ENERGY CONSERVATION

CONS/5084-1
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APPLICATION OF THERMAL ENERGY STORAGE IN THE CEMENT INDUSTRY

FINAL REPORT FOR THE
PERIOD SEPTEMBER 1977–MARCH 1978

F. A. Jaeger
D. G. Beshore
Dr. F. M. Miller
Dr. E. M. Gartner

Date Published–October 1978

Work Performed Under Contract No. EC-77-C-01-5084

MARTIN MARIETTA AEROSPACE
DENVER DIVISION

PORTLAND CEMENT ASSOCIATION
SKOKIE, ILLINOIS

U. S. DEPARTMENT OF ENERGY

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I. ABSTRACT

In the manufacture of cement, literally trillions of Btu's are rejected to the environment each year. The purpose of this feasibility study program was to determine whether thermal energy storage could be used to conserve or allow alternative uses of this rejected energy. This study identifies and quantifies the sources of rejected energy in the cement manufacturing process, establishes use of this energy, investigates various storage system concepts, and selects energy conservation systems for further study. Thermal performance and economic analyses are performed on candidate storage systems for four typical cement plants representing various methods of manufacturing cement. Through the use of thermal energy storage in conjunction with waste heat electric power generation units, an estimated 2.4×10^{13} Btu/year, or an equivalent of 4.0×10^{6} barrels of oil per year, can be conserved. Attractive rates of return on investment of the proposed systems are an incentive for further development.

II. INTRODUCTION

The cement industry is the most energy-intensive industry in the United States in terms of energy cost as a percentage of total cost of the material according to a report issued by the Cost of Living Council in 1973. Considerably less energy, however, is required to produce cement than competitive building materials (cement requires about 6 million Btu/ton, aluminum requires about 170 million Btu/ton, and steel requires about 19 million Btu/ton). Therefore, as energy shortages in the United States become more acute, the demand for cement will most probably increase over other building materials.

The U.S. cement industry is composed of 52 companies with an annual capacity of about 95 million tons of cement. The manufacturing plants are well dispersed throughout the country and are located near population centers. The cement industry is the sixth largest industrial energy consumer, requiring about 550 trillion Btu annually. Well over 80 percent of this energy is used to heat the kilns, but only 20 to 50 percent of this energy is required to bring about the chemical reaction forming the cement clinker. The remaining 50 to 80 percent of the energy is lost from clinker cooling, in kiln exit gases, and through the kiln walls. Thus, cement is an attractive industry for the application of waste heat recovery and thermal energy storage systems, having a theoretical potential for recovering from 2.4×10^{14} to 4.0×10^{14} Btu annually.

The objective of this research program was to develop an economical and industry-acceptable concept for a system that will recover waste thermal energy from cement production processes, store the energy, and return the recovered energy to the process or to the public domain. The research program was conducted by Martin Marietta Aerospace with the Portland Cement Association providing technical consultation.

The program was divided into seven major tasks which are described as follows:

Task I - Cement Industry Process Study. Define the energy consumption by process, the sources of waste heat and corresponding amount and temperature, the potential for recovery, the in-process uses of stored thermal energy, typical plant equipment layouts, and potential energy savings. Select the most promising energy sources.

Four plants, typical of the various types of plants in this country, were selected for use in the subsequent analyses in this program.

Task II Storage System and Application Selection. Review the various types of thermal storage techniques and identify those most suitable for use in the cement industry. Identify the potential applications of the stored thermal energy and select the most promising. Prepare a process flow diagram for each selected concept and define system conditions at significant points. Based on these diagrams, prepare conceptual designs of the system components (i.e., heat exchangers, pumps, etc) sufficient to perform a preliminary economic evaluation of each concept.

Task III - Storage System Plan and Incorporation Study. Establish interface requirements and operational restrictions for incorporating the selected systems into the model plants selected in Task I. Review plant layouts to determine the optimum location of the storage system. Prepare layout showing equipment and location of interfaces.

Task IV - Industry Survey. Conduct a survey to assess the industry's acceptance of the candidate energy conservation systems.

Task V - Storage System Sizing, Preliminary Design, and Performance Analysis. Select the candidate source/storage system/application from the results of Tasks I and II for further analysis. Prepare flow diagrams of each showing process flowrates, temperatures, and pressures. Perform analyses to describe size and requirements for major items of equipment. For each concept prepare a computer model capable of predicting the transient performance of the system.

Task VI - Preliminary Economic Analysis. Perform an economic analysis of the conceptual designs of Task V to determine the economic feasibility of the systems.

Task VII - Storage System Development Plan. Evaluate the overall economics and technical feasibility of full-scale commercialization of cement plant waste heat usage. Provide a detailed program plan for the required analysis, design, development testing and system demonstration testing of the concept.

Results from this study have shown that approximately 4×10^{13} Btu/year rejected energy can easily be recovered and applied for in-plant use. The major part of the rejected energy is from kiln exit gases, which is a high quality heat source. This energy source, with temperatures ranging from 700°F to 1800°F, depending on process type, can be used for on-site power generation. Five plants in the U.S. are now using this energy source for such purposes.

Thermal energy storage can aid in the production of power when the kiln is shut down for scheduled or unscheduled maintenance. Electricity is required when the kiln is down to support other operations such as raw feed grinding, finish grinding, and other facilities. Thermal storage system sizes were estimated to provide electrical power for a 24-hour duration. Storage systems recommended for further development are rockbed storage units and liquid molten salt systems. A conceptual implementation of a rockbed storage system with a four-stage preheater kiln is s shown in Figure II-1. Through the use of thermal energy storage, returns on investment can be greater over a waste heat recovery system without storage. The waste heat recovery/storage systems proposed in this study can realize up to 50 to 90% return on investment.

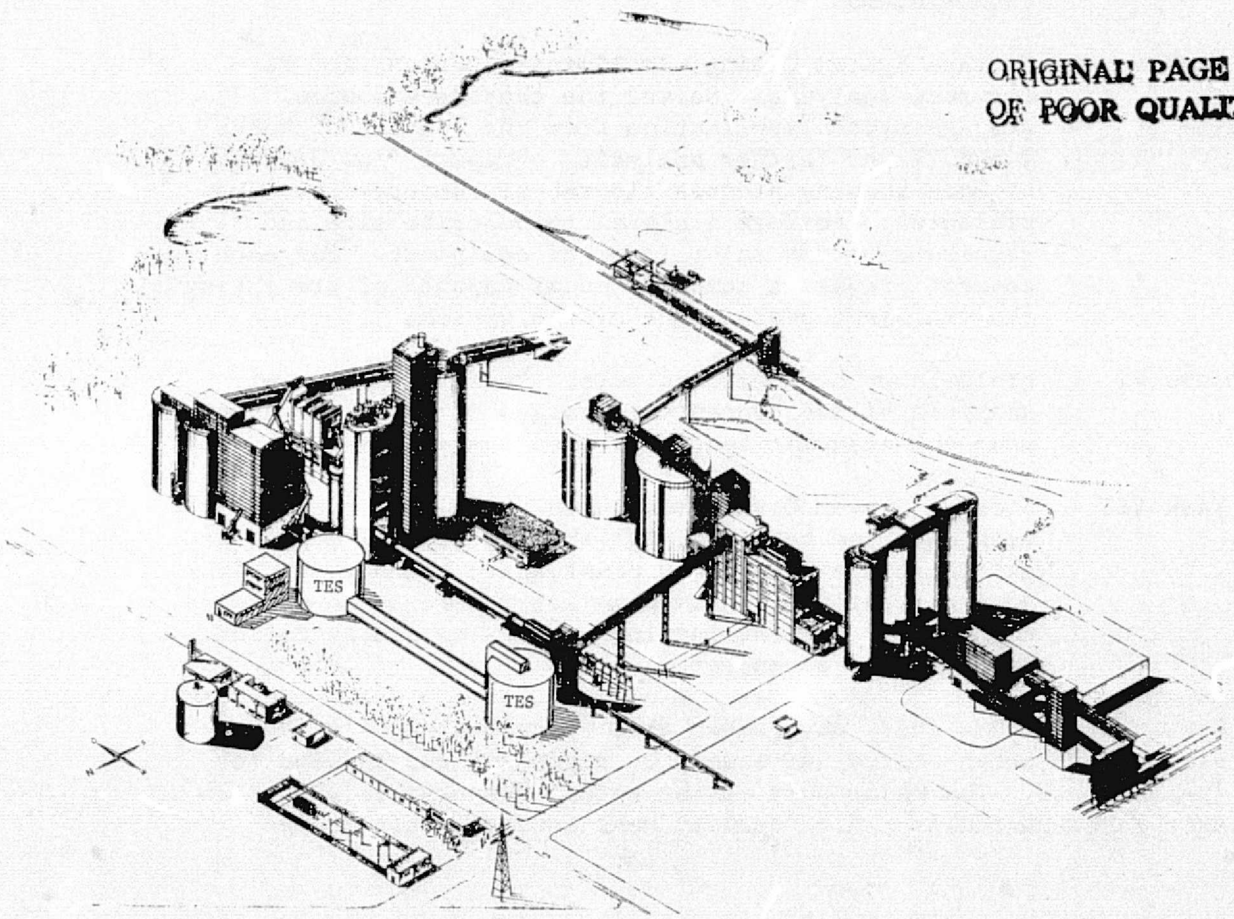


Figure II-1
Rockbed Thermal Energy Storage in Four-Stage Preheater Plan (Conceptual)

III. CEMENT INDUSTRY PROCESS STUDY

The objectives of this task were to define the sources of potentially recoverable thermal energy and the applications for that recovered energy, and to select four representative, existing plants to be used in succeeding tasks.

Before describing the specific results of this task, a description of the basic cement manufacturing process and general background discussion of the industry is provided.

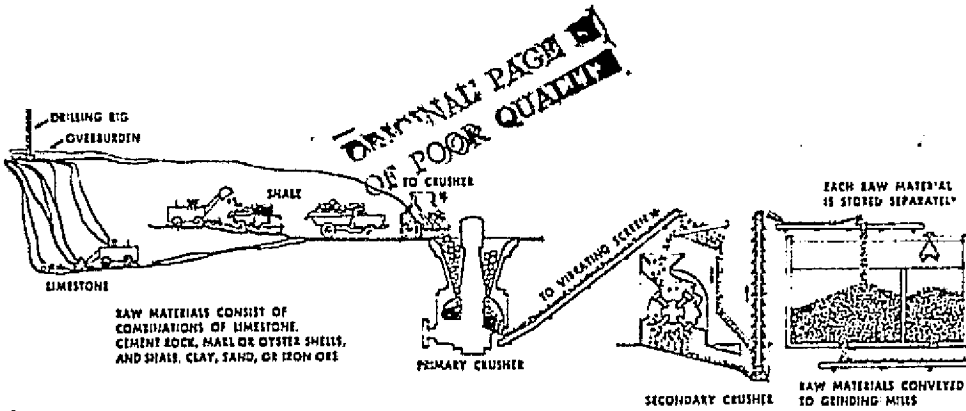
A. PROCESS DESCRIPTION

Two processes are used for manufacturing portland cement--wet and dry--as illustrated in Figure III-1. When rock is the principal raw material, the first step in both processes is primary crushing. Pieces of rock the size of an oil drum are fed through crushers that reduce the rock to about 5-in. size. Secondary crushers or hammer mills then reduce the material to about 3/4-in. size.

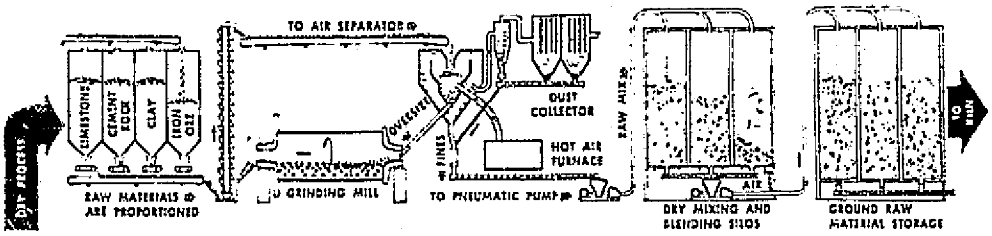
In the wet process, the crushed raw materials, properly proportioned, are ground with water, thoroughly mixed, and fed into the kiln in the form of "slurry." In the dry process, the raw materials are ground, mixed, and fed into the kiln in their dry state. In other respects, the wet and dry processes are essentially alike.

The raw material is heated to about 2700°F in huge cylindrical steel rotary kilns lined with firebrick or special burning zone brick. A modern cement kiln probably is the largest piece of moving equipment used in any industry. Some kilns have a diameter of as much as 25 ft and can be 750 ft long. The kiln axis is slightly inclined, and the raw material is fed into the higher end. At the lower end an intensely hot flame is produced by the precisely controlled burning of coal, oil, or gas under forced draft.

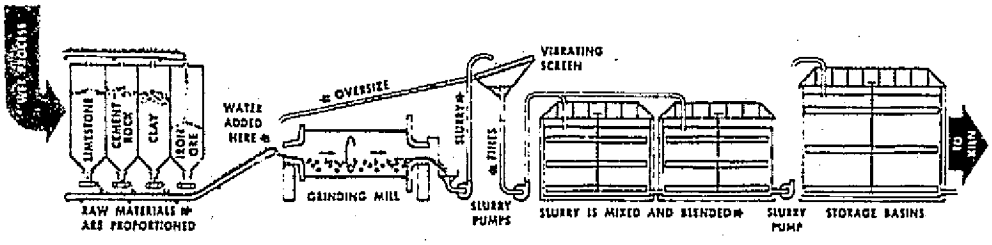
As the raw material moves countercurrent to the flow of hot gases through the kiln, certain elements are driven off in the form of gases. The remaining elements combine to form a substance with raw physical and chemical characteristics. It is called "clinker" and usually takes the form of grayish-black pellets about the size



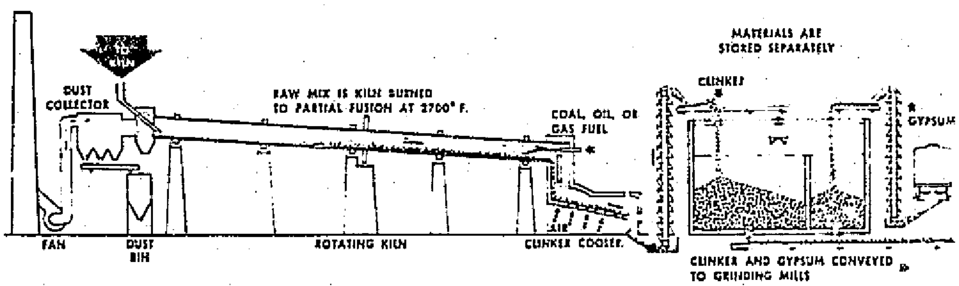
1 Stone is first reduced to 5-in. size, then ¾-in., and stored.



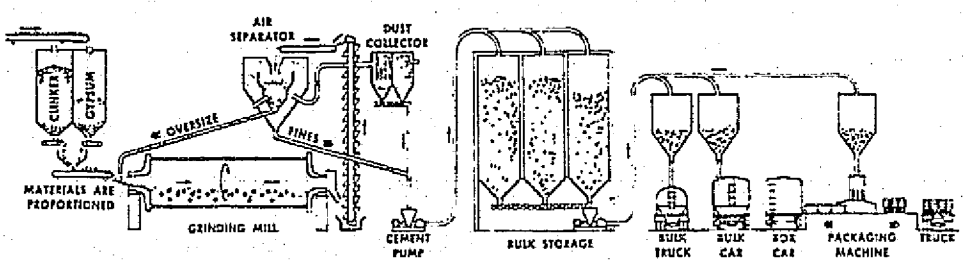
OR 2 Raw materials are ground to powder and blended, or



2 Raw materials are ground, mixed with water to form slurry, and blended.



3 Burning changes raw mix chemically into cement clinker.



4 Clinker with gypsum is ground into portland cement and shipped.

Figure III-1 Steps in the Manufacture of Portland Cement of marbles. The hot clinker discharged from the kiln is cooled to manageable temperatures by one of the various types of coolers, most of the heat from which is returned to the kiln to increase heating efficiency.

The clinker may be stockpiled for future use, or conveyed immediately to a series of grinding mills. Here gypsum is added in the grinding process and the cycle is completed. This final grinding reduces clinker to a fine powder. This extremely fine powder is portland cement.

B. INDUSTRY BACKGROUND

The U.S. cement industry is composed of 52 companies with an annual capacity of about 95 million tons of cement. The names of companies and their annual capacities are listed in Table III-1. Figure III-2 shows the location of the manufacturing plants, which are well dispersed throughout the country, although the mountain region is less widely represented than are other sections. By the very nature of the process and product involved, cement plants are located fairly near population centers.

Cement is produced in kilns of widely varying production capacity. The average kiln produces about 280,000 tons of cement annually, with kilns ranging from 1,200,000 tons down to those producing 65,000 tons annually. Plants produce from 100,000 to 2,500,000 tons of cement annually with an average of about 550,000 tons.

The age and condition of U.S. cement plants are as widely variable as capacity. Of the 385 kilns currently producing portland cement clinker, 65 were put into operation before 1931, and 40 have been installed since 1971.

Table III-1 Cement Company Capacities

Rank	Cement (1000 ton)	Percent Industry	Name
1	6,370	6.7	Ideal
2	5,217	5.5	General
3	5,125	5.4	Martin Marietta
4	4,493	4.7	Lone Star
5	4,268	4.5	Marquette
6	4,084	4.3	Amcord
7	3,856	4.1	Medusa
8	3,806	4.0	Universal Atlas
9	3.743	3.9	Kaiser
10	3.482	3.7	National Gypsum
11	3,030	3.2	California Portland
12	2,955	3.1	Lehigh
13	2,660	2.8	Southwestern
15	2,580	2.7	Citadel
16	2,217	2.3	Penn-Dixie
17	2,180	2.3	Louisville
18	2,150	2.3	Dundee
19	2,140	2.3	Flintkote
20	2,050	2.2	Alpha
21	1,550	1.6	Atlantic
22	1,504	1.6	Texas Industries
23	1,410	1.5	Gifford-Hill
24	1,306	1.4	Ash Grove
25	1,200	1.3	River
26	1,130	1.2	Coplay
27	1,125	1.2	OKC
28	1,120	1.2	Santee
29	1,050	1.1	Northwestern States
30	1,041	1.1	Centex
31	3,000	1.1	Maule
32	942	1.0	Columbia
33	855	0.9	Giant
34	850	0.9	Arkansas Cement
35	840	0.9	Oregon Portland
36	790	0.8	Whitehall
37	750	0.8	Hudson
38	725	0.8	National Cement
39	700	0.7	Monolith
40	660	0.7	Keystone
41	600	0.6	Monarch
42	570	0.6	South Dakota Cement
43	565	0.6	Gulf Coast
44	560	0.6	Fla. Mining/Material
45	495	0.5	Rinker Portland Cement
46	450	0.5	Cyprus Hawaiian Cement
47	400	0.4	Wyandotte
48	390	0.4	San Antonio Port.
49	355	0.4	Capitol Aggregates
50	350	0.4	Utah Portland
51	282	0.3	National Portland
52	270	0.3	Jefferson Marine

Source - Economic Research Department, Portland Cement Association Old Orchard Road, Skokie, Illinois 60076

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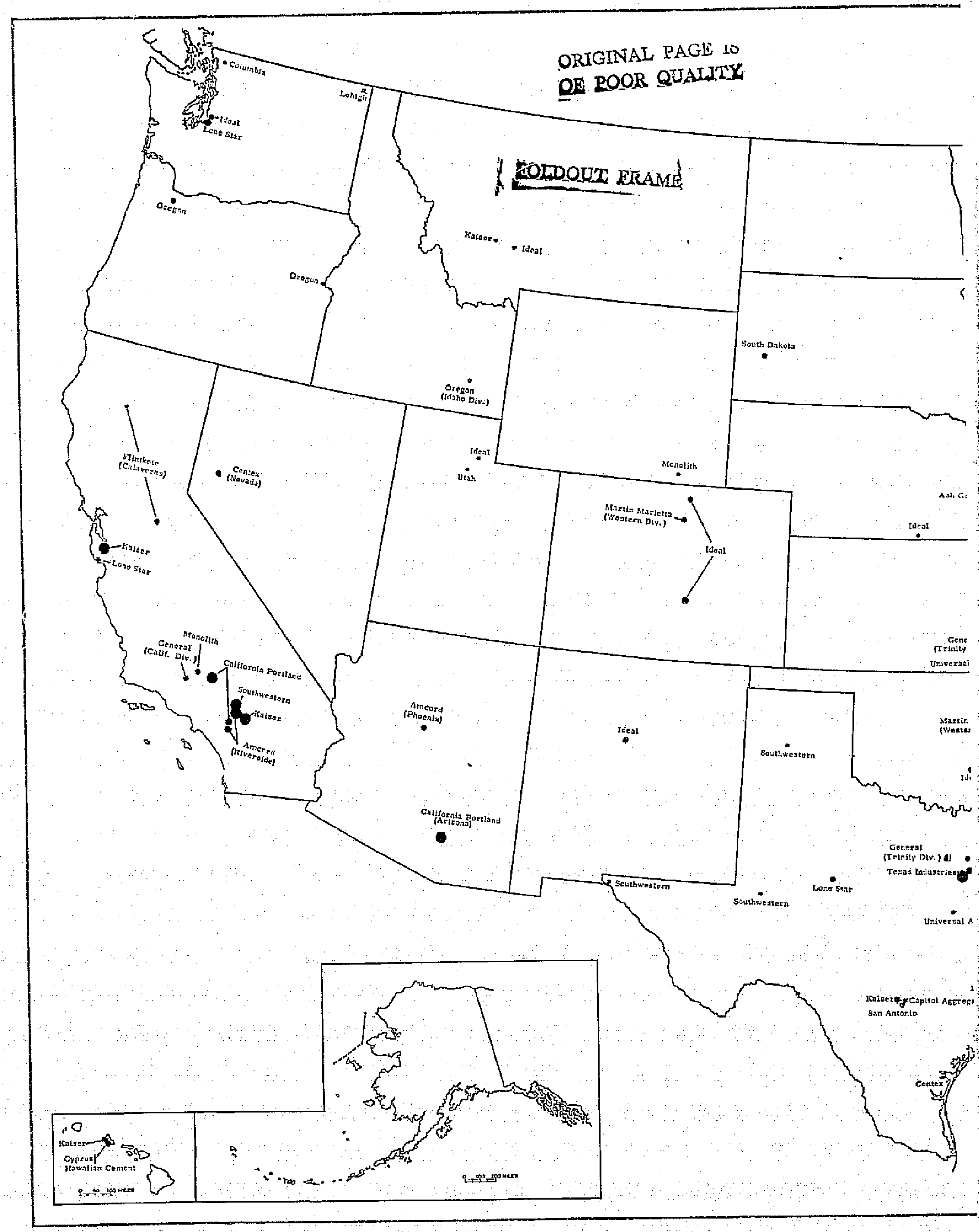
Columbia
Lehigh
Ideal
Lone Star
Oregon
Oregon
Kaiser
Ideal
South Dakota
Oregon
(Idaho Div.)
Ideal
Utah
Monolith
Martin Marietta
(Western Div.)
Ideal
Ideal
Flintkote
(Calaveras)
Centex
(Nevada)
Kaiser
Lone Star
Monolith
General
(Calif. Div.)
California Portland
Southwestern
Kaiser
Amcord
(Riverside)
Amcord
(Phoenix)
Ideal
Southwestern
California Portland
(Arizona)
Southwestern
Southwestern
Lone Star
General
(Trinity Div.)
Texas Industries
Universal
Kaiser
Capitol Aggreg
San Antonio
Centex
Kaiser
Cyprus
Hawaiian Cement

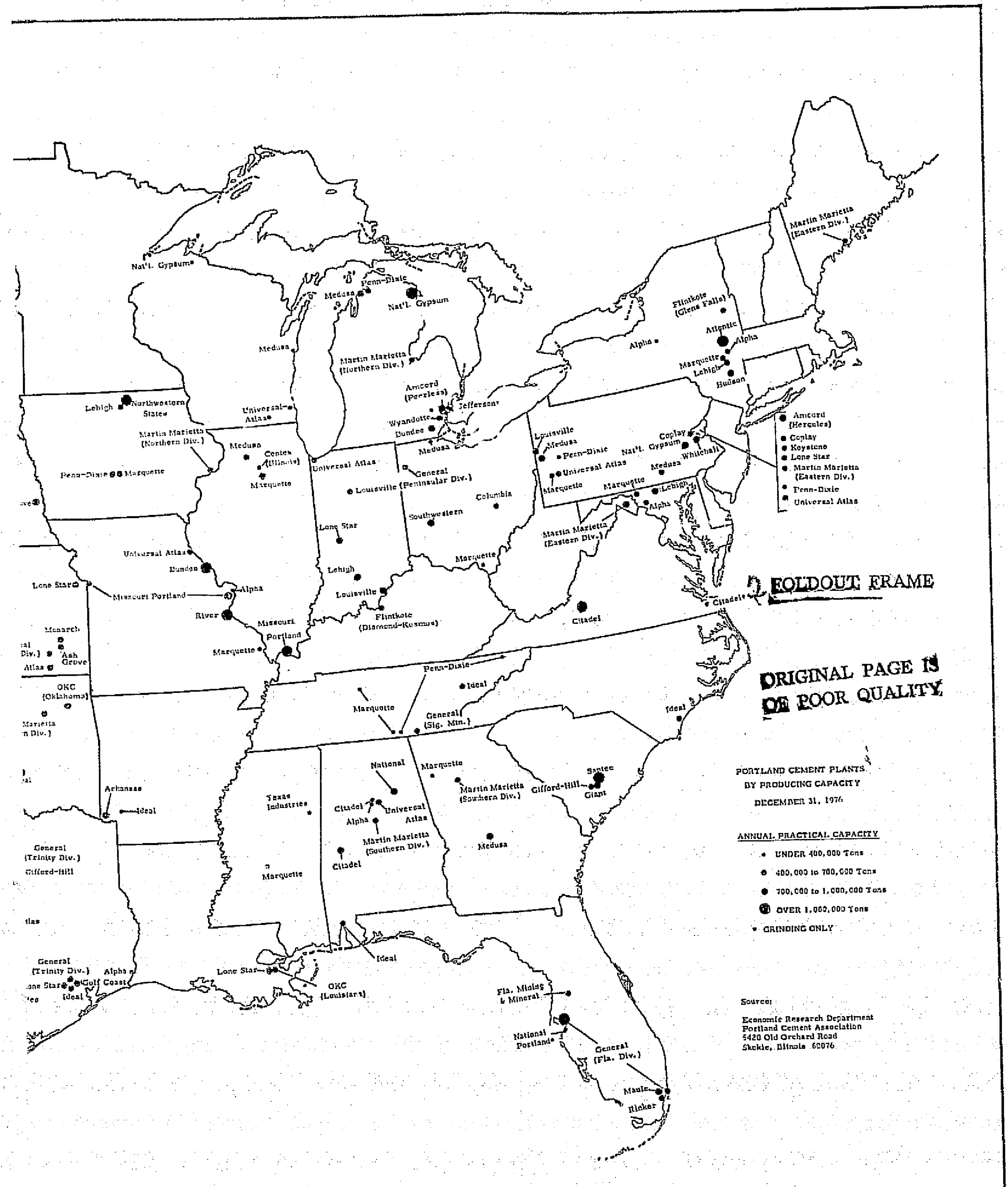

Figure III-2 Cement Plant Locations

C. PRESENT ENERGY CONSUMPTION OF THE U.S. CEMENT INDUSTRY

The most recent figures available from the Portland Cement Association's (PCA) Economic Research Department reveal that energy consumption has decreased since 1972. The data are shown in Table III-2. For dry process kilns only, the kiln consumes an average 4.94 million Btu/ton fuel energy and 29.3 kWh/ton electrical requirements. The overall totals for all plants are 5,760,000 Btu/ton total fuel energy and 148.3 kWh/ton electrical energy. The most recent figures on energy cost reveal that the industry is paying about $1.15-$1.20/million Btu for fuel energy, and about 2.8¢/kWh for electrical energy. The fuel costs range from about $1.00/million Btu for certain coals to slightly more than $2.00/million Btu for imported oil. Electrical power costs were minimum in areas with hydroelectric and nuclear generation, and maximum where imported oil was used.

Table III-2 Present Energy Consumption for All Plants

Department	Energy (Fuel + Electric), Equivalent Btu/ton Clinker: Average	Range
Quarry and Crushing	48,000	0 to 175,000
Drying	231,000	0 to 1,000,000
	239,000 (Dry Process Only)	0 to 1,000,000
Raw Milling	117,000	
Kiln Operations	5,779,000	
	5,680,000 (Fuel Only)	3,000,000 to 10,100,000
Finish Grinding	200,300	
Total Grinding*	307,400	150,000 to 525,000

*Most recent data not as yet apportioned into raw and finish grinding.

1. Present Fuel Consumption & Forecast for 1983

At present, the fossil fuel consumption of the industry is as follows:

Coal + coke – 62% of total Btu

Natural gas – 25%

Oil – 13%

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By 1933, it is estimated that more than 80% of the production will be manufactured using coal.

2. Process Trends

As of 1976, the industry produced about 54.9% of cement with the wet process and 45.1% by the dry process. Table III-3 shows the projected additions and closings for the next few years. At the end of five years, it is projected that the industry will be producing over 50% of the product using dry process systems. Most of the new dry process capacity will be preheater and precalciner systems, and will replace primarily wet process systems. The longer range trend will be more strongly to dry process installations, with most of the less efficient dry process installations employing some form of waste heat utilization.

D. RATIONALE FOR PLANT SELECTION

The four plant models selected for waste heat recovery represent the process types most amenable to energy recovery and those will predominate in the future for the U.S. cement industry. They include a long-dry-process kiln with chains, a one-stage suspension preheater kiln with chains, a four-stage suspension preheater kiln, and a long dry kiln with waste heat boiler. Suspension preheater kilns will be used in many plants where capital is available to change, because the heat exchange of kiln exit gases with incoming raw materials is very efficient, and energy requirements for pyroprocessing are minimized. However, because the ASTM specifications provide for an optional limit on alkali content (0.6% as Na_2O), and the suspension preheater system entraps alkalies in the kiln system more efficiently than do other systems, many plants may be unable to convert to this system. Another constraint to the wholesale adoption of preheater technology is the incidence of plugging and buildups in the preheater system arising when alkali, sulfur, and chlorine compounds condense during heat exchange. For these reasons, it was decided to include the single-stage preheater system, which is gaining popularity for applications in which a minor degree of these alkali or sulfur problems exist, and the long dry kiln, which will continue to be popular in plants that have major problems in these areas.

Although the wet process will continue to be used in many plants for the foreseeable future, because of material constraints or because capital may not be available for conversion, the low gas temperatures and high moisture contents characteristic of exit gases from wet kilns make them much less attractive for heat recovery. Similarly, although a few grate preheater kilns are in

Table III-3 Announced Cement/Clinker Capacity Changes as of Sept 19, 1977

Plant name	Location	Process	Tons (1,000) From	To		
	1977					
New						
No activity for period shown						
Expansions						
Ideal	Tijeras, N.M.	Dry	420	500	+	80
Louisville Cement	Speed, Ind.	Dry	880	1040	+	160
South Dakota	Rapid City, S.D.	Dry	570	1140	+	570
Closing/Reduction						
General	Houston, Texas	Wet	245	0	-	245
Total 1977					+	565
	1978					
New						
Centex	Buda, Texas	Dry		470	+	470
Expansions						
Coplay	Nazareth, Pa.	Dry	580	1025	+	445
Lehigh	Mason City, Iowa	Dry	605	750	+	145
Closing/Reduction						
No activity for period shown						
Total 1978					+	1060
	1979					
New						
Oregon Portland	Durkee, Oregon	Dry		500	+	500
Expansions						
Ideal	Boettcher, Colo.	Dry	410	460	+	50
Ideal	Knoxville, Tenn.	Dry	470	583	+	113
Lone Star	Davenport, Calif.	Dry	395	725	+	330
Closing/Reduction						
Oregon Portland	Huntington, Oregon	Wet	200	0	-	200
Total 1979					+	793
	1980					
New						
No activity for period shown						
Expansions						
Kaiser	Permanente, Calif.	Dry	1600	1600		--
Marquette	Cape Girardeau, Mo.	Dry	335	1000	+	665
Closing/Reduction						
Marquette	Nashville, Tenn.	Wet	235	0	-	235
Marquette	Cowan, Tenn.	Wet	233	0	-	233
Marquette	Rockmart, Ga.	Dry	255	0	-	255
Marquette	Superior, Ohio	Dry	285	0	-	285
Total 1980					-	343
	1981					
New						
Ideal	Theodore, Ala.	Dry		1500	+	1500
Expansions						
No activity for period shown						
Closing/Reduction						
No activity for period shown						
Total 1981					+	1500
Subtotal of changes with date given					+	3575
	No Date Given					
New						
No activity for period shown						
Expansions						
Maule Industries	Hialeah, Fla.	Wet	1000	2068	+	1068
OKC	Florida	Dry		585	+	585
Southwestern	Odessa, Texas	Dry	?			
Closing/Reduction						
No activity for period shown						
Subtotal of changes with no date given					+	1653
GRAND TOTAL					+	5228

operation, their exit gas temperatures are extremely low (250 to 300°F), and it is doubtful that any economical heat recovery could be accomplished. Also, the number of grate preheater plants is not likely to increase substantially, since successful operation of these systems requires appropriate raw materials not generally available. The clinker cooler exhaust and kiln shell provide potential for heat recovery in these plants as well. However, in the case of wet process plants, the secondary air requirement is so high that the cooler exhaust is not at temperatures sufficient to make recovery attractive (often less than 200°F).

It will be noted that all four model plant systems are equipped with grate-type clinker coolers. This type of cooler is predominant in the U.S.; only a few planetary coolers and rotary coolers are used--chiefly in older plants. In addition, none of these latter cooler types has exhaust air, so no heat recovery potential exists from the cooler.

E. WASTE HEAT SOURCES IN THE SELECTED PLANTS

To assess the various waste heat sources in the selected plants, energy and material balances were necessary. This section describes the calculations and lists the characteristics for each of the model plants.

The four plants chosen all had different kiln and heat recuperation systems:

1) Plant 1: Long, dry-process kiln (with chains) with grate cooler. Kiln exit gases cooled by water spray before entering precipitator.

2) Plant 2: Intermediate length dry-process kiln (with chains), plus a one-stage cyclone preheater (two cyclones in parallel), and grate cooler.

3) Plant 3: Short kiln with four-stage suspension preheater and grate cooler.

4) Plant 4: Long, dry-process kiln with grate clinker cooler. Waste heat boiler system is used for on-site power generation.

The following discussion provides specific data on each of the selected model plants. Production rates, fuel usage, and process flowrates represent average operation of the plant based on the plant's experience and history.

1. Plant 1: Long, Dry-Process Kiln with Chains

a. *Data Provided by the Plant*

Kiln Dimension - The kiln is 520 ft long with a discharge end diameter of 15 ft, and a feed end diameter of 17 ft. The diameter is constant up to 415 ft from the discharge end, then widens to 17 ft over a 15-ft-long tapered section, then remains constant again to the feed end.

Clinker Production Rate - Typically 67 tons/hr, which indicates a raw feed rate of 104 tons/hr, disregarding kiln dust.

Fuel Usage - About 12 tons/hr.

Waste Air from Clinker Cooler - This is estimated to be 89,000 acfm at 350°F, and is presently being vented to the atmosphere.

Kiln Exit Gas - The gas contains about 1.6% by volume O_2 measured on a dry basis. The volume of gas was not given, but the gas is cooled to 780°F by a water spray of 45-55 gal/min into the back end of the kiln.

b. Energy and Material Balance - Using the data provided by the plant, the following heat and material flows were calculated.

Heat Input - All four plants use coal as the kiln fuel. Since no detailed data were available on the composition of the coal used, a "typical" bituminous coal was used in all the calculations. The dry coal composition was as follows:

Carbon	(C) = 62.3% by weight
Hydrogen	(H) = 6.0% by weight
Oxygen	(O) = 18.4 % by weight
Sulfur	(S) = 3.3% by weight
Inert constituents (ash)	= 10.0% by weight.

The gross calorific value of this coal is 11,500 Btu/lb (23 MBtu/ton).

For complete combustion, it can be calculated that 1 lb of this coal requires 8.57 lb of air (106.2 cu ft at 32°F), and gives the following composition of combusted gases:

Component in Combustion Gas	Coal, cu ft/lb (at 32°F)	Coal, lb/lb
CO_2	18.61	2.283
SO_2*	0.37	0.065
H_2O (as vapor)	10.80	0.539
N_2	83.95	6.583
Total	113.73	9.470

*SO_2 in the kiln exhaust gas will probably be considerably lower than expected due to reaction with the kiln feed, and so can be ignored.

The heat input for this kiln is Q = 23 MBtu/ton x 12 ton/hr = 276 MBtu/hr.

Kiln Shell Losses - Kiln shell heat losses were estimated from the kiln shell temperatures using the relationship given in Fig. 64 of *Modern Refractory Practice* (published by Harbison-Walker Refractories Co., 1961). This relationship is for combined radiative and convective heat losses from a vertical wall to still air at 70°F, and hence is an approximation in the case of a rotating metal-shelled kiln. Accurate calculations of shell heat losses were not warranted during this phase of the project. The shell losses are 25.6 MBtu/hr or 0.38 MBtu/ton.

Clinker Cooler Waste Gas - The amount of heat in the clinker cooler gas is simply the product of the mass flow, specific heat, and temperature difference.

$$Q = \dot{\omega}\ C_p \Delta T$$

The clinker cooler gas is air and the reference temperature used in the calculations was 32°F.

Therefore:

$$Q = 89{,}000\ ft^3/min \times 0.049\ lb/ft^3 \times 0.241\ Btu/lb°F \times (350-32)°F$$

$$= 334{,}218\ Btu/min$$

Kiln Exit Gas - To determine the composition of the kiln exit gas, it was assumed that for every 1 ton of clinker produced, 1.55 tons of dry raw feed are required, consisting of 1.16 tons of $CaCO_3$ and 0.39 tons of clay. This raw feed will give rise to 0.51 tons of CO_2 and 0.04 tons of H_2O in the kiln exit gases. Combining this with the combustion gas composition calculated previously, the kiln gas composition is as follows:

Gas Reaching Spray Zone	scfm	% by Volume	lb/min	% by Weight	Heat Content, Btu/min
N_2	36,860	60.9	2890	54.3	836,500
O_2	870	1.4	78	1.5	20,800
CO_2	16,730	27.6	2052	38.5	562,200
H_2O	6,110	10.1	305	5.7	166,800
Total	60,570	100.0	5325	100.0	1,586,300
Heat of condensation of water					324,500
Gross heat content of exit gas					1,900,800

In calculating the total heat content of wet exit gases, the heat content of water was estimated as a vapor between 32°F and the temperature of the gas concerned, and then 1064 Btu/lb was added for the latent heat of vaporization of water.

An unknown amount of heat will be lost as kiln dust, which may in part account for the discrepancy in the heat balance for the kiln and clinker cooler (Table III-4).

Table III-4 Energy and Materials Balance for Plant 1

Inputs/Outputs	lb/min	Gross MBtu/ min	Tons/ ton Clinker	Gross MBtu/ ton Clinker	Temp,* °F
Raw Feed	3460	--	1.55	--	A
Coal	400	4.60	0.18	4.12	A
Combustion Air	3753	--	1.68	--	U
Water Spray	420	--	0.19	--	A
Total Heat Input		4.60		4.12	
Outputs					
Clinker Sensible Heat	2233	0.06 - 0.11	1	0.05 - 0.10	150 250
Kiln Shell Heat Loss	--	0.43	--	0.38	650
Clinker Cooler Excess Air	4363	0.34	1.95	0.30	350
Radiation	--	0.01 - 0.02	--	0.01 - 0.02	U
Kiln Exit Gas	5325	1.90	2.38	1.70	1150
Theoretical Heat of Reaction	--	1.68	--	1.50	--
Total Heat Output		4.42-4.148		3.94-4.00	

*A = Ambient Temperature, U = Unknown

2. Plant 2: Intermediate, Dry-Process Kiln, with Single-Stage Cyclone Preheater

a. Data Provided by the Plant

Kiln Dimensions - The kiln is 360 ft long, with a discharge end diameter of 11.5 ft, and a feed end diameter of 13 ft. An F. L. Smidth single-stage cyclone preheater unit consists of two cyclones in parallel.

Kiln Shell Temperature Profile

Distance from Discharge End of Kiln, ft	Kiln Shell Temp, °F	Distance from Discharge End of Kiln, ft	Kiln Shell Temp, °F
0	est. 500-600	200	220
30	700	225	300
75	600	250	420
100	520	275	460
125	340	300	420
150	210	325	380
175	220	360	330

Note: There is a second shell temperature maximum at about 275 ft, which is presumably due to the chain section.

Clinker Production Rate - Typical, 30 tons/hr, i.e., raw feed rate is about 46.5 tons/hr.

Fuel Usage - This was estimated to be 4 MBtu/ton clinker, which is about 120 MBtu/hr, or 5 tons of coal/hr.

Waste Air from Clinker Cooler - Under ideal operating conditions this should amount to about 55,000 acfm at 350°F. However, under actual conditions, it may often reach as much as 75,000 acfm at 450°F.

Kiln (Preheater) Exit Gas - Gas enters the preheater at about 1200°F, and leaves it at about 720°F, with a typical flow of 90,580 acfm.

b. Heat and Materials Flows Calculated from these Data

Kiln Shell Heat Losses - By assuming the kiln shell to be at 600°F for the first 100 ft and 300°F for the remaining 260 ft, shell heat is estimated to be 14.7 MBtu/hr or 0.50 MBtu/ton clinker.

Clinker Cooler Waste Gas - Under typical conditions, this loss will be 75,000 acfm of air at 450°F containing 19.82 MBtu/hr, or 0.66 MBtu/ton clinker.

Preheater Exit Gas - The gases leaving the preheater amount to about 90,580 acfm at 720°F. Assuming that the kiln uses 174 lb of coal per minute, and that any excess gas volume is due to air in-leakage, the following composition is obtained for the preheater exit gas at 720°F:

Gas Leaving Preheater	scfm	% by Volume	lb/min	% by Weight	Heat Content, Btu/min
N_2	24,900	66.1	1954	60.5	340,000
O_2	2,700	7.2	241	7.4	38,100
CO_2	7,400	19.6	907	28.0	144,200
H_2O	2,700	7.1	134	4.1	44,100
Total	37,700	100.0	3236	100.0	566,400
Heat of Condensation of Water Vapor at 32°F					142,600
Gross Heat Content of Exit Gas					709,000

The oxygen content of the preheater exit gas is very high in this system, due to in-leakage of air at that point (before the electrostatic precipitators). Any reduction of air in-leakage would serve to increase the temperature of the preheater exit gas over 720°F.

The overall heat and materials balance for this kiln system is given in Table III-5. Estimates of heat losses from the clinker cooler as sensible heat in the clinker, have been included. A small amount of heat may also be lost in the dust, and as radiation from the preheater cyclones, but this has not been estimated.

3. <u>Plant 3: Short Kiln with Four-Stage Suspension-Preheater and Bypass</u>

a. Data Provided by Plant

Kiln Dimensions - The kiln is 15 ft in diameter by 220 ft long. The suspension preheater consists of three pairs of cyclones for the first three stages, feeding into a single fourth stage. The total surface area of the preheater system is about 9300 sq ft.

Kiln Shell Temperatures - The kiln itself has a shell temperature ranging from about 500°F at either end to about 600°F in the center, and averaging about 550°F. The preheater cyclone shell temperatures range from 470 to 160°F and average a surface temperature of about 250°F.

Table III-5 Heat and Materials Balance for Plant 2

Inputs/Outputs	lb/min	Gross MBtu/ min	Tons/ ton Clinker	Gross MBtu/ ton Clinker	Temp, * °F
Raw Feed	1550	--	1.55	--	A
Coal	174	2.0	0.174	4.0	A
Combustion Air	2537	--	2.54	--	U
Total Heat Input		2.0		4.0	
Outputs					
Clinker Sensible Heat	1000	0.02	1	0.04	200
Kiln Shell Heat Loss	--	0.25	--	0.50	200 700
Clinker Cooler Excess Air	3270	0.33	3.27	0.66	450
Preheater Exit Gas	3263	0.71	3.26	1.42	720
Theoretical Heat of Reaction	--	0.75	--	1.50	--
Total Heat Losses		2.06		4.12	

*A = Ambient Temperature, U = Unknown

Clinker Production Rate - This typically ranges from 83 to 96 tons/hr. The higher figure has been used throughout the heat balance calculations given here. The rate of dust loss from the preheater system is given as 13 tons/hr and from the bypass as about 4 tons/hr, so that raw feed rate is about 176 tons/hr at the maximum production rate.

Fuel Usage - The net energy requirement is 3.288 MBtu/ton of clinker, which is equivalent to about 3.44 MBtu/ton gross, or 0.15 tons of coal/ton clinker.

Waste Air from the Clinker Cooler - At 96 tons/hr production, the waste air is 237,000 acfm at 350°F.

Exit Gas from Preheater and Bypass - For a production rate of 96 tons/hr, the preheater exit gas flow is 204,500 acfm at 800°F. The composition of this gas is 1.9% O_2, 61.0% N_2, 30.9% CO_2, 6.2% H_2O, and it contains 13 tons/hr of dust.

The bypass gas leaves the kiln at 1500°F and amounts to 0.974 lb of gas per lb of clinker. Its composition is 1.79% O_2, 65.63% N_2, 26.48% CO_2 and 6.04% H_2O, and it contains 0.0415 lb of dust per lb of clinker. This gas is cooled to 1000°F by the addition of air (0.0772 lb air per lb of clinker).

b. Heat and Materials Flows Calculated from These Data

Preheater Exit Gas - The composition in terms of heat, weight, and volume is as follows:

Gas	scfm	% by Volume	lb/min	% by Weight	Heat Content, Btu/min
N_2	45,052	61.0	3513	52.7	681,500
O_2	1,403	1.9	125	1.9	22,250
CO_2	22,821	30.9	2797	42.0	500,650
H_2O	4,579	6.2	230	3.5	84,650
Total	73,855	100.0	6665	100.0	1,289,050
Heat of Condensation of Water at 32°F =					244,700
Gross Heat Content of Gases =					1,533,750
Plus 433 lb/min as dust, heat content =					78,000
Total, Including Dust =					1,611,750

Preheater Bypass Gas - At a production rate of 96 tons/hr the flowrate of bypass gas is 311.1 lb/min or 3524 scfm. Its composition in terms of heat, weight, and volume is as follows:

Gas	scfm	% by Volume	lb/min	% by Weight	Heat Content, Btu/min
N_2	2314	65.7	180.4	58.0	68,550
O_2	63	1.8	5.6	1.8	2,010
CO_2	934	26.5	114.4	36.8	42,560
H_2O	213	6.0	10.7	3.4	7,890
Total	3524	100.0	311.1	100.0	121,010
Heat of Condensation of Water at 32°F =					11,380
Gross Heat Content of Gases =					132,390
Heat Content of 133 lb/min Dust =					48,000
Total Including Dust =					180,390

The overall heat and materials balance for this system is given in Table III-6. The correlation between heat input and output is excellent, although the values for clinker sensible heat and radiated heat from the cooler are estimates based on experience.

Table III-6 Heat and Materials Balance for Plant 3

Inputs/Outputs	lb/min	Gross MBtu/ min	Tons/ ton Clinker	Gross MBtu/ ton Clinker	Temp,* °F
Inputs					
Raw Feed (including Dust Loss)	5,567	--	1.74	--	A
Coal	480	5.49	0.15	3.44	A
Combustion Air	4,800	--	1.50	--	U
Total Heat Input		5.49		3.44	
Outputs					
Clinker Sensible Heat	3,194	0.10	1	0.06	200
Kiln Shell Heat Loss	--	0.30	--	0.19	400 - 500
Preheater Shell Heat Loss	--	0.07	--	0.04	160 - 470
Clinker Cooler Excess Air	10,750	0.83	3.37	0.52	350
Radiated Heat	--	0.03	--	0.02	U
Bypass Gas	311	0.13	0.10	0.08	1500
Bypass Dust	133	0.05	0.04	0.03	1500
Preheater Exit Gas	6,665	1.53	2.09	0.96	800
Theoretical Heat of Reaction	--	2.40	--	1.50	--
Total Heat Losses		5.52		3.45	

*A = Ambient Temperature

U = Unknown

4. Plant 4: Long, Dry Kiln with Waste Heat Boiler

a. Kiln Production Rate - Each kiln produces 70 tons/hr of clinker. The raw feed contains 20% of a kerogenous shale, which has a calorific value of 1,350 Btu/lb. About 1.75 tons of raw mix are required per ton of clinker.

b. Kiln Fuel Usage - Each kiln uses about 13 tons of 12,300 Btu/lb coal per hour. This represents a gross heat input of 4.57 MBtu/ton of clinker. A further 0.95 MBtu/ton of clinker is released by the kerogenous shale in the raw feed, so the total heat input is about 5.52 MBtu/ton (gross).

c. Kiln Exit Gases - The kiln exit gases contain 0.20 to 0.75% oxygen. However, a large in-leakage of air occurs around the kiln seals before this exit gas enters the boilers. The composition of the kiln exit gas, which would be expected for combustion with no excess oxygen, given the actual coal and shale composition used at the plant, is about 1.740 lb N_2, 1.110 lb CO_2, and 0.106 lb H_2O for every lb of clinker produced. Evidence from the plant suggests that about a further 30% air infiltration occurs between the kiln exit and the boiler entrance (the gases entering the boiler are at 1500°F, which implies that the kiln exit gases are actually about 1850°F). Assuming a 30% infiltration by weight, and including the 0.135 lb dust/lb clinker which is typically present in the kiln exit gases, the composition and heat content of the gases entering the boiler are listed in Table III-7.

Table III-7 Plant 4 Energy and Material Balances

Gas	lb/lb Clinker	Flow Rates, lb/min	Gas Flow, scfm x 10^3	Net Heat in MBtu/min at: 1,500°F	425°F
N_2	2.305	5378	68.6	2.044	0.530
O_2	0.169	394	4.4	0.141	0.034
CO_2	1.110	2590	21.1	0.963	0.221
H_2O	0.106	247	4.9	0.182	0.046
Total Gas	3.690	8609	99.0	3.330	0.831
Dust	0.135	315	--	0.120	0.030
Total Gas and Dust	3.825	8924	---	3.450	0.861
Latent Heat of Steam				0.194	0.194
Total Gross Heat Content of Gases				3.644	1.055

d. Operating Conditions of the Boilers - The kiln exit gases plus infiltrated air enter the boilers at 1500°F and leave at 550°F. The gases are further cooled to about 425°F in the economizer; temperatures are not reduced much below 425°F because of the high SO_x content of the waste gases. Temperatures much below 425°F approach the dew point of condensible gas species such as sulfuric acid.

As can be seen from Table III-7, the gas flow through each boiler is estimated to be 99,000 scfm, i.e., 394,000 acfm at 1500°F. The net heat input to the boiler, including the sensible heat of the kiln dust, is 2.589 MBtu/min, or 2.219 MBtu/ton of clinker.

Each boiler produces an average of 139,500 lb/hr of steam at 225 psig and 525°F. The boiler feed water returns at about 218°F and 350 psig. The heat taken up by the steam is 1,092 Btu/lb, or 152.3 MBtu/hr or 2.176 MBtu/ton clinker.

e. Steam to Electricity Conversion Efficiency - Steam from all the boilers at this plant passes into the five turbines, which have conversion efficiencies in the range of 12.5 lb steam/kWh to 17.5 lb/kWh, with an average of about 14.6 lb/kWh. With this average figure, each of the boilers considered above produces 9555 kW of electricity, which is equivalent to 32.6 MBtu/hr or 0.466 MBtu/ton clinker. The conversion efficiency is about 21.4% relative to the steam generated, due to the low temperature and pressure at which the generating system operates.

To summarize, the heat flows are as follows:

Heat Inputs to Kiln	Gross MBtu per Ton of Clinker
Kiln Fuel (coal)	4.57
Kerogenous Shale in Raw Feed	0.95
Total	5.52
Heat Losses from Kiln	
Kiln Exit Gases at 1500°F	3.12
Approximate Theoretical Heat of Reaction	1.50
Balance = Heat Losses through Kiln Shell, and from Clinker Cooler	0.90
Total	5.52
Heat Inputs to Electricity Generation System	
Kiln Exit Gases at 1500°F	3.12
Heat Outputs from Generating System	
Kiln Exit Gases at 425°F	0.90
136.5 kWh electricity Generated/ton Clinker	0.47
Waste Heat from Generating System (balance)	1.75
Total	3.12

f. Heat Balance for the Clinker Cooler - Assuming that the clinker leaves the kiln at about 2250°F, and leaves the clinker cooler at about 200°F, it rejects about 1.04 MBtu/ton of its heat in the cooler. According to plant data, 80% of kiln combustion air is secondary air coming from the hot end of the cooler at 900°F, and 20%, as primary air, comes from the cold end of the cooler at 200°F, making a total of about 2.30 lb of combustion air/lb clinker. Thus, the heat reclaimed in the combustion air is approximately 410 Btu/lb clinker or 0.82 MBtu/ton. The remaining 0.22 MBtu/ton will mainly be taken up by the excess air. If this waste air is rejected at 350°F or more, then it will amount to approximately 2860 lb waste air/ton of clinker. The overall heat balance for the kiln is shown in Table III-8.

Table III-8 Overall Energy Balance for Plant 4

Inputs/Outputs	lb/min	Gross MBtu/ min	Tons/ ton Clinker	Gross MBtu/ ton Clinker	Temp,* °F
Inputs					
Raw Feed	4080	1.10	1.74	0.95	A
Coal	433	5.33	0.186	4.57	A
Combustion Air	5370	--	2.30	--	200 - 900
Air In-Leakage	1374	--	0.59	--	A
Total Heat Input	--	6.43	--	5.52	--
Outputs					
Clinker (Sensible Heat)	2333	0.07	1	0.06	200
Clinker Cooler Excess Air	2860	0.26	1.23	0.22	350
Kiln Exit Gases Plus Dust & Infiltrated Air	8924	3.64	3.83	3.12	1500
Kiln Shell† Heat Loss	--	0.71	--	0.62	--
Theoretical Heat of Reaction	--	1.75	--	1.50	--
Total Heat Output	--	6.43	--	5.52	--

*A = Ambient Temperature

†Obtained by Difference.

F. THE POTENTIAL FOR RECOVERY OF WASTE HEAT

The significant sources of waste heat for the model cement plants are summarized in Table III-9. Although all three sources appear to offer considerable quantities of waste heat per unit of clinker produced, suitable for recovery and storage, the problems of realizing this heat are different in each case.

Table III-9 Summary of Possible Heat Sources

Source	Description	Kiln System No.*	Maximum Temp of Source, °F	Net Heat Available: MBtu/ton of Clinker	Net Heat Available: Btu per Actual ft^3 of Gas at Maximum Temperature
Kiln Shell	Radiative and Convective Heat Losses	1	650	0.38	—
		2	700	0.50	—
		3	600	0.19†	—
		4	700	0.62	—
Clinker Cooler	Waste Air	1	350	0.30	3.78
		2	450	0.66	4.40
		3	350	0.52	3.49
		4	350	0.22	4.45
Kiln System Exit Gas	Exhaust Gas from the Kiln or Preheater, Considered Before Entering the Precipitator	1	1150	1.41	7.95
		2	720	1.13	6.25
		3	800	0.81	6.30
		4	1500	2.96	8.45

*Numbers 1-4 refer to model plants 1-4 as discussed previously.
†A further 0.05 MBtu/ton is lost from the suspension preheater.

1. Kiln Shell Heat Losses

Heat Lost through the kiln shell is "clean" in the sense that it has no corrosive or abrasive properties. The proportion of the heat that is radiated depends to some extent on the temperature of the shell; at about 600°F probably over 65% of the heat is radiated, whereas a smaller fraction is radiated at lower temperatures.

The majority of the remainder of the heat is removed by convection. If this heat is to be collected as effectively as possible, it would be best to collect it at the shell, e.g., by a water cooling jacket or similar device. However, this will appreciably increase the rate of conduction through the kiln shell, if it lowers the shell temperature to below its normal equilibrium value. This in turn will alter the heat balance within the kiln slightly. Any form of cooling jacket will also increase the weight loading and possibly increase stresses in the kiln shell and refractory lining, and may alter the power requirements for the kiln-drive motors.

As an alternative, it would be possible to collect the kiln shell heat at a distance, e.g., by radiative transfer to a heat collector around the shell, or by using a manifold with a suction fan to collect hot air from around the shell. In this case, the effect on kiln temperature would probably be much less, but the heat which could be recovered would also be limited, and would depend on the area of the collector. The kiln shell heat emission is most intense in the burning zone. The first 100 ft of the kiln usually has an average temperature of 600°F, and would have a radiative heat transfer coefficient of 1600 Btu/hr/sq ft to a background at 70°f; whereas the rest of the kiln shell typically averages about 300°F, which only radiates about 350 Btu/sq ft/hr. Therefore, any attempt to collect radiative heat from the shell should concentrate on the hot zone. Furthermore, it is important that any heat collection device must not interfere with normal access to the kiln shell for maintenance and inspection.

2. Waste Air from the Clinker Cooler

The amount of hot waste air from the clinker cooler varies appreciably from plant to plant, and also from time to time depending on the operating conditions at any one plant. The more efficient the kiln system is, the larger will be the amount of waste cooler air, since less of it will be required as secondary air in the kiln itself. However, at some plants this air is already used to dry the raw feed or fuel, or to reduce oil viscosity. The air is ideally suited for these purposes since it contains virtually no alkalies, SO_2, or water vapor. Nevertheless, at most plants this waste air is still vented to the atmosphere, after removal of the abrasive clinker dust. The temperature of clinker cooler exhaust air is in the range of 350 to 450°F for the dry plants studied here. At wet process plants, there is much less waste air (and it is at a lower temperature), due to the higher secondary air requirements of the kiln.

In a dry process plant, cooler excess air represents a good source of waste heat at intermediate temperatures. It is not corrosive, but it does contain some clinker dust which is highly abrasive. Use of this heat source should have no harmful side effects on the cement manufacturing process at most plants. The energy density of the clinker cooler waste heat in the gas ranges from 3.5 to 4.4 Btu/acf in the three plants, and as such represents a considerably lower energy density than that of the kiln exit gases.

3. Exit Gases

In almost all kiln systems, the exit gases still represent the greatest heat loss. However, in wet process kilns these gases contain a large amount of water vapor and are generally at too low a temperature to be useful. The four dry process kilns studied all show exit gas temperatures of over 700°F, which makes this gas an attractive heat source. The major problems expected in using this gas are high dust content and high alkali salt and sulfur oxide content.

a. High Dust Content - Kiln exit gas from a long dry kiln may contain 20% or more by weight of the raw feed as dust, and even an efficient suspension preheater kiln will probably lose at least 5% as dust.

b. High Alkali Salt and Sulfur Oxide Content - Kiln exit gas from a long dry kiln generally contains appreciable amounts of alkali sulfates and chlorides that coat the dust particles. These, together with gaseous SO_2 and SO_3 (especially from coal-burning plants) can give rise to a highly corrosive liquid mist if the gas is cooled below its dew point. The presence of the salts and sulfur oxides also raises the dew point of the gas, which intensifies this effect.

Both of these problems must be considered when designing a heat exchanger for the kiln exit gas. A further problem will be the effect of the change in temperature of the exit gases on the efficiency of the electrostatic precipitators. In many cement plants the precipitators are designed to run "hot" (600 to 800°F) If gas temperatures fall below 600°F or so, the precipitator efficiency drops dramatically as dust resistivity increases (Ref. III-1). To regain high efficiency, the gas temperature must be lowered to below 350°F and the relative humidity increased, which will probably involve the installation of a water spray or evaporator. Even so, the efficiency of a precipitator designed for hot gases may be lower when run on cool, wet gas. However, if the plant already uses a low-temperature precipitator, the effect of further lowering the gas temperature will probably not be serious.

4. <u>Minor Heat Sources</u>

There are minor heat sources that may vary considerably from plant to plant, as well as the three major heat sources discussed. For example, a suspension preheater plant will usually have a bypass to reduce the alkali content of the cement (as in Plant 3). This represents a small source of high-temperature gas (1500°F) which is wasted at most plants, because the high-alkali dust contained in the bypass gas cannot be returned to the raw feed. Unfortunately, this gas will tend to have a high dust and SO_2 content that will make it fairly corrosive.

A further small source of heat in a suspension preheater plant will be heat lost through the preheater walls. However, this is at such a low temperature that it is doubtful if it would be worth recovering. This is true for most of the other minor heat sources at cement plants.

The initial stages of cement manufacture involve quarrying the limestone or calcareous component, crushing the material to approximately 2 in. maximum size, preblending the quarry rock with other raw components, and storing the materials in preparation for raw milling. Although these processes require energy, as shown in Table III-2, recovery of this energy is highly doubtful because the magnitudes of the energy increments are low, and the processes are not for the most part carried out in closed systems amenable to heat recovery.

There seems to be no possibility of using any of the waste heat generated in the raw meal grinding process. In a wet process, the average grinding energy requirement is about 30 kWh/ton of clinker, i.e., about 100,000 Btu/ton. However, although most of this energy is converted to heat, it is generally all taken up by the raw feed slurry itself, which usually contains 32 to 42% water by weight. This amount of heat is sufficient, in theory, to raise the temperature of the slurry by about 50°F and so is unlikely to be recoverable--it may serve as a heat input to the kiln system, or contribute toward drying the slurry.

In the case of the dry process raw feed grinding, slightly more energy is required (averaging about 37 kWh/ton of clinker, or 126,000 Btu/ton) in the grinding process. However, in most cases all the heat generated in the grinding process is used to aid drying of the raw feed, whic always contains a small amount of moisture. There is a trend to use hot waste gases from the kiln system to aid drying during the grinding process. Therefore, neither wet nor dry process grinding can be seen as a potential source of waste heat; they are more likely to be a potential user of waste heat in the evaporation of raw feed moisture.

The grinding of clinker plus gypsum to produce finished cement uses appreciably more energy than does raw meal grinding in most plants. Since there is virtually no moisture in the clinker, water evaporation is not an integral part of the process. The average energy requirement is about 58 kWh/ton (200,000 Btu/ton), of which over 98% is released as heat in the grinding mill. In most U.S. plants, air-swept ball mills are used for the grinding, and these mills are usually operated in a closed circuit with an air separator. The heat released in the mill is, therefore, carried out of the mill by the air which then flows into the air separator or into the dedusting unit, depending on the details of the grinding mill design (a dedusting baghouse or similar device is usually installed before the induced-draft fan to remove fine cement dust from the exhaust airstream).

A typical closed-circuit mill of this type is discussed in Ref. III-2. This mill takes clinker at 150°F and grinds it at temperatures up to about 210°F. The mill is cooled by introducing cold air at the air separator, so that the cement and air recycled to the mill are at about 190°F. Exhaust air leaves the dedusting system at about 170°F. A major reason for the low temperature in the mill system is that excessive dehydration of gypsum to hemihydrate must be avoided, as this may otherwise cause false setting of the finished cement. Mill temperatures in excess of 220°F are avoided and in some cases small amounts of water are sprayed into the hot zone of the mill to prevent excessive temperature rise. So, clearly, the waste heat produced by clinker grinding will only be available at temperatures of 210°F or less, and it is therefore unlikely that this will provide a useful source of waste heat.

To summarize, it is unlikely that the waste heat from either raw meal or clinker grinding will be of any value as a source of heat.

G. PLANT USES OF REJECTED ENERGY

In certain plants, kiln waste heat is being directly used for power generation, for drying raw materials and solid fuel, and for reducing the viscosity of heavy oil. The advantages and constraints of such uses are functions of parameters unique to each plant.

1. Raw Material Drying

In dry process plants, where the alkali and sulfur contents of the kiln or preheater exit gas permit, kiln exit gases are often used for drying moist raw materials. This drying step may be carried out in grinding mills, rotary dryers, or flash evaporating systems. The drying efficiency is highest in roller mill applications, because of good heat exchange, but the alkali and sulfur capture potential is also higher. The clinker cooler exhaust can also be used for drying, particularly in dry process plants that have very wet raw materials, or grate preheater systems with low kiln exit gas temperatures. Where practical, the use of kiln waste heat for drying raw materials will continue as an efficient means of using waste heat.

2. Fuel Drying

Solid fuels, particularly coal, are often dried in the coal mill with waste heat from the clinker cooler. The application of heat during grinding is a good drying method, but has the disadvantage that the water vapor usually is carried into the kiln with primary air and pulverized fuel. Systems have been developed whereby the coal mill exhaust is passed into a cyclone and the moist air vented to the atmosphere. A fresh increment of primary air from the cooler then serves to convey the dry coal into the kiln.

However, the cooler can usually supply more heat than is required for fuel drying, so that waste heat should still be available.

3. Oil Viscosity Reduction

The strong dependence of the flowability of heavy No. 6 oil on temperature creates a need for oil preheating prior to atomization into the kiln. Some plants use heat exchange from cooler exhaust air to warm the oil to an acceptable viscosity. Since oil-firing will probably continue at west coast and northeast plants, this application will also probably continue. Again, however, the actual heat requirement is usually only a relatively minor fraction of the available heat.

4. Power Generation Using Waste Heat

The use of waste heat boilers to produce steam from kiln exit gases and thus generate electricity on-site is an attractive means of using waste heat, especially in dry process plants with a high kiln exit gas temperature. There are now eight plants in the U.S. (five of which use waste heat) generating a total of 655×10^6 kWh per year between them (equivalent to 2.2×10^6 Mbtu). This is about 6.4% of the total electrical usage in the cement industry. Details of the waste heat boiler operations at one of these plants are given in the Plant 4 description.

5. Summary of In-Plant Uses of Waste Energy

The use of waste heat for raw materials and fuel drying and oil viscosity reduction is fairly common and the methods are well tested. However, only a small fraction of the available heat at each plant is usually required. Use of waste heat to generate electricity is attractive in terms of rejected energy conserved and in providing electrical energy needs for most of the plant's requirements. As will also be shown in later discussion, the economics of incorporating such waste heat utilization are very favorable in terms of return on investment.

H. REFERENCES

III-1 H. J. White: *Journal of the Air Pollution Control Association*. Vol 27, March 1977, p 215.

III-2 J. A. Mitchell: "Cement Cooling Methods." PCA Mill Session Paper MP-102, p 29.

IV. STORAGE SYSTEM SELECTION AND APPLICATIONS

Present thermal energy storage (TES) techniques or those under development were reviewed and storage systems most suitable for recovering and storing thermal energy in the cement industry were identified. Consideration was given to the uses of thermal energy in: (1) the cement process; (2) other off-site industrial processes; and (3) for district heating and for cooling. Preliminary economic evaluations of candidate storage techniques were performed to aid in subsequent screening. The results of these studies are described in the following paragraphs.

A. THERMAL ENERGY STORAGE TECHNOLOGY

Storage system technologies can be classified under the broad categories of sensible heat storage, latent heat storage, and chemical heat storage. Sensible and latent heat storage at high temperatures is difficult due to the requirement of maintenance of the material at those temperatures. Chemical energy storage is attractive from the standpoint of storing the energy at a low temperature and then generating high quality energy at higher temperature (heat pump effect).

1. Sensible Heat Storage

This classification of energy storage is the oldest and congruently the most advanced in terms of development and demonstrated feasibility. The most practical form of sensible heat storage is liquid or solid phases. Current materials used for energy storage are listed below:

Liquids	Solids
1. Water	1. Refractory pebbles
2. Oils	2. Rock beds
3. Organic fluids	3. Metals
4. Molten salts	4. Brick
5. Metals	

Liquid media are advantageous in serving both as a storage medium and as a heat transfer medium. A list of liquid heat transfer media is shown in Table IV-1. Solid bed storage systems can be used with either a gas or liquid heat transfer medium to transport thermal energy from the source to the solid.

Table IV-1 Heat Transfer Media Characteristics (Ref IV-2)

This listing is representative rather than complete. Information has been gathered from apparently reliable sources.

Chemical name	Common or trade name	Used in: Liquid phase	Vapor phase	Eutectic mixture	Operating range, deg F: Min	Max	Freezing point, deg F	Pour point, deg F	Boiling point (atmospheric pressure), deg F	Dissociation point, deg F	Fire point (Cleveland open cup), deg F
REFRIGERANTS											
Monochlorodifluoromethane	F-22[3] [15]		X		—140	300	—256		—41.44	550	None
Dichlorodifluoromethane	F-12[3] [15]		X		—130	250	—252		—21.62	1,000	None
Methyl chloride	Methyl chloride[3]		X		—80	600	—143.7		—10.76	795	
Sulfur dioxide	Sulfur dioxide		X				—103.9		14.0	3,000+	None
Ammonia	Ammonia[3]		X				—107.9		—28.0	1,100+	1,100
ANTIFREEZES (Alcohols)											
Methyl alcohol	Methanol[3] (wood)	X		X			—164		148.37[9]		
Ethyl alcohol	Ethanol (grain)	X		X			—94		173.3[9]		
Ethylene glycol	SR-1[2]	X		X	—20	300	—40		386.96[9]		250
Glycerol	Glycerine	X		X			—60.4		544[9]		
Polalkylene glycol	50-HB280-X[8]	X			50	500		—35		600	600
	H 400[5]	X						—35			600
	LB-300-X[8]	X			200	500		—40		600	585
BRINES											
Calcium chloride	Calcium salt brine	X		X			—67				None
Sodium chloride	Ordinary salt brine	X		X			—6.03				None
HYDROCARBON OILS (Petroleum Products)[13]											
	Hytherm C[1]	X			40	450		0	646		460
	Hytherm F[1]	X			40	475		0	669		485
	Hytherm K[1]	X			40	550		0	674		560
	Hytherm M[1]	X			40	600		0	698		575
ORGANIC CHEMICALS											
Isopropylbenzene (Cumene)	Para cymene[4] [7]	X	X		50	500	—100.3		350		152
Phenyl methyl ether	Anisole[3]	X	X		0	500	—35.14		308.84		125[14]
O-Dichlorobenzene	Dowtherm E[2]		X		50	500	—7		352		285
Tetrachlorobiphenyl	Aroclor 1248[6]	X			50	600		19.4	652	650	640
	H 500[5]	X									360[14]
Tetra-hydro-naphthalene	Tetralin[3]						—85		404.36	840	172[14]
Diphenyl–diphenyloxide	Dowtherm A[2]	X	X	X	60	720	53.2		495.8	800+	275
Phenolic	H 800[5]	X				875		—60			
Diphenyl[10]							157		491.5		
O-Terphenyl (ortho)[12]	Santowax O[6]	X	X		175	800	133		630		390

Table IV-1 (concl)

M-Terphenyl (meta)[12]	Santowax M[6]	X	X		225	800	189		687		445
P-Terphenyl (para)[12]	Santowax P[6]	X	X		450	825	415		725		460
O/M/P-Terphenyl[12]	Santowax R[6] [16]	X	X		325	825	293		687+		460
Chlorinated Biphenyl[12]	Biphenyl[6]	X	X		200	850	156		491		255
Isopropylbiphenyl[12]	Isopropylbiphenyl[6]	X	X		0	700	−65		570		306
Chlorinated Polyphenyl	Aroclor 1221[6]	X			70	600		34	527		349
	Aroclor 1232[6]	X			0	600		−32	554		460
	Aroclor 1242[6]	X			70	600		2	617		610+
	Aroclor 1254[6]	X			100	600		50	689		690+
ORGANO-SILICATE CHEMICALS[11]											
Tetra aryl silicate	H 700-130[5]	X			−50	300		−100	400+		450
Aliphatic silicate	H 700B[5]	X			−50	500		−100	700+		
Tetra aryl silicate	H 700-155[5]	X			0	500		−65	600+		
	H 700-160[5]	X			0	600		−40	800+		
	H 700-10A[5]	X			50	600		−30	700+		
Tetra aryl silicate (cont.)	H 700-180[5]	X			50	650		−10	850+		
	H 700-190[5]	X			50	675		30	800+		
	H 750-200[5]	X			50	700		5	800		
	H 700[5]	X			0	650		−45	770+		512
FUSED SALTS											
Eutectic salt	H 1200[5]	X		X	300	1,100	285				
Sodium nitrite–sodium nitrate–potassium nitrate (40–7–53) alloy	Hitec[3]	X		X	300	1,000	288			1,500	
MOLTEN METALS											
Mercury		X					−37.9		674.42		
Sodium–potassium alloy		X	X						1,518		
Sodium		X					207.5		1,616		
Lead–tin (50–50) alloy		X					437				
Tin		X					449.4		4,100		
Bismuth		X					520		2,640		
Lead–tin (67–33) alloy		X					527				
Lead–bismuth alloy		X							3,038		
Lead		X					621.3		3,170		

[1] Atlantic Refining Co. tradename.
[2] Dow Chemical Co. tradename.
[3] E.I. du Pont de Nemours & Co. Inc. tradename.
[4] Hercules Powder Co. tradename.
[5] American Hydrotherm Corp. tradename.
[6] Monsanto Chemical Co. tradename.
[7] Newport Industries Co. (Div. Heyden Newport Chemical Corp.) tradename.
[8] Union Carbide Co. tradename.
[9] Boiling point for undiluted alcohol (not eutectic mixture).
[10] For comparison only.
[11] Manufactured by Dow Corning Corp. for American Hydrotherm Corp.
[12] Resistant to nuclear radiation.
[13] Other hydrocarbon high-temperature oils include "S/V HT Oil" (Socony-Vacuum Oil Co.); "Ideal," "Eureka," "Eclipse" (Atlantic Refining Co.); "Redind" (Continental Oil Co.); "HT Oil" (Gulf Oil Corp.); "Pure Mineral" Oil (Pure Oil); "Turbo," "Tellus," "Valvata" (Shell Oil Co.); "Rubiiene," "Ladito," "Penn," "Gear Oil" (Sinclair Refining Co.); "Calol OC Turbine Oil" (Cal. Standard Oil Co.); "12586 Oil" (Ind. Standard Oil Co.); "Sohivis" (Ohio Standard Oil Co.); "Sunvis 51" (Sun Oil Co.); "Ursa Oil P," "Regal Oil" (Texas Oil Co.); "Tycol Avalon 90" (Tidewater Assoc. Oil Co.).
[14] Flash point.
[15] Other fluorinated hydrocarbon compounds available are F-13, F-13B1, F-11, F-113, and F-114.
[16] Other polyphenyl alkyl derivatives and mixtures include diisopropyl biphenyl, tertiary eutectic, monoisopropyl biphenyl, and isopropyl Santowax[6].

Both liquid and solid storage systems are limited by thermal stability at high temperatures and resistance to thermal cycling. Oils and organic chemicals suffer from thermal degradation at high temperatures, thus limiting their applications. Shown in Table IV-2 are the operational temperature ranges for sensible heat storage systems. Typical degradation times for an organic chemical, Dowtherm "A", are shown in the following tabulation taken from Ref IV-1.

Mean Temp, °F	Time, Months (based on 15% degraded products)
650	45-60
700	35-37
725	10-14
750	3-4
775	1.5-2

For high temperature applications (>500°F) and for storage system life times of 20 to 30 years, the maintenance required to replenish degraded products can be substantial.

2. Latent Heat Storage

Storage of thermal energy as heat of fusion is attractive relative to sensible heat storage because the latent heat of fusion of many materials is greater than the product of the specific heat and storage temperature range. As of this date, large-scale application of these materials to thermal storage systems is primarily in the development stage.

A phase change material selection is dictated primarily on melting point and latent heat of fusion. Additional properties that must be considered are reversibility of hysteresis on melting or freezing, subcooling of liquid phase, and nucleation of solid phase from liquid phase plus irreversible changes in the material on thermal cycling. These changes alter the melting temperature and heat of fusion. A large number of these materials have been surveyed, studied, and developed as phase change materials (PCM). The materials consist chiefly of pure compounds or eutectic mixtures of metal hydrides, hydroxides, fluorides, nitrites, chlorides, bromides, carbonates, sulfates, and phosphates. A representative list of PCMs and their qualities are shown in Table IV-3.

Heat transfer rates through PCMs are frequently limited by the thermal conductivity of the liquid and solid states. Micro- and macro-encapsulation techniques in small pellets and suspension of the pellets in a liquid heat transfer medium has been developed to increase heat transfer and inhibit migration of phases in the storage vessel.

Table IV-2 Operational and Conceptual Sensible Heat Storage System (Ref IV-2)

Storage Configuration	Storage Medium	Applications	Status	Temperature (°C) T_{MAX}	Temperature (°C) $T_{MAX}-T_{MIN}$	MW_t-hr	Capacity kW_t-hr/m^3	Capacity kW_t-hr/kg	Input Rate kW_t	Output Rate kW_t	Cost \$/kW_t-hr	Heat Exchanger	Comments
Above Ground Tank H=10m, R=0.5m	Water	Solar Central Receiver	Engineering Design	210 300	87 87	4.1 4.1	85	0.086		42,500 to 5640	8.0 22.0	Conventional-External to Tank	Capacity figures based upon modules of seven tanks
Above Ground Tank H=3.15m, R=0.89m	Water, Therminol	Solar Total Energy System	Preliminary Testing	232 343	56 56	.41	64.6	0.064	100-120	25-50	—	Conventional-External to Tank	Instrumented with thermocouples
Steam Accumulator H=14.6m, R=1.83	Water	Solar Central Receiver	Engineering Design	200 300		14 37	89.3 262.4	0.11 0.28		33,300 41,800	3.0 6.0		Indicated output is peak value
Underground Tank H=30m, R=13m Depth=60m	Water	Storage for Nuclear Plant	Preliminary Design	217	141	4370	146	0.146		624	0.4	Conventional	Pressurized cavern eliminates need for thick-walled vessels. Storage used for feedwater heating
Acquifers	Water and Sand	Waste Heat Storage	Conceptual	170	110	42,000	31.5		18,400*	19,400	0.003	Conventional	Simple performance calculations discussed
Above Ground Tanks (Other Fluids)	Therminol-55 Therminol-66 Caloria-HT-43 HITEC	Solar Central Receiver	Engineering Design	315 315 302 500	55 55 83 300	226 226	24.4 24.4 47.2 220	0.032 0.032 0.068 0.12		452,000 452,000	62 27 11 4		
Solid Storage Materials	Cast Iron	Industrial Space Heating Paint Manufacture	Operational Operational	750 700	480 430	0.75 0.64	60	0.17 0.1	65 80	~60 180	? ?	Core to Air	Electrical resistance heaters used for input
Packed Beds H=17.3m, R=9.7m	Granite Caloria-HT-43	Solar Central Receiver	Preliminary Design	302	84	105	60	0.027	42,200	30,400	5.13	Direct Contact	Some small scale experiments complete
Fluidized Bed	Sand Fly Ash	Storage for Power Plant	Conceptual	800	400	4000	64	0.04	500,000	500,000	?	Fluidized Bed Heat Exchanger	
Underground	Soil	Sink for Waste Heat for Underground Power Sources	Preliminary Design	100	65	500	52		1000		0.4-0.8	Grid of Pipes	Excellent review of soil properties, detailed modeling
	Limestone or Granite	Solar Central Receiver	Conceptual	500	400	500,000				625,000	?	9000 Vertical Holes	

Table IV-3 Operational and Conceptual Heat-of-Fusion Storage Systems (Ref IV-2)

Storage Configuration	Storage Medium	Application	Status	TEMP. (°C) T_{MAX}	TEMP. (°C) $T_{MAX}-T_{MIN}$	Capacity kW_t-hr	Capacity kW_t-hr/m^3	Capacity kW_t-hr/kg	Input Rate kW_t	Output Rate kW_t	Cost \$/kW_t-hr	Heat Exchanger	Comments	Ref
Annulus R_i=0.114m, R_0=0.127m H=0.349m	LiH	Orbital Solar Energy Storage	Lab Scale Experiment	688		1.87	496	0.71	8-12	43		Inner and Outer Cylinder Surfaces* A_I=0.251 m^2, A_0=0.279 m^2	Geometry with internal fins also tested. Detailed mathematical modelling	3.20, 3.21
Cylinder R=0.058m, H=0.042m	LiH	Orbital Solar Energy Storage	Lab Scale Experiment	680		0.281	381	0.66	0.61	0.53		Coiled Tube with Fins A=0.037 m^2	Lower capacity/m^3 due to heat exchanger tubes	3.22
Annulus	LiH	Orbital Solar Energy Storage	Lab Scale Experiment	588		0.2		0.75	0.66	0.31*		Thermoelectric Convertors in LiH	*Output was electric, 0.31 is kW_t	3.23
Cylinder R=0.037m, H=0.905m	LiF/LiOH Eutectic	Underwater Propulsion	Lab Scale Experiment	427		3.51	902	0.64		1.17		Single Straight Tube A=0.031 m^2	Input was electrical resistance heater eutectic has low volume change upon melting larger system designed and built, but never tested	3.24
Cylinder R=0.343m, H=0.914m	NaOH	Space Heater	Lab Scale Experiment	510	458	40	[illegible]	0.31	6.9	2	?	U-Tubes, A=0.66 m^2	Input was electrical resistance heater	3.26
Cylinder R=0.305m, H=1.52m	NaOH	Hot Water	Operational Units	482	361	193	434	0.29	20	20	4.60	Coiled Tube, A=1.7 m^2	Input was electrical resistance heater. Extensive field testing	3.27
Rectangular Models	NaOH	Space Heater	Operational Units	482	361	117		0.29	12	7.3	5.10	External Surface of Modules	Input was electrical resistance heater extensive field testing	3.27
Cylinder R=16.8m, H=33.5m	NaF/FeF_2 Eutectic	Storage for Nuclear Reactor	Conceptual	680		9.6×10^6	423	0.19	8×10^5	8×10^5	21**	Direct Contact With Molten Lead	**Cost of lead and NaF/FeF_2 only	3.30
Required Volume =1622 m^3	KNO_2 - $NaNO_2$ (0.21 - 0.79)	Solar Central Receiver	Preliminary Design	254		1.8×10^5	96	0.043	4.9×10^4	3×10^4	17	Straight Tubes*With Scraping	Other salts being considered, small scale scraping experiments promising	3.31
Large Tank	$Ge_{0.4}S_{0.6}$	Storage for Electrical Utilities	Conceptual	590										3.32

3. Chemical Energy Storage

Of the three categories of thermal storage systems, chemical energy storage requires the most development for large scale applications. Use of chemical reactions in thermal storage may be considered under four subheadings: (1) single, irreversible reactions; (2) single, semireversible reactions; (3) single, reversible reactions; and (4) paired, reversible reactions. The advantage of chemical energy storage over sensible and latent heat storage is the ability to store more energy in considerably less material. Table IV-4 shows some of the candidate reversible chemical reactions considered for thermal energy storage.

Other potential candidate reactions include paired ammoniated salt reactions. These reactions are listed in the following tabulation.

Reaction	T, °F	Δ H Btu/lb reactants
(1) $CaCl_2 \cdot 8\ NH_3(s) \leftrightharpoons CaCl_2 \cdot 4NH_3(s) + 4NH_3(g)$	88	285.7
(2) $CaCl_2 \cdot 4NH_3(s) \leftrightharpoons CaCl_2 \cdot 2NH_3(s) + 2NH_3(g)$	108	203.1
(3) $CaCl_2 \cdot 2NH_3(s) \leftrightharpoons CaCl_2 \cdot NH_3(s) + NH_3(g)$	329	180.0
(4) $MgCl_2 \cdot 6NH_3(s) \leftrightharpoons MgCl_2 \cdot 2NH_3(s) + 4NH_3(g)$	266	461.8
(5) $MgCl_2 \cdot 2NH_3(s) \leftrightharpoons MgCl_2 \cdot NH_3(s) + NH_3(g)$	522	161.6
(6) $MgCl_2 \cdot NH_3(s) \leftrightharpoons MgCl_2 + NH_3(g)$	702	198.9
(7) $MnCl_2 \cdot 6NH_3(s) \leftrightharpoons MnCl_2 \cdot 2NH_3(s) + 4NH_3(g)$	197	386.5
(8) $MnCl_2 \cdot 2NH_3(s) \leftrightharpoons MnCl_2 \cdot NH_3(s) + NH_3(g)$	480	192.3
(9) $NH_4Cl \cdot 3NH_3 \leftrightharpoons NH_4Cl + 3NH_3$	40	533.3

By pairing low-temperature reactions with high-temperature reactions a chemical heat pump can be realized. These reactions are unique in that the forward or reverse reactions can be driven to completion by varying the NH_3 decomposition pressure in the system. These reactions are presently being studied for various applications (Ref. IV-3). Totally gas phase reactions are limited to partial completion by the thermodynamic chemical equilibrium relationships at the system operating temperature and total pressure. Chemical energy storage can theoretically generate energy at the original quality but is necessarily limited to recovering energy at a narrow temperature range. For example, if a noncondensing gas from a cement kiln at 1150°F is passed through a high temperature chemical reactor at 1100°F, the sensible heat extracted from the gas stream would only be $Q = \dot{\omega}\ \bar{C}p\ (1150\text{-}1100)$. The discharged gas at 1100°F would still be "energy rich." On the other hand, if the 1150°F stream were passed through a 600°F bed, the high quality energy (at 1150°F) would never be recovered, since upon regeneration the bed could only produce 600°F heat transfer fluid.

Table IV-4 Reversible Chemical Reactions for Thermal Energy Storage (Ref IV-2)

Proposed Reaction	Heat of Reaction, Q		Temp	Cost (Material)	Status	Comments	Ref
	kw_r-hr/kg	kw_t-hr/m^3	C°	\$/kw_t-hr			
$Mg(OH)_2 + Q \rightleftharpoons MgO + H_2O(g)$	0.288	340	375	0.62	Lab Scale		3.34, 3.35
$Ca(OH)_2 + Q \rightleftharpoons CaO + H_2O(g)$	0.366	411	520	0.07	Experiments		
$SO_3 + Q \rightleftharpoons SO_2 + \frac{1}{2} O_2$	0.343	262^{+}	722	16.4^{++}	Conceptual	$^{+}$Gas stored at 200 atmospheres $^{++}$Storage system cost	3.36
$CH_4 + H_2O + Q \rightleftharpoons CO + 3H_2$	1.8	6.8*	800		Conceptual	*Assumes gaseous products are stored at a pressure of 10 atmospheres and 273°K	3.37
$NiCl_2 \cdot 6NH_3 + Q \rightleftharpoons NiCl_2 \cdot 2NH_3 + 4NH_3$	0.29	7.5*	175	7.60	?		3.40
$LaNi_5H_5 + Q \rightleftharpoons LaNi + 5/2\ H_2$	0.048	3.5*	100	1060.	Conceptual		
$SmCo_5H_{2.5} + Q \rightleftharpoons SmCo_5 + 5/4\ H_2$	0.024	7.4*	100	4410.			3.41
$VH_2 + Q \rightleftharpoons VH + 1/2\ H_2$	0.105	9.8*	100	105.			
$FeTiH + Q \rightleftharpoons FeTi + 1/2\ H_2$	0.078	14.1	100	28.			
Coupled System:					Conceptual		3.42, 3.43, 3.44
$FeTiH + Q \rightleftharpoons FeTi + H_2$	0.118	92	400	17.9			
and							
$MgH_2 + Q \rightleftharpoons Mg + H_2$							
$H_2SO_4(dilute) + Q \rightleftharpoons H_2O(g) + H_2SO_4(conc)$	0.107	452	238	0.45	Lab Scale Experiments	Concept requires real time use of large amount of energy at 100°C during storage cycle	3.45, 3.46

B. TES APPLICATION

Storage system sizing and selection depends on the use of recovered waste heat. Some presently existing dry process plants recover the energy in kiln exit gases through waste heat boilers and generate their own electric power for in-process electrical requirements. Therefore, the first use of the high temperature heat from the cement kiln could be for the production of electrical power. Using Plant 1 as an example, energy in the high-temperature, 1150°F, kiln gas could generate steam to drive turbines for electrical power generation. The amount of electricity that could be generated is (assuming a 25% thermal energy to electrical energy efficiency of the steam power plant):

$$kWe = \frac{\dot{\omega} Cp \left(To - T_{final}\right) \times 0.25}{3413}$$

$$kWe = \frac{(5325)(60)(0.28)(1150-300) \times 0.25}{3413} = 5570$$

These calculations illustrate that kiln gas can continuously generate electricity at around 5.6 MWe while the kiln is operating. For the dry process, electrical energy requirements can range from 60 to 150 kWh/ton clinker. Using clinker production rate of 67 tons/hr, Plant 1 requires between 4 to 10 MWe in the operations of grinding, clinkering, and finishing of cement. The actual daily power demands depend on plant operation, i.e., when the grinding, clinkering, and finishing processes are operating. Clinkering is usually a continuous process, except for infrequent maintenance shutdowns. However, the grinding and finishing mills may not be operated on a continuous around-the-clock basis.

Thermal energy storage may then be used to store excess energy when the process does not demand 5 MWe of power. Storage may also be used to improve the efficiency of the power plant operation through the application of TES reheaters or feedwater heaters. TES locations in a power plant are illustrated in Figure IV-1.

The uses of thermal energy storage in power applications can be summarized as:

1) Reserve energy for steam production;

2) Steam reheating;

3) Feedwater Heating;

4) Storage of waste heat from power cycle for in-process use or district use.

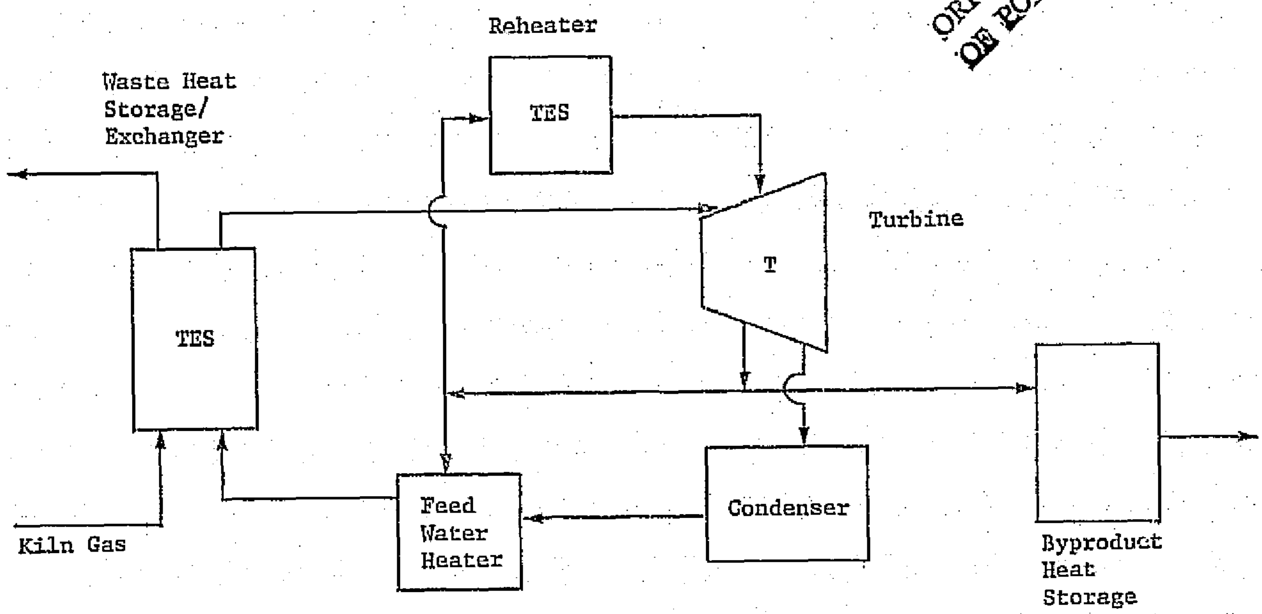

Figure IV-1 TES Applications in Power Plant Cycles

C. INITIAL TES SELECTION

Candidate thermal storage materials were selected based on temperature levels of prominent waste heat sources in the cement manufacturing process. Preliminary system concepts were also developed to recover energy from waste heat sources and apply the stored energy.

The materials selected for thermal energy storage (TES) were based on the temperature level of application and proven feasibility of the system. As described earlier, the temperature levels of interest are storage of waste heat from the kiln gas at a temperature level ranging from 800°F to 1500°F and the waste heat from the clinker cooler air at 350°F to 450°F. Several storage media candidates were reviewed for applicability in these temperature ranges, particularly from Ref IV-2, IV-4, and IV-5. Candidate TES media were initially selected based on demonstrated technical feasibility as well as temperature levels.

Eleven materials were selected from the sensible, latent, and chemical energy storage categories for high-temperature applications. Shown in Table IV-5 are storage media properties of these candidates. The candidate material/system concepts are briefly described in the following paragraphs.

Table IV-5 Heat Storage Media Properties

Candidate	Density lb/ft^3	Cp, Btu/lbm °F	Cp, Btu/ft^3 °F	Temp Min, °F	Temp Max, °F	$/lbm	($/kWt·hr) Storage Medium Only
Sensible Heat Storage							
1. MgO	223	0.32	71.4	400	900	0.15	3.20
					1000		2.66
					1100		2.29
					1200		2.00
2. Granite	168	0.28	47.0	400	900	0.0038	0.13
		0.20	33.6		1000		0.11
					1100		0.09
					1200		0.08
3. Limestone	153	0.22	33.7	400	900	0.0038	0.11
					1000		0.10
					1100		0.08
					1200		0.07
4. Draw Salt	111	0.37	41.1	430	900	0.10	1.96
					1000		1.62
5. Oil							
Dowtherm	62.2	0.53	33.0	400	600	0.60	19.32
					750		11.04
Caloria	44.3	0.69	30.6	400	600	0.13	3.21
6. NaOH	100	0.50	50.0	600	900	0.250	5.69
					1000		4.26
					1100		3.41
					1200		2.84
7. Rock + Oil (Granite + Caloria Void Fraction = 0.25)	137.1	0.24	32.9	150	600	0.014	1.90
Latent Heat Storage							
8. Li_2CO_3 $-Na_2CO_3$ $-K_2CO_3$	144 @25°C	110	17136	747		0.33	9.46
9. NaOH	133 @25°C 100 @600°F	69	6900	606		0.25	12.37
Chemical Energy Storage							
10. SO_3	13.20 @200 atm	531	7013	1170	1308	0.20	1.285
11. $MgCl_2 \cdot 2NH_3$ + $CaCl_2 \cdot 8NH_3$	30.	333	9990	530	560	0.185	1.895

1. MgO

This system uses magnesia bricks stacked in a checkerboard pattern in horizontal cylindrical tanks. The kiln gas would be passed through the beds and the heat exchange would occur via direct contact with the bricks. The basic problem associated with this system is incompatibility of the kiln gas constituents (SO_x, H_2O, CO_2) and the magnesia.

2. Granite or Limestone

This system consists of beds of crushed rock (average diameter 1 to 2 in.) in which the kiln gas is passed through the bed in the charge mode; ambient or preheated air passes through the bed during discharge. The granite durability to kiln gas constituent species is expected to be quite high. Limestone durability must be determined at high kiln gas SO_x loadings. Accumulation of kiln gas dust in the storage bed, leading to excessive pressure drops, may be another potential problem. Air and kiln gas would be drawn through the bed using existing induced draft fans. The advantage of this material/system concept is its low investment cost. Not shown in Table IV-5, is the use of clinker as a storage medium. The material is similar to limestone in physical properties and is also similar to limestone in reactivity with kiln exit gas species (H_2O, SO_x, CO_2).

3. Draw Salt

This material is a mixture of sodium and potassium nitrates. The material has a melting point of 420°F and is a stable liquid to 1000°F. This concept would use one tank for the storage of both hot and cool fluids by incorporating a thermocline movement through the tank as the TES unit is charged and discharged. Draw salt is corrosive and would require stainless steels in containers and heat exchangers.

4. Oil

Some heat transfer oils are available for operating temperatures up to 750°F. However, these oils require replenishment schedules at a minimum of every 5 years. The oil is compatible with carbon steel but still requires relative high container costs due to low density characteristics. This concept would require two storage vessels for hot and cold fluids, with one storage volume being empty at all times.

5. NaOH

This material is highly corrosive and requires cautious handling. This concept requires two storage volumes for hot and cold fluids.

6. Granite plus Oil

This concept (patent pending by Rocketdyne) uses a dual media of rock and oil for the storage of energy. Oil is passed through a solid rock bed and energy is transferred for application by the oil. The thermocline characteristic of the bed as it is being charged and discharged is used to reduce the number of storage vessels by half over conventional two-container (hot and cold) liquid systems. However, the system is temperature limited to 600°F (Caloria HT 43 decomposition temperature) and the oil requires total replenishment after 5 years.

7. Li_2CO_3-Na_2CO_3-K_2CO_3

The Institute of Gas Technology is testing this phase change material in high temperature applications (Ref IV-6). In concept the latent heat of fusion and liquid sensible heat to 1000°F is used as a technique for storage. The material does not have severe corrosion problems, but material costs appear prohibitive in relation to other materials. Low heat transfer rates during solidification of material around internal heat transfer tubes raise total heat exchange area requirements and thus the cost of heat exchangers.

8. NaOH

This concept uses the latent heat of fusion and liquid sensible heat to 1000°F. Heat exchanger tubes are immersed in a liquid/solid bed. This storage media concept is presently being funded by DOE (Ref IV-7) for high temperature applications. The system requires special container and heat exchanger materials, and will exhibit low heat transfer rates during material solidification.

9. SO_3

This system uses the decomposition of sulfur trioxide to sulfur dioxide and oxygen at high temperatures for thermal storage. The high temperatures required (∿1200°F) for the shift in equilibrium of the reaction $SO_3 \rightleftharpoons SO_2 + \frac{1}{2} O_2$ limits its applicability in the cement industry. The system requires a great deal of equipment (compressors, heat exchangers, distillation columns, etc) thus dictating high capital costs.

10. $MgCl_2 \cdot 2NH_3$

This concept would use the paired ammoniated reactions:

$$MgCl_2 \cdot 2NH_3 \rightleftharpoons MgCl_2 \cdot NH_3 + NH_3$$
$$CACl_2 \cdot 8NH_3 \rightleftharpoons CaCl_2 \cdot 4NH_3 + 4NH_3$$

for energy storage. These reactions have been tested on a laboratory scale at the Denver Division of Martin Marietta. The concept would use the high temperature magnesium chloride reaction to condense steam during the charge mode at approximately 500°F. Some other form of storage would be required to extract sensible heat energy from the superheated steam and subcooled water since the salt bed could operate only in a narrow temperature range. Since low heat transfer coefficients are characteristics of this system, heat exchanger costs are high.

Table IV-5 shows each of the various storage material candidates, their pertinent properties and the material cost per kilowatt hour of thermal storage. From these costs the most promising candidates are granite, limestone, draw salt, rock and oil, and chemical energy storage candidates.

D. ENERGY CONSERVATION SYSTEM CONCEPTS

Results from the process study (Chapter III) illustrate the large quantities of rejected heat from the kiln exit gas and clinker cooler air. The use of this wasted energy could best be served by producing electricity for in-process use with the high temperature kiln exit gas and using the low temperature energy for feedwater heating for an on-site power generator or preheating materials. As will be shown in later discussion off-site use of low temperature energy for district cooling does not appear to be as economically attractive given current energy costs.

For a typical dry cement process the electrical energy requirements for various phases of cement production are:

1) Raw feed grinding, 37 kWh/ton clinker;

2) Finish grinding, 58 kWh/ton clinker;

3) Kiln, 30 kWh/ton clinker;

4) Facilities, 25 kWh/ton clinker.

This totals approximately 150 kWh/ton clinker including power requirements of facilities. Using Plant 4 as an example, while the kiln is operating, approximately 136.5 kWh/ton of clinker is generated from an on-site generator. That is approximately 91%

of the plant electrical requirements are met with on-site generation (using the figure of 150 kWh/ton requirement). However, when the waste heat source for the steam boiler is not available when the kiln is down for maintenance repairs of the clinker cooler grate, the kiln itself, or dust collector systems, then the power demand for other cement operations must be obtained from a public service utility. Such an occurrence necessitates either curtailing the other cement operations, i.e., raw and finish milling, while the kiln is down or demanding large amounts of power from the utilities for short periods of time (5 to 10 MWe for 2 to 24 hr). This problem can be alleviated by using a TES unit to level the utility load demand of the cement operations. By charging TES units while the kiln is operating, the stored energy can then be discharged when the kiln is down for repairs to supply electricity for milling operations and facilities.

Figures IV-2 and IV-3 represent schematic locations of TES units for reserve energy in power plant applications for retrofitting existing installation (Fig. IV-2 and for new installations (Fig. IV-3). Concepts 1 thru 4 represent possible configurations in relation to gas-steam waste heat boilers. Concept 1 shows a TES unit being charged with kiln gas energy with the gas being passed directly through the TES unit. Heat exchange in this concept is done either by directly contacting the gas with the storage media or by using internal heat exchange tubing to separate the media and gas. When the TES unit is discharged, ambient air or preheated air is passed through the bed and the heated high temperature air is passed through the waste heat boiler. Concept 2 employs a gas-heat transfer fluid heat exchanger to extract from the kiln gas stream and transfer the high temperature energy to the TES unit with a high temperature fluid. In most cases this fluid may be the storage media itself but may be different through the use of internal heat exchanger tubing. The unit in Concept 2 is then discharged by passing the high temperature fluid through a fluid-steam boiler (preheater, vaporizer, and superheater) system to produce steam for power generation. In Concept 3 energy is extracted and generated solely on the steam loop side of the waste heat boiler with a heat exchanger external to the TES unit (condenser/boiler). In the charge mode, steam is desuperheated, condensed, and subcooled via the heat transfer fluid from the TES unit. The condensed water is returned to the feed water line. Upon discharging the TES unit, feedwater is pumped back through the heat exchanger and vaporized using the high temperature fluid from the thermal storage unit. The steam is used for power generation. Concept 4 is similar to Concept 3 in operation but uses internal heat exchangers for transfer of energy from the water/steam to the thermal storage material.

Concepts 5 and 6 represent two basic configurations for new installations of on-site power plants with TES units. Concept 5 uses a gas-liquid heat exchanger to extract energy from the kiln

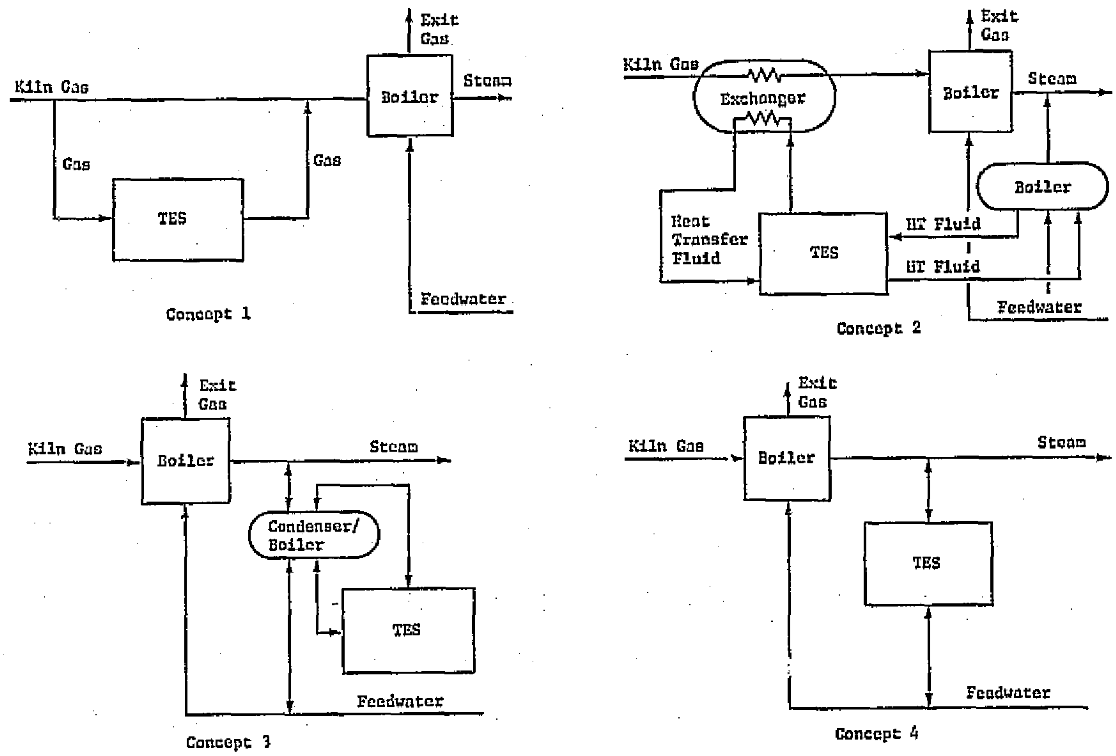

Figure IV-2 TES Retrofit Applications

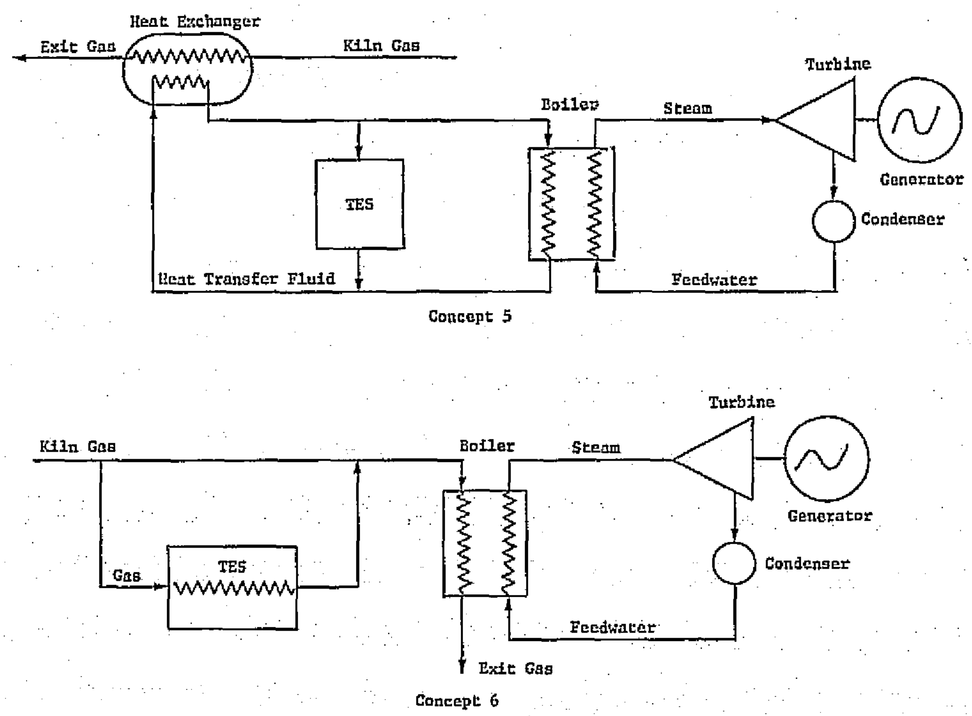

Figure IV-3 TES New Installation Applications gas. The high temperature liquid then follows two paths during charging of the TES unit through the TES unit and the liquid-steam boiler. When kiln gas energy is no longer available, then the stored high temperature fluid is pumped through the boiler and the exit liquid from the boiler returned to the TES for further charging in the next cycle. Concept 6 is similar to Concept 1 but is used to distinguish costs between retrofit and new installation costs.

E. PRELIMINARY SIZING AND ECONOMIC ANALYSIS

Using the six system concepts for reserve power production and the 11 candidate materials discussed earlier, a preliminary sizing and cost estimate of major expenditure items (containers, heat exchangers, and storage materials) was performed. These systems were sized on the following basis:

1) Provide electrical generation at 7 MWe for 24 hr, assuming a thermal-to-electric conversion efficiency based on conditions of produced steam at turbine throttle (temperature and pressure);

2) Steam boiler efficiency of 90%;

3) Charge/discharge time of 7/1 days;

4) Storage life of 30 years;

5) No TES container heat loss;

6) TES unit efficiency (energy output/input) of 100%;

7) Maximum or minimum TES temperature based on either material solidification temperature or heat exchanger pinch points. The TES units for the system concepts were sized based on the boiler/steam/electricity conversion schedule as shown.

Steam Temp, °F/Pressure, psia	fficiency, % Steam Electric	Efficiency, % (liquid/Steam)	Storage Required Btu x 10^9
900/900	25.3	90	2.52
750/700	24.2	90	2.63
550/225	22.2	90	2.87

The required energy storage figures in the last column of the table were calculated for the 7 MWe 24-hr (168 MWe-hr) sizing requirement.

Using the criteria listed above, candidate storage materials and appropriate system concepts were sized and costs were estimated. Tables IV-6 and IV-7 contain tabulated results of costs for materials, containers, and heat exchangers; maximum and minimum storage temperatures; and the system cost based solely on storage media, containers, and heat exchangers. Table IV-8 contains the system vessel container size associated with each storage medium.

A comparison of the system costs of TES units/system concepts show that the solid and liquid sensible heat concepts are favored. The added costs of replenishing oil in the oil and oil plus granite systems once every 5 years increase the life cycle costs of these systems prohibitively. Sodium hydroxide material costs and handling problems negate the high storage density of this system. The possible compatibility problem of magnesia brick with species in kiln gases and the high relative cost of the brick with the other solid storage media eliminates this system.

Therefore, based upon capital costs, material compatibility with high temperature gases, ease of operability, and reliability of system, the candidate materials selected for further analysis were granite, limestone, cement clinker, and draw salt.

All four materials are applicable for high temperature thermal storage, while the first three are also applicable for thermal storage of the low temperature clinker cooler air waste heat.

STORAGE SYSTEM COMPARISON WITH ALTERNATIVE METHODS OF POWER GENERATION

Methods of producing on-site electricity when the kiln is down for repairs by using auxiliary power generators were rejected based on estimates of fuel and operating costs. Power generation systems using diesel engines and gas turbines were evaluated. An auxiliary fossil fuel-fired boiler (coal or oil) to produce steam for an existing on-site power generation set was also evaluated based on initial capital investment and operating costs.

Investment costs and operating expenses were calculated for four power generation systems (see Table IV-9). The auxiliary fossil-fired boiler installed costs were based upon field-erected units (Ref. IV-10). These particular costs include only the boiler unit (i.e., excludes turbine-generator set which is currently on-site). The gas turbine and diesel generators costs include the cost of the generator. All costs are referenced to 4th quarter 1977 (Marshall:Stevens equipment index = 523).

Table IV-6 TES Retrofit Applications for Concepts 1 Thru 4

Candidate	System Concept	Power Plant Efficiency	Material Cost, $\$ \times 10^6$	Container Cost, $\$ \times 10^6$	HT X Cost, $\$ \times 10^6$	Min Temp, °F	Max Temp, °F	System Cost, $\$ \times 10^6$	Notes
1. MgO	1	25.3%	1.97	0.11	DC	400	1000	2.1	1
2. Granite Limestone	1	25.3%	0.08	0.23	DC	400	1000	0.3	1
3. Draw Salt	2	25.3%	1.61	0.26	0.38	450	1000	2.2	2
	3	25.3%	1.61	0.26	0.26	450	1000	2.1	2
4. Oil	2	22.2%	2.40	0.86	0.49	375	600	3.7	3
	3	33.3%	2.40	0.86	0.46	375	600	3.7	3
5. NaOH	2	25.3%	3.60	0.66	0.23	650	1000	4.5	2
	3	25.3%	3.60	0.66	0.18	650	1000	4.4	2
6. Granite + Oil	2	22.2%	0.85	0.38	0.49	375	600	1.7	3
	3	22.2%	0.85	0.38	0.46	375	600	1.7	3
7. Li_2CO_3 Na_2CO_3 K_2CO_3	1	23.5%	4.08	0.09	0.56	750	1000	4.7	
8. NaOH	1	22.2%	2.39	0.07	0.60	600	1000	3.1	
9. SO_3	1	25.3%				1170	1308	11.0	
10. $MgCl_2 \cdot 2NH_3$ + $CaCl_2 \cdot 8NH_3$	4	25.3%	1.18	0.30	3.0	530	560	4.5	

Notes:

1. Direct contact (DC) heat exchange.
2. Stainless steel hardware.
3. Oil will need replenishment every 5 years (not costed).

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Table IV-7 New Installation Preliminary Costs

Candidate	System Concept	Power Plan Efficiency	Material Cost, $\$x10^6$	Container Cost, $\$x10^6$	HT X Cost, $\$x10^6$	Boiler Cost, $\$x10^6$	Min Temp, °F	Max Temp, °F	System Cost, $\$x10^6$
1. MgO	6	25.3	1.97	0.11	DC	0.20	400	1000	2.28
2. Granite	6	25.3	0.08	0.23	DC	0.20	400	1000	0.53
3. Draw Salt	5	25.3%	1.61	0.53	1.20	—	450	1000	3.33
4. Oil	5	22.2%	2.40	0.86	1.11	—	375	600	4.37
5. NaOH	5	25.3%	3.6	0.66	1.15	—	650	1000	5.41
6. Granite + Oil	5	22.2%	0.8	0.38	1.11	—	375	600	2.34
7. Li_2CO_3 Na_2CO_3 K_2CO	6	23.5%	4.08	0.09	0.56	0.20	750	1000	4.93
8. NaOH	6	22.2%	2.39	0.07	0.60	0.20	600	1000	3.26
9. SO_3	6	25.3%					1170	1308	11.0+
10. $NgCl_2 \cdot NH_3$ + $CaCl_2 \cdot 8NH_3$	5	22.2%	1.18	0.30	2.01	0.20	530	560	~3.60

Table IV-8 TES Vessel Dimensions

Candidate	Total Storage Volume ft^3	No. of Vessels	Vessel Dimension, L/D	Vessel Shape	Notes
1. MgO	5.877×10^4	2	122/19		
2. Granite	1.784×10^5	2	49/49	Cylinder	
3. Draw Salt	1.114×10^5	1	52/52	Cylinder	Thermocline
4. Oil	2.597×10^5 2.597×10^5	2 2	–/63 –/63	Sphere Sphere	2 Storage 2 Empty
5. NaOH	1.439×10^5	1	–/65 –/65	Sphere Sphere	1 Storage 1 Empty
6. Rock + Oil	3.901×10^5	5	47/47	Cylinder	Thermocline
7. Li_2CO_3 Na_2CO_3 K_2CO_3	8.70×10^4	1	48/48	Cylinder	
8. NaOH (PCM)	7.193×10^4	1	45/45	Cylinder	
9. SO_3	N/A	N/A	N/A		
10. $MgCl_2 \cdot NH_3$ + $CaCl_2 \cdot 8NH_3$	3.708×10^5	2 1	58/58 45/45	Cylinder Cylinder	

Table IV-9
Costs of Alternative Methods of Power Generation 10 MWe Capacity (10% Use)[1]

	Base Power Boiler		Gas Turbine	Diesel Engine
	Coal	Oil		
Installed Cost, $	2,078,000	1,520,700	1,596,000[2]	3,060,000[3]
Operation & Maintenance, ¢/kWe.h	0.122[2]	0.122[2]	0.500[3]	0.400[3]
Fuel Cost[4], ¢/kWe.h	1.37	2.74	4.11	2.74
Total Generating Cost, ¢/kWe.h	1.492	2.862	4.48	3.14
Total Lifetime Operating Cost, $[5]	3,921,000	7,521,000	11,773,000	8,252,000

[1]Costs based on 4th Quarter 1977.
[2]Estimated from base costs, Ref. IV-8.
[3]Estimated from costs, Ref. IV-9.
[4]Costs based on thermal-to-electric conversion efficiency of 25% and:
a. Coal - $1.00/MBtu
b. Oil - $2.00/MBtu
c. Gas - $3.00/MBtu
[5]Thirty-year system life, 10% use, 0% fuel or labor rate escalation.

Based on initial capital costs of the storage systems selected for further study (granite, limestone, cement clinker, and draw salt), the alternate methods of generation are not cost competitive. The lowest cost alternative method, coal-fired boiler, costs a total of $5,999,000 ($2,078,000 capital investment plus $3,921,000 for fuel and operating costs) in current 1977 dollars. In comparison the most expensive of the selected storage systems, draw salt, will cost $3.3 million. (This figure will be revised downward in detailed economic evaluation, pg. 109.) Therefore, one can conclude that the thermal storage costs can be justified using only the fuel, operation and maintenance costs of the alternative methods of power generation.

G. OUTSIDE USE OF WASTE HEAT ENERGY

As discussed earlier, high quality energy from the kiln gas could best be used through the production of electricity on site. Since the electrical energy requirements of the cement manufacturing process exceed those that can be produced, there is little incentive to sell the electricity off site. However, if an off-site customer could be found to use byproduct steam from the power generation cycle, the sale of steam may be advantageous. In this case, the question of steam availability if the kiln is shown down would need resolution before this would become practical.

The clinker cooler air waste heat energy is of low quality and quantity. If the energy at 350°F could be used to heat water for a district heating system, then typical costs for capital investment of a distribution system to a community approximately ½ mile from the plant may be:

Distribution lines (5000 ft)	$ 50,000
Pumps and heat exchangers	27,000
Storage system	18,000
Architectural & engineering	10,000
	$105,000

Using Plant 3, which has more available energy in the clinker cooler gas than the other three plants in this study, 481,000 Btu/hr is available at 350°F, using a ΔT of 150°F. The cost savings shown are compared for cities in which either electrical resistance heating or oil is the predominant form of heating.

Electrical energy savings:

(481,000 Btu/hr)(1/3413 kW·hr/Btu)($0.036/kW hr)(8769 hr/yr) = $44,400/yr

Oil energy savings:

(481,000 Btu/hr)($4.49/$10^6$ Btu)(8769 hr/yr) = $18,000/yr

One can readily see that the payback on electrical resistance heating savings is much more attractive than oil energy savings. The capital cost estimated in this example do not include a distribution heating system for the community which could be substantial if such a distribution system does not exist.

Exporting this low quality energy would also involve the problem of being accountable for the energy when kiln operation has ceased. Approximately once a year, the kiln may be down for 2 to 3 weeks for major brick repairs. Large quantities of storage media (such as ponds) could be heated for such a shutdown, thus, utilizing low temperature heat.

The use of low quality energy off site is extremely sensitive to the particular plant location, the type of energy now used in that area, the proximity to the user, and the type of distribution system required. The estimates given here indicate that in certain cases, off-site use of low quality energy may be economically attractive. However, it would involve a study of each individual plant to make that determination. This effort is beyond the scope of the present program but, might be investigated in a future study.

H. CONCLUSIONS

Results from this phase of the study indicated that thermal energy storage for on-site power generation would offer the most economical and technically viable application for near-term energy conservation. Several energy storage techniques were evaluated and screened for further study. The most promising thermal energy storage media are solids (granite, limestone, or cement clinker) or olten salts. Other techniques were dropped based upon either higher relative costs, lack of demonstrated reliability during temperature cycling, or lack of data on concepts. The primary application of stored energy is the reserve thermal energy required for power production when the cement kiln is down for scheduled or unschedule repairs. Load leveling effects of thermal engy storage are certain to increase plant productivity, but detailed evaluation could not be performed because of lack of actual electrical power requirements for the manufacturing operation on an hour-to-hour basis. Low temperature storage for district heating was shown to be less attractive based on today's energy prices. Long term benefits may be derived from low temperature storage as fuel and electricity rates increase.

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V. ENERGY CONSERVATION SYSTEM SIZING AND PERFORMANCE ANALYSIS

The two storage system concepts, rockbeds and draw salt, were analyzed in detail to determine system performance and sizing for the four model plants considered in this study. Flow diagrams and conceptual designs of the hardware and process equipment were prepared. Analytical computer models were developed for the two storage systems to aid in assessing the performance of candidate systems. These models couple the cement manufacturing process with the thermal energy storage system and the power generation application.

Both storage systems have been tested and technically evaluated under a number of investigations. Research programs that are in progress (Ref V-1) have aided in the evaluation of these candidate systems for cement industry applications. Solar power programs are currently evaluating similar storage concepts for reserve energy utilization when solar energy is not available.

Two storage systems were chosen for further analysis of specific advantages and potential problems. Both systems exhibit a cost advantage over the other storage candidates considered (see Chapter IV). Of the two systems, the rockbed storage system will be lower in cost. However, if the potential problem of dust plugging the rockbed cannot be resolved, then the draw salt system would have to be employed. Development work is necessary to evaluate the effect of fine cement dust passing through the bed before a decision can be made as to which system should be recommended.

A. ROCKBED SYSTEM PERFORMANCE

The rockbed storage units, consisting of either granite, limestone, or cement clinker, offer the most simple means of energy storage of the candidates considered. Therefore, this system will probably require lower capital investment from cement industrial applications. Shown in Figure V-1 are rockbed thermal energy storage (TES) units coupled with the kiln gas exit duct and power generation equipment. High-temperature energy is stored by passing a portion of the kiln gas over the rockbed surface. Similarly, low-temperature energy from the clinker cooler excess air is stored by passing this air over the rockbed. Upon discharge, ambient air is passed through the low-temperature TES unit, heated, and passed to the high-temperature bed. This air from the high-temperature TES unit is then sent through the waste heat boiler to generate steam and thus electrical power.

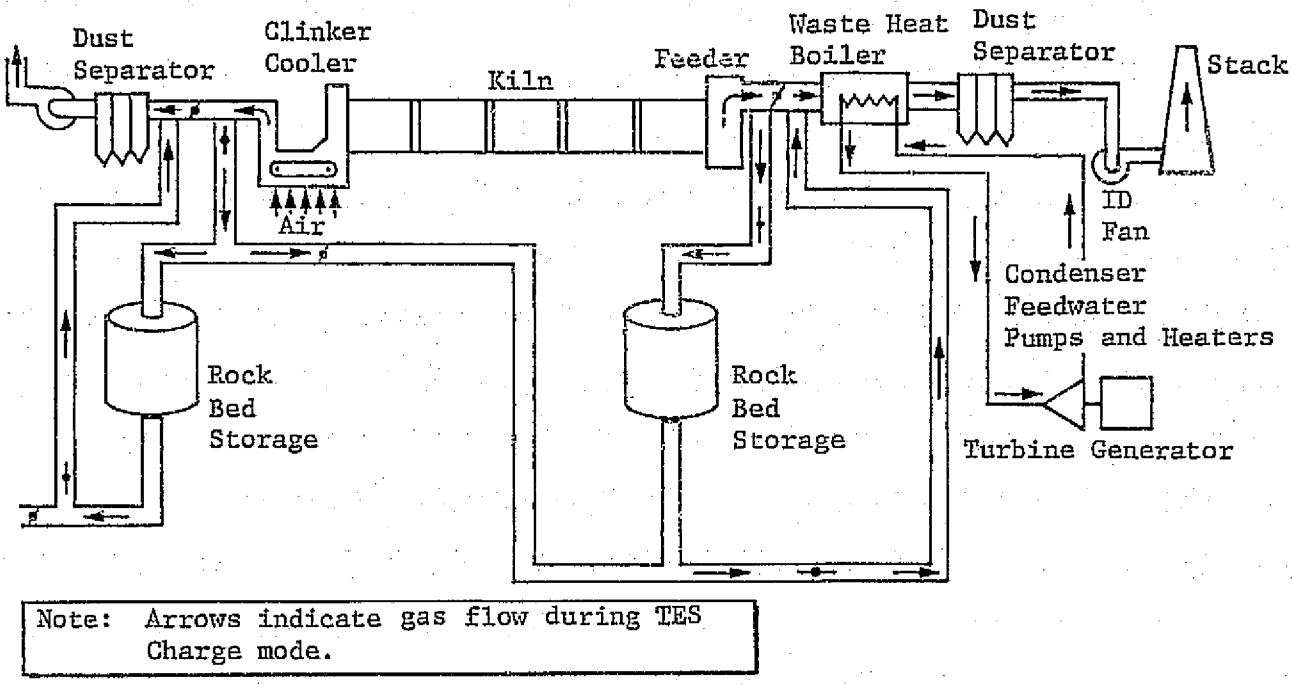


Figure V-1 Rock Bed/Waste Heat Boiler/Power Plant System Diagram

As seen in Figure V-1, the low-temperature and high-temperature storage modules are charged independently. During discharge, however, the storage modules (low-temperature beds and high-temperature beds) are connected in series to heat ambient air to high temperatures for steam generation in a waste heat boiler. The low-temperature or clinker cooler storage units will thus operate between ambient air temperature and the cooler excess air temperature, or in the range of 80°F to 350°F. The high-temperature TES units will nominally operate between 350°F and the kiln exit gas temperature ranging from approximately 700°F for suspension preheater kilns to a maximum of 1800°F for long, dry process kilns.

This system configuration was selected on specific process interface considerations. This arrangement, not only recovers and uses low-temperature energy from the clinker cooler excess air, but also prevents kiln exit gas constituents from condensing in the high-temperature beds. Through the use of low-temperature beds for preheating air during discharge, the high-temperature bed is maintained at a minimum temperature of 350°F, well above the dew point of the kiln exit gases. This concept will prevent the condensation of such corrosive compounds as sulfuric acid or nitrogen containing oxides or acids in the high-temperature bed. If the low-temperature bed were not used, ambient air flowing through the high-temperature bed would cool the bed to ambient temperature. During charging, hot gases from the kiln exit would then be cooled to rock temperatures that are initially at ambient temperatures, approximately 0 to 100°F. At these temperatures water, sulfur, and possibly nitrogen compounds would condense in the bed, on the rock, and promote corrosion of storage media, container walls, decrease heat transfer from gas to rock, and promote gas channeling through the bed.

The detailed design of the rockbed TES units has considered the size of the storage containers, system pressure drops, thermal performance of the rockbeds, and optimum system configurations. The pressure drop across a bed is a function of the geometry of the bed, bed particle size, and local gas conditions in the bed. Several useful empirically derived correlations are available to determine the pressure drop, ΔP, across rockbeds. One such correlation presented in a paper by Dunkel (Ref V-2) was used in the initial performance assessment:

$$\Delta P = \frac{f L G_o^2}{2 d_p \rho} \qquad \text{[V-1]}$$

where

f = friction factor = 42 + 3500/Re,

L = length of bed,

G_o = Gas mass flux through bed,

d_p = particle size,

ρ = gas density,

Re = Reynolds Number.

Particle size and bed height were varied to determine their effects on bed pressure drop. Shown in Figure V-2 are the results of a parametric evaluation of a 51-ft-diameter bed with varying bed heights and particle sizes. This gas flowrate chosen in this example, 760 lb/min, would be the approximate flowrate of kiln exit gases passing through a bed during charging of the TES unit. The void fraction in this evaluation was held at a constant value of 0.3 (volume of void/total volume of bed). These results indicate that excessive pressure drops will occur for particle sizes less than 1 in. in diameter; no significant reduction in pressure drop will occur for particle sizes greater than 2.0 to 2.5 in. in diameter.

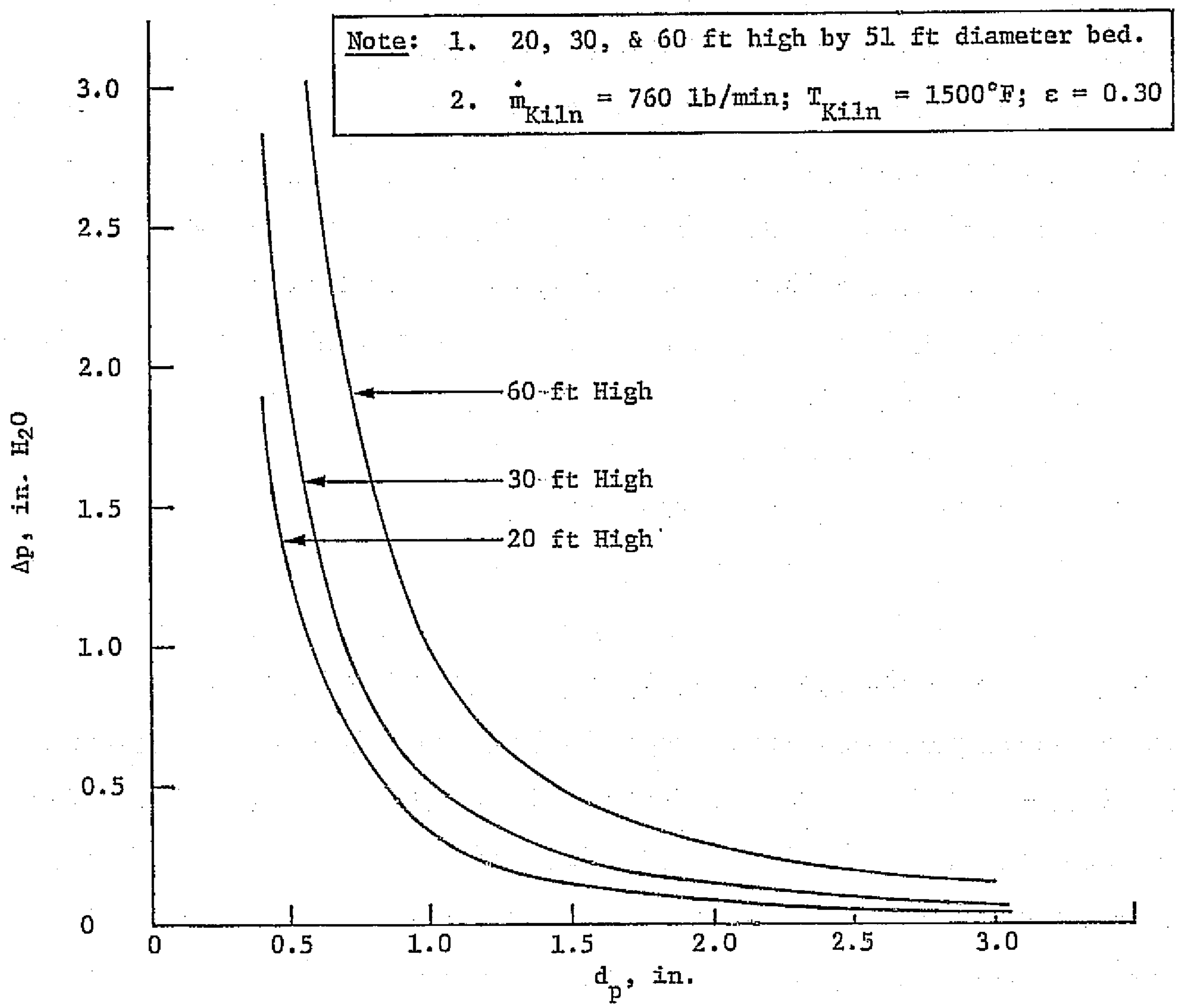


Figure V-2 Pressure Drop across Granite Bed

Using the same correlation, Eqn [V-1], the effect of bed length-to-diameter ratio on ΔP was examined. Shown in Figure V-3 is the pressure drop across a bed for given kiln exit gas flowrate, particle size, and bed void fractions. The results as shown in Figure V-3 indicate that for a bed L/D of greater than one (30 ft/30 ft), bed pressure drop increases excessively and an L/D of less than 0.5 (30 ft/60 ft) offers no significant reduction in pressure drop.

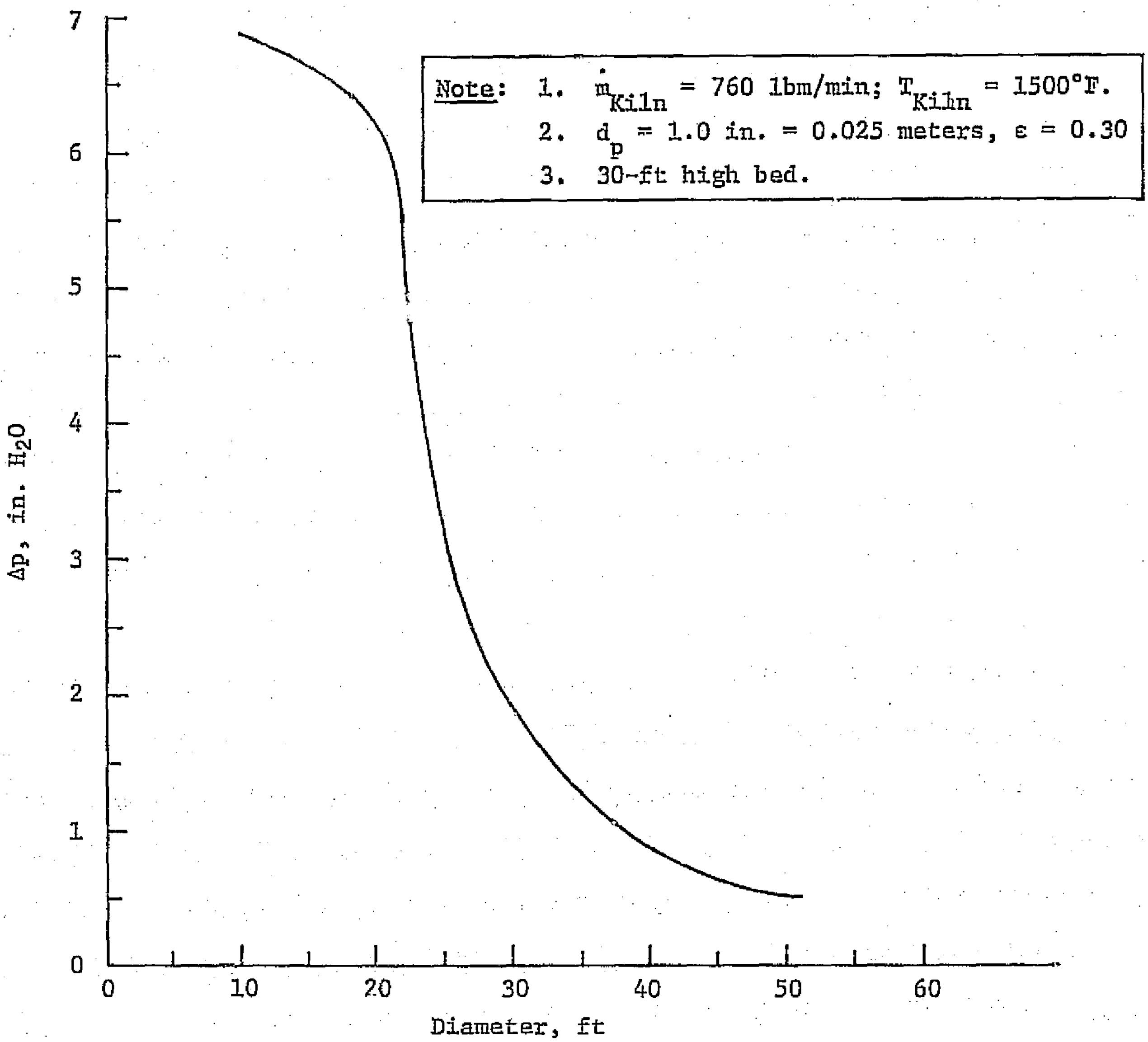


Figure V-3 Pressure Drop across Bed as a Function of Diameter

The heat transfer characteristics of rockbeds are another important design consideration. The kiln heat transfer coefficient between the gas and the rock material is strongly dependent on the superficial gas velocity through the bed. Correlations that were used in determing the effect of gas velocity on heat transfer coefficient were developed by Yoshida, et al. (Ref V-3) as follows:

[V-2] $$\frac{h}{C_{p_b} G_o} = 0.9 \, Re^{-0.51} \, Pr^{-0.67} \quad (Re<50)$$

[V-3] $$\frac{h}{C_{p_b} G_o} = 0.61\ Re^{-0.41}\ Pr^{-0.67} \quad (Re>50)$$

where

h = gas-particle film coefficient,

C_{p_b} = particle or bed specific heat,

G_o = gas mass flux = ρV,

Re = Reynolds number = $G_o\ d_p/6(1-\varepsilon)\mu$,

Pr = fluid Prandtl number = $C_p\ \mu/K$,

C_p = fluid specific heat,

μ = fluid viscosity,

K = fluid thermal conductivity,

ε = void fraction of bed,

V = gas superficial velocity,

ρ = fluid density,

d_p = particle diameter.

Equations [V-2] and [V-3] indicate that the heat transfer coefficient is roughly proportional to the square root of superficial gas velocity for Reynolds numbers less than 50 and proportional to $V^{0.59}$ for Re>50. Therefore, from a heat transfer point of view, the greater the gas velocity and thus the smaller the bed diameter, the better the exchange of energy from hot gases to cool rock or hot rocks to cool gases. However, recognizing that an upper limit occurs at bed L/D = 1 for reasonable pressure drop narrows the consideration of tank or vessel geometry. Also, a cylindrical tank of L/D = 1 would provide the minimum surface area for a given volume. This configuration minimizes heat loss to the environment and also minimizes construction materials and insulation costs. Therefore, from a cost standpoint, and as a compromise between heat transfer benefits and pressure drop evaluations, a cylindrical tank was chosen as the baseline container for the rock storage material with a length-to-diameter ratio of one. Other container shapes were considered (i.e., spheres, ellipsoids, etc) but the cylindrical tanks offer the best method of even flow distribution of gas through the bed.

Since the gases coming from the kiln exit and the clinker cooler are dust laden, the effect of dust accumulation in the beds was determined. The amount of dust loading in the gases, of course, depends on the particular kiln operation and process type. Also, the amount of dust entering the thermal storage rockbeds depends on the availability of existing dust separation equipment to be used before gas enters the TES. Typical dust loadings range between 3% to 20% of kiln gases on a weight basis. If no separation equipment is used before the kiln exit gas flows through the beds, and using 760 lb/min of gas entering the bed, then dust accumulation in the bed could be between 3.28×10^5 to 2.19×10^6 lb of dust over a 10-day period. Assuming a dust particle density of 94 lbm/ft^3 and a dust void fraction of 0.6, then dust accumulation could amount to 1.2 ft to 8.2 ft above the bed for one bed 60-ft in diameter. However, using existing dust separation equipment (i.e., multicyclones, electrostatic precipitators, gravel bed filters) dust loadings of gases can be reduced by 85% and more. The dust existing from such separation equipment and entering the rockbed storage units will have a very small particle size (less than 10 microns). How such dust accumulates in rockbeds consisting of 1- to 2-in. rock is not known at present. Possibly such dust would pass through the bed if gas velocities were high. It is obvious from this discussion that dust separation must be considered to avoid dust accumulation and hence increased pressure drop through the rockbed. The accumulation of dust in a gravel medium has been studied, evaluated, and tested on an industrial scale in the cement industry. Results from these applications (Ref V-4 through V-7) show that gravel beds themselves are effective filter devices and must be cleaned periodically.

The general rockbed storage system thus envisaged consisted of two modules, low-temperature storage for excess clinker cooler air and high-temperature for kiln exit gases, and one vessel per module. Each storage vessel was sized to the end use application, power generation for 24 hr, with an aspect ratio, L/D, equal to one.

1. Rockbed Storage System Sizing

Storage systems were sized for each of the four model plants described earlier in this report. The size of the storage system was estimated on the basis of power production at the cement plants during unscheduled maintenance shutdowns of the kiln. Nominally these shutdowns occur for a period of approximately 24 hr. Therefore, energy storage would be required to produce electricity when the prime source of energy, the kiln exit gases, is no longer available. As a basis for the sizing of TES units at the four model plants chosen in this study, energy storage requirements were determined for producing power at peak generating capability for a period of 24 hr.

Using the calculated rejected energy from four model plants, peak generating capability was determined for a waste heat boiler system and turbogenerator set. An upper waste heat boiler steam production limit of 600 psig/700°F steam was selected to keep equipment costs low. Higher quality steam would require expensive stainless steel construction. The minimum kiln gas exiting from the waste heat boiler was chosen as 350°F. This high exit temperature is necessary in some plants due to the possibility of sulfuric acid vapor condensation in the waste heat boiler at lower temperatures. However, for system evaluation comparison purposes, the lower limit of 350°F for exit gases from the waste heat boiler (WHB) was used for four model plants. Shown in Table V-1 is a summary of the major rejected energy streams from the four plants.

Table V-1 Gas Stream Summary of Four Model Plants

	Plant 1	Plant 2	Plant 3	Plant 4
Clinker Cooler Excess Air				
Flowrate, lbm/hr	2.62×10^5	1.96×10^5	6.45×10^5	1.72×10^5
Temperature, °F	350	350	350	350
Kiln Exit Gas				
Flowrate, lbm/hr	3.20×10^5	1.94×10^5	4.00×10^5	5.17×10^5
Temperature, °F	1150	720	800	1500

The amount of power that could be generated from these gas streams was calculated from the available kiln exit gas energy multipled by the thermal-to-electric conversion efficiency of typical turbogenerator systems using steam in the 700°F/600 psig range. Therefore, using Plant 4 as an example, the amount of power generated is:

[V-4] $$\text{Electrical power (KWe)} = \frac{\dot{\omega} C_p \Delta T}{3413} \times \text{(thermal to electric conversion efficiency)}$$

$$= \frac{5.17 \times 10^5 (0.28)(1500-450) 0.23}{3413}$$

$$= 1.024 \times 10^4 \text{ KWe.}$$

where:

$\dot{\omega}$ = gas mass flowrate,

C_p = gas heat capacity,

ΔT = Temperature difference of gas entering and exiting waste heat boiler.

Thus, Plant 4 can produce approximately 10 MW of electrical energy from one kiln. For single-kiln plants of this production capacity, electrical energy requirements of the cement plant exceed this generating capability. Therefore, the plant can use all of its generated power. For larger plants, however, with multikiln operation, it may be possible to generate more electricity per kiln system than the plant requires.

As discussed in previous chapters, the main benefit of thermal energy storage would be the capability to generate power while the kiln is shut down for unscheduled repairs and maintain the operations of raw feed grinding, finish grinding, and facilities. If the production rate of one kiln is 70 tons of clinker per hour and the industry-wide average electrical energy usage is 150 kWh/ton, then the energy usage is 10.5 MWe for one kiln and associated equipment. When the kiln is down, one can expect a 20 to 30 kWh/ton reduction in power requirements. Thus assuming a 120 to 130 kWh/ton generation requirement for 24 hr while the kiln is down then the thermal energy storage requirement is:

[V-5] $$\text{Energy Storage (kWe} \cdot \text{hr)} = \text{kWh/ton} \times \text{tons/hr} \times \text{hr}$$

$$= 130 \times 70 \times 24$$

$$= 2.184 \times 10^5 \text{ kWe} \cdot \text{hr.}$$

In sizing the thermal energy storage rockbed system, the kiln gas or high temperature storage requirement would be slightly greater than the above figure, since all the energy extracted from the units would not be usable (this will become evident in later discussion). Therefore, using a figure of 90% of the energy stored as being usable raises the TES energy requirement to 2.43×10^5 ($2.184 \times 10^5/0.90$) kWe/hr. In terms of thermal energy requirements, using a factor of 0.23 for thermal-to-electric conversion efficiency, then the storage requirement is 1.05×10^5 kWt · hr or 3.61×10^9 Btu ($2.43 \times 10^5 \times 3413/0.23$).

The clinker cooler storage unit was sized on the basis of the amount of preheat required for the high temperature beds during the discharge mode for power production. In our example, the air flowrate requirement is 4.67 lbm/hr $\{3.61 \times 10^9$ Btu/[24 hr $\times$ 0.28 Btu/lbm-°F $\times$ (1500°F − 350°F)]$\}$ and the low temperature storage must heat ambient air at 80°F to 350°F, then the clinker cooler excess air storage unit requirement is:

[V-6] Energy Storage (Btu) = $\dot{\omega} C_p \Delta T$ x discharge time

$$= 4.67 \times 10^5 \times 0.24 \times (350 - 80) \times 24$$

$$= 7.26 \times 10^8 \text{ Btu.}$$

And again assuming 90% of energy stored is usable gives an energy storage requirement of 8.07×10^8 Btu.

The amount of storage material (i.e., granite, limestone, cement clinker) is then calculated from the known heat capacity of rock and the temperature difference of the rock during charging. Using the variable, Q, as the energy storage requirement. The amount of rock is calculated as:

[V-7] Weight of storage medium = $Q/C_p \Delta T$

$$= 8.07 \times 10^8 / 0.2(350 - 80)$$

$$= 1.49 \times 10^7 \text{ lbm.}$$

Using a rock density of 150 lbm/ft^3 and a bed void fraction of 0.3 results in a volume requirement of 1.42×10^5 ft^3 {1.49×10^7 lbm/[150 x (1 - 0.3)]}.

The method described above was used in determining the thermal energy storage unit sizes for the four model plants. Shown in Table V-2 are the various sizes of storage tanks and storage material required for the various plants. Calculations indicate that the low temperature and high temperature storage units are of approximately equivalent size. Again for each plant, a total of two storage vessels would be required.

Waste heat boiler performance is strongly dependent on the manufacturers' individual design. Some manufacturers do not have off-the-shelf waste heat boilers for gas streams less than 1000°F. Figure V-4 shows a typical waste heat boiler configuration outfitted with soot blowers and soot hopper for dust laden gases. Table V-3 lists typical data and performance of the waste heat boiler shown in Figure V-4. In this example, the gas temperature leaving the economizer is 320°F. The energy transferred from the gas to the steam is thus 4.956×10^7 Btu/hr. Assuming an efficiency of 0.21 thermal to electric, which is typical for these storage conditions, this unit would provide steam for power production of 3.05 MWe. The cement kiln used in this example is small in comparison to the kiln analyzed from Plant 4.

Table V-2 Rockbed Storage Sizing Results for Four Model Plants

	Plant 1	Plant 2	Plant 3	Plant 4
Clinker Cooler Air Storage				
Thermal Storage Required, kWt·hr	1.53×10^5	1.29×10^5	1.91×10^5	2.47×10^5
Btu	5.22×10^8	3.17×10^8	6.53×10^8	8.44×10^8
Temperature Range, °F	80-350	80-350	80-350	80-350
Weight of Rocks, lbm	1.07×10^7	6.53×10^6	1.34×10^7	1.74×10^7
Volume Required, ft^3	1.02×10^5	6.21×10^4	1.28×10^5	1.65×10^5
Number of Storage Vessels	1	1	1	1
Vessel Dimensions (L/D), ft/ft	50.7/50.7	42.9/42.9	54.6/54.6	59.4/59.4
Kiln Exit Gas Energy Storage				
Thermal Storage Required, kWt·hr	5.04×10^5	1.42×10^5	3.55×10^5	1.17×10^6
Btu	1.72×10^9	4.83×10^8	1.21×10^9	3.99×10^9
Temperature Range, °F	350-1150	350-720	350-800	350-1500
Weight of Rock, lbm	1.19×10^7	7.25×10^6	1.47×10^7	1.93×10^7
Volume Required, ft^3	1.14×10^5	6.90×10^4	1.42×10^5	1.84×10^5
Number of Storage Vessels	1	1	1	1
Vessel Dimensions (L/D), ft/ft	52.5/52.5	44.5/44.5	55.6/55.6	61.6/61.6

Other prime movers were considered for Rankine cycle power production. Specifically, organic fluids instead of steam were investigated to determine if any beneficial effect could be realized for cement industry power production either technically or economically. Thermo Electron has shown that for certain flue gas temperatures (500 to 1000°F) an organic Rankine cycle power generation may be more advantageous in terms of cost than steam systems (Ref V-9). However, they have also shown that these systems are only competitive in the small power generation capability (i.e., less than 1 MWe). Therefore, based on the amount of rejected energy from the kiln for all process types (long dry, suspension preheater, etc), the organic vapor system was ruled out as a possibility.

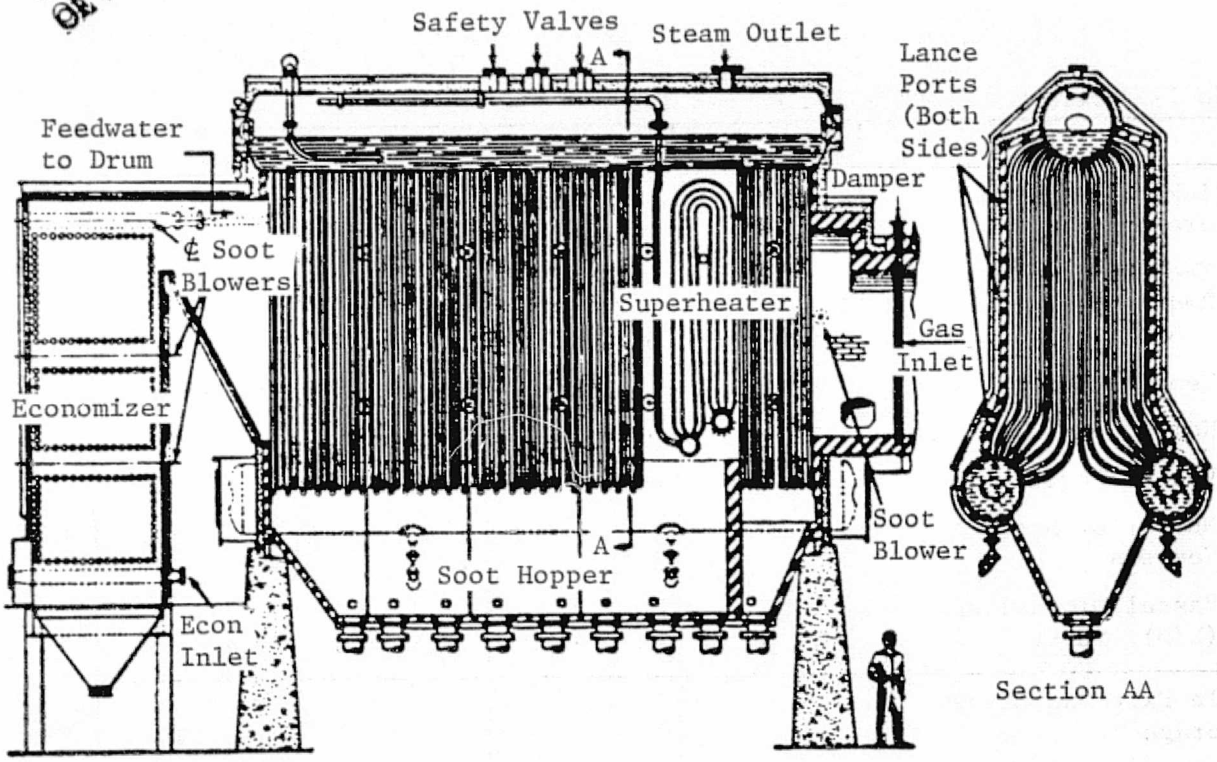


Figure V-4
Three-Drum Bent-Tube Waste-Heat Boiler Fitted with Lance Ports and Soot Blowers

Table V-3
Performance of Three-Drum Unit (Fig. V-4)
Waste Gas from Cement Kiln

Boiler Heating Surface, sq ft	12,000
Superheater Surface, sq ft	523
Steam Flow, lb/hr	43,000
Flue Gas Entering Boiler, lb/hr	150,000
Gas Temperature Entering Boiler, °F	1,500
Gas Temperature Leaving Boiler, °F	438
Gas Temperature Leaving Economizer, °F	320
Steam Pressure at Superheater Outlet, psi	200
Steam Temperature at Superheater Outlet, °F	480
Feedwater Temperature Entering Economizer, °F	212
Draft Loss, Boiler, Superheater, and Economizer, in. Water	9.6
Reference V-8	

2. Rockbed System Model Development and Performance Analysis

A computer model was developed to aid in the analysis and performance assessment of rockbed storage units. This model was structured to describe the rockbed performance coupled with waste heat boiler performance over the anticipated charge and discharge cycle. More detailed discussion of this model is contained in Appendix A. Specifically, the model calculates temperatures, flowrates, pressure drops, heat exchanger performance, and power generation as functions of time throughout storage charge and discharge cycling.

Two different techniques were used in predicting the performance of the rockbed storage systems. The rockbed storage model uses one of two options to predict the exit gas temperature from the TES unit as a function of time. One option is a correlative analytical solution developed by Dunkle (Ref. V-2). This particular model predicts outlet gas temperatures in terms of nondimensional characteristic parameters of fluid flow through the bed. The advantage of this model option is its simplicity, fast solution, and verification with experiment. The disadvantage, however, is that the solution requires an initial isothermal bed. Shown in Figures V-5 and V-6 are the outlet temperatures and quantity of stored/extracted energy for high temperature and low temperature TES units using the Dunkle solution for the conditions expressed on the graphs.

The second option of the rockbed TES system model exercises a finite difference nodal network scheme to predict temperature profiles through the bed as well as output gas temperature. This model option is also capable of prediction of TES exit gas temperatures starting with nonisothermal beds, making it more general than the Dunkle model. However, this model requires more time to execute than the Dunkle model. Both options were programmed so results from each solution could be compared.

The rockbed storage model contains a detailed heat exchanger performance subprogram. This subprogram is capable of determining two fluid stream temperatures of a heat exchanger given the other two fluid temperatures, overall heat transfer coefficient, heat exchange surface area, and heat exchanger tube and shell configuration. This routine provides direct information on whether a heat exchanger has been sized sufficiently for a given duty. The methods developed by Kays and London (Ref V-10) for heat exchanger performance analysis have been used to develop this routine. These methods determine specific heat exchanger performance for pure countercurrent, crossflow, and various configurations of shell-and-tube heat exchangers.

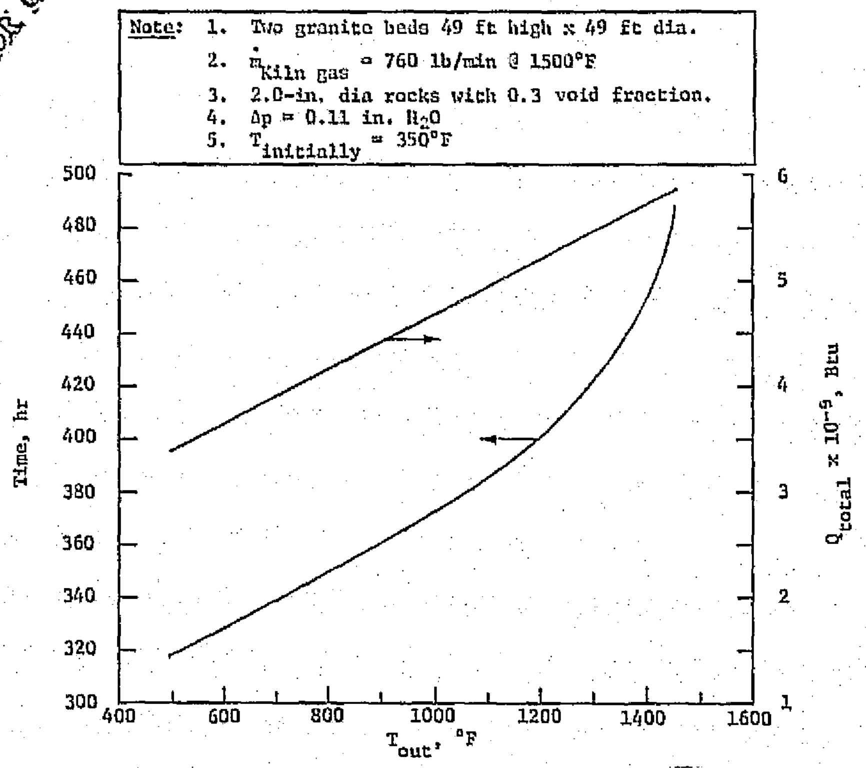


Figure V-5 High Temperature Rock Bed Performance

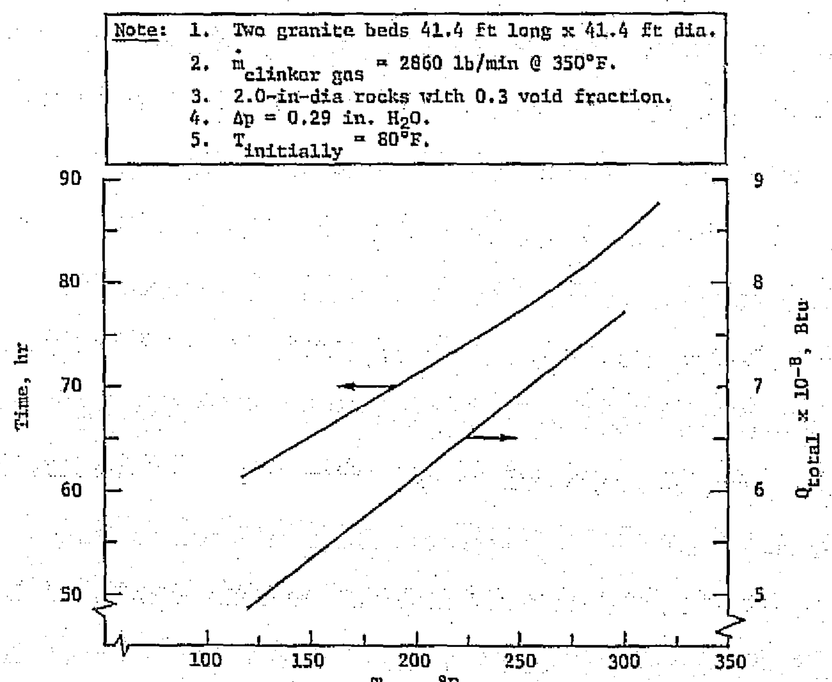


Figure V-6 Low Temperature Rock Bed Performance

As an initial check on model accuracy, both models were formulated and executed to compare performance prediction results. Shown in Table V-4 are exit temperatures predicted by both models as functions of time for a 49-ft by 49-ft cylindrically shaped rockbed. As one can see in this table, predicted exit temperatures disagree considerably. This discrepancy led to a critical examination of both methods and resulted in the following conclusions. Exit temperatures from the rockbed should not reach the charging gas temperature unless the bed has been fully charged. The Dunkle formulation has indicated that the bed is fully charged after 500 hr for the conditions presented in Table V-4. However, the finite difference technique shows lower predicted temperatures over the charging time than the Dunkle model. According to the time integrated method of calculating energy stored in the rock material by the finite difference technique, more energy is capable of being stored after 500 hr (i.e., the bed should not be fully charged). The reasons for the discrepancies of prediction of exit gas temperature can be summarized as:

1) The Dunkle formulation relies on interpolation of parameterized functions consisting of values of bed geometry and gas flow conditions that can be grossly inaccurate during initial and final charging phases.

2) The Dunkle formulation relies on average gas and rock material thermophysical properties (i.e., heat capacities, viscosities, densities), whereas the finite difference technique calculates these properties throughout the bed at nodal points.

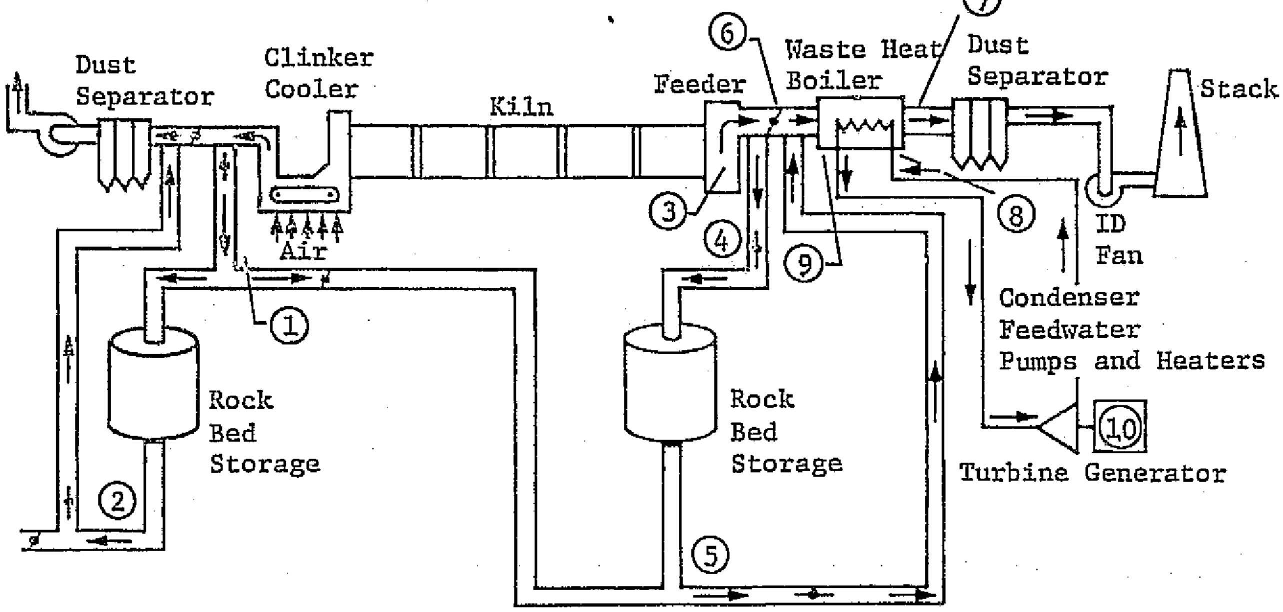
3) Film heat transfer coefficients were estimated using correlations unique to each model and each supported by experimental evidence. Therefore, the finite difference technique was judged to be more accurate in terms of predicted temperatures, energy stored, and overall system performance. The finite difference model was thus the primary model used to assess system performance. Using the computer model, calculations were performed for the rejected energy conditions from the kiln exit gas and clinker cooler excess air for Plant 4. The anticipated charge condition for the high temperature beds was 10% of the kiln exit gas flowrate through a bed 61.6 ft in diameter and 61.6 ft long. All of the clinker cooler excess air was passed through a low temperature bed 59.4 ft by 59.4 ft. The charge phase of the cycle lasted 240 hr or 10 days. During discharge ambient air at a flowrate of 4.75×10^5 lbm/hr was passed through the low temperature and high temperature beds connected in series. Performance was evaluated for discharging over a 24-hr period.

Table V-4 Comparison of Models, 49-ft x 49-ft Bed

Time, hr	Dunkle, °F	Finite Difference, °F	Time, hr	Dunkle, °F	Finite Difference, °F
Charge Conditions: 1500°F Temperature, Flowrate = 4.56 x 10^4 lb/hr; Initial Bed Temperature: 350°F					
Gas Exit Temperatures					
0	350	350	260	426	351
20	353	350	280	439	355
40	356	350	300	526	364
60	359	350	320	636	385
80	362	350	340	796	424
100	365	350	360	962	488
120	368	350	380	1140	580
140	371	350	400	1270	698
160	374	350	420	1340	833
180	379	350	440	1400	974
200	399	350	460	1470	1108
220	414	350	480	1490	1223
240	417	350	500	1500	1315

Various conditions in the process flow diagram were calculated by the computer model for the assumptions described above. Shown in Figure V-7 are the process flow points of interest. Table V-5 describes the conditions at these various points over the charge and discharge cycle. Also shown in Figures V-8, V-9, and V-10 are the computed results of model calculations. The figures show the kiln gas exit temperatures, quantity of stored energy, and power generated over the charge and discharge times. These results show that over 8 MWe can be generated for up to 18 hr during discharge for an air flowrate of 4.75 x 10^5 lbm/hr. Air flowrate could be varied, however, during discharge to match demand requirements.

Shown in Figure V-8 is the exit temperature of a kiln exit gas storage bed during charge and discharge. The temperature of the exit gas does not increase until the seventh day of a 10-day charge cycle. Upon discharge, exit temperatures immediately rise to 1500°F as gas flow is reversed through the bed and are maintained at that temperature for approximately 18 hr. Temperatures begin to degrade thereafter finally decreasing to 1100°F



Note: See Table V-5 for system constants.

Figure V-7 Rock Bed/Waste Heat Boiler/Power Plant System Diagram

Table V-5 Rockbed Computer Model Performance Prediction

System Modeled:		Initial Conditions:	
Plant 4 Storage System Size and Mass and Energy Flowrates Clinker Cooler Excess Air Storage Unit - 59.4 ft diameter x 59.4 ft high Kiln Exit Gas Storage Unit - 61.6 ft diameter x 61.6 ft high		Low Temperature Bed - 80°F High Temperature Bed - 350°F	
System Constants:			
Charge:		Discharge:	
1)*	350°F	2)	4.75×10^5 lb/hr, 80°F
2)	1.72×10^5 lb/hr	3)	0.0 lb/hr
3)	5.17×10^5 lb/hr, 1500°F	4)	4.75×10^5 lb/hr
4)	5.17×10^4 lb/hr, 1500°F	6)	4.75×10^5 lb/hr
6)	4.65×10^5 lb/hr	8) & 9)	9.127×10^4 lb/hr
8) & 9)	9.127×10^4 lb/hr		

*Refer to Figure V-7 for Source Locations.

Table V-5 (concl)

Time, hr	°F (1)	°F (2)	ΔP psia (1)-(2)	°F (4)	°F (5)	ΔP, PSIA (4)-(5)	°F (6)	°F (7)	°F (8)	°F (9)	Power MWe (10)
Charge											
0		80	0.017		350	0.078	1385	426	882	142	8.78
10		80	0.017		350	0.078	1385	426	882	142	8.78
20		80	0.017		350	0.078	1385	426	882	142	8.78
30		80	0.017		350	0.078	1385	426	882	142	8.78
40		80	0.017		350	0.078	1385	426	882	142	8.78
50		80	0.018		350	0.078	1385	426	882	142	8.78
60		87	0.018		350	0.078	1385	426	882	142	8.78
70		118	0.018		350	0.078	1385	426	882	142	8.78
80		186	0.019		350	0.078	1385	426	882	142	8.78
90		263	0.020		350	0.078	1385	426	882	142	8.78
100		317	0.021		350	0.078	1385	426	882	142	8.78
110		341	0.021		350	0.078	1385	426	882	142	8.78
120		348	0.021		350	0.078	1385	426	882	142	8.78
130		350	0.021		350	0.078	1385	426	882	142	8.78
140		350	0.022		350	0.078	1385	426	882	142	8.78
150		350	0.022		350	0.078	1385	426	882	142	8.78
160		350	0.022		350	0.078	1385	426	882	142	8.78
170		350	0.022		351	0.078	1385	426	882	142	8.78
180		350	0.022		353	0.078	1385	426	882	142	8.78
190		350	0.022		358	0.079	1386	426	882	142	8.78
200		350	0.022		367	0.079	1387	426	882	141	8.79
210		350	0.022		385	0.080	1388	426	883	140	8.80
220		350	0.022		413	0.081	1391	425	884	139	8.85
230		350	0.022		455	0.082	1396	425	886	137	8.89
240		350	0.022		514	0.085	1401	425	889	135	8.95
Discharge											
243	350		-0.105	1500	350	0.220	1500	421	928	163	9.16
246	350		-0.105	1500	350	0.220	1500	421	928	163	9.16
249	350		-0.105	1500	350	0.220	1500	421	928	164	9.15
252	350		-0.105	1497	350	0.220	1497	422	927	166	9.12
255	350		-0.105	1478	350	0.220	1478	423	919	176	8.81
258	349		-0.105	1418	349	0.210	1418	427	893	193	8.37
261	347		-0.104	1291	347	0.200	1291	436	839	358	6.62
264	334		-0.104	1107	334	0.182	1107	448	759	300	5.45

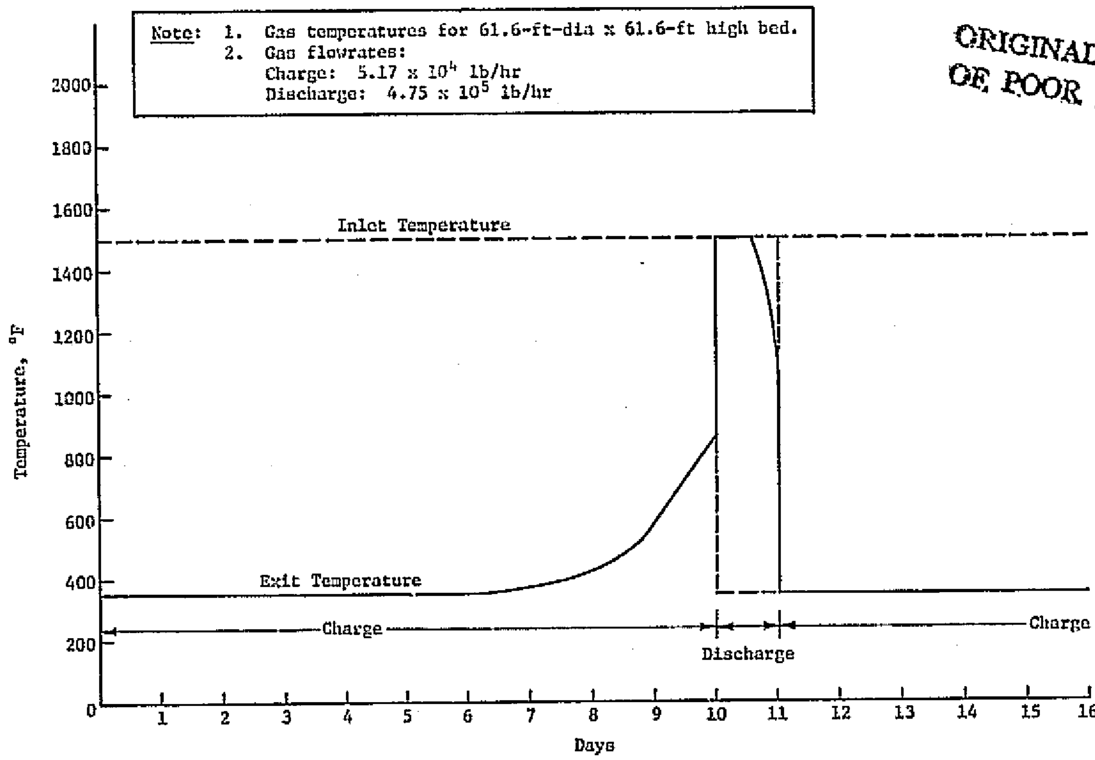


Figure V-8 Rockbed Gas Temperatures during Cycling

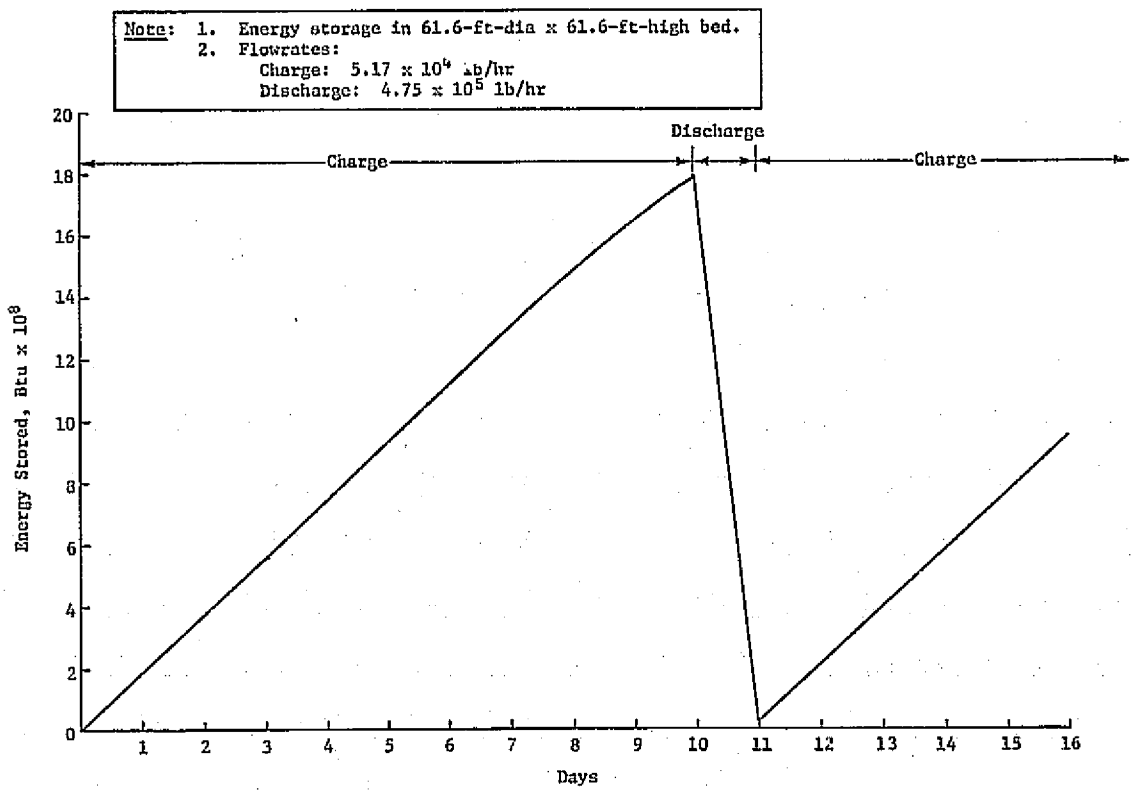


Figure V-9 Rockbed Energy Storage during Cycling

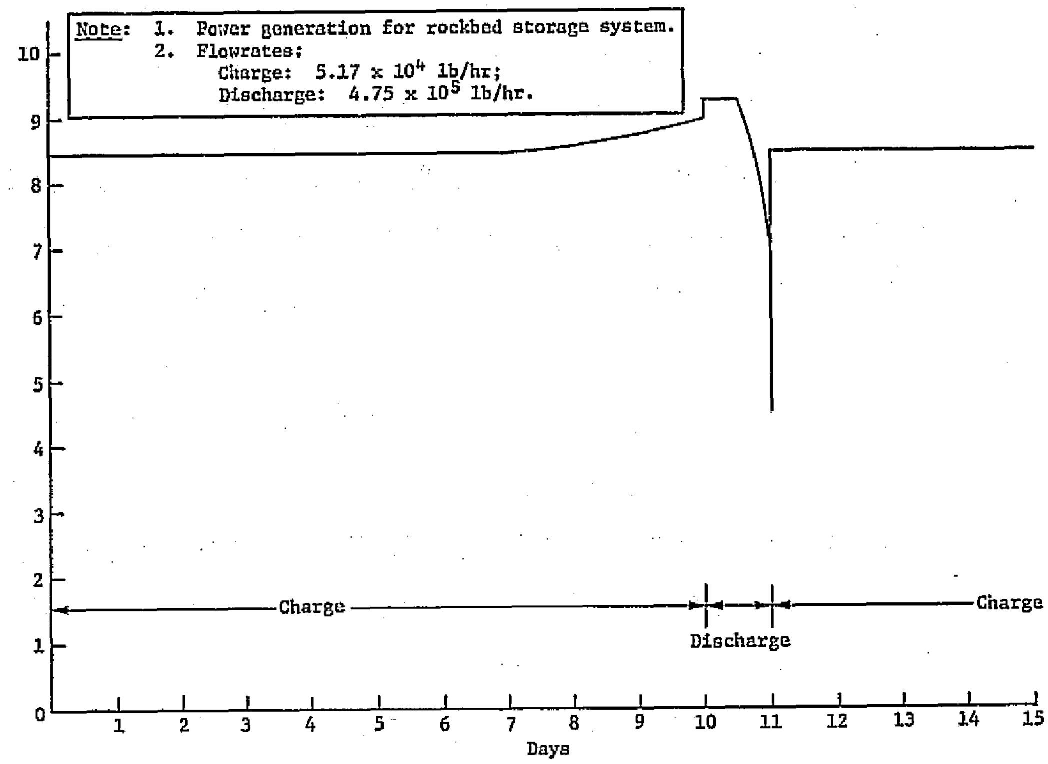


Figure V-10 Power Generation during Cycling

at the end of the 24-hr discharge cycle. The power generated during charging and discharging of the beds is shown in Figure V-10. Note that approximately 9 MWe is produced continuously over the period of time, even when the kiln is down for a 24-hr period.

The model, as formulated, assumes that steam/water flowrate is constant. In actuality, however, steam flowrate would be varied to achieve desired superheated steam conditions. The model indicates that during the latter part of the discharge cycle, superheated steam temperatures decrease and feedwater temperatures increase. In actual operation, the steam/water flowrate would be varied using an essentially constant feedwater condition and providing constant steam temperatures for the turbine. Such a control method would have been useful in the computer model, but was beyond the scope of this program. The calculated power generated would be approximately the same in either case because the calculation is based on energy transferred in the waste heat boiler and an assumed 0.227 conversion factor for the thermal-to-electric conversion efficiency.

Results from computer-aided analysis have shown that rockbed storage units can be used effectively for power generation when the kiln rejected heat is no longer available. Total system pressure drops that occur primarily across the rockbeds are less than 10 in. of water (<0.3 psia) even during maximum discharge flow conditions. Power generated during discharge can be sustained 75% of the time at maximum power generation capability and 100% of the time for at least 60% of maximum generation capability.

B. DRAW SALT SYSTEM PERFORMANCE

The molten draw salt TES system coupled with the kiln gas heat exchanger and power production system is shown in Figure V-11. During the TES charge mode, energy is extracted from the kiln gas via a heat exchanger which has molten salt on the tube side serving as a heat transfer medium. This draw salt, once heated by the kiln gas is returned in part to a TES vessel containing both hot and cold salt. A major portion of the salt is sent to a salt/steam boiler system. The hot and cold salt is separated by a thermal gradient between the salts. This gradient, or thermocline, can be maintained for a long period of time due to the relatively low thermal conductivity of the salt. The minimum storage temperature of the salt is limited to its melting point of 430°F.

When the kiln is down, the stored hot salt is pumped out of the TES unit through the steam generation system. The cooled salt from the preheat heat exchanger is returned to the bottom of the TES vessel. Steam is generated until the hot salt has been expended. Typical charge and discharge cycles for this system would consist of diverting approximately 10% of the hot salt from the gas-salt heat exchanger to storage for a period of 10 days and then expending the stored salt for power production during a discharge period of 24 hr.

The system concept uses three separate heat exchangers for the production of steam. To minimize material costs of the heat exchangers, a maximum superheated steam condition of 600 psig 700°F was considered as in the waste heat boiler system for rockbed TES system. The superheat exchanger is a single pass shell and tube heat exchanger with counterflow between the salt on the shell side and steam on the tube side. The design pressure would be 100 psig on the shell side and approximately 500 to 700 psig on the steam side. The boiler is a horizontal U-tube, kettle-type configuration. Salt flow is on the tube side with water/steam on the shell side. The design pressure is 500 to 700 psig on the shell and 100 psig on the tube side. The feedwater

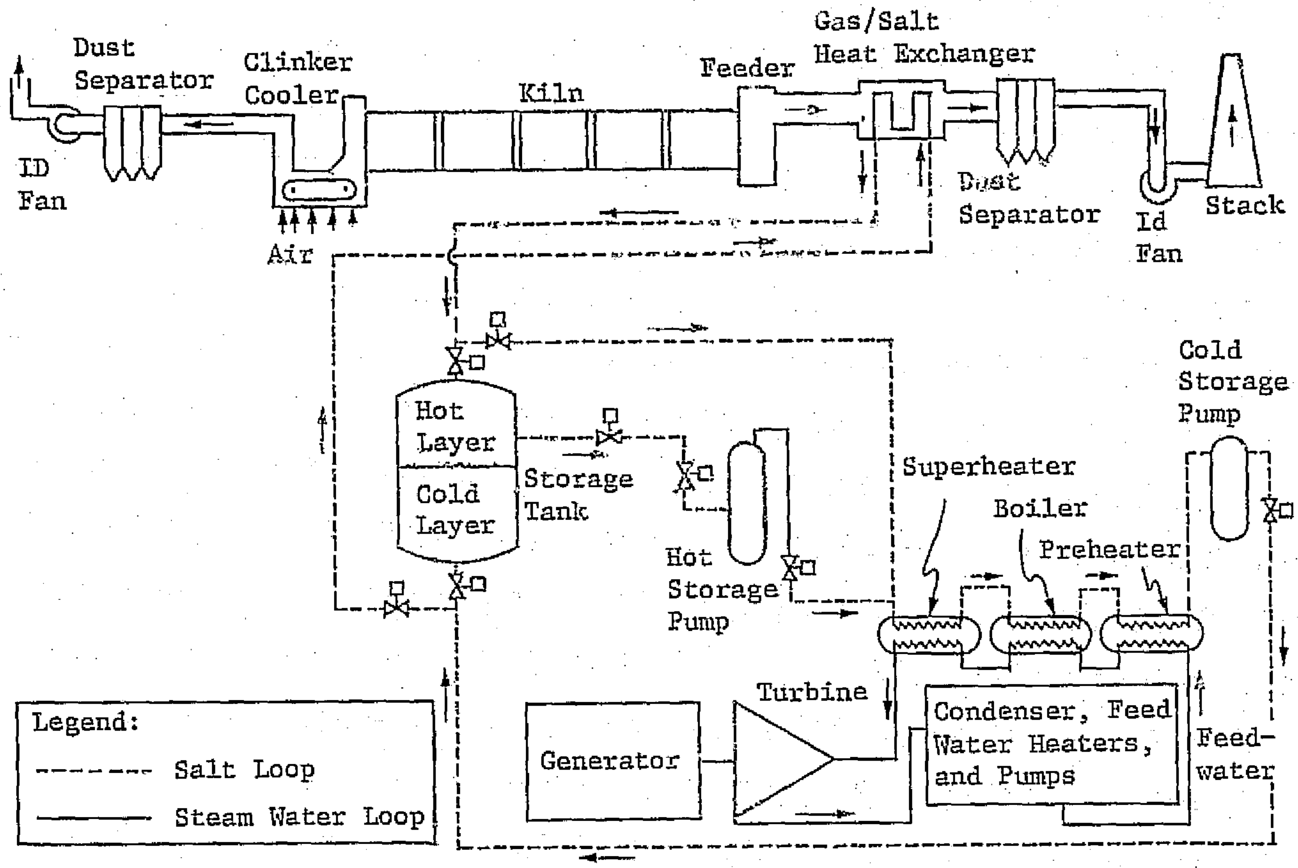


Figure V-11 Draw Salt/Steam Generator/Power Plant System Diagram

preheater may be a multipass shell and tube heat exchanger with counter flow between the salt on the shell side and water on the tube side. The shell side is at a design pressure of 100 psig, and the tube side at 500 to 700 psig.

Key design considerations for the draw salt system are the construction of the thermal energy storage vessel, corrosion of materials in contact with the salt, and adequate safeguards to prevent freezing of salt in transport lines and storage tanks. Another important consideration is the salt's compositional stability over the anticipated 30-year lifetime.

At Martin Marietta's Denver Division current efforts are assessing the design requirements of the draw salt storage system (Ref V-1). Tests being performed in these programs will determine corrosion rates of various materials in contact with the salt at high temperatures, stability of the thermocline in storage tanks, heat transfer coefficients at low and high temperatures, and structural requirements of materials in contact with the salt. Preliminary results from these programs for solar power applications have aided considerably in assessing materials of construction, thermocline behavior, and heat transfer characteristics of the draw salt storage system.

Of primary concern in the design of a thermal storage tank for the draw salt is the minimization of thermal stress in the container walls. In the exposed wall surface next to the thermocline, temperature differences of 50°F to 600°F can be experienced in a vertical distance from 1 to 3 ft. One method to minimize the effects of this thermal gradient on wall stresses would be to use an internal insulation in a cylindrical tank. This insulation would need to be compatible with the salt and stable over the low- and high-temperature excursions of the salt. Another possible method would be through the use of spherical rather than cylindrical tanks. Bending stresses for spherical tanks may be less than comparable volume cylindrical tanks, thus alleviating the need for internal insulation or large wall thicknesses.

Corrosion by draw salt on carbon steel can be substantial. However, tests conducted at Martin Marietta (Ref V-1) have shown that minimal corrosion is realized with a mild grade of alloy steel. Therefore, any equipment in contact with the draw salt, including transport lines, pumps, heat exchangers, and storage vessels should be composed of an alloy steel material. Stainless steels may be required if temperatures exceed 900°F.

System design must contain measures to prevent freezing of the salt in storage vessels, transport lines, and heat exchangers. An electric or fossil-fueled heater must be incorporated into the storage vessel to be used in startup operation after long-term shutdown. Transport lines should be steam traced and provided with adequate insulation. To minimize salt solidification in heat exchangers and transport lines, equipment external to the storage vessel should be drained before long-term system shutdown.

The draw salt compositionally consists of 54% of KNO_3 and 46% of $NaNO_3$ by weight. Other nitrate-nitrite salts were considered even though they have a proven record of instability at high temperatures. Salt stability increases as the nitrite concentration is decreased. Also, as nitrite concentration is decreased, the melting point of the eutectic mixture increases. Minimizing the nitrite composition in the heat transfer salt assures long-term stability of the salt mixture. When maintained in a storage vessel, the draw salt mixture is covered by an oxygen "blanket" to minimize nitrite forming tendencies at high temperatures.

1. Draw Salt System Sizing

Equipment sizes required for installation of the draw salt system at the four model plants were estimated. Tanks, heat exchangers, piping, and pumps were sized according to the amount of rejected energy at each plant as itemized in Table V-1. Draw salt requirements for power generation during a 24-hr period at maximum capability of an on-site electrical power generator were determined.

Again, based on the conditions at the four model plants, molten-salt flowrates and temperature ranges, and optimized steam conditions as previously set forth, heat exchanger surface areas were estimated and are itemized in Table V-6. Overall heat transfer coefficients, U_o, were estimated using correlations for tube and shell side film coefficients presented in Ref V-11 and estimated fluid flow conditions. Surface areas were determined for specific flow configurations as itemized below:

1) Gas-salt heat recovery exchanger - pure counter-current flow;

2) Superheater - shell and tube - 1 shell pass, 2 tube passes;

3) Boiler - shell and tube - 1 shell pass, 2 tube passes;

4) Preheater - shell and tube (multipass) depending on duty - 1, 2, or 3 shell passes, 2, 4, or 6 tube passes.

Fluid stream temperatures were calculated for each of the three steam generator heat exchangers, given the steam saturation conditions of temperature and pressure. These conditions varied from plant to plant to match salt flow conditions in the heat exchangers. The tables and equations presented by Kays and London (Ref V-10) were used to determine the required heat exchanger surface areas once temperatures and thus quantity of heat transferred were calculated. The number of transfer units, NTU, is a measure of the required duty of a heat exchanger and is defined as:

[V-8] $$NTU = \frac{U_o A}{C_{MIN}}$$

where

U_o = overall transfer coefficient,

A = heat exchange surface area,

C_{MIN} = minimum capacity flowrate of the two streams passing through heat exchanger $(\dot{\omega} C_p)_{MIN}$,

Table V-6 Draw Salt System Heat Exchanger Performance Summary

	Flowrate, lb/hr		T_{IN}, °F		T_{OUT}, °F		Surface Area, ft^2	U_o, Btu/hr °F ft^2	NTU
	(1)	(2)	(1)	(2)	(1)	(2)			
Plant 1									
Gas-Salt (1) (2)	3.195 x 10^5	3.654 x 10^5	1150	450	470	900	6.262 x 10^4	10	7.0
Superheater Salt-Steam (1) (2)	3.654 x 10^5	5.38 x 10^4	900	486	841	700	1.486 x 10^3	19	0.75
Boiler Steam-Salt (1) (2)	5.38 x 10^4	3.65 x 10^5	485.9	841	486	550	2.769 x 10^3	83	1.7
Preheater Salt-Water (1) (2)	3.65 x 10^5	5.38 x 10^4	550	234	450	485.9	2.188 x 10^3	59	2.4
Plant 2									
Gas-Salt (1) (2)	1.942 x 10^5	1.836 x 10^5	720	450	470	650	2.989 x 10^4	10	5.5
Superheater Salt-Steam (1) (2)	1.836 x 10^5	1.260 x 10^4	650	467	632	600	743	19	1.6
Boiler Steam-Salt (1) (2)	1.260 x 10^4	1.836 x 10^5	466.9	632	467	492	1.432 x 10^3	83	1.8
Preheater Salt-Water (1) (2)	1.836 x 10^5	1.260 x 10^4	492	238	450	467	587	59	2.8
Plant 3									
Gas-Salt (1) (2)	4.0 x 10^5	4.0 x 10^5	800	450	470	700	7.838 x 10^3	10	7.0
Superheater Salt-Steam (1) (2)	4.0 x 10^5	3.426 x 10^4	700	467	678	600	1.20 x 10^3	19	0.9
Boiler Steam-Salt (1) (2)	3.426 x 10^4	4.0 x 10^5	466.9	678	467	503	3.11 x 10^3	83	1.75
Preheater Salt-Steam (1) (2)	4.0 x 10^5	3.426 x 10^4	403	274	450	466.9	1.452 x 10^3	59	2.5

Table V-6 (concl.)

	Flowrate, lb/hr		T_{IN}, °F		T_{OUT}, °F		Surface Area, ft^2	U_o, Btu/hr °F ft^2	NTU
	(1)	(2)	(1)	(2)	(1)	(2)			
Plant 4									
Gas-Salt (1) (2)	5.165 x 10^5	7.816 x 10^5	1500	450	466	967	1.01 x 10^5	10	6.98
Superheater Salt-Steam (1) (2)	7.034 x 10^5	1.252 x 10^5	967	486	886	727	3.67 x 10^5	19	0.805
Boiler Steam-Salt (1) (2)	1.252 x 10^5	7.034 x 10^5	485.9	886	486	509	8.901 x 10^3	89	2.84
Preheater Salt-Water (1) (2)	7.034 x 10^5	1.252 x 10^5	509	250	450	485.9	5.393 x 10^3	59	2.54

$\dot{\omega}$ = mass flowrate,

C_p = heat capacity of fluid.

The method described above, called the effectiveness-number of transfer units method, or ε - NTU, is described in more detail in a later section on model development.

Storage vessel sizes and draw salt material requirements were based on a charge/discharge cycle of 10/1 days. The quantities of stored draw salt, storage requirements, and vessel dimensions for draw salt systems at the various model plants are listed in Table V-7. Expected temperature excursions of the draw salt are also shown. Salt circulation pump sizes were also estimated based on the power generation capability when no salt was being stored.

Table V-7 Draw Salt Storage System Sizes

Storage Requirements	Plant 1	Plant 2	Plant 3	Plant 4
Thermal Storage				
kWt·hr	4.28 x 10^5	9.55 x 10^4	2.60 x 10^5	1.00 x 10^6
Btu	1.46 x 10^9	3.26 x 10^8	8.87 x 10^8	3.43 x 10^9
Temperature Range, °F	450-900	450-650	450-700	450-1000
Draw Salt, lbm	8.77 x 10^6	4.41 x 10^6	9.60 x 10^6	1.88 x 10^7
Volume Required, ft	8.35 x 10^4	4.20 x 10^4	9.14 x 10^4	1.79 x 10^5
Vessel Size (L/D), ft/ft	47.3/47.3	37.7/37.7	48.8/48.8	61.0/61.0
Circulation Pump Size, gpm	415	209	454	886

Line sizes and insulation thicknesses of the draw salt system would involve an optimization analysis of economic costs. A preliminary optimization study was conducted to determine the economic pipe diameter. A correlation extracted from Ref V-11 was used to determine the optimum pipe diameter for piping between the waste heat recovery gas-salt heat exchanger and steam generator system. For turbulent flow this equation is:

[V-9] $$Di_{opt} = 3.9\ q_f^{0.45}\rho^{0.13}$$

for $0.02 \leq \mu < 20$ centipoise

and $Di > 1$ in.

where

Di_{opt} = optimum internal pipe diameter, in.,

q_f = fluid flowrate, ft^3/sec,

ρ = fluid density (lbm/ft^3).

As an example, the flow conditions required at Plant 4 are 7.816×10^5 lb/hr if no salt is being diverted to storage. Assuming a salt density of 105 lb/ft^3 results in the following calculation of optimum pipe diameter.

$$Di_{opt} = 3.9(2.068)^{0.45}(105)^{0.13} = 9.90 \text{ in.}$$

Therefore, a 9.90-in. inside diameter pipe would result in economic savings in pumping costs versus piping material costs for Plant 4. Optimum insulation thickness is dependent on the type of insulation (in this case calcium silicate) and projected energy loss costs. As a rule of thumb, heat loss from the piping system and storage vessel should amount to less than 1% of stored energy per day.

2. Draw Salt System Modeling and Performance Analysis

The draw salt system model consists of detailed heat exchanger analysis for the four heat exchangers (kiln gas, superheater, boiler, and preheater) and heat loss calculations from the transport system, i.e., insulated piping and insulated storage vessel. This model also predicts the pump sizes required to transport the salt based on calculated pressure drops in the system. The salt model was coded to give a quasi-steady state solution and output. That is, salt temperatures to and from heat exchangers were assumed to be invariant with time. Calculation of heat loss to the environment were not used to vary salt temperature internally to the program, but were used in determining optimum insulation thickness. This quasi-steady state assumption was necessary to simplify the model and to provide timely results. Significant heat loss should not occur in a well-designed system, thus validating this assumption.

Detailed heat exchanger performance prediction is provided by a subprogram using equations developed by Kays and London (Ref V-10) for specific heat exchanger configurations. Equations were developed and computer coded that determined a heat exchanger's effectiveness, ε, based on the flow conditions through the heat exchanger, heat exchanger configuration and size, and an overall heat transfer coefficient. Specifically, the heat exchanger effectiveness is defined as:

[V-10] $$\varepsilon = \frac{C_h}{C_{MIN}} \frac{\left(t_{h_i} - t_{h_o}\right)}{\left(t_{h_i} - t_{c_i}\right)} \frac{C_c}{C_{MIN}} \frac{\left(t_{c_o} - t_{c_i}\right)}{\left(t_{h_i} - t_{c_i}\right)}$$

where

C = capacity flowrate = $\dot{\omega} C_p$,

$\dot{\omega}$ = fluid mass flowrate,

C_p = fluid heat capacity,

t = fluid stream temperature.

Subscripts:

h = hot fluid ($t_h > t_c$),

c = cold fluid,

i = inlet stream,

o = outlet stream

MIN = minimum capacity flowrate.

Kays and London have developed the effectivenss, ε, of a heat exchanger based on the number of transfer units, NTU, (previously defined), the ratio of the capacity flowrates, C_{MIN}/C_{MAX}, and the heat exchanger configuration. Several configuration options have been coded into the draw salt model. These include:

1) Pure countercurrent;

2) Parallel Flow;

3) Cross flow (mixed and unmixed);

4) Cross-countercurrent flow;

5) Parallel-counter flow;

6) Multipass shell and tube with or without baffles.

These options provide the user the option to select or modify heat exchanger configurations for a given duty and understand any benefits of one configuration over another.

Heat loss calculations were performed by the model, through film coefficient estimation methods presented in Ref V-11. Fouling coefficients are inputs to the model. Heat loss determinations are thus calculated using standard equations for heat transfer through multilayer pipe for piping systems and multilayer flat plates for the storage vessel. Heat loss calculations performed by the model for a storage vessel at Plant 4 are shown in Table V-8. These calculations result from an insulation thickness of 10 in. on the tank and 5 in. on the piping systems. This insulation provides for system heat loss of less than 0.5% of stored energy per day. According to these calculations, these insulation thicknesses are more than adequate to meet the goal of less than 1% per day of stored energy.

Table V-8

Typical Draw Salt Storage Vessel Performance for 7-Day Charge Cycle

Storage Vessel Volume, ft^3	1.2150×10^5
Storage Vessel Inside Diameter, ft	53.69
Storage Vessel Outside Diameter (including insulation), ft	55.69
Storage Vessel Height, ft	53.66
Insulation Thickness, in.	10.0
Thermocline Velocity during Charge, ft/hr	0.318
Thermocline Initial Height, ft	56.83
Time to Fully Charge, hr	178.77
Storage Vessel Surface Area, ft^3	17.261
Overall Heat Transfer Coefficient, Btu/hr-ft^2-°F	3.1250×10^{-2}
Heat Loss from Fully Charged Tank, Btu/hr	4.7844×10^5
Heat Loss from Fully Discharged Tank, Btu/hr	1.9958×10^5
Temperature Degradation in Fully Charged Tank, °F/hr	9.7999×10^{-2}
Temperature Degradation in Fully Discharged Tank, °F/hr	3.6842×10^{-2}

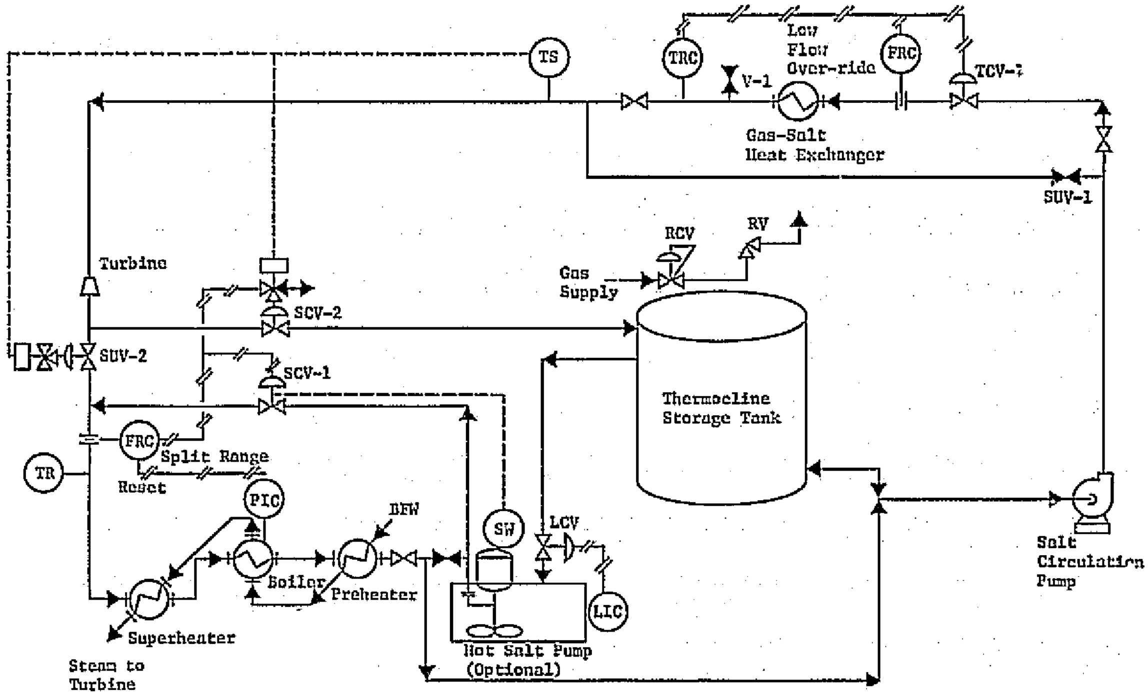
System pressure drops (i.e., piping and heat exchangers) are also calculated from the model. Equations developed in Ref V-11 were used to determine draw salt line pressure drops and heat exchanger pressure drops. Model pressure drop computations are shown in Table V-9 for 200 ft of 8-in. diameter pipe. If one counts the storage vessel height in addition to the pressure drop, a pumping requirement of at least 250 psia discharge pressure is necessary at the flow capacity of about 900 gpm.

Table V-9
Total Pressure Drop and Heat Losses of Draw Salt System for Plant 4

Boiler System Steam Pressure Drop, psia	34.956
Salt Loop Pressure Drop, psia	217.0
Kiln Gas Pressure Drop on Shell Side, psia	20.328
Energy Transport Heat Loss, Btu/hr	2.1837×10^5
Energy Loss from Charged Tank, Btu/hr	4.7844×10^5
Energy Loss from Discharged Tank, Btu/hr	1.9958×10^5

Unlike the rockbed storage system, nearly all of the stored energy in the storage medium can be used for power production. Hot draw salt can be pumped from the tank until the onset of the thermocline region. This thermocline band of salt will be approximately 1 to 3 ft in height. With appropriate steam flowrate control, part of the thermocline barrier can be used. Assuming a 60-ft high tank and a 1.5-ft thermocline region, over 97% of the stored salt can be used for optimum power generation. The actual height of this thermocline depends on the length of time both hot and cold salts are in contact.

Instrumentation and controllers required in the draw salt system loop are shown in Figure V-12. The hot salt pump shown in this diagram is only required if a discharge flowrate capacity is much different than the salt circulation pump flowrate. In any case, flow control is necessary to vary the salt flowrate through the heat exchangers to optimize their performance and minimize the occurrence of salt freezing.



Nomenclature

TS - Temperature Sensor
TRC - Temperature Reset Control
TR - Temperature Recorder
FRC - Flowrate Reset Control
PIC - Pressure Integral Control
SW - Switch
LCV - Level Control Valve
LIC - Level Integral Control
SUV - Start-Up Valve
TCV - Temperature Control Valve
SCV - Start Control Valve
BFW - Boiler Feedwater
RV - Relief Valve
RCV - Relief Control Valve

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Figure V-12 Preliminary Instrumentation Diagram for Salt Storage System

C. COMPARISON OF THE TWO STORAGE SYSTEMS

While each system can recover rejected energy, store part of the recovered energy, and exchange that energy to produce on-site electrical power, each system has its own advantages and disadvantages. Technical problems foreseen in each system and previously described can be solved with minimal development effort. The rockbed storage system will require two storage vessels--one for low temperature storage and one for high temperature storage. The draw salt system will use one large cylindrically shaped container for storage. Container material and insulation costs will be higher for the rockbed system.

Although the required amounts of storage medium will be greater for the rocks (due to lower heat capacity), the draw salt can be expected to be more expensive than rocks. In a later chapter on preliminary economics, salt is shown to be considerably more expensive than rocks. Also, the salt will require preprocessing on-site before installation. During normal installation, the draw salt components, $NaNO_3$ and KNO_3, are shipped separately and mixed on-site in a contaminant-free environment. Rockbeds will require detailed manifold designs to evenly distribute the gases through the bed and prevent gas stream channeling.

The effect of dust on rockbed performance must be accurately determined. The nature of the thermocline during long periods of storage time and its effect on thermal strain of the walls of the storage vessel must be assessed for both systems. In terms of system simplicity, the rockbed storage system represents the most attractive means of energy storage, if dust accumulation does not degrade performance. For reliability, salt-steam generation methods have a proven record over the last 30 to 40 years. The chemical process industry has been using heat transfer salts over the last half century in heating reactor vessels. Since the 1950's other companies have used salt for steam generation with proven reliability and low maintenance requirements. Questions still remain unanswered about some of the details of salt storage, but these are presently being resolved in solar power programs (Ref V-1). These draw salt programs will provide timely information required for full-scale development considerations of thermal energy storage applications in the cement industry.

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VI. SYSTEM INCORPORATION IN THE CEMENT PLANT AND INDUSTRY ACCEPTANCE

Under this phase of the study, interfacing requirements and operational restrictions for incorporating the thermal energy storage systems--rockbeds and draw salt--were determined. Drawings were prepared to show the interfacing of the waste heat recovery system and the thermal energy storage units with existing plant equipment. This study has indicated the ease of interfacing with the cement manufacturing process resulting in minimal impact to existing plant operationsl easy accessibility, and environmental safety. Figures VI-1 and VI-2 are conceptual equipment diagrams showing the interfacing of the storage systems with a modern suspension preheater kiln. Gas and liquid flows are indicated for operation during storage charging.

An industry-wide survey was conducted to assess the acceptability of the candidate systems. This survey was written to assure maximum industry response. Response from this survey is discussed in this chapter.

A. OPTIMUM LOCATION OF STORAGE SYSTEMS AT THE FOUR MODEL PLANTS

Typically, the TES systems for both kiln exit gases and clinker cooler waste air will consist of two pebble-bed tanks nominally 50 ft in diameter and 50 ft high. Alternatively, a single 60-ft-diameter spherical storage tank would be required if the liquid draw salt system is used. To simplify the selection of a location for the storage tanks, the TES rockbed system was represented by two 60x60-ft rectangles on the large scale plant diagrams. If the liquid salt system were to be chosen, the area required for storage was represented by a 60x60-ft rectangle.

Sufficient space exists to incorporate both kiln exit gas and clinker cooler waste air TES units at all four plants. The following discussion explains the situation at each of the four plants. Typical locations of the TES units are shown in Figures VI-3 through VI-6.

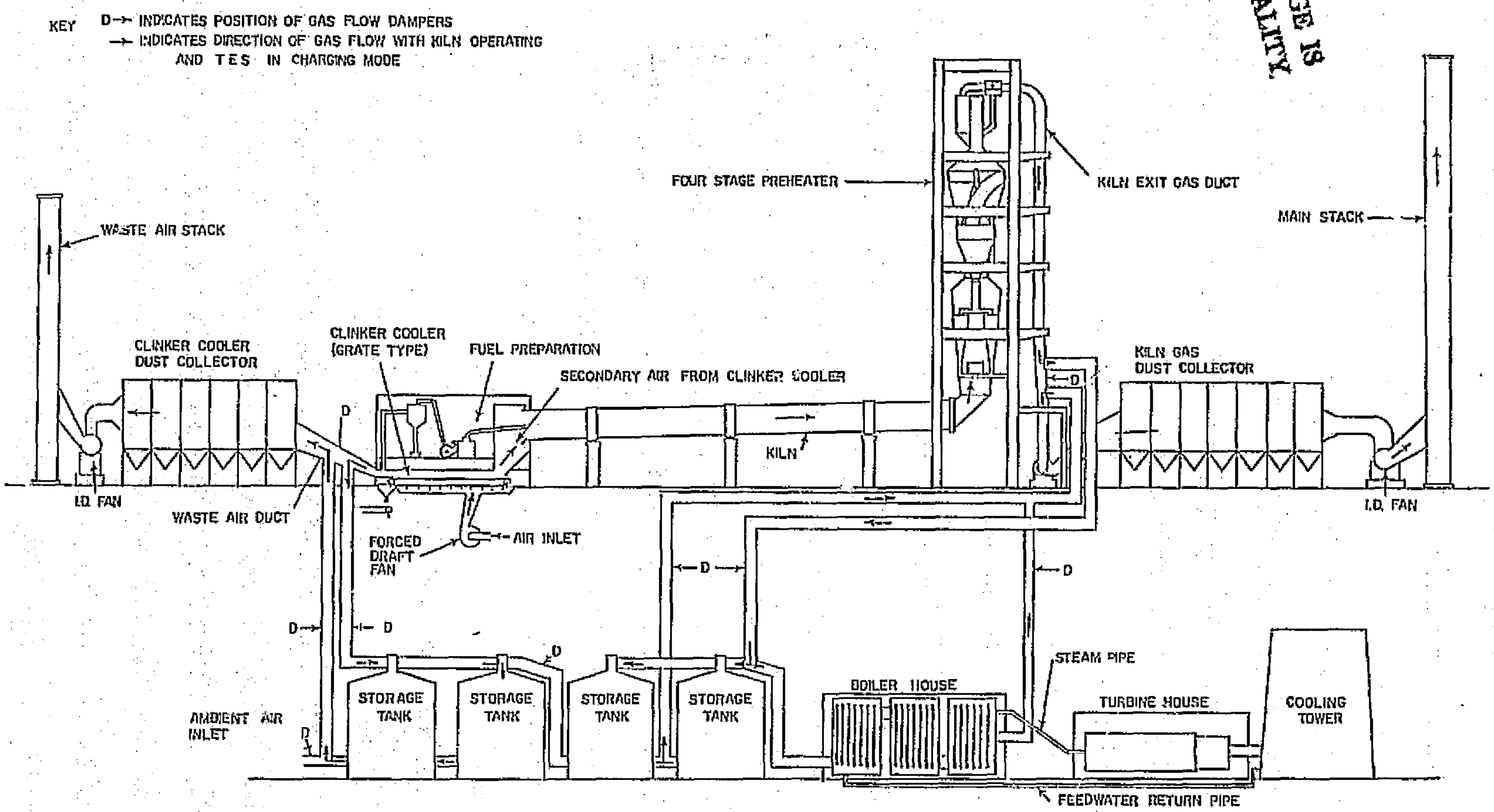

Figure VI-1 Suspension-Preheater Kiln with Pebble Bed TES System

C-2

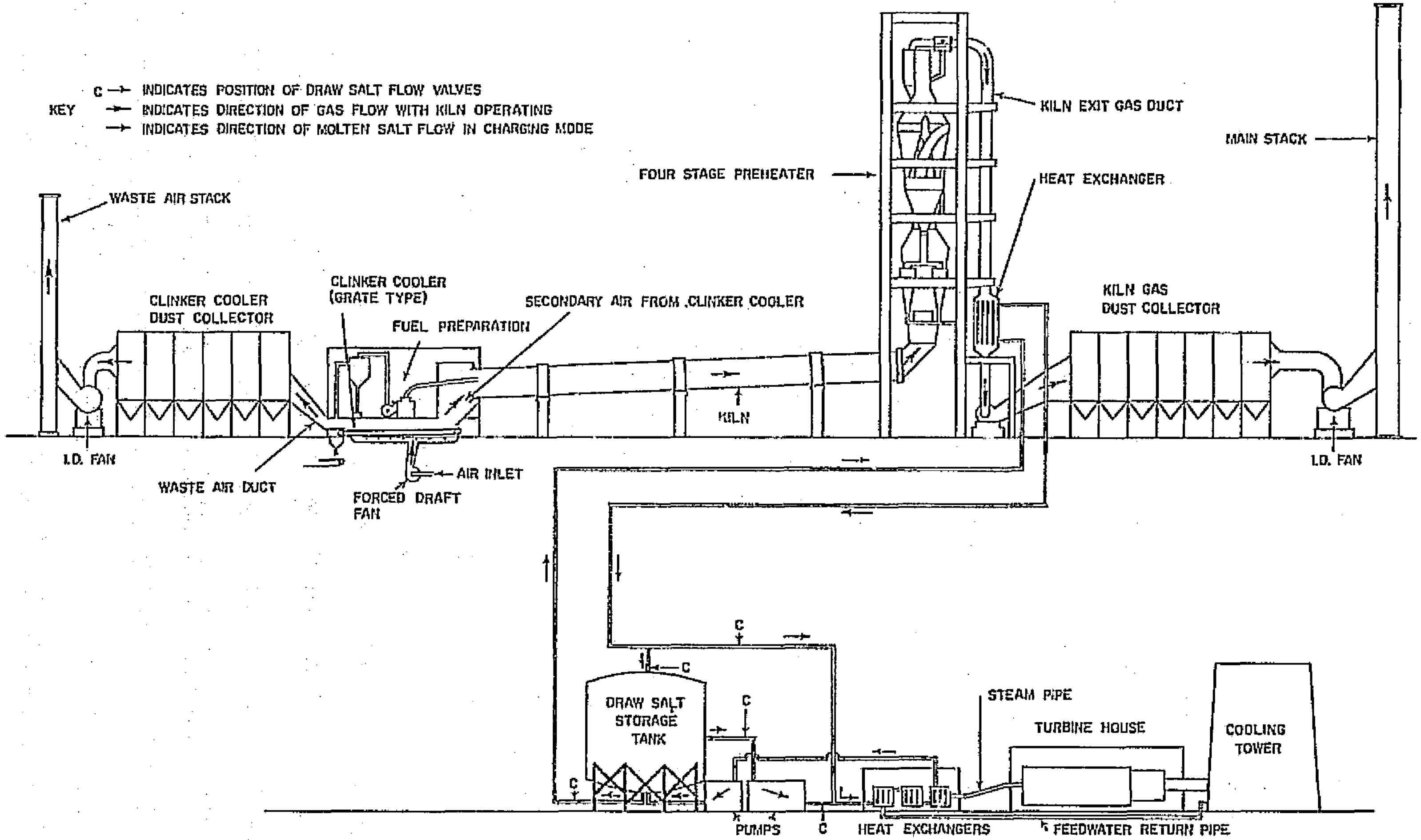

Figure VI-2 Suspension Preheater Kiln With Draw Salt TES System

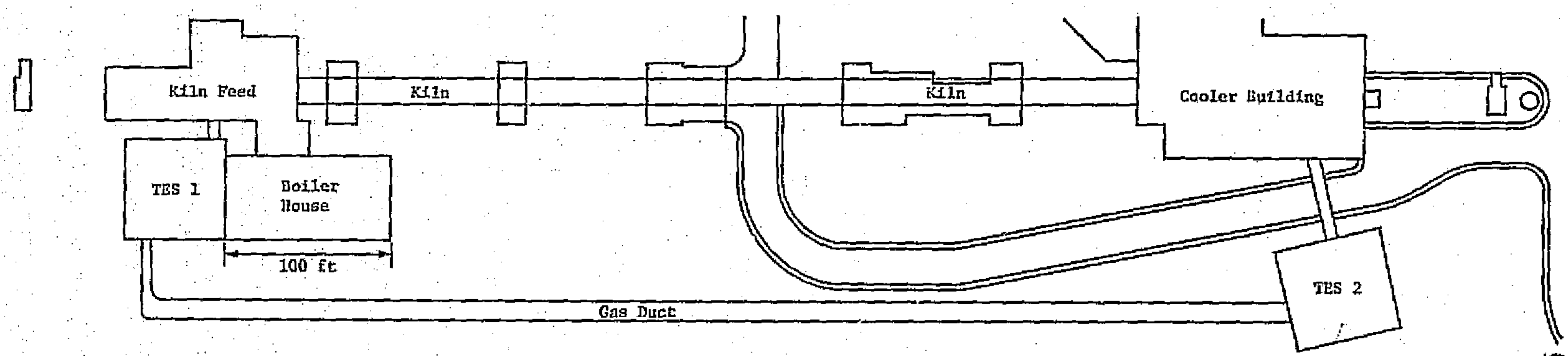

Figure VI-3 Positioning of TES Units (Pebble Bed Type) for Plant 1

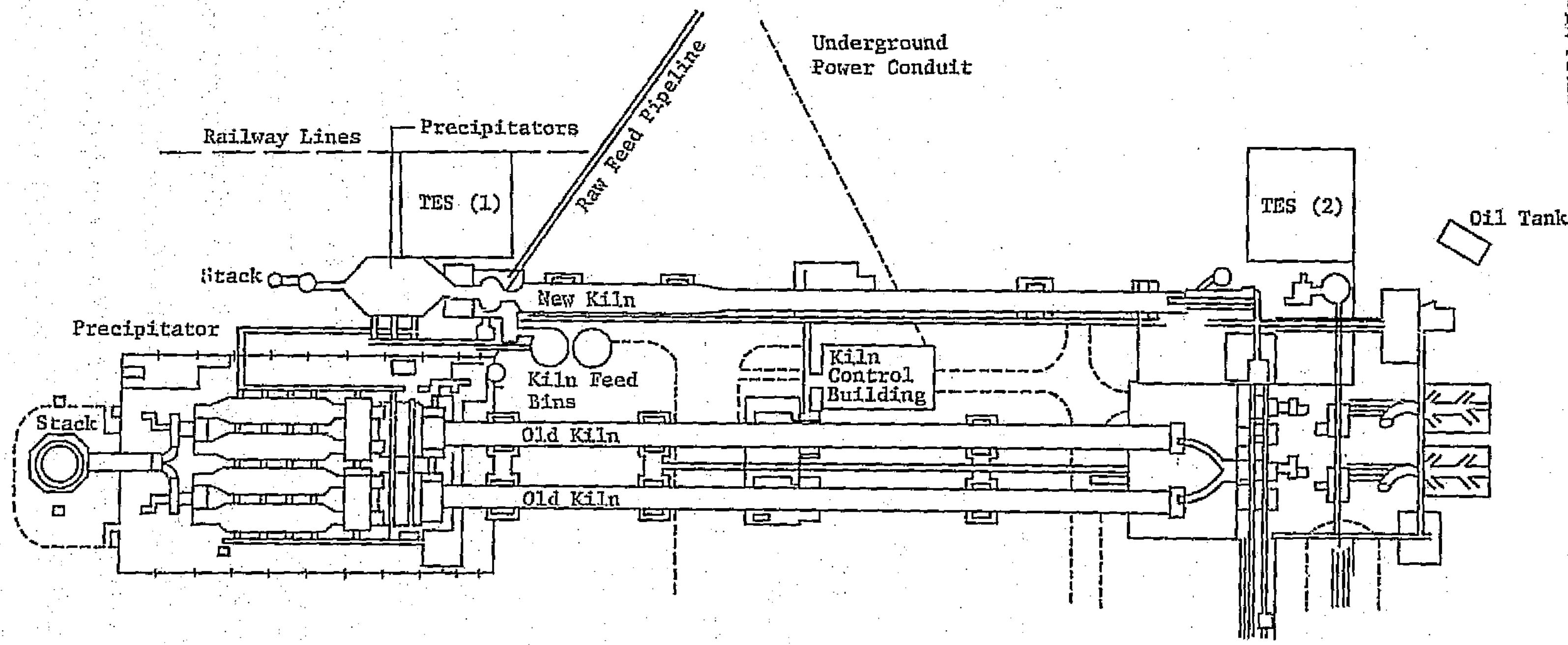

Figure VI-4 Plan of Plant 2 Showing New Kiln

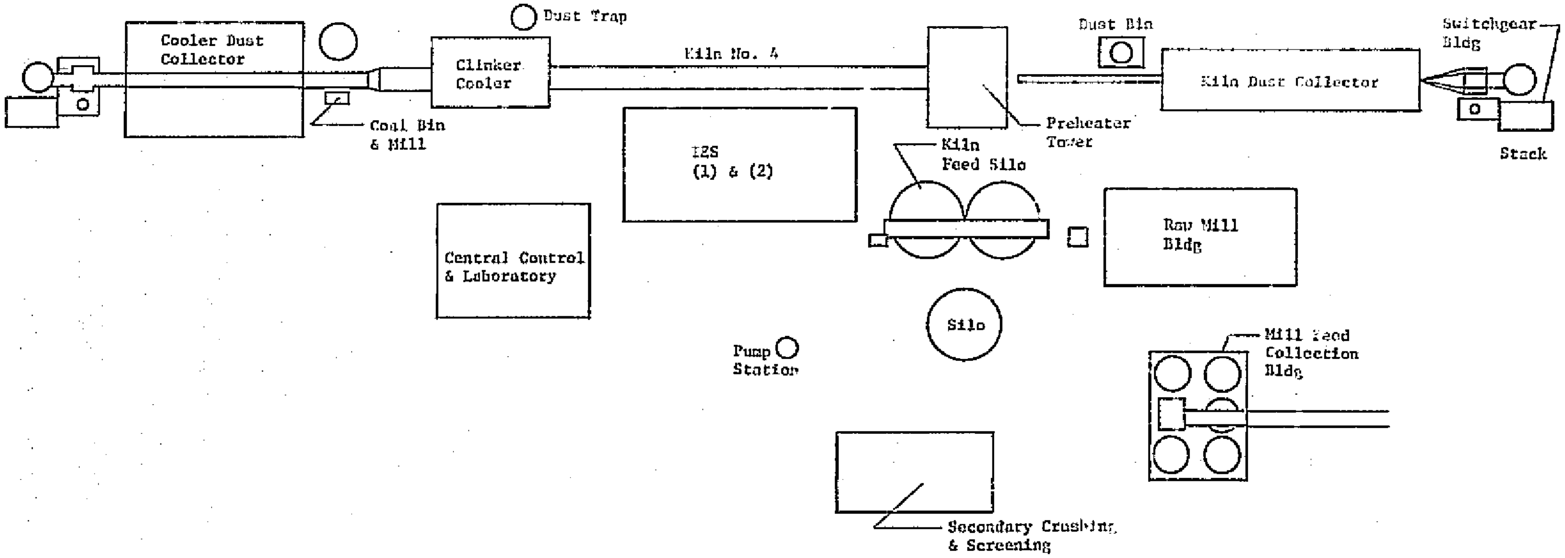

Figure VI-5 Plant 3 Positioning of TES Units

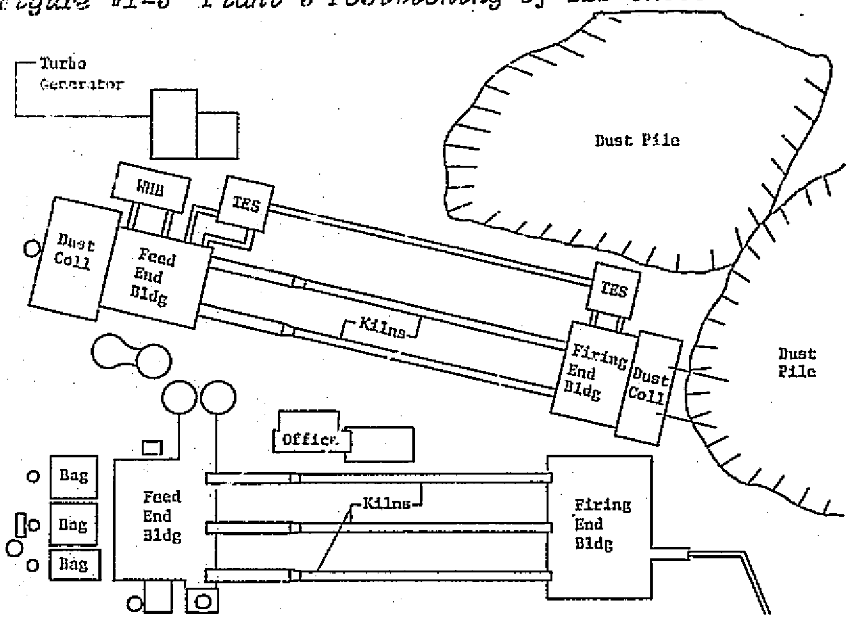

Figure VI-6 Plant 4 Positioning of TES Units

1. Plant 1

At this plant, there is open space to the south of the kiln; the kiln runs west to east (in the direction of the feed). At the feed end, there is ample space for a TES unit very close to the kiln feed area. However, at the clinker cooler end, there is a roadway just south of the cooler building, and since there is not space on the other side of the kiln, the TES unit would have to be on the south side of the existing roadway.

2. Plant 2

At Plant 2 only the new kiln (which runs east to west) is being used as a model; there are two old kilns to the north of it which are still in use, and which limit the space on the north side of the new kiln. To the south, however, there is open space all along the kiln, i.e., next to both kiln feed and clinker cooler buildings. The only inhibiting factor is a railway line that approaches to within less than 50 ft of the electrostatic precipitator at the kiln feed end. This leaves insufficient room for a 60-ft-diameter storage tank for the kiln exit gases. So, whether or not the 60-ft-diameter liquid salt tanks are used, they will have to be moved further west to a position alongside the kiln itself. There is no shortage of space at the clinker cooler end.

3. Plant 3

At Plant 3 the kiln under consideration is the new kiln, which runs east and west. The three old kilns lie to the north and prohibit installation of TES units on that side. The control laboratory and feed buildings restrict space to the south of the feed end and the clinker cooler. The only suitable space lies to the south of the center of the kiln. There is sufficient space for two heat stores (i.e., 60x120 ft) in this position. So both clinker cooler and kiln exit waste heat store would have to be put there, adjacent to each other. Since the kiln is fairly short, the length of ducting required would not be excessive.

4. Plant 4

At this plant, kilns 22 and 23 are being considered; several older kilns are also still in operation. The two kilns in question are in parallel, about 50 ft apart and running approximately north to south. There is insufficient space for TES units to the west, due to the presence of older kilns and associated buildings. However, on the eastern side there are no buildings (although there is a dust pile within about 80 ft of the firing end building). There is ample space for building TES units for one or both of the new kilns on the east side.

B. GENERAL LAYOUT CONSIDERATIONS

It is clearly possible to find sufficient space for TES units at all four plants. If the major use of the stored heat is to generate electricity, then a waste heat boiler will be required and it will also have to be positioned close to the TES units; it should preferably also be close to the main precipitator, since the gases will have to be deducted after passage through the boiler. It is estimated that an 8 to 10 MW boiler using hot air as the heat transfer medium would require a ground space of 98x46 ft (maximum). Thus, there is sufficient space close to the precipitators at Plants 1, 2, and 4 to install a boiler without any problem. At Plant 3, however, there is very little space and the boiler would probably have to be south of the TES units, probably at least 200 ft from the gas take-off point at the preheater tower. Alternatively, the boiler could be next to the kiln, but the TES units would then have to be further away. The turbine building and associated cooling tower for a 10 MW (max) generating system will require areas of 91x59 ft and 59x59 ft, respectively. However, these may be placed a considerable distance from the heat source if necessary, since the steam pipes can readily be insulated as they are much smaller in diameter than hot air ducts.

The liquid draw salt system has a smaller heat storage area requirement than the solid pebble-bed system. A single spherical 60-ft-diameter storage tank can be used, because it is possible to maintain a thermal gradient in the tank. The pipes carrying the molten salt can be fairly narrow and well insulated; thus distance is not a serious problem. However, the heat exchange unit will be fairly large (probably occupying a 30 ft length of 10x10-ft gas ducting). The installation of such a unit will involve diverting kiln exit gases if there is insufficient space in the existing ducts. With the liquid draw salt system, the boiler itself can be smaller; it will probably only require an area of 30x40 ft in total (three 10x40-ft areas for the heat exchangers). It should probably be placed close to the heat store to minimize heat losses, but this is not absolutely essential.

C. DETAILED INTERFACE ANALYSIS

Using the data given in the previous section and detailed plans and elevations of all four plants, detailed interface drawings for installation of both pebble-bed and liquid draw salt waste heat storage/utilization systems were prepared. These drawings show the gas take-off points, dampers, and ducting required at each plant, including the ducting required to convey the TES exit gases to the dust collector.

1. Gas Duct Sizing

To obtain an idea of the size of gas ducts required for the rock-bed systems, a relationship for pressure drop versus diameter for circular ducting (using the formulas given in *Fan Engineering* published by Buffalo Forge Company) for turbulent gas flow in steel ducts was derived.

This relationship, assuming that the absolute pressure is close to 1 atmosphere, is as follows:

$$\text{[VI-1]} \quad \frac{\text{Pressure drop (in. of water)}}{\text{Length of pipe, (ft)}} = \frac{1.8 \times 10^{-3}(T + 460)\ \mu^{0.16}\ V^{1.84}\rho'}{d^{4.92}}$$

where

T = temperature, °F,

ρ' = relative density of gas with respect to air,

μ = gas viscosity, lb/ft/sec,

V = gas flowrate, lb/min,

d = duct diameter, in.

For a typical maximum pressure drop per unit length of 1-in. water per hundred feet of ducting, the following relationship for the minimum duct diameter was obtained:

$$\text{[VI-2]} \quad d_{(min)} = \left[0.18(T + 460)\mu^{0.16} \cdot \rho' \cdot V^{1.84}\right]^{0.2033}$$

Since d is only weakly dependent on μ, the viscosity of air was used in all calculations; these values are given in reference tables for various temperatures.

The design of the rockbed units is such that pressure drop across the units should be less than 10 in. of water under normal operating conditions. Therefore, the associated ducting was designed to give a total pressure drop of less than 1 in. of water, if possible, so as not to put too great a load on the existing I.D. fans. In the following sections, the optimum location of TES systems at each plant is considered in more detail.

2. Plant 1

Clinker Cooler - A detailed plan of the layout inside the clinker cooler building is shown in Figure VI-7. There is already a duct in position for diverting a small amount of waste air from the clinker cooler to the coal mill. The remainder of the waste air passes through a mechanical dust separator, and then along about 30 ft of divided ducting before entering an electrostatic precipitator. In Figure VI-7, take-off and return ducts have been added for use with the rockbed system. Since there are two parallel ducts, two take-off and return ports are shown. They are separated by a damper, which should be of the "guillotine" type (because there is insufficient space for sideways-moving dampers).

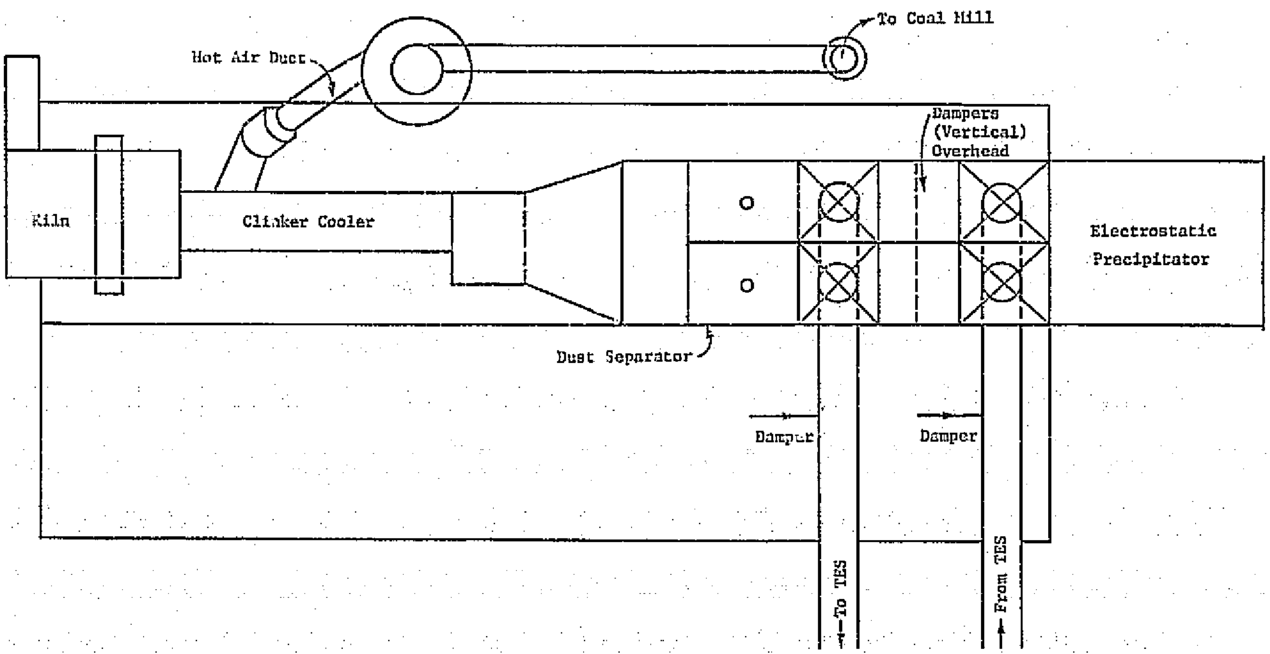

Figure VI-7
Interface Drawing for Plant 1 Clinker Cooler (Adapted for Pebble-Bed TES Units)

Typical waste air flows from the clinker cooler at this plant are about 4,400 lb/min at 350°F. The total length of ducting to and from the TES unit (as shown in Fig. VI-3) would be about 300 ft. To achieve a pressure drop of less than 1 in. of water over this length of ducting, the ducts must be at least 55 in. in diameter.

If the draw salt system is to be used, there is apparently sufficient space in the existing ducting (between the mechanical dust collectors and the precipitator) to install the necessary heat exchange pipes without any serious difficulty.

Kiln Exit - Figure VI-8 shows an elevation through the kiln feed end. The gases pass through a multicyclone dust separator and a guillotine damper before entering the electrostatic precipitator unit. It would seem plausible, if a rockbed system is used, to take off the kiln exit gas from the multicyclone unit, since some dust will have been removed from the gases at that point, without any great drop in temperature. A gas take-off port has been shown on the side of the multicyclone unit, although the exact position of this duct would depend on the internal details of the multicyclone unit. The gas return duct has been shown entering the electrostatic precipitator duct after the existing damper. Dampers would, of course, be required in the take-off and return ducts as well.

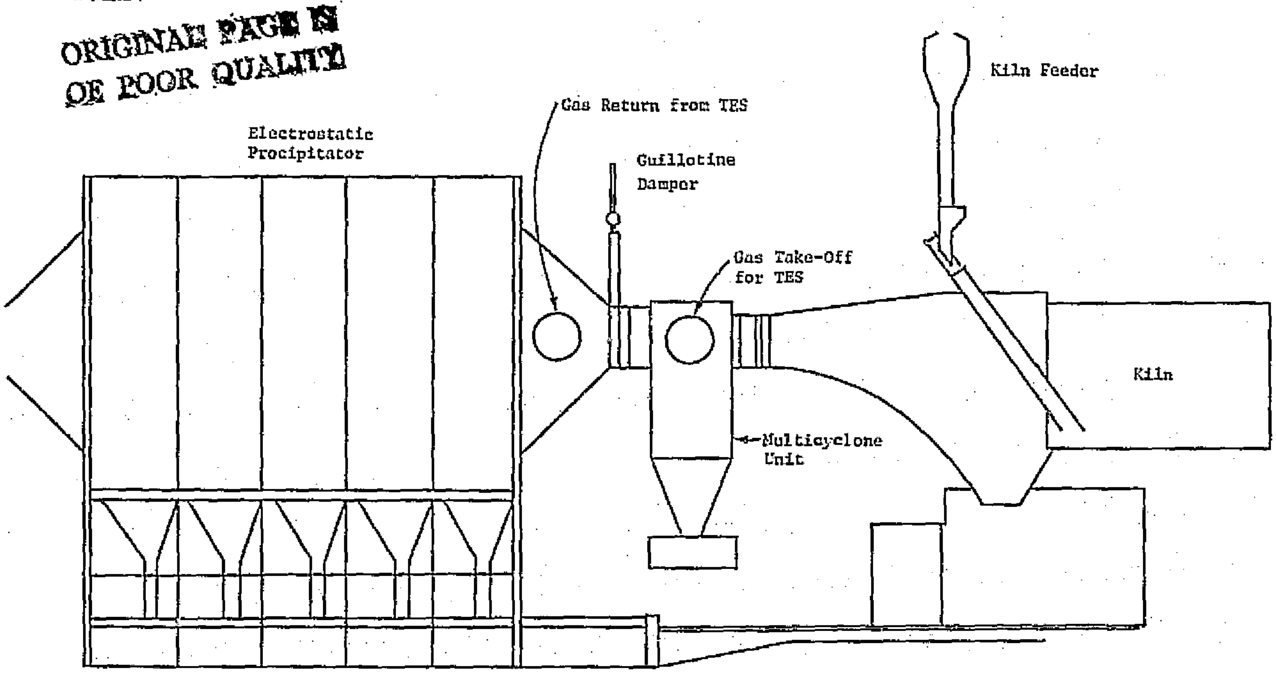

Figure VI-8 Interface Drawing for Plant 1 Kiln Feed End

Assuming that the total duct length on the kiln exit gas storage system would be about 200 ft, and that the kiln exit gas flow is typically about 5300 lb/min at 1150°F, ducting of at least 66 in. diameter for a 1-in. maximum pressure drop would be required. An additional 700 ft of 66-in. ducting would be required for the linkage of the two storage modules during discharge.

If draw salt system at the kiln exit were used, then some modification to the existing layout would be required. To install the heat exchanger, which requires a volume of about 3000 ft^3, the multicyclone unit and damper would have to be moved slightly closer to the kiln exit. The heat exchanger could then be placed in the ducting just before the electrostatic precipitator unit.

3. Plant 2

Clinker Cooler - No detailed plan of the clinker cooler was obtained from Plant 2. However, it is similar to the cooler at Plant 1, so there would be no difficulty in installing the inlet and outlet ducts for the rockbed system. Ducting required for clinker cooler storage was estimated at 200 ft (60 in. diameter), with 700 ft required in linking the clinker cooler storage units to kiln exit gas storage units.

Kiln Exit - Details of the kiln feed end arrangement are given in Figure VI-9. There is a single-stage preheater consisting of two cyclones in parallel. On the upper diagram, possible take-off and return ports for the rockbed system are indicated.

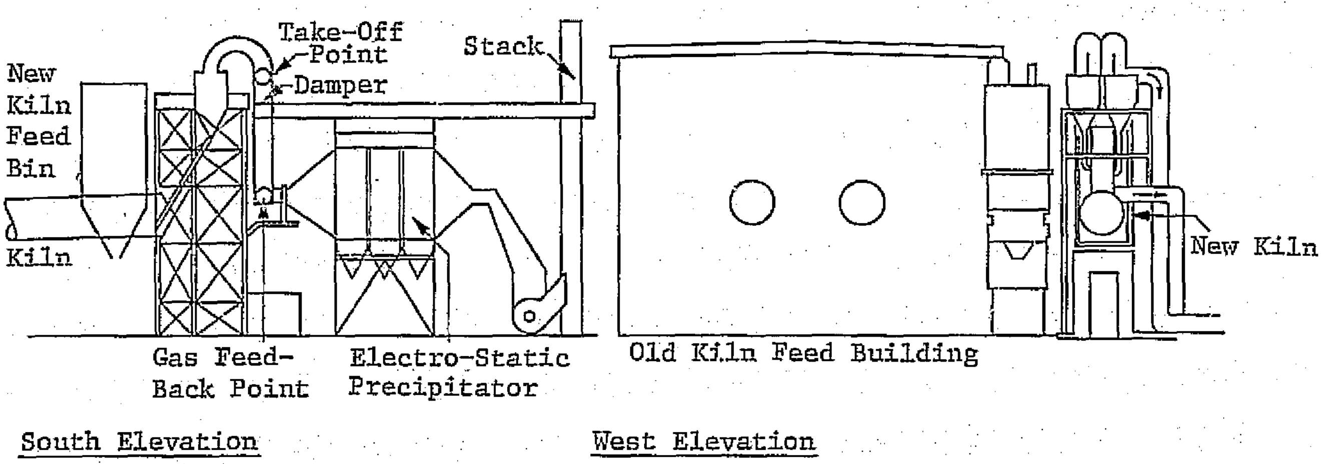

Figure VI-9 Interface Drawing for Plant 2 Kiln Feed End

The typical kiln exit gas flow at this plant is about 3300 lb/min at 720°F. The kiln exit gases will have to traverse up to 800 ft of ducting if the layout shown in Figure VI-4 is used. For a pressure drop of less than 1 in., ducting of 67 in. in diameter would be required.

If the draw salt system is to be used at Plant 2, it should be fairly straightforward to enlarge the downcoming duct from the preheater to permit installation of a heat exchanger (in a position between the two take-off ports shown in Figure VI-9).

4. Plant 3

Figure VI-10 shows the take-off points for the gas ducts, using the rockbed system. If the draw salt system is to be used, there is ample space for the installation of a heat exchanger on the downcoming duct from the preheater. A possible arrangement is shown in Figure VI-11.

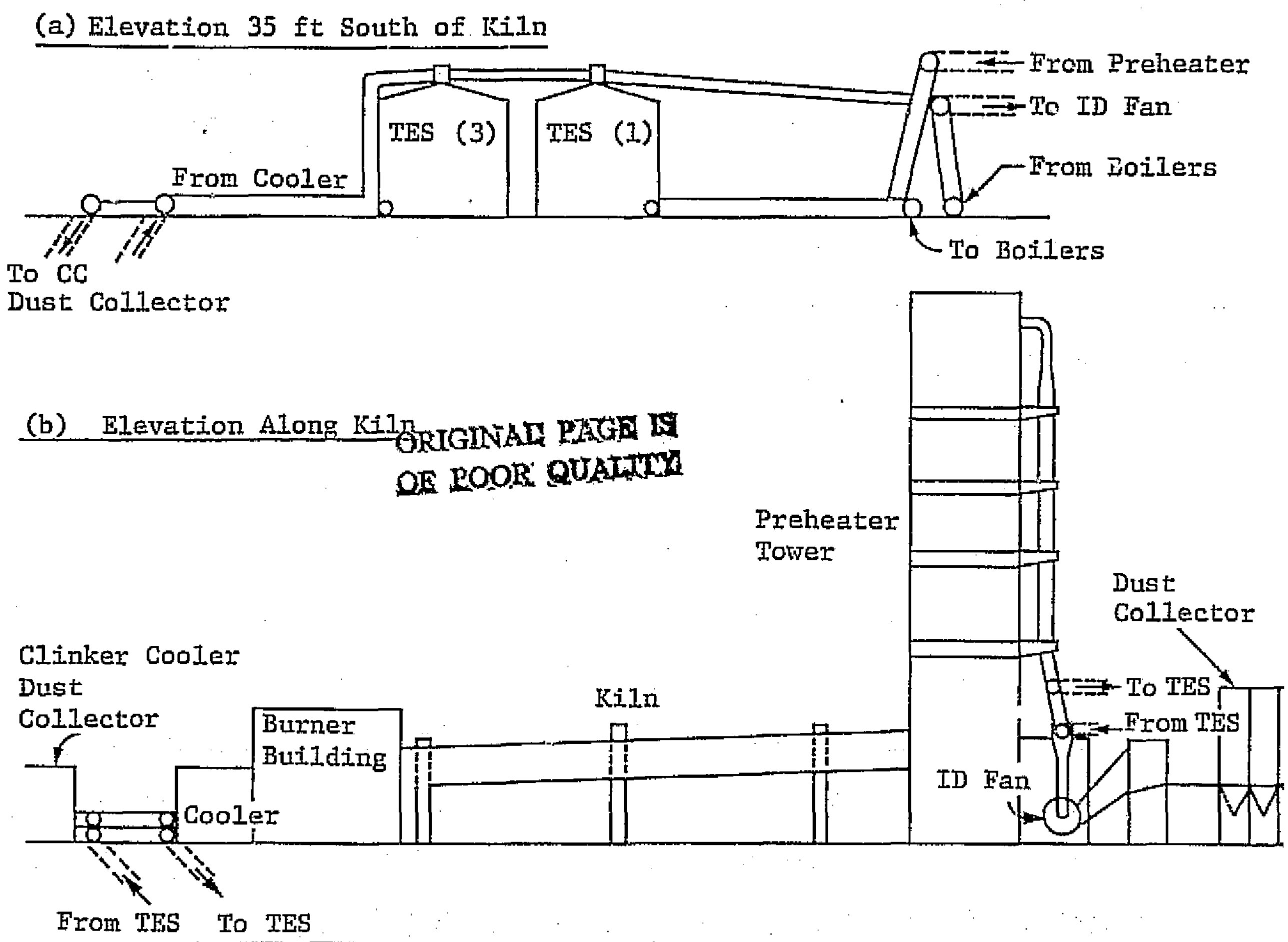

Figure VI-10 Elevation Drawing for Plant 3 with Pebble-Bed TES Units

If the rockbed system is to be used at Plant 3, then the sizing of the gas ducts will be as follows:

Kiln exit gas: up to 400 ft of ducts; gas flow = 6,700 lb/min at 800°F; minimum duct diameter = 78 in. for a 1-in. pressure drop.

Clinker cooler gas: up to 500 ft of ducts; gas flow = 10,800 lb/min of 350°F; minimum duct diameter - 86 in. for a 1-in. pressure drop.

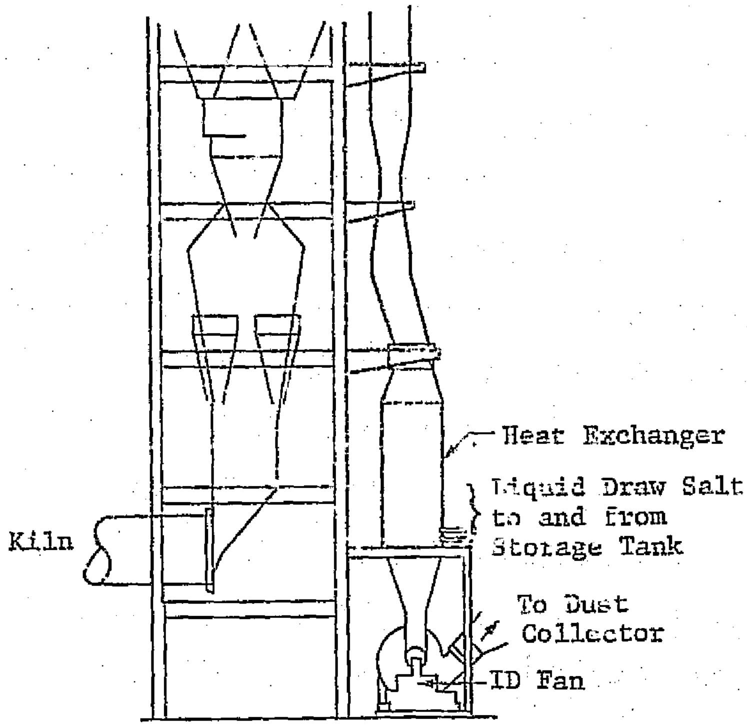

Figure VI-11
Preheater Tower Adapted for Liquid Draw Salt Heat Exchanger Unit for Plant 3

5. Plant 4

Plant 4 differs from the other plants in that it already has a waste heat utilization system in operation. Thus, the siting of the boilers and turbine is already fixed, and only the interfacing of the TES units need be determined. The present study was concerned only with the two newest kilns (Kilns 22 and 23).

The detailed interface is shown (for Kiln 23) in Figure VI-12. This is a plan of the existing boilder and kiln exit, to which ducts have been added leading to and from the TES unit. Gas take-off is from the feeder housing; however, the kiln feed pipe comes down vertically from the top of this housing, so the take-off duct must be behind this pipe. The gases are returned to a point on the side of the multicyclone unit, so the gases pass through this unit and then out via the precipitator. The air inlet is shown for use during discharge.

The diameter of the ducting should be at least 72 in., based on a gas flow of 8,900 lb/min at 1500°F through 100 ft of ducts. Total estimated duct lengths are:

1) Kiln exit gas storage module: 300 ft;

2) Clinker cooler storage module: 300 ft;

3) Ducting to link the two modules: 700 ft.

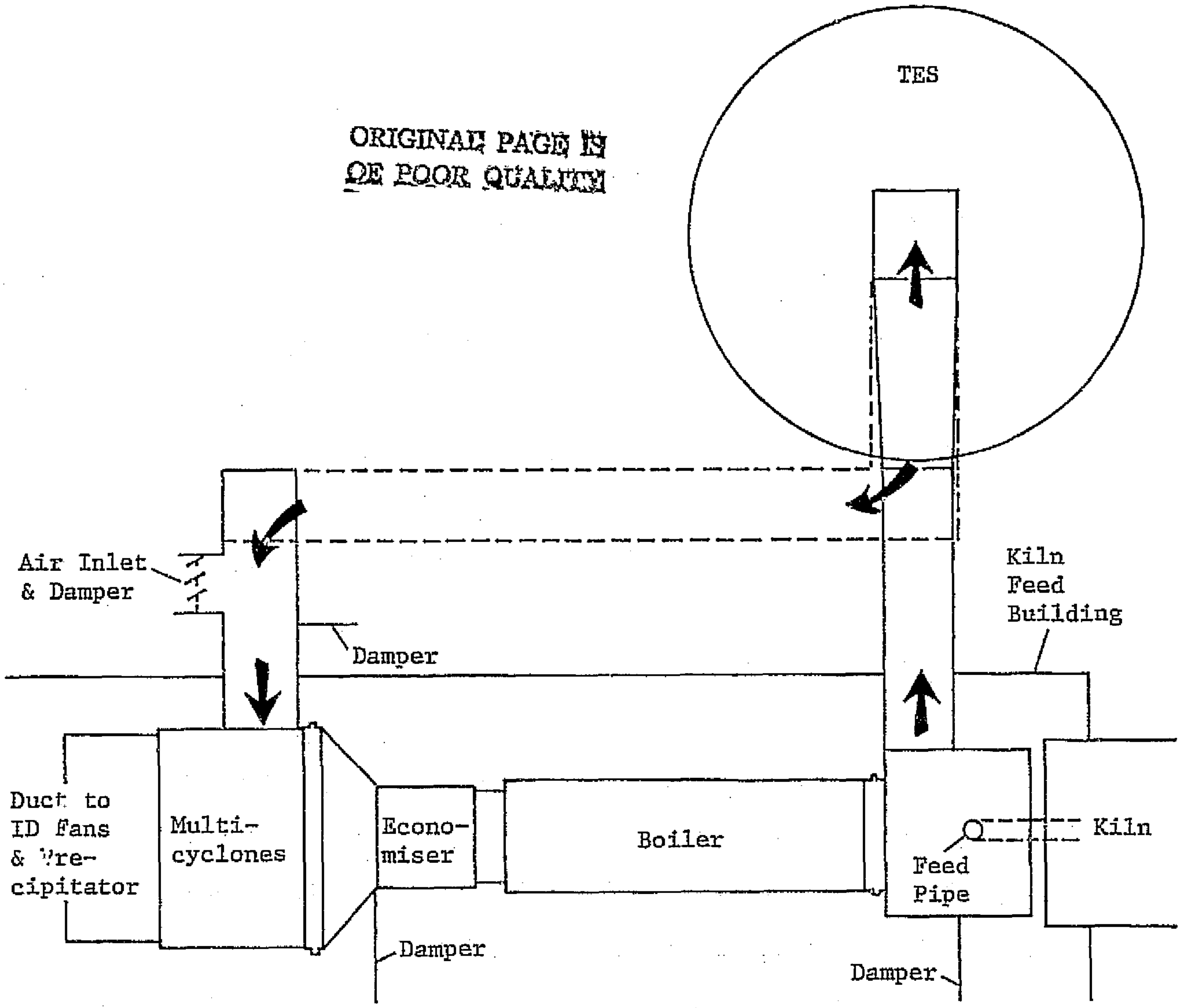

Figure VI-12 Interface Drawing for Kiln Exit at Plant 4

D. INDUSTRY AND GOVERNMENT ACCEPTANCE SURVEY

A survey in the form of a letter-questionnaire was prepared and sent to 13 cement companies that represent approximately 60% of the U.S. productive capacity. This letter-questionnaire consisted of material informing the companies of the type of study being conducted by Martin Marietta Aerospace/Portland Cement Association/Department of Energy, and of questions relating to their acceptance of the waste heat recovery/thermal storage systems under consideration.

1) Most plants would be interested in power generation from waste heat if it could be shown to be economically attractive. Many plants have considered it in the past but found it uneconomical at that time.

2) Stabilization of clinker cooler waste air and kiln exit gas temperatures would be an advantage in many cases. Reduction of these gas temperatures might aid dust collection and fan operation, which would be an attractive bonus.

3) Partial dust, SO_x, and NO_x removal would be an advantage as long as there are no deleterious effects to the TES units.

4) In some cases, stored heat could be used for drying coal or preheating residual oil; this could be especially helpful when starting up a kiln after a short-term shut down.

5) Some plants would be interested in using the waste heat for space heating, in which case a TES unit could give added flexibility.

   Another point that could be helpful during start-up after a short-term shutdown is as follows. Since the charge time for the clinker cooler store is appreciably shorter than that for the kiln store, heat remaining in the former after discharge could be used for heating combustion air. This would have a beneficial effect on the quality of the product initially obtained after start-up and would permit earlier actuation of the electrostatic precipitator (since CO levels are reduced at higher combustion air temperatures), thus eliminating potential environmental problems.

E. CONCLUSIONS

There is a vast potential for waste heat recovery and on-site power generation in the cement industry. Only eight plants in the U.S. are currently producing their own electrical energy requirements. The reason for the lack of incorporation of these systems in the past has been the availability of cheap power from the utilities.

Projected electrical energy costs and shortages in the future, however, will force this industry to carefully examine on-site power generation. Rockbed storage units can benefit the process by:

1) Reducing particulate emissions;

2) Possibly reducing NO_x and SO_x emissions;

3) Damping temperature fluctuations to baghouses;

4) Allowing for combustion air preheat;

5) Most importantly providing power for grinding operations and facility support during short kiln shutdowns. Either the rockbed or draw salt systems could be incorporated into the plant process with minimal impact on operations.

VII. PRELIMINARY ECONOMIC ANALYSIS

A preliminary economic analysis was conducted for the conceptual storage system designs presented in previous chapters. These analyses were used to determine the economic feasibility of the selected systems in terms of stored energy costs versus current and projected energy costs and the rate of return on investment. Data from previous effort on this study were used for extrapolating costs over a wide range of variables. Specifically, costs were determined for thermal energy storage installation at each of the four model plants. Energy savings in terms of electrical power were estimated for the entire industry.

Return on investment methodology was developed under this phase of the study. The methodology involved the use of calculated electrical power savings realized by producing the electrical energy on-site and the capital investment. Capital costs were estimated from literature references and vendor quotes. Investment for a waste heat recovery system, turbogenerator, and appropriate facilities (site-work, buildings, electrical, etc) amount to $800 to $1000/kW. With the present industry-wide average of 2.5¢ to 2.8¢/kWh, return on investment can be as high as 80 to 90% considering an 11% escalation rate of electricity over a 30-year system life. Investments of up to 20% of the capital costs of on-site power generation systems in thermal energy storage can realize even greater return on investments. A system without storage thus has a payout period of about 1.25 years. With storage the payout period is even less. A complete return on investment analysis including cost of capital has been completed and is included in this chapter.

Total rejected heat from the cement industry using either the long dry process or the suspension preheater amounts to 8.11×10^{13} Btu per year. If 60% of this energy could be used for power generation, an electrical production capacity of 4.07×10^{4} MWe, industry-wide, for these processes would result.

CAPITAL COST ESTIMATION

Capital costs were estimated for the two systems, rockbed and draw salt. Costs include both direct and indirect costs. Methods developed by Guthrie (Ref VII-1) have been adopted in determining the total costs of installed equipment including both materials and labor. Guthrie's method of "module" costing includes certain factors for each piece of equipment in estimating total cost of installation. These factors are approximately broken down as:

1) Direct Costs -

a) Equipment, F.O.B. Cost,

b) Materials (62% of factor 1.a),

c) Labor [36% of factor 1 (a + b)];

2) Indirect Costs (34% of factor 1) -

a) Freight, Insurance, Taxes (6% of factor 1),

b) Construction Overhead (18% of factor 1),

c) Engineering (10% of factor 1);

3) Contractor's Fee (8% of factors 1 and 2);

4) Contingency (10% of factors 1, 2, and 3).

All costs presented in this section are based on a Marshall and Stevens (M&S) equipment cost index of 500 which was the chemical industry-wide average for the second quarter of 1977. Cost estimates have a better than ±20% accuracy based on the guidelines presented by the American Association of Cost Engineers (Ref VII-2).

Installed equipment costs, including both direct and indirect costs, were determined for the equipment previously sized for the rockbed and draw salt storage/waste heat recovery/and power generation systems. Tables VII-1 through VII-4 show the equipment schedules and capital costs required for each plant model and each storage system. Complete breakdowns of power cycle equipment are also shown. These costs were verified with vendor quotes, internal cost estimates, and Guthrie's method (Ref VII-1) for a 10 MWe power plant. Costs for the power facilities at other model plants were estimated using an exponential scale factor of 0.75 recommended by Guthrie. Estimated investments in rockbed storage amount to between 10.3 and 22.3% of the total system costs while the draw salt storage system represents 30.2% to 36.9% of the total draw salt system costs depending on plant size.

Significant differences are evident in the costs of rock storage related equipment and the draw salt. The cost of limestone at a plant is approximately $0.11/lb. Tank costs differ between the two systems because only one tank is required for draw salt and two tanks are used for rockbed storage. Waste heat recovery systems in the form of a waste heat boiler for the rockbed system and a three-heat exchanger unit for the draw salt do not vary much in capital investment required. As expected the installed costs of piping are much less than the cost of ducting. However, these costs represent a very small fraction of total investment.

Table VII-1 Equipment and Material Specifications for Draw Salt System

No. Reqd	Equipment and Material	Plant 1	2	3	4	Matl Const
Storage						
1	ST-1, Draw Salt Storage Vessel, $ft^3 \times 10^4$	8.35	4.20	9.14	17.90	AS
1	Draw Salt, $lbm \times 10^6$	8.77	4.41	9.60	18.8	—
1	Piping Insulated: Traced, ft	200	800	400	100	AS
1	P-1, Circulation Pump, gpm	425	225	475	100	AS
Power Conversion						
1	E-1, Waste Heat Recovery Heat Exchanger, $ft^2 \times 10^3$	6.26	2.99	0.784	10.10	SS
1	E-2, Superheater, $ft^2 \times 10^3$	1.49	0.743	1.20	3.67	AS
1	E-3, Kettle-Type Boiler Shell and Tube, $ft^2 \times 10^3$	2.77	1.432	3.12	8.90	CS
1	E-4, Preheater, $ft^2 \times 10^3$	2.19	0.587	1.45	5.40	CS
1	Set of Soot Blowers for E-1					
1	TG-1, Turbogenerator, MWe	4.0	0.9	2.4	10.1	—
1	C-1, Condenser, $Btu/hr \times 10^8$	—	—	—	1.0	CS
1	CT-1, Cooling Tower, $Btu/hr \times 10^8$	—	—	—	0.95	CS
1	Deaerator	—	—	—	—	—
1	P-2, Circulating Water Pump, gpm	—	—	—	9000	CS
1	P-3, Cooling Tower Makeup Pump, gpm	—	—	—	280	CS
1	P-4, Condenser Makeup Pump, gpm	—	—	—	3	CS
1	P-5, Condensate Pump, gpm	—	—	—	210	CS
1	P-6, Boiler Feed Pump, gpm	—	—	—	210	CS

*Nomenclature:

CS - Carbon Steel
AS - Alloy Steel
SS - Stainless Steel

Table VII-2
Draw Salt System Capital Cost Estimates - Installed Costs (Direct and Indirect)

	Plant 1	Plant 2	Plant 3	Plant 4
Equipment & Materials				
<u>Storage</u>				
Storage Tanks	$ 344,600	$ 219,900	$ 344,200	$ 479,000
Draw Salt	970,200	490,600	1,061,500	2,069,100
Salt Circulation Pump	24,800	16,100	27,900	44,600
Subtotal	$1,329,600	$ 726,600	$1,433,600	$ 2,592,700
Power Conversion				
Heat Exchangers				
Waste Heat Recovery	$ 233,000	$ 111,200	$ 291,600	$ 375,700
Superheater	44,600	22,300	36,000	110,100
Boiler	69,200	35,800	77,900	222,500
Preheater	43,800	11,700	29,000	107,900
Soot Blowers	5,000	3,000	6,000	7,000
Power Generation Equipment				
Turbogenerator	720,000	162,000	432,000	1,818,000
Condenser	451,700	184,600	332,500	787,400
Pumps	4,900	2,000	3,600	8,500
Cooling Tower and Pumps	157,800	64,500	116,100	275,000
Subtotal	$1,730,000	$ 597,100	$1,324,700	$ 3,712,100
BUILDINGS/STRUCTURES				
Steam Generator Bldg & Foundation	$ 158,000	$ 75,000	$ 122,000	$ 250,000
Turbine Bldg & Foundation	598,000	284,000	463,000	950,000
Cooling Tower Foundation	44,000	21,000	34,000	70,000
SITE WORK	10,000	10,000	10,000	10,000
PIPING INSULATION				
Piping (pipes, valves, tees, etc) Insulated -Traced	6,500	26,200	13,100	4,500
Storage Tank Insulation	82,000	52,100	87,300	136,400
INSTRUMENTATION/ELECTRICAL	714,000	492,000	628,000	900,000
Subtotal	$1,612,500	$ 960,300	$1,357,400	$ 2,320,900
Contractors' Fee (8%)	$ 373,800	$ 182,700	$ 329,300	$ 690,100
Contingency (10%)	504,600	246,700	444,500	931,600
Total (M&S = 500, 2nd Quarter 1977)	$5,550,500	$2,713,400	$4,889,500	$10,274,400
Total (M&S = 523, 4th Quarter 1977)	$5,805,800	$2,838,200	$5,114,400	$10,718,800

Table VII-8 Equipment and Material Specifications for Rockbed System

No. Reqd	Equipment and Material	Plant 1	2	3	4	Mtl Const
Storage						
1	ST-1, Low Temperature TES Tank, $ft^3 \times 10^5$	1.02	0.62	1.28	1.65	CS
1	ST-2, High Temperature TES Tank, $ft^3 \times 10^5$	1.14	0.69	1.42	1.84 SS	CS
1	Granite Rock (1.5–2.0 in. dia), $lbm \times 10^7$	2.26	1.38	2.81	3.67	--
1	Ducts, Insulated, ft	1200	1200	1700	1300	GS
7	Dampers (dia), ft	7	7	7	7	
Power Conversion						
1	WHB-1, Waste Heat Boiler, lbm steam/hr $\times 10^4$	5.38	1.26	3.43	12.52	CS
1	TG-1, Turbogenerator, MWe	4.0	0.9	2.4	10.1	--
1	C-1, Condenser, Btu/hr $\times 10^8$	--	--	--	1.0	CS
1	CT-1, Cooling Tower, Btu/hr $\times 10^8$	--	--	--	0.95	--
1	Deaerator	--	--	--	--	--
1	Circulating Water Pump, gpm	--	--	--	9000	CS
1	Cooling Tower Makeup Pump, gpm	--	--	--	280	CS
1	Condenser Makeup Pump, gpm	--	--	--	3	CS
1	Condensate Pump, gpm	--	--	--	210	CS
1	Boiler Feed Pump, gpm	--	--	--	210	CS

*Nomenclature:

CS - Carbon Steel
SS - Stainless Steel
GS - Galvanized Steel

Table VII-4
Rockbed System Capital Cost Estimates - Installed Costs (Direct and Indirect)

	Plant 1	Plant 2	Plant 3	Plant 4
Equipment & Materials				
<u>Storage</u>				
Storage Tanks	$ 310,700	$ 227,500	$ 353,700	$ 487,600
Limestone Rock	8,090	4,800	10,000	12,800
Dampers	70,000	70,000	70,000	70,000
Subtotal	$ 388,700	$ 302,300	$ 433,700	$ 570,400
<u>Power Conversion</u>				
Waste Heat Boiler	$ 803,800	$ 262,600	$ 548,000	$1,610,000
Power Generation Equipment				
Turbogenerator	720,000	162,000	432,000	1,818,000
Condenser	451,700	184,600	332,500	787,400
Pumps	4,900	2,000	3,600	8,500
Cooling Tower and Pumps	157,800	64,500	116,100	275,000
Subtotal	$2,138,200	$ 675,700	$1,432,200	$4,498,900
BUILDINGS/STRUCTURES				
Waste Heat Boiler Bldg & Foundation	$ 158,000	$ 75,000	$ 122,000	$ 250,000
Turbine Bldg & Foundation	598,000	284,000	463,000	950,000
Cooling Tower Foundation	44,000	21,000	34,000	70,000
SITE WORK	10,000	10,000	10,000	10,000
DUCTING/INSULATION				
Ducts, Insulated	86,900	86,900	123,100	94,100
Storage Tank Firebrick Insulation	76,100	54,700	88,500	104,900
INSTRUMENTATION/ELECTRICAL	714,000	492,000	628,000	900,000
Subtotal	$1,687,000	$1,023,500	$1,418,600	$2,379,000
Contractors' Fee (8%)	$ 337,100	$ 160,100	$ 262,800	$ 595,900
Contingency (10%)	455,100	216,200	328,400	804,400
Total (M&S = 500, 2nd Quarter 1977)	$5,006,100	$3,377,800	$3,875,700	$8,848,600
Total (M&S = 523, 4th Quarter 1977)	$5,236,400	$2,487,200	$4,054,000	$9,255,600

Total capital costs of the waste heat recovery system and thermal storage can be broken down into a per-unit basis for system comparisons. Power generation capital costs (direct and indirect), including 8% contractor fee and 10% contingency), for waste heat boiler system and draw salt heat exchanger system are approximately 800 to 1300 $/kWe and 700 to 2000 $/kWe, respectively, without storage. Assuming that 97% of the energy stored in a draw salt storage vessel can be used for power production and 90% of stored energy in a charge cycle in a rockbed can be used, capital costs for storage on a per kWe-hr unit basis range are:

	$/kWe-hr	$/kWt-hr
Draw Salt	12.22-43.43	2.81-9.99
Rockbed	3.39-15.47	0.78-3.56

In the first column a thermal-to-electrical conversion efficiency of 25% was used as a conservative value for these system sizes.

B. SYSTEM OPERATION COSTS AND POWER UTILITY COSTS

Once capital costs had been estimated, a discounted cash flow analysis was used to determine average costs over the anticipated system life. This method for profitability evaluation by discounted cash flow takes into account the time value of money and is based on the amount of unreturned investment at the end of each year over the estimated system life. A trial-and-error method is used to determine the rate of return on a project. This rate of return is applied to the yearly cash flow so the original capital investment is reduced to zero (Ref VII-3). The rate of return calculated from this procedure is then the maximum interest rate of funds borrowed to finance the project.

In our analysis, the discounted flow analysis was used in a somewhat backward fashion to determine what is called "levelized busbar energy" costs *given* an interest rate. Busbar energy costs were determined for interest rates (called either capital cost rates or internal rates of return) varying between 0 to 15% after taxes. A computer program by JPL/EPRI/ERDA (Ref VII-4) for required revenue methodology in the evaluation of utility owned solar power system was exercised in determining the cost of the power generated. These costs were also estimated over a complete spectrum of capital investment costs covering the estimated thermal energy storage system costs previously documented for the four model plants.

By definition, the levelized busbar energy cost is the average electricty cost that must be charged to recover all of the expenses incurred over the project lifetime. These expenses include operating and maintenance charges, property and income taxes, and interest and principal payments on borrowed capital. Shown in Figure VII-1 is the levelized energy cost, $\overline{BBEC}$, in relation to the growing energy production costs of a system life. The $\overline{BBEC}$ then represents the uniform costs over the system lifetime (y_{co} to y_{co} + N) that has the same present value as the growing distribution costs ($BBEC_o$-$BBEC_t$) present value. For more details on this method the reader is referred to Ref VII-4.

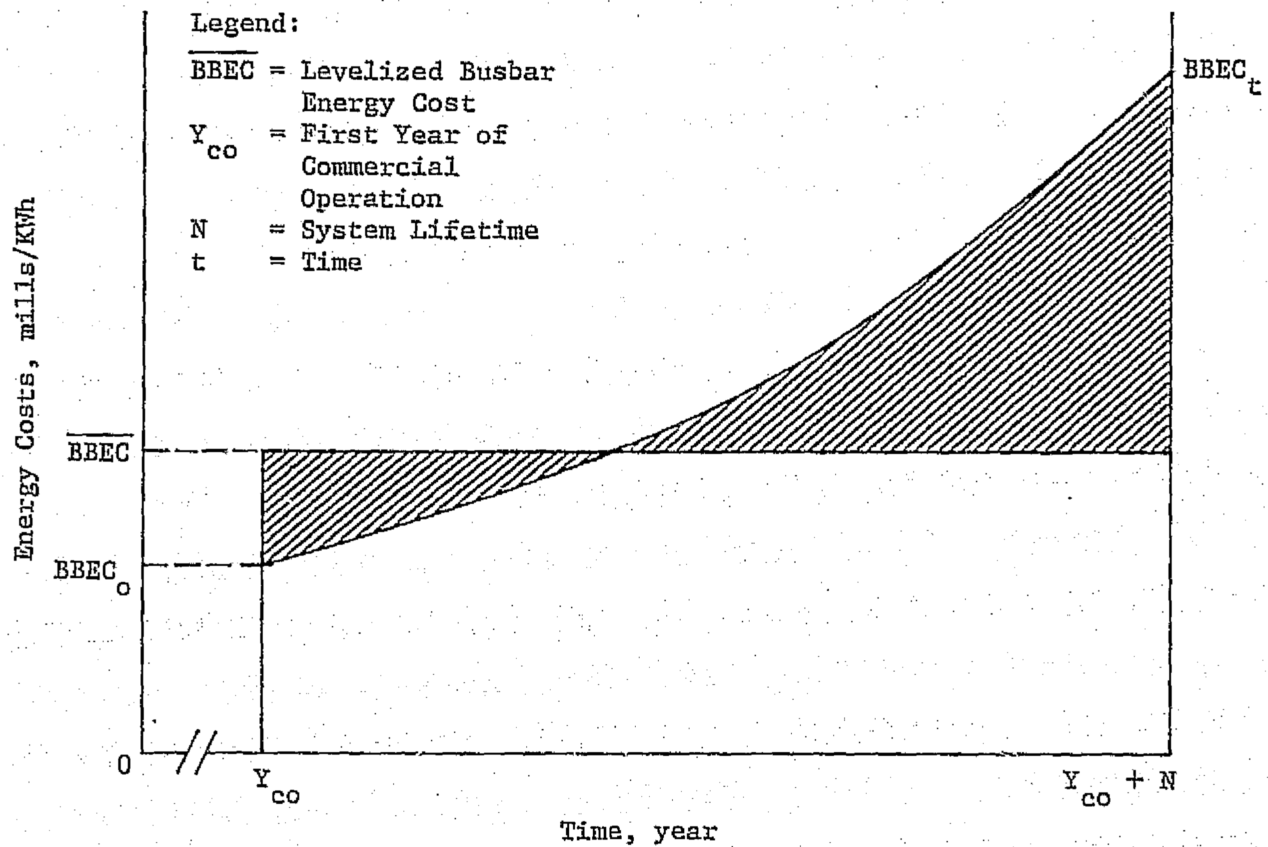

Figure VII-1
Comparison of Levelized Energy Cost with Growing Energy Costs

The levelized busbar energy costs of on-site power generation were computed for various interest rates and capital investments. The assumptions used (or inputs to the computer model) in estimating these costs are:

1) Costs include internal rate of return varying from 0-15% after tax;

2) 30-year system lifetime;

3) Depreciation method - straight line over 30-year system life;

4) Income tax rate (allowing for depletion allowance) - 40%;

5) Other taxes and insurance premiums - 0.0225% of capital investment;

6) Operating and maintenance cost/year -

   a) Power plant - \$0.003/kWe-hr generation,

   b) Storage - \$0.20/kWe-hr storage capability;

7) Escalation rates -

   a) General inflation - 6%/year;

   b) Capital costs - 6%/year,

   c) Operating and maintenance costs - 6%/year;

8) 3-year construction period to commercial operation.

Figures VII-2 through VII-5 show the levelized busbar energy costs for power generation systems sized for Plants 1 through 4. After-tax interest rates of 0, 10, and 15% are shown. For the 0.9 MWe a capital investment of \$1.6 x 10^6 and an after-tax cost of capital of 15% would result in a levelized 72 mills/kWh cost of producing on-site power over a 30-year life. On the other hand, the 10 MWe power plant sized for model Plant 4 shows a cost of 42 mills/kWh for a \$10 million investment of 15% after-tax cost of capital. Again, these costs represent the average costs incurred over the system life to reduce the original investment to zero. In a sense these costs would represent the maximum costs incurred to an investor to realize an after-tax return on investment of 15% (25% before tax).

The cost of on-site power generation must also be compared to purchased power from a utility on a levelized basis. The costs for a 0.9 MWe and 10 MWe power plant must not be compared with present-day energy costs. Instead, levelized or averaged costs of purchased power must be compared with the computed levelized costs of producing power on-site. Levelized utility costs are shown in Table VII-5, assuming a 6% general inflation rate and 6% and 11% electrical power escalation rates over a 30-year system lifetime. These costs are tabulated for various present electrical energy costs.

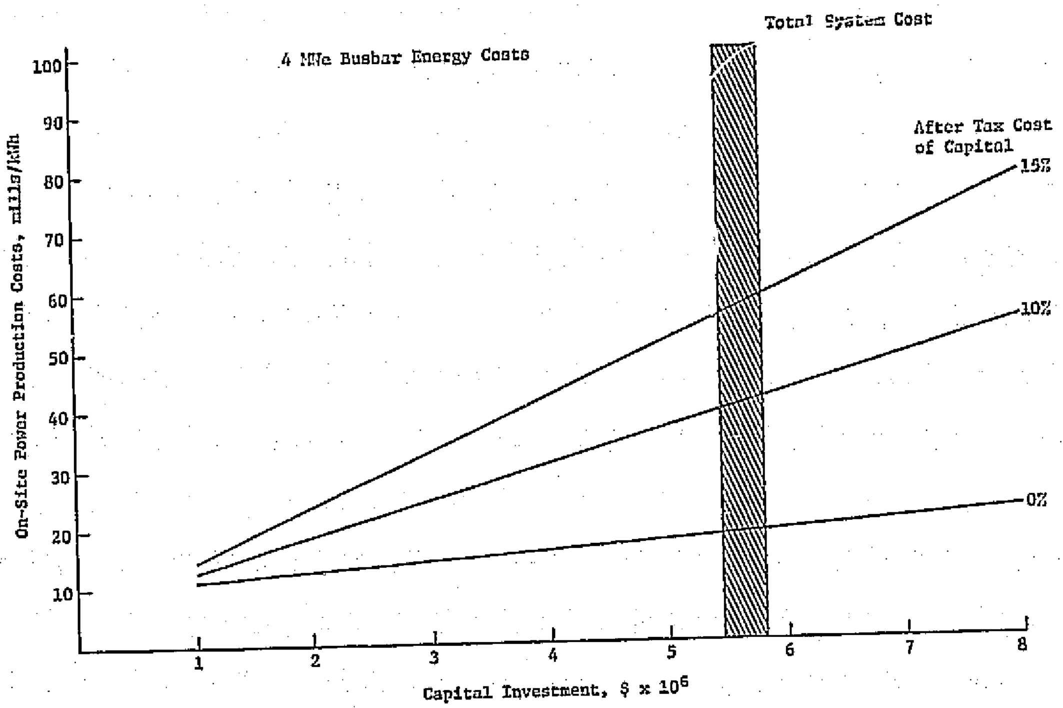

Figure VII-2 Plant 1 Power Production Costs

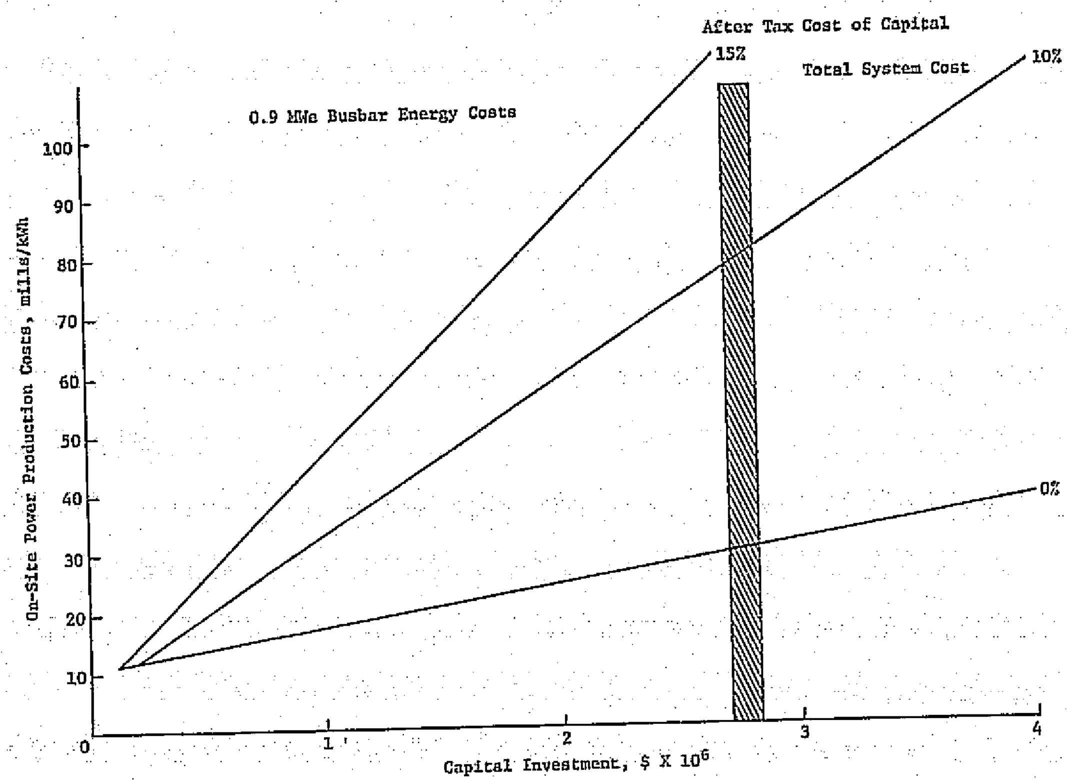

Figure VII-3 Plant 2 Power Production Costs

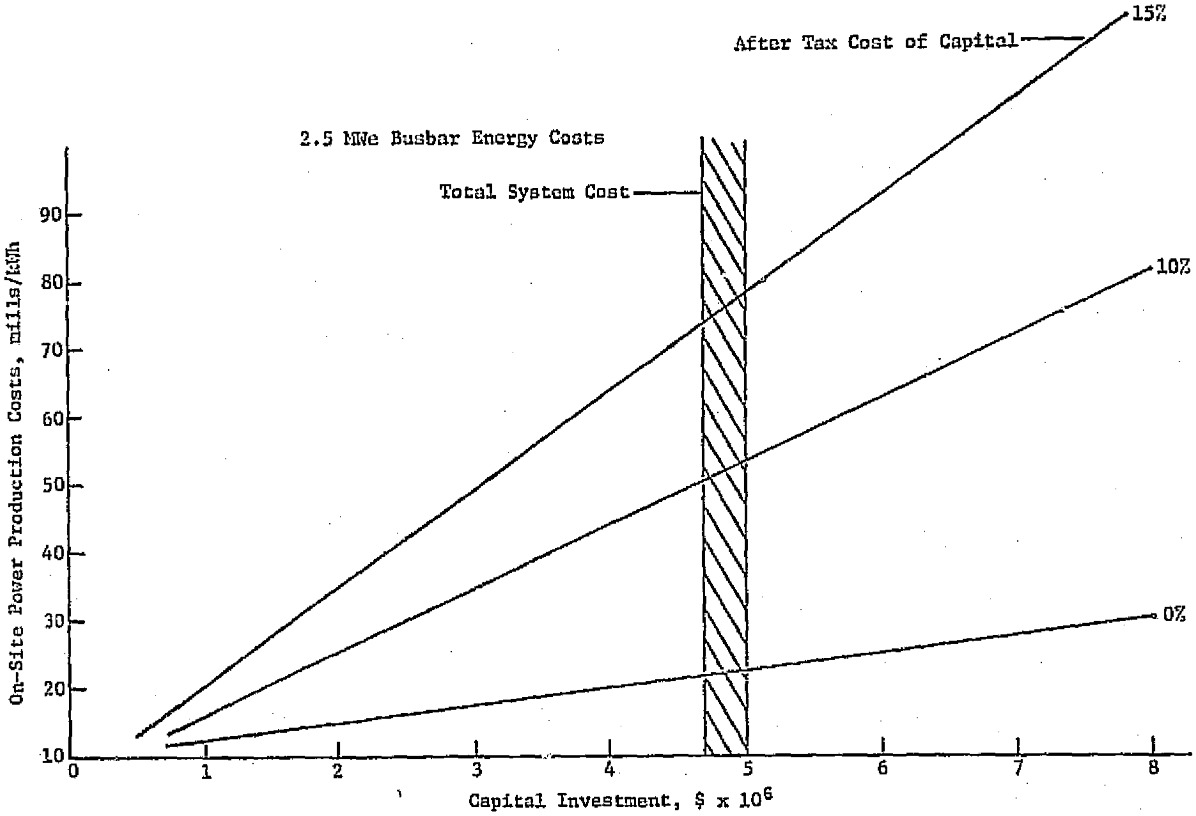

Figure VII-4 Plant 3 Power Production Costs

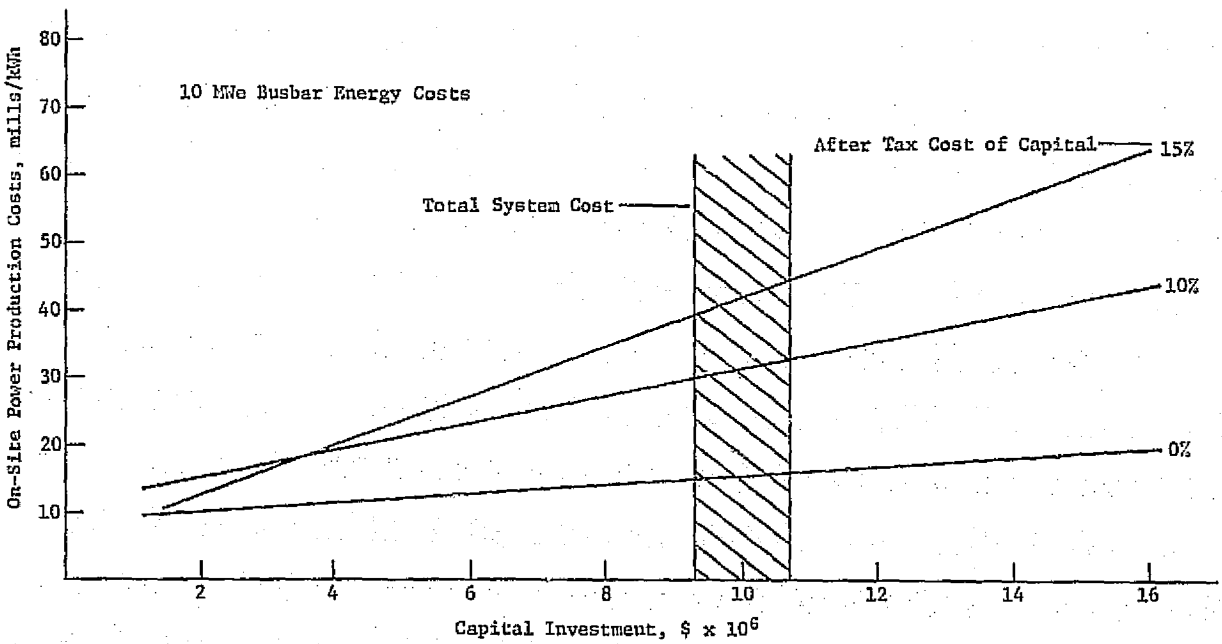

Figure VII-5 Plant 4 Power Production Costs

Table VII-5 Utility Levelized Costs

Present Energy Costs, mills/kWh	Utility Levelized Costs, mills/kWh, 6% Power Cost Escalation	Utility Levelized Costs, mills/kWh, 11% Power Cost Escalation
10	17.55	51.9
20	35.10	103.8
30	52.65	155.7
40	70.20	207.6
50	87.75	259.5

Therefore, using our previous example of 0.9 MWe plant on-site energy cost of 72 mills/kWh, one sees that present utility charges of greater than 40 mills/kWh escalating at 6%/year to a cement plant would be required before an after-tax return on investment of 15% could be realized. However, if electricity escalates at 11%/year over the next 30 years, present energy costs of between 10 to 20 mills/kWh would make on-site power generation attractive. The industry-wide average of electricity costs in the cement industry are currently 25 to 28 mills/kWh, indicating that on-site power generation would provide even greater return than 15% after tax in this case. Similar comparisons can be made for the 10 MWe plant and show that the return is even better for investors. One can conclude that depending on the local rates of purchased power, waste heat recovery systems for power production may be economically viable for suspension preheater systems as well as long dry processes. The rate of actual return can be expected to be higher for the waste heat recovery system coupled with a long dry kiln. Thermal energy storage advantages will become apparent in detailed analysis of return on investment.

C. THERMAL ENERGY STORAGE RETURN ON INVESTMENT

Return on investment calculations using on-site power generating costs with those utility costs likely to occur over cement plant life were performed. Rates of return were compared for waste heat power generation systems only and those having a thermal energy storage capability. Results will show that a rockbed storage system is an economically viable investment while the draw salt storage system is marginal.

A basic definition of return on investment for energy conservation expenditures is energy savings divided by the sum of original capital investment and yearly working capital. Energy savings are realized when purchased power costs from a utility are greater than on-site produced power costs. Small amounts of working capital are required to pay monthly operating expenses, such as salaries, wages, and raw materials; accounts payable; and taxes payable. Other assumptions leading to return on investment calculations are itemized below:

1) No sales of electricity back to a utility;

2) Utility electricity cost escalation rate - 6% to 11%;

3) General inflation rate - 6%/year;

4) Investment tax credits - 0%, 10%, 20%;

5) Working capital - 0.005 of capital investment;

6) Electricity demand charge - add 50% of base rate to base rate;

7) Storage utilization rate - 10%/year.

One of the benefits of thermal energy storage is the virtual elimination of demand on time-of-day charges. These costs can be substantial depending on a plant's location. An electrical rate schedule for large power users in the State of Colorado is shown in Figure VII-6. If a cement plant has a power generating capability of 9 MWe and the kiln goes down while the plant still requires 9 MWe for a period of 24 hours, the demand charge would be approximately 1.42 times the base commodity charge. In other areas of the country, especially the northeast, rates in excess of 1000% of base rates for time-of-day schedules exist. (Ref VII-5).

For the various model plants, return on investments were determined for on-site power plants only and power plants with thermal energy storage. Equations were developed for rates of return in each case. These equations are listed below.

[VII-1] Return on Investment (Power Plant Only)

$$\text{Return on Investment (Power Plant Only)} = \frac{LF \times kWe \times 8760 \left[\overline{BBEC}_{UT} - \overline{BBEC}_{ON} - SUF \times \overline{BBECD}_{UT}\right]}{\text{Capital Investment} + \text{Working Capital}}$$

Colo. P.U.C. No. 5 Electric

Ninth Revised Sheet No. 143
Cancels
Sub. Eighth Revised Sheet No. 143

ELECTRIC RATES LARGE LIGHTING AND POWER SERVICE	Territory Urban Fringe Rural	
SCHEDULE LLP	RATE	
AVAILABILITY Available in the entire territory of the Company		
APPLICABILITY Applicable to Large Lighting and Power Service Supplied at primary voltage. Not applicable to standby, auxiliary, or resale service.		
MONTHLY RATE		
Demand Charge:		R
First 25 kilowatts or less of billing demand	$ 98.00	
Next 75 kilowatts of billing demand, per kW	3.64	
Next 200 kilowatts of billing demand, per kW	3.46	
All over 300 kilowatts of billing demand, per kW	3.28	
Commodity Charge:		
First 20,000 kilowatt hours used, per kWh	.01910	R
Next 100,000 kilowatt hours used, per kWh	.01596	R
Next 160,000 kilowatt hours used, per kWh	.01488	R
Next 220,000 kilowatt hours used, per kWh	.01407	R
All over 500,000 kilowatt hours used, per kWh	.01223	I
MONTHLY MINIMUM The Demand Charge but not less than	98.00	R
FUEL COST ADJUSTMENT This rate schedule is subject to the fuel cost adjustment set forth on sheet number 280.		
PAYMENT Bills for electric service are due and payable within ten days from date of bill.		
DETERMINATION OF BILLING DEMAND Billing demand, determined by meter measurement, will be the average kilowatts used during the fifteen minute period of maximum demand during the month, or as set forth in the Industrial Rules and Regulations. However, the billing demand for the current month will be not less than seventy-five percent of the highest fifteen minute		
(Continued on Sheet No. 143A)		

Figure VII-6 Colorado Utility Power Schedule for 1977

[VII-2] $$\text{Return on Investment (Power Plant + Storage)} = \frac{LF \times kWe \times 8760 \left[\overline{BBEC}_{UT} - \overline{BBEC}_{ON}\right]}{\text{Capital Investment + Working Capital}}$$

where:

LF = load factor of peak generation capability (since in most cases on-site power can be used totally, this represents the fraction of time the kiln is up to produce power),

kWe = peak generation capability of on-site power station, kW,

8760 = hours/year,

$\overline{BBEC}_{UT}$ = levelized busbar energy costs purchased from a utility over system lifetime (base rate only),

$\overline{BBEC}_{ON}$ = levelized busbar energy costs of on-site power station,

$\overline{BBECD}_{UT}$ = levelized busbar energy costs of electricity under demand or time-of-day charge rates,

SUF = Storage utilization factor (represents the fraction of power produced from energy storage to eliminate demand or time-of-day charges).

If tax credits are considered, the entire credit can probably be claimed during the first year of operation, thus reducing the original capital investment in the above equation by the amount of the tax credit. That is, if a 10% tax credit could be claimed, then a $\$10 \times 10^6$ investment would be reduced to $\$9 \times 10^6$. Shown in Figures VII-7 through VII-10 are the calculated return on investments based on the equations and assumptions described above for no tax credits.

Using Plant 4 as an example, the economic advantage of rockbed thermal energy storage units is readily apparent. In these calculations a load factor (LF in Eq [VII-1]) of 0.9 was assumed for this plant as well as for Plants 1, 2, and 3. In Eq [VII-2], the load factor, LF, represents: 1.0 minus the energy that is demanded for the manufacturing operation diverted to storage. If kiln gas is diverted to storage during plant shifts when the power requirements for plant opration are less than the on-site produced power, then the load factor in Eq [VII-2] is 1.0. Such situations exist during third shift of a working day. Also, for plants producing a small portion of plant demand, such a situation would be realized by purchasing power from a utility during these off-peak hours. Both of these example situations are depicted in Figures VII-11 and VII-12.

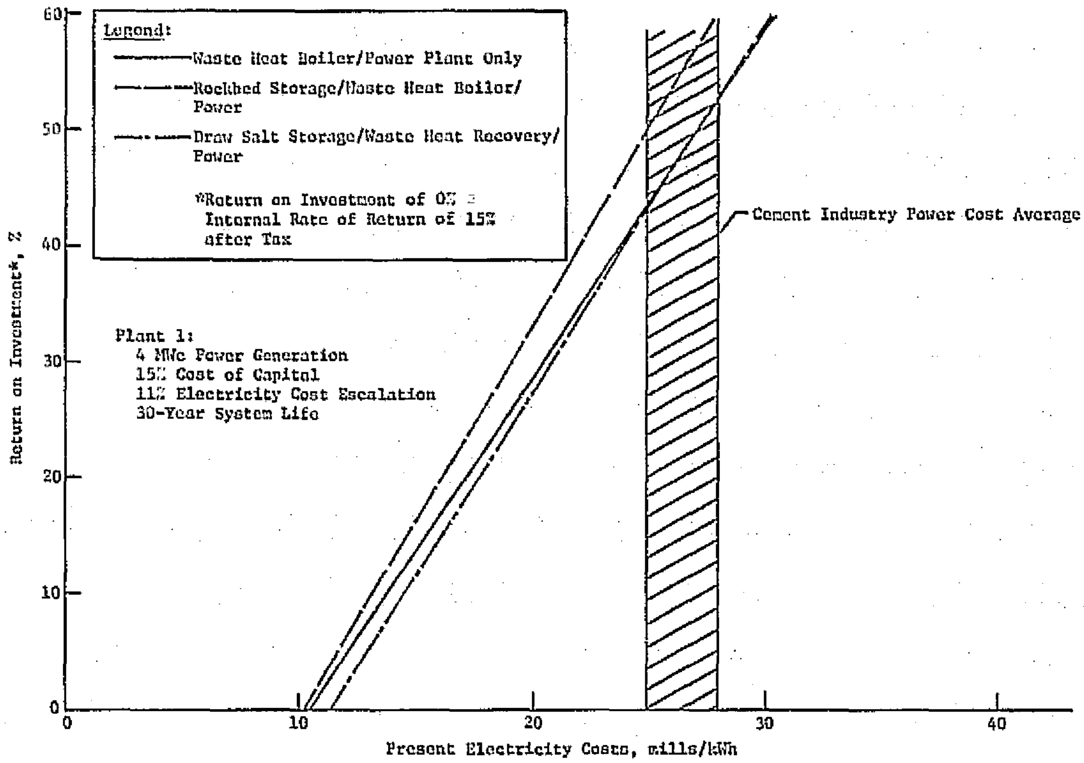

Figure VII-7 Plant 1 Energy Savings Rate of Return

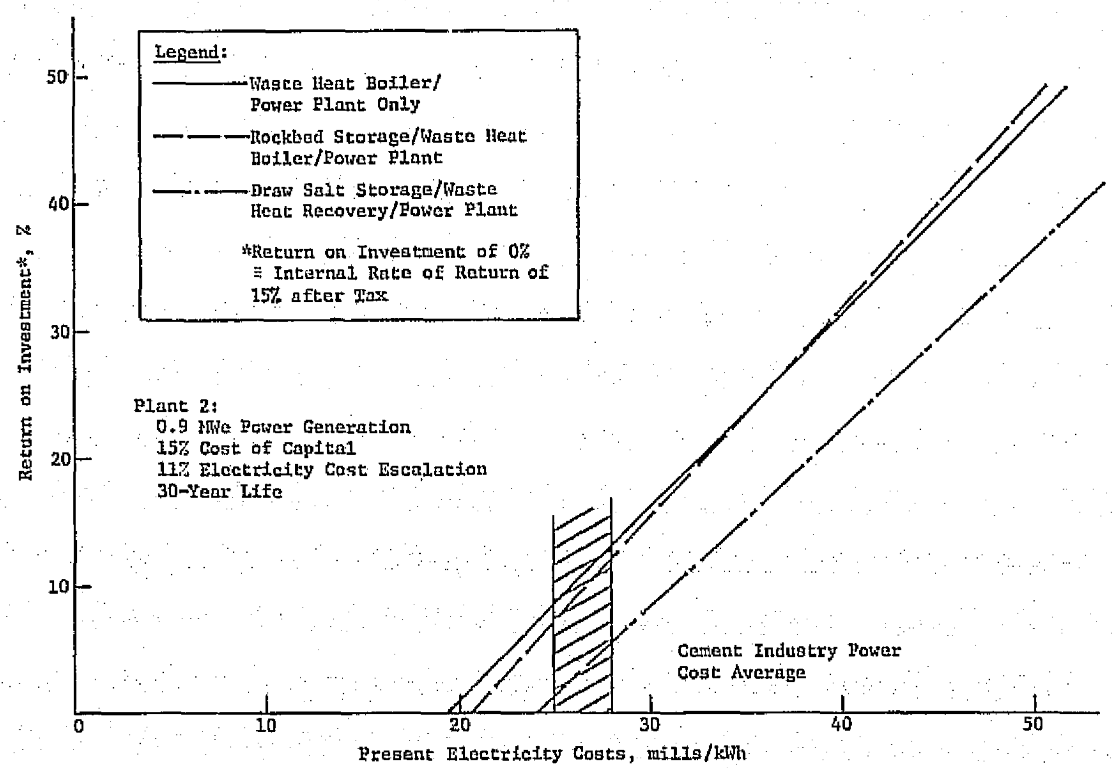

Figure VII-8 Plant 2 Energy Savings Rate of Return

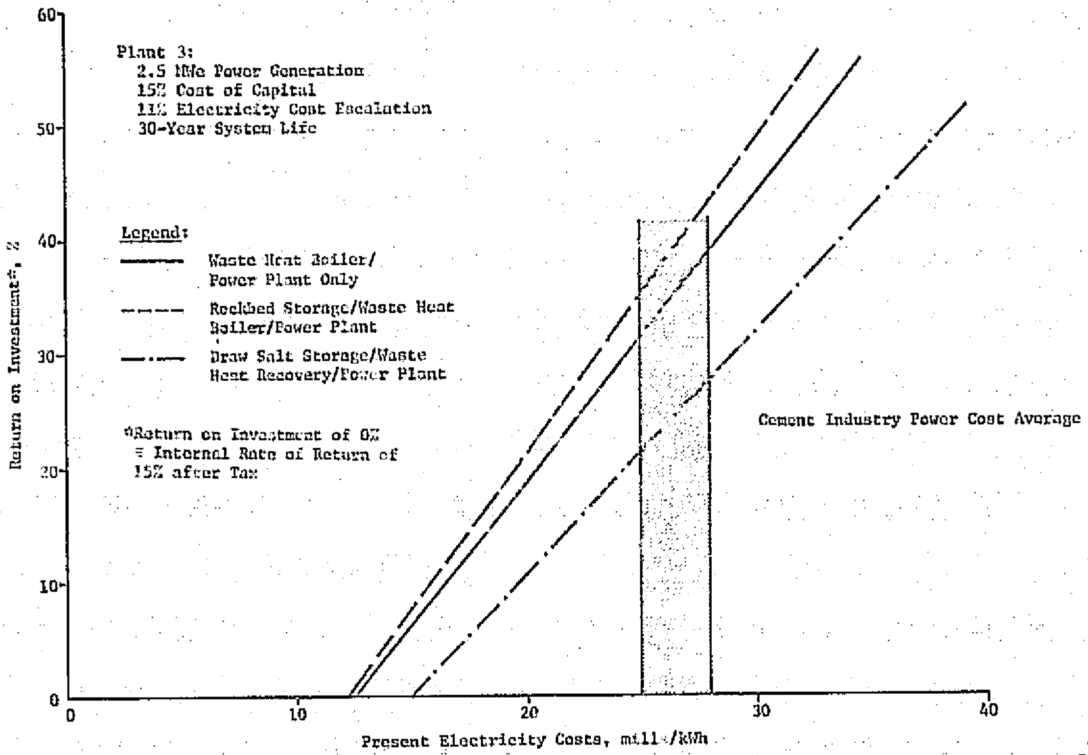

Figure VII-9 Plant 3 Energy Savings Rate of Return

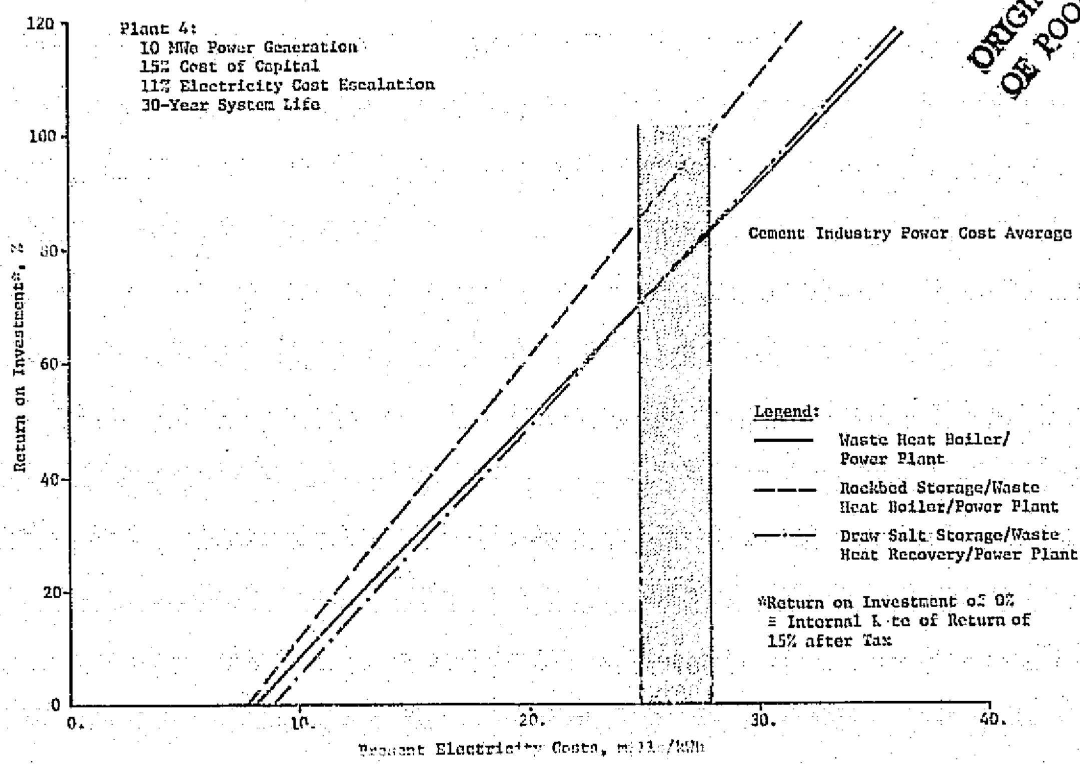

Figure VII-10 Plant 4 Energy Savings Rate of Return

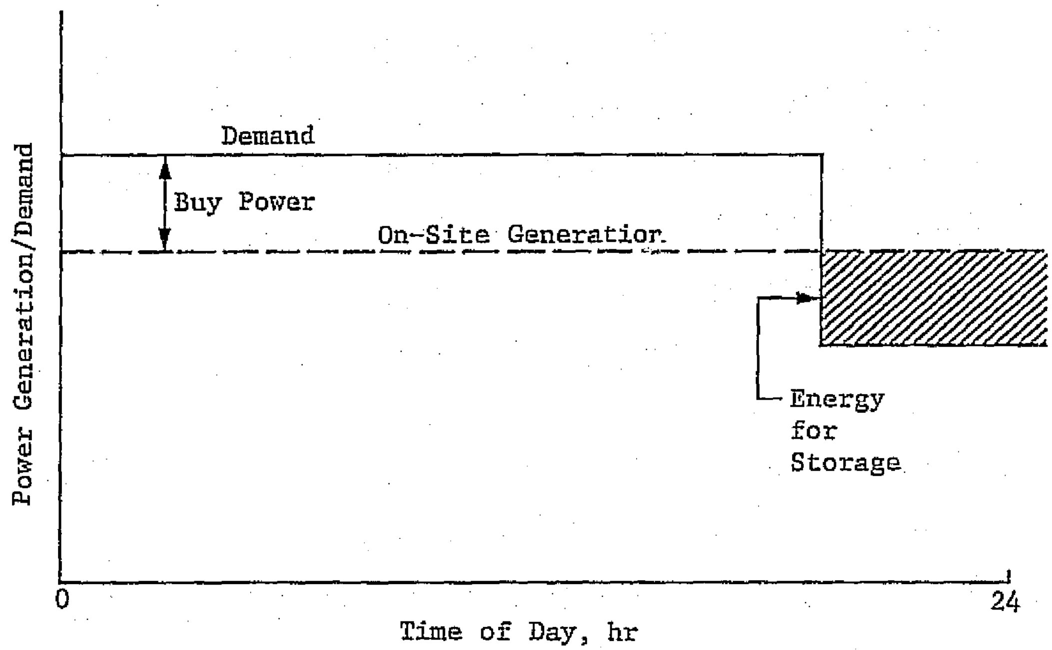

Figure VII-11
Energy Storage for Time of Day Load Leveling for Large On-Site Power Plant

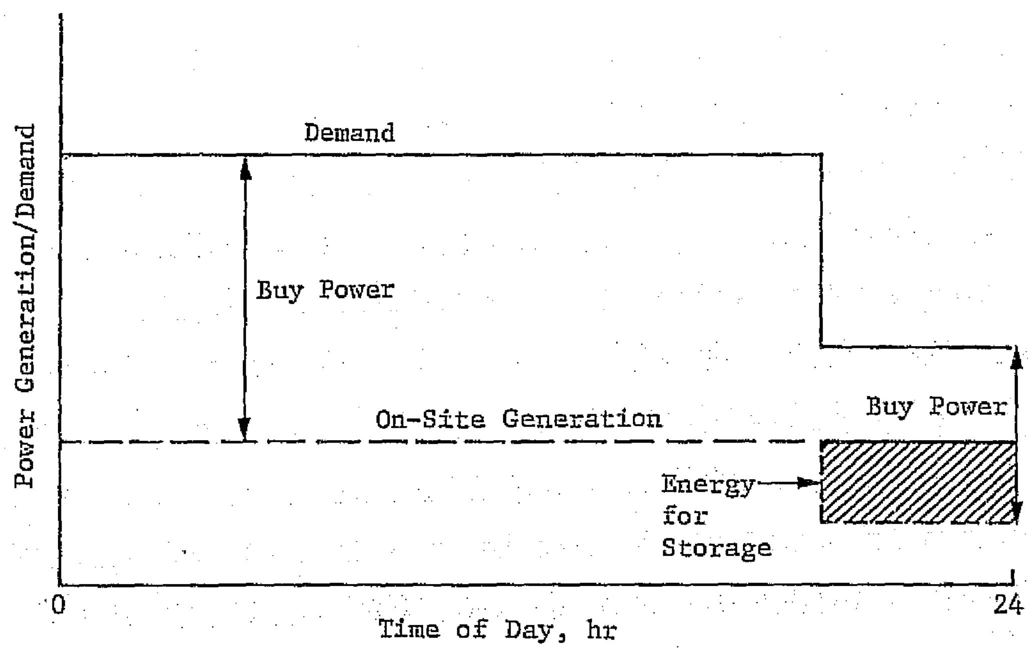

Figure VII-12
Energy Storage for Time of Day Load Leveling for Small On-Site Power Plant

This load factor in Eq [VII-1] represents the fraction of time the kiln is operating during the year based upon historical operating data for cement plants. The levelized cost of utility power, $\overline{BBEC}_{UT}$, was calculated using the levelized costs shown in Table VII-5 for an 11% power cost escalation. Levelized busbar energy costs for on-site power generation, $\overline{BBEC}_{ON}$, were obtained for the capital investments required for each system from Figure VII-5 for a 15% cost of capital. A storage utilization factor, SUF, of 0.10 was assumed. This factor represents the fraction of power produced from thermal storage during the year. The levelized demand charge, $\overline{BBECD}_{UT}$ from a utility was assumed to be 1.5 times levelized utility rate, $\overline{BBEC}_{UT}$. Capital investments of the waste heat recovery/power plant and waste heat recovery/power plant/storage systems were estimated and obtained from Tables VII-2 and VII-4.

The rate of return for the rockbed storage/power system is substantially greater than just a waste heat recovery/power plant system for Plant 4. Figure VII-10 shows that for the current industry-wide average of 2.8¢/kWh an additional 17% return on investment can be realized with rockbed storage over the system without storage. The draw salt system, however, provides no additional rate of return on investment over a system without storage. These graphs also show that:

1) Return on investment increases with present energy costs (as one would expect).

2) Greater returns are realized with plants with larger rejected heat from the kiln (i.e., long dry process kilns offer the largest incentive for investment).

3) Thermal energy storage utilization eliminating demand charges when the kiln is down is economically attractive up to a capital cost limit (approximately 20% of capital investment assuming a 10% storage utilization factor).

4) Draw salt storage for this application shows marginal to negative return on thermal storage investment.

5) Rockbed storage offers greater return on investment due to elimination of demand charges.

6) Return on investment depicted in these charts are returns after cost of capital has been considered. That is, if a plant had a minimum investment criteria of 15% after tax, then the graphs depicting 15% cost of capital could show a return on investment of 0% for their present energy costs and the investment would meet the investment criteria.

Other economic benefits of thermal energy storage could not be addressed due to their plant specific nature. The use of thermal energy storage in conjunction with waste heat recovery for power production could increase production capacity of a plant. Without energy storage, large amounts of power during kiln shutdowns or community brownouts may not be available to continue plant operation. The potential benefit of using thermal storage generated hot air for combustion air preheat to shorten kiln startup time can have a definite benefit on increased production capacity. Thermal energy storage in leveling the power load and generation during plant operation could have a definite benefit in increased cement production. Specific operating data required for detailed evaluation could not be obtained from a specific plant during this study phase.

D. STATE OF THE CEMENT INDUSTRY AND POTENTIAL ENERGY SAVINGS

Presently, the cement industry is in a dynamic state of developing energy conservation methods. Wet kilns are being replaced by dry process kilns with or without preheaters depending on raw materials nad fuel burning properties. The preheater method results in annual savings in fuel requirements. However, the electrical energy required in these new processes is greater than that for their wet kiln predecessors on a kWh/ton of clinker basis. The method proposed in this report to realize further savings is in on-site power generation. It is highly possible that with the present trend of electrical power cost escalation rates exceeding fuel cost escalation rates, on-site power generation may be more advantageous than converting a long dry kiln to a suspension preheater kiln.

Current costs of converting a long dry kiln to a four-stage suspension preheater is about $30/annual ton of clinker for production rates less than 700,000 tons per year and $28/ton for production rates greater than 1 million tons per year. Therefore, the costs of converting a 70-ton/hr long dry kiln would be approximately $18.4 million. The costs of installation of a waste heat boiler system with rockbed storage would be $9.8 million. One system would be saving fuel costs and the other system would be saving electricity costs or ultimately utility fuel costs. Waste heat recovery methods would involve about half the capital required of investment over preheater conversion methods. As a general trend, electricity costs will keep pace with and most probably exceed escalation rates of fuel costs, making waste heat recovery/power generation schemes very attractive.

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VIII. RECOMMENDED DEVELOPMENT PLAN

The results of the tasks discussed previously have shown that the most cost-effective use of waste heat in the cement industry is to generate electricity, which can be used within the cement plant. Therefore, no distribution system is needed and none of the problems attendant to distributing energy to users outside the plant are encountered. Our study showed that only the dry kiln processes have the quantity and quality of energy to be attractive for power generation, and the amount of energy that can be saved is considerable. For example, if all of the long dry process kilns in the United States were converted to generate electricity, 3.71 to 3.60 x 10^{13} Btu would be used and up to 2.43 x 10^6 MWh of electricity would be generated resulting in a savings equivalent to 4.5 to 6.0 million barrels of oil per year. If the 42 suspension preheater kilns were converted, an additional 0.95 to 1.27 x 10^{13} Btu could be saved. Thus from an energy conservation standpoint, the generation of electricity using waste heat is very attractive.

The system also offers an attractive rate of return on investment. As discussed in the previous chapter, the rate is up to 80% for long dry kilns and about 35% for suspension preheat kilns, depending on the present cost of electricity at the plant site. In addition, the system has no adverse effect on the environment, and does not impact the cement process.

The major drawbacks to power generation in the past have been: (1) low return on investment compared to other alternatives; (2) the availability and cost of power during 15 to 20 times per year that the kiln is shut down for emergency repairs; and (3) the fear of loss of production due to failures in the power generation system. The amount of potential return on investment has increased considerably over the past few years due to the rapid increase in cost of electricity. Therefore, studies that in the past have shown power generation to have low economic value may now result in the opposite conclusion.

The problem of obtaining power and the high cost of guaranteeing the availability of that power for those periods of time when the kiln must be shut down for emergency repairs can be overcome by the use of thermal storage. In fact, thermal storage can increase the rate of return on investment. The problem of an unreliable steam generation system causing shutdown of the plant can only be addressed through proper design and the possible use of redundancy in certain components.

To promote the use of waste heat power generation in the cement industry, it is necessary to prove that:

1) The system provides an attractive return on investment;

2) All technology problems have been solved;

3) The system operates reliably and will not increase down time.

The program discussed in the following sections is designed to accomplish these objectives. The program is separated into two elements. The first consists of development testing of small-scale storage systems, followed by testing of the selected storage system in parallel with an actual plant process. The system size would be sufficient to demonstrate thermal performance (1/4 scale) and would be installed on a plant with an existing power generation system.

A. PHASE II - DEMONSTRATION PROGRAM

This phase consists of three major tasks: subscale testing to prove feasibility of the rockbed storage concept; design and analysis to select either the rockbed or draw salt storage system and design the full scale system; and demonstration testing in which a system (1/4 capacity) will be tested at an operating cement plant. The task sequence is shown in Figure VIII-1 and the program is described in the following paragraphs.

1. Pilot Plant Testing

The objective of this task is to determine whether the rockbed storage systems will operate properly when subjected to fume conditions typical of those found in a cement plant.

The testing will be performed using the 30 lb/hr pilot kiln that is under construction at PCA. This kiln will be completed in June of 1978 and will be available for use throughout the program. A rockbed storage system will be designed and fabricated to simulate the full-scale unit.

A schematic of the rockbed system is shown in Figure VIII-2. Kiln gases are drawn through the rockbed storage unit using induction fans for charging. Discharge of the storage system will be simulated by drawing ambient air through the bed. The flow will be controlled by use of the dampers shown on the schematic. The direction of flow through the storage bed will be reversed from charge to discharge to take advantage of the particle removal effect. The instrumentation indicated on the schematic will allow measurement of temperatures, pressures, and flowrate throughout the system. The rockbed storage unit will be fitted with a temperature rake to allow measurement of the thermocline

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OF POOR QUALITY

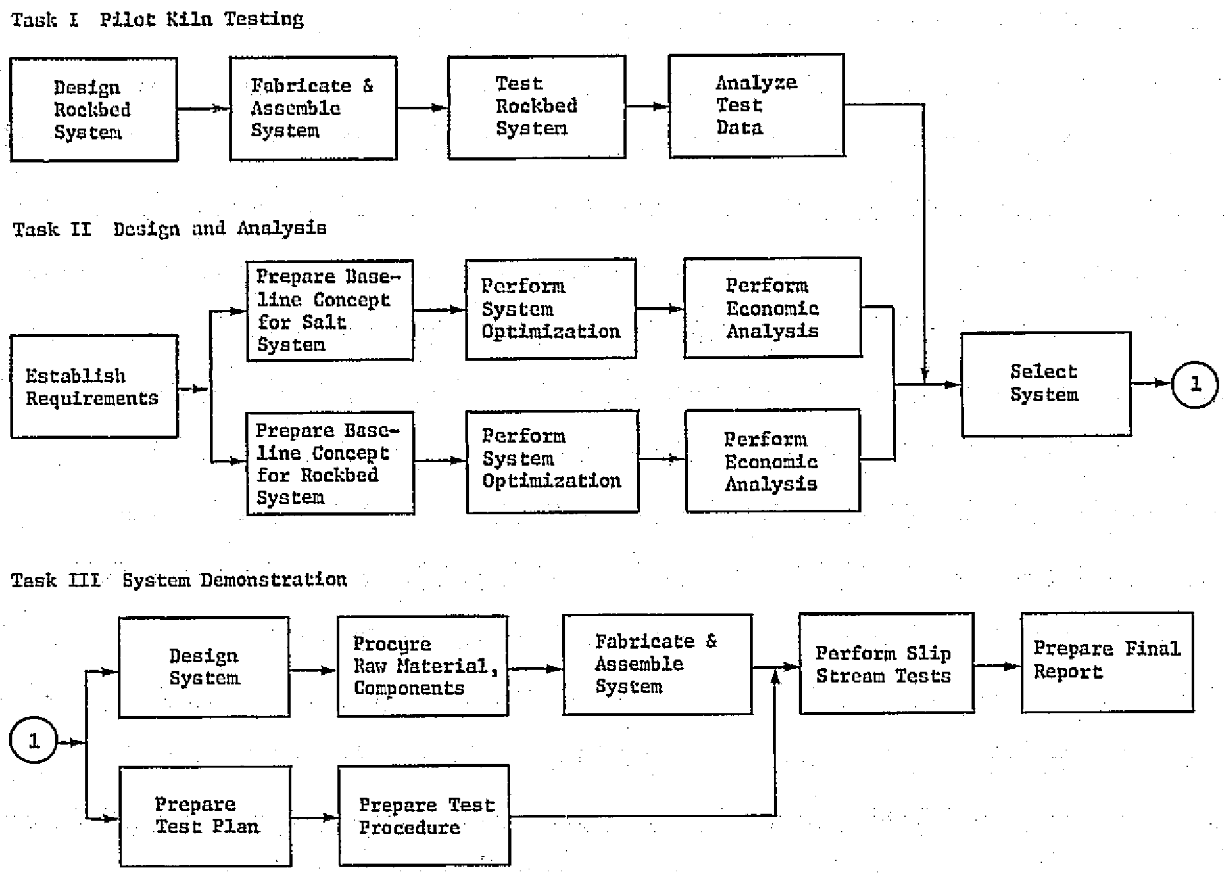


Figure VIII-1 Phase II Development Testing

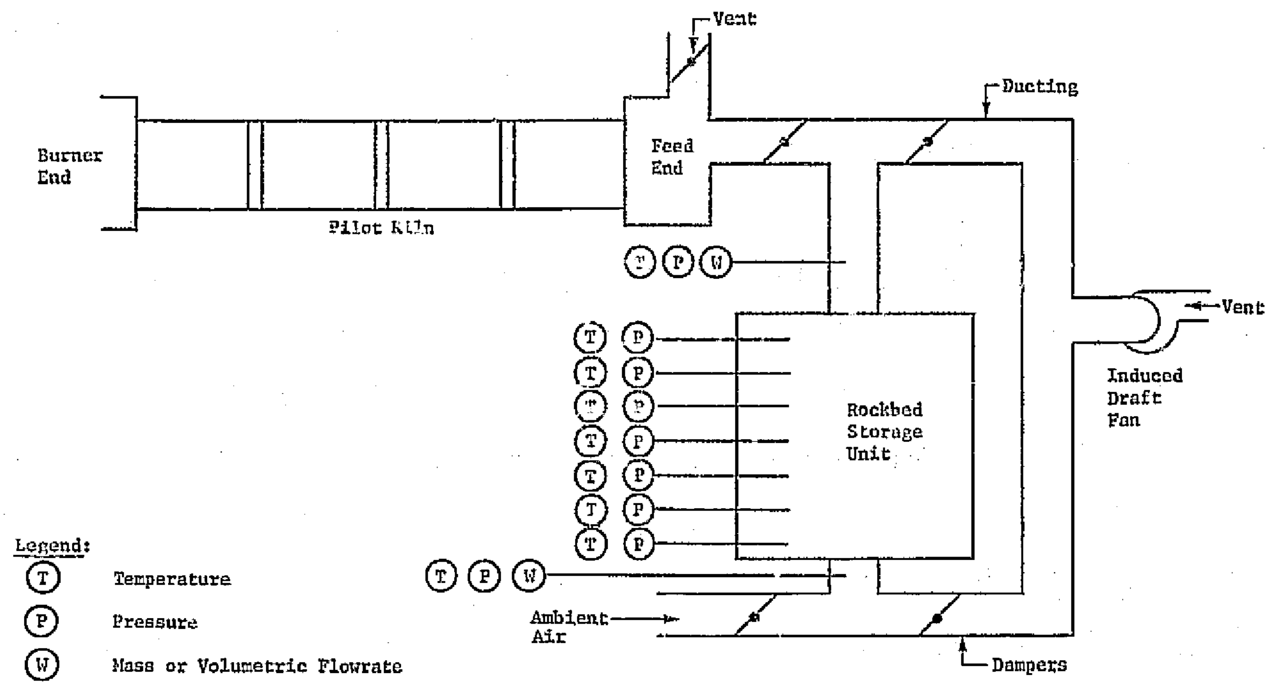


Figure VIII-2 Subscale Test Layout Using Pilot Kiln

movement as a function of time. Chemical analysis and particulate counts of the gases entering and leaving the storage unit will also be performed.

The storage system size is determined by scaling from the system designed for model Plant 1, the long dry kiln. Since the major objectives of this test are concerned with plugging of the bed due to particle deposition, heat transfer rates, and quantity of energy stored, apparent velocity was chosen as the scaling parameter. That is:

$$\frac{\dot{w}}{A} = \frac{\dot{w}_p}{A_p}$$

where:

$\dot{w}$ = gas flowrate, lb/hr,
A = cross sectional area of storage container, ft^2
p = subscript denoting pilot plant.

The container used will be cylindrical with a length-to-diameter ratio of one. These assumptions result in a container of 3-ft diameter by 3-ft long containing about 1 ton of granite, limestones, or clinker.

The tests performed will consist of cycling the bed a sufficient number of times (approximately 40) to allow determination of the performance over a 30-year life. A cycle is defined as charging the bed using kiln exit gases until the temperature of the gas leaving the storage bed is 2/3 that of the inlet gas temperature (approximately 1000°F), then discharging the bed using ambient air until the temperature of the gas leaving the bed drops below 400°F. Forty cycles will be run to determine the effective life of the bed. Pressure loss across the bed will be measured and plotted versus cycle number and extrapolated to determine how long it takes for the pressure losses to become excessive. After completion of 40 cycles, or when the pressure losses become excessive, the storage system will be disassembled and the limestone will be examined for evidence of degradation due to temperature cycling or chemical reactions. The effect on cycle life will then be estimated from these test results. Samples of the container will be taken and analyzed on a macro and micro basis for evidence of corrosion or stress problems to determine the impact of these parameters on cycle life.

In addition, material tests on granite, clinker, or limestones, both calcitic and dolomitic will be run. In this test, four samples with varying amounts of dolomite, and possibly also quartz will be subjected to temperature cycles between 400 and 1500°F, under conditions simulating kiln gas composition. This test will determine whether the expansion of the quartz when it makes the transition from α to β is large enough to break up the stone, and also to ascertain whether the dolomite is calcined.

Upon conclusion of the test, a report documenting the equipment used, method of performance, and test results will be prepared and submitted for approval.

2. <u>Design and Analysis</u>

The purpose of this task is to define the system requirements, conduct trade studies and optimize the design concept for each type of storage system, and select one of these systems.

The requirements for the thermal storage system will be derived using a cement plant with an existing waste heat power generation capability. This plant will be used for the system demonstration testing to avoid the cost of installing the power generation equipment. The requirements to be defined will include kiln gas conditions (temperature, pressure, flowrate, chemical composition, particle quantity, etc), storage unit performance (total heat stored, discharge rate, heat loss), system design life, maintenance, reliability, safety, workmapship, etc. These requirements will then be documented in a thermal storage system design criteria document.

Using this criteria document, a baseline design will be prepared, and design tradeoffs and optimization studies will be conducted on each system. In choosing between alternative designs, low life-cycle cost will be the major criterion. Other factors considered will be reliability, performance, availability, and maintainability. On completion of the optimization studies, a detailed cost estimate and economic analysis of each system will be performed. Supplier quotations will be obtained for each component and item of raw material. Estimates of the site preparation, assembly, and installation cost will be obtained from an architectural and engineering, firm. Operation and maintenance costs will be estimated. These estimates will then be used to calculate the rate of return on investment for each system. From the results of these analyses, the system to be used in the remainder of the program will be selected.

3. System Demonstration Testing

The objective of this task is to obtain operating and performance data on a reduced-scale storage system installed at an operating cement plant, designed so that it will not impact the cement manufacturing process.

The system shown in Figure VIII-3 will include clinker cooler gas storage module, a kiln gas storage module, interconnecting ducting, and an induced draft fan. The storage capacity is 1/4 the size of a full-scale system. However, the interfaces with the kiln, interconnecting ducting, and dampers will be full scale. The shaded areas of the figure indicate the equipment that must be added to convert to full scale. A single storage tank on the clinker cooler and kiln will be used. These tanks will be 1/4 the length of the required units. Thus, the slipstream units can be left in place and easily converted to a full-scale system.

Although the storage capacity is 1/4 of the full scale, the flowrate will be full flow in order to maintain the gas velocity through the bed equal to that required for the full-scale unit. The unit will be able to provide 100% of the power for 6 hr.

The testing will consist of normal and high flow cyclic testing. Four cycles at normal charging flowrates (5% of kiln gas flow) will be run to verify operating procedures, thermal stress, charge and discharge rates, pressure losses, and thermal cycling effects. The span time for these tests will be about four days each. To maximize the number of cycles, the charging flowrate will be increased to 40% of the kiln gas flow thus reducing the charge time by a factor of 8 to about 10 hr. The discharge time is about 12 hr at normal flowrates resulting in a total cycle time of approximately one day. Thirty cycles would be run to demonstrate the equivalent of 1½ years of actual plant operation. From the

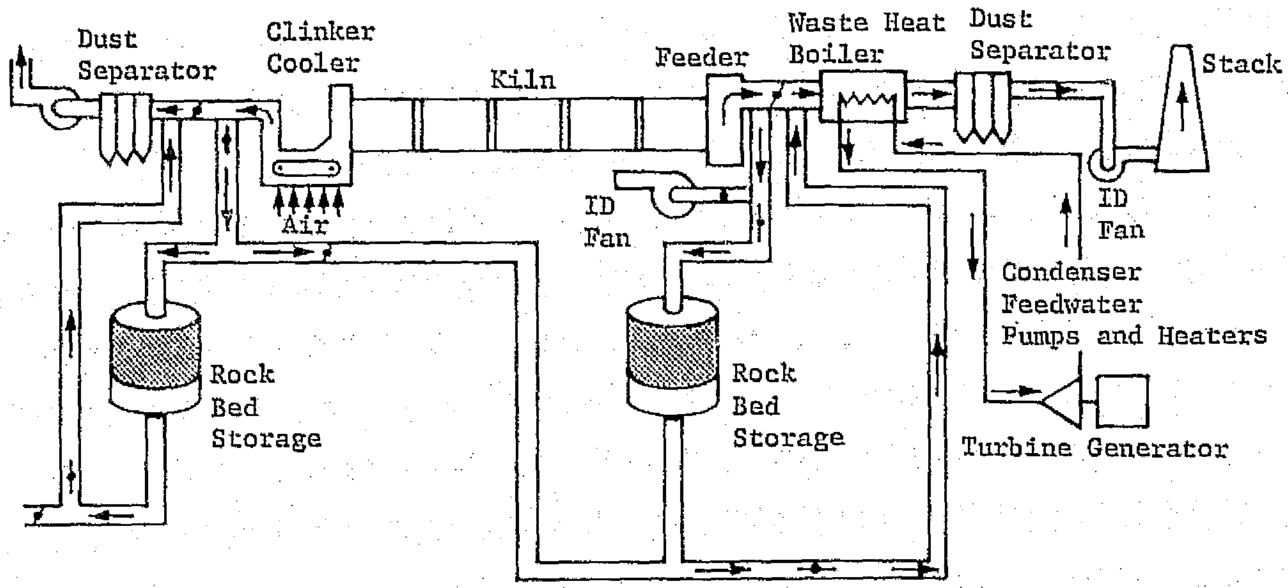


Figure VIII-3 Rockbed/Waste Heat Boiler/Power Plant System Diagram

standpoint of determining the effect of particles on the performance of the bed, the testing provides some design margin because the velocity of the charging gas is 8 times that during normal operation and will carry the particles further into the bed. Since the discharge flow velocity is the same as normal, the particle removal may not be as effective as anticipated in a full-scale system.

In addition to determining the effect of particles on storage system performance (i.e., pressure losses, charge and discharge rates), thermal cycling effects will be determined. These effects will also be magnified by the charge rate. Performance will be compared against the original cycles by running two more tests at design flowrates.

During the 4-month test program, the probability of a kiln shutdown is very high. To demonstrate the capability and the interface compatibility of the system, it will discharge through the waste heat boiler to generate power. Depending on the state of charge of the storage system, it will be capable of generating 100% of the normal power for up to 6 hr. A minimum of two of these cycles will be planned when the kiln is shutdown for emergency repairs.

B. REPORTING

Monthly reports summarizing technical and financial status will be submitted. A final report documenting the work performed and the results of the program will be prepared.

To assist in commercialization of the system, a short program summary will be distributed to all cement companies. In addition, articles will be submitted to the industry publications during and at the completion of the program.

C. SCHEDULE

The program schedule is shown in Figure VIII-4. The pilot kiln testing is completed in the first 6 months of the program to demonstrate technical feasibility of the rockbed storage system. Trade studies, design optimization, and system selection are completed within the same time span. Design of the full-scale system and the 1/4 capacity system for the demonstration test will span 5 months. Procurement lead time is estimated at 4 to 5 months and construction time of 5 months is based on Martin Marietta's experience on the program with Georgia Power and Light Company. This program involved design, fabrication, and test of a combined oil-molten salt thermal storage system of 2 MWt capacity. Testing of the system at the cement plant will take 4 months. Testing is followed by a 2-month period for preparation of the final report draft.

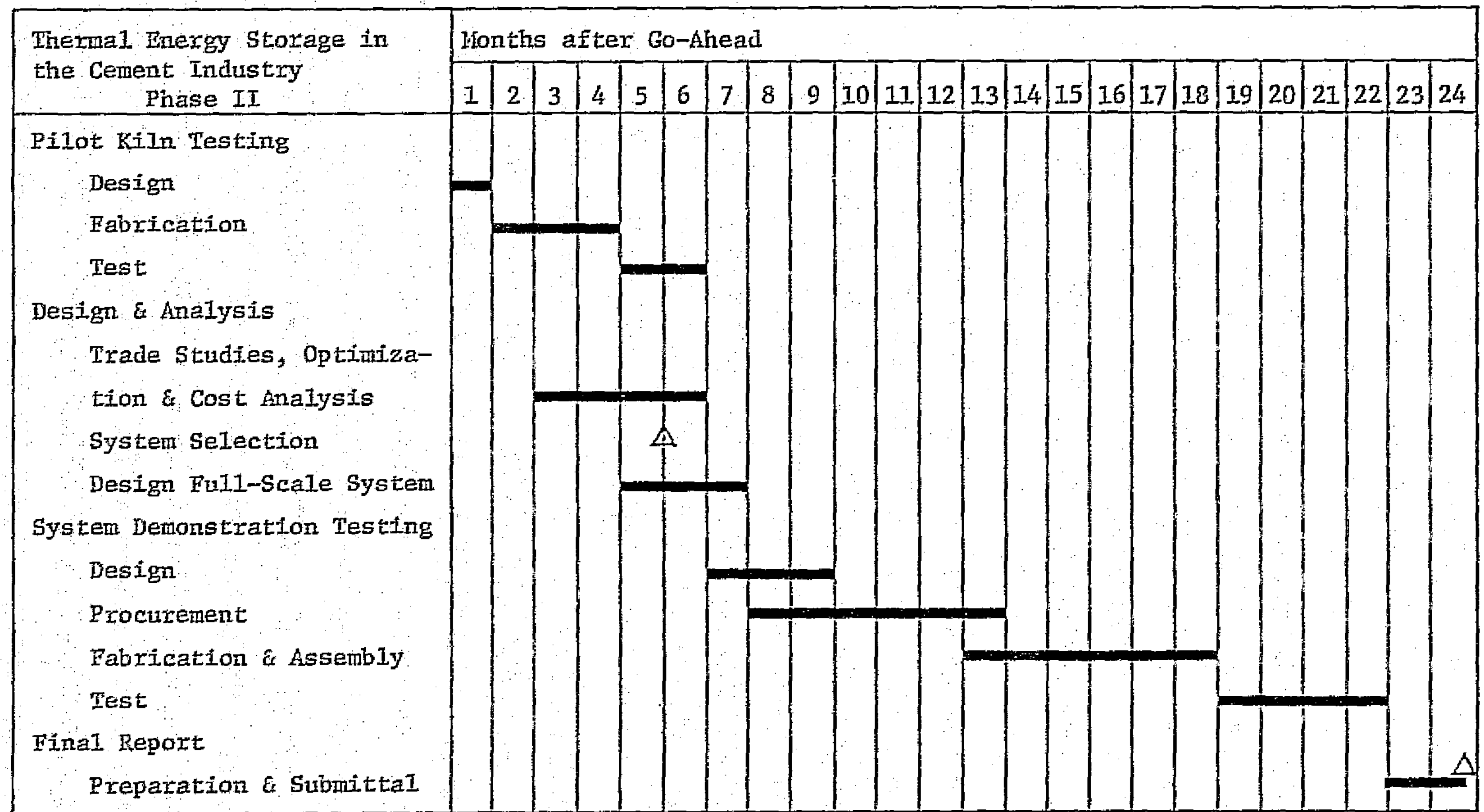


Figure VIII-4 Phase II Tentative Program Schedule

IX. CONCLUSION

This study has shown that the use of thermal energy storage in conjunction with waste heat power generation in the cement industry can save up to 6.7 million barrels of oil per year and provide an attractive rate of return on investment. Specific conclusions reached in each portion of the study are discussed in the following paragraphs.

Sources of Waste Heat - The dry process kilns were determined to be the only practical sources of waste heat as opposed to the wet process kilns whose lost energy is at too low a temperature to be of major use within the plant. Of the types of dry process kilns, the long dry kilns have the highest quality and quantity of recoverable energy, followed by the single-stage suspension preheater, and the four-stage suspension preheater. Of the sources of waste heat in each plant, the kiln exit gas was by far the best source. It contains 80% of the waste heat and is the highest temperature source in the plant. The clinker cooler exhaust gas was also found to be a practical source of heat used in conjunction with the kiln exit gas system. The heat in each of these sources is concentrated and easily recoverable.

Uses for the Waste Heat - The use of the kiln exit gas and clinker cooler gas to generate electricity for use in the cement plant was found to be the most cost effective of the method considered.

Storage System Selection - A rockbed-type storage system was found to be the most economical type of storage. This system could use granite, cement clinker or limestone as the storage medium. A system using molten salt as the storage medium was the next best and is recommended for large plants if technical problems develop with a rockbed system.

System Size and Performance - System size and performance was determined for both types of storage systems using the four typical plant models. The size of the equipment was within that normally fabricated for other uses and the performance can easily meet the requirements of the plant operation. No problems were encountered in physically locating and installing the system in any of the plants. The system could be installed with only a few days or weeks of halted production.

Economic Analysis - Generation of electricity using waste heat is economically attractive for long dry and single-stage preheater kilns. Assuming an 11% escalation rate in the cost of electricity, a 15% after tax cost of capital and a 25 mil/kWh of electricity, the ROI is 44% for the long dry kiln (Plant 1) and 31% for the single-stage preheater kiln (Plant 3). When rockbed thermal storage is used, the ROI increases to 50% for Plant 1. The rockbed storage/power system ROI is 30% for Plant 3. The analysis of Plant 2 (0.9 MWe) shows that for small power generation rates, thermal storage is not desirable if the required power during kiln shut down can be purchased on short notice.

Alternative fossil-fired power generation systems were evaluated for comparison with energy storage systems to be used for power generation when the kiln is shut down for repairs. It has been shown (Section IV.F) that the capital investment in the selected storage systems of rockbed or draw salt are less than the fuel required for the alternative methods of auxiliary boilers, gas turbines, or diesel engines. In addition, the fossil-fired alternative methods do not have the rapid response times required for continuous cement plant operation. Conversely thermal energy storage devices demonstrate rapid response which is crucial when the kiln is shut down for unscheduled repairs.

Some technical questions exist relative to the feasibility of the rockbed and draw salt storage systems. The draw salt storage concept is being developed under another contract related to solar electricity power generation. It is recommended that a program such as that described in Chapter VIII be undertaken to answer those technical questions pertaining to the rockbed system and then to demonstrate commercial operation with a ¼ scale system in a cement plant.

APPENDIX A

ROCKBED STORAGE SYSTEM MODEL

APPENDIX A ROCKBED SYSTEM MODEL

A computer model was developed to aid in the evaluation and performance assessment of rockbed thermal energy storage units coupled with the cement manufacturing process and the end use application-power generation. The model predicts material and energy flowrates through the storage units and power generation loop based upon the conservation laws of mass, momentum, and energy. This model also analyzes the performance of various heat exchanger components in the system. Time-dependent output enables the user to evaluate system performance over anticipated charge and discharge cycles.

Two rockbed performance options were considered in the formulation of this model. One method, developed by Dunkle (Ref A-1), uses nondimensional variables in predicting bed outlet temperatures for a given inlet gas temperature. This formulation relies heavily on empirical correlations derived from performance data from actual rockbeds. However, the model mandates that the bed be isothermal to begin calculations, limiting its utility over charge and discharge analysis. The other option is a more rigorous one-dimensional nodal network that is developed and computer coded. This option predicts and stores temperatures at axial-locations in the bed as gases are passed through the rock. Inlet temperatures to the rockbed can be varied at any time during the performance cycle. This program is written in FORTRAN IV and was formulated for execution on CDC computers. A listing of this program is included at the end of this report section.

A simplified flow diagram of the rockbed system model is shown in Figure A-1. The program begins by reading input data and initializing variables. Using the inputs, an analysis of the clinker cooler excess air thermal energy storage module is first performed. Any number of beds per module may be specified. Knowing the number of beds per module, gas flowrates through the beds are calculated. Using inputs for bed dimensions and the number of temperature nodes, an axial thermal network is constructed.

Currently, the Dunkle formulation is not integrated into this model so the finite difference method is the only option. However, the Dunkle formulation has been coded into a separate model and a program listing is included at the end of this appendix.

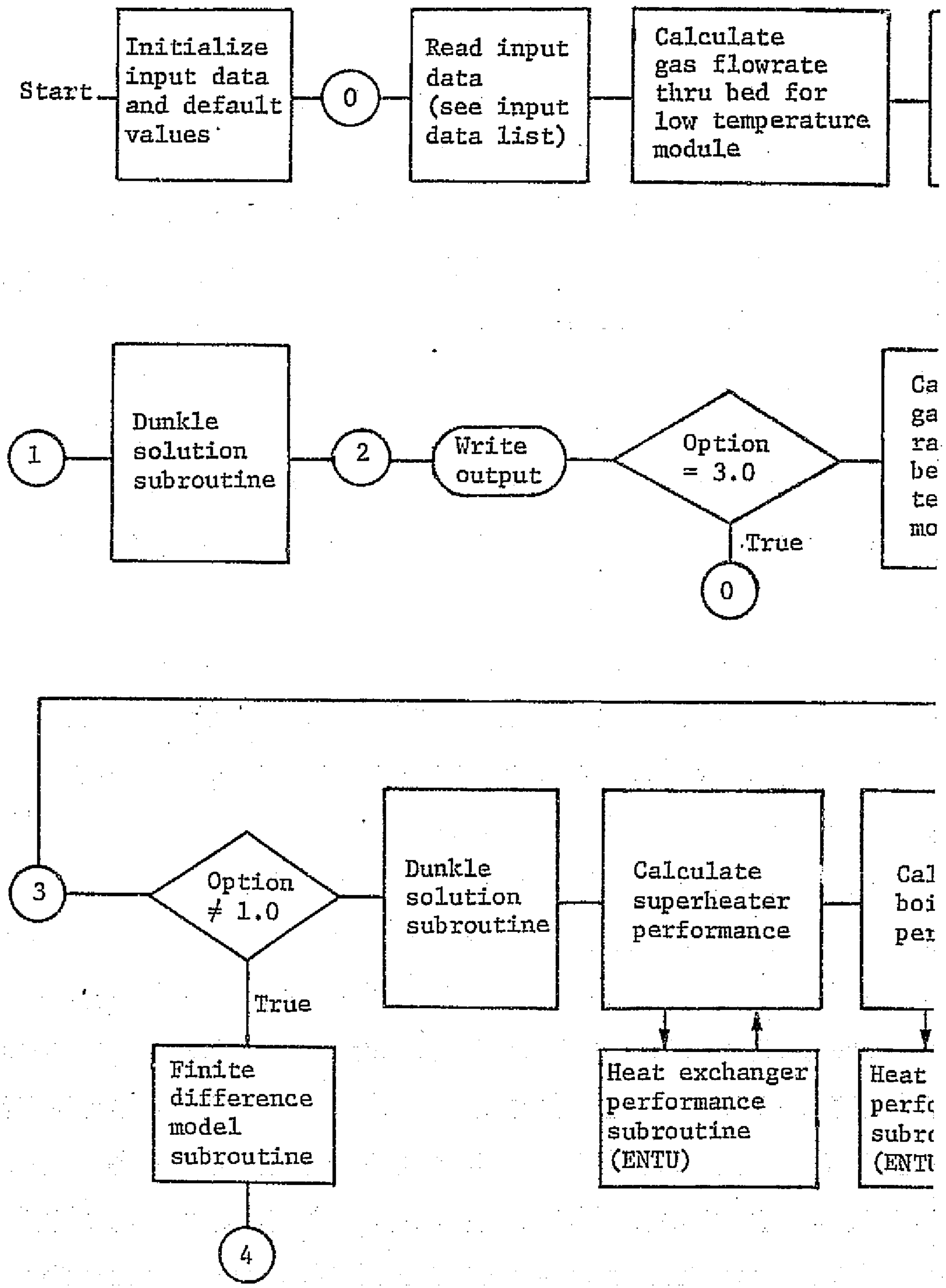
The finite difference method of rockbed performance prediction was derived from differential equations in which temperature is a function of both axial distance and time. Using nodal network techniques, a finite difference technique was developed to predict nodal temperatures dependent on time and distance. Up to a maximum of 100 equidistant nodes can be used to determine rockbed temperatures. Both gas and rock temperatures are predicted at each node. The clinker cooler performance is completed when the charge/discharge time limit (input) is reached.

Upon completion of the low temperature storage analysis, the kiln exit gas thermal energy storage module performance is conducted. The finite difference solution is performed in a similar manner as described previously for the low temperature bed. The exit gases (during charge) are passed partially through the storage system and partially through the waste heat boiler, or are passed in their entirety (during discharge) to the waste heat boiler. A detailed heat exchanger analysis is performed for the waste heat boiler using the inlet gas temperature and flowrate and the input steam saturation conditions and flowrates. Using inputs of heat exchanger configuration and heat transfer coefficients, inlet and exit stream temperatures are predicted for the three heat exchanger modules of the waste heat boiler. The power generation is then calculated using the superheated steam conditions, feedwater temperature, steam flowrates, and user input thermal-to-electric conversion efficiencies. Upon completion of the calculations in the program, the nodal network in the beds are inverted to analyze the next cycle when the gas flow through the bed is reversed.

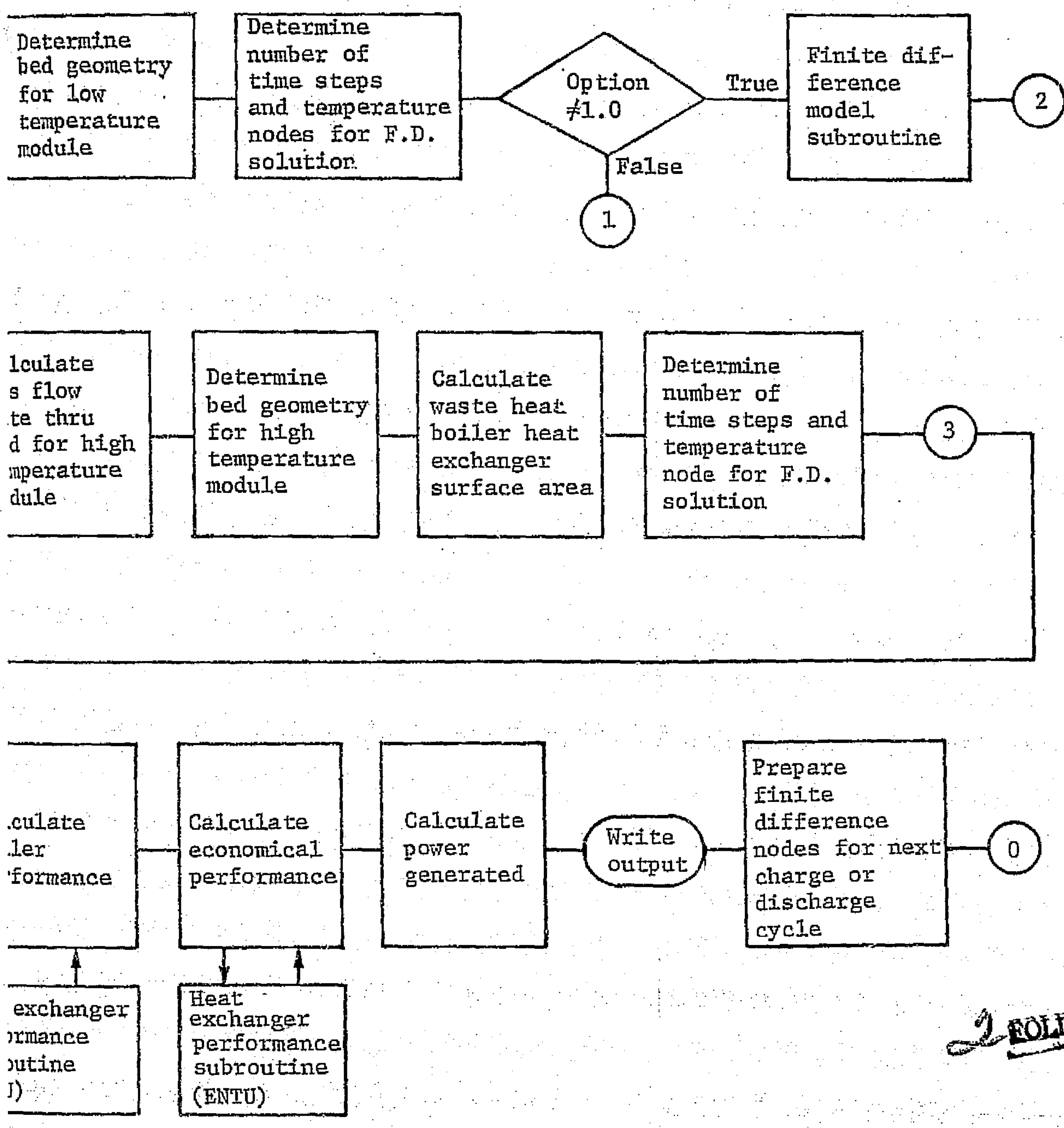
This model has been generalized both for inputs and structure. Rockbeds of various compositions and geometry can be assessed. The model is not confined to a system analysis with the cement manufacturing process or for power applications. Thus, a general analysis of rockbed performance may be conducted with this model.

INPUT

Input to the model is in the form of namelist input. The input is organized into various sections for user ease-of-use. Some input values have defaults coded into the program (see program input).



Start
Initialize input data and default values
0
Read input data (see input data list)
Calculate gas flowrate thru bed for low temperature module
1
Dunkle solution subroutine
2
Write output
Option = 3.0
True
0
3
Option ≠ 1.0
True
Finite difference model subroutine
4
Dunkle solution subroutine
Calculate superheater performance
Heat exchanger performance subroutine (ENTU)



FOLDOUT FRAME

Figure A-1
Rockbed Model Simplified Flow Diagram of Main Program

NAMELIST TPP - THERMOPHYSICAL PROPERTIES OF GASES AND LIQUIDS

The purpose of this group of data is to define the kiln exit gas and clinker cooler air thermophysical properties. Properties input include density, viscosity, thermal conductivity, and heat capacity as functions of temperatures and pressures. The program uses two dimensional interpolation techniques to predict properties at specified conditions of temperature and pressure.

COMMENT CARDS

FORMAT	VARIABLE CODE	DESCRIPTION
(18A4)	AMAT(1), I = 1,72	Case Identification (4 cards)

$TPP

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
NTR1	1	1	1-10	Number of temperatures for kiln gas density tables	-
NPR1	1	1	1-5	Number of pressures for kiln gas density tables	-
TTR1(I)	10	1500	-	Kiln gas density temperature tables	^oF
TTP1(I)	5	14.696	-	Kiln gas density pressure tables	PSIA
RHOG1(I,J)	I = 10 J = 5	0.0217	-	Kiln gas density	lb/ft^3
NTV1	1	1	1-10	Number of temperatures for kiln gas viscosity tables	-
NPV1	1	1	1-5	Number of pressures for kiln gas viscosity tables	-
TTV1	10	1500	-	Kiln gas viscosity temperature tables	^oF
TPV1	5	14.696	-	Kiln gas viscosity pressure tables	PSIA
VISCG(I,J)	I = 10 J = 5	0.0223	-	Kiln gas viscosity	lb/ft sec
NTC1	1	1	1-10	Number of temperatures for kiln gas thermal conductivity	-

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
NPC1	1	1	1-5	Number of pressures for kiln gas thermal conductivity tables	-
TTC1(I)	10	1500	-	Kiln gas thermal conductivity temperature tables	^{o}F
TPC1(I)	5	14.696	-	Kiln gas thermal conductivity pressure tables	PSIA
CONDG1(I,J)	I = 10 J = 5	0.03	-	Kiln gas thermal conductivity	$\frac{Btu}{Hr \cdot Ft \cdot {}^{o}F}$
NTCP1	1	1	1-10	Number of temperatures for kiln gas heat capacity tables	-
NPCP1	1	1	1-5	Number of pressures for kiln gas heat capacity tables	-
TTCP1(I)	10	1500	-	Kiln gas heat capacity temperature tables	^{o}F
TPCP1(I)	5	14.696	-	Kiln gas heat capacity pressure tables	PSIA
CPG1(I,J)	I = 10 J = 5	0.28	-	Kiln gas heat capacity	$\frac{Btu}{Lb \cdot {}^{o}F}$
NTR2	1	1	1-10	Number of temperatures for air density tables	-
NPR2	1	1	1-5	Number of pressures for air density tables	-
TTR2(I)	10	1500	-	Air density temperature tables	^{o}F
TPR2(I)	5	14.696	-	Air density pressure tables	PSIA
RHOG2(I,J)	I = 10 J = 5	0.0808	-	Air density	Lb/Ft^3
NTV2	1	1	1-10	Number of temperature for air viscosity tables	-
NPV2	1	1	1-5	Number of pressures for air viscosity tables	-
TTV2	10	77.0	-	Air viscosity temperature tables	^{o}F
TPV2	5	14.696	-	Air viscosity pressure tables	PSIA
VISCG2(I,J)	I = 10 J = 5	0.018	-	Air viscosity	Lb/Ft.Sec
NTC2	1	1	1-10	Number of temperatures for air thermal conductivity tables	-

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
NPC2	1	1	1-5	Number of pressures for air thermal conductivity tables	-
TTC2(I)	10	77.0	-	Air thermal conductivity temperature tables	^{o}F
TPC2(I)	5	14.696	-	Air thermal conductivity pressure tables	PSIA
CONDG2(I,J)	I = 10 J = 5	0.015	-	Air thermal conductivity	$\frac{Btu}{Hr \cdot Ft \cdot {}^{o}F}$
NTCP2	1	1	1-10	Number of temperatures for air heat capacity	-
NPCP2	1	1	1-5	Number of pressures for air heat capacity	-
TTCP2(I)	10	77.0	-	Air heat capacity temperature tables	^{o}F
TPCP2(I)	5	14.696	-	Air heat capacity pressure tables	PSIA
CPG2(I,J)	I = 10 J = 5	0.24	-	Air heat capacity	$\frac{Btu}{Lb \cdot {}^{o}F}$

$END

NAMELIST STORE - THERMAL ENERGY STORAGE DATA

This group of data is used to define the characteristics of the rockbed thermal storage units and the interface requirements with the energy source and applications. Data input includes initial bed temperatures, storage vessel sizes, and duct lengths. Specific bed properties such as rock particle size, void fraction, and specific heat are also input.

$STORE

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
ASVVOL(I)	2	0.	-	Storage vessel volume (I = 1, clinker cooler bed, I = 2, kiln gas bed)	ft^3
ASVDII(I)	2	0.	-	Storage vessel internal diameter	ft
ASVDIO(I)	2	0.	-	Storage vessel outside diameter	ft
ASVL(I)	2	0.	-	Storage vessel height or length	ft
ASVIT(I)	2	0.	-	Storage vessel insulation thickness	in
ATRTNR(I)	2	0.	-	Storage tank thermal conductivity	$\frac{Btu}{Hr \cdot Ft \cdot {}^oF}$
ANSV(I)	2	0.	-	Number of storage vessels per month	-
AEPS(I)	2	-	-	Rockbed void fraction	-
ARHOB(I)	2	-	-	Rockbed particle density	lb/ft^3
DPART(I)	2	-	-	Rockbed particle in diameter	in
NNODE(I)	2	-	-	Number of thermal network nodes in rockbed (Max. = 100)	-
TNODE(I,J,K)	I = 100 J = 4 K = 2	-	-	Initial temperatures at rockbed nodes	^oF

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
TSOMAX	2	-	-	Maximum expected rockbed temperature	^oF
TSOMIN	2	-	-	Minimum expected rockbed temperature	^oF
OPTION	1	-	-	Rockbed performance calculation option:	-
			0.	Thermal nodal network used - finite difference technique	-
			1.	Dunkle analytical formulation used (not operational)	-
			2.	(Not functional)	-
			3.	One storage module will be analyzed only	-
			4.	Two storage modules will be analyzed connected in series	-
ATHETA(I)	2	-	-	Maximum time limit for rockbed storage solution (charge/discharge internal)	Hrs
ADLTS(I)	2	-	-	Length of ducting to storage module	ft
ADLFS(I)	2	-	-	Length of ducting from storage module	ft
AEQULT(I)	2	-	-	Equivalent length of ducting for bends, fittings, etc. to storage module	ft
AEQULF(I)	2	-	-	Equivalent length of ducting for bends, fittings, etc. from storage module	ft
APTDII(I)	2	-	-	Duct inside diameter to storage module	ft
APFDIO(I)	2	-	-	Duct outside diameter from storage module	ft
ATHINS(I)	2	-	-	Duct insulation thickness	in

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
DISTAB	1	-	-	Distance of duct between clinker cooler bed and kiln gas bed	ft
ABINS	1	-	-	Insulation thickness on duct between clinker cooler bed and kiln gas bed	in
WGAS(I)	2	-	-	Gas flowrate through storage bed module	lb/hr
TCCAIR	1	-	-	Clinker cooler air temperature	^oF
TAMB	1	-	-	Ambient air temperature	^oF
WVELO	1	-	-	Wind velocity	ft/sec
HOAIR	1	-	-	Air-container wall film coefficient	$\frac{Btu}{Hr \cdot Ft^2 \cdot {}^oF}$

$END

NAMELIST WASTEB - WASTE HEAT BOILER PERFORMANCE

This group of data describes the waste heat boiler heat exchanger configuration. Overall heat transfer coefficients and heat exchanger configuration options are input. The specific configurations are:

1. Counter current
2. Parallel flow
3. Crossflow - hot unmixed
4. Crossflow - cold unmixed
5. Crossflow - both unmixed (not functional)
6. 1 shell pass - 2 (4, 6, 8, etc.) tube passes, Parallel - counterflow - shell side mixed, tube unmixed
7. Multishell pass - multitube pass overall counterflow
8. One shell pass, one tube pass - baffled crossflow

$WASTEB

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
NCONF(I)	3	-	1-8	Heat exchanger configuration option	-
				(See above list) First input is for superheater, second-boiler, third-preheater	-
TUBL(I)	3	-	-	Heat exchanger tube length	ft
TUBDO(I)	3	-	-	Tube outside diameter	in
TUBDI(I)	3	-	-	Tube inside diameter	in
NTUB1(I)	3	-	-	Number of tubes per heat exchange section	-
NTBCP(I)	3	-	-	Number of tubes in center plane of exchanger	-
EXTSU(I)	3	-	-	Extended surface area per tube	ft^2
NROW(I)	3	-	-	Number of tube rows	-
NPASS(I)	3	-	-	Number of tube passes	-

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
PITCH(I)	3	-	-	Tube pitch	in
EPSH(I)	3	-	-	Tube surface roughness	in
NSHLP(I)	3	-	-	Number of shell passes	-
UØ(I)	3	-	-	Overall heat transfer coefficient	$\frac{Btu}{Hr \cdot Ft^2 \cdot {}^oF}$
NBAF(I)	3	-	-	Number of baffles in heat exchanger	-
RRATIØ(I)	3	-	-	Tube side mass recirculation ratio	-
BI(I)	3	-	-	Friction correction factor for tubeside	-
BØ(I)	3	-	-	Friction correction factor for shellside	-
PHI(I)	3	-	-	Correction factor for non-isothermal flow	-

NAMELIST STEAM - POWER GENERATION CYCLE

The data input for this group is for calculating the generated power from the steam generation equipment. Steam/water flowrates are input as well as tables of power generation efficiencies for various turbine throttle conditions.

$STEAM

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
NTCE	1	-	-	Number of temperatures for cycle efficiency tables	-
NPCE	1	-	-	Number of pressures for cycle efficiency tables	-
TTCE(I)	10	-	-	Temperatures for cycle efficiency tables	-
TPCE(I)	5	-	-	Pressures for cycle efficiency tables	PSIA
CEFF(I,J)	I = 10 J = 5	-	-	Cycle efficiencies (thermal to electric)	-
WSTEAM	1	-	-	Steam/water flowrate through waste heat boiler	lb/hr
PSTEAM	1	-	-	Steam pressure at turbine throttle	PSIA
TSSAT	1	-	-	Saturation temperature of steam	^oF
SHOT	1	-	-	Estimated superheater steam outlet temperature	^oF
FWIT	1	-	-	Feedwater inlet temperature to waste heat boiler	^oF

$END

NAMELIST CNTL - PROGRAM CONTROL

The purpose of these inputs are to control the printout of data and the time of computation.

$CNTL

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
DELT	1	-	-	Time step interval for finite difference rock-bed solution	sec
PF	1	.False.	.True. .False.	Printout of temperatures for each node in finite difference solution	-
IPR	1	-	-	Printout interval for regular output (10 recommended)	-

$END

ROCKBED STORAGE SYSTEM MODEL PROGRAM LISTING


```
      PROGRAM MAIN(INPUT,OUTPUT,TAPE7,TAPE5=INPUT,TAPE6=OUTPUT)
C
C        HEAT STORAGE MODEL FOR ROCK BED/WASTE HEAT BOILER SYSTEM
C             DEFAULT VALUES ARE FOR GRANITE STORAGE UNITS
C
C             SYSTEM CONSISTS OF TWO MODULES OF ROCK BEDS
C                    A. LOW TEMPERATURE ROCK BED ()500 DEG F)
C                    B. HIGH TEMPERATURE ROCK BED (#500 DEG F)
C               AND WASTE HEAT BOILER SYSTEM CONSISTING OF
C                    A. SUPERHEATER
C                    B. BOILER
C                    C. PREHEATER (OR ECONOMIZER)
C
C             ENERGY AND MECHANICAL ENERGY LOSSES ARE DETERMINED FOR
C               THE TRANSPORT SYSTEM AND STORAGE SYSTEM
C
C                PROGRAMMERS: D G BESHORE (MMC,DEPT/0482)
C                             J O BUNTING (MMC,DEPT/0482)-DUNKLE RTN
C
C             FLUID NO. 1 - KILN GAS
C             FLUID NO. 2 - AIR
C             FLUID NO. 3 - WATER
C             FLUID NO. 4 - STEAM
C
      LOGICAL KUP, PF
      DIMENSION AMAT(72), JK(20), TOCC(10000)
      COMMON /STR/ ASVVOL(2), ASVDII(2), ASVDIO(2), ASVL(2),   ASVIT(2),
     1             ANSV(2),    AEPS(2),   ADLTS(2),  ADLFS(2),  AEQULT(2)
     2            ,AEQULF(2), APTDII(2), APTDIO(2), APFDII(2), APFDIO(2)
     3            ,ATHINS(2), ATKINS(2), ATKTNK(2), WGAS(2),    WAIR(2),
     4     GBED, KBAR,  RE,
     4             TSOMAX(2), TSOMIN(2), DPART(2),  ARHOB(2),  ATHETA(2)
     5            ,NNODE(2),   TNODE(100,4,2), CPB(2)
      COMMON /PROP/ RHOG1(10,5), VISCG1(10,5), CONDG1(10,5), CPG1(10,5),
     1              TTR1(10),     TPR1(5),      TTV1(10),      TPV1(5),
     2              TTC1(10),     TPC1(5),      TTCP1(10),     TPCP1(5),
     3              RHOG2(10,5), VISCG2(10,5), CONDG2(10,5), CPG2(10,5),
     4              TTR2(10),     TPR2(5),      TTV2(10),      TPV2(5),
     5              TTC2(10),     TPC2(5),      TTCP2(10),     TPCP2(5),
     6              NTR1,         NPR1,         NTV1,          NPV1,
     7              NTC1,         NPC1,         NTCP1,         NPCP1,
     8              NTR2,         NPR2,         NTV2,          NPV2,
     9              NTC2,         NPC2,         NTCP2,         NPCP2
      COMMON /HEAT/ TUBL(3),   TUBDO(3),   TUBDI(3),   NPASS(3),  NCONF(3),
     1              NSHLP(3),  PITCH(3),   FFT(3),     FFS(3),    CONT(3),
     2              UO(3),     NTUB1(3),   NTBCP(3),   EXTSU(3),
     3              NROW(3),   EPSH(3),    BI(3),      BO(3),     PHI(3),
     4             RRATIO(3),  NBAF(3)
      COMMON /STMC/ CEFF(10,5),  TTCE(10),  TPCE(5),  NTCE,  NPCE
      DATA  JK/20*1/, PI/3.14159/, GC/32.174/, PSTP/14.696/
      NAMELIST /TPP/ RHOG1,VISCG1,CONDG1,CPG1,
     1               TTR1,TPR1,NTR1,NPR1,TTV1,TPV1,NTV1,NPV1,
     2               TTC1,TPC1,NTC1,NPC1,TTCP1,TPCP1,NTCP1,NPCP1,
     3               RHOG2,VISCG2,CONDG2,CPG2,
     4               TTR2,TPR2,NTR2,NPR2,TTV2,TPV2,NTV2,NPV2,
     5               TTC2,TPC2,NTC2,NPC2,TTCP2,TPCP2,NTCP2,NPCP2
      NAMELIST /STORE/ ASVVOL,ASVDII,ASVDIO,ASVL,ASVIT,ANSV,AEPS,ARHOB,
     1                 ADLTS, ADLFS, AEQULT, AEQULF, ATHETA,
     2                 APTDII,APTDIO,APFDII,APFDIO,ATHINS,DISTAB,ABINS,
     3                 NNODE, TNODE, OPTION, DPART,
     4                 WGAS,  WAIR , TAMB, WVELO, HOAIR, CPB,
     5                 ATKINS, ATKTNK , TSOMAX, TSOMIN, TCCAIR
      NAMELIST /WASTEB/ TUBL,TUBDO,TUBDI,NPASS,NSHLP,PITCH,FFT,FFS,EPSH,
```

```
     1                   CONT,UO,NTUB1,NTBCP,TKG,WKG,NROW,EXTSU,
     2              RRATIO,  NBAF, NCONF, BI, BO, PHI
      NAMELIST /STEAM/  CEFF,TTCE,TPCE,NTCE,NPCE,WSTEAM,PSTEAM,SHOT,
     1                  FWIT,TSSAT
      NAMELIST /CNTL/ DELT,PF, IPR
C
C        INITIALIZE INPUT DATA AND DEFAULT VALUES FOR STORAGE MODEL
C
      ITAPE=5
      IPR=10
      NTR1=NPR1=NTV1=NPV1=NTC1=NPC1=NTCP1=NPCP1=1
      NTR2=NPR2=NTV2=NPV2=NTC2=NPC2=NTCP2=NPCP2=1
      TTR1(1)=TTC1(1)=TTV1(1)=TTCP1(1)=1500.
      TPR1(1)=TPC1(1)=TPV1(1)=TPCP1(1)=14.696
      RHOG1(1,1)=0.0217
      VISCG1(1,1)=.0223
      CONDG1(1,1)= 0.03
      CPG1(1,1)=0.28
      TTR2(1)=TTC2(1)=TTC2(1)=TTCP2(1)=77.0
      TPR2(1)=TPC2(1)=TPC2(1)=TPCP2(1)=14.696
      RHOG2(1,1) = 0.0808
      VISCG2(1,1)= 0.018
      CONDG2(1,1)= 0.015
      CPG2(1,1)=0.24
      HOAIR = -1.0
      ASVVOL(1)=ASVDII(1)=ASVDIO(1)=ASVL(1)=0.0
      ASVVOL(2)=ASVDII(2)=ASVDIO(2)=ASVL(2)=0.0
      KUP=.TRUE.
      PF =.FALSE.
C
C        READ INPUT DATA
C
    1 READ(5,15) AMAT
      IF(EOF(5)) 10,2
    2 WRITE(6,18) AMAT
      READ(ITAPE,TPP)
      READ(5,STORE)
      READ(5,WASTEB)
      READ(5,STEAM)
      READ(5,CNTL)
      WRITE(6,TPP)
      WRITE(6,STORE)
      WRITE(6,WASTEB)
      WRITE(6,STEAM)
      WRITE(6,CNTL)
C
C       CHARGING CYCLE CALCULATIONS FOR KILN GAS STORE
C
C
C       CLINKER COOLER BED CALCULATIONS
C
      WGASA = WGAS(1)/ANSV(1)
      IF(ASVVOL(1).LE.0.0)    ASVVOL(1)= PI*ASVDII(1)**2.*ASVL(1)/4.0
      IF(ASVDII(1).LE.0.0)  ASVDII(1)= SQRT(4.0*ASVVOL(1)/(PI*ASVL(1)))
      IF(ASVL(1).LE.0.0)  ASVL(1)= 4.0*ASVVOL(1)/(PI*ASVDII(1)**2.)
      NTSTP = INT(ATHETA(1)/DELT)
      WRITE(6,1000)
      TIME = 0.0
      QTOT = 0.0
      DELX = ASVL(1)/FLOAT(NNODE(1)-1)
      TBOUT = TNODE(NNODE(1),3,1)
      IZPR = 0
      IZ = 1
```

```
      IGT = INT(ATHETA(1)/DELT) - IPR
      DO 300 I=1,NTSTP
      IF(OPTION.NE.1) GO TO 200
C
C
C         DUNKLE SOLUTION
C
C
C
      GO TO 400
  200 CONTINUE
      TBAVG = (TBOUT+TCCAIR)/2.0
      CONCC= GINTRP(TBAVG,TTC2(1),NTC2,PSTP,TPC2(1),NPC2,CONDG2(1,1),
     1   10,JK(1),JK(2),0)
      VISCC = GINTRP(TBAVG,TTV2(1),NTV2,PSTP,TPV2(1),NPV2,VISCG2(1,1),
     1   10,JK(3),JK(4),0)
      CPCC  = GINTRP(TBAVG,TTCP2(1),NTCP2,PSTP,TPCP2(1),NPCP2,CPG2(1,1),
     1   10,JK(5),JK(6),0)
      CALL FINITE(TBOUT,QS,DELP,TCCAIR,PF,1,CPCC,VISCC,CONCC,WGASA,
     1   DELX,DELT,1)
      TOCC(I) = TBOUT
      QTOT = QTOT + QS
      QTOTN= QTOT+ANSV(1)
  400 TIME = TIME + DELT
      IF(IZ.GE.IGT) GO TO 380
      IF(IZ.LT.IZPR) GO TO 350
      IZPR = IZPR + IPR
  380 WRITE(6,1020) TIME,TCCAIR,TBOUT,QS,QTOT,QTOTN,DELP,WGASA,WGAS(1)
  350 CONTINUE
      IZ = IZ + 1
  300 CONTINUE
      IF(OPTION.EQ.3.0) GO TO 1
C
C        KILN GAS STORE - CHARGE CALCULATIONS
C
      WGASB = WGAS(2)/ANSV(2)
      IF(ASVVOL(2).LE.0.0) ASVVOL(2)=PI*ASVDII(2)**2.0*ASVL(1)/4.0
      IF(ASVDII(2).LE.0.0) ASVDII(2)=SQRT(4.0*ASVVOL(2)/(PI*ASVL(2)))
      IF(ASVL(2).LE.0.0) ASVL(2)=4.0*ASVVOL(2)/(PI*ASVDII(2)**2.0)
      IF(OPTION.NE.4.0) NTSTP=INT(ATHETA(2)/DELT)
      IF(OPTION.EQ.4.0) WKG=WGAS(1)
      TIME = 0.0
      QTOT = 0.0
      TBOUT = TNODE(NNODE(2),3,2)
      DELX = ASVL(2)/FLOAT(NNODE(2)-1)
      AHTX1 = NTUB1(1)*TUBL(1)*(PI*TUBDO(1)/12.+EXTSU(1))
      AHTX2 = NTUB1(2)*TUBL(2)*(PI*TUBDO(2)/12.+EXTSU(2))
      AHTX3 = NTUB1(3)*TUBL(3)*(PI*TUBDO(3)/12.+EXTSU(3))
      IZ = 1
      IZPR = 0
      IGT = INT(ATHETA(2)/DELT) - IPR
      WRITE(6,1030)
C
      DO 600 I=1,NTSTP
      IF(OPTION.EQ.4.0) TKG=TOCC(I)
      IF(OPTION.NE.1) GO TO 700
C
C        DUNKLE SOLUTION
C
C
      GO TO 800
  700 CONTINUE
C
```

```
C         NUMERICAL SOLUTION
C
      TBAVG = (TBOUT+TKG)/2.0
      CONKG = GINTRP(TBAVG,TTC1(1),NTC1,PSTP,TPC1(1),NPC1,CONDG1(1,1),
     1   10,JK(7),JK(8),0)
      VISKG = GINTRP(TBAVG,TTV1(1),NTV1,PSTP,TPV1(1),NPV1,VISCG1(1,1),
     1   10,JK(9),JK(10),0)
      CPKG = GINTRP(TBAVG,TTCP1(1),NTCP1,PSTP,TPCP1(1),NPCP1,CPG1(1,1),
     1   10,JK(11),JK(12),0)
      CALL FINITE(TBOUT,QSB,DPB,TKG,PF,2,CPKG,VISKG,CONKG,WGASB,DELX,
     1   DELT,1)
  800 QTOT = QTOT + QSB
      QTOTN = QTOT*ANSV(2)
C
C        DETERMINE POWER GENERATION DURING CHARGE
C
      CPSHS = CPS((TSSAT+SHOT)/2.0)
      TAVGKG = TKG + WGAS(2)*(TBOUT-TKG)/WKG
      CPKG1 = GINTRP(TAVGKG,TTCP1(1),NTCP1,PSTP,TPCP1(1),NPCP1,
     1   CPG1(1,1),10,JK(11),JK(12),0)
      CALL ENTU(SHOT ,TKGO1,QSHA,EFSH,XNTUSH,RSH,TSSAT,TAVGKG,CPSHS,
     1   CPKG1,WSTEAM,WKG,UO(1),AHTX1,NPASS(1),NSHLP(1),NBAF(1),NCONF(1)
     2   ,3)
C
C         BOILER  CALCULATIONS
C
      CPKG2 = GINTRP(TKGO1,TTCP1(1),NTCP1,PSTP,TTCP1(1),NPCP1,
     1   CPG1(1,1),10,JK(11),JK(12),0)
      CALL ENTU(TIST,TKGO2,QBA,EFB,XNTUB,RB,TSSAT,TKGO1,9999.,CPKG2,
     1   WSTEAM*RRATIO(2),WKG,UO(2),AHTX2,NPASS(2),NSHLP(2),NBAF(2),
     2   NCONF(2),1)
C
C         PREHEATER CALCULATIONS
C
      CALL CPSW((TSOMIN(2)+TIST)/2.0,CPWB)
      CPKG3 = GINTRP(TKGO2,TTCP1(1),NTCP1,PSTP,TPCP1(1),NPCP1,
     1   CPG1(1,1),10,JK(11),JK(12),0)
      CALL ENTU(TFW,TKGO3,QPH,EFPH,XNTUPH,RPH,TIST,TKGO2,CPWB,CPKG3,
     1   WSTEAM*RRATIO(3),WKG,UO(3),AHTX3,NPASS(3),NSHLP(3),NBAF(3),
     2   NCONF(3),1)
      TIME = TIME + DELT
      QST = QSHA + QBA + QPH
C
C
C         CALCULATE POWER GENERATED
C
      CF = GINTRP(SHOT,TTCE(1),NTCE,PSTEAM,TPCE(1),NPCE,CEFF(1,1),
     1   10,JK(13),JK(14),0)
      PGEN = QST*CF/3413.
C
      IF(IZ.GT.IGT) GO TO 880
      IF(IZ.LT.IZPR) GO TO 850
      IZPR = IZPR + IPR
  880 WRITE(6,1040) TIME,TKG,TBOUT,QSB,QTOT,QTOTN,DPB,WGASB,
     1   TAVGKG,TKGO1,TKGO2,TKGO3,WKG,SHOT,TSSAT,TIST,TFW,QST,PGEN,CF
  850 CONTINUE
      IZ = IZ + 1
  900 CONTINUE
  600 CONTINUE
      J = NNODE(1)
      K= NNODE(2)
      LIMIT=NNODE(1)
      DO 110 I=2,LIMIT
```

```
      TNODE(I,1,1) = TNODE(J,2,1)
      TNODE(I,3,1) = TNODE(J,4,1)
      J = J - 1
 110  CONTINUE
      DO 105 I=2,LIMIT
      TNODE(I,2,1) = TNODE(I,1,1)
      TNODE(I,4,1) = TNODE(I,3,1)
  105 CONTINUE
      LIMIT = NNODE(2)
      DO 100 I=2,LIMIT
      TNODE(I,1,2) = TNODE(K,2,2)
      TNODE(I,3,2) = TNODE(K,4,2)
      K = K - 1
  100 CONTINUE
      DO 120 I=2,LIMIT
      TNODE(I,2,2) = TNODE(I,1,2)
      TNODE(I,4,2) = TNODE(I,3,2)
  120 CONTINUE
      GO TO 1
   10 STOP
C
C         FORMAT STATEMENTS
C
   15 FORMAT(18A4)
   18 FORMAT(1H1,18X,18A4,3(/,19X,18A4))
 1000 FORMAT(1H1,10X,"CLINKER COOLER AIR STORAGE PERFORMANCE",///,
     1 5X,"TIME",9X,"TCCAIR",8X,"TBOUT",10X,"QBED",8X,"QBEDTOT",7X,
     2    "QBEDSTOT",8X,"DELP",9X,"GFLOW",8X,"GFLOWTOT",/,3X,"(HOURS)",
     3    7X,"(DEG F)",7X,"(DEG F)",8X,"(BTU)",9X,"(BTU)",9X,"(BTU)",
     4    9X,"(PSIA)",7X,"(LB/HR)",7X,"(LB/HR)")
 1020 FORMAT(9(E14.4))
 1030 FORMAT(1H1,10X,"KILN GAS ENERGY STORAGE PERFORMANCE",///,
     1    4X,"TIME",10X,"TKG",9X,"TBOUT",8X,"QBED",8X,"QBEDTOT",5X,
     2    "QBEDSTOT",6X,"DELP",9X,"GFLOW",7X,"TAVGKG",7X,"TOKGSH",8X,
     3    /,3X,"(HOURS)",6X,"(DEG F)",6X,"(DEG F)",7X,"(BTU)",8X,"(BTU)",
     4    8X,"(BTU)",7X,"(PSIA)",7X,"(LB/HR)",6X,"(DEG F)",6X,"(DEG F)",
     5    //,6X,"TOKGB",7X,"TOKGPH",7X,"WKGTOB",8X,"TOSSH",8X,"TOSB",9X,
     6    "TOWPH",8X,"TIWPH",7X,"QTRANS",8X,"POWER",8X,"CEFF",
     7    /,5X,"(DEG F)",6X,"(DEG F)",6X,"(LB/HR)",6X,"(DEG F)",6X,
     8    "(DEG F)",6X,"(DEG F)",6X,"(DEG F)",5X,"(BTU/HR)",5X,
     9    "(KWATTS)",5X,"(E/THER)")
 1040 FORMAT((10(E13.4),/,2X,10(E13.4)))
      END
      SUBROUTINE FINITE(TOUT,QS,DELP,TIN,PF,NT,CP,VIS,COND,WG,DELX,DELT,
     1    NCD)
C         FINITE DIFFERENCE ROUTINE (DELTA-X,DELTA-TIME) TO DETERMINE
C           ROCK BED OUTLET GAS TEMPERATURE AND BED TEMPERATURE PROFILE
C
C           PROGRAMMER: D G BESHORE (MMC DEPT/0482)
C
      LOGICAL PF
      COMMON /STR/ ASVVOL(2), ASVDII(2), ASVDIO(2), ASVL(2),   ASVIT(2),
     1             ANSV(2),   AEPS(2),   ADLTS(2),  ADLFS(2),  AEQULT(2)
     2            ,AEQULF(2), APTDII(2), APTDIO(2), APFDII(2), APFDIO(2)
     3            ,ATHINS(2), ATKINS(2), ATKTNK(2), WGAS(2),   WAIR(2),
     4    GBED, KBAR, RE,
     4             TSOMAX(2), TSOMIN(2), DPART(2),  ARHOB(2),  ATHETA(2)
     5        ,NNODE(2),  TNODE(100,4,2),  CPB(2)
      COMMON /PROP/ RHOG1(10,5), VISCG1(10,5), CONDG1(10,5), CPG1(10,5),
     1              TTR1(10),    TPR1(5),      TTV1(10),     TPV1(5),
     2              TTC1(10),    TPC1(5),      TTCP1(10),    TPCP1(5),
     3              RHOG2(10,5), VISCG2(10,5), CONDG2(10,5), CPG2(10,5),
     4              TTR2(10),    TPR2(5),      TTV2(10),     TPV2(5),
```

```
     5              TTC2(10),     TPC2(5),      TTCP2(10),    TPCP2(5),
     6              NTR1,         NPR1,         NTV1,         NPV1,
     7              NTC1,         NPC1,         NTCP1,        NPCP1,
     8              NTR2,         NPR2,         NTV2,         NPV2,
     9              NTC2,         NPC2,         NTCP2,        NPCP2
      DIMENSION  JK(12)
      DATA  JK/12*1/, PI/3.14159/, GC/32.174/, PSTP/14.696/
C
C
C
C        CALCULATE PHYSICAL PROPERTIES BASED ON AVERAGE CONDITIONS
C
      AC = PI*ASVDII(NT)**2.0/4.0
      GO = WG/AC
C         0.34446  = 1./(F*60*12*6.72E-04
      RE = 5.7411E-03*GO*DPART(NT)/((1.0-AEPS(NT))*VIS)
C         2.4192 = 3600*6.72E-04
      PR = 2.4192*CP*VIS/COND
      IF(RE.LE.50.) HB = 0.9*RE**(-0.51)*PR**(-2./3.)*CPB(NT)*GO
      IF(RE.GT.50.) HB = 0.61*RE**(-0.41)*PR**(-2./3.)*CPB(NT)*GO
      KBAR1  = WG*CP
      KBAR2  = 72.*HB*(1.0-AEPS(NT))*AC*DELX/DPART(NT)
      GBED =  AC*DELX*(1.0-AEPS(NT))*ARHOB(NT)*CPB(NT)
      IF(JK(NT).NE.1) GO TO 100
      JK(NT)  = 0
C
C
C
      LIMIT=NNODE(NT)
      DO 200  I=1,LIMIT
      TNODE(I,2,NT) = TNODE(I,1,NT)
      TNODE(I,4,NT) = TNODE(I,3,NT)
  200 CONTINUE
C
  100 CONTINUE
      LIMIT=NNODE(NT)
      DO 300  I=1,LIMIT
      TNODE(I,1,NT) = TNODE(I,2,NT)
      TNODE(I,3,NT) = TNODE(I,4,NT)
  300 CONTINUE
       TNODE(1,3,NT) = TIN
      NNM1 = NNODE(NT) - 1
      DO 400  I=1,NNM1
      TNODE(I+1,2,NT)=TNODE(I+1,1,NT)+DELT*KBAR1*KBAR2*(TNODE(I,3,NT)-
     1   TNODE(I+1,1,NT))/(GBED*(KBAR1+KBAR2))
      TNODE(I+1,4,NT)=(KBAR1*TNODE(I,3,NT)+KBAR2*TNODE(I+1,2,NT))/
     1   (KBAR1+KBAR2)
  400 CONTINUE
      TOUT  = TNODE(LIMIT,4,NT)
      LIMIT=NNODE(NT)
      TNODE(1,4,NT) = TIN
      QS = WG*CP*(TNODE(1,4,NT)-TNODE(LIMIT,4,NT))*DELT
      IF(PF) WRITE(6,1000)
      IF(PF) WRITE(6,1010) (TNODE(I,4,NT),I=1,LIMIT)
      RHOF=GINTRP((TNODE(1,4,NT)+TNODE(LIMIT,4,NT))/2.0,TTR2(1),NTR2,
     1    PSTP,TPR2(1),NPR2,RHOG2(1,1),10,JK(3),JK(4),0)
      IF(NT.EQ.2.AND.NCD.EQ.1)
     1RHOF=GINTRP((TNODE(1,4,NT)+TNODE(LIMIT,4,NT))/2.0,TTR1(1),NTR1,
     2    PSTP,TPR1(1),NPR1,RHOG1(1,1),10,JK(5),JK(6),0)
      DELP = GO**2.*ASVL(NT)*(1.0-AEPS(NT))*(25./RE+1.75)/(GC*
     1   RHOF*DPART(NT)*AEPS(NT)**3.0*1.5552E+08)
      RETURN
 1000 FORMAT(10X,"TEMPERATURES AT NODES")
```

```
1010 FORMAT(10E12.5)
     END
```



```
*DECK,DENST
      FUNCTION  DENST(TEMP,PRES)
C
C        DETERMINES THE SPECIFIC DENSITY OF STEAM
C             BASED ON FORMULA OF KEYES, SMITH, AND GERRY
      TT =(TEMP + 459.)/1.8
      PP =  PRES/14.696
      TAU = 1.0/TT
      BO = 1.89 -2641.62*TAU*10.**(80870.*TAU**2)
      G1T = 82.546*TAU - 1.6246E+05*TAU**2.
      G2T = 0.21828 - 1.2697E+05*TAU**2.
      G3T = 3.635E-04 - 6.768E+64*TAU**24.
      BETA = BO + BO*BO*G1T*TAU*PP + BO**4*G2T*TAU**3*PP**3 - BO**13*
     1   G3T*TAU**12*PP**12
      VOL = 4.55504*TT/PP + BETA
      DENST = 62.335/VOL
      RETURN
      END
*DECK,VISCT
      FUNCTION VISCST(TEMP,PRES)
C
C
C        DETERMINES THE VISCOSITY OF STEAM(CENTIPOISE)
C             BASED ON FORMULA OF KEENAN AND KAYES
C
      TT = (TEMP + 459.)/1.8
      PP = 0.07031*PRES
      TAU = 1.0/TT
      VISCO = 1.501E-05*TT**0.5/(1.0 + 446.8*TAU)
      VISC = VISCO +1.0E-04*(TAU*(6.36-2.31E-03*10**(1340.*TAU))*PP +
     1   3.89E-02*10**(-5.476E-03*TT)*PP*PP)
```

```
      VISCST= VISC/100.
      RETURN
      END
*DECK,DEW
      FUNCTION DEW(TEMP)
C
C
C         DETERMINES THE DENSITY OF WATER
C              BASED ON FORMULA BY SMITH AND KEYES
C
      TT =(TEMP - 32)/1.8
      TC = 374.11
      VC = 3.1975
      TD = TC - TT
      VS = (VC-0.3151548*TD**(1./3.)-1.203374E-03*TD+7.48908E-13*TD**4)
     1    /(1.0+0.1342489*TD**(1./3.)-3.946263E-03*TD)
      DEW = 62.335/VS
      RETURN
      END
*DECK,ENPHW
      SUBROUTINE ENPHW(T, P, XH)
      IF(T.GT.650.0)  GO TO 10
      IF(T.LT. 32.0)  GO TO 11
      IF(T.GT.375.0)  GO TO 13
C  CURVE FIT FOR ENTHALPY OF SATURATED WATER BETWEEN 32DEGF AND 400 DEGF
      A0 = -3.22199E+01
      A1 =  1.00988E+00
      A2 = -1.09370E-04
      A3 =  3.22658E-07
      XH = A0+A1*T**1+A2*T**2+A3*T**3
      RETURN
   13 CONTINUE
C  CURVE FIT FOR ENTHALPY OF SATURATED WATER BETWEEN 350DEGF AND 650DEGF
      B0 =  5.80426E+02
      B1 = -7.33017E+00
      B2 =  4.70552E-02
      B3 = -1.41586E-04
      B4 =  2.39875E-07
      B5 = -2.16585E-10
      B6 =  8.21180E-14
      XH = B0+B1*T+B2*T**2+B3*T**3+B4*T**4+B5*T**5+B6*T**6
      RETURN
   10 WRITE(6,1)
    1 FORMAT(32H WATER TEMPERATURE EXCEEDS 650 F)
      GO TO 12
   11 WRITE(6,2)
    2 FORMAT(33H WATER TEMPERATURE LESS THAN 32 F)
   12 CONTINUE
      END
*DECK,ENPHS
      SUBROUTINE ENPHS(TEMP,P, HTOTAL)
      T =(TEMP - 32.0)/1.8
      TAU= 1./(273.16 + T)
      P1= P/14.696
      B0 = 1.89-2641.62*TAU*10.0**(80870.0 * TAU**2)
      G1 =82.546*TAU - 1.6246E5*TAU**2
      G2 = 0.21828 -1.2697E5*TAU**2
      G3 = 3.635E -4 - 6.768E64*TAU** 24
      SY1=B0**2 *G1 * TAU
      SY3=B0**4 *G2 * TAU**3
      SY12=B0**13+G3* TAU**12
      BOP = -2641.62*10.**(80870*TAU**2)*(2.0*80870.0*TAU**2*ALOG(10.)+
     11.0)
```

```
      G1P = 82.546 -2*1.624E5*TAU
      G2P = -1.2697E5 * 2.0* TAU
      G3P = -6.768E64 *24.0* TAU**23
      SY1P =2.0*BO*BOP*G1*TAU+BO**2*G1P*TAU+BO**2*G1
      SY3P =4.0*BO**3*BOP*G2*TAU**3+BO**4*G2P*TAU**3+BO**4*G2*3.0*TAU**2
      SY12P=13.*BO**12*BOP*G3*TAU**12+BO**13*G3P*TAU**12+BO**13*G3*12.*
     1TAU**11.0
      F = BO +TAU* BOP
      F1= SY1 + TAU* SY1P
      F3= SY3 + TAU* SY3P
      F12=SY12 + TAU* SY12P
      XH =F*P1 + F1/2.0 *P1**2.+F3/4.*P1**4 +F12/13. *P1**13
      T1 =1/TAU
      YH = 1.4720*(T1-273.16)+7.5566E-4/2.*(T1**2-273.16**2)+47.836*
     1ALOG(T1/273.16) + 2502.36
      HTOTAL = XH*.0435578+ YH * .42993
      RETURN
      END
*DECK,FRIC
      FUNCTION FRIC(RE,EPS,DIA)
      A =(2.457*ALOG(1./((7./RE)**0.9+0.27*EPS/DIA)))**16.
      B = (37530./RE)**16
      FRIC =((8.0/RE)**12.+(A+B)**(-1.5))**0.08333
      RETURN
      END
*DECK,UOVER
      FUNCTION UOVER(DI,DO,DOINS,HI,HO,TKP,TKI,FFI,FFO)
C
C           CALCULATE EACH RESISTANCE BASED  ON OUTSIDE DIAMETER
C
      DOO = DOINS
      IF(DOINS.LE.DO) DOO = DO
      RDI = DOO/(DI*HI)
      RDO = DOO*ALOG(DO/DI)/(24.*TKP)
      IF(DOINS.GT.DO)    RDOI = DOO*ALOG(DOINS/DO)/(24.*TKI)
C
C           CALCULATE OVERALL HEAT TRANSFER COEFFICIENT
C
      UOVER=1.0/(RDI+FFI*DOO/DI+RDO+1.0/HO+FFO)
      IF(DOINS.GT.DO) UOVER= 1.0/(RDI+FFI*DOO/DI+RDO+RDOI+1.0/HO+FFO)
      RETURN
      END
*DECK,HTXDPT
      SUBROUTINE HTXDPT(DPT,RE,EPS,DI,WDOTT,NTPASS,RHOT,BI,PHII,NTUBE,
     1     XLTUBE,VISC)
      DATA GC/32.174/, PI/3.14159/
C
C         CALCULATE TOTAL FLOW AREA, MASS FLUX, AND PRESSURE DROP
C
      AREA = PI*DI*DI/576.*NTUBE
      GFLOW = WDOTT/AREA
      RE =  GFLOW*DI/VISC*0.03445
      FF = FRIC(RE,EPS,DI/12.)
      DPT = FF*GFLOW**2*XLTUBE*BI*NTPASS/(540000.*GC*RHOT*DI*PHII)
      RETURN
      END
*DECK,HTXDPS
      SUBROUTINE HTXDPS(DPS,RE,DO,WDOTS,NTPASS,RHOS,BO,NTUBCP,XLTUBE,
     1  VISC,PITCH,NROW)
C
C           SUBROUTINE DETERMINES THE PRESSURE DROP ON SHELL SIDE OF
C                           HEAT EXCHANGERS
C
```

```
      DATA GC/[illegible].174/, PI/3.14159/
      BAFL = [illegible]E/NTPASS
      FAREA =  NTUBCP*(PITCH-DO)*BAFL/12.
      GFLOW =  W[illegible]OTS/FAREA
      RE = GFLOW*DO/VISC*0.03445
      FF = 0.23 + 0.11*(PITCH/DO-1.0)**(-1.08)*RE**(-0.15)
      DPS = NTPASS*FF*NROW*GFLOW**2/(GC*RHOS*6.48E06)
     1      *80
      RETURN
      END
*DECK,CPS
      FUNCTION CPS(TEMP)
      TW =(TEMP+ 459.7)/1.8
      CPS= 0.4031 + 0.12767*TW*1.E-3 + 0.01572*TW*TW*1.E-6
      RETURN
      END
*DECK,ENTU
      SUBROUTINE ENTU(T3,T4,Q,E,XNTU,R,T1,T2,CPC,CPH,WC,WH,UO,AO,NTP,
     1    NSP,NBAFF,OPTION,NTOP)
      INTEGER OPTION
C
C         SUBROUTINE CALCULATES THE HEAT EXCHANGER EFFECTIVENESS OF
C                VARIOUS CONFIGURATIONS - DETERMINES THE EXIT TEMPERATURE
C                OF HEAT EXCHANGER KNOWING OTHER 3 TEMPERATURES OF STREAMS
C
C         OPTIONS:
C                    1 - COUNTERCURRENT OR COUNTERFLOW
C                    2 - PARALLEL FLOW
C                    3 - CROSS FLOW - HOT UNMIXED
C                    4 - CROSS FLOW - COLD UNMIXED
C                    5 - CROSS FLOW - BOTH UNMIXED (NOT AVAILABLE)
C                    6 - 1-2(,4,6,8,ETC) PARALLEL-COUNTER FLOW - SHELL MX
C                    7 - MULTIPASS - OVERALL COUNTERFLOW
C                    8 - ONE SHELL PASS, ONE TUBE PASS, BAFFLED CROSSFLOW
C         EQUATIONS OBTAINED FROM [COMPACT HEAT EXCHANGERS[, KAYS AND
C                LONDON, 1958
C                             PROGRAMMER: D.G. BESHORE(MMC,D/0482)
      KPASS = 1
      CH = WH*CPH
      CC = WC*CPC
      CMAX = AMAX1(CH,CC)
      CMIN = AMIN1(CH,CC)
      R = CMIN/CMAX
      XNTU = UO*AO/CMIN
      GO TO (10,20,30,40,50,60,70,80,90) OPTION
C
C         COUNTERFLOW  HEAT  EXCHANGER
C
   10 E = (1.0 - EXP(-XNTU*(1.0-R)))/(1.0-R*EXP(-XNTU*(1.0-R)))
      GO TO 800
C
C         PARALLEL FLOW HEAT EXCHANGER
C
   20 E = (1.0-EXP(-XNTU*(1.0+R)))/(1.0+R)
      GO TO 800
C
C         CROSSFLOW - HOT STREAM UNMIXED
C
   30 IF((CMAX-CC).LE.0.0001)  GO TO 35
   31 E = 1.0-EXP((EXP(-XNTU*R)-1.0)/R)
      GO TO 800
   35 E = (1.0-EXP((EXP(-XNTU)-1.0)*R))/R
      GO TO 800
```

```
C
C          CROSSFLOW - CULD STREAM UNMIXED
C
   40 IF((CMAX-CH).LE.0.0001) GO TO 35
      GO TO 31
C
C          CROSSFLOW - BOTH UNMIXED
C
   50 WRITE(6,100)
  100  FORMAT("0 OPTION 5 NOT AVAILABLE")
      CALL EXIT
C
C          1.- 2(,4,6,8,ETC) PARALLEL COUNTERFLOW HEAT EXCHANGER
C
   60 GAMMA = XNTU*SQRT(1.0+R**2)
      E = 2.0/(1.0+R+SQRT(1.0+R**2)*(1.0+EXP(-GAMMA))/(1.0-EXP(-GAMMA)))
      GO TO 800
C
C
C          MULTIPASS - OVERALL COUNTERFLOW HEAT EXCHANGER
C
  800 IF(OPTION.EQ.7.AND.KPASS.EQ.2) GO TO 200
      IF(OPTION.EQ.8.AND.KPASS.EQ.2) GO TO 200
      IF(OPTION.EQ.9.AND.KPASS.EQ.2) GO TO 200
      GO TO 500
C
C          MULTISHELL PASS - EVEN NUMBERED TUBE PASS HEAT EXCHANGER
C
   70 XNTU = XNTU/NSP
      NTO = NSP
      KPASS = 2
      GO TO 60
C
C         ONE SHELL PASS - ONE TUBE PASS BAFFLED HEAT EXCHANGER
C
   80 IF(KPASS.EQ.2) GO TO 200
      XNTU = XNTU/NBAFF
      NTO = NBAFF
      KPASS = 2
      GO TO 40
C
C          DETERMINE EFFECTIVENESS OF MULTIPASS HEAT EXCHANGERS
C
   90 RETURN
  200 EFF = E
      IF(R.GT.0.98)  E = EFF*NTO/(1.0+(NTO-1.0)*EFF)
      IF(R.LE.0.98)  EPP =((1.0-EFF*R)/(1.0-EFF))**NTO
      IF(R.LE.0.98)  E = (EPP-1.0)/(EPP-R)
C
C     CALCULATE EXIT TEMPERATURE OF FLUID STREAM
C
  500 CONTINUE
      GO TO (510,520,530)     NTOP
  510 T3 =(CC*T1 - E*CMIN*T2)/(CC - E*CMIN)
      Q  = CC*(T1 - T3)
      T4 = T2 - Q/CH
      GO TO 600
  520 T4 = (E*CMIN*T1 - CH*T2)/(E*CMIN - CH)
      Q  = CH*(T4 - T2)
      T3 = T1 + Q/CC
      GO TO 600
 530  CONTINUE
      T3=T1+E*CMIN*(T2-T1)/CC
```

```
      Q =CMIN*(T2-T1)*E
      T4=T2+E*CMIN*(T1-T2)/CH
  600 RETURN
      END
*DECK,CPSW
      SUBROUTINE CPSW(T,CP)
      IF(T.GT.650.0)   GO TO 10
      IF(T.LT.32.0)    GO TO 11
      IF(T.GT.375.0)    GO TO 13
      A0 = -32.2199
      A1 = 1.00988
      A2 = -1.09370E-04
      A3 = 3.22658 E-07
      CP = A1 +A2*2.0*T + A3*3.0*T**2
      RETURN
 13   CONTINUE
      B0 =-6.41287E+01
      B1 = 1.27331
      B2 = -8.39448E-04
      B3 = 1.00122E-06
      B4 = 0.0
      B5 = 0.0
      B6 = 0.0
      CP = B1+B2*2.0*T+B3*3.0*T**2+B4*4.0*T**3
     1       +B5*5.0*T**4+B6*6.0*T**5
      RETURN
 10   WRITE(6,1)
 1    FORMAT(32H WATER TEMPERATURE EXCEEDS 650 F     )
      GO TO 12
 11   WRITE(6,2)
 2    FORMAT(33H WATER TEMPERATURE LESS THAN 32 F    )
 12   CONTINUE
      END
*DECK,LOCFAC
      SUBROUTINE  LOCFAC(JK, X,TX,NX, JX,FX)
C       IF JK EQ. 1, CHECKS ORDER OF TX ARRAY (NX ITEMS) FOR
C         CONSISTANTLY INCREASING OR DECREASING VALUES.
C       FINDS LOCATION OF FIRST (OR ONLY) ARRAY ITEM FOR SCALING
C         LOCATION OF X FROM TX(JX)
C       CALCULATES SCALING FACTOR FX = (X-TX(JX)) / (TX(JX+1)-TX(JX))
      DIMENSION  TX(1)
      JX = 1
      FX = 0.
      IF(NX.LE.1)  GO TO 200
      S = 1.
      IF(TX(1).GT.TX(NX))  S = -1.
      XR2 = ABS(TX(NX)-TX(1))*0.5
      IF(JK.NE.1)  GO TO 90
      JK = 0
      IF(S.GT.0.)  GO TO 30
        DO 20 I=2,NX
        IF(TX(I).GT.TX(I-1))  GO TO 50
   20   CONTINUE
      GO TO 90
   30   DO 40 I=2,NX
        IF(TX(I).LT.TX(I-1))  GO TO 50
   40   CONTINUE
      GO TO 90
   50 WRITE(6,60)
   60 FORMAT(1H1 41X 27HE R R O R   I N   T A B L E )
   70  WRITE(6,80)  X,(TX(I),I=1,NX)
   80   FORMAT(1H0 41X 27HREFER TO SUBROUTINE  LOCFAC  //
     1          5X 3HX = 1PE15.4 / 4X 4HTX = 6E15.4 / (8X 6E15.4) )
```

```
C  ************      NO SYSTEM SUBROUTINE   ERRTRA          *******
C     CALL ERRTRA
C  ************************                             ***********
         CALL  EXIT
         STOP
   90 NX1 = 2
      IF(NX.LE.20)  GO TO 110
        DO 100 I=10,NX,10
        JX = I
        IF((TX(I)-X)*S) 100,200,110
  100   NX1 = I + 1
  110     DO 120 I=NX1,NX
          JX = I
          IF((TX(I)-X)*S) 120,200,130
  120     CONTINUE
  130 IF(JX.GT.1)  JX = JX-1
      FX = (X-TX(JX)) / (TX(JX+1)-TX(JX))
        IF(X.LT.AMIN1(TX(1),TX(NX))-XR2)  GO TO 150
        IF(X.GT.AMAX1(TX(1),TX(NX))+XR2)  GO TO 150
          GO TO 200
  150 WRITE(6,160)
  160 FORMAT(1H1 22X 64HE R R O R  -  EXTRAPOLATION OF TABLE IS BEYOND R
     1EASONABLE LIMITS )
      GO TO 70
  200     RETURN
      END
*DECK,GINTRP
      FUNCTION GINTRP(X1,T1,N1,X2,T2,N2,YT,N,JK1,JK2,L)
C
C
C       GENERAL INTERPOLATION ROUTINE --- INTERPOLATES ONE AND
C           TWO DIMENSIONAL ARRAYS AND BYPASSES PREVIOUSLY SCALED
C           INDEPENDENT VARIABLES
C
C           PROGRAMMER: D G BESHORE
C
      DIMENSION T1(1),T2(1),YT(1)
C       L  IS  BYPASS  INDICATOR
      IF(L.EQ.1)  GO TO 10
      CALL LOCFAC(JK1,X1,T1,N1,I1,F1)
      CALL LOCFAC(JK2,X2,T2,N2,I2,F2)
         F3 = 1.-F2
        I11 = (I2-1)*N + I1
        I21 = I11 + 1
        I12 = I11 + N
        I22 = I12 + 1
        D1 = 1.
        D2 = 1.
      IF(I1.GT.N .OR. I2.GT.1000)  GO TO 30
   10 IF(F1.LT.1.E-50) F1 = 0.
      IF(F1.EQ.0.)  GO TO 20
        D1 = YT(I21)-YT(I11)
      IF(F2.EQ.0) GO TO 20
        D2 = YT(I22)-YT(I12)
   20 GINTRP = YT(I11) + F1*D1
      IF(F2.LT.1.E-50) F2=0.
      IF(F2.NE.0.)  GINTRP = F3*GINTRP + F2*(YT(I12)+F1*D2)
      RETURN
   30 WRITE(6,40) I1,N,I2,X1,X2
   40 FORMAT(10X," ERROR DETECTED IN GINTRP.....I1 =",I3,3X," N =",I3,
     1  3X," I2 =",I5,3X," X1 =",E12.6,3X," X2 =",E12.6)
C    *********                           **********
C     CALL ERRTRA

C    ********      REMOVE CALL TO SYSTEM SUBROUTINE ERRTRA
        CALL  EXIT
        STOP
      END
```

DUNKLE ROCKBED STORAGE MODEL PROGRAM LISTING

```
      PROGRAM MAIN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      REAL L,N,M   ,LAM,MU
      DIMENSION TZY(16),TY(11),TAU(16,11)
      DATA JK1/1/,JK2/1/,KTZY/16/,KTY/11/
      DATA TZY/.01,.1,.2,.3,.4,.5,.6,.7,.8,.9,1.,1.1,1.2,1.3,1.4,100./
      DATA TY/15.,20.,30.,40.,50.,60.,70.,80.,90.,100.,10000./
      DATA TAU/.0012,.016,.038,.048,.064,.08,.15,.24,.31,.38,.5,.59,
     1 .69,.80,.84,.88,
     1 .0011,.01,.02,.03,.04,.05,.10,.20,.27,.33,.5,.62,.74,.83,.87,.91,
     1 .95,.0064,.0058,.0116,.0174,.0232,.029,.07,.1,.2,.285,.5,.68,
     1 .83,.88,.94,.99,
     1 .00062,.0056,.0112,.0168,.0224,.028,.068,.09,.175,.28,.5,.7,.84,
     1  .90,.97,1.,.0006,.0054,.0108,.0162,.0216,.027,.066,.08,.15,.275,
     1 .5,.71,.85,.92,1.,1.,
     1 .00058,.0052,.0104,.0156,.0208,.026,.064,.075,.13,.27,.5,.73,
     1 .86,.93,1.,1.,
     1 .0056,.005,.01,.015,.02,.025,.062,.07,.11,.265,.5,.75,.87,.95,
     1 1.0,1.0,
     1 .0053,.0048,.0096,.0144,.0192,.024,.06,.065,.09,.255,.5,.76,.875,
     1 .965,1.,1.,.00051,.0046,.0092,.0138,.0184,.023,.055,.06,
     1.08,.25,.5,.78,.88,.98,1.,1.,
     1 .00049,.0044,.0088,.0132,.0176,.022,.054,.055,.075,.245,.5,.8,
     1 .89,.99,1.,1./
C     READ IN THE BED PARAMETERS
      READ(5,500) L,D,CM,E,DP,RHOA,N,NX
  500 FORMAT(7E10.3,I3)
C     READ IN GAS CONDITIONS
      READ(5,505) M,P,TIN,TM,THETA
  505 FORMAT(5E10.3)
      WRITE(6,510)
  510 FORMAT(10X,1HL,13X,1HD,12X,2HCM,13X,1HE,12X,2HDP,12X,4HRHOA,8X,
     1  1HN,//)
      WRITE(6,515)L,D,CM,E,DP,RHOA,N
  515 FORMAT(5X,7(E10.3,4X))
      WRITE(6,520)
  520 FORMAT(10X,1HM,13X,1HP,13X,3HTIN,13X,2HTM,13X,5HTHETA,//)
      WRITE(6,525) M,P,TIN,TM,THETA
  525 FORMAT(5X,5(E10.3,4X))
C     COMPUTE GAS VISCOSITY
      MU=(5.882E-5*((5./9.)*(TIN+460.))**1.5)/(110.8+(5./9.)*(TIN+460.))
C     COMPUTE DIMENSIONLESS BED LENGTH AND REYNOLDS NUMBER
      RE = (M*DP*4.)/(MU*3.142*N*D**2.)
      LAM =  RE**0.3/2.4
      Y =  L/(DP*LAM)
C     COMPUTE APPARENT DENSITY OF BED, GAS SPECIFIC HEAT,AND MASS FLUX
      RHOM = (1. - E)*RHOA
      CP = (1030.1-0.19762*(5./9.)*(TIN+460.)+ 3.947E-4*((5./9.)*(TIN
     1   +460.))**2.)/3991.6
      G =  (M*4.)/(3.142*N*D**2.)
      RHOG =(2.70 * P)/(TIN + 460.)
      WRITE(6,529)
  529 FORMAT(10X,4HTOUT,13X,3HTAU,13X,5HTHETA,13X,4HDELP,//)
C     COMPUTE PRESSURE DROP
      BETA  = (RE**0.65)*((8.75*RE + 729.)**0.5)
      DELP = ((1.658E-6 * Y)/RHOG) *((BETA* MU/DP)**2.)
      DO  10 I=1,NX
      ZY  = (THETA*CP*G*60.)/(RHOM+CM*L)
C      USING  ZY AND Y PERFORM LINEAR INTERPERLATION FOR TAU
      STAU = GINTRP(ZY,TZY(1),KTZY,Y,TY(1),KTY,TAU(1,1),11,JK1,JK2,0)
      TOUT = TM - STAU*(TM - TIN)
      WRITE(6,530)TOUT,STAU,THETA,DELP
  530 FORMAT(5X,4(E10.3,4X))
```

```
   10 THETA = THETA + 5.
      WRITE(6,535)
  535 FORMAT(10X,1HL,13X,4HTOUT,//)
      DL = 0.1*L
C     COMPUTE TEMPERATURE LEVELS ALONG LENGTH OF BED
      DO 20  I=1,10
      Y =  L/(DP*LAM)
      ZY = (THETA * CP * 60. * G)/(RHOM * CM * L)
      STAU = GINTRP(ZY,TZY(1),KTZY,Y,TY(1),KTY,TAU(1,1),11,JK1,JK2,0)
      TOUT = TM - STAU * (TM - TIN)
      WRITE(6,540)L,TOUT
  540 FORMAT(5X,2(E10.3,4X))
   20 L  = L - DL
      STOP
      END
*DECK,LOCFAC
      SUBROUTINE  LOCFAC(JK, X,TX,NX, JX,FX)
C       IF JK EQ. 1, CHECKS ORDER OF TX ARRAY (NX ITEMS) FOR
C         CONSISTANTLY INCREASING OR DECREASING VALUES.
C       FINDS LOCATION OF FIRST (OR ONLY) ARRAY ITEM FOR SCALING
C         LOCATION OF X FROM TX(JX)
C       CALCULATES SCALING FACTOR FX = (X-TX(JX)) / (TX(JX+1)-TX(JX))
      DIMENSION  TX(1)
      JX = 1
      FX = 0.
      IF(NX.LE.1)  GO TO 200
      S = 1.
      IF(TX(1).GT.TX(NX))  S = -1.
      XR2 = ABS(TX(NX)-TX(1))*0.5
      IF(JK.NE.1)  GO TO 90
      JK = 0
      IF(S.GT.0.)  GO TO 30
        DO 20 I=2,NX
        IF(TX(I).GT.TX(I-1))  GO TO 50
   20   CONTINUE
      GO TO 90
   30   DO 40 I=2,NX
        IF(TX(I).LT.TX(I-1))  GO TO 50
   40   CONTINUE
      GO TO 90
   50 WRITE(6,60)
   60 FORMAT(1H1 41X 27HE R R O R   I N   T A B L E )
   70  WRITE(6,80)  X,(TX(I),I=1,NX)
   80   FORMAT(1H0 41X 27HREFER TO SUBROUTINE  LOCFAC  //
     1            5X 3HX = 1PE15.4 / 4X 4HTX = 6E15.4 / (8X 6E15.4) )
        CALL  ERRTRA
         CALL  EXIT
         STOP
   90 NX1 = 2
      IF(NX.LE.20)  GO TO 110
        DO 100 I=10,NX,10
        JX = I
        IF((TX(I)-X)*S) 100,200,110
  100   NX1 = I + 1
  110     DO 120 I=NX1,NX
          JX = I
          IF((TX(I)-X)*S) 120,200,130
  120     CONTINUE
  130 IF(JX.GT.1)  JX = JX-1
      FX = (X-TX(JX)) / (TX(JX+1)-TX(JX))
        IF(X.LT.AMIN1(TX(1),TX(NX))-XR2)  GO TO 150
        IF(X.GT.AMAX1(TX(1),TX(NX))+XR2)  GO TO 150
          GO TO 200
```

```
 150 WRITE(6,160)
 160 FORMAT(1H1 22X 64HE R R O R  -  EXTRAPOLATION OF TABLE IS BEYOND R
    1EASONABLE LIMITS )
     GO TO 70
 200     RETURN
     END
C
     FUNCTION GINTRP(X1,T1,N1,X2,T2,N2,YT,N,JK1,JK2,L)
C
C
C      GENERAL INTERPOLATION ROUTINE --- INTERPOLATES ONE AND
C          TWO DIMENSIONAL ARRAYS AND BYPASSES PREVIOUSLY SCALED
C          INDEPENDENT VARIABLES
C
C          PROGRAMMER: D G BESHORE
C
     DIMENSION T1(1),T2(1),YT(1)
C      L  IS  BYPASS  INDICATOR
     IF(L.EQ.1)  GO TO 10
     CALL LOCFAC(JK1,X1,T1,N1,I1,F1)
     CALL LOCFAC(JK2,X2,T2,N2,I2,F2)
        F3 = 1.-F2
       I11 = (I2-1)*N + I1
       I21 = I11 + 1
       I12 = I11 + N
       I22 = I12 + 1
       D1 = 1.
       D2 = 1.
     IF(I1.GT.N .OR. I2.GT.1000)  GO TO 30
  10 IF(F1.LT.1.E-50) F1 = 0.
     IF(F1.EQ.0.)  GO TO 20
       D1 = YT(I21)-YT(I11)
     IF(F2.EQ.0) GO TO 20
       D2 = YT(I22)-YT(I12)
  20 GINTRP = YT(I11) + F1*D1
     IF(F2.LT.1.E-50) F2=0.
     IF(F2.NE.0.)  GINTRP = F3*GINTRP + F2*(YT(I12)+F1*D2)
     RETURN
  30 WRITE(6,40) I1,N,I2,X1,X2
  40 FORMAT(10X," ERROR DETECTED IN GINTRP.....I1 =",I3,3X," N =",I3,
    1  3X," I2 =",I5,3X," X1 =",E12.6,3X," X2 =",E12.6)
       CALL  ERRTRA
       CALL  EXIT
       STOP
     END
     SUBROUTINE ERRTRA
C   ************                          *************
C
C        DEFUNCT SYSTEM SUBROUTINE
C
C   ************                          *************
 900  FORMAT("0  DEFUNCT SUBROUTINE ERRTRA")
     WRITE(6,900)
     RETURN
     END
 49.       49.       .24       .30       .167      1.68  E02  2.      100
7.60  E02 1.47  E01 1.500 E03 3.50  E02 5.0
```

REFERENCE

A-1 R. V. Dunkle: "Randomly-Packed Particle Bed Regenerators and Evaporative Coolers," *Mechanical and Chemical Engineering Trans. I. E. Aust.* Vol MC8, No. 2, 1972, pp. 117-121.

APPENDIX B

DRAW SALT STORAGE SYSTEM MODEL

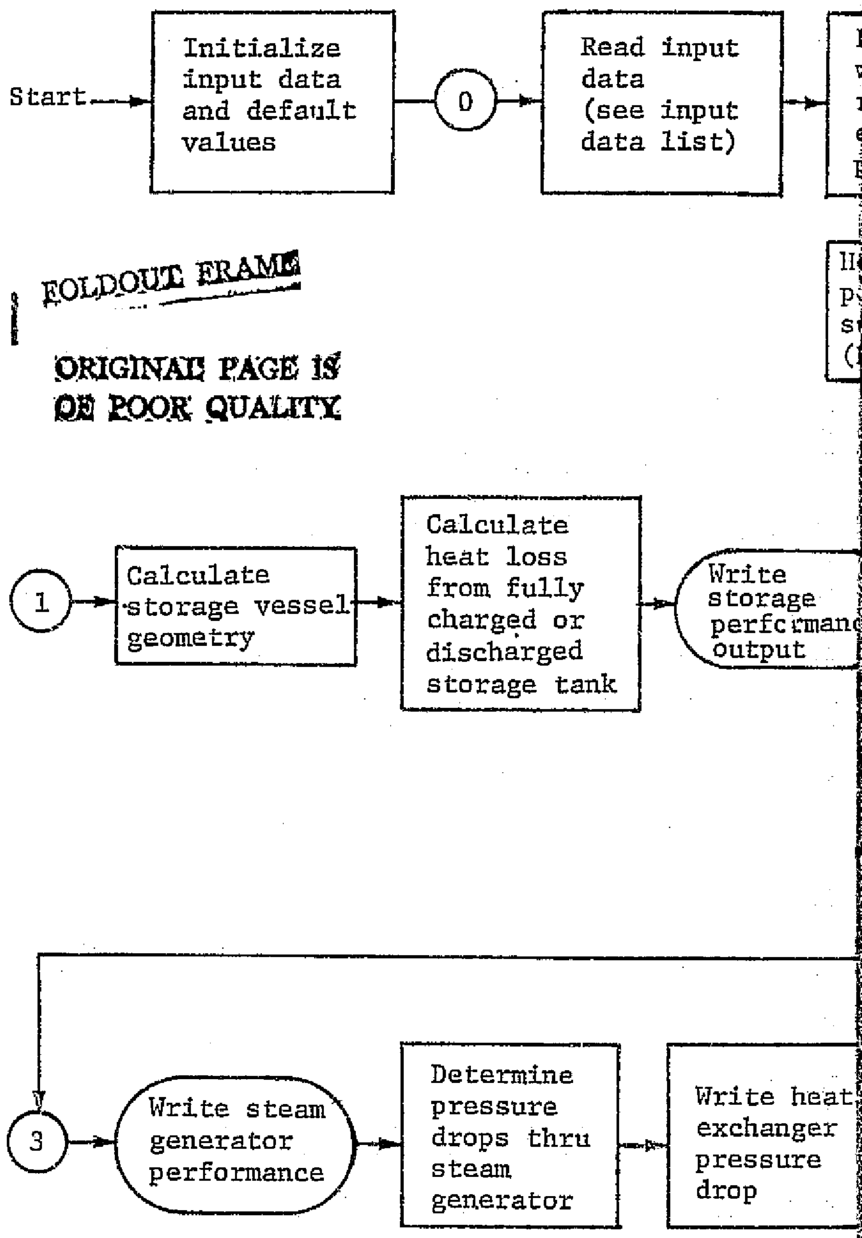
APPENDIX B DRAW SALT SYSTEM MODEL

This computer model was formulated to evaluate the performance of draw salt storage units coupled with the cement manufacturing process and steam generation equipment. The model calculates the heat loss in the piping system as well as the storage vessel based on conservation of energy formulations. Detailed heat exchanger analysis is performed for the wast heat recovery exchanger, and the three-unit steam generator--superheater, boiler, preheater--based on equations developed in Ref B-1. Pressure drops are calculated for the draw salt loop and the steam/water flow through the steam generator from correlations presented in Ref B-2.

This program provides specific information on temperature degradation of the salt in storage during charge and discharge cycles. Although the solution of equations in this model does step in time, the steady-state output is useful in projecting total heat losses during charge and discharge cycles. This program is written in FORTRAN IV and was formulated specifically for execution on CDC computers. A listing of this program is included at the end of this appendix.

A simplified flow diagram of the computer model is shown in Figure B-1. The program starts by initializing values of variables and reading input. The waste heat recovery exchanger performance is determined by using a detailed heat exchanger analysis subroutine, based on the equations developed in Ref B-2. Both heat loss and pressure drops are calculated on the insulated pipe between the salt storage vessel and the wast heat recovery heat exchanger. Pressure drops through the waste heat recovery exchanger both on the draw salt tube side and the kiln gas side are then computed. After the vessel size and shape have been determined, the heat loss from a fully charged and discharged tank are calculated.

The program then calculates the performance of equipment associated with the salt loop between the storage vessel and the steam generator. Heat losses and pressure drops are determined in the salt transport lines. A detailed heat exchanger analysis is then performed on the three unit steam generator. Inlet and exit stream temperatures are calculated based on user specified heat exchanger configuration and size. Pressure drops on the salt and steam sides are also determined for each exchanger in the steam generator module. As a final calculation, the power generated is calculated using the steam conditions produced from the superheater, the feedwater conditions entering the preheater, the steam flow rate, and user input thermal-to-electric conversion efficiency. The program then returns to the beginning of the program for the next case.


Start
Initialize input data and default values
0
Read input data (see input data list)
1
Calculate storage vessel geometry
Calculate heat loss from fully charged or discharged storage tank
Write storage
output
3
Write steam generator performance
Determine pressure drops thru steam generator
Write heat exchanger pressure drop

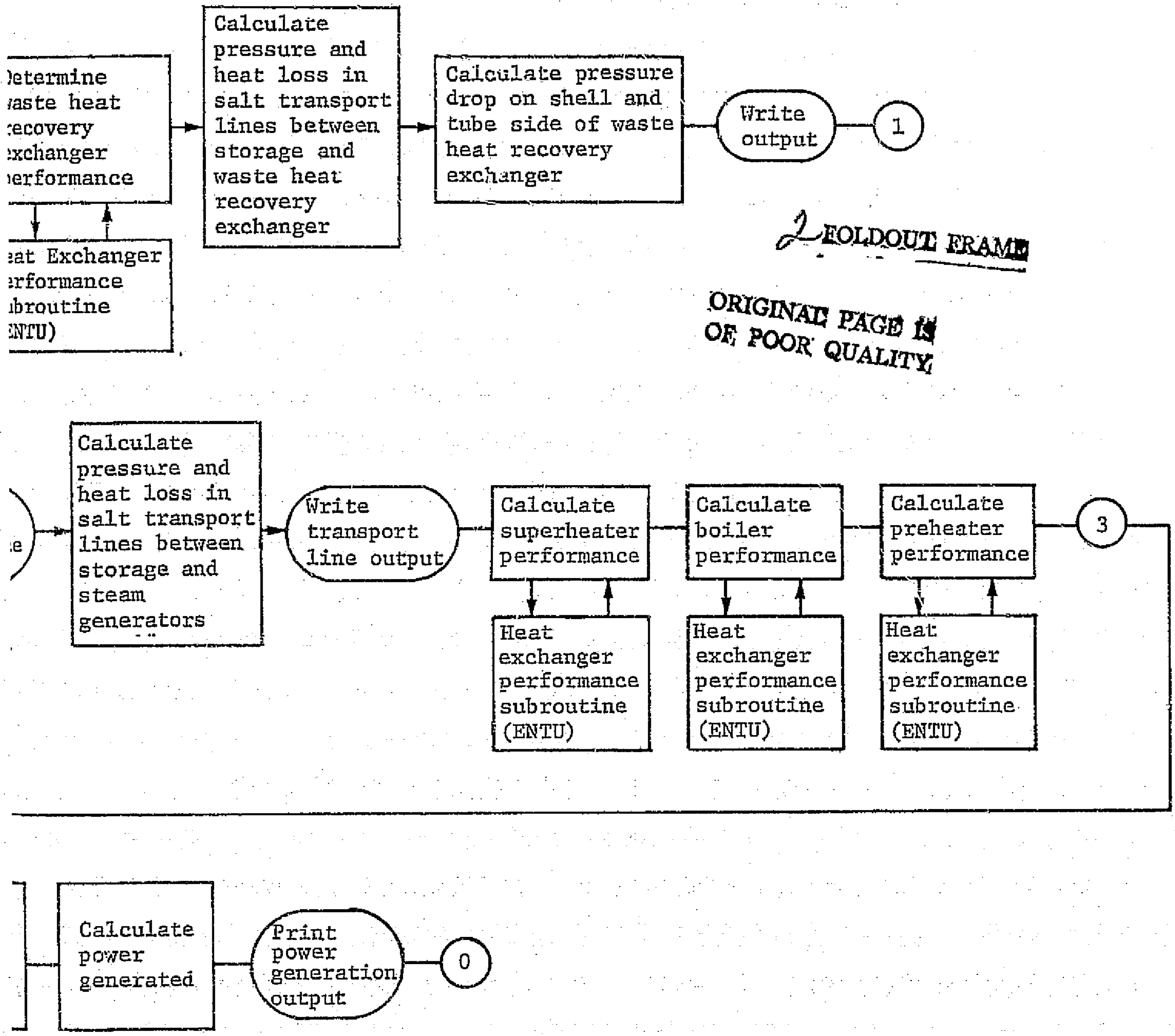


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Figure B-1 Draw Salt Model Main Program Simplified Flow Diagram

INPUT

Input to the model is in the form of namelist input. The input is organized into various sections for user ease-of-use. Some input values have defaults coded into the program (see program input).

NAMELIST TPP - THERMOPHYSICAL PROPERTIES OF GASES AND LIQUIDS

The purpose of this group of data is to define the kiln exit gas and draw salt thermophysical properties. Properties input include density, viscosity, thermal conductivity, and heat capacity as functions of temperatures and pressures. The program uses two dimensional interpolation techniques to predict properties at specified conditions of temperature and pressure.

COMMENT CARDS

FORMAT	VARIABLE CODE	DESCRIPTION
(18A4)	AMAT(1), I = 1,72	Case Identification (4 cards)

$TPP

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
NTR1	1	1	1-10	Number of temperatures for kiln gas density tables	-
NPR1	1	1	1-5	Number of pressures for kiln gas density tables	-
TTR1(I)	10	1500	-	Kiln gas density temperature tables	^oF
TTP1(I)	5	14.696	-	Kiln gas density pressure tables	PSIA
RHOG1(I,J)	I = 10 J = 5	0.0217	-	Kiln gas density	lb/ft^3
NTV1	1	1	1-10	Number of temperatures for kiln gas viscosity tables	-
NPV1	1	1	1-5	Number of pressures for kiln gas viscosity tables	-
TTV1	10	1500	-	Kiln gas viscosity temperature tables	^oF
TPV1	5	14.696	-	Kiln gas viscosity pressure tables	PSIA
VISCG(I,J)	I = 10 J = 5	0.0223	-	Kiln gas viscosity	lb/ft sec
NTC1	1	1	1-10	Number of temperatures for kiln gas thermal conductivity	-

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
NPC1	1	1	1-5	Number of pressures for kiln gas thermal conductivity tables	-
TTC1(I)	10	1500	-	Kiln gas thermal conductivity temperature tables	^{o}F
TPC1(I)	5	14.696	-	Kiln gas thermal conductivity pressure tables	PSIA
CONDG1(I,J)	I = 10 J = 5	0.03	-	Kiln gas thermal conductivity	$\frac{Btu}{Hr.Ft.^{o}F}$
NTCP1	1	1	1-10	Number of temperatures for kiln gas heat capacity tables	-
NPCP1	1	1	1-5	Number of pressures for kiln gas heat capacity tables	-
TTCP1(I)	10	1500	-	Kiln gas heat capacity temperature tables	^{o}F
TPCP1(I)	5	14.696	-	Kiln gas heat capacity pressure tables	PSIA
CPG1(I,J)	I = 10 J = 5	0.28	-	Kiln gas heat capacity	$\frac{Btu}{Lb.^{o}F}$
NTR2	1	6	1-10	Number of temperatures for draw salt density tables	-
NPR2	1	1	1-5	Number of pressures for draw salt density tables	-
TTR2(I)	10	500. 600. 700. 800. 900. 1000.	-	Draw salt density temperature tables	^{o}F
TPR2(I)	5	15.0	-	Draw salt density pressure tables	PSIA

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUES	OPTIONAL VALUES	DESCRIPTION	UNITS
RHOL2(I,J)	I = 10 J = 5	120.5	-	Draw salt density pressure tables	PSIA
		118.0			
		115.5			
		113.6			
		111.1			
		108.6			
NTV2	1	6	1-10	Number of temperature for draw salt viscosity tables	-
NPV2	1	1	1-5	Number of pressures for draw salt viscosity tables	-
TTV2	10	500.	-	Draw salt viscosity temperature tables	°F
		600.			
		700.			
		800.			
		900.			
		1000.			
TPV2	5	15.0	-	Draw salt viscosity pressure tables	PSIA
VISCG2(I,J)	I = 10 J = 5	4.0	-	Draw salt viscosity	Centipoise
		2.8			
		2.05			
		1.65			
		1.45			
		1.00			
NTC2	1	1	1-10	Number of temperatures for draw salt thermal conductivity tables	-

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
NPC2	1	1	1-5	Number of pressures for draw salt thermal conductivity tables	-
TTC2(I)	10	800.	-	Draw salt thermal conductivity temperature tables	^oF
TPC2(I)	5	15.0	-	Draw salt thermal conductivity pressure tables	PSIA
CONDL2(I,J)	I = 10 J = 5	0.33	-	Draw salt thermal conductivity	$\frac{Btu}{Hr \cdot Ft \cdot {}^oF}$
NTCP2	1	1	1-10	Number of temperatures for draw salt heat capacity	-
NPCP2	1	1	1-5	Number of pressures for heat capacity	-
TTCP2(I)	10	800.	-	Draw salt heat capacity temperature tables	^oF
TPCP2(I)	5	15.0	-	Draw salt heat capacity pressure tables	PSIA
CPL2(I,H)	I = 10 J = 5	0.37	-	Draw salt heat capacity	$\frac{Btu}{Lb \cdot {}^oF}$

$END

NAMELIST STORE - THERMAL ENERGY STORAGE DATA

This data group is used to define the characteristics of the draw salt thermal storage units and the interface requirements with the energy source and steam generation equipment. Data input includes storage vessel size, pipe lengths, and heat exchanger size and configuration.

$STORE

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
SVVOL	1	0.	-	Storage vessel volume	ft^3
SVDIAI	1	0.	-	Storage vessel internal diameter	ft
SVDIAØ	1	0.	-	Storage vessel outside diameter	ft
SVL	1	0.	-	Storage vessel height or length	ft
SVIT	1	0.	-	Storage vessel insulation thickness	in
TKTANK	1	0.	-	Storage tank thermal conductivity	$\frac{Btu}{Hr \cdot Ft \cdot {}^\circ F}$
TKINS	1	-	-	Insulation thermal conductivity	$\frac{Btu}{Hr \cdot Ft \cdot {}^\circ F}$
DLTS	1	-	-	Distance of pipeline from gas-salt (waste heat recovery) heat exchanger to storage	ft
DLFS	1	-	-	Distance of pipeline from storage to gas-salt heat exchanger	ft
DLTB	1	-	-	Distance of pipeline from storage ro steam generator	ft
DLFB	1	-	-	Distance of pipeline from steam generator to storage	ft
EQULB	1	-	-	Equivalent length of fittings, valves, bends, etc. from storage to steam generator	ft

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
EQUFB	1	-	-	Equivalent length of fittings, etc. from steam generator to storage	ft
EQULS	1	-	-	Equivalent length of fittings, etc. from gas-salt heat exchanger to storage	ft
EQUFS	1	-	-	Equivalent length of fittings etc., from storage to gas-salt heat exchanger	ft
PTSDII	1	-	-	Pipe to storage internal diameter	in
PTSDIO	1	-	-	Pipe to storage outside diameter	in
PFSDII	1	-	-	Pipe from storage internal diameter	in
PFSDIO	1	-	-	Pipe from storage outside diameter	in
THIPCL	1	-	-	Insulation thickness on cold pipeline	in
THIPHL	1	-	-	Insulation thickness on hot pipeline	in
EPSLT	1	-	-	Pipe surface roughness on cold pipeline	ft
EPSHT	1	-	-	Pipe surface roughness on hot pipeline	ft
TSTORH	1	-	-	Hot salt storage temperature estimate	^oF
TSTORL	1	-	-	Cold salt storage temperature estimate	^oF
WLTK	1	-	-	Mass flowrate of salt to the gas-salt heat exchanger	lb/hr
WLTS	1	-	-	Mass flowrate of salt diverted to storage	lb/hr
AMCLS	1	-	-	Initial mass of cold salt in storage tank	lb

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
AMHLS	1	-	-	Initial mass of hot salt in storage tank	lb
CHTIME	1	-	-	Charge cycle time	hrs
DITIME	1	-	-	Discharge cycle time	hrs
TIMELG	1	-	-	Time lag between charge and discharge cycles	hrs
TAMB	1	-	-	Ambient air temperature	^oF
WVELØ	1	-	-	Wind velocity	ft/sec
HOAIR	1	-	-	Convective heat transfer coefficient of airtank surface	$\frac{Btu}{Hr \cdot Ft^2 \cdot {}^oF}$

NAMELIST HTX HEAT EXCHANGER PERFORMANCE

This group of data describes the waste heat recovery heat exchanger and steam generator configuration. Overall heat transfer coefficient and heat exchanger configuration options are input. The specific configurations are:

1. Counter current
2. Parallel flow
3. Crossflow - hot unmixed
4. Crossflow - cold unmixed
5. Crossflow - both unmixed (not functional)
6. 1 shell pass - 2 (4, 6, 8, etc.) tube passes, Parallel - counterflow - shell side mixed, tube unmixed
7. Multishell pass - multitube pass overall counterflow
8. One shell pass, one tube pass - baffled crossflow

$HTX

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
NCONF(I)	4	-	1-8	Heat exchanger configuration option	-
				(See above list) First input is for gas-salt heat exchanger, second - superheater, third - boiler, fourth - preheater	-
TUBL(I)	4	-	-	Heat exchanger tube length	ft
TUBDO(I)	4	-	-	Tube outside diameter	in
TUBDI(I)	4	-	-	Tube inside diameter	in
NTUB1(I)	4	-	-	Number of tubes per heat exchange section	-
NTBCP(I)	4	-	-	Number of tubes in center plane of exchanger	-
EXTSU(I)	4	-	-	Extended surface area per tube	ft^2
NROW(I)	4	-	-	Number of tube rows	-
NPASS(I)	4	-	-	Number of tube passes	-

VARIABLE	MAX. NO. OF INPUTS	DEFAULT VALUE	OPTIONAL VALUES	DESCRIPTION	UNITS
PITCH(I)	4	-	-	Tube pitch	in
EPSH(I)	4	-	-	Tube surface roughness	in
NSHLP(I)	4	-	-	Number of shell passes	-
UØ(I)	4	-	-	Overall heat transfer coefficient	$\frac{Btu}{Hr \cdot Ft^2 \cdot {}^\circ F}$
NBAF(I)	4	-	-	Number of baffles in heat exchanger	-
RRATIØ(I)	4	-	-	Tube side mass recirculation ratio	-
BI(I)	4	-	-	Friction correction factor for tubeside	-
BØ(I)	4	-	-	Friction correction factor for shellside	-
PHI(I)	4	-	-	Correction factor for non-isothermal flow	-

DRAW SALT STORAGE SYSTEM MODEL PROGRAM LISTING

```
*DECK,MAIN
      PROGRAM MAIN(INPUT,OUTPUT,TAPE7,TAPE5=INPUT,TAPE6=OUTPUT)
C
C      HEAT STORAGE MODEL FOR LIQUID SENSIBLE TES AND BOILER SYSTEM
C               DEFAULT VALUES ARE FOR DRAW SALT STORAGE
C           SYSTEM CONSISTS OF FOUR HEAT EXCHANGERS ---
C                  1.   GAS-HEAT TRANSFER LIQUID
C                  2.   STEAM-HT LIQUID SUPERHEATER
C                  3.   STEAM/WATER-HT LIQUID BOILER
C                  4.   WATER-HT LIQUID PREHEATER
C           ENERGY LOSSES(THERMAL AND MECHANICAL) ARE ALSO CALCULATED
C                       FOR ENERGY TRANSPORT SYSTEM
C
C                PROGRAMMER: D G BESHORE (MMC,DEPT-0482)
C                 WRITTEN:  DECEMBER 1977
C
C             FLUID NO.1 - GAS
C             FLUID NO.2 - LIQUID STORAGE MEDIA
C             FLUID NO.3 - WATER
C             FLUID NO.4 - STEAM
C
C
C
      LOGICAL  KUP,FSTOR
      DIMENSION  AMAT(72), JK(20)
      COMMON /HEAT/  TUBL(4),   TUBDO(4),   TUBDI(4),   NPASS(4), NCONF(4),
     1               NSHLP(4), PITCH(4),   FFT(4),     FFS(4),
     2               CONT(4),   UO(4),      NTUB1(4),  NTBCP(4),
     3              NROW(4),    EPSH(4),    BI(4),     BO(4),    PHI(4),
     4          EXTSU(4),    NBAF(4)
      COMMON /PROP/  RHOG1(5,3),  VISCG1(5,3),  CONDG1(5,3),  CPG1(5,3),
     1               RHOL2(7,3),  VISCL2(7,3),  CONDL2(5,3),  CPL2(5,3),
     2               VISCL3(5,3), CONDL3(5,3),  VISCG4(5,3),
     3               CONDG4(5,3) ,
     4               TTR1(5),   TPR1(3),   TTV1(5),   TPV1(3),
     5               TTC1(5),   TPC1(3),   TTCP1(5),  TPCP1(3),
     6               TTR2(7),   TPR2(3),   TTV2(7),   TPV2(3),
     7               TTC2(5),   TPC2(3),   TTCP2(5),  TPCP2(3),
     8               TTV3(5),   TPV3(3),   TTC3(5),   TPC3(3),
     9               TTV4(5),   TPV4(3),   TTC4(5),   TPC4(3),
     X               NTR1,      NPR1,      NTV1,      NPV1,
     X               NTC1,      NPC1,      NTCP1,     NPCP1,
     X               NTR2,      NPR2,      NTV2,      NPV2,
     X               NTC2,      NPC2,      NTCP2,     NPCP2,
     X               NTV3,      NPV3,      NTC3,      NPC3,
     X               NTV4,      NPV4,      NTC4,      NPC4
      COMMON /STMC/  CEFF(7,5), TTCE(7), TPCE(5),  NTCE,  NPCE
      NAMELIST /TPP/  RHOG1,VISCG1,CONDG1,CPG1,
     1                RHOL2,VISCL2,CONDL2,CPL2,
     2                VISCL3,CONDL3,VISCG4,CONDG4,
     3                  TTR1,TPR1,TTV1,TPV1,TTC1,TPC1,TTCP1,TPCP1,
     4                  TTR2,TPR2,TTV2,TPV2,TTC2,TPC2,TTCP2,TPCP2,
     5                  TTV3,TPV3,TTC3,TPC3,TTV4,TPV4,TTC4,TPC4,
     6                  NTR1,NPR1,NTV1,NPV1,NTC1,NPC1,NTCP1,NPCP1,
     7                  NTR2,NPR2,NTV2,NPV2,NTC2,NPC2,NTCP2,NPCP2,
     8                  NTV3,NPV3,NTC3,NPC3,NTV4,NPV4,NTC4,NPC4
      NAMELIST /STORE/  DLTS,DLFS,DLTB,DLFB,EQULB,EQULS,EQUFS,EQUFB,
     1                  THIPHL,SVVOL,SVDIAI,SVDIAO,SVL,SVIT,
     2                  PTSDII,PFSDII,PTSDIO,PFSDIO,THIPCL,
     3                  TSTORH,TSTORL,EPSHT,EPSLT,HOAIR,
     4                  WLTK,WLTS,CHTIME,DITIME,TIMELG,
     5                  AMCLS,AMHLS,TAMB,WVELO,TKINS,TKTANK
      NAMELIST /HTX/    TUBL,TUBDO,TUBDI,NPASS,NSHLP,PITCH,FFT,FFS,EPSH,
```

```
     1                   CONT,UO,NTUB1,NTBCP,TKG,WKG,DCAREA,NROW,
     2   NCONF,EXTSU,NBAF,BI,BO,PHI
      NAMELIST /STEAM/  CEFF,WSTEAM,PSTEAM,SHOT,FWIT
     1         ,TTCE,  TPCE,   NTCE,  NPCE, TSSAT
      DATA JK /20*1/, PI/3.14159/, GC/32.174/, PSTP/14.696/
C
C          INITIALIZE INPUT DATA AND DEFAULT VALUES FOR DRAW SALT
C
      ITAPE=5
      NTR1=NPR1=NTC1=NPC1=NTCP1=NPCP1=NTV1=NPV1=1
      NPR2=NPV2=NTC2=NPC2=NTCP2=NPCP2=1
      TTR1(1)=TTC1(1)=TTV1(1)=TTCP1(1)=1500.
      TPR1(1)=TPC1(1)=TPV1(1)=TPCP1(1)=14.696
      RHOG1(1,1)=0.0217
      VISCG1(1,1)= 2.23 0.0223
      CONDG1(1,1)= 0.03
      CPG1(1,1) = 0.28
      NTR2=NTV2=6
      TPR2(1)=TPR2(1)=TPC2(1)=TPCP2(1)=15.0
      TTC2(1)=TTCP2(1)= 800.
      CONDL2(1,1)=0.33
      CPL2(1,1)=0.37
      TTR2(1)=TTV2(1)=500.
      TTR2(2)=TTV2(2)=600.
      TTR2(3)=TTV2(3)=700.
      TTR2(4)=TTV2(4)=800.
      TTR2(5)=TTV2(5)=900.
      TTR2(6)=TTV2(6)=1000.
      RHOL2(1,1) = 120.5
      RHOL2(2,1) = 1118.0 118.0
      RHOL2(3,1) = 115.5
      RHOL2(4,1) = 113.6
      RHOL2(5,1) = 111.1
      RHOL2(6,1) = 108.6
      VISCL2(1,1) = 4.0
      VISCL2(2,1) = 2.8
      VISCL2(3,1) = 2.05
      VISCL2(4,1) = 1.65
      VISCL2(5,1) = 1.45
      VISCL2(6,1) = 1.00
      KUP =.TRUE.
      FSTOR = .TRUE.
      SVVOL = SVDIAI = SVL = 0.0
      HOAIR = -1.0
      WLTK = 0.0
      WLTS = 0.0
      WLTB = 0.0
C
C          READ INPUT DATA
C
    1 READ(5,15) AMAT
      IF(EOF(5)) 10,2
    2 WRITE(6,18) AMAT
      READ(ITAPE,TPP)
      READ(5,STORE)
      READ(5,HTX)
      READ(5,STEAM)
      WRITE(6,TPP)
      WRITE(6,STORE)
      WRITE(6,HTX)
      WRITE(6,STEAM)
C
      IF(HOAIR.LT.0.0) HOAIR = 1.6 + 0.29*WVELO
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ORIGINAL PAGE IS
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```
      IF(.NOT.KUP) GO TO 100
C
C          CALCULATE THE ENERGY TRANSFERED FROM KILN GAS
C
      IF(WLTK.LE.0.0.AND.SVVOL.GT.0.0) WLTK = SVVOL*RHOS/CHTIME
      TAVG1S =(TSTORH+TSTORL)/2.
      CPSS = GINTRP(TAVG1S,TTCP2(1),NTCP2,PSTP,TPCP2(1),NPCP2,CPL2(1,1),
     1   5,JK(1),JK(2),0)
      RHOS = GINTRP(TSTORH,TTR2(1),NTR2,PSTP,TPR2(1),NPR2,RHOL2(1,1),
     1   7,JK(3),JK(4),0)
      QTS=WLTK*CPSS*(TSTORH-TSTORL)
      AHTX1 = NTUB1(1)*PI*TUBDO(1)*TUBL(1)/12.
     1     +EXTSU(1)*NTUB1(1)*TUBL(1)
C
C          CALCULATE  KILN EXIT GAS TEMPERATURE
C
      CPKG = GINTRP(TKG,TTCP1(1),NTCP1,PSTP,TPCP1(1),NPCP1,CPG1(1,1),
     1   5,JK(11),JK(12),0)
      TOKGE = TKG - QTS/(WKG*CPKG)
      CPKG = GINTRP((TKG+TOKGE)/2.,TTCP1(1),NTCP1,PSTP,TPCP1(1),NPCP1,
     1   CPG1(1,1),5,JK(11),JK(12),0)
      CALL ENTU(TSTORA,TOKG,QKGS,EFKGS,XNTUKG,RKG,TSTORL,TKG,CPSS,CPKG,
     1    WKG,WLTK,UO(1),AHTX1,NPASS(1),NSHLP(1),NBAF(1),
     2    NCONF(1),3)
      TSTORH=TSTORA
C
C          CALCULATE  MECHANICAL AND THERMAL ENERGY LOSS IN TRANSPORT
C                                  TO STORAGE
C
      VISS = GINTRP(TSTORH,TTV2(1),NTV2,PSTP,TPV2(1),NPR2,VISCL2(1,1),
     1   7,JK(5),JK(6),0)
      RE1S = 19.841*WLTK/(PI*PTSDII*VISS)
      FFACS = FRIC(RE1S,EPSHT,PTSDII/12.)
      TLENTH = DLTS + EQULS
      DELP=.0042667*FFACS*WLTK**2*TLENTH/(PI*PI*PTSDII**5*GC*RHOS)
C
      DOIN = PTSDIO+THIPHL*2.0
      CPSP = GINTRP(TSTORH,TTCP2(1),NTCP2,PSTP,TPCP2(1),NPCP2,CPL2(1,1),
     1   5,JK(1),JK(2),0)
      CONDS = GINTRP(TSTORH,TTC2(1),NTC2,PSTP,TPC2(1),NPC2,CONDL2(1,1),
     1   5,JK(9),JK(10),0)
      PRNTLS = CPSP*VISS*2.4192/CONDS
      IF(RE1S.LE.10000) HIS =22.32*CONDS/PTSDII*(RE1S*PRNTLS*PTSDII/
     1   DLTS)**(1./3.)
      IF(RE1S.GT.10000.) HIS = 0.276*CONDS/PTSDII*RE1S**0.8*PRNTLS**
     1     (1./3.)
      UOP = UOVER(PTSDIO,PTSDII,DOIN,HIS,HOAIR,CONT(1),TKINS,FFT(1),
     1   0.)
      QLLOSH = UOP*PI*DOIN*(TSTORH-TAMB)
      QLOSHT = QLLOSH*DLTS
C
C          CALCULATE LOSSES FROM COLD TRANSFER LINE
C
      RHOSL = GINTRP(TSTORL,TTR2(1),NTR2,PSTP,TPR2(1).NPR2,RHOL2(1,1),
     1   7,JK(3) ,JK(4) ,0)
      VISSL=GINTRP(TSTORL,TTV2(1),NTV2,PSTP,TPV2(1),NPV2,VISCL2(1,1),
     1   7,JK(5), JK(6), 0)
      RE1SL = 19.841*WLTK/(PI*PFSDII*VISSL)
      FFACSL = FRIC(RE1SL,EPSLT,PFSDII/12.)
      TLENTL = DLFS + EQUFS
      DELPL=.0042667*FFACSL*WLTK**2*TLENTL/(PI*PI*PFSDII**5*GC*RHOSL)
      DOINL = PFSDIO + THIPCL*2.0
      CPSPL = GINTRP(TSTORL,TTCP2(1),NTCP2,PSTP,TPCP2(1),NPCP2,CPL2(1,1)
```

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     1   ,5,JK(1), JK(2), 0)
      CONDSL = GINTRP(TSTOPL,TTC2(1),NTC2,PSTP,TPC2(1),NPC2,CONDL2(1,1),
     1   5,JK(9), JK(10),0)
      PRTLSL = 2.4192*CPSPL*VISSL/CONDSL
      IF(RE1SL.LE.10000.) HISL =22.32*CONDSL/PFSDII*(RE1SL*PRTLSL*PFSDII
     1   /DLFS)**(1./3.)
      IF(RE1SL.GT.10000.) HISL=0.276*CONDSL/PFSDII*RE1SL**0.8*PRTLSL**
     1   (1./3.)
      UOPL = UOVER(PFSDIO,PFSDII,DOINL,HISL,HOAIR,CONT(1),TKINS,FFT(1),
     1      0.)
      QLLOSL = UOPL*PI*DOINL*(TSTOPL-TAMB)
      QLOSLT = QLLOSL*DLFS
C
C        WRITE OUTPUT FOR HEAT EXCHANGER NO.1 AND ENERGY TRANSPORT TO
C                             STORAGE VESSEL
C
C        CALCULATE PRESSURE DROP IN HEAT EXCHANGER NO.1
      RHOSAV = GINTRP(TAVG1S,TTR2(1),NTR2,PSTP,TPR2(1),NPR2,RHOL2(1,1),
     1   7,JK(3),JK(4),0)
      VISCAV = GINTRP(TAVG1S,TTV2(1),NTV2,PSTP,TPV2(1),NPV2,VISCL2(1,1),
     1   7,JK(5),JK(6),0)
      CALL HTXDPT(DP1T,RE1T,EPSH(1),TUBDI(1),WLTK,NPASS(1),RHOSAV,BI(1),
     1   PHI(1),NTUB1(1),TUBL(1),VISCAV)
      TAVG1G = (TKG + TOKG)/2.0
      RHOGAV = GINTRP(TAVG1G,TTR1(1),NTR1,PSTP,TPR1(1),NPR1,RHOG1(1,1),
     1   5,JK(11),JK(12),0)
      VISCG = GINTRP(TAVG1G,TTV1(1),NTV1,PSTP,TPR1(1),NPR1,VISCG1(1,1),
     1   5,JK(13),JK(14),0)
      CALL HTXDPS(DP1S,RE1SS,TUBDO(1),WKG,NPASS(1),RHOGAV,BO(1),NTBCP(1)
     1   ,TUBL(1),VISCG,PITCH(1),NROW(1))
      WRITE(6,1320)
      WRITE(6,1000)
      WRITE(6,1120) WLTK,TSTORL,TSTORA,WKG,TKG,TOKG
      WRITE(6,1130) UO(1),AHTX1,NPASS(1),NSHLP(1),NBAF(1),NCONF(1),
     1   QTS,QKGS,EFKGS,XNTUKG,RKG
      WRITE(6,1020)
      WRITE(6,1030)
      WRITE(6,1040) WLTK,TSTORH,RE1S,DLTS,EQULS,PTSDIO,PTSDII,THIPHL,
     1   UOP,QLLOSH,QLOSHT,DELP
      WRITE(6,1080)
      WRITE(6,1040) WLTK,TSTORL,RE1SL,DLFS,EQUFS,PFSDIO,PFSDII,THIPCL,
     1   UOPL,QLLOSL,QLOSLT,DELPL
C
C        DETERMINE  STEAM GENERATION HEAT EXCHANGERS PERFORMANCE DURING
C                   CHARGE, DISCHARGE, AND/OR TIME LAG
C
C        CALCULATE  STORAGE PERFORMANCE AND HEAT LOSS WHEN FULLY OR
C                           PARTIALLY CHARGED
C
  100 IF(SVVOL.LE.0.0) SVVOL = PI*SVDIAI**2.*SVL/4.0
      IF(SVDIAI.LE.0.0) SVDIAI = SQRT(4.0*SVVOL/(PI*SVL))
      IF(SVL.LE.0.0) SVL = 4.0*SVVOL/(PI*SVDIAI**2.)
      VTCLIN  = WLTS/(RHOS  *PI*SVDIAI**2./4.0)
      HTHFI = 4.0*AMCLS/(PI*SVDIAI**2*RHOS)
      TIMECH = HTHFI/VTCLIN
C
C        CALCULATE HEAT LOSS FROM STORAGE WHEN FULLY CHARGED AND
C        DISCHARGED
C
      DOT = 2*SVIT + SVDIAO
      SVAREA=PI*DOT*DOT/4.0+PI*DOT*SVL
      UOT=1.0/(1.0/HOAIR+(SVDIAO-SVDIAI)/(2.*TKTANK)+SVIT/(12.*TKINS))
      QTANKH = UOT*SVAREA*(TSTORA-TAMB)
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      QTANKL = UOT*SVAREA*(TSTORL - TAMB)
      TRATEH = QTANKH/(SVVOL*RHOS*CPSP)
      TRATEL = QTANKL/(SVVOL*RHOSL*CPSPL)
C
C        PRINT OUTPUT FOR STORAGE PERFORMANCE
C
      WRITE(6,1050)
      WRITE(6,1060) SVVOL,SVDIAI,SVDIAO,SVL,VTCLIN,HTHFI,TIMECH,SVAREA,
     1    UOT,QTANKH,QTANKL,TRATEH,TRATEL
C
C        DETERMINE HEAT EXCHANGER NO.2 (SUPERHEATER) PERFORMANCE
C
      IF(WLTB.LE.0.0) WLTB=SVVOL*RHOS/DITIME
      IF(KUP.AND.FSTOR) WSTOB = WLTK - WLTS
      IF(.NOT.KUP)  WSTOB = WLTB
      IF(.NOT.FSTOR.AND.KUP) WSTOB = WLTK
      IF(.NOT.FSTOR.AND..NOT.KUP)     GO TO 1
C
C        CALCULATE ENERGY AND MECHANICAL ENERGY LOSSES TO/FROM BOILER
C
      RHOS = GINTRP(TSTORH,TTR2(1),NTR2,PSTP,TPR2(1),NPR2,RHOL2(1,1),
     1   7,JK(3),JK(4),0)
      VISS = GINTRP(TSTORH,TTV2(1),NTV2,PSTP,TPV2(1),NPR2,VISCL2(1,1),
     1   7,JK(5),JK(6),0)
      RE1S = 19.841*WSTOB/(PI*PTSDII*VISS)
      FFACS = FRIC(RE1S,EPSHT,PTSDII/12.)
      TLENTH = DLTB + EQULB
      DELP=0.0042667*FFACS*WSTOB**2*TLENTH/(PI*PI*PTSDII**5*GC*RHOS)
      DOIN = PTSDIO + THIPHL*2
      CPSP = GINTRP(TSTORH,TTCP2(1),NTCP2,PSTP,TPCP2(1),NPCP2,CPL2(1,1),
     1   5,JK(1),JK(2),0)
      CONDS = GINTRP(TSTORH,TTC2(1),NTC2,PSTP,TPC2(1),NPC2,CONDL2(1,1),
     1   5,JK(9),JK(10),0)
      PRNTLS = CPSP*VISS*2.4192/CONDS
      IF(RE1S.LE.10000.) HIS = 22.32*CONDS/PTSDII*(RE1S*PRNTLS*PTSDII/
     /   DLTB)**(1./3.)
      IF(RE1S.GT.10000.) HIS = 0.276*CONDS/PTSDII*RE1S**0.8*PRNTLS**
     1   (1./3.)
      UOP = UOVER(PTSDIO,PTSDII,DOIN,HIS,HOAIR,CONT(1),TKINS,FFT(1),
     1     0.)
      QLLOSH = UOP*PI*DOIN*(TSTORA-TAMB)
      QLOSH  = QLLOSH*DLTB
C
C        CALCULATE LOSSES IN COLD TRANSFER LINE FROM BOILER
C
      RHOSL = GINTRP(TSTORL,TTR2(1),NTR2,PSTP,TPR2(1),NPR2,RHOL2(1,1),
     1   7,JK(3),JK(4),0)
      VISSL=GINTRP(TSTORL,TTV2(1),NTV2,PSTP,TPV2(1),NPV2,VISCL2(1,1),
     1   7,JK(5),JK(6),0)
      RE1SL = 19.841*WSTOB/(PI*PFSDII*VISSL)
      FFACSL = FRIC(RE1SL,EPSLT,PFSDII/12.)
      TLENTL = DLFB + EQUFB
      DELPL=0.0042667*FFACSL*WSTOB**2*TLENTL/(PI*PI*PFSDII**5*GC*RHOSL)
      DOINL = PFSDIO + THIPCL*2
      CPSL = GINTRP(TSTORL,TTCP2(1),NTCP2,PSTP,TPCP2(1),NPCP2,CPL2(1,1)
     1   ,5,JK(1),JK(2),0)
      CONDSL = GINTRP(TSTORL,TTC2(1),NTC2,PSTP,TPC2(1),NPC2,CONDL2(1,1),
     1   5,JK(9),JK(10),0)
      PRTLSL = 2.4192*CPSL*VISSL/CONDSL
      IF(RE1SL.LE.10000.) HISL = 22.32*CONDSL/PFSDII*(RE1SL*PRTLSL*
     1   PFSDII/DLFB)**(1./3.)
      IF(RE1SL.GT.10000.) HISL=0.276*CONDSL/PFSDII*RE1SL**0.8*PRTLSL**
     1   (1./3.)
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      UOPL = UOVER(PFSDIO,PFSDII,DOINL,HISL,HOAIR,CONT(1),TKINS,FFT(1),
     1     0.)
      QLLOSL = UOPL*PI*DOINL*(TSTORL-TAMB)
      QLOSL  = QLLOSL*DLFB
C
C        PRINT OUTPUT FOR LOSSES IN ENERGY TRANSPORT TO/FROM BOILER
C
      WRITE(6,1070)
      WRITE(6,1030)
      WRITE(6,1040) WSTOB,TSTORH,RE1S,DLTS,EQULB,PTSDIO,PTSDII,THIPHL,
     1   UOP,QLLOSH,QLOSHT,DELP
      WRITE(6,1080)
      WRITE(6,1040)WSTOB,TSTORL,RE1SL,DLFS,EQUFB,PFSDIO,PFSDII,THIPCL,
     1   UOPL,QLLOSL,QLOSLT,DELPL
C
C        DETERMINE  WHICH HEAT EXCHANGER TO BEGIN CALCULATIONS
C
      IF(FWIT.GT.0.0) GO TO 200
      CALL  ENPHS(TSSAT,PSTEAM,HSSAT)
      CALL  ENPHS(SHOT,PSTEAM,HSSHT)
      DELH = HSSHT - HSSAT
      QSHT = DELH*WSTEAM
C
C        CALCULATE ACTUAL HEAT TRANSFER AND TOUT-SALT, TIN-STEAM  OF SH
C
      AHTX2=NTUB1(2)*PI*TUBDO(2)*TUBL(2)/12.
     1     +EXTSU(2)*NTUB1(2)*TUBL(2)
      CPSHS=CPS((TSSAT+SHOT)/2.)
      TSOEST = TSTORH - QSHT/(WSTOB*CPSP)
      CPSSH=GINTRP((TSTORH+TSOEST)/2.,TTCP2(1),NTCP2,PSTP,TPCP2(1),
     1   NPCP2,CPL2(1,1),5,JK(1),JK(2),0)
      CALL ENTU(SHOT,TSAO,QSHA,EFSH,XNTUSH,RSH,TSSAT,TSTORH,
     1   CPSHS,CPSSH,WSTEAM,WSTOB,UO(2),AHTX2,NPASS(2),NSHLP(2),NBAF(2),
     2    NCONF(2),3)
      WRITE(6,1110)
      WRITE(6,1120) WSTOB,TSTORH,TSAO,WSTEAM,TSSAT,SHOT
      WRITE(6,1130) UO(2),AHTX2,NPASS(2),NSHLP(2),NBAF(2),NCONF(2),
     1   QSHT,QSHA,EFSH,XNTUSH,RSH
C
      IF(TSAO.LE.TSSAT)     WRITE(6,1100) TSAO,TSSAT
      IF(TSAO.LE.TSSAT)     GO TO 1
C        CALCULATE BOILER HEAT TRANSFER AND STREAM TEMPERATURES
C
      CALL  ENPHW(TSSAT,PSTEAM,HWSAT)
      DELHB = HSSAT - HWSAT
      QB = DELHB*WSTEAM
      AHTX3=NTUB1(3)*PI*TUBDO(3)*TUBL(3)/12.
      CPST = CPS(TSSAT)
      CPSB = GINTRP(TSAO,TTCP2(1),NTCP2,PSTP,TPCP2(1),NPCP2,CPL2(1,1),
     1   5,JK(1),JK(2),0)
      CALL  ENTU(TSTBI,TSABO,QBA,EFB,XNTUB,RB,TSSAT,TSAO,
     1   9999.,CPSB,WSTEAM,WSTOB,UO(3),AHTX3,NPASS(3),NSHLP(3),NBAF(3),
     2   NCONF(3),1)
      WRITE(6,1150)
      WRITE(6,1120) WSTOB,TSAO,TSABO,WSTEAM,TSTBI,TSSAT
      WRITE(6,1130) UO(3),AHTX3,NPASS(3),NSHLP(3),NBAF(3),NCONF(3),
     1   QB,QBA,EFB,XNTUB,RB
C
      IF(TSABO.LE.TSSAT)      WRITE(6,1100) TSABO,TSSAT
      IF(TSABO.LE.TSSAT)      GO TO 1
C        CALCULATE PREHEATER HEAT TRANSFER AND STREAM TEMPERATURES
C
      QPH = WSTOB*CPSB*(TSABO - TSTORL)
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      AHTX4=NTUB1(4)*PI*TUBDO(4)*TUBL(4)/12.
     1     +EXTSU(4)*NTUB1(4)*TUBL(4)
      CALL CPSW(TSTORL,CPWB)
      CPSPH = GINTRP((TSABO+TSTORL)/2.,TTCP2(1),NTCP2,PSTP,TPCP2(1),
     1   NPCP2,CPL2(1,1),5,JK(1),JK(2),0)
      CALL  ENTU(TWPHI,TSAPHO,QPHA,EFPH,XNTUPH,RPH,TSSAT,
     1   TSABO,CPWB,CPSPH,WSTEAM,WSTOB,UO(4),AHTX4,NPASS(4),NSHLP(4),
     2   NBAF(4),NCONF(4),1)
      WRITE(6,1180)
      WRITE(6,1120) WSTOB,TSABO,TSAPHO,WSTEAM,TWPHI,TSSAT
      WRITE(6,1130) UO(4),AHTX4,NPASS(4),NSHLP(4),NBAF(4),NCONF(4),
     1   QPH,QPHA,EFPH,XNTUPH,RPH
C
 200  CONTINUE
C
C        DETERMINE PRESSURE DROP ACROSS HEAT EXCHANGERS 2 THRU 4
C
      TSAAVG = (TSTORH + TSAO)/2.
      RHOSSH = GINTRP(TSAAVG,TTR2(1),NTR2,PSTP,TPR2(1),NPR2,RHOL2(1,1),
     1   7,JK(3),JK(4),0)
      VISSH = GINTRP(TSAAVG,TTV2(1),NTV2,PSTP,TPV2(1),NPV2,VISCL2(1,1),
     1   7,JK(5),JK(6),0)
      CALL HTXDPS(DP2S,RE2S,TUBDO(2),WSTOB,NPASS(2),RHOSSH,BO(2),
     1   NTBCP(2),TUBL(2),VISSH,PITCH(2),NROW(2))
      TSTAVG = (SHOT+TSSAT)/2.
      RHOSTH = DENST(TSTAVG,PSTEAM)
      VISSTH = VISCST(TSTAVG,PSTEAM)
      CALL HTXDPT(DP2T,RE2T,EPSH(2),TUBDI(2),WSTEAM,NPASS(2),RHOSTH,
     1   BI(2),PHI(2), NTUB1(2),TUBL(2),VISSTH)
C
      TSAAVG = (TSAO+TSABO)/2.
      RHOSSH = GINTRP(TSAAVG,TTR2(1),NTR2,PSTP,TPR2(1),NPR2,RHOL2(1,1),
     1   7,JK(3),JK(4),0)
      VISSH = GINTRP(TSAAVG,TTV2(1),NTV2,PSTP,TPV2(1),NPV2,VISCL2(1,1),
     1   7,JK(5),JK(6),0)
      CALL HTXDPT(DP3T,RE3T,EPSH(3),TUBDI(3),WSTOB,NPASS(3),RHOSSH,
     1   BI(3),PHI(3), NTUB1(3),TUBL(3),VISSH)
      RHOSTH = DENST(TSSAT,PSTEAM)
      VISSTH = VISCST(TSSAT,PSTEAM)
      CALL HTXDPS(DP3S,RE3S,TUBDO(3),WSTEAM,NPASS(3),RHOSSH,BO(3),
     1   NTBCP(3),TUBL(3),VISSH,PITCH(3),NROW(3))
C
      TSAAVG = (TSABO+TSAPHO)/2.
      RHOSSH = GINTRP(TSAAVG,TTR2(1),NTR2,PSTP,TPR2(1),NPR2,RHOL2(1,1),
     1   7,JK(3),JK(4),0)
      VISSH = GINTRP(TSAAVG,TTV2(1),NTV2,PSTP,TPV2(1),NPV2,VISCL2(1,1),
     1   7,JK(5),JK(6),0)
      CALL HTXDPS(DP4S,RE4S,TUBDO(4),WSTOB,NPASS(4),RHOSSH,BO(4),
     1   NTBCP(4),TUBL(4),VISSH,PITCH(4),NROW(4))
      CALL HTXDPT(DP4T,RE4T,EPSH(4),TUBDI(4),WSTEAM,NPASS(4),55.0,
     1   BI(4),PHI(4), NTUB1(4),TUBL(4), 1.0)
C
C
C        WRITE HEAT EXCHANGER PRESSURE DROP
C
      WRITE(6,1090)
      WRITE(6,1000)
      WRITE(6,1210)
      WRITE(6,1220) DP1S,RE1S,WKG,TUBDO(1),NPASS(1),NTBCP(1),TUBL(1),
     1     PITCH(1),NROW(1),BO(1)
      WRITE(6,1230)
      WRITE(6,1240) DP1T,RE1T,WLTK,TUBDI(1),EPSH(1),NPASS(1),TUBL(1),
     1     BI(1),PHI(1)
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      WRITE(6,1110)
      WRITE(6,1210)
      WRITE(6,1220) DP2S,RE2S,WSTOB,TUBDO(2),NPASS(2),NTBCP(2),TUBL(2),
     1   PITCH(2),NROW(2),BO(2)
      WRITE(6,1230)
      WRITE(6,1240) DP2T,RE2T,WSTEAM,TUBDI(2),EPSH(2),NPASS(2),TUBL(2),
     1   BI(2),PHI(2)
      WRITE(6,1150)
      WRITE(6,1210)
      WRITE(6,1220) DP3S,RE3S,WSTEAM,TUBDO(3),NPASS(3),NTBCP(3),TUBL(3),
     1   PITCH(3),NROW(3),BO(3)
      WRITE(6,1230)
      WRITE(6,1240) DP3T,RE3T,WSTOB,TUBDI(3),EPSH(3),NPASS(3),TUBL(3),
     1   BI(3),PHI(3)
      WRITE(6,1180)
      WRITE(6,1210)
      WRITE(6,1220) DP4S,RE4S,WSTOB,TUBDO(4),NPASS(4),NTBCP(4),TUBL(4),
     1    PITCH(4),NROW(4),BO(4)
      WRITE(6,1230)
      WRITE(6,1240) DP4T,RE4T,WSTEAM,TUBDI(4),EPSH(4),NPASS(4),TUBL(4),
     1    BI(4),PHI(4)
C
C        WRITE OUT SYSTEM ENERGY BALANCE SUMMARY
C
      DPST =         DP2T + DP3S + DP4T
      DPTT = DP1T + DP2S + DP3T + DP4S
      QTOTTS = QLOSHT + QLOSLT + QLOSH + QLOSL
      WRITE(6,1300) DPST,DPTT,DP1S,QTOTTS,QTANKH,QTANKL
C
C
C        CALCULATE POWER GENERATED
C
      STEFF = GINTRP(SHOT,TTCE(1),NTCE,PSTEAM,TPCE(1),NPCE,CEFF(1,1),
     1   7,JK(11),JK(12),0)
      CALL ENPHW(TWPHI,PSTEAM,HPHIN)
      CALL ENPHS(SHOT,PSTEAM,HSSHT)
      PGEN = STEFF*(HSSHT-HPHIN)*WSTEAM/3413.
      WRITE(6,1310) PGEN,STEFF,SHOT,PSTEAM,WSTEAM,HSSHT,HPHIN,TWPHI
      GO TO 1
 10   STOP
C
C          FORMAT STATEMENTS
C
   15 FORMAT(18A4)
   18 FORMAT(1H1,18X,18A4,3(/,19X,18A4))
 1000 FORMAT(///,10X,"KILN GAS-TRANSFER FLUID HEAT EXCHANGER PERFORMANCE
     1  ")
 1020 FORMAT(1H1,10X,"ENERGY TRANSPORT BETWEEN KILN GAS HEAT EXCHANGER A
     1IND STORAGE VESSEL - ENERGY LOSSES")
 1030 FORMAT(//,15X,"HIGH TEMPERATURE TRANSFER LINE")
 1040 FORMAT(//,20X,"SALT FLOWRATE (LBM/HR)",29X,1PE15.4,
     1        //,20X,"SALT TEMPERATURE (DEG F)",27X,E15.4,
     2        //,20X,"SALT REYNOLDS NO.",34X,E15.4,
     3        //,20X,"LINE LENGTH (FT)",35X,E15.4,
     4        //,20X,"EQUIVALENT LENGTH - FITTINGS/BENDS (FT)",12X,E15.4,
     5        //,20X,"PIPE OUTSIDE DIAMETER (IN)",25X,E15.4,
     6        //,20X,"PIPE INSIDE DIAMETER (IN)",26X,E15.4,
     7        //,20X,"INSULATION THICKNESS (IN)",26X,E15.4,
     8        //,20X,"OVERALL HEAT TRANSFER COEFFICIENT (BTU/HR*FT2*DEGF)
     9"          ,E15.4,
     A        //,20X,"HEAT LOSS PER FT (BTU/HR*FT)",23X,E15.4,
     B        //,20X,"TOTAL LINE HEAT LOSS (BTU/HR)",22X,E15.4,
     C        //,20X,"TOTAL PRESSURE DROP (LBF/INZ)",22X,E15.4)
```

```
1080 FORMAT(//,15X,"LOW TEMPERATURE TRANSFER LINE")
1050 FORMAT(1H1,10X,"STORAGE VESSEL PERFORMANCE")
1060 FORMAT(//,15X,"STORAGE VESSEL VOLUME (FT3)",38X,1PE15.4,
    1          //,15X,"STORAGE VESSEL INSIDE DIAMETER (FT)",30X,E15.4,
    2          //,15X,"STORAGE VESSEL OUTSIDE DIAMETER (FT)",29X,E15.4,
    3          //,15X,"STORAGE VESSEL HEIGHT (FT)",39X,E15.4,
    4         //,15X,"THERMOCLINE VELOCITY DURING CHARGE (FT/HR)",23X,
    5    E15.4,
    6          //,15X,"THERMOCLINE INITIAL HEIGHT (FT)",34X,E15.4,
    7          //,15X,"TIME TO FULLY CHARGE (HR)",40X,E15.4,
    8          //,15X,"STORAGE VESSEL SURFACE AREA (FT2)",32X,E15.4,
    9          //,15X,"OVERALL HEAT TRANSFER COEFFICIENT (BTU/HR*FT2*DEGF)
    A"            ,14X,E15.4,
    B          //,15X,"HEAT LOSS FROM FULLY CHARGED TANK (BTU/HR)",23X,
    C    E15.4,
    D          //,15X,"HEAT LOSS FROM FULLY DISCHARGED TANK (BTU/HR)",20X,
    E    E15.4,
    F          //,15X,"TEMPERATURE DEGRADATION IN FULLY CHARGED TANK (DEG
    GF/HR)",9X,E15.4,
    H          //,15X,"TEMPERATURE DEGRADATION IN FULLY DISCHARGED TANK (D
    IEG F/HR)",6X,E15.4)
1070 FORMAT(1H1,10X,"ENERGY TRANSPORT BETWEEN STORAGE VESSEL AND BOILER
    1 SYSTEM - ENERGY LOSSES")
1090 FORMAT(1H1,10X,"HEAT EXCHANGER PRESSURE DROP CALCULATIONS")
1100 FORMAT(////,"HEAT EXCHANGER PINCH POINT EXCEEDED--CHECK HEAT EXCHA
    1NGER DESIGN"/" OUTLET TEMPERATURE OF SALT (DEGF)",1PE15.4,5X,
    2 "INLET STEAM TEMPERATURE (DEGF)",E15.4)
1110 FORMAT(1H1,10X,"HEAT EXCHANGER NO.2 (SUPERHEATER) PERFORMANCE")
1120 FORMAT(//,15X,"FLOWRATES AND TEMPERATURES",
    1          //,20X,"SALT FLOWRATE (LBM/HR)",10X,1PE15.4,
    2          //,20X,"INLET SALT TEMPERATURE (DEG F)",2X,E15.4,
    3          //,20X,"OUTLET SALT TEMPERATURE (DEG F)",1X,E15.4,
    4          //,20X,"STEAM FLOWRATE (LBM/HR)",9X,E15.4,
    5          //,20X,"INLET STEAM TEMPERATURE (DEG F)",1X,E15.4,
    6          //,20X,"OUTLET STEAM TEMPERATURE (DEG F)",E15.4)
1130 FORMAT(///,15X,"HEAT EXCHANGER PERFORMANCE AND CONFIGURATION",
    1          //,20X,"OVERALL HEAT TRANSFER COEFFICIENT (BTU/HR*FT2*DEGF)
    2"           ,1PE15.4,
    3          //,20X,"HEAT TRANSFER SURFACE AREA (FT2)",19X,E15.4,
    4          //,20X,"NUMBER OF TUBE PASSES",40X,0PI5,
    5          //,20X,"NUMBER OF SHELL PASSES",39X,I5,
    6          //,20X,"NUMBER OF BAFFLES",44X,I5,
    7          //,20X,"CONFIGURATION OPTION NUMBER",34X,I5,
    8          //,20X,"DESIRED HEAT TRANSFER RATE (BTU/HR)",16X,1PE15.4,
    9          //,20X,"ACTUAL HEAT TRANSFER RATE (BTU/HR)",17X,E15.4,
    A          //,20X,"HEAT EXCHANGER EFFECTIVENESS",23X,E15.4,
    B          //,20X,"NUMBER OF TRANSFER UNITS (NTU)",21X,E15.4,
    C          //,20X,"RATIO OF CAPACITY FLOWRATES (CMIN/CMAX)",12X,
    D    1PE15.4)
1150 FORMAT(1H1,10X,"HEAT EXCHANGER NO.3 (BOILER) PERFORMANCE")
1180 FORMAT(1H1,10X,"HEAT EXCHANGER NO.4 (PREHEATER) PERFORMANCE")
1210 FORMAT(//,15X,"SHELL SIDE PERFORMANCE")
1230 FORMAT(//,15X,"TUBE SIDE PERFORMANCE")
1220 FORMAT(//,20X,"PRESSURE DROP (LBF/IN2)",3X,1PE15.4,
    1          //,20X,"REYNOLDS NUMBER",11X,E15.4,
    2          //,20X,"FLUID FLOW RATE (LBM/HR)",2X,E15.4,
    3          //,20X,"TUBE OUTSIDE DIAMETER (IN)",E15.4,
    4          //,20X,"TUBE PASSES",25X,0PI5,
    5          //,20X,"NUMBER OF CENTER PLANE TUBES",8X,I5,
    6          //,20X,"TUBE LENGTH (FT)",10X,1PE15.4,
    7          //,20X,"TUBE PITCH (IN)",11X,1PE15.4,
    8         //,20X,"ROWS OF TUBES FOR SHELL FLUID FLOW",2X,I5,
    9         //,20X,"FLOW CORRECTION FACTOR, BO",E15.4)
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 1240 FORMAT(//,20X,"PRESSURE DROP (LBF/IN2)",4X,1PE15.4,
     1        //,20X,"REYNOLDS NUMBER",12X,E15.4,
     2        //,20X,"FLUID FLOW RATE (LBM/HR)",3X,E15.4,
     3        //,20X,"TUBE INSIDE DIAMETER (IN)",2X,E15.4,
     4        //,20X,"TUBE SURFACE ROUGHNESS (IN)",E15.4,
     5        //,20X,"TUBE PASSES",26X,0PI5,
     6        //,20X,"TUBE LENGTH (FT)",11X,1PE15.4,
     7        //,20X,"FLOW CORRECTION FACTOR, BI",1X,E15.4,
     8        //,20X,"FLOW CORRECTION FACTOR, PHI",E15.4)
 1300 FORMAT(1H1,10X,"TOTAL SYSTEM PRESSURE DROP AND HEAT LOSSES",
     1         //,15X,"BOILER SYSTEM STEAM PRESSURE DROP (PSIA)",3X,
     2       1PE15.4,
     3         //,15X,"SALT LOOP PRESSURE DROP (PSIA)",13X,E15.4,
     4         //,15X,"KILN GAS PRESSURE DROP ON SHELL SIDE (PSIA)",
     5         E15.4,
     6         //,15X,"ENERGY TRANSPORT HEAT LOSS (BTU/HR)",8X,E15.4,
     7         //,15X,"ENERGY LOSS FROM CHARGED TANK (BTU/HR)",5X,E15.4,
     8         //,15X,"ENERGY LOSS FROM DISCHARGED TANK (BTU/HR)",2X,
     9         E15.4)
 1310 FORMAT(1H1,10X,"POWER GENERATION CALCULATIONS",
     1         //,15X"ELECTRICAL POWER GENERATED (KILOWATTS)"5X,
     2       1PE15.4,
     3         //,15X,"POWER CYCLE EFFICIENCY (ELECTRICAL/THERMAL)",
     4         E15.4,
     5         //,15X,"TURBINE THROTTLE TEMPERATURE (DEG F)",7X,E15.4,
     6         //,15X,"TURBINE THROTTLE PRESSURE (PSIA)",11X,E15.4,
     7         //,15X,"STEAM FLOWRATE (LBM/HR)",20X,E15.4,
     8         //,15X,"STEAM SUPERHEAT ENTHALPY (BTU/LBM)",9X,E15.4
     9         //,15X,"FEEDWATER ENTHALPY (BTU/LBM)",15X,E15.4,
     A         //,15X,"FEEDWATER TEMPERATURE (DEG F)",14X,E15.4)
 1320 FORMAT(1H1)
      END
*DECK,DENST
      FUNCTION  DENST(TEMP,PRES)
C
C        DETERMINES THE SPECIFIC DENSITY OF STEAM
C            BASED ON FORMULA OF KEYES, SMITH, AND GERRY
      TT =(TEMP + 459.)/1.8
      PP =  PRES/14.696
      TAU = 1.0/TT
      BO = 1.89 -2641.62*TAU*10.**(80870.*TAU**2)
      G1T = 82.546*TAU - 1.6246E+05*TAU**2.
      G2T = 0.21828 - 1.2697E+05*TAU**2.
      G3T = 3.635E-04 - 6.768E+64*TAU**24.
      BETA = BO + BO*BO*G1T*TAU*PP + BO**4*G2T*TAU**3*PP**3 - BO**13*
     1   G3T*TAU**12*PP**12
      VOL = 4.55504*TT/PP + BETA
      DENST = 62.335/VOL
      RETURN
      END
*DECK,VISCT
      FUNCTION VISCST(TEMP,PRES)
C
C
C       DETERMINES THE VISCOSITY OF STEAM(CENTIPOISE)
C            BASED ON FORMULA OF KEENAN AND KAYES
C
      TT = (TEMP + 459.)/1.8
      PP = 0.07031*PRES
      TAU = 1.0/TT
      VISCO = 1.501E-05*TT**0.5/(1.0 + 446.8*TAU)
      VISC = VISCO +1.0E-04*(TAU*(6.36-2.31E-03*10**(1340.*TAU))*PP +
     1   3.89E-02*10**(-5.476E-03*TT)*PP*PP)
```

```
      VISCST= VISC/100.
      RETURN
      END
*DECK,DEW
      FUNCTION DEW(TEMP)
C
C
C        DETERMINES THE DENSITY OF WATER
C             BASED ON FORMULA BY SMITH AND KEYES
C
      TT =(TEMP - 32)/1.8
      TC = 374.11
      VC = 3.1975
      TD = TC - TT
      VS = (VC-0.3151548*TD**(1./3.)-1.203374E-03*TD+7.48908E-13*TD**4)
     1   /(1.0+0.1342489*TD**(1./3.)-3.946263E-03*TD)
      DEW = 62.335/VS
      RETURN
      END
*DECK,ENPHW
      SUBROUTINE ENPHW(T, P, XH)
      IF(T.GT.650.0)  GO TO 10
      IF(T.LT. 32.0)  GO TO 11
      IF(T.GT.375.0)  GO TO 13
C  CURVE FIT FOR ENTHALPY OF SATURATED WATER BETWEEN 32DEGF AND 400 DEGF
      A0 = -3.22199E+01
      A1 =  1.00988E+00
      A2 = -1.09370E-04
      A3 =  3.22658E-07
      XH = A0+A1*T**1+A2*T**2+A3*T**3
      RETURN
   13 CONTINUE
C  CURVE FIT FOR ENTHALPY OF SATURATED WATER BETWEEN 350DEGF AND 650DEGF
      B0 =  5.80426E+02
      B1 = -7.33017E+00
      B2 =  4.70552E-02
      B3 = -1.41586E-04
      B4 =  2.39875E-07
      B5 = -2.16585E-10
      B6 =  8.21180E-14
      XH = B0+B1*T+B2*T**2+B3*T**3+B4*T**4+B5*T**5+B6*T**6
      RETURN
   10 WRITE(6,1)
    1 FORMAT(32H WATER TEMPERATURE EXCEEDS 650 F)
      GO TO 12
   11 WRITE(6,2)
    2 FORMAT(33H WATER TEMPERATURE LESS THAN 32 F)
   12 CONTINUE
      END
*DECK,ENPHS
      SUBROUTINE ENPHS(TEMP,P, HTOTAL)
      T =(TEMP - 32.0)/1.8
      TAU= 1./(273.16 + T)
      P1= P/14.696
      B0 = 1.89-2641.62*TAU*10.0**(80870.0 * TAU**2)
      G1 =82.546*TAU - 1.6246E5*TAU**2
      G2 = 0.21828 -1.2697E5*TAU**2
      G3 = 3.635E -4 - 6.768E64*TAU** 24
      SY1=B0**2 *G1 * TAU
      SY3=B0**4 *G2 * TAU**3
      SY12=B0**13*G3* TAU**12
      BOP = -2641.62*10.**(80870*TAU**2)*(2.0*80870.0*TAU**2*ALOG(10.)+
     11.0)
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      G1P = 82.546 -2*1.624E5*TAU
      G2P = -1.2617E5 * 2.0* TAU
      G3P = -6.768E64 *24.0* TAU**23
      SY1P =2.0*BO*BOP*G1*TAU+BO**2*G1P*TAU+BO**2*G1
      SY3P =4.0*BO**3*BOP*G2*TAU**3+BO**4*G2P*TAU**3+BO**4*G2*3.0*TAU**2
      SY12P=13.*BO**12*BOP*G3*TAU**12+BO**13*G3P*TAU**12+BO**13*G3*12.*
     1TAU**11.0
      F = BO +TAU* BOP
      F1= SY1 + TAU* SY1P
      F3= SY3 + TAU* SY3P
      F12=SY12 + TAU* SY12P
      XH =F*P1 + F1/2.0 *P1**2.+F3/4.*P1**4 +F12/13. *P1**13
      T1 =1/TAU
      YH = 1.4720*(T1-273.16)+7.5566E-4/2.*(T1**2-273.16**2)+47.836*
     1ALOG(T1/273.16) + 2502.36
      HTOTAL = XH*.0435578+ YH * .42993
      RETURN
      END
*DECK,FRIC
      FUNCTION FRIC(RE,EPS,DIA)
      A =(2.457*ALOG(1./((7./RE)**0.9+0.27*EPS/DIA)))**16.
      B = (37530./RE)**16
      FRIC =((8.0/RE)**12.+(A+B)**(-1.5))**0.08333
      RETURN
      END
*DECK,UOVER
      FUNCTION UOVER(DI,DO,DOINS,HI,HO,TKP,TKI,FFI,FFO)
C
C         CALCULATE EACH RESISTANCE BASED  ON OUTSIDE DIAMETER
C
      DOO = DOINS
      IF(DOINS.LE.DO) DOO = DO
      RDI = DOO/(DI*HI)
      RDO = DOO*ALOG(DO/DI)/(24.*TKP)
      IF(DOINS.GT.DO)   RDOI = DOO*ALOG(DOINS/DO)/(24.*TKI)
C
C         CALCULATE OVERALL HEAT TRANSFER COEFFICIENT
C
      UOVER=1.0/(RDI+FFI*DOO/DI+RDO+1.0/HO+FFO)
      IF(DOINS.GT.DO) UOVER= 1.0/(RDI+FFI*DOO/DI+RDO+RDOI+1.0/HO+FFO)
      RETURN
      END
*DECK,HTXDPT
      SUBROUTINE HTXDPT(DPT,RE,EPS,DI,WDOTT,NTPASS,RHOT,BI,PHII,NTUBE,
     1     XLTUBE,VISC)
      DATA GC/32.174/, PI/3.14159/
C
C        CALCULATE TOTAL FLOW AREA, MASS FLUX, AND PRESSURE DROP
C
      AREA = PI*DI*DI/576.*NTUBE
      GFLOW = WDOTT/AREA
      RE =  GFLOW*DI/VISC*0.03445
      FF = FRIC(RE,EPS,DI/12.)
      DPT = FF*GFLOW**2*XLTUBE*BI*NTPASS/(540000.*GC*RHOT*DI*PHII)
      RETURN
      END
*DECK,HTXDPS
      SUBROUTINE HTXDPS(DPS,RE,DO,WDOTS,NTPASS,RHOS,BO,NTUBCP,XLTUBE,
     1  VISC,PITCH,NROW)
C
C         SUBROUTINE DETERMINES THE PRESSURE DROP ON SHELL SIDE OF
C                        HEAT EXCHANGERS
C
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```
      DATA GC/32.174/, PI/3.14159/
      BAFL = XLTUBE/NTPASS
      FAREA =  NTUBCP*(PITCH-DO)*BAFL/12.
      GFLOW =  WDOTS/FAREA
      RE = GFLOW*DO/VISC*0.03445
      FF = 0.23 + 0.11*(PITCH/DO-1.0)**(-1.08)*RE**(-0.15)
      DPS = NTPASS*FF*NROW*GFLOW**2/(GC*RHOS*6.48E06)
     1     *BO
      RETURN
      END
*DECK,CPS
      FUNCTION CPS(TEMP)
      TW =(TEMP+ 459.7)/1.8
      CPS= 0.4031 + 0.12767*TW*1.E-3 + 0.01572*TW*TW*1.E-6
      RETURN
      END
*DECK,ENTU
      SUBROUTINE ENTU(T3,T4,Q,E,XNTU,R,T1,T2,CPC,CPH,WC,WH,UO,AO,NTP,
     1    NSP,NBAFF,OPTION,NTOP)
      INTEGER OPTION
C
C         SUBROUTINE CALCULATES THE HEAT EXCHANGER EFFECTIVENESS OF
C              VARIOUS CONFIGURATIONS - DETERMINES THE EXIT TEMPERATURE
C              OF HEAT EXCHANGER KNOWING OTHER 3 TEMPERATURES OF STREAMS
C
C         OPTIONS:
C                     1 - COUNTERCURRENT OR COUNTERFLOW
C                     2 - PARALLEL FLOW
C                     3 - CROSS FLOW - HOT UNMIXED
C                     4 - CROSS FLOW - COLD UNMIXED
C                     5 - CROSS FLOW - BOTH UNMIXED (NOT AVAILABLE)
C                     6 - 1-2(,4,6,8,ETC) PARALLEL-COUNTER FLOW - SHELL MX
C                     7 - MULTIPASS - OVERALL COUNTERFLOW
C                     8 - ONE SHELL PASS, ONE TUBE PASS, BAFFLED CROSSFLOW
C         EQUATIONS OBTAINED FROM {COMPACT HEAT EXCHANGERS{, KAYS AND
C              LONDON, 1958
C                          PROGRAMMER: D.G. BESHORE(MMC,D/0482)
      KPASS = 1
      CH = WH*CPH
      CC = WC*CPC
      CMAX = AMAX1(CH,CC)
      CMIN = AMIN1(CH,CC)
      R = CMIN/CMAX
      XNTU = UO*AO/CMIN
      GO TO (10,20,30,40,50,60,70,80,90) OPTION
C
C         COUNTERFLOW  HEAT  EXCHANGER
C
   10 E = (1.0 - EXP(-XNTU*(1.0-R)))/(1.0-R*EXP(-XNTU*(1.0-R)))
      GO TO 800
C
C         PARALLEL FLOW HEAT EXCHANGER
C
   20 E = (1.0-EXP(-XNTU*(1.0+R)))/(1.0+R)
      GO TO 800
C
C         CROSSFLOW - HOT STREAM UNMIXED
C
   30 IF((CMAX-CC).LE.0.0001)  GO TO 35
   31 E = 1.0-EXP((EXP(-XNTU*R)-1.0)/R)
      GO TO 800
   35 E = (1.0-EXP((EXP(-XNTU)-1.0)*R))/R
      GO TO 800
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C
C         CROSSFLOW - COLD STREAM UNMIXED
C
   40 IF((CMAX-CH).LE.0.0001) GO TO 35
      GO TO 31
C
C         CROSSFLOW - BOTH UNMIXED
C
   50 WRITE(6,100)
  100  FORMAT("0 OPTION 5 NOT AVAILABLE")
      CALL EXIT
C
C         1.- 2(,4,6,8,ETC) PARALLEL COUNTERFLOW HEAT EXCHANGER
C
   60 GAMMA = XNTU*SQRT(1.0+R**2)
      E = 2.0/(1.0+R+SQRT(1.0+R**2)*(1.0+EXP(-GAMMA))/(1.0-EXP(-GAMMA)))
      GO TO 800
C
C
C         MULTIPASS - OVERALL COUNTERFLOW HEAT EXCHANGER
C
  800 IF(OPTION.EQ.7.AND.KPASS.EQ.2) GO TO 200
      IF(OPTION.EQ.8.AND.KPASS.EQ.2) GO TO 200
      IF(OPTION.EQ.9.AND.KPASS.EQ.2) GO TO 200
      GO TO 500
C
C         MULTISHELL PASS - EVEN NUMBERED TUBE PASS HEAT EXCHANGER
C
   70 XNTU = XNTU/NSP
      NTO = NSP
      KPASS = 2
      GO TO 60
C
C        ONE SHELL PASS - ONE TUBE PASS BAFFLED HEAT EXCHANGER
C
   80 IF(KPASS.EQ.2) GO TO 200
      XNTU = XNTU/NBAFF
      NTO = NBAFF
      KPASS = 2
      GO TO 40
C
C         DETERMINE EFFECTIVENESS OF MULTIPASS HEAT EXCHANGERS
C
   90 RETURN
  200 EFF = E
      IF(R.GT.0.98)  E = EFF*NTO/(1.0+(NTO-1.0)*EFF)
      IF(R.LE.0.98)  EPP =((1.0-EFF*R)/(1.0-EFF))**NTO
      IF(R.LE.0.98)  E = (EPP-1.0)/(EPP-R)
C
C     CALCULATE EXIT TEMPERATURE OF FLUID STREAM
C
  500 CONTINUE
      GO TO (510,520,530)      NTOP
  510 T3 =(CC*T1 - E*CMIN*T2)/(CC - E*CMIN)
      Q  = CC*(T1 - T3)
      T4 = T2 - Q/CH
      GO TO 600
  520 T4 = (E*CMIN*T1 - CH*T2)/(E*CMIN - CH)
      Q  = CH*(T4 - T2)
      T3 = T1 + Q/CC
      GO TO 600
 530  CONTINUE
      T3=T1+E*CMIN*(T2-T1)/CC
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      Q =CMIN*(T2-T1)*E
      T4=T2+E*CMIN*(T1-T2)/CH
  600 RETURN
      END
*DECK,CPSW
      SUBROUTINE CPSW(T,CP)
      IF(T.GT.650.0)   GO TO 10
      IF(T.LT.32.0)    GO TO 11
      IF(T.GT.375.0)     GO TO 13
      A0 = -32.2199
      A1 = 1.00988
      A2 = -1.09370E-04
      A3 = 3.22658 E-07
      CP = A1 +A2*2.0*T + A3*3.0*T**2
      RETURN
 13   CONTINUE
      B0 =-6.41287E+01
      B1 = 1.27331
      B2 = -8.39448E-04
      B3 = 1.00122E-06
      B4 = 0.0
      B5 = 0.0
      B6 = 0.0
      CP = B1+B2*2.0*T+B3*3.0*T**2+B4*4.0*T**3
     1       +B5*5.0*T**4+B6*6.0*T**5
      RETURN
 10   WRITE(6,1)
 1    FORMAT(32H WATER TEMPERATURE EXCEEDS 650 F     )
      GO TO 12
 11   WRITE(6,2)
 2    FORMAT(33H WATER TEMPERATURE LESS THAN 32 F    )
 12   CONTINUE
      END
*DECK,LOCFAC
      SUBROUTINE  LOCFAC(JK, X,TX,NX, JX,FX)
C       IF JK EQ. 1, CHECKS ORDER OF TX ARRAY (NX ITEMS) FOR
C         CONSISTANTLY INCREASING OR DECREASING VALUES.
C       FINDS LOCATION OF FIRST (OR ONLY) ARRAY ITEM FOR SCALING
C         LOCATION OF X FROM TX(JX)
C       CALCULATES SCALING FACTOR FX = (X-TX(JX)) / (TX(JX+1)-TX(JX))
      DIMENSION  TX(1)
      JX = 1
      FX = 0.
      IF(NX.LE.1)  GO TO 200
      S = 1.
      IF(TX(1).GT.TX(NX))  S = -1.
      XR2 = ABS(TX(NX)-TX(1))*0.5
      IF(JK.NE.1)  GO TO 90
      JK = 0
      IF(S.GT.0.)  GO TO 30
        DO 20 I=2,NX
        IF(TX(I).GT.TX(I-1))  GO TO 50
   20   CONTINUE
      GO TO 90
   30   DO 40 I=2,NX
        IF(TX(I).LT.TX(I-1))  GO TO 50
   40   CONTINUE
      GO TO 90
   50 WRITE(6,60)
   60 FORMAT(1H1 41X 27HE R R O R   I N   T A B L E )
   70  WRITE(6,80)  X,(TX(I),I=1,NX)
   80   FORMAT(1H0 41X 27HREFER TO SUBROUTINE  LOCFAC  //
    1           5X 3HX = 1PE15.4 / 4X 4HTX = 6E15.4 / (8X 6E15.4) )
```

```
C  ************       NO SYSTEM SUBROUTINE   ERRTRA          *******
C     CALL ERRTRA
C  *************************                             ***********
        CALL  EXIT
        STOP
   90 NX1 = 2
      IF(NX.LE.20)  GO TO 110
        DO 100 I=10,NX,10
        JX = I
        IF((TX(I)-X)*S) 100,200,110
  100   NX1 = I + 1
  110     DO 120 I=NX1,NX
          JX = I
          IF((TX(I)-X)*S) 120,200,130
  120     CONTINUE
  130 IF(JX.GT.1)  JX = JX-1
      FX = (X-TX(JX)) / (TX(JX+1)-TX(JX))
        IF(X.LT.AMIN1(TX(1),TX(NX))-XR2)  GO TO 150
        IF(X.GT.AMAX1(TX(1),TX(NX))+XR2)  GO TO 150
          GO TO 200
  150 WRITE(6,160)
  160 FORMAT(1H1 22X 64HE R R O R  -  EXTRAPOLATION OF TABLE IS BEYOND R
     1EASONABLE LIMITS )
      GO TO 70
  200     RETURN
      END
*DECK,GINTRP
      FUNCTION GINTRP(X1,T1,N1,X2,T2,N2,YT,N,JK1,JK2,L)
C
C
C       GENERAL INTERPOLATION ROUTINE --- INTERPOLATES ONE AND
C            TWO DIMENSIONAL ARRAYS AND BYPASSES PREVIOUSLY SCALED
C            INDEPENDENT VARIABLES
C
C            PROGRAMMER: D G BESHORE
C
      DIMENSION T1(1),T2(1),YT(1)
C       L  IS  BYPASS  INDICATOR
      IF(L.EQ.1)  GO TO 10
      CALL LOCFAC(JK1,X1,T1,N1,I1,F1)
      CALL LOCFAC(JK2,X2,T2,N2,I2,F2)
         F3 = 1.-F2
        I11 = (I2-1)*N + I1
        I21 = I11 + 1
        I12 = I11 + N
        I22 = I12 + 1
        D1 = 1.
        D2 = 1.
      IF(I1.GT.N .OR. I2.GT.1000)  GO TO 30
   10 IF(F1.LT.1.E-50) F1 = 0.
      IF(F1.EQ.0.)  GO TO 20
        D1 = YT(I21)-YT(I11)
      IF(F2.EQ.0) GO TO 20
        D2 = YT(I22)-YT(I12)
   20 GINTRP = YT(I11) + F1*D1
      IF(F2.LT.1.E-50) F2=0.
      IF(F2.NE.0.)  GINTRP = F3*GINTRP + F2*(YT(I12)+F1*D2)
      RETURN
   30 WRITE(6,40) I1,N,I2,X1,X2
   40 FORMAT(10X," ERROR DETECTED IN GINTRP.....I1 =",I3,3X," N =",I3,
     1  3X," I2 =",I5,3X," X1 =",E12.6,3X," X2 =",E12.6)
C   *********                            **********
C     CALL ERRTRA

C     ********        REMOVE CALL TO SYSTEM SUBROUTINE ERRTRA
        CALL  EXIT
        STOP
      END
```

REFERENCES

B-1 W. M. Kays and A. L. London: *Compact Heat Exchangers*. McGraw-Hill Book Company, New York, N.Y., 1964.

B-2 M. S. Peters and K. D. Timmerhaus: *Plant Design and Economics for Chemical Engineers*. McGraw-Hill Book Company, New York, N.Y., 1968.