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Potential Industrial Applications for Composite Phase-Change Materials as Thermal Energy Storage Media

**G. E. Spanner
G. L. Wilfert**

July 1989

**Prepared for the U.S. Department of Energy
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POTENTIAL INDUSTRIAL APPLICATIONS FOR
COMPOSITE PHASE-CHANGE MATERIALS AS
THERMAL ENERGY STORAGE MEDIA

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Pacific Northwest Laboratory
Richland, Washington 99352

PREFACE

This report is based largely upon interviews with representatives of firms engaged in the subject industries. To help ensure complete and candid cooperation from the interviewees, they were promised anonymity for themselves and their employers in any publications resulting from this research. Therefore, none of the interviewees are listed as references nor are they included in the distribution list of this report. Because almost all of the interviewees expressed an interest in receiving a copy of this report however, they will each receive one.

SUMMARY

Considerable effort has been spent by the U.S. Department of Energy and its contractors over the last few years to develop composite phase-change materials (CPCMs) for thermal energy storage (TES). This patented TES medium consists of a phase-change material (typically a salt or metal alloy) that is retained within the porous structure of a supporting material (typically a ceramic) (Claar and Petri 1983, 1985).

Materials chosen for the phase-change component exhibit high latent heats of fusion so as to maximize the heat storage density of the TES system in which they are employed. Energy is stored in the form of heat by passing a hot fluid or gas by or through the CPCM, which melts the retained phase-change component as it absorbs latent heat. In addition, sensible heat is also stored by raising the temperature of the supporting material and by raising the temperature of the phase-change component beyond its melting point. At some later time, the energy stored in the CPCM can be reclaimed by exposing it to a cooler fluid flow, which causes the stored heat to dissipate. This storage and reclamation process is reversible and repeatable, so that the CPCM can be reused indefinitely. The specific materials used in a given application are selected to store heat at the appropriate temperature and to ensure chemical compatibility with the heat transfer fluid.

The objectives of this study were to 1) introduce CPCMs to industries that may not otherwise be aware of them, 2) identify potentially attractive applications for CPCM in industry, 3) determine technical requirements that will affect the design of CPCMs for specific applications, and 4) generate interest among industrial firms for employing CPCM TES in their processes.

The approach in this study was to examine a wide variety of industries using a series of screens to select those industries that would be most likely to adopt CPCM TES in their processes. The screens used in this study were process temperature, presence of time-varying energy flows, energy intensity of the industry, and economic growth prospects over the next 5 years. After identifying industries that passed all of the screens, representatives of

each industry were interviewed by telephone to introduce them to CPCM TES, assess technical requirements for CPCM TES in their industry, and determine their interest in pursuing applications for CPCM TES.

Seventeen industries that constitute five industry groups were found to satisfy all of the screens and are, therefore, considered potential candidates for employing CPCM TES in their processes. The five groups are pulp and paper, metal heat treating, pottery products, glass manufacturers, and primary aluminum producers. Two industry groups that satisfied all of the screens except economic outlook are steel and iron producers and brick and tile manufacturers. These industries have traditionally been viewed as attractive applications for TES and they are the focus of the substantial European research effort in industrial TES. While the overall economic outlook for these industries may not be strong, a follow-on study of these applications may be justified.

Of the five industry groups that passed all of the screens, all but pottery products were found to have potential applications for CPCM TES that warrant further investigation. Further investigations, if performed, should be in the areas of life-cycle cost analysis, technical assessments, and application-specific energy balances.

ACKNOWLEDGEMENTS

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The authors would like to acknowledge the essential contribution that was made to this report by the representatives from industry who were interviewed during the course of this project. Their uncompensated participation was a key element in our efforts to identify potential applications for composite phase-change materials in industry.

Several staff at PNL have assisted the authors in the preparation of this document. E. K. Straalsund helped screen industries to find ones that are most likely to have applications for thermal energy storage using composite phase-change material. R. L. Eckert made the initial telephone contacts with prospective industries to identify and recruit individuals who would participate in the interview process. Finally, S. J. Arey was responsible for typing and publication preparation.

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POTENTIAL INDUSTRIAL APPLICATIONS FOR COMPOSITE PHASE-CHANGE MATERIALS AS THERMAL ENERGY STORAGE MEDIA

1.0 INTRODUCTION

Considerable effort has been spent by the U.S. Department of Energy and its contractors over the last few years to develop composite phase-change materials (CPCMs) for thermal energy storage (TES). This patented TES medium consists of a phase-change material (typically a salt or metal alloy) that is retained within the porous structure of a supporting material (typically a ceramic) (Claar and Petri 1983, 1985).

Materials chosen for the phase-change component exhibit high latent heats of fusion so as to maximize the heat storage density of the TES system in which they are employed. Energy is stored in the form of heat by passing a hot fluid or gas by or through the CPCM, which melts the retained phase-change component as it absorbs latent heat. In addition, sensible heat is also stored by raising the temperature of the supporting material and by raising the temperature of the phase-change component beyond its melting point. At some later time, the energy stored in the CPCM can be reclaimed by exposing it to a cooler fluid flow, which causes the stored heat to be released. This storage and reclamation process is reversible and repeatable, so that the CPCM can be reused indefinitely. The specific materials used in a given application are selected to store heat at the appropriate temperature and to ensure chemical compatibility with the heat transfer fluid.

For use in thermal energy storage systems, composite phase-change material can be formed into pellets or briquettes and packed into a containment vessel; or it can be formed into bricks that can then be stacked, as in a checkerwork regenerator. The shape of a CPCM in a TES system is designed to minimize pressure drop while maximizing heat transfer rate and heat storage capacity.

CPCMs exhibit a number of advantages over other more conventional media for thermal energy storage. Latent heat storage systems, such as CPCM, are more compact than sensible storage systems, and this means that they require less space and less extensive supporting structures. Because CPCMs are used in direct contact with heat transfer fluids, no heat exchange surfaces are required between the storage and transfer media. Avoiding the need for heat exchange surfaces is advantageous in two ways: heat transfer is more efficient, and TES system capital costs are reduced. CPCMs provide heat at a more constant temperature than sensible heat materials, which can be an advantage in some applications. Component materials for CPCMs can be chosen that will work at temperatures as high as 1648°C (3000°F), which is higher than many conventional TES systems.

The objectives of the research described in this report are to 1) introduce CPCMs to industries that may not otherwise be aware of them, 2) identify potentially attractive applications for CPCM in industry, 3) determine technical requirements that will affect the design of CPCMs for specific applications, and 4) generate interest among industrial firms for employing CPCM TES in their processes.

Section 2.0 describes the approach followed to perform this study. Results of the study are presented in Section 3.0. Section 4.0 contains conclusions and recommendations from the study.

2.0 APPROACH

A nine-step approach was devised to achieve the objectives of the project. In general, the approach consisted of a series of screens to select industries that would be most likely to adopt CPCM TES in their processes, followed by telephone contact with a sampling of firms from the industries selected. The nine steps were:

1. group similar manufacturing activities
2. identify industries with high-temperature unit operations
3. rank industries with high-temperature unit operations according to energy intensiveness
4. assess each industry's economic growth prospects
5. identify batch and continuous operating patterns in each industry
6. identify representative plants in the most energy-intensive industries
7. contact plants by telephone to designate individuals for detailed interviews
8. mail introductory letters and interview questions to designated individuals
9. conduct detailed interviews by telephone.

Each of these steps is discussed in detail below.

2.1 STEP 1: GROUP INDUSTRIES WITH SIMILAR PROCESS ACTIVITIES

As with other structured studies of industrial-sector activities, this assessment capitalizes on a broadly accepted statistical classification standard for organizing manufacturing operations. The standard is known as the Standard Industrial Classification (SIC) code (U.S. Department of Commerce 1977). The code has been used as a standard for many years and was recently updated by the Office of Management and Budget through the Technical Committee on Industrial Classification, comprised of members from several federal government agencies.

The SIC code groups manufacturing operations having similar process activities. The manufacturing division of the SIC code comprises 459 four-digit industries, which are divided into 143 three-digit industry groups and 20 two-digit major groups. In this classification system, the industrial coverage is progressively narrow with the successive addition of digits. The 459 four-digit industries define the finest breakout of industry activities, but taken together, they define the manufacturing sector of the U.S. economy.

2.2 STEP 2: IDENTIFY INDUSTRIES WITH HIGH-TEMPERATURE UNIT OPERATIONS

In a two-part process, the manufacturing sector was examined at the four-digit level to identify industries requiring process temperatures of 315°C (600°F) or greater. In the first part, the manufacturing activities for two hierarchical tiers of process information were examined in detail for 60 of the most energy-intensive industries. The first tier of information contains details of manufacturing operations at the industrial process level (for example, cement, wet process). Within the 60 industries, 112 manufacturing processes were identified.

The second tier of process information disaggregated these manufacturing processes into units of operation (for example, calcining). Over 1500 second-tier (unit) operations were identified. One important aspect of unit operation information is the temperature at which each unit operates. Therefore, unit operations were screened to identify manufacturing operations having temperatures $\geq 315^{\circ}\text{C}$ (600°F). That screening identified 26 of the 60 four-digit industries as using high-temperature operations in producing their industries' products.

In the second part of this step, the knowledge and insight gained from examining industries from the first part were applied to processes not included in the 60 industries to identify additional processes containing high-temperature unit operations. This information was obtained by searching for process similarities between industries. As a result, 38 four-digit industries were added to the list of candidates. Thus, 64 of the 459 four-digit industries were identified that use high-temperature [$\geq 315^{\circ}\text{C}$ (600°F)] operations (referred to as priority industries in this report).

2.3 STEP 3: RANK INDUSTRIES WITH HIGH-TEMPERATURE OPERATIONS

In this step, each of the 64 priority industries was examined for its energy intensity. Energy intensity was calculated based on the amount of thermal energy (purchased fuel in Btu) (U.S. Department of Commerce 1983) and the value (dollars) of product shipped (U.S. Department of Commerce 1988b). Energy intensity ranged from greater than 100 to less than 1 Btu/\$ of product shipped.

2.4 STEP 4: ASSESS INDUSTRY GROWTH PROSPECTS

The forecast of expected industry growth is based on information from the 1988 U.S. Industrial Outlook (U.S. Department of Commerce 1988a). This publication provides industry growth forecasts primarily for two- and three-digit industries, with an occasional forecast for a four-digit industry. When no forecast was available for a particular four-digit industry, the corresponding three- or two-digit industry forecast was shared downward to the four-digit level. As with any forecast of economic activity, actual industrial growth may differ from the forecasted growth used in this analysis. The strengths of the 1988 U.S. Industrial Outlook forecast are that it is broadly used and that it provides a single source of comparable forecasts for many industries. Industry growth ranged from strong growth prospects to substantial declines in industry production.

2.5 STEP 5: ASSESS OPERATING PATTERNS

For each of the priority four-digit industries from Step 4, this step provides a first indication as to whether the high-temperature operations encompass significant thermal-cycling characteristics that would be amenable to using thermal energy storage. High-temperature batch operations were sought because of the thermal cycling, whereas most high-temperature continuous operations don't present opportunities to apply CPCM TES. Thus, industrial processes having short- and intermediate-term thermal cycling of high-temperature operations were identified.

2.6 STEP 6: IDENTIFY PLANTS WITH LARGE INDUSTRIAL PROCESSES

In Step 6, a search was conducted for manufacturing operations typical of the larger industrial plants for each of the priority industries from Step 5. These plants, which are considered likely early-adopters of CPCM TES, made up the list from which firms were selected for detailed interviews. For most four-digit SICs, from 10 to 20 large industrial plants with at least 100 employees were identified. Other firms were added to the list from industrial directories and from contacts on previous projects at PNL.

2.7 STEP 7: MAKE PRELIMINARY TELEPHONE CONTACTS

After identifying firms in industries that appear to offer opportunities for applying CPCM TES, the next step was to contact the individual firms so that arrangements could be made to conduct detailed interviews. The goal in this step was to identify at least five people from each industry group who would commit to participating in a detailed interview about CPCM applications in their industry. Working from the lists generated during Step 6, a list of 35 interviewees was developed who could be contacted later for detailed interviews. Up to this point, the interviewees had received only general information about CPCMs.

2.8 STEP 8: MAIL INTRODUCTORY LETTERS AND QUESTIONS

To obtain informed and thoughtful responses during the detailed interviews, each of the interviewees selected in the previous step was mailed a packet containing a letter describing CPCM TES in some detail and a copy of the questions that we intended to ask during the upcoming interviews. A copy of the interview questions is contained in the Appendix.

2.9 STEP 9: CONDUCT DETAILED INTERVIEWS

The final step in this study was to conduct interviews with representatives of each of the industries that were found to have potential applications for CPCM TES. A total of 25 interviews were conducted via telephone during

November and December, 1988. Most of the interviewees were either plant managers, plant engineers, energy engineers, or consultants. Interviewees were promised anonymity for themselves and their firms so that they would be as open as possible in their responses.

Each interview followed the same structured format and took approximately 20 minutes to complete. First, the interviewer introduced himself and PNL, and mentioned that the study was being done for the Department of Energy. He then reviewed the objectives of the interview and the project, and described the screening process that had led PNL to contact the interviewee's firm. After describing the potential advantages of CPCM TES, the interviewer sought to answer any questions that would clarify things for the interviewee. The interviewee was then asked a series of questions covering the following topics: sources and uses of waste heat, current energy recovery measures, specifics of potential CPCM TES applications, source and cost of thermal energy (e.g., natural gas), economic requirements for energy conservation measures, similarities among firms in the industry, and interest on the part of the interviewee to pursue CPCM TES. Throughout the interview, respondents were encouraged to take the perspective of their entire industry as well as their own plant. For consistency, the same PNL staff member conducted every interview.

3.0 RESULTS

The screening approach described above yielded 17 four-digit industries that appear to be potential candidates for employing CPCM TES in their processes. These 17 industries were combined into five groups that share common high-temperature processes. A total of 25 detailed telephone interviews were then conducted with representatives of each of the industry groups. The interviews identified several potential applications for CPCM TES in industrial processes.

3.1 INDUSTRY SCREENING

More than 150,000 industrial process heating systems are estimated to be currently in use by U.S. industry. These systems include all types of furnaces, ovens, kilns, and process heaters. A sample of some of the obvious uses of high temperatures in industrial processes are shown in Table 3.1.

Manufacturing operations were examined to identify industrial processes that use high temperatures. As discussed in Section 2.0 on approach, the search for industrial heating focused on unit operations within industrial processes that require operating temperatures of $\geq 315^{\circ}\text{C}$ (600°F). The search

TABLE 3.1. A Sample of Industrial Processes Requiring High-Temperature Heating

Annealing	Ladle preheating
Brazing	Non-ferrous heat treating
Calcining	Non-ferrous melting
Clay firing	Non-ferrous smelting
Curing	Ore roasting
Distillation	Reactors
Drying	Regeneration
Ferrous heat treating	Roasting
Ferrous smelting	Sintering
Forging	Soaking pits
Glass melting	Steel making
Iron agglomeration	Steel melting
Iron melting	Steel preheating

identified 64 industries out of the 469 four-digit industries as meeting the screening criteria of $\geq 315^{\circ}\text{C}$ (600°F) operating temperature. Table 3.2 lists the title of each of the 64 industries and its corresponding four-digit SIC number.

The 64 industries cover a wide range of manufacturing companies and processes. Two factors that influence the rate that an industry may adopt new technology such as thermal energy storage include: 1) the energy intensiveness of the industrial process, and 2) the industry's prospects for strong growth. Both of these factors were reviewed. Energy intensiveness information was developed using Census of Manufacturers' information on fuel consumed (U.S. Department of Commerce 1983) and value of shipments (U.S. Department of Commerce 1988b). The industrial growth information is based on data from the Department of Commerce's 1988 U.S. Industrial Outlook. The review indicates that a large range exists among the 64 industries on both accounts. Therefore, on the basis of these two factors, some industries appear to hold more promise for near-term adoption and integration of new thermal energy storage technology than do other industries.

Table 3.3 shows the 64 four-digit SIC industries ranked by energy intensity. For this initial assessment, energy intensity is based on the amount of purchased fuel (as defined by the Census of Manufacturers survey data) and is expressed in terms of thousands of Btu per dollar value of output. Efforts to identify industries with high-temperature unit operations that vary with time were concentrated in industries with energy intensities of more than 5,000 Btu per dollar of product shipped and industries with a positive growth outlook over the 1988-1993 time period.

Column 3 of Table 3.3 indicates each industry's positive or negative growth prospects for the 5-year period 1988-1993. The fourth column in Table 3.3 indicates which industries have unit operations both with high temperature and with temperatures that vary significantly over short or intermediate time periods. Comments about the high-temperature unit operation and economic growth prospects are provided in column 5. Many of the industries operate their high-temperature unit operations on a continuous basis. Some

TABLE 3.2. Industries with Manufacturing Processes $\geq 315^{\circ}\text{C}$ (600°F)

SIC	Industry
2062	Cane sugar refining
2063	Beet sugar
2611	Pulp mills
2621	Paper mills, except building paper mills
2631	Paperboard mills
2661	Building paper and building board mills
2824	Synthetic organic fibers, except cellulosic
2851	Paints and applied products
2861	Gum and wood chemicals
2865	Cyclic (coal tar) crudes, and cyclic intermediates
2869	Industrial organic chemicals, nec
2873	Nitrogenous fertilizers
2874	Phosphatic fertilizers
2911	Petroleum refining
3211	Flat glass
3221	Glass containers
3229	Pressed and blown glass and glassware, nec
3241	Cement, hydraulic
3251	Brick and structural clay tile
3253	Ceramic wall and floor tile
3255	Clay refractories
3259	Structural clay products, nec
3261	Vitreous plumbing fixtures
3262	Vitreous china table and kitchen articles
3263	Semivitreous table and kitchenware
3264	Porcelain electrical supplies
3269	Pottery products, nec
3274	Lime
3291	Abrasive products
3296	Mineral wool
3312	Blast furnaces (including coke ovens), steel
3313	Electrometallurgical products
3321	Gray iron foundries
3322	Malleable iron foundries
3324	Steel investment foundries
3325	Steel foundries, nec
3331	Primary smelting and refining of copper
3333	Primary smelting and refining of zinc
3334	Primary production of aluminum
3339	Primary smelting/refining of nonferrous metals nec
3341	Secondary smelting/refining of nonferrous metals
3356	Rolling/drawing/extruding of nonferrous metals,
3361	Aluminum foundries (castings)
3362	Brass, bronze, copper, copper base alloy foundries
3369	Nonferrous foundries (castings), nec
3398	Metal heat treating

TABLE 3.2. (contd)

SIC	Industry
3421	Cutlery
3423	Hand and edge tools, except machine tools
3425	Hand saws and saw blades
3429	Hardware, nec
3462	Iron and steel forgings
3463	Nonferrous forgings
3511	Steam/gas/hydraulic turbines/turbine generators
3519	Internal combustion engines, nec
3523	Farm machinery and equipment
3524	Garden tractors and lawn and garden equipment
3531	Construction machinery and equipment
3532	Mining machinery and equipment, except oil field
3533	Oil field machinery
3534	Elevators and moving stairways
3535	Conveyors and conveying equipment
3536	Hoists, industrial cranes, and monorail systems
3537	Industrial trucks, tractors, trailers, and stackers
3562	Ball and roller bearings

industries have a mixture of both continuous operations (designed principally for products with little or no product variation) and batch operations (used in production processes requiring a great deal of flexibility to meet the needs of a changing product line).

Table 3.4 lists the 17 industries that passed all of the screens and are, therefore, considered to be potential candidates for employing CPCM TES in their high-temperature operations. Each of the industries has at least one unit operation above 315°C (600°F), is energy intensive, has varying temperatures in its processes, and is expected to experience positive economic growth over the next 4 years. As shown in the table, the 17 industries fall into five groups: pulp and paper, glass, pottery articles, primary aluminum, and industries that use batch heat treating.

3.2 PULP AND PAPER MILLS

Four SICs in the pulp and paper classifications were found to have process characteristics that may be amenable to employing CPCM TES. These four industries are 2611 (pulp mills), 2621 (paper mills), 2631 (paperboard mills), and

TABLE 3.3 Ranking of Industries by Purchased Fuel Intensity

Four-Digit SIC Number	Purchased Fuel Intensity, 1000 Btu/\$ Shipment	Outlook Annual Growth 1988-1993, %	Time-Varying High-Temperature Unit Operation	Comment
3274	165.51	2.91	NO	Continuous operation
3241	101.97	1.73	NO	Continuous operation
2873	73.74	4.35	NO	Continuous operation
3259	72.12	-0.89	YES	Batch operated kilns, negative growth rate
3251	71.11	-0.89	YES	Batch operated kilns, negative growth rate
2661	63.22	2.89	YES	Digester may be batch operated
2063	47.14	2.73	NO	Continuous operation
2631	42.31	2.89	YES	Digester may be batch operated
3313	40.93	-0.15		Not considered due to negative annual growth rate
3312	31.60	-0.15		Not considered due to negative annual growth rate
2869	30.49	2.83		Class of products very broad, unit operations undefined
3255	27.52	-0.89	YES	Batch operated kilns, negative growth rate
2621	25.21	2.89	YES	Digester may be batch operated
3211	23.82	2.53	NO	Reverse air flow through checker brick regenerator
3333	23.55	1.52	NO	Continuous operation
3221	21.15	2.77	NO	Reverse air flow through checker brick regenerator
3229	20.84	2.77	NO	Reverse air flow through checker brick regenerator
3263	20.81	2.91	YES	Batch operated kilns, negative growth rate
2611	20.50	2.89	YES	Digester may be batch operated
3296	19.82	2.53	NO	Continuous operation
3331	19.14	1.52	NO	Continuous operation
3253	19.09	-0.89	YES	Kilns may be batch operated, negative growth rate
3261	18.82	2.91	YES	Kilns may be batch operated
3322	17.53	-0.63		Not considered due to negative annual growth rate
3334	15.75	1.52	NO	Continuous operation
2865	15.21	2.83		Class of products very broad, unit operations undefined
2824	14.95	4.68	NO	Continuous operation
3398	14.29	1.52	YES	Batch heat treating
3321	13.79	-0.63		Not considered due to negative annual growth rate

TABLE 3.3 (contd)

Four-Digit SIC Number	Purchased Fuel Intensity, 1000 Btu/ \$ Shipment	Outlook Annual Growth 1988-1993, %	Time- Varying High-Temper- ature Unit Operation	Comment
3262	13.18	2.91	YES	Batch operated ovens
2861	12.30	2.83	NO	Continuous operation
3462	11.61	1.63	YES	Batch heat treating
3269	11.10	2.91		Class of products very broad, unit operations undefined
2874	10.53	4.35	NO	Continuous operation
3264	10.08	2.91	NO	Continuous operation
2062	9.86	2.73	NO	Continuous operation
3325	9.70	-0.63		Not considered due to negative annual growth rate
3341	8.05	1.52	YES	Batch heat treating
3339	8.04	1.52	NO	Continuous operation
3369	7.97	1.52	YES	Batch heat treating
3362	5.60	1.52	YES	Batch heat treating
3291	5.20	2.53	NO	Continuous operation
2911	5.01	0.13	NO	Continuous operation
3463	4.87	1.63	YES	Batch heat treating
3369	4.56	1.52	YES	Batch heat treating
3562	3.67	2.96	NO	Continuous operation
3324	2.70	-0.63		Not considered due to negative annual growth rate
3423	2.69	2.38	YES	Not considered due to low energy intensity
3356	2.66	1.52		Not considered due to low energy intensity
3531	2.50	7.56		Not considered due to low energy intensity
3523	2.13	-0.54		Not considered due to low energy intensity
3429	1.92	2.38		Not considered due to low energy intensity
3421	1.78	2.38	YES	Not considered due to low energy intensity
3519	1.71	-0.54		Not considered due to low energy-intensity
3511	1.69	-0.54		Not considered due to low energy-intensity

TABLE 3.3 (contd)

Four-Digit SIC Number	Purchased Fuel Intensity, 1000 Btu/ \$ Shipment	Outlook Annual Growth 1988-1993, %	Time- Varying High-Temper- ature Unit Operation	Comment
3536	1.66	7.56		Not considered due to low energy intensity
3425	1.59	2.38		Not considered due to low energy intensity
2851	1.56	2.04		Not considered due to low energy intensity
3532	1.29	7.56		Not considered due to low energy intensity
3533	1.25	7.56		Not considered due to low energy intensity
3537	1.15	7.56		Not considered due to low energy intensity
3535	0.89	7.56		Not considered due to low energy intensity
3534	0.88	7.56		Not considered due to low energy intensity
3524	0.88	-0.54		Not considered due to low energy intensity

**TABLE 3.4 Industries That are Potential Candidates for
Employing CPCM TES**

<u>SIC</u>	<u>Industry Title</u>
2611	Pulp mills
2621	Paper mills, except building paper mills
2631	Paperboard mills
2661	Building paper and building board mills
3211	Flat glass
3221	Glass containers
3229	Pressed and blown glass and glassware, nec
3261	Vitreous plumbing fixtures
3262	Vitreous china table and kitchen articles
3263	Fine earthenware (whiteware) table and kitchen
3334	Primary production of aluminum
3341	Secondary smelting/refining of non-ferrous metals
3362	Brass, bronze, copper, copper base alloy foundries
3369	Non-ferrous foundries (casings), nec
3398	Metal heat treating
3462	Iron and steel forgings
3463	Non-ferrous forgings

2661 (building paper and building board mills). All four of these industries have several processing steps in common, and two of the steps in combination passed the screening criteria for potential CPCM TES implementation: lime kiln operation and batch digesting of pulp. Lime kilns operate continuously at high temperature while batch digesters operate periodically at much lower temperatures [approximately 176°C (350°F)].

Lime kilns are fueled by natural gas or oil, and most of the mills' other thermal energy is supplied by burning black liquor and hog fuel, both byproducts of the pulp making process. It is inappropriate to generalize about the cost of energy in pulp and paper mills because each mill is in its own unique situation regarding byproduct availability, sales, and purchases. Some mills can generate excess energy while others must purchase fuel to meet their needs. Depending upon each mill's situation, required simple payback from energy conservation projects varies from less than 1 year to up to 3 years.

In the simplest terms, the pulp and paper process consists of two major steps. In the first step, wood chips are "digested" in a vessel under various combinations of thermal, mechanical, and chemical energy to make pulp. The second step consists of drying the pulp to make paper by passing it over a series of heated cylinders. Depending upon process specifics, the digesting is done as either a continuous or batch operation. Continuous digesters are generally preferred from an energy consumption standpoint, but batch digesters are widely used in situations that require them; in particular when a variety of woods are processed or when the mill is producing a number of different papers. One of the firms contacted in this study has about an even split between continuous and batch digesters in their plants.

The degree of energy recovery currently employed in the pulp and paper industry varies greatly among the plants in the U.S. Some of the plants discussed in this study have energy recovery systems that operate at temperatures as low as 26°C (80°F). The most common approach to energy recovery in the pulp and paper industry is to burn black liquor and hog fuel to produce process steam and electricity. Newer lime kilns have recuperators installed on their exhaust flues to recover energy that is wasted with older equipment. To make batch digesters more energy efficient, two approaches were cited by interviewees. Some batch digesters have heat exchangers installed on their discharge lines to recover energy by heating process water. Others use liquid thermal energy storage systems to preheat subsequent batches.

The most frequently mentioned source of waste heat in pulp mills is the batch digester when it is not already equipped with energy recovery devices. Batch digesters discharge a stream that is made up mostly of wood organic material, sodium sulfite, sodium hydroxide, and water vapor, all at a temperature of about 176°C (350°F). Typical batch digester cycle time is approximately 3 hours. Digesters mentioned in this study range in size from 4000 to 8000 cubic feet. Another source of thermal energy in pulp mills is the lime kiln. These kilns operate continuously with exhaust temperatures between 93°C (200°F) and 315°C (600°F), depending upon energy recovery devices installed.

Three potential periodic uses for recovered energy were described by interviewees in this study. The first and most frequently mentioned use is to preheat batches of wood and chemicals prior to entering the digester. The second periodic energy use is to save the energy and use it to produce electricity during peak hours.

In addition to the sources and uses described above, there was one potential application for CPCM TES that was cited by all of the respondents. This application involves recovery of energy in the event of paper breaking in the dryer. At irregular intervals in the paper making process, paper passing through the dryer section sometimes breaks. When this happens, the machine is shut down and excess steam is vented to the atmosphere while the paper jam is cleared up and boiler output is reduced. These paper breaks occur as frequently as hourly in some plants and every few days in others. From an energy systems standpoint, there are two major impacts from these occurrences. First and most obvious, when steam is vented there is energy wasted. Second, when the paper machine is brought back on-line, the resulting sudden demand for steam can disrupt operations throughout the mill.

It was suggested that perhaps a CPCM thermal energy storage system could be installed in the steam system so that excess steam would be routed through it to recover the steam's energy before venting. When the paper machine is restarted, the CPCM TES would then be used to generate the necessary steam. The TES would need to store energy for about 15 minutes to a few hours while the paper machine is cleared and restarted. In the steam generator mode, the TES would need to supply saturated steam at approximately 50 pounds per square in. for several minutes. Using a CPCM TES in this application would accomplish two purposes: energy would be recovered, and surge demand at the boiler would be reduced upon restart.

In Scandinavian countries where energy is more costly than in the U.S., steam accumulators have been installed in paper mills to recover energy during a paper break. Some domestic mills have also been equipped with accumulators for this purpose. It should be noted that about a decade ago, the DOE sponsored studies investigating the feasibility of carbonate salt energy storage systems for recovering energy during paper breaks.

To summarize this industry, there were two potential applications for CPCM TES mentioned frequently. The first is to preheat batches of digester feed using excess heat from prior batches or lime kilns; the second is to recover energy in the event of a paper break. The feasibility of both of these applications is highly dependent upon specific factors present at individual mills, such as existing energy recovery practices and frequency of paper breaks.

3.3 METAL HEAT TREATING

Batch heat treating of metal parts is a unit operation that satisfied all of the screens in this study. This operation was found to occur in a total of six SICs, including 3398, which is called "metal heat treating". Other SICs with batch heat treating as one of their unit operations include 3341 (secondary nonferrous metals), 3362 (brass, bronze, and copper foundries), 3369 (other non-ferrous foundries), 3462 (iron and steel forgings), and 3463 (non-ferrous forgings). It was found that firms in the heat treating SIC (3398) actually service a large number of other SICs, including those listed above. For this reason, only firms in 3398 were contacted in this study but findings in this SIC apply to heat treating operations in all of the SICs listed above. Five interviews were conducted with heat treating firms that work on a wide variety of materials including steel, stainless steel, cast iron, aluminum, copper and its alloys, and titanium. The materials treated are in the form of castings, machined parts, and forgings. Specific heat treating processes mentioned by the interviewees include annealing, carburizing, and tempering.

Each of the firms interviewed has an assortment of heat treating furnaces (between 20 and 50), most of which are fueled by natural gas. Electricity is the second most common source of thermal energy among the firms contacted. Reported fuel costs range from \$2.50 to \$5.00 per million Btu for gas.

Heat treating operations can be classified as either continuous or batch. The continuous operations are truly continuous, but from a thermal energy perspective, the batch operations are actually quasi-batch operations. It is true that parts to be treated are loaded into the furnace in batches, but the

furnaces themselves remain at fairly constant temperature throughout the work week. Continuous heat treating is done in several types of furnaces such as rotary, belt, and push furnaces. One interviewee estimated that the industry is about evenly split, by dollar value of products treated, between continuous and batch operations. Continuous furnaces typically operate 7 days per week while batch furnaces operate 5 or 6 days per week, even when both types are located at the same plant.

Most cycle times in the batch operations vary from 1 to 6 hours at temperatures between 148°C (300°F) and 1204°C (2200°F). The heat treaters schedule their operations so that the furnace is only empty between batches for a short period, typically less than 15 minutes. It is significant when considering thermal energy storage applications in this industry to note that the furnaces are idled at temperatures as high as 537°C (1000°F) during periods of nonactivity, such as weekends and holidays. This is done because maintenance costs are minimized if the furnace temperature remains more constant instead of cycling through wide variations.

Regarding the heat treating industry on the whole, it is not possible to generalize about furnace sizes or energy consumption because the industry is so diverse. Furnace sizes vary from less than 1 cubic foot to greater than 1000 cubic feet. Just to give some idea of energy consumption at heat treating plants, however, one firm that has about 20 furnaces uses approximately 12,500 mega Btu per month of natural gas. Energy conservation measures in this industry are expected to result in simple payback in less than 1 or 2 years.

The only source of excess heat identified in this industry is flue gasses from gas-fired furnaces. Depending upon the internal temperature of a furnace, exhaust flues can be as hot as 982°C (1800°F). Recuperators are currently used, or being considered for use, by all of the firms contacted, although none of them have recuperators installed on all of their furnaces. Exhaust temperatures from furnaces with recuperators range from 37°C (100°F) to 148°C (300°F). Several potential uses were mentioned for excess heat, including preheating product, preheating combustion air, maintaining furnaces at idling temperature, water heating, and space heating.

Of the potential heat uses listed, preheating product and maintaining furnaces at idling temperature appear to offer the greatest opportunities for CPCM TES because they would take fullest advantage of the time shifting available from thermal energy storage. Heat treating plants typically have overhead cranes and/or rail systems for transporting products about the plant, so it would be relatively convenient to also transport a CPCM TES unit to various locations to store and discharge thermal energy. For example, after energy is recovered from a furnace, the TES unit could be moved to a product preparation area where a subsequent batch of product could be preheated prior to insertion into a furnace. Because temperature control is not too critical when a furnace is idling, a CPCM TES unit that has been charged up during the week could be used to maintain a furnace at idling temperature through the weekend.

3.4 POTTERY AND RELATED PRODUCTS

This group of industries includes three SICs: 3261, 3262, and 3263 (vitreous plumbing fixtures, vitreous china table and kitchenware, and semi-vitreous table and kitchenware, respectively). The three SICs are considered together because they share very similar high-temperature processes and use clays as their raw material. The general process steps in this group are 1) form wet clay into articles with the desired shape, 2) dry the articles, 3) heat the articles in a kiln, and 4) glaze or decorate the articles and refire, as necessary. The unit operation in this group that passed all of the screens is batch firing of the articles in kilns, although most of the products are processed in continuous fashion rather than in batches.

Seven interviews were conducted with firms in this industry group, and they were found to be fairly homogeneous with regard to their high-temperature processes. Natural gas is typically the source of heat in this group, and its cost ranges from about \$2.80 to \$3.50 per million Btu. Energy conservation measures adopted by the firms interviewed are expected to achieve simple payback in 1 to 2 years.

Most of these industries' output is produced in tunnel kilns, which are continuous processes that operate 24 hours per day, 7 days per week. The kilns typically operate at a maximum temperature of approximately 1260°C (2300°F) at the hot end, with temperatures at the cold end as low as 93°C (200°F). Many of the plants in this industry group have batch kilns in addition to tunnel kilns. The batch kilns serve one of two purposes, depending on the specifics of each plant. At some plants, the batch kilns are used only to rework defective ware, while at others they are used to produce ware in excess of the tunnel kiln's baseline capacity in response to changes in demand. Batch kilns are considered much more costly to operate than tunnel kilns, but they are more cost-effective than operating a tunnel kiln for small lot sizes. It was found that up to one-third of this group's output is processed in batch kilns. Batch kilns operate on a variety of schedules, with some operating as infrequently as twice per week, and others operating every day. Energy conservation measures currently installed vary considerably among the firms contacted, with recuperators on tunnel kilns being the most frequently cited measure.

There are two major sources of waste heat and a number of potential uses for waste heat. The two sources are flue gasses from the kilns, and cooling air that is blown over the ware as it leaves the kiln. Flue gasses from tunnel kilns vary in temperature from 93°C (200°F) to 371°C (700°F), depending on kiln and process specifics. Exhaust from batch kilns can exceed 537°C (1000°F). Among the uses for waste heat cited are preheating combustion air, preheating ware, drying ware [60°C (140°F) to 176°C (350°F)], heating clay mixtures [37°C (100°F)], and space and water heating. No general information with regard to the magnitudes of either the heat sources or heat uses was found in this study, because they vary significantly among the plants.

Due to the preponderance of continuous processing in tunnel kilns that occurs in these industries, no widespread use for CPCM for thermal energy storage was identified. However, because a sizeable portion of the total output is processed in batch kilns, there may well be viable opportunities to employ CPCM TES in certain applications. For instance, it may be economically

feasible to use waste heat from a batch kiln to preheat either combustion air or ware for subsequent cycles. Another potential application mentioned by interviewees is to recover waste heat from tunnel kilns or batch kilns and use it to provide space heat or hot water.

3.5 GLASS MANUFACTURERS

Three segments of the glass manufacturing industry were identified as having potential applications for CPCM in thermal energy storage systems. These three segments are 3211 (flat glass), 3221 (glass containers), and 3229 (pressed and blown glass). All three of these segments share certain process characteristics that make them amenable to thermal energy storage approaches. Specifically, they all involve "melting" raw materials at very high temperatures to form glass, and each segment is fairly high in energy intensity. The one process characteristic that is lacking in this industry, and that is present in other candidate industries, is temperature variations in the process over time. In fact, glass melting equipment typically operates at full temperature for 6 to 12 years, after which it is shut down and rebuilt or replaced with new equipment. The glass industry passed all of the screens in this project, however, because the melting furnaces are currently equipped with regenerators that may be a likely place to employ CPCM TES.

Furnaces in the glass industry are operated at temperatures as high as 1510°C (2750°F), with exit port temperatures between 1093°C (2000°F) and 1426°C (2600°F). Natural gas is the source of most of the heat used in this industry, although some furnaces are electric and others are fueled by oil. Reported costs for natural gas range from \$2.50 to \$5.00 per million Btu. Energy conservation measures in this industry are expected to have simple payback periods of 1 year or less, although technical risk is probably a greater barrier to process changes than financial risk. The reason for this is because with furnace campaign lives of 6 years or more, the consequences of an unsuccessful process change can be enormous.

The only potential source of heat for TES that was cited by interviewees in this study is flue gasses from glass furnaces. These flue gasses typically

exit the furnace at temperatures as high as 1426°C (2600°F), and they are made up of several components in addition to combustion products. Sodium sulfate is included in the flue gasses in the form of particulates. Also included are sulfur dioxide, silica, sulfites, and other glass components that are carried over from the furnace. The acid dew point of the flue gasses is in the range from 648°C (1200°F) to 815°C (1500°F).

Two uses for excess thermal energy are frequently mentioned in this industry. The least common use of the two is to preheat batch before it is fed to the furnace. Because glass melting is a continuous process, batch preheating is not compatible with thermal energy storage. The most common use for excess heat is to preheat combustion air. Combustion air is currently preheated in almost all glass furnaces by means of checkerwork regenerators. These regenerators store heat in sensible form in bricks that are typically made of magnesium oxide. Each furnace is equipped with two regenerators so that while one is preheating air the other is storing excess heat from the flue gasses. Combustion air and exhaust flows are reversed every 15 or 20 minutes so that the two regenerators can reverse their roles. Exit temperatures from the regenerators vary from 232°C (450°F) to 593°C (1100°F) depending upon the number of passes through the regenerator and the point in time of the cycle at which a measurement is taken. For a given glass furnace, the number of passes (and hence the range of exit temperatures) is limited by the economic tradeoffs between cost to build and operate versus fuel savings that were expected when the furnace was designed.

The most likely use for CPCM in the glass industry is to substitute it for the sensible heat storage materials currently in use in checkerwork regenerators. The advantages of CPCM over conventional materials in this application are that CPCM is more compact and that it will supply heat at more constant temperature. It is acknowledged that CPCM is more costly per pound than conventional regenerator materials, but due to CPCM's compactness, savings can be expected in construction costs for the supporting structure. One interviewee did state, however, that operating life and strength of regenerator bricks are more important factors in selecting TES material than heat

capacity. As an example, there are regenerator bricks available that are in shapes that are more efficient in terms of heat transfer and air flow (chimney bricks), but these bricks have not found widespread use in the U.S. Chimney bricks are roughly twice as costly as conventional regenerator bricks and they have been shown to save up to 12% in energy costs (Garrett-Price, Fassbender and Bruno 1986).

3.6 PRIMARY PRODUCTION OF ALUMINUM

Primary production of aluminum falls entirely into SIC 3334. In this industry, aluminum is produced continuously by electrolytically reducing alumina (Al_2O_3) using the Hall-Heroult process. The cells in which the process takes place are known as pots. After reduction in the pots, molten aluminum is transferred to holding furnaces where it is alloyed and cast into ingots or billets.

There are two basic types of cells used in the aluminum production process: those with prebaked anodes and those with self-baking anodes. While the vast majority of energy used in the aluminum industry is in the form of electricity, a certain amount of natural gas or oil is also used in supporting processes. The major users of natural gas are the holding furnaces, process boilers, and in the case of plants with prebaked anodes, anode baking ovens. Anode baking is the unit operation that satisfied all of the screens in this study, so only plants that use prebaked anodes were contacted in seeking potential applications for CPCM TES.

Three sources of excess thermal energy were described by interviewees in this industry: holding furnace exhaust, anode baking exhaust, and waste gas from the potlines. Holding furnace flue gasses exit the plant at temperatures between $129^{\circ}C$ ($265^{\circ}F$) and $593^{\circ}C$ ($1100^{\circ}F$) depending upon how much cooling air is added to the exhaust and how much the exhaust is cooled in the pollution control equipment. In anode baking ovens, anodes are baked at about $1148^{\circ}C$ ($2100^{\circ}F$) (Katter 1979). The ovens are arranged so that flue gasses from the oven being fired are routed to other ovens to preheat subsequent electrodes prior to baking. Consequently, flue gasses exit the ovens at about $190^{\circ}C$ ($375^{\circ}F$) and are further cooled to $43^{\circ}C$ ($110^{\circ}F$) to $148^{\circ}C$ ($300^{\circ}F$) in the

pollution control equipment. Waste gasses from the potlines are routed through the primary pollution control system and then exit the plant at approximately 98°C (210°F). Prior to treatment in the air pollution control systems, the three sources of thermal energy described above contain a variety of contaminants including fluxes, salts (aluminum fluoride and sodium fluoride), hydrocarbons, and sulfur dioxide.

Only one potential use for stored excess heat was described by interviewees in the aluminum industry: heating anode paste during mixing. In this operation, petroleum byproducts, coal tar pitch, and anode butts are mixed in a paste that is subsequently baked to become electrodes. Steam from a gas-fired boiler is used to heat the paste to 137°C (280°F) to 204°C (400°F) during mixing. Anode mixing is a batch operation that is performed during 7 to 10 shifts per week. Each batch requires about 1 hour for mixing, and aluminum plants have a number of mixers (10 at one plant contacted) operating simultaneously.

The most promising application for CPCM TES in the aluminum industry identified in this study is to recover excess heat from the continuously operating holding furnaces and periodically supply the heat to anode mixing. Alternatively, it may be possible to use excess heat from the potlines or the anode baking ovens as the source of heat. In this application, the CPCM TES would store heat from hot gasses and supply heat as steam.

4.D CONCLUSIONS AND RECOMMENDATIONS

The screening approach used in this study identified 17 separate industries with process and economic outlook characteristics that indicate that the industries may have potential applications for composite phase-change material for thermal energy storage. These 17 industries can be combined into five industry groups with manufacturing processes common to all members of each group. After screening industries, interviews were conducted with representatives of firms in each group. All but a few of the individuals interviewed expressed an interest in DOE's Thermal Energy Storage Research Program and would be willing to participate further if any subsequent research is performed in their industry.

Four of the five industry groups studied appear to have at least one candidate application for CPCM TES that warrants further investigation. The group with the least potential for applying CPCM TES in its processes is the pottery products group. For the groups that do have potential applications for CPCM, it will be necessary to perform technical and life-cycle cost analyses of the applications to make further determinations of their suitability. The interviews yielded little information regarding the magnitudes of energy flows involved in each of the potential applications, so this information will need to be gathered for each of them as part of the technical feasibility assessments. In many cases, this study determined that temperatures associated with each of the applications vary from firm to firm and this also will require further investigation on a case by case basis.

In the pulp and paper group, the most prominent potential application for CPCM TES is to recover energy lost during a paper break in the dryer. This application is interesting because it will require the thermal storage system to perform as a steam generator when the energy is put back into the process.

Two potential applications were identified in the metal heat treating industry. The first is to preheat batches of parts prior to heat treatment and the second is to keep furnaces hot during idle periods, such as weekends

and holidays. The apparent technical feasibility of the latter application is promising enough that the question to be answered here is whether or not CPCM TES can supply heat more cost effectively than natural gas in a rather straightforward substitution.

The most promising application in the aluminum industry is to heat batches of anode mixture at fairly low temperature using continuously available waste heat from other processes in the plant. For this application, it will be necessary to perform an energy balance of the sources and uses of heat to determine feasibility of applying CPCM TES.

In the glass industry, application of phase-change materials will call for substituting a latent heat storage medium for a sensible heat storage medium in commonly used regenerators. There are significant barriers to change in this industry because the glass melting furnaces are operated for years at a time, which increases the consequences of process changes.

Because the pottery group was found to operate in a mostly continuous mode, opportunities for applying CPCM TES were least promising of all the industries studied. A certain amount of this industry's products are produced in batch furnaces, however, so there may be opportunities at firms with higher proportions of batch processing.

Several industries were not examined in this study because they failed the economic outlook screen, which called for expected positive economic growth over the next 5 years. Most notable in this group are the brick and tile and the steel and iron industries. Both of these industries have high-temperature processes whose energy flows vary with time. The brick industry has been the subject of much DOE-sponsored research in the area of thermal energy storage using composite phase-change material (Petri 1987a,b; Institute of Gas Technology 1982). Research in this industry is quite promising for CPCM TES and its exclusion from this study should not be taken to mean that brick industry applications do not warrant further research. In fact, the brick industry may well present greater energy savings potential through thermal energy storage than any of the applications described in this report.

The domestic steel industry has been in a period of decline for a number of years. Among the mills still operating there has been a trend toward specialty steels using electricity as the source of thermal energy. One potential application for CPCM TES in the electric steel industry is to preheat ladles that transfer molten steel from the melter to the ingot-casting molds. These ladles are currently preheated using natural gas burners, but it may be possible to use stored thermal energy for this purpose. A potential source of continuous thermal energy to charge the TES unit is flue gasses from soaking pits.

There is one potential application for CPCM that does not fit into any single industry or group that was nonetheless suggested by several of the interviewees. This application, which came from interviews in the glass and aluminum industries, is to substitute CPCM as the thermal energy storage medium in regenerative burners. Regenerative burners are industrial burners equipped with a bed of nuggets for thermal energy storage. The nuggets store energy as sensible heat when flue gasses are passed through the bed. Used always in pairs, the burners are cycled on and off every 20 seconds so that one burner is storing heat (in the off condition) while the other is preheating combustion air (in the on condition). Because of its higher heat storage density relative to sensible heat materials, using CPCM in regenerative burners would result in more compact burner assemblies. Regenerative burners are proprietary devices manufactured by North American Manufacturing Company of Cleveland, Ohio.

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APPENDIX

CPCM TES INTERVIEW QUESTIONS

APPENDIX

CPCM TES INTERVIEW QUESTIONS

Interviewer: _____ Date: _____
Interviewee: _____ Phone Number: _____
Firm: _____ SIC: _____
Address: _____

- 1) Does your plant produce any waste heat that might be available for recovery, storage, and later use?
- 2) What is the nature of the available heat (flue gas, steam, etc.)?
- 3) Is any energy recovery currently employed? How effective is it?
- 4) Does your plant have any uses for recovered energy?
- 5) What are the time-varying operations in your plant (source or use of heat, hourly, daily, etc.)?
- 6) What is the source of thermal energy in your plant (gas, oil, electricity, etc.)?
- 7) How much do you pay for energy (\$/Btu)?
- 8) What economic requirement would a new TES system need to satisfy for implementation (payback, IRR, etc.)?
- 9) What are the potential energy source and use temperatures at your plant?
- 10) What are the magnitudes of energy available and energy to be used?
- 11) What are some details of specific TES applications?
 - a) chemical composition of waste stream
 - b) temperature of waste stream
 - c) time variance of temperature of waste stream
 - d) charging, storing, and discharging periods
 - e) temperature of heat uses
- 12) What is the industry trend regarding batch vs. continuous processing (present and future)?

- 13) How similar is your plant's situation to other plants in the industry?
To related SICs?
- 14) Are you interested in receiving further information or otherwise participating in our research program further?
 - a) review and comment on draft report
 - b) receive copy of final report
 - c) receive copies of later results
 - d) provide input or guidance to subsequent research
- 15) Is there anyone else we should/could talk to?

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