NOTICE

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CANDIDATE THERMAL ENERGY STORAGE TECHNOLOGIES FOR SOLAR INDUSTRIAL PROCESS HEAT APPLICATIONS

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Edward R. Furman
National Aeronautics and Space Administration
Lewis Research Center

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U.S. DEPARTMENT OF ENERGY
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Prepared for
Solar Industrial Process Heat Conference
sponsored by the Solar Energy Research Institute
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E. Furman
NASA-Lewis Research Center
Cleveland, Ohio

ABSTRACT

The successful application of solar industrial process heat (SIPH) will depend, in part, on the use of thermal energy storage (TES) to provide continuous operation during periods of solar isolation. A number of candidate TES system elements have been identified as having the potential of meeting this need. These elements which include storage media, containment and heat exchange are shown. Recently completed system studies on selected industries have identified a number of processes where TES appears attractive. These systems and the suggested TES subsystems are shown and discussed.

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INTRODUCTION

A necessary requirement for the successful application of solar thermal energy to industrial processes is the need to provide continuous operation of the processes during periods of solar isolation. The degree of acceptance and utilization of solar energy will therefore depend upon the successful development and integration of thermal energy storage (TES) subsystems with the solar industrial process heat (SIPH) installation. The technology base for candidate TES subsystems is being investigated and expanded by DOE-funded programs to include a wide selection of media, containment, and heat exchange in a temperature range of 250-1100°C (500-2000°F). Current TES emphasis for solar application is on buffered storage (.5 to 2 hours), however, some of the same technologies could be applied to larger storage capacities (diurnal applications). Studies and development of advanced storage subsystems are being undertaken to identify solar industrial process heat systems in the intermediate to high temperature range. These activities will provide the basis for a detailed technical and economic evaluation of the most promising storage subsystems. Selected storage approaches will be coupled with specific applications and analyzed in detail.

The Department of Energy Division of Energy Storage Systems (DOE/STOR) has the responsibility for formulating and managing research and development in energy storage technologies. Major responsibility for project management in selected areas has been assigned to DOE national laboratories and other government agencies. The current management structure and major area of development for the lead laboratories is shown in Figure 1. The lead center will provide overall management for the TES program including planning, integration and coordination of the involved lead laboratories. Lead laboratories will be delegated prime responsibility and appropriate authority for the day-to-day management and implementation of activities in their designated areas.

THERMAL ENERGY STORAGE TECHNOLOGIES

Figure 2 illustrates the interdependency of the various system elements. The end use application will define the TES subsystem design and operational requirements. The designer's function will be to select the TES subsystem elements which best meets these requirements while considering the many constraints including technical, economic, environmental, institutional and other factors. It is evident that with the variety of storage media available and various types of containment and heat exchange, a large number of combinations are possible. To minimize the development complexity and costs, it has been necessary to limit the number of TES concepts. For near-term applications, the major development effort has been directed to the utilization of existing technologies. This has included sensible heat media, low pressure containment and above ground installations. For advanced systems, both sensible and latent heat media are being studied and tested. Figures 3a, b and c illustrate the variety of media currently being considered, the planned operational temperature range for the media and the investigators or proponents for the concept. An attempt is being made to cover the anticipated end use operational temperature range with the selection of at least one medium for a given temperature. This is shown in Figures 3a, b and c, where various types of media have been selected to cover any given temperature range.

TES Containment, Figure 4, shows the divergent technologies which have been proposed for TES media containment. Most of these advanced concepts have addressed the containment problem associated with high temperature, high pressure water. Descriptions for the various concepts can be obtained from the designated references. Similarly, for latent heat applications of molten salts a variety of heat exchange concepts have been proposed, Figure 5. The withdrawal of heat energy from the molten salt at the solidification temperatures results in the deposition of a solid salt layer on the heat transfer surface. Since salts generally have low heat transfer coefficients, this results in a high and variable resistance to heat transfer. The active heat exchange concepts are being developed to minimize this problem. Figure 6 illustrates a concept currently under investigation at Honeywell Inc. The system employs a molten $NaNO_3$-NaOH mixture as the energy source. The molten salt is pumped into the reflux boiler and water from the condensate stream is directly injected into the salt. The saturated water vapor which is generated is conducted to the condenser as a result of the existing pressure differential within the system and the energy is transferred to the cycle working fluid. The molten salt in passing through the boiler loses only a small amount of its energy. Under these conditions, the selected salt mixture (a dilute eutectic) forms a two-phase slush which is returned to the storage tank where phase separation occurs and the molten salt is recycled.

INDUSTRIAL PROCESS AND REJECT HEAT APPLICATIONS

The "Energy Policy and Conservation Act" (EPCA) Public Law 97-163 was passed by the 94th Congress on December 22, 1975. Part D of Title III of this Act required that FEA establish a program to promote increased energy efficiency in the United States industry. This program included the identification and ranking of major energy-consuming manufacturing industries, the establishment of energy efficiency improvement targets for the ten most energy consumptive industries, and the identification of major energy-consuming corporations within the targeted industries for the purpose of reporting industry progress in improving energy efficiency.

DOE assigned with the responsibility of conservation released a Program Research and Development Announcement (PRDA) in January 1977 to identify industrial processes where process or reject heat recovery systems using TES could be beneficial. Recently completed system studies on selected industries have identified a number of processes where TES appears attractive. These included the food processing, paper and pulp, iron and steel, and cement industries. Subsequent to these studies, it was discovered that the Scandinavian paper and pulp industry and a few companies within the United States are already using TES in their processes. As a result, a contract has been placed for the collection and dissemination of the available TES information to the American paper and pulp industry.

Food Processing

The food processing industry is a major user of low temperature (below 120°C) process heat. The industry requires energy at the rate of 1×10^{15} BTU/YR (1 Quad), and this places the industry sixth among the nations largest energy consumers. Within the food industry the canning segments (SIC 2032 and 2033, canned specialties and canned fruits and vegetables) require 70×10^{12} BTU input annually which represents about 7% of the food industry total. Low pressure steam 0.7 MPa (100 psig) produced on site is generally the source of energy, and it is directly used by infusion and by processes that require a steam atmosphere. Other processes require hot water which is produced by steam/water heat exchange or by cold water-steam infusion. These processes or process-related operations include: cooking, sterilizing, pasteurizing, can- washing and clean-up. This study was performed by the Westinghouse Electric Corporation in cooperation with the Heinz USA - Pittsburgh Division of the H. J. Heinz Company and was funded by the U.S. Department of Energy (Contract EC-77-C-01-5002) and managed by the Oak Ridge National Laboratory. A schematic of a proposed TES/Waste Heat Recovery System in a Food Processing Plant is shown in Figure 7 for the Heinz USA - Pittsburgh plant. Waste heat from these operations are in the 40-95°C (100-200°F) temperature range and can be separated into high temperature (above 60°C) and low temperature (below 60°C) streams. The energy in the high temperature stream only will be used recuperatively through conventional heat exchange to fresh water. This isolation will prevent contamination of the water used in the food processes. The recuperated fresh water is sent to the TES module for later usage or heated to process temperatures by steam heat exchange or hot water infusion and returned to the process. Water that is accumulated in storage during the production period will be used for clean-up operations during the night shift. The estimated energy savings for this installation is in excess of 32 TJ/YR ($3x10^{10}$ BTU/YR), and based on a duplicate system cost of $190,000 the return-on-investment is computed to be better than 30%. A sole-source procurement is currently being negotiateo with Heinz USA to install a demonstration system in their Pittsburgh facility.

Iron and Steel

The primary iron and steel industry consumes about 11% of the total national industrial energy usage. The Rocket Research Company with support from the Bethlehem Steel Company and the City of Seattle Lighting Department conducted a study entitled "Application of Thermal Energy Storage Techniques to Process Heat and Waste Recovery in the Iron and Steel Industry". Waste heat recovery in the temperature range of 315-1540°C (600-2800°F) was indicated as being potentially recoverable. The system selected in the study is shown in Figure 8. Waste energy from the primary arc furnace evacuation system is passed through an operational store TES module which acts as a buffer to dampen the temperature variations which are inherent in the furnace discharge. The fume stream is then passed through the peaking store TES module where the energy is stored as sensible heat in a packed bed (refractory brick, slag or scrap steel) and is exhausted through the baghouse. During discharge from storage, the gas flow in the peaking store TES loop is reversed and the heated gases are blended with the discharge gases from the operational store TES discharge in the mixing valve, passes through the heat exchanger and into another mixing valve. Part of the flow is recirculated through the peaking store TES module and the remainder passes to the baghouse. A steam-driven turbine operates to generate power for peak shaving (either in-plant or for utility area demand peaks).

The proposed conceptual system for the Bethlehem plant could result in an estimated payback period of five years depending on the combination of electricity costs and the size of the power generation equipment. Assuming fossil fuel is used to produce peak power, the potential oil savings for a 7 MW_e generator operating 300 days/year would be 16,000 bbl. Overall industry oil savings could approach $2x10^6$ bbl.

Cement

The cement industry is the sixth largest user of industrial energy in the United States. The majority of this energy (80%) is consumed as fuel in the operation of the kilns, however, less than 50% of the energy input is required in the chemical reaction to form clinkers. Martin Marietta Aerospace with team members Martin Marietta Cement and the Portland Cement Association, investigated the use of TES in conjunction with current reject heat usage in the cement industry. Details of this study are contained in the final report "Application of Thermal Energy Storage in the Cement Industry". Waste heat from the kiln is obtained from the gas effluent and from the clinker cooler excess air. This is illustrated in Figure 9 where two TES modules using solid sensible heat storage material, such as, magnesia brick, granite, limestone or cement clinkers are shown. The exhaust gas heats the high temperature bed to 815°C (1500°F) while the clinker cooling gases heats the low temperature bed to about 235°C (450°F). The modules are discharged in a series flow to supply ambient air heated to 650°C (1200°F) to the waste heat boiler where steam is generated to produce electricity. A 10 MW_e output is planned to operate continuously. This requires that 80-90% of the exhaust flow go directly to the boiler with the balance going into storage. At this rate, storage would be fully charged (240 MW_ehr capacity) in one week.

The economic analyses of the system indicates that for the proposed installation the cost would be 10 million dollars and a ROI of 90% is anticipated for a 30 year system life and an average energy cost of 2.8¢/kwh. About 15% of this ROI is attributed to the TES system. The potential energy savings for the cement industry is $4x10^6$ bbl of oil.

SOLAR POWER GENERATION

A concept which utilizes a moving bed of free-flowing solid granules or microspheres as a mechanism for heat absorption, storage, and transfer to a working fluid has been proposed by the Babcock and Wilcox Company for Solar application. This concept is shown in Figure 10. Silica sand or fused silica microspheres are transferred upward by Archimedes pumps from the steam generator discharge to the solar collector where the free-flowing sand is heated to 540°C (1000°F) as it flows downward through vertical tubes in the collector. A portion of this heated sand is directed to the steam generator via the central supply tube and the remainder is put into storage. The heated sand refills the storage bin as cool sand is displaced from the bottom until the heating cycle is completed. During the night, high temperature sand from storage supplies the energy input to the boiler. The solar collector is by-passed during this period by opening the sliding baffle in the upper pump conduit. The lift pump speed is controlled to maintain the desired temperature profiles in the cycle. Sufficient energy is collected and stored to provide 28.5 MW_t continuously over a 24 hour period. This energy is converted to steam at 5.2 MPa, 430°C (750 psia, 800°F) and to an electrical output of 10 MW.

CONCLUDING REMARKS

Industrial production energy requirements are about 40% of the total energy consumed in the United States. The major share of the energy is derived from fossil fuels and significant savings are possible through the use of solar generated process heat coupled with thermal energy storage. DOE/STOR's current activities are directed to the development of generic storage subsystems which will be applicable to solar industrial process heat systems in the intermediate to high temperature range. In-house studies are planned during the current fiscal period to identify technology requirements for SIPH applications. These studies will provide the course for future research and directed development efforts. The ultimate objective of this effort is the demonstration of cost-effective thermal energy storage systems capable of complementing the solar generated process heat source and contributing to energy conservation in the industrial sector.

In addition to the contents of this paper, a panel summary on Storage for Solar Process Heat should also be noted (reference 11). The panel recommended that primary emphasis for the near-term (1980-85) and mid-term (1985-90) should be directed to the transfer of developed industrial process heat storage technologies to solar applications. In support of SIPH applications for the far term (beyond 1990), an aggressive program should be planned and implemented within the next five years to develop the technologies required for the transport of solar process heat to the industrial users (via chemical reactions or hydrogen).

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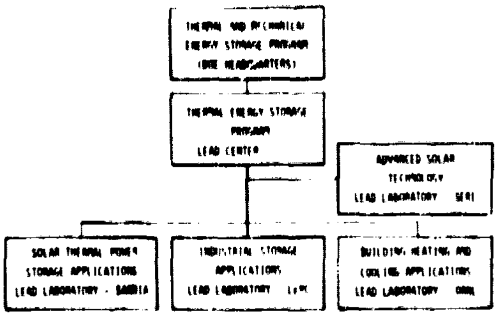

FIGURE 1 - PROPOSED MANAGEMENT STRUCTURE

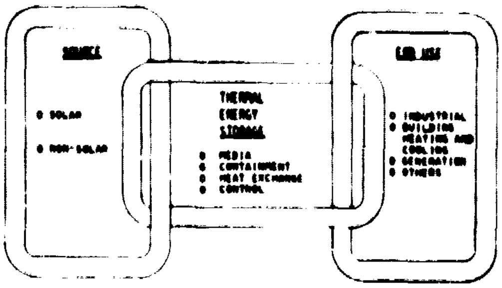

FIGURE 2 - THERMAL ENERGY STORAGE SYSTEM

LIQUIDS		INVESTIGATOR/PROPONENT
● WATER - LOW TEMPERATURE	(≤ 250°C)	WESTINGHOUSE/HEIW-USA
- HIGH TEMPERATURE	(260-560°C)	DR. P. V. GILLI (2)(4,) R/D ASSOCIATES (4) ONTARIO HYDRO (4)
● ORGANIC COMPOUNDS		
- OILS	(200-350°C)	EXXON (4), McDONNELL-DOUGLAS (4), MARTIN-MARIETTA (4)
● INORGANIC COMPOUNDS - FUSED		
- SALTS	(290-540°C)	ORNL/GENERAL ATOMIC (4) MARTIN MARIETTA (4)
- ELEMENTAL SULFUR	(115-440°C)	DR. A. SELZ (4)

FIGURE 3a - SENSIBLE HEAT STORAGE MEDIA

SOLIDS		INVESTIGATOR/PROPONENTS
● METALS		
- IRON, STEEL	(UP TO 1100°C)	ROCKET RESEARCH (2)
● MINERALS		
- ROCK	(UP TO 550°C)	U. OF MINNESOTA (1-2)
- SAND	(UP TO 815°C)	JPL (2), BABCOCK & WILCOX (9)
TACONITE	(UP TO 550°C)	SANDIA L. L. (8)
● CERAMICS		
- ALUMINA	(UP TO 900°C)	BOEING ENG. & CONSTRUCTION COMPANY (10)
- MAGNESIA	(UP TO 900°C)	BOEING ENG. & CONSTRUCTION COMPANY (1)

FIGURE 3a - SENSIBLE HEAT STORAGE MEDIA

SOLID-LIQUID PHASE CHANGE		INVESTIGATOR/PROPONENT
● NITRATES	(240-340°C)	HONEYWELL INC. (3,4)
● HYDROXIDES	(295-475°C)	COMSTOCK & WESCOTT INC. (1-4)
● CHLORIDES	(370-800°C)	GRUMMAN A. CORP. (1-4), ORL (1-4)
● CARBONATES	(400-800°C)	INST. OF GAS TECHNOLOGY (1-4)
● FLOURIDES	(640-850°C)	ARGONNE NATIONAL LABORATORY (2,5) BOEING ENGINEERING & CONSTRUCTION COMPANY (4)
● METALS	(330-950°C)	U. OF DELAWARE (1-5)
SOLID-SOLID PHASE CHANGE		
● SODIUM SULFATE	(240°C)	CALMAC INC. (7)

FIGURE 3c - LATENT HEAT STORAGE MEDIA

ABOVE GROUND	INVESTIGATOR/PROPONENT
● HIGH PRESSURE TANKS	
- WELDED STEEL	CHICAGO BRIDGE & IRON (6)
- PRESTRESSED CAST IRON VESSEL	DR. P. V. GILLI (2,4)
- PRESTRESSED CONCRETE PRES. VESSEL	ORNL/R. M. PARSONS (4)
● LOW PRESSURE TANKS	
- OIL/ROCK	McDONNEL DOUGLAS (4)
- WATER	WESTINGHOUSE/HEIW USA (5)
- MOLTEN SALT	ORNL/GENERAL ATOMIC (4)
UNDERGROUND	
● STEEL-LINED CAVITY/ROCK SUPPORT	R/D ASSOCIATES (4)
● STEEL TANK/AIR SUPPORT/UNLINED CAVITY	ONTARIO HYDRO (4)

FIGURE 4 TES CONTAINMENT

PASSIVE	INVESTIGATOR/PROPONENT
• TUBE/SHELL	GRUMMAN AIRCRAFT CORP. (1-4)
• REFLUX CELL - CANNED MEDIUM	NAVAL RESEARCH LABS (1-4)
ACTIVE	
• DIRECT CONTACT - INTERMEDIATE FLUID	GRUMMAN (3-4) HONEYWELL INC. (3-4)
• MECHANICAL SCRAPER	HONEYWELL (4), GRUMMAN (3)
• FLUIDIZED BED - ENCAPSULATED MEDIA	BABCOCK & WILCOX (9)

FIGURE 5 - HEAT EXCHANGE - FUSED SALTS

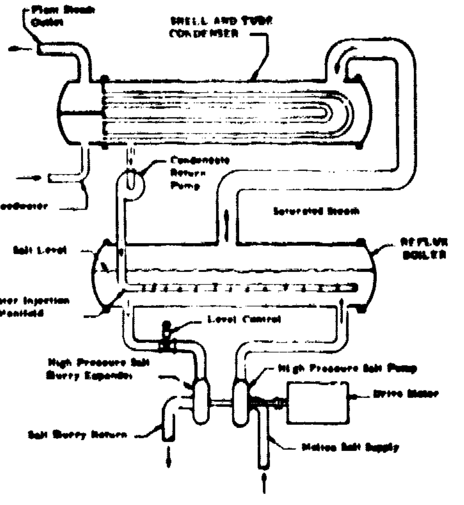

Figure 6 - Continuous Salt Flow Reflux Boiler With Hydraulic Head Recovery

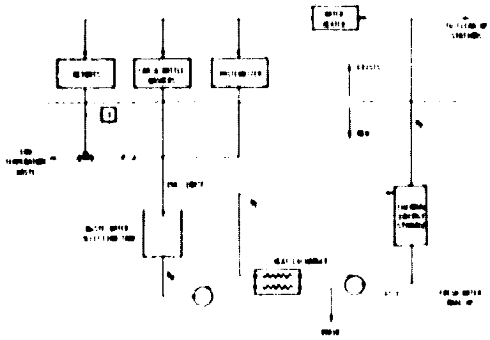

Figure 7 - [illegible] Heat Recovery System Schematic - Meat Products Building

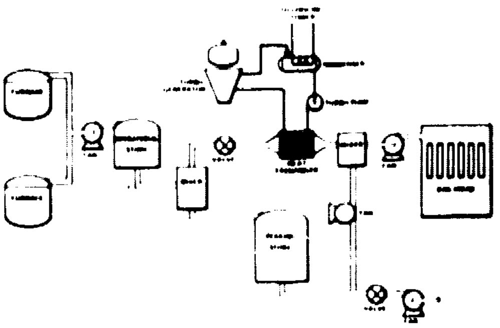

Figure 8 - [illegible] Furnace Energy Recovery and Storage System

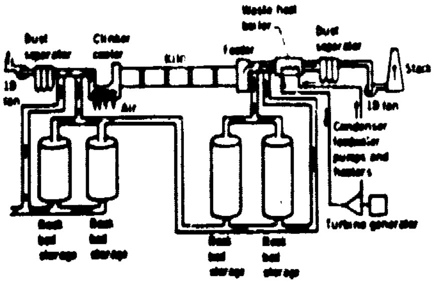

Figure 9 Cement plant energy recovery and storage system

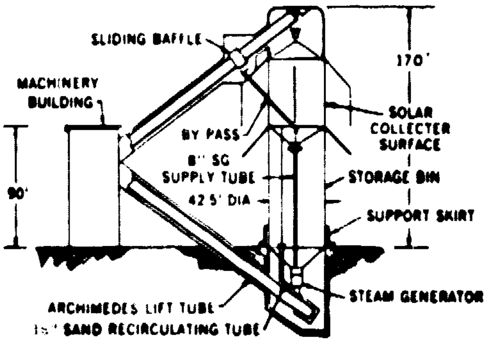

Figure 10 - General Arrangement - Babcock & Wilcox Moving Bed Solar Power Plant

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