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ABSTRACT

Industrial production uses about 40% of the total energy consumed in the United States. The major share of this is derived from fossil fuel. Potential savings of scarce fuel is possible through the use of thermal energy storage (TES) of reject or process heat for subsequent use. Results of study contracts awarded by the Department of Energy (DOE) and managed by the NASA Lewis Research Center have identified three especially significant industries where high temperature TES appears attractive - paper and pulp, iron and steel, and cement. Potential annual fuel savings with large scale implementation of near-term TES systems for these three industries is nearly 9×10^6 bbl of oil.

INTRODUCTION

One of the many responsibilities of the Department of Energy (DOE) is administering the Voluntary Business Energy Conservation Program. This program, under the guidelines of the 1975 Energy Policy and Conservation Act, requires major energy consuming firms within industries for which energy efficiency improvement targets have been set to report directly to DOE on their energy efficiency. The fact that industrial production uses about 40% of the total energy consumed in the United States indicates the tremendous potential that exists for significant energy savings through a concerted effort by all concerned.

Major energy consuming industries, arranged by the two-digit Standard Industrial Classification (SIC) Code, were assigned 1980 goals for improvement in energy efficiency over their 1972 base level. As of the first six months of 1977, the index of energy efficiency was at an estimated 9.2 per cent above the 1972 base level [1]. Although very encouraging in regards to the overall energy savings implicit in this index, the decline in the use of natural gas was offset by an increase in the use of fuel oil.

As with every major problem, the solution for achieving maximum energy savings lies in many approaches. One approach, known for decades but relegated to the sidelines because of the past availability of relatively cheap energy in the United States, is the recovery and use of industrial waste heat. Recognizing the increased importance of waste heat recovery and use, the former Energy Research and Development Administration (ERDA) funded a study to determine the economic and technical feasibility of thermal energy storage (TES) in conjunction with waste heat recovery [2]. This study was directed toward identifying industrial processes characterized by fluctuating energy availability and/or demand, a key criterion for TES applicability.

At least 20 industries were identified as areas where thermal energy storage had potential application to some degree. Responses to a Program Research and Development Announcement (PRDA) issued by ERDA shortly after the conclusion of the feasibility study program resulted in contract awards to study three industries in the high temperature ($>250^oC$) TES area with potential significant energy savings. These industries were paper and pulp, iron and steel, and cement. DOE's Division of Energy Storage Systems awarded the contracts, and the NASA Lewis Research Center provided the technical management. Major emphasis was given to TES systems and applications that have potential for early commercialization within each specific industry.

PAPER AND PULP

The forest products industry, as a whole, is one of the largest users of fossil fuels for in-plant process steam generation. Boeing Engineering and Construction, with team members Weyerhaeuser Corp. and SRI International, investigated the application of process heat storage and recovery in the paper and pulp industry [3]. For this investigation, Weyerhaeuser's paper and pulp mill at Longview, Washington [4] was selected to assess the potential energy savings and to evaluate the effectiveness of thermal energy storage in achieving these savings.

The paper and pulp operation at Longview consists of process systems and a power plant which supplies steam to the processes and the power generation turbines. Figure 1 shows schematically the energy supply characteristics without energy storage. The recovery (liquor-kraft black and sulfite from conventional chemical wood pulping) and waste (hog fuel-wood waste produced by the various machining processes) boilers provide a base load of steam generation while the oil/gas boilers provide the time dependent load. The primary goal of using thermal energy storage at Longview (and similar paper and pulp mills throughout the industry) is to substitute usage of more hog fuel for the oil/gas fossil fuels.

The inability to follow rapidly changing steam demands with hog fuel boilers requires the reduction of hog fuel firing in favor of increased fossil fuel firing. However, this can be overcome by the use of thermal energy storage. The hog fuel boiler would be operated at a higher base load, the excess steam would be stored when the demand is low, and storage would be discharged when the demand is high. The economics of steam swing smoothing in the paper and pulp industry depends on the capacity of the swing smoothing system and the number of hours per year the system will allow hog fuel substitution for fossil fuel.

Daily operational data from the Longview plant was used to evaluate the effectiveness of thermal energy storage. This plant was considered representative of paper and pulp mills where the potential exists for the economic use of thermal energy storage. The analyses using this typical mill data indicated that for a system as shown on Figure 2, a storage time of about 0.5 hours with a steaming rate capacity of 100,000 lb/hr would result in 60,000 lb/hr of steam load transfer from fossil fuel boilers to the hog fuel boiler. This corresponds to about a 50% reduction in fossil fuel consumption for load following.

Initial sizing and cost estimates for storage system concepts were generated for a range of steaming rates and storage times. The results indicated that for storage times less than one hour, direct storage of steam using a variable pressure steam accumulator was more economically attractive than indirect sensible heat storage using media such as rock/oil or rock/glycol combinations.

Figure 3 shows the variable pressure accumulator TES concept. Steam used for charging storage from either the high pressure or intermediate pressure header bubbles through the saturated water contained under pressure in the vessel. The steam condenses and transfers energy to the water, raising the water's temperature and pressure. Upon discharging to the low pressure header, the steam pressure above the water surface is reduced causing the water to evaporate, supplying steam but lowering the water's temperature and pressure.

Oil savings estimated for the Longview plant is 100,000 bbl/yr based on the transfer of 60,000 lb/hr of steam load from the fossil fuel boilers to the hog fuel boiler. A survey performed using data supplied by the American Paper Institute indicated that there are 30 candidate mills that either have now or will have by 1980, operating characteristics similar to the Longview plant. Therefore, potential near-term (1985) fossil fuel savings are projected as being 3×10^6 bbl/yr.

Energy resource and environmental impact studies completed by SRI International indicates potential long-term (2000) fuel savings of 18×10^6 bbl/yr based on a 10% shift in steam generation from gas and oil to hog fuel and coal due to TES use. This also takes into account the additional cogeneration accompanying this shift and the resultant decrease in purchased electricity. This displacement of gas and oil will decrease the national sulfur dioxide emissions but will result in an increase in the nation's particulate emissions - roughly two pounds of SO_2 removed for each pound of particulate added.

Preliminary economic evaluation shows a potential return on investment (ROI) for this TES system in excess of 30% over a 15-year return and depreciation period. The conceptual system using a steam accumulator appears technically and economically feasible. Because of the availability of all the required technology, implementation would not require technology development or a reduced scale technology validation. Installation at full scale in one of the candidate mills utilizing commercially available equipment could be accomplished within a two-year time period for a cost of less than one million dollars.

IRON AND STEEL

The primary iron and steel industry accounts for about 11% of the total national industrial energy usage. Rocket Research, with team members Bethlehem Steel Corporation and Seattle City Light, investigated the use of thermal energy storage with recovery and reuse of reject heat from steel processing in general and electric arc steel plants specifically [5]. Thermal analysis of the complex heat availability patterns from steel plants indicates significant potentially recoverable energy at temperatures of 600 to 2800°F.

A detailed assessment for Bethlehem's Seattle scrap metal refining plant was made of the energy sources, energy end uses, thermal energy storage systems, and system flow arrangements. This plant is typical of electric arc furnace installations throughout the United States, allowing results of this site-specific study to be extrapolated to a national basis.

The hot gas in the primary fume evacuation system from a pair of electric arc steel remelting furnaces was selected as the best reject energy source. Presently, the dust laden fume stream is water quenched and then ducted to the dust collection system prior to discharge to the atmosphere. The new flow arrangement shown in Figure 4 would have the unquenched fume stream flowing through the energy storage media prior to discharge. The solid sensible heat storage media would have to be able to withstand the hot gas temperature which could be as high as 3000°F while averaging about 1750°F. Potential materials are refractory brick, slag or scrap steel.

Two energy storage beds are required. The operational storage bed serves to time average the widely fluctuating temperature of the energy source. The peaking storage bed serves to hold energy until the demand arises. During charging, all of the furnace-gas discharge flow goes through both storage beds and is exhausted through the baghouse, the dust collection system.

During peak demand periods, the combined streams from the furnace (through the operational storage) and the peaking storage (in a reversed flow direction) would flow through the heat exchanger to create steam to drive the turbogenerator. Upon initial discharge of the peaking store, ambient air is drawn in through the lower fan/valve arrangement. When the required flow rate through the peaking bed is established, the ambient air valve is closed. At the exit of the heat exchanger, gas flow is divided, with a portion going to the baghouse and the rest providing the peaking storage discharge gas stream.

To complement the assessment, Seattle City Light provided data on electricity costs. The economic benefits to be derived from the use of energy storage to provide peak power generation is a direct function of either a demand charge, time of day pricing, or a combination of both. The conceptual system proposed for the Bethlehem plant would result in a payback period of about five years depending on the combination of electricity costs and size of the power generation equipment. For example, a system providing a four-hour peak storage capability and generating 7MW of peak demand electricity would result in a five-year payback period if it were displacing peak power at a cost of 10¢/kwh.

Assuming fossil fuel is required to produce peak power, annual oil savings attributed to TES at a plant with a daily production of 1200 tons for 300 days/yr would be about 16,000 bbl. The potential electric arc steel industry annual oil savings could approach 2×10^6 bbl based on a projected annual production of 50×10^6 tons by 1985. In this case, there would be a direct reduction in sulfur dioxide emissions without an associated increase in particulates as for the paper and pulp projections.

The TES concept development in this study yielded favorable predictions of fossil fuel displacement and investment returns. However, the approach isn't ready to be applied directly to a full scale demonstration without an interim concept development period. Experimental scale studies of large, granular masses in the high temperature region (up to 1500°F) are required. Data from these studies would provide design criteria needed to verify analytical models for high temperature applications. The effect of the particulates in the furnace exhaust stream on the heat storage media must also be determined and resolved if detrimental. Successful completion of such a development phase could lead to a small scale demonstration followed by a full-scale system demonstration in an operating electric arc steel plant. Such a program would take about 8 years and cost between 5 and 10 million dollars.

CEMENT

The cement industry is the sixth largest user of energy in the United States. Eighty percent of the energy used is consumed as fuel for the kiln operation. Martin Marietta Aerospace, with team members Martin Marietta Cement and the Portland Cement Association, investigated the use of thermal energy storage in conjunction with reject heat usage in the cement industry [6]. Thermal performance and economic analyses were performed on candidate storage systems for four typical cement plants representing various methods of manufacturing cement. Basically, plants with long, dry-process kilns and grate-type clinker coolers offer the best choice for reject energy recovery.

An assessment of potential uses of the recovered energy determined that the best use for it would be in a waste heat boiler to produce steam fordriving a turbogenerator to produce electricity for in-process use. Approximately 75% of a plant's electrical 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 either the clinker cooler grate or the kiln. At this time, the power demand for other cement plant operations must be obtained from a utility. This would require demanding large amounts of utility power for short periods of time, e.g. 5 to 10 MW for 2 to 24 hours. The cost to the plant in peak power rates and to the utility in maintaining excess peaking capacity is significant. The other alternative is to curtail other plant operations such as raw or finish milling.

This problem could be alleviated by using thermal energy storage to reduce the utility load demand. By charging the storage unit while the kiln is operating, the stored thermal energy would be available when the kiln is down. The storage concept proposed in conjunction with dry-process kilns uses a solid sensible heat storage material such as magnesia brick, granite, limestone, or even cement clinker. The storage system would use two separate thermal stores as shown on Figure 5. One would store high temperature (1500°F) reject heat from the kiln exit gas. The other would store low temperature (450°F) heat from the clinker cooler excess air. These two separate storages would be charged independently but discharged in series. Ambient air would be passed through the low temperature TES units and heated to about 400°F. It would then be heated to about 1200°F while passing through the high temperature TES units. The heated air would then flow through the waste heat boiler and generate steam to produce electricity.

Storage system sizing for typical cement plants indicates that provision for 24 hours of power production at about 10 MW would be a beneficial size in relation to normal plant operation. During kiln operation 80-90% of the kiln exit gas would go directly to the waste heat boiler to produce electricity while the rest would pass through the high temperature storage unit. Therefore, it would take roughly one week to charge the system to its full 24 hour withdrawal capacity.

An economic evaluation of the system indicates that a 10 MW waste heat boiler/power plant/TES installation would cost about 10 million dollars. A 90% ROI was calculated for a 30-yr system life and an average energy cost of 2.8¢/kwh. About 15% of this ROI can be attributed to the TES system. Again, assuming fossil fuel is originally required to produce this waste-heat derived power, a potential energy savings of about 4 x 10^6 bbl of oil per year is projected. This is based on utilizing the cement industry's current installations of about 120 long dry kilns. As with the steel industry storage/generation systems, this represents a potential direct reduction of sulfur dioxide emissions.

There is another similarity between the cement plant and steel plant systems. The necessity for a phased technology development and validation program through full scale demonstration also exists for the cement plant system. Estimates of 8 years and 5 to 10 million dollars appear to be valid for such a program.

SUMMARY

From the response to ERDA's FY 77 Industrial Applications PRDA, three attractive industries which could utilize high temperature thermal energy storage were selected for study. These industries are paper and pulp, iron and steel, and cement which account for 25% of the total national industrial energy usage. Potential annual fuel savings with large scale implementation of near-term thermal energy storage systems for these industries is nearly 9 x 10^6 bbl of oil. This savings is due to both direct fuel substitution in the paper and pulp industry and reduction in electric utility peak fuel use through in-plant production of electricity from utilization of reject heat in the steel and cement industries. Economic analyses for all of these systems indicate potential return on investments from 30 to 90%.

CONCLUDING REMARKS

The results of these three studies appear to be so attractive that the question immediately arises - "If it looks so good, why aren't the industries involved already doing it on their own?" Perhaps the answer to this question can be found in a recent article on energy related capital investment [7]. The point being made in this article is primarily that most companies set the rate of return from energy-saving investments at a level about twice as high as that for mainstream business investments. Discretionary investments that do not increase productivity have a low priority. In addition, paper studies without the visible proof of a working demonstration do not stimulate the flow of working capital that is already in limited supply.

The ultimate objective of the effort summarized in this paper is the demonstration of cost-effective thermal energy storage systems capable of contributing significantly to energy conservation. To achieve this the Department of Energy's role is that of a catalyst to bring these systems to the point that they will be accepted and widely implemented throughout the various industries. This effort has shown that a full scale working system for the paper and pulp industry could be available in the very near term at moderate cost. Other systems, although dependent on further technology development and significant capital investment, appear capable of being implemented within the next eight years.

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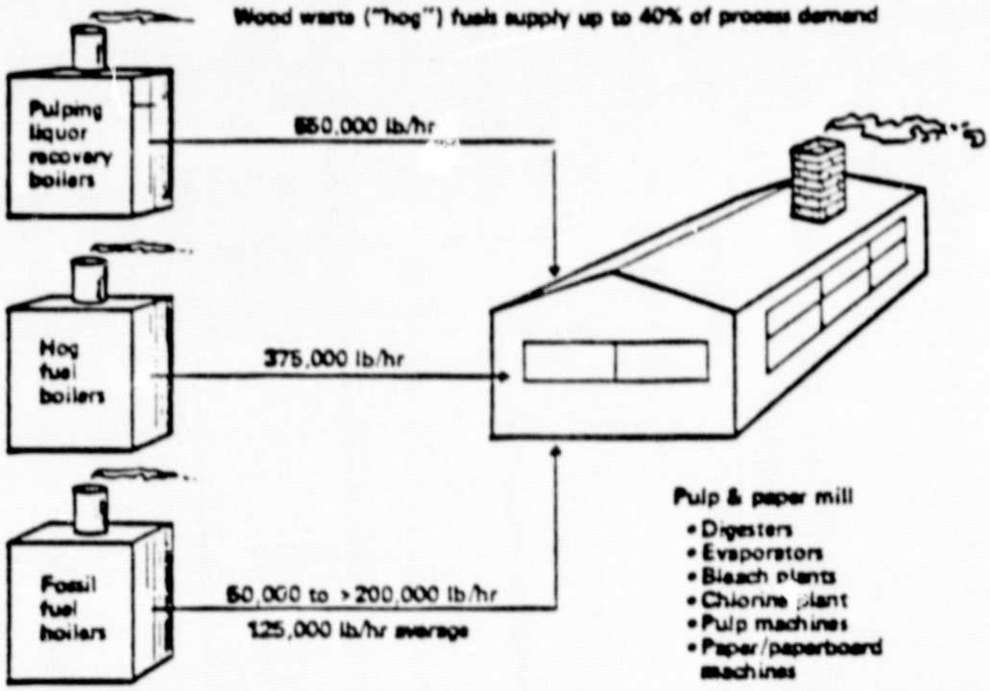

Figure 1. - Paper and Pulp Energy Supply Characteristics

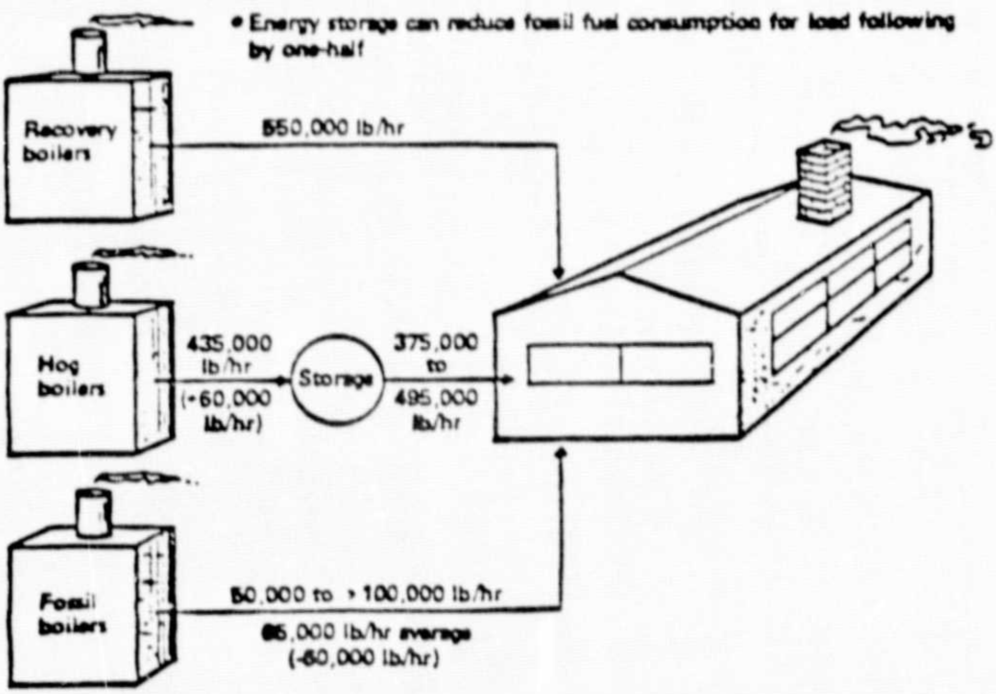

Figure 2. - Energy Supply With Thermal Energy Storage

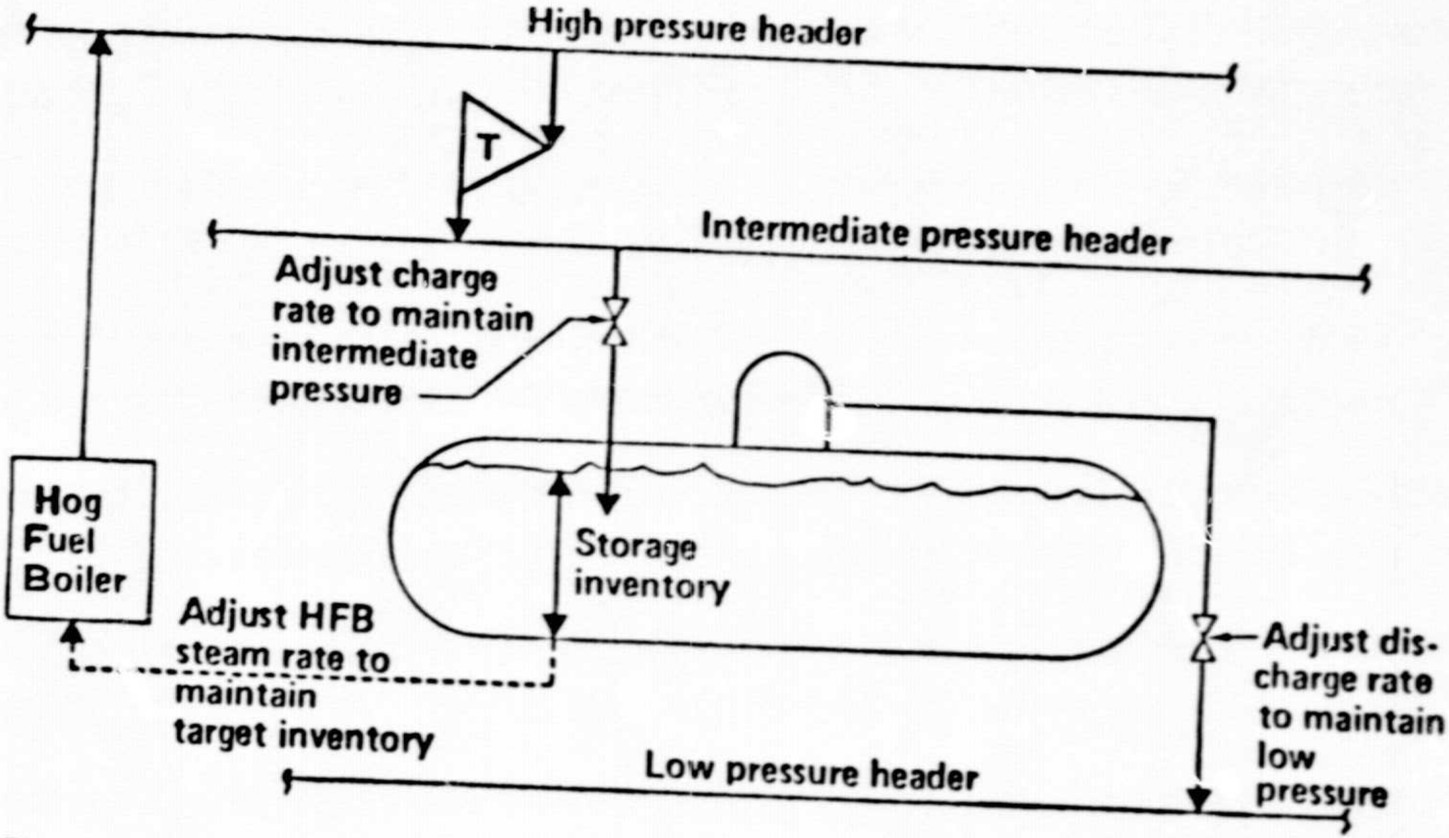

Figure 3. - Variable Pressure Accumulator TES Concept

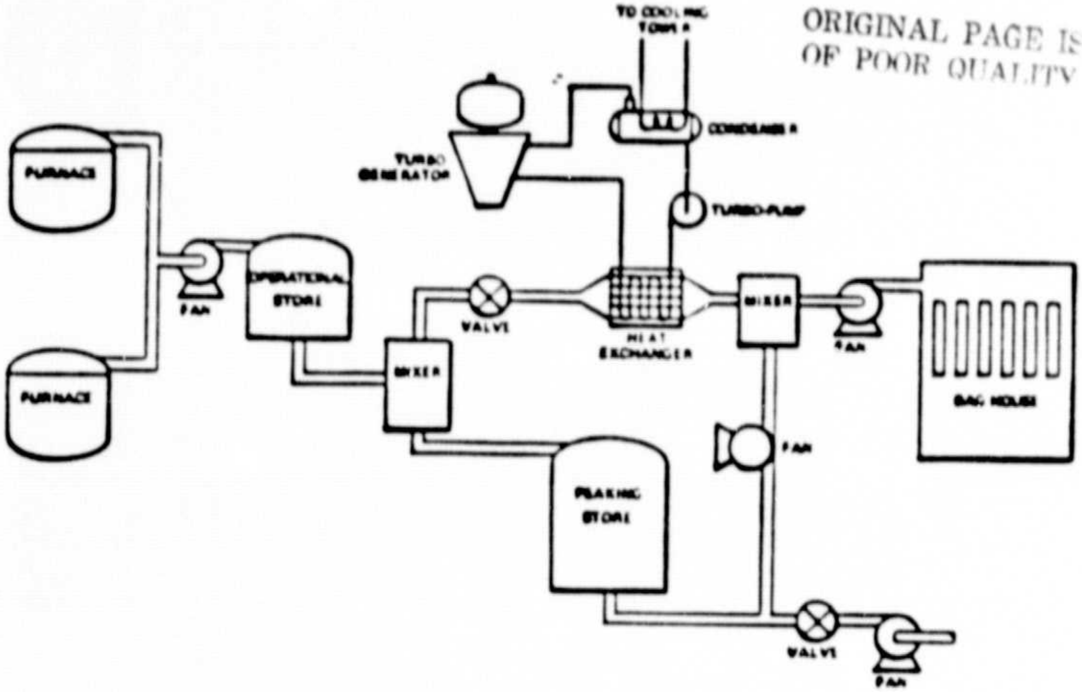

Figure 4. - Steel Arc Furnace Energy Recovery and Storage System

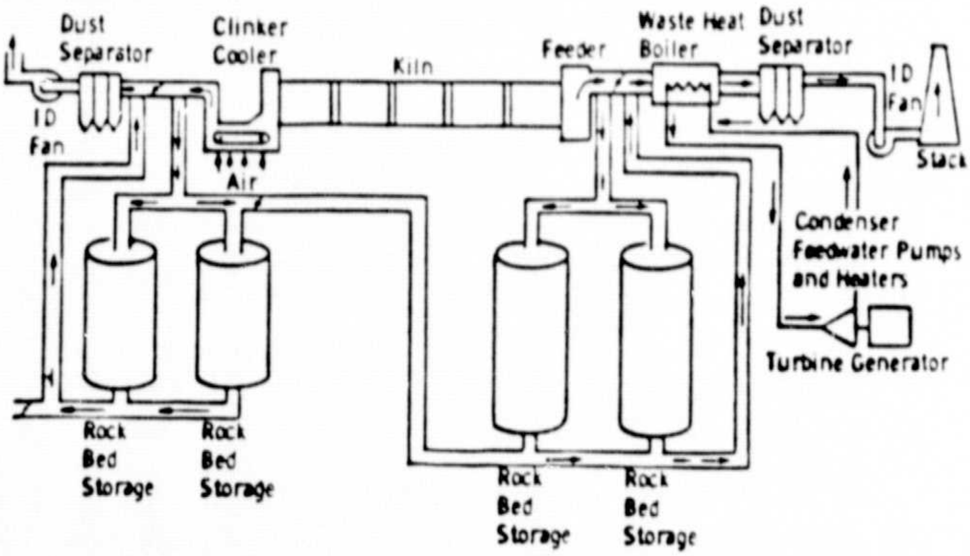

Figure 5. - Cement Plant Energy Recovery and Storage System