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PROOF OF CONCEPT TESTING OF AN INTEGRATED DRY INJECTION SYSTEM FOR SO_x/NO_x CONTROL

Quarterly Technical Progress Report

January - March, 1989

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1.0 Introduction

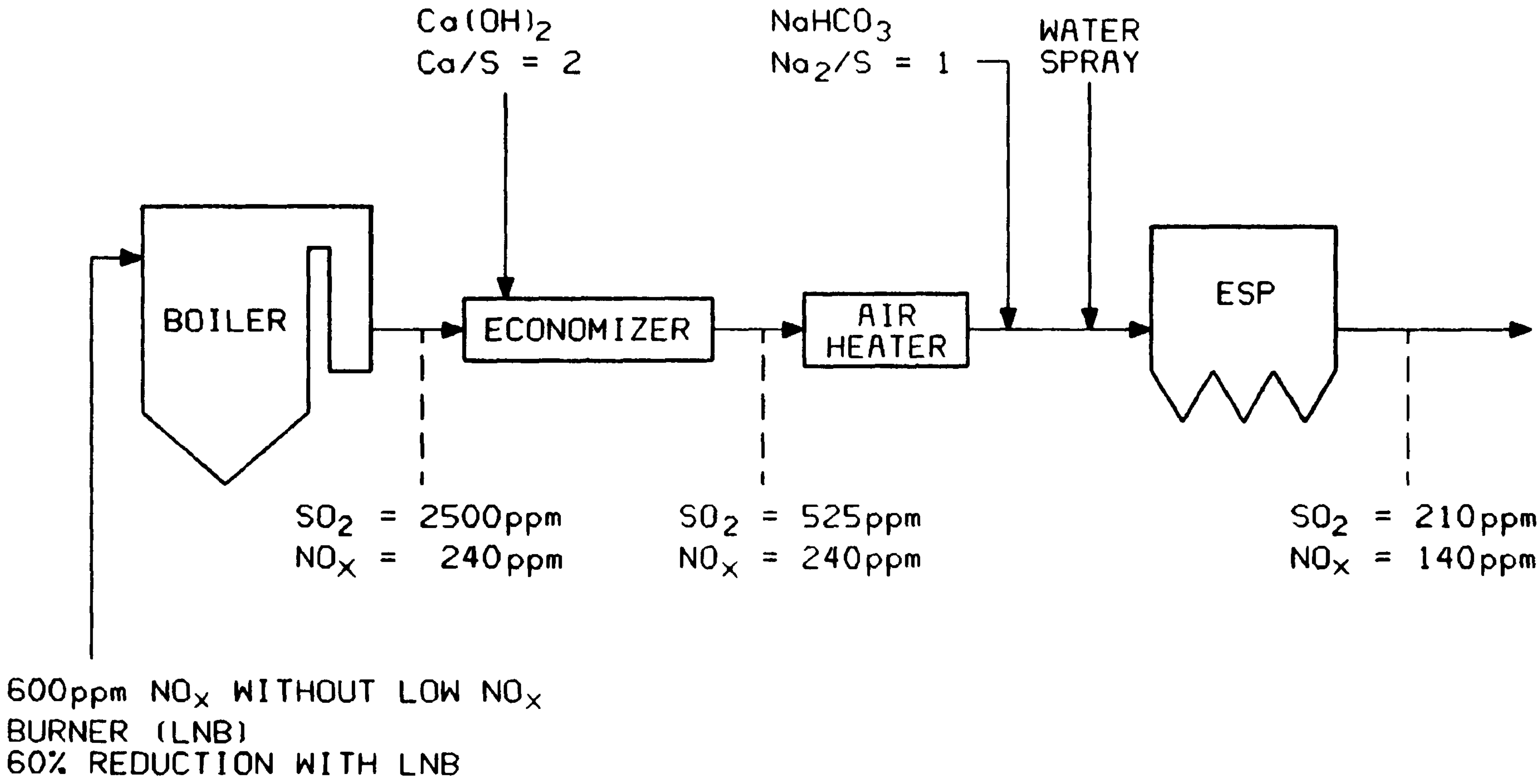
The team of Cottrell Environmental Sciences, KVB and Riley Stoker will conduct a proof of concept demonstration of an Integrated Dry Injection Process. The process consists of combustion modification using low NO_x burners to reduce NO_x (i.e., $NO + NO_2$) emissions, dry injection of hydrated lime at economizer temperatures for primary capture of SO_2, and addition of a commercial grade sodium bicarbonate at the air heater exit for additional SO_2 and NO_x removal. This concept is illustrated in Figure 1. The Integrated Dry Injection Process offers the potential for simultaneously achieving 90+% SO_2 removal, and 75+% NO_x removal from a high sulfur flue gas. The proposed process is well suited for new or retrofit applications since it can be incorporated within the existing economizer and downstream duct. In addition, the capital costs are kept to a minimum since no large system components such as catalytic beds, spray dryers or scrubbers are required. Preliminary economic analysis indicate a capital requirement of $50/kw and a total levelized operating cost of about 10 mills/kwh.

Tests conducted by KVB on a bench scale and a small pilot plant unit have demonstrated that hydrated lime addition at economizer temperatures is capable of capturing 79% of the inlet SO_2 with a feed stoichiometric ratio of 2. The simultaneous removal of SO_2 and NO_x in the presence of sodium bicarbonate or hydroxide has also been demonstrated by KVB at the Araphoe test facility of EPRI. A low NO_x burner has been developed by Riley Stoker for sizes up to 100 million Btu/hr.

The proof of concept demonstration will be conducted on the large combustor at the Riley Stoker research facility in Worcester, MA. The scope of the program includes system engineering and design, equipment procurement, modification and installation, system commissioning, operation and testing, data analysis and reporting. A preliminary sorbent screening test program will be conducted at the KVB test facility in Irvine, California. CES is the primary contractor and has overall project management responsibility, KVB, Inc. and the Riley Stoker Corp. are the major subcontractors.

Figure 1.

INTEGRATED DRY INJECTION PROCESS



The demonstration plant consists of a combustor equipped with a low NO_x burner firing at a rate of 50 million Btu/hr. A slip stream of 10,000 scfm of flue gas from the combustor will be indirectly cooled to the target economizer inlet temperature. Hydrated lime will be injected in the pilot economizer section at representative inlet temperatures and quench rates. Exit gases will be cooled to typical preheater outlet temperatures in an air cooled exchanger. Dry sodium bicarbonate will be injected in the flue gas exiting the air preheater. Subsequent humidification of the flue gas with a water spray after the sodium bicarbonate injection is expected to enhance precipitator performance.

A twenty-four month program is planned with startup of the demonstration facility about twelve months after project inception. Two coals will be tested: a medium (2.5%) sulfur and high (3.5%) sulfur coal in order to demonstrate the process over an inlet SO_2 concentration of about 2200 to 3000 ppm.

2.0 Status

During the January - March 1989 time period major efforts were directed toward a finalization of the test parameters and their order of testing and toward the system design. A kickoff meeting, a Utility Review Committee meeting and a design review meeting were held during this period in order to gain direction on these objectives. The test parameter matrix has been modified several times as a result of these meetings. The current version will be discussed in this report.

The equipment design has also evolved through several changes, and the current design will be presented in this report.

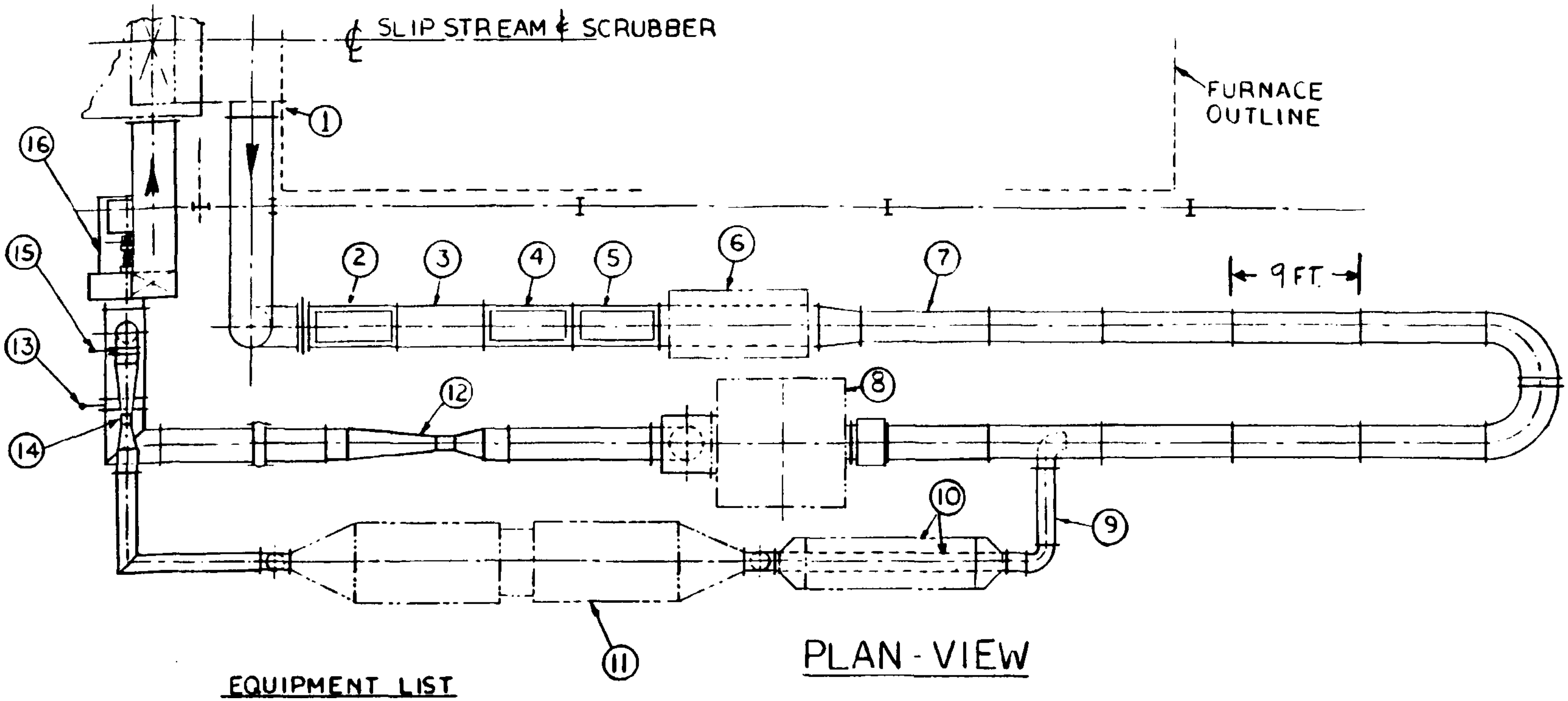
Work during the next three months period will be devoted to detailed design, and equipment specification and purchase.

3.0 System Design

Flue gas will be taken from the Riley Research CBTF at the furnace exit just upstream of the spraydown and scrubber. The gas will leave the furnace at about 1200F, and will be routed to a heat exchanger in order to reduce the temperature of the gas entering the simulated economizer to the 900-1100 F range. A 6-ft long section of open duct will separate this heat exchanger from the economizer tube banks in order to accommodate sorbent injectors. The economizer will be simulated with two heat exchangers each having the following construction: 6-ft long, 3-ft x 5-ft in cross section; 10 tubes/row, 1.91-inch OD tubes on 3.6-inch centers, 17 rows in in the direction of flow; air cooled tubes. The superficial velocity for 50 million Btu/hr gas flow will be about 27 ft/s (at 800 F). The gas will exit the economizer section at 650-750 F and will then be cooled in a simulated air heater to 300 F. The air heater will be of parallel plate construction. The air heater exit gas will enter a 30-inch ID duct, nominally 100 feet in length, and providing about 2 s isothermal residence time at 50 ft/s and 300 F. The duct will be straight except for one 180 degree turn to bring the flue gas back to the particulate control devices. The 30-inch duct will continue into the pulse-jet baghouse; a 15-inch duct will take a portion of the flow into the ESP. Separate venturies and dampers will be used in the exit lines to control flow through the baghouse and ESP. The gas streams will then be combined and returned to the scrubber using a booster fan. Figure 2 shows a plan view of the equipment arrangement. Figure 3 shows the design flue gas time-temperature profile for the described system. The residence times and temperatures are considered to be representative of the U.S. boiler population.

A combustion calculation and a material and heat balance computer program have been written which allows a rapid determination of material flows and heat transfer within the system. The flow system is shown in Figure 4. A typical input page to the program is shown in Exhibit 1. A Riley Research combustion program is used to generate the flue gas constituents, and an example of the input and output of this program is given in Exhibits 2 and 3. For the examples shown, the output of the

Figure 2. Equipment Arrangement



EQUIPMENT LIST

① SLIP STREAM TAKE-OFF 1200°F. 36"Ø
② HEAT EXCHANGER, AIR-COOLED TEMP. CONTROL TO 900-1100°F.
③ EMPTY DUCT FOR SORBENT INJECTORS
④ ECONOMIZER SECT. 1 } AIR COOLED TUBE BANKS IN 3'×5' DUCT
⑤ ECONOMIZER SECT. 2 } VELOCITY = 28 FT. PER SEC.
⑥ AIR HEATER SYSTEM
⑦ DUCT 30"Ø × 100 FT. LENGTH.
⑧ BAG HOUSE
⑨ ELECTROSTATIC PRECIPITATOR TAKE-OFF
⑩ HUMIDIFICATION CHAMBER OR 15"Ø DUCT
⑪ ELECTROSTATIC PRECIPITATOR (ESP)
⑫ BAGHOUSE VENTURI
⑬ BAGHOUSE DAMPER
⑭ ESP VENTURI
⑮ ESP DAMPER
⑯ BOOSTER FAN

"N" MATERIAL NOT FURNISHED BY
"F" MATERIAL FURNISHED BY

DO NOT USE THIS DRAWING FOR CONSTRUCTION UNLESS IT CONTAINS DATE AND SIGNATURE OF APPROVAL

FIRST USED ON CONTRACT NO
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CF	DRAWN		
CI	DATE	3-10-89	
DF	CHECKED		
DI	DATE		
W	APP'D		
E	DATE		

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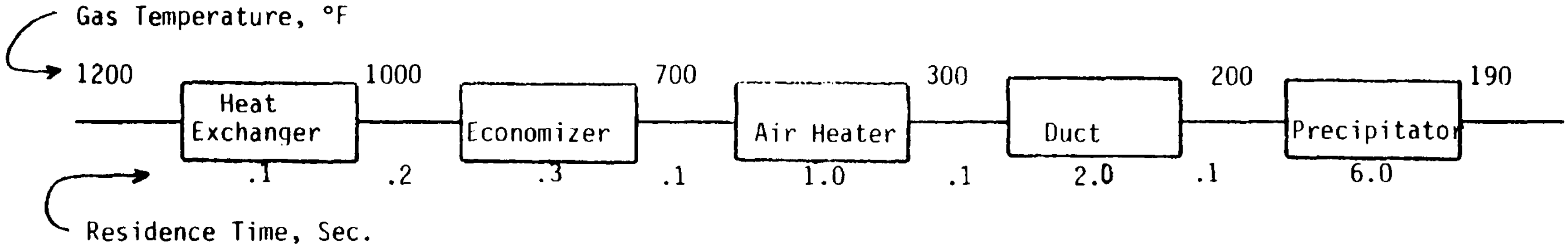
RILEY STOKER CORPORATION
WORCESTER, MASS.

GENERAL LAYOUT OF EQUIPMENT
SORBENT INJECTION PROJECT
REASEARCH-COTTRELL

DWG. NO. 89801-01-PD1

Figure 3. Flue Gas Time/Temperature Profile



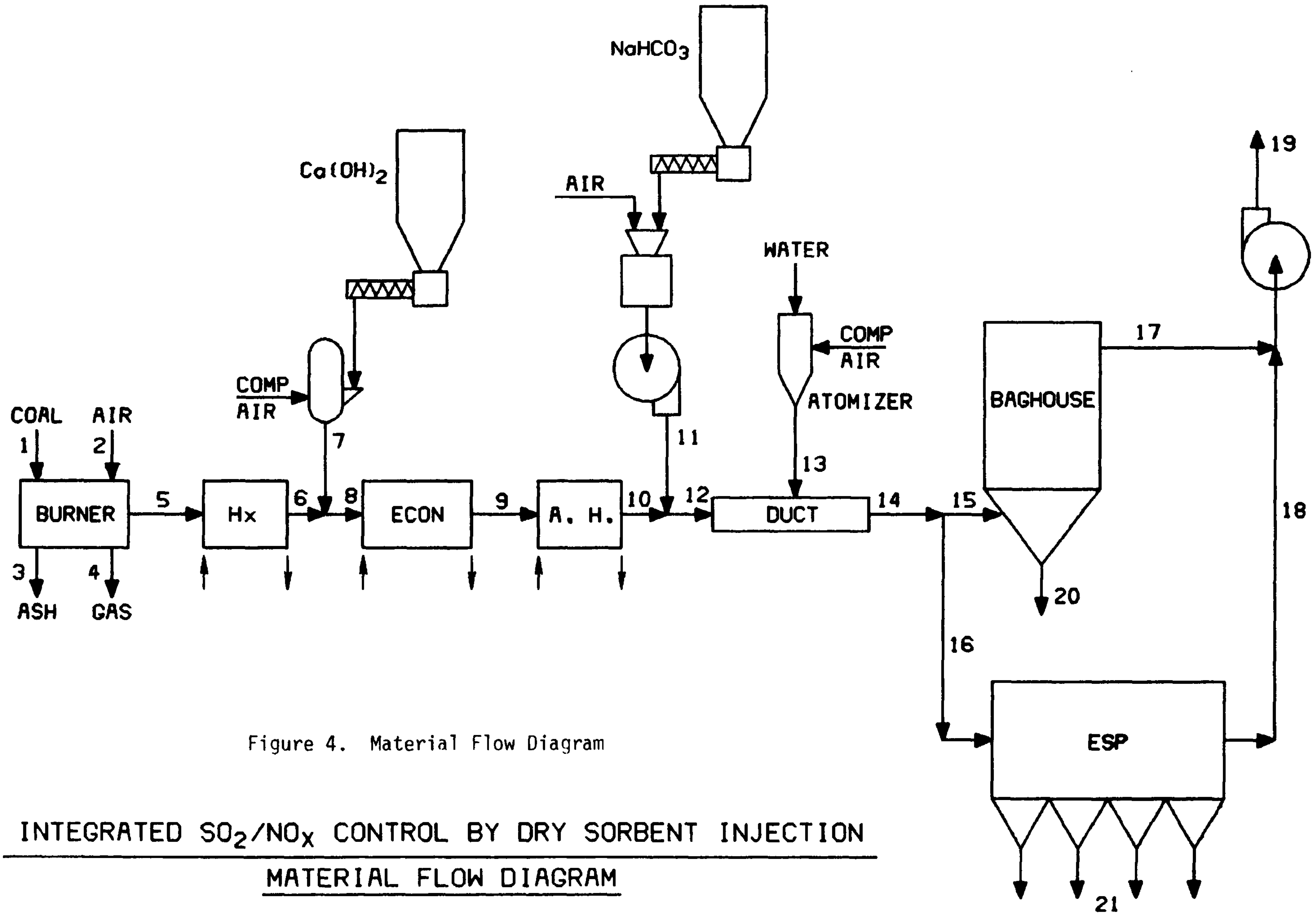


Figure 4. Material Flow Diagram

INTEGRATED SO_2/NO_X CONTROL BY DRY SORBENT INJECTION

MATERIAL FLOW DIAGRAM

Exhibit 1. Material/Heat Balance Input

```
         MASS AND ENERGY FLOW CALCULATIONS

COAL CONSTITUENT          WT. %

         C                58.50
         H                 4.00
         N                 1.00
         O                 6.00
         S                 2.50
         ASH              18.00
         WATER            10.00                10500.00 BTU/LB

SLIPSTREAM FLOW = 10000.00 WSCFM (1 ATM, 60 DEG F) @ 5.00E+07 BTU/HR

COMBUSTION CALCULATION RESULT  SR =        1.17

GAS CONSTITUENT                  LB/HR                 LB AIR/LB COAL @ SR [illegible]

N2%            73.34            33445.62                         [illegible]
O2%             3.71             1370.18
CO2%           14.17             9850.98
SO2ppm       2270.00              229.54
NOppm         240.00               11.78
H2O%            8.56             2718.36
ASH,GR/CF       8.41              720.36               WSCF/LB COAL =       [illegible]

REACTION CONSTANTS --- A ...  N IN LB MOLE / HOUR

A*Ca(OH)2 + B*SO2 = C*CaSO3 + D*CaSO4 + E*CaCO3 + F*CaO + G*Ca[illegible]

I*NaHCO3 + J*SO2 + K*NO = L*Na2SO4 + M*NaNO3 + N*Na2CO3

CALCIUM NSR = A/B =              2.00

SO2 CAPTURE EFF = (C+D)/B =     0.79           COOLING AIR FLOW  LB/HR

CaSO3/CaSO4 = C/D =             1.00           HX        12500.00
                                               ECON      27000.00
CaCO3/(SO3+SO4) = E/(C+D) =     0.50           AH        75000.00

CaO/(SO3+SO4) = F/(C+D) =       0.25                   STREAM TEMPERATURE

SODIUM NSR = I/(2J+K) =         1.00                   DEG F     DEG R

SO2 CAPTURE EFF = L/J =         0.60           HX IN     1200.00  1660.00
                                               ECON IN   1000.00  1460.00
NO CAPTURE EFF = M/K =          0.42           AH IN      700.00  1160.00
                                               DUCT IN    300.00   760.00
LB INJECT AIR / LB Ca(OH)2      4.00           DUCT OUT   200.00   660.00
LB INJECT AIR / LB NaHCO3 =     1.00

LB ATOMIZER AIR / LB WATER      0.50

REFERENCE TEMPERATURE = AMBIENT =        70.00 =          530.00 DEG R
```

Exhibit 2. Combustion Calculation Input

```
LOTUS123 FILE FUELSTO.WK1                             PAGE 1/2
USER ENTERS VALUES MARKED *

                  FLUE GAS COMPOSITION FROM COAL ANALYSIS

FUEL*:   #2, 3/7/89 FAX

                  MOL O2   MOL PRODUCED/LB COAL, 0% O2 IN DRY AIR
WT% IN COAL AF    RQD/LB   ---------------------------------------------
----------------- -------- CO2      H2O      SO2      N2       FLUE GAS
CARBON*     58.50 4.88E-02 4.88E-02                   1.83E-01 2.32E-01
HYDROGEN*    4.00 1.00E-02          2.00E-02          3.76E-02 5.76E-02
NITROGEN*    1.00 0.00E+00                            3.57E-04 3.57E-04
OXYGEN*      6.00 -1.9E-03                            -7.1E-03 -7.1E-03
SULFUR*      2.50 7.81E-04                   7.81E-04 2.94E-03 3.72E-03
ASH*        16.00 0.00E+00                                     0.00E+00
MOISTURE*   12.00 0.00E+00          6.67E-03                   6.67E-03
-------- -------- -------- -------- -------- -------- -------- --------
TOTAL       100.0 5.77E-02 4.88E-02 2.67E-02 7.81E-04 2.17E-01 2.93E-01


STOICHIOMETRIC COMBUSTION IN DRY AIR, PER LB FUEL:

                  AIR RQD(MDA0)     DRY FG(MDFG0)     WET FG
MOLES             2.75E-01          2.67E-01          2.93E-01
M.W.              2.90E+01          3.10E+01          2.98E+01
LBS               7.96E+00          8.28E+00          8.76E+00

Y(0), MOL H2O/MOL DRY FG, STOICH COMB IN DRY AIR:     1.00E-01

BTU/LB*     10500

LBS SO2/10E6 BTU      4.76
LBS ASH/10E6 BTU     15.24
```

Exhibit 3. Combustion Calculations Output

```
LOTUS123 FILE FUELSTO.WK1                                   PAGE 2/2
USER ENTERS VALUES MARKED *


YA, AMBIENT HUMIDITY, MOL/DRY MOL*: 2.00E-02


DRY %O2*              0.00      1.00      2.00      3.00      4.00      5.00
SR                   1.000     1.050     1.105     1.167     1.235     1.313
DRY BASIS:

CO2, %               18.27     17.40     16.53     15.66     14.79     13.92
N2, %                81.43     81.32     81.20     81.09     80.97     80.85
SO2, PPM              2928      2789      2649      2510      2371      2231
MOL WT               31.03     30.92     30.82     30.72     30.61     30.51
DSCF/LB COAL         103.2     108.4     114.1     120.5     127.5     135.5
DSCF/1E6 BTU          9833     10325     10868     11472     12147     12906
ASH, GR/DSCF         10.85     10.33      9.81      9.30      8.78      8.27

Y, MOL/MOL DRY FG    0.120     0.115     0.110     0.106     0.101     0.096

WET BASIS:

O2, %                 0.00      0.90      1.80      2.71      3.63      4.56
CO2, %               16.32     15.61     14.89     14.17     13.44     12.70
N2, %                72.71     72.92     73.13     73.34     73.55     73.76
SO2, PPM              2615      2501      2386      2270      2153      2035
H2O, %               10.71     10.33      9.95      9.56      9.17      8.77
MOL WT               29.63     29.59     29.55     29.50     29.46     29.41
WSCF/LB COAL         115.6     120.9     126.7     133.2     140.4     148.5
WSCF/1E6 BTU         11012     11514     12068     12684     13372     14147
ASH,GR/WSCF           9.69      9.26      8.84      8.41      7.98      7.54

Y TAKEN AS Y(0)/SR + YA  (WITHIN 1% RELATIVE FOR COAL, 2%REL FOR GAS)
SR DEFINED AS 21/(21-DRY O2)
DRY CONCENTRATION = DRY CONC(@0% O2)/SR
WET CONCENTRATION = DRY CONC/(1+Y)
```

combustion program (Exhibit 3), for the case of an air to fuel stoichiometric ratio of 1.167, is the input for the material balance program (Gas Constituent column of Exhibit 1).

Material balances are then calculated for the various streams of Figure 3, assuming the following reactions occur:

$$Ca(OH)_2 + SO_2 \longrightarrow CaSO_3 + H_2O$$

$$Ca(OH)_2 + SO_2 + O \longrightarrow CaSO_4 + H_2O$$

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$$

$$Ca(OH)_2 \longrightarrow CaO + H_2O$$

$$2\,NaHCO_3 + SO_2 + O \longrightarrow Na_2SO_4 + H_2O + 2CO_2$$

$$2\,NaHCO_3 \longrightarrow Na_2CO_3 + CO_2 + H_2O$$

The stoichiometric ratios, capture efficiencies and product ratios of Exhibit 1 allow a determination of the percentage of sorbent entering into each reaction above. The reaction constants shown in Exhibit 1 were selected for the purpose of demonstration, but are considered to be realistic. The actual values of these constants will be determined by solids composition testing and measured SO_2 and NO_x removal efficiencies. Other inputs needed in order to complete a material balance are the air to sorbent and air to water ratios. The calculated material flows are given in Exhibits 4 and 5. Exhibit 4 gives material flows in lb/hr for the principal streams. Exhibit 5 gives material flows for all the streams of Figure 3 in conventional units.

Once the material flows are established and the temperatures are specified, a heat balance is determined by calculating the sensible heat

Exhibit 4. Material Flows 1

MATERIAL FLOWS, LB/HR

COMPONENT	ECON INLET	Ca(OH)2 INJECT	ECON OUTLET	NaHCO3 +WATER	DUCT OUTLET	VOL
N2, LB/HR	32445.62	1628.53	34074.16	539.03	34560.1[illegible]	[illegible]
O2	1370.18	492.60	1840.1[illegible]	151.23	1974.7[illegible]	[illegible]
CO2	9850.98		9788.65		9853.52	[illegible]
SO2	229.54		48.20		19.28	0.[illegible]
NO	11.38		11.38		6.[illegible]	[illegible]
H2O	2718.86		2808.12	1077.14	[illegible]899.66	[illegible]
TOTAL GAS	46626.56	2121.14	48570.61	1767.40	503[illegible]	[illegible]
						MA
ASH, LB/HR	576.69		576.69		576.69	[illegible]
CaSO3	0.00		170.00		170.00	[illegible]
CaSO4	0.00		192.67		192.67	13.[illegible]
CaCO3	0.00		141.67		141.67	[illegible]
CaO	0.00		39.67		39.67	[illegible]
Ca(OH)2	0.00	530.82	163.89		163.89	[illegible]
Na2SO4	0.00		0.00		64.17	4.5[illegible]
NaNO3	0.00		0.00		13.[illegible]4	0.[illegible]
Na2CO3	0.00		0.00		43.59	3.1[illegible]
NaHCO3	0.00		0.00	158.39	0.00	0.[illegible]
TOTAL SOLIDS	576.69	530.82	1284.59	158.39	1405.59	100.[illegible]
TOTAL MASS	47203.24	2651.96	49855.20	1925.79	51715.31	

Exhibit 5. Material Flows 2

STREAM NUMBER

	1	2	3	4	5	6
AIR, SCFM		10812.97				
WATER, GPM						
COAL, LB/HR	5238.10					
Ca(OH)2, LB/HR						
NaHCO3, LB/HR						
FLUE GASES, WSCFM				1623.57	10000.00	[illegible]
ASH&SOLIDS, LB/HR			167.65	43.90	576.07	[illegible]

	7	8	9	10	11	12
AIR, SCFM	471.84				[illegible]	
WATER, GPM						
COAL, LB/HR						
Ca(OH)2, LB/HR	530.82					
NaHCO3, LB/HR					158.59	
FLUE GASES, WSCFM		10471.84	9971.16	9971.16		[illegible]
ASH&SOLIDS, LB/HR		1107.50	1284.59	1284.59		[illegible]

	13	14	15	16	17	18
AIR, SCFM	119.24					
WATER, GPM	2.14					
COAL, LB/HR						
Ca(OH)2, LB/HR						
NaHCO3, LB/HR						
FLUE GASES, WSCFM		10432.13	7451.52	2980.61	7451.52	[illegible]
ASH&SOLIDS, LB/HR		1405.89	1004.21	401.68		

	19	20	21
AIR, SCFM			
WATER, GPM			
COAL, LB/HR			
Ca(OH)2, LB/HR			
NaHCO3, LB/HR			
FLUE GASES, WSCFM	10432.13		
ASH&SOLIDS, LB/HR		1004.21	401.68

of each component within a flow stream and summing the individual sensible heats. The sensible heats for the gas are calculated from the equation:

$$\Delta H = \int_{T\,ref}^{T} Cpdt$$

where the specific heat for each gas, Cp, is represented by an approximation in the form of

$$Cp = a + bT + cT^2$$

The specific heats of the solids are assumed to be constants. The results of such a calculation for the input values given in Exhibit 1 is shown in Exhibit 6. The difference in sensible heat of the total gas and solids from point to point represents the amount of heat which must be removed by the heat exchangers. This heat is represented by the temperature increase of the cooling air. Finally, the flow rate of spray water is calculated, based upon the desired final temperature of the gas and the latent heat of evaporation of the water.

4.0 The Test Program Planning

The overall test program includes subscale sorbent screening tests at KVB and a pilot scale parametric test series at the Riley CBTF.

The KVB subscale tests will evaluate eleven hydrates at 900, 1000 and 1100°F in the pilot scale reactor system shown in Figure 5. For each test, O_2, CO_2, CO, NO, NO_2 and SO_2 concentration will be monitored.

Exhibit 6. Heat Flows

```
                                HEAT BALANCE

ALL COOLING AIR AND INJECTED SOLIDS AND GASES AT AMBIENT TEMPERATURE

                                SENSIBLE HEAT, BTU/HR, REF   70.00 DEG F

COMPONENT          HX       ECON     AH       DUCT     DUCT
                   INLET    INLET    INLET    INLET    OUTLET

N2                 9.29E+06 7.58E+06 5.33E+06 1.92E+06 1.09E+06
O2                 3.43E+05 2.80E+05 2.32E+05 9.06E+04 5.47E+04
CO2                2.69E+06 2.16E+06 1.40E+06 4.78E+05 2.67E+05
SO2                4.31E+04 3.46E+04 4.72E+03 1.62E+03 7.59E+02
NO                 3.04E+03 2.48E+03 1.66E+03 5.97E+02 1.95E+02
H2O                4.69E+06 4.33E+06 3.95E+06 3.30E+06 4.36E+06

ASH                1.56E+05 1.29E+05 3.72E+04 2.18E+04 1.30E+04
CaSO3              0.00E+00 0.00E+00 2.57E+04 9.38E+03 5.30E+03
CaSO4              0.00E+00 0.00E+00 2.43E+04 8.86E+03 5.01E+03
CaCO3              0.00E+00 0.00E+00 1.87E+04 6.84E+03 3.87E+03
CaO                0.00E+00 0.00E+00 4.75E+03 1.73E+03 9.80E+02
Ca(OH)2            0.00E+00 0.00E+00 2.99E+04 1.09E+04 6.18E+03
Na2SO4             0.00E+00 0.00E+00 0.00E+00 0.00E+00 1.75E+03
NaNO3              0.00E+00 0.00E+00 0.00E+00 0.00E+00 4.75E+02
Na2CO3             0.00E+00 0.00E+00 0.00E+00 0.00E+00 1.47E+03
NaHCO3             0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

FLUE GAS+SOLIDS    1.72E+07 1.45E+07 1.11E+07 5.86E+06 5.84E+06

WALL CONDUCTION    0.00E+00 2.66E+04 3.36E+04 5.21E+04 2.00E+04
COOLING AIR        0.00E+00 2.66E+06 3.36E+06 5.21E+06 0.00E+00

TOTALS             1.72E+07 1.72E+07 1.45E+07 1.11E+07 5.36E+06

COOL AIR OUT DEG F             947.37   590.40   362.93

SPRAY WATER, GPM   =             2.14
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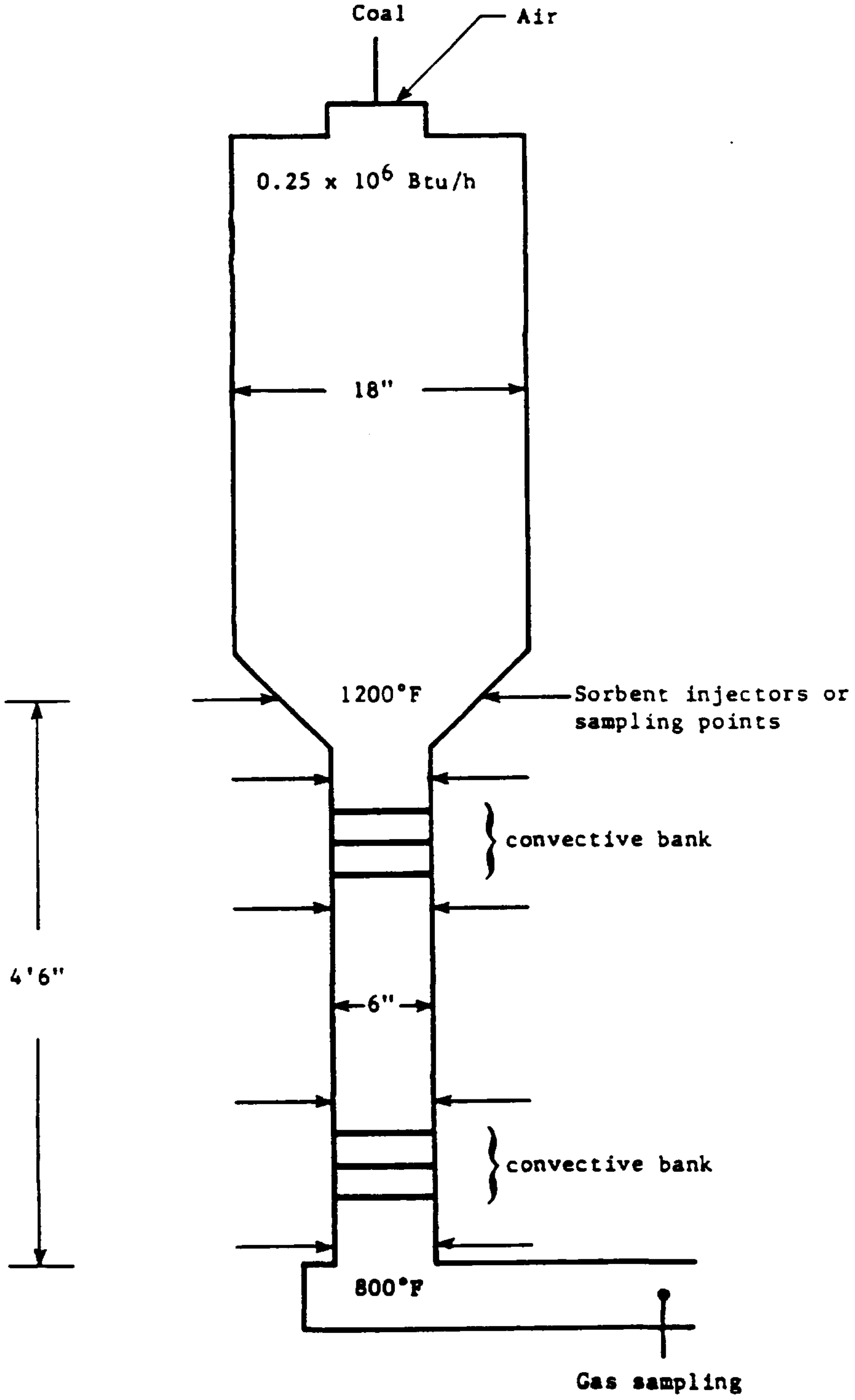


Figure 5. Subscale Test Reactor

The hydrates are:

Hydrate	Source
1. Missisippi Lime Co.	Ste. Genevieve, MO
2. Marblehead Lime Co.	Chicago, IL
3. Bellefonte Lime Co.	Bellefonte, PA
4. Tenn-Luttrell Co.	Lutrell, TN
5. & 6. Chemical Lime Co.	Clifton, TX
5. Regular (17-20 m^2/g)	
6. High (30-40 m^2/g)	
7. Colton Lime Co.	Colton, CA
8. Rheinische Kalksteinwerke	Wulfrath W. Germany
9. Alcohol Hydrate	KVB Lab
10. Lignosite Additive 1	KVB Lab
11. Lignosite Additive 2	KVB Lab

Hydrates 1,2,3,4,5 and 7 are commercial hydrates selected on the basis of a high surface area. Hydrate 6 is currently produced on a pilot scale by Chemical Lime Co. and they claim special process could be quickly commercialized. Hydrate 8 is from a commercial alcohol/water hydration plant in West Germany, which will be compared to hydrate 9, an alcohol water hydrate made in the KVB laboratory. Hydrates 10 and 11 will be made with 2% and 3% lignosulfonate. The commercial hydrates will be milled on-line prior to injection, while the additive enhanced hydrates will not be milled on line. One commercial hydrate and one additive enhanced hydrate will be selected for the demonstration program.

The same pilot scale furnace will be used to evaluate the effectiveness of the NO_2 suppression additive to the sodium bicarbonate. In these tests calcium hydroxide will be injected at $1000^{o}F$ with a $Ca/S = 2$. The coal burner will also be run under staged conditions so that approximately 400 ppm NO_x is generated. Sodium bicarbonate will then be injected upstream of the baghouse at a temperature between 300 and $350^{o}F$. Urea and activated carbon will be added to the bicarbonate and the resultant NO_x removal and NO_2 generation will be studied. The optimum additive will be selected based on NO_2 suppression, effect on NO_x removal and any potentially detrimental byproducts formed. These subscale tests are scheduled for March through May, 1989.

Prior to conducting the parametric tests, a series of experiments will be performed to optimize the hydrate mixing rate with the flue gas above the economizer. Three injection parameters will be varied independently -- the injector number, the exit velocity and the transport air to flue gas ratio. Tests would generally be run at Ca/S ratios of both 1 and 2. At the conclusion of the tests the nozzle number and injection velocity would be fixed at optimum values for the parametric and long term experiments.

The parametric test program will consist of a series of short tests, 4 to 8 hours each, for the purpose of demonstrating SO_2 and NO_x reductions. The test matrix for achieving these objectives is given in Table 1. The matrix is designed to allow a determination of the influence of each parameter independently of the other parameters. Thirty four test runs are planned. All runs are scheduled for eight hours, except those marked with an asterisk, which signifies four hours. Except where otherwise indicated, all tests will be run using a 2 1/2% sulfur coal (2200 ppm SO_2), the Riley CCV low NO_x burner, and a commercial hydrate milled prior to injection.

The first five runs are designed to determine the importance of bicarbonate injection and humidifier cool down temperature on precipitator performance. The first run will establish base case precipitator performance for fly ash only. Run #2 will show how this performance changes resulting from hydrate injections, run #3 will show how precipitator performance changes resulting from bicarbonate injection, and runs # 4 and 5 will demonstrate the effects of humidification. Following run #5, a humidified temperature will be chosen that yields acceptable precipitator performance, and this temperature will be used for the remaining tests.

Runs #6 - 8 will be used to determine the amount of additive needed for good NO_2 control. The value established by these runs will be used for the remaining tests.

Runs #9 - 11 will be used to establish an economizer hydrate injection temperature for optimum SO_2 removal. This temperature will be used for the remaining runs.

Table 1.

TEST MATRIX FOR THE DEMONSTRATION FACILITY

	RUN	ECON INLET TEMP	Ca/S	AH EXIT TEMP	Na/(2S + NO)	HUMID TEMP	NO_2 CONTROL ADDITIVE % OF BICARB
	1	1000	0	300	0	300	
	2	1000	2.0	300	0	300	
	3				1.0	300	
	4					200	
	5					250	
	6					Best	2
	7						5
	8	↓					10
	9*	1000					Best
	10*	1100					
	11*	900		↓			
	12*	Best		270			
	13*			350	↓		
	14*			300	1.0		
	15*				1.5		
	16*		↓		0.5		
	17		2.0		1.0		
	18		2.5				
	19	↓	1.5				
Hydrate with additive	20	1000	2.0				
	21	1100	2.0				
	22	900	2.0				
	23	Best	2.5				
	24	Best	1.5				
Coal 2	25*	Best From Run 12	2.0				
	26*		2.5				
	27*		1.5			↓	
	28*		2.0			200	
	29*					160	
	30*				↓	180	
Std. (high NOx) burner	31*				0	Best From Run 6	
	32*				1.5		
	33*				1.0		
	34*	↓	↓	↓	0.5	↓	↓

* Indicates two runs per day

The effect of air heater exit temperature is investigated in runs #12 - 14, the effect of bicarbonate mole ratio in runs # 14 - 16, and the effect of hydrate mole ratio in runs #17 - 19.

The additive enhanced hydrate will be evaluated in runs # 20 - 24. Both the hydrate to sulfur mole ratio and the injection temperature will be varied during these tests.

The effects of burning a 3 1/2% sulfur coal will be investigated in runs # 25 - 27.

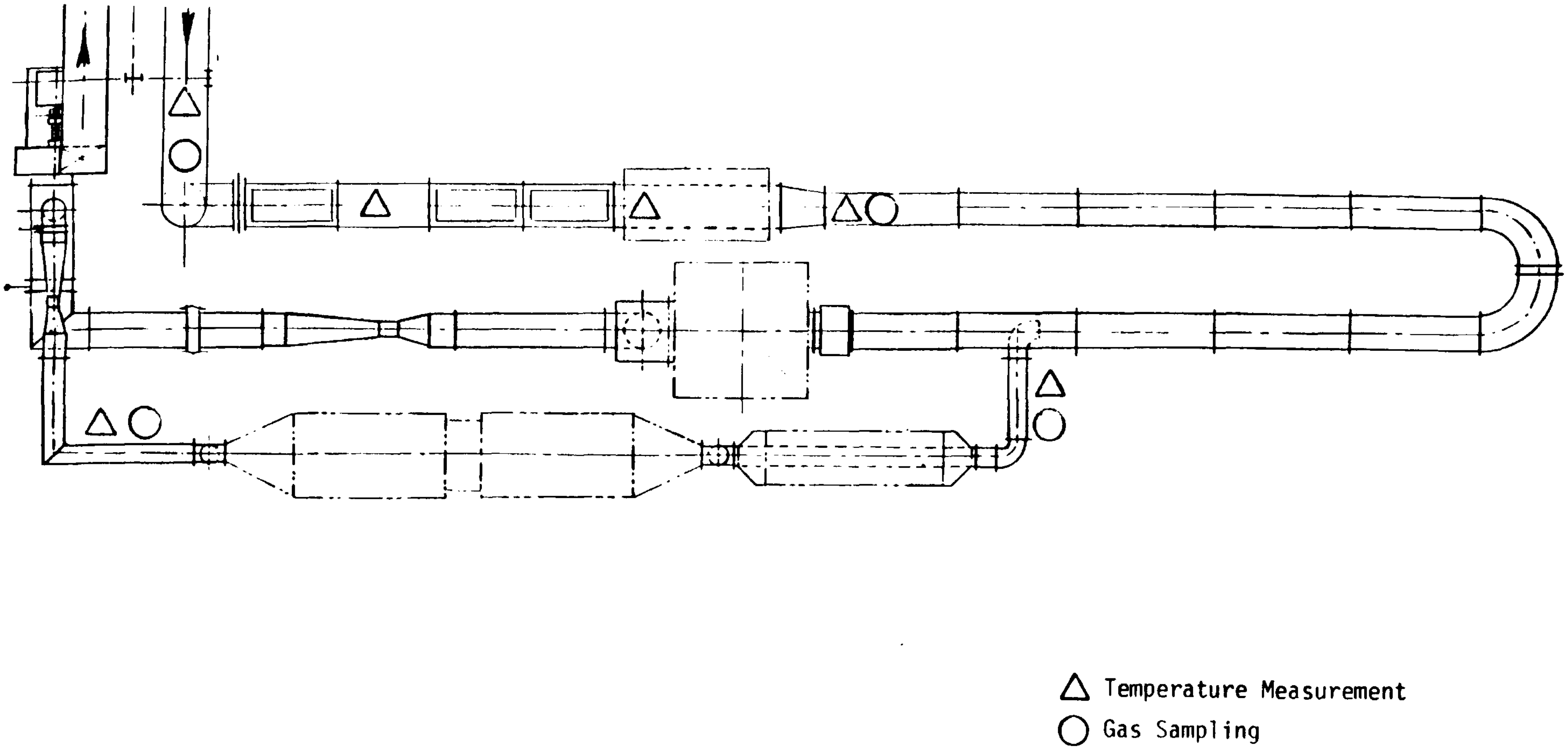
An effort to enhance SO_2 capture through humidification to a close approach to the adiabatic saturation temperature will be made in runs # 28 - 30. During these runs an additional cooling water atomizer will be located in a large diameter duct section just upstream of the precipitator.

Finally, the CCV burner will be replaced by a standard burner, and the ability to handle higher NO_x levels will be investigated in runs #31 - 34.

Figure 6 shows the locations of the temperature measurement and gas sampling points. All temperatures will be routinely recorded once per hour. Gas monitoring will be by the KVB mobile lab. The gases measured and the methods to be used are:

Gas	Method
SO_2	Ultraviolet Photometric
NO_x	Chemiluminescent
O_2	Fuel Cell
CO_2	Nondispersive Infrared
CO	" "

Figure 6. Temperature and Gas Measurement



Solid samples will be taken from the precipitator hopper once per test run. These samples will be analysed for Ca, Mg, Na, NO_2, NO_3, SO_3, S, and CO_3. In addition, ASTM 0698-70 will be used to evaluate the disposibility of the solids. In this method, water is added to the material until maximum denisty is achieved, whereupon a 1.5 inch diameter tube is filled with 6" of the material. This material is allowed to cure for periods of 1 to 28 days, after which 10 to 100 psi of water is applied to the top of the material and the rate of water flow through the material is measured. This leachate is analyzed for nitrate and sodium content, and in this way permeability of the fixed material and the nitrate and sodium concentrations in the leachate are determined.

5.0 Heat Exchanger Specifications

5.1 Economizer

The design for the economizer simulation is based on the results of a survey of utility convective sections performed by KVB. Here are KVB's recommendations:

- 6 ft. of open space upstream of the economizer to accomodate sorbent injectors.
- 6 injector ports at two locations.
- Economizer inlet controllable at 900-1100 F.
- Economizer outlet controllable at 650-750 F.
- Maximum velocity between tubes of 40-60 ft/s (corresponds to 20-30 ft/s superficial velocity with typical tube spacing).
- Typical residence time of 0.3 s
- Temperature drop through the economizer of 200 F.

In order to supplement this information, the economizer sections of three Riley boilers were examined. All were pulverized coal fired, 1967-1970 construction, and ranged from 250-410 MWe. Here is some information from the boiler design data:

- The economizer in each boiler was divided into two parallel passes with the area split ranging from 75/25 to 67/33%. This is a common design feature allowing controlof upstream superheat/reheat temperatures by varying the proportion of flow through each pass. At full load, the flow through each pass should be approximatley proportional to area. (At reduced load, the gas flow through each pass would not be proportional to area since most of the flow would be directed through the main pass.) Since the amount of heat transfer surface upstream of each economizer pass is different, inlet temperatures can be significantly different in each pass. This issue is not addressed in the simulation, but should be kept in mind for full scale application.

- The calculated superficial velocity at full load was 18-19 ft/s, and the maximum (intertube) velocity calculated at an assumed temperature of 800 F, was 35-42 ft/s. These velocities are based on the full duct cross section. Unbalanced flow could increase the velocity in one pass.

- Tube patterns were either 2.0-inch OD on 4.0-inch centers, or 2.5-inch OD on 4.5-inch centers.

- The number of rows varied from 17 to 27 deep in the direction of flow, or a tube-bank depth of 6 to 9 ft.

- Two of the three economizers included a cavity about 3 feet deep.

- The superficial residence time within the tube banks (excluding the cavity) ranged from 0.33 to 0.5 s (proportional flow and identical temperatures throught he two passes assumed).

- Calculated inlet/outlet temperatures were 850/750, 922/721, and 935/715 F, with corresponding quench rates (based on tube bank depth excluding the cavity) of 275, 590, and 400 F/S.

These particular economizers had a lower velocity and quench rate and longer residence time that the average from the survey. However, the recommendations from the survey appear to be sound. The design superficial velocity will be taken as the mid to upper part of the 20-30 ft/s range recommended by KVB. Tube bank depth and temperature drop capability will be increased to ensure adequate performance. Two separately cooled tube banks and the use of air cooling will allow the heat removal to be controlled as required.

Water temperatures in the three Riley economizers ranged from 481 to 553F. Since tube metal temperature will closely approach water temperature, and since we wish to avoid a pressurized system for the simulator, this indicates that air cooling must be used to maintain realistic tube tempera-ture.

5.2 Air Heater

The heat exchanger simulating the air heater will be capable of cooling the flue gas to 300 F from the maximum economizer outlet temperature of 750F. The most common utility air heater by far is the regenerative type, typified by the Lungstrom. However, this type of air heaater exhibits excessive leaskage between the flue gas and air streams at this scale (20 - 40%, compared to about 5% in large units). A parallel plate type recuperative heater will be used in order to roughly simulate the geometry of the regenerative heater, and because it is more compact that the cross flow tube type of exchanger.

5.3 Cold Side Duct

SO_2 removal by sodium bicarbonate injected downstream of the air heater will depend on the residence time available in the duct connecting the air heater and the ESP. Since the primary air of the project is to demonstrate a retrofit technology, the duct will be designed with a realistic residence time and velocity. Based on information provided by

DOE, the duct will be designed to provide about 2 s residence time at 50 ft/s and 300 F. The duct diverting part of the gas flow into the ESP will be scaled to maintain the same velocity. In addition, a small chamber will be available to substitute for a section of duct immediately preceeding the ESP. This will be used only if required for humidification to a low approach temperature. Normal operation will entail only moderate humidification within the straight duct section.

6.0 Electrostatic Precipitator and Baghouse

The electrostatic precipitator that will be used for the program is an existing Research-Cottrell pilot unit and is shown in Figure 7. The precipitator is a two-field unit and is designed as a small segment of a standard R-C precipitator. The gas passage width is 9" and the discharge electrodes consist of the weighted wire design. The collecting surface is the G-Opzel design and is the same as in a full-scale precipitator, with the exception of height, and the total collecting surface is 792 square feet. This yields an SCA of approximately 200 Sq. Ft./1000 ACFM.

The gas passing through a full-sized ESP does not normally lose more than a few degrees of temperature from inlet to outlet; but the ratio of gas volume to outside surface is so much smaller on the pilot ESP that the shell is heated to prevent a large temperature change.

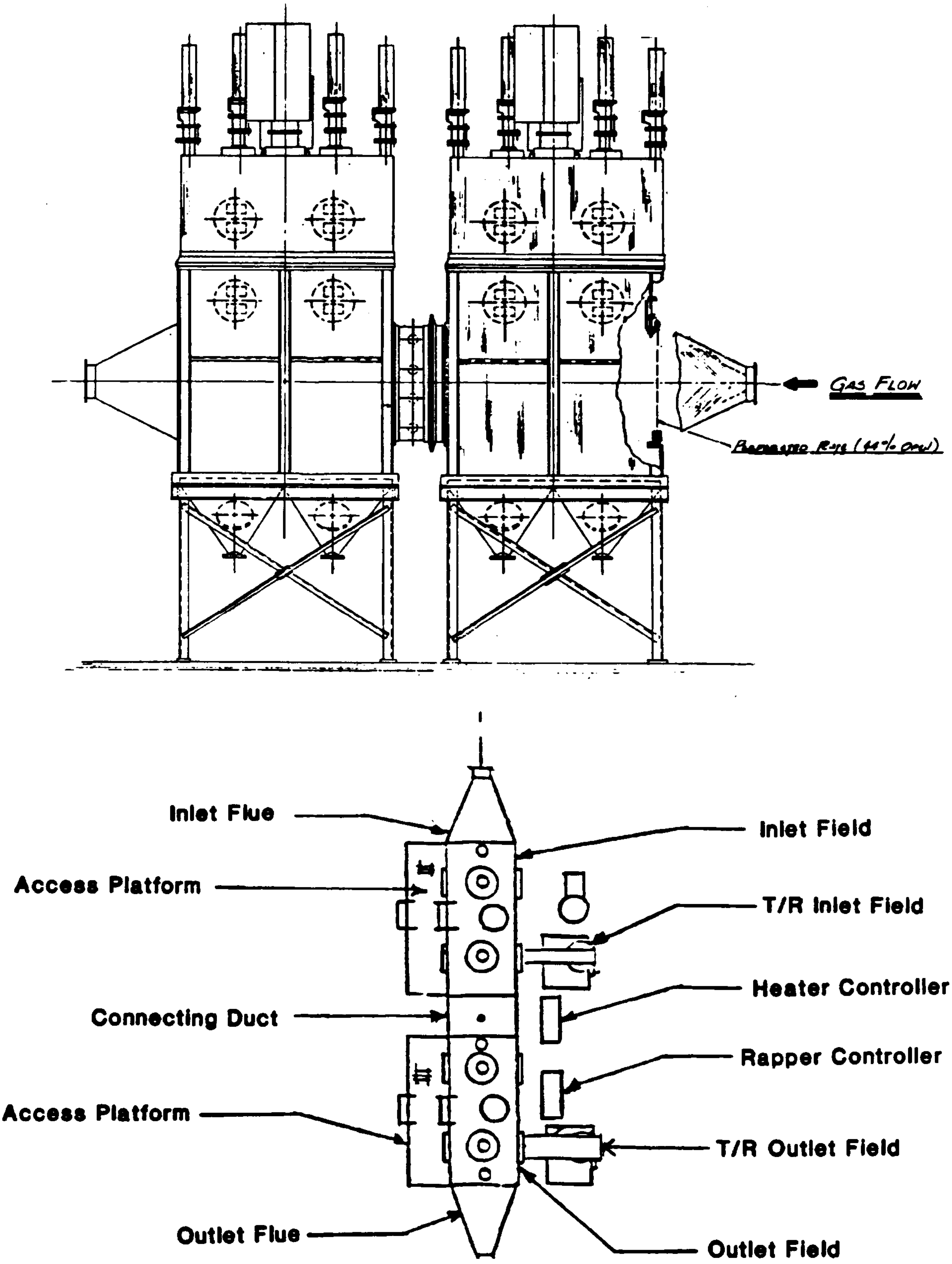


Figure 7.

R-C PILOT PRECIPITATOR EQUIPMENT

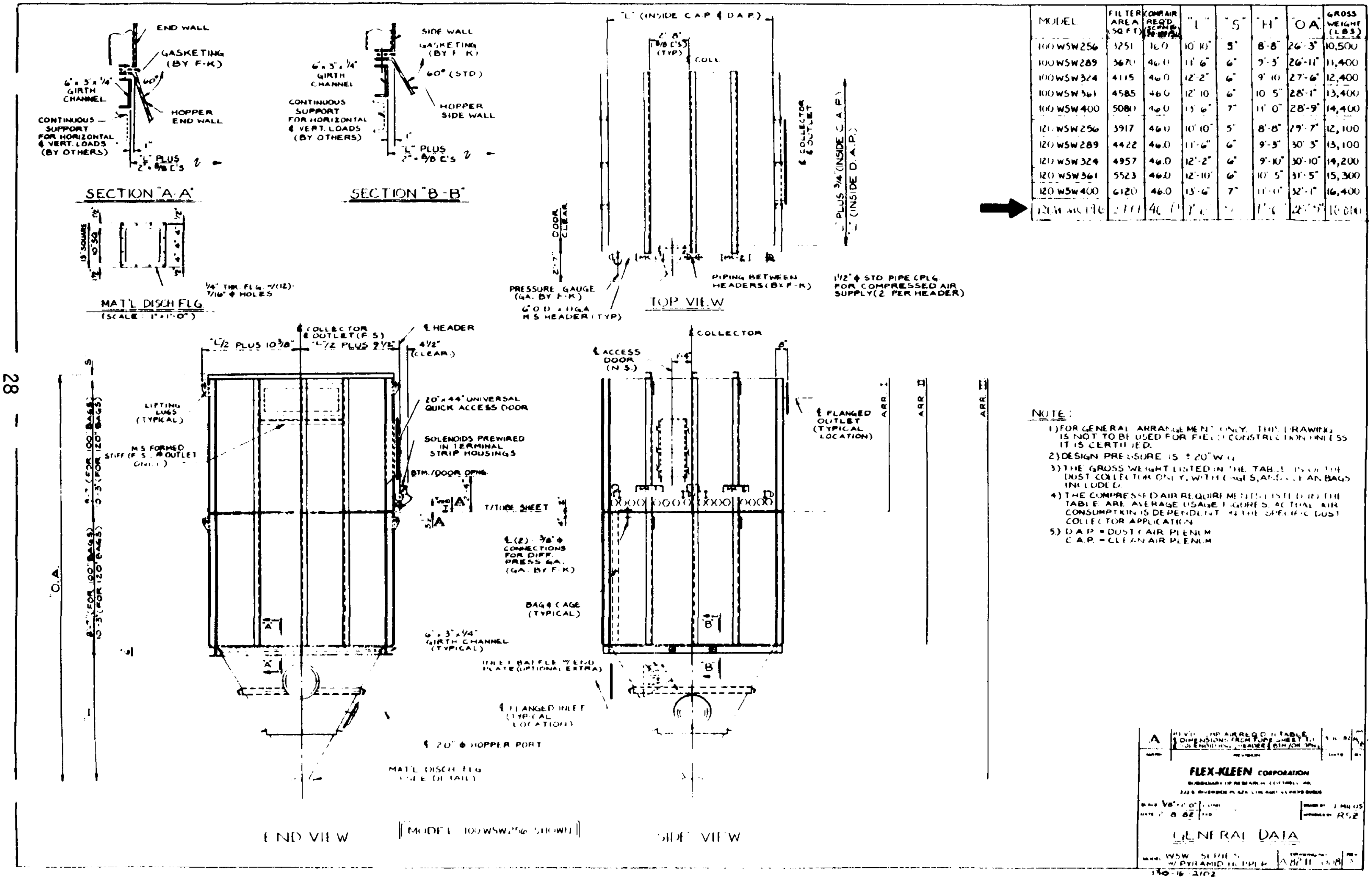
GENERAL ARRANGEMENT

Pertinent physical characteristics of the precipitator are given below:

Number of Chambers	1
Number of Fields	2
Number of Gas Passages per Field	4
Length of Field	9 Ft.
Size of Gas Passages	9" x 5.5'
Type of Collecting Surfaces	G-Opzel
Type of Discharge Electrodes	Weighted WIre
Number of Hoppers	2
Number of Rappers	4
Number of T-R's	1
Type of T-R	NWL Model 30140 6 kVA Single Phase 60 Hz. 460 VAC. 14A Input 140 KVDC Peak, 50 mA Output

The baghouse will be a pulse jet type, containing approximately 3,000 sq. ft. of filter fabric, yielding an air cloth ratio of 3 ACFM/Sq. Ft. The filter fabric will be acid resistant Nomex felt and on-line pulse jet cleaning will be employed. The baghouse will be insulated with 3 inches of fiberglass wool. The baghouse vendor has not yet been chosen, but a baghouse typical of the specifications given above is shown in Figure 8.

Figure 8. Pulse Jet Baghouse



MODEL	FILTER AREA (SQ FT)	COMP. AIR REQ'D (SCFM)	"L"	"S"	"H"	"O.A."	GROSS WEIGHT (LBS)
100 WSW 256	3251	46.0	10'-10"	5"	8'-8"	26'-3"	10,500
100 WSW 289	3670	46.0	11'-6"	6"	9'-3"	26'-11"	11,400
100 WSW 324	4115	46.0	12'-2"	6"	9'-10"	27'-6"	12,400
100 WSW 361	4585	46.0	12'-10"	6"	10'-5"	28'-1"	13,400
100 WSW 400	5080	46.0	13'-6"	7"	11'-0"	28'-9"	14,400
120 WSW 256	3917	46.0	10'-10"	5"	8'-8"	29'-7"	12,100
120 WSW 289	4422	46.0	11'-6"	6"	9'-3"	30'-3"	13,100
120 WSW 324	4957	46.0	12'-2"	6"	9'-10"	30'-10"	14,200
120 WSW 361	5523	46.0	12'-10"	6"	10'-5"	31'-5"	15,300
120 WSW 400	6120	46.0	13'-6"	7"	11'-0"	32'-1"	16,400
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

NOTE:

1) FOR GENERAL ARRANGEMENT ONLY. THIS DRAWING IS NOT TO BE USED FOR FIELD CONSTRUCTION UNLESS IT IS CERTIFIED.
2) DESIGN PRESSURE IS ± 20" W.G.
3) THE GROSS WEIGHT LISTED IN THE TABLE IS OF THE DUST COLLECTOR ONLY, WITH CAGES, AND CLEAN BAGS INCLUDED.
4) THE COMPRESSED AIR REQUIREMENTS LISTED IN THE TABLE ARE AVERAGE USAGE FIGURES. ACTUAL AIR CONSUMPTION IS DEPENDENT ON THE SPECIFIC DUST COLLECTOR APPLICATION.
5) D.A.P. = DUST AIR PLENUM
C.A.P. = CLEAN AIR PLENUM

MARK	REVISION	DATE	BY
A	REVISED COMP AIR REQ'D IN TABLE & DIMENSIONS FROM TUBE SHEET TO SOLENOID HSG. HEADER (BTM./OR TOP)	[illegible]	[illegible]

FLEX-KLEEN CORPORATION

SCALE 1/8" = 1'-0"
DATE [illegible] 8 82
DRAWN BY [illegible]
APPROVED BY RS2

GENERAL DATA

MODEL WSW SERIES W/ PYRAMID HOPPER
DRAWING NO. A 82 11 [illegible] 08

130-16-2/02

APPENDIX I Material And Heat Balances

The results of calculations for the material and heat balances of the system shown in Figure 4 are reported here. The calculations are for 2.5 and 3.5% sulfur coal and for calcium to sulfur mole ratios of 1 and 2. For each value of coal sulfur level, the combustion calculation is followed by the material and heat balances for two values of Ca/S.

```
LOTUS123 FILE FUELSTO.WK1                             PAGE 1/2
USER ENTERS VALUES MARKED *

                  FLUE GAS COMPOSITION FROM COAL ANALYSIS

FUEL*:   #2, 3/7/89 FAX

                  MOL O2   MOL PRODUCED/LB COAL, 0% O2 IN DRY AIR
WT% IN COAL AF    RQD/LB   ---------------------------------------------
----------------- -------- CO2      H2O      SO2      N2       FLUE GAS
CARBON*     58.50 4.88E-02 4.88E-02                   1.83E-01 2.32E-01
HYDROGEN*    4.00 1.00E-02          2.00E-02          3.76E-02 5.76E-02
NITROGEN*    1.00 0.00E+00                            3.57E-04 3.57E-04
OXYGEN*      6.00 -1.9E-03                            -7.1E-03 -7.1E-03
SULFUR*      2.50 7.81E-04                   7.81E-04 2.94E-03 3.72E-03
ASH*        16.00 0.00E+00                                     0.00E+00
MOISTURE*   12.00 0.00E+00          6.67E-03                   6.67E-03
-------- -------- -------- -------- -------- -------- -------- --------
TOTAL       100.0 5.77E-02 4.88E-02 2.67E-02 7.81E-04 2.17E-01 2.93E-01


STOICHIOMETRIC COMBUSTION IN DRY AIR, PER LB FUEL:

                  AIR RQD(MDAO)      DRY FG(MDFGO)      WET FG
MOLES             2.75E-01          2.67E-01          2.93E-01
M.W.              2.90E+01          3.10E+01          2.98E+01
LBS               7.96E+00          8.28E+00          8.76E+00

Y(0), MOL H2O/MOL DRY FG, STOICH COMB IN DRY AIR:     1.00E-01

BTU/LB*     10500

LBS SO2/10E6 BTU      4.76
LBS ASH/10E6 BTU     15.24
```

LOTUS123 FILE FUELSTO.WK1 PAGE 2/2
USER ENTERS VALUES MARKED *

YA, AMBIENT HUMIDITY, MOL/DRY MOL*: 2.00E-02

DRY %O2*	0.00	1.00	2.00	3.00	4.00	5.00
SR	1.000	1.050	1.105	1.167	1.235	1.313
DRY BASIS:						
CO2, %	18.27	17.40	16.53	15.66	14.79	13.92
N2, %	81.43	81.32	81.20	81.09	80.97	80.85
SO2, PPM	2928	2789	2649	2510	2371	2231
MOL WT	31.03	30.92	30.82	30.72	30.61	30.51
DSCF/LB COAL	103.2	108.4	114.1	120.5	127.5	135.5
DSCF/1E6 BTU	9833	10325	10868	11472	12147	12906
ASH, GR/DSCF	10.85	10.33	9.81	9.30	8.78	8.27
Y, MOL/MOL DRY FG	0.120	0.115	0.110	0.106	0.101	0.096
WET BASIS:						
O2, %	0.00	0.90	1.80	2.71	3.63	4.56
CO2, %	16.32	15.61	14.89	14.17	13.44	12.70
N2, %	72.71	72.92	73.13	73.34	73.55	73.76
SO2, PPM	2615	2501	2386	2270	2153	2035
H2O, %	10.71	10.33	9.95	9.56	9.17	8.77
MOL WT	29.63	29.59	29.55	29.50	29.46	29.41
WSCF/LB COAL	115.6	120.9	126.7	133.2	140.4	148.5
WSCF/1E6 BTU	11012	11514	12068	12684	13372	14147
ASH,GR/WSCF	9.69	9.26	8.84	8.41	7.98	7.54

Y TAKEN AS Y(0)/SR + YA (WITHIN 1% RELATIVE FOR COAL, 2%REL FOR GAS)
SR DEFINED AS 21/(21-DRY O2)
DRY CONCENTRATION = DRY CONC(@0% O2)/SR
WET CONCENTRATION = DRY CONC/(1+Y)

```
            MASS AND ENERGY FLOW CALCULATIONS

COAL CONSTITUENT          WT  %

            C               58.50
            H                4.00
            N                1.00
            O                6.00
            S                2.50
            ASH             16.00
            WATER           12.00            10800.00 BTU/LB

FLUESTREAM FLOW = 1[illegible]000.00 WSCFM  1 ATM  60 DEG F) @  5.[illegible]E+07 FT [illegible]

COMBUSTION CALCULATION RESULT, SR =      1.17

GAS CONSTITUENT                 LB/HR               LB AIR/LB COAL @ SR

N2%           73.04          32445.60                              7.[illegible]
O2%            2.71           1370.18
CO2%          14.17           9950.98
SO2ppm      2270.00            229.54
NOppm        240.00             11.38
H2O%           9.56           2718.86
ASH GR/CF      8.41            720.86           WSCF/LB COAL =        133.[illegible]

REACTION CONSTANTS --- A . .. N IN LB MOLE / HOUR

A*Ca(OH)2 + B*SO2 = C*CaSO3 + D*CaSO4 + E*CaCO3 + F*CaO + [illegible]

I*NaHCO3 + J*SO2 + K*NO = L*Na2SO4 + M*NaNO3 + N*Na2CO3

CALCIUM NSR = A/B =                 1.00

SO2 CAPTURE EFF = (C+D)/B =         0.50            COOLING AIR FLOW, LB/H

CaSO3/CaSO4 = C/D =                 1.00            Hx          12500.00
                                                    ECON        27000.00
CaCO3/(SO3+SO4) = E/(C+D) =         0.20            AH          75000.00

CaO/(SO3+SO4) = F/(C+D) =           0.10                        STREAM TEMPERATURE

SODIUM NSR = I/(2J+K) =             1.00                        DEG F     DEG R

SO2 CAPTURE EFF = L/J =             0.60            HX IN       1200.00   1660.00
                                                    ECON IN     1000.00   1460.00
NO CAPTURE EFF = M/K =              0.42            AH IN        700.00   1160.00
                                                    DUCT IN      300.00    760.00
LB INJECT AIR / LB Ca(OH)2          4.00            DUCT OUT     200.00    660.00

LB INJECT AIR / LB NaHCO3 =         1.00

LB ATOMIZER AIR / LB WATER          0.50

REFERENCE TEMPERATURE = AMBIENT =        70.00 =            530.00 DEG R
```

MATERIAL FLOWS LB/HR

COMPONENT	ECON INLET	Ca(OH)2 INJECT	ECON OUTLET	NaHCO3 +WATER	DUCT OUTLET	[illegible]
N2 LB/HR	32445.62	814.27	33259.89	639.48	3428[illegible]	[illegible]
O2	1370.18	246.30	1602.13	193.43	1[illegible]88.06	[illegible]
CO2	9850.98		9835.[illegible]		[illegible]	[illegible]
SO2	219.54		114.77		15.[illegible]	[illegible]
NO	11.30		11.78		[illegible]	[illegible]
H2O	2718.86		27[illegible].83	1001.13	[illegible].18	[illegible]
TOTAL GAS	46625.56	1060.57	47584.17	1834.14	[illegible]	[illegible]
ASH LB/HR	576.69		576.69		576.69	48.[illegible]
CaSO3	0.00		107.60		107.60	[illegible]
CaSO4	0.00		121.94		121.94	10.17
CaCO3	0.00		35.87		35.87	2.[illegible]
CaO	0.00		10.04		10.04	0.84
Ca(OH)2	0.00	265.41	92.89		92.89	7.[illegible]
Na2SO4	0.00		0.00		152.79	12.74
NaNO3	0.00		0.00		13.54	1.[illegible]
Na2CO3	0.00		0.00		87.59	7.31
NaHCO3	0.00		0.00	333.13	0.00	0.[illegible]
TOTAL SOLIDS	576.69	265.41	945.03	333.13	1199.05	100.00
TOTAL MASS	47203.24	1325.98	48529.22	2167.27	511[illegible]4.92	

```
                            STREAM NUMBER

                       1         2         3         4         5         6

AIR, SCFM                     10312.97
WATER, GPM
COAL, LB/HR          5238.10
Ca(OH)2, LB/HR
NaHCO3, LB/HR
FLUE GASES, WSCFM                                  1628.57 [illegible] [illegible]
ASH&SOLIDS, LB/HR                        167.65     93.92    576.59  [illegible]

                       7         8         9        10        11        12

AIR, SCFM             235.92                                  74.03
WATER, GPM
COAL, LB/HR
Ca(OH)2, LB/HR        265.41
NaHCO3, LB/HR                                                300.10
FLUE GASES, WSCFM              10275.92   9732.45   9732.45             9806.48
ASH&SOLIDS, LB/HR                842.09    945.03    945.03             1278.16

                      13        14        15        16        17        18

AIR, SCFM             111.25
WATER, GPM              2.00
COAL, LB/HR
Ca(OH)2, LB/HR
NaHCO3, LB/HR
FLUE GASES, WSCFM              10336.79   7383.42   2953.37   7383.42  [illegible]
ASH&SOLIDS, LB/HR               1199.05    856.46    342.59

                      19        20        21

AIR, SCFM
WATER, GPM
COAL, LB/HR
Ca(OH)2, LB/HR
NaHCO3, LB/HR
FLUE GASES, WSCFM   10336.79
ASH&SOLIDS, LB/HR                856.46    342.59
```

```
                              HEAT BALANCE

ALL COOLING AIR AND INJECTED SOLIDS AND GASES AT AMBIENT TEMPERATURE

                              SENSIBLE HEAT, BTU/HR , REF   70.00 DEG F

COMPONENT             HX       ECON     AH       DUCT     DUCT
                      INLET    INLET    INLET    INLET    OUTLET

N2                    9.29E+06 7.58E+06 5.21E+06 1.87E+06 1.09E+06
O2                    3.43E+05 2.80E+05 2.19E+05 7.89E+04 6.20E+04
CO2                   2.69E+06 2.16E+06 1.40E+06 4.80E+05 2.70E+05
SO2                   4.31E+04 3.46E+04 1.12E+04 3.85E+03 2.36E+03
NO                    3.04E+03 2.48E+03 1.66E+03 5.97E+02 1.95E+02
H2O                   4.69E+06 4.33E+06 3.88E+06 3.29E+06 4.27E+06

ASH                   1.56E+05 1.29E+05 8.72E+04 3.18E+04 1.30E+04
CaSO3                 0.00E+00 0.00E+00 1.63E+04 5.94E+03 3.36E+03
CaSO4                 0.00E+00 0.00E+00 1.54E+04 5.61E+03 3.17E+03
CaCO3                 0.00E+00 0.00E+00 4.75E+03 1.73E+03 9.79E+02
CaO                   0.00E+00 0.00E+00 1.20E+03 4.39E+02 2.48E+02
Ca(OH)2               0.00E+00 0.00E+00 1.70E+04 6.20E+03 3.50E+03
Na2SO4                0.00E+00 0.00E+00 0.00E+00 0.00E+00 4.17E+03
NaNO3                 0.00E+00 0.00E+00 0.00E+00 0.00E+00 4.75E+02
Na2CO3                0.00E+00 0.00E+00 0.00E+00 0.00E+00 2.96E+03
NaHCO3                0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

FLUE GAS+SOLIDS       1.72E+07 1.45E+07 1.09E+07 5.73E+06 5.71E+06

WALL CONDUCTION       0.00E+00 2.66E+04 3.62E+04 5.08E+04 [illegible]
COOLING AIR           0.00E+00 2.66E+06 3.62E+06 5.08E+05 0.00E+00

TOTALS                1.72E+07 1.72E+07 1.45E+07 1.09E+07 5.73E+06

COOL AIR OUT DEG F             947.37   629.68   355.47

SPRAY WATER, GPM  =               2.00
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          MASS AND ENERGY FLOW CALCULATIONS

COAL CONSTITUENT            WT. %

          C                58.50
          H                 4.00
          N                 1.00
          O                 6.00
          S                 2.50
          ASH              18.00
          WATER            10.00             10500.00 BTU/LB

SLIPSTREAM FLOW = 10000.00 WSCFM (1 ATM 60 DEG F) @ 5.30E+03 [illegible]

COMBUSTION CALCULATION RESULT  SR =        1.17

GAS CONSTITUENT                    LB/HR              LB AIR/LB COAL @ SR = [illegible]

N2%              73.34          23445.67                        [illegible]
O2%               2.71           1370.18
CO2%             14.17           9850.98
SO2ppm         2070.00            229.54
NOppm           240.00             11.38
H2O%              9.56           2718.86
ASH GR/CF         3.41            720.86              WSCF/LB COAL =        133.[illegible]

REACTION CONSTANTS --- A ... N IN LB MOLE / HOUR

A*Ca(OH)2 + B*SO2 = C*CaSO3 + D*CaSO4 + E*CaCO3 + F*CaO + G*Ca(OH)2

I*NaHCO3 + J*SO2 + K*NO = L*Na2SO4 + M*NaNO3 + N*Na2CO3

CALCIUM NSR = A/B =                 2.00

SO2 CAPTURE EFF = (C+D)/B =     0.79              COOLING AIR FLOW LB/HR

CaSO3/CaSO4 = C/D =             1.00              HX          12500.00
                                                  ECON        27000.00
CaCO3/(SO3+SO4) = E/(C+D) =     0.50              AH          75000.00

CaO/(SO3+SO4) = F/(C+D) =       0.25                          STREAM TEMPERATURE

SODIUM NSR = I/(2J+K) =         1.00                          DEG F     DEG R

SO2 CAPTURE EFF = L/J =         0.60              HX IN       1500.00   1960.00
                                                  ECON IN     1000.00   1460.00
NO CAPTURE EFF = M/K =          0.42              AH IN        700.00   1160.00
                                                  DUCT IN      300.00    760.00
LB INJECT AIR / LB Ca(OH)2      4.00              DUCT OUT     200.00    660.00
LB INJECT AIR / LB NaHCO3 =     1.00

LB ATOMIZER AIR / LB WATER      0.50

REFERENCE TEMPERATURE = AMBIENT =        70.00 =          530.00 DEG R
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MATERIAL FLOWS, LB/HR

COMPONENT	ECON INLET	Ca(OH)2 INJECT	ECON OUTLET	NaHCO3 +WATER	DUCT OUTLET	[illegible]
N2, LB/HR	32445.62	1628.54	34074.16	573.03	34560.1[illegible]	[illegible]
O2	1370.18	492.60	1840.11	151.23	1974.[illegible]	[illegible]
CO2	9850.98		9788.65		9883.[illegible]	[illegible]
SO2	229.54		48.20		19.78	[illegible]
NO	11.38		11.38		[illegible]	[illegible]
H2O	2718.[illegible]		2808.12	1073.14	[illegible]899.6[illegible]	[illegible]
TOTAL GAS	466[illegible]	2121.14	48570.61	1797.40	503[illegible]	[illegible]
						[illegible]
ASH, LB/HR	576.[illegible]		576.69		576.69	4[illegible]
CaSO3	0.00		170.00		[illegible]	[illegible]
CaSO4	0.00		192.67		192.67	13.7[illegible]
CaCO3	0.00		141.67		141.67	[illegible]
CaO	0.00		39.67		39.67	[illegible]
Ca(OH)2	0.00	530.82	163.89		163.8[illegible]	[illegible]
Na2SO4	0.00		0.00		64.17	4.5[illegible]
NaNO3	0.00		0.00		13.7[illegible]	0.[illegible]
Na2CO3	0.00		0.00		43.59	3.10
NaHCO3	0.00		0.00	158.39	0.00	0.00
TOTAL SOLIDS	576.69	530.82	1284.59	158.39	14[illegible]5.59	100.00
TOTAL MASS	47203.24	2651.96	49855.20	1925.79	517[illegible]	

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                                   STREAM NUMBER

                         1          2          3          4          5          6

AIR, SCFM                       10812.97
WATER, GPM
COAL, LB/HR           5238.10
Ca(OH)2, LB/HR
NaHCO3, LB/HR
FLUE GASES, WSCFM                                     1602.57 [illegible]  [illegible]
ASH&SOLIDS, LB/HR                           167.05      43.91    576.67  [illegible]

                         7          8          9         10         11         12

AIR, SCFM              471.84                                     35.[illegible]
WATER, GPM
COAL, LB/HR
Ca(OH)2, LB/HR         500.82
NaHCO3, LB/HR                                                     158.39
FLUE GASES, WSCFM               10471.84    9971.16    9971.16            10[illegible]
ASH&SOLIDS, LB/HR                1107.50    1284.59    1284.59             1442.[illegible]

                        13         14         15         16         17         18

AIR, SCFM              119.24
WATER, GPM               0.14
COAL, LB/HR
Ca(OH)2, LB/HR
NaHCO3, LB/HR
FLUE GASES, WSCFM               10432.13    7451.52    2980.61    745[illegible]  [illegible]
ASH&SOLIDS, LB/HR                1405.89    1004.21     401.68

                        19         20         21

AIR, SCFM
WATER, GPM
COAL, LB/HR
Ca(OH)2, LB/HR
NaHCO3, LB/HR
FLUE GASES, WSCFM 10432.13
ASH&SOLIDS, LB/HR                1004.21     401.68
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                           HEAT BALANCE

ALL COOLING AIR AND INJECTED SOLIDS AND GASES AT AMBIENT TEMPERATUR

                           SENSIBLE HEAT, BTU/HR,   REF    70.00 DEG F

COMPONENT            HA       ECON     AH       DUCT     DUCT
                     INLET    INLET    INLET    INLET    OUTLET

N2                 9.29E+06 7.58E+06 5.33E+06 1.92E+06 1.09E+06
O2                 3.43E+05 2.80E+05 2.32E+05 9.06E+04 5.47E+04
CO2                2.69E+06 2.16E+06 1.40E+06 4.78E+05 2.67E+05
SO2                4.31E+04 3.46E+04 4.72E+03 1.62E+03 7.59E+02
NO                 3.04E+03 2.48E+03 1.66E+03 5.97E+02 1.95E+02
H2O                4.69E+06 4.33E+06 3.95E+06 3.30E+06 4.36E+06

ASH                1.56E+05 1.29E+05 3.72E+04 3.18E+04 1.30E+04
CaSO3              0.00E+00 0.00E+00 2.57E+04 9.38E+03 5.30E+03
CaSO4              0.00E+00 0.00E+00 2.43E+04 8.86E+03 5.01E+03
CaCO3              0.00E+00 0.00E+00 1.87E+04 6.84E+03 3.87E+03
CaO                0.00E+00 0.00E+00 4.75E+03 1.73E+03 9.80E+02
Ca(OH)2            0.00E+00 0.00E+00 2.99E+04 1.09E+04 6.18E+03
Na2SO4             0.00E+00 0.00E+00 0.00E+00 0.00E+00 1.75E+03
NaNO3              0.00E+00 0.00E+00 0.00E+00 0.00E+00 4.75E+02
Na2CO3             0.00E+00 0.00E+00 0.00E+00 0.00E+00 1.47E+03
NaHCO3             0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

FLUE GAS+SOLIDS    1.72E+07 1.45E+07 1.11E+07 5.86E+06 5.84E+06

WALL CONDUCTION    0.00E+00 2.66E+04 3.36E+04 5.21E+04 2.00E+04
COOLING AIR        0.00E+00 2.66E+06 3.36E+06 5.21E+06 0.00E+00

TOTALS             1.72E+07 1.72E+07 1.45E+07 1.11E+07 5.86E+06

COOL AIR OUT DEG F             947.37   590.40   362.93

SPRAY WATER, GPM   =             2.14
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LOTUS123 FILE FUELSTO.WK1                                      PAGE 1/2
USER ENTERS VALUES MARKED *

                  FLUE GAS COMPOSITION FROM COAL ANALYSIS

FUEL*:    #1, 3/7/89 FAX

                       MOL O2   MOL PRODUCED/LB COAL, 0% O2 IN DRY AIR
WT% IN COAL AF         RQD/LB   -------------------------------------------------
-----------------    --------   CO2      H2O      SO2      N2       FLUE GAS
CARBON*        57.50 4.79E-02 4.79E-02                   1.80E-01 2.28E-01
HYDROGEN*       4.00 1.00E-02          2.00E-02          3.76E-02 5.76E-02
NITROGEN*       1.00 0.00E+00                            3.57E-04 3.57E-04
OXYGEN*         6.00 -1.9E-03                            -7.1E-03 -7.1E-03
SULFUR*         3.50 1.09E-03                   1.09E-03 4.11E-03 5.21E-03
ASH*           16.00 0.00E+00                                     0.00E+00
MOISTURE*      12.00 0.00E+00          6.67E-03                   6.67E-03
-------- -------- -------- -------- -------- -------- -------- --------
TOTAL          100.0 5.71E-02 4.79E-02 2.67E-02 1.09E-03 2.15E-01 2.91E-01


STOICHIOMETRIC COMBUSTION IN DRY AIR, PER LB FUEL:

                    AIR RQD(MDA0)       DRY FG(MDFG0)       WET FG
MOLES               2.72E-01            2.64E-01            2.91E-01
M.W.                2.90E+01            3.10E+01            2.99E+01
LBS                 7.89E+00            8.21E+00            8.69E+00

Y(0), MOL H2O/MOL DRY FG, STOICH COMB IN DRY AIR:           1.01E-01

BTU/LB*      10500

LBS SO2/10E6 BTU       6.67
LBS ASH/10E6 BTU      15.24
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LOTUS123 FILE FUELSTO.WK1                                  PAGE 2/2
USER ENTERS VALUES MARKED *


YA, AMBIENT HUMIDITY, MOL/DRY MOL*: 2.00E-02


DRY %O2*                  0.00     1.00     2.00     3.00     4.00     5.00
SR                       1.000    1.050    1.105    1.167    1.235    1.313
DRY BASIS:

CO2, %                   18.13    17.27    16.40    15.54    14.68    13.81
N2, %                    81.46    81.34    81.22    81.11    80.99    80.87
SO2, PPM                  4138     3941     3744     3547     3350     3153
MOL WT                   31.05    30.94    30.84    30.73    30.63    30.52
DSCF/LB COAL             102.3    107.4    113.1    119.3    126.4    134.3
DSCF/1E6 BTU              9742    10229    10767    11365    12034    12786
ASH, GR/DSCF             10.95    10.43     9.91     9.39     8.86     8.34

Y, MOL/MOL DRY FG        0.121    0.116    0.111    0.106    0.102    0.097

WET BASIS:

O2, %                     0.00     0.90     1.80     2.71     3.63     4.56
CO2, %                   16.17    15.47    14.76    14.04    13.32    12.59
N2, %                    72.67    72.88    73.09    73.30    73.51    73.73
SO2, PPM                  3692     3531     3369     3206     3041     2874
H2O, %                   10.79    10.40    10.01     9.62     9.23     8.83
MOL WT                   29.64    29.60    29.55    29.51    29.46    29.42
WSCF/LB COAL             114.7    119.9    125.6    132.0    139.2    147.3
WSCF/1E6 BTU             10919    11416    11965    12575    13257    14024
ASH,GR/WSCF               9.77     9.34     8.91     8.48     8.05     7.61

Y TAKEN AS Y(0)/SR + YA  (WITHIN 1% RELATIVE FOR COAL, 2%REL FOR GAS)
SR DEFINED AS 21/(21-DRY O2)
DRY CONCENTRATION = DRY CONC(@0% O2)/SR
WET CONCENTRATION = DRY CONC/(1+Y)
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          MASS AND ENERGY FLOW CALCULATIONS

COAL CONSTITUENT          WT %

           C            57.50
           H             4.00
           N             1.00
           O             6.00
           S             3.50
           ASH          16.00
           WATER        12.00              10500.00 BTU/LB

SLIPSTREAM FLOW = 10000.00 WSCFM (1 ATM, 60 DEG F) @ 5.5[illegible]

COMBUSTION CALCULATION RESULTS  SR =       1.17

GAS CONSTITUENT                 LB/HR                LB AIR/LB COAL @ SR

N2%          73.30           31427.92                          7.89
O2%           3.71            1370.18
CO2%         14.04            9760.61
SO2ppm     3206.00             324.19
NOppm       240.00              11.38
H2O%          9.62            2735.93
ASH GR/CF     3.48             726.84                WSCF/LB COAL =       [illegible]

REACTION CONSTANTS --- A ... N IN LB MOLE / HOUR

A*Ca(OH)2 + B*SO2 = C*CaSO3 + D*CaSO4 + E*CaCO3 + F*CaO + G*H2O

I*NaHCO3 + J*SO2 + K*NO = L*Na2SO4 + M*NaNO3 + N*Na2CO3

CALCIUM NSR = A/B =                1.00

SO2 CAPTURE EFF = (C+D)/B =       0.50             COOLING AIR FLOW, LB/HR

CaSO3/CaSO4 = C/D =               1.00             HX          12500.00
                                                   ECON        27000.00
CaCO3/(SO3+SO4) = E/(C+D) =       0.20             AH          75000.00

CaO/(SO3+SO4) = F/(C+D) =         0.10                        STREAM TEMPERATURES

SODIUM NSR = I/(2J+K) =           1.00                        DEG F      DEG R

SO2 CAPTURE.EFF = L/J =           0.60             HX IN      1200.00   1660.00
                                                   ECON IN    1000.00   1460.00
NO CAPTURE EFF = M/K =            0.42             AH IN       700.00   1160.00
                                                   DUCT IN     300.00    760.00
LB INJECT AIR / LB Ca(OH)2        4.00             DUCT OUT    200.00    660.00

LB INJECT AIR / LB NaHCO3 =       1.00

LB ATOMIZER AIR / LB WATER        0.50

REFERENCE TEMPERATURE = AMBIENT =       70.00 =           530.00 DEG. R.
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MATERIAL FLOWS, LB/HR

COMPONENT	ECON INLET	Ca(OH)2 INJECT	ECON OUTLET	NaHCO3 +WATER	DUCT OUTLET	VOL
N2,LB/HR	32427.92	1150.03	33577.95	728.04	34931.11	[illegible]
O2	1370.18	347.86	1697.77	220.21	2092.[illegible]	[illegible]
CO2	9760.61		9738.32		9928.47	[illegible]
SO2	324.19		162.10		64.[illegible]	[illegible]
NO	11.38		11.38		[illegible]	[illegible]
H2O	2735.93		2795.19	993.[illegible]	[illegible]	[illegible]
TOTAL GAS	46630.20	1497.88	47982.70	1931.95	[illegible]	[illegible]
ASH,LB/HR	581.49		581.49		581.49	[illegible]
CaSO3	0.00		151.96		151.96	[illegible]
CaSO4	0.00		172.23		172.23	[illegible]
CaCO3	0.00		50.65		50.65	[illegible]
CaO	0.00		14.18		14.18	[illegible]
Ca(OH)2	0.00	374.85	131.30		131.10	[illegible]
Na2SO4	0.00		0.00		215.79	14.[illegible]
NaNO3	0.00		0.00		13.34	[illegible]
Na2CO3	0.00		0.00		119.14	8.21
NaHCO3	0.00		0.00	457.35	0.00	[illegible]
TOTAL SOLIDS	581.49	374.85	1101.71	457.35	1450.08	[illegible]
TOTAL MASS	47211.68	1872.73	49084.41	2389.21	52753.21	

STREAM NUMBER

	1	2	3	4	5	6
AIR, SCFM		10717.85				
WATER, GPM						
COAL, LB/HR	5238.10					
Ca(OH)2, LB/HR						
NaHCO3, LB/HR						
FLUE GASES, WSCFM				1523.81	[illegible]	[illegible]
ASH&SOLIDS, LB/HR			167.52	88.61	58.49	[illegible]

	7	8	9	10	11	12
AIR, SCFM	333.20				101.[illegible]	
WATER, GPM						
COAL, LB/HR						
Ca(OH)2, LB/HR	374.85					
NaHCO3, LB/HR					459.05	
FLUE GASES, WSCFM		10333.20	9820.45	9820.45		[illegible]
ASH&SOLIDS, LB/HR		956.33	1101.71	1101.71		[illegible]

	13	14	15	16	17	18
AIR, SCFM	109.37					
WATER, GPM	1.96					
COAL, LB/HR						
Ca(OH)2, LB/HR						
NaHCO3, LB/HR						
FLUE GASES, WSCFM		10537.18	7526.56	7010.62	7526.56	[illegible]
ASH&SOLIDS, LB/HR		1450.08	1035.77	414.31		

	19	20	21
AIR, SCFM			
WATER, GPM			
COAL, LB/HR			
Ca(OH)2, LB/HR			
NaHCO3, LB/HR			
FLUE GASES, WSCFM	10537.18		
ASH&SOLIDS, LB/HR		1035.77	414.31

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                              HEAT BALANCE

ALL COOLING AIR AND INJECTED SOLIDS AND GASES AT AMBIENT TEMPERATURE

                              SENSIBLE HEAT (BTU/HR), REF  [illegible] DEG F

COMPONENT            HX        ECON      AH        DUCT      DUCT
                     INLET     INLET     INLET     INLET     OUTLET

N2                   9.28E+06 7.58E+06 5.26E+06 1.89E+06 1.11E+[illegible]
O2                   3.43E+05 2.80E+05 2.30E+05 8.[illegible] [illegible]
CO2                  2.67E+06 2.14E+06 1.39E+06 4.75E+05 2.[illegible]4E+05
SO2                  6.09E+04 4.89E+04 1.59E+04 5.14E+03 1.21E+0[illegible]
NO                   3.04E+03 2.49E+03 1.56E+03 5.97E+02 1.95E+02
H2O                  4.72E+06 4.36E+06 3.93E+06 3.29E+06 4.[illegible]

ASH                  1.58E+05 1.30E+05 8.79E+04 3.21E+04 1.81E+04
CaSO3                0.00E+00 0.00E+00 2.30E+04 8.39E+03 4.74E+03
CaSO4                0.00E+00 0.00E+00 2.17E+04 7.92E+03 4.49E+03
CaCO3                0.00E+00 0.00E+00 5.70E+03 2.45E+03 1.38E+03
CaO                  0.00E+00 0.00E+00 1.70E+03 6.20E+02 3.50E+02
Ca(OH)2              0.00E+00 0.00E+00 2.40E+04 8.75E+03 4.95E+03
Na2SO4               0.00E+00 0.00E+00 0.00E+00 0.00E+00 5.89E+03
NaNO3                0.00E+00 0.00E+00 0.00E+00 0.00E+00 4.75E+0[illegible]
Na2CO3               0.00E+00 0.00E+00 0.00E+00 0.00E+00 4.02E+03
NaHCO3               0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+0[illegible]

FLUE GAS+SOLIDS      1.72E+07 1.45E+07 1.10E+07 5.80E+06 5.78E+0[illegible]

WALL CONDUCTION      0.00E+00 2.66E+04 3.52E+04 5.13E+04 [illegible]
COOLING AIR          0.00E+00 2.66E+06 3.52E+06 5.13E+06 0.[illegible]E+00

TOTALS               1.72E+07 1.72E+07 1.45E+07 1.10E+07 5.80E+0[illegible]

COOL AIR OUT DEG F             947.42    613.72    358.59

SPRAY WATER, GPM  =            1.96
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          MASS AND ENERGY FLOW CALCULATIONS

COAL CONSTITUENT          WT. %

          C               57.50
          H                4.00
          N                1.00
          O                1.00
          S                3.50
          ASH             15.00
          WATER           12.00            10500.00 BTU/LB

SLIPSTREAM FLOW = 10000.00 WSCFM (1 ATM, 60 DEG F) @ 5.50%+ 7 [illegible]

COMBUSTION CALCULATION RESULT  SR =       1.17

GAS CONSTITUENT                LB/HR              LB AIR/LB COAL @ SR

N2%            73.30         32427.92                        7.89
O2%             3.71          1370.18
CO2%           14.04          9760.61
SO2ppm       3206.00           324.19
NOppm         240.00            11.38
H2O%            9.62          2735.93
ASH,GR/CF       3.48           726.86             WSCF/LB COAL =       132.[illegible]

REACTION CONSTANTS --- A .... N IN LB MOLE / HOUR

A*Ca(OH)2 + B*SO2 = C*CaSO3 + D*CaSO4 + E*CaCO3 + F*CaO + G*Ca(OH)2

I*NaHCO3 + J*SO2 + K*NO = L*Na2SO4 + M*NaNO3 + N*Na2CO3

CALCIUM NSR = A/B =             2.00

SO2 CAPTURE EFF = (C+D)/B =     0.79          COOLING AIR FLOW, LB/HR

CaSO3/CaSO4 = C/D =             1.00          HX         12500.00
                                              ECON       27000.00
CaCO3/(SO3+SO4) = E/(C+D) =     0.50          AH         75000.00

CaO/(SO3+SO4) = F/(C+D) =       0.25                     STREAM TEMPERATURE

SODIUM NSR = I/(2J+K) =         1.00                     DEG F      DEG R

SO2 CAPTURE EFF = L/J =         0.60          HX IN      1200.00    1660.00
                                              ECON IN    1000.00    1460.00
NO CAPTURE EFF = M/K =          0.42          AH IN       700.00    1160.00
                                              DUCT IN     300.00     760.00
LB INJECT AIR / LB Ca(OH)2      4.00          DUCT OUT    200.00     660.00

LB INJECT AIR / LB NaHCO3 =     1.00

LB ATOMIZER AIR / LB WATER      0.50

REFERENCE TEMPERATURE = AMBIENT =       70.00 =          530.00 DEG R
```

MATERIAL FLOWS, LB/HR

COMPONENT	ECON INLET	Ca(OH)2 INJECT	ECON OUTLET	NaHCO3 +WATER	DUCT OUTLET	VOL %
N2 LB/HR	32427.92	2300.05	34727.97	577.70	35373.98	71.1[illegible]
O2	1370.18	695.71	2033.98	174.74	2213.97	3.[illegible]
CO2	9760.61		9672.57		9759.30	12.[illegible]
SO2	324.19		68.08		27.23	[illegible]
NO	11.38		11.33		6.60	[illegible]
H2O	2735.93		2861.98	1085.26	3971.24	12.4[illegible]
TOTAL GAS	46630.20	2995.77	49375.86	1837.70	51352.3[illegible]	[illegible]
						MASS
ASH, LB/HR	581.49		581.49		581.49	33.3[illegible]
CaSO3	0.00		240.10		240.10	13.[illegible]
CaSO4	0.00		272.12		272.12	15.[illegible]
CaCO3	0.00		200.09		200.09	11.4[illegible]
CaO	0.00		56.02		56.02	3.22
Ca(OH)2	0.00	749.69	231.47		231.47	13.29
Na2SO4	0.00		0.00		90.63	5.20
NaNO3	0.00		0.00		13.54	0.78
Na2CO3	0.00		0.00		56.76	3.26
NaHCO3	0.00		0.00	210.56	0.00	0.00
TOTAL SOLIDS	581.49	749.69	1581.28	210.56	1742.21	100.00
TOTAL MASS	47211.68	3745.46	50957.14	2048.26	53094.53	

STREAM NUMBER

	1	2	3	4	5	6
AIR, SCFM		10717.88				
WATER, GPM						
COAL, LB/HR	5238.10					
Ca(OH)2, LB/HR						
NaHCO3, LB/HR						
FLUE GASES, WSCFM				1523.81	10000.00	10000.00
ASH&SOLIDS, LB/HR			167.52	38.61	581.49	581.49

	7	8	9	10	11	12
AIR, SCFM	666.39				46.79	
WATER, GPM						
COAL, LB/HR						
Ca(OH)2, LB/HR	749.69					
NaHCO3, LB/HR					210.56	
FLUE GASES, WSCFM		10666.39	10157.73	10157.73		10204.52
ASH&SOLIDS, LB/HR		1331.18	1581.28	1581.28		1791.85

	13	14	15	16	17	18
AIR, SCFM	120.58					
WATER, GPM	2.17					
COAL, LB/HR						
Ca(OH)2, LB/HR						
NaHCO3, LB/HR						
FLUE GASES, WSCFM		10671.98	7622.35	3049.14	7622.35	3049.14
ASH&SOLIDS, LB/HR		1742.21	1244.44	497.78		

	19	20	21
AIR, SCFM			
WATER, GPM			
COAL, LB/HR			
Ca(OH)2, LB/HR			
NaHCO3, LB/HR			
FLUE GASES, WSCFM	10671.98		
ASH&SOLIDS, LB/HR		1244.44	497.78

```
                            HEAT BALANCE

ALL COOLING AIR AND INJECTED SOLIDS AND GASES AT AMBIENT TEMPERATURE

                           SENSIBLE HEAT, BTU/HR., REF   70.00 DEG F

COMPONENT          HX       ECON     AH       DUCT     DUCT
                   INLET    INLET    INLET    INLET    OUTLET

N2                 9.28E+06 7.58E+06 5.44E+06 1.95E+06 1.12E+06
O2                 3.43E+05 2.80E+05 2.79E+05 1.00E+05 6.14E+04
CO2                2.67E+06 2.14E+06 1.38E+06 4.72E+05 2.65E+05
SO2                6.09E+04 4.89E+04 6.67E+03 2.29E+03 5.08E+02
NO                 3.04E+03 2.48E+03 1.66E+03 5.97E+02 1.95E+02
H2O                4.72E+06 4.36E+06 4.02E+06 3.37E+06 4.46E+06

ASH                1.58E+05 1.30E+05 8.79E+04 3.21E+04 1.81E+04
CaSO3              0.00E+00 0.00E+00 3.63E+04 1.33E+04 7.49E+03
CaSO4              0.00E+00 0.00E+00 3.43E+04 1.25E+04 7.08E+03
CaCO3              0.00E+00 0.00E+00 2.65E+04 9.66E+03 5.46E+03
CaO                0.00E+00 0.00E+00 6.71E+03 2.45E+03 1.38E+03
Ca(OH)2            0.00E+00 0.00E+00 4.23E+04 1.54E+04 6.73E+03
Na2SO4             0.00E+00 0.00E+00 0.00E+00 0.00E+00 2.47E+03
NaNO3              0.00E+00 0.00E+00 0.00E+00 0.00E+00 4.75E+02
Na2CO3             0.00E+00 0.00E+00 0.00E+00 0.00E+00 1.92E+03
NaHCO3             0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

FLUE GAS+SOLIDS    1.72E+07 1.45E+07 1.14E+07 5.98E+06 5.96E+06

WALL CONDUCTION    0.00E+00 2.66E+04 3.15E+04 5.32E+04 2.00E+04
COOLING AIR        0.00E+00 2.66E+06 3.15E+06 5.32E+06 0.00E+00

TOTALS             1.72E+07 1.72E+07 1.45E+07 1.14E+07 5.98E+06

COOL AIR OUT DEG F            947.42   558.14   369.14

SPRAY WATER, GPM  =             2.17
```

APPENDIX II Heat Exchanger Design

Air vs. Water Cooling

As mentioned previously, air cooling is preferred to give reasonable tube metal tempertures without the use of pressurized water or stream. Air also offers better control, since the range of water temperature, and hence the driving force for heat transfer, is limited in a non-pressurized system. A large supply of cooling air is available from the FD fan, since the furnace is operated at 50 rather than the nominal 100 million Btu/hr rating.

Annular vs. Hollow Tube

In the preceding example, the internal coefficient was about 4.4 Btu/hr F Ft^2, and the cooling air delta p through tube was 0.2 IWC. The internal coefficient can be increased significantly at a given flow by using an annular arrangement and taking a higher pressure drop through the tube (eg, h=20 at delta p = 8 IWC). Since cooling air is available at up to 27 IWC, this approach is preferable. Annular construction can also be used to advantage in reducing expansion problems, since the air inlet and outlet are both at the fixed end of the tube, and the other end is not restricted.

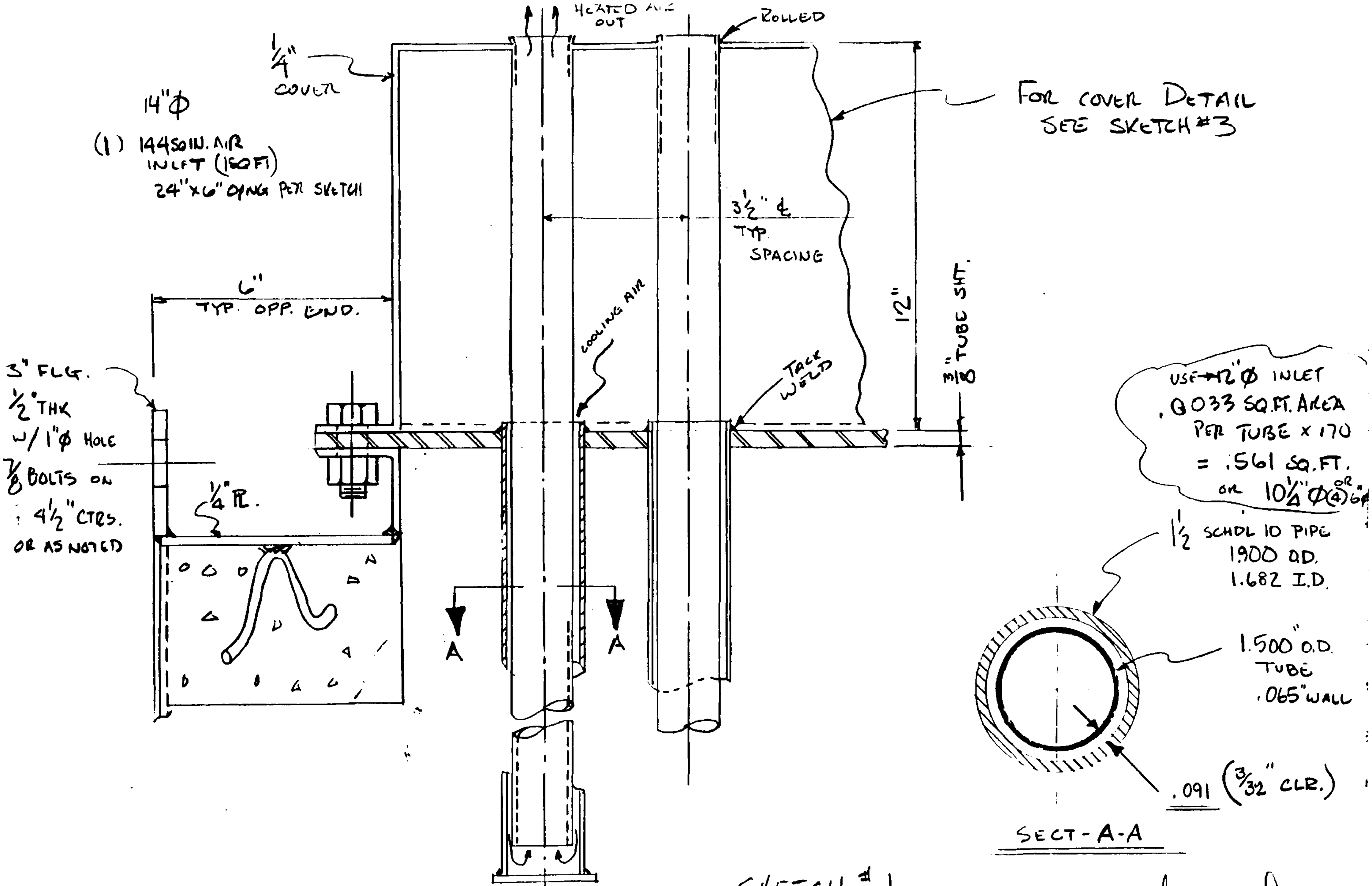
Modular Design

Three Heat exchanger modules will be constructed as follows:

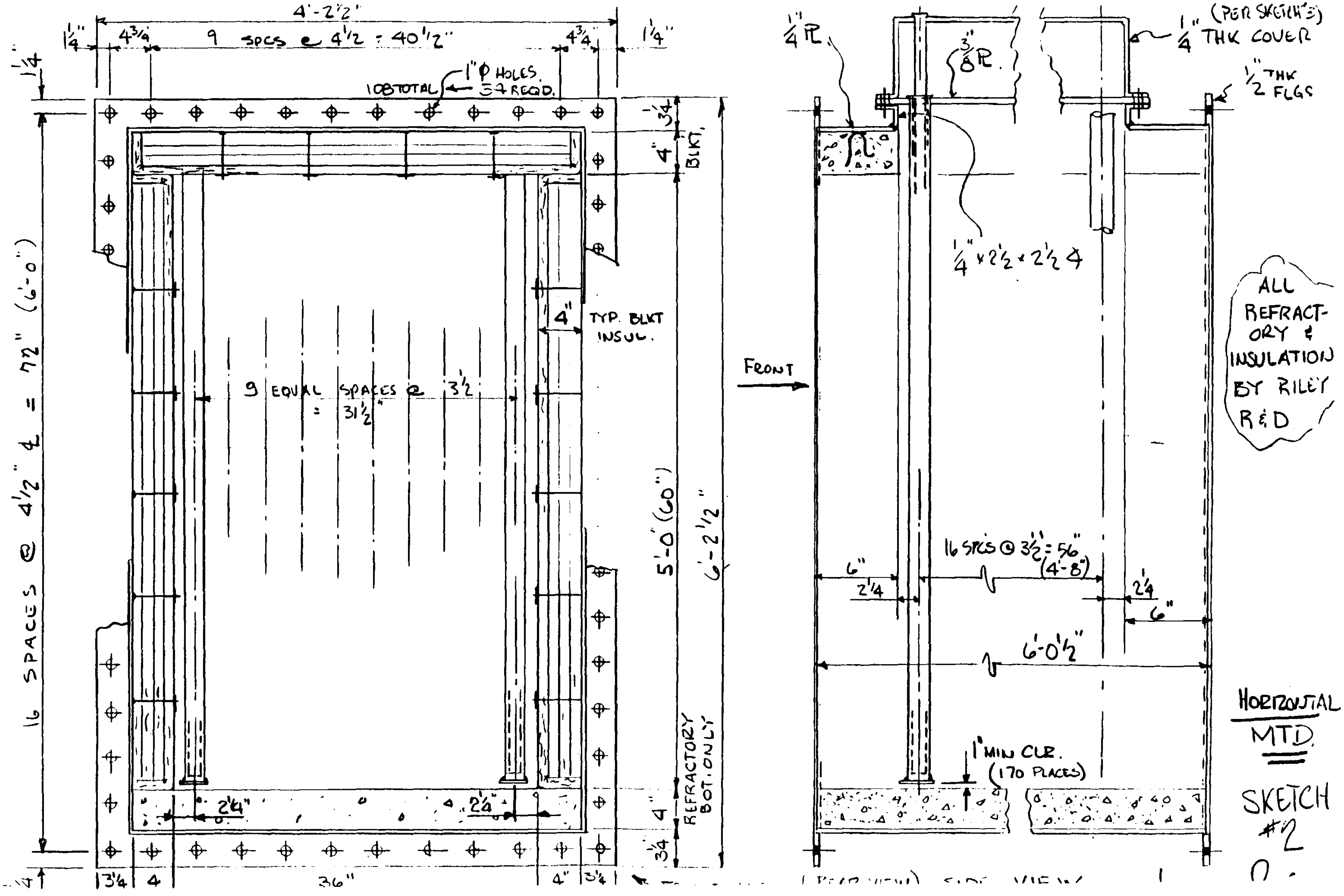
- 3' X 5' duct cross section, 6 ft. long. Superficial velocity about 27 ft/s for 50E6 Btu/hr, 800 F gas.
- 1.91" OD tubes (sch 10 2-inch pipe) on 3.5" centers, 10 tubes/row, 17 rows/section.
- Annular air cooling.
- Lined with insulating refractory.

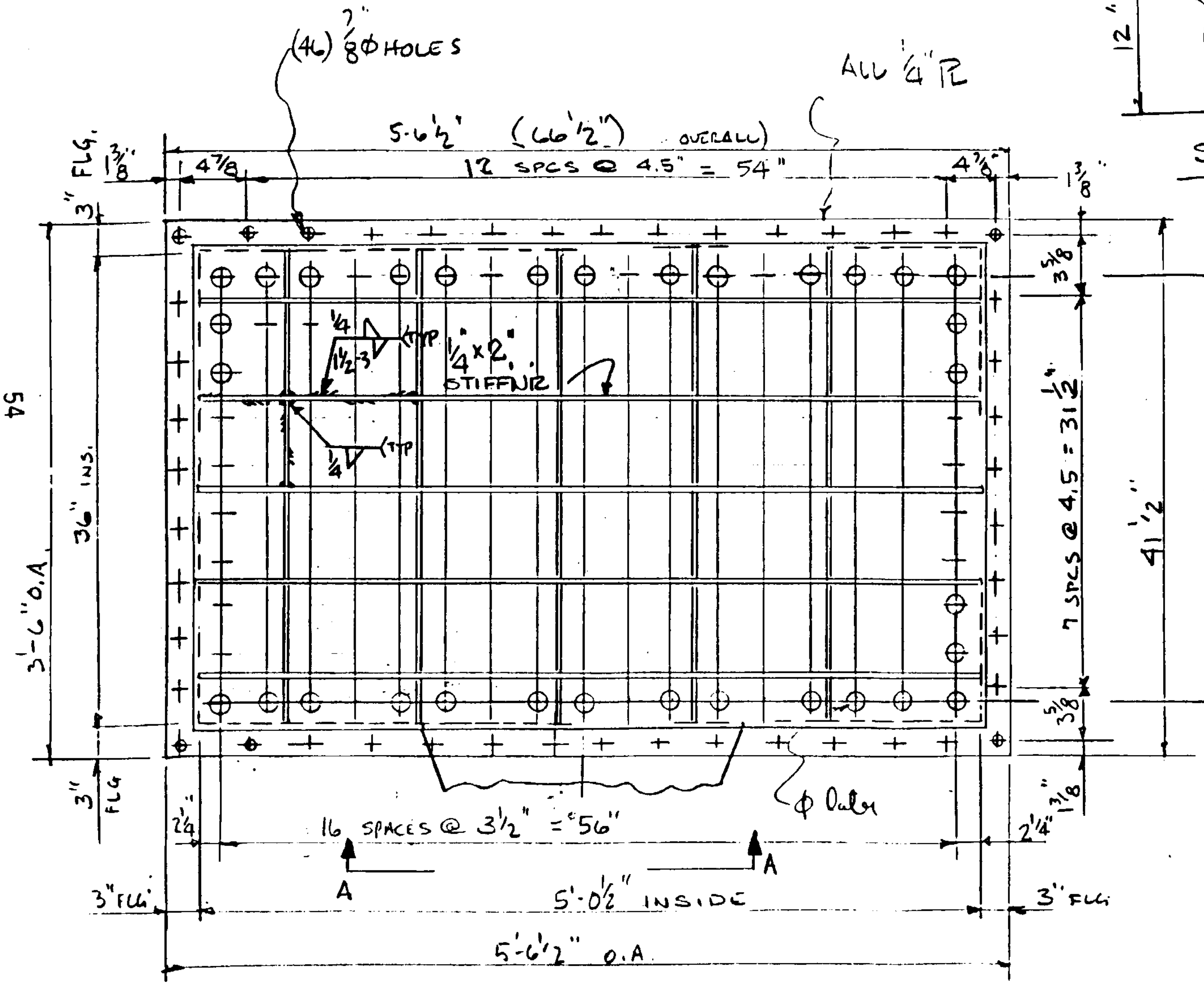
Sketches 1, 2 and 3 show the proposed heat exchanger module.

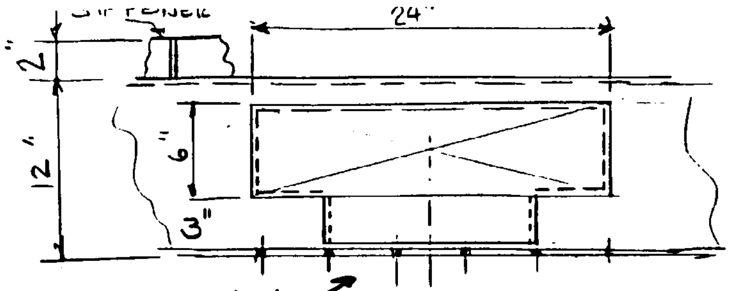
One exchanger will be constructed with stainless tubing and used to control the inlet temperature. Two additional exchangers will be used for the economizer section. A duct with the same cross section, but without tubes, will accommodate the sorbent injectors upstream of the economizer.


HEATED AIR OUT
ROLLED
1/4" COVER
14"Φ
(1) 144 SQ IN. AIR INLET (1 SQ FT) 24"x6" OPNG PER SKETCH
FOR COVER DETAIL SEE SKETCH #3
3 1/2" ℄ TYP. SPACING
6" TYP. OPP. END.
12"
3/8" TUBE SHT.
COOLING AIR
TACK WELD
3" FLG. 1/2" THK w/ 1"Φ HOLE
7/8 BOLTS ON 4 1/2" CTRS. OR AS NOTED
1/4 PL.
A
A
USE ~~12"~~Φ INLET .0033 SQ.FT. AREA PER TUBE x 170 = .561 SQ.FT. OR 10 1/4"Φ OR (4) 6"Φ
1 1/2 SCHDL 10 PIPE 1.900 O.D. 1.682 I.D.
1.500" O.D. TUBE .065" WALL
.091 (3/32" CLR.)
SECT-A-A

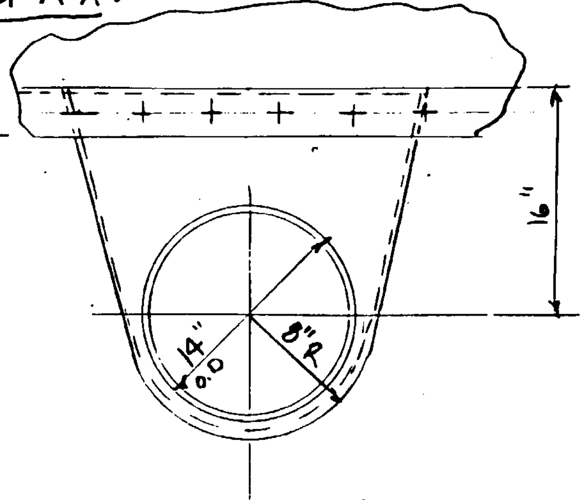
SKETCH # 1


4'-2½"
1¼"
4¾
9 SPCS @ 4½ = 40½"
4¾
1¼"
1¼
1" ϕ HOLES
108 TOTAL
57 REQ'D.
¾
4"
BLKT.
4"
TYP. BLKT INSUL.
9 EQUAL SPACES @ 3½ = 31½"
16 SPACES @ 4½" ⌀ = 72" (6'-0")
5'-0" (60")
6'-2½"
REFRACTORY BOT. ONLY
2¼"
2¼"
4"
¾
1¾
4
36"
4"
3¾
¼" PL
⅜ PL
¼" THK COVER (PER SKETCH 3)
½" THK FLGS
¼" × 2½ × 2½ ∠
ALL REFRACTORY & INSULATION BY RILEY R&D
FRONT
16 SPCS @ 3½" = 56" (4'-8")
6"
2¼
2¼
6"
6'-0½"
1" MIN CLR. (170 PLACES)
(REAR VIEW) SIDE VIEW
HORIZONTAL MTD.
SKETCH #2





SECT A-A



BOTTOM VIEW
COOLING AIR ENTRY

APPENDIX III Heat Exchanger Calculations

An existing BASIC program was used to size the tube banks in the inlet heat exchanger and economizer. This section describes the equations used in the program, and checks the validity of the approximations used.

External to tube banks. Heat transfer correlations for tube banks generally involve graphical methods for geometry and arrangement, for example, the method given in B&W's Steam. However, a correlation given by Douglas and Churchill for single tubes in cross flow gives reasonable results if the maximum (intertube) velocity is substituted for the superficial velocity. The single-tube equation is:

$$h_0D/k = 0.46RE^{0.5} + 0.00128RE$$

Here is a comparison of the two methods for 800 F air flow at a superficial velocity of 20 ft/s:

tube OD x OC1 x OC2	h (eqn.)	h (B&W)
2.0 x 4.0 x 3.0	10.3	10.8
2.0 x 4.0 x 4.0		10.0
2.0 x 4.0 x 8.0		9.8
2.0 x 4.0 x 12.0		9.0
2.0 x 3.0 x 4.0	14.2	12.5
2.0 x 2.5 x 4.0	18.0	18.6

The heat transfer coefficient h (Btu/hr ft^2 F) varies slightly with spacing in the direction of gas flow (OC2 in the table). However, the single-tube equation gives a good approximation at typical tube spacings, and is used in the BASIC program.

Tube wall. The tube wall resistance in the usual form is:

$$\text{Resistance} = \frac{\ln(R2/R1)}{2Pi\ k\ L}\quad , \text{ hr ft F/Btu}$$

In the example following, resistances are all normalized to the external tube surface area:

$$R_w = \frac{R2\ln(R2/R1)}{k}\quad , \text{ hr ft}^2\text{ F/Btu (outside area)}$$

For the case of a clean tube, the tube wall resistance is insignificant. However, a similar equation can be used to add the resistance of a hypothetical uniform layer of ash.

Internal tube flow. The Dittus-Boelter equation is used for internal flow:

$$h_i D/k \quad = \quad 0.023 RE^{0.8} PR^{0.4}$$

For annular flow, the same equation is used with RE based on equivalent hydraulic diameter.

Overall coefficient. The overall coefficient is calculated as:

$$U = 1/(1/h_o + 1/h_i + R_w) \text{ , Btu/hr F ft}^2 \text{ outside area}$$

(all based on outside area)

Example calculation. One other approximation used in the BASIC program is the use of average driving force instead of log-mean difference. (The program originally emphasized high-temperature cases where radiation is important and very large temperature differentials made the log-mean correction insignificant.) The following example is used to check the program calculations by hand.

-4' x 5' cross section duct

-46,500 lb/hr flue gas (50E6 Btu/hr)

-1.91 OD x 1.61 ID tubes (sch 40 2" pipe)

-16 tubes/row, 27 rows of tubes in cross flow

-900 F gas inlet, 70 F air inlet

-30,150 lb/hr air, once-through each tube in parallel

Evaluate at 800 F average gas temperature, 250 F average air temperature:

Internal

v = 24 ft/s
RE = 12,000
NU = 36.4

h_i = 5.18 Btu/hr ft^2, inside area
= 4.37 Btu/hr ft^2, outside area

External

v (between tubes) = 55.3 ft/s
RE = 13,470

h_o = 12.9 Btu/hr F ft^2 outside area, based on single tube equation
(= 14.5 from B&W method)

Wall

k = 23 Btu/hr ft F

R_w = 5.9E-4 hr F ft^2/Btu (outside area)

Overall

U = 1/(1/4.37 + 1/12.9 + 5.9E-4)

= 3.26 Btu/hr ft2 F (3.35 for h_o = 14.5)

Q = UAF(DTlm) = mCp(Tin - Tout)

(where DTlm is log-mean temperature based on countercurrent flow, and F is a correction for cross-flow tube banks, eg, Welty, Wicks, and Wilson, Figure 22.10.)

F = 0.98

A = 1079 ft^2

T out flue gas = 740 F

Gas properties should be reevaluated at (900+740)/2, but this will not change the result much. If the example geometry and flow is evaluated with the BASIC program, the exit temperature is 724 F. If the program is modified to exclude radiant heat transfer (which is not included in the hand calculation above), the calculated exit temperature is 733 F. This is taken as a validation of the program.

Tube bank pressure drop.

The BASIC program includes a tube bank pressure drop based on the approximation given in Perry, p 5-51:

delta p = 0.32 x velocity head