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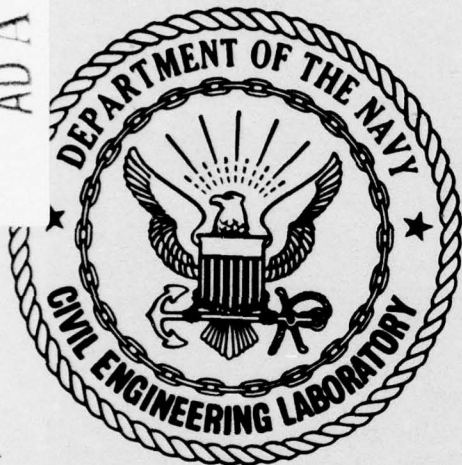
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CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California

Sponsored by
NAVAL FACILITIES ENGINEERING COMMAND

COAL GASIFICATION STUDY HANDBOOK

April 1977

An Investigation Conducted by

BECHTEL CORPORATION
San Francisco, California

N68305-76-C-0009

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CR-77.014	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) COAL GASIFICATION STUDY HANDBOOK,		5. TYPE OF REPORT & PERIOD COVERED Final Report, April 1977
7. AUTHOR(s)		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Bechtel Corporation P.O. Box 3965 San Francisco, CA 94119		8. CONTRACT OR GRANT NUMBER(s) N68305-76-C-0009
11. CONTROLLING OFFICE NAME AND ADDRESS Civil Engineering Laboratory Naval Construction Battalion Center Port Hueneme, CA 93043		10. PROGRAM ELEMENT PROJECT, TASK AREA & WORK UNIT NUMBERS 62765N;F57.571;ZF57.571.001;ZF57.571.001.01.015
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Facilities Engineering Command 200 Stovall Street Alexandria, VA 22332		12. REPORT DATE April 1977
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		13. NUMBER OF PAGES 104
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) F57571 ZF57571001		15. SECURITY CLASS. (of this report) Unclassified
18. SUPPLEMENTARY NOTES		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Coal; coal gasification; cost analysis; emission reduction; fuels; clean burning; plant design		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The purpose of this handbook is to provide: first, a procedure for evaluating the costs of a coal gasification plant in terms of the capital investment and operating costs. These are to be sensitive to several parameters defining coal, fuel gas, and sulfur emissions; second, a procedure for the derating of Navy base boilers, to reflect the change in performance resulting		

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The gas plant analysis is based in part on a detailed analysis of the gas treatment section of the plant. The remaining part of the plant performance is based on conventional stoichiometry and near approach to equilibrium in the gas production section. The boiler derating method is based on observations of the relative contribution to heat transfer made by radiation and convection, and on conventional relations describing these transfer processes.

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CONTENTS

<u>Section</u>		<u>Page</u>
1	INTRODUCTION	1-1
	Purposes	1-1
	Background	1-1
	Proficiency	1-2
	Glossary	1-2
2	GASIFICATION PLANT ANALYSIS	2-1
	Summary	2-1
	System Data and Nomenclature	2-1
	Procedure and Examples	2-6
3	BOILER DERATING	3-1
	Summary	3-1
	System Data and Nomenclature	3-1
	Procedure and Examples	3-7

WORKSHEETS

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ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
3-1	Theoretical Adiabatic Combustion Temperature Variation with Percent Excess Air for Various Boiler Fuels	3-4
3-2	Radiant Heat Transfer Function Variation with Combustion Reaction Temperature	3-4
3-3	Combustion Product Gas Emissivity Variation with Adiabatic Combustion Temperature	3-5
3-4	Overall Convection Heat Transfer Coefficient Variation with that of the Outer Tube Surface	3-6
3-5	Relative Convection Heat Transfer Coefficient Variation with Relative Combustion Products Gas Mass Flow	3-6

TABLES

<u>Table</u>		<u>Page</u>
2-1	Gasifier Plant Characteristics - Data Supporting Use of the Hand Method	2-7
3-1	Fuel in Air Combustion Product Gas Quantities	3-5
3-2	Estimating Procedure Work Sheet for Effects of Fuel Changes on Industrial Saturated Steam Boiler Performance	3-13

Section 1

INTRODUCTION

PURPOSES

The function of this handbook is to provide:

- A procedure for evaluating the costs of a coal gasification plant in terms of the capital investment and operating costs. These are to be sensitive to several parameters defining coal, fuel gas, and sulfur emissions. Hand calculation is practical.
- A procedure for the derating of Navy base boilers, to reflect the change in performance resulting from introduction of fuel gas in place of coal or oil. Hand calculation is practical.

BACKGROUND

The techniques of computation are based on principles discussed in the final report on the subject contract.*

The gas plant analysis is based in part on a detailed analysis of the gas treatment section of the plant. The remaining part of the plant performance is based on conventional stoichiometry and near approach to equilibrium in the gas production section.

The boiler derating method is based on observations of the relative contribution to heat transfer made by radiation and convection, and on conventional relations describing these transfer processes.

*Civil Engineering Laboratory. Contract Report CR 77.013, "Coal Gasification Study," Bechtel Corporation, San Francisco, CA, 1977.

PROFICIENCY

Both procedures below are to some extent the extrapolations of performances calculated in detail. Their accuracy is tied in part to the validity of the base system.

- The gas plant analysis is expected to be capable at nearly all heating values of coal (perhaps down to 6,000 Btu/lb). Fortunately, the thermodynamic character of the gasifier performance forces the calculated effects to apply. The method has not been tried on low heating value coals. There are, furthermore, limits to the range of performance which can be reasonably described by the gas treatment process. These are the ranges covered in the computer runs and presented in graphical form in the contract report.
- The boiler derating method is of a proficiency sufficient for conceptual design, falling off in accuracy as extrapolation is lengthened. Some comments on validity appear in the contract report.

GLOSSARY

1. Combustibles - Considered in this report to be the gaseous components of useful fuel value, exclusive of H₂S.
2. Fire Tube Boiler - A boiler in which the hot gases pass through the main exchanger tube bundle "in-tube."
3. Fuel Gas - Considered in this report to be the gases from the reactor exclusive of water vapor.
4. Hot Fuel Gas - Considered in this report to be all the hot raw gases from the reactor. Cool fuel gas is considered to be the same, but leaving the waste heat recovery section at perhaps 350°F.
5. High Heating Value, HHV - Considered in this report to be the higher heating value of the 100 lb coal used as the basis for the reactor performance analysis.
6. Product Gas - The gas exported from the plant for consumption.

7. Quench Water - The low pressure steam injected for quench purposes in the entrained solids reactor.
8. Savings Investment Rates (SIR) - The ratio of the present value of savings offered by the subject investment program divided by the present value of the investment required for instituting that program.
9. Service Factor - The percentage of time for which a plant, or section of a plant, is operating usefully.
10. Sour Gas - A gas containing hydrogen sulfide and other minor sulfur compounds.
11. Sweet Gas - A gas free of sulfur components.
12. Waste Heat Recovery - Generally, the recovery of sensible heat from hot gases, but more specifically in the present analysis considered as the recovery of heat from the raw hot reactor gases.
13. Water Tube Boiler - A boiler in which the main exchanger carries water "in-tube."

Section 2

GASIFICATION PLANT ANALYSIS

SUMMARY

The computation scheme for analysis of a coal gasification plant is presented in this section. The main features of the scheme are:

- Evaluation of gasifier performance
- Evaluation of gas treatment for sulfur removal
- Evaluation of the capital and operating costs, including unit product cost, using discounted future costs

The method applies to typical reactors operating in a fluidized or entrained solids mode with either air/steam or oxygen/steam as blast. The rationale for the analysis is given in the final report to the Navy for the present contract. The results of the analysis are considered to support a conceptual design. Within several sets of results developed from the analysis, comparisons can be drawn about the performance and costs of gasification and gas cleanup.

SYSTEM DATA AND NOMENCLATURE

Each of the nominal cases represents a different gasifier type and blast mode. The performance of each can be characterized by a set of values set out in Table 2-1. With these it is possible to fix approximately the rates of flow of oxygen, steam, and coal necessary to operate in a manner which extends the past experience with the reactors. Similar data are presented to support the calculations in subsequent parts of the procedure.

The list of nomenclature contains the symbols used in the computation procedure. Units are identified in computation steps.

NOMENCLATURE

Variables

C_p, C'_p	= Molal heat capacity; Specific heat
C	= Capital cost, dollars
$e(SO_2)$	= Emission of SO_2 , lb per 10^6 Btu HHV (Coal)
E	= Energy, Btu or kWhr
ΔH	= Enthalpy change, Btu/mol
ΔH_c	= Heat of combustion, Btu/mol
ΔH_f	= Heat of formation, Btu/mol
HHV(coal)	= High heating value of coal, dry, Btu/100 lb of moist coal charged to gasifier
HHV'(coal)	= High heating value of coal, dry, Btu/100 lb of moist coal charged to gasifier, for which the fraction of carbon converted becomes γ
n	= Number of mols
Σn_i	= Total number of mols
O	= Operating cost, dollars per year
P	= Pressure
Q	= Heat effect, Btu
ΣQ	= Total heat effect, Btu
R_{wc}	= Ratio of total water to carbon charged to the gasifier, mol/mol
R_{qc}	= Ratio of quench water to carbon charged to the gasifier, mol/mol
R_{oc}	= Ratio of free oxygen to carbon charged to the gasifier, mol/mol
R_{bc}	= Ratio of blast gas (not steam) to carbon charged to the gasifier, mol/mol
R_{ps}	= Fraction of high pressure steam going to process (165 psia) use
T	= Temperature, degrees F
W	= Weight
α	= Fraction of gasified carbon which is carbon monoxide
γ	= Fraction of carbon in coal which is gasified

Subscripts

Certain quantities, usually mols of a species representing some portion of a large quantity or associated with some feature of the system will be identified by the subscripts below, if not by other commonly recognized symbols.

blst	=	Blast
CFG	=	Cool fuel gas, from reactor, moist, sour
c	=	Combustion
cmbsl	=	Combustible
evap	=	Evaporation
FG	=	Fuel gas, from reactor, dry basis, sour
HFG	=	Hot fuel gas from reactor, raw
H ₂ ,CO	=	Hydrogen/carbon monoxide mixture
H ₂ O _d	=	Water that undergoes decomposition
H ₂ ,fc	=	Hydrogen, net, in coal after some loss to combination with oxygen in coal
H ₂ ,n,fg	=	Hydrogen net in fuel gas after some loss to combination with oxygen and sulfur in coal
hp	=	High pressure
i	=	i the component, or process features
j	=	j the component, or process feature
N ₂ ,O ₂	=	N ₂ /O ₂ mixture
PG	=	Product gas
qnch	=	Quench water
rctr	=	Reactor
Stm	=	Steam
x	=	Expansion

Numeral Subscripts - Performance Study

0	=	Denotes association with feed coal to gasifier.
1	=	Denotes association with blast to gasifier
2	=	Denotes association with hot raw fuel gas
3	=	Denotes association with waste heat recovery

Numerical Subscripts - Cost Study

1,2,3, etc	=	Used to identify capital or operating cost items as indicated
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Superscripts

o	=	Used to identify a cost item as belonging to the nominal case, as opposed to a variant case
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Table 2-1

GASIFIER PLANT CHARACTERISTICS
DATA SUPPORTING USE OF THE HAND METHOD*

Gasifier Rates and Conditions	Nominal Cases*		
	Case 1	Case 2	Case 3
(1) Oxygen blast/gaseous carbon, R_{oc} : $R_{oc} = n_1(O_2 \text{ blst}) \div n_o(C) =$	0.450	0.365	0.489
(2) Water/gaseous carbon, R_{wc} : $R_{wc} = [n_2(H_2O) + n_2(H_2O_d)] \div n_o(C) =$	0.5475	1.193	0.490
(3) Water quench/gas carbon, R_{qc} : $R_{qc} = \frac{n_1(qnch)}{n_o(C)} =$	0.1966	0	0
(4) Blast gas (not steam)/gaseous carbon $R_{Bc} = \frac{n_1(N_2, O_2)}{n_1(O_2)} \times R_{oc} =$	0.459	0.372	2.329
(5) Enthalpy, generated steam, ref. (liquid water at 70°F, Btu/lb:			
a. h(stm, blst); sat'd, 900°F, 900°F; 65 psia.	1,133	1,440	1,440
b. h(stm, hp); 900°F; 1,055 psia	1,410	1,410	1,410
(6) $C_p(N_2, O_2)$, Molar heat capacity, blast gas:	7.1	7.1	7.1
(7) $C_p(\text{Fuel gas, hot})$ Btu/mol°F=	8.43	8.52	7.96
(8) $C_p(\text{Fuel gas, cool})$ Btu/mol°F =	7.35	7.35	7.1
(9) $C_p(\text{slag})$ Btu/lb°F =	0.25	0.25	0.25
(10) Reactor temperature:			
T(reactor)	>200°F +MP (ASH)	<200°F -SP (ASH)	>200°F -SP (ASH)
(11) Fraction of gaseous carbon which is CO: $\alpha =$	0.85	0.672	0.802

*Note: Typical values only; calculate actual values in procedure.
Conversion constant: 3,415.2 Btu = 1 kWhr.

	Case 1	Case 2	Case 3
(12) Fraction of carbon in coal converted to gas:			
γ = Anthracite	0.87	0.83	0.83
γ = Eastern/Midwest coal	0.95	0.89	0.89
γ = Western coal	0.98	0.95	0.95
(13) Energy consumption, grinding and miscellaneous, kW, plant-wide	900	550	550
(14) Fraction of high pressure steam going to process use from 165 psia header R_{ps}	0.34	0.21	0.26
(15) Compression energy:			
(a) Air-to-oxygen plant, Btu/mol	21,296	21,296	21,296
(b) Dry blast to gasifier, Btu/mol	9,218	9,218	9,218
(c) Raw gas compression, Btu/mol	2,676	2,676	2,676
(16) Recovered energy expansion of fuel gas, Btu/mol	1,354	1,354	1,354
(17) Gas treatment section, constants:			
a:	0.124	0.016	0.160
b:	0.110	0.076	0.294
(18) Capital cost/field cost ratio, (C_8/C_7)	1.355	1.308	1.33
(19) Gas need at Claus plant, $Q(\text{Claus})$ Btu/hr	1×10^6	1×10^6	2×10^6
(20) Gas requirement for drying coal Btu/lb evaporation	3,163	3,163	3,163
(21) Gas treatment pressure, psia	150	150	150
(22) Identification of nominal cases			
Basis			
Blast Mode	O_2/steam	O_2/steam	Air/steam
Gasifier Type	Entrained solids	Fluidized solids	Fluidized solids
Sulfur Content in Coal, %	2	2	2
Sulfur Emission in Gases lb SO_2 per 10^6 Btu HHV of Coal	1.2	1.2	1.2
Gas Treatment Pressure, Optimum, psia	150	150	150

PROCEDURE AND EXAMPLES

A worker using the computation scheme starts with the ultimate analysis of the coal received at the plant and considers the behavior of the gasification process on the basis of 100 lb of this coal. Later, he converts his performance numbers to a basis of one hour's operation of the plant, and still later, to the 25-year basis for finding the costs and life-cycle production of gas.

Table 2-1 is the source of characteristic performance data necessary to several steps in the computation. The values are more or less self-evident in their development, and their validity or replacement with values pertinent to still other schemes of operation is straightforward.

The worker starts with the ultimate analysis of coal and on the basis of 100 lb of coal entering the plant. The subsequent drying of coal to a lower moisture content will be accounted for in the necessary diversion of fuel gas to support drying operations.

The final form for the computation of average gas cost is the same one used in displaying costs in the report. The present prices of coal and electricity are used in computing the recurring annual costs of these items.

The examples attached show the manner of executing the computations.

WORKSHEET FOR PLANT ANALYSIS

DESIGN BASIS

CASE I VARIANT

Reactor Capacity:

Heating value of reactor output, sour, Btu/hr = 250×10^6

Emission Of SO₂:

Product from combustion of fuel gas,
 1b SO₂/10⁶ Btu HHV (coal), 0.6 e(SO₂)

Ultimate Analysis Of Coal:

	% or lb per 100 lb coal	
Carbon	<u>60.47</u>	W(C)
Hydrogen	<u>3.70</u>	W(H ₂)
Oxygen	<u>5.96</u>	W(O ₂)
Nitrogen	<u>1.41</u>	W(N ₂)
Sulfur	<u>2.00</u>	W(S)
Moisture	<u>5.00</u>	W(H ₂ O)
Ash	<u>21.46</u>	W(Ash)
	Total	100
Ash Softening Temperature	=	<u>2500</u> °F
Ash Melting Temperature	=	<u>2650</u> °F

Note: $W(\text{evap}) = W(\text{H}_2\text{O}) - W_{\text{O}}(\text{H}_2\text{O})$

REACTOR PERFORMANCE

Basis: 100 lb coal, with moisture

Carbon gasification See Table 2-1, items (11) and (12).

Carbon conversion, expected fraction $\gamma = \frac{0.95}{1} \quad (1)$

Ratio CO/(CO + CO₂), expected value $\alpha = \frac{0.85}{1} \quad (2)$

Feedstock and resulting char

Carbon: $\frac{60.47}{W_o(C)} \times \frac{0.95}{12} = \frac{4.787}{n_o(C)} \text{ Mol} \quad (3)$

Hydrogen: $\frac{3.70}{W_o(H_2)} \frac{1}{2} - \frac{5.96}{W_o(O_2)} \frac{1}{16} = \frac{1.478}{n_o(H_2,fc)} \text{ Mol} \quad (4)$

Oxygen: $\frac{5.96}{W_o(O_2)} \frac{1}{32} = \frac{0.186}{n_o(O_2)} \text{ Mol} \quad (5)$

Nitrogen: $\frac{1.41}{W_o(N_2)} \frac{1}{28} = \frac{0.050}{n_o(N_2)} \text{ Mol} \quad (6)$

Sulfur: $\frac{2.00}{W_o(S)} \frac{1}{32} = \frac{0.0625}{n_o(S)} \text{ Mol} \quad (7)$

Moisture: $\frac{1.94}{W_o(H_2O)} \frac{1}{18} = \frac{0.1078}{n_o(H_2O)} \text{ Mol} \quad (8)$

Char: $\frac{21.46}{W_o(\text{Ash})} + \frac{(0.05) \times 60.47}{(1-\gamma) \times W_o(C)} = \frac{24.48}{W_o(\text{char})} \text{ lb} \quad (9)$

Heat of combustion @ carbon conversion γ , HHV' coal:

$$\frac{4.787 \times (173,934) + 1.478 \times (122,976) + 0.0625 \times (184,640)}{n_o(C) \times \Delta H_c(C) + n_o(H_2,fc) \times \Delta H_c(H_2) + n_o(S) \times \Delta H_c(S)} = \frac{1,025,920 \text{ Btu}}{\text{HHV}'(\text{coal})} \quad (10)$$

$(\Delta H_c(S) = \text{At. wt.} \times 5,770 \text{ Btu/lb})$

Heat of combustion @ full conversion, HHV (coal)

$$\frac{1,025,920}{\text{HHV}(\text{coal})} + \frac{0.05263 \times 4.787 \times 173,934}{[1-\gamma]/\gamma \times n_o(C) \times \Delta H_c(C)} = \frac{1,069,717 \text{ Btu}}{\text{HHV}(\text{coal})} \quad (11)$$

Basis: 100 lb coal, with moisture

Blast

$$\text{Steam: } \frac{0.5475 \times 4.787}{R_{wc} \times n_o(C)} - \frac{[0.108 + 2 \times 0.186 + 0.941]}{[n_o(H_2O) + 2N_o(O_2) + n_1(\text{Quench})]} = \frac{1.200}{n_1(\text{stm})} \quad (12)$$

$$\text{Quench: } \frac{0.1966 \times 4.787}{R_{qc} \times n_o(C)} = \frac{0.941}{n_1(\text{quench})} \quad (13)$$

$$\text{Oxygen: } \frac{0.450 \times 4.787}{R_{oc} \times n_o(C)} = \frac{2.154}{n_1(O_2 \text{ blst})} \quad (14)$$

$$\text{Nitrogen: } \frac{[(.454 - .450) : .450] \times 2.154}{[(R_{bc} - R_{oc}) : R_{oc}] \times n_1(O_2 \text{ blst})} = \frac{0.0431}{n_1(N_2 \text{ blst})} \quad (15)$$

Reactor Gases

$$\text{Carbon monoxide: } \frac{0.85 \times 4.787}{\alpha \times n_o(C)} = \frac{4.069}{n_2(CO)} \quad (25)$$

$$\text{Carbon dioxide: } \frac{0.15 \times 4.787}{(1-\alpha) \times n_o(C)} = \frac{0.718}{n_2(CO_2)} \quad (26)$$

$$\text{Water decomposed: } \frac{(2 - 0.85) \times 4.787 - 2 \times 2.154}{(2 - \alpha) \times n_o(C) - 2 \times n_1(O_2 \text{ blst})} = \frac{1.197}{n_2(H_2O_d)} \quad (27)$$

$$\text{Hydrogen: } \frac{1.478 - 0.0625 + 1.197}{n_o(H_2, fc) - n_o(S) + n(H_2O_d)} = \frac{2.613}{n_2(H_2)} \quad (28)$$

$$\text{Nitrogen: } \frac{0.050 + 0.043}{n_o(N_2) + n_1(N_2 \text{ blst})} = \frac{0.093}{n_2(N_2)} \quad (29)$$

$$\text{Sulfur as hydrogen sulfide: } \frac{0.0625}{n_o(S)} = \frac{0.0625}{n_2(S)} \quad (30)$$

$$\text{Water Vapor: } \frac{0.1078 + 1.200 + 0.941 + 2 \times 0.186 - 1.197}{n_o(H_2O) + n_1(\text{stm}) + n_1(\text{quch}) + 2 \times n_o(O_2) - n_2(H_2O_d)} = \frac{1.424}{n_2(H_2O)} \quad (31)$$

*See Table 2-1.

Basis: 100 lb coal, with moisture

$$\text{Combustibles: } \frac{2 \times 4.787 - 2 \times 2.154 + 1.478 - 0.0625}{2n_o(C) - 2n_1(O_2, \text{blst}) + n_o(H_2, \text{fc}) - n_o(S)} = \frac{6.682 \text{ Mol}}{N_2(\text{cmbstl})} \quad (32)$$

$$\text{Total hot raw gas: } \frac{4.787 + 1.4155 + 2.621 + 0.093 + 0.0625}{n_o(C) + n_2(H_2, N, \text{fg}) + n_{1,2}(H_2O) + n_2(N_2) + n_2(H_2S)} = \frac{8.979 \text{ Mol}}{\sum n_i} \quad (33)$$

Heat Effects

Heating value of fuel gas, excepting H₂S:

$$\frac{6.682}{n_o(H_2, CO)} \times 122,157 = \frac{816,620 \text{ Btu}}{Q_c(\text{Sweet Gas})} \quad (34)$$

Heat release in reactor:

$$\frac{4.787 \times 173,934 - [4.787 - 2.153] \times [2 \times 122,157]}{n_o(C) \times \Delta H_c(C) - [n_o(C) - n_1(O_2)] \times [2\Delta H_c(H_2, CO)]} = \frac{189,099 \text{ Btu}}{Q(\text{reactor})} \quad (35)$$

Heat release in combustion of H₂S:

$$\frac{0.0625 \times 241,092}{n_2(H_2S) \times \Delta H_c(H_2S)} = \frac{15,068 \text{ Btu}}{Q_c(H_2S)} \quad (36)$$

Sum of heat release effects:

$$\frac{816,620 + 189,099 + 15,068}{Q_c(\text{Sweet gas}) + Q(\text{reactor}) + Q_c(H_2S)} = \frac{1,020,800 \text{ Btu}}{\Sigma Q} \quad (37)$$

Heating value of unconverted carbon in char:

$$\frac{173,934 \times 4.787 \times [(1-95)/95]}{\Delta H_c(C) \times n_o(C) \times [(1-\gamma)/\gamma]} = \frac{43,822}{Q_c(\text{Char})} \quad (38)$$

Miscellaneous

$$n_o(H_2, \text{fc}) - n_o(S) = \frac{1.4155}{n_2(H_2, n, \text{fg})} \quad (41)$$

$$n_2(H_2O) + n_2(H_2O_d) = \frac{2.621}{n_{1,2}(H_2O)} \quad (42)$$

Basis: 100 lb coal, with moisture

Estimation of Steam Generation

Heat addition to reactor as steam blast (ref'd to 70°F), Btu:

$$\frac{1,200}{n_1(\text{stm})} \times 18 \times \frac{1133}{h(\text{stm})} = \frac{24,473}{Q_1(\text{stm})} \text{ Btu} \quad (50)$$

Heat addition to reactor as blast gas (N₂, O₂), Btu:

$$\frac{[2.154 + 0.043]}{n_1(\text{O}_2) + n_1(\text{N}_2)} \times 7.1 \frac{(220 - 70^\circ\text{F})}{C_p(T_{in} - 70^\circ\text{F})} = \frac{2340}{Q_1(\text{N}_2, \text{O}_2)} \text{ Btu} \quad (51)$$

Heat addition to reactor as warm coal from drying process:

$$\frac{(100 - 3.06) \times 0.25 \times (250 - 70)}{(100 \text{ lb} - W_{\text{evap}}) \times C_p} = \frac{4362}{Q_0(\text{coal})} \text{ Btu} \quad (52)$$

Heat loss from reactor as hot slag:

$$\frac{24.48 \times 0.25 \times (2000 - 70)}{W(\text{slag}) \times C_p} = \frac{11813}{Q(\text{slag})} \text{ Btu} \quad (53)$$

Heat loss from reactor as exit cool fuel gas:

$$\frac{8.979 \times 7.35 \times (350 - 70)}{(\Sigma n_i) \times C_p(\text{CFG})} = \frac{18479}{Q(\text{CFG})} \text{ Btu} \quad (54)$$

Total heat release to hot raw product gas:

$$\frac{184099 + 24473 + 2340 + 4362 - 11813}{Q(\text{retr}) + Q_1(\text{stm}) + Q(\text{N}_2, \text{O}_2) + Q(\text{coal}) - Q(\text{char})} = \frac{208447}{Q(\text{HFG})} \text{ Btu} \quad (55)$$

Temperature reached in reactor:

$$\frac{208447 / [8.43 \times 8.979] + 70}{Q(\text{HFG}) / [C_p(\text{HFG}) \times \Sigma n_i] + 70} = \frac{2824}{T(\text{retr})} \quad (56)$$

Case 1: This temperature should be at least 2800°F

Cases 1, 2, & 3: See Item (10), Table 2-1.

* See Table 2-1.

** See Design Basis.

Basis: 100 lb coal, with moisture

Generation of high pressure steam by waste heat recovery:

Case 1 only:

$$\frac{[208447 - 18479 - 24473]}{[Q(\text{HFG}) - Q(\text{CFG}) - Q_1(\text{Stm})]} : \frac{1410}{h(\text{stm, hp})} = \frac{117.4 \text{ lb}}{W_3(\text{stm, hp})} \quad (57)$$

(55) (54) (5b), Table 2-1

Case 3 only:

$$\frac{[\quad]}{[Q(\text{HFG}) - Q(\text{CFG})]} : \frac{\quad}{h(\text{stm, hp})} = \frac{\quad \text{lb}}{W_3(\text{stm, hp})} \quad (58)$$

(55) (54) (5b), Table 2-1

Case 3 only:

$$\frac{[\quad - \quad - \quad]}{[Q(\text{HFG}) - Q(\text{CFG}) - Q_1(\text{N}_2, \text{O}_2)]} : \frac{\quad}{h(\text{stm, hp})} = \frac{\quad}{W_3(\text{stm, hp})} \quad (59)$$

ENERGY MANAGEMENT

Basis: 100 lb coal, with moisture

Compression Energy

Oxygen Plant Compressor (Oxygen Blast System Only):

Air is raised from 14.7 to 165 psia @ 70°F, and liquified.

$$\frac{21,296 \times 2.154}{21,296 \times n_1(O_2)} = \frac{45,872 \text{ Btu}}{E_c(\text{AIR})} \quad (60)$$

(15a)*

Air Blast Compressor (Air Blast System Only):

Air feed is raised from 14.7 to 50 psia @ 70°F:

$$\frac{9,218 \times \quad}{9,218 \times n_1(O_2)} = \frac{\quad \text{Btu}}{E_c(\text{AIR})} \quad (61)$$

(15b)* (14)

Raw Gas Compression, dry:

Raw Gas Compression from 35 to 165 psia @ 100°F:

$$\frac{2,676 \times [8.979 - 1.424]}{2,676 \times [\sum n_i - n_2(H_2O)]} = \frac{20,230 \text{ Btu}}{E_c(\text{FG})} \quad (63)$$

(15c)* (33) (31)

Recovered Energy

Fuel Gas Expansion: 135 to 40 psia:

$$\frac{1,354 \times [8.979 - 1.424]}{1,354 \times [\sum n_i - n_2(H_2O)]} = \frac{10,236 \text{ Btu}}{E_x(\text{FG})} \quad (64)$$

(16)* (33) (31)

Steam Expansion: 1,055 to 2.89, 165, 422 psia:

$$\frac{(117.4) \times [327 + 149 \times .343] - 322 [117.4 \times .343 + 20]}{W(\text{stm, hp}) \times [327 + 149 \times Rps] - 332 [W(\text{stm, hp}) \times Rps + W_1(\text{stm})]} = \frac{31,019 \text{ Btu}}{E_x(\text{stm})} \quad (65)$$

(14)*

Where $W_1(\text{stm}) = 18 \times n_1(\text{stm}) \text{ lb}$; this value to be entered for Cases 2 & 3 only
(12)

* See Table 2-1.

PLANT SCALE PERFORMANCE
 COAL HANDLING AND GASIFICATION

Basis: 100 lb coal or 1.0 hour, as noted

Coal Rate, lb/hr

$$\frac{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb}}{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb} : [Q_c(\text{H}_2, \text{CO}) + Q_c(\text{H}_2\text{S})]} = \frac{[816620 + 15068]}{W(\text{Coal})} = \frac{30060}{W(\text{Coal})} \text{ lb/hr} \quad (70)$$

Assemble previous results in 71_i or 72_i; compute entries for 73_i, 74_i, 76_i. (See note).

Source Component Item Sub i	Basis: 100 lb Coal		Basis: 1 Hour's Operation			
	lb	n _i Mols	N _i Mols	Mol/Fract.	Mol/wt.	lb
	71 _i	72 _i	73 _i	74 _i	75 _i	76 _i
Feed						
(70) a Coal Blast	● 100		●	—	NA	● 30060
(12) b Stm	21.62	1.200	361	—	18.016	6504
(14) c O ₂	68.93	2.154	647		32.000	20764
(15) d N ₂	1.16	0.0431	13		28.010	364
e (SubΣ)	● 91.72	3.397	● 1021	NA	NA	● 27572
(13) f Quench	● 16.95	0.944	● 283	NA	18.016	● 5046
g Total	● 208.68	4.340	● 1304	NA	NA	● 62728
Effluent						
* h Evapn Sour Gas	● 3.06		●	—	NA	● 920
(25) j CO	113.97	4.069	1223	0.538	28.010	34526
(26) k CO ₂	31.60	0.718	216	0.095	44.010	9506
(28) l H ₂	5.27	2.613	786	0.346	2.016	1585
(29) m N ₂	2.61	0.093	28	0.0123	28.016	784
(30) n (H ₂ S)	2.13	0.0625	19	0.0083	34.076	644
o Dry FG	155.58	7.5555	2271	1.000		46775
(31) p H ₂ O	25.65	1.424	428	—	18.016	7710
(33) q (HFG)	● 181.26	8.979	● 2699	—		● 54466
(9) r Char	● 24.48		●	—	NA	● 7358
s Total	● 208.80		●	—	NA	● 62764

Note: 73_i/72_i = 76_i/71_i = W(Coal)/100
 71_i/72_i = 76_i/73_i = 75_i

* See Design Basis.

PLANT SCALE PERFORMANCE
ENERGY EFFECTS

Basis: 100 lb coal or 1.0 hour, as noted

Mechanical Energy			Basis: 100 lb Coal		Basis: 1 Hour's Operation	
Source Item	Component Sub.		Btu 80 _i	kWhr 81 _i	Btu 82 _i	kWhr 83 _i
Compression						
(60)	a	Oxy plant	45 872	13.432	13.791×10^6	4 633
(61)	b	Air blast	—	—	—	—
(63)	c	Raw fuel gas	20 230	5.924	6.081	1 781
(13)*	d	Misc.	10 225	2.994	3.074	900
	e	Total	● 76 327	● 22.350	● 22.946×10^6	● 6 714
Recovery Expansion						
(64)	f	Fuel gas	10 236	2,997	3.077	901
(65)	g	Steam	31 020	9.083	9.324	2 732
	h	Total	● 41 255	● 12.080	● 12.401×10^6	● 3 633
Net Demand						
(e,h)	j	Electric pwr	● 35 071	● 10.270	● 10.542×10^6	● 3 086
Heat Release Effects: Progressive combustion of coal to final products.						
(34)	k	Sweet gas	816 620		245.476×10^6	
(36)	l	H ₂ S	15 068		4.529	
(35)	m	Reactor	184 099		56.843	
(38)	n	Char	43 822		13.172	
	o	Total	● 1 064 609		● 320.026×10^6	
(11)	p	Coal	● 1 064 717		● 321.557×10^6	
Total Energy to Plant (j,p)			● 1 104 788		● 332.049×10^6	
Note: $82_i/80_i = 83_i/81_i = W(\text{Coal})/100$ $81_i/80_i = 83_i/82_i = 0.29281 \times 10^{-3}$						

*See Table 2-1.

PLANT COSTS

<u>Capital Costs</u>	<u>\$1000</u>
Oxygen/Air Plant:	(85)
$\frac{[(647 + 13) / (648 + 13)]^{0.6}}{[(N_c + N_d) / (N_c^o + N_d^o)]^{0.6}} \times \frac{7064}{c_1} = \frac{7064}{C_1}$ <p style="text-align: center;">(73_c) (73_d) (See Note)</p>	
Gasification Module:	(86)
$\frac{[2699/2738] \times 5426}{[N_q / N_q^o] \times C_2} = \frac{5379}{C_2}$ <p style="text-align: center;">(73_q) (see note)</p>	
Compression/Expansion:	(87)
$\frac{(2271/2210) \times 1706}{(N_o / N_o^o) \times C_3} = \frac{1748}{C_3}$ <p style="text-align: center;">(73_o) (see note)</p>	
Gas Treatment Module:	(88)
$\frac{\{1 + .124 \times [2.00 - 2.00]\} \times \{1 - .110 \times \ln[0.60 / 1.2]\} \times 230^3}{\{1 + a \times [W_o(S) - W_o^o(S)]\} \times \{1 - b \times \ln[e(SO_2) / e^o(SO_2)]\} \times C_4^0.75} = \frac{2478}{C_4}$ <p style="text-align: center;">(17a)* (7) (17b)* (See Design Basis)</p>	

*See Table 2-1.

Note: Values for C^o, for the nominal cases, are in the Final Report, Appendix F.

Coal Preparation Module:	\$1,000
$\frac{[30060 / 30100]^{.5} \times 2850}{[W(\text{Coal}) / W^0(\text{Coal})]^{.5} \times C_5^0} =$	$\frac{2846}{C_5}$ (89)
Utilities, Piping, Waste Disposal: constant	$\frac{2727}{C_6}$ (90)
Direct Field Cost:	$\frac{22124}{C_7}$ (91)
Sum: $C_1 + C_2 + C_3 + C_4 + C_5 + C_6 =$	$\frac{29978}{C_8}$ (92)
Total Capital Cost	$\frac{22124 \times (1.355)}{C_7 \times (C_8/C_7)} =$
	$\frac{29978}{C_8}$
<u>Operating Costs, Annual, Based on 90% Service Factor</u> \$1,000	
Coal @ W(Coal) lb/hr:	(96)
$\frac{(30060 / 2,000) \times (7,889 \text{ hr/yr})}{(W(\text{Coal}) / 2,000) \times (7,889 \text{ hr/yr})} \therefore (\$/\text{ton}) = \frac{25}{0(\text{coal})} = \frac{2964}{0(\text{coal})}$	$\frac{2964}{0(\text{coal})}$
Electric power @ E_D kW:	(97)
$\frac{3086 \times 7889 \times 0.030}{(E_D) \times (7,889 \text{ hr/yr}) (\$/\text{kWhr})} =$	$\frac{730}{0(\text{pwr})}$
(83)	
Catalyst, Chemicals, from Nominal Case: Equipment, Supplies, Utilities Operating Personnel Maintenance Materials and Labor	$\frac{1488}{0(\text{Misc})}$ (98)
From Report, Subtotal, $0^0(\text{Misc}) =$	$\frac{1488}{0(\text{Misc})}$

*See Table 2-1.

Fuel Gas Production over 25 Years, based on hourly rates

$$\frac{[245.5 \times 10^6 - 920 \times 3,163 - 1 \times 10^6] \times 0.197 \times 10^6}{[Q_c (\text{Sweet Gas}) - W_o (\text{evap}) \times 3,163 - Q(\text{Claus})] \times 0.197 \times 10^6} =$$

(82k)
(76h)
(20)
(19)*

$$\frac{47.59 \times 10^{12} \text{ BTU}}{\Sigma Q(\text{PG})} \quad (99)$$

Next use the Discounted Costs of Gas Production form provided for summing discounted future costs.

Note 1: Capital costs of the nominal plant, C^0 , are in the Final Report.

*See Table 2-1.

DISCOUNTED COSTS OF GAS PRODUCTION

Line Number	Cost Element	Differ- ential Inflation Rate	Project Year	Amount, Thousands of Dollars		Discount Factor	Discounted Cost, Thousands of Dollars
				One Time	Recurring		
(1)	First-Year Construction	+0	2	5 096	17%	0.867	4 418
(2)	Second-Year Construction	+0	3	10 193	34%	0.788	3 052
(3)	Third-Year Construction	+0	4	14 681	49%	0.717	10 532
(4)	● Total Investment			● 29 978			● 22 982
(5)	Coal	+5	5-29		2964	12.268	36 362
(6)	Electricity	+6	5-29		730	14.057	10 262
(7)	Operating Labor and Materials	+0	5-29		1488	6.505	9 679
(8)	● Total Operating Costs				● 5182		● 56 303
(9)	● Total Project Costs						● 79 285
(10)	Fuel Oil Alternative	+8	5-29		4 765	18.611	88 172
(11)	Energy Available over 25 years, billions of Btu						47 542
(12)	Product Gas Unit Cost, \$/million Btu (line 9 divided by line 11)						1.67
(13)	Fuel Oil Alternative Unit Cost, \$ million Btu (line 10 divided by line 11)						1.87
(14)	Savings/Investment Ratio, SIR = (line 10 - line 8)/line 4						1.32

Cost of gas from GASPLANT program, #/10⁶ Btu

1.63

WORKSHEET FOR PLANT ANALYSIS

DESIGN BASIS

CASE 2 VARIANT

Reactor Capacity:

Heating value of reactor output, sour, Btu/hr - 250×10^6

Emission Of SO_2 :

Product from combustion of fuel gas,
 lb $SO_2/10^6$ Btu HHV (coal), 0.60 e(SO_2)

Ultimate Analysis Of Coal:

	% or lb per 100 lb coal	
Carbon	<u>60.47</u>	W(C)
Hydrogen	<u>3.70</u>	W(H_2)
Oxygen	<u>5.96</u>	W(O_2)
Nitrogen	<u>1.41</u>	W(N_2)
Sulfur	<u>2.00</u>	W(S)
Moisture	<u>5.00</u>	W(H_2O)
Ash	<u>21.46</u>	W(Ash)

Total 100

Ash Softening Temperature = 2500 °F

Ash Melting Temperature = 2650 °F

Note: $W(\text{evap}) = W(H_2O) - W_o(H_2O)$

REACTOR PERFORMANCE

Basis: 100 lb coal, with moisture

Carbon gasification See Table 2-1, items (11) and (12).

$$\text{Carbon conversion, expected fraction} \quad \gamma = \frac{0.89}{\quad} \quad (1)$$

$$\text{Ratio CO/(CO + CO}_2\text{), expected value} \quad \alpha = \frac{0.672}{\quad} \quad (2)$$

Feedstock and resulting char

$$\text{Carbon: } \frac{60.47 \times 0.89 / 12}{W_o(C) \times (\gamma) / 12} = \frac{4.485 \text{ Mol}}{n_o(C)} \quad (3)$$

$$\text{Hydrogen: } \frac{3.70 / 2 - 5.96 / 16}{W_o(H_2) / 2 - W_o(O_2) / 16} = \frac{1.478 \text{ Mol}}{n_o(H_2, fc)} \quad (4)$$

$$\text{Oxygen: } \frac{5.96 / 32}{W_o(O_2) / 32} = \frac{0.1863 \text{ Mol}}{n_o(O_2)} \quad (5)$$

$$\text{Nitrogen: } \frac{1.41 / 28}{W_o(N_2) / 28} = \frac{0.0504 \text{ Mol}}{n_o(N_2)} \quad (6)$$

$$\text{Sulfur: } \frac{2.00 / 32}{W_o(S) / 32} = \frac{0.0625 \text{ Mol}}{n_o(S)} \quad (7)$$

$$\text{Moisture: } \frac{5.00 / 18}{W_o(H_2O)} = \frac{0.278 \text{ Mol}}{n_o(H_2O)} \quad (8)$$

$$\text{Char: } \frac{21.46 + (1-0.89) \times 60.47}{W_o(\text{Ash}) + (1-\gamma) \times W_o(C)} = \frac{28.11 \text{ lb}}{W_o(\text{char})} \quad (9)$$

Heat of combustion @ carbon conversion γ , HHV' coal:

$$\frac{4.485 \times (173,934) + 1.478 \times (122,976) + 0.0625 \times (184,640)}{n_o(C) \times \Delta H_c(C) + n_o(H_2, fc) \times \Delta H_c(H_2) + n_o(S) \times \Delta H_c(S)} = \frac{973,505 \text{ Btu}}{\text{HHV}'(\text{coal})} \quad (10)$$

$$(\Delta H_c(S) = \text{At. wt.} \times 5,770 \text{ Btu/lb})$$

Heat of combustion @ full conversion, HHV (coal)

$$\frac{973,505 + [(1-0.89)/0.89] \times 4.485 \times 173,934}{\text{HHV}(\text{coal}) + [(1-\gamma)/\gamma] \times n_o(C) \times \Delta H_c(C)} = \frac{1,069,718 \text{ Btu}}{\text{HHV}(\text{coal})} \quad (11)$$

Basis: 100 lb coal, with moisture

Blast

$$\text{Steam: } \frac{1.193 \times 4.485 - [0.278 + 2 \times 0.1863 + 0.00]}{(2)^*} = \frac{4.700}{n_1(\text{stm})} \text{ Mol} \quad (12)$$

$$\text{Quench: } \frac{0.00 \times 4.485}{(3)^*} = \frac{-0-}{n_1(\text{quench})} \text{ Mol} \quad (13)$$

$$\text{Oxygen: } \frac{0.365 \times 4.485}{(1)^*} = \frac{1.637}{n_1(\text{O}_2 \text{ blst})} \text{ Mol} \quad (14)$$

$$\text{Nitrogen: } \frac{[(.372 - .365) : .365] \times 1.637}{(4)^* (1)^*} = \frac{0.0314}{n_1(\text{N}_2 \text{ blst})} \text{ Mol} \quad (15)$$

Reactor Gases

$$\text{Carbon monoxide: } \frac{.612 \times 4.485}{\alpha \times n_o(\text{C})} = \frac{3.014}{n_2(\text{CO})} \text{ Mol} \quad (25)$$

$$\text{Carbon dioxide: } \frac{(1 - .612) \times 4.485}{(1 - \alpha) \times n_o(\text{C})} = \frac{1.471}{n_2(\text{CO}_2)} \text{ Mol} \quad (26)$$

$$\text{Water decomposed: } \frac{(2 - .612) \times 4.485 - 2 \times 1.637}{(2 - \alpha) \times n_o(\text{C}) - 2 \times n_1(\text{O}_2 \text{ blst})} = \frac{2.682}{n_2(\text{H}_2\text{O}_d)} \text{ Mol} \quad (27)$$

$$\text{Hydrogen: } \frac{1.478 - 0.0625 + 2.682}{n_o(\text{H}_2, \text{fc}) - n_o(\text{S}) + n(\text{H}_2\text{O}_d)} = \frac{4.098}{n_2(\text{H}_2)} \text{ Mol} \quad (28)$$

$$\text{Nitrogen: } \frac{0.050 + 0.031}{n_o(\text{N}_2) + n_1(\text{N}_2 \text{ blst})} = \frac{0.081}{n_2(\text{N}_2)} \text{ Mol} \quad (29)$$

$$\text{Sulfur as hydrogen sulfide: } \frac{0.0625}{n_o(\text{S})} = \frac{0.0625}{n_2(\text{S})} \text{ Mol} \quad (30)$$

$$\text{Water Vapor: } \frac{0.278 + 4.701 + 0.00 + 2 \times 0.186 - 2.682}{n_o(\text{H}_2\text{O}) + n_1(\text{stm}) + n_1(\text{quch}) + 2 \times n_o(\text{O}_2) - n_2(\text{H}_2\text{O}_d)} = \frac{2.669}{n_2(\text{H}_2\text{O})} \text{ Mol} \quad (31)$$

*See Table 2-1.

Basis: 100 lb coal, with moisture

$$\text{Combustibles: } \frac{2 \times 4.485 - 2 \times 1.637 + 1.478 - 0.0625}{2n_o(C) - 2n_1(O_2, \text{blst}) + n_o(H_2, \text{fc}) - n_o(S)} = \frac{7.112 \text{ Mol}}{N_2(\text{cmbstl})} \quad (32)$$

$$\text{Total hot raw gas: } \frac{4.485 + 1.4155 + 5.351 + 0.081 + 0.0625}{n_o(C) + n_2(H_2, N, \text{fg}) + n_{1,2}(H_2O) + n_2(N_2) + n_2(H_2S)} = \frac{11.395 \text{ Mol}}{\Sigma n_i} \quad (33)$$

Heat Effects

Heating value of fuel gas, excepting H₂S:

$$\frac{7.112 \times 122,157}{n_o(H_2, CO) \times \Delta H_c(H_2, CO)} = \frac{868,780 \text{ Btu}}{Q_c(\text{Sweet Gas})} \quad (34)$$

Heat release in reactor:

$$\frac{4.485 \times 173,934 - [4.485 - 1.637] \times [2 \times 122,157]}{n_o(C) \times \Delta H_c(C) - [n_o(C) - n_1(O_2)] \times [2\Delta H_c(H_2, CO)]} = \frac{84,288 \text{ Btu}}{Q(\text{reactor})} \quad (35)$$

Heat release in combustion of H₂S:

$$\frac{0.0625 \times 241,092}{n_2(H_2S) \times \Delta H_c(H_2S)} = \frac{15,068 \text{ Btu}}{Q_c(H_2S)} \quad (36)$$

Sum of heat release effects:

$$\frac{868,780 + 84,288 + 15,068}{Q_c(\text{Sweet gas}) + Q(\text{reactor}) + Q_c(H_2S)} = \frac{968,136 \text{ Btu}}{\Sigma Q} \quad (37)$$

Heating value of unconverted carbon in char:

$$\frac{173,934 \times 4.485 \times [(1-.89)/.89]}{\Delta H_c(C) \times n_o(C) \times [(1-\gamma)/\gamma]} = \frac{96,416 \text{ Btu}}{Q_c(\text{Char})} \quad (38)$$

Miscellaneous

$$n_o(H_2, \text{fc}) - n_o(S) = \frac{1.4155}{n_2(H_2, n, \text{fg})} \quad (41)$$

$$n_2(H_2O) + n_2(H_2O_d) = \frac{5.351}{n_{1,2}(H_2O)} \quad (42)$$

Basis: 100 lb coal, with moisture

Estimation of Steam Generation

Heat addition to reactor as steam blast (ref'd to 70°F), Btu:

$$\frac{4.700}{n_1(\text{stm})} \times \frac{18 \times 1440}{18 \times h(\text{stm})} = \frac{121\ 824 \text{ Btu}}{Q_1(\text{stm})} \quad (50)$$

(12) (5a)*

Heat addition to reactor as blast gas (N₂, O₂), Btu:

$$\frac{[1.637 + 0.031]}{n_1(\text{O}_2) + n_1(\text{N}_2)} \times \frac{7.1(70 - 70^\circ\text{F})}{C_p(T_{\text{in}} - 70^\circ\text{F})} = \frac{-0- \text{ Btu}}{Q_1(\text{N}_2, \text{O}_2)} \quad (51)$$

(14) (6)*

Heat addition to reactor as warm coal from drying process:

$$\frac{(100 - 6.0) \times 0.25 \times (70 - 70)}{(100 \text{ lb} - W_{\text{evap}}) \times C_p \times (T_{\text{coal}} - 70)} = \frac{-0- \text{ Btu}}{Q_0(\text{coal})} \quad (52)$$

**

Heat loss from reactor as hot slag:

$$\frac{28.11 \times 0.25 \times (70 - 70)}{W(\text{slag}) \times C_p \times (T_{\text{slag}} - 70)} = \frac{-0- \text{ Btu}}{Q(\text{slag})} \quad (53)$$

(9)

Heat loss from reactor as exit cool fuel gas:

$$\frac{11.395 \times 7.35 \times (350 - 70)}{(\sum n_i) \times C_p(\text{CFG}) \times (350 - 70)} = \frac{23\ 450 \text{ Btu}}{Q(\text{CFG})} \quad (54)$$

(33) (8)*

Total heat release to hot raw product gas:

$$\frac{84\ 288 + 121\ 824 + 0.0 + 0.0 - 0.0}{Q(\text{retr}) + Q_1(\text{stm}) + Q(\text{N}_2, \text{O}_2) + Q(\text{coal}) - Q(\text{char})} = \frac{206\ 112 \text{ Btu}}{Q(\text{HFG})} \quad (55)$$

Temperature reached in reactor:

$$\frac{206\ 112 / [8.52 \times 11.395] + 70}{Q(\text{HFG}) / [C_p(\text{HFG}) \times \sum n_i] + 70} = \frac{2192}{T(\text{retr})} \quad (56)$$

(7)*

Case 1: This temperature should be at least 2800°F

Cases 1, 2, & 3: See Item (10), Table 2-1.

* See Table 2-1.

** See Design Basis.

Basis: 100 lb coal, with moisture

Generation of high pressure steam by waste heat recovery:

Case 1 only:

$$\left[\frac{Q(\text{HFG}) - Q(\text{CFG}) - Q_1(\text{Stm})}{(55) \quad (54)} \right] : \frac{h(\text{stm, hp})}{(5b), \text{ Table 2-1}} = \frac{1b}{W_3(\text{stm, hp})} \quad (57)$$

Case 2 only:

$$\left[\frac{206112 - 23450}{(55) \quad (54)} \right] : \frac{1410}{(5b), \text{ Table 2-1}} = \frac{129.55 \text{ lb}}{W_3(\text{stm, hp})} \quad (58)$$

Case 3 only:

$$\left[\frac{Q(\text{HFG}) - Q(\text{CFG}) - Q_1(\text{N}_2, \text{O}_2)}{(55) \quad (54)} \right] : \frac{h(\text{stm, hp})}{(5b), \text{ Table 2-1}} = \frac{1b}{W_3(\text{stm, hp})} \quad (59)$$

ENERGY MANAGEMENT

Basis: 100 lb coal, with moisture

Compression Energy

Oxygen Plant Compressor (Oxygen Blast System Only):

Air is raised from 14.7 to 165 psia @ 70°F, and liquified.

$$\frac{21,296 \times 1.637}{21,296 \times n_1(O_2)} = \frac{34,862}{E_c(AIR)} \text{ Btu} \quad (60)$$

(15a)*

Air Blast Compressor (Air Blast System Only):

Air feed is raised from 14.7 to 50 psia @ 70°F:

$$\frac{9,218 \times 0.0}{9,218 \times n_1(O_2)} = \frac{-0}{E_c(AIR)} \text{ Btu} \quad (61)$$

(15b)* (14)

Raw Gas Compression, dry:

Raw Gas Compression from 35 to 165 psia @ 100°F:

$$\frac{2,676 \times [11.395 - 2.669]}{2,676 \times [\sum n_i - n_2(H_2O)]} = \frac{23,351}{E_c(FG)} \text{ Btu} \quad (63)$$

(15c)* (33) (31)

Recovered Energy

Fuel Gas Expansion: 135 to 40 psia:

$$\frac{1,354 \times [11.395 - 2.669]}{1,354 \times [\sum n_i - n_2(H_2O)]} = \frac{11,815}{E_x(FG)} \text{ Btu} \quad (64)$$

(16)* (33) (31)

Steam Expansion: 1,055 to 2.89, 165, 422 psia:

$$\frac{(129.55) \times [327 + 149 \times .21] - 322 [129.55 \times .21 + 8462]}{W(stm, hp) \times [327 + 149 \times Rps] - 332 [W(stm, hp) \times Rps + W_1(stm)]} = \frac{9290}{E_x(stm)} \text{ Btu} \quad (65)$$

(14)*

Where $W_1(stm) = 18 \times n_1(stm) \text{ lb}$
(12)

* See Table 2-1.

PLANT SCALE PERFORMANCE
 COAL HANDLING AND GASIFICATION

Basis: 100 lb coal or 1.0 hour, as noted

Coal Rate, lb/hr

$$\frac{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb: } [868780 + 15068]}{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb: } [Q_c(\text{H}_2, \text{CO}) + Q_c(\text{H}_2\text{S})]} = \frac{28285}{W(\text{Coal})} \text{ (70) lb/hr}$$

Assemble previous results in 71_i or 72_i; compute entries for 73_i, 74_i, 76_i (See note).

Source Component Item Sub i	Basis: 100 lb Coal		Basis: 1 Hour's Operation			
	Lb	n _i Mols	N _i Mols	Mol/Fract.	Mol/wt.	Lb
	71 _i	72 _i	73 _i	74 _i	75 _i	76 _i
Feed						
(70) a Coal Blast	● 100		● NA	—	NA	● 28285
(12) b Stm	84.68	4.700	1329.7	—	18.016	23456
(14) c O ₂	52.38	1.637	463.0		32.000	14816
(15) d N ₂	6.88	0.0314	8.8		28.010	246
e (SubΣ)	● 137.94		●	NA	NA	● 37018
(13) f Quench	● —	—	● —	NA	18.016	● —
g Total	● 237.94		●	NA	NA	● 67303
Effluent						
* h Evapn Sour Gas	● —	—	● —	—	NA	● —
(25) j CO	84.42	3.014	852.5	0.345	28.010	23878
(26) k CO ₂	64.74	1.471	416.1	0.169	44.010	18313
(28) l H ₂	8.26	4.098	1154.1	0.479	2.016	2357
(29) m N ₂	2.27	0.081	22.9	0.009	28.016	642
(30) n (H ₂ S)	2.13	0.0625	17.7	0.007	34.076	603
o Dry FG	161.82	8.7265	2468.3	1.000		45773
(31) p H ₂ O	44.08	2.669	754.9	—	18.016	13600
(33) q (HFG)	● 209.91	11.395	● 3223.2	—		● 59373
(9) r Char	● 28.11		●	—	NA	● 7951
s Total	● 238.02		●	—	NA	● 67324

Note: 73_i/72_i = 76_i/71_i = W(Coal)/100
 71_i/72_i = 76_i/73_i = 75_i

* See Design Basis.

PLANT SCALE PERFORMANCE
ENERGY EFFECTS

Basis: 100 lb coal or 1.0 hour, as noted

Mechanical Energy			Basis: 100 lb Coal		Basis: 1 Hour's Operation	
Source	Component		Btu	kWhr	Btu	kWhr
Item	Sub.		80 _i	81 _i	82 _i	83 _i
Compression						
(60)	a	Oxy plant	34 862	10,208	9.86×10^6	2887
(61)	b	Air blast	—	—	—	—
(63)	c	Raw fuel gas	23 351	6,837	6,605	1934
(13)*	d	Misc.	6 641	1,945	1,878	550
	e	Total	● 64 854	● 18,990	● $18,343 \times 10^6$	● 5371
Recovery Expansion						
(64)	f	Fuel gas	11 815	3,460	3,343	979
(65)	g	Steam	9 290	2,720	2,626	769
	h	Total	● 21 105	● 6,180	● $5,969 \times 10^6$	● 1748
Net Demand						
(e,h)	j	Electric pwr	● 43 749	● 12,810	● $12,374 \times 10^6$	● 3 623
Heat Release Effects: Progressive combustion of coal to final products.						
(34)	k	Sweet gas	868 780		$245,737 \times 10^6$	
(36)	l	H ₂ S	15 068		4,262	
(35)	m	Reactor	84 288		23,841	
(38)	n	Char	96 416		27,271	
	o	Total	● 1064 552		● 301,108	
(11)	p	Coal	● 1 069 718		● $302,570 \times 10^6$	
Total Energy to Plant						
(j,p)	q		● 1 113 467		● $314,944 \times 10^6$	
Note: $82_i / 80_i = 83_i / 81_i = W(\text{Coal}) / 100$ $81_i / 80_i = 83_i / 82_i = 0.29281 \times 10^{-3}$						

*See Table 2-1.

PLANT COSTS

Capital Costs	\$1000
Oxygen/Air Plant:	(85)
$\frac{[(463 + 8.5)/(470 + 10)]^{0.6}}{[(N_c + N_d) / (N_c^o + N_d^o)]^{0.6}} \times \frac{5992}{C_1^o} = \frac{5930}{C_1}$ <p style="text-align: center;">(73_c) (73_d) (See Note)</p>	
Gasification Module:	
$\frac{[3223/5326] \times 0.16}{[N_q / N_q^o] \times C_2^o} = \frac{5812}{C_2}$ <p style="text-align: center;">(73_q) (see note)</p>	(86)
Compression/Expansion:	
$\frac{2468 \cdot 2319}{(N_o / N_o^o) \times C_3^o} = \frac{1871}{C_3}$ <p style="text-align: center;">(73_o) (see note)</p>	(87)
Gas Treatment Module:	
$\frac{\{1 + 0.16 \times [2.0 - 2.0]\}}{\{1 + a \times [W_o(S) - W_o^o(S)]\}} \times \{1 - 0.2 \times \ln[0.6 / 1.2]\} \times 3843 = \frac{4045}{C_4}$ <p style="text-align: center;">(17a)* (7) (17b)* (See Design Basis)</p>	(88)

*See Table 2-1.

Note: Values for C^o, for the nominal cases, are in the Final Report, Appendix F.

Coal Preparation Module:	\$1,000	
$\left[\frac{28285}{27310} \right]^{.5} \times \frac{2228}{[W(\text{Coal}) / W^0(\text{Coal})]^{.5} \times C_5^0} =$	<u>2189</u>	(89)
	C_5	
Utilities, Piping, Waste Disposal: constant	<u>2343</u>	(90)
	C_6	
Direct Field Cost:	<u>21957</u>	(91)
Sum: $C_1 + C_2 + C_3 + C_4 + C_5 + C_6 =$	C_7	
Total Capital Cost		(92)
$\frac{21957 \times (1.308)}{C_7 \times (C_8/C_7)} =$	<u>28,720</u>	
	C_8	
<u>Operating Costs, Annual, Based on 90% Service Factor</u>		<u>\$1,000</u>
Coal @ W(Coal) lb/hr:		(96)
$\frac{(28285 / 2,000) \times (7,889 \text{ hr/yr})}{(W(\text{Coal}) / 2,000) \times (7,889 \text{ hr/yr})} \times \frac{25}{(\$/\text{ton})} =$	<u>2789</u>	
	0(coal)	
Electric power @ E_D kW:		(97)
$\frac{3623 \times 2789 \times 0.030}{(E_D) \times (7,889 \text{ hr/yr})} =$	<u>857</u>	
	0(pwr)	
(83g)		
Catalyst, Chemicals, from Nominal Case:		
Equipment, Supplies, Utilities		
Operating Personnel		
Maintenance Materials and Labor	<u>1488</u>	(98)
From Report, Subtotal, $O^0(\text{Misc}) =$	$O^0(\text{Misc})$	

*See Table 2-1.

DISCOUNTED COSTS OF GAS PRODUCTION

Line Number	Cost Element	Differential Inflation Rate	Project Year	Amount, Thousands of Dollars		Discount Factor	Discounted Cost, Thousands of Dollars
				One Time	Recurring		
(1)	First-Year Construction	+0	2	4 880	17%	0.867	4 230
(2)	Second-Year Construction	+0	3	9 770	34%	0.788	7 700
(3)	Third-Year Construction	+0	4	14 070	49%	0.717	10 090
(4)	● Total Investment			● 28 720			● 22 020
(5)	Coal	+5	5-29		2 789	12.268	34 22
(6)	Electricity	+6	5-29		857	14.057	12 050
(7)	Operating Labor and Materials	+0	5-29		1 488	6.505	9 680
(8)	● Total Operating Costs				● 5 134		● 53 98
(9)	● Total Project Costs						● 77 970
(10)	Fuel Oil Alternative	+8	5-29		4 820	18.631	89 801
(11)	Energy Available over 25 years, billions of Btu						48 200
(12)	Product Gas Unit Cost, \$/million Btu (line 9 divided by line 11)						1.62
(13)	Fuel Oil Alternative Unit Cost, \$ million Btu (line 10 divided by line 11)						1.86
(14)	Savings/Investment Ratio, SIR = (line 10 - line 8)/line 4						1.54

Cost of gas from GASPLANT program, \$/10⁶ Btu

1.62

Section 3

BOILER DERATING

SUMMARY

This section contains the pertinent data and computational worksheets for boiler derating estimate analyses when changing boilers to coal-derived gas fuels. The methods result in estimated derating factors for boiler efficiency steam capacity and combustion product flow rates resulting from the fuel change.

SYSTEM DATA AND NOMENCLATURE

Definition of Typical Boilers

Three types of boilers are included in this study:

- Water tube boilers up to 200,000 lb/hr of steam production
- Fire tube boilers up to 10,000 lb/hr of steam production
- Stoker feed, coal-fired water tube boilers up to 200,000 lb/hr of steam production

The representative (or standard) boiler configuration for each boiler type is assumed to be rated at the maximum capacity stated above. It is assumed that the rating change factors defined for the maximum capacity boiler for each boiler type will generally apply to lower capacity boilers of that type.

All boilers are used for heating service, generating saturated steam at maximum pressures of 150 psig and minimum of 80 psig. No units

deliver superheated steam. The oldest boilers were installed in 1942, and the majority of all boilers were installed in the 1940's. They are predominantly fueled with oil ranging from No. 6 Venezuelan crude to No. 2 diesel with limited natural gas.

Based on the above information, additional general assumptions for these boiler designs can be made. Saturation pressures at 150 psig correspond to steam temperatures of 366^oF. These conditions along with the age of boilers support an assumption of natural steam circulation in the boilers. The low steam temperatures, boiler age, and heating application to military bases support an assumption that air preheaters are not used with the subject boilers.

Water Tube Boiler. The standard boiler of this type is assumed to be oil-fired and to deliver saturated steam at 150 psig and 366^oF. It is assumed that no air preheaters are used and that the boiler probably was field erected in the 1940's, although today it would be bought as a packaged unit.

Based on relative heat absorption data, the heat transferred to steam by radiation to the water walls and by convection to the boiler tube banks are approximately equal. For this boiler, the total heat transfer is assumed to be 0.5 by radiation and 0.5 by convection.

Fire Tube Boiler. The standard fire tube boiler is assumed to be oil-fired and working with steam conditions of 100 psig and 338^oF. This boiler is assumed to function without an air preheater and to have been field erected in the early 1940's. Heat transfer in fire tube boilers is expected to be greater by the convection mode rather than the radiant mode. This is based on the more compact designs for fire tube boilers with combustion product flow being forced through the tubing at greater velocities than in water tube boilers. The total heat transfer in this unit is assumed to be 0.4 by radiation and 0.6 by convection.

Stoker Feed, Coal-Fired Water Tube Boiler. This boiler is assumed to be similar in requirements to the oil-fired, water tube boiler, except for the coal-firing. Steam conditions are again assumed to be 150 psig and 366^oF. No air preheaters are used, and the unit is assumed to have been field erected in the 1940's. Total heat transfer in this unit is assumed to be 0.5 by radiation and 0.5 by convection.

Nomenclature

- q = Heat transfer rate, Btu/sec.
δ = Stefan-Boltzman constant.
A = Effective heat transfer area, ft².
T₁ = Temperature of combustion gas, ^oR.
T₂ = Temperature of water walls, ^oR.
e = Effective emissivity of combustion gas.
U_o = Outer tube wall heat transfer coefficient, Btu/ft²-hr-^oF.
U_L = Inner tube wall heat transfer coefficient, Btu/ft²-hr-^oF.
G = Mass velocity or mass flow of gas over the tubes, lb/hr ft² of cross-sectional area.
C_p = Specific heat at constant pressure, Btu/lb-^oF.
k = Conductivity of gas, Btu-ft/ft²-hr-^oF.
D_o = Outside tube diameter, ft.
U = Absolute gas viscosity, lb/ft-hr.
F_a = Arrangement factor.
T_b = Average bulk absolute temperature of gas, ^oR.
T_f = Average film absolute temperature, ^oR.

NOTE: The reference heat transfer is identified by subscript 1 (prior to fuel change) and the new heat transfer case by subscript 2 (after change to low-Btu gas fuel).

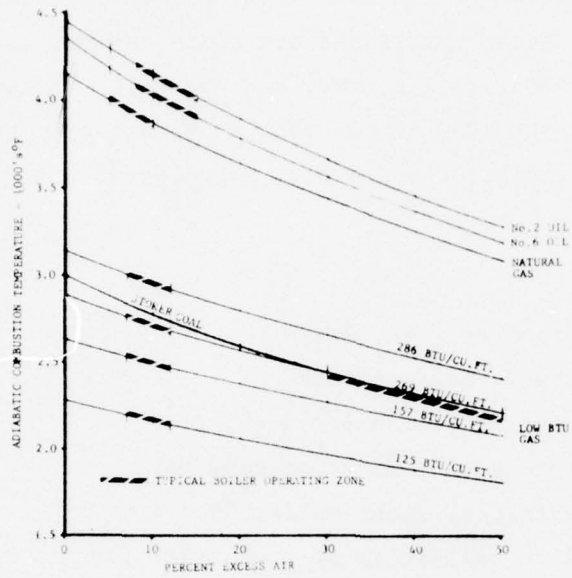


Figure 3-1. Theoretical Adiabatic Combustion Temperature Variation with Percent Excess Air for Various Boiler Fuels

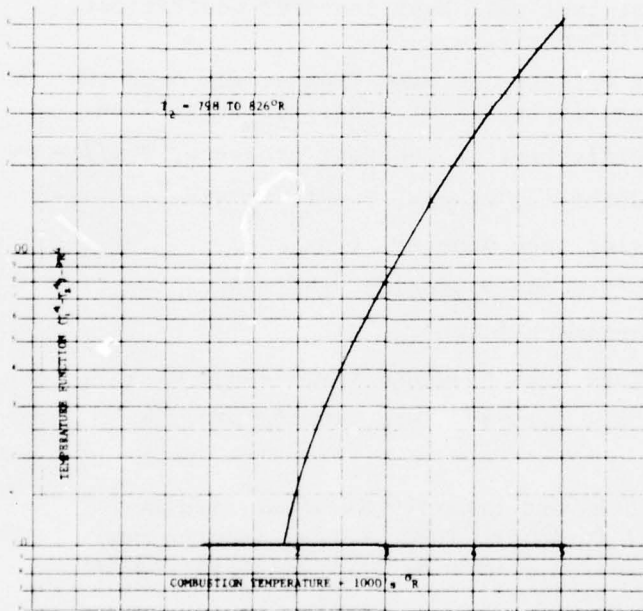


Figure 3-2. Radiant Heat Transfer Function Variation with Combustion Reaction Temperature

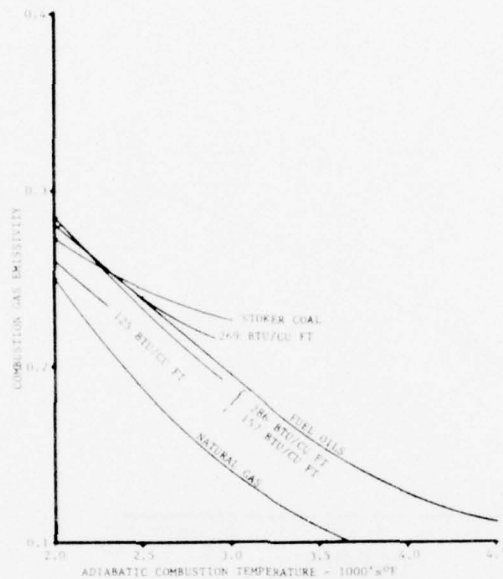


Figure 3-3. Combustion Product Gas Emissivity Variation with Adiabatic Combustion Temperature

Table 3-1

FUEL IN AIR COMBUSTION PRODUCT GAS QUANTITIES

Fuel	Stoichiometric Air/Fuel Ratio	Excess Air (%)	Actual Air/Fuel Ratio	High Heating Value (Btu/lb)	Combustion Gas (lb/lb fuel)	Products Flow (lb/10,000 Stu)
No. 2 Diesel Oil	13.051	12	14.617	19,600	15.617	7.968
No. 6 Residual Oil	12.845	12	14.386	18,600	15.386	8.272
Natural Gas	16.434	8	17.749	23,250	18.749	8.064
Coal, Unit Mine	11.545	40	16.163	10,709	17.163	16.03
Low-Btu Gas, 286 Btu/cu ft	4.6154	10	5.0769	5,280	6.0769	11.51
Low-Btu Gas, 269 Btu/cu ft	4.9449	10	5.4284	5,314	6.4284	12.10
Low-Btu Gas, 157 Btu/cu ft	2.3730	10	2.6103	2,708	3.6103	13.33
Low-Btu Gas, 125 Btu/cu ft	2.3977	10	2.6375	1,921	3.6375	18.94

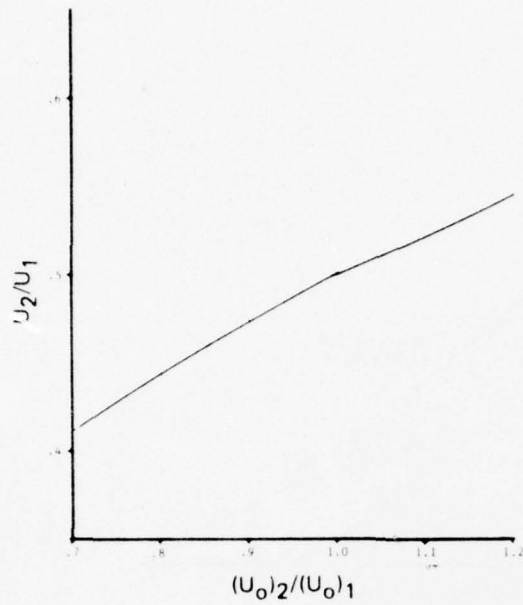


Figure 3-4. Overall Convection Heat Transfer Coefficient Variation with That of the Outer Tube Surface

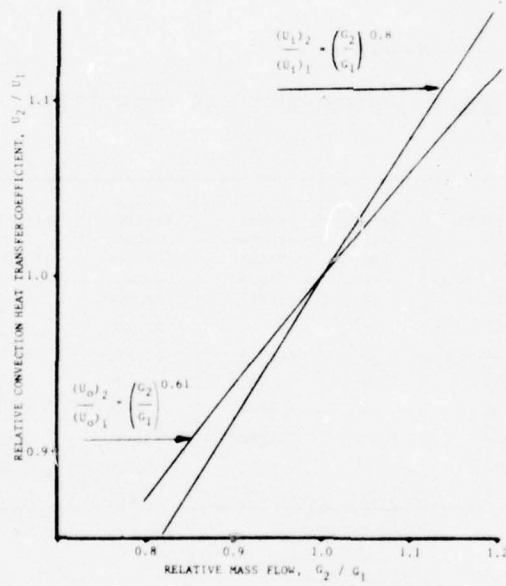


Figure 3-5. Relative Convection Heat Transfer Coefficient Variation with Relative Combustion Products Gas Mass Flow

PROCEDURE AND EXAMPLES

The worksheet shows the computation necessary to estimate the boiler performance rating factors for conversion to the three fuels for each of the three boiler types. The three fuel changes are to low-Btu gases of 286, 269, and 125 Btu/ft³. Additional worksheets are included.

The computational methodology is best explained by defining each computational step. These definitions are numbered to correspond with those on the worksheet.

- ① Boiler Type. Identify the type of boiler by entering the letters WT for water tube or FT for fire tube boilers.
- ② Steam Temperature, °F. Enter the saturated steam temperature for the boiler being analyzed. In the sample computations, the assumed temperatures are 366° F for water tube boilers and 338° F for fire tube boilers.
- ③ Fuel. Identify the fuel for which the boiler was originally designed.
- ④ Excess Air, %. Enter the percent of excess air supplied to the furnace section for combustion of the original fuel.
- ⑤ Fraction of Heat Transferred by Radiation. Enter the fraction of total heat transferred (steam generated) that occurs in the furnace section of the boiler.
- ⑥ Fraction of Heat Transferred by Convection. Enter the fraction of total heat transferred (steam generated) that occurs in the convection tube bundles of the boiler.
- ⑦ Check. The sum of ⑤ and ⑥ must equal 1.00 to account for all heat transferred in the boiler.
- ⑧ Combustion Temperature, °F. Enter the temperature from Figure 3-1 as a function of fuel ③ and excess air ④ .
- ⑨ Combustion Temperature, R. Add 460 to ⑧ .

- ⑩ Temperature Function. Enter the temperature function from Figure 3-2 as a function of combustion temperature ⑨ .
- ⑪ Emissivity. Enter the emissivity from Figure 3-3 as a function of fuel ③ and combustion temperature ⑧ .
- ⑫ Combustion Products Rate, lb/10,000 Btu. Enter the combustion products rate from Table 3-1 as a function of fuel ③ and excess air ④ .
- ⑬ Fuel, Type, and High Heating Value, Btu/cu ft. Enter here the type and high heating value of the coal-derived gas fuel to be burned in the boiler. In the sample computations, gases of 286, 269, and 125 Btu/ft³ are used.
- ⑭ Excess Air, %. Enter the percent of excess air supplied to the furnace air for combustion of the conversion gas to be used in place of the original design fuel. In the sample computations 10 percent excess air is used for all gas fuels.
- ⑮ Combustion Temperature, °F. Enter the temperature from Figure 3-1 as a function of fuel ⑬ and excess air ⑭ .
- ⑯ Combustion Temperature, R. Add 460 to ⑮ .
- ⑰ Temperature Function. Enter the temperature function from Figure 3-2 as a function of combustion temperature ⑯ .
- ⑱ Emissivity. Enter the emissivity from Figure 3-3 as a function of fuel ⑬ and combustion temperature ⑮ .
- ⑲ Combustion Products Rate, lb/10,000 Btu. Enter the combustion products rate from Table 3-1 as a function of fuel ⑬ and excess air ⑭ .
- ⑳ Ratio of Products. Compute the ratio of combustion products rate with conversion gas fuel to that with the original fuel (⑲ ÷ ⑫) . The result indicates the change in combustion products flow rate through the boiler per unit of fuel heat release.

A number greater than 1.00 means an increase in flow rate is required to obtain the same fuel heat release.

Flow rate increases are limited to 1.10 in order to exclude cases requiring major rebuilding of boiler systems to accommodate large gas flow increases.

A number less than 1.00 means a decrease in flow rate is required to obtain the same fuel heat release. For such cases, the ratio used is 1.00, which means that boiler capacity can be increased by injecting additional fuel to maintain the original gas flow rate. This occurs for boilers originally designed for stoker coal-fueling.

- (21) Compute the ratio of radiant heat transfer with conversion gas fuel to that with the original fuel $[(18) / (11)] \times [(17) / (10)]$. The result indicates the change in radiant heat transfer performance in the furnace section of the boiler. A number less than 1.00 means that the heat transfer rate is reduced.
- (22) Compute the ratio of combustion product gas temperature decrease by radiant heat transfer with conversion gas fuel to that with the original fuel $(21) / (20)$. A number less than 1.00 means that the temperature decrease in the furnace is reduced.
- (23) Stack Temperature, °F. Enter the measured stack gas temperature or estimate it as the saturated steam temperature plus 100°F for water tube boilers $(2) + 100$ or + 200°F for fire tube boilers $(2) + 200$.
- (24) Compute the approximate temperature decrease of the original fuel combustion gases resulting from radiant heat transfer in the furnace section of the boiler $(5) \times (8 - (23))$.
- (25) Compute the approximate temperature of the original fuel combustion gases entering the convection tube bundle section of the boiler $(8) - (24)$.
- (26) Compute the approximate temperature of the conversion gas fuel combustion gas entering the convection tube bundle section of the boiler $(15) - (22) \times (24)$.
- (27) Compute the convection heat transfer driving temperature difference ratio of the conversion gas fuel case to the original fuel case $[(26) - (2)] / [(25) - (2)]$.

- (28) Enter the relative convection heat transfer coefficient from Figure 3-5. The factor $(U_o)_2/(U_o)_1$ is for water tube boilers. The factor $(U_i)_2/(U_i)_1$ is for fire tube boilers. Both factors are a function of the ratio of products (20) .
- (29) Enter the overall convective heat transfer coefficient from Figure 3-4 as a function of $U_o = (U_o)_2/(U_o)_1 = (28)$. This step is required only for water tube boilers.
- (30) Compute the overall convective heat transfer coefficients ratio of the conversion gas fuel case to the original fuel case. For water tube boilers, this ratio is (29) /0.5. For fire tube boilers this ratio is (28) .
- (31) Compute the ratio of convection heat transfer with conversion gas fuel to that with the original fuel ((30) x (27)). The result indicates the change in convection heat transfer performance in the tube bundle section of the boiler. A number less than 1.00 means that the heat transfer rate is reduced.
- (32) Compute the ratio of combustion product gas temperature decrease by convection heat transfer with conversion gas fuel to that with the original fuel ((31) / (20)). A number less than 1.00 means that the temperature decrease in the tube bundle section is reduced.
- (33) Compute the total boiler heat transfer performance effect (ratio of steam generation) as ((5) x (21)) + ((6) x (31)). This sums the effects in the radiant furnace and convection tube bundle sections of the boiler.
- (34) Compute the total boiler combustion gas temperature decrease effect (ratio of available energy extraction) as ((5) x (22)) + ((6) x (32)).
- (35) Compute the temperature increase by combustion in the furnace of the original fuel ((8) - 70.F).
- (36) Compute the temperature increase by combustion in the furnace of the conversion gas fuel ((15) - 70.F).

③⑦ Compute the overall boiler efficiency effect of the fuel change as $(\textcircled{34} \times \textcircled{35}) / \textcircled{36}$. This value indicates the efficiency change expected to occur with the change in boiler fuel. This value times the original fuel boiler efficiency estimates the boiler efficiency with the conversion gas fuel.

Table 3-2

ESTIMATING PROCEDURE WORKSHEET FOR EFFECTS OF FUEL CHANGES
ON INDUSTRIAL SATURATED STEAM BOILER PERFORMANCE

STEP NO.	COMPUTATIONAL STEP	UNITS	A	B	C	D	E	F	G	H	I
1	BOILER TYPE WT WATER TUBE FT FIRE TUBE										
2	STEAM TEMPERATURE	F	366	366	366	366	366	366	338	338	338
INITIAL CONDITIONS											
3	FUEL		Oil	Oil	Oil	Coal	Coal	Coal	Oil	Oil	Oil
4	EXCESS AIR	%	12	12	12	40	40	40	12	12	12
5	FRACTION OF HEAT TRANSFERRED BY RADIATION		.50	.50	.50	.50	.50	.50	.40	.40	.40
6	FRACTION OF HEAT TRANSFERRED BY CONVECTION		.50	.50	.50	.50	.50	.50	.60	.60	.60
7	CHECK (5) + (6) = 1.00		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	COMBUSTION TEMPERATURE, F (1 AND 4)	F	3980	3980	3980	2370	2370	2370	3980	3980	3980
9	COMBUSTION TEMPERATURE, °F + 460	R	4446	4446	4446	2810	2810	2810	4446	4446	4446
10	TEMPERATURE FUNCTION, F (9)		.375	.375	.375	.60	.60	.60	.375	.375	.375
11	EMISSIVITY, F (3 AND 8)		.128	.128	.128	.244	.244	.244	.128	.128	.128
12	COMBUSTION PRODUCTS RATE, F (3 AND 4)	IN 10,000 BTU	8.272	8.272	8.272	17.13	17.13	17.13	8.272	8.272	8.272
NEW FUEL CONDITIONS											
13	FUEL GAS HIGH HEATING VALUE	BTU CU FT	286	269	125	286	269	125	286	269	125
14	EXCESS AIR	%	10	10	10	10	10	10	10	10	10
15	COMBUSTION TEMPERATURE, F (13 AND 14)	F	2950	2710	2170	2150	2710	2170	2950	2710	2170
16	COMBUSTION TEMPERATURE, °F + 460	R	3410	3170	2630	2610	3170	2630	3410	3170	2630
17	TEMPERATURE FUNCTION, F (16)		.133	.101	.49	.133	.101	.49	.133	.101	.49
18	EMISSIVITY, F (13 AND 15)		.192	.221	.246	.192	.221	.246	.192	.221	.246
19	COMBUSTION PRODUCTS RATE, F (13 AND 14)	IN 10,000 BTU	11.51	12.10	18.94	11.51	12.10	18.94	11.51	12.10	18.94
20	RATIO OF PRODUCTS (19) - (12) ≤ 1.18		(1.39)	(1.46)	(2.29)	(.718)	(.765)	(1.18)	(1.39)	(1.46)	(2.29)
			1.10	1.10	1.10	1.00	1.00	1.10	1.10	1.10	1.10

Table 3-2 (Continued)

STEP NO	COMPUTATIONAL STEP	UNITS	A	B	C	D	E	F	G	H	I
EFFECTS ON RADIANT HEAT TRANSFER											
21	$\left(\frac{q_2}{q_1}\right)_r = \frac{18}{11} \times \frac{17}{10}$.532	.465	.251	1.676	1.465	.741	.512	.747	.242
22	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_r = \frac{21}{29}$.484	.423	.228	1.676	1.465	.719	.465	.406	.220
23	STACK TEMPERATURE, WATER TUBE - (2) + 100 FIRE TUBE - (2) + 200	F	466	466	466	466	466	466			
24	$\Delta T_s = (5) \times (8) - (23)$	F	1757	1757	1757	917	917	917	538	538	538
25	$T_{s1} = (8) - (24)$	F	2223	2223	2223	1383	1383	1383	2603	2603	2603
26	$T_{s2} = (15) - (22) + (24)$	F	2106	1967	1769	1413	1367	1511	2310	2151	867
EFFECTS ON CONVECTIVE HEAT TRANSFER											
27	$\frac{T_{s2} - T_1}{T_{s1} - T_1} = \frac{26 - (2)}{25 - (2)}$.934	.862	.756	1.029	.984	1.124	.871	.800	.675
28	$(u_2/u_1)_c$ F 20 $(u_2/u_1)_c$ FOR FIRE TUBE		1.06	1.06	1.06	1.00	1.00	1.06		1.078	1.078
29	u_2 F 28		.512	.512	.512	.500	.500	.512	-	-	-
30	u_2/u_1 WATER TUBE - (29) - (29) FIRE TUBE - (29)		1.024	1.024	1.024	1.000	1.000	1.024		1.078	1.078
31	$\left(\frac{q_2}{q_1}\right)_c = (30) \times (27)$.956	.883	.774	1.029	.984	1.153	.939	.862	.728
32	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_c = \frac{31}{28}$.869	.803	.704	1.029	.984	1.048	.854	.784	.662

Table 3-2 (Continued)

STEP NO.	COMPUTATIONAL STEP	UNITS	A	B	C	D	E	F	G	H	I
	TOTAL PERFORMANCE EFFECTS										
31	$\left(\frac{N_2}{N_1}\right)_{TOTAL} = (5 \times 21) + (8 \times 31)$.744	.674	.512	1.352	1.224	.972	.768	.676	.534
32	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_{TOTAL} = (5 \times 22) + (8 \times 32)$.676	.613	.466	1.352	1.224	.884	.678	.633	.485
33	$\Delta T_{comb 1} = (8) - 78$	F	3910	3910	3910	2230	2230	2230	3110	3910	3910
34	$\Delta T_{comb 2} = (15) - 78$	F	2880	2690	2100	2880	2690	2100	2880	2690	2100
37	$\left(\frac{EFF. 2}{EFF. 1}\right)_{TOTAL} = \frac{(34) \times (35)}{38}$.918	.908	.868	1.047	1.034	.939	.948	.938	.912

WORKSHEET FOR PLANT ANALYSIS

DESIGN BASIS

Reactor Capacity:

Heating value of reactor output, sour, Btu/hr - 250×10^6

Emission Of SO₂:

Product from combustion of fuel gas,
 1b SO₂/10⁶ Btu HHV (coal), _____ e(SO₂)

Ultimate Analysis Of Coal:

	% or lb per 100 lb coal
Carbon	_____ W(C)
Hydrogen	_____ W(H ₂)
Oxygen	_____ W(O ₂)
Nitrogen	_____ W(N ₂)
Sulfur	_____ W(S)
Moisture	_____ W(H ₂ O)
Ash	_____ W(Ash)
Total	100
Ash Softening Temperature =	_____ °F
Ash Melting Temperature =	_____ °F

Note: $W(\text{evap}) = W(\text{H}_2\text{O}) - W_o(\text{H}_2\text{O})$.

REACTOR PERFORMANCE

Basis: 100 lb coal, with moisture

Carbon gasification See Table 2-1, items (11) and (12).

Carbon conversion, expected fraction $\gamma = \underline{\hspace{2cm}}$ (1)

Ratio CO/(CO + CO₂), expected value $\alpha = \underline{\hspace{2cm}}$ (2)

Feedstock and resulting char

Carbon: $\frac{x}{W_o(C)} \times \frac{12}{12} = \frac{\text{Mol}}{n_o(C)}$ (3)

Hydrogen: $\frac{12}{W_o(H_2)/2} - \frac{16}{W_o(O_2)/16} = \frac{\text{Mol}}{n_o(H_2,fc)}$ (4)

Oxygen: $\frac{32}{W_o(O_2)/32} = \frac{\text{Mol}}{n_o(O_2)}$ (5)

Nitrogen: $\frac{28}{W_o(N_2)/28} = \frac{\text{Mol}}{n_o(N_2)}$ (6)

Sulfur: $\frac{32}{W_o(S)/32} = \frac{\text{Mol}}{n_o(S)}$ (7)

Moisture: $\frac{18}{W_o(H_2O)} = \frac{\text{Mol}}{n_o(H_2O)}$ (8)

Char: $\frac{+ () \times}{W_o(\text{Ash}) + (1-\gamma) \times W_o(C)} = \frac{\text{lb}}{W_o(\text{char})}$ (9)

Heat of combustion @ carbon conversion γ , HHV' coal:

$$\frac{x(173,934) + n_o(H_2,fc) \times 122,976 + n_o(S) \times 184,640}{n_o(C) \times \Delta H_c(C) + n_o(H_2,fc) \times \Delta H_c(H_2) + n_o(S) \times \Delta H_c(S)} = \frac{\text{Btu}}{\text{HHV}'(\text{coal})}$$
 (10)

$(\Delta H_c(S) = \text{At. wt.} \times 5,770 \text{ Btu/lb})$

Heat of combustion @ full conversion, HHV (coal)

$$\text{HHV}(\text{coal}) + \frac{+ [1-\gamma]/\gamma \times x \times 173,934}{n_o(C) \times \Delta H_c(C)} = \frac{\text{Btu}}{\text{HHV}(\text{coal})}$$
 (11)

Basis: 100 lb coal, with moisture

Blast

$$\text{Steam: } \frac{x}{R_{wc} \times n_o(C)} - \frac{[n_o(H_2O) + 2N_o(O_2) + n_1(\text{Quench})]}{(2)^*} = \frac{\text{Mol}}{n_1(\text{stm})} \quad (12)$$

$$\text{Quench: } \frac{x}{R_{qc} \times n_o(C)} = \frac{\text{Mol}}{n_1(\text{quench})} \quad (13)$$

$$\text{Oxygen: } \frac{x}{R_{oc} \times n_o(C)} = \frac{\text{Mol}}{n_1(O_2\text{blst})} \quad (14)$$

$$\text{Nitrogen: } \frac{[(R_{bc} - R_{oc}) : R_{oc}]}{(4)^*} \times \frac{n_1(O_2\text{blst})}{(1)^*} = \frac{\text{Mol}}{n_1(N_2\text{blst})} \quad (15)$$

Reactor Gases

$$\text{Carbon monoxide: } \frac{x}{\alpha \times n_o(C)} = \frac{\text{Mol}}{n_2(CO)} \quad (25)$$

$$\text{Carbon dioxide: } \frac{x}{(1-\alpha) \times n_o(C)} = \frac{\text{Mol}}{n_2(CO_2)} \quad (26)$$

$$\text{Water decomposed: } \frac{(2 -)x}{(2 - \alpha) \times n_o(C)} - \frac{2x}{2n_1(O_2\text{blst})} = \frac{\text{Mol}}{n_2(H_2O_d)} \quad (27)$$

$$\text{Hydrogen: } \frac{-}{n_o(H_2,fc)} + \frac{+}{n_o(S) + n(H_2O_d)} = \frac{\text{Mol}}{n_2(H_2)} \quad (28)$$

$$\text{Nitrogen: } \frac{-}{n_o(N_2) + n_1(N_2\text{blst})} = \frac{\text{Mol}}{n_2(N_2)} \quad (29)$$

$$\text{Sulfur as hydrogen sulfide: } \frac{-}{n_o(S)} = \frac{\text{Mol}}{n_2(S)} \quad (30)$$

$$\text{Water Vapor: } \frac{+}{n_o(H_2O)} + \frac{+}{n_1(\text{stm})} + \frac{+}{n_1(\text{qnch})} + \frac{+ 2x}{2n_o(O_2)} - \frac{-}{n_2(H_2O_d)} = \frac{\text{Mol}}{n_2(H_2O)} \quad (31)$$

*See Table 2-1.

Basis: 100 lb coal, with moisture

$$\text{Combustibles: } \frac{2x}{2n_o(C)} - \frac{2x}{2n_1(O_2 \text{ blst})} + \frac{x}{n_o(H_2, \text{fc})} - \frac{x}{n_o(S)} = \frac{\text{Mol}}{N_2(\text{cmbstl})} \quad (32)$$

(14)

Total hot raw gas:

$$\frac{n_o(C)}{(41)} + \frac{n_2(H_2, N, \text{fg})}{(41)} + \frac{n_{1,2}(H_2O)}{(42)} + \frac{n_2(N_2)}{(41)} + \frac{n_2(H_2S)}{(41)} = \frac{\text{Mol}}{\sum_i} \quad (33)$$

Heat Effects

Heating value of fuel gas, excepting H₂S:

$$\frac{n_o(H_2, CO)}{(32)} \times \frac{122,157}{\Delta H_c(H_2, CO)} = \frac{\text{Btu}}{Q_c(\text{Sweet Gas})} \quad (34)$$

Heat release in reactor:

$$\frac{n_o(C) \times 173,934 - [n_o(C) - n_1(O_2)] \times [2 \times 122,157]}{(14)} = \frac{\text{Btu}}{Q(\text{reactor})} \quad (35)$$

(14) (32)

Heat release in combustion of H₂S:

$$\frac{n_2(H_2S) \times 241,092}{\Delta H_c(H_2S)} = \frac{\text{Btu}}{Q_c(H_2S)} \quad (36)$$

Sum of heat release effects:

$$\frac{Q_c(\text{Sweet gas}) + Q(\text{reactor}) + Q_c(H_2S)}{\Sigma Q} = \frac{\text{Btu}}{\Sigma Q} \quad (37)$$

Heating value of unconverted carbon in char:

$$\frac{173,934 \times n_o(C) \times [(1-\gamma)/\gamma]}{\Delta H_c(C)} = \frac{\text{Btu}}{Q_c(\text{Char})} \quad (38)$$

Miscellaneous

$$n_o(H_2, \text{fc}) - n_o(S) = \text{_____} = n_2(H_2, n, \text{fg}) \quad (41)$$

$$n_2(H_2O) + n_2(H_2O_d) = \text{_____} = n_{1,2}(H_2O) \quad (42)$$

(27)

Basis: 100 lb coal, with moisture

Estimation of Steam Generation

Heat addition to reactor as steam blast (ref'd to 70°F), Btu:

$$\frac{n_1(\text{stm}) \times 18 \times h(\text{stm})}{(12) \quad (5a)^*} = \frac{\text{Btu}}{Q_1(\text{stm})} \quad (50)$$

Heat addition to reactor as blast gas (N₂, O₂), Btu:

$$\left[\frac{n_1(\text{O}_2) + n_1(\text{N}_2)}{(14)} \right] \times 7.1(-70^\circ\text{F}) = \frac{\text{Btu}}{Q_1(\text{N}_2, \text{O}_2)} \quad (51)$$

(6)*

Heat addition to reactor as warm coal from drying process:

$$\frac{(100 - W_{\text{evap}}) \times 0.25 \times (T_{\text{coal}} - 70)}{(100 \text{ lb} - W_{\text{evap}}) \times C'_p \times (T_{\text{coal}} - 70)} = \frac{\text{Btu}}{Q_o(\text{coal})} \quad (52)$$

**

Heat loss from reactor as hot slag:

$$\frac{W(\text{slag}) \times 0.25 \times (T_{\text{slag}} - 70)}{(9) \times C'_p \times (T_{\text{slag}} - 70)} = \frac{\text{Btu}}{Q(\text{slag})} \quad (53)$$

Heat loss from reactor as exit cool fuel gas:

$$\frac{\sum n_i \times C_p(\text{CFG}) \times (350 - 70)}{(33) \quad (8)^*} = \frac{\text{Btu}}{Q(\text{CFG})} \quad (54)$$

Total heat release to hot raw product gas:

$$Q(\text{rctr}) + Q_1(\text{stm}) + Q(\text{N}_2, \text{O}_2) + Q(\text{coal}) - Q(\text{char}) = \frac{\text{Btu}}{Q(\text{HFG})} \quad (55)$$

Temperature reached in reactor:

$$\frac{Q(\text{HFG}) / [C_p(\text{HFG}) \times \sum n_i]}{(7)^*} + 70 = \frac{\text{Btu}}{T(\text{rctr})} \quad (56)$$

Case 1: This temperature should be at least 2800°F
 Cases 1, 2, & 3: See Item (10), Table 2-1.

* See Table 2-1.

** See Design Basis.

Basis: 100 lb coal, with moisture

Generation of high pressure steam by waste heat recovery:

Case 1 only:

$$\left[\frac{\quad - \quad - \quad}{Q(\text{HFG}) - Q(\text{CFG}) - Q_1(\text{Stm})} \right] : \frac{\quad}{h(\text{stm, hp})} = \frac{\quad \text{lb}}{W_3(\text{stm, hp})} \quad (57)$$

(55) (54) (5b), Table 2-1

Case 2 only:

$$\left[\frac{\quad}{Q(\text{HFG}) - Q(\text{CFG})} \right] : \frac{\quad}{h(\text{stm, hp})} = \frac{\quad \text{lb}}{W_3(\text{stm, hp})} \quad (58)$$

(55) (54) (5b), Table 2-1

Case 3 only:

$$\left[\frac{\quad - \quad - \quad}{Q(\text{HFG}) - Q(\text{CFG}) - Q_1(\text{N}_2, \text{O}_2)} \right] : \frac{\quad}{h(\text{stm, hp})} = \frac{\quad}{W_3(\text{stm, hp})} \quad (59)$$

ENERGY MANAGEMENT

Basis: 100 lb coal, with moisture

Compression Energy

Oxygen Plant Compressor (Oxygen Blast System Only):

Air is raised from 14.7 to 165 psia @ 70°F, and liquified.

$$\frac{21,296 \times}{21,296 \times n_1(O_2)} = \frac{\text{Btu}}{E_c(\text{AIR})} \quad (60)$$

(15a)*

Air Blast Compressor (Air Blast System Only):

Air feed is raised from 14.7 to 50 psia @ 70°F:

$$\frac{9,218 \times}{9,218 \times n_1(O_2)} = \frac{\text{Btu}}{E_c(\text{AIR})} \quad (61)$$

(15b)* (14)

Raw Gas Compression, dry:

Raw Gas Compression from 35 to 165 psia @ 100°F:

$$\frac{2,676 \times \left[\frac{-}{\sum n_i - n_2(H_2O)} \right]}{2,676 \times \left[\sum n_i - n_2(H_2O) \right]} = \frac{\text{Btu}}{E_c(\text{FG})} \quad (63)$$

(15c)* (33) (31)

Recovered Energy

Fuel Gas Expansion: 135 to 40 psia:

$$\frac{1,354 \times \left[\frac{-}{\sum n_i - n_2(H_2O)} \right]}{1,354 \times \left[\sum n_i - n_2(H_2O) \right]} = \frac{\text{Btu}}{E_x(\text{FG})} \quad (64)$$

(16)* (33) (31)

Steam Expansion: 1,055 to 2.89, 165, 422 psia:

$$\frac{\left(\frac{-}{-} \right) \times \left[\frac{327 + 149 \times \left(\frac{-}{-} \right)}{327 + 149 \times \text{Rps}} \right] - 322 \left[\frac{\left(\frac{-}{-} \right) \times \left(\frac{-}{-} \right) + \left(\frac{-}{-} \right)}{W(\text{stm, hp}) \times \text{Rps} + W_1(\text{stm})} \right]}{(14)*} = \frac{\text{Btu}}{E_x(\text{stm})} \quad (65)$$

Where $W_1(\text{stm}) = 18 \times n_1(\text{stm})$ lb entered only for Cases 2 and 3.
(12)

* See Table 2-1.

PLANT SCALE PERFORMANCE
 COAL HANDLING AND GASIFICATION

Basis: 100 lb coal or 1.0 hour, as noted

Coal Rate, lb/hr

$$\frac{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb}}{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb} : [Q_c(\text{H}_2, \text{CO}) + Q_c(\text{H}_2\text{S})]} = \frac{\text{lb/hr}}{W(\text{Coal})} (70)$$

Assemble previous results in 71_i or 72_i; compute entries for 73_i, 74_i, 76_i (See note).

Source Component Item Sub i	Basis: 100 lb Coal		Basis: 1 Hour's Operation			
	Lb	n _i Mols	N _i Mols	Mol/Fract.	Mol/wt.	Lb
	71 _i	72 _i	73 _i	74 _i	75 _i	76 _i
Feed						
(70) a Coal Blast	●100		●	—	NA	●
(12) b Stm					18.016	
(14) c O ₂					32.000	
(15) d N ₂					28.010	
e (SubΣ)	●		●	NA	NA	●
(13) f Quench	●		●	NA	18.016	●
g Total	●		●	NA	NA	●
Effluent						
* h Evapn Sour Gas	●		●	—	NA	●
(25) j CO					28.010	
(26) k CO ₂					44.010	
(28) l H ₂					2.016	
(29) m N ₂					28.016	
(30) n (H ₂ S)					34.076	
o Dry FG				1.000		
(31) p H ₂ O				—	18.016	
(33) q (HFG)	●		●	—		●
(9) r Char	●		●	—	NA	●
s Total	●		●	—	NA	●

Note: 73_i/72_i = 76_i/71_i = W(Coal)/100
 71_i/72_i = 76_i/73_i = 75_i

* See Design Basis.

PLANT SCALE PERFORMANCE
ENERGY EFFECTS

Basis: 100 lb coal or 1.0 hour, as noted

Mechanical Energy		Basis: 100 lb Coal		Basis: 1 Hour's Operation	
Source	Component	Btu	kWhr	Btu	kWhr
Item	Sub.	80 _i	81 _i	82 _i	83 _i
Compression					
(60)	a	Oxy plant			
(61)	b	Air blast			
(63)	c	Raw fuel gas			
(13)*	d	Misc.			
	e	Total	•	•	•
Recovery Expansion					
(64)	f	Fuel gas			
(65)	g	Steam			
	h	Total	•	•	•
Net Demand					
(e,h)	j	Electric pwr	•	•	•
Heat Release Effects: Progressive combustion of coal to final products.					
(34)	k	Sweet gas			
(36)	l	H ₂ S			
(35)	m	Reactor			
(38)	n	Char			
	o	Total	•	•	
(11)	p	Coal	•	•	
Total Energy to Plant					
(j,p)	q		•	•	
Note: $82_i/80_i = 83_i/81_i = W(\text{Coal})/100$ $81_i/80_i = 83_i/82_i = 0.29281 \times 10^{-3}$					

*See Table 2-1.

PLANT COSTS

Capital Costs	\$1000
Oxygen/Air Plant:	(85)
$\frac{[(C_c + C_d) / (N_c + N_d)]^{0.6}}{[(N_c + N_d) / (N_c^o + N_d^o)]^{0.6}} \times \frac{C_1^o}{C_1} =$	$\frac{C_1}{C_1}$
(73 _c) (73 _d) (See Note)	
Gasification Module:	
$\left[\frac{N_q}{N_q^o} \right] \times \frac{C_2^o}{C_2} =$	$\frac{C_2}{C_2}$
(73 _q) (see note)	(86)
Compression/Expansion:	
$\left(\frac{N_o}{N_o^o} \right) \times \frac{C_3^o}{C_3} =$	$\frac{C_3}{C_3}$
(73 _o) (see note)	(87)
Gas Treatment Module:	
$\frac{\{1 + a \times [W_o(S) - W_o^o(S)]\} \times \{1 - b \times \ln[e(SO_2)/e^o(SO_2)]\} \times C_4^o}{\{1 + a \times [W_o(S) - W_o^o(S)]\} \times \{1 - b \times \ln[e(SO_2)/e^o(SO_2)]\} \times C_4} =$	$\frac{C_4}{C_4}$
(17a)* (7) (17b)* (See Design Basis)	(88)

*See Table 2-1.

Note: Values for C^o, for the nominal cases, are in the Final Report, Appendix F.

Coal Preparation Module:	\$1,000
$\left[\frac{\text{W(Coal)}}{\text{W}^0(\text{Coal})} \right]^{.5} \times \frac{\text{C}_5}{\text{C}_5^0} =$	(89)
Utilities, Piping, Waste Disposal: constant	(90)
Direct Field Cost:	(91)
Sum: $C_1 + C_2 + C_3 + C_4 + C_5 + C_6 =$	(92)
Total Capital Cost	(92)
$\frac{\text{C}_7 \times (\text{C}_8/\text{C}_7)}{(18)*} =$	(93)
<u>Operating Costs, Annual, Based on 90% Service Factor</u>	<u>\$1,000</u>
Coal @ W(Coal) lb/hr:	(96)
$\frac{(\text{W(Coal)} / 2,000) \times (7,889 \text{ hr/yr})}{(\text{W(Coal)} / 2,000) \times (7,889 \text{ hr/yr})} =$	0(coal)
Electric power @ E _D kW:	(97)
$\frac{(E_D) \times (7,889 \text{ hr/yr}) (\$/\text{kWhr})}{(83g)}$	0(pwr)
Catalyst, Chemicals, from Nominal Case: Equipment, Supplies, Utilities Operating Personnel Maintenance Materials and Labor	(98)
From Report, Subtotal, 0 ⁰ (Misc) =	0(Misc)

*See Table 2-1.

DISCOUNTED COSTS OF GAS PRODUCTION

Line Number	Cost Element	Differential Inflation Rate	Project Year	Amount, Thousands of Dollars		Discount Factor	Discounted Cost, Thousands of Dollars
				One Time	Recurring		
(1)	First-Year Construction	+0	2		17%	0.867	
(2)	Second-Year Construction	+0	3		34%	0.788	
(3)	Third-Year Construction	+0	4		49%	0.717	
(4)	● Total Investment			●			●
(5)	Coal	+5	5-29			12.268	
(6)	Electricity	+6	5-29			14.057	
(7)	Operating Labor and Materials	+0	5-29			6.505	
(8)	● Total Operating Costs				●		●
(9)	● Total Project Costs						●
(10)	Fuel Oil Alternative	+8	5-29			18.631	
(11)	Energy Available over 25 years, billions of Btu						
(12)	Product Gas Unit Cost, \$/million Btu (line 9 divided by line 11)						
(13)	Fuel Oil Alternative Unit Cost, \$ million Btu (line 10 divided by line 11)						
(14)	Savings/Investment Ratio, SIR = (line 10 - line 8)/line 4						

WORKSHEET FOR PLANT ANALYSIS

DESIGN BASIS

Reactor Capacity:

Heating value of reactor output, sour, Btu/hr - 250×10^6

Emission Of SO₂:

Product from combustion of fuel gas,
 lb SO₂/10⁶ Btu HHV (coal), _____ e(SO₂)

Ultimate Analysis Of Coal:

	% or lb per 100 lb coal
Carbon	_____ W(C)
Hydrogen	_____ W(H ₂)
Oxygen	_____ W(O ₂)
Nitrogen	_____ W(N ₂)
Sulfur	_____ W(S)
Moisture	_____ W(H ₂ O)
Ash	_____ W(Ash)
Total	100
Ash Softening Temperature =	_____ °F
Ash Melting Temperature =	_____ °F

Note: $W(\text{evap}) = W(\text{H}_2\text{O}) - W_o(\text{H}_2\text{O})$

REACTOR PERFORMANCE

Basis: 100 lb coal, with moisture

Carbon gasification See Table 2-1, items (11) and (12).

Carbon conversion, expected fraction $\gamma = \frac{\quad}{\quad}$ (1)

Ratio CO/(CO + CO₂), expected value $\alpha = \frac{\quad}{\quad}$ (2)

Feedstock and resulting char

Carbon: $\frac{W_o(C) \times \gamma / 12}{W_o(C) \times (\gamma) / 12} = \frac{\text{Mol}}{n_o(C)}$ (3)

Hydrogen: $\frac{W_o(H_2) / 2 - W_o(O_2) / 16}{W_o(H_2) / 2 - W_o(O_2) / 16} = \frac{\text{Mol}}{n_o(H_2, fc)}$ (4)

Oxygen: $\frac{W_o(O_2) / 32}{W_o(O_2) / 32} = \frac{\text{Mol}}{n_o(O_2)}$ (5)

Nitrogen: $\frac{W_o(N_2) / 28}{W_o(N_2) / 28} = \frac{\text{Mol}}{n_o(N_2)}$ (6)

Sulfur: $\frac{W_o(S) / 32}{W_o(S) / 32} = \frac{\text{Mol}}{n_o(S)}$ (7)

Moisture: $\frac{W_o(H_2O) / 18}{W_o(H_2O) / 18} = \frac{\text{Mol}}{n_o(H_2O)}$ (8)

Char: $\frac{W_o(Ash) + (1-\gamma) \times W_o(C)}{W_o(Ash) + (1-\gamma) \times W_o(C)} = \frac{\text{lb}}{W_o(char)}$ (9)

Heat of combustion @ carbon conversion γ , HHV' coal:

$$\frac{n_o(C) \times \Delta H_c(C) + n_o(H_2, fc) \times \Delta H_c(H_2) + n_o(S) \times \Delta H_c(S)}{\quad} = \frac{\text{Btu}}{\text{HHV}' (coal)} \quad (10)$$

$(\Delta H_c(S) = \text{At. wt.} \times 5,770 \text{ Btu/lb})$

Heat of combustion @ full conversion, HHV (coal)

$$\frac{\text{HHV} (coal) + [1-\gamma]/\gamma \times n_o(C) \times \Delta H_c(C)}{\quad} = \frac{\text{Btu}}{\text{HHV} (coal)} \quad (11)$$

Basis: 100 lb coal, with moisture

Blast

$$\text{Steam: } \frac{x}{R_{wc} \times n_o(C)} - \left[\frac{n_o(H_2O) + 2N_o(O_2) + n_1(\text{Quench})}{n_1(\text{stm})} \right] = \frac{\text{Mol}}{n_1(\text{stm})} \quad (12)$$

$$\text{Quench: } \frac{x}{R_{qc} \times n_o(C)} = \frac{\text{Mol}}{n_1(\text{quench})} \quad (13)$$

$$\text{Oxygen: } \frac{x}{R_{oc} \times n_o(C)} = \frac{\text{Mol}}{n_1(O_2 \text{ blst})} \quad (14)$$

$$\text{Nitrogen: } \frac{\left[\frac{R_{bc} - R_{oc}}{R_{bc} - R_{oc}} \right] \times n_1(O_2 \text{ blst})}{(4)^* \quad (1)^*} = \frac{\text{Mol}}{n_1(N_2 \text{ blst})} \quad (15)$$

Reactor Gases

$$\text{Carbon monoxide: } \frac{x}{\alpha \times n_o(C)} = \frac{\text{Mol}}{n_2(CO)} \quad (25)$$

$$\text{Carbon dioxide: } \frac{x}{(1-\alpha) \times n_o(C)} = \frac{\text{Mol}}{n_2(CO_2)} \quad (26)$$

$$\text{Water decomposed: } \frac{(2 -)x}{(2 - \alpha) \times n_o(C)} - \frac{2x}{2n_1(O_2 \text{ blst})} = \frac{\text{Mol}}{n_2(H_2O_d)} \quad (27)$$

$$\text{Hydrogen: } \frac{-}{n_o(H_2, fc) - n_o(S) + n(H_2O_d)} = \frac{\text{Mol}}{n_2(H_2)} \quad (28)$$

$$\text{Nitrogen: } \frac{-}{n_o(N_2) + n_1(N_2 \text{ blst})} = \frac{\text{Mol}}{n_2(N_2)} \quad (29)$$

$$\text{Sulfur as hydrogen sulfide: } \frac{-}{n_o(S)} = \frac{\text{Mol}}{n_2(S)} \quad (30)$$

$$\text{Water Vapor: } \frac{n_o(H_2O) + n_1(\text{stm}) + n_1(\text{qnch}) + 2x}{(5) \quad (27)} - \frac{n_2(H_2O_d)}{(27)} = \frac{\text{Mol}}{n_2(H_2O)} \quad (31)$$

*See Table 2-1.

Basis: 100 lb coal, with moisture

$$\text{Combustibles: } \frac{2x}{2n_o(C)} - \frac{2x}{2n_1(O_2 \text{ blst})} + \frac{x}{n_o(H_2, fc)} - \frac{x}{n_o(S)} = \frac{\text{Mol}}{N_2(\text{cmbsl})} \quad (32)$$

Total hot raw gas:

$$\frac{n_o(C)}{(41)} + \frac{n_2(H_2, N, fg)}{(41)} + \frac{n_{1,2}(H_2O)}{(42)} + \frac{n_2(N_2)}{(42)} + \frac{n_2(H_2S)}{(42)} = \frac{\text{Mol}}{\sum n_i} \quad (33)$$

Heat Effects

Heating value of fuel gas, excepting H₂S:

$$\frac{n_o(H_2, CO)}{(32)} \times 122,157 \times \Delta H_c(H_2, CO) = \frac{\text{Btu}}{Q_c(\text{Sweet Gas})} \quad (34)$$

Heat release in reactor:

$$\frac{n_o(C) \times 173,934 - [n_o(C) - n_1(O_2)] \times [2 \times 122,157]}{(14)} = \frac{\text{Btu}}{Q(\text{reactor})} \quad (35)$$

Heat release in combustion of H₂S:

$$\frac{n_2(H_2S) \times 241,092}{\Delta H_c(H_2S)} = \frac{\text{Btu}}{Q_c(H_2S)} \quad (36)$$

Sum of heat release effects:

$$\frac{Q_c(\text{Sweet gas}) + Q(\text{reactor}) + Q_c(H_2S)}{\sum Q} = \frac{\text{Btu}}{\sum Q} \quad (37)$$

Heating value of unconverted carbon in char:

$$\frac{173,934 \times n_o(C) \times [(1-\gamma)/\gamma]}{\Delta H_c(C)} = \frac{\text{Btu}}{Q_c(\text{Char})} \quad (38)$$

Miscellaneous

$$n_o(H_2, fc) - n_o(S) = n_2(H_2, n, fg) \quad (41)$$

$$n_2(H_2O) + n_2(H_2O_d) = n_{1,2}(H_2O) \quad (42)$$

Basis: 100 lb coal, with moisture

Estimation of Steam Generation

Heat addition to reactor as steam blast (ref'd to 70°F), Btu:

$$\frac{n_1(\text{stm}) \times 18 \times h(\text{stm})}{(12) \quad (5a)^*} = \frac{\text{Btu}}{Q_1(\text{stm})} \quad (50)$$

Heat addition to reactor as blast gas (N₂, O₂), Btu:

$$\left[\frac{n_1(\text{O}_2) + n_1(\text{N}_2)}{(14)} \right] \times 7.1(-70^\circ\text{F}) = \frac{\text{Btu}}{Q_o(\text{coal})} \quad (51)$$

Heat addition to reactor as warm coal from drying process:

$$\frac{(100 - W_{\text{evap}}) \times 0.25 \times (T_{\text{coal}} - 70)}{(100 \text{ lb} - W_{\text{evap}}) \times C'_p \times (T_{\text{coal}} - 70)} = \frac{\text{Btu}}{Q_o(\text{coal})} \quad (52)$$

Heat loss from reactor as hot slag:

$$\frac{W(\text{slag}) \times 0.25 \times (T_{\text{slag}} - 70)}{W(\text{slag}) \times C'_p \times (T_{\text{slag}} - 70)} = \frac{\text{Btu}}{Q(\text{slag})} \quad (53)$$

Heat loss from reactor as exit cool fuel gas:

$$\frac{\sum n_i \times C_p(\text{CFG}) \times (350 - 70)}{(\sum n_i) \times C_p(\text{CFG}) \times (350 - 70)} = \frac{\text{Btu}}{Q(\text{CFG})} \quad (54)$$

Total heat release to hot raw product gas:

$$\frac{Q(\text{rctr}) + Q_1(\text{stm}) + Q(\text{N}_2, \text{O}_2) + Q(\text{coal}) - Q(\text{char})}{Q(\text{HFG})} = \frac{\text{Btu}}{Q(\text{HFG})} \quad (55)$$

Temperature reached in reactor:

$$\frac{Q(\text{HFG}) / [C_p(\text{HFG}) \times \sum n_i]}{[C_p(\text{HFG}) \times \sum n_i]} + 70 = \frac{\text{Btu}}{T(\text{rctr})} \quad (56)$$

Case 1: This temperature should be at least 2800°F
 Cases 1, 2, & 3: See Item (10), Table 2-1.

Basis: 100 lb coal, with moisture

Generation of high pressure steam by waste heat recovery:

Case 1 only:

$$\left[\frac{Q(\text{HFG}) - Q(\text{CFG}) - Q_1(\text{Stm})}{(55) \quad (54)} \right] \div h(\text{stm, hp}) = \frac{\text{lb}}{W_3(\text{stm, hp})} \quad (57)$$

(5b), Table 2-1

Case 2 only:

$$\left[\frac{Q(\text{HFG}) - Q(\text{CFG})}{(55) \quad (54)} \right] \div h(\text{stm, hp}) = \frac{\text{lb}}{W_3(\text{stm, hp})} \quad (58)$$

(5b), Table 2-1

Case 3 only:

$$\left[\frac{Q(\text{HFG}) - Q(\text{CFG}) - Q_1(\text{N}_2, \text{O}_2)}{(55) \quad (54)} \right] \div h(\text{stm, hp}) = \frac{\text{lb}}{W_3(\text{stm, hp})} \quad (59)$$

ENERGY MANAGEMENT

Basis: 100 lb coal, with moisture

Compression Energy

Oxygen Plant Compressor (Oxygen Blast System Only):

Air is raised from 14.7 to 165 psia @ 70°F, and liquified.

$$\frac{21,296 \times}{(15a)*} \frac{21,296 \times n_1(O_2)}{21,296 \times n_1(O_2)} = \frac{\text{Btu}}{E_c(\text{AIR})} \quad (60)$$

Air Blast Compressor (Air Blast System Only):

Air feed is raised from 14.7 to 50 psia @ 70°F:

$$\frac{9,218 \times}{(15b)*} \frac{9,218 \times n_1(O_2)}{9,218 \times n_1(O_2)} = \frac{\text{Btu}}{E_c(\text{AIR})} \quad (61)$$

Raw Gas Compression, dry:

Raw Gas Compression from 35 to 165 psia @ 100°F:

$$\frac{2,676 \times}{(15c)*} \frac{2,676 \times [\sum n_i - n_2(H_2O)]}{2,676 \times [\sum n_i - n_2(H_2O)]} = \frac{\text{Btu}}{E_c(\text{FG})} \quad (63)$$

Recovered Energy

Fuel Gas Expansion: 135 to 40 psia:

$$\frac{1,354 \times}{(16)*} \frac{1,354 \times [\sum n_i - n_2(H_2O)]}{1,354 \times [\sum n_i - n_2(H_2O)]} = \frac{\text{Btu}}{E_x(\text{FG})} \quad (64)$$

Steam Expansion: 1,055 to 2.89, 165, 422 psia:

$$\frac{(\quad) \times [327 + 149 \times \quad] - 322 [\quad \times \quad + \quad]}{W(\text{stm, hp}) \times [327 + 149 \times \text{Rps}] - 332 [W(\text{stm, hp}) \times \text{Rps} + W_1(\text{stm})]} = \frac{\text{Btu}}{E_x(\text{stm})} \quad (65)$$

Where $W_1(\text{stm}) = 18 \times n_1(\text{stm})$ lb entered only for Cases 2 and 3.
(12)

* See Table 2-1.

PLANT SCALE PERFORMANCE
 COAL HANDLING AND GASIFICATION

Basis: 100 lb coal or 1.0 hour, as noted

Coal Rate, lb/hr

$$\frac{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb: } [\quad]}{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb: } [Q_c(\text{H}_2, \text{CO}) + Q_c(\text{H}_2\text{S})]} = \frac{\text{lb/hr}_{(70)}}{W(\text{Coal})}$$

Assemble previous results in 71_i or 72_i; compute entries for 73_i, 74_i, 76_i (See note).

Source Component Item Sub i	Basis: 100 lb Coal		Basis: 1 Hour's Operation			
	Lb	n _i Mols	N _i Mols	Mol/Fract.	Mol/wt.	Lb
	71 _i	72 _i	73 _i	74 _i	75 _i	76 _i
Feed						
(70) a Coal Blast	•100		•	--	NA	•
(13) b Stm					18.106	
(14) c O ₂					32.000	
(15) d N ₂					28.010	
e(SubΣ)	•		•	NA	NA	•
(12) f Quench	•		•	NA	18.016	•
g Total	•		•	NA	NA	•
Effluent						
(43) h Evapn Sour Gas	•		•	--	NA	•
(25) j CO					28.010	
(26) k CO ₂					44.010	
(28) l H ₂					2.016	
(29) m N ₂					28.016	
(30) n (H ₂ S)					34.076	
o Dry FG				1.000		
(31) p H ₂ O	•			--	18.106	
(33) q (HFG)	•		•	--		•
(9) r Char	•		•	--	NA	•
s Total	•		•	--	NA	•

Note: 73_i/72_i = 76_i/71_i = W(Coal)/100
 71_i/72_i = 76_i/73_i = 75_i

PLANT SCALE PERFORMANCE
ENERGY EFFECTS

Basis: 100 lb coal or 1.0 hour, as noted

Mechanical Energy			Basis: 100 lb Coal		Basis: 1 Hour's Operation	
Source	Component		Btu	kWhr	Btu	kWhr
Item	Sub.		80 _i	81 _i	82 _i	83 _i
Compression						
(60)	a	Oxy plant				
(61)	b	Air blast				
(63)	c	Raw fuel gas				
(13)*	d	Misc.				
	e	Total				
Recovery Expansion						
(64)	f	Fuel gas				
(65)	g	Steam				
	h	Total				
Net Demand						
(e,h)	j	Electric pwr.				
Heat Release Effects: Progressive combustion of coal to final products.						
(34)	k	Sweet gas				
(36)	l	H ₂ S				
(35)	m	Reactor				
(38)	n	Char				
	o	Total				
(11)	p	Coal				
Total Energy to Plant						
(j,p)	q					
Note: $82_i/80_i = 83_i/81_i = W(\text{Coal})/100$ $81_i/80_i = 83_i/82_i = 0.29281 \times 10^{-3}$						

*See Table 2-1.

PLANT COSTS

<u>Capital Costs</u>	<u>\$1000</u>
Oxygen/Air Plant:	(85)
$\frac{[(73_c + 73_d) / (N_k + N_l)]^{0.6}}{[(N_k^o + N_l^o)]^{0.6}} \times \frac{C_1^o}{C_1} =$	$\frac{C_1^o}{C_1}$
	(See Note)
Gasification Module:	
$\frac{[73_q / N_h]}{[N_h^o / N_h^o]} \times \frac{C_2^o}{C_2} =$	(86)
	(see note)
Compression/Expansion:	
$\frac{(73_o / N_f)}{(N_f / N_f^o)} \times \frac{C_3^o}{C_3} =$	(87)
	(see note)
Gas Treatment Module:	
$\frac{\{1 + a \times [W_o(s) - W_o^o(S)]\} \times \{1 - b \times \ln[e(SO_2) / e^o(SO_2)]\} \times C_4^o}{(17a)* (7) \quad (17b)* \quad (See Design Basis)} =$	(88)
	C_4

*See Table 2-1.

Note: Values for C^o , for the nominal cases, are in the Final Report, Appendix F.

Coal Preparation Module:	<u>\$1,000</u>	
$\left[\frac{\quad}{W(\text{Coal}) / W^{\circ}(\text{Coal})} \right]^{.5} \times \frac{\quad}{.5 \times C_5^{\circ}} =$	<u>C₅</u>	(89)
Utilities, Piping, Waste Disposal: constant		(90)
	<u>C₆</u>	
Direct Field Cost:		(91)
Sum: C ₁ + C ₂ + C ₃ + C ₄ + C ₅ + C ₆ =	<u>C₇</u>	
Total Capital Cost		(92)
$\frac{\quad \times (\quad)}{C_7 \times (C_8/C_7)} =$ (18)*	<u>C₈</u>	
<u>Operating Costs, Annual, Based on 90% Service Factor</u>		<u>\$1,000</u>
Coal @ W(Coal) lb/hr:		(96)
$\frac{(\quad / 2,000) \times (7,889 \text{ hr/yr})}{(W(\text{Coal}) / 2,000) \times (7,889 \text{ hr/yr})} =$ (\$/ton)	<u>0(coal)</u>	
Electric power @ E _D kW:		(97)
$\frac{(E_D) \times (7,889 \text{ hr/yr})}{(83g)} =$ (\$/kWhr)	<u>0(pwr)</u>	
Catalyst, Chemicals, from Nominal Case: Equipment, Supplies, Utilities Operating Personnel Maintenance Materials and Labor		(98)
From Report, Subtotal, 0 ⁰ (Misc) =	<u>0(Misc)</u>	

*See Table 2-1.

DISCOUNTED COSTS OF GAS PRODUCTION

Line Number	Cost Element	Differ- ential Inflation Rate	Project Year	Amount, Thousands of Dollars		Discount Factor	Discounted Cost, Thousands of Dollars
				One Time	Recurring		
(1)	First-Year Construction	+0	2		17%	0.867	
(2)	Second-Year Construction	+0	3		34%	0.788	
(3)	Third-Year Construction	+0	4		49%	0.717	
(4)	● Total Investment						●
(5)	Coal	+5	5-29			12.268	
(6)	Electricity	+6	5-29			14.057	
(7)	Operating Labor and Materials	+0	5-29			6.505	
(8)	● Total Operating Costs						● ●
(9)	● Total Project Costs						● ●
(10)	Fuel Oil Alternative	+8	5-29			18.631	
(11)	Energy Available over 25 years, billions of Btu						
(12)	Product Gas Unit Cost, \$/million Btu (line 9 divided by line 11)						
(13)	Fuel Oil Alternative Unit Cost, \$ million Btu (line 10 divided by line 11)						
(14)	Savings/Investment Ratio, SIR = (line 10 - line 8)/line 4						

WORKSHEET FOR PLANT ANALYSIS

DESIGN BASIS

Reactor Capacity:

Heating value of reactor output, sour, Btu/hr - 250×10^6

Emission of SO₂:

Product from combustion of fuel gas,
 lb SO₂/10⁶ Btu HHV (coal), _____ e(SO₂)

Ultimate Analysis Of Coal:

	% or lb per 100 lb coal
Carbon	_____ W(C)
Hydrogen	_____ W(H ₂)
Oxygen	_____ W(O ₂)
Nitrogen	_____ W(N ₂)
Sulfur	_____ W(S)
Moisture	_____ W(H ₂ O)
Ash	_____ W(Ash)
Total	100
Ash Softening Temperature =	_____ °F
Ash Melting Temperature =	_____ °F

Note: $W(\text{evap}) = W(\text{H}_2\text{O}) - W_o(\text{H}_2\text{O})$

REACTOR PERFORMANCE

Basis: 100 lb coal, with moisture

Carbon gasification See Table 2-1, items (11) and (12).

$$\text{Carbon conversion, expected fraction} \quad \gamma = \text{_____} \quad (1)$$

$$\text{Ratio CO/(CO + CO}_2\text{), expected value} \quad \alpha = \text{_____} \quad (2)$$

Feedstock and resulting char

$$\text{Carbon: } \frac{x}{W_o(C)} \times \frac{12}{\gamma} = \frac{\text{Mol}}{n_o(C)} \quad (3)$$

$$\text{Hydrogen: } \frac{1/2 - \quad /16}{W_o(H_2)/2 - W_o(O_2)/16} = \frac{\text{Mol}}{n_o(H_2,fc)} \quad (4)$$

$$\text{Oxygen: } \frac{1/32}{W_o(O_2)/32} = \frac{\text{Mol}}{n_o(O_2)} \quad (5)$$

$$\text{Nitrogen: } \frac{1/28}{W_o(N_2)/28} = \frac{\text{Mol}}{n_o(N_2)} \quad (6)$$

$$\text{Sulfur: } \frac{1/32}{W_o(S)/32} = \frac{\text{Mol}}{n_o(S)} \quad (7)$$

$$\text{Moisture: } \frac{1/18}{W_o(H_2O)} = \frac{\text{Mol}}{n_o(H_2O)} \quad (8)$$

$$\text{Char: } \frac{\quad + (\quad) \times \quad}{W_o(\text{Ash}) + (1-\gamma) \times W_o(C)} = \frac{\text{lb}}{W_o(\text{char})} \quad (9)$$

Heat of combustion @ carbon conversion γ , HHV' coal:

$$\frac{x(173,934) + \quad x(122,976) + \quad x(184,640)}{n_o(C) \times \Delta H_c(C) + n_o(H_2,fc) \times \Delta H_c(H_2) + n_o(S) \times \Delta H_c(S)} = \frac{\text{Btu}}{\text{HHV}'(\text{coal})} \quad (10)$$

($\Delta H_c(S) = \text{At. wt.} \times 5,770 \text{ Btu/lb}$)

Heat of combustion @ full conversion, HHV (coal)

$$\frac{\quad + \quad \times \quad \times 173,934}{\text{HHV}(\text{coal}) + [1-\gamma]/\gamma \times n_o(C) \times \Delta H_c(C)} = \frac{\text{Btu}}{\text{HHV}(\text{coal})} \quad (11)$$

Basis: 100 lb coal, with moisture

Blast

$$\text{Steam: } \frac{x}{R_{wc} \times n_o(C) - [n_o(H_2O) + 2N_o(O_2) + n_1(\text{Quench})]} = \frac{\text{Mol}}{n_1(\text{stm})} \quad (12)$$

$$\text{Quench: } \frac{x}{R_{qc} \times n_o(C)} = \frac{\text{Mol}}{n_1(\text{quench})} \quad (13)$$

$$\text{Oxygen: } \frac{x}{R_{oc} \times n_o(C)} = \frac{\text{Mol}}{n_1(O_2\text{blst})} \quad (14)$$

$$\text{Nitrogen: } \frac{[(R_{bc} - R_{oc}) \div R_{oc}] \times n_1(O_2\text{blst})}{(4)^* (1)^*} = \frac{\text{Mol}}{n_1(N_2\text{blst})} \quad (15)$$

Reactor Gases

$$\text{Carbon monoxide: } \frac{x}{\alpha \times n_o(C)} = \frac{\text{Mol}}{n_2(\text{CO})} \quad (25)$$

$$\text{Carbon dioxide: } \frac{x}{(1-\alpha) \times n_o(C)} = \frac{\text{Mol}}{n_2(\text{CO}_2)} \quad (26)$$

$$\text{Water decomposed: } \frac{(2 - \alpha)x}{(2 - \alpha) \times n_o(C) - 2xn_1(O_2\text{blst})} = \frac{\text{Mol}}{n_2(H_2O_d)} \quad (27)$$

$$\text{Hydrogen: } \frac{-n_o(H_2,fc) - n_o(S) + n(H_2O_d)}{(27)} = \frac{\text{Mol}}{n_2(H_2)} \quad (28)$$

$$\text{Nitrogen: } \frac{n_o(N_2) + n_1(N_2\text{blst})}{(27)} = \frac{\text{Mol}}{n_2(N_2)} \quad (29)$$

$$\text{Sulfur as hydrogen sulfide: } \frac{n_o(S)}{(27)} = \frac{\text{Mol}}{n_2(S)} \quad (30)$$

$$\text{Water Vapor: } \frac{n_o(H_2O) + n_1(\text{stm}) + n_1(\text{qnch}) + 2xn_o(O_2) - n_2(H_2O_d)}{(5) (27)} = \frac{\text{Mol}}{n_2(H_2O)} \quad (31)$$

Basis: 100 lb coal, with moisture

$$\text{Combustibles: } \frac{2x}{2n_o(C)} - \frac{2x}{2n_1(O_2 \text{ blst})} + \frac{x}{n_o(H_2, fc)} - \frac{x}{n_o(S)} = \frac{\text{Mol}}{N_2(\text{cmbsl})} \quad (32)$$

Total hot raw gas:

$$\frac{n_o(C)}{(41)} + \frac{n_2(H_2, N, fg)}{(42)} + \frac{n_{1,2}(H_2O)}{(42)} + \frac{n_2(N_2)}{(42)} + \frac{n_2(H_2S)}{(42)} = \frac{\text{Mol}}{\sum n_i} \quad (33)$$

Heat Effects

Heating value of fuel gas, excepting H₂S:

$$\frac{n_o(H_2, CO)}{(32)} \times \frac{122,157}{\Delta H_c(H_2, CO)} = \frac{\text{Btu}}{Q_c(\text{Sweet Gas})} \quad (34)$$

Heat release in reactor:

$$\frac{n_o(C) \times 173,934 - [n_o(C) - n_1(O_2)] \times [2 \times 122,157]}{(14) \quad (32)} = \frac{\text{Btu}}{Q(\text{reactor})} \quad (35)$$

Heat release in combustion of H₂S:

$$\frac{n_2(H_2S) \times 241,092}{\Delta H_c(H_2S)} = \frac{\text{Btu}}{Q_c(H_2S)} \quad (36)$$

Sum of heat release effects:

$$\frac{Q_c(\text{Sweet gas}) + Q(\text{reactor}) + Q_c(H_2S)}{\Sigma Q} = \frac{\text{Btu}}{\Sigma Q} \quad (37)$$

Heating value of unconverted carbon in char:

$$\frac{173,934 \times n_o(C) \times [(1-\gamma)/\gamma]}{\Delta H_c(C)} = \frac{\text{Btu}}{Q_c(\text{Char})} \quad (38)$$

Miscellaneous

$$n_o(H_2, fc) - n_o(S) = \text{_____} n_2(H_2, n, fg) \quad (41)$$

$$n_2(H_2O) + n_2(H_2O_d) = \text{_____} n_{1,2}(H_2O) \quad (42)$$

(27)

Basis: 100 lb coal, with moisture

Estimation of Steam Generation

Heat addition to reactor as steam blast (ref'd to 70°F), Btu:

$$\frac{n_1(\text{stm}) \times 18 \times h(\text{stm})}{(12) \quad (5a)^*} = \frac{\text{Btu}}{Q_1(\text{stm})} \quad (50)$$

Heat addition to reactor as blast gas (N₂, O₂), Btu:

$$\frac{[n_1(\text{O}_2) + n_1(\text{N}_2)] \times 7.1(-70^\circ\text{F})}{(14) \quad \times C_p(T_{\text{in}} - 70^\circ\text{F})} = \frac{\text{Btu}}{Q_o(\text{coal})} \quad (51)$$

Heat addition to reactor as warm coal from drying process:

$$\frac{(100 - W_{\text{evap}}) \times 0.25 \times (T_{\text{coal}} - 70)}{(100 \text{ lb} - W_{\text{evap}}) \times C'_p \times (T_{\text{coal}} - 70)} = \frac{\text{Btu}}{Q_o(\text{coal})} \quad (52)$$

Heat loss from reactor as hot slag:

$$\frac{W(\text{slag}) \times 0.25 \times (T_{\text{slag}} - 70)}{W(\text{slag}) \times C'_p \times (T_{\text{slag}} - 70)} = \frac{\text{Btu}}{Q(\text{slag})} \quad (53)$$

Heat loss from reactor as exit cool fuel gas:

$$\frac{(\Sigma n_i) \times C_p(\text{CFG}) \times (350 - 70)}{(\Sigma n_i) \times C_p(\text{CFG}) \times (350 - 70)} = \frac{\text{Btu}}{Q(\text{CFG})} \quad (54)$$

Total heat release to hot raw product gas:

$$\frac{Q(\text{rctr}) + Q_1(\text{stm}) + Q(\text{N}_2, \text{O}_2) + Q(\text{coal}) - Q(\text{char})}{Q(\text{HFG})} = \frac{\text{Btu}}{Q(\text{HFG})} \quad (55)$$

Temperature reached in reactor:

$$\frac{Q(\text{HFG}) / [C_p(\text{HFG}) \times \Sigma n_i] + 70}{[C_p(\text{HFG}) \times \Sigma n_i] + 70} = \frac{\text{Btu}}{T(\text{rctr})} \quad (56)$$

Case 1: This temperature should be at least 2800°F
 Cases 1, 2, & 3: See Item (10), Table 2-1.

Basis: 100 lb coal, with moisture

Generation of high pressure steam by waste heat recovery:

Case 1 only:

$$\left[\frac{\quad - \quad - \quad}{Q(\text{HFG}) - Q(\text{CFG}) - Q_1(\text{Stm})} \right] \div \frac{\quad}{h(\text{stm, hp})} = \frac{1 \text{ b}}{W_3(\text{stm, hp})} \quad (57)$$

(55) (54) (5b), Table 2-1

Case 2 only:

$$\left[\frac{\quad}{Q(\text{HFG}) - Q(\text{CFG})} \right] \div \frac{\quad}{h(\text{stm, hp})} = \frac{1 \text{ b}}{W_3(\text{stm, hp})} \quad (58)$$

(55) (54) (5b), Table 2-1

Case 3 only:

$$\left[\frac{\quad - \quad - \quad}{Q(\text{HFG}) - Q(\text{CFG}) - Q_1(\text{N}_2, \text{O}_2)} \right] \div \frac{\quad}{h(\text{stm, hp})} = \frac{\quad}{W_3(\text{stm, hp})} \quad (59)$$

ENERGY MANAGEMENT

Basis: 100 lb coal, with moisture

Compression Energy

Oxygen Plant Compressor (Oxygen Blast System Only):

Air is raised from 14.7 to 165 psia @ 70°F, and liquified.

$$\frac{21,296 \times}{21,296 \times n_1(O_2)} = \frac{\text{Btu}}{E_c(\text{AIR})} \quad (60)$$

(15a)*

Air Blast Compressor (Air Blast System Only):

Air feed is raised from 14.7 to 50 psia @ 70°F:

$$\frac{9,218 \times}{9,218 \times n_1(O_2)} = \frac{\text{Btu}}{E_c(\text{AIR})} \quad (61)$$

(15b)* (14)

Raw Gas Compression, dry:

Raw Gas Compression from 35 to 165 psia @ 100°F:

$$\frac{2,676 \times \left[\frac{-}{\sum n_i - n_2(H_2O)} \right]}{2,676 \times \left[\sum n_i - n_2(H_2O) \right]} = \frac{\text{Btu}}{E_c(\text{FG})} \quad (63)$$

(15c)* (33) (31)

Recovered Energy

Fuel Gas Expansion: 135 to 40 psia:

$$\frac{1,354 \times \left[\frac{-}{\sum n_i - n_2(H_2O)} \right]}{1,354 \times \left[\sum n_i - n_2(H_2O) \right]} = \frac{\text{Btu}}{E_x(\text{FG})} \quad (64)$$

(16)* (33) (31)

Steam Expansion: 1,055 to 2.89, 165, 422 psia:

$$\frac{\left(\frac{\quad}{W(\text{stm, hp})} \right) \times \left[327 + 149 \times \frac{\quad}{Rps} \right] - 322 \left[\frac{\quad}{W(\text{stm, hp})} \times \frac{\quad}{Rps} + \frac{\quad}{W_1(\text{stm})} \right]}{\left(\frac{\quad}{W(\text{stm, hp})} \right) \times \left[327 + 149 \times \frac{\quad}{Rps} \right] - 322 \left[\frac{\quad}{W(\text{stm, hp})} \times \frac{\quad}{Rps} + \frac{\quad}{W_1(\text{stm})} \right]} = \frac{\text{Btu}}{E_x(\text{stm})} \quad (65)$$

(14)*

Where $W_1(\text{stm}) = 18 \times n_1(\text{stm})$ lb entered only for Cases 2 and 3.
(12)

* See Table 2-1.

PLANT SCALE PERFORMANCE
 COAL HANDLING AND GASIFICATION

Basis: 100 lb coal or 1.0 hour, as noted

Coal Rate, lb/hr						
$\frac{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb: } [\quad]}{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb: } [Q_c(\text{H}_2, \text{CO}) + Q_c(\text{H}_2\text{S})]} = \frac{\text{lb/hr}_{(70)}}{W(\text{Coal})}$						
Assemble previous results in 71 _i or 72 _i ; compute entries for 73 _i , 74 _i , 76 _i (See note).						
Source Component Item Sub i	Basis: 100 lb Coal		Basis: 1 Hour's Operation			
	Lb	n _i Mols	N _i Mols	Mol/Fract.	Mol/wt.	Lb
	71 _i	72 _i	73 _i	74 _i	75 _i	76 _i
Feed						
(70) a Coal Blast	•100		•	--	NA	•
(13) b Stm				--	18.106	
(14) c O ₂					32.000	
(15) d N ₂					28.010	
e(SubΣ)	•		•	NA	NA	•
(12) f Quench	•		•	NA	18.016	•
g Total	•		•	NA	NA	•
Effluent						
(43) h Evapn Sour Gas	•		•	--	NA	•
(25) j CO					28.010	
(26) k CO ₂					44.010	
(28) l H ₂					2.016	
(29) m N ₂					28.016	
(30) n (H ₂ S)					34.076	
o Dry FG				1.000		
(31) p H ₂ O				--	18.106	
(33) q (HFG)	•		•	--		•
(9) r Char	•		•	--	NA	•
s Total	•		•	--	NA	•

Note: 73_i/72_i = 76_i/71_i = W(Coal)/100
 71_i/72_i = 76_i/73_i = 75_i

PLANT SCALE PERFORMANCE
ENERGY EFFECTS

Basis: 100 lb coal or 1.0 hour, as noted

Mechanical Energy			Basis: 100 lb Coal		Basis: 1 Hour's Operation	
Source	Component		Btu	kWhr	Btu	kWhr
Item	Sub.		80 _i	81 _i	82 _i	83 _i
Compression						
(60)	a	Oxy plant				
(61)	b	Air blast				
(63)	c	Raw fuel gas				
(13)*	d	Misc.				
	e	Total				
Recovery Expansion						
(64)	f	Fuel gas				
(65)	g	Steam				
	h	Total				
Net Demand						
(e,h)	j	Electric pwr.				
Heat Release Effects: Progressive combustion of coal to final products.						
(34)	k	Sweet gas				
(36)	l	H ₂ S				
(35)	m	Reactor				
(38)	n	Char				
	o	Total				
(11)	p	Coal				
Total Energy to Plant						
(j,p)	q					
Note: $82_i/80_i = 83_i/81_i = W(\text{Coal})/100$ $81_i/80_i = 83_i/82_i = 0.29281 \times 10^{-3}$						

*See Table 2-1.

PLANT COSTS

<u>Capital Costs</u>	<u>\$1000</u>
Oxygen/Air Plant:	(85)
$\frac{\left[\frac{(N_k + N_l)}{(N_k^o + N_l^o)} \right]^{0.6}}{\left[\frac{(N_k + N_l)}{(N_k^o + N_l^o)} \right]^{0.6}} \times \frac{C_1^o}{C_1} =$ <p style="margin-left: 40px;">(73_c) (73_d) (See Note)</p>	<hr style="width: 100px; margin: 0 auto;"/>
Gasification Module:	(86)
$\left[\frac{N_h}{N_h^o} \right] \times \frac{C_2^o}{C_2} =$ <p style="margin-left: 40px;">(73_q) (see note)</p>	<hr style="width: 100px; margin: 0 auto;"/>
Compression/Expansion:	(87)
$\left(\frac{N_f}{N_f^o} \right) \times \frac{C_3^o}{C_3} =$ <p style="margin-left: 40px;">(73_o) (see note)</p>	<hr style="width: 100px; margin: 0 auto;"/>
Gas Treatment Module:	(88)
$\frac{\{1 + a \times [W_o(s) - W_o^o(S)]\} \times \{1 - b \times \ln[e(SO_2)/e^o(SO_2)]\} \times C_4^o}{(17a)* (7) \quad (17b)* \quad (See Design Basis)} =$	<hr style="width: 100px; margin: 0 auto;"/>
	C_4

*See Table 2-1.

Note: Values for C^o, for the nominal cases, are in the Final Report, Appendix F.

Coal Preparation Module:	<u>\$1,000</u>	
$\left[\frac{\quad}{W(\text{Coal}) / W^{\circ}(\text{Coal})} \right]^{.5} \times \frac{\quad}{.5 \times C_5^{\circ}} =$	<u> </u>	(89)
Utilities, Piping, Waste Disposal: constant	<u> </u>	(90)
	<u> </u>	C_5
Direct Field Cost:	<u> </u>	(91)
Sum: $C_1 + C_2 + C_3 + C_4 + C_5 + C_6 =$	<u> </u>	(92)
Total Capital Cost	<u> </u>	(93)
$\frac{\quad \times (\quad)}{C_7 \times (C_8/C_7)} =$ (18)*	<u> </u>	C_6
<u>Operating Costs, Annual, Based on 90% Service Factor</u>	<u>\$1,000</u>	
Coal @ $W(\text{Coal})$ lb/hr:		(96)
$\frac{(\quad / 2,000) \times (7,889 \text{ hr/yr})}{(W(\text{Coal}) / 2,000) \times (7,889 \text{ hr/yr})} = \frac{\quad}{(\$/\text{ton})}$	<u> </u>	$O(\text{coal})$
Electric power @ E_D kW:		(97)
$\frac{(E_D) \times (7,889 \text{ hr/yr})}{(83g)} = \frac{\quad}{(\$/\text{kWhr})}$	<u> </u>	$O(\text{pwr})$
Catalyst, Chemicals, from Nominal Case: Equipment, Supplies, Utilities Operating Personnel Maintenance Materials and Labor		(98)
From Report, Subtotal, $O^{\circ}(\text{Misc}) =$	<u> </u>	$O(\text{Misc})$

*See Table 2-1.

DISCOUNTED COSTS OF GAS PRODUCTION

Line Number	Cost Element	Differential Inflation Rate	Project Year	Amount, Thousands of Dollars		Discount Factor	Discounted Cost, Thousands of Dollars
				One Time	Recurring		
(1)	First-Year Construction	+0	2		17%	0.867	
(2)	Second-Year Construction	+0	3		34%	0.788	
(3)	Third-Year Construction	+0	4		49%	0.717	
(4)	● Total Investment						●
(5)	Coal	+5	5-29			12.268	
(6)	Electricity	+6	5-29			14.057	
(7)	Operating Labor and Materials	+0	5-29			6.505	
(8)	● Total Operating Costs						● ●
(9)	● Total Project Costs						● ●
(10)	Fuel Oil Alternative	+8	5-29			18.631	
(11)	Energy Available over 25 years, billions of Btu						
(12)	Product Gas Unit Cost, \$/million Btu (line 9 divided by line 11)						
(13)	Fuel Oil Alternative Unit Cost, \$ million Btu (line 10 divided by line 11)						
(14)	Savings/Investment Ratio, SIR = (line 10 - line 8)/line 4						

ESTIMATING PROCEDURE WORK SHEET FOR EFFECTS OF FUEL CHANGES
ON INDUSTRIAL SATURATED STEAM BOILER PERFORMANCE

STEP NO.	COMPUTATIONAL STEP	UNITS
1	BOILER TYPE, WT WATER TUBE FT FIRE TUBE	
2	STEAM TEMPERATURE	F
INITIAL CONDITIONS		
3	FUEL	
4	EXCESS AIR	%
5	FRACTION OF HEAT TRANSFERRED BY RADIATION	
6	FRACTION OF HEAT TRANSFERRED BY CONVECTION	
7	CHECK, (5) + (6) = 1.00	
8	COMBUSTION TEMPERATURE, F (3) AND (4)	F
9	COMBUSTION TEMPERATURE (8) + 460	R
10	TEMPERATURE FUNCTION, F (9)	
11	EMISSIVITY, F (3) AND (8)	
12	COMBUSTION PRODUCTS RATE, F (3) AND (4)	lb 10,000 BTU
NEW FUEL CONDITIONS		
13	FUEL GAS HIGH HEATING VALUE	BTU CU FT
14	EXCESS AIR	%
15	COMBUSTION TEMPERATURE, F (13) AND (14)	F
16	COMBUSTION TEMPERATURE, (15) + 460	R
17	TEMPERATURE FUNCTION, F (16)	
18	EMISSIVITY, F (13) AND (15)	
19	COMBUSTION PRODUCTS RATE, F (13) AND (14)	lb 10,000 BTU
20	RATIO OF PRODUCTS, (19) -- (12) ≤ 1.10	

STEP NO.	COMPUTATIONAL STEP	UNITS
21	EFFECTS ON RADIANT HEAT TRANSFER $\left(\frac{q_2}{q_1}\right)_c = \frac{(18)}{(17)} \times \frac{(10)}{(11)}$	
22	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_c = \frac{(21)}{(20)}$	
23	STACK TEMPERATURE, WATER TUBE = (2) + 100 FIRE TUBE = (2) + 200	F
24	$\Delta T_r = (5) \times ((8) - (23))$	F
25	$T_{th1} = (8) - (24)$	F
26	$T_{th2} = (15) - (22) \times (24)$	F
27	EFFECTS ON CONVECTIVE HEAT TRANSFER $\frac{T_{th2} - T_1}{T_{th1} - T_1} = \frac{(28) - (2)}{(25) - (2)}$	
28	$(U_2)_2 / (U_1)_1$ F 20	
29	$(U_1)_2 / (U_1)_1$ FOR FIRE TUBE	
30	U_2 F 28 U_2 / U_1	
31	WATER TUBE = (28) - (8.5) FIRE TUBE = (28) $\left(\frac{q_2}{q_1}\right)_c = (30) \times (27)$	
32	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_c = \frac{(31)}{(28)}$	

STEP NO.	COMPUTATIONAL STEP	UNITS
31	TOTAL PERFORMANCE EFFECTS	
	$\left(\frac{S_2}{A_1} \right)_{TOTAL} = (5 \times 21) + (6 \times 31)$	
	$\left(\frac{\Delta T_2}{\Delta T_1} \right)_{TOTAL} = (5 \times 22) + (6 \times 32)$	
	$\Delta T_{comb 1} = 8 - 70$	F
	$\Delta T_{comb 2} = 15 - 70$	F
	$\left(\frac{EFF. 2}{EFF. 1} \right)_{TOTAL} = \frac{34 \times 35}{35}$	

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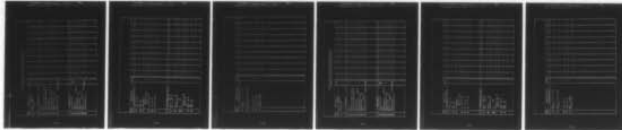
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ESTIMATING PROCEDURE WORK SHEET FOR EFFECTS OF FUEL CHANGES
ON INDUSTRIAL SATURATED STEAM BOILER PERFORMANCE

STEP NO.	COMPUTATIONAL STEP	UNITS
1	BOILER TYPE, WT WATER TUBE FT FIRE TUBE	
2	STEAM TEMPERATURE	F
3	INITIAL CONDITIONS	
4	FUEL	X
5	EXCESS AIR	
6	FRACTION OF HEAT TRANSFERRED BY RADIATION	
7	FRACTION OF HEAT TRANSFERRED BY CONVECTION	
8	CHECK (5) + (6) = 1.00	
9	COMBUSTION TEMPERATURE, F (3 AND 4)	F
10	COMBUSTION TEMPERATURE (8) + 460	R
11	TEMPERATURE FUNCTION, F (9)	
12	EMISSIVITY, F (3 AND 8)	
	COMBUSTION PRODUCTS RATE, F (3 AND 4)	lb 10,000 BTU
	NEW FUEL CONDITIONS	
13	FUEL GAS HIGH HEATING VALUE	BTU CU FT.
14	EXCESS AIR	X
15	COMBUSTION TEMPERATURE, F (13 AND 14)	F
16	COMBUSTION TEMPERATURE, (15) + 460	R
17	TEMPERATURE FUNCTION, F (16)	
18	EMISSIVITY, F (13 AND 15)	
19	COMBUSTION PRODUCTS RATE, F (13 AND 14)	lb 10,000 BTU
20	RATIO OF PRODUCTS (19) / (12) ≤ 1.10	

STEP NO.	COMPUTATIONAL STEP	UNITS
21	EFFECTS ON RADIANT HEAT TRANSFER $\left(\frac{q_2}{q_1}\right) = \frac{18}{11} \times \frac{17}{10}$	F
22	$\left(\frac{\Delta T_2}{\Delta T_1}\right) = \frac{21}{20}$	F
23	STACK TEMPERATURE. WATER TUBE = 2 + 100. FIRE TUBE = 2 + 200.	F
24	$\Delta T_1 = 5 \times (8 - 23)$	F
25	$T_{th1} = 8 - 24$	F
26	$T_{th2} = 15 - 22 \times 24$	F
27	EFFECTS ON CONVECTIVE HEAT TRANSFER $\frac{T_{th2} - T_2}{T_{th1} - T_1} = \frac{26 - 2}{25 - 1}$	
28	$(u_2)_2 / (u_1)_1$ F 20	
29	$(u)_2 / (u)_1$, FOR FIRE TUBE	
30	u_2 F 20	
31	u_2 / u_1	
32	WATER TUBE = 29 - 6.5	
33	FIRE TUBE = 20	
34	$\left(\frac{q_2}{q_1}\right)_c = 30 = 27$	
35	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_c = \frac{31}{28}$	

STEP NO.	COMPUTATIONAL STEP	UNITS
33	TOTAL PERFORMANCE EFFECTS $\left(\frac{92}{91} \right)_{TOTAL} = (5) \times (21) + (6) \times (31)$	
34	$\left(\frac{\Delta T_2}{\Delta T_1} \right)_{TOTAL} = (5) \times (22) + (6) \times (32)$	
35	$\Delta T_{comb 1} = 8 - 70$	F
36	$\Delta T_{comb 2} = 15 - 70$	F
37	$\left(\frac{EFF. 2}{EFF. 1} \right)_{TOTAL} = \frac{(34) \times (35)}{35}$	

STEP NO	COMPUTATIONAL STEP	UNITS
21	EFFECTS ON RADIANT HEAT TRANSFER $\left(\frac{q_2}{q_1}\right)_r = \frac{17}{11} \times \frac{10}{10}$	F
22	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_r = \frac{21}{20}$	F
23	STACK TEMPERATURE. WATER TUBE = 2 + 100 FIRE TUBE = 2 + 200	F
24	$\Delta T_1 = 5 \times (8 - 23)$	F
25	$T_{wb1} = 8 - 24$	F
26	$T_{wb2} = 15 - 22 \times 24$	F
27	EFFECTS ON CONVECTIVE HEAT TRANSFER $\frac{T_{wb2} - T_1}{T_{wb1} - T_1} = \frac{28 - 2}{25 - 2}$	
28	$(u_2)_2 / (u_1)_1 = F \cdot 20$	
29	$(u_2)_2 / (u_1)_1 \text{ FOR FIRE TUBE}$	
30	$u_2 = F \cdot 20$	
31	u_2 / u_1	
32	WATER TUBE = 28 - 8.5 FIRE TUBE = 28	
33	$\left(\frac{q_2}{q_1}\right)_c = 30 \times 27$	
34	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_c = \frac{31}{28}$	

STEP NO.	COMPUTATIONAL STEP	UNITS
33	$\left(\frac{92}{91} \right)_{TOTAL} = (5 + 21) + (6 + 31)$	
34	$\left(\frac{\Delta T_2}{\Delta T_1} \right)_{TOTAL} = (5 + 22) + (6 + 32)$	
35	$\Delta T_{comb 1} = 8 - 78$	F
36	$\Delta T_{comb 2} = 15 - 78$	F
37	$\left(\frac{EFF. 2}{EFF. 1} \right)_{TOTAL} = \frac{34 \times 35}{35}$	