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ENERGY CONVERSION ALTERNATIVES STUDY (ECAS)

CONCEPTUAL DESIGN AND IMPLEMENTATION ASSESSMENT OF A UTILITY STEAM PLANT WITH CONVENTIONAL FURNACE AND WET LIME STACK GAS SCRUBBERS

Dale H. Brown
Corporate Research and Development
General Electric Company
Schenectady, New York 12301

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FOREWORD

The technical work described in this report is part of the Energy Conversion Alternatives Study (ECAS), a cooperative effort of the Energy Research and Development Administration, the National Science Foundation and the National Aeronautics and Space Administration. This effort, performed under NASA Contract NAS3-19406, was sponsored by the Tennessee Valley Authority, under their activity TV-41967A and under Interagency Agreement EP-1-AG-D5-0721 with the Environmental Protection Agency.

The evaluation reported here in was undertaken on a basis consistent with Phase II of the Energy Conversion Alternatives Study. However, the various aspects of this evaluation are completely and independently presented. The basis for this study is presented in an appendix.

In addition to the principal author listed, members of the technical staffs of the following organizations developed information for this study:

General Electric Company

Electric Utility Systems Engineering Department
Corporate Research and Development
Large Steam Turbine-Generator Department
Technical Resources Planning, Turbine Operations
Technical Resources Staff

Bechtel Corporation

Foster Wheeler Energy Corporation

A summary of ECAS reports is as follows:

Energy Conversion Alternatives Study (ECAS), General Electric Phase II Final Report, NASA CR-134949, Westinghouse Phase II Final Report (NASA CR-134942); Burns and Roe/United Technologies Phase II Final Report (NASA CR-134955); and NASA Report (NASA TM X-73515).

SUMMARY

Conceptual Design and Implementation Assessment of a Utility Steam Plant with Conventional Furnace and Wet Lime Stack Gas Scrubbers

A conventional steam power plant with a radiant furnace and a wet lime stack gas scrubber system was evaluated to determine its potential use for baseload power generation. A conceptual design was established, including major components, plot plans, and power plant arrangement drawings. The wet lime scrubbing system was sized to remove 90 percent of the sulfur from the stack gas when coal having up to 4.5 percent sulfur was fired. The reheat of the scrubbed gas at 125 F was accomplished by adding steam-heated air; in a base case study, the stack gas is reheated to 250 F and in an alternate case the stack gas is reheated to 175 F.

The evaluations were made using the same groundrules and methodology as those followed for the Atmospheric Fluidized Bed (AFB) and the Pressurized Fluidized Bed (PFB) advanced steam power plants and other advanced energy conversion systems in Reference 1. A comparison of the results from this study and from Reference 1 for advanced steam power plants (all plants meet environmental emission targets) is presented in Table A.

Table A

SUMMARY OF PERFORMANCE AND COSTS FOR FOUR STEAM POWER PLANTS

	Conventional Furnace	Conventional Furnace	Atmospheric Fluidized Bed	Pressurized Fluidized Bed
Stack Temperature	250 F	175 F	250 F	300 F
Total Capital Cost, $/kWe	835	771	632	723
Cost of Electricity,* mills/kWh	39.8	37.0	31.7	34.1
Overall Efficiency, %	31.8	33.8	35.8	39.2

*At an assumed capacity factor of 65%

All elements of the conventional plants are state-of-the-art, whereas the AFB and PFB plants incorporate major components that are not state-of-the-art. The use of steam to provide stack gas reheat for the conventional plants reduced the net plant electrical output and overall efficiency and increased plant cost per kilowatt of net output relative to conventional plants without scrubbers.

The total capital cost is based on estimated mid-1975 plant costs plus escalation and interest over a five and one-half year construction period beginning in 1975. The cost of electricity was based on coal at $1 per million Btu, an 18% per year fixed charge rate on capital costs, and included estimates of operating and maintenance costs.

1. Corman, J. C., et al., Energy Conversion Alternatives Study (ECAS), General Electric Phase II Final Report, NASA CR-134949, 3 vols., NASA Lewis Research Center Contract NAS3-19406, GE Corporate Research and Development, Schenectady, N. Y., December 1976.

A qualitative implementation assessment was made for the conventional steam power plants against a set of implementation factors for application in electric power generation. These factors were selected as representative of both the tangible and the intangible considerations that influence a power plant selection by an electric utility. The rating was performed by a panel of suppliers of equipment and services to the end user, the Nation's utilities, but not by utility representatives. No attempt was made to weight the factors nor to develop an index of their composite effect on the competitiveness of alternate energy conversion systems.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES (Cont'd)

LIST OF TABLES (Cont'd)

Section 1

INTRODUCTION

A steam power plant with wet gas scrubber to reduce stack gas emissions has characteristics distinctly different from the numerous conventional coal-burning steam power plants that cannot meet today's emission standards except by burning low-sulfur coal or converting to oil firing. There will be a direct competition between plants with conventional furnaces with stack gas cleanup, and alternatives such as fluidized bed furnaces that capture sulfur products during the combustion process. In this study a wet lime scrubber was specified for use in the study of a conventional steam plant with stack gas scrubber.

A simplified cycle schematic presented as Figure 1 shows the major pieces of equipment. The coal and air are fired with staged combustion of the pulverized coal to limit generation of thermal NO_x products. The boiler, steam turbine, condenser, and cooling towers are all proven conventional elements. Gas leaves the unit at 300 F (422 K) after passing through electrostatic precipitators that reduce the burden of fly ash in the flue gas. The gas enters the scrubber and is quenched to 125 F (325 K) with lime slurry sprays. Sulfur is removed as calcium sulfite and calcium sulfate, which precipitates out in the sludge pond. Lime is continually replenished, using an on-site calciner for limestone.

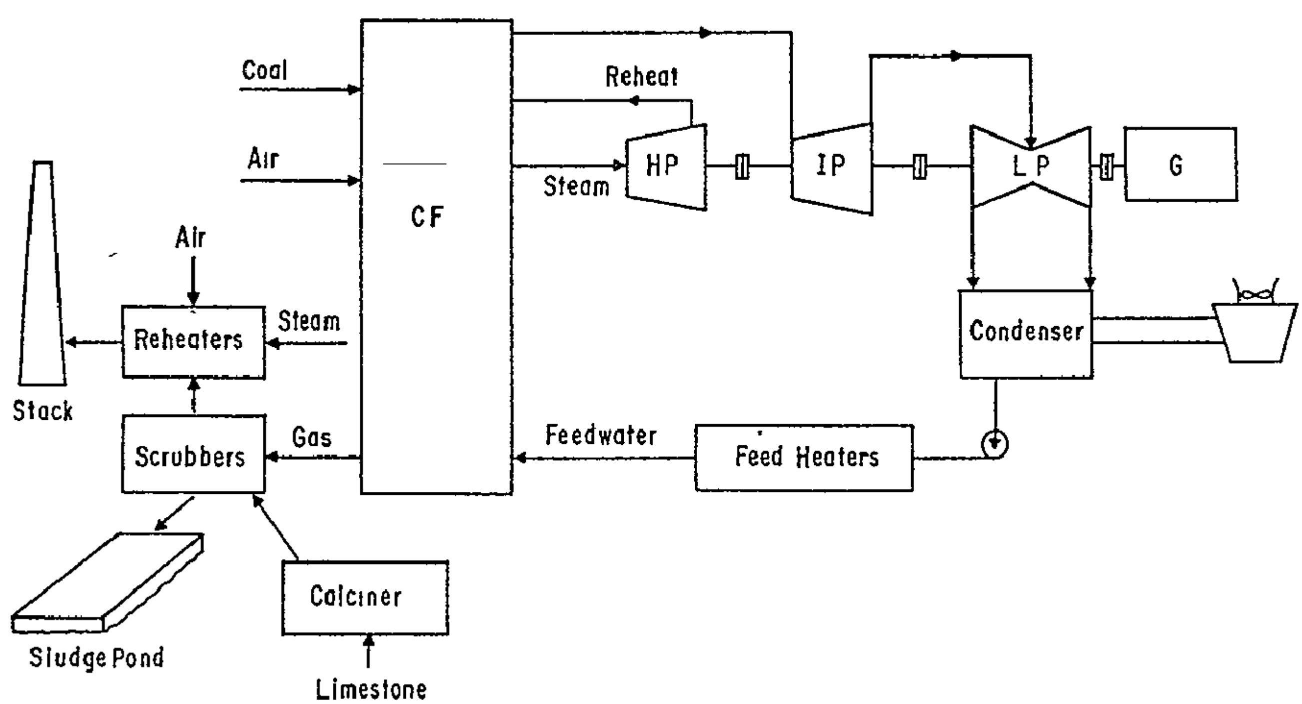


Figure 1. Conventional Steam Plant—with Wet Gas Scrubbing

The water-vapor-saturated flue gas at 125 F (325 K) is next reheated to the final stack temperature. In this investigation two stack temperatures were studied: 250 F (394 K) and 175 F (353 K). The means of raising the temperature is a blending of the flue gas with a large quantity of air that has been preheated above that temperature by steam extracted from the steam turbine cycle.

The system parameters are presented in Table 1. The Illinois No. 6 coal contains 3.9 percent sulfur. Eighty-three percent of the sulfur must be captured to meet the environmental emission limit of 1.2 pounds of sulfur dioxide per million Btu of fuel heat release (0.52 kg/GJ.) However, the wet scrubbers were specified to capture 90 percent of the flue gas sulfur burden when 4.5 percent sulfur was present in the coal, to provide margin in the design to enable burning of coals with sulfur content higher than 3.9 percent. With the specified margin of performance capability, the plant operation is assured of meeting current standards for flue gas emissions. The consumption of lime is minimized by the intimate mixing in the wet scrubbers. In addition the recirculating system provides for reuse of lime in solution in the clarified water recirculated from the sludge pond.

Table 1

SYSTEM PARAMETERS
CONVENTIONAL STEAM—WET GAS SCRUBBERS

PARAMETER	VALUE OR DESCRIPTION
FUEL	
ILLINOIS NO. 6	10788 Btu/LB HIGHER HEATING VALUE 1 $/MBtu
LIMESTONE	FOR SULFUR CAPTURE 0 16 LB/LB COAL
FURNACE	
RADIANT SECTION	PULVERIZED COAL FIRED
CONVECTION SECTION	SUPERHEAT AND REHEAT
PRIME CYCLE — STEAM PLANT	
WORKING FLUID	STEAM
TURBINE INLET	3500 PSI, 1000 F
REHEAT	659 PSI, 1000 F
CONDENSER	2 3" Hga, 106 F
FINAL FEEDWATER	4378 PSI 505 F
HEAT REJECTION	
WET MECHANICAL DRAFT COOLING TOWERS	20 CELLS
STACK GAS TEMPERATURE	250 F

The steam cycle uses conventional conditions for a supercritical reheat unit with seven feedwater heaters. The large extraction of steam at the turbine crossover pressure for stack gas reheat approaches the limit set for conventional practice. The condenser back pressure was chosen to optimize the total cost of electricity with respect to turbine output and cost, heat rejection system cost, and auxiliary power consumption.

The stack gas temperature was set at 250 F (394 K) in conformance with conventional steam power plant practice. The influence of stack gas temperature, however, is far greater than normal for this steam plant configuration. Because corrosive component dew points in the flue gas are at or below 125 F (325 K) as a result of the scrubbing process, a lower stack temperature was deemed to be of interest. A subsequent evaluation was therefore made for 175 F (353 K) stack temperature in addition to 250 F (394 K). Details of this case will be presented after a complete appraisal of the 250 F (394 K) stack base case.

Section 2

CYCLE DESCRIPTION

A more detailed plant schematic for the 250 F (394 K) stack temperature case is presented in Figure 2. State points and stream flows are shown wherein the enthalpy values are referenced to 32 F (273 K) water for steam and water and to an 80 F (300 K) zero reference for air, combustion gases, and solids. The advanced feature of this power system is the use of wet flue gas scrubbers with a conventional boiler to generate steam from high-sulfur coal for a conventional steam turbine cycle with a single reheat of the steam.

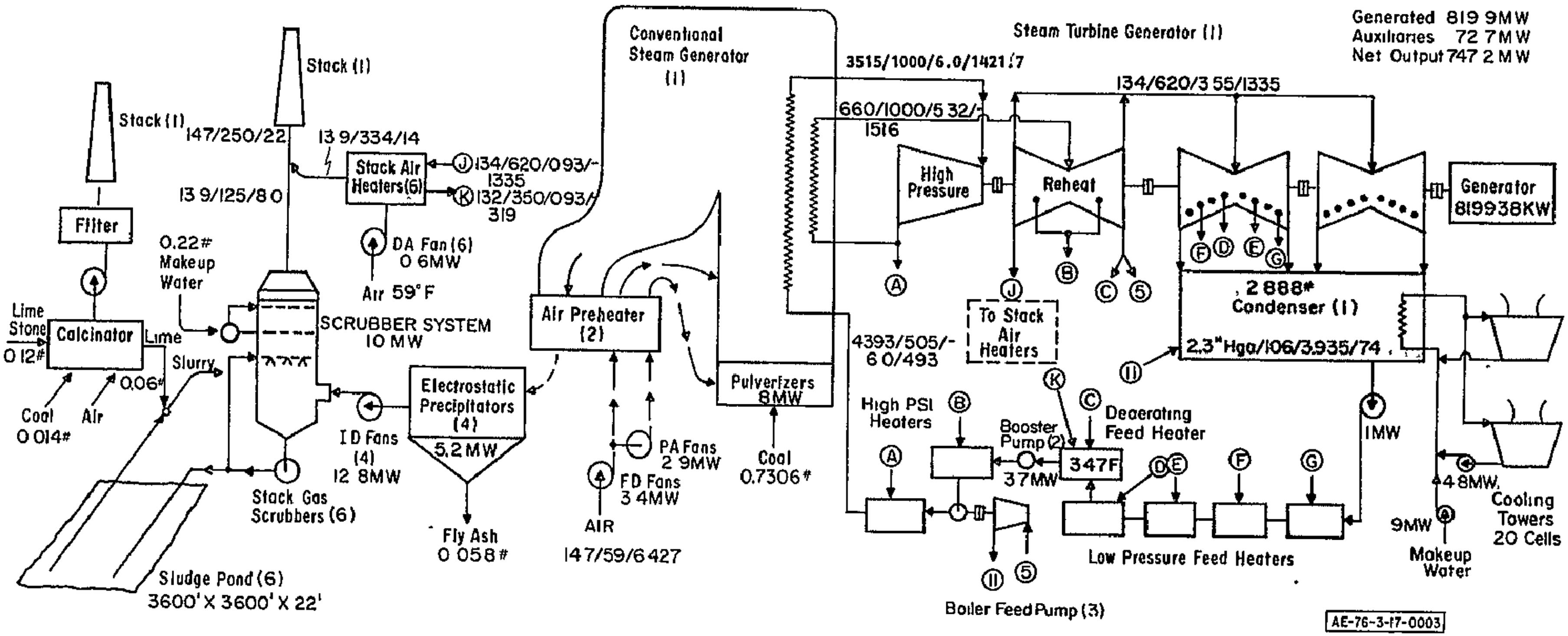
STEAM TURBINE-GENERATOR CYCLE

The steam turbine is contained in four shells connected in tandem with a single 820 MW generator. The low pressure stages have four parallel flows exhausting downward into a common condenser. The condenser coolant is water recirculated in a closed circuit to evaporative cooling towers. The regenerative feedwater heating cycle has four low-pressure feedwater heaters, a deaerating feedwater heater, and two high-pressure feedwater heaters. Part of the steam exhausted from the high-pressure turbine is used in feedwater heating, while the rest is returned to the boiler to be reheated to 1000 F (811 K). Part of the steam from the reheat turbine exhaust is used for driving the boiler feedpump. The exhausts from the three drive turbines are routed to the main condenser. All other pump drives are electric motor driven and appear in the detailed account of auxiliary losses. The boiler feedpump and its drive are an integral part of the steam cycle and are fully accounted for in the heat balance for the steam turbine-generator.

The final feedwater would be 505 F (536 K) for the 100 percent operation. All major components were specified for continuous performance capability at a flow margin of 5 percent above the intended plant operating flow. The steam cycle at the valves wide open (VWO) point would pass the intended flow with margin, and the designated 510 F (539 K) feed temperature would then exist. It is important in conventional steam systems that the operations be evaluated at the 100 percent operating point where performance is guaranteed, and not at the specification condition for design with margin.

CONVENTIONAL STEAM GENERATOR

The coal to be fired is dried by the primary air-flow at the eight ball mill pulverizers. Between 15 and 20 percent of the total air is heated to 633 F in the hottest



LEGEND: Pressure/Temperature/Flow Rate/Enthalpy
PSIA/°F/Million Pounds Per Hour/BTU Per Pound
#Million Pounds Per Hour

Figure 2. Conventional Steam Cycle with Wet Gas Scrubbers

sector of the air preheater as primary air. This air serves to dry the coal, to convey the pulverized coal to the burners, and to consummate the initial combustion process. The remainder of the air is preheated to 585 F (580 K) and delivered to the burners as secondary air.

The water circuitry in the steam generator provides water walls, radiant energy absorption surfaces, convection and radiant surfaces for superheating and reheating of steam, and an econimizer to bring the flue gas to 740 F (666 K) as it leaves the boiler and enters the air preheater. Slag is removed from the boiler furnace beneath the firing zone, fly ash from a hopper just before the air preheater. These solids, representing 15 and 10 percent of the total ash, respectively, are sluiced to the sludge pond. The electrostatic precipitators, with an efficiency of 98.6 percent, collect another 75 percent of the total ash, leaving only 0.75 percent in the gas flow to the wet scrubbers. The collected fly ash is stored in dry silos for shipment off-site. Induced draft fans follow the electrostatic precipitators.

WET GAS SCRUBBERS

The wet gas scrubbers apply a spray of recirculated hot water that is rich in lime in order to capture sulfur compounds. The remaining fly ash will be washed out of the flue gas also. Following the main reactive spray there is a demisting spray that recirculates a makeup water and captured drift mixture. Carry over of the slurry and lime are avoided by this means.

LIME AND SLUDGE SYSTEMS

A continual removal of sludge and a continual replenishment of lime and water is required. The sludge is flushed to the sludge settling ponds in a stream comprising 10 percent undissolved solids. The return water from the pond is enriched with lime produced in the coal-fired calcinator from limestone feedstock.

The makeup water moves in a counterflow mode. It is first used in the mist eliminator recycle wash; the bleedoff replenishes the SO_2 absorber recycle liquids; ultimately the makeup water becomes part of the sludge and water mixture that accumulates in the settled portion of the sludge pond.

STACK AND REHEAT SYSTEM

The flue gas at 125 F (325 K) leaves the wet scrubber saturated with water vapor and with many constituents at or near their dew point temperatures. It has been determined that normal gas heaters cannot have suitable service lives when heating such a corrosive gas mixture. The alternative to direct heating is to blend into the flue gas a large flow of air that has been separately heated. Figure 2 shows that 14 Mlb/h (1764 kg/s) of air heated to 334 F (441 K) blend with 8 Mlb/h (1008 kg/s) of flue gas to produce a 250 F (394 K) stack temperature. The stack air heaters use steam withdrawn from the steam cycle as their heating medium. The stack and flues are lined to withstand attack from the flue gases.

OVERVIEW

The major components of this system are conventional and of proven reliability in utility service. The wet scrubber system introduces added equipment requiring maintenance, and also the need to avoid the corrosive effects of lime and of cool flue gas. The subdivision of scrubber duty into six parallel scrubbers and the subdivision of critical pumping functions in the scrubber system should assure that at most one-sixth of the capacity would be down at any time.

Section 3

MAJOR CYCLE COMPONENTS

Components for conventional steam plants are specified for continuous operation with flows 5 percent greater than required for normal operation. Insofar as Figure 2 depicts 100 percent plant operation on a 59 F (288 K) day, the individual specifications for the boiler, turbine, and scrubber will require greater capacities at their design points. The exact matching has been accomplished on the basis of an exact steam-turbine heat balance, which dictates the heat to steam for the boiler, and the boiler efficiency, which in turn dictates the fuel requirement.

This section will consider the specified performance for the steam turbine-generator, the boiler, the scrubber system, and the heat rejection system. The latter two are furnished as balance of plant equipment. All other balance of plant items will be specified in a subsequent section.

CONVENTIONAL FURNACE—STEAM GENERATOR

The general layout of the conventional supercritical once-through steam generator is shown in Figure 3. Eight ball mill coal pulverizers are located at the base elevation. The burners are arrayed about the radiant furnace section. The combustion gas flows upward over superheater sections, then downward in parallel paths through the reheater and the primary superheater, and finally emerges from the economizer. Figure 4 presents a preliminary heat-and-mass balance at the specified design flows. The final configuration differed from that shown in that the induced draft fans (IDF) were located after the electrostatic precipitators instead of ahead of these units. All other features were the same and the flows, temperatures, and pressures are correct as shown. The heat to steam for this boiler was 87.1346 percent of the fuel higher heating value.

STEAM TURBINE-GENERATOR

The heat balance for the steam cycle is presented in Figure 5 for operation at the 100 percent rated power condition of 820 MW. The rating at the valves wide open (VWO) point would be 860 MW. The seven feedwater heaters and the throttle and reheat conditions are typical for supercritical reheat units today. The unusual feature is the extraction of 926,000 lb/h (117 kg/s) of steam for stack gas heating service. The effect on the steam turbine cycle is as if a separate condenser were located at the 134 psi level.

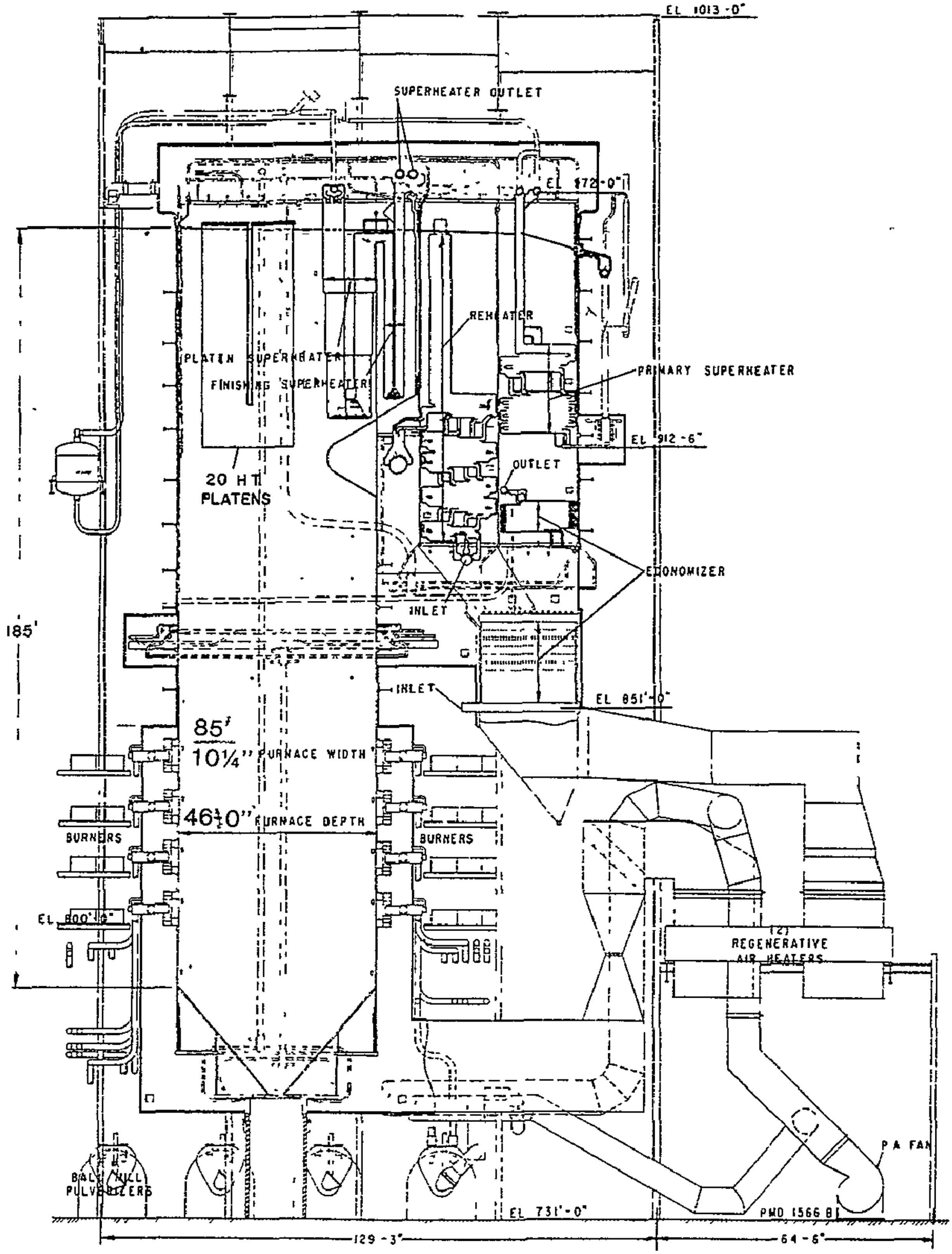


Figure 3. ECAS-II Conventional Boiler—Supercritical Once-Through Coal Firing; 860 MWe

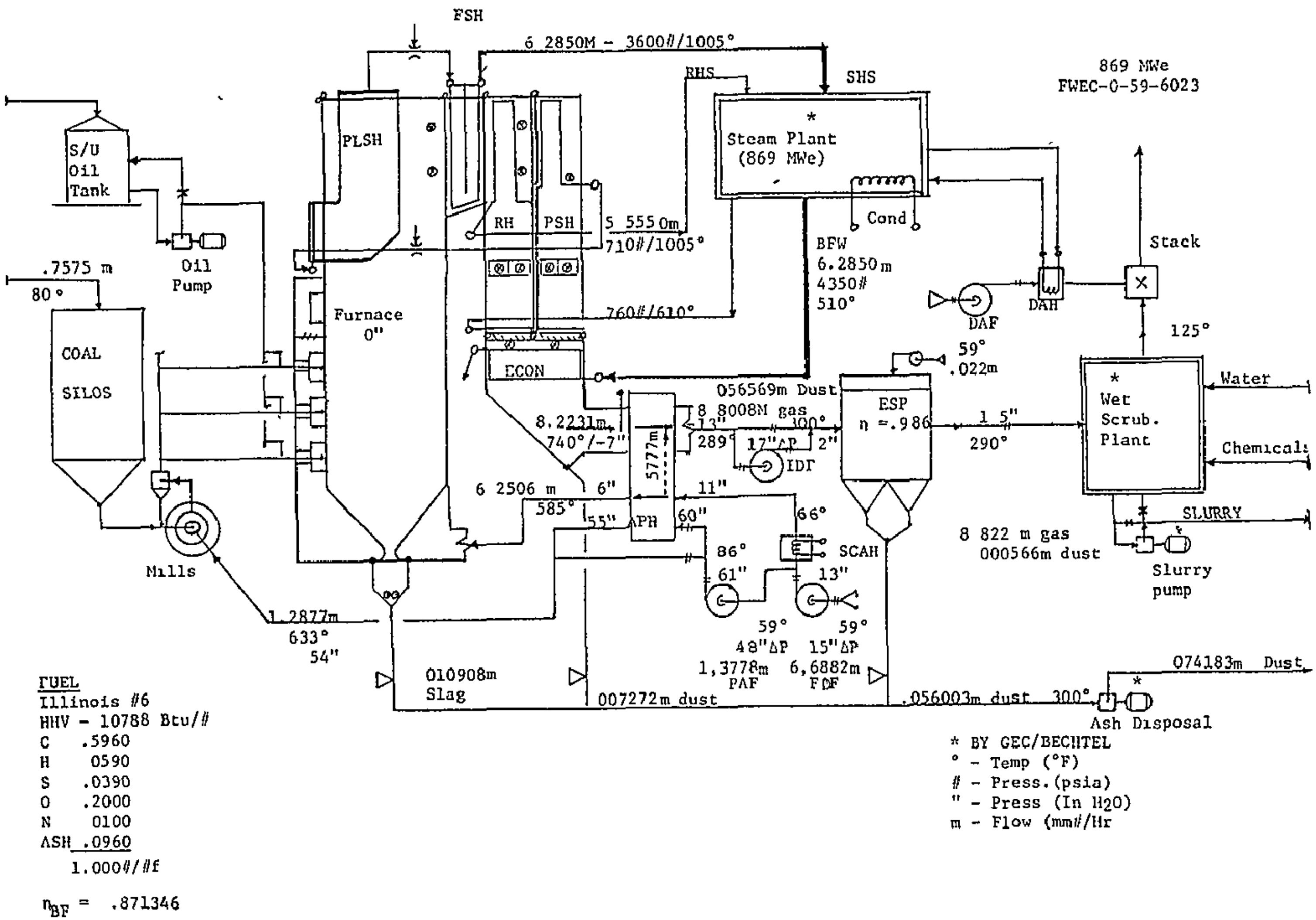


Figure 4. Conventional Steam Plant Flow—860 MWe

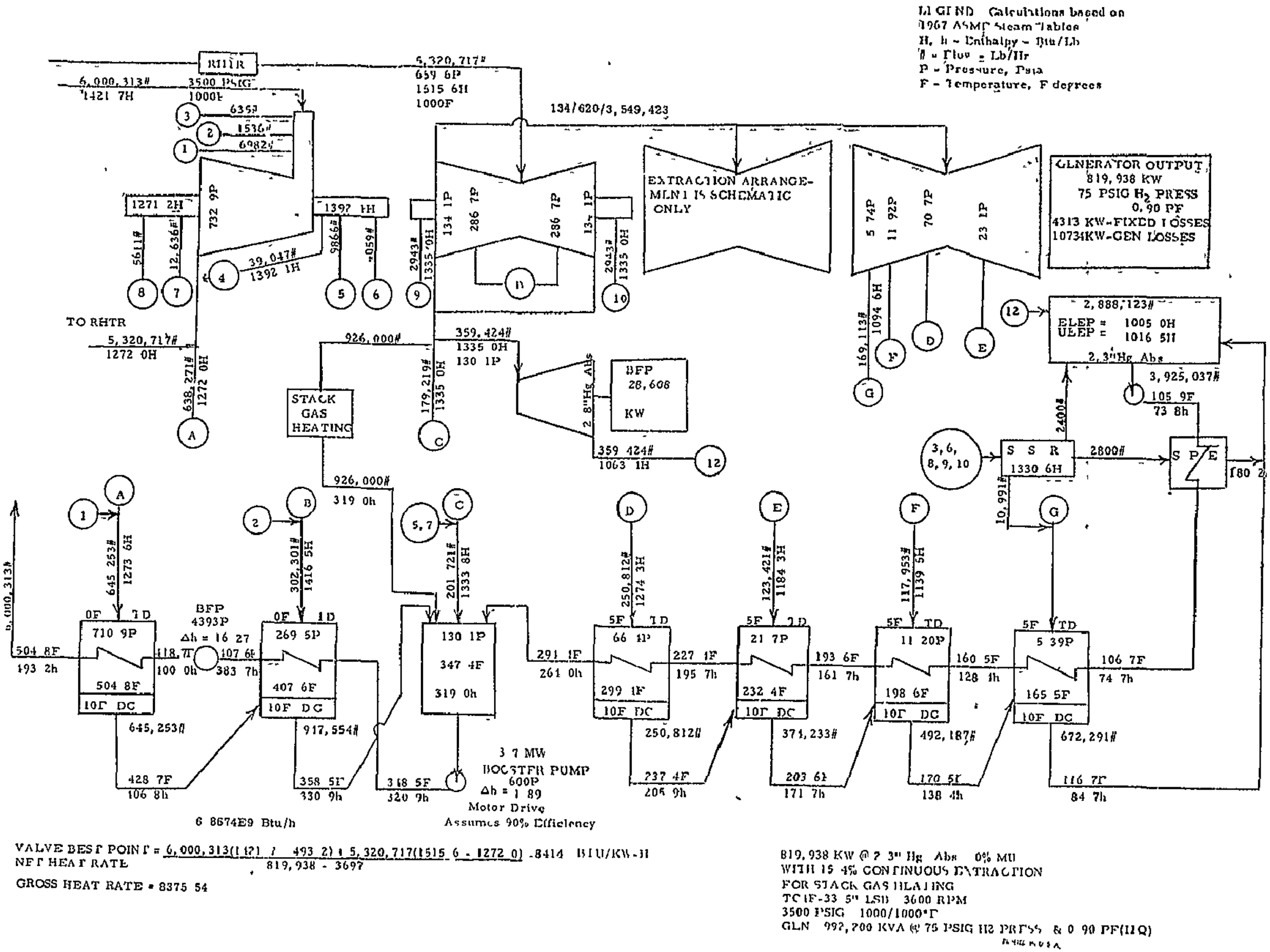


Figure 5. Conventional Furnace with Wet Scrub—250 F Stack

The reduction of steam flow to the low pressure stages reduces generator output and also the condenser and cooling-tower heat rejection load.

The steam turbine comprises four shells. The high-pressure turbine, the reheat turbine, and two double-flow low-pressure condensing turbines are arranged in tandem with the single generator.

The foundation and arrangement drawing of Figure 6 gives the overall dimensions of the unit. The last-stage turbine buckets are 33.5 inches (851 mm) long. These are the largest buckets applied to 3600 rpm turbines for fossil-fired service. The unit is characterized as "TC4F33.5," indicating tandem compound, four exhaust flows, with 33.5 inch (851 mm) last-stage buckets.

The heat to the steam cycle at 100 percent operating conditions would be 6867.4 MBtu/hr (2.01 GJ/s). The heat input would be 8375.54 Btu/kWh (8.84 kJ/kWh) for generator output.

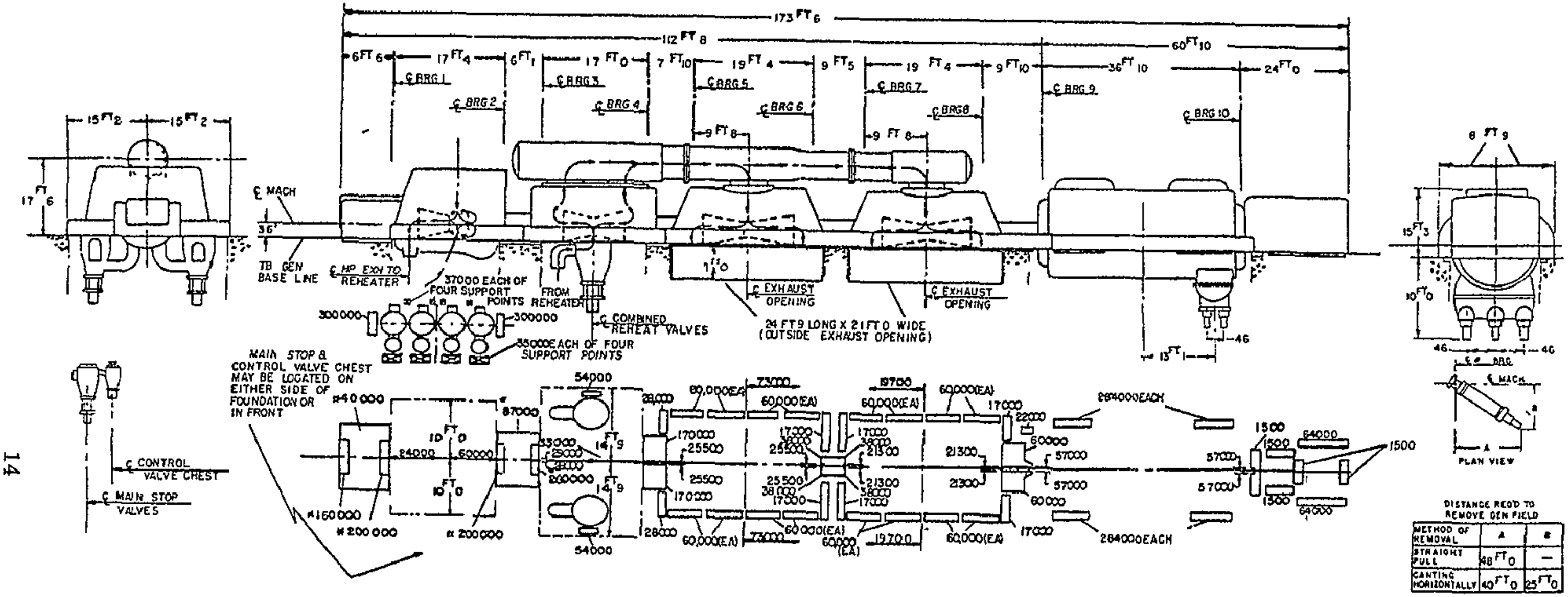
STACK GAS SCRUBBER SYSTEM

Although all elements of the wet gas scrubber system would be furnished as balance of plant equipment, the unique aspects of this system suggest that it be discussed as a major cycle component.

The entire scrubber system is illustrated in Figure 7 along with process flow charts appropriate for operation at the specified 5 percent flow margin, using 4.5 percent sulfur coal. The sulfur capture would be 90 percent. The two process flow charts do not differ in respect to the sulfur capture system; only the reheating of stack gas to 250 F (394 K) in the upper chart and to 175 F (353 K) in the lower chart are different.

The lime requirement is met by calcining limestone in a rotary kilm fired with coal. There is on-site a 60 day supply of limestone. The coal is stacked in a four day storage bin by front-end loaders. The emission requirements for the calciner are met by the use of a baghouse dust collector and a separate stack. No reduction in sulfur gases is expected for the coal fired in the calciner.

The lime product is expected to be in excess of 95 percent available lime. It is stored in silos with a capacity sufficient for five days' operation. With the 1500 tons per day (378 kg/s) of limestone calcining capacity, this part of the plant need not operate continuously to support plant operations. There should be sufficient time to accomplish



NOTES

1 STEAM CONDITIONS: 3500 PSIG-1000/1000 °F REHEAT WITH 33½ IN LAST STAGE BUCKETS

2. HEAVIEST PIECE DURING ERECTION - (GENERATOR STATOR) 760000 LBS
HEAVIEST PIECE AFTER ERECTION - (GENERATOR FIELD ROTOR 16U000 LBS

*3 160000 & 200000 LB LOADINGS DO NOT OCCUR SIMULTANEOUSLY BUT ARE SUPERIMPOSED ON 40000 LB LOAD 160000 LB LOAD IS ZERO FOR NORMAL OPERATION FOR FULL VALUE OF 160000 LB LOAD 200000 LB LOAD IS ZERO

4 THE COMBINED REHEAT VALVE ARRANGEMENT INCLUDES THE REHEAT STOP AND INTERCEPT VALVES

5 SHAFT ROTATION IS CLOCKWISE WHEN VIEWED FROM COLLECTOR END OF GENERATOR

6 LOAD VALUES SHOWN ARE FOR TURBINE-GENERATOR UNIT ONLY ADDITIONAL LOAD CONTRIBUTED BY CONDENSER NOT INCLUDED

7 DISTANCE REQUIRED TO REMOVE MAJOR PARTS - NOT INCLUDING SLINGS:

A GENERATOR STATOR - 14 FT 3 FROM TB-GEN BASE LINE WITHOUT TERMINAL BOX ATTACHED
B GENERATOR COOLERS - 19 FT 0 IN HORIZONTALLY FROM VERTICAL ℄ OF GEN

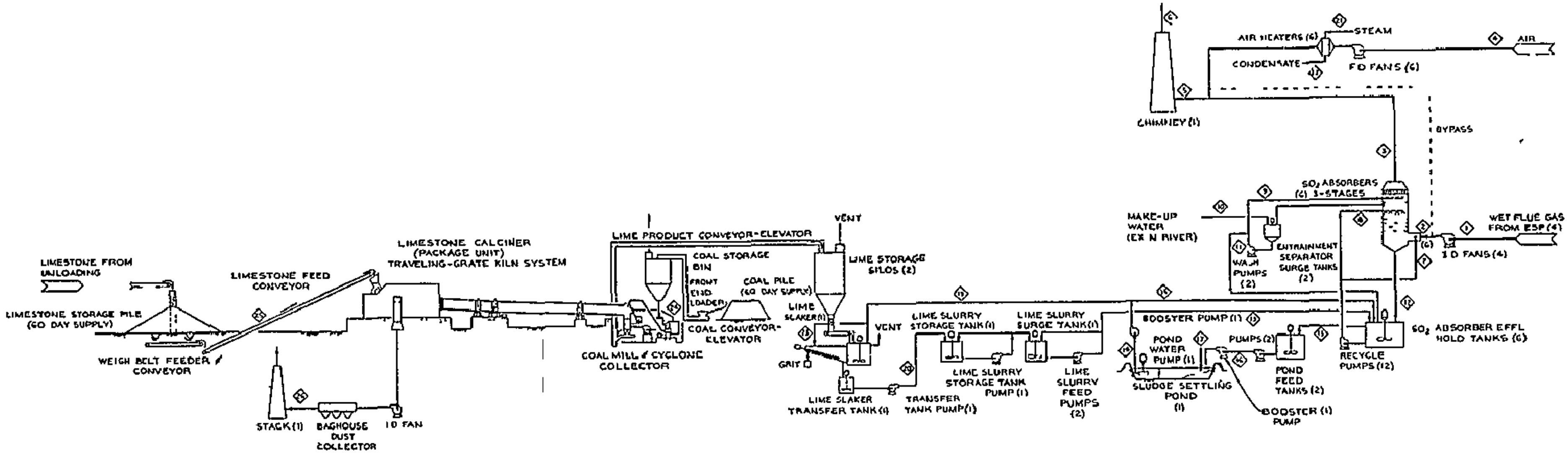
8 THIS OUTLINE SHALL NOT BE USED FOR CONSTRUCTION PURPOSES THE GENERAL EQUIPMENT ARRANGEMENT, DIMENSIONS AND LOADINGS ARE TO BE CONSIDERED PRELIMINARY AND SUBJECT TO LATER MODIFICATION

9 RECOMMENDED MINIMUM CRANE HOOK HEIGHT ABOVE TB. GEN BASE LINE - 33 FT 7 IN

10 RECOMMENDED MINIMUM FOUNDATION HEIGHT - 40 FT 0 IN

11 THE HORIZONTAL FORCES ACTING AT THE KEYS INCLUDE A SEISMIC FACTOR OF 0.12G

Figure 6. Steam Turbine-Generator, Preliminary Outline



STREAM NO.	1	2	3	4	5	6	7	8	9	10	11	12	13
DESCRIPTION	GAS TO I D FAN	GAS TO ABSORBER	GAS TO REHEAT	AIR TO HEATERS	GAS TO STACK	GAS TO ATMOSPHERE	SLURRY TO PRE SAT'R	RECYCLE SLURRY TO ABS	MIST ELIM RECYCLE WASH	RAW MAKE UP WATER	ENTR. SEPR BLEED-OFF	SLURRY TO SAE HT	LIME SLURRY TO SAE HT
M LBS/HR	8,178.5	1,363	1,3075	2 438	22,911	22 911	386.0	11 567	720	229.6	76.5	11 930	668
M ACFM (GPM)	2 444	425	841	551	6 622		(730)	(21 825)	(4,440)	(453)	(153)	(22,509)	(116)
TEMPERATURE, °F	300	312	125	59	250								
PRESSURE IN WG (PSIG)	-13	10	1	0	0	0							
PARTICULATES, LBS/HR	725	725	3,170		4,330	4,338							
SULFUR DIOXIDE, LBS/HR	67 800	11,300	1,130		6,780	6,780							
UNDISSOLVED SOLIDS, %							10	10				10	20
SPECIFIC GRAVITY							1.06	1.06	1.0	1.0	1.0	1.06	1.13
M LBS/HR TOTAL	8,178.5	8,178.5	8,835	14,586	22,911	22,911	1,321	69,402	4,920	459.1	459.1	71,878	400.8

STREAM NO.	14	15	16	17	18	19	20	21	22	23	24	25	26
DESCRIPTION	POND WATER TO SAE HT	SAE HT OVERFLOW	USED SLURRY TO POND	SETTLED USED SLURRY	RECYCLE POND WATER	SLAKE & DILN WATER	LIME SLURRY TRANSFER	STEAM TO AIR HEATER	CONDENSATE RTN	LIME TO SLAKER	COAL TO CALINER	LIMESTONE TO CALINER	GAS TO STACK
M LBS/HR	121.2	240.7	722	375.5	1,069	341.8	400.8	160.5	962.8	62.5	14.5	125	203
M ACFM (GPM)	(242)	(454)	(4,362)	(573)	(2 138)	(683)	(709)	(321)	(1926)				74.3
TEMPERATURE, °F								620	356				500
PRESSURE IN WG (PSIG)								(130.3)	(130.3)				
PARTICULATES, LBS/HR													<15
SULFUR DIOXIDE, LBS/HR													<150
UNDISSOLVED SOLIDS, %		10	10	40			20						
SPECIFIC GRAVITY	1.0	1.06	1.06	1.31	1.0	1.0	1.13						
M LBS/HR TOTAL	727.2	1444	1444	875.5	1,069	341.8	400.8	962.8	962.8	62.5	14.5	125	203

STREAM NO.	1	2	3	4	5	6	7	8	9	10	11	12	13
DESCRIPTION	GAS TO I D FAN	GAS TO ABSORBER	GAS TO REHEAT	AIR TO HEATERS	GAS TO STACK	GAS TO ATMOSPHERE	SLURRY TO PRE SAT'R	RECYCLE SLURRY TO ABS	MIST ELIM RECYCLE WASH	RAW MAKE UP WATER	ENTR. SEPR BLEED-OFF	SLURRY TO SAE HT	LIME SLURRY TO SAE HT
M LBS/HR	8,178.5	1,363	1,3875	844.5	11,672	11,692	386.8	11 567	720	229.6	76.5	11 930	668
M ACFM (GPM)	2 644	425	841	173	3,095		(730)	(21 825)	(1 440)	(459)	(153)	(22,500)	(818)
TEMPERATURE °F	300	312	125	57	115								
PRESSURE IN WG (PSIG)	-13	10	1	0	0	0							
PARTICULATES, LBS/HR	725	725	3,170		4,330	4,330							
SULFUR DIOXIDE, LBS/HR	67 800	11,300	1,130		6,780	6,780							
UNDISSOLVED SOLIDS, %							10	10				10	20
SPECIFIC GRAVITY							1.06	1.06	1.0	1.0	1.0	1.06	1.13
M LBS/HR TOTAL	8,178.5	8,178.5	8,325	3,267	11,892	11,892	1,321	69,402	4,920	459.1	459.1	71,578	400.8

STREAM NO.	14	15	16	17	18	19	20	21	22	23	24	25	26
DESCRIPTION	POND WATER TO SAE HT	SAE HT OVERFLOW	USED SLURRY TO POND	SETTLED USED SLURRY	RECYCLE POND WATER	SLAKE & DILN WATER	LIME SLURRY TRANSFER	STEAM TO AIR HEATER	CONDENSATE RTN	LIME TO SLAKER	COAL TO CALINER	LIMESTONE TO CALINER	GAS TO STACK
M LBS/HR	121.2	240.7	722	375.5	1,069	341.8	(400.8)	35.6	213.4	62.5	14.5	125	203
M ACFM (GPM)	(242)	(454)	(1,362)	(573)	(2 138)	(683)	(709)	(71)	(423)				74.3
TEMPERATURE °F								620	356				500
PRESSURE IN WG (PSIG)								(130.3)	(130.3)				
PARTICULATES, LBS/HR													<15
SULFUR DIOXIDE, LBS/HR													<150
UNDISSOLVED SOLIDS, %		10	10	40			20						
SPECIFIC GRAVITY	1.0	1.06	1.06	1.31	1.0	1.0	1.13						
M LBS/HR TOTAL	727.2	1,444	1,444	375.5	1069	341.8	400.8	213.4	213.4	62.5	14.5	125	203

Figure 7. Process Flow Diagram

all usual maintenance and refurbishment on a scheduled basis. The entire left half of Figure 7 represents on-site capital investment and operations that would be eliminated if lime rather than limestone were available for purchase in suitable quantities at a suitable price.

The right half of Figure 7 is the scrubbing system that causes lime to react with sulfur in the flue gas to form solids that accumulate in the sludge ponds. The lime replenishment is slacked with pond recycle water to a 16 hour storage tank. The slacked lime and remaining pond recycle water are discharged to the SO_2 absorber effluent holding tanks. Table 2 presents the major parameters of the limestone/lime system considered to this point.

Table 2

LIMESTONE/LIME SYSTEM PARAMETERS
CONVENTIONAL FURNACE—STEAM CYCLE

Parameter	Value or Description
Lime Product Quality	95% available CaO
Limestone/Lime Product	2 tons/ton
Limestone Storage	60-day supply 90,000 tons
Limestone Calciner (Traveling Grate Kiln)	
Nominal Production	650 tons/day
Capacity	880 tons/day
Fuel Requirements (Ill. No. 6)	5 MBtu/ton lime
Lime Storage Capacity	5-day supply
Lime Slaker Capacity	800 tons/day
Slaking Temperature	~190 F
Slaked Lime Slurry Solids (After Dilution)	20% weight
Lime Slurry Surge Capacity	16 hours

The three-stage SO_2 absorbers operate on flue gas that has been quenched from 300 F (422 K) and saturated with water vapor at 125 F (325 K) by the presaturation sprays at each absorber gas inlet. The flue gas then flows upward through the three absorber stages, each of which comprises a 6 inch (152 mm) bed of spheres. The liquid-to-gas ratio maintains 110 percent of lime-to-sulfur stoichiometric ratio. The effluent wet gas is further washed in the mist eliminator sprays. These sprays receive all of the fresh makeup water intended for all replenishment of the scrubber system. This final wash captures carry over or large droplets of drift of recycle wash liquids. Table 3 identifies the parameters of the wet absorber system and keys the stream functions to Figure 7.

Table 3

WET LIME ABSORBER SYSTEM PARAMETERS
CONVENTIONAL FURNACE—STEAM CYCLE
(Basis: 90% SO_x Removal for 4.5% Sulfur Coal)

Parameter	Value or Description
SO_2 Absorbers (6)	TCA type
Number of Stages	3 (6" of spheres/stage)
Superficial Gas Velocity	8 ft/s
Total Pressure Drop	9 in. H_2O
Liquid/Gas Ratio ◇8	72 gal/mscf
Presaturation Sprays ◇7	2.5 gal/mscf
Mist Eliminator Wash Sprays ◇9	2 gpm/ft^2
Lime: SO_2 Stoichiometric Ratio	110%
Absorber Hold Tank Residence Time	5 min
Recycle Slurry Solids ◇15 ◇8 ◇7	10% weight
Lime Makeup Slurry Solids ◇13	20% weight
Spent Slurry Pond Solids ◇17	40% weight

◇ = Stream Identification, Figure 7
TCA = Turbulent Contact Absorber

The flue gas at 125 F (325 K) and saturated with water vapor is highly corrosive and chemically active. Normal heat exchangers that would reheat the flue gas to an appropriate stack temperature would not withstand the chemical attack of the flue gas. Even the flues and stack must be lined, to avoid attack. The necessary stack temperature is achieved by steam-heating additional air and blending the heated air with the flue gas. This requires six low head fans and six heaters. Two alternatives of stack temperature were examined: 250 F (394 K) and 175 F (353 K). Table 4 presents the parameters of the blend air and its heat requirements for these alternatives at their 100 percent operating point. The blending means of gas heating is increasingly inefficient as the stack temperature is increased toward the air temperature of 333 F (440 K), accounting for the great differences between these two alternatives.

The wet gas scrubber arrangement shown in Figure 8 connects these several elements with the four induced draft fans that service the four electrostatic precipitators. There is a total of six absorber and stack reheater trains. The induced draft fans feed a cross-duct that is normally isolated by dampers from the startup bypass path. Connecting in a downward fan-like duct are the presaturation spray ducts to each absorber. The redundancy dictated by the size of the absorbers should produce a high level of availability for the scrubber system.

Table 4

FLUE GAS HEATERS
FOR WET SCRUBBER SYSTEMS

PARAMETER	STACK GAS REHEAT TEMPERATURE 250 F	175 F
HEAT DUTY, MBtu/HR	971	217
STEAM	620 ⟶ 356 F	620 ⟶ 356 F
AIR	333 ⟵ 59 F	333 ⟵ 59 F
AIR VELOCITY, FT/MIN	900	900
AIR RATE, M LB/HR	14.586	3.267
PRESSURE DROP, IN H_2O	1.5	1.0
HEAT TRANSFER RATE, Btu/(HR SQ FT °F)	5 5	10.4
FINNED SURFACE, SQ FT	645,000	86,500

The sludge ponds are the remaining element of the wet scrubber system. Each pond would measure 3600 feet (1097 m) by 3600 feet (1097 m) by 22 feet (6.7 m) deep. Six ponds would accommodate 30 years of plant operations. The accumulation rate of solids would equal the solids delivery rate of 150,000 lb/h (18.9 kg/s) of calcium sulfite and excess unreacted lime. Because water would accumulate at a rate 50 percent greater, in situ solids concentration would be 40 percent. It is important to recognize these two accumulations, because the tables on Figure 7 represent steady-state balances for the absorbers but nonsteady states for lime, makeup water, and sludge accumulation.

SCRUBBER COSTS

The direct costs for the scrubber system comprise material costs and direct field labor costs as detailed in Table 5 for a 250 F (394 K) stack and in Table 6 for a 175 F (353 K) stack. These costs are not complete insofar as balance-of plant construction must bear a prorated share of the indirect field expenses and additional electrical, civil, process, and yardwork must be done. Tables 7 and 8 present the complete costs, with the first two items on line 1.0 carried over from Tables 5 and 6. The allocations for indirect labor, fees, contingency, and escalation will be discussed in the subsection concerned with balance of plant in Section 5, "System Performance and Cost." All of these items of expense will also be included in the comprehensive list of balance of plant accounts. Presentation here with all elements of costing is done to facilitate identification of the incremental cost due

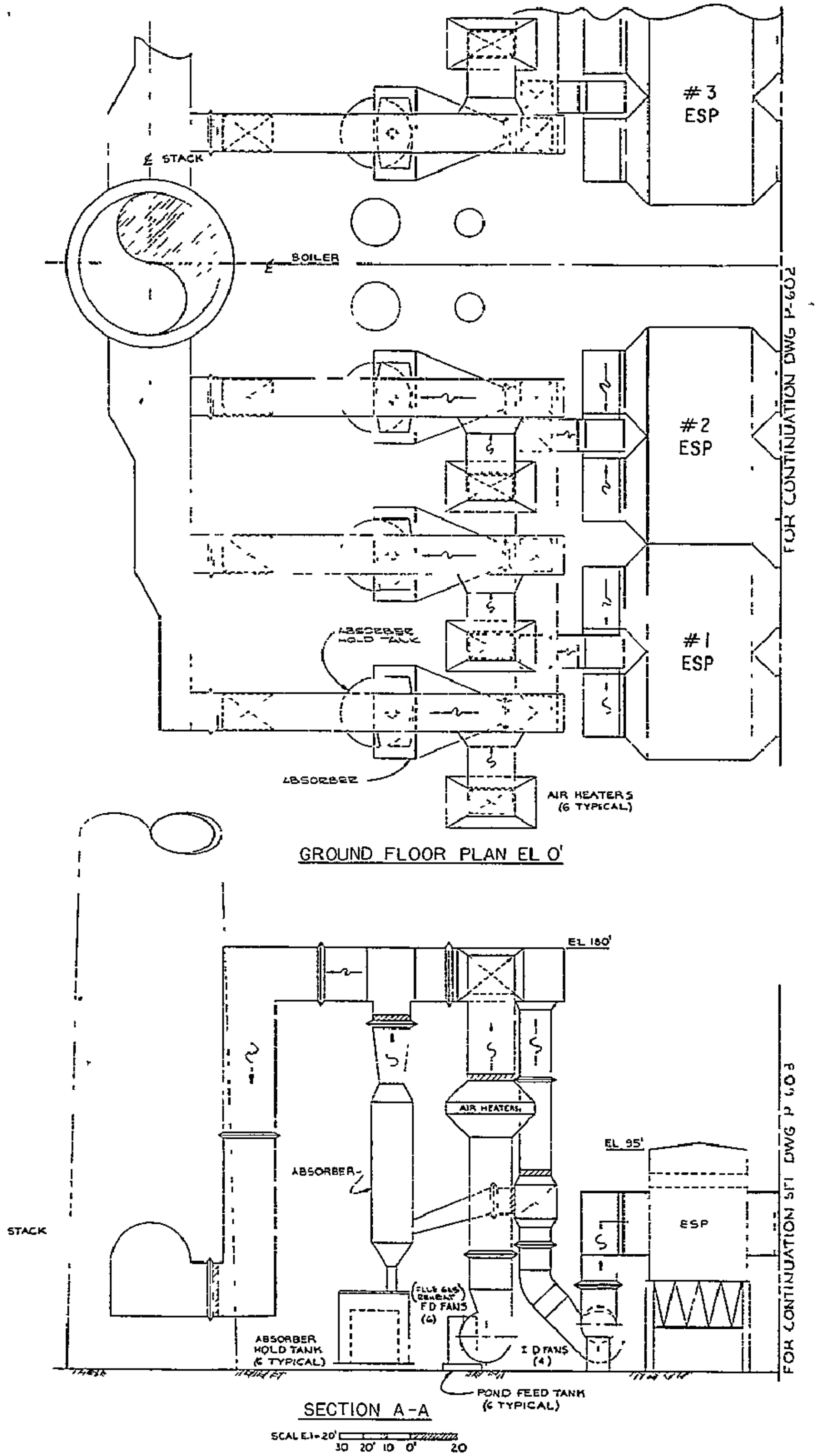


Figure 8. Wet Gas Scrubber Arrangement—Conventional Steam Plant

to the wet scrubber system. For the 250 F (394 K) stack case, a total of $51.9 million for this major system is comparable to a steam turbine-generator cost of $26 million, and a boiler component cost of $39.7 million. The wet scrubber is a major addition.

Table 5

SCRUBBER EQUIPMENT DIRECT FIELD COSTS
(250 STACK TEMPERATURE)

MAJOR MECHANICAL EQUIPMENT	MATERIALS M$	DIRECT LABOR M$	TOTAL M$
LIMESTONE HANDLING	1.25	0.25	1.50
LIMESTONE/LIME SYSTEM	3.66	0.78	4.44
SO_2 SCRUBBER VESSELS	6.93	1.01	7.94
SCRUBBER SYSTEM PUMPS	1.08	0.12	1.20
SCRUBBER SYSTEM TANKS	2.18	0.05	2.23
SCRUBBER DUCTWORK	3.27	2.43	5.70
SCRUBBER FLUE GAS EQUIPMENT	3.09	0.32	3.41
TOTAL	21.46	4.96	26.42

Table 6

SCRUBBER EQUIPMENT DIRECT FIELD COSTS
(175 STACK TEMPERATURE)

MAJOR MECHANICAL EQUIPMENT	MATERIALS M$	DIRECT LABOR M$	TOTAL M$
LIMESTONE HANDLING	1.25	0.25	1.50
LIMESTONE/LIME SYSTEM	3.66	0.78	4.44
SO_2 SCRUBBER VESSELS	6.93	1.01	7.94
SCRUBBER SYSTEM PUMPS	1.08	0.12	1.20
SCRUBBER SYSTEM TANKS	2.18	0.05	2.23
SCRUBBER DUCTWORK *	1.95	1.41	3.36
SCRUBBER FLUE GAS EQUIPMENT *	0.90	0.08	0.98
TOTAL *	17.95	3.70	21.65

*CHANGED FROM 250 STACK CASE

Table 7

WET LIME SCRUBBER CAPITAL COST BREAKDOWN CONVENTIONAL FURNACE—STEAM CYCLE (250 F STACK TEMPERATURE)

CATEGORIES	MATERIALS M$	DIRECT LABOR M$	INDIRECT FIELD M$	TOTAL M$
1 0 PROCESS MECHANICAL EQUIPMENT (LIMESTONE HANDLING, LIME SYSTEM, ABSORBERS, TANKS, PUMPS, AIR HEATERS, F.D. FANS, DUCTWORK)	21 5	5 0	4.5	31.0
2 0 ELECTRICAL	0.7	0 9	0.8	2 4
3 0 CIVIL AND STRUCTURAL	3.7	2 1	1.8	7.6
4 0 PROCESS PIPING AND INSTRUMENTATION	4.3	2 6	2.3	9.2
5.0 YARDWORK AND MISCELLANEOUS	—	0 9	0.8	1.7
				51 9
A/E ENGINEERING, HOME OFFICE & FEE @ 15%				7 8
TOTAL PLANT COST				59.7
CONTINGENCY @ 20%				11 9
TOTAL CAPITAL COST				71.6
ESCALATION & INTEREST DURING CONSTRUCTION				39 2
TOTAL PLANT INVESTMENT				110 8

Table 8

WET LIME SCRUBBER CAPITAL COST BREAKDOWN CONVENTIONAL FURNACE—STEAM CYCLE (175 F STACK TEMPERATURE)

CATEGORIES	MATERIALS M$	DIRECT LABOR M$	INDIRECT FIELD M$	TOTAL M$
1 0 PROCESS MECHANICAL EQUIPMENT (LIMESTONE HANDLING, LIME SYSTEM, ABSORBERS, TANKS, PUMPS, AIR HEATERS, F D. FANS, DUCTWORK)	17 95	3 7	3.3	25.0
2 0 ELECTRICAL	0.7	0.9	0.8	2 4
3 0 CIVIL AND STRUCTURAL	3 7	2 1	1 8	7 6
4 0 PROCESS PIPING AND INSTRUMENTATION	3 8	2 5	2 2	8 5
5 0 YARDWORK AND MISCELLANEOUS	—	0 9	0 8	1 7
				45.2
A/E ENGINEERING, HOME OFFICE & FEE@15%				6 8
TOTAL PLANT COST				52 0
CONTINGENCY @ 20%				10 4
TOTAL CAPITAL COST				62 4
ESCALATION & INTEREST DURING CONSTRUCTION				34 2
TOTAL PLANT INVESTMENT				96 6

Section 4

PLANT ARRANGEMENT

A group of plant arrangement drawings were prepared by the architect-engineer as a preliminary step to evaluating construction costs.

PLOT PLAN

The plant plot arrangement is based on receiving coal and limestone by rail and shipping fly ash off-site by rail. A 60 day pile of coal and limestone is provided. Silos to hold 15 days' accumulation of dry fly ash are provided adjacent to the rail terminal. A series of small ponds catch run-off water from the site and provide for treatment of all water returned to the North River.

Figure 9 shows the plot arrangement. The smaller overall plot layout indicates the dominant aspect of one 3600 foot by 3600 foot (1097 by 1097 m) sludge pond. The upper detail shows that at the active site half the area will be used for coal storage and for cooling towers. The boiler house abuts the turbine building. The electrostatic precipitators are of substantial size in order to achieve 98.6 percent particle removal. A single stack serves the entire plant. The land area for the power generation plant is 92 acres (372,311 m^2); the sludge ponds must aggregate an additional 1785 acres (7,223,640 m^2) in close proximity to the main plant. A total area of 3 square miles will be required. This requirement will severely constrain the siting opportunities for these plants.

The coal feed system provides transportation by belt conveyor from the line storage pile to the transfer tower. Tramp iron is removed and large size frozen coal is crushed to small size. Next, the coal is conveyed to the surge bin in the boiler house, where vibrating feeders and two conveyor belts feed eight coal silos disposed on opposite sides of the building. The filled silos guarantee eight hours of boiler output. Each silo feeds a single coal pulverizer by a gravimetric feed. Coal drying and conveyance to the burners is by hot [illegible] air. For startup and warmup an oil system firing no. 2 fuel oil is provided, along with [illegible]0,000 gallons (379 m^3) of fuel storage in two tanks.

GENERAL ARRANGEMENT

A more detailed general arrangement plan for the turbine hall and boiler is presented in Figure 10. The eight silos on either side of the boiler each hold an 8 hour coal

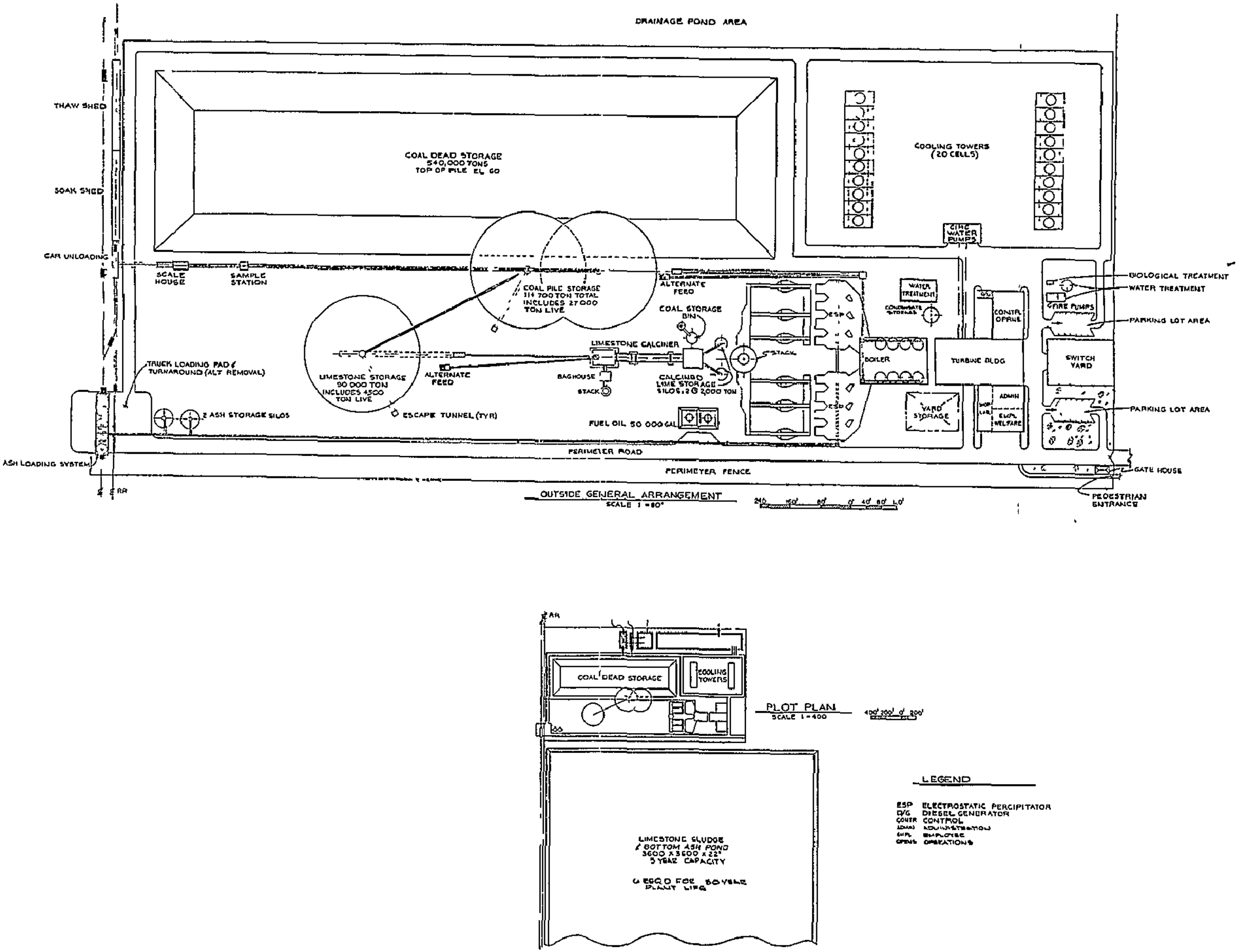


Figure 9. Plot Plan for Conventional Steam Plant

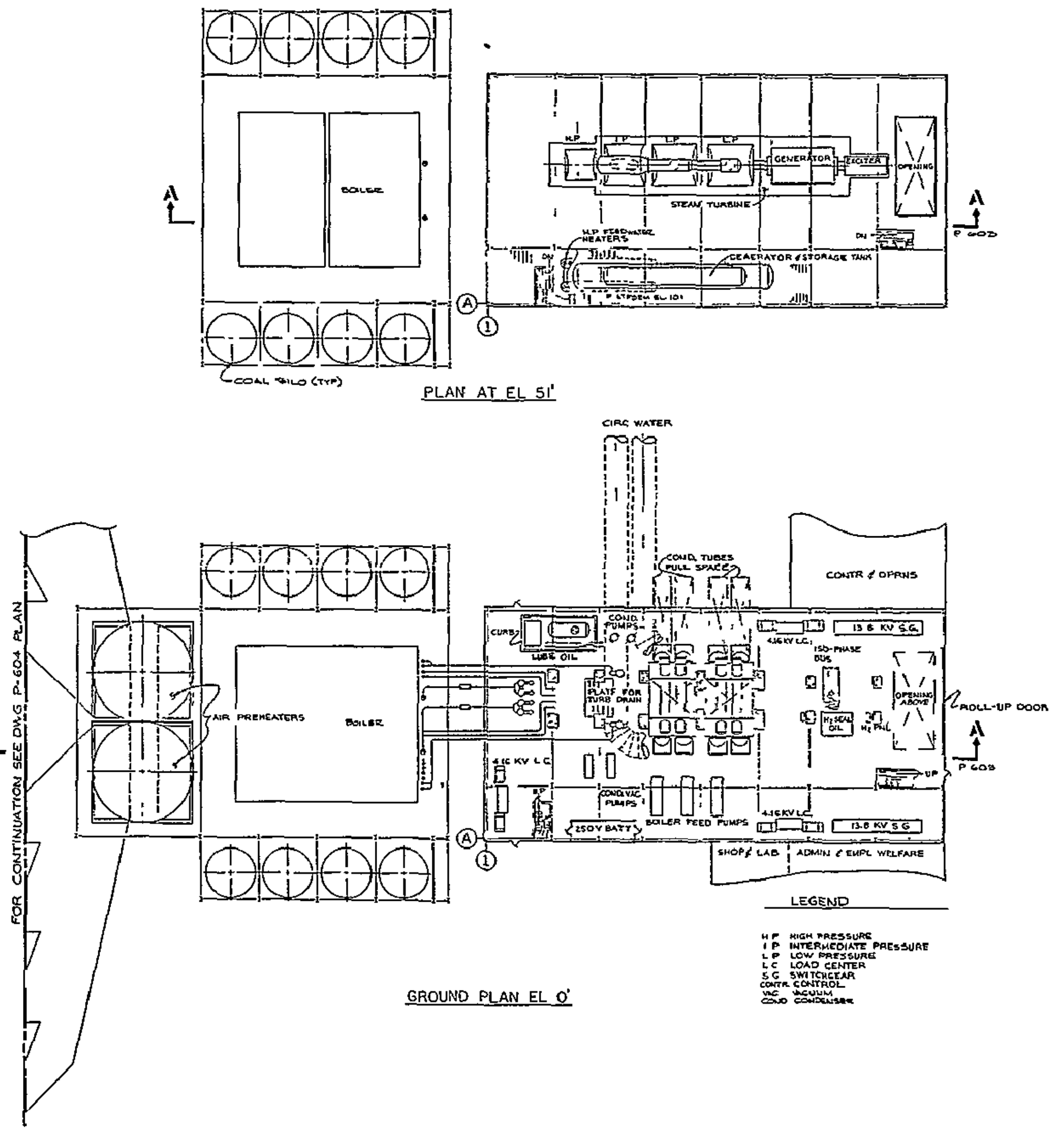


Figure 10. Turbine and Boiler Buildings

supply, and all feed to one coal pulverizer. The air preheaters and fuels to the electrostatic precipitators of Figure 8 dominate the leftside. The ground level of the turbine hall on the right indicates the arrangement of the many support functions for the steam turbine cycle.

The general arrangement elevation view shown in Figure 11 combines the boiler details of Figures 3 and 4 in a proper orientation to the turbine hall and the flue gas exhaust system detailed in Figure 8. The arrangement provides short steam lines and liberal access space for all apparatus. At the extreme left, the gas enters the flue gas system of Figure 8 at the electrostatic precipitators.

The four electrostatic precipitators shown in Figure 8 are especially voluminous, to provide the low gas velocities essential to the capture of 98.6 percent of the entrained fly ash. Each unit is 54 feet (16.5 m) high, 93 feet (28.4 m) wide, and 44 feet (13.4 m) deep. The entry and exits are divided in two to retain normal flue connections. Each unit is serviced by one induced draft fan working in the cleaned gas leaving the unit. The six wet gas scrubbers and reheaters then deliver the flue gas to a single 500 foot (152 m) stack.

ELECTRICAL SCHEMATIC

Figure 12 is a single-line diagram showing major electrical equipment. The single steam turbine-generator at 24kV feeds two main transformers to 500 kV and two auxiliary transformers to 13.8 kV. A startup transformer may also feed the 13.8 kV bus from the 500 kV transmission line. Major and subsidiary buses are identified, as well as major auxiliary electrical loads.

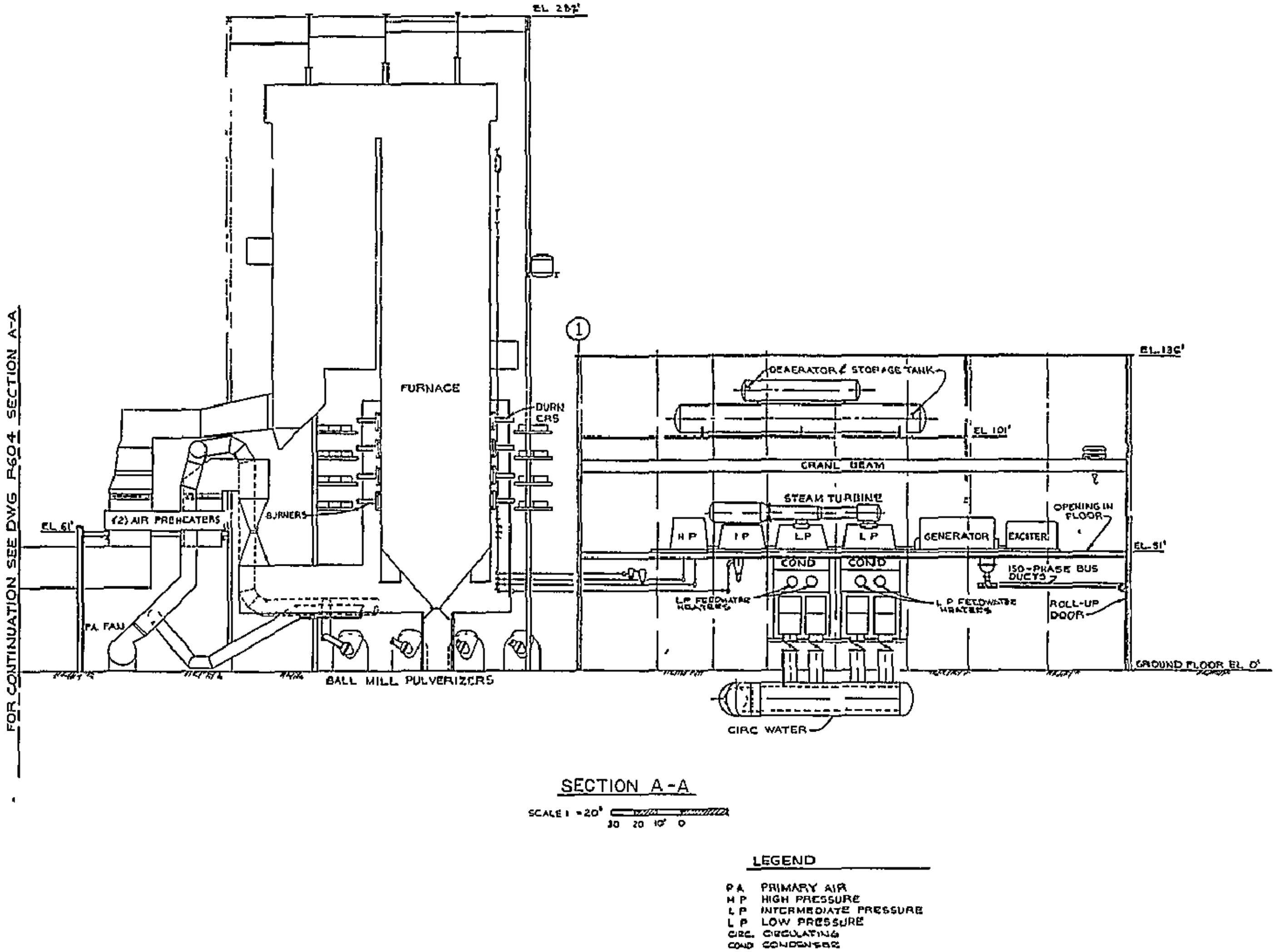


Figure 11. Elevation View of General Arrangement

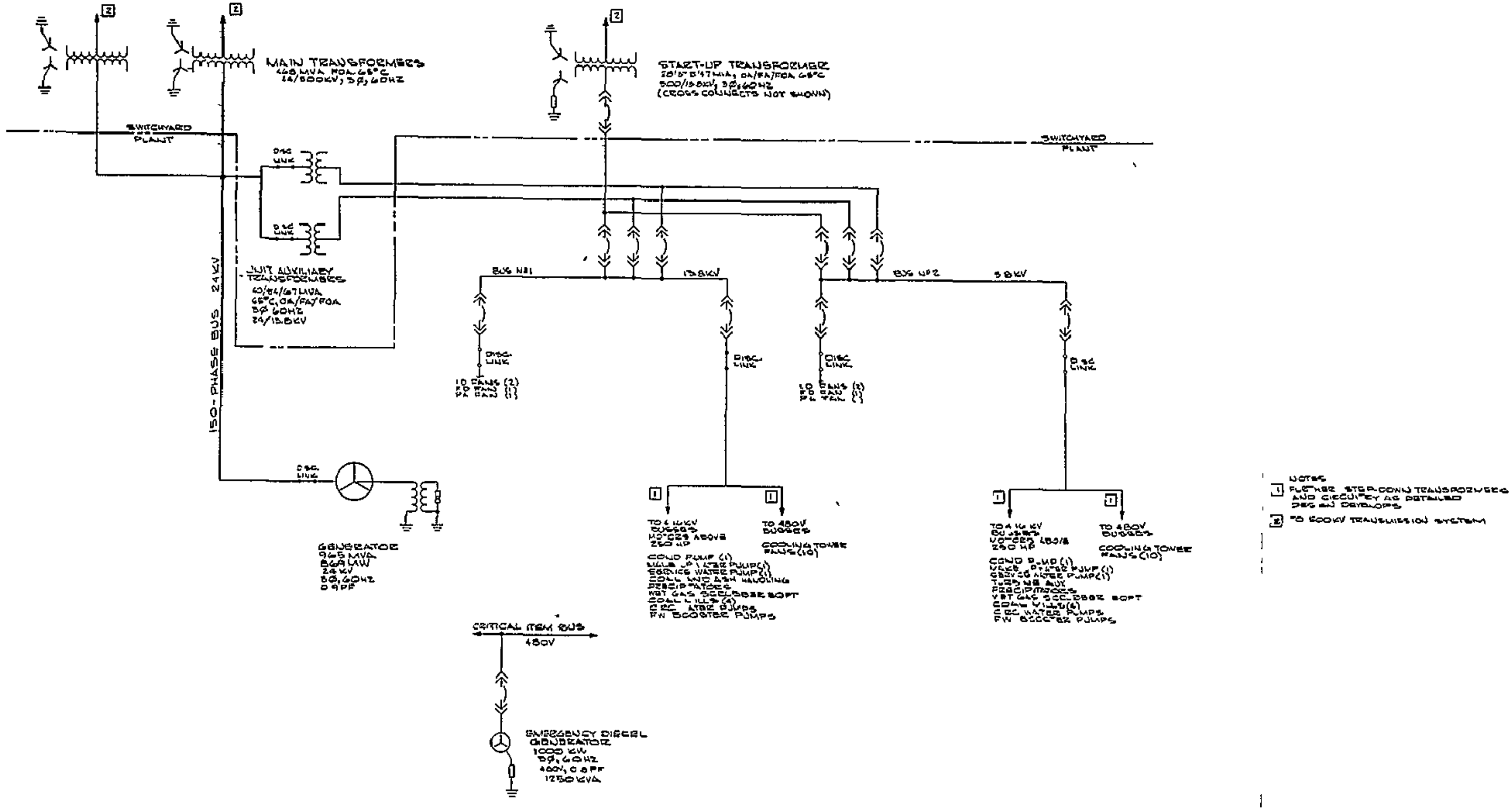


Figure 12. Major Electrical Equipment

Section 5

SYSTEM PERFORMANCE AND COST

PERFORMANCE INTEGRATION

Evaluation was made of plant performance on the average 59 F (288 K) day with all equipment operating at 100 percent condition with respect to its design and specification point. To adjust performance data so that an exact integration results, a detailed steam turbine heat balance had been made at the 100 percent operating point, as presented in Figure 5. The required 6867.4 MBtu/h (1.13 GJ/s) from the boiler were deemed to be provided at the exact boiler efficiency (87.1346) that prevails with the 5 percent margin condition detailed in the boiler heat balance (Figure 4). Typically, boiler efficiency improves slightly at reduced firing rates.

In addition to the coal fired at the boiler, the rate of coal usage for calcining was evaluated on the basis that the mass flows of the wet gas scrubber process flow diagram (Figure 7) represent operation at a 5 percent margin above the required 100 percent level. Table 9 presents the basis and results for the integration into the steam cycle of boiler and wet gas scrubber operating flow rates.

Table 9

ENERGY BALANCE—100 PERCENT RATING, 59 F DAY
CONVENTIONAL STEAM PLANT—WET SCRUBBERS—250 F STACK

Parameter	Value	
Generated Power	819938	kW
Heat-to-Steam Cycle[1]	6867.4	MBtu/Hr
HHV of Fuel Fired[2]	7881.4	MBtu/Hr
Coal Fired at Boiler[3]	730570	pph
Coal Fired at Calciner[4]	13810	pph
Total Coal Rate	744380	pph
Effective Boiler Efficiency	85.52	percent
Limestone Feed Rate[4]	119050	pph
Scrubber Makeup Water Rate	917	gpm

Notes: 1 From 100 percent steam cycle heat balance, Figure 5

2 Boiler efficiency 0.871346 from heat balance, Figure 4

3 Based on 10788 Btu/pound higher heating value (HHV)

4 Rates proportioned 1/1.05 for wet scrubber, Figure 7

SYSTEM OUTPUT

For the 100 percent operating point Table 10 shows that the 820 MW of generator output was reduced to 747 MW net plant output by the 73 MW required for auxiliaries. The auxiliary loss breakdown is presented in Table 11. The induced fan power requirement

Table 10

SYSTEM OUTPUT
CONVENTIONAL STEAM PLANT—WET SCRUBBERS—250 F STACK

Parameter	Evaluation
Steam Cycle Output	819.9 MW
Total Auxiliary Losses	72.7 MW
Net Power Plant Output (60 Hz AC-500kV)	747.2 MW

Table 11

AUXILIARY LOSS BREAKDOWN
CONVENTIONAL STEAM PLANT—WET GAS SCRUBBERS—250 F STACK

ITEM	ASSUMPTIONS	NO. OF UNITS	TOTAL MW_e
FURNACE			
FD FANS	19" Δ P, 0.82 EFF	4	7.3
PA FANS	42" Δ P, 0.82 EFF	4	2.9
ID FANS	23" Δ P 0 78 EFF	4	8.8
ESP	695,000 CFM, 300 F, 0 986 EFF	4	5 2
PULVERIZERS		8	7.6
			31 8
TURBINE AUXILIARY	0.33% OF GROSS kW	1	2 8
WET SCRUBBER			10 0
MAJOR PUMPS			
BOOSTER	600 PSI, 6 MILLION #, 75% x 90%	2	3 7
CONDENSATE	185 PSI, 3 9 MILLION #, 70% x 90%	2	1.0
CIRC WATER	PROPORTION TO COOLING HEAT DUTY	3	4 8
			9 5
WATER INTAKE	A/E ESTIMATE	2	0 9
SOLIDS HANDLING	BASED ON RATES AND LIFTS	1	3.0
"HOTEL" LOADS	A/E ESTIMATE 1% OF GENERATION	1	8.3
COOLING TOWER FANS	PROPORTIONAL TO HEAT DUTY	20	2 3
TRANSFORMERS	0 5% OF GROSS GENERATION	4	4 1
	TOTAL AUXILIARY POWER =		**72.7**

was 4 MW greater than normal as a result of the additional 9 inch drop in water pressure in the wet gas scrubbers; the scrubber system itself consumes 10 MW. All other values are typical of current steam plants. These auxiliary loads consume 8.9 percent of the generator output in the plant.

COSTS-GENERAL

Costs were synthesized from the costs of major components, balance of plant materials, and balance of plant labor. An equipment list of major items in the balance of plant was made to assure completeness and to assure that the selected equipment ratings would match the extreme requirements for continuous operation. A detailed breakdown of balance of plant direct labor in man-hours and of material costs completes the identification of all items of construction and installation costs. To these are added indirect field labor costs and major component costs. An architect-engineering fee is added in proportion to the engineering effort. To the sum total a contingency is applied, to be expended on items not directly counted in a preliminary appraisal such as this. Finally, a factor of 0.548 is added to the total for escalation and interest during construction for the 5.5 year period.

MAJOR COMPONENT CHARACTERISTICS

The steam generator characteristics are listed in Table 12. The heat-delivered efficiency of 87.1 percent would improve approximately 1.2 percent if the flue gas were reduced in temperature to 250 F (394 K) rather than the 300 F (422 K) level dictated by the high level of sulfur in the fuel. The radiant surfaces in the furnace experience a heat flux four times the average, while the more extensive convection surfaces experience twothirds the average heat flux.

Table 12

HEAT EXCHANGER CHARACTERISTICS
CONVENTIONAL STEAM—WET GAS SCRUBBERS—250 F STACK

HEAT EXCHANGER	NO. OF UNITS	VESSEL SIZE OR TYPE	OUTPUT OR DUTY PER UNIT MBtu	EFFICIENCY	UNIT WEIGHT (FOB) M LB	UNIT COST (FOB) M$	SURFACE AREA FT²	HEAT FLUX AVERAGE Btu/(HR FT²)
STEAM GENERATOR	1	130′ x 90′ x 282′	6867	87.1%	40.35	39.73	610,000	11,670
							72,000*	44,745*
							538,000†	7,247†

* RADIANT FURNACE SURFACES
† CONVECTION SURFACES

The cost of $39.73 million (mid-1975) includes the air preheater, flues and ducts, coal pulverizers, and supporting steel and platforms. Excluded are the cost of the fans which appear as balance of plant, and the 6.15 million dollar cost of the electrostatic precipitators with their support steel.

Table 13 shows the cost of the steam turbine-generator at $26 million and expresses the cost per pound and per unit of energy concerned.

Table 13

MAJOR COMPONENT AND SUBSYSTEM WEIGHTS AND COSTS SUMMARY
CONVENTIONAL STEAM—WET GAS SCRUBBERS—250 F STACK

MAJOR COMPONENT OR SUBSYSTEM	WEIGHT (FOB) M LBS	COMPONENT OR SUBSYSTEM COSTS (FOB) M$	OUTPUT OR DUTY	COST PER UNIT OUTPUT OR DUTY	COST PER LB
PRIME CYCLE					
STEAM TURBINE-GENERATOR	6 5	26.0	819.9 MW_e	31.7 $/$kW_e$	4.0 $/LB
(GENERATOR ALONE)	(0 940)	—	819.9 MW_e		--
STEAM GENERATOR	40.35	39.73	2013 MW_{th}	19.74 $/$kW_{th}$	0.98 $/LB

MAJOR COMPONENT AND SUBSYSTEM CAPITAL COST

A more detailed discussion of ultimate costs can be made by including the balance of plant materials and direct and indirect labor costs. Table 14 shows such a compilation.

Table 14

MAJOR COMPONENT AND SUBSYSTEM CAPITAL COST SUMMARY
CONVENTIONAL STEAM PLANT—WET SCRUBBERS—250 F STACK

MAJOR COMPONENT OR SUBSYSTEM	NO OF UNITS	COST/UNIT (FOB) M$	COMPONENT OR SUBSYSTEM COSTS (FOB) M$	BOP MATERIALS M$	SITE LABOR (DIRECT + INDIRECT) M$	TOTAL INSTALLED COST M$
FUEL HANDLING & PREPARATION						
COAL AND SOLIDS HANDLING	—	—	—	9 22	2 72	11 94
PRIME CYCLE						
STEAM TURBINE-GENERATOR	1	26 0	26 0	0,10	2 68	28 78
CONVENTIONAL STEAM GENERATOR	1	39 73	39 73	8 48	23 1	71 31
ELECTROSTATIC PRECIPITATORS	4	1 54	6 15	0 22	2 34	8 71
COOLING TOWERS	20	—	—	3 61	3 17	6 78
PUMPS, HEAT EXCHANGERS, STACKS	—	—	—	11 32	3 48	14 80
PIPING, ETC	—	—	—	14 00	22 33	36 33
GAS CLEANUP SYSTEM						
WET LIME SCRUBBERS				30 36	21 54	51 90

The conventional steam generator with the coal and solids handling aggregate $85 million; the gas cleanup comprising electrostatic precipitators and wet lime scrubber subsystem total $60 million. The steam turbine generator is of the order of $30 million.

It is evident that comparisons based on component costs alone would give proportions totally different from that for the item, including installation costs. Balance of plant equipment and costs therefore merit a detailed evaluation.

BALANCE OF PLANT EQUIPMENT LIST

Specifications for balance of plant equipment are presented in Table 15 as prepared by the architect-engineer (Bechtel). The specifications are based on continuous operation at the valves wide open (VWO) condition for the steam turbine flow rates. The boiler and wet scrubbers have comparable margins.

The electric motor drives for pumps and fans are sized for additional margins of 10 percent on flow, 20 percent on static pressure rise, and approximately 30 percent on power. All of these specifications are for equipment more than sufficient to match the 100 percent operating condition.

BALANCE OF PLANT CAPITAL COSTS

Table 16 presents the architect-engineer's detailed breakdown of the direct manual field labor in thousands of man-hours (MH 1000's), and of balance of plant material cost in thousands of dollars ($1000's) for each major category of the balance of plant. An average hourly field labor rate of $11.75 in mid-1975 dollars is used to convert man-hours to dollars. Where indirect field labor is allocated to individual items rather than the total labor for the job, it is apportioned as 90 percent of the direct field labor, which is equivalent to $10.58 per hour.

The seven major categories used by the architect-engineer relate to the principal field labor skills to be applied. An approximate distribution of costs was also made, using the following categories:

1. Land improvements and structures
2. Coal handling
3. Prime cycle plant equipment
4. Bottoming cycle (not applicable to this plant)
5. Electrical plant and instrumentation

The appropriate subdivision number for each item or major category in Table 16 is indicated in parentheses after its title.

Table 15

BALANCE OF PLANT EQUIPMENT LIST
CONVENTIONAL STEAM PLANT WITH WET LIME SCRUBBERS
250 F EXHAUST GAS TEMPERATURE

Eqpt. No.	Service	Description
	1.0 Coal & Limestone Handling Systems	
C-1	Coal Conveyor Belt	60 in wide, 340 ft long, 3000 tph
C-2	" " "	" " " 760 ft " " "
C-3	" " "	" " " 190 ft " " "
C-4	" " "	42 in " 980 ft " 500 tph
C-5	" " "	" " " 540 ft " " "
C-6	" " "	" " " 170 ft " " "
C-7	" " "	" " " 110 ft " " "
C-8	" " " (2 req'd.)	30 in " 160 ft " 300 tph
C-9	Limestone Conveyor Belt	60 in " 500 ft " 3000 tph
C-10	" " "	24 in " 630 ft " 65 tph
C-11	" " "	" " " 420 ft " " "
C-12	Limestone Bucket Conveyor	" " " 120 ft " 100 tph
C-13	Traveling Grate-Kiln System (Package)	650 ton/day nominal lime production (880 ton/day design capacity), 12 ft wide x 48 ft long traveling grate, 13 ft I.D. x 180 ft long rotary kiln with Niems-type cooler. Includes coal grinding/firing equipment, control panel/instrumentation, all refractories and drives, induced draft fan, baghouse dust collector and ducting.
C-14	Coal Conveyor Belt	18 in wide, 60 ft long, 20 tph
C-15	Lime Bucket Conveyor (2 req'd.)	24 in wide, 140 ft long, 40 tph
C-16	Fly Ash Silos (2 req'd.)	Total Volume 833,184 ft , 80 ft dia x 85 ft high
	2.0 Electrical Systems	
E-1	Main Transformers (2 req'd)	468 MVA, FOA, 65 C, 24/500 kV
E-2	Unit Auxiliary Transformers (2 req'd.)	40/54/67 MVA, 65 C, OA/FA/FOA, 24/13.8 kV, 30, 60Hz

(sheet 1 of 3)

Table 15

BALANCE OF PLANT EQUIPMENT LIST
CONVENTIONAL STEAM PLANT WITH WET LIME SCRUBBERS
250 F EXHAUST GAS TEMPERATURE

Eqpt No.	Service	Description
E-3	Emergency Diesel Generator	1000 kW, 30, 60 Hz, 480 V, 0.8 PF
E-4	Start-up Transformer	28/37.5/47 MVA, OA/FA/FOA, 500/13.8 kV, FOA, 65 C, 30, 60 Hz
E-5	Miscellaneous 480V LCC Transformers (14 req'd.)	1689 kVA, OA, 65 C, 13.8 kV/489V/277V, 30, 60 Hz
E-6	Boiler Auxiliary Transformers (2 req'd.)	5500 kVA, OA, 65 C, 13.8/4.16kV, 30, 60 Hz
E-7	LCC Transformers (2 req'd.)	7000 kVA; OA, 65 C, 13.8/4.16 kV, 30, 60 Hz
E-8	Scrubber Transformers (2 req'd.)	5,000 kVA, OA, 65 C, 13.8/4.16 kV, 30, 60 Hz
	3.0 Main Fluid Systems	
F-1	Main Condenser	3.31 x 10 ft of Heat Transfer Area Std. material.
F-2	Piping:	
	Circulating Water	I. D. = 114 in
	Main Steam	I. D. = 15.3 in, tm = 3.97 in
	Boiler Feed Water	I. D. = 26.53 in, tm = 0.675 in
	Cold Reheat	I. D. = 32.54 in, tm = 1.57 in
	Hot Reheat	I. D. = 18.1 in, tm = 2.25 in

F-3 Feedwater Heaters:

	Shell Press/Temp. psia/ F	Tube Press/Temp. psia/ F	Flow (100%) lb/hr	Heat Transfer Area ft
LP #1	5/163	210/158	4.05 x 10	14,330
LP #2	11/195	210/190	4.05 x 10	13,550
LP #3	20/228	210/223	4.05 x 10	13,720
LP #4	67/300	210/295	4.05 x 10	18,770
IP	296/416	1040/415	6.22 x 10	45,660
H.P.	745/510	5,700/519	6.22 x 10	49,700
DFT	6.22x10 lb/hr, @ 353 F			

Eqpt No.	Service	Description
F-4	Main Condensate Pumps and Motors (2 req'd.)	Vertical Centerline, 4250 gpm, 600 hp motor, 410 ft TDH
F-5	Feedwater Booster Pumps & Motors (2 req'd.)	7,300 gpm, 3850 hp, 1510 ft TDH

(sheet 2 of 3)

Table 15

BALANCE OF PLANT EQUIPMENT LIST
CONVENTIONAL STEAM PLANT WITH WET LIME SCRUBBERS
250 F EXHAUST GAS TEMPERATURE

Eqpt. No.	Service	Description	
F-6	Main Boiler Feed Pumps & Turbine Drivers (3 req'd.)	4900 gpm, 12,600 hp, 8,300 ft TDH	
F-7	Main Circulating Pumps and Motors (3 req'd.)	82,000 gpm, 2250 hp, 75 ft TDH	
F-8	Cooling Towers (20 Cells)	246,000 gpm	
F-9	Forced Draft Fans (2 req'd.)	Operating	971,000 cfm @ 80°F, S.P. = 19 in wg
		Test Block	1,165,000 cfm @ 105°F, S.P. = 24.7 in wg
		Motor	6500 hp
F-10	Primary Air Fans (2 req'd.)	Operating	161,750 cfm @ 96 F, S.P. inlet 19 in wg, S.P. outlet = 42 in wg
		Test Block	194,000 cfm @ 121 F, S.P. inlet 19 in wg, S.P. outlet = 54.6 in wg
		Motor	2250 hp
F-11	Electrostatic Precipitators (4 req'd.)	Each 54 ft high x 92 ft wide x 44 ft long, 1,262,000 lb, 1296 kVA, 99% particulate removal efficiency, 695,000 acfm @ 300°F.	
F-12	Scrubber - Turbulent Contact Absorber (6 req'd.)	Each 60 ft high x 40 ft wide x 18 ft long, 316L-S.S., neoprene lined, 3 stages, 450,000 acfm @ 312°F & 13.9 psia.	
F-13	Air Heater (6 req'd.)	Each 4.5 ft high x 21.5 ft wide x 37.5 ft long .	
F-14	Induced Draft Fans (4 req'd.)	Operating	660,000 cfm @ 300°F, Total S.P. = 23 in wg
		Test Block	800,000 cfm @ 325°F, Total S.P. = 30 in wg
		Motor	5,000 hp
F-15	Forced Draft Fans for Reheater Air (6 req'd.)	Operating	545,000 cfm @ 80°F, Total S.P. = 3.5 in wg
		Test Block	654,000 cfm @105°F, Total S.P. = 4.55 in wg
		Motor	650 hp
F-16	Exhaust Stack	40 ft I.D., 500 ft high	

(sheet 3 of 3)

Table 16

BALANCE OF PLANT ESTIMATE DETAIL FOR CONVENTIONAL STEAM CYCLE—WET GAS SCRUBBER—250 F STACK

	Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
1.0 STEAM GENERATOR (3)		
1.1 Steam Generator Erection		
- Erect only (supply by others): includes heat transfer surface and pressure parts; buckstays, braces and hangers; fuel-burning equipment; accessories; soot and ash equipment; control systems; brickwork, refractory and insulation	544	
- Supply and erect: includes support steel and access steel for above; miscellaneous materials and labor operations	296	6,800
1.2 Steam Generator Auxiliaries		
- Erect only (supply by others): includes P.A. fans, air preheater; flues and ducts to precipitators; insulation for flues and ducts; pulverizers, feeders and hoppers	185	
- Supply and erect: includes F.D. Fans (2 @ $390,000 ea*); I.D. fans (4 @ $220,000 ea.*)	12	1,680
1.3 Electrostatic Precipitators		
- Erect only (supply by others): includes electrostatic precipitators	99	
- Supply and erect: includes support steel for precipitators	4	220
	1,140	8,700
2.0 TURBINE GENERATOR (3)		
- Install only (supply by others): includes 835 MWe steam turbine; generator; exciter, auxiliary equipment, integral steam and auxiliary piping; insulation; miscellaneous labor operations	120	100

*based on suppliers' verbal budgetary quotations

(sheet 1 of 7)

Table 16

BALANCE OF PLANT ESTIMATE DETAIL FOR CONVENTIONAL STEAM CYCLE—WET GAS SCRUBBER—250 F STACK

		Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
3.0	PROCESS MECHANICAL EQUIPMENT		
3.1	Boiler Feedwater Pumps (3)		
	includes turbine-driven main feedwater pumps and drivers (3@ $940,000 ea.*); feedwater booster pumps and motors (2 @ $125,000 ea.*)	10	3,220
3.2	Main Circ. Water Pumps (3)		
	includes main circ. water pumps and motors (3 @ $220,000 ea*)	3	700
3.3	Other Pumps (3)		
	includes condensate pumps and motors (2@ $85,000 ea.*); and other pumps and drivers not listed elsewhere	5	650
3.4	Main Condenser* (3)		
	includes shells; tubes; air ejectors	16	2,120
3.5	Heaters, Exchangers, Tanks and Vessels (3)		
	includes l.p. feedwater heaters (4): i.p. feed water heater; h.p. feedwater heater; deaerating heater and storage tank; miscellaneous heaters and exchangers; tanks and vessels	9	3,060
3.6	Stack and Accessories (3)		
	includes concrete stack and liner*; lights and marker painting; hoists and platforms, stack foundation	113	1,570
3.7	Turbine Hall Crane (1)		
	includes crane and accessories	3	410
3.8	Coal Handling (2)		
	includes railcar dumping equipment; dust collectors; primary and secondary crushing equipment; belt scale; sampling station; magnetic cleaners; mobile equipment; conveyors to pile; reclaiming feeders; conveyors to coal silos; coal silos	61	5,640

*based on suppliers' verbal budgetary quotations

(sheet 2 of 7)

Table 16

BALANCE OF PLANT ESTIMATE DETAIL FOR CONVENTIONAL STEAM CYCLE—WET GAS SCRUBBER—250 F STACK

	Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
3.9 Limestone Handling (3)		
includes magnetic cleaners; conveyor to lime stone pile; reclaiming feeders; belt scale; conveyors to calciner	22	1,250
3.10 Ash Handling (2)		
includes bottom ash system, fly ash handling system for precipitators and air preheater; ash conveyors; ash storage silos (2) with feeders, unloaders and foundations; railcar loading equipment	61	3,580
3.11 Cooling Towers* (3)		
includes mechanical draft towers with fans and motors	52	2,230
3.12 Other Mechanical Equipment (3)		
includes water treatment and chemical injection; air compressors and auxiliaries; fuel oil ignition and warm-up; screenwell, miscellaneous plant equipment, equipment insulation	30	1,660
3.13 Scrubber Ductwork (3)	207	3,270
- includes flue gas duct outboard of electrostatic precipitators; duct lining; duct insulation; dampers and expansion joints		
3.14 Scrubber Flue Gas Equipment (3)	27	3,090
- includes F.D. fans for flue gas reheat (6 @ $200,000 ea.*), air heaters for flue gas reheat (6 @ $280,000 ea*)		
3.15 Wet Lime SO2 Scrubbers (3)	86	6,930
- includes complete SO2 scrubber vessels with presaturator and mist eliminator systems (6 @ $1,000,000 ea*)		

*based on suppliers' verbal budgetary quotations

(sheet 3 of 7)

Table 16

BALANCE OF PLANT ESTIMATE DETAIL FOR CONVENTIONAL STEAM CYCLE—WET GAS SCRUBBER—250 F STACK

		Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
	3.16 Scrubber Lime System (3)	66	3,660
	- includes limestone calciner with travelling grate kiln ($2,700,000*); Kiln stack; coal conveyor, bucket elevator and storage bin for kiln; lime conveyor, bucket elevator and storage silos; lime slaker ($120,000*)		
	3.17 Scrubber System Pumps (3)	10	1,080
	- includes slurry recycle (18 @ $40,000 ea*); mist eliminator wash (3 @ $25,000 ea.*); slurry storage and transfer (4 @ $4,000 ea*); slurry feed (3 @ $5,000 ea*), pond feed tank (3 @ $10,000 ea*); pond feed booster (2 @ $15,000 ea*); pond water recycle and booster (4 @ $12,500 ea*),		
	3.18 Scrubber System Tanks (3)	4	2,180
	- includes tanks and agitators for absorber effluent hold, pond feed, entrainment separator surge, slurry surge, slurry storage, slurry transfer		
		785	46,300
4.0	ELECTRICAL (5)		
	4.1 Main Transformers*	4	2,020
	4.2 Other Transformers* and Main Bus	17	1,280
	- includes startup transformer; station service transformers including those for scrubber system, generator main bus		
	4.3 Switchgear and Control Centers	42	3,400
	- includes switchgear and load centers; motor control centers, local control stations, distribution panels, relay and meter boards		
	4.4 Other Electrical Equipment	363	2,010
	- includes communications, grounding, cathodic and freeze protection; lighting, pre-operational testing		

*based on suppliers' verbal budgetary quotations

(sheet 4 of 7)

Table 16

BALANCE OF PLANT ESTIMATE DETAIL FOR CONVENTIONAL STEAM CYCLE—WET GAS SCRUBBER—250 F STACK

		Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
4.5	Auxiliary Diesel Generator	2	110
-	includes diesel generator, batteries and associated d.c. equipment		
4.6	Conduit, Cable Trays, Wire and Cable	632	4,080
		1,060	12,900
5.0	CIVIL AND STRUCTURAL		
5.1	Concrete Substructures and Foundations (1)	340	2,800
-	includes turbine and boiler building substructure; coal, limestone and ash handling foundations, pits and tunnels; miscellaneous equipment foundations; auxiliary buildings substructures; miscellaneous concrete		
5.2	Superstructures (1)	275	7,960
-	includes turbine building, auxiliary yard buildings; boiler enclosure		
5.3	Earthwork (1)	130	300
-	includes building excavations; coal, limestone and ash handling excavations; circ. water system excavations, miscellaneous foundation excavations; dewatering and piling		
5.4	Cooling Tower Basin and Circ. Water System (3)	90	1,380
-	includes circ. water pump pads, riser and concrete envelope for pipe; cooling tower basin; circ. water pipe; cooling tower miscellaneous steel and fire protection		
5.5	SO2 Scrubber Civil and Structural (1)	180	3,660
-	includes foundations, earthwork and structures particular to scrubber equipment		
		1,015	16,100

(sheet 5 of 7)

Table 16

BALANCE OF PLANT ESTIMATE DETAIL FOR CONVENTIONAL STEAM CYCLE—WET GAS SCRUBBER—250 F STACK

		Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
6.0	PROCESS PIPING AND INSTRUMENTATION		
6.1	Steam and Feedwater Piping (3)	81	3,850
-	includes main steam; extraction steam; hot reheat; cold reheat; feedwater and condensate large piping, valves and fittings		
6.2	SO2 Scrubber System Large Piping (3)	53	2,630
-	includes make-up water; resaturation slurry water; mist eliminator wash; absorber slurry effluent tank overflow; pond feed; pond recycle water; lime slurry piping; recycle slurry piping; air heater steam supply; air heater condensate return		
6.3	Other Large Piping (3)	231	4,050
-	includes auxiliary steam; process water; auxiliary systems		
6.4	Small Piping (3)	152	1,350
-	includes all piping, valves and fittings of 2 inch diameter and less		
6.5	Hangers and Misc. Labor Operations (3)	420	1,460
-	includes all hangers and supports; material handling; scaffolding; misc. labor operations		
6.6	Pipe Insulation (3)	63	660
6.7	Instrumentation and Controls (5)	220	4,900
		1,220	18,900
7.0	YARDWORK AND MISCELLANEOUS (1)		
7.1	Site Preparation and Improvements	87	10
-	includes soil testing; clearing and grubbing; rough grading; finish grading; landscaping		
7.2	Site Utilities	5	50
-	includes storm and sanitary sewers; non-process service water		

(sheet 6 of 7)

Table 16

BALANCE OF PLANT ESTIMATE DETAIL FOR CONVENTIONAL STEAM CYCLE—WET GAS SCRUBBER—250 F STACK

		Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
7.3	Roads and Railroads	27	740
-	includes railroad spur; roads, walks and parking areas		
7.4	Yard Fire Protection, Fences and Gates	52	600
7.5	Water Treatment Ponds	88	20
-	includes earthwork; pond lining; offsite pipeline		
7.6	Lab, Machine Shop and Office Equipment	1	280
		260	1,700

(sheet 7 of 7)

PLANT COST ESTIMATE

The major components from Table 14 and the balance of plant costs appropriate to each of the categories of field labor skills used in Table 15 are combined in Table 17 show a total of $301.62 million.

Table 17

PLANT CAPITAL COST BREAKDOWN
CONVENTIONAL STEAM PLANT—WET GAS SCRUBBERS—250 F STACK

CATEGORIES		COSTS (MILLIONS OF DOLLARS) COMPONENTS	DIRECT LABOR (1)	INDIRECT FIELD (2)	MATERIALS (3)	TOTAL
1.0	STEAM GENERATORS	45.88	13 40	12.06	8.70	80 04
2 0	TURBINE GENERATOR	26.00	1 41	1 27	0.10	28.78
3 0	PROCESS MECHANICAL EQUIPMENT		9 22	8 30	46 30	63 82
4 0	ELECTRICAL		12.46	11 21	12 90	36 57
5 0	CIVIL AND STRUCTURAL		11 93	10.73	16 10	38 76
6 0	PROCESS PIPING AND INSTRUMENTATION		14.34	12.90	18.90	46.14
7 0	YARDWORK AND MISCELLANEOUS		3.06	2.75	1.70	7 51
		71 88	65.82	59.22	104.70	301 62
		BOP LABOR, MATERIALS & INDIRECTS (SUM OF 1 + 2 + 3)			229.74	
		A/E HOME OFFICE & FEE @ 15%				34 50
		TOTAL PLANT COST				336 12
		CONTINGENCY @ 20%				67 22
		TOTAL CAPITAL COST				403 34

The home office and fee of 15 percent is applied only to the balance of plant costs. A contingency of 20 percent of all prior costs is applied to cover expected costs not specifically included in the original estimating process. The total capital cost of $403 million represents $492/kW based on total generation, or $540/kW based on net station output.

A reallocation of costs according to equipment function is presented in Table 18. Items 1 through 6 include everything in the preceding table. Item 7 adds the value of escalation and interest during the 5.5 year construction time. This item is 55 percent of the prior total. The result is a final plant cost of $761/kW of total generation, or $835/kW of net station output.

Table 18

PLANT CAPITAL COST ESTIMATE SUMMARY
CONVENTIONAL STEAM PLANT—WET SCRUBBERS—250 F STACK
(Approximate Distribution)

	MAJOR COMPONENTS M$	BOP MATERIALS M$	SITE LABOR (DIRECT & INDIRECT M$	TOTAL M$
1 0 LAND IMPROVEMENTS & STRUCTURES (LAND, PLANT AREA 92 ACRES) (LAND, 30-YEAR DISPOSAL 1785 ACRES)*	0	16.8	26 5	43.4
2 0 COAL HANDLING	0	9 2	2.7	11.9
3 0 PRIME CYCLE PLANT EQUIPMENT	71 9	60 9	67.2	199.9
4 0 BOTTOM CYCLE NOT APPLICABLE				
5 0 ELECTRICAL PLANT & INSTRUMENTATION	0	17 8	28 6	46 4
SUBTOTAL	71.9	104 7	125 0	301 6
6 0 A-E SERVICE & CONTINGENCY				101 7
7 0 ESCALATION & INTEREST DURING CONSTRUCTION				221 0
			TOTAL M$	624.3
			PLANT OUTPUT MW	747.2
			TOTAL $/kW	835.4

*COST INCLUDES LAND PREPARATION FOR 5 YEAR DISPOSAL.

Section 6

NATURAL RESOURCES AND ENVIRONMENTAL INTRUSIONS

The natural resources required for this plant are listed in Table 19. The sorbent use is low because of the highly efficient chemical system. The high coal use reflects a reduced generation due to steam diversion for reheating and, in addition, added auxiliary power consumed in the wet gas scrubber system and in the induced draft fans. The water usage is mostly for the cooling tower and is at conventional levels.

Table 19

NATURAL RESOURCE REQUIREMENTS
CONVENTIONAL STEAM PLANT—WET GAS SCRUBBERS—250 F STACK

Parameter	Value
Sorbent, Limestone lb/kWh	0.16
Coal, lb/kWh	0.996
Water, Total (gal/kWh)	
Cooling	
Evaporation	0.56
Blowdown	0.18
Plant General Use	0.01
Sulfur Cleanup Use	0.07
Total Land, acres/100 MW_e	
Main Plant	12.3
Disposal Land	239.0

The large land area consigned to sludge accumulation suggests that some innovative exploitation of the sludge might reduce this element of resource wastage. To a certain degree the sludge ponds may represent an ongoing threat to the surroundings. Their reclamation for agriculture or their use as a chemical resource could offset the liability of their accumulation.

The environmental intrusions are enumerated in Table 20. The sulfur emissions are three-quarters of the allowed 1.2 lb/MBtu (2.5 Kg/GJ). This results from 90 percent capture, whereas 83 percent capture would just equal the limit. The NO_x released would be just under the current limit by the use of staged combustion in firing the boiler. The stack gas reheaters place a greater fraction of heat rejection at the stack as compared with other plants.

Table 20

ENVIRONMENTAL INTRUSION
CONVENTIONAL STEAM PLANT—WET GAS SCRUBBERS—250 F STACK

EMISSIONS	LB/MBtu INPUT	LB/kWh OUTPUT
SO_X	0.867	0.0093
NO_X	0.65	0.0070
HC		
PARTICULATES	0.092	0.00099

THERMAL POLLUTION

HEAT, REJECTED COOLING TOWERS, Btu/kWh	4188
HEAT, REJECTED STACK, Btu/kWh	3130*
HEAT, REJECTED TOTAL, Btu/kWh	7318

WASTES	LB/kWh	M LB/DAY
WATER DISCHARGE	1.59	28 4
DRY FLY ASH	0.07	1.30
SLUDGE	0 19	3.46

*INCLUDES ALL SYSTEM LOSSES EXCEPT THE HEAT REJECTED BY THE COOLING TOWER SYSTEM.

SENSITIVITY TO EMISSION TARGETS

The chemical processes in use for wet scrubbing and for combustion do not lend themselves to drastic changes in current emission targets. If the sulfur emission target were to be half the current level, the scrubbers would increase in size and gaseous pressure drop by a factor of 50 percent. The auxiliary power loss in the scrubber system would tend to increase by approximately 5 MW. Reduction in particulate emissions would require an increase of electrostatic precipitators of 100 percent to reach 0.05 lb/MBtu (0.1 kg/GJ), or half the current standard.

The reduction of NO_X would be particularly difficult, since there is already a burden of fuel-bound nitrogen to which the thermal NO_X is added. Reduction to half the current standard is not currently deemed feasible.

Section 7

SUMMARY OF PERFORMANCE AND COST

Table 21 summarizes the performance and cost for a 747 MW steam plant using wet gas scrubbers with 250 F stack temperature. The low overall plant efficiency of 32 percent is due to steam diversion for stack gas reheating and parasitic auxiliary loads imposed by the wet gas scrubbing system. The coal rate of 1 lb/kWh was a typical plant value 45 years ago.

Table 21

SUMMARY PERFORMANCE AND COST
CONVENTIONAL STEAM PLANT—WET GAS SCRUBBERS—250 F STACK

ITEM		
NET POWER PLANT OUTPUT (MW_e - 60Hz - 500 kV)		747.2
THERMODYNAMIC EFFICIENCY (%)		40.7
POWER PLANT EFFICIENCY (%)		31.8
OVERALL ENERGY EFFICIENCY (%)		31.8
COAL CONSUMPTION (LB/kWh)		0.996
TOTAL WASTES (LB/kWh)		0.27
PLANT CAPITAL COST ($ MILLION)		624.3
PLANT CAPITAL COST ($/$kW_e$)		835.4
COST OF ELECTRICITY, CAPACITY FACTOR = 0 65		
CAPITAL	(MILLS/kWh)	26.4
FUEL	(MILLS/kWh)	10.7
MAINTENANCE & OPERATION	(MILLS/kWh)	2.6
TOTAL	(MILLS/kWh)	39.8
ESTIMATED TIME OF CONSTRUCTION (YEARS)		5.5

The high plant costs result from the additional costs of the scrubber system and the reduction of net output already noted. The net result is a cost of electricity (COE) of 39.8 mills/kWh, or 4 cents/kWh at the power plant boundary. The sensitivity of the cost of electricity to these factors is presented in Table 22.

Table 22

COST OF ELECTRICITY (COE) SENSITIVITY
CONVENTIONAL STEAM PLANT WITH WET GAS SCRUBBERS
(250 F Stack Temperature)

	Base Capacity Factor 0.65	Fuel Cost Increase 50%	Labor Cost Increase 50%	Materials Increase 50%	Capacity Factor Change 0.5	Capacity Factor Change 0.8
COE, Capital	26.4	26.4	32.2	33.9	34.3	21.5
COE, Fuel	10.7	16.1	10.7	10.7	10.7	10.7
COE, O&M	2.6	2.6	2.6	2.6	2.7	2.6
Total COE	39.8	45.2	45.5	47.2	47.8	34.8

Section 8

ALTERNATIVE PLANT CONSIDERATIONS

STACK GAS REHEAT TO 175 F

An appraisal was made for the identical boiler and scrubber configuration wherein the stack gas was reheated to 175 F (353 K) instead of 250 F (394 K). Table 23 indicates those elements that were unchanged, those elements that were significantly changed, and some details of the greatly reduced stack gas reheat effect. The requirement for stack gas reheat would be reduced by a factor of 2.5. The reheat energy release from air heated to 335 F (441 K) would increase by a factor of 1.9. The combined effect reduces the heat duty on the steam reheaters to 23 percent of that required heretofore.

Table 23

CONVENTIONAL STEAM PLANT WET GAS SCRUBBERS—175 F STACK
FOR 175 F STACK IN PLACE OF 250 F STACK

NOT CHANGED

- COAL RATE, AIR RATE, GAS RATE
- SCRUBBER CONFIGURATION
- HEAT TO STEAM CYCLE

CHANGED

- HEAT TO REHEAT STACK GAS
- REHEAT AIR FLOW
- STEAM TO STACK GAS REHEATERS
- STEAM TURBINE CYCLE
- GENERATED POWER
- HEAT TO COOLING TOWERS

REHEAT EFFECTS	250 F	175 F	RATIO
STACK GAS REHEAT FROM 125 F	125 F	50 F	2.5
AIR HEAT RELEASE FROM 335 F	85 F	160 F	1/1.9
AIR AND STEAM FLOW RATIOS	1	0 23	4.3

A revised steam-turbine cycle heat balance was made to reflect these changes. The major changes over values found on Figure 5 are tabulated in Table 24. The overall energy balance of Table 9 would be unchanged except for the generated power. The changes in Table 24 and the fixed values from Table 2 were used to reassess the auxiliary power losses as presented in Table 25.

The system output as shown in Table 26 becomes 795.5 MW, an increase of 6 percent over the previous case with 250 F (394 K) stack.

Table 24

STEAM TURBINE CYCLE CHANGES
FOR 175 F STACK VERSUS 250 F STACK

Parameter	250 F Stack	175 F Stack
Turbine Type	TC4F33.5	TC4F33.5
Heat to steam, cycle, MBtu/Hr	6867.4	6867.4
Generator output, kW	819938	868620
Gross heat rate, Btu/kWh	8375.54	7906.13
Steam-to-gas reheater, lb/Hr	926,000	213,426
Last stage flow, lb/Hr	2,888,123	3,472,980
Condensate pump flow, lb/Hr	3,925,037	4,668,000
Heat to condenser, MBtu/Hr	3086	3638
Turbine cost, M$	26.0	26.75

Table 25

AUXILIARY LOSS BREAKDOWN
CONVENTIONAL STEAM PLANT—WET GAS SCRUBBERS—175 F STACK

ITEM	ASSUMPTIONS	NO. OF UNITS	TOTAL MW_e
FURNACE			
FD FANS	19" Δ P, 0 82 EFF	4	7.3
PA FANS	42" Δ P, 0.82 EFF	4	2 9
ID FANS	23" Δ P, 0.78 EFF	4	8 8
ESP	695000 CFM, 300F, 0 986 EFF	4	5 2
PULVERIZERS		8	7 6
			31 8
TURBINE AUXILIARY	0 33% OF GROSS kW	1	2.9
WET SCRUBBER			8 6
MAJOR PUMPS			
BOOSTER	600 PSI, 6 MILLION #, 75% x 90%	2	3 7
CONDENSATE	185 PSI, 4 7 MILLION #, 70% x 90%	2	1.2
CIRC WATER	PROPORTION TO COOLING HEAT DUTY	3	5 6
			10 5
WATER INTAKE	A/E ESTIMATE	2	0 9
SOLIDS HANDLING	BASED ON RATES AND LIFTS	1	3 0
"HOTEL" LOADS	A/E ESTIMATE 1% OF GENERATION	1	8 4
COOLING TOWER FANS	PROPORTIONAL TO HEAT DUTY	20	2 7
TRANSFORMERS	0 5% OF GROSS GENERATION	4	4.3
	TOTAL AUXILIARY POWER =		**73.1**

Table 26

SYSTEM OUTPUT
CONVENTIONAL STEAM PLANT—WET SCRUBBERS—175 F STACK

Parameter	Evaluation
Steam Cycle Output	868.6 MW
Total Auxiliary Losses	73.1 MW
Net Powerplant Output (60 Hz AC-500 kV)	795.5 MW

The revisions to the wet scrubber system relate entirely to the reduced steam and air flows for the stack gas reheat. The lower table on Figure 7 shows these details for the 175 F (353 K) stack configuration. Tables 4, 6, and 8 show the changes in the scrubber system cost details.

The overall plant arrangement details would not be changed. The increased generation does change the size of electrical apparatus, as shown on Figure 13.

The balance of plant equipment list is presented in Table 27. The balance-of-plant direct labor man-hours and material costs are presented in Table 28. These combine with the major equipment costs to determine a plant cost of $396 million as detailed in Table 29. Table 30 redistributes the costs and adds on the escalation and interest during construction. The results is a plant capital cost of $771 per kilowatt of net plant output.

PERFORMANCE AND COST—175 F STACK

Table 31 summarizes the system performance and cost with 175 F (353 K) stack reheat, and Table 32 compares the influence of 250 F (394 K) and 175 F (353 K) stack reheat cases. On every measure the 175 F (353 K) stack shows advantage over the 250 F (394 K) stack. The sensitivity of the cost of electricity to the several major variables is presented in Table 33.

Natural resource usage and environmental intrusions would be comparable to values in Tables 19 and 20, but there would be a 6 percent reduction where the basis was kilowatt-hours.

NO SCRUBBER, 250 F (394 K) STACK ALTERNATIVE

It is instructive to apply the methodology of these evaluations to a plant in which low-sulfur coal would be burned and the wet gas scrubbing system dispensed with. An

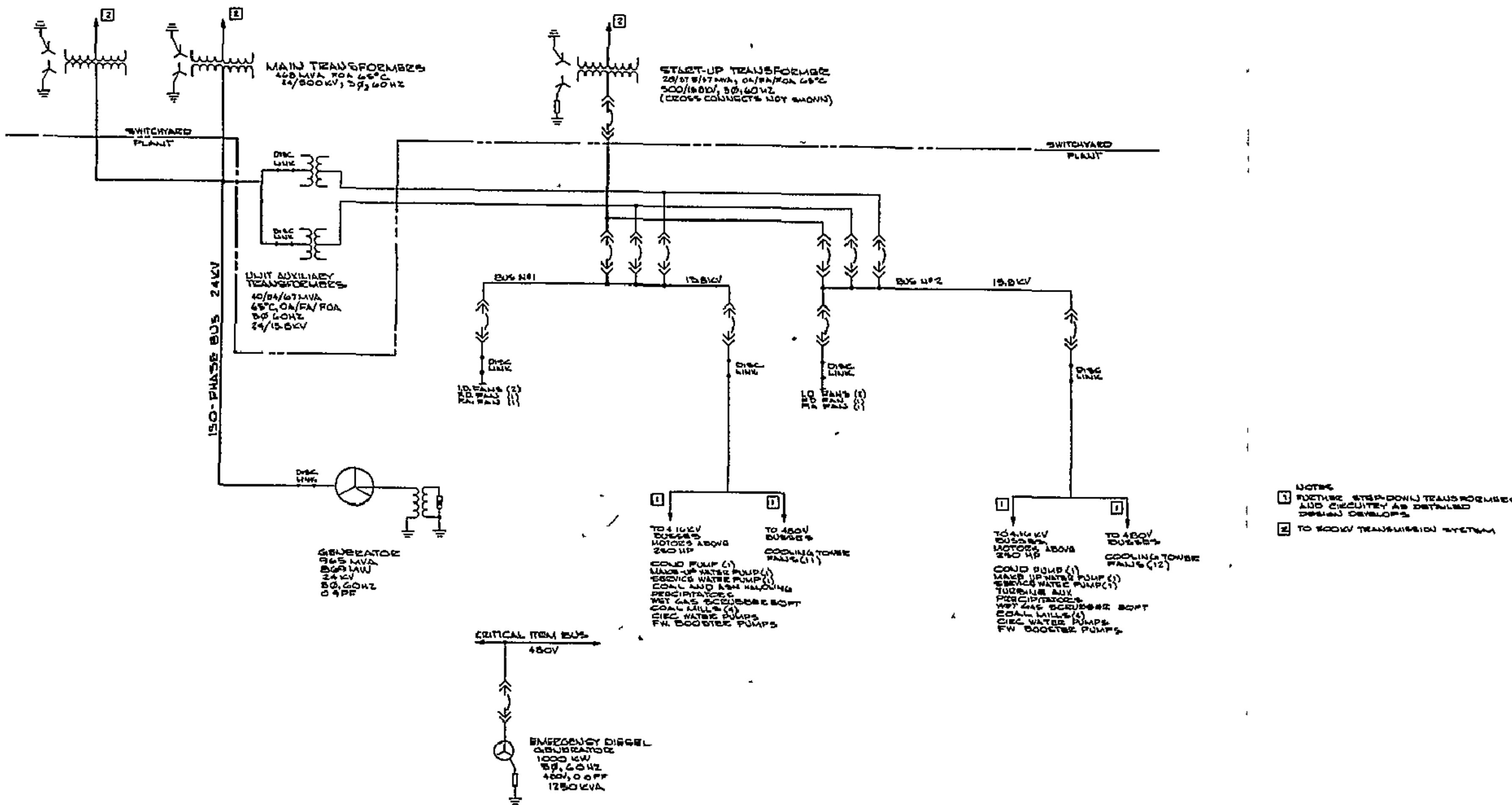


Figure 13. Conventional Steam Plant with Wet Gas Scrubber—175 F

Table 27

EQUIPMENT LIST FOR CONVENTIONAL STEAM CYCLE—
WET SCRUBBERS, 175 F STACK

EQPT. NO.	SERVICE	DESCRIPTION
	1. Coal,& Limestone Handling Systems	
C-1	Coal Conveyor Belt	60 in wide, 340 ft long, 3000 tph
C-2	" " "	60 in " 760 ft " 3000 "
C-3	" " "	60 in " 190 ft " 3000 "
C-4	" " "	42 in " 980 ft " 500 "
C-5	" " "	42 in " 540 ft " 500 "
C-6	" " "	42 in " 170 ft " 500 "
C-7	" " "	42 in " 110 ft " 500 "
C-8	" " " (2)	30 in " 160 ft " 300 "
C-9	Limestone Conveyor Belt	60 in " 500 ft " 3000 "
C-10	" " "	24 in " 630 ft " 65 "
C-11	" " "	24 in " 420 ft " 65 "
C-12	Limestone Bucket Conveyor	24 in " 120 ft " 100 "
C-13	Traveling Grate Kiln System (Package)	650 ton/day nominal lime production (880 ton/day design capacity), 12 ft wide x 48 ft long traveling grate, 13 ft I.D. x 180 ft long rotary kiln with Niems type cooler. Includes coal grinding/firing equipment, control panel/instrumentation, all refractories and drives, induced draft fan, baghouse dust collector and ducting.
C-14	Coal Conveyor Belt	18 in wide 60 ft long 20 tph
C-15	Lime Bucket Conveyor (2)	24 in " 140 ft " 40 "
C-16	Fly Ash Silos (2)	Total Volume 833,184 ft^3, 80 ft dia x 85 ft high

(sheet 1 of 4)

Table 27

EQUIPMENT LIST FOR CONVENTIONAL STEAM CYCLE—
WET SCRUBBERS, 175 F STACK

EQPT. No.	SERVICE	DESCRIPTIONS
	2. Electrical Systems	
E-1,2	Main Transformers (2)	468 MVA FOA 65°C, 24/500 kV
E-3,4	Unit Aux. Transformers (2)	40/54/67 MVA 65°C, OA/FA/FOA,24/13.8 kV, 3Ø, 60Hz
E-5	Emergency Diesel Gen.	1000 kW 3Ø, 60 Hz, 480 V, 0.8 PF
E-6	Start-up Transformer	28/37.5/47 MVA,OA/FA/FOA,500/13.8 kV FOA 65°C 3Ø, 60 Hz
E-7 thru 20	Miscellaneous 480V LCC Transformers(14)	1689 kVA, OA, 65°C, 13.8 kV/ 480V/277V 3Ø, 60 Hz
E-21 & 22	BLR. Aux. Transformers (2)	5500 kVA, OA, 65°C, 13.8/4.16kV,3Ø, 60 Hz
E-23 & 24	LCC Transformers (2)	7000 kVA, OA, 65°C, 13.8/4.16 kV, 3Ø, 60 Hz
E-25 &26	Scrubber Transformers (2)	5,000 kVA, OA, 65°C, 13.8/4.16 KV, 3Ø, 60 Hz
	3. Main Fluid Systems	
F-1	Main Condenser	3.97×10^5 ft^2 of Heat Transfer Area
F-2	Piping	
	Circ. Water	I. D. = 123 in

(sheet 2 of 4)

Table 27

EQUIPMENT LIST FOR CONVENTIONAL STEAM CYCLE—
WET SCRUBBERS, 175 F STACK

EQPT. No.	SERVICE	DESCRIPTION
	Main Steam	I. D. = 15.3 in, tm = 3.97 in
	B.F.W.	I. D. = 26.52 in, tm = 0.675 in
	Cold R. H.	I. D. = 32.54 in, tm = 1.57 in
	Hot R. H.	I. D. = 18.1 in, tm = 2.25 in

EQPT. No.	SERVICE	Shell Press/Temp psia/°F	Tube Press/Temp psia/°F	Flow (100%) lb/hr	Heat Transfer Area ft²
F-3	Feedwater Heaters				
	LP #1	5/163	210/158	4.75×10^6	17,170
	LP #2	11/195	210/190	4.75×10^6	16,260
	LP #3	20/228	210/223	4.75×10^6	16,600
	LP #4	67/300	210/295	4.75×10^6	22,710
	IP	296/416	1040/416	6.22×10^6	45,660
	H.P.	745/510	5,700/519	6.22×10^6	49,700
	DFT	6.22×10^6 lb/hr , @ 353°F			

EQPT. No.	SERVICE	DESCRIPTION
F-4	Main Cond. Pumps and motors (2)	Vert. Cent. 5100 gpm, 750 hp motor, 410 ft TDH
F-5	F.W. Booster Pumps & Motors (2)	7,300 gpm, 3850 hp, 1510 ft TDH
F-6	Main Boiler Feed Pumps & Turbine Drivers (3)	4900 gpm, 12,600 hp, 8,300 ft TDH
F-7	Main Circ. Pumps and Motors (3)	95,000 gpm 2500 hp, 75 ft TDH
F-8	Cooling Towers (23 Cells)	242,058 gpm.
F-9	F.D.Fans (2)	Operating 971,000 cfm @ 80°F, S.P. = 19 in wg Test Block 1,165,000 cfm @105°F, S.P. = 24.7 in wg Motor 6500 hp

(sheet 3 of 4)

Table 27

EQUIPMENT LIST FOR CONVENTIONAL STEAM CYCLE—
WET SCRUBBERS, 175 F STACK

EQPT. No.	SERVICE	DESCRIPTION
F-10	P.A. Fans (2)	Operating 161,750 cfm @ 96°F, S.P. inlet in wg S.P. outlet = 42 in wg Test Block 194,000 cfm @ 121°F, S.P. inlet 19 in wg S.P. outlet = 54.6 in wg Motor 2250 hp
F-11	Electrostatic Precipitators (4)	Each 54 ft high x 92 ft wide x 44 ft long, 1,262,000 lb, 1296 kVA, 99% particulate removal efficiency, 695,000 acfm @ 300°F.
F-12	Scrubber - Turbulent Contact Absorber (6)	Each 60 ft high x 40 ft wide x 18 ft long, 316L-S.S, neoprene lined, 3 stages, 450,000 acfm @312°F & 13.9 psia.
F-13	Air Heaters (6)	Each 2.5 ft high x 18.2 ft wide x 10.7 ft long.
F-14	I.D. Fans (4)	Operating 660,000 cfm @300°F, Total S.P.=23 in wg Test Block 800,000 cfm @325°F, Total S.P.=30 in wg Motor 5,000hp
F-15	F.D. Fans for Reheater Air (6)	Operating 123,000 cfm @ 80°F, Total S.P.=3.5 in wg Test Block 147,000 cfm @105°F, Total S.P.=4.55 in wg Motor 150 hp
F-16	Exhaust Stack (1)	27 ft I.D., 500 ft high

(sheet 4 of 4)

Table 28

BALANCE OF PLANT ESTIMATE DETAIL CONVENTIONAL STEAM CYCLE—
WET LIME STACK GAS SCRUBBER, 175 F STACK GAS

	Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
1.0 STEAM GENERATOR		
1.1 Steam Generator Erection (3)		
- Erect only (supply by others): includes heat transfer surface and pressure parts; buckstays, braces and hangers; fuel burning equipment; accessories; soot and ash equipment; control systems; brickwork; refractory and insulation	544	
- Supply and erect: includes support steel and access steel for above; miscellaneous materials and labor operations	296	6,800
1.2 Steam Generator Auxiliaries (3)		
- Erect only (supply by others): includes P.A. fans; air preheater; flues and ducts to precipitators; insulation for flues and ducts; pulverizers, feeders and hoppers	185	
- Supply and erect: includes F.D. Fans (2 @$390,000 ea*); I.D. fans (4 @$220,000 ea.*)	12	1,680
1.3 Electrostatic Precipitators (3)		
- Erect only (supply by others): includes electrostatic precipitators	99	
- Supply and erect: includes support steel for precipitators	4	220
	1,140	8,700
2.0 TURBINE GENERATORS (3)		
- Install only (supply by others): includes 835 MWe steam turbine; generator; exciter; auxiliary equipment; integral steam and auxiliary piping; insulation; miscellaneous labor operations	120	100

*based on suppliers' verbal budgetary quotations

(sheet 1 of 7)

Table 28

BALANCE OF PLANT ESTIMATE DETAIL CONVENTIONAL STEAM CYCLE—
WET LIME STACK GAS SCRUBBER, 175 F STACK GAS

		Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
3.0	PROCESS MECHANICAL EQUIPMENT		
3.1	Boiler Feedwater Pumps (3)		
-	includes turbine-driven main feedwater pumps and drivers (3 @ $940,000 ea.*); feedwater booster pumps and motors (2 @$125,000 ea.*)	10	3,220
3.2	Main Circ. Water Pumps (3)		
-	includes main circ. water pumps and motors (3 @ $235,000 ea*)	3	750
3.3	Other Pumps (3)		
-	includes condensate pumps and motors (2 @ $95,000 ea.*); and other pumps and drivers not listed elsewhere	5	670
3.4	Main Condenser* (3)		
-	includes shells; tubes; air ejectors	17	2,440
3.5	Heaters, Exchangers, Tanks and Vessels (3)		
-	includes l.p. feedwater heaters (4); i.p. feed water heater; h.p. feedwater heater; deaerating heater and storage tank; miscellaneous heaters and exchangers; tanks and vessels	9	3,160
3.6	Stack and Accessories (3)		
-	includes concrete stack and liner*; lights and marker painting; hoists and platforms; stack foundation	86	1,240
3.7	Turbine Hall Crane (1)		
-	includes crane and accessories	3	410
3.8	Coal Handling (2)		
-	includes railcar dumping equipment; dust collectors; primary and secondary crushing equipment; belt scale; sampling station; magnetic cleaners; mobile equipment; conveyors to pile; reclaiming feeders; conveyors to coal silos; coal silos	61	5,640

*based on suppliers' verbal budgetary quotations

(sheet 2 of 7)

Table 28

BALANCE OF PLANT ESTIMATE DETAIL CONVENTIONAL STEAM CYCLE—WET LIME STACK GAS SCRUBBER, 175 F STACK GAS

	Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
3.9 Limestone Handling (3)		
- includes magnetic cleaners; conveyor to lime stone pile; reclaiming feeders; belt scale; conveyors to calciner	22	1,250
3.10 Ash Handling (2)		
- includes bottom ash system; fly ash handling system for precipitators and air preheater; ash conveyors; ash storage silos (2) with feeders, unloaders and foundations; railcar loading equipment	61	3,580
3.11 Cooling Towers* (3)		
- includes mechanical draft towers with fans and motors	60	2,580
3.12 Other Mechanical Equipment (3)		
- includes water treatment and chemical injection; air compressors and auxiliaries; fuel oil ignition and warm-up; screenwell; miscellaneous plant equipment; equipment insulation	30	1,660
3.13 Scrubber Ductwork (3)	120	1,950
- includes flue gas duct outboard of electrostatic precipitators; duct lining; duct insulation; dampers and expansion joints		
3.14 Scrubber Flue Gas Equipment (3)	7	900
- includes F.D. fans for flue gas reheat (6 @$85,000 ea.*); air heaters for flue gas reheat (6 @$50,000 ea.*)		
3.15 Wet Lime SO2 Scrubbers (3)	86	6,930
- includes complete SO2 scrubber vessels with pre-saturator and mist eliminator systems (6 @ $1,000,000 ea.*)		

*based on suppliers' verbal budgetary quotations

(sheet 3 of 7)

Table 28

BALANCE OF PLANT ESTIMATE DETAIL CONVENTIONAL STEAM CYCLE— WET LIME STACK GAS SCRUBBER, 175 F STACK GAS

		Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
	3.16 Scrubber Lime System (3)	66	3,660
	- includes limestone calciner with travelling grate kiln ($2,700,000*); Kiln stack; coal conveyor, bucket elevator and storage bin for kiln; lime conveyor, bucket elevator and storage silos; lime slaker ($120,000*)		
	3.17 Scrubber System Pumps (3)	10	1,080
	- includes slurry recycle (18 @$40,000 ea.*); mist eliminator wash (3 @$25,000 ea.*); slurry storage and transfer (4 @$4,000 ea.*); slurry feed (3 @$5,000 ea.*); pond feed tank (3 @$10,000 ea.*); pond feed booster (2 @ $15,000 ea.*); pond water recycle and booster (4 @$12,500 ea.*)		
	3.18 Scrubber System Tanks (3)	4	2,180
	- includes tanks and agitators for absorber effluent hold, pond feed, entrainment separator surge, slurry surge, slurry storage, slurry transfer		
		660	43,300
4.0	ELECTRICAL (5)		
	4.1 Main Transformers*	4	2,020
	4.2 Other Transformers* and Main Bus	17	1,280
	- includes startup transformer; station service transformers including those for scrubber system; generator main bus		
	4.3 Switchgear and Control Centers	42	3,400
	- includes switchgear and load centers; motor control centers; local control stations; distribution panels, relay and meter boards		
	4.4 Other Electrical Equipment	363	2,010
	- includes communications; grounding; cathodic and freeze protection; lighting; pre-operational testing		

*based on suppliers' verbal budgetary quotations

(sheet 4 of 7)

Table 28

BALANCE OF PLANT ESTIMATE DETAIL CONVENTIONAL STEAM CYCLE—
WET LIME STACK GAS SCRUBBER, 175 F STACK GAS

		Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
4.5	Auxiliary Diesel Generator	2	110
-	includes diesel generator, batteries and associated d. c. equipment		
4.6	Conduit, Cable Trays, Wire and Cable	632	4,080
		1,060	12,900
5.0	CIVIL AND STRUCTURAL		
5.1	Concrete Substructures and Foundations (1)	340	2,800
-	includes turbine and boiler building substructures; coal, limestone and ash handling foundations, pits and tunnels; miscellaneous equipment foundations; auxiliary buildings substructures; miscellaneous concrete		
5.2	Superstructures (1)	275	7,960
-	includes turbine building; auxiliary yard buildings; boiler enclosure		
5.3	Earthwork (1)	130	300
-	includes building excavations; coal, limestone and ash handling excavations; circ. water system excavations; miscellaneous foundation excavations; dewatering and piling		
5.4	Cooling Tower Basin and Circ. Water System (3)	105	1,680
-	includes circ. water pump pads, riser and concrete envelope for pipe; cooling tower basin; circ. water pipe; cooling tower miscellaneous steel and fire protection		
5.5	SO2 Scrubber Civil and Structural (1)	180	3,660
-	includes foundations, earthwork and structures particular to scrubber equipment		
		1,030	16,400

(sheet 5 of 7)

Table 28

BALANCE OF PLANT ESTIMATE DETAIL CONVENTIONAL STEAM CYCLE— WET LIME STACK GAS SCRUBBER, 175 F STACK GAS

			Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
6.0	PROCESS PIPING AND INSTRUMENTATION			
	6.1	Steam and Feedwater Piping (3)	81	3,850
	-	includes main steam; extraction steam; hot reheat; cold reheat; feedwater and condensate large piping, valves and fittings		
	6.2	SO2 Scrubber System Large Piping (3)	51	2,370
	-	includes make-up water; resaturation slurry water; mist eliminator wash; absorber slurry effluent tank overflow; pond feed; pond recycle water; lime slurry piping; recycle slurry piping; air heater steam supply; air heater condensate return		
	6.3	Other Large Piping (3)	231	4,050
	-	includes auxiliary steam; process water; auxiliary systems		
	6.4	Small Piping (3)	152	1,350
	-	includes all piping, valves and fittings of 2 inch diameter and less		
	6.5	Hangers and Misc. Labor Operations (3)	419	1,420
	-	includes all hangers and supports; material handling; scaffolding; misc. labor operations		
	6.6	Pipe Insulation (3)	62	640
	6.7	Instrumentation and Controls (5)	219	4,820
			1,215	18,500
7.0	YARDWORK AND MISCELLANEOUS (1)			
	7.1	Site Preparation and Improvements	87	10
	-	includes soil testing; clearing and grubbing; rough grading; finish grading; landscaping		
	7.2	Site Utilities	5	50
	-	includes storm and sanitary sewers; non-process service water		

(sheet 6 of 7)

Table 28

BALANCE OF PLANT ESTIMATE DETAIL CONVENTIONAL STEAM CYCLE—
WET LIME STACK GAS SCRUBBER, 175 F STACK GAS

		Direct Manual Field Labor MH 1000's	Balance of Plant Material $ 1000's
7.3	Roads and Railroads	27	740
-	includes railroad spur; roads, walks and parking areas		
7.4	Yard Fire Protection, Fences and Gates	52	600
7.5	Water Treatment Ponds	88	20
-	includes earthwork; pond lining; offsite pipeline		
7.6	Lab, Machine Shop and Office Equipment	1	280
		260	1,700

Table 29

BALANCE OF PLANT CAPITAL COST BREAKDOWN
CONVENTIONAL STEAM PLANT—WET GAS SCRUBBERS—175 F STACK

		COSTS (MILLIONS OF DOLLARS)				
CATEGORIES	COMPONENTS	DIRECT LABOR (1)	INDIRECT FIELD (2)	MATERIALS (3)	TOTAL
1 0 STEAM GENERATORS	45.88	13.40	12.06	8.70	80.04
2 0 TURBINE GENERATOR	26.75	1 41	1.27	0.10	29.53
3 0 PROCESS MECHANICAL EQUIPMENT		7.76	6.98	43.30	58.04
4 0 ELECTRICAL		12.46	11.21	12.90	36.57
5.0 CIVIL AND STRUCTURAL		12.10	10.89	16.10	39.39
6 0 PROCESS PIPING AND INSTRUMENTATION		14.27	12.85	18.50	45.62
7 0 YARDWORK AND MISCELLANEOUS		3 06	2.75	1.70	7.51
	72.63	64.46	58.01	101.30	296.40

BOP LABOR, MATERIALS & INDIRECTS (SUM OF 1 + 2 + 3)	223 2	
A/E HOME OFFICE & FEE @ 15%		33.57
TOTAL PLANT COST		329.97
CONTINGENCY @ 20%		65.99
TOTAL CAPITAL COST		395 96

Table 30

PLANT CAPITAL COST ESTIMATE SUMMARY
CONVENTIONAL STEAM PLANT—WET SCRUBBERS—175 F STACK
(Approximate Distribution)

		MAJOR COMPONENTS M$	BOP MATERIALS M$	SITE LABOR (DIRECT & INDIRECT M$	TOTAL M$
1 0	LAND IMPROVEMENTS & STRUCTURES (LAND, PLANT AREA 92 ACRES) (LAND, 30-YEAR DISPOSAL 1785 ACRES)*	0	16 8	26.5	43 4
2 0	COAL HANDLING	0	9 2	2 7	11 9
3 0	PRIME CYCLE PLANT EQUIPMENT STEAM CYCLE/CF 868 2 MW_e	72 6	57 6	64 7	194 8
4 0	BOTTOM CYCLE NOT APPLICABLE				
5 0	ELECTRICAL PLANT & INSTRUMENTATION	0	17 7	28 6	46 3
	SUBTOTAL	72 6	101 3	122 5	296 4
6 0	A E SERVICE & CONTINGENCY				99 6
7 0	ESCALATION & INTEREST DURING CONSTRUCTION				217.5
				TOTAL M$	613.6
				PLANT OUTPUT MW_e	795.5
				TOTAL $/$kW_e$	771.3

*COST INCLUDES LAND PREPARATION FOR 5 YEAR DISPOSAL.

Table 31

SUMMARY PERFORMANCE AND COST
CONVENTIONAL STEAM PLANT—WET GAS SCRUBBERS—175 F STACK

ITEM		
NET POWER PLANT OUTPUT (MW_e - 60Hz - 500 kV)		795 5
THERMODYNAMIC EFFICIENCY (%)		43 1
POWER PLANT EFFICIENCY (%)		33 8
OVERALL ENERGY EFFICIENCY (%)		33 8
COAL CONSUMPTION (LB/kWh)		0.936
TOTAL WASTES (LB/kWh)		0 25
PLANT CAPITAL COST ($ MILLION)		613 6
PLANT CAPITAL COST ($/$kW_e$)		771 3
COST OF ELECTRICITY, CAPACITY FACTOR = 0 65		
CAPITAL	(MILLS/kWh)	24 4
FUEL	(MILLS/kWh)	10 1
MAINTENANCE & OPERATION	(MILLS/kWh)	2 5
TOTAL	(MILLS/kWh)	37.0
ESTIMATED TIME OF CONSTRUCTION (YEARS)		5.5
APPROXIMATE DATE OF FIRST COMMERCIAL SERVICE		1980-1982

Table 32

INFLUENCE OF STACK REHEAT TEMPERATURE
CONVENTIONAL STEAM PLANT—WET GAS SCRUBBERS

PARAMETER	250 F STACK	175 F STACK
STEAM TO GAS REHEATER, LB/HR	926,000	213,426
GENERATOR OUTPUT, kW	819,938	868,620
NET PLANT OUTPUT, kW	747,200	795,500
OVERALL ENERGY EFFICIENCY, %	31 8	33.8
CAPITAL COST, M$	624	614
CAPITAL COST, $/kW	835	771
ELECTRICITY COST, MILLS/kWh		
CAPITAL	26.4	24.4
FUEL	10.7	10.1
O&M	2.6	2.5
TOTAL	**39.8**	**37.0**

Table 33

COST OF ELECTRICITY (COE) SENSITIVITY
CONVENTIONAL STEAM PLANT—WET GAS SCRUBBERS—175 F STACK

	BASE CAPACITY FACTOR 0.65	FUEL COST INCREASE 50%	LABOR COST INCREASE 20%	MATERIALS INCREASE 20%	CAPACITY FACTOR CHANGE 0.5 & 0.8	
COE, CAPITAL	24.4	24.4	26.5	27 2	31.7	19.8
COE, FUEL	10.1	15.1	10.1	10.1	10.1	10.1
COE, O&M	2.5	2 5	2.5	2.5	2.6	2.5
TOTAL COE	37 0	42.1	39.1	39.8	44.4	32.4

identical boiler would be used. An air preheater increased in size by 62 percent would bring the stack gas to 250 F (394 K) as appropriate for low-sulfur fuel. The coal, air, and gas rates and boiler auxiliary losses would be scaled downward 1.4 percent by the boiler efficiency improvement. The electrostatic precipitator would precede the air preheater, to operate on the high-temperature low-sulfur gas stream. The heat to the steam cycle would be unchanged.

The steam turbine cycle would be identical with that of another system that has been analyzed in detail as to balance of plant man-hour and material costs. Use of the available data with the boiler and other data used with the wet scrubber cases permitted the synthesis of a cost breakdown and performance on a comparable basis.

Table 34 presents the breakdown of auxiliary losses, and Table 35 compares the performance and costs to the wet scrubber cases. The overall efficiency would be 36.2 percent. The cost of electricity would be 30.5 mills/kWh if the fuel cost remained at $1/MBtu. The price of low-sulfur coal at exact parity with the 175 F (353 K) wet scrubber case would be $1.68/MBtu. A dominant plant difference would be the absence of the large sludge ponds. The reduced operating and maintenance cost reflects elimination of the costs of limestone, maintenance of the wet scrubber system, and operators for the wet scrubber system.

Table 34

AUXILIARY LOSS BREAKDOWN
CONVENTIONAL STEAM PLANT—NO SCRUBBERS—250 F STACK

ITEM	MW	SUBTOTAL MW
FURNACE		26.55
FD FANS	3.35	
PA FANS	2.81	
ID FANS	7.84	
ESP	5 10	
PULVERIZERS	7 45	
TURBINE AUXILIARY	2 90	
WET SCRUBBERS — NONE	0 00	
MAJOR PUMPS		11.07
BOOSTER	3.37	
CIRCULATING	4.70	
OTHER	3 00	
SOLIDS HANDLING	3 00	
HOTEL LOADS	8.50	
COOLING TOWER FANS	2 80	
TRANSFORMER LOSS	4.40	
TOTAL AUXILIARY POWER =	**59.22MW**	

Table 35

SYSTEM OUTPUT
CONVENTIONAL STEAM PLANTS

Parameter	250 F Wet Scrubbers	175 F Wet Scrubbers	250 F No Scrubbers
Generator Output, MW	819.9	868.6	883.9
Auxiliary Losses, MW	72.7	73.1	59.2
Net Plant Output, MW	747.2	795.5	824.7
Output Ratio	0.94	1	1.04
Overall Energy Efficiency, %	31.8	33.8	36.2
Capital Cost, M$	624	614	511
Capital Cost, $/kW	835	771	620
Electricity Cost, mills/kWh			
Capital	26.4	24.4	19.6
Fuel	10.7	10.1	9.5*
O&M	2.6	2.5	1.4
Total	39.8	37.0	30.5*

*Low sulfur coal at $1.68/MBtu would increase fuel cost to just equal cost total with scrubbers, and 175 F stack temperature.

Section 9

COMPARISON OF FUTURE ALTERNATIVES

Future steam power plants may use atmospheric fluidized beds (AFB) for burning coal in the presence of limestone to provide sulfur capture during combustion. A more advanced concept would be the use of pressurized fluidized beds (PFB) with dolomite for sulfur capture and gas turbines for pressurizing. Such plants have been evaluated in the Energy Conversion Alternatives Study (ECAS)(Ref. 1) on the identical basis and to the same degree of detail as the steam plants of this evaluation.

Table 36 compares these alternatives to conventional steam plants with wet lime flue gas scrubbers and stack gas reheat to the designated temperatures (CF 175 F and CF 250 F). The basis for all table entries is $/kW of net plant output. The cost combination for Furnace Modules, Hot Gas Filtering, Solids Handling, and Stack Gas

Table 36

CAPITAL COST DISTRIBUTIONS AS $/kW
FOR 3500 PSI, 1000 F, 1000 F STEAM POWER PLANTS

	AFB 1550 F	PFB 1650 F	CF 175 F	CF 250 F
MAJOR COMPONENTS				
STEAM TURBINE-GENERATOR	33 2	27 7	33 6	34 8
FURNACE MODULES	55 8	16 3	57 7	61 4
GAS TURBINES		28 3		
HOT GAS FILTERING		71 4		
ECONOMIZER		2 5		
SOLIDS HANDLING	11 4	35 6	15 0	15 9
SUBTOTAL	**100.3**	**182.0**	**106.2**	**112.2**
BALANCE OF PLANT				
STACK GAS SCRUBBERS	—	—	56 8	69 5
SITE LABOR	117 8	108 4	126 8	134 9
ALL OTHER	122 1	98 7	123.8	133.3
SUBTOTAL	**239.9**	**207.1**	**307.5**	**337.7**
CONTINGENCY	68 0	77 8	84 2	90 0
ESCALATION AND INTEREST	223 8	255 8	273 0	295 8
TOTAL CAPITAL COST	**632.**	**723**	**771**	**835**
	31.7	**34.1**	**37.0**	**39.8**

(1) Corman, J.C., et al., Energy Conversion Alternatives Study (ECAS), General Electric Phase II Final Report, NASA CR-134949 (3 Vol.), NASA Lewis Research Center Contract NAS3-19406, GE Corporate Research and Development, Schenectady, N.Y., February 1976.

Scrubbers shows most of the cost of heat release and sulfur and particulate capture. These accounts aggregate $67/kW for the AFB, $123/kW for the PFB, and $130/kW to $147/kW for the CF. The total capital cost and the cost of electricity (COE) follow a similar progression.

The consumption of coal relates directly to the overall efficiency of a power plant. A number of alternatives were evaluated here and in the ECAS study, and are presented in Table 37 in the order of decreasing efficiency. The two "no scrubber" cases would require a coal with less than 0.65 percent sulfur for a 10,788 Btu/lb (25.1 MJ/kg) higher heating value if they were to meet the emission standards common to all of these plants. The boiler efficiency follows the same progression as the overall efficiency . The steam turbine cycle efficiency equal to 3412 divided by the heat rate also decreases toward the bottom of the table.

Table 37

EFFICIENCY ORDER OF STEAM PLANTS

TYPE PLANT	CONDITIONS	STACK	OVERALL EFFICIENCY	ELECTRICITY MILLS/kWh	BOILER EFFICIENCY	HEAT RATE
PFB	1750F BEDS	300F	40 0%	34 1	—	—
PFB	1650F BEDS	300F	39 2%	34 1	—	—
CF	NO SCRUBBER	250F	36 2%	30.5*	88.3%	7800
AFB	1550F BEDS	250F	35 8%	31 7	87.4%	7800
CF	NO SCRUBBER	300F	35 7%	31 6*	87 1%	7800
CF	WET SCRUBBER	175F	33.8%	37 0	85 5%	7940
CF	WET SCRUBBER	250F	31 8%	39 8	85 5%	8415

*3.9% S IN COAL NOT PERMITTED

The comparative amounts of sorbent required for sulfur capture are presented in Figure 14. Both the conventional steam plant with wet scrubbers and the AFB plant use limestone. The excess applied as compared with a stoichiometric ratio is 10 percent for the former and 100 percent for the latter. The PFB plant uses dolomite, which has only half the concentration of available lime found in limestone. The conventional plant consumes the least sorbent material. The solid wastes combine the ash and the solid products from sorbent reactions.

The major water usage is evaporation from the cooling towers. The major water waste that must be treated would be the cooling tower blowdown. Figure 15 shows the same progression in water conservation that would be found in coal requirement.

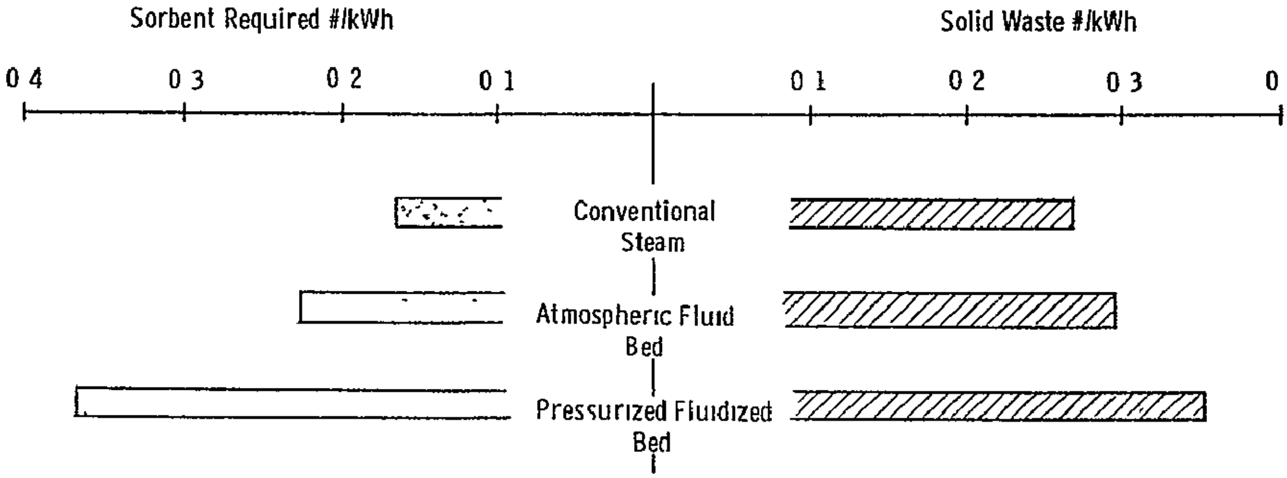


Figure 14. Solids Requirement

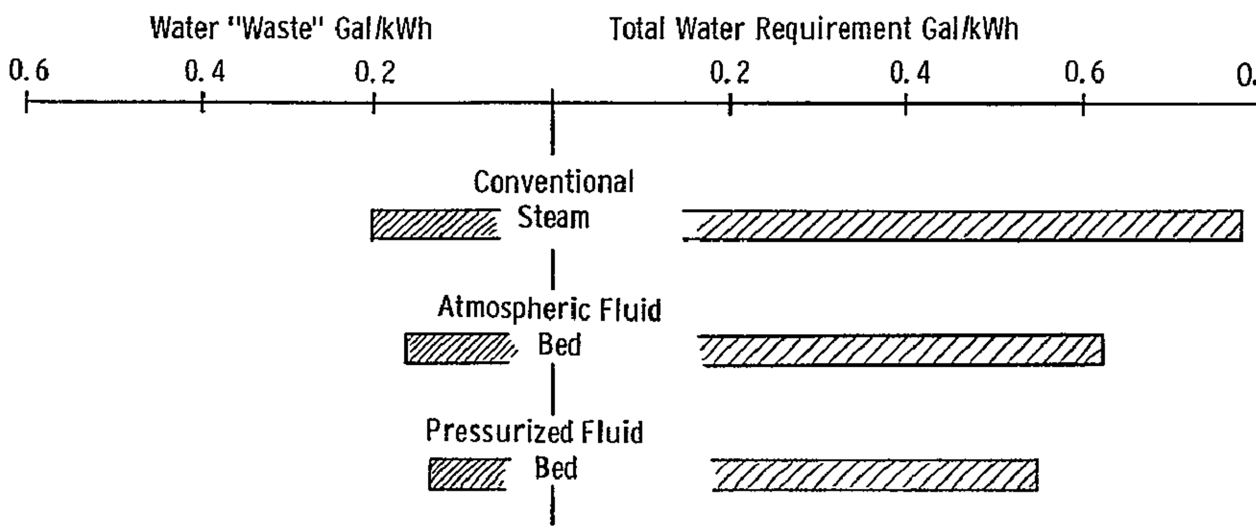


Figure 15. Water Requirement

The gaseous emissions of SO_x and NO_x are compared in Figure 16. The AFB and PFB, with combustion in beds at 1550 F (1116 K) and 1650 F (1172 K) respectively, have produced notably low levels of NO_x. The conventional furnace requires a well balanced, staged combustion system in order to meet current NO_x limitations. All plants satisfy the SO_x limits, with the PFB showing the greatest margin.

OVERVIEW

The conventional steam plant with wet gas scrubbers is the only technology currently in use that permits use of high-sulfur coal while meeting current environmental standards. A large economic penalty results from the added capital cost of the wet scrubbers and from the reduced power generation caused by diversion of steam to reheat

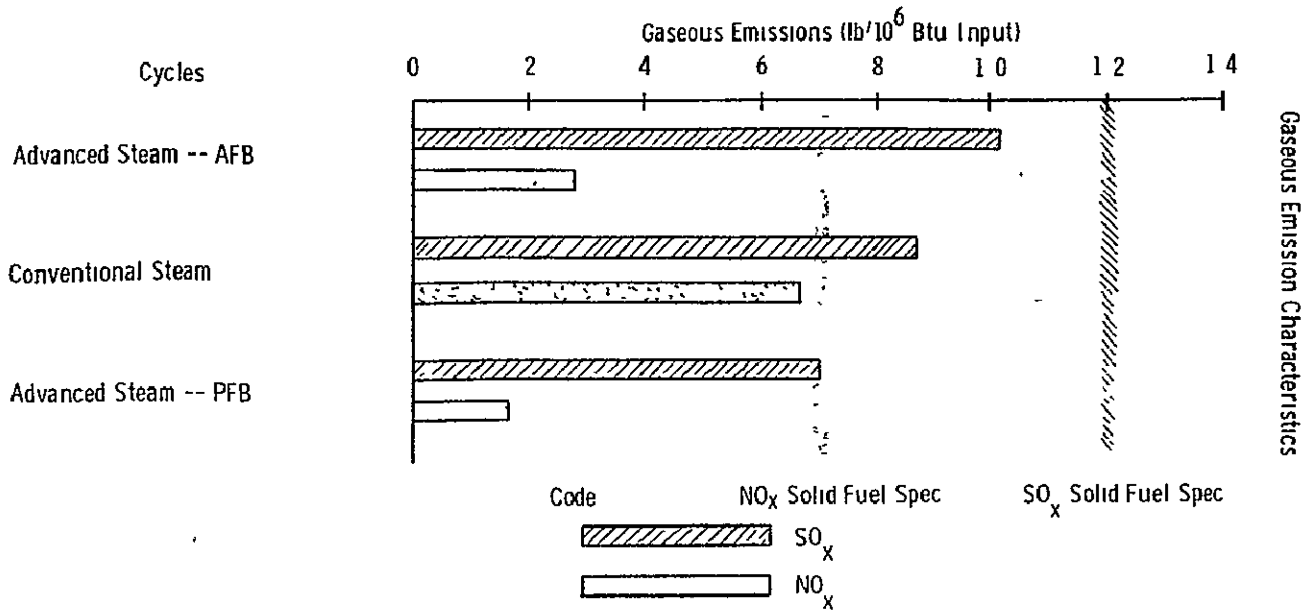


Figure 16. Gaseous Emission Characteristics (Lb/10^{6}Btu Input)

the quenched stack gas. These penalties could be progressively reduced as the technology of wet gas scrubbing matures.

The use of atmospheric fluidized beds, when fully developed, for advanced steam power plants could provide a more economic alternative for meeting current environmental standards while burning high-sulfur coal.

The pressurized fluidized bed steam power plant would deploy gas turbines in the gas stream of the coal and dolomite fluid bed combustion. Results shown in this report show higher efficiency than CWS and AFB. However, the ability to clean the gas stream chemically and mechanically remains to be demonstrated. The achievement of technical and economic targets for this type of power plant is believed to be uncertain pending considerable development and demonstration effort.

Section 10

IMPLEMENTATION ASSESSMENT

The process of implementation assessment devised for the seven power plants selected for Task II of the General Electric portion of the Energy Conversion Alternatives Study (ECAS) was applied to the conventional steam plant with wet lime scrubbers and 175 F (353 K) stack temperature as if it were a new generation of power plant.

A brief review of important plant features, which follows, was presented to the Implementation Assessment Panel. Members of this panel were staff consultants from the Foster Wheeler Energy Company, from the Bechtel Company, and from the General Electric Company. They discussed each factor for assessment as applied to this plant and reached a concensus as to rating. The criteria for rating each assessment factor are presented in Appendix II to this report as derived from the full account in the ECAS Task II and Task III reports by General Electric. No attempt was made to develop a composite rating or to determine relative weights to be accorded each assessment factor.

Despite severe adverse economic impact at the present time, the conventional steam power plant with wet lime stack gas scrubbers is the only plant capable of burning high-sulfur coal for power generation while meeting environmental sulfur emission limits. Other advanced steam power plants with this capability will not be ready for utility use until the 1980s.

The plant studied produces 3500 psig, 1000 F throttle steam with a subsequent reheat to 1000 F (24.2 MN/m^2, 811 K/811 K). Net plant output is 796 MWe at an overall efficiency of 33.8 percent. The plant capital cost was estimated to be \$771 per kilowatt (as compared with \$620 per kilowatt for the same plant without wet gas scrubbers). The higher cost of \$151 per kilowatt included the cost of a calcination plant on site to produce lime from limestone. The large continuous consumption of lime favors this arrangement.

The stack gas would require an electrostatic precipitator of 98.6 percent efficiency to avoid overloading the scrubbers with particulates. The ESPs would be twice the size normally found on conventional plants. Table 38 shows that the stack gas scrubbing system has a cost equal to that for all other major components. The steam used to reheat the stack gas to 175 F (353 K) reduces turbine output so that the compounded effects total the \$151 per kilowatt cited earlier. The evaluated cost of electricity would be 37 mills per kilowatt hour; this is 20 percent greater than electricity cost without scrubbers (assuming the plant without scrubbers could meet the environmental specifications).

Table 38

COST DISTRIBUTION—STEAM POWER PLANT
WITH WET LIME STACK GAS SCRUBBERS

Major Components	Cost ($/kW)
Steam turbine generator	34
Boiler	58
Stack gas scrubbing system	89
Balance of Plant	317
Escalation and Interest During Construction	273
TOTAL	771

Aside from diversion of some steam to reheat stack gases, there is nothing unusual about the supercritical steam cycle. The wet scrubber system introduces a most unusual feature for the power plant. This is the sludge pond. Every five years the sludge formed in the scrubbers would accumulate in a pond approximately one-half of a square mile in area. Six ponds would be required over the life of the plant. This plant feature caused the Implementation Assessment Panel to sharply downgrade the siting flexibility for the plant and to question the risks to public safety and to the local groundwater supply.

Although most of the scrubber system is a proven practice in the process industry, one part of the system was subjected to very close examination. This was the duct system conveying the scrubbed gas to the blending point where heated air was added as a means of reaching 175 F (353 K) stack temperature. The scrubbed gas would be at 125 F (325 K) and would be saturated with water vapor. The refractory-lined ducts were judged to be adequate for that service.

The wet lime scrubbing system of this study is representative of current state-of-the-art technology. A list of flue gas wet lime scrubbing systems is presented in Table 39 to indicate the widespread applications in both demonstration and full-scale commercial utility plants. It is notable that many vendors are supplying equipment so that both cost reductions and technical developments could be expected to evolve from the ongoing competition.

IMPLEMENTATION ASSESSMENT FACTORS

The ratings good, fair, or poor were assigned to the conventional steam power plant with wet lime stack gas scrubbers by the Implementation Assessment Panel for each of

Table 39

SUMMARY OF OPERATIONAL FLUE GAS DESULFURIZATION SYSTEMS

	New or Retrofit	MW Served By Unit	Vendor Process	Percentage of Sulfur in Coal	Month/ Year
Duquesne Light Phillips	R	410	Chemico Lime Scrubbing	1.0-2.8	7/73
Duquesne Light Elrama	R	510	Chemico Lime Scrubbing	1.0-2.8	10/75
Kentucky Utilities Green River Units 1 and 2	R	64	American Air Filter Lime Scrubbing	3.8	9/75
Louisville Gas and Electric Paddys Run No. 6	R	65	Combustion Engineering Lime Scrubbing	3.5-4.0	4/73
Montana Power Company Colstrip No. 1	N	360	Combustion Equipment Association Lime Scrubbing	0.8	10/75
Tennessee Valley Authority Shawnee No. 10A	R	10	Universal Oil Products Lime/Limestone Scrubbing	2.9	4/72
Tennessee Valley Authority Shawnee No. 10B	R	10	Chemico Lime/Limestone Scrubbing	2.9	4/72
Arizona Public Service Four Corners No. 5A	R	160	SCE Lime Scrubbing	0.7-0.75	2/76
Columbus and Southern Ohio Electric Conesville No. 5	N	400	Universal Oil Products Lime Scrubbing	4.5-4.9	6/76
Louisville Gas and Electric Cane Run No. 4	R	178	American Air Filter Lime Scrubbing	3.5-4.5	6/76
Louisville Gas and Electric Cane Run No. 5	R	183	Combustion Engineering Lime Scrubbing	3.4-4.5	12/77
Louisville Gas and Electric Mill Creek No. 3	N	425	American Air Filter Lime Scrubbing	3.5-4.0	7/77
Montana Power Company Colstrip No. 2	N	360	Combustion Equipment Association Lime Scrubbing	0.8	7/76
Pennsylvania Power Company Bruce Mansfield No. 1	N	835	Chemico Lime Scrubbing	4.3	4/76
Pennsylvania Power Company Bruce Mansfield No. 2	N	835	Chemico Lime Scrubbing	4.3	4/77
Rickenbacker AFB Rickenbacker	R	20	Research Cottrell Lime Scrubbing	5.0	3/76

the rated implementation factors. These ratings, together with a brief summary of the rationale for them, follow (see also Appendix II, "Criteria for Implementation Assessment Factors").

1. Economic Viability

a. System Capital Cost—Fair

The system capital cost for the conventional steam power plant would be $771/kW including interest and escalation during construction.

b. Cost of Electricity—Fair

The cost of electricity at 65 percent plant capacity factor and $1/million Btu coal would be 37.0 mills/kWh.

2. Efficiency and Fuel Conservation Potential—Fair

The net station output divided by fuel energy input would be 33.8 percent.

3. Natural Resource Requirements—Good

Coal and limestone are consumed natural resources. The stack scrubber using wet lime captures the sulfur from the coal. As a result vast resources of high-sulfur coal can be used in place of the more scarce low-sulfur coal. The limestone use rate is 10 percent greater than the ideal rate to assure adequate sulfur capture. Limestone is a plentiful resource. Depletion of limestone and coal resources would be measured in centuries rather than years for the conventional plant.

4. Environmental Intrusion

a. Atmospheric Intrusion

The atmospheric environmental intrusion would be within EPA standards. Using staged combustion in firing the boiler, the NO_x released would be held just under the emission limit. The sulfur emissions would be 90 percent of the emission limit as a result of the generous stack gas scrubbing sizing, which permits meeting SO_2 limits while operating on coal with a sulfur content as high as 4.5 percent. The actual operation would most likely reduce lime concentration or wash solution flow rate in order to reduce operating cost. Operation just under the sulfur limit would result.

b. Requirements for Waste Handling and Disposal—Fair

The solid wastes accumulate in a lime-rich slurry pond. Each pond is large, approximately one-half of a square mile in area. These sludge ponds are a potential threat to groundwater supply. Flooding rains may overflow the pond, discharging the chemical wastes into the stream runoff system.

5. Reliability and Availability Potential

a. Forced Outage Rate—Poor

The forced outage rate for a conventional steam power plant without wet gas scrubbers was the criterion for "good" forced outage experience. The wet scrubber system would be subdivided into six sections for gas scrubbing. The outage of any one scrubber would force a plant output reduction by 16 percent. These additional outages would cause a total plant outage of the order of 5 percent or more. The single calciner would appear to be a source of added vulnerability. However, a five-day accumulation of lime would be stored at all times to assure continuous lime availability.

b. Planned Outage Rate—Good

The planned outages would be exactly those now experienced for conventional steam plants. The scrubber systems can be readily refurbished at such times. Recovery from single scrubber outages would be a routine service on a single plant item and would not induce a planned outage.

c. Design Features to Obtain 90 Percent Availability

Since the wet scrubber system is the source of incremental forced outage, that is where a solution for greater availability must be found. The scrubber pumps that might fail can be readily duplicated in place. They are low cost items. Loss of one of six wet scrubbers is the critical concern. The addition of scrubber capacity so that any five of six scrubbers could carry full plant output would regain the lost availability. Such a design change would require added induced draft fan capacity to overcome the added resistance to flow with fewer scrubbers in service.

6. Safety

a. In-Plant Safety—Good

The addition of the wet scrubber system does not appreciably alter the "good" safety rating accorded to conventional power plants.

b. Outside Plant Safety—Fair

Today's conventional power plants rate "good" for general public safety in the proximity of the plant. The extensive sludge ponds near these power plants would represent a threat to trespassers who might penetrate the fences that safeguard the ponds. In addition the chemical nature of the runoff from flash flooding, dam rupture, or pool liner failure might pose a health hazard. It should be noted that some ponds are now planned that would use solidifying agents so that the sludge would become totally immobilized.

c. Design Features for Safe Operation

The conventional steam turbine power plant has evolved into a highly safe unit through application of safety standards such as the ASME boiler code for design of heated pressure parts, and through proof-testing such as steam turbine stage overspeed tests. The conservatism of the industry has the effect of preserving the proven past safety experience. The wet lime scrubbing system is not pressurized and has peak temperature of 125 F.(325 K). Compared with chemical process plants this is a very safe operation.

7. Siting Flexibility

a. Flexibility of Siting—Poor

The nature of any large steam power plant is to require an industrial or rural setting with space for cooling towers, reserve coal storage, and tall stacks. Such plants would be restricted from residential sites, sites without bulk delivery facilities for coal, and sites without water. The wet scrubber sludge ponds further restrict these plants. They would be unsuited to porous grounds and to undulating land. Evaporation loss from the sludge ponds would exclude them from dry climates.

b. Independence of Other Systems—Good

The conventional steam plant could operation independently of other plants in the utility grid; this independence includes the ability to start up from a cold down condition. Its steam turbine-generator would support the stiffness of the overall grid system.

8. Life-Limiting Factors

a. Life-Expectancy—Good

Conventional steam power plants have assured useful lives of 30 years or more. The added wet scrubber system can be maintained to give useful service over the same life span.

b. Life-Limiting Phenomena

A potential life-limiting phenomenon exists in the equipment to reheat the cleaned gas leaving the scrubber at 125 F (325 K). Direct heating of the gas has usually resulted in rapid deterioration of the heater. In the configuration of this study there is no direct stack gas reheater. Instead a separate airflow is heated and then blended into the stack gas to produce the needed mixture temperature. No life-limiting phenomena were identified for the configuration chosen for this study.

9. Flexibility of Application

a. Load Following—Good

The conventional steam plant is fully capable of following load changes. Early supercritical steam plants had a restricted turndown ratio that limited their turndown. Recent configuration and control modifications have alleviated those restrictions so that turndown to minimum load or even to prolonged operation carrying only plant auxiliaries is now possible. Restarting from a warm shutdown would require less than 4 hours.

b. Partial Load Efficiency—Good

As the load is reduced, the boiler efficiency tends to improve on a conventional boiler. The steam turbine first stage is served by several valves so that local "best efficiency" points are available. The part load efficiency will be good so that cycling load following can be an economic operation.

c. Minimum Load—Good

The capabilities described for load following permit sustained operation at minimum steam turbine load. Some of the earliest supercritical boilers were restricted to 30 percent turndown. By dumping steam to the condenser, they could achieve turndown to 6 percent load. The supercritical plant of this study was evaluated on the basis of recent steam cycle improvements that permit full-range boiler operation.

10. Ease of Operation and Control

a. System Operating and Maintenance Requirements—Fair

The criterion of evaluation was a conventional steam power plant without scrubbers. The addition of scrubbers makes the operation somewhat more complex. At this time the rating is "fair."

It was noted that the scrubber function is capable of full automation. The steam plant will not be fully automated for unattended operation and did not merit a "good" rating.

b. Manpower Requirements

Personnel to operate the scrubber system were added to the personnel requirements for a conventional power plant to arrive at the following staffing:

Supervisors	16
Operators-plant	40
Fuel system personnel	12
Guards, clerks, laborers	23
Total personnel	91

11. Ease of Maintenance—Fair

The maintenance procedures for large steam turbines and for the conventional supercritical boiler require highly skilled and qualified personnel. The operations to be performed are exacting; they are not simple substitutions of renewal components.

12. Potential for Factory Modular Construction

The conventional steam power plant does not benefit from subdivision into numerous small modules. Maximum economy is realized in a single large boiler and a single large steam turbine. These items require a large amount of field construction labor in erecting and connecting components. There is low potential for modular construction.

13. Manufacture Capability—Good

There are adequate manufacturing facilities for the manufacture of all components of large steam turbine power plants.

14. Fuel Flexibility

a. Adaptability to Different Fuels—Fair

The distribution of radiation and convection heat absorption surfaces in a conventional boiler depends critically on the fuel to be burned. Often the boiler may be adapted to burn oil or gas, but the changeover is time consuming, and the efficiency of the boiler is reduced for the alternate fuels.

b. Adaptability to Coal Variation—Fair

The conventional plant of this study could accept coal with a sulfur content of up to 4.5 percent. If low-sulfur coal were burned, the performance of the electrostatic precipitator would be reduced. Hence there is a limited range of acceptable sulfur content. The ash formed by the coal is also important. A nonslagging coal would be burned poorly in a slagging furnace. Conventional furnaces are designed very specifically to operate well with a particular coal and have a limited adaptability to alternate coals.

15. Compatibility of Fluids and Materials

a. Working Fluid Compatibility—Good

Steam and water are fully compatible with all materials used in the boiler, turbine, and condenser. A tube leakage in the boiler can be tolerated until the leakage exceeds 3 percent of the steam rate. Most leaks do not force a shutdown. The rupture would be repaired during the routine weekend unit shutdown.

b. Combustion Gas Compatibility—Fair

The sulfur compounds in the combustion gas make it moderately aggressive as it approaches its dewpoint temperature. The near-saturated gases leaving the scrubbers at 125 F (325 K) are difficult to contain by the usual metals. A refractory-lined pipe must be used to avoid chemical erosion of the containing pipe up to the point of stack gas reheat.

16. Working Fluid Stability—Good

Water and steam are stable fluids. Boiler quality water is produced in the plant from the available water supply.

17. Potential for Retrofit—Fair

The adaptation of wet lime stack gas scrubbing to many existing steam plants depends on several factors. The gas must be cleaned to the 98.6 percent level of particulates to avoid fouling the scrubbers. The electrostatic precipitator requirement would be twice that of conventional practice. The space to double the electrostatic precipitator and to add the wet scrubbers may preclude the addition at some sites. A more critical consideration would be the availability of pondage to accumulate the sludge that is formed. Few sites are sufficiently rural to provide such large land areas. Older steam plants are usually located on a waterfront and at or near a city. The low probability of satisfying these requirements led to a rating that was less than the best.

18. Opportunity for By-product Sale—Poor

The sludge, composed of calcium sulfate and ash and other compounds, has no known by-product value.

19. Manpower Limitation

a. Field Labor Availability—Good

The skills and numbers of field construction personnel are adequate for conventional steam power plant construction.

b. Factory Labor Availability—Good

The availability of factory labor with the skills required should be adequate for the foreseeable future.

20. Electrical Performance

a. Supportive of Electric Grid—Good

The steam turbine-generator would operate harmoniously with all other modes of power generation applied to the electric grid. Even during major disturbances, it would be supportive of the utility system in holding voltage and frequency.

b. Startup Power Requirement—Good

The startup requirement would be less than 5 percent of rated output. Provision is made to start up with no outside source of power.

21. Probability for Development Success—Good

The components of the wet scrubber system are all of proven performance in other fields. Numerous demonstrator installations are now being made of comparable systems at existing steam plants. Problems of chemical erosion and attack are susceptible to the same countermeasures that have proven successful in the chemical process industry. Technical success is highly probable.

Appendix I

EVALUATION BASIS

The methodology and ground rules used in this evaluation of a conventional steam plant with wet-lime stack gas scrubbers for sulfur removal are identical with those applied to steam power plants and other cycles in the Energy Conversion Alternatives Study. Those elements that are not dealt with in the detailed text of this report will be briefly reviewed here.

The focus was on baseload plants with 30 years' useful life, and a 90 percent plant availability target. The capital costs were estimated in mid-1975 dollars as if all elements were fully developed. All plants were treated as mature and no development costs were included. During construction, prices were assumed to escalate 6 1/2 percent per year. Interest during construction was charged at 10 percent per year; the fixed charged rate per year of operation was 18 percent of plant final cost. The time for construction, 5.5 years, was determined on the basis of the total man-hours of field labor content. The S-curve for expenditures resulted in escalation and interest during construction of 0.548 times the total plant costs without those factors.

The fuel was a high-sulfur Illinois coal (No. 6) with the characteristics defined in Table 40. The emission standards for flue gas are presented in Table 41.

Table 40

FUEL CHARACTERISTICS

ILLINOIS #6 COAL

HIGHER HEATING VALUE (BTU/LB)	10788
COST (DELIVERED) ($/MILLION BTU)	$1.00

COMPOSITION ANALYSIS	% BY WEIGHT	REQUIRED REDUCTION FOR EMISSIONS LIMITS (%)
C	59.6	—
H	5.9	—
S	3.9	83
N	1.0	—
O	20.0	—
ASH	9.6	98.8
	100.0	

Table 41

EMISSION STANDARDS

Pollutant	Fuel	Standard (lb/MBtu heat input)
SO_x	Solid	1.2
NO_x	Solid	0.7
Particulates	All Fuels	0.1

Several efficiencies are reported for each type of plant. For steam plants the thermodynamic efficiency was the generator output divided by the heat input tothe steam cycle. The power plant efficiency and the overall efficiency were both equal to net station output divided by the higher heating value of the coal fired.

The heat rejection from condensers was to mechanical draft evaporative cooling towers. Power plant operation was evaluated for a 59 F (288 K) air ambient with 60 percent relative humidity. The resulting wet-bulb temperature was 51.5 F (284 K).

Uniformity of treatment of all steam plants was assured by use of the same team as contributors. The heat input for combustion and heat exchange to steam were studied by the Foster Wheeler Energy Corporation. The pressurizing gas turbines for the PFB were evaluated by the General Electric Gas Turbine Products Division. Investigations of the steam turbine and its cycle specifications were done by the General Electric Large Steam Turbine Department. The wet lime scrubber system, the heat rejection equipment, and all balance of plant labor and equipment were evaluated by the Bechtel Corporation. Bechtel also provided architect-engineer layouts of the plant site and plant arrangement. The systems integration was done by the General Electric project team.

Operating and maintenance costs were assessed to each plant on the basis of estimates provided by the boiler manufacturer, the steam turbine manufacturer, the architect-engineer for the scrubber system, and the architect-engineer for consumables such as limestone. The operation manning requirement was evaluated by the Installation and Service Engineering staff of General Electric. For the conventional plant with wet scrubbers producing 747.2 MW with 250 F (394 K) stack, the annual costs for 65 percent capacity factor are enumerated in Table 42.

For the 175 F (353 K) stack case at 795.5 MW the dollars per year were held fixed, but the kilowatt-hours per year increased. For evaluation of cases without the scrubber system the basic cost estimated would be $7.37 million per year.

Table 42

OPERATING AND MAINTENANCE COSTS PER YEAR

ITEM	M$	
Maintenance Costs		
Steam turbine-generator and boiler		2.54
Makeup water treatment		0.04
Water intake system		0.04
Electrostatic precipitators		0.32
Balance of plant except scrubbers		1.96
Scrubber system		1.69
Subtotal	6.59	
Operating Labor		
Scrubber system		0.26
Rest of plant		1.56
Total	1.82	
Operating Consumables		
Conventional		0.91
Limestone at $5/ton		1.78
Total	2.69	
Conventional Plant with Scrubbers Total		11.10

Appendix II

CRITERIA FOR IMPLEMENTATION ASSESSMENT FACTORS

OBJECTIVE

The potential adaptability of advanced energy conversion systems into a utility grid is influenced by the intangible as well as the tangible characteristics of the system. The objective of this evaluation is to analyze these characteristics by establishing a set of factors which will influence ultimate implementation and rate each system in relation to these factors. No attempt is made to assess the relative merits of the various factors or to combine the results for tangible and intangible factors.

EVALUATION APPROACH

A list of factors which would affect the implementation of an energy conversion system was prepared, and a merit rating for each factor was then assigned to the system. The list of factors, their descriptions, and a definition of the rating system are presented in the following subsection, "Implementation Factors."

The energy conversion system was evaluated for each implementation assessment factor. This evaluation was performed by a panel whose members have a strong background and experience in power generation systems. The evaluation was performed from the viewpoint of suppliers of equipment and services to utilities and not directly from the viewpoint of the users. The composition of this panel is given in Table 43.

The approach in the panel deliberations was to have the person responsible for the evaluation and technical integration of the energy conversion system present the performance characteristics and conceptual design to the panel. This person was available for answering specific questions during the deliberation but did not participate in the formulation of the rating. The result of this evaluation was a rating of each factor for the energy conversion system and a rationale for these ratings.

IMPLEMENTATION FACTORS

The energy conversion system was rated for each of 21 implementation factors. A rating scale consisting of good, fair, and poor was applied to each factor.

Table 43

IMPLEMENTATION ASSESSMENT PANEL

MAJOR COMPONENT SUPPLIERS

Power Generation Equipment

Project Engineer, Electric Utility Systems Engineering
General Electric Company

Staff Associate to the Vice President for Technical Resources
General Electric Company

Consultant, Engineering and Manufacturing Services
General Electric Company

Manager, Technical Resources Planning Turbine Operations
General Electric Company

Heat Input Systems

Manager, Utility Equipment Sales
Foster Wheeler Energy Corporation

Manager, Advanced Development
Foster Wheeler Energy Corporation

ENGINEERING SERVICE

Architect-Engineering

Project Engineer, New System Development
Bechtel Corporation

Project Engineer, Power Division
Bechtel Corporation

The emphasis of the evaluations was placed on rating the intangible factors and tangible factors that are not quantified at the present time. Although a quantitative rating scale was established for many of the factors, a qualitative and subjective evaluation was necessary in most cases because of the present status of the data base.

1. Economic Viability

The economic viability of a system is expressed in a tangible manner by the presentation of quantitative values for capital cost and cost of electricity. The following items describe the subjective measurements for these parameters.

a. System Capital Cost

A system would be judged good if system capital cost (including interest and escalation during construction) is expected to be less than $500/installed kW. A fair rating would apply between $500 and $800/kW, and poor would apply for higher capital costs.

b. Cost of Electricity

A system is judged good if the cost of electricity is less than 32 mills/kWh, fair between 32 and 38 mills/kWh, and poor if it exceeds 38 mills/kWh.

2. Efficiency and Fuel Conservation Potential

The power plant efficiency is defined here as the net power output from the plant step-up transformer divided by the rate of fuel energy input to the plant. For fossil fuels, the higher heating value is used, and the heating value applies to the fuel that crosses the power plant boundary, not to the fuel derived at the power plant site. (For example, where low-Btu gas is produced from coal in an on-site gasifier, the heating value of the coal, not the gas, is used.)

A power plant efficiency of 38 percent or better is considered good, 30 to 38 percent is fair, and below 30 percent is considered poor.

3. Natural Resource Requirements — Utilization of Fuel and Additive Material

Natural resources refer here to materials consumed or converted in the energy conversion process, but not to those materials used in system construction or in the working fluid inventory. Natural resources include fuel and materials used in the processing or cleanup of fuels, stack gases, or waste. This criterion is significant because consumption of a resource for power generation makes this resource unavailable for other uses.

Since all systems studied used coal—a plentiful resource—all of the ratings depend upon the additives required. A system is considered good if the additive materials are plentiful and there is little competitive demand for them; fair if either of these requirements is not met; poor if neither requirement is met.

4. Environmental Intrusion

a. Atmospheric Intrusion

It is anticipated that in the time period in which these advanced cycles may be applied, environmental considerations will have matured to the point that they represent constraints rather than measures of goodness. It is assumed that all energy conversion systems studied will meet the standards used in Task II; no extra credit is given for bettering these standards.

b. Requirements for Waste Handling and Disposal

A good system is one in which the waste is nonpolluting and of small enough magnitude to permit disposal at the generating site by conventional landfill methods. A fair system is one in which the waste is of sufficient magnitude and pollution potential that it must be disposed of off site, or with special provisions on site. A poor system is one in which the wastes are toxic and of such potential danger to public health that special handling is required, with remote disposal at special sites.

5. Reliability and Availability Potential

a. Forced Outage Rate

For purposes of this study, the forced outage rate is defined as the percentage of total elapsed time that the plant cannot operate because of unexpected failure. A good plant will have a forced outage rate of less than 5 percent. Between 5 and 10 percent will be judged fair, and greater than 10 percent will be judged poor. These forced outage rates are assumed to apply to plants that are mature in design and operation.

b. Planned Outage Rate

The planned outage rate is the percentage of total elapsed time that the plant cannot be operated because of scheduled maintenance and repair. A good plant will have a planned outage rate of less than 10 percent. A fair plant will have between 10 and 17 percent, and a poor plant will have greater than 17.

c. Design Features to Obtain 90 Percent Availability

This criterion was not rated, but these aspects of the conceptual designs are discussed.

6. Safety

a. In-Plant Safety

In case of a major accident within the plant boundary, the potential for fatalities to plant personnel was rated.

b. Outside Plant Safety

In case of a major accident within the plant boundary, the potential for fatalities to the external public including the release of a significant amount of hazardous materials was rated.

c. Design Features for Safety

This factor was not rated but is discussed.

7. Siting Flexibility

a. Flexibility of Siting

A good system is one whose siting is not limited by noise, appearance, size, need for cooling water, bulk fuel delivery, or severe public objections. A fair system is one for which 50 percent of potential sites are unavailable because of these considerations; a poor system is one in which 90 percent of potential sites are unavailable.

b. Independence of Other Systems

A good system is one which may be applied at any physical or electrical location in a power system without dependence upon any other energy system for its operation or economic viability. A fair system must operate in conjunction with and in proximity to other energy systems needed (e.g., to absorb by-products or provide fuel inputs) which are fairly widespread in their occurrence. A poor system is one which requires a unique combination with another energy system whose frequency of occurrence is small.

8. Life-Limiting Factors

a. Life Expectancy

Life is defined here as the span of time after which there is no economic justification for operation of the plant because of performance degradation and/or excessive maintenance costs. A good system is one whose life is estimated to be 30 years or more. A fair system is one whose life is estimated to be 20 to 30 years. A poor system is one whose life is estimated to be less than 20 years even though the design life is set at 30 years.

b. Life-Limiting Phenomena

This factor was not rated but is discussed.

9. Flexibility of Application

No data have been generated under this program to allow more than a qualitative assessment of this factor.

a. Load Following

This criterion refers to mechanical and thermal characteristics that limit the rate of response of a system to changes in load, or that restrict the time required for startup or shutdown.

The rating of a system with respect to this criterion will be expressed in terms of the time required to reach full load from a warm start, and the risk of damage due to a transient.

	Time required to reach full load (hr)	Risk of damage due to transient
Good	Less than 4	Low
Fair	4 to 8	Fair
Poor	Greater than 8	High

b. Part Load Efficiency

Part load efficiency will be expressed as the power plant efficiency when the system is operating at one-half its full load rating. At this condition, a system is considered good if its efficiency is greater than 90 percent of its full load efficiency. Fair will be between 75 percent and 90 percent, and poor will be less than 75 percent.

c. Minimum Load

The minimum load will be that power output below which the plant cannot operate. A good system is defined as one that can have continuous operating at outputs as low as 20 percent of its full load rating. The minimum load of a fair system will be between 20 and 60 percent; a poor system cannot operate below 60 percent.

10. Ease of Operation and Control

a. System Operating and Maintenance Requirements

The tangible effects of operating and maintenance requirements are accounted for directly in the estimated cost of electricity. The intangible effects will be reflected in rating the energy conversion systems as follows: A good system would be one in which the starting and operating procedures are inherently so simple that it can reasonably be considered an unattended, remote, or automatically operated plant. A fair system would be one more nearly like the present generation of steam plants in which operation is more complex and not easily automated. A poor system would be one in which the operational procedures are complex and perhaps not yet fully worked out.

b. Manpower Requirements

The estimated manpower requirements are presented in lieu of a rating for this factor.

11. Ease of Maintenance

A good system would be one in which the maintenance operations would be simple, consisting largely of replacement of expensive parts at predictable times with normally available skilled labor. A fair system is one in which maintenance procedures are more time-consuming and more specialized in terms of labor skills. A poor system is one in which relatively new and unfamiliar processes require specially trained personnel for maintenance.

12. Potential for Factory Modular Construction

This factor was not rated but is discussed for each of the respective systems.

13. Manufacture Capability

This criterion refers to the capability for manufacture of system components (for example, large turbine wheels of high-temperature alloys) after technology development is completed. A system would be rated good if machine tools and process equipment currently in place can manufacture all system components, fair if new specialized machine tools and process equipment using existing manufacturing technology would have to be purchased, and poor if a large (more than $25 million) manufacturing development program would have to be undertaken.

14. Fuel Flexibility

a. Adaptability to Different Fuels

This criterion refers to the capability of a plant to adapt to the use of various kinds of fossil fuels so that the utility can select at any time the lowest cost fuel or the fuel most readily available.

A system will be considered good with respect to this criterion if the system can be designed and constructed to make possible the burning of solid, liquid, or gaseous fuels, without a major modification of the plant. A fair system is capable of utilizing only one of the above three fuel types but can adapt to several grades or varieties of the fuel type without major modification. A poor system either is not adaptable to various types or grades of fuel, or a major modification is needed to adapt the system for various types or grades.

b. Adaptability to Coal Variations

The combustion subsystems were rated on their ability to utilize variations in coal types, e.g., significant fraction of fines, caking coals, high moisture content, high sulfur content, high ash, low ash fusion temperature.

15. Compatibility of Fluids and Materials

a. Working Fluid Compatibility

The compatibility of the cycle working fluid and its containment material was rated.

b. Combustion Gas Compatibility

The compatibility of the containment materials with the combustion gas at system operating conditions was rated.

16. Working Fluid Stability

The stability of the prime and bottoming cycle working fluids under normal or transient system operational conditions and environments was rated.

17. Potential for Retrofit

The ability of the prime energy conversion system, combustion subsystem, or fuel processing system to replace an existing oil- or gas-fired baseload utility power plant was rated.

18. Opportunity for By-product Sale

The opportunity to offer any waste by-products of the power plant for commercial sale was rated.

19. Manpower Limitation

a. Field Labor Availability

The potential shortage in field labor to construct the energy conversion system was rated.

b. Factory Labor Availability

The potential shortage in factory labor to manufacture the major components in the energy conversion system was rated.

20. Electrical Performance

a. Supportive of Electric Grid

This criterion covers a wide range of electrical operating characteristics. A good system would be one whose inherent or modified characteristics permit it to operate stably in synchronism with other generating units on the system, and which would automatically react under emergency conditions to support the system voltage and frequency.

A poor system would be one incapable of supplying reactive kVA to the system and whose power response or control characteristics make it incapable of supporting the power system's need for power in an emergency. Its inertial and impedance characteristics would result in questionable stability except in locations which have the stiffest power systems. Its instantaneous power response would be zero or negative, and its long-time response would be 0.5 percent per minute or less.

A fair system falls between these two extremes.

b. Startup Power Requirements

With respect to this criterion, a good system will require a starting power of less than 5 percent of rated capacity. A fair system will need a starting power between 5 and 25 percent of rated capacity, and a poor system will require a starting power of more than 25 percent.

21. Probability for Development Success

Development success is defined here as meeting the development goals of performance and cost for the Task II conceptual design within the estimated development time and development cost.

A probability of 90 percent or higher is considered good, between 70 and 90 percent fair, and below 70 percent poor.

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Project Manager, G.J. Barna
NASA Lewis Research Center
Cleveland, Ohio 44135

G.R. Fox, Program Manager
G.E. Corporate Research and Development
Schenectady, New York 12301

16. Abstract

A study was performed to estimate the technical/economic characteristics of a steam power plant (3500 psig, 1000 F/1000 F) with a coal-burning radiant furnace and a wet lime stack gas scrubber to control sulfur emissions. Particulate emissions were controlled by an electrostatic precipitator operating at 300 F. The stack gas from the scrubber was reheated from 125 F to 250 F as a base case, and from 125 F to 175 F as an alternate case. The study was performed on a basis consistent with the General Electric ECAS Phase II evaluation of advanced energy conversion systems for electric utility baseload applications using coal or coal-derived fuels. A conceptual design of the power plant was developed, including the on-site calcination of limestone to lime and the provision of sludge ponds to store the products of flue gas scrubbing. From this design, estimates were derived for power plant efficiency, capital cost, environmental intrusion characteristics, natural resource requirements, and cost of electricity at an assumed capacity factor of 65%. An implementation assessment was performed where factors affecting applicability of the conceptual design power plant in electric utility generation systems were appraised. At 250 F and 175 F stack gas temperatures respectively, the plants showed a cost of electricity of 39.8 and 37.0 mills/kWh and overall plant efficiencies of 32% and 34%.

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