DOE/NASA/1034-78/2
NASA TM-78953

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(NASA-TM-78953) THERMAL ENERGY STORAGE FOR INDUSTRIAL WASTE HEAT RECOVERY (NASA) 10 p HC A02/MF A01 CSCL 10C
N78-29576
Unclas
G3/44 28508

Work performed for
U.S. DEPARTMENT OF ENERGY
Office of Energy Technology
Division of Energy Storage Systems

TECHNICAL PAPER to be presented at the
Thirteenth Intersociety Energy
Conversion Engineering Conference
San Diego, California, August 20-25, 1978

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Prepared for
U.S. Department of Energy
Office of Energy Technology
Division of Energy Storage Systems
Washington, D.C. 20545
Under Interagency Agreement EC-77-A-31-1034

Thirteenth Intersociety Energy
Conversion Engineering Conference
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ABSTRACT

The United States Department of Energy — Division of Energy Storage Systems — has contracted with several industrial teams to examine the potential for waste heat recovery and reuse through thermal energy storage in five specific industrial categories: primary aluminum, cement, food processing, paper and pulp, and iron and steel. Preliminary results from Phase 1 feasibility studies suggest energy savings through fossil fuel displacement approaching 0.1 quad/yr in the 1985 period. Early implementation of recovery technologies with minimal development appears likely in the food processing and paper and pulp industries; development of the other three categories, though equally desirable, will probably require a greater investment in time and dollars.

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PROLOGUE

U.S. industry — in concert with all other segments of our economic and social community — has achieved wealth (as measured by the level of capital production per unit of human labor expended) unprecedented in mankind's history. It is a truism, of course, to note that this "house of affluence" rests on a foundation of cheap energy deriving from the profligate consumption of the world's natural resources and the deficits in standard-of-living of other nations in comparison with ours. It is obvious also, perhaps, that this base is losing its strength as the tides of nationalism and individual self-determination sweep the world. To carry these thoughts one step further, it should be equally clear that no people — no matter how altruistic their disposition — will give up without struggle their position on the ladder of economic ease and consequent personal freedom. President Carter has spoken to the effect that the American people must recognize in the developing "energy crisis" the initial phases of a war — a war not against other nations nor against the aspirations of other peoples but against our own sloth and waste. Coupled with the challenge to develop new energy sources that are less abusive of people and nature and to invent new energy use technologies that are both renewable and more efficient, we indeed have a national goal that is worthy of the dedication and ingenuity of our American society. This paper speaks to one part of this war and challenge — the recovery and reuse of energies currently wasted in material production.

In 1976, the Department of Energy (then the Energy Research and Development Administration), and in particular the elements of DOE identified as the Division of Energy Storage Systems (STOR) and the Division of Industrial Energy Conservation (INDUS), recognized the imperative for industrial waste recovery and reuse and called on U.S. industry to submit — in their wisdom — ideas to this end. From this call resulted the five exciting projects described in some detail in the subsequent sections of this paper.

INTRODUCTION

The objective of this DOE effort is the identification, development, and validation (proof-of-concept) of thermal energy storage (TES) systems capable of contributing significantly to energy conservation through the recovery, storage, and subsequent use of industrial process and waste heat. Major emphasis has been directed to TES systems that have potential for early commercialization.

Industrial production uses about 40% of the total energy consumed in the United States. The major share of this energy is derived from fossil fuels; substantial savings in consumption of these non-renewable energy sources are conceived possible through the use of thermal energy storage of waste/process heat for later use in the production process or for off-site utilization. At least twenty industrial categories have been identified as areas where thermal energy storage appears to be both economically and technologically feasible and a necessary component of the energy recovery and reuse system; some of these industries are listed in Table 1.

Responses to the Program Research and Development Announcement (PRDA) issued in January 1977 produced three especially significant prospects in the high-temperature TES area — cement, paper and pulp, and iron and steel — and two in the low-temperature TES area — food processing and aluminum. These five industries represent 35% of the total national industrial fossil fuel usage (Table 1). A total

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*Research sponsored by the U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation and interagency agreement EC-77-A31-1034.A002 with the National Aeronautics and Space Administration.

Table 1 - Energy Use in the United States According to Industry Category
(Compiled from Bureau of Census 1972 Census of Manufacturers, MC72(SR)-6, July 1973)

Industry	Electrical Energy Consumption (10^9 kW-hr)	% National Industrial Electrical Usage	Fossil Fuel Consumption (10^{12} btu)	% National Industrial Fossil Fuel Usage	% Total National Industrial Energy Usage	Waste Heat Temperature Range C
Aluminum Primary	43.9	8.48	215	1.89	2.78	90-980
Automobile Manufacturing	15.8	3.05	195	1.71	1.89	150-1370
Cement	8.5	1.64	430	3.78	3.49	620-730 (dry) 430-590 (wet)
Ceramics	1.9	0.37	157	1.38	1.24	540-1320
Chemicals	82.3	15.9	1,959	17.2	17.3	90-1650
Copper (primary)	0.71	0.14	66.9	0.59	0.59	1090-1370
Electronics (Electrical Manufacturing)	23.6	4.56	193	1.70	2.08	90-1090
Food Processing	35.4	6.84	911	8.01	7.85	40-150
Glass	6.5	1.26	262	2.30	2.16	650-1540
Lumber	9.1	1.76	150.5	1.32	1.38	70-180
Paints	0.8	0.15	17.7	0.16	0.16	90-200
Paper and Pulp	35.0	6.76	1,196	10.52	10.01	150-320
Petroleum and Coal	23.7	4.58	1,513	13.3	12.1	90-590 (petroleum) 90-1090 (coal)
Pharmaceutical	2.8	0.54	57.0	0.50	0.51	40-150
Plastics	11.8	2.28	346	3.05	2.94	90-200
Rubber	18.3	3.53	234	2.06	2.26	90-200
Steel and Iron Primary	50.0	9.65	1,256	11.04	10.85	260-1540
Textiles	30.5	5.89	325	2.86	3.27	40-150
Total	400.61	77.38	9,484	83.37	82.86	

potential energy savings in excess of 0.05 quad/yr is deemed achievable by nationwide implementation of near-term TES systems throughout these five industries.

Contracts for systems studies in each of the five industrial areas identified were awarded in September 1977; Table 2 lists the "teams" involved in each of these areas. In each case, the first organization named is "prime" on the contract; those shown subsequently constitute the necessary specific industry component. Note further that in accord with the management structure established by DOE-STOR, the high-temperature projects are managed by NASA-Lewis Research Center and the low-temperature projects by the Oak Ridge National Laboratory.

The studies described below are listed alphabetically by industrial category; the order thus reflects no comment on priority.

PRIMARY ALUMINUM

A team composed of Rocket Research Company (as prime contractor) supported by Intalco Aluminum Corporation and the Bonneville Power Administration has conducted a detailed technical and economic evaluation of the benefits to be derived from application of thermal energy storage techniques to process and waste heat recovery in the aluminum industry.

The primary aluminum smelting industry is responsible for about 8.5% of the total national industrial electricity usage (Table 1). Most of the waste energy available is low grade, though of high magnitude. It is the latter factor that makes energy recovery from this industry of interest. Admittedly, there are few developed uses for large quantities of low-grade heat in the United States today. One can envision such prospects as heating of large greenhouse complexes, alcohol distillation (for gasoline augmentation), and enhanced crop production through open-field soil warming. However, space conditioning for human comfort appears to be the only concept that might come to early fruition. Since comfort conditioning is strongly cyclic in energy demand (both in the diurnal and seasonal contexts), energy storage is necessary to take full advantage of the constant energy supply from aluminum processing.

This particular study, while site-specific with respect to application, does indicate significant industry-wide conservation potential. One of several types of electrolytic alumina reduction cells is pictured in Fig. 1. The hot gaseous emissions from collections of these cells are presently carried to scrubbers and filters to remove noxious and hazardous fumes and particulates and then discharged to the atmosphere as clean air at temperatures approaching 300°F. It is proposed that this reject heat be used to heat water that is in turn transported and stored in conventional steel tanks for use in district heating distribution systems in nearby communities (Fig. 2). Less expensive storage systems (e.g., surface ponds and aquifers), when fully developed, may allow improved cost competitiveness. Extensive design trade-off studies for a specific Intalco site in the state of Washington and the surrounding communities of Ferndale and Bellingham indicate that a heating demand equivalent to 12,000 single-family residences can be supplied by the waste energy collected from the Intalco plant.

Table 2 - Contractor Teams Involved in Studies for the Department of Energy on the Role of Thermal Energy Storage in Energy Conservation through Waste Heat Recovery

Industry Category	Prime Contractor	Supporting Components
Aluminum (Primary)	Rocket Research Company	Intalco Aluminum Corporation Bonneville Power Administration
Cement	Martin Marietta Aerospace	Martin Marietta Cement Company Portland Cement Association
Food Processing	Westinghouse Electric Corporation (Advanced Energy Systems Division)	H. J. Heinz Company (USA Division)
Paper and Pulp	Boeing Engineering and Construction	Weyerhaeuser Corporation SRI International
Steel and Iron (Primary)	Rocket Research Company	Bethlehem Steel Company Seattle City Light Company

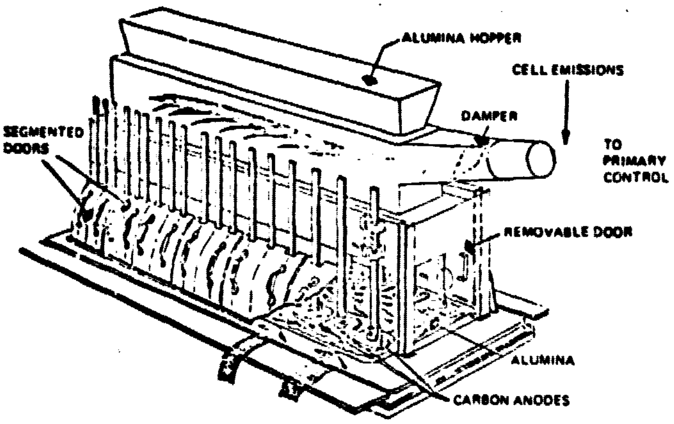

Fig. 1 - Hooding collects waste heat from a center-work prebake cell for electrolytic alumina reduction

The 31 primary aluminum plants in the United States tend to cluster near sources of low-cost electrical power; hence, competition from other heating modes (such as heat pumps) can be significant.

Using a 30-year payback criterion (with an energy cost escalation of 5% above the general inflation rate), the average cost of the energy supplied over the system's useful lifetime is projected as one-third the average cost of fossil fuel; an average return on investment (ROI) of 63% is estimated. The exact distribution of this savings between the customer and the utility remains for the moment moot; however, this preliminary study does indicate sufficient economic attractiveness and an absence of incapacitating technical problems to warrant furtherance of this concept. For the 12,000 user case, a net capital outlay (for recovery, storage, and distribution systems) of about $63 million (1977 dollars) with a net displacement of about 1.4×10^{12} Btu/yr (0.0014 quad/yr equivalent to about 250,000 bbl oil/yr) is indicated.

CEMENT

Assessment of prospects for recovery and reuse of industrial process and reject heat through thermal energy storage is being carried out by the Martin Marietta Aerospace Corporation with the assistance of Martin Marietta Cement Company and the Portland Cement Association.

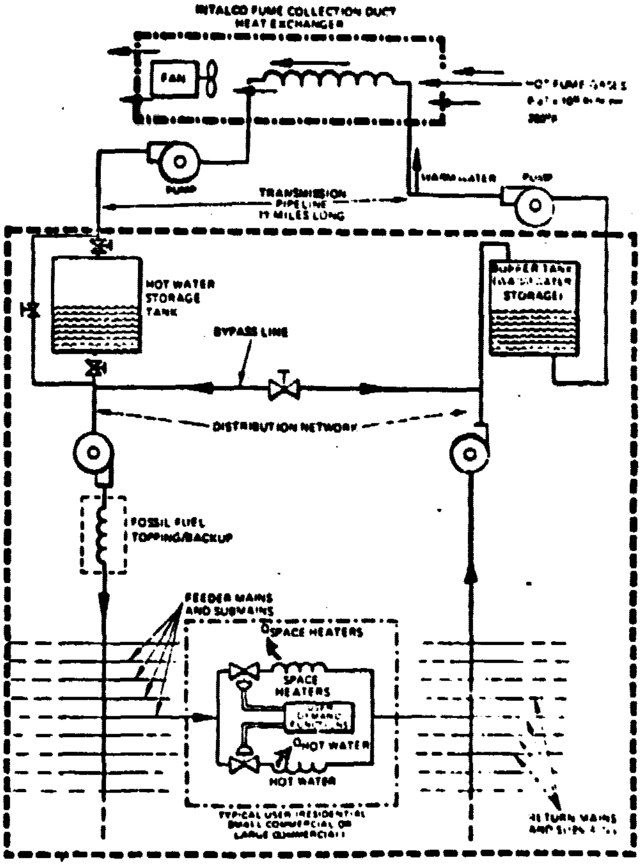

Fig. 2 - District heating system utilizes waste heat recovered in primary aluminum production

The cement industry is the sixth largest industrial user of energy in the United States; 80% of this energy is consumed in the kiln operation. Plants with long, dry-process kilns and grate-type clinker coolers have been indicated as the best choice for reject energy recovery; by way of reference, the flow diagram for a typical cement plant is given in Fig. 3.

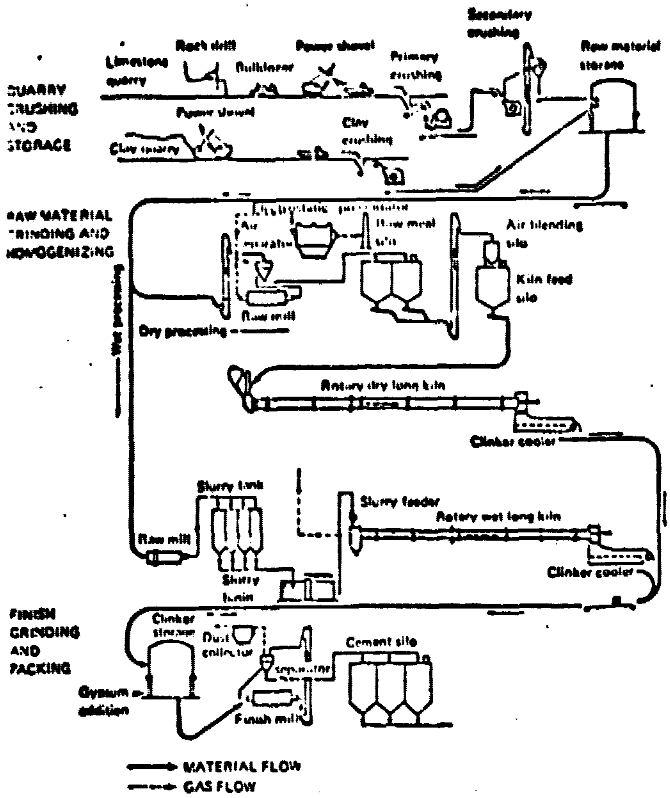

Fig. 3 - Kilns and clinker coolers offer principal opportunities for waste heat recovery in cement manufacture

An evaluation of possible uses for the recovered energy suggests the following scenario as best: a waste heat boiler to form steam that in turn drives a turbogenerator to produce electricity for in-process use. It is estimated that approximately 75% of a plant's electricity requirements could be met with on-site power generation. However, this reject heat source for the steam boiler is not available when the kiln is down for maintenance of the clinker cooler grate or the kiln itself. At such times, the needed electrical power — that may be as much as 5-10 MW over short time periods of 2-24 hrs — must be obtained from either a utility or through curtailment of other plant operations, such as raw and finish milling. The cost to the plant (in peak power rates) and to the utility (in maintaining excess peaking capacity) is significant. This problem could be alleviated by using thermal energy storage to level the on-site energy availability and, hence, reduce the utility demand load. Excess heat from the kiln (i.e., heat beyond that needed to supply immediate needs) could be charged to the store and then recalled when the kiln is down.

The storage concept proposed for use with dry-process kilns involves a solid sensible heat storage material such as magnesia brick, granite, limestone, or even cement clinker. Two thermal stores are conceived (Fig. 4): one accepting high-temperature reject heat from the kiln exit gas at about 1500°F, and the other storing heat from the clinker cooler at about 450°F. These systems would be charged independently but discharged in series; i.e., ambient air would be passed through the low-temperature unit and heated to about 400°F and then introduced to the high-temperature TES unit in which it would reach a temperature of 1200°F. This hot air would then "fuel" the waste heat boiler. Storage system sizing indicates that provision of capacity for 10 MW over 24 hrs would be a beneficial size. During kiln operation, 80-90% of the kiln exit gas would go directly to the waste heat boiler, while the remainder would pass through the high-temperature storage unit; thus, it will take roughly one week to charge the system to its full 24-hr withdrawal capacity.

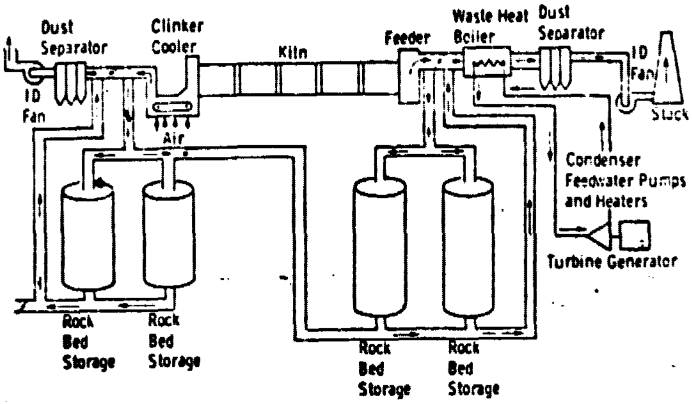

Fig. 4 - Two-stage rock bed storage appears feasible for waste heat recovery in cement production (charge mode shown)

Economic evaluations are incomplete; however, preliminary estimates suggest that a 10-MW waste heat boiler/power plant/TES installation and demonstration would cost about $10 million and extend over an eight-year period. A 70% ROI has been calculated, assuming a 30-year system life and an average energy cost of 2.5¢/kWh. Annual energy savings based on current industry installations (118 dry kilns) of about 7×10^6 bbl of oil ($\sim 4 \times 10^{13}$ Btu or 0.04 quad) is postulated. A phased technology development and validation program through full-scale demonstration at a cement plant is seen as desirable.

FOOD PROCESSING

The Westinghouse Electric Corporation (Advanced Energy Systems Division) in cooperation with the H. J. Heinz Company (USA Division), is engaged in a study to identify practical waste heat recovery systems for application in the food processing industry.

The food process industry is a major user of low-temperature (below 250°F) process heat; only chemicals, petroleum and coal, steel and iron, and paper and pulp exceed the approximately 8% of total national industrial energy use consumed by food processing (Table 1). It is estimated that 85% of the fuel utilized by the industry goes to produce process steam and hot water at low temperatures for cooking, sterilization, and equipment and work area washing, sanitizing, and cleanup. Much of this heat is then wasted to the environment as steam or hot water. It is proposed that most of this waste can

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be recovered and utilized, through storage, in subsequent process steps and/or in cleanup operations.

This study concentrated on two Heinz-USA facilities: a Pittsburgh, Pennsylvania, factory processing canned or bottled foods and sauces; and a Lake City, Pennsylvania, plant processing frozen desserts. These examples were deemed typical of the food processing, with differences in product and temperature in other parts of the industry contributing to differences in amount, distribution, and reuse of hot water but not to the essential capacity of the industry for energy conservation through storage. A reference concept for recovery and reuse of hot water is shown in Fig. 5. The ground rules established were that the primary function of the system would be the recovery of process waste heat for immediate reuse during the two production shifts of each working day and that, after meeting those needs most efficiently, the remaining waste heat would be stored for third shift clean-up operations. The nature of this industry, involving significant numbers of small producers, dictates that the recovery and storage systems be simple, reliable, and easily maintained.

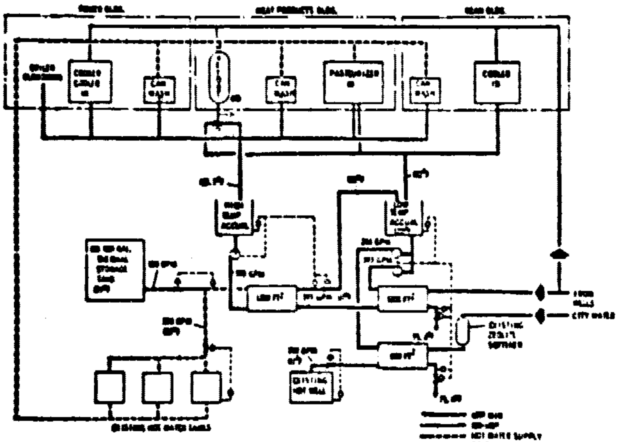

Fig. 5 - Accumulators store high- and low-temperature waste water from food processing for subsequent manufacturing and/or cleanup operations

For this reference design, the yearly waste heat recovery is projected to be about 11,400 bbl of oil equivalent having an annual value of about $225,000; combined with an estimated initial cost for the recovery system of about $325,000, an annual return-on-investment of about 69% is indicated. Estimates of industry-wide savings are too product and site-specific for detailed accounting at this time. Installation for demonstration could be accomplished at Heinz USA-Pittsburgh within one year.

PAPER AND PULP

Boeing Engineering and Construction, with team members Weyerhaeuser Corporation and SRI International, is investigating the application of process heat storage and recovery in the paper and pulp industry.

The forest products industry as a whole is one of the largest users of fossil fuels for in-plant process steam generation. In this study, Weyerhaeuser's paper and pulp mill at Longview, Washington, is used to assess the potential for energy savings and to evaluate the effectiveness of thermal energy storage in achieving such savings. The energy requirements of this plant are dictated by the mill process steam demand and by the electric power need.

In current practice, hog fuels (wood waste produced by the various machining operations) and recovered liquors (Kraft, black, and sulfite from chemical wood pulping) fuel the boilers for base-load operation, while oil/gas boilers provide for the fluctuating load; about 40% of the base load is supplied from hog fuel. Thermal energy storage is conceived as a means for substituting usage of more hog fuel for the oil/gas fossil fuels. This could be accomplished by operating the hog fuel boiler at a higher base-load level, storing the excess steam when demand is low, and discharging the store when demand is high. As shown schematically in Fig. 6, analysis using typical mill data indicates that a storage time of about 0.5 hr with a steaming rate capacity of 100,000 lb/hr produces a system effecting a transfer of 60,000 lb/hr in steam load from the fossil fuel boilers to the hog fuel boiler. This corresponds to a reduction of about half in the fossil fuel consumption for load following. Further, for storage times less than one hour direct storage of steam using a variable pressure accumulator (Fig. 7) is more attractive (economically) than indirect sensible heat storage involving rock/oil or rock/glycol media.

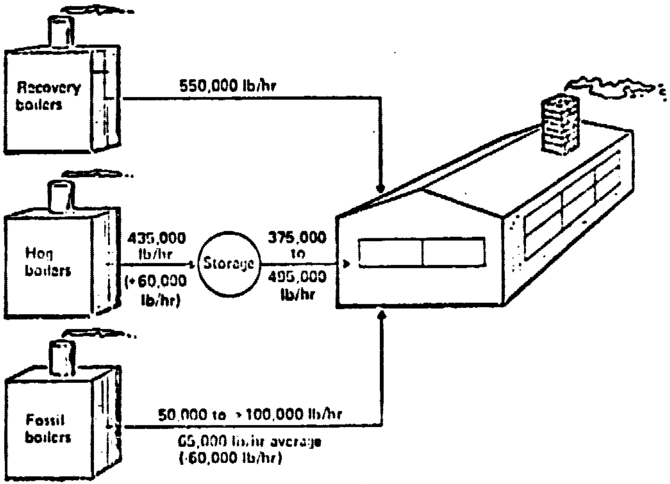

Fig. 6 - Use of TES in conjunction with hog boilers in pulp and paper processing effects eases load following requirement on fossil boilers

Preliminary economic evaluation shows a potential ROI for this system of about 40% over a 15-year return and depreciation period. Near-term (1985) fossil fuel savings are projected conservatively (American Paper Institute data) at about 3×10^6 bbl oil/yr based on 30 candidate mills with operating characteristics similar to the Longview plant. Energy resource impact studies completed by SRI International suggest long-term (year 2000) oil/gas savings of 13×10^6 bbl/yr (about 0.07 quad/yr).

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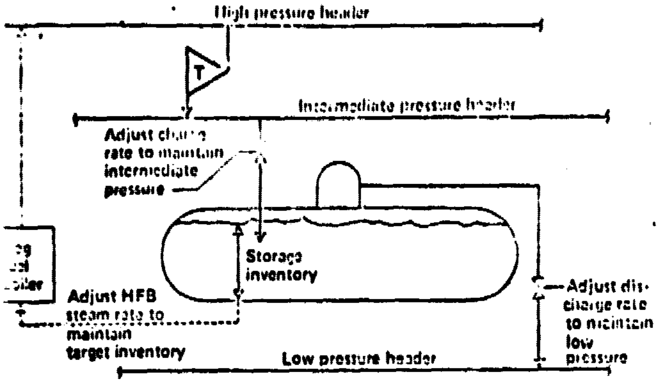

Fig. 7 - Variable pressure accumulator provides TES capability in pulp and paper processing

Implementation of this TES system would require neither technology development nor reduced-scale technology validation. The conceptual system using a variable pressure accumulator charging from either the high-pressure (600 psig) or intermediate pressure (140 psig) steam supply headers and discharging to the low pressure (40 psig) supply header appears both technically and economically feasible. Installation at full-scale utilizing commercially available equipment could be accomplished at the Longview plant in about two years.

PRIMARY IRON AND STEEL

Rocket Research Company is teamed with Bethlehem Steel Corporation and Seattle Light Company to investigate the use of TES in the recovery and reuse of reject heat from steel processing in general and electric steel plants specifically.

This industry consumes slightly less than 11% of the total national industrial energy usage; the about 9.5% of electrical use is second only to the about 16% of the broad chemicals category. A thermal analysis of the complex heat availability patterns from steel plants indicates significant recoverable energy at temperatures of 600 to 2800°F.

The electric arc furnace fume stream was selected through this study as the best reject energy source. This heat would be charged to a solid sensible heat storage medium capable of withstanding temperatures to 3000°F (such as refractory brick, slag, or scrap steel) and discharged on demand through a heat exchanger to produce steam. This steam, in turn, would drive a turbogenerator to produce electricity, thus reducing the mills energy peaking requirements. Presently, the dust-laden fume stream from the electric arc furnace is water quenched and then ducted to the dust collection system before discharge to the atmosphere. The new flow arrangement (Fig. 8) would have the unquenched fume stream flowing from the furnace through the energy storage medium prior to being discharged through the existing dust collection system. During peak demand periods, the combined streams from the furnace and the store would flow through the heat exchanger to create the steam for the turbogenerator.

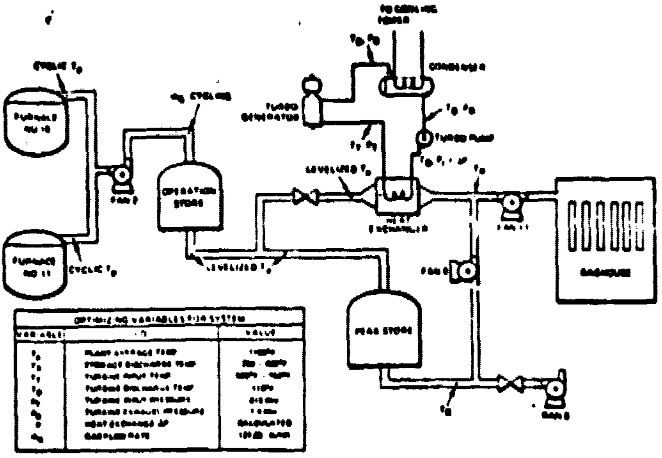

Fig. 8 - Operation and peak thermal energy stores optimize use of waste heat recovered from steel electric arc furnaces

The conceptual system proposed on the basis of Bethlehem's Seattle plant characteristics would result in a payback period of about five years, assuming four-hr storage capability and 7-MW peak on-site electricity generation displacing purchased power at 10¢/kWh. Assuming further that fossil fuel is required to produce the peak power, projected conservative annual energy savings from present nationwide electric arc furnace installations are in excess of 10^6 bbl of oil equivalent (5.6×10^{12} or 0.006 quad). If the majority of the to-be-phased-out open hearths were replaced by electric arc furnaces and if water-cooled chill technology were implemented completely in steel manufacture by the electric arc process, potential savings could approach 4×10^6 bbls oil/yr (∿0.03 quad/yr). Implementation of this concept through a single demonstration could take about 8 yrs at a cost of about $10 million.

SUMMARY

An examination of the potential for energy conservation in five industrial categories has been completed under the first phase of a DOE study into the recovery and reuse of industrial waste heat through thermal energy storage. These five industries — aluminum, cement, food processing, paper and pulp, and iron and steel — represent only a part (albeit a significant part) of the total potential for energy savings. As shown in Table 3, a possible savings of more than 12×10^6 bbls oil/yr (0.07 quad/yr) appears possible. Some of this savings (about 4×10^6 bbl/yr) could be available in the very near term (1-2 yrs) at moderate costs; demonstration for recovery of the remainder, being dependent on further technology development and significant capital investment, appears feasible on a 10-yr time scale. Other categories consuming more than 2% of the total national industrial energy usage (e.g., electronics and electrical equipment, glass, petroleum and coal, plastics, rubber, and textiles) must still be considered before a picture of the total energy savings potential in the industrial sector can be fully developed.

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Table 3 - Summary of Results on Potential for Waste Heat Recovery through TES in Five Industrial Categories

Industry	Near-Term (1985) Projected Annual Energy Savings		Technical Validation		Full-Scale Demonstration	
	10^6 bbl	10[illegible] quad	yrs	10[illegible] $	yrs	10[illegible] $
Aluminum	0.3	1.4	4-5	5	>8	30-40
Cement	7	40	3	2-3	7	~10
Food	0.5	2.3	---	---	1	0.4
Paper & Pulp	3	17	---	---	2	1
Iron & Steel	>1	>6	4-5	2-3	8	~10

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EPILOGUE

Energy is the lifeblood of the "American way of life." We like to believe that our system in its economic, social, and political manifestations provides the model for universal contentment and health. Indeed, through much of this world — be we emulated or disparaged — our condition is the target. Since we are then a forcing function generating increased worldwide energy use, we also have a responsibility to lead the way toward a more rational energy economy based on conservation through reduced usage, improved processes, and waste energy recovery and on substitution of alternative renewable and hopefully cheaper fuels to replace the rapidly depleting fossil fuels. It is befitting that American industry be the carrier of this charge.

ACKNOWLEDGEMENT

In preparing this paper, access has been made to various progress and summary reports and oral presentations contractually required of the several organizations performing studies on industrial waste heat recovery feasibility under the DOE-STOR PRDA awards. The authors are, thus, indebted to the unnamed many whose imaginations and efforts have led to the concepts summarized.