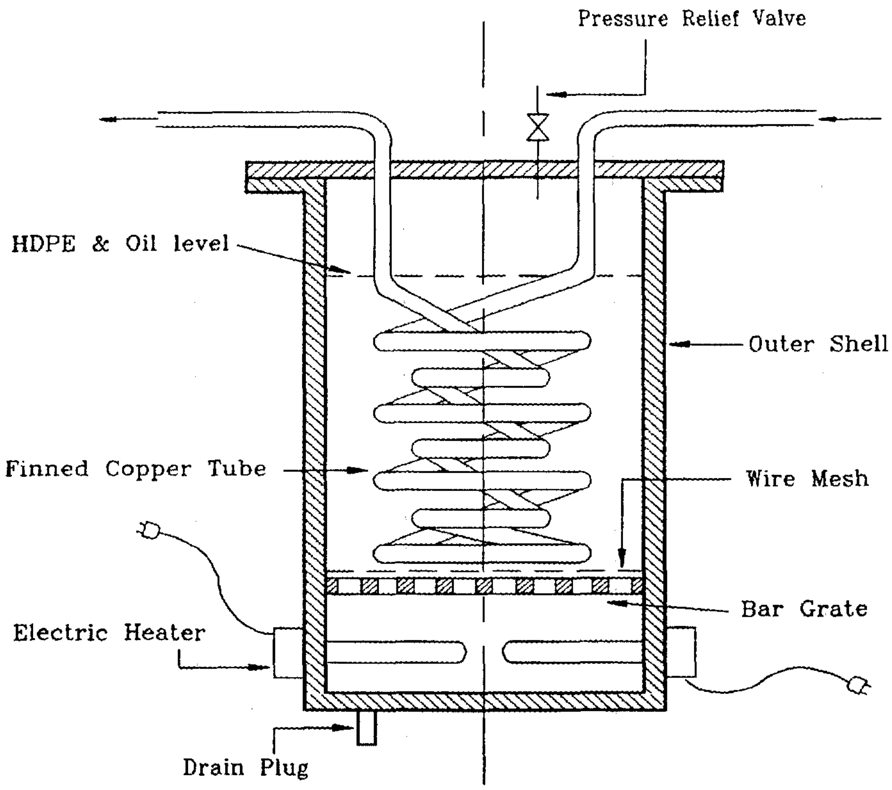

Fig. 2.2.1. HDPE Pellet Bed Storage Water Heater.

cases the storage bed temperature at the end of the run was in the range of 55 to 95°C when the outlet temperature of water reached 40°C. This means that some useful heat still remains in the storage bed due to the heat transfer limitations.

This configuration was also tested using an intermittent withdrawal of water. For each of these runs water was passed through the heat exchanger coil for a fixed time period (about 10 minutes); water flow was stopped for a period of one hour, and then turned on again. No appreciable change was observed in the amount of energy extracted between the continuous water draw and intermittent water draw.

The system design tested above had some drawbacks such as, long charging time (about 14 to 16 hrs), and a large quantity of propylene glycol required. Therefore, a new design was selected and fabricated. It is shown in Figure 2.2.2. The new design has a

TABLE 2.2.1				
Test Results for Pellet Bed Storage Water Heater Continuous Testing				
Flow Rate	Run No.	Run Time	Heat Out	Heat Stored
gpm		min	kW-h	kWh
1	1	41.5	9.04	11.65
1	2	37.5	8.81	11.65
1	3	40	8.86	11.65
1.5	1	28	7.36	11.65
1.5	2	36.5	8.91	11.65
1.5	3	30.5	9.153	11.65
2	1	22	8.803	11.65
2	2	28.5	8.29	11.65
2	3	20.5	7.523	11.65
2.5	1	19.5	7.57	11.65
2.5	2	19.5	8.96	11.65
2.5	3	17.5	8.26	11.65
3	1	17.5	8.114	11.65
3	2	16.5	8.319	11.65
3	3	15	7.321	11.65

*Heat stored in the pellet bed is in the temperature range of 60°C to 140°C.

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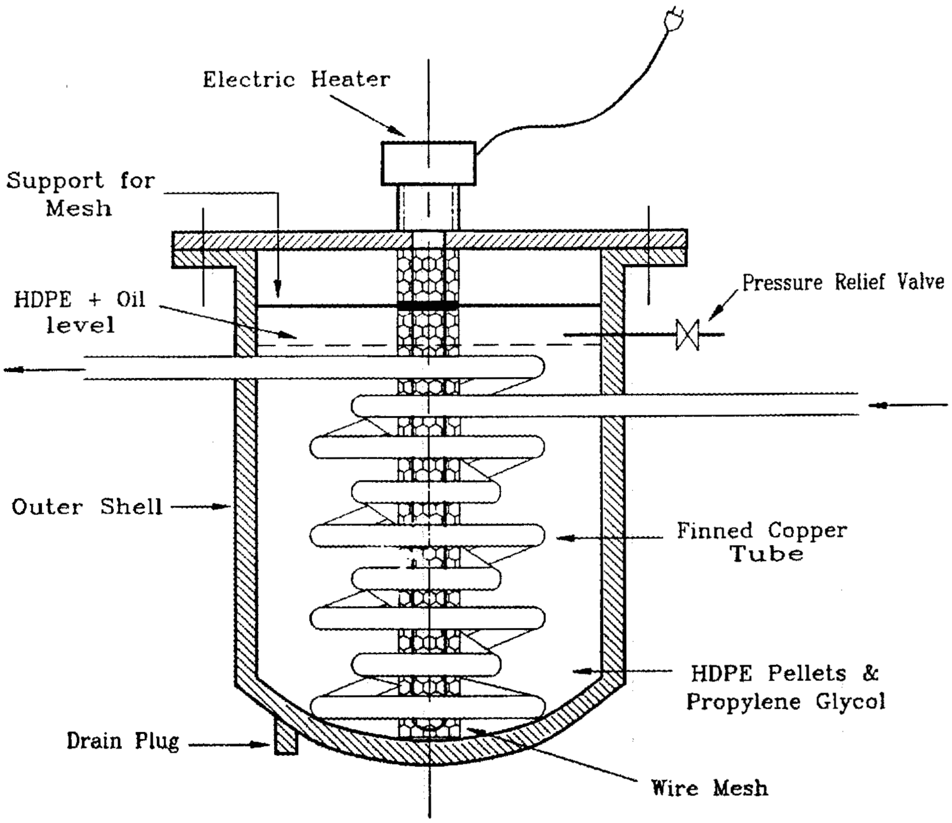

Fig. 2.2.2. Optimized Design of HDPE Pellet Bed Storage Water Heater.

central heating element along the axis of the cylindrical tank providing radial heating. The total charging time has been reduced to about 8 hours in the new design. Preliminary discharging tests were completed for the new system. Initial results indicate that the amount of heat recovered in the new design is about 25% higher than in this previous design. These preliminary results also indicate that the design goal of doubling the thermal capacity has been realized.

2.2.2 ENCAPSULATED PCM CONCEPT

Development activities for the encapsulated PCM concept focused on characterizing potential PCMs, encapsulating them and testing their performance in thermal cycling tests, and developing a numerical model that could be used to predict the performance of the storage component of the water heater. Details of these activities are provided in the following sections.

2.2.2.1 Characterization and Cycling Stability of PCMs

Based on the conclusions from the first phase of this project two salt hydrates, ammonium alum and trisodium phosphate dodechahydrate (TSP), were selected for further studies. Since both of these salts supercool, the first step was to find ways to prevent supercooling. In the case of ammonium alum supercooling was prevented by a small crystal of calcium fluoride. However, it was effective only when molten ammonium alum was continuously stirred during cooling. After several experiments it was concluded that ammonium alum required continuous stirring during cooling to prevent supercooling and the crystal growth of ammonium alum was very slow. A eutectic of ammonium alum with ammonium nitrate was also investigated. Several compositions of ammonium alum-ammonium nitrate were tried. However, only one composition, consisting of 50-50 wt% of ammonium alum and ammonium nitrate, was found to work well. Since this eutectic has a transition temperature of 45°C, it is not suitable for hot water applications.

In the case of TSP, it was found that it does not dissolve completely in its water of hydration when heated. Hence extra water is required for complete dissolution. As reported in the literature, sodium hydroxide (4 to 15 wt%) was found to be a suitable nucleating agent to prevent supercooling. Several compositions of TSP with extra water and sodium hydroxide (NaOH) were tested. Two compositions - 80% TSP, 16% water, 4% NaOH; and 85% TSP, 11% water, 4% NaOH - were selected for further investigation. Several attempts were made to determine the heat of transition of TSP using DSC. However, due to the failure of the pans that hold the sample repeatable results were not obtained. Therefore, it was decided to determine the enthalpy of TSP in a drop calorimeter. For a composition of 80% TSP, 16% water and 4% NaOH an enthalpy value of 129 kJ/kg was observed in the temperature range of 61 and 75°C. For the composition of 85% TSP, 11% water and 4% NaOH, total enthalpy was found to be 155 kJ/kg in the temperature range of 60 and 75°C. These values are close to those reported in the literature. A composition of 85% TSP, 4%NaOH and 11% water was subjected to several heating and cooling cycles. Results showed that for about 800 cycles there was no appreciable change in the enthalpy value. A thickening agent, attapulgite clay, was also added to the TSP mixture to compare it with unthickened TSP. When about 5% of clay was added to a composition of 85% TSP mixture, no appreciable change in enthalpy values was observed for about 700 cycles.

2.2.2.2 Encapsulation and Cyclic Test

Two methods for encapsulation that have been investigated are heat sealed/ultrasonic sealed laminated aluminum pouches and plastic balls. Six type of laminated aluminum foils having different compositions and thicknesses were received from Reynold Metals. They were tested for the strength of the joints when the joint was made using a heat sealer. Ultrasonic sealing of these pouches was not successful. Of the six laminated foil samples, two were rejected because they were laminated on only one side. The remaining four were subjected to static load tests to determine the strength of their seals. Based on the seal strength data two foils were selected for encapsulation tests. TSP was encapsulated in pouches made from these foils and cycled through several hundred heating and cooling cycles. Of these two pouches only one lasted for a large number of cycles. This pouch completed 1040 cycles during the reporting period.

For encapsulation in plastic balls, two type of materials, high density polyethylene and polypropylene, were selected. Open neck balls with 1 inch internal diameter and 15 mm thickness were purchased. Sealing of balls after they have been filled with TSP has been a problem and will be addressed in future work.

2.2.2.3 Validation of PCM Numerical Model by Experiments

An experiment was performed to validate the numerical model used to predict the thermal performance of a PCM water heater. The test apparatus consisted of three major components: the test cell, a light source, and a camera, as shown in Fig. 2.2.3. The test cell consists of a wooden frame that is covered on two sides by lexan windows (see Fig. 2.2.4). To reduce the convection heat loss from these windows, outer windows are fitted and separated from the inner windows by a small distance. A heater is provided at the

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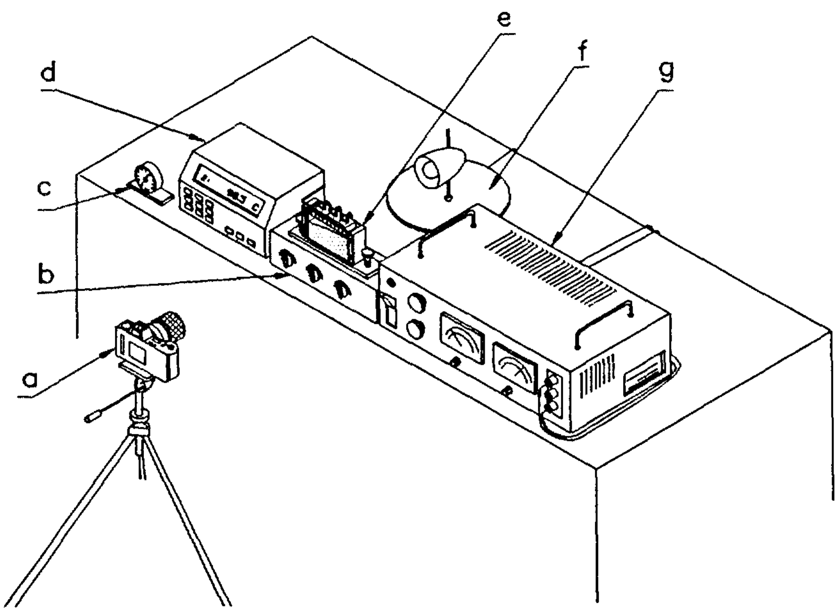

a. Camera
b. Temperature control console
c. Timer
d. Digital thermometer
e. Test cell
f. Light source
g. Power supply

Fig. 2.2.3. Experimental Setup.

top of the cell. Copper-constantan thermocouples are set at the lower side of the heater so that they measure the temperature imposed on the PCM (paraffin wax). The cell is placed in an upright position with the heater at the top during the tests. This causes the wax to be heated from above, a position which effectively suppresses the free convection circulation in the cell. As a further precaution for minimizing convection, screws are used to adjust the interface position so that it is leveled at all time in the course of the experiment.

Experimental results are presented in Figure 2.2.5, which shows the positions of the phase change interface. Clearly, the agreement between the experiment and analysis is good. Only over the middle section of the curves, are there discrepancies and this is

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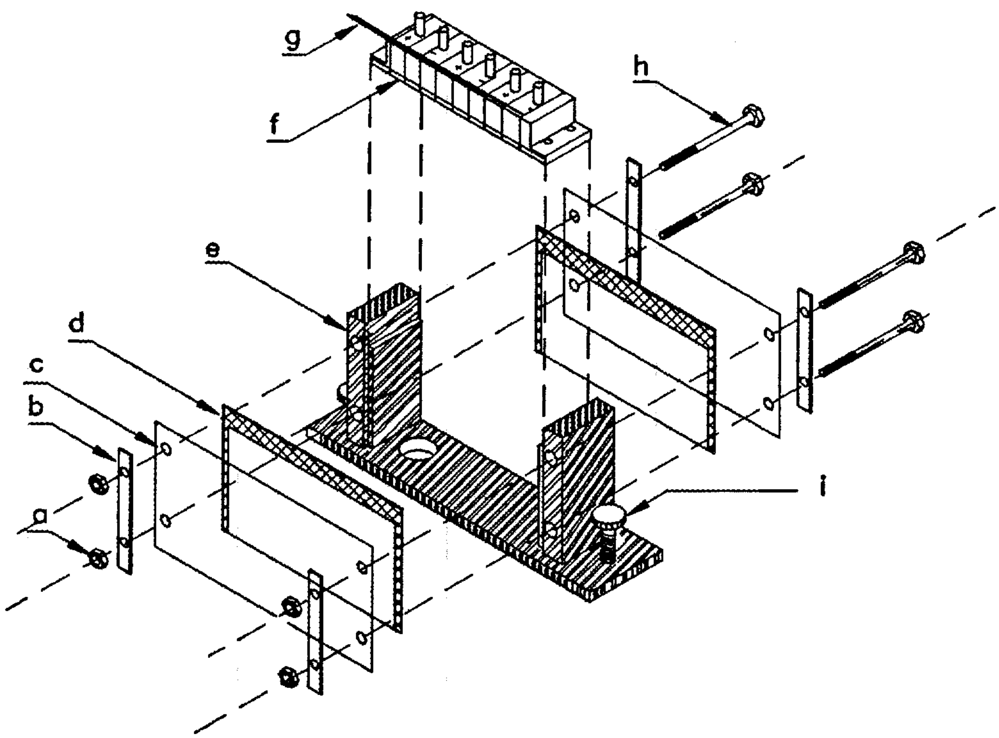

a. Nuts
b. Gaskets
c. Outer windows
d. Inner windows
e. Frame
f. Electric heater assembly
g. Thermocouple wires
h. Bolts
i. Levelling screws

Fig. 2.2.4. Detailed Drawing for Construction of the Test Cell.

attributed to the curvature of the phase change interface position curve, which is not exactly linear. The levelling screws described in the experiment were used to adjust the slope of the middle section of the interface curves. A levelling of this section of the curves upsets the slope at two ends. As a result, convection cannot be totally eliminated from the cell, causing a slight disagreement between the prediction and the experiment.

2.2.3 HIGH TEMPERATURE SENSIBLE HEAT STORAGE

In order to study the behavior of high temperature sensible heat storage water heating system, an experimental system was set up as shown in Figure 2.2.6. This experimental

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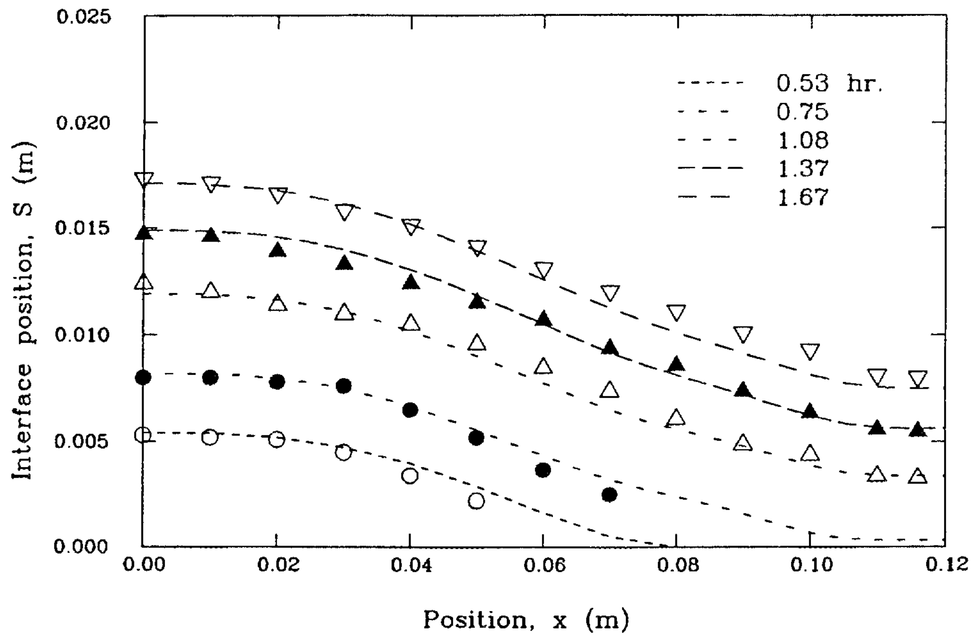

Fig. 2.2.5. Comparison of Interface Position.

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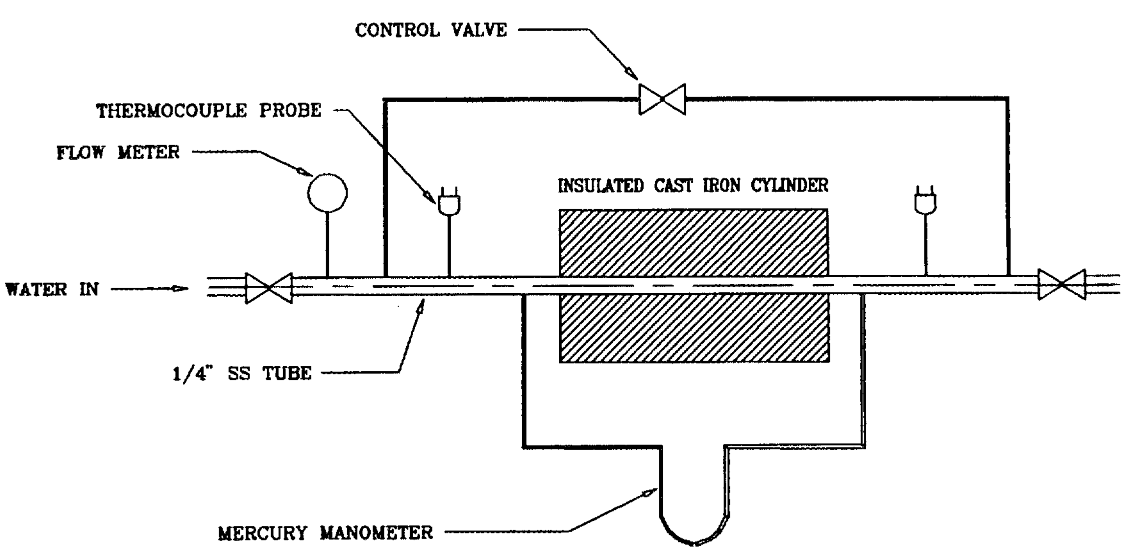

Fig. 2.2.6. Experimental Setup for High Temperature Sensible Heat Storage.

setup consists of a 4 inch diameter cast iron shaft with a 1/4 inch diameter stainless steel tube running through its center. The cast iron shaft is insulated with high temperature insulation purchased from American Microtherm Inc. The cast iron was heated to about 700°C by the heating tape wrapped around the shaft. A mercury manometer was placed between the inlet and outlet of the tube running through the cast iron shaft. In the preliminary runs, water was passed through the stainless steel tube and the pressure fluctuations/drop and the temperature rise was recorded. It was observed that the maximum flow rate through the 1/4 inch stainless steel tube was about 1 gpm. Pressure fluctuations in the range of 4 - 7 inches of mercury were observed only for a few seconds when cold water was passed through the tube. After that a pressure drop of 4 inches of mercury was recorded for the remaining period. A graph of temperature vs time is shown in Figure 2.2.7 for the flow rate of 0.94 gpm. It can be observed from this figure, a maximum outlet temperature of 65°C was recorded at the start of the run when the temperature at the surface of cast iron was 650°C. It took about 36 minutes for the outlet temperature of water to drop from 65 to 40°, which means that 33.48 gallons of water was obtained in the useful (for residential water heating) temperature range. During the period the temperature of the outer surface of the cast iron dropped from 650 to 302°C.

From these results it seems that the problem of pressure fluctuation, which was first thought to be a major problem in high temperature storage systems, is not of much concern because small pressure fluctuation last only for a few seconds. A computer program was developed to model the performance of the sensible heat storage system. In this program, contact resistance between the cast iron and the stainless steel tube was unknown and was assumed to vary with temperature. Therefore a trial and error method was used to attain this value. A value of the contact resistance was selected that matched the theoretical results with the experimental values. By using two different values of contact resistance - 0.0011 for large temperature differences between the water and the cast iron, and 0.00025 for small temperature differences - the deviation from experimental results was reduced considerably. Figure 2.2.8 shows the deviation between the experimental and theoretical values. Since the contact resistance seems to play a major role in this particular application, a more detailed study is required to determine its value. In order to do so, two new experiments are in progress. One consists of a cast iron cylindrical block in which a 1/2 inch stainless steel tube passes

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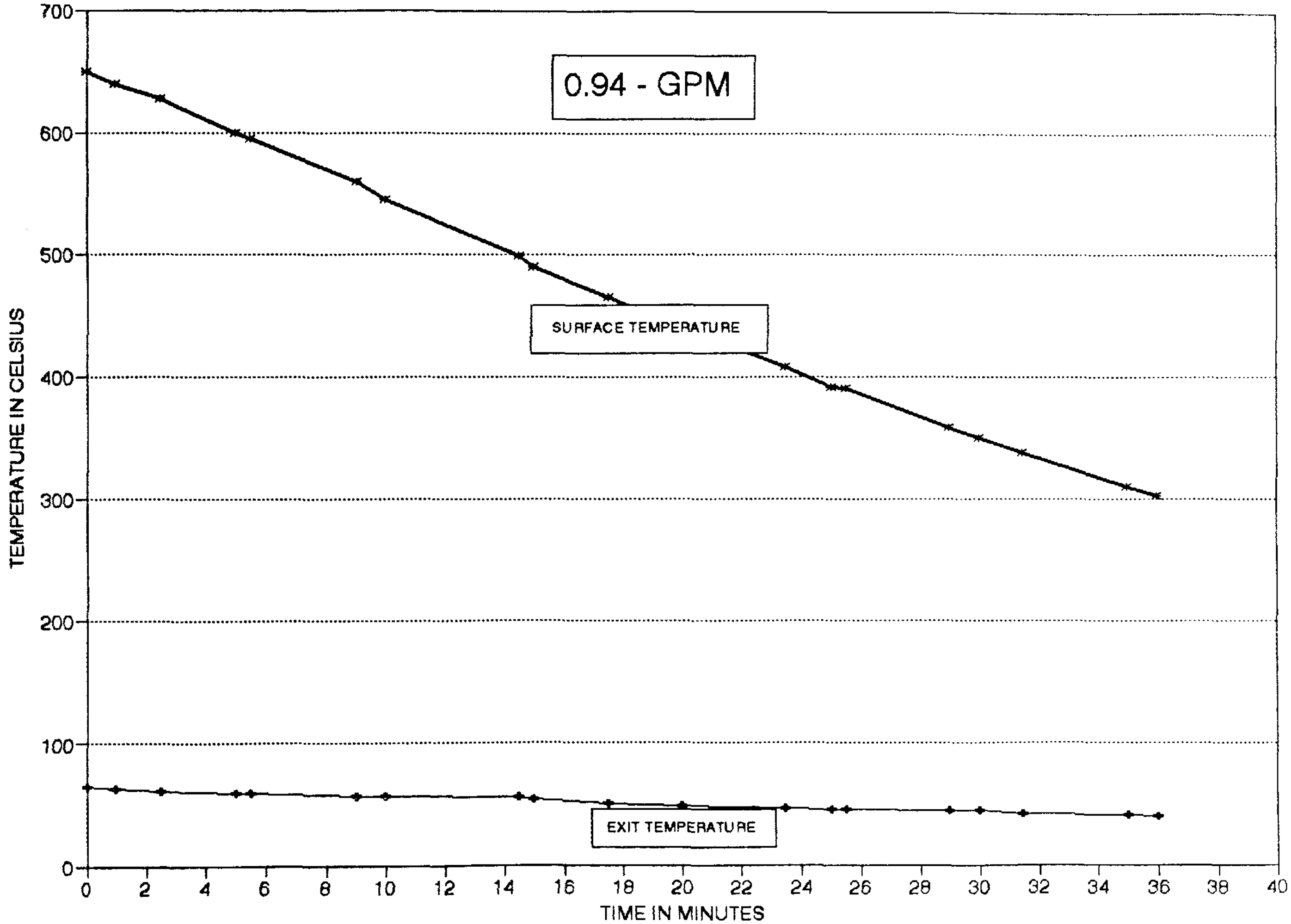

Fig. 2.2.7. Temperature vs. Time for Flow Rate 0.94 GPM.

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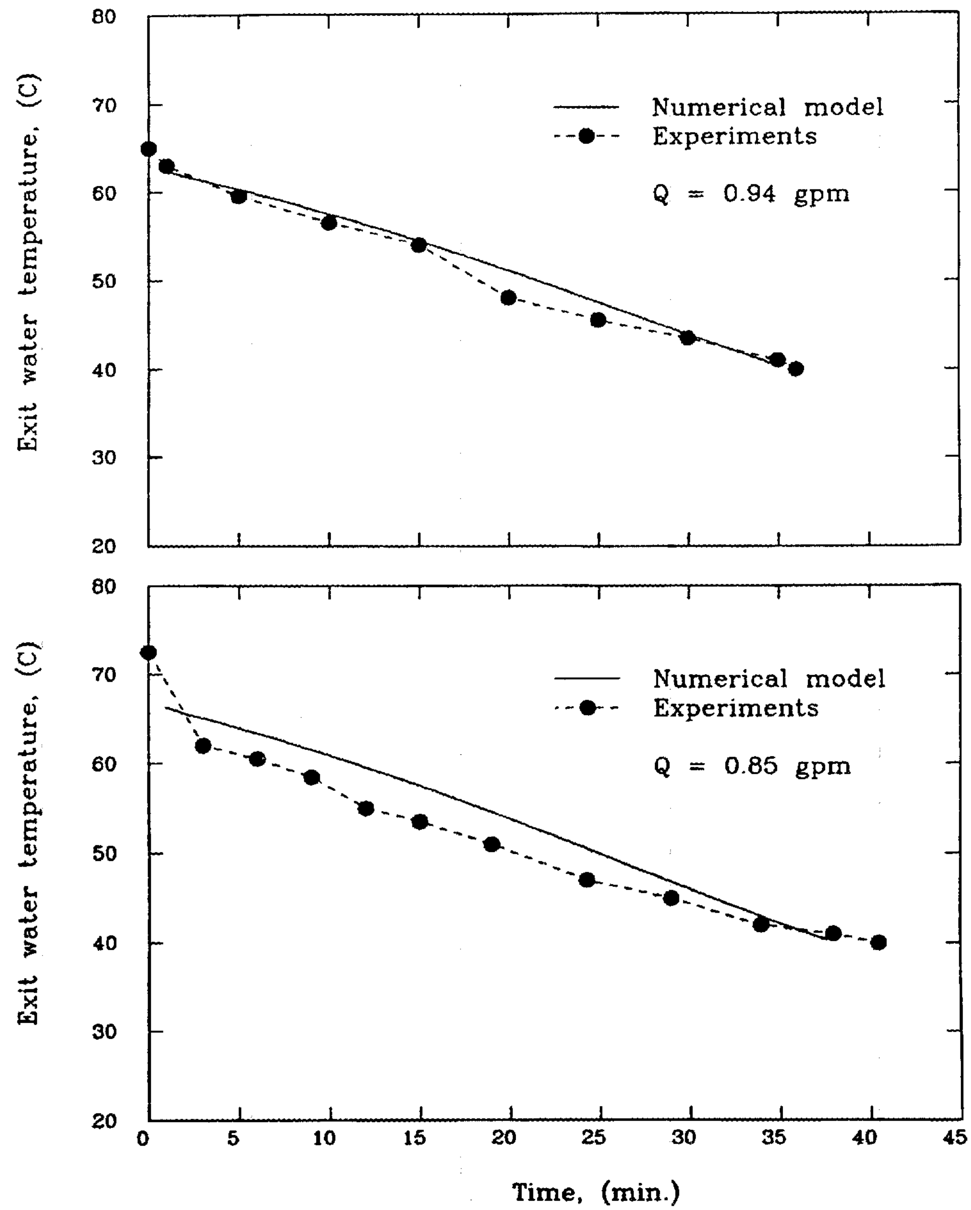

Fig. 2.2.8. Deviation Between Experimental and Numerical Model.

through the center. In the other, taconite bricks are used as the storage material. In this case a 1/2 inch stainless steel tube passes through a hole in the taconite bricks. This type of configuration is expected to give high contact resistance as compared to cast iron.

2.3 PCM WALLBOARD DEVELOPMENT

Work was continued in the development of building materials with enhanced heat capacity. Prior work demonstrated that paraffin blends can be used as room temperature PCMs and can be incorporated into plasterboard at up to 33 wt.% of composite. Two processes were developed to add the PCM to the wallboard. A post-manufacturing process was demonstrated. This process involved imbibing the PCM into the wallboard by dipping boards into a molten wax bath. The amount of PCM incorporated into the board was shown to be a function of the soak time. A second process was developed because wallboard manufacturers wanted a process that could be accomplished on their current production lines. Thus a process was developed that added the PCM as a dry powder to the wet mix during wallboard manufacturing. The dry powder is obtained by mixing the molten paraffin wax with fine silica particles. This produces a dry powder with 65% PCM that has excellent flowability and can be added directly to the wet mix at the wallboard plant. Efforts during the current reporting period focused on developing the manufacturing process to the point where a plant run of about 200 boards could be made and determining the potential for the PCM wallboard to provide a load management function within a residential structure.

2.3.1 DEVELOPMENT OF MANUFACTURING PROCESS FOR PCM WALLBOARD

A cooperative effort between the University of Dayton Research Institute (UDRI), PPG, Industries, U. S. Gypsum (USG) , and ORNL focused on producing about 200 PCM wallboards in a plant run at an existing USG plant to demonstrate the feasibility of the manufacturing process wherein the PCM dry powder is added to the wallboard mix prior to forming the wallboards. The dry mix consisted of K-18 paraffin wax supplied by Witco chemicals and BXS-320 silica supplied by PPG. The powder is formed by adding the silica particles to the molten wax. The final composition of the dry powder is 65 wt.% wax. Tests completed by UDRI demonstrated that the dry powder possessed excellent flowability characteristics. The manufacturing concept was that the dry powder would become another feed in the wallboard plant and that it would be added to the wet mix (stucco) just before the stucco was poured into the mold.

UDRI used this process to make wallboard samples and conduct a series of tests to determine if the wallboard had sufficient flexural and compressive strength and the adhesion of the paper to the board core had sufficient strength. The tests indicated that the compressive strength of the wallboard decreases with increasing PCM concentration. At 10% PCM the compressive strength is 514 psi. Since this is above the required value of 300 psi, this was acceptable. At 15% PCM the compressive strength was 271 psi, which is marginally below the minimum acceptable value. The tests also indicated that the flexural strength stays remains fairly constant with increasing PCM concentration and is in an acceptable range.

To test paper-to-plaster adhesion UDRI used a T-peel test method. This method is based on ASTM D1781, "Method for Climbing Drum Peel Test for Adhesives". It consists of pulling a 1-inch strip of paper from the wallboard at a constant pull rate to a minimum length of 3 inches. Adhesion is judged to be poor when failure occurs between the paper and the board (paper peel). In cases where failure occurs between paper layers (paper split), adhesion is judged to be acceptable. T-peel tests for wallboard samples produced with the K-18/BXS-320 dry powder were graded as Good, Fair, or Poor depending upon how many samples exhibited paper splitting and the mean load for splitting. An arbitrary value of 0.45 psi mean load was selected for the lower limit of mean load. On this basis the 10% composite wt. PCM was graded Fair to Good, the 12.5% PCM was graded Fair, and the 15% PCM was graded Fair to Poor.

The K-18/BXS-320 dry powder was supplied to USG and plans were made to schedule a plant run of 200 sheets of plasterboard at their Gypsum, Ohio plant. Before proceeding with the plant run they attempted to make several sheets on a trial basis. Poor adhesion between the paper and wallboard core was noted and further laboratory work was undertaken by USG in an attempt to determine the cause of the problem and identify a solution. The testing program focused on the 90/90 test. In this test the board sample is placed in a room at 90 F and 90% relative humidity until it is equilibrium with the room conditions. Paper adhesion is then tested for periods of 2 and 16 hours. The test results indicated that the board samples did not have sufficient paper adhesion to be acceptable. However, during the course of the testing program it was determined that an alternative silica material did provide an acceptable PCM wallboard product. This silica had triple the waterproofing of the BXS-320 material. Plans were then developed to change the silica used in the dry powder and use that mix in the plant run. This work will be completed in the next reporting period.

2.3.2 ANALYSIS OF LOAD SHIFTING POTENTIAL FOR PCM WALLBOARD

Winter savings in Boston and summer savings in Miami were estimated for a variety of PCM-wallboard configurations. Specifically, the use of two wallboards with different phase change temperatures has been examined. Additionally, each load management estimate is based on careful control of the thermostat, found to be an essential element of all the PCM energy storage arrangements.

The wallboard is expected to cost ~\$12/ft^2 more than conventional wallboard. For the small (1990 ft^2) house used in the model, that corresponds to an incremental cost of \$1,085. For the economic analysis, the on-peak energy cost is assumed to be \$0.10/kWh and the off-peak cost is \$0.04/kWh. This cost structure is similar to the differential offered by Boston Edison. Up front incentive payments of ~\$200/kW (based on seasonal peak reduction) are also considered to be reasonable based on utility avoided costs. The on-peak period was defined to last from 8AM to 2PM during the winter and from 11AM to 5PM during the summer. The central strategy sought to eliminate on-peak energy usage and maintain the house within the following comfort zones: winter 65 to 70°F, summer 73 to 77°F.

2.3.2.1 Winter Savings Opportunities

In Boston, a comparison was made between a base case with no PCM energy storage, no load control, and traditional thermostat management to two test cases. The first test case used one PCM with a melting temperature slightly less than the desired room temperature. The second test case used two PCMs. The interior wall had a melt temperature equal to the desired room temperature and the exterior walls were at a lower temperature. Both PCM test cases controlled the room temperature within the upper half of the acceptable temperature range during the off-peak hours, thereby allowing the PCM to melt more fully. Both PCM test cases also had an override feature so that if the room temperature fell below the desired range during the on-peak period, the furnace would override the clock-thermostat signal and heat the room. All three estimates of energy use cover a 7-month time period from October 1 to April 30. A shorter time period from December 1 to February 28 was also examined with similar results.

The results for the two PCM cases was improved over the single PCM case in all areas of consideration: total energy use, on-peak energy use, and resident comfort. However the differences are slight and may not be significant. The use of energy storage showed comfort increasing by about 30%. Also, both PCM energy storage/load management cases showed measurable annual cost and on-peak energy savings. The annual cost savings is about $190 for the house modeled. If the utility offered an up-front incentive payment of $86/kW of peak savings, this approach would show a 5-yr payback. Without an incentive program, the PCM load management installation would have a 6-year payback.

2.3.2.2 Summer Savings Opportunities

In Miami, a comparison was made between a base case with no PCM energy storage, no load control, and traditional thermostat management to five test cases. The first test case used one PCM with a melting temperature slightly greater than the desired room temperature. The second test case used two PCMs. The interior wall had a melt temperature equal to the desired room temperature and the exterior walls were at a higher temperature. Both of these PCM test cases controlled the room temperature within the lower half of the acceptable temperature range during the off-peak hours, thereby allowing the PCM to more fully freeze.

The other three test cases were based on an arrangement where the air is routed from the air conditioner through internal wall cavities before it is introduced to the conditioned space. In other words, the PCM wallboard is used as a supply air plenum. Current house construction techniques often use such spaces for return air plenums, so this is a reasonable assumption. This arrangement offers two significant advantages: (1) the air speed at the interior wall surfaces is very high, allowing improved convective heat transfer without uncomfortable drafts around the occupants and (2) the temperature difference between the supply air and the melt temperature is increased, again improving the overall heat transfer. In all the plenum cases, the interior walls were given a melt temperature between the desired heating and cooling temperature ranges. The exterior walls were given a melt temperature near the bottom of the winter-time temperature band. This could offer significant winter savings and possibly permit the use of cool night temperatures during the summer. Controlled use of nighttime exterior ventilation air was not examined for Miami's humid climate, but would be appropriate for drier climates.

Test case four is a base case for the plenum arrangement with no latent storage and no load control. Test case five used the PCM wallboard's latent storage capabilities and a time clock to disable the air conditioner from 11AM to 5PM. Based on the results, a sixth test case was made with the same arrangement but with the addition of an override feature to avoid overheating during the on-peak period. The base case plenum arrangement uses traditional thermostat management. The load management plenum arrangement modifies the thermostat control with the addition of a time-clock and a separate fan-control thermostat. One case was also modified to allow a clock-thermostat override feature. All six estimates of energy use cover a 3-month time period from June 1 to August 31.

The first two PCM test cases showed nearly identical energy use over the three-month period. This total energy use was about 8% greater than the base case. The relative humidity was unaffected, based on an examination of the average, maximum, and hourly distribution of this variable. Although these two tests did not include a clock-thermostat override feature, the room temperature exceeded the desired range only 4 hours, or 0.2% during the entire summer test period and the overall discomfort was cut in half. The two-PCM case showed slightly better comfort results than the one-PCM case. Because of the increase in overall energy use, these first two load management cases only resulted in an annual saving of $30, giving a simple payback of 36 years. In order to achieve a 5 year payback, the utility would have to offer an incentive of $930/kW, unrealistic at today's prices. In summary then, the summer-time application of the two-PCM/thermostat control strategy provides successful load management but is not economically viable.

The plenum tests offered quite different results. The plenum arrangement without load control and no PCM energy storage (i.e., the plenum base case) used 7% less total energy than the base case, although there was a slight increase in the on-peak energy consumption. The comfort level of these two cases was very similar. The plenum arrangement showed a slight advantage in the drybulb temperature, but was more humid, with 15% of the time spent at relative humidity values greater than 70%, compared to only 3% of the time for the base case. The plenum test case with storage and load management without the override feature showed improved humidity control but with unacceptably high dry-bulb temperatures 14% of the time. This case showed a 50% energy savings but was considered unacceptable because of the temperature distribution. When the case was reanalyzed with a drybulb temperature override feature to maintain reasonable temperature control, total energy savings amounted to 40%. This case provided adequate temperature control but elevated the relative humidity within the structure. Also, the on-peak energy savings were very small, and the annual cost savings were only $24. The plenum arrangement for hot, humid climates therefore appears unsuccessful under both technical and economic criteria.

A similar comparison was then made for Nashville's milder summer climate for the plenum load management arrangement. Here, the drybulb temperature exceeded the desirable range 11% of the time, but was within 1 °C of the desirable range 99% of the time. Therefore, the thermostat override feature was not implemented. The load management case showed total energy savings of 15%, with 100% of the on-peak energy use shifted to off-peak periods. The relative humidity was relatively unaffected with the load management case showing a slight improvement over the base case. The arrangement therefore was a technical success when applied to a moderately hot climate. However, the annual savings amounted to only $30. Future examination of winter-time load management saving for the same house (since the PCM temperatures chosen for this arrangement suit both seasons) may increase the savings to an economically justifiable level.

The results indicate that the use of phase change energy storage within wallboards shows significant load management potential. Success depends on the critical interactions between the thermostat control strategy, PCM melting temperatures, and

PCM placement. For every case, the thermostat control strategy must focus on providing fully charged energy storage at the start of the on-peak period. Using two different melting temperatures within one structure can improve comfort, overall energy savings, and permit possible year-round applications with seasonal variations in temperature requirements.

3. TECHNICAL PROGRAM - INDUSTRIAL TES

3.1 DEVELOPMENT/TESTING OF TES MEDIA FOR INDUSTRIAL APPLICATIONS

Over a period of several years, the TES program has continued the development of an advanced high temperature TES material for industrial applications. This material was developed to capture heat from flue gases in periodic industrial processes, store the energy as sensible and latent heat in a packed bed of the material, and release the heat at a later time back into the industrial process as needed. Utilization of both sensible and latent heat components provides a compact medium for regeneration of heat by industry. The unique storage material is a porous ceramic containing a PCM in its microstructure. As the material is carried above the melting point of the PCM, latent heat is stored as the PCM melts. This is in addition to the sensible heat stored in the ceramic matrix and PCM. The large surface area of the ceramic microstructure effectively retains the liquified PCM so that a "form-stable" material with a high effective heat capacity around the PCM melting point is produced. In prior years, the material, a composite PCM or CPCM, was carried through laboratory development. However, the performance of this material when used in a large packed bed storage system with flue gas and air as working fluids was not determined. Further, the thermodynamic performance of a packed bed containing this material had not been verified. A project is currently underway at MSU to design, construct, install and operate a packed bed TES system to study the metallurgical performance of the CPCM and to verify and validate a thermodynamic model of the packed bed system. The purpose of the model is to facilitate optimal designs of a full-scale packed bed systems.

During the reporting period, efforts were continued by MSU toward the near-term objective of building and operating a high temperature packed bed facility for testing the CPCM. The facility was constructed at MSU. Characteristics of the test bed are presented in Table 3.1.1 and the flow logic for the facility is shown in Fig. 3.1.1. The high temperature ducting arrangement allows the facility to be operated in both parallel and counterflow modes during discharge. Testing during the reporting period focused on physical examination of a sensible heat storage material, evaluation of the thermal

TABLE 3.1.1

CHARACTERISTICS OF THE TEST BED

1. Dimensions:		
Length	2	ft
Inside diameter	2	ft
Pellet diameter	3/4	in (nominal)
Pellet length	3/4	in (nominal)
Wall thickness	6	in
2. Materials:		
Pellet	Zirconium oxide (ZrO_2)	
Containment wall	High-alumina (Al_2O_3) refractory	
3. Thermophysical properties:		
Pellets:		
Density	337	lbm/ft^3
Conductivity	1.18	Btu/hr.ft.°F
Containment wall:		
Density	140	lbm/ft^3
Conductivity	0.50	Btu/hr.ft.°F
4. Operating Fluid:		
Storage process	Flue gas (combustion of natural gas)	
Recovery process	Ambient air	

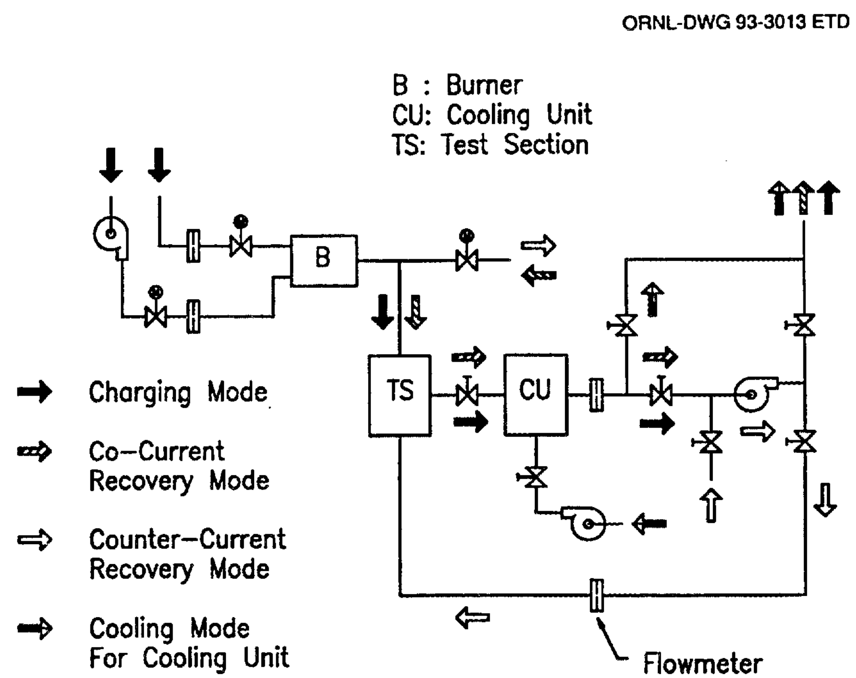

Fig. 3.1.1. Schematic and Flow Logic of the Experimental Facility.

behavior of the test bed using sensible media, collection of experimental data for verification of the packed bed mathematical model[4], and improvement of the instrumentation in preparation for tests with the CPCM.

Over one hundred thermal cycles were completed with sensible heat storage pellets. The pellets, supplied by Didier, were made of zirconium oxide. Pellet samples were removed from the packed bed periodically and examined for physical stability. It was observed that very few of the pellets (less than 0.04%) were found broken. Superficial discoloration was observed, particularly with the pellets at the upper levels of the test bed, but this was the only physical change noted in the media.

During the initial thermal cycling tests it was noted that instrumentation changes and minor modifications of the test bed would be necessary to obtain performance data of sufficient accuracy. Thus the shielded thermocouples were replaced with suction pyrometers to measure gas temperatures in the plenums of the test bed. This offered significant improvement in gas temperature measurement accuracies. In addition a metal stand installed to support the pellet bed rather than the stack of bricks originally used. This reduced the thermal lag in the bed and provided for more uniform distribution of gas through the pellet bed. A more accurate pressure transducer was also installed to allow measurements of low flow rates with reasonable accuracy.

A series of tests were performed to establish the operating boundaries of the facility in terms of the mass flow rate and the maximum attainable temperature at the inlet and exit of the test bed. As indicated in Fig. 3.1.2, the facility is operable at flow rates ranging from 250 to 1350 lbm/hr during the storage mode. The operating temperature is controllable, but its maximum limit increases with the mass flow rate. The highest operating temperature is about 1900°F and is dictated in part by the capacity of the cooling unit. The temperature is attainable at a flow rate of 1300 lbm/hr.

Tests were also conducted to examine the spatial temperature variations in the top and bottom plenums of the test section. The data were then used to develop a technique for determining an average fluid temperature at each plenum. This average temperature is required for comparison of the experimental results and the model predictions. The temperature profiles also provided valuable information concerning the behavior of the

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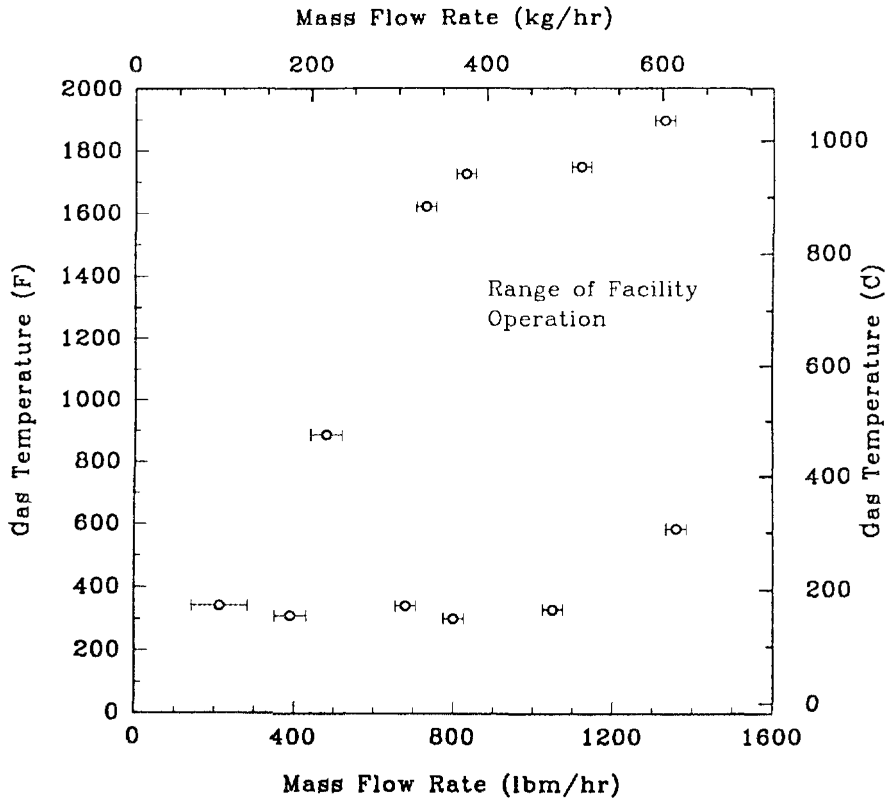

Fig. 3.1.2. Summary of the envelope tests.

packed bed. Substantial variations were observed within the test planes at the inlet and exit. Analyses of these profiles led to the conclusion that the mean gas temperature at each test plane can be represented with reasonable accuracy by an arithmetic average of two pyrometer measurements, one at the center and one at about one inch from the wall.

The heat transfer coefficients between the pellets and gas (h) and the gas and the wall (h_{wi}) were also determined experimentally to determine if the correlations used in the model were of sufficient accuracy. Instrumented copper pellets within the bed and wall probed were used to obtain the needed thermal data. The results show that the value of h obtained from the experiments is lower than that obtained using the correlation in the model. They also show that the values of h_{wi} obtained from the experiments are higher than those predicted by the correlation used in the model. The results indicate that factors of 0.8 and 1.4 should be applied to the correlations for h and h_{wi}, respectively. The packed bed model predictions obtained after the factors from the experimental measurements of the heat transfer coefficients have been applied shows excellent agreement with performance data obtained for sensible media in the experimental packed bed as indicated in Figs. 3.1.3 through 3.1.5.

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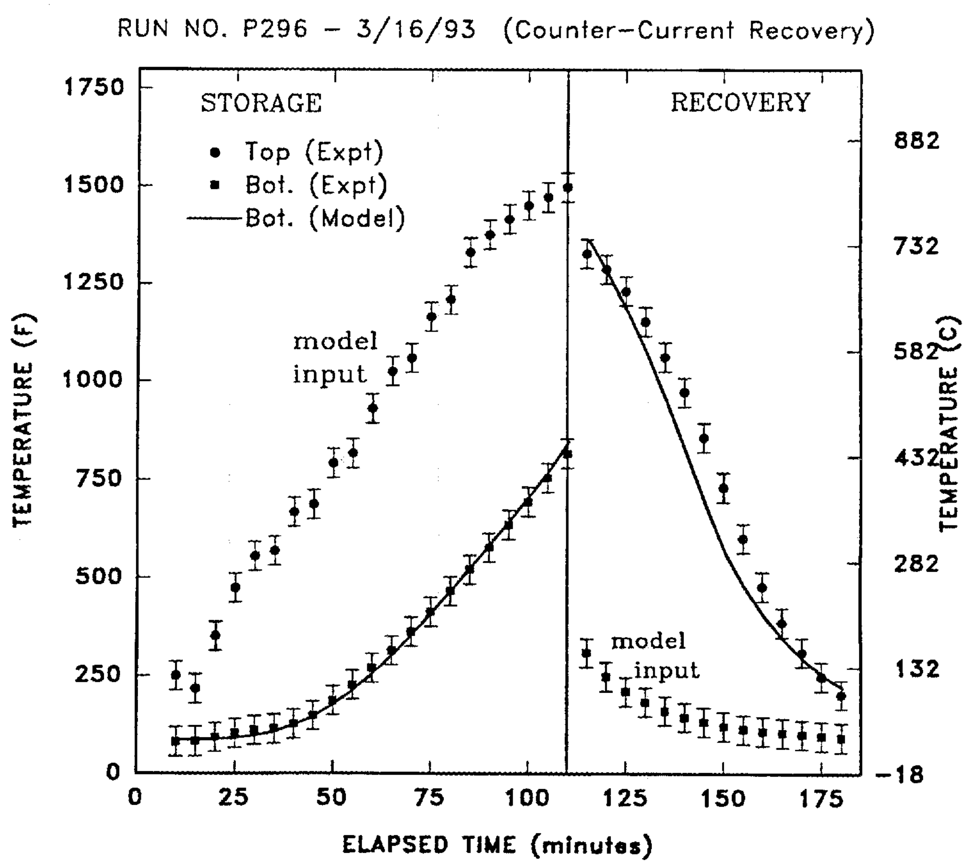

Fig. 3.1.3. Experiment/Model Comparison of Bed Exit Temperatures at the Plenum.

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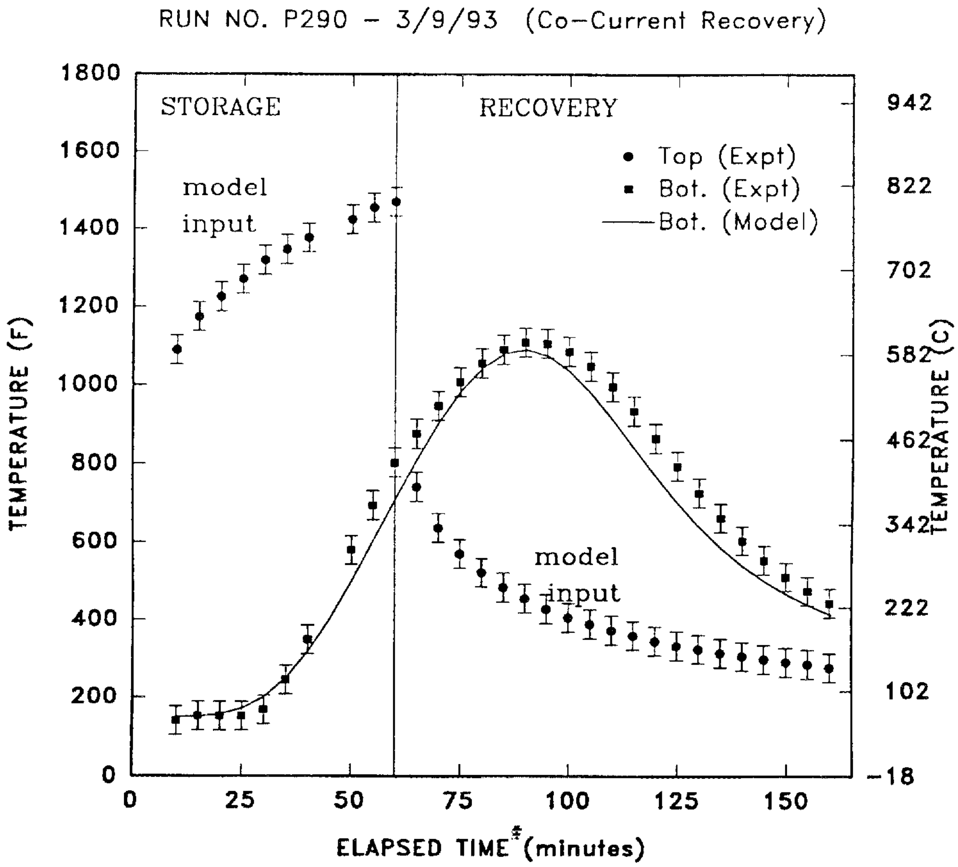

Fig. 3.1.4. Comparison of Embedded Bottom Temperature with Model Prediction.

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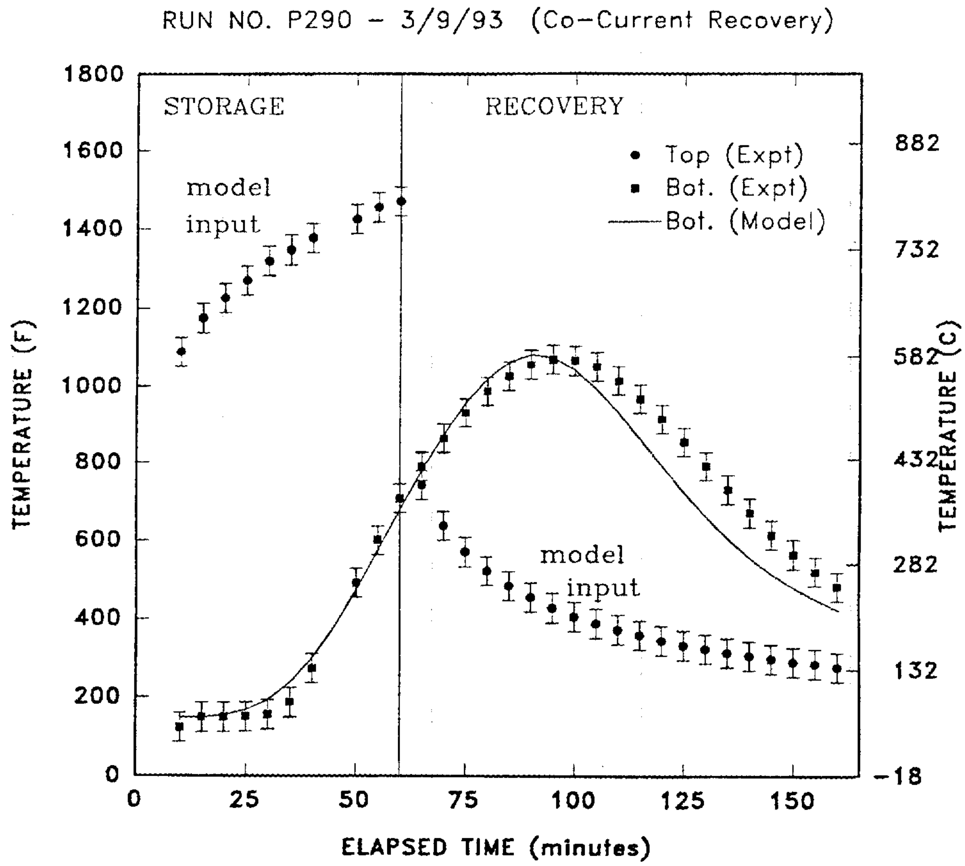

Fig. 3.1.5. Experiment/Model Comparison of Bottom Plenum Temperature.

4. CONCLUSIONS

The diurnal and industrial TES Program is focused primarily on providing cost-effective solutions to the utility peak load problem. It also has an emphasis on providing energy efficiency options for the industrial sector. During the reporting period significant progress was made in the development of TES technologies for these applications. The coordinated research performed was directed at four important applications: (1) development of low temperature chill TES for refrigeration applications, (2) development of an advanced TES water heater, (3) development of building materials with enhanced heat capacity, and (4) development of compact and effective high-temperature regenerator technology. In each case the research performed supports ultimate commercialization of the technology. Research to develop the chill TES system resulted in one manufacturer demonstrating a small unit in a spinoff application and another becoming interested in designing, manufacturing, and testing a full-scale prototype unit for the targeted refrigeration application. This was an important step in making the transition from the laboratory to manufacturing. As a result of these developments, work is being cofunded by the DOE and the manufacturing partner to construct and test a full-scale prototype unit.

The TES water heater effort is developing three concepts in an effort to double the heat storage capacity of water heaters without increasing the volume required. The HDPE pellet bed and sensible heat storage concepts appear to hold the most promise for meeting this design objective, and manufacturers have expressed an interest in the concepts. The encapsulated PCM concept will require an alternative PCM that has a higher energy storage density if it is to accomplish the design goal. The ability to shift peak load will be demonstrated in the next phase of the program when prototype units are placed into service in field tests.

There was significant progress in the development of a PCM wallboard and a substantial industrial partnership exists in this effort. The concept preferred by the industrial partners is one where the PCM is added to the wallboard wet mix in the form of a dry powder. the dry powder is made by mixing the molten paraffin wax, which is used as the PCM, with silica particles. The initial attempt to make wallboard in this manner produced a wallboard product that came close to but did not meet the manufacturer's board strength and paper adhesion specification. It was, however, determined that an alternative silica material that had a higher concentration of surface waterproofing appeared to produce a wallboard product that would meet manufacturer specifications. As a result of these findings, further work will be performed to verify these preliminary results. If the additional studies confirm expectations, the manufacturer will demonstrate manufacturability by conducting a plant run to produce about 200 boards.

Research to confirm the performance of the high temperature CPCM for packed bed regenerator applications took a major step forward with the completion of test facility construction and initiation of performance tests for sensible heat media. The test results indicated that correction factors to the heat transfer coefficients used in the computer model were required. Applying these correction factors resulted in close agreement between the computer predictions and the actual measured performance of the packed bed. The next step is to load the CPCM in the test section and determine its performance.

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