4a.1.9.4 Current Density

In runs conducted at 1000 pounds per square inch (gage) and above 1800°F, the average current density of the immersed portion of the 1.5-inch electrode was between 3 and 4 A per square inch of surface area and only caused slight pitting of the center electrode surface. If sporadic fluidization occurred caused by a sudden pressure drop in the system or steam channeling through the bed, however, a short-circuit condition in any part of the bed could cause damage to the electrode. Such damage can be attributed to the significant difference in temperature between the center electrode and the bed, as noted in studies conducted at atmospheric pressure at Iowa State University.[7, 8]

4a.1.9.5 Magnetic "Flip Coil" Tests

The transient electrical characteristics (flicker) of the electro-fluid bed operation could be detrimental to other loads connected to the same source. To minimize the surges in current and power caused by the arcing mode of current flow and bubbling action of the fluidized-bed, a magnetic coil was installed in the reactor in an attempt to suppress this arcing condition. Current passing through a coil perpendicular to the current flow in the reactor would tend to rotate or flip the current path inthe char bed radially. The hoped-for effect would be to provide a longer current path and less pronounced overall transient effect on the power circuit as shown in Figure 4a.1-22.

The current fluctuations observed during the experiments were at frequencies of 2 to 6 cycles per second, and at magnitudes comparable to those observed in arc furnaces. This could add considerable cost to a commercial power supply.

Suppression of the "flicker" condition would result in:

- Reduced power supply costs
- Increased electrode life by minimizing destructive arcing
- By increasing the overall impedance of the system (the longer current path) a higher power density per center electrode current density could be obtained.

The "flip coil" consisted of 78 turns of 0.5-inch O.D. x 0.60-inch wall copper tubing encased in high-temperature epoxy insulation. The coil extended 45 inches and was inserted into the pressure shell of the reactor (21.5 inches I.D.). Figure 4a.1-23 depicts the installation. The set-up operated at 1 cycle per second frequency, and up to 6 kilowatt power output supply by a direct-current motor generator. The coil was internally water cooled.

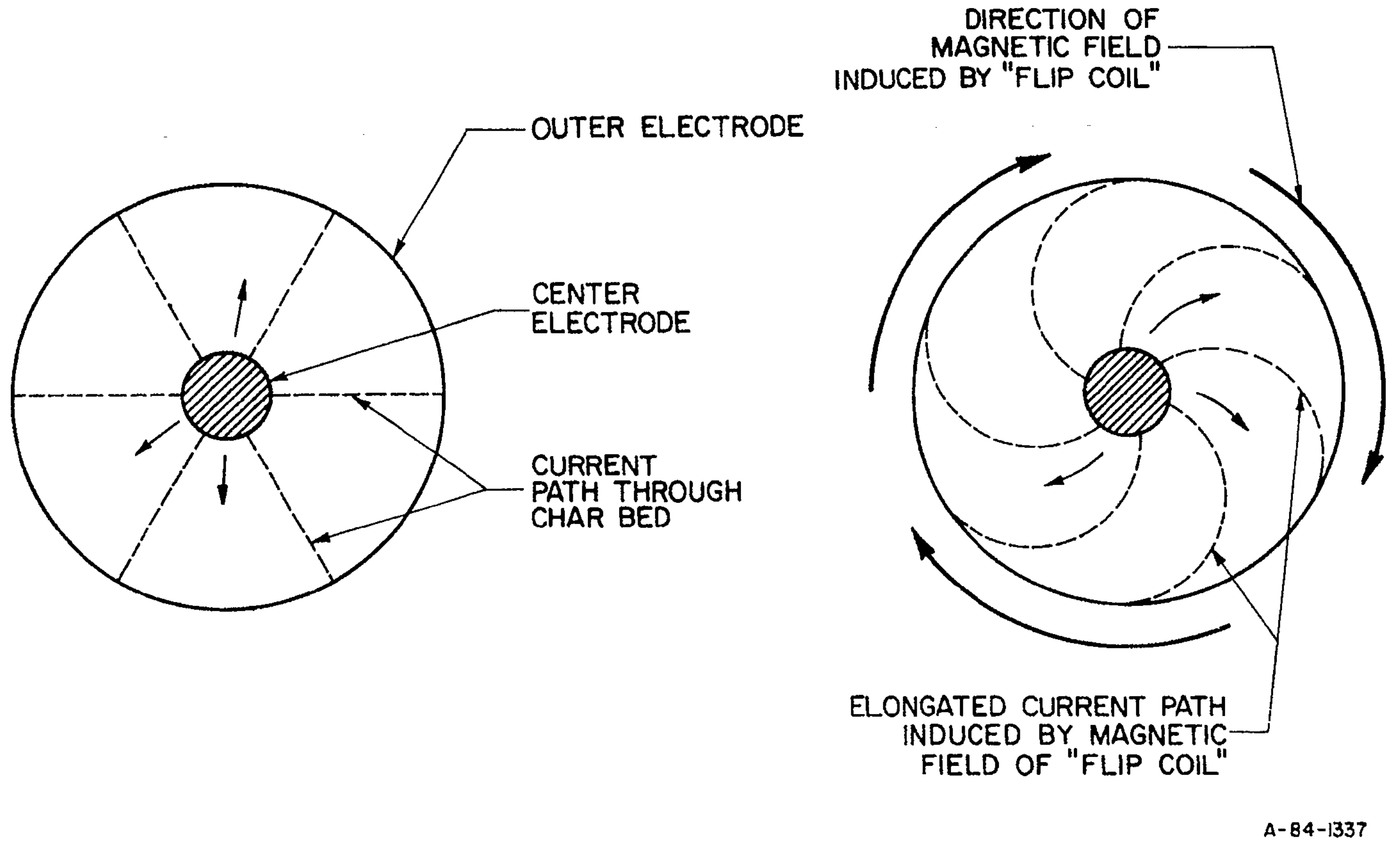


Figure 4a.1-22. EFFECT OF MAGNETIC FIELD OF "FLIP COIL" ON CURRENT OF ELECTROTHERMAL GASIFIER

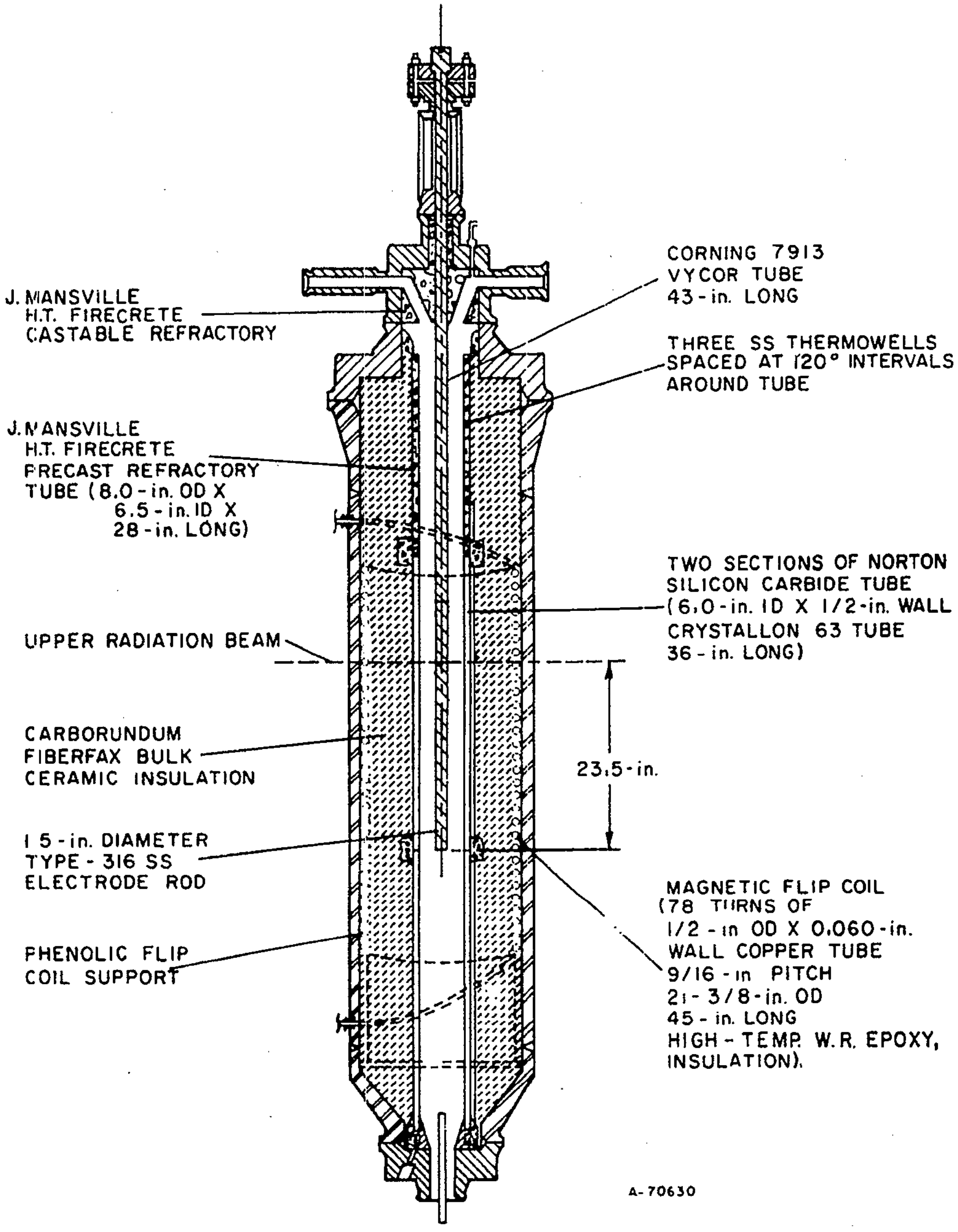


Figure 4a.1-23. CUTAWAY VIEW OF REACTOR VESSEL WITH "FLIP COIL" INSTALLED

Electrical characteristics observed during several tests with the "flip coil" showed that the coil did, in fact, reduce the current fluctuation frequencies in the gasifier, but that the variation in current magnitude was the same with or without the flip coil in operation.

Because of time constraints, further tests using higher flip coil currents were cancelled. In addition, HYGAS planners decided not to install a flip coil in the planned 2-megawatt unit due to the apparent fabrication and installation difficulties. The concept still remains valid, however, and for future units, methods should be investigated for locating the flip coil on the exterior of the bed, and for operations at much higher coil-current. The use of a cryogenic or superconducting coil might also be considered. The possibility still exists that this method could recude the resistance fluctuations of of the bed to a low level. This improvement would eliminate the need for special controls of the power supply, and would reduce capital costs of the power supply section of a commercial plant.

4a.1.9.6 Alternating versus Direct Current

The selection of direct current power to conduct the 6-inch electrothermal gasification program was based on development of advanced power systems at that time, such as Magnetohydrodynamic (MHD) generators, which produce direct current at high efficiency. Today, (mid-1974) the MHD concept looks particularly promising because the residue char from the electrothermal gasifier is an ideal fuel for this type of power generation where low hydrogen in the fuel is desired.

The use of an alternating current power supply for concentric electrodes in electrothermal gasification leads to a number of constraints, the most serious of which is the requirement for maintaining a balance in the three-phase system, particularly at high power levels. This means that at least three reactor beds must be used at all times with a fourth bed on standby to avoid unbalanced operation should one reactor system require a shutdown. Further, noise filtering of an alternating current system is much more complicated and costly than on a direct-current system.

Using a direct current power supply for electrothermal gasification provides a means for decoupling the alternating current power system from the load. It also is easier to control the rectifier output, to one or several beds, than to try to control three single-phase beds connected to a three-phase alternating current system.

4a.1.9.7 Polarity

During one test of the 6-inch diameter reactor, while at steady-state conditions, the polarity of the circuit was reversed and voltage-current data were taken for comparison with data obtained previously to observe whether symmetrical operation would be obtained. Figure 4a.1-24 illustrates the mean V-I characteristics observed during the period of reversed polarity. The curve as shown corresponds to approximately $I \sim V^{2,9}$ compared to the $I \sim V^{1,10}$ in other successful tests. Although the data show the characteristics to differ somewhat, it is not sufficiently extensive to conclude a symmetry in a reversed polarity or alternating current operation, and more tests should be conducted to determine alternating current symmetry in a concentric configuration.

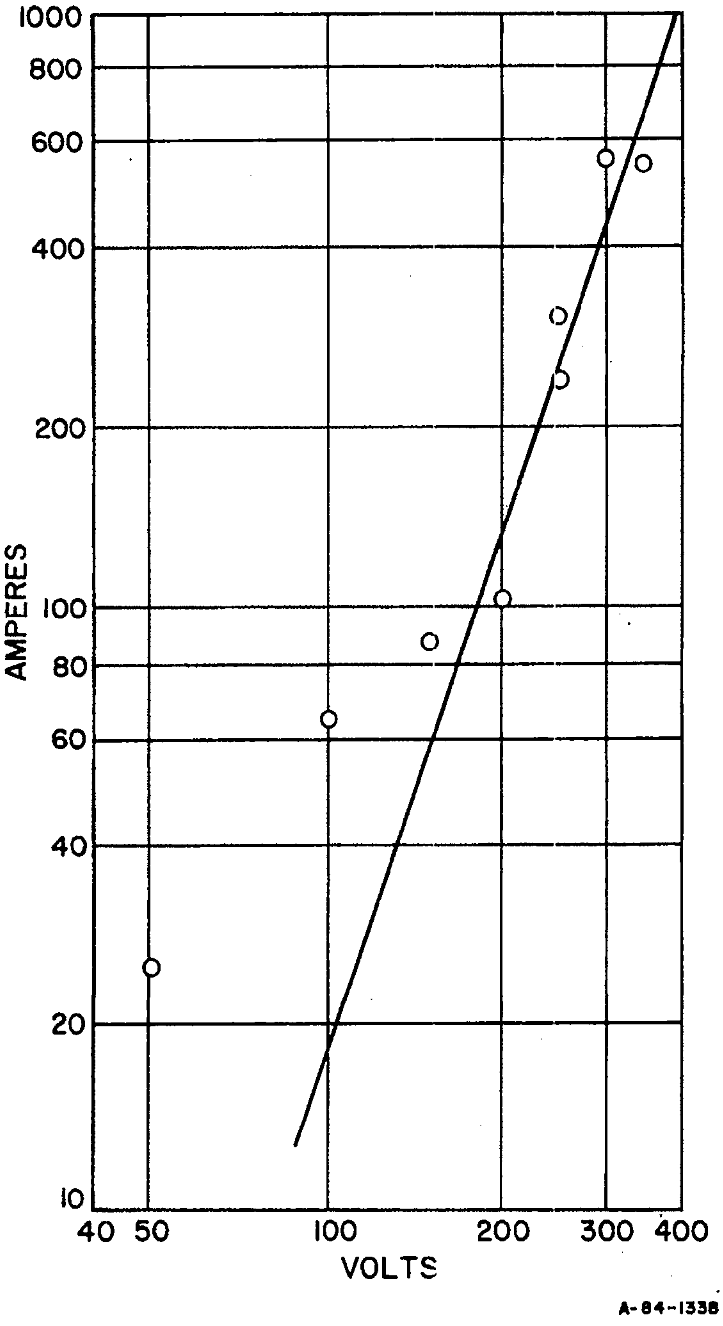


Figure 4a.1-24. MEAN V-I CHARACTERISTICS OF THE ELECTROTHERMAL GASIFIER BED – REVERSED POLARITY

The effect of reverse polarity was not pursued for two reasons: because of the successful operation of the 300 kilowatt electrothermal gasifier, using the center electrode as the high-potential terminal, and the reactor as the low potential, grounded terminal, and 2) because of the more complicated electrical isolation requirements should the reactor be used as the high-potential terminal.

4a.1.10 References Cited

1. Lee, B. S., Pyrcioch, E. J., and Schora, F. C., Paper presented at the 61st Annual A.I.Ch.E. Meeting, Los Angeles (December 1-5, 1968).
2. Reed, A. K., and Goldberger, W. M., Chem. Eng. Progr. Symp. Ser. 62, 71 (1966).
3. Johnson, J. S., Can.J. Chem. Eng. 39, 145 (1961).
4. Goldberger, W. M., Hanway, J. E., Jr., and Langston, B. G., Chem. Eng. Progr. 61, 63 (1965).
5. Iowa State University, 2nd Quarterly Progress Report on Contract No. 14-01-0001-479, Dept. of the Interior, Office of Coal Research, Washington, D.C. (1968).
6. Paquet, J. L., and Foulkes, P. B., Can. J. Chem. Eng. 43, 94 (1965).
7. Iowa State University, "Coal Processing by Electrofluidics," Phase I Report (May 11, 1965-April 1, 1967).
8. Ballain, M. D., and Pulsifer, A. H., Paper presented at the 62nd Annual Meeting of A.I.Ch.E., Washington, D.C., November 16-20, 1969.
9. Graham, W., and Harvey, E. A., Can. J. Chem. Eng. 43, 146 (1965).
10. Graham, W., and Harvey, E. A., Can. J. Chem. Eng. 44, 17 (1966).

NOMENCLATURE AND SUMMARY OF EQUATIONS FOR BED RESISTANCE

A = Area of bed
E = Electric field intensity
I = Current
J = Current density
k = Constant used in equation $\rho = kJ^n$
k' = Constant used in equation $V = k'I^{n+1}$
ℓ = Length of bed
n = Superscript related to the nonlinearity of the electrogasifier bed
r = Radius
V = Voltage
ρ = Resistivity
$\overline{\rho}$ = Mean or average resistivity

Subscripts

i = Inside
o = Outside
a-c = Alternating current
d-c = Direct current

APPENDIX 4a.1-A

Operating Results and Analyses

Table 4a.1–A1: Part 1. OPERATING CONDITIONS AND RESULTS OF ELECTROTHERMAL GASIFICATION

Run No.	EG-5		EG-6	
Period	1	2	1	2
OPERATING CONDITIONS				
Char Feed	Ireland Mine Hydrogasified Char			
Bed Height, in	62	62	62	62
Sieve Size, USS	−10, +80			
Reactor Pressure, lb/sq in gage	5.53	94.0	120.0	136.7
Avg Bed Temp, °F	1629	1710	1737	1780
Char Feed Rate, lb/hr	Batch	34.2	16.5	25.0
Steam Feed Rate, lb/hr	29.5	29.3	24.[illegible]	24.2
Steam Char Ratio, lb/lb	--	0.86	1.47	0.97
Char Residence Time, min	--	29.9	61.9	40.8
Nitrogen Purge Rate, std cu ft/hr	171.4	158.5	233.5	232.1
Product Gas Rate, std cu ft/hr	539.1	589.1	670.1	747.7
Bed P, in w.c.	40.8	42.5	30.6	25.5
Avg Voltage, V	150	150	182	199
Avg Current, A	100	150	130	140
Avg Power Input, kW	15.0	22.5	23.7	27.9
Avg Overall Resistance,	1.5	1.0	1.4	1.4
PRODUCT GAS PROPERTIES				
Composition, mole % (dry)				
Carbon Monoxide	20.8	23.0	43.3	37.4
Carbon Dioxide	17.0	15.0	12.2	5.4
Hydrogen	60.1	59.5	42.4	55.5
Methane	2.1	2.5	2.1	1.7
Total	100.0	100.0	100.0	100.0
Specific Gravity (Air = 1.0)	0.6572	0.6119	0.7159	0.5845
OPERATING RESULTS				
Product Gas Rate, std cu ft/hr	367.7	430.6	505.0	600.4
Product Gas Yield, std cu ft/lb	15.99*	12.63	30.61	24.02
Carbon Oxides Yield, std cu ft/lb	6.05*	3.51	12.79	8.24
Hydrogen Yield, std cu ft/lb	9.61	5.48	9.76	10.71
Residue, lb/lb char fed	0.817*	0.824	0.440	0.662
Liquid Products, lb/hr	19.97	18.61	[illegible]	16.48
Char Gasified, wt %	18.33*	17.6	56.0	33.8
Carbon Gasified, wt %	23.0	22.9	73.1	44.1
Steam Decomposed, lb/hr	9.53	10.70	10.20	13.72
Steam Conversion, wt % steam fed	32.3	36.5	46.3	56.7

*Based on 23.0–lb char in reactor during batch test

Table 4a.—A1: Part 2. OPERATING CONDITIONS AND RESULTS OF ELECTROTHERMAL GASIFICATION

Run No.	EG-10	EG-11	EG-12	EG-14	EG-15	EG-16
Char Feed	Ireland Mine Hydrogasified Char			FMC	FMC	Ireland Mine
Sieve Size, USS	−10+80	−10+80	−10+80	−10+80	−10+80	−10+80
Duration of Test, hr	5.3	3.2	5.5	3.[illegible]	2.8	1.5
Steady State Operating Period, min	135	140	165	60	30	85
Electrode Material	316 SS	316 SS	316 SS	316 SS	316 SS	316 SS
OPERATING CONDITIONS						
Bed Height, ft	3.75	3.75	3.75	3.75	3.75	3.75
Reactor Pressure, psig	206.3	232.4	262.5	201.0	203.8	54[illegible]
Reactor Temp, °F Inches From Bottom						
6	995	1275	1538	1610	1540	1360
12	1450	1670	1410	1690	1630	1200
18	1430	1720	1688	1715	1715	1550
24	1720	1733	1718	1745	1750	1610
30	1790	1779	1817	1767	1731	--
36	1820	1804	1801	1770	1787	1660
39	1816	1809	1825	1785	--	--
42	1890	1870	1868	1830	1880	1900
45	1858	1830	1832	1783	1835	1802
48	1860	1849	1878	1856	1845	1855
51	1860	1851	1929	--	--	
54	1860	1850	1856	1785	1840	1830
57	1860	1860	1873	1810	1846	1855
60	--	1878	1905	1865	--	--
72	1860	1860	1882	1530	1805	1620
96	1720	1840	1881	1530	1800	1568
104	1138	1583	1495	725	1400	1400
Average (top 3.75 ft)	1836	1823	1840	1792	1804	1787
(top 2.75 ft)	1847	1840	1861	1806	1824	1817
Steam Feed Rate, lb/hr	27.5	41.0	46.0	48.0	39.0	72.0
Steam Superficial Velocity, ft/s	0.21	0.28	0.28	0.37	0.30	0.22
Steam Residence Time, min	0.28	0.22	0.22	0.17	0.21	0.28
Steam/Char Feed Ratio, lb/lb	0.75	1.24	1.29	0.85	0.97	0.99
Char Feed Rate, lb/hr (dry)	36.6	33.2	35.6	56.5	40.0	73.0
Char Residence Time, min	26.5	24.9	25.3	21.5	33.0	13.9
Nitrogen Purge Rate, SCF/hr	155.4	152.5	184.6	195.5	213.0	174.0
Voltage, V	102.5	145.0	145.9	154.0	145.0	269.2
Current, A	175	229	232	270	256	271.0
Power Input, kW	17.9	33.2	33.9	41.6	37.2	72.9
Overall Resistance, ohm	0.55	0.63	0.63	0.57	0.57	0.99
OPERATING RESULTS						
Product Gas Rate, SCF/hr (dry)	610.2	771.9	1029.8	989.1	1144.0	2169.2
Product Gas Yield, SCF/lb (dry)	16.7	23.3	28.9	17.5	28.3	29.9
Hydrogen Yield, SCF/lb	9.2	12.4	15.4	9.6	16.4	16.6
Carbon Monoxide Yield, SCF/lb	4.9	7.0	8.4	4.8	7.8	7.4
Carbon Oxides Yield, SCF/lb	6.9	9.9	12.3	7.3	11.1	12.0
Residue, lb/lb[a]	0.77	0.60	0.59	--	--	--
Char Gasified, wt %	23.3	39.7	40.6	33.6	43.1	46.6
Carbon Gasified, wt %	30.5	43.6	48.4	32.8	49.2	53.4
Liquid Products, lb/hr	12.1	18.2	18.1	23.6	5.2	11.5
Steam Decomposed, lb/hr	15.4	22.8	27.9	24.4	33.8	60.5
Steam Conversion, wt %	56.1	55.5	60.6	50.9	86.8	84.0
Overall Material Balance, %	100.6	93.3	103.9	95.7	90.0	95.9
Carbon Balance, %	102.4	98.1	105.9	94.9	99.6	99.6
Hydrogen Balance, %	104.4	92.8	99.6	103.9	95.3	100.0
Oxygen Balance, %	99.3	93.3	98.3	99.1	81.0	90.4
PRODUCT GAS PROPERTIES						
Composition, mole % (dry)						
CO	29.6	29.9	29.1	27.7	27.5	24.9
CO_2	11.8	12.7	13.6	14.0	11.7	15.1
H_2	55.3	53.3	53.3	55.1	58.0	55.6
CH_4	3.3	4.1	4.0	3.2	2.8	4.4
Total	100.0	100.0	100.0	100.0	100.0	100.0
Specific Gravity (Air = 1.00)	--	--	--	0.536	0.499	0.533

[a] By ash balance.

Table 4a.1–A1: Part 3. OPERATING CONDITIONS AND RESULTS OF ELECTROTHERMAL GASIFICATION

Run No.	EG-17	EG-18	EG-19
Char Source	IGT	IGT	FMC
Sieve Size, USS	–10+80	–10+80	–10+80
Duration of Test	3.2	3.1	3.8
S. S. Operating Period, min	90	88	80
Electrode Material	316 SS	316 SS	316 SS
OPERATING CONDITIONS			
Bed Height, ft	3.75	2.75	2.75
Reactor Pressure, psig	528	521	536
Reactor Temp, °F			
Inches From Bottom			
6	870	1040	700
12	1092	890	900
18	1510	1735	1330
24	1540	1205	910
36	1650	1885	1780[a]
42	1816	1755	1000
45	1811	1855	1780[a]
48	1901	1055	840
54	1822	1740	1690[a]
57	1856	1800	1580
72	1604	1480	–
96	1570	1355	–
104	1286	1350	–
Average, (Top 3.75 ft)	1771	–	–
(Top 2.75 ft)	1809	1806	1750
Steam Feed Rate, lb/hr	67	67	72.0
Steam Superficial Velocity, ft/s	0.21	0.20	0.21
Steam Residence Time, min	0.28	0.22	0.22
Steam/Char Feed Ratio, lb/lb	1.00	1.40	1.26
Char Feed Rate, lb/hr (dry)	66.4	47.7	57.2
Char Residence Time, min	15.5	16.3	17.0
Nitrogen Purge Rate, SCFH	159	217	217
Voltage, V	254	320	354
Current, A	213	182	179
Power Input, kW	54	58	63.4
Overall Resistance, ohm	1.2	1.8	1.98
OPERATING RESULTS			
Product Gas Rate, SCF/hr (dry)	1399.0	1812.0	1738
Product Gas Yield, SCF/lb char (dry	21.1	38.0	30.4
Hydrogen Yield, SCF/lb	11.3	20.7	16.8
Carbon Monoxide Yield, SCF/lb	5.2	10.8	8.7
Carbon Oxides Yield, SCF/lb	8.7	15.8	12.5
Char Gasified, wt %	34.1	55.6	48.4
Carbon Gasified, wt %	40.1	75.8	58.9
Liquid Products, lb/hr	22.8	22.9	29.8
Steam Decomposed, lb/hr	42.5	44.1	42.2
Steam Conversion, wt %	66.0	65.9	58.7
Overall Material Balance, %	91.3	102.9	101.3
Carbon Balance, %	90.3	100.8	–
Hydrogen Balance, %	93.0	107.3	107.7
Oxygen Balance, %	91.5	100.5	100.6
PRODUCT GAS PROPERTIES			
Composition, mole % (dry)			
CO	24.6	28.4	28.7
CO_2	16.5	13.3	12.4
H_2	53.8	54.4	55.1
CH_4	5.0	3.8	3.8
H_2S	0.1	0.1	–
Total	100.0	100.0	100.0
Specific Gravity (Air = 1.0)	–	–	0.525

[a] Temperatures used in average variations of other bed temperatures attributed to channeling and settled bed areas.

Table 4a. 1–A1: Part 4. OPERATING CONDITIONS AND RESULTS OF ELECTROTHERMAL GASIFICATION

Run No.	EG-24	EG-26	EG-28	EG-29	EG-34
Feed Char	FMC	FMC	FMC	FMC	Indiana Hydrogasified Char
Sieve Size, USS	−10+80	−10+80	−10+80	−10+80	−10+80
Duration of Test, hr	2.57	2.28	2.87	3.50	5.6
Steady-State Operating Period, min	40	60	90	80	60
Electrode Material	316 SS	316 SS	316 SS	316 SS	316 SS
OPERATING CONDITIONS					
Bed Height	3.5	2.75	2.75	2.75	2.75
Reactor Pressure, psig	1040	1020	1024	1024	996
Reactor Temp, °F Inches From Bottom					
6	930	700	915	960	545
12	910	850	950	1090	--
18	1120	925	1195	1240	550
24	1230	1250	1525	1605	--
30	1390	1250	1470	1300	--
36	1460	1440	1600	1670	--
39	1470	1400	--	--	1400
42	1535	1450	1710	1170	1820
45	1650	1550	1670	1460	--
48	1680	1600	1700	--	1830
51	1680	1690	1700	1760	--
54	1770	1400	1715	1860	--
57	1780	1450	1710	1840	1870
60	1800	1650	1720	1840	1830
72	1845	1730	1770	1760	--
96	1875	1620	1780	1820	--
104	1865	1850	1770	1640	--
Average (top 3.5 ft)	1677	1570	--	--	--
(top 2.75 ft)	1723	1600	1725	1765	1845
Steam Feed Rate, lb/hr	145.0	135.0	155	145	125
Steam Residence Time, min	0.24	0.23	0.19	0.21	0.22
Steam Superficial Velocity, ft/s	0.22	0.22	0.24	0.22	0.21
Steam/Char Feed Ratio, lb/lb	1.46	1.01	1.23	0.88	1.06
Char Feed Rate, lb/hr (dry)	99.3	133.0	125.6	165.6	118.2
Char Residence Time, min	11.6	7.3	7.6	6.1	6.7
Nitrogen Purge Rate, SCF/hr	1802	1594	647	375	861
Voltage, V	235	222	181	258	361
Current, A	438	342	338	275	231
Power Input, kW	103	75.9	61.1	71.0	83.2
Overall Resistance, ohm	0.54	0.65	0.54	0.94	1.57
OPERATING RESULTS					
Product Gas Rate, SCF/hr (dry)	2447	1902	3228	3098	2160
Product Gas Yield, SCF/lb char (dry)	24.6	14.3	25.7	18.7	18.3
Hydrogen Yield, SCF/lb	11.7	7.0	12.0	9.0	9.1
Carbon Monoxide Yield, SCF/lb	7.8	5.0	6.0	4.4	3.3
Carbon Oxides Yield, SCF/lb	11.2	6.4	11.1	7.9	7.4
Char Gasified, wt %	37.6	25.4	49.2	37.4	34.9
Carbon Gasified, wt %	54.3	29.5	57.4	39.6	37.2
Liquid Products, lb/hr	78.5	86.6	63.6	57.4	58.7
Steam Decomposed, lb/hr	66.5	50.4	91.4	87.6	68.9
Steam Conversion, wt %	45.9	37.3	59.0	60.4	55.1
Overall Material Balance, %	102.5	97.8	99.4	96.7	96.8
Carbon Balance, %	111.6	100.0	99.3	95.4	95.2
Hydrogen Balance, %	100.0	100.0	100.0	100.0	100.0
Oxygen Balance, %	98.0	97.0	100.5	98.5	99.4
PRODUCT GAS PROPERTIES					
Composition, mole % (dry)					
CO	31.6	35.5	23.3	23.7	18.3
CO_2	13.7	9.0	19.8	18.4	22.1
H_2	47.6	49.1	46.6	48.0	49.5
CH_4	6.8	6.4	9.7	9.5	10.1
H_2S	0.3	--	0.6	0.4	--
Total	100.0	100.0	100.0	100.0	100.0
Specific Gravity (Air = 1.000)	0.584	0.549	0.619	0.599	0.603

Table 4a.1–A1: Part 5. OPERATING CONDITIONS AND RESULTS OF ELECTROTHERMAL GASIFICATION

Run No.	EG-37	EG-46	EG-47	EG-48
Feed Char	HV Bituminous Hydrogasified Char			
Sieve Size, USS	−10+80	−10+80	−10+80	−10+80
Duration of Test, hr	5.75	4.65	5.28	5.62
Steady-State Operating Period, min	60	90	80	90
Electrode Material	316 SS	316 SS	316 SS	316 SS
OPERATING CONDITIONS				
Bed Height, ft	2.75	2.75	2.75	2.75
Reactor Pressure, psig	959	1008	1004	1010
Reactor Temp, °F Inches From Bottom				
39	--	1930	1950	2035
42	1840	1805	1940	1850
45	--	1815	1935	1845
48	--	1945	1930	1900
51	--	1870	1960	1920
54	--	1890	1905	1900
57	--	1950	1880	1980
60	1780	1910	1825	--
63	1800	--	--	1880
72	--	--	--	1915
Average	1805	1889	1916	1914
Steam Feed Rate, lb/hr	142	104	140	121
Steam Residence Time, min	0.19	0.22	0.17	0.19
Steam Superficial Velocity, ft/s	0.24	0.20	0.28	0.24
Steam/Char Feed Ratio, lb/lb	1.08	0.78	1.22	1.45
Char Feed Rate (dry), lb/hr	131.5	132.6	114.4	83.2
Char Residence Time, min	6.2	5.3	6.1	8.8
Nitrogen Purge Rate, SCF/hr	640	682	558	856
Voltage, V	288	213	285	235
Current, A	331	344	221	286
Power Input, kW	95.3	73.3	63.0	67.2
Overall Resistance, ohm	0.87	0.62	1.3	0.82
OPERATING RESULTS				
Product Gas Rate (dry), SCF/hr	2271	2419	2294	2138
Product Gas Yield (dry), SCF/lb char	17.3	18.2	20.1	25.7
Hydrogen Yield, SCF/lb	8.4	8.5	10.6	13.1
Carbon Monoxide Yield, SCF/lb char	5.7	5.9	4.9	7.0
Carbon Oxides Yield, SCF/lb	7.4	8.1	8.0	9.7
Char Gasified, wt %	30.5	34.0	33.7	34.5
Carbon Gasified, wt %	36.3	41.9	33.0	47.0
Liquid Products, lb/hr	81.0	36.2	70.4	57.0
Steam Decomposed, lb/hr	61.0	67.8	69.6	64.0
Steam Conversion, wt %	43.0	65.2	49.7	52.9
Overall Material Balance, %	97.4	97.7	95.5	98.8
Carbon Balance %	99.0	101.0	98.0	109.3
Hydrogen Balance, %	100.0	100.0	100.0	100.0
Oxygen Balance, %	93.9	92.2	88.7	92.6
PRODUCT GAS PROPERTIES				
Composition, mole %				
CO	32.7	32.6	24.3	27.3
CO_2	9.9	11.9	15.5	13.9
H_2	48.7	46.5	53.0	51.1
CH_4	8.7	9.0	[illegible].2	7.7
H_2S	--	--	--	--
Total	100.0	100.0	100.0	100.0
Specific Gravity (Air = 1.00)	0.549	0.578	0.547	0.553

B7506 1557D

Table 4a.1–A1: Part 6. OPERATING CONDITIONS AND RESULTS OF ELECTROTHERMAL GASIFICATION

Run No.	EG-62	EG-70	EG-72
Feed Char	FMC	FMC	FMC
Sieve Size, USS	–10+80	–10+80	–10+80
Duration of Test, hr	4.7	4.7	4.[illegible]
Steady-State Operating Period, min	60	30	111
Electrode Material	316 SS	316 SS (inner) 430 SS (outer)	316 SS (inner) 430 SS (outer)
OPERATING CONDITIONS			
Bed Height, ft	2.75	2.5	2.5
Reactor Pressure, psig	985	988	986.7
Reactor Temperature, °F Inches From Bottom			
6	1060	1100	1500
12	1420	560	410
18	1370	480	410
24	1620	750	1500
30	1620	1300	1130
33	1540	1650	1700
36	1540	1650	1700
39	1780	1710	1620
42	1740	1710	1730
45	1760	1690	1730
48	--	1740	1630
51	1850	1740	1750
54	1810	1750	1750
57	1820	1750	1690
60	1820	1750	1690
63	1820	--	1690
72	1820	1660	1690
78	--	1630	1690
Average (top 2.5 ft)	1800[a]	1725	1700
Steam Feed Rate, lb/hr	117.0	153	99.5
Steam Residence Time, min	0.24	0.17	0.26
Steam Superficial Velocity, ft/s	0.19	0.24	0.16
Steam/Char Feed Ratio, lb/lb	2.1	1.2	0.86
Char Feed Rate (dry), lb/hr	55.3	129.4	114.9
Char Residence Time, min	17.4	7.4	8.4
N_2 Purge Rate, SCF/hr	--	375	1575.0
Voltage, V	165	319	220
Current, A	368	225	281
Power Input, kW	61	72	62
Overall Resistance, ohm	0.46	0.71	0.78
OPERATING RESULTS			
Product Gas Rate (dry), SCF/hr	1525	1783	1268
Product Gas Yield (dry), SCF/lb char	27.6	13.8	11.0
Hydrogen Yield, SCF/lb char	13.5	13.8	5.6
Carbon Monoxide Yield, SCF/lb char	7.4	3.9	2.8
Carbon Oxides Yield, SCF/lb char	11.9	5.6	4.5
Char Gasified, %	54.8	32.0	23.8
Carbon Gasified, %	57.0	26.0	20.6
Liquid Products, lb/hr	76.1	100.1	63.[illegible]
Steam Decomposed, lb/hr	40.0	52.0	37.8
Steam Conversion, %	34.5	34.0	38.0
Overall Material Balance, %	97.4	93.1	95.7
Carbon Balance, %	94.8	90.8	95.4
Hydrogen Balance, %	100.0	100.0	100.0
Oxygen Balance, %	98.7	94.5	97.[illegible]
PRODUCT GAS PROPERTIES			
Composition, mole %			
CO	27.1	28.5	25.3
CO_2	16.1	12.2	15.3
H_2	48.9	50.1	50.9
CH_4	7.7	9.2	8.3
H_2S	0.2	--	--
Total	100.0	100.0	100.0
Specific Gravity (Air = 1.00)	0.585	0.547	0.561

[a] Average Top 2.75 ft.

Table 4a. 1–A1: Part 7. OPERATING CONDITIONS AND RESULTS OF ELECTROTHERMAL GASIFICATION

Run No.	EG-75	EG-76	EG-77	EG-78
Feed Char	North Dakota Lignite			Montana Lignite
Sieve Size, USS	–10+80	–10+80	–10+80	–10+80
Duration of Test, hr	5	4.9	4.5	4.4
Steady-State Operating Period, min	40	112	50	120
Electrode Material				
Inner	316 SS	316 SS	316 SS	316 SS
Outer	430 SS	430 SS	430 SS	430 SS
OPERATING CONDITIONS				
Bed Height, ft	2.5	2.5	2.5	2.5
Reactor Pressure, psig	990	1016	1000	1000
Reactor Temperature, °F Inches From Bottom				
6	720	1250	1060	1150
13	400	660	700	740
24	460	530	540	530
32	580	1310	1405	1490
37	500	820	1210	1300
40	790	1680	1550	1600
43	790	1680	1550	1640
50	1250	1690	1670	1680
54	1250	1690	1670	1680
57	1330	1690	1670	1680
63	1570	1690	1670	1680
66	1660	1530	1680	1680
73	1680	1660	1670	1680
76	1725	1720	1670	1680
79	1725	1720	1670	1680
Average (top 2.5 ft)	1524	1664	1641	1665
Steam Feed Rate, lb/hr	117	115	127	134
Steam Residence Time, min	0.23	0.24	0.22	0.20
Steam Superficial Velocity, ft/s	0.18	0.17	0.19	0.21
Steam/Char Feed Ratio, lb/lb	1.20	0.76	1.40	0.93
Char Feed Rate (dry), lb/hr	97.3	151.1	83.3	144.3
Char Residence Time, min	7.87	5.40	9.67	8.2
Nitrogen Purge Rate, SCF/hr	1765	1757.2	1148.6	1278
Voltage, V	340	334	358	445
Current, A	212.5	287	200	183.3
Power Input, kW	72.2	96.0	69.8	81.4
Overall Resistance, ohms	1.60	1.16	2.03	2.43
OPERATING RESULTS				
Product Gas Rate (dry), SCF/hr	2157	3165	2509	2792
Product Gas Yield (dry), SCF/lb char	22.2	20.9	30.1	19.3
Hydrogen Yield, SCF/lb char	10.5	9.1	15.5	9.9
Carbon Monoxide Yield, SCF/lb char	7.9	8.1	8.9	5.2
Carbon Oxides Yield, SCF/lb char	10.7	11.2	12.7	8.2
Char Gasified, %	37.0	40.9	--[a]	27.0
Carbon Gasified, %	46.9	48.4	60.1	38.0
Liquid Products, lb/hr	63.0	25.8	--	48.8
Steam Decomposed, lb/hr	55.1	68.6	--[a]	77.7
Steam Conversion, %	47.1	59.7	60.3[b]	58.0
Overall Material Balance, %	103	96.3	--[a]	99.6
Carbon Balance, %	102	97.3	--[a]	108.0
Hydrogen Balance, %	100	100.0	--[a]	100.0
Oxygen Balance, %	106	97.8	--[a]	90.0
PRODUCT GAS PROPERTIES				
Composition, mole %				
CO	32.7	38.7	29.3	26.5
CO_2	13.8	10.0	12.8	15.6
H_2	47.3	43.5	51.6	51.3
CH_4	6.2	7.8	6.3	6.6
H_2S	--	--	--	--
Total	100.0	100.0	100.0	100.0
Specific Gravity (Air = 1.00)	0.593	0.599	0.548	0.576

[a] No Sample of residue available.

[b] Estimated, neglecting hydrogen in char.

Table 4a.1—A2: Part 1. CHEMICAL AND SCREEN ANALYSES OF ELECTROTHERMAL GASIFICATION FEEDS AND RESIDUES

Run No.	EG-5		EG-6		EG-10		EG-11		EG-12		EG-14	
Sample	Feed	Residue	Feed	Residue	Feed	Residue	Feed	Residue	Feed	Residue	Feed	Residue
Proximate Analysis, wt %			same as EG-5									
Moisture	1.0	0.2		0.0	1.1	0.3	1.5	1.3	1.5	0.3	2.2	0.3
Volatile Matter	2.8	2.6		2.1	3.1	3.1	5.3	3.4	4.3	3.9	5.0	2.6
Fixed Carbon	77.3	72.3		68.8	76.7	71.2	77.2	68.8	77.0	66.6	75.3	70.2
Ash	18.9	24.9		29.1	19.1	25.3	16.0	26.5	17.2	29.2	17.5	26.9
Total	100.0	100.0		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Ultimate Analysis, wt %												
Carbon	76.6	72.9		68.9	77.50	72.90	79.10	71.40	78.70	68.40	76.00	71.10
Hydrogen	1.17	0.49		0.64	0.79	0.56	1.41	0.63	0.99	0.69	0.92	0.55
Nitrogen	0.67	0.39		0.14	0.51	0.32	0.73	0.28	0.61	0.34	1.14	0.70
Oxygen	1.13	1.16		0.09	0.51	0.00	0.97	0.11	0.63	0.21	1.81	0.27
Sulfur	1.37	0.11		1.16	1.36	0.97	1.58	0.70	1.65	1.04	2.22	0.40
Ash	19.06	24.95		29.07	19.33	25.37	16.21	26.88	17.42	29.32	17.91	26.98
Total	100.00	100.00		100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Screen Analysis, USS, wt %												
+20	5.4	1.3		1.0	6.7	3.5	17.6	3.2	11.3	3.7	14.9	11.7
+30	17.9	9.3		9.1	16.5	13.8	15.3	3.2	12.2	11.8	9.6	14.5
+40	29.2	33.5		31.4	24.5	27.1	23.4	8.5	26.8	20.3	19.7	25.4
+60	27.2	35.8		36.9	30.5	32.6	26.4	22.3	29.7	30.4	27.7	29.3
+80	12.1	12.9		13.8	15.0	15.7	11.8	24.5	13.0	19.4	15.1	11.3
+100	3.9	3.1		3.3	4.3	4.2	2.6	8.5	3.5	6.9	4.9	2.5
+200	3.9	2.5		2.7	2.1	2.7	2.3	17.0	2.9	6.1	6.6	4.2
+325	0.2	0.6		0.6	0.2	0.2	0.3	3.2	0.3	0.7	0.0	0.0
−325	0.2	1.0		1.2	0.2	0.2	0.3	9.6	0.3	0.7	1.5	1.1
Total	100.0	100.0		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 4a.1–A2: Part 2. CHEMICAL AND SCREEN ANALYSES OF ELECTROTHERMAL GASIFICATION FEEDS AND RESIDUES

Run No.	EG-15		EG-16		EG-17		EG-18		EG-19		EG-24	
Sample	Feed	Residue	Feed	Residue	Feed	Residue	Feed	Residue	Feed	Residue**	Feed	Residue
Proximate Analysis, wt %												
Moisture	2.0	0.1	0.9	0.3	0.7	1.0	0.4	0.2	0.7		2.4	0.5
Volatile Matter	5.2	4.1	8.5	4.2	5.3	4.6	4.4	11.1	5.5		4.8	3.2
Fixed Carbon	76.2	66.1	75.0	66.1	74.3	61.6	71.4	35.0	72.6		75.5	68.0
Ash	16.6	29.7	15.6	29.4	19.7	32.8	23.8	53.7	21.2		17.3	28.3
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		100.0	100.0
Ultimate Analysis, wt %												
Carbon	76.70	68.00	78.90	68.20	76.90	64.30	72.10	40.60	73.50		75.00	68.90
Hydrogen	0.85	0.54	0.87	0.86	0.84	0.55	1.15	0.47	0.82		0.69	0.56
Nitrogen	1.09	0.33	0.39	0.34	0.46	0.29	0.61	0.60	0.88		1.13	0.56
Oxygen	2.34	0.58	3.86	0.00	0.80	1.07	0.81	3.27	1.70		3.02	0.30
Sulfur	2.09	0.81	0.25*	1.64	1.16	0.62	1.48	1.28	1.75		2.44	1.27
Ash	16.93	29.74	15.73	29.47	19.84	33.17	23.85	53.78	21.35		17.72	28.41
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00		100.00	100.00
Screen Analysis, USS, wt %												
+20	23.7	15.6	2.7	1.1	1.3	3.0	2.8	4.5	10.7		16.7	11.5
+30	15.7	11.0	9.5	6.0	4.6	9.1	5.7	5.1	13.0		17.3	15.6
+40	20.6	22.7	34.6	25.1	20.0	20.4	22.0	9.6	25.2		23.2	24.2
+60	23.1	28.7	35.3	38.4	39.8	30.0	37.0	18.5	30.7		25.9	28.8
+80	10.2	13.5	13.6	17.1	22.5	16.8	22.0	17.0	12.8		11.0	11.1
+100	2.4	3.9	3.5	4.0	6.2	5.6	6.0	7.8	2.8		2.8	2.9
+200	2.6	4.6	0.8	6.3	4.3	9.3	3.2	17.7	3.0		1.8	3.3
+325	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9		0.6	1.2
−325	1.7	0.0	0.0	2.0	1.3	5.8	1.3	19.8	0.9		0.7	1.4
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		100.0	100.0

*Discrepancy in sulfur content of feed and residue char (0.25 and 1.64) attributed to sample contamination.

**Unable to obtain representative sample; sample contaminated with metal from melted electrode.

Table 4a.1–A2: Part 3. CHEMICAL AND SCREEN ANALYSES OF ELECTROTHERMAL GASIFICATION FEEDS AND RESIDUES

Run No.	EG-26		EG-28		EG-29		EG-34		EG-37		EG-46	
Sample	Feed	Residue	Feed	Residue	Feed	Residue	Feed	Residue	Feed	Residue	Feed	Residue
Proximate Analysis, wt %												
Moisture	1.1	1.2	2.5	0.6	1.8	0.5	3.9	8.5	3.5	2.2	2.5	0.7
Volatile Matter	3.6	3.7	4.2	2.6	3.7	3.0	[illegible]	2.5	3.3	1.9	2.9	1.9
Fixed Carbon	79.7	72.2	[illegible]	61.6	77.3	68.7	75.5	64.0	74.9	69.2	73.5	65.4
Ash	15.6	22.9	17.6	35.2	17.2	27.8	17.1	25.0	18.3	26.7	21.1	32.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Ultimate Analysis, wt %												
Carbon	78.20	72.60	75.00	61.70	76.80	68.90	78.80	70.30	77.40	71.40	74.60	66.80
Hydrogen	0.95	0.75	1.06	0.66	1.12	0.78	1.13	0.71	1.04	0.44	1.42	0.56
Nitrogen	1.20	0.77	1.16	0.33	1.21	0.49	0.69	0.49	0.58	0.28	0.76	0.22
Oxygen	1.50	1.06	1.76	1.28	0.88	0.87	0.88	0.81	0.81	0.00	1.77	0.21
Sulfur	2.37	1.68	2.99	0.57	2.50	1.01	0.75	0.41	1.19	0.81	0.20	0.03
Ash	15.78	23.14	18.03	35.46	17.49	27.95	17.75	27.28	18.98	27.31	21.25	32.18
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.24	100.00	100.00
Screen Analysis, USS, wt %												
+20	15.8	15.6	14.6	6.7	14.0	8.7	5.3	7.0	7.2	2.3	[illegible]	[illegible]
+30	15.0	10.7	18.4	21.1	16.4	13.3	18.9	15.5	15.7	9.0	23.0	13.4
+40	22.1	21.6	24.0	27.6	21.5	19.9	26.9	[illegible]	[illegible]	24.5	23.9	[illegible]
+60	28.0	29.3	27.8	28.1	29.1	27.2	30.2	29.2	30.8	38.1	28.2	[illegible]
[illegible]	11.9	12.6	10.2	10.0	13.1	14.5	12.9	13.3	11.3	16.9	[illegible]	[illegible]
[illegible]	3.2	3.5	2.3	2.4	3.5	5.4	3.4	4.0	2.7	4.7	[illegible]	3.1
[illegible]	[illegible]	[illegible]	1.7	3.3	2.0	7.4	[illegible]	4.4	1.6	3.2	1.1	[illegible]
[illegible]	[illegible]	1.4	[illegible]	0.6	[illegible]	2.2	[illegible]	1.2	0.4	0.5	--	0.7
[illegible]	[illegible]	1.2	0.5	[illegible]	[illegible]	1.4	0.2	2.1	0.8	0.8	--	0.7
[illegible]tal	[illegible]	100.0	100.0	100	[illegible]	100.0	100.0	100.0	[illegible]	100.0	100.0	[illegible]

Table 4a.1–A2: Part 4. CHEMICAL AND SCREEN ANALYSES OF ELECTROTHERMAL GASIFICATION FEEDS AND RESIDUES

Run No.	EG-47		EG-48		EG-62		EG-70		EG-72		EG-75	
Sample	Feed	Residue	Feed	Residue	Feed	Residue	Feed	Residue	Feed	Residue	Feed	Residue
Proximate Analysis, wt %												
Moisture	1.9	0.9	1.2	7.4	5.4	0.9	0.7	6.4	0.7	1.9	1.8	1.6
Volatile Matter	2.2	2.3	2.5	1.5	4.9	1.3	2.8	2.4	2.8	2.1	7.7	10.5
Fixed Carbon	91.4	90.0	85.2	75.2	75.6	65.2	85.0	75.2	84.9	80.9	76.7	76.7
Ash	4.5	6.8	11.1	15.9	14.1	32.6	11.5	16.0	11.6	15.1	13.8	21.9
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	110.7
Ultimate Analysis, wt %												
Carbon	92.40	90.50	85.90	81.70	78.20	65.40	83.9	80.3	11.72	15.37	79.0	69.5
Hydrogen	0.81	0.81	1.02	0.93	0.99	0.48	0.84	0.48	83.6	82.0	1.18	0.71
Nitrogen	0.65	0.46	0.69	0.40	1.19	0.33	1.45	0.74	1.09	0.73	0.49	0.39
Oxygen	1.47	1.11	0.57	--	2.54	0.59	1.62	1.02	51	0.37	4.49	6.93
Sulfur	0.12	0.26	0.57	0.11	2.19	0.28	0.66	0.42	1.63	0.71	0.80	0.91
Ash	4.55	6.86	11.25	17.17	14.89	32.92	11.53	17.04	1.45	0.83	14.04	22.
Total	100.00	100.00	100.00	100.31	100.00	100.00	100.00	100.00	100.00	100.00	100.00	10[illegible]
Screen Analysis, USS, wt %												
+20	5.8	0.2	6.[illegible]	2.7	15.6	11.5	21.6	24.6	21.4	21.5	17.2	1.4
+30	19.3	0.4	16.3	17.1	23.0	24.2	16.4	21.0	16.8	18.3	22.6	[illegible]
+40	22.6	0.7	17.3	20.8	22.2	23.0	16.0	17.2	15.4	15.8	21.4	8.9
+60	32.4	4.6	35.5	32.3	26.7	25.6	24.7	21.8	24.6	22.9	24.2	29.0
+80	13.9	18.5	16.8	15.7	10.0	9.5	12.4	8.6	13.6	12.1	9.9	23.0
+100	3.5	13.3	4.1	4.9	1.9	3.0	4.4	3.3	4.9	4.9	3.5	12.3
+200	1.9	32.5	2.9	5.1	0.6	2.6	3.2	2.4	2.4	3.5	1.2	14.9
+325	0.2	9.0	0.1	0.7	0.0	0.3	0.6	0.5	0.4	0.5	--	2.9
−325	0.4	20.8	0.4	0.7	0.0	0.3	0.7	0.6	0.5	0.5	--	4.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.3

Table 4a.1–A2: Part 5. CHEMICAL AND SCREEN ANALYSES OF ELECTROTHERMAL GASIFICATION FEEDS AND RESIDUES

Run No.	EG-76		EG-77		EG-79	
Sample	Feed	Residue	Feed	Residue*	Feed	Residue
Proximate Analysis, wt %						
Moisture	2.7	15.5	8.5		3.8	9.2
Volatile Matter	8.2	11.2	8.6		7.3	10.1
Fixed Carbon	73.0	49.7	68.7		73.4	60.7
Ash	16.1	23.6	14.2	--	15.5	20.0
Total	100.0	100.0	100.0		100.0	100.0
Ultimate Analysis, wt %						
Carbon	77.5	64.2	77.0		77.9	74.1
Hydrogen	1.06	0.63	1.04		1.23	1.08
Nitrogen	0.38	0.23	0.47	--	0.41	0.39
Oxygen	4.48	5.97	4.94		4.02	1.59
Sulfur	0.64	1.02	1.02		0.37	0.81
Ash	16.58	27.95	15.53		16.07	22.03
Total	100.64	100.00	100.00		100.00	100.00
Screen Analysis, USS, wt%						
+20	5.7	1.7	3.6		4.3	3.9
+30	15.2	4.7	14.7		14.8	15.0
+40	28.3	12.8	32.4		23.8	24.8
+60	33.0	28.1	32.2		32.2	33.8
+80	11.9	20.1	11.6		15.4	16.2
+100	3.9	9.8	3.8		5.4	4.4
+200	1.6	12.9	1.3		3.8	1.6
+325	0.1	3.0	0.2		0.2	0.1
−325	0.3	6.8	0.2	--	0.1	0.2
Total	100.0	99.9	100.0		100.0	100.0

*No representative solid residue available.

PART 4a.2

Electrothermal/2.25 MW (30-Inch) Unit

TABLE OF CONTENTS, PART 4a.2

LIST OF FIGURES, PART 4a.2

LIST OF FIGURES, PART 4a.2
(Continued)

LIST OF TABLES, PART 4a.2

4a. 2. 0 Summary of Electrothermal/2. 25 MW (30-Inch) Unit

A summary of this work appears in section 4.0.

4a. 2. 1 Introduction

4a. 2. 1. 1 Process

Test results obtained in the 6-inch diameter process development unit proved the technical feasibility of electrothermal gasification at pressures of 1000 pounds per square inch, and reactor temperatures higher than 1900 °F. Operating conditions in the 6-inch unit were readily arranged so that the hydrogen requirements of the hydrogasifier were met or exceeded in all operating cases planned for study in the HYGAS process with lignite, bituminous and subbituminous hydrogasified chars. The desired synthesis gas yields and carbon gasification were consistently obtained at char residence times of 10 to 20 minutes, and at steam-to-char feed ratios of 1.0 to 1.5 pound per pound. Run data provided information necessary to size the reactor vessel and auxiliaries of a large-scale electrothermal gasification system for integration into the HYGAS plant.

Development of reliable operating techniques and analysis of the electrical characteristics led to the decision to apply the concentric configuration to the larger system. Also, familiarity with operation and favorable technical considerations led to the use of direct-current power supply. Heat requirements for bringing reactants to temperature, for the endothermic steam-carbon reaction, and estimated losses indicated that a 2. 25-megawatt power supply would be sufficient for the system.

4a. 2. 1. 2 Equipment

The primary consideration was to provide an adequate system for supplying the hydrogen requirements of the HYGAS pilot plant. The system would utilize spent char from the hydrogasifier to replace the steam reforming of methane that had been used for the early production of hydrogen.

The equipment design philosophy was based on a short-life pilot plant concept rather than on a more costly production-type plant design. Heat recovery and high efficiency features were not meant to be incorporated into the design, and only critical equipment required to maintain code, safety and practical operational standards were spared. Engineering standards and procedures for covering all portions of the design and construction were in accordance with those used in the HYGAS facility.

Where practical, efforts were also made to obtain equipment compatible with that installed previously for the initial operation of the HYGAS plant, in order to facilitate operation and maintenance of the integrated system.

4a. 2. 2 Basis for Design

4a. 2. 2. 1 Material Balance

Data acquired from studies performed in the 6-inch diameter process development unit were applied to a preliminary material balance depicting process requirements of:

- Maximum hydrogen to the hydrogasification reactor.

- Maximum steam flow to the electrothermal reactor.

- Maximum char feed from the hydrogasification section to the electrothermal reactor.

- Corresponding residue char to slurry.

Figure 4a. 2-1 illustrates the conditional material balance that was issued to the construction engineering firm for cost bids on the design and construction of the system.

4a. 2. 2. 2 Heat Requirements

The theoretical heat requirement excluding losses, corresponding to the material balance of Figure 4a. 2-1, is listed in Table 4a. 2-1. The 2.148-megawatt total corresponds to the most stringent requirements of the stream flows, but it is expected that run conditions will be such that the heat requirements will generally be less than 2.0 megawatts. For design purposes, the power requirement was set at 2.25 megawatt, including allowance for heat loss.

4a. 2. 2. 3 Operating Conditions

The 2.25-megawatt electrothermal gasification section was designed to be integrated into the HYGAS plant in two stages. In the first, the electrothermal reactor, operating at pressure, receives char from the hydrogasification reactor to allow continuous operation and the product gas is desuperheated, let down in pressure, quenched, and sent to the HYGAS flare for disposal. The char is discharged to the slurry system previously used by the HYGAS plant but rerouted to accept electrothermal char residue. The hydrogasifier will continue to operate with hydrogen supplied by the natural gas steam reforming plant. The block diagram in Figure 4a. 2-2 depicts the initial phase of operation.

In the second stage, Figure 4a. 2-3 after successful shakedown of the electrothermal system the product gas will be sent directly to the hydrogasifier, thus replacing the steam-reformer and completing the integration of the HYGAS process with a char-based hydrogen source.

The operating conditions selected to allow the detailed design of the system are as follows:

a) Design of the reactor and feed system for pressure of 1500 pounds per square inch (gage) and the reactor to be internally refractory lined and water-jacketed.

b) Maximum char input, 4000 pounds per hour at a bulk density of 25 pounds per cubic foot.

c) Maximum char discharge, 2500 pounds per hour at a bulk density of 20 pounds per cubic foot.

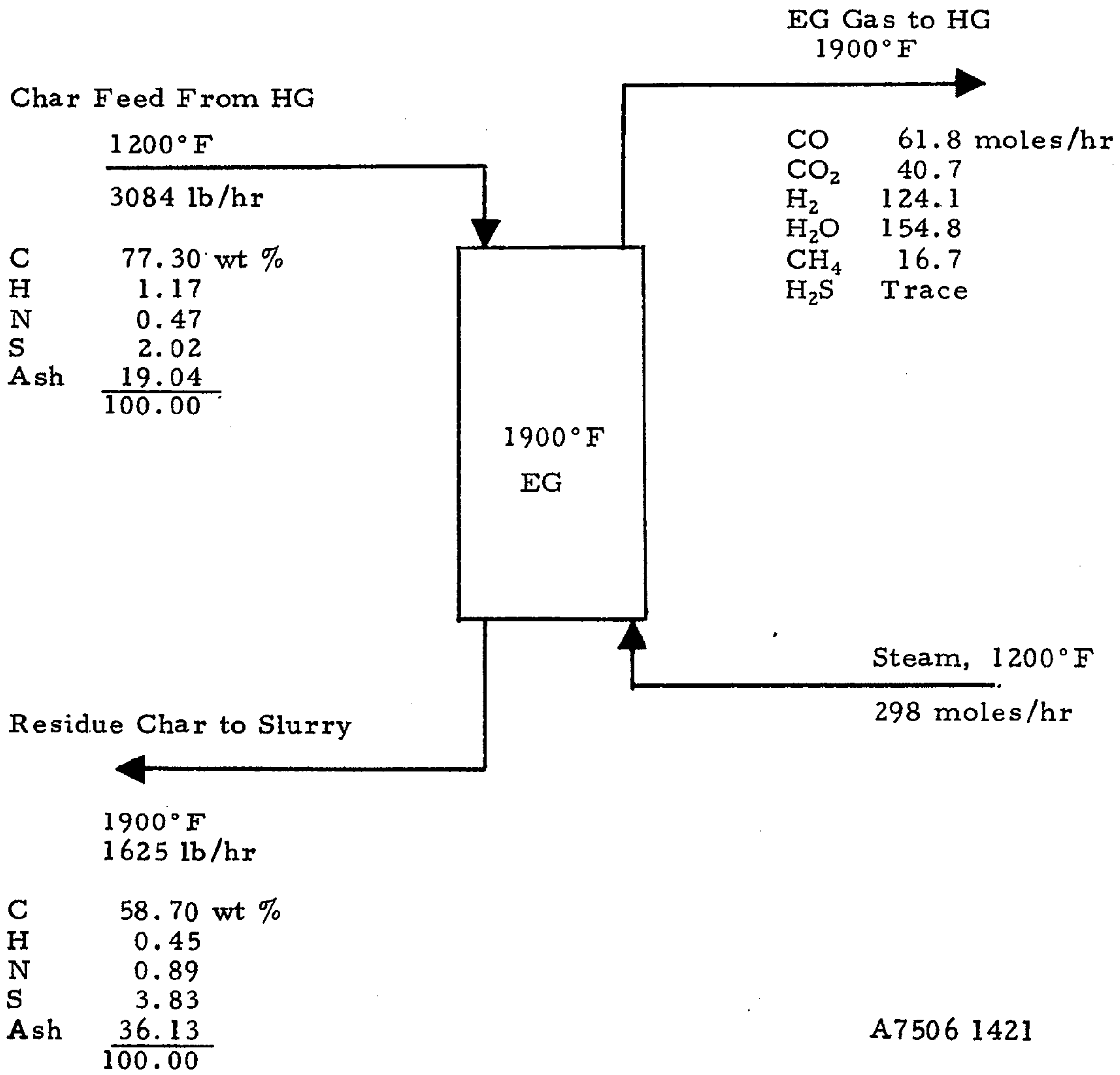


Figure 4a. 2-1. MATERIAL BALANCE USED FOR DESIGN CASE OF THE 2.25 MEGAWATT ELECTROTHERMAL GASIFICATION SYSTEM

Table 4a.2-1. THEORETICAL HEAT REQUIREMENT FOR DESIGN CASE OF THE 2.25 MEGAWATT ELECTROTHERMAL GASIFIER

Reactor Conditions: 1900°F
1000 lb/sq in
Figure 3 stream compositions

Steam in [1200°F → 1900°F]:

$$298\,\frac{\text{lb moles}}{\text{hr}} \times 18.02\,\frac{\text{lb}}{\text{lb mole}} \times (2000-1617)\,\frac{\text{Btu}}{\text{lb}} \qquad = +2.056,695 \text{ Btu}$$

Hydrogasified Char in [1250°F → 1900°F]:

$$3084\,\frac{\text{lb}}{\text{hr}} \times 0.37\,\frac{\text{Btu}}{\text{lb }^\circ\text{F}} \times (1900-1250) \qquad = +741,702 \text{ Btu}$$

Exit Char [1900-1250):

Assume Exchange of Sensible Heat With Incoming Steam@75%

$$75 \text{ x}.37\,\frac{\text{Btu}}{\text{lb}^\circ\text{F}} \times 1625\,\frac{\text{lb}}{\text{hr}} \times (1900-1250) \qquad = -293,109 \text{ Btu}$$

Heats of Reaction [1900°F]:

$C + H_2O \rightarrow CO + H_2$

$$+58,863\,\frac{\text{Btu}}{\text{lb mole}} \times 102.5 \text{ lb mole} \qquad = +6,033,458 \text{ Btu}$$

$CO + H_2O \rightarrow CO_2 + H_2$

$$-13,672\,\frac{\text{Btu}}{\text{lb mole}} \times 40.7 \text{ lb mole} \qquad = -556,450 \text{ Btu}$$

$C + 2H_2 \rightarrow CH_4$

$$-38,923\,\frac{\text{Btu}}{\text{lb mole}} \times 16.7 \text{ lb mole} \qquad = -650,014 \text{ Btu}$$

Total 7,332,282 Btu

$$\frac{7,332,282 \text{ Btu}}{3413\,\frac{\text{Btu}}{\text{kW}}} = \frac{2148 \text{ kW}}{1000\,\frac{\text{kW}}{\text{MW}}} = 2.148 \text{ MW}$$

A7506 1559

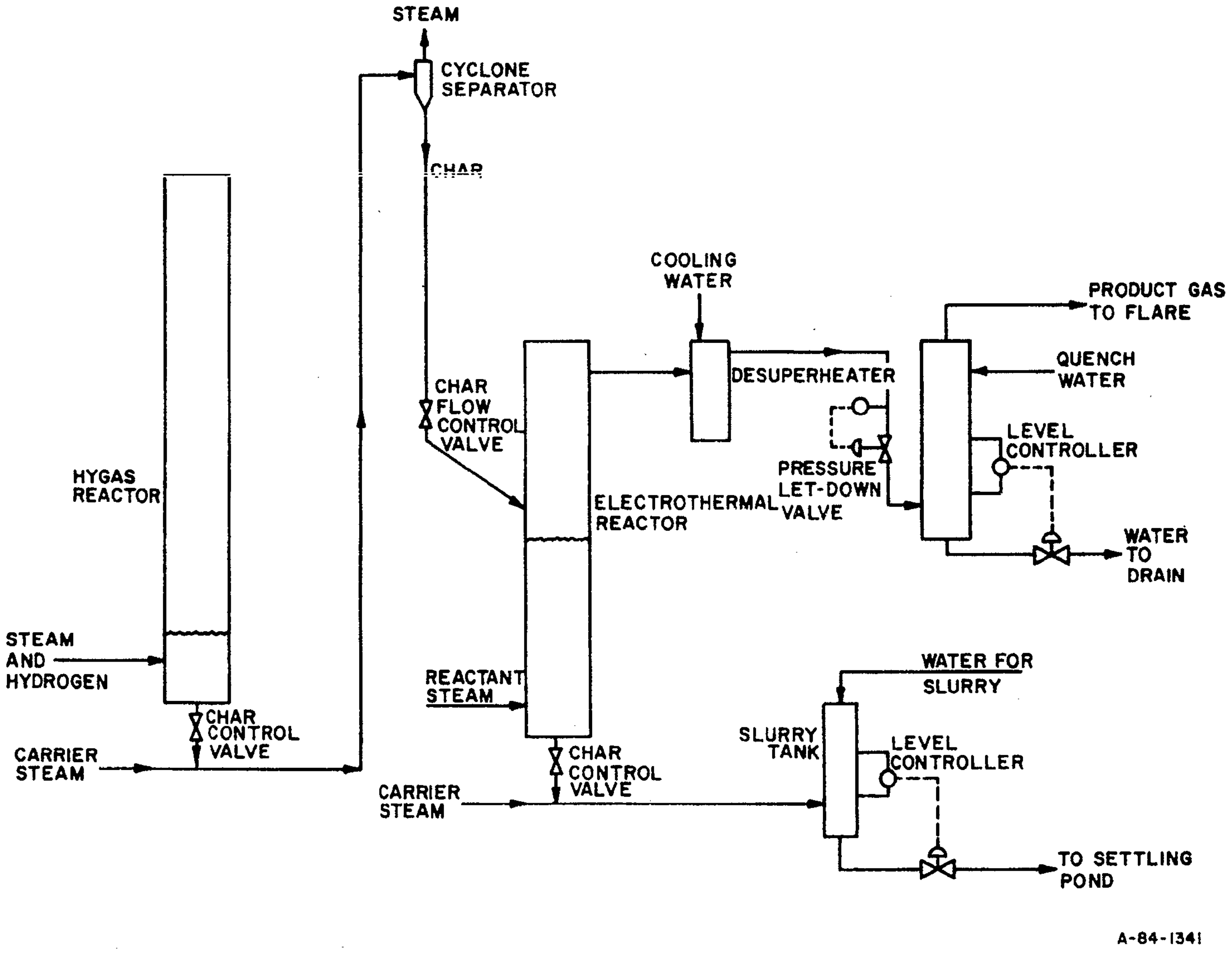


Figure 4a.2-2. BLOCK DIAGRAM OF INITIAL ELECTROTHERMAL-HYGAS OPERATION

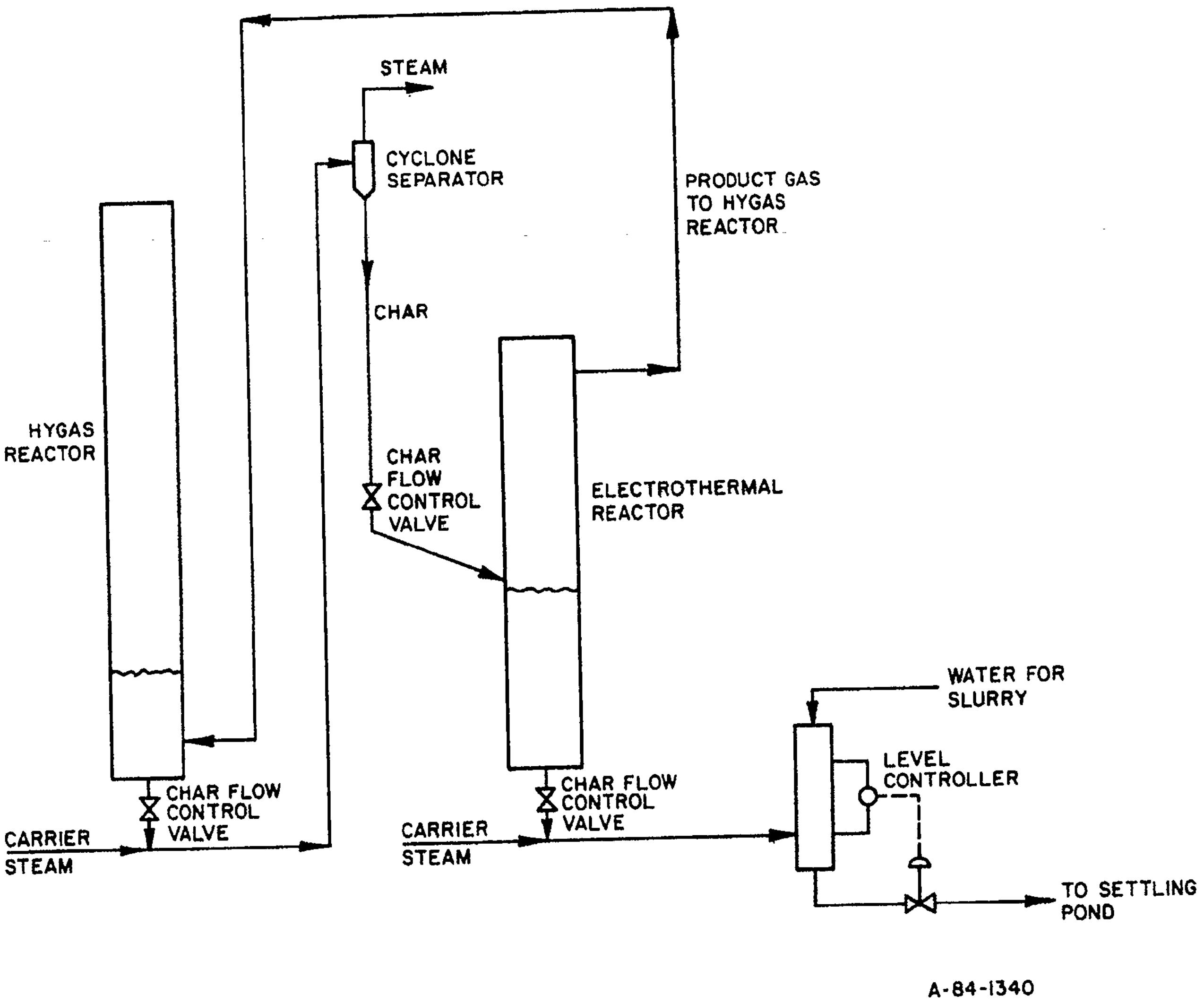


Figure 4a.2-3. BLOCK DIAGRAM OF INITIAL ELECTROTHERMAL-HYGAS OPERATION

d) Maximum char residence time, 45 minutes.

e) Maximum steam input, 300 moles per hour; minimum steam input, 200 moles per hour.

f) Maximum power requirement 2100 kilowatts, plus heat losses.

g) Minimum fluidization velocity, 0.2 feet per second at reactor conditions.

4a. 2. 3 Detailed Design

4a. 2. 3. 1 Reactor

A water-jacketed vessel was incorporated; the vessel included both high-temperature internal insulation and low-temperature external insulation, with the water pressure balanced at reaction system pressure. It is a double-walled vessel, similar in construction to the second stage, high temperature section of the hydrogasification reactor. The water temperature in the jacket is kept at the equilibrium temperature of steam, ~600 °F, at the design pressure of 1500 pounds per square inch.

This temperature is above the dewpoints of the fluids in the reactor and will prevent condensation of vapor at the refractory and shell wall interface, a condition favorable to refractory life and reliability. Also at 600 °F, an inner shell of carbon — 1/2 molybdenum steel is employed for hydrogen corrosion protection, and the outer pressure-containing shell is of carbon steel.

The electrothermal reactor operates at a higher temperature than the second-stage hydrogasifier (1900 + °F versus 1700 °F) thus increasing the possibility of steam generation in the reactor water jacket. Provisions were made in the jacket system to utilize the steam generated by combining it with the process steam going into the reactor, and returning the condensate to the reactor water jacket. This differs from the hydrogasifier system where steam generated in the jacket is refluxed back to the water jacket system. Figure 4a. 2-4 is a block diagram illustrating the water jacket system of the electrothermal reactor.

The reactor, designed in accordance with the specifications listed previously, resulted in the configuration shown in Figure 4a. 2-5. The outside diameter of the straight side is 6 feet 0.875 inch, and the overall length is 39 feet 7.0 inches. The bottom head is hemispherical and the top head is conically narrowed down to accept a 60 by 40 inches bolted-head closure and gasket.

The vessel was constructed in accordance with ASME (American Society of Mechanical Engineers) Boiler and Pressure Vessel Code, Section I, to meet power boiler specifications. A corrosion allowance of 0.125 inch thickness was applied to the inner shell wall. The outer pressure bearing shell was 3.435 inch thick as a minimum, and the inner shell was designed for 150 pounds per square inch pressure and was 1.25 inches thick. The water jacket annulus was a nominal 1.125-inch between the inner and outer

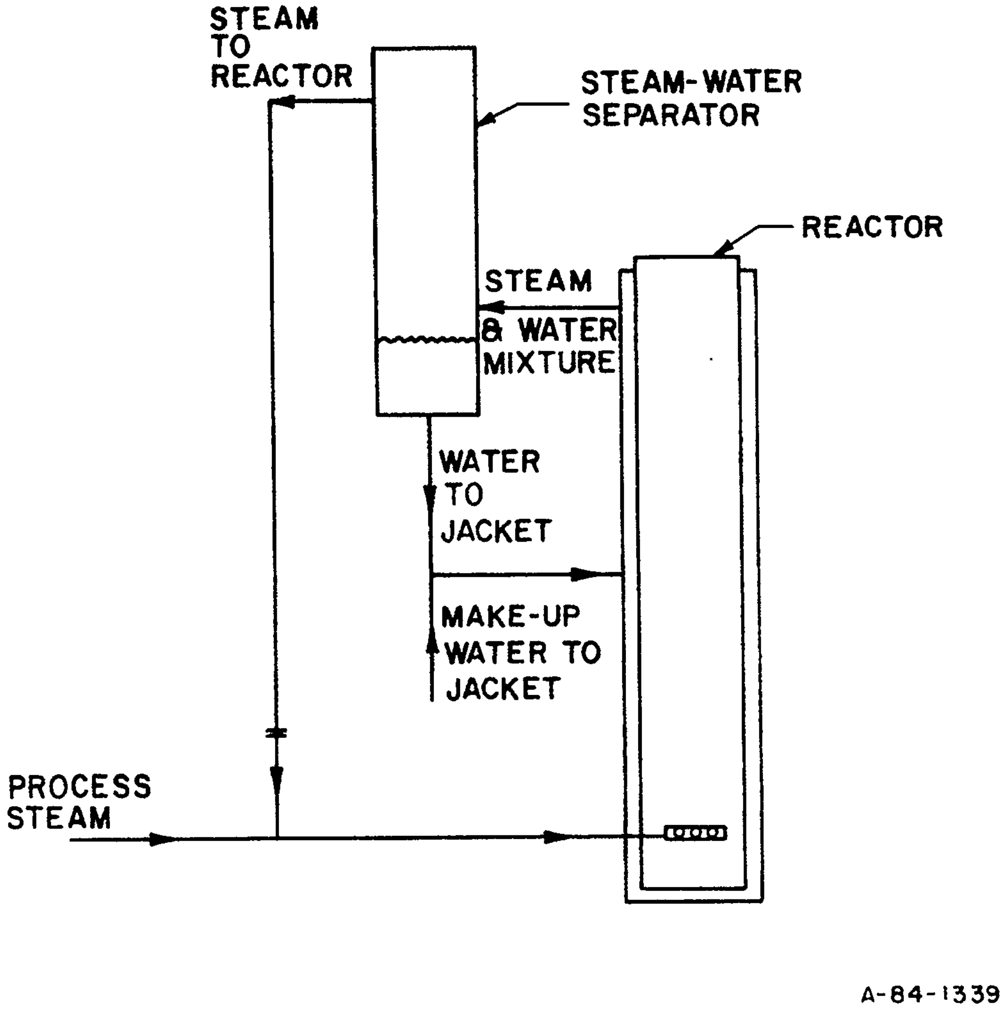
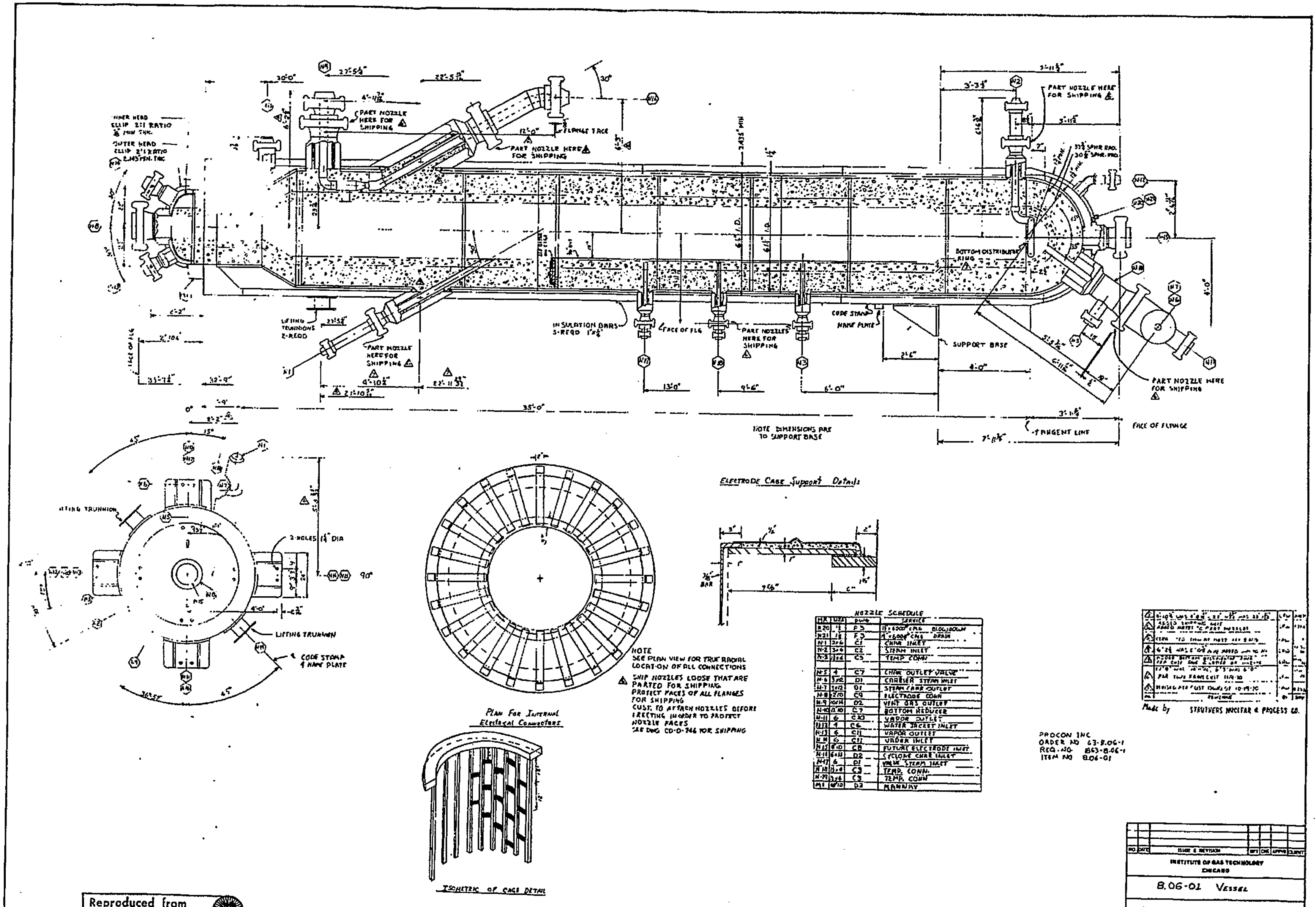


Figure 4a.2-4. REACTOR WATER JACKET SYSTEM



NOTE
SEE PLAN VIEW FOR TRUE RADIAL LOCATION OF ALL CONNECTIONS

△ SHIP NOZZLES LOOSE THAT ARE PARTED FOR SHIPPING
PROTECT FACES OF ALL FLANGES FOR SHIPPING
CUST. TO ATTACH NOZZLES BEFORE ERECTING IN ORDER TO PROTECT NOZZLE FACES
SEE DWG CD-D-746 FOR SHIPPING

NOZZLE SCHEDULE

MK	SIZE	DWG	SERVICE
N20	1½	F3	1½"×6000# CPLG BLOWDOWN
N21	1	F3	1"×6000# CPLG DRAIN
N-1	3×6	C1	CHAR INLET
N-2	3×6	C2	STEAM INLET
N-3	1×4	C5	TEMP CONN
N-5	4	C7	CHAR OUTLET VALVE
N-6	3×12	D1	CARRIER STEAM INLET
N-7	3×12	D1	STEAM/CHAR OUTLET
N-8	2/10	C9	ELECTRODE CONN
N-9	10×14	D2	VENT GAS OUTLET
N-10	12×10	C7	BOTTOM REDUCER
N-11	6	C10	VAPOR OUTLET
N-12	4	C6	WATER JACKET INLET
N-13	6	C11	VAPOR OUTLET
N-14	6	C11	VAPOR INLET
N-15	6×10	C8	FUTURE ELECTRODE INLET
N-16	6×12	D2	CYCLONE CHAR INLET
N-17	6	D1	VALVE STEAM INLET
N-18	1½×4	C3	TEMP. CONN.
N-19	3/4	C3	TEMP. CONN
M1	18/10	D3	MANWAY

Reproduced from best available copy.

Figure 4a.2-5. CUTAWAY VIEW OF REACTOR VESSEL

4a.2-9 - A

4a. 2-9 - B

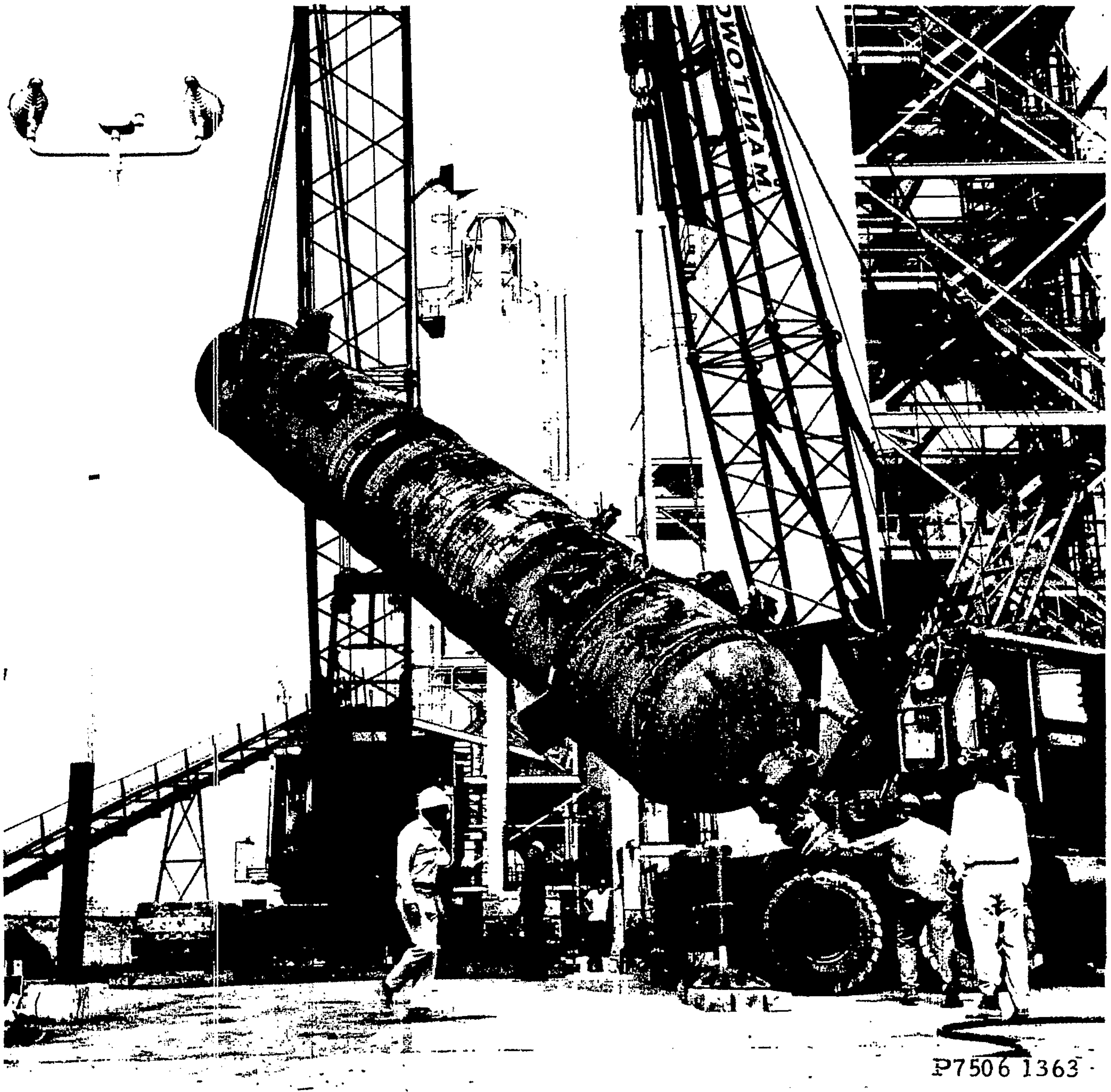


Figure 4a. 2-6. REACTOR VESSEL AT SITE

Preceding page blank

shell. A series of six support rings 1.5 inches thick by 6 inches wide were welded to the inner wall of the inside shell to maintain its shape during construction and operation.

The nozzle arrangement was such as to allow the entrance of the inner electrode at either the reactor top or bottom through 12-inch diameter closures, marked N-8 and N-15 in Figure 4a.2-5. The feed char inlet nozzle, N-1, at 25 ft from the reactor bottom and is slanted at 30 degrees to facilitate the gravity feeding of hydrogasified char; it is also 13.5 inches off-center so the incoming char will not impinge upon the center electrode. After going through an internal cyclone, the product gas exits via nozzle N-9, and char fines from the cyclone flow by gravity down into nozzle N-16. Three apertures, N-19, N-18 and N-3, were placed radially at 120° of each other and at various elevations to monitor bed temperatures and differential pressures for bed-height control. In the lower section of the reactor incoming reactant steam enters through nozzle N-2 and into a distributing ring.

The nozzle configuration at N-10 provides for the discharge of char from the vessel by a solids-control valve arrangement which can be installed through either N-5 or N-17 and into the carrier steam (N-6, N-7) line for transport to the slurry disposal system. Nozzles N-11, N-12, N-13 and N-14 were installed to handle flow in the water jacket, and N-20 and N-21 were installed for blowdown of, and chemical addition to the water jacket. The top closure, M-1, is a 40-inch ID accessway for inspection and maintenance inside the reactor.

The internal refractory lining consists of two layers of monolithic castable insulation. Nearest the inner shell wall, a layer of lightweight, high alumina, 11.125-inches thick is applied; and over it is a 4.5-inch thick layer of a hard-faced refractory. The combination of the lightweight low-density refractory, with its superior insulating quality, and the lower insulating quality but excellent wear characteristics of the high-density lining, helps to maintain reactor wall temperature at 600°F. The inside diameter of the vessel, after installing the refractory, is 30 inches in the straight side and reduces to 24 inches at both the top conical section and a 4-foot length at the reactor bottom. The lining configuration allows for a heat-transfer section of incoming steam and down-flowing char, and permits increasing the superficial velocity of the incoming steam. Figure 4a.2-6 shows the reactor vessel being erected at the HYGAS site.

4a.2.3.2 Power Supply

The power supply was designed by incorporating the electrical characteristics observed in the 6-inch development unit, and applying the correlations to the concentric electrode configuration of the larger reactor. It was sized to provide a continuous 2.25-megawatt source of direct-current power.

The manner in which the system load current varies from a mean value during time intervals of 0.5 to 5 seconds, at between 0.5 to 2.00 of the average direct current in the 6-inch development unit, necessitated that the power supply be rated above that required for normal operation. The power system was designed for continuous operation of 2.25 megawatts at conditions from 700 to 1185 volts and 1900 to 3200 amperes direct current, but had to be rated at 3.8 megawatts to meet the requirements of operating at the maximum voltage and current (1185 and 3200). The equipment was designed to sustain a fault on the direct current bus for a period of 7 cycles with one diode out in any rectifier leg. Power factor and efficiencies were calculated by NEMA standards.

Figure 4a. 2-7 is a one-line diagram showing the connections to the 2.25-megawatt power supply system, with a block diagram of the electrothermal power supply and control. The utility-supplied 13-kilovolt three-phase power is stepped down at the HYGAS pilot plant to 4.16 kilovolts using an on-site 5 MVA transformer. The electrothermal gasification power supply is fed directly from the 4.16 kilovolt bus, and consists of:

4a. 2. 3. 2. 1 A 2.25 MVA Transformer

The transformer steps down the 4.16 KV voltage to a voltage adjustable between 600 and 960 volts line-to-line. The transformer is equipped with a motor-operated tap changer capable of regulating the transformer secondary voltage between 600 and 960 volts in increments of about 20 volts. The tap changer can be operated manually or automatically, depending on the selected control mode, under full voltage conditions.

4a. 2. 3. 2. 2 A Silicon Controlled Rectifier (SCR) Power Controller

The output of the transformer is connected to the silicon-controlled rectifier (SCR) power controller, and voltage regulation at a particular tap setting is controlled from 0 voltage to the maximum at a particular tap location by adjusting the time the SCR's conduct voltage. This in turn sets the level of alternating-current voltage applied to the rectifier assembly.

4a. 2. 3. 2. 3 Rectifier

The three-phase alternating-current voltage is rectified to six-phase direct-current voltage by a full-wave rectifier bridge network as shown in Figure 4a. 2-8. The alternating-current line-to-neutral voltages applied to the bridge are shown in Figure 4a. 2-8a, and the corresponding line-to-line voltage applied at the bridge are shown in Figure 4a. 2-8b. If the SCR's are fired (turned on) so that the maximum direct-current voltage is obtained, the direct-current output is simply the crest or peak values of each of the line-to-line voltages over the range 30° before and after the crest. The solid line marked "V_d" in Figure 4a. 2-8b is the direct-current output voltage wave form. To obtain the maximum voltage, each SCR must be fired at a time as indicated in Figure 4a. 2-8e. Figure 4a. 2-8c and -8d show the individual SCR currents and one alternating-current line current for this firing pattern.

Table 4a. 2-2 shows the operating parameters and their relationship to the direct-current output voltage, power and current for full-wave bridge rectifiers, as are used in the electrothermal gasifier power supply.

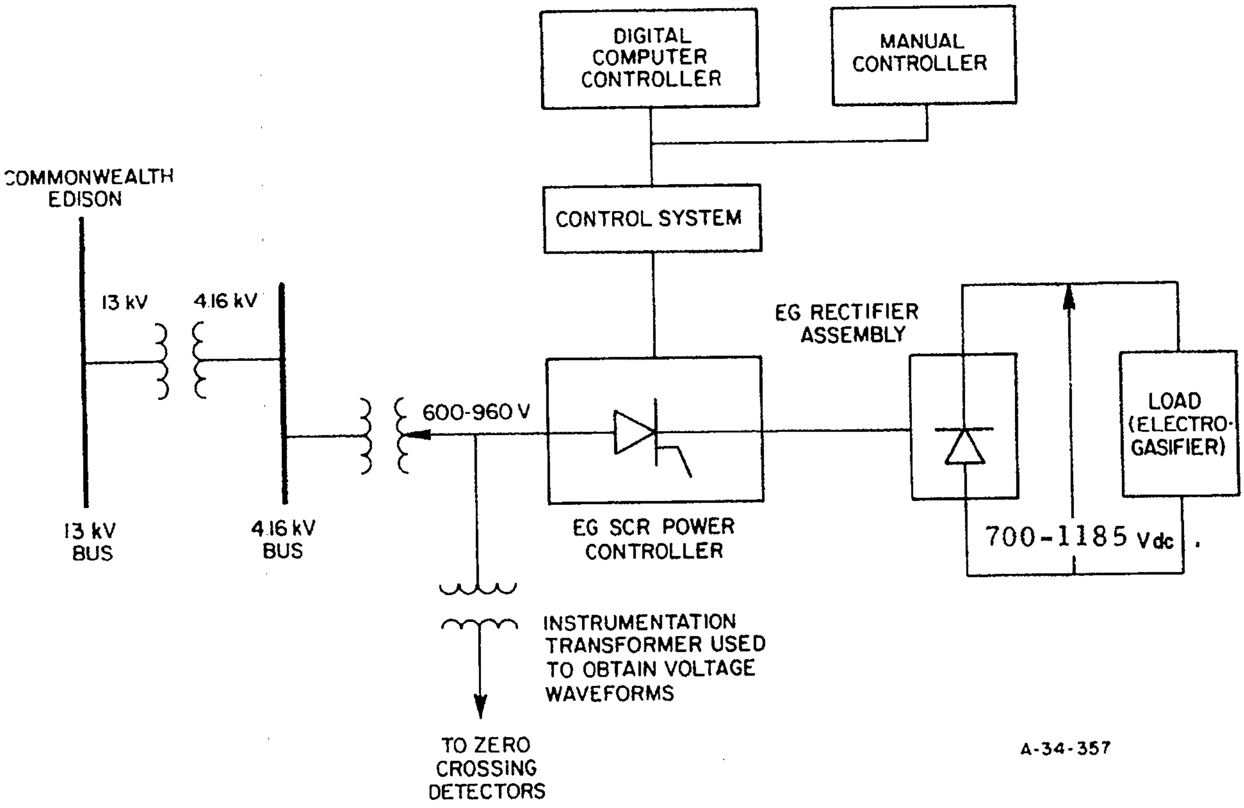


Figure 4a.2-7. CONNECTIONS TO 2.25-MW ELECTROTHERMAL GASIFICATION POWER SUPPLY SYSTEM

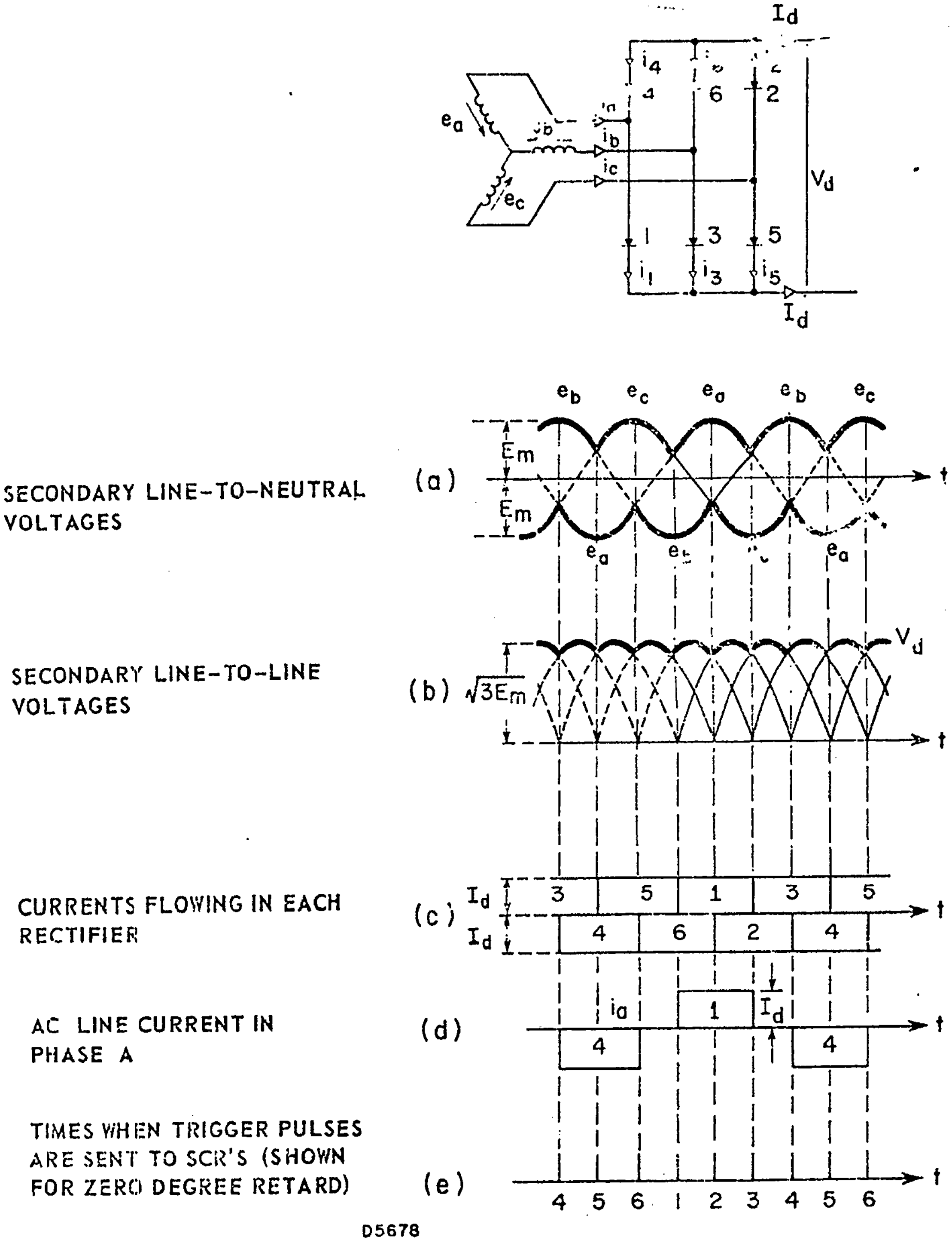
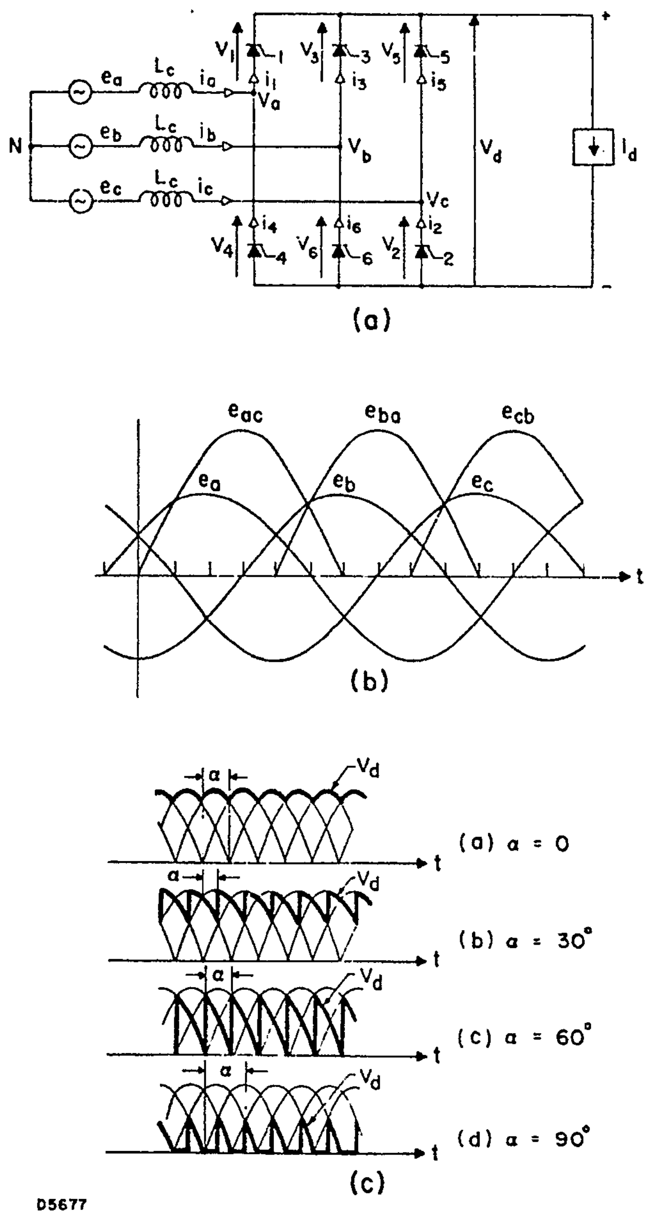


Figure 4a. 2-8. THE VOLTAGES AND CURRENTS ASSOCIATED WITH A FULL WAVE RECTIFIER



(A) TYPICAL FULL WAVE BRIDGE NETWORK

(B) CORRESPONDING LINE-TO-NEUTRAL AND LINE-TO-LINE VOLTAGES

(C) SKETCH SHOWING EFFECTS ON THE DC OUTPUT VOLTAGE (V_d) OF VARYING THE RETARD ANGLE (α).

A7506 1422

Figure 4a. 2-9. TYPICAL FULL WAVE BRIDGE NETWORK, AND VOLTAGE RELATIONSHIPS

Table 4a.2-2. OPERATING PARAMETERS ASSOCIATED WITH A FULL WAVE RECTIFIER

Name of Circuit	3-Phase Bridge
Figure Number	2
Number of Diodes	6
Pulse Number	6
Currents:	
Diode, peak	1.000 I_d
Diode, average	0.333 I_d
Transformer, rms	
Secondary	0.816 I_d
Primary	0.816 I_d/T
Voltages:	
DC Ripple, peak to peak	0.140 V_d
Diode, peak inverse	1.047 V_d
Transformer, rms	
Primary	0.428 TV_d
Each secondary	0.428 V_d
Volt Amperes:	
All Diodes*	2.094 P_d
Transformer, primary	1.047 P_d
Transformer, secondary	1.047 P_d

I_d, V_d and P_d are the current, voltage, and power of the DC line.

T is the turns ratio of the transformer.

*Based on average current and peak inverse voltage.

A7506 1560

The detailed technical specifications of the transformer, rectifier and SCR switch unit are included in Appendix 4a. 2-A for reference.

4a. 2. 3. 3 Power Control

As shown in Figure 4a. 2-7, both an automatic digital computer-control mode and manual control mode are incorporated. The manual mode was installed as a back-up control to be used when the computer control mode is inoperative. Both schemes use many common logic systems, fault detection and alarm circuitry, but the manual mode allows operation with the digital computer removed from the system.

4a. 2. 3. 3. 1 Manual Mode

To obtain varying output voltage levels, the firing of each SCR is delayed in time. Figure 4a. 2-9 shows the circuit, alternating-current voltage, and resulting output waveforms for various delay times, more frequently referred to as retard angles. Angle α of Figure 4a. 2-9c is the retard angle. It can be observed that, as α increases, the level of the output voltage becomes more chopped, and decreases in amplitude. The manual control system provides means to control the angle α over the range 0° to 120°, as desired and, when combined with tap-position changes on the transformer, permits any voltage between 0 and 1185 volts direct current to be obtained at the reactor load.

The control concept for the Manual Control Mode is illustrated in Figure 4a. 2-10. Two instrumentation transformer banks are used to reduce the amplitude (without shifting the phase) of the main alternating current line input voltages to levels compatible with 5-volt integrated circuit logic (IC's). The input to the IC's duplicates the main alternating-current line voltages; this input is used to establish the zero crossings of the alternating-current voltages which are used as a reference for firing the silicon-controlled rectifiers (SCR's) in the power supply system.

The transformer output voltages are transferred to a logic card whose function is to provide square-wave outputs in phase with the corresponding alternating-current line voltage. This is accomplished by using over-driven voltage comparators to establish the precise time when a given voltage changes sign (plus to minus, or vice-versa). The output signals of the zero crossing logic card are transferred to a second logic card, where the square waves are converted to several microsecond logic pulses (one shots) occurring at a time corresponding to the zero crossing of the alternating-current line voltages. These short-duration pulses are then transferred to a logic card designated the "Manual Retard Board." The function of this logic card is to output pulses delayed in time by the desired amount of firing retard; the firing retard is changed by varying the timing of logic pulses through the use of ganged potentiometers, one in each phase. From here, the firing-control signals are transferred to a Line Driver Logic board, where the signal level is increased and sent to the SCR trigger pulse generators.

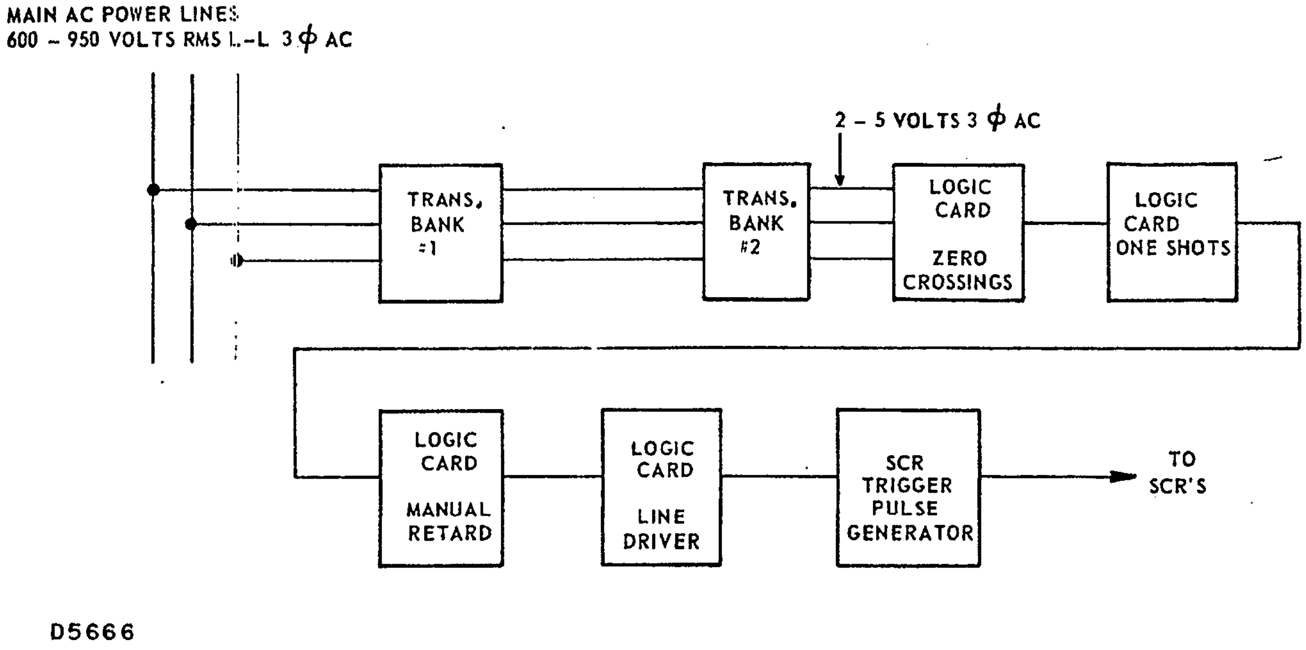


Figure 4a.2-10. BLOCK DIAGRAM OF THE MANUAL CONTROL MODE SIGNAL PATH

4a. 2. 3. 3. 2 Automatic Control

The manual mode method for controlling the output voltage to the reactor load by delaying or retarding the conduction angle in the SCR's is a simple straightforward technique. However, high retard angles (Figure 4a. 2-9c) lead to low power factors and inefficient power usage. To prevent this occurrence, a control algorithm was developed that would allow conduction at low retard angles, and the average voltage was adjusted by omitting or skipping a number of conduction periods. This concept required the speed of a digital computer, programmed in "real time", to allow application of this control scheme. The computer control program contains necessary instructions so that a combination of load tap changing, retard angles, and non-firing of the SCR's can be utilized to achieve the control range desired.

Two modes of automatic control are available, current and power. In the current mode, an operating current is specified at a main control panel and the digital computer program will automatically adjust conduction voltage to maintain the current setting. The current mode was installed primarily as a safety measure during shakedown and initial operation of the system.

The power mode is the preferred automatic control. A power input to the reactor load is set and the computer program adjusts the voltage as the bed current varies to maintain a constant power input to the load (V x I).

By using a finite number of skipping patterns, a pseudo-linear load characteristic is achieved in the automatic control. The basic plan incorporated has a fundamental firing pattern that entails ten sequential phase-voltage zero crossings with ten possible firing pattern combinations. Three patterns are used: eight firings and two skips; six firings and four skips; and four firings and six skips. Table 4a. 2-3 shows that, by using combinations of these basic patterns and holding the initial retard angle (α_o) and subsequent retard angles (α) at a minimum, the power to the load can be controlled discreetly over a range 0.101 unit power at each transformer tap setting. Figure 4a. 2-11 illustrates the direct current output voltage and line-to-line voltages for a skip pattern corresponding to four conduction cycles and six non-conduction cycles. As can be seen from Figure 4a. 2-11, the individual phase current are not balanced in each skip pattern, but over a period of continuous operation the overall current through the transformer is balanced to zero in order to maintain symmetrical operation.

4a. 2. 3. 4 Electrodes

The center-electrode design was based on the configuration successfully tested in the 6-inch development unit and scaled to the dimensions of the larger reactor. Acting as the positive electrode in the circuit it had to be electrically isolated from the reactor structure as well as placed into the vessel through a pressure-containing closure. A cut-away view of the upper portion of the center electrode is shown in Figure 4a. 2-12. Table 4a. 2-4 lists the various components corresponding to Figure 4a. 2-12 and Appendix 4a. 2-A contains details of the various items incorporated in the fabrication.

Table 4a.2-3. OPERATING VALUES FOR VARIOUS CONSTANT-POWER LEVELS

Index "n"		Firing* Pattern	a_o (Initial Delay), degrees	a (Subsequent Delay), degrees	Per Unit Power
Decimal	Octal				
1	1	8-2	10.0	0	1.0
2	2	8-2	45.0	5.5	0.974
3	3	8-2	54.0	9.0	0.949
4	4	8-2	60.5	12.0	0.923
5	5	8-2	64.0	14.0	0.897
6	6	8-2	68.5	16.5	0.872
7	7	8-2	71.5	18.5	0.850
8	10	8-2	74.5	20.5	0.820
9	11	8-2	76.5	22.0	0.795
10	12	8-2	79.5	24.0	0.769
11	13	8-2	81.5	25.5	0.743
12	14	6-4	54.0	9.0	0.718
13	15	6-4	61.5	12.5	0.692
14	16	6-4	66.5	15.5	0.666
15	17	6-4	71.5	18.5	0.641
16	20	6-4	75.5	21.0	0.615
17	21	6-4	78.0	23.0	0.589
18	22	6-4	81.5	25.5	0.564
19	23	6-4	84.5	27.5	0.538
20	24	6-4	87.0	29.5	0.512
21	25	4-6	55.0	9.5	0.486
22	26	4-6	64.0	14.0	0.461
23	27	4-6	70.5	18.0	0.435
24	30	4-6	76.0	21.5	0.409
25	31	4-6	80.0	24.5	0.382
26	32	4-6	85.0	28.0	0.358
27	33	4-6	88.5	31.0	0.332
28	34	4-6	92.5	34.0	0.307
29	35	4-6	96.0	37.0	0.281
30	36	4-6	99.0	40.0	0.255
31	37	4-6	102.5	43.0	0.230
32	40	4-6	105.5	46.0	0.204
33	41	4-6	109.5	49.5	0.178
34	42	4-6	113.0	53.0	0.153
35	43	4-6	117.0	57.0	0.134
36	44	4-6	121.0	61.0	0.101

*8-2 means eight firings and no firing for the next two zero crossings. 6-4 and 4-6 signify a similar pattern.

A7506 1561

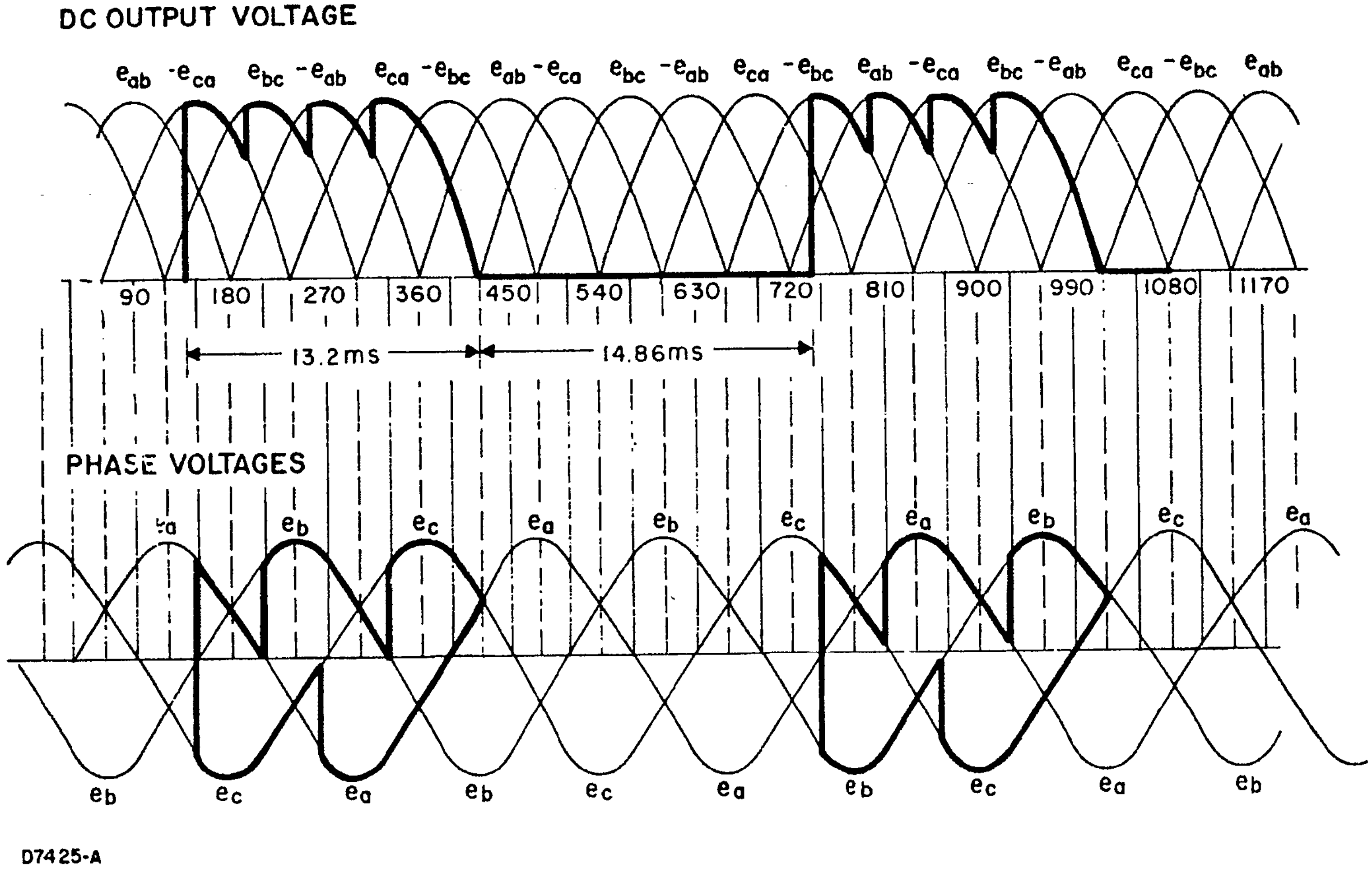
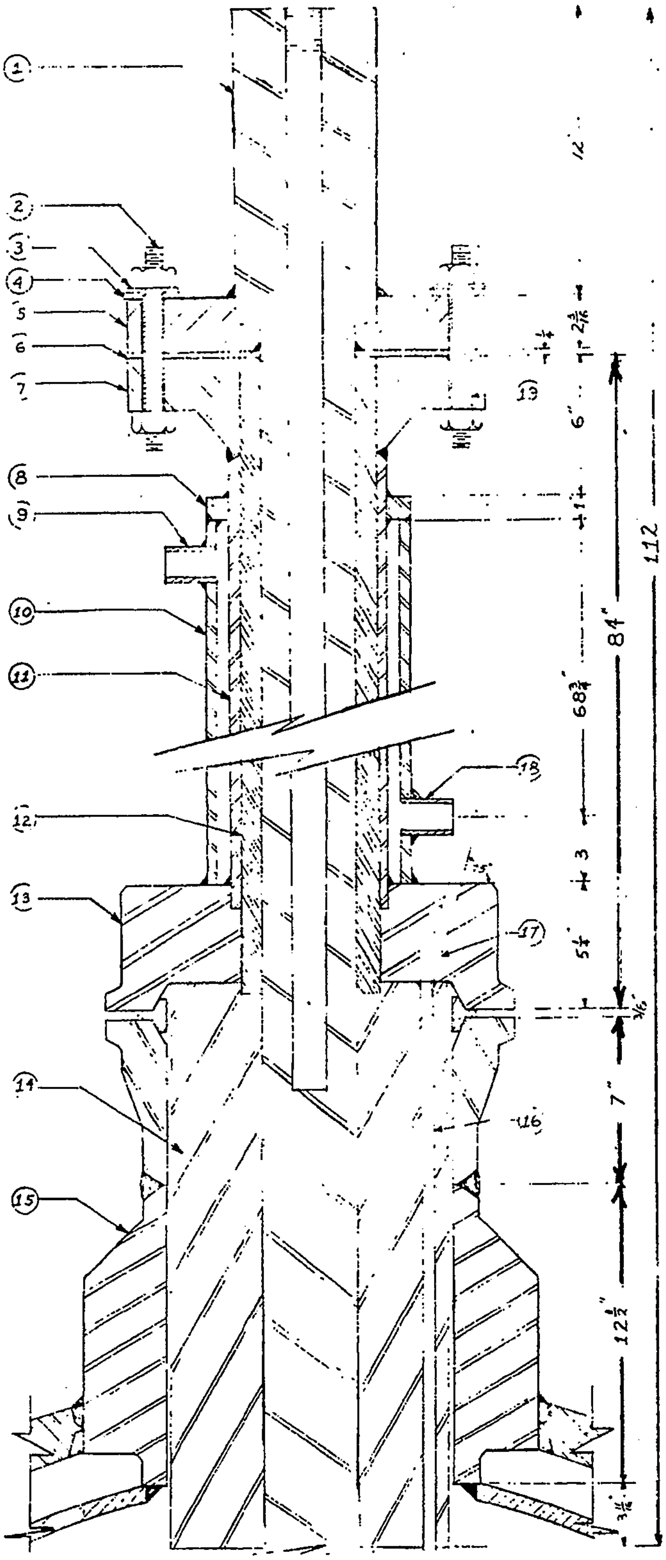


Figure 4a.2-11. DIRECT-CURRENT OUTPUT VOLTAGE AND LINE-TO-LINE VOLTAGES FOR SKIP PATTERN CORRESPONDING TO FOUR CONDUCTING CYCLES AND SIX NON-CONDUCTING CYCLES



A7506 1473

Figure 4a. 2-12. CUTAWAY VIEW OF THE CENTER ELECTRODE AT ITS ENTRANCE INTO THE REACTOR

Table 4a.2-4. LEGEND FOR FIGURE 4a.2-12

Item	
1.	316 S.S. Rod Connected to DC Power Supply. See Drawing No. 3 For Details.
2.	Stud Bolts - 8, 1-1/8" Diam with Hex Nuts.
3.	1/4" Thick, C.S. Retaining Ring. 15" O.D. x 11" I.D. w/8 1-1/4" Diam Holes.
4.	Teflon Gasket, 1/4" Thick. 15-1/2" O.D. x 10" I.D. w/8 1-1/4" Diam Holes.
5.	C.S. Blind Flange, Flat-Faced. 6" 900 lb, ASA, Bored as Shown.
6.	Teflon Gasket, 1/4" Thick. 15-1/2" O.D. x 4" I.D. w/8 1-1/4" Diam Bolt Holes.
7.	C.S. Weld-Neck Flange, Flat-Faced. 6" 900 lb ASA, Bored to 5.189" I.D.
8.	C.S. Plate, 1" Thick. 8.625" O.D. x 6.625" I.D.
9.	C.S. Coupling, 1-1/2" Diam x 2" Lg.
10.	C.S. Pipe, 8" Sch. 40, A-53 Grade.
11.	C.S. Pipe, A-106-B. 6" Sch. 160
12.	Teflon Sheath, 5.375" O.D. x 4" I.D. x 84" Lg.
13.	Grayloc Blind Hub 14 GR 120, 316 S.S. Bore to 5.189" I.D. With 6.625" O.D. Offset 1" Deep.
14.	Castable Refractory (Alumina) 12" O.D. x 4" I.D. x 23" Lg.
15.	Reactor Nozzle N-8. See Struthers-Wells Dwg. for Details.
16.	S.S. Tubing 1/2" TYP 316, 20GA, .035" Wall Thickness.
17.	Drill and Tap for 1/2" NPT @ 75°.
18.	C.S. Coupling 1-1/2" Diam x 2" Lg.
19.	Teflon Tubing 1-1/4" I.D.

The center electrode material is Type 316 stainless steel rod 4 inches in diameter, except for the upper 12 inches which is expanded to a 6-inch diamter. This 6-inch portion increases the surface area for contact with the power lead connectors. The rod is fitted through and welded to one-half of a 6-inch high-pressure flat-faced flange closure.

The pressure gasket for the flange connection consists of 0.25-inch thick teflon, which electrically isolates the upper flange from the lower flange while it also seals against the system pressure.

To complete the electrical isolation, the studs and bolts are teflon-sheathed and made up with micarta washers. The annulus between the 4-inch diameter rod and the water-jacketed cooling section is sheathed with 0.75-inch thick teflon. The portion of the center electrode passing through the 12-inch diameter reactor nozzle is covered with a cast section of high alumina content refractory which acts as a heat shield from the process conditions of the reactor; because it is electrically non-conducting, it also provides electrical isolation from the vessel wall.

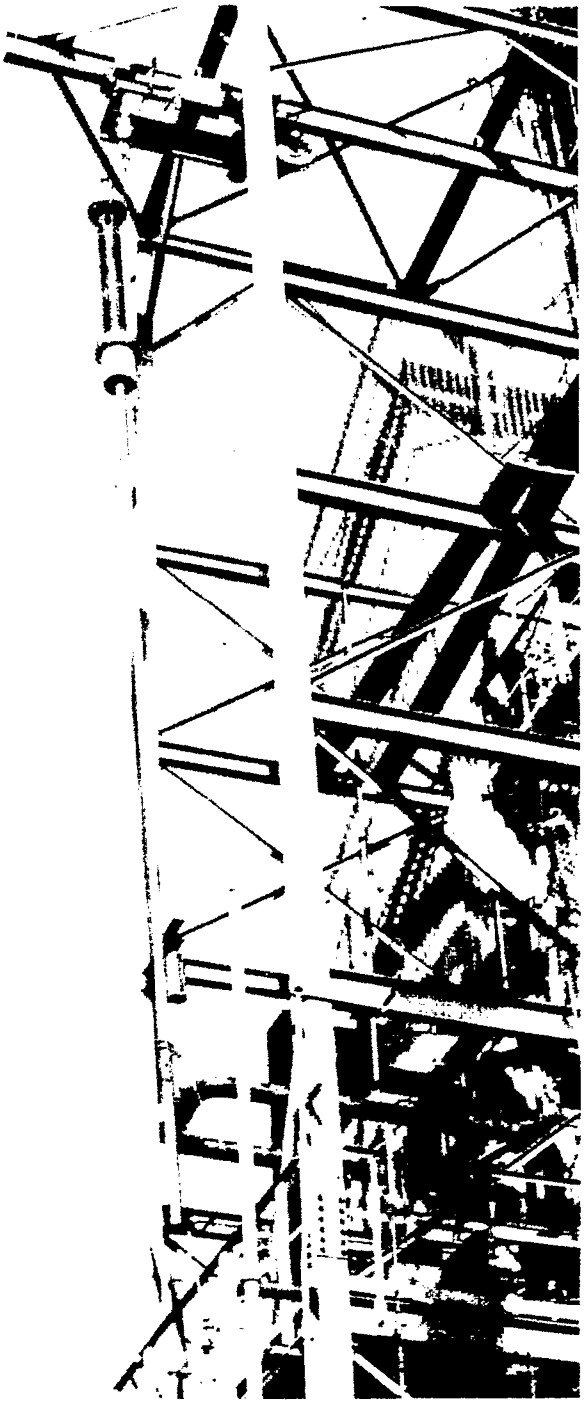
Internal water cooling is supplied to the top 7 feet of the center electrode. The upper 10 feet of the center electrode is a continuous section with the end machined such that various lengths of similarly machined 4-inch rod can be connected by a special coupling so that the electrode length and therefore immersion into the char bed can be adjusted. The portion of the 4-inch diameter rod immersed in the char bed provides sufficient surface area to limit the current density on the rod surface at levels which will prevent overheating of the metal. Figure 4a.2-13 shows the completed center electrode during installation.

The negative electrode of the system consists of a circular "cage-like" configuration fabricated of Type 316 stainless steel and supported from one of the stiffener rings attached to the inner shell of the reactor vessel. It fits into the reactor inside the 30-inch refractory lining and extends downward 15 feet.

The cage is composed of 59 equally spaced 0.375-inch square Type 316 stainless steel bars; these are aligned vertically with spacer bars appropriately attached between the vertical sections for alignment purposes. The vertical bars are welded at one end to a 1-inch thick, 2.5-inch wide support ring. An isometric drawing depicting the details of the cage is shown in Figure 4a.2-5.

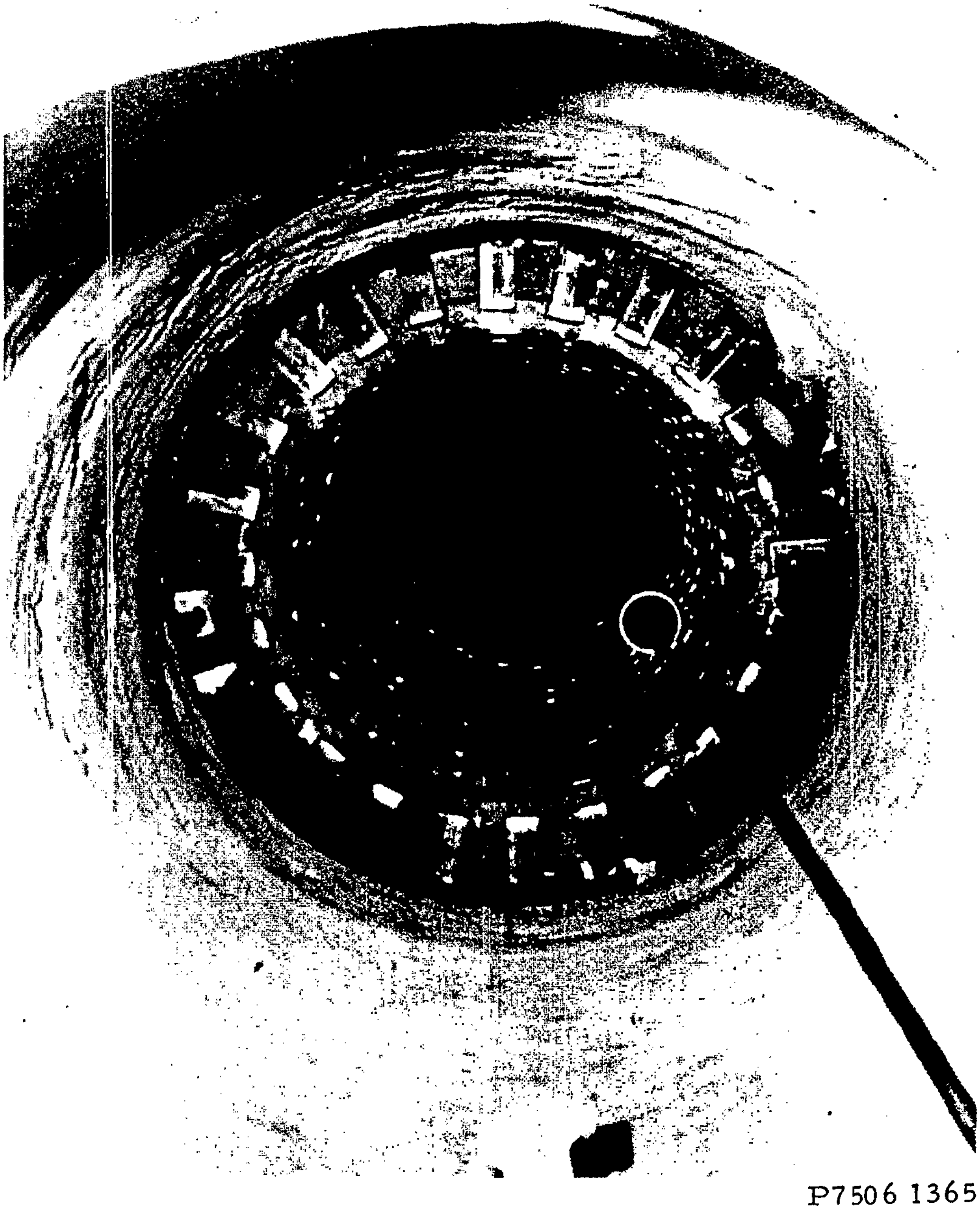
Twenty-four Type 316 stainless steel bars (0.5 inch thick and 2 inches wide) are radially fitted and welded at one end to the top of the cage support, and at other end to the stiffener ring of the inner reactor shell. They provide the conduction path from the negative electrode to the reactor wall. The details of the electrode support and layout of the connectors is also shown in Figure 4a.2-5. A view of the cage from the unheaded reactor during its installation is shown in Figure 4a.2-14.

The electrical connection from the reactor to the rectifier is completed by a clamp and cable attached to nozzle N-5 of the reactor, and to bus from the rectifier as illustrated in Figure 4a.2-15. A similar connection is provided for attaching the center electrode to the positive bus.



P7506 1364

Figure 4a. 2-13. CENTER ELECTRODE DURING INSTALLATION



P7506 1365

Figure 4a.2-14. INSTALLATION OF NEGATIVE ELECTRODE — VIEW FROM TOP OF UNHEADED REACTOR

P7506 1366

Figure 4a.2-15. ELECTRICAL CONNECTION TIEING REACTOR TO NEGATIVE SIDE OF THE RECTIFIER

The "cage" type construction was incorporated to minimize the weight of the negative electrode. The current density at the negative electrode surface in the larger diameter reactor is at a sufficiently low level that it did not require a continuous metal surface for heat distribution, as was required in the 6-inch development unit. Additionally, stress analysis indicated a free-standing solid metal liner would have buckled under its own weight at the operating temperatures of the electrothermal gasifier. Supporting the electrode from above permits the weight of the cage itself to keep it in vertical alignment, and prevents it from warping. Thermal expansion at the lower free-hanging section was also readily accommodated by this arrangement.

4a.2.3.5 Special Piping

Special piping design considerations were necessary for transporting the hot (1900°F) product gas, at pressure, from the electrothermal reactor to the hydrogasifier.

An internally insulated multiple-wall piping concept was developed as shown in Figure 4a.2-16. It consists of a 10-inch schedule 140 pressure-containing shell designed for operating at 600°F in the reducing atmosphere of the product gas (carbon-1/2 molybdenum steel).

Sections of 4-inch schedule 40 Incoloy* pipe capable of withstanding the hot synthesis gas was balanced at operating pressure by high-pressure nitrogen in the insulated 2-inch annulus between the pipe walls.

The 10-inch pipe was jacketed by a 14-inch diameter carbon steel pipe through which low-pressure water was directed to protect against overheating of the 10-inch pipe, should breaks occur in the internal insulation.

At the flange connections between each pipe section (typically 10 to 12 feet long) the 4-inch inner pipe is welded to an alloy seal ring which also isolates each pipe section annulus from the adjoining section. To accommodate thermal expansion in the 4-inch pipe a "slip joint" was fabricated in each individual pipe section to allow movement of the pipe and is detailed in Figure 4a.2-17. A gap of several inches is left in the 4-inch pipe. The gap is sheathed with a larger diameter pipe that is welded to the outer wall of one end of the 4-inch pipe. The sheath pipe overlaps both ends of 4 inch pipe for about 6 inches. The insulation in the annulus is notched at the free end of the sheath, and both ends of the pipe can slip, as required, during operation. The sheath keeps the 4-inch pipe in alignment. Each pipe section is individually purged with high-pressure nitrogen to prevent process gas from entering the annulus. The surface of the outer wall of the portion of the 4-inch pipe, which is in contact with the inner wall of the sheath, is coated with a 0.010-inch thick deposit of alumina to facilitate movement along the pipe surfaces. A description of the specifications developed for applying the alumina coating is listed in Appendix 4a.2-A.

---

[*] International Nickel Co. trademark.

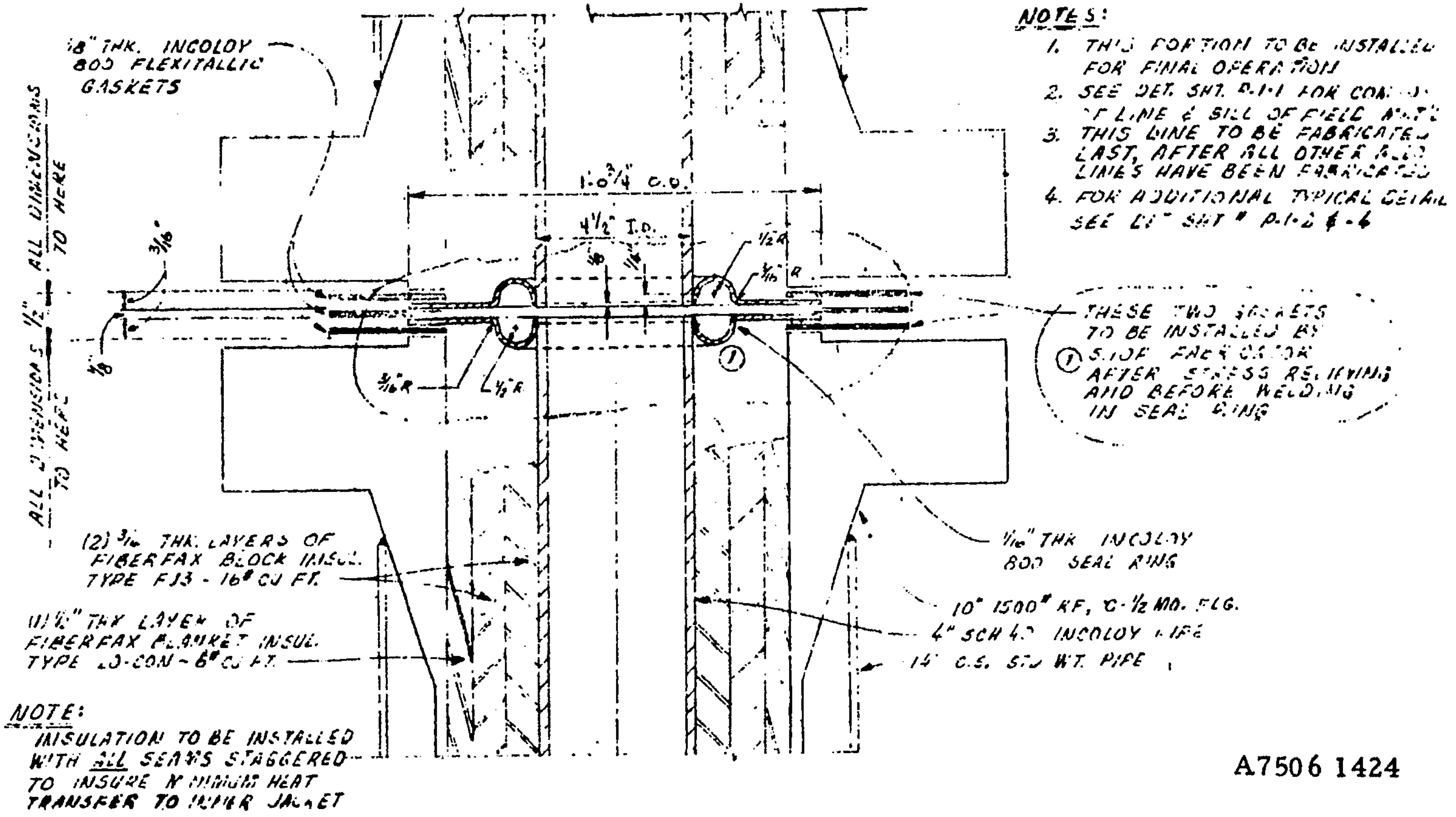


Figure 4a.2-16. TYPICAL FABRICATION DETAIL OF ALL FLANGED JOINTS, INTERNAL INSULATION AND SEAL RINGS OF PRODUCT GAS TRANSFER PIPE

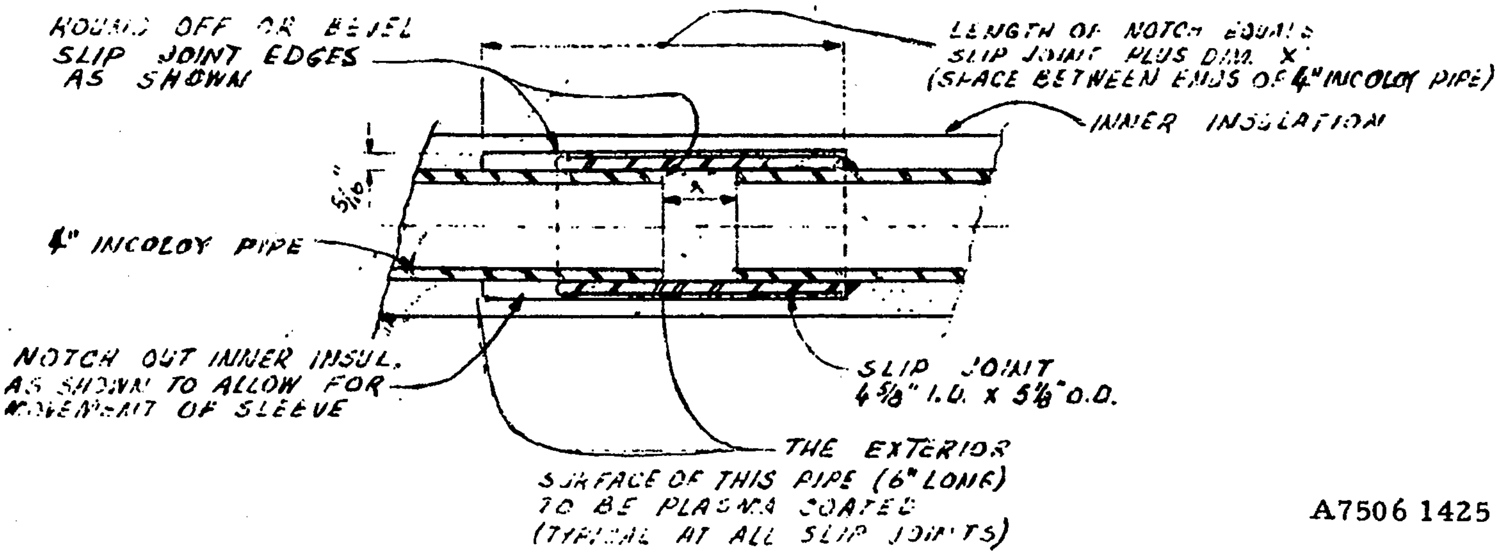


Figure 4a.2-17. TYPICAL ASSEMBLY OF SLIP-JOINT OF JACKETED PIPE

4a. 2. 4 Process Flow and Stream Properties

The Process Flow Diagram and associated stream properties upon which the detailed design and construction of the 2.25-megawatt electrothermal unit was based are shown in Figure 4a. 2-18.

Hydrogasified char is gravity discharged from the hydrogasification reactor (stream 1) where it is mixed and conveyed by high-pressure saturated steam (stream 2) to a cyclone which separates the char from the carrier steam. After heat exchange in the transfer line, the stream temperature at the cyclone is nominally 1200 °F.

Char leaving the cyclone is then gravity fed to the electrothermal reactor. After undergoing reaction at 1900 °F, the spent char exits at the reactor bottom (stream 4). It is heat-exchanged and conveyed with high-pressure saturated steam (stream 5) that has been combined, for steam conservation purposes, with the steam separated in the char-lift cyclone. This mixture picks up additional char fines (stream 15) which have been removed from the product-gas stream by a cyclone internal to the reactor. The mixture is next conveyed (stream 6) to a water-slurry mix drum. The steam-char mixture is made into a water slurry, let down in pressure, filtered, and sent to disposal.

High-pressure superheated steam (streams 3 and 16), used as a reactant in the process, is combined with high-pressure steam generated in the reactor water jacket (stream 14), and let into the reactor through a distributing ring at the reactor bottom.

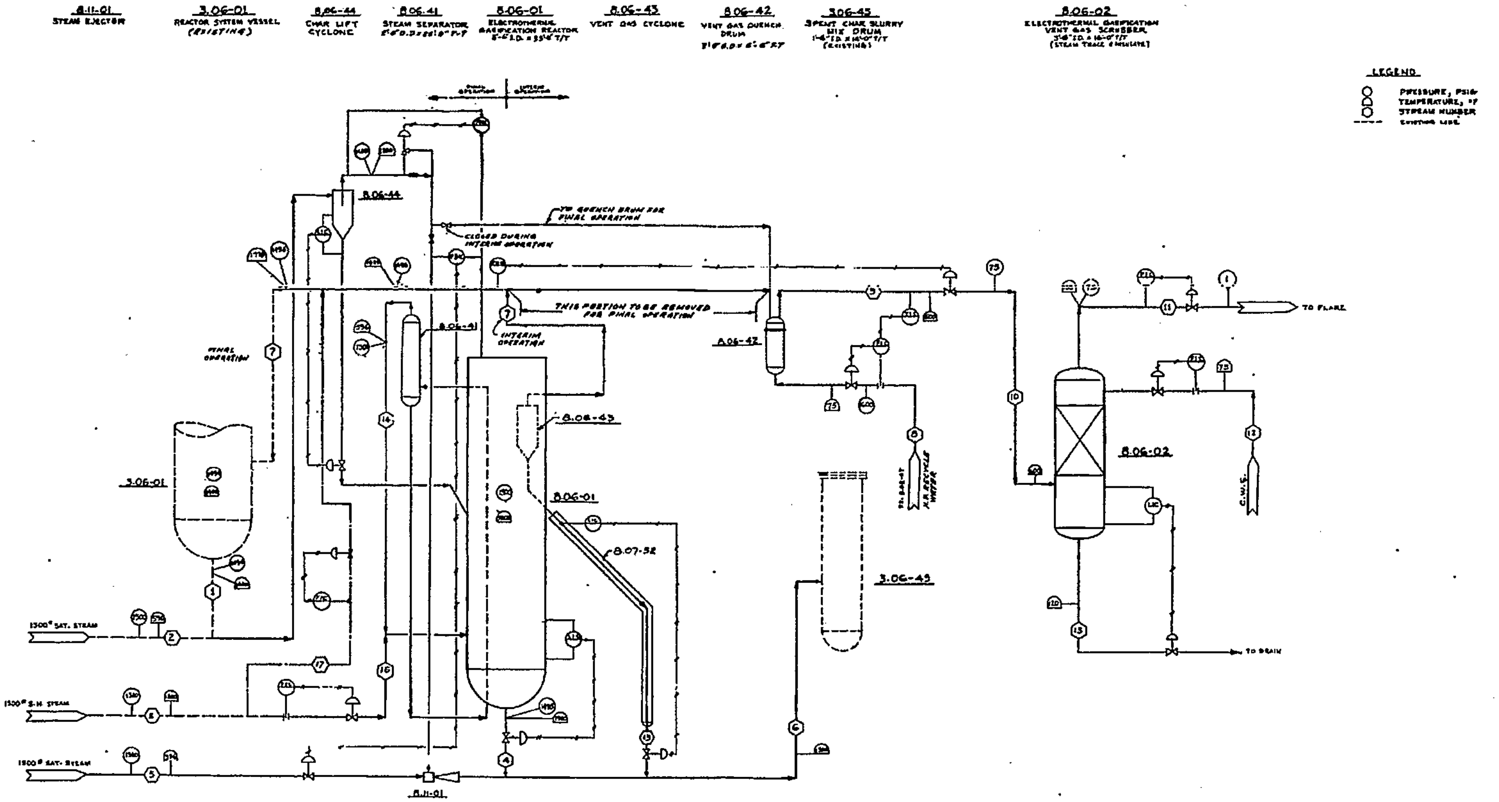
Product gas leaves the reactor through the internal cyclone at 1900 °F and, for the initial operation of the system, is desuperheated to 600° by a high-pressure water quench (stream 8) and let down in pressure (streams 9 and 10) to 75 pounds per square inch. The gas is scrubbed with water to 100 °F (stream 12), the condensibles disposed to the plant sewer system (stream 13) and, after sampling, the product gas is flared (stream 11).

After shakedown testing of the electrothermal systems is completed, the product gas will be sent directly to the hydrogasification reactor (stream 7) to complete the integration of the HYGAS process. The desuperheater, pressure letdown and quench system will be utilized to remove excess steam from the char-lift cyclone system. Once in integrated operation, additional high pressure steam, as required, can be added to the product gas going to the hydrogasifier via stream 17.

4a. 2. 5 Piping and Instrument Diagrams

4a. 2. 5. 1 Initial Operation

The piping and instrumentation diagram illustrating the initial operating phase is shown in Figure 4a. 2-19. The control and monitoring instrumentation are of the pneumatic type, with the exception of two radiation-type level



STREAM NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
STREAM DESCRIPTION	SPENT CHAR FROM HG	TRANSFER STEAM	STEAM TO EG & HG	[illegible] CHAR TO SLURRY	MOTIVE STEAM	CHAR STEAM TO SLURRY	EG GAS TO HG	QUENCH H2O TO EG VENT	QUENCHED EG VENT GAS	SCRUBBER INLET GAS	SCRUBBER VENT GAS	SCRUBBER H2O INLET	SCRUBBER DRAIN	STEAM FROM SEPARATOR	CHAR-DUST FROM EG	[illegible]	[illegible]
PRESSURE, PSIG	1494	1500	1500	1498	1500	1496	1498	1600	1490	72	75	90	75	1500	1497	1500	1500
TEMPERATURE, °F	1400	596	1200	1900	596	1800	1900	75	800	600	100	75	120	596	1800	1800	1800
COMPONENTS:																	
CHAR	3,084	—	—	1,625	—	2028	*	—	*	*	—	—	*	—	400	—	—
CO	—	—	—	—	—	—	1,731	—	1,731	1,731	1,731	—	—	—	—	—	—
CO2	—	—	—	—	—	—	1,792	—	1,792	1,792	1,792	—	—	—	—	—	—
H2	—	—	—	—	—	—	251	—	251	251	251	—	—	—	—	—	—
CH4	—	—	—	—	—	—	268	—	268	268	268	—	—	—	—	—	—
H2S	—	—	—	—	—	—	3	—	3	3	3	—	—	—	—	—	—
H2O	—	3000	4,370	—	1070	4070	2,790	4,150	6,940	6,940	47	186,666	193,559	1000	—	3050	1320
TOTAL, LBS/HR.	3,084	3000	4,370	1,625	1070	6098	6,835	4,150	10,983	10,983	4,092	186,666	193,559	1000	400	3,050	1,320
TOTAL, MOLS/HR.	—	166.48	242.51	—	59.38	—	398.41	230.30	628.71	628.71	246.19	10,358.81	10,741.34	55.49	—	169.26	73.25
MOLECULAR WEIGHT	—	18.02	18.02	—	18.02	—	17.16	18.02	17.47	17.47	16.62	18.02	18.02	18.02	—	18.02	18.02
VAPOR																	
LBS./FT.³ @ OP. COND.	—	3.617	1.583	—	3.617	—	1.007	—	2.587	0.1532	0.2491	—	—	3.617	—	1.583	1.583
ACFM @ OP. COND.	—	13.82	46.01	—	4.93	—	113.12	—	70.77	1,195.06	273.79	—	—	4.61	—	32.11	13.90
LIQUID																	
GPM @ OPER. COND.	—	—	—	—	—	—	—	8.30	—	—	—	375.33	387.12	—	—	—	—
VISCOSITY, CP @ OP. COND.	—	—	—	—	—	—	—	0.90	—	—	—	0.90	0.56	—	—	—	—

* SMALL AMOUNT OF FINES

Figure 4a. 2-18. PROCESS FLOW DIAGRAM

4a. 2-33

©

ALTERATIONS AND ADDITIONS
REVISED TO DATE
REVISED TO DATE
REVISED TO DATE

PROCON INCORPORATED
PROCESS FLOW DIAGRAM
OF
ELECTROTHERMAL GASIFICATION REACTOR SECTION
COAL HYDROGASIFICATION PILOT PLANT
FOR
INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS
DWG. NO. 1863-800-1-J

4a-2-33-B

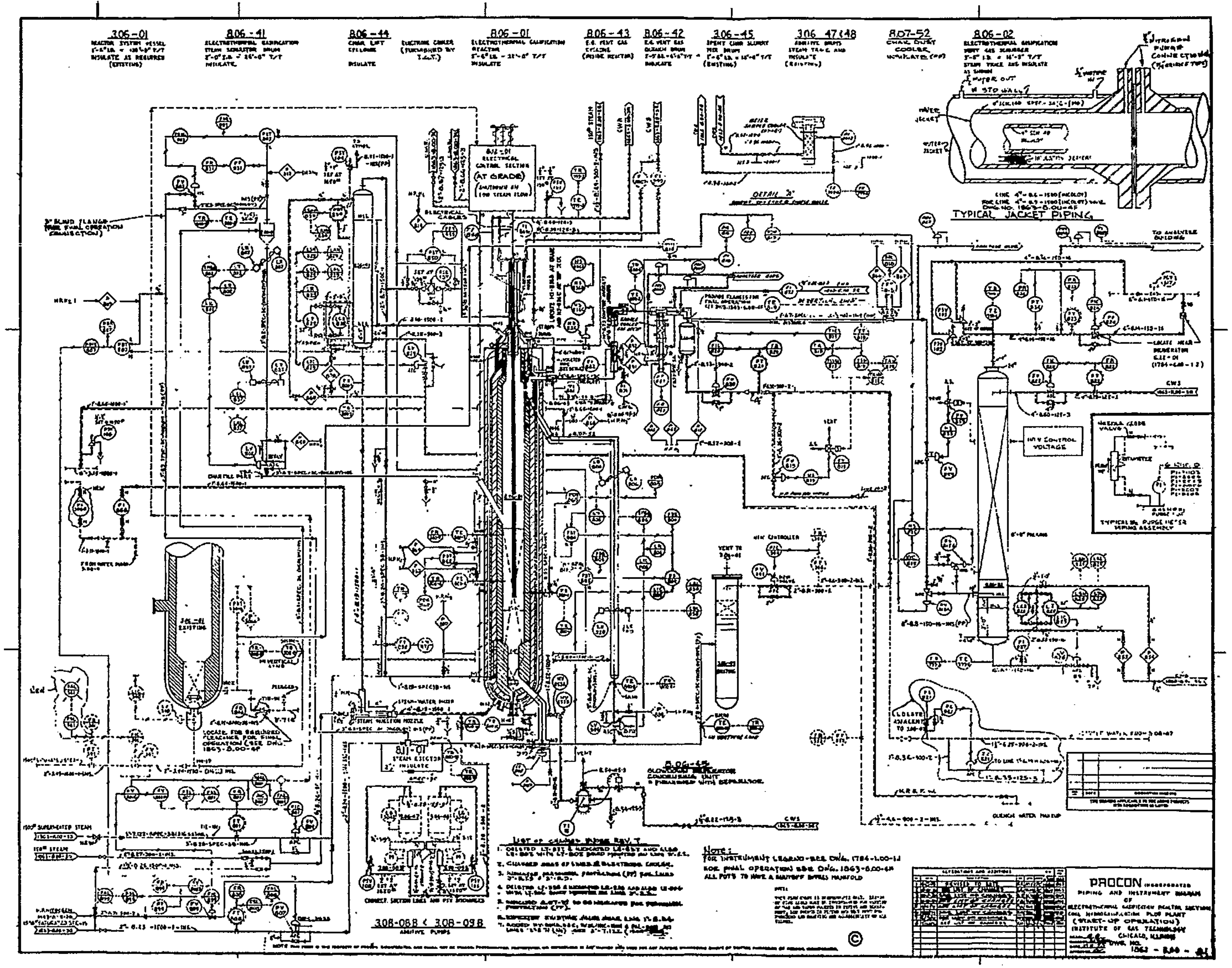


Figure 4a.2-19. PIPING AND INSTRUMENTATION DIAGRAM – INITIAL OPERATION

4a.2-55-6

detectors used to monitor solids levels in high-pressure piping. The combination of field- and panel-mounted controllers, recorders and alarm indicators provide proper and adequate information necessary to maintain stable operation of the system.

4a. 2.5.1.1 Char Feed and Discharge

The high-pressure saturated steam, which conveys char from the hydrogasifier to the char-lift cyclone, is controlled by the FIC 341 station. Under FIC 341 control, steam flows at a rate to maintain the appropriate superficial velocity in the 3-inch transfer line to deliver the steam-char mixture from near grade to the char lift cyclone at an elevation of 130-feet. The char exiting the cyclone flows into a vertical transfer pipe with a butterfly-type throttling valve (LV-802), installed about 80-feet below the cyclone, which maintains a char level in the line. The elevation of the cyclone was set to correspond to a height above the butterfly valve that would enable a leg of the various hydrogasified chars, 10 to 15 pounds per cubic foot bulk density, to seal against the electrothermal gasification reactor pressure. The char then flows by gravity into the reactor. The control scheme of the char feed consists of maintaining the required solids leg in the pipe as indicated by a radiation-type detector (LX-802) located at a specified level and linked to a pneumatic level controller (LIC-802) for adjusting the position of valve LV-802. Four high-pressure nitrogen purge stations are situated along the transfer line to provide adequate aeration of the char and also can be used to "blast" packed solids should this occur.

4a. 2.5.2 Reactor

The reactor system is a single-stage fluidized bed operated under bed-level control (LIC 805), which activates a solids discharge valve at the reactor bottom (LV-805) as required to maintain the desired bed height.

Additional bed-pressure drop and temperature indicating devices are located at various reactor levels to monitor bed conditions. The spent char leaving the reactor is carried by high-pressure saturated steam (PV-807) which has been combined with the carrier steam from the char-lift cyclone and, after picking up additional char fines, is conveyed to the water slurry-mixing drum. The char fines exit the reactor from the underflow of an internal cyclone, down through a water-cooled transfer line, and are picked up by the steam-char mixture from the reactor bottom. The flow rate of the char fines is determined by a level-control system similar to that of the char feed. A radiation-type detector (LX-806) is linked with a pneumatic controller and butterfly-type throttling valve (LV-806) that maintains a bed level in the char fines transfer line that allows the fines to flow by gravity into the steam-carrier system.

High-pressure water flow to the slurry mix drum is controlled by FIC-344 to cool the char, condense the carrier steam and make up a char-water slurry of aboug 30 to 70 weight-percent distribution. The slurry is let down in pressure and sent to disposal as previously described in the HYGAS operation.

Instrument tubing lines to the reactor, char feed and discharge lines, and product gas lines all have nitrogen purge and blowback systems to prevent plugging by solids.

The char bed is fluidized with high-pressure nitrogen during the start-up of the system, controlled by FIC-899, until the reactor temperature is well above the boiling point of steam at operating pressure. The nitrogen is then replaced by high-pressure superheated reactant steam through FIC-801, and the unit is brought to the desired operating conditions. A settled bed of hydrogasified char is essentially a short-circuit condition in the electrothermal reactor. It is imperative, therefore, that proper fluidization be maintained at all times when power is applied to the load. To prevent a fault condition from occurring, should fluidizing gas flow suddenly be lost to the reactor bed, a control system is included to monitor the flow of either fluidizing nitrogen or steam. The control system is so arranged that, if a minimum flow setting required for fluidization is not maintained, a signal opens the main circuit breaker to prevent an overcurrent situation in the bed (PDSL 8011).

Pressure balancing between the reactor and water jacket is critical because the inner reactor shell is designed for 150 pounds per square inch operation, and is monitored by a pressure differential station (PDT-850) between the reactor (8.06-01) and the water-jacket steam separator drum (8.06-41). A pressure rupture disk set at 100 pounds per square inch is located in the line connecting the two vessels. The disk protects against high-pressure differentials caused by process upsets.

The steam-water mixture in the water jacket passes to the steam separator drum. Excess steam flows through a fixed orifice (FT-832), combines with reactant steam from FIC-801, and is let into the reactor. A water level is maintained in the steam separator by LIC-829, adding make-up water as required, and returns it to the water jacket at the reactor bottom. This stream is combined with saturated steam through a steam-water mixer should make-up steam by required.

Protection of the reactor system against pressure in excess of the design value of 1650 pounds per square inch is provided by a pressure relief valve (PSV-104) located at the steam-separator drum and open to the atmosphere.

A manual blowdown system is attached to the water jacket at the reactor bottom for periodic flushing of the jacket. A water sampling station is also installed, as well as provision for the addition of chemicals to the water jacket to maintain water quality.

4a.2.5.1.3 Product Gas Handling

The product synthesis gas leaves the reactor vessel through the internal cyclone (8.06-43) into the first jacketed piping section (described under 4a.2.3.5 Special Piping). After passing through a venturi flow indicator (FT-841), product gas enters a desuperheater (8.06-42) where the 1900°F gas is quenched with high-pressure water (FIC-820) and cooled to 600°F.

The gas stream passes through another venturi (FR-818) and is then let down in pressure to 75 pounds per square inch (PV-815A and 815B). The saturated gas is water quenched in the vent gas scrubber (8.06-02), metered (FT-823), a side stream is continually analyzed, and then is sent to the HYGAS plant gas-flare header. Cooling water to the vent-gas scrubber is controlled by FIC-822. Water discharge is by level control (LIC-825), and waste water is sent to the plant sewer system.

A high-pressure valve (FV-859) is located in the product gas line before pressure letdown for emergency "blocking in" of the high-pressure side of the unit. It will automatically close in the event of a power failure or air loss, and also can be manually operated by a board-mounted hand switch.

4a.2.5.2 Final Operation

The piping and instrument diagram of the system for the integrated operation is shown in Figure 4a.2-20. The char feed, char discharge and reactor operate as in the initial operating phase. The product gas, instead of going into the desuperheater, will be transported by the jacketed pipe (section 4a.2.3.5 Special Piping) directly to the hydrogasification reactor.

A steam ring is installed in the jacketed line so that additional steam to the hydrogasification section can be added through FIC-880, if conditions require additional steam. Also shown are the various cooling water and nitrogen flowmeters for the jacketed pipe.

4a.2.6 Construction

The construction program was developed following definition of the process, and was developed in accordance with the detailed design of the system components as described previously. Space had been allocated in the original plot plan developed for the initial construction phase of the HYGAS pilot plant. Long-delivery items were placed on order before the Guaranteed Maximum Price (GMP) Contract was executed with the subcontractor. The system vessels, switch gear, power supply and alloy material composed the bulk of these long-delivery items, and were purchased during the second half of 1970.

The subcontract with the fabricator was negotiated in February, 1971 according to schedule. It called for mobilization at the construction site on April 12, 1971 and the installation to be completed the week of November 4, 1971.

Figures 4a.2-21, -22, -23, and -24 compare the scheduled-versus-actual progress to completion of the engineering, purchasing, material received and construction phases of the program.

No major problems were encountered during the construction of the electrothermal unit but, because of conflicts in scheduling and testing near the end of construction, the unit was completed at year-end 1971 instead of mid-November, 1971.

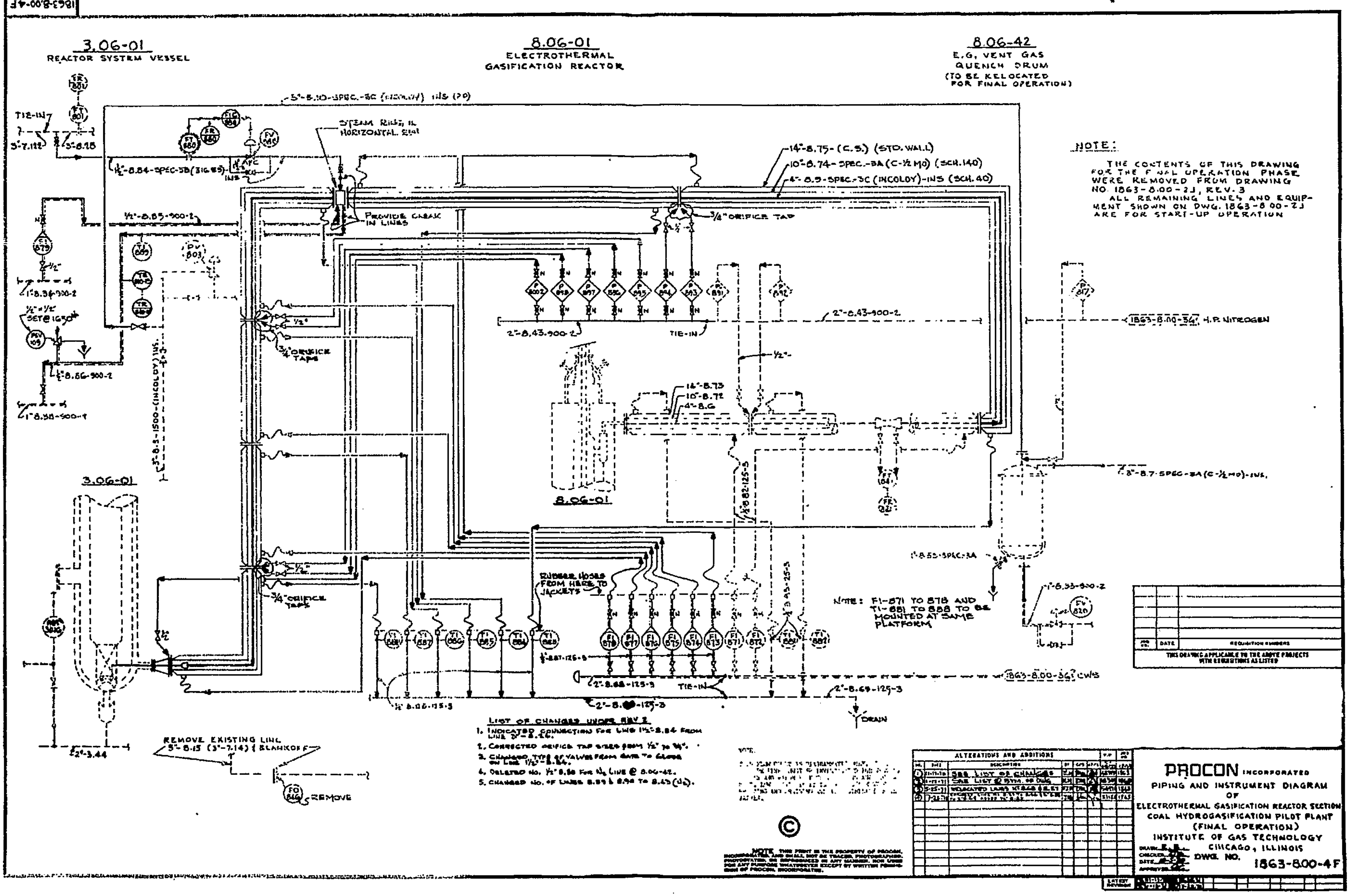
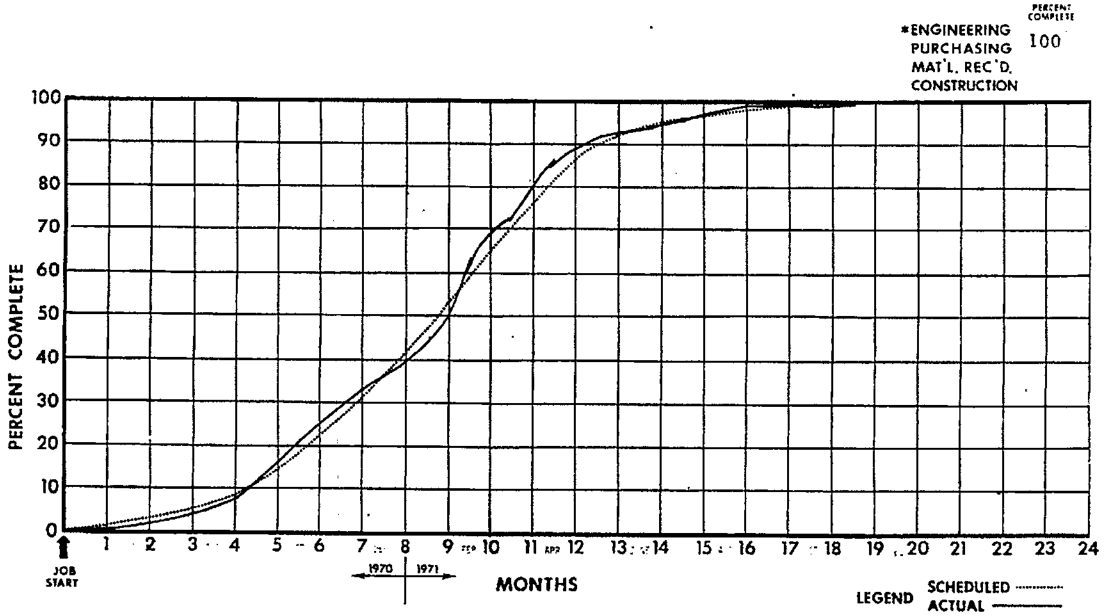


Figure 4a.2-20. PIPING AND INSTRUMENT DIAGRAM – INTEGRATED OPERATION

4a.2-46-B



A7506 1426

Figure 4a.2-21. ENGINEERING COMPLETION CHART — SCHEDULED VERSUS ACTUAL

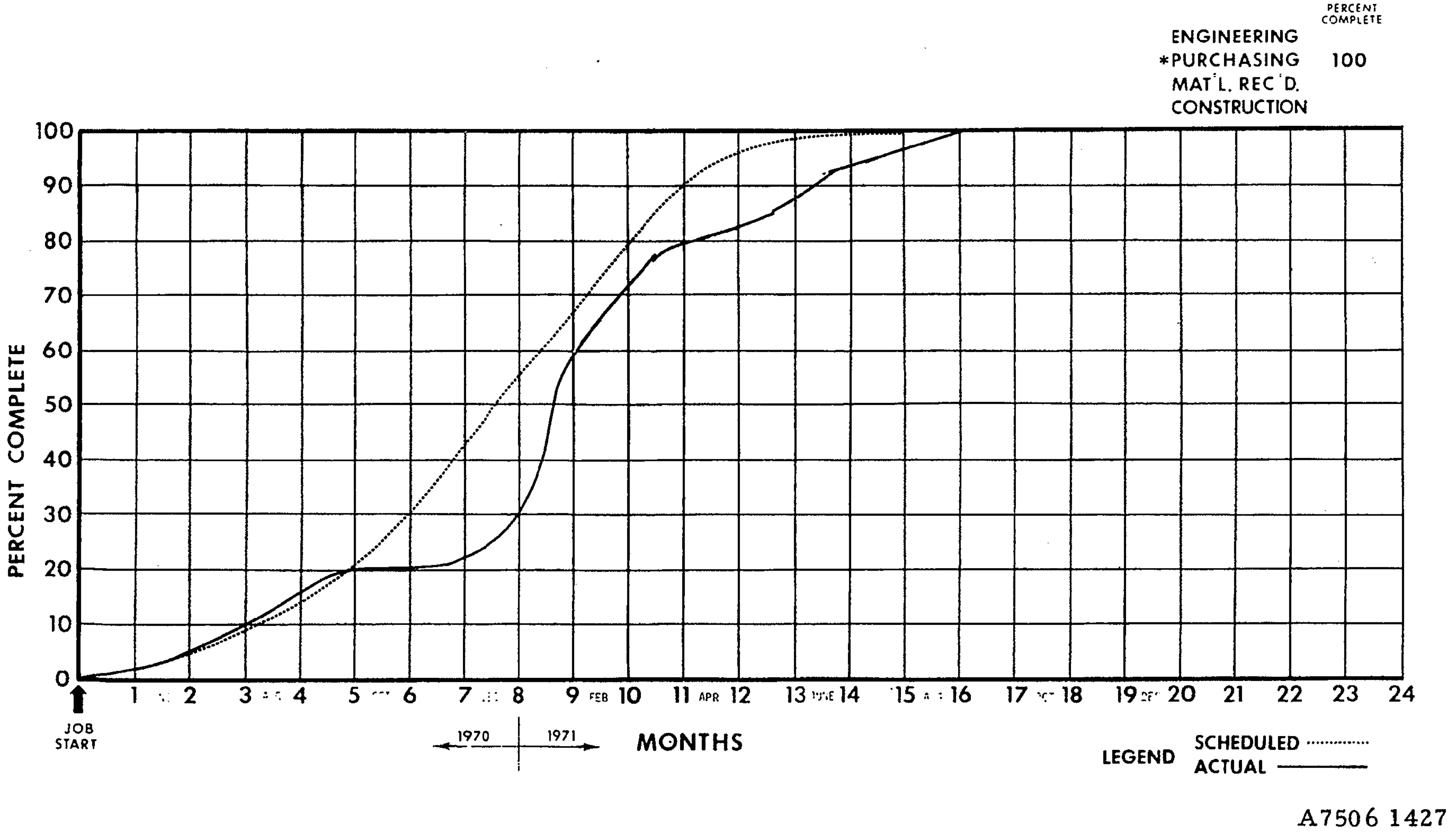
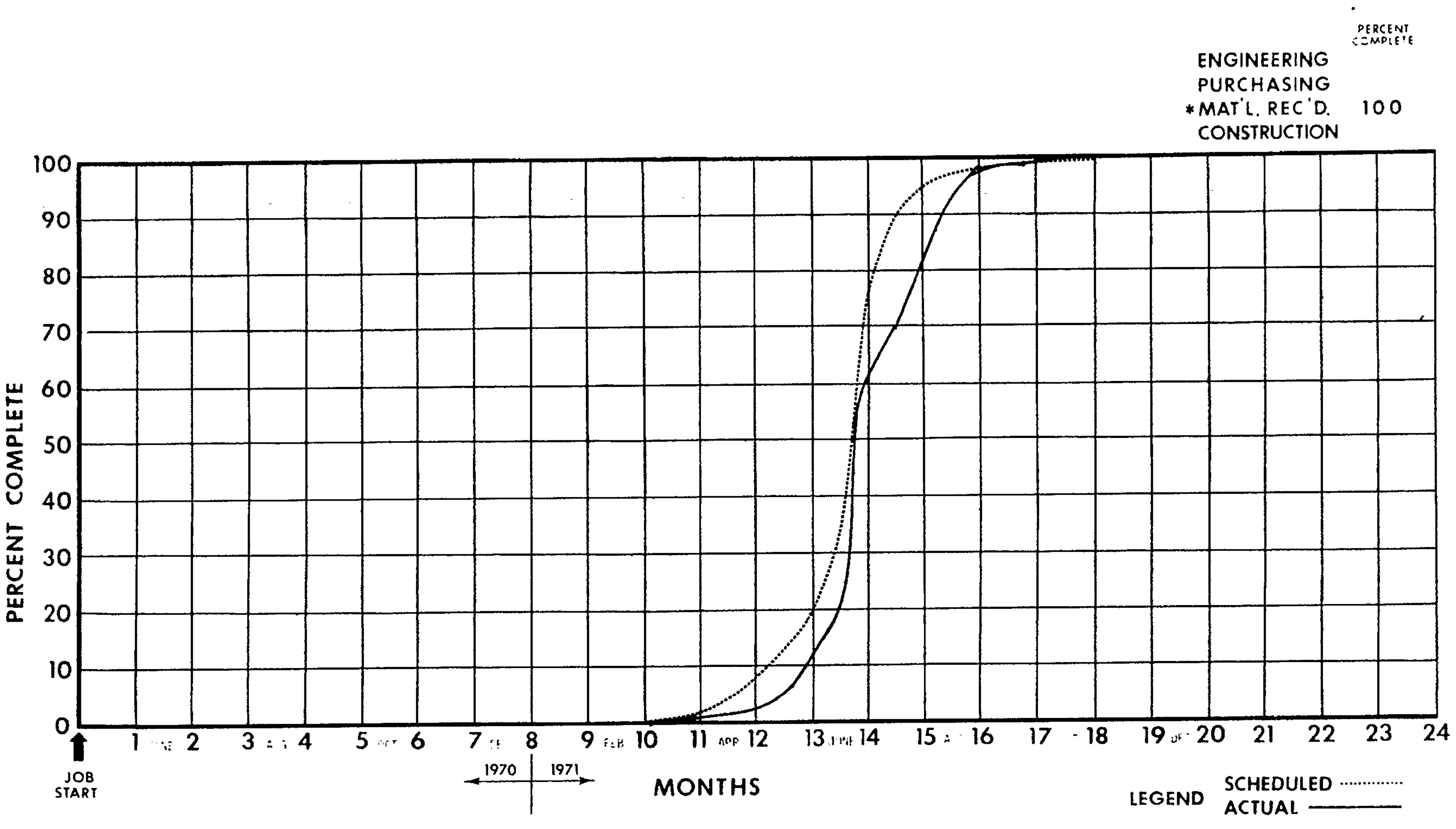
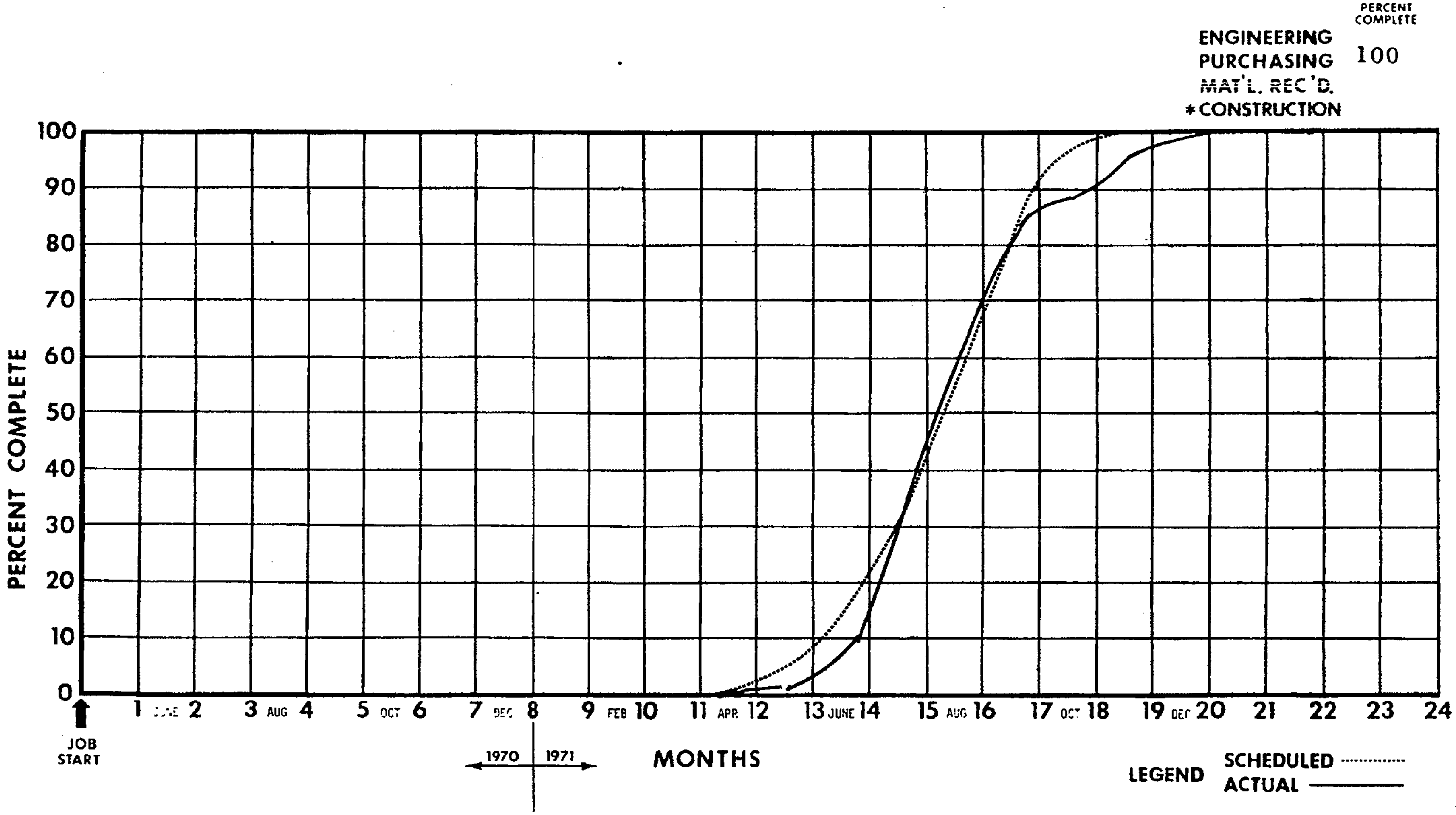


Figure 4a.2-22. PURCHASING COMPLETION CHART – SCHEDULED VERSUS ACTUAL



A7506 1428

Figure 4a.2-23. MATERIAL RECEIVED COMPLETION CHART – SCHEDULED VERSUS ACTUAL



A7506 1429

Figure 4a.2-24. CONSTRUCTION COMPLETION CHART — SCHEDULED VERSUS ACTUAL

APPENDIX 4a.2-A

Construction of Equipment

This appendix contains detailed specifications and drawings of the special equipment items used in construction of the 2.25 megawatt electrothermal gasification system.

4a.2-A1. General Description of Transformer and Rectifier

The equipment will be used to supply electric power to an electrothermal gasifier. It is located at an altitude of less than 5940 feet.

The following ambient temperatures are not to be exceeded, all temperatures in degrees, centigrade.

1. Absolute maximum, 40°C
2. Average 24 hour temperature 30°C
3. Maximum water temperature 24°C (75°F)

This proposal covers dc power supplies, utilizing silicon rectifying devices designed to operate from a 12.00 KV, 3 phase, 60 HZ system, utility system which is transformed through a 5000 KVA, 3 phase, 60 HZ transformer to 4.16 KV. The transformer has a minimum impedance of 5.86% on tap position 1.

The substation equipment covered by this proposal consists of a combination regulating rectifier transformer, silicon rectifier with heat exchanger, a disconnect switch compartment and a set of unmounted control components.

The regulation of the rectifier is based on a system which has an impedance of 2.79 ohms on a 12 KV base at the low voltage terminals of the stepdown transformers (which corresponds to approximately 7600 amperes symmetrical),

The regulating-rectifier transformer will have an impedance of 10% on a 4 MVA base with 4160 volts on the primary and the tap changer in the position of minimum impedance.

The regulator will vary the voltage from 703 VDC at 3200 amps to 1185 VDC at 1900 amps. The load will be a constant 2.25 MW over the range.

The rectifier will be rated 100% continuous. This rating will apply with one diode out in any rectifier leg.

The rectifier will be designed to provide a current output which oscillates between 0.5 and 2 times the DC average value corresponding to an average load of 2.25 MW when the voltage is in the range of 703 VDC to 1185 VDC.

The equipment will be designed to sustain a fault on the DC bus for a period of 7 cycles with one diode out in any rectifier leg. Since our experience indicates that no more than 70% of the calculated theoretical DC bolted fault current has been obtained on similar installations on the DC bus the diode compliment has been determined accordingly. The impedance of the line from the stepdown transformer to the rectifier transformer, the impedance of the anode bus, the impedance of the rectifier bus work, the impedance of the DC bus to the point of fault and lack of a firmly bolted joint at the point of fault account for the difference.

Our calculation indicated that the maximum fault that can be obtained at the terminals of the rectifier transformer is 14,150 amperes symmetrical.

Power factor and efficiencies, if requested, will be calculated by NEMA standards.

Applicable standards of the United States of America Standards Institute, Institute of Electrical and Electrical and Electronic Engineers, and National Electrical Manufacturers Association shall apply unless exception is stated.

The assembled components of equipment included in this proposal are listed in the Bill of Material on the following pages.

Detailed descriptions of these assembled components are included in separate sections of this proposal.

4a.2-A2 Transformer Specification and Tests Performed

SCOPE AND BASIS OF SPECIFICATION

This specification proposes apparatus designed, manufactured and tested in accordance with Westinghouse practice and the latest applicable IEEE, USA and NEMA Standards.

This apparatus will have a continuous rating as indicated on page 1. The hot-spot rise will not exceed 65°C rise and by resistance will not exceed 55°C. The transformer may be operated continuously at rated output kva at 105% normal rated output voltage, or at zero load and 110% normal rated output voltage without exceeding 55°C rise by resistance. All based on load power factor of 80% or higher.

WESTINGHOUSE SUPER-INSULDUR SYSTEM OF INSULATION

This system of insulation will permit operation of a 55°C rise transformer at 12% increase in capacity continuously with a resulting temperature of approximately 65°C rise by resistance with normal life expectancy. The kva overload permitted by USA Guides based on the 55°C average rise rating may be <u>added</u> to the 65°C average rise rating without increase in rate of loss of life. PDL 48-069-14A.

AIR COOLING (OA)

Cooling equipment will be supplied to provide a self air-cooled rating as indicated on page 1.

LOAD TAP CHANGER, TYPE UTT

The three-phase load tap changer will be designed to vary the AC voltage applied to the rectifier transformer in 16 steps. The voltage range will be as indicated on page 1 of this specification. All steps below rated voltage will be at a current to the transformer current at rated kva. PDL 48-064-26.

ALTITUDE

The transformer is designed for operation at an altitude of 3300 feet or less.

COVER MOUNTED BUSHINGS

Transformer will be equipped with cover mounted bushings of 8.66 KV class with terminations suitable for flexible connectors.

LV THROAT

A flanged cover-mounted throat will surround the low voltage epoxy bushings and will be suitable for connection to a silicon rectifier.

LV TERMINALS

The LV terminals will be arranged non-standard R1, R4, R6, R2, etc. for an external USA-25 or 26 connection made outside the transformer.

AUTOMATIC RESETTING RELIEF DEVICE

The device is factory set to operate at 10 psi, relieving any excessive pressure build-up resulting from internal disturbance. Upon relief of pressure the relief cover resets preventing entrance of moisture. The unit will include alarm contacts. PDL 48-065-4A.

PRESSURE RELAY

A Westinghouse sudden-pressure relay will be mounted in the gas space above the oil for detection of internal faults. The manually-reset alarm circuit will be suitable for operation at 120 volts AC. PDL 48-065-1A.

DIAL-TYPE HOT-OIL THERMOMETER

One unit complete with alarm contacts will be provided to indicate the temperature of the hottest liquid. The dial will be located on the tank wall convenient to the design. PDL 46-716-5B.

LIQUID-LEVEL GAUGE

A magnetic gauge with low-level alarm contacts is provided to indicate continuously the level of the insulating liquid. PDL 48-062-1B.

INSULATING OIL

Sufficient Wemco "C" oil will be supplied for filling the unit to the normal oil level. The physical characteristics of the oil are listed on PDL 45-063-100 included in the proposal.

Unit will be shipped with oil.

OIL PROTECTION

SEALEDAIRE construction will be supplied for preservation of transformer oil and insulation. PDL 48-063-2B.

TANK PRESSURE STRENGTH

The transformer tank will be designed to withstand full vacuum.

BASE

The base will be designed for ease of skidding or rolling in both directions.

PAINT FINISH

Paint finish will be Westinghouse dark blue-grey, USA #24 color paint applied to a properly prepared surface.

POWER SUPPLY

A source of 240 volts with a 120-volt, center tap, single-phase power supply for operation of the tap-changer motor and control equipment will be supplied with the transformer.

ALARM DEVICES - CONTACT RATINGS

(all devices except sudden-pressure relay)

Voltage	Non-inductive Load Amps.	* Inductive Load Amps.
125 AC	10	10
250 AC	5	5
125 DC	0.5	0.05
250 DC	0.25	0.025

* = L/R Less than 0.026
L = Inductive in henries
R = Resistance in ohms

Sudden-pressure Relay

(seal-in relay contact ratings)

Make (All Loads) Amps.	Carry (All Loads) Amps.	Break Type of Load for N.O. & N.C. Contacts (Amps.)		Contact Voltage
		Resistive	* Inductive	
20	10	10	5	115 AC
20	10	5	2.5	230 AC
20	10	5	3.0	24 DC
20	10	2	1	48 DC
20	10	.5	.25	125 DC
20	10	.1	.05	250 DC

* = L/R equal or less than 0.026
L = Inductive in henries
R = Resistance in ohms

TRANSFORMER ACCESSORIES

The transformer will include the following standard accessories:

a) Stainless steel nameplate.
b) Two tapped grounding pads for grounding of the tank.
c) Combination oil drain and filter press valve. A built-in 3/8-inch sampling device will be located between the main valve seat and the pipe plug.
d) Upper filter press valve.
e) Jack bosses for jacking the assembled transformer.
f) Lifting lugs for lifting the assembled transformer.
g) Lifting eyes for lifting the transformer cover.
h) Necessary manholes and filling plug in the transformer cover.
i) All alarm and control leads wired to a metal control cabinet.

STANDARD TESTS

1. Resistance measurements of all windings on the rated voltage connection of each unit and at the tap extremes of one unit only of a given rating.
2. Ratio tests on the rated voltage connection and on all tap connections.
3. Polarity and phase relation tests on the rated voltage connection.
4. Iron loss and exciting current at rated voltage on the rated voltage connection.
5. Impedance and load loss at rated current on the rated voltage connection of each unit and on the tap extremes of one unit only of a given rating.
6. Temperature test or tests shall be made on one unit only when one or more units of a given rating are produced at the same time, except that these tests shall be omitted when a record of a temperature test on a duplicate or essentially duplicate unit is available. On units equipped with auxiliary cooling equipment to provide more than one kva rating, temperature tests shall be made at the self-cooled, intermediate, and maximum auxiliary cooled ratings.
7. Applied potential tests.
8. Induced potential tests.

REGULATING & RECTIFIER TRANSFORMER PERFORMANCE SPECIFICATION

FOR

NEG. NO. NCGI-4152 SPECIFICATION NO. 331124 DATE 11/30/70

CLASS	FORM	KVA FOR	PHASE	CYCLES	A-C. WINDING	D-C. WINDING	SERVICE
OA	Core	2752 KVA [illegible] KW.	3	60	4160	SUITABLE FOR** 1185 VOLTS D-C. @ 1900 amps	Electro-Chemical

ADDITIONAL APPROXIMATE VOLTAGES

A-C. WINDING	16 positions under load from approximately 925 volts to**** 515 volts AC
D-C. WINDING	None

CONNECTIONS FOR OPERATION

TRANSFS. IN BANK	TO TRANSFORM FROM	PHASE	CON-NECTED	TO REQUIRED A-C. VOLTS FOR	PHASE	CON-NECTED
1	4160 VOLTS	3	***** Wye	1185** VOLTS D-C. @ 1900 amps		*** Delta

TEMPERATURE RISE

COOLING

LOAD IN PER CENT OF RATED KVA	HOURS	MAX. RISE BY RESIST.	INSULATING LIQUID	
100	UNTIL CONSTANT			METHOD OF COOLING Self-air (future forced air)
FOLLOWED BY	100%	55	Oil	COOLING WATER ______ GAL. PER MIN. AT ______ P.S.I. AT THE TRANSF.

DIELECTRIC TESTS

KV. BASIC IMPULSE LEVEL:- A-C. WINDING 75 DC Winding 60 BIL

APPLIED VOLTAGE TESTS (TO OTHER WINDINGS AND GROUND)			INDUCED VOLTAGE TEST
A-C. WINDING	D-C. WINDING		2 TIMES NORMAL VOLTAGE
19 KV	15 KV	KV	

APPROXIMATE DIMENSIONS AND WEIGHTS (NOT FOR CONSTRUCTION PURPOSES)

APPROXIMATE DIMENSIONS IN INCHES		APPROXIMATE NET WEIGHT IN POUNDS	
OUTLINE NO.	47-060-77	CORE AND COILS	8000
HEIGHT OVERALL —A	97	CASE AND FITTINGS	6600
PROJECTED FLOOR SPACE (BXC) —B	109	T.C.U.L. (DRY)	2550
—C	109	INSULATING LIQUID	6900
HEIGHT OVER CASE—D	87	TOTAL WEIGHT	24,050
		GALLONS INS. LIQUID	140

*Nominal rating; maximum operating 2,250 KW

**1185 volts DC when secondary connected Delta

***External connections permits wye or delta connection.

****Range for delta secondary connection

*****Westinghouse to have option to make primary wye or delta with agreement from Procon

4a. 2-A3 Transformer Tap-Changer

The load tap changing mechanism will be equipped with the following:

1. EXTERNAL MECHANICAL POSITION INDICATOR
2. OPERATION COUNTER - to record the number of tap changer operations.
3. SAFETY SWITCH - interlocked with the hand-crank mechanism so that the motor circuit is opened when the mechanism is operated by hand.

REMOTE-LOCAL MANUAL LOAD-TAP-CHANGER CONTROL

Remote-local manual control of the load tap changing mechanism will consist of the following equipment mounted in a weatherproof enclosure on the unit:

1. CONTROL RELAY - for operation of tap changer motor in response to manual control switch.
2. "RAISE" - - - "LOWER" manual control switch to operate the tap changer.
3. MOTOR PROTECTION - thermal magnetic breaker for protection of the motor and control circuits.
4. "REMOTE-LOCAL" CONTROL SWITCH - to connect the control circuit for operation either at the transformer or at the customer's control panel. Control from both locations cannot exist simultaneously.
5. TERMINALS for energizing the control circuit from an external source for testing. Normal supply source must be disconnected before test voltage is applied.

The following will also be supplied for mounting on a 1/8-inch panel:

6. RED LAMP - to indicate tap changer "off" position.
7. "RAISE" - - - "LOWER" manual control switch to operate the tap changer mechanism.
8. SYNCHROTIE remote electric position indicator.

4a.2-A4 Rectifier Specifications

Description

SILICON RECTIFIER

Silicon rectifier 3200 amperes continuous, 1185 volts dc, one silicon section connected in a double way 6 phase circuit. Rating applies with one diode out in any rectifier leg. See General Description for overload ratings. Based on maximum ambient temperature of 24°C for the cooling water with the water to be less than 20 GPM at a pressure of 90 PSI.

RECTIFIER CONSTRUCTION

Each rectifier unit will be housed in a welded steel cubicle. When specified, the device will be equipped with interlocks so should a door be opened while the unit is energized, the AC breaker will be tripped. Observation ports will be included and so located that inspection can be accomplished without personnel entering the cubicle.

Rectifier AC buses will be located to make possible connecting to the ac bus to be provided by others.

AC and DC buses will be of welded aluminum construction. This includes connections to the reactor bus, reactor bus and straps, heat sink assemblies, and DC collector bus. Weld cross-sections will be equal to or greater than the cross section of the smaller bus to which the electrical connection is made.

All insulation will be of a highly track resistant glass polyester material. Supporting insulators will be of conventional design and shape for easy inspection or replacement in case of damage. Air baffles, while not part of the primary insulation system, are of the same material to provide maximum, high integrity electrical spacing.

Diodes, current limiting diode fuses, surge networks, surge network fuses, surge network fuse indicating lights, diode overtemperature relays (alarm and trip) are all located for easy access, and arranged for convenient replacement.

CURRENT BALANCE BETWEEN DIODES

Forced current balancing is employed to avoid unequal heating of the diode junctions in the various parallel paths. This forced current balancing is accomplished by a "C" core reactor scheme. This scheme effectively overcomes the inherent differences in lead reactances, diode forward drop, variation in fuse voltage drops, and other factors which tend to cause unequal distribution in the parallel connected diodes. In addition to requiring no maintenance, this scheme enables the user to avoid the necessity of replacing failed diodes with devices with matched forward drop characteristics or subsequent "trimming" of reactors when the unit is placed back in service.

These simple, low loss (approximately one watt at rated current) "C" core reactors assure that the maximum resultant unbalance will not exceed 1% per parallel path. The rectifier will be designed to deliver rated current with maximum current unbalance between paralleled diodes and with one diode out per leg at the same time.

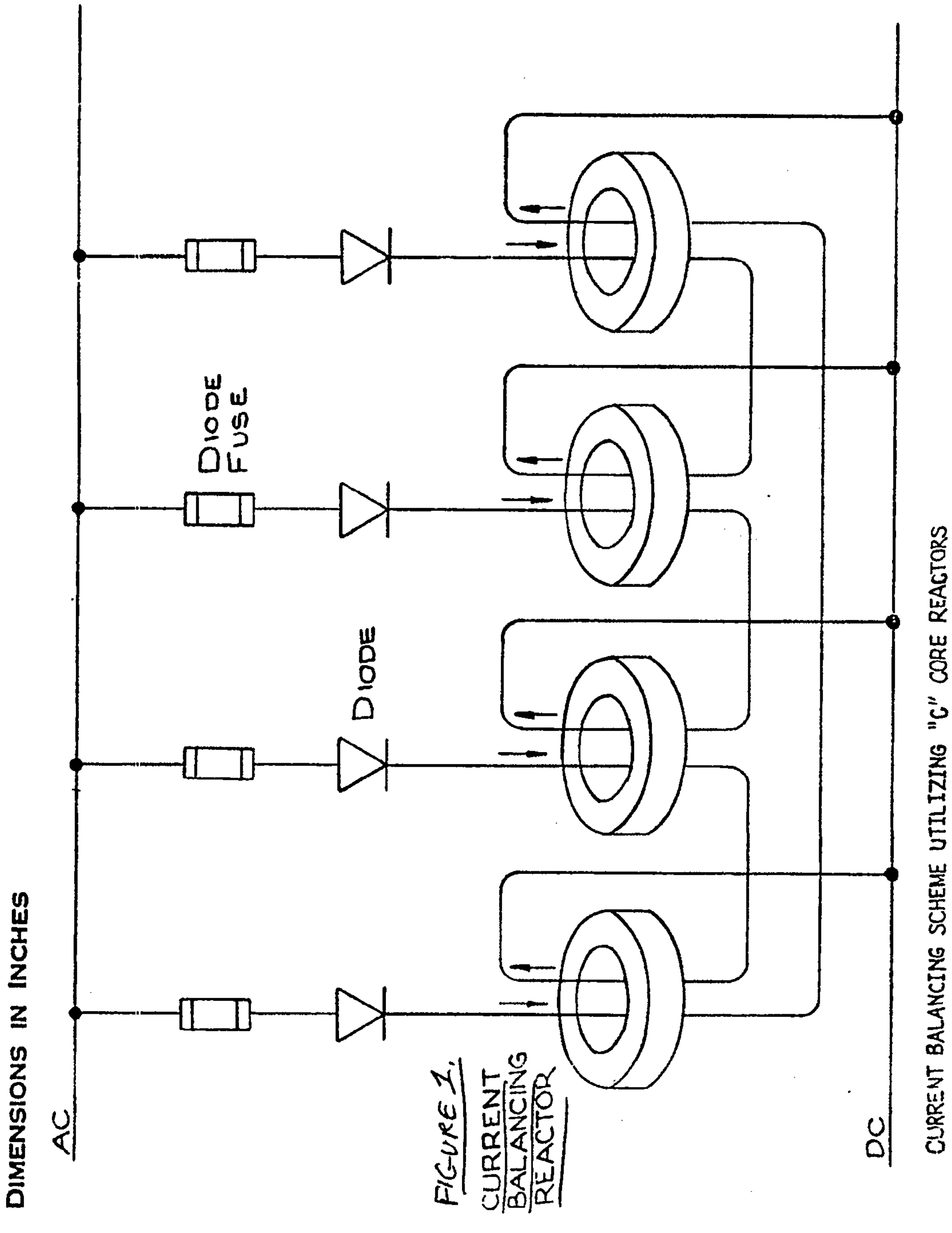


Figure 4a.2-A-1. CURRENT BALANCING REACTOR

DIODE FUSING

Proper application of the silicon diodes requires close coordination of the diode and series connected semiconductor fuse characteristics. The fuse selected must have (1) thermal capacity to enable the equipment to furnish its nameplate rating without fuse failure, (2) current limiting ability compatible with the diode short time rating and the available system short circuit currents, (3) voltage rating adequate for supporting the peak voltage to which it is subjected. The fuse selected for this application is consistent with the above requirements.

Fuse failure indication will be accomplished by paralleling the fuses, with a neon lamp in series with a resistor. Diode fuse failure lamps are mounted on an insulated panel, are equipped with long creepage distance current limiting resistors, and can be easily viewed through the cubicle observation ports.

DESCRIPTION OF SILICON RECTIFIER CUBICLE

Cooling - Air-to-water heat exchanger

Air-to-water heat exchangers are employed when a rectifier must be sealed from the outside atmosphere and an adequate source of raw water is available.

The rectifier cooling system consists of a recirculating closed air cooling system for the diodes, fuses and AC bus, DC bus and other auxiliary losses and consists of an air-to-water heat exchanger and fans. Air is circulated in a closed air system through the air-to-water heat exchanger. The heat losses are transmitted to the water circulated through the air-to-water heat exchanger.

The heat exchangers have copper water tubes with aluminum fins. Heat exchangers and fans are manufactured by the Sturtevant Division of Westinghouse.

The fans and the heat exchangers are sized to cool the air to the desired temperature at the maximum ambient temperature.

An air overtemperature thermometer is to give a trip contact operation when the maximum permissible temperature is reached.

The water will be brought into the cubicle through copper plumbing and will permit cleaning the strainer.

The water will flow into the heat exchanger. The heat exchanger is equipped with a drain line and valve.

The water from the heat exchanger will leave the heat exchanger through copper plumbing

CONTINUED

AIR-TO-WATER HEAT EXCHANGERS

This type of cooling offers the following advantages:

1. A single heat exchanger to remove all losses
2. Minimum maintenance due to the use of a direct connected fans and a captive air system
3. Eliminates the need for deionizers, distilled water, a second water system with it's associated pumps, flow devices, etc., and all the maintenance required for their operation.
4. Eliminates the hazards inherent with the systems in which water is used as a coolant in electrically energized bus and devices. Minimizes leak possibilities, now restricted to a remote location. Eliminates potential problems caused by condensation.

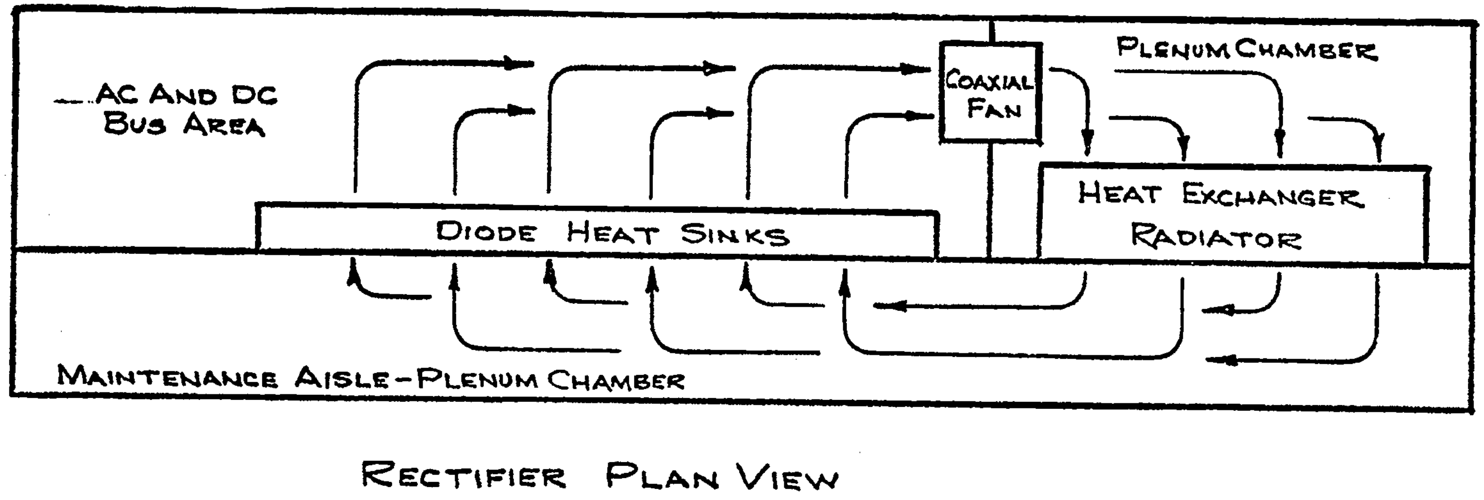


Figure 4a.2-A-2. AIR-to-WATER HEAT EXCHANGER SCHEME

4a.2-A5. SCR Switch Module Specification

Electrothermal Gasification Power Unit

Description of Service

Duty: Continuous

Input from transformer secondary:

Primary voltage	4160 volts
Configuration	delta-delta
Line-line secondary voltage	600-960 volts
Primary tap changer	8 or 16 position for voltage range
Primary circuit breaker	7 cycle
Transformer rating	2725 kva over full range

Output: To six phase uncontrolled bridge rectifier and load.

Load: Fluctuating non-linear resistance with instantaneous current approximately proportional to square of the applied voltage. Approximately 3% reactance from power leads. For the load:

$$I = K(t)\ V^2$$

where K(t) is a function of time which typically various thru a factor of four over periods of 5-10 seconds due to natural fluctuations of load physical characteristics. Primary function of AC switches is to regulate power flow to this load. However, in this prototype unit, the unregulated mode of operation must also be accomodated, so that the switches must handle the 5-10 second fluctuations in load current.

Rectifier rating: 2250 kw average over full input voltage range.

AC switch line current: 2560 amperes rms averaged over ten (10) seconds at 30° retard (1-1). During normal operation in the unregulated mode, the DC output current can oscillate between one third and 5/3 of the long time (greater than ten second) DC average value corresponding to the 2560 rms line current. The solid state devices should be selected on the basis that this oscillation takes the shape of a square wave about the DC average current with a period of ten seconds. This service is continuous. Thus, the rms line current can oscillate between 4230 and 860 amperes with the ten second period.

Fault conditions: The AC switches shall handle the anticipated short circuit faults where the ultimate protection is the 7 cycle primary breaker

Description of Service (Continued)

Rms symmetrical fault current: 14130 amperes
Peak symmetrical fault current: 20,000 amperes
Unsummetrical (DC offset) peak fault current:

35,000 amperes approx. 1st cycle
27,000 amperes approx. 2nd cycle
22,000 amperes approx. 3rd cycle
20,000 amperes succeeding

Redundancy: The design shall handle the anticipated load with one parallel branch out of the circuit due to operation of a fault protection device.

Rating vs. retard: The modules shall supply the full DC current rating of the rectifier (3200 amperes) at retard angles up to 90° (l-l) or 60° (l-n).

Protection: Fuses, voltage dividers, RC networks, etc. shall be provided as required to protect the modules against voltage surges and to remove a faulted solid state device from service. In addition, electrical indication of a faulted device shall be provided to the control unit.

Cooling: Modules will be water cooled with clean water which will be circulated and passed thru a heat exchanger against 20 gpm raw water at not more than 24°C.

Pressurization: The cabinet housing the modules will be pressurized by filtered air to prevent admittance of solid contaminents.

Description of Modules

Quantity	Description
3	Single phase AC switch module, liquid cooled, 925 volt rms line-line, 2560 amp rms (average) line current

Description of Modules (Continued)

The 88-0087 modules shall each include:

Quantity	Description
24	SCR's 6 in parallel by 2 in series each direction of current.
12	Balancing reactors
12	Fuses and holders
12	Resistive voltage divider networks
24	Fault detectors and indicators
1 or more	RC snubber networks
1	KSP 40 DDE 4" x 4" x 20" clip cell assembly

Associated heat sinks, hoses, piping, mounting, buswork, etc. as required.

Modules will be mounted with the long 36" dimension vertical.

The solid state devices will be closely matched by the vendor with the objective of obtaining satisfactory performance in the series-parallel arrangement in the present service.

The AC switch modules will be warrantied from the first day of the calendar month following the date indicated by the date code on each module to be free from defects in materials and workmanship and to conform to specifications furnished or approved by the seller.

4a.2-A6 Specifications for the Plasma Spray Deposition of Alumina On Incoloy Alloy 800 Pipe

PROCESS

The deposition of alumina shall be performed by the plasma arc spray process.

BASE MATERIAL

The base material shall be International Nickel's "Incoloy Alloy 800". The material shall be in the solution annealed condition.

SURFACE COATING MATERIAL

Alumina with an aluminum oxide content of 98.0% minimum. The particle size shall be - 270 mesh + 15 microns. Metco No. 105 or equivalent can be used.

POSITION

The base material shall be set up in any position that will provide a uniform coating.

PREPARATION OF BASE MATERIAL

The material surface to be coated shall be degreased, all foreign material removed and abraded according to plasma equipment manufacturer's recommendations for optimum particle adherence.. The general contour of the base material surface to be plasma arc sprayed should contain no corners.

PREHEATING

The base material shall be preheated uniformly to 200°F.

ALUMINA DEPOSITION

The alumina shall be uniformly deposited to a thickness of 0.010 ± 0.002" in the presence of a suitable gas in order to maintain concentricity with the base material. The deposition technique shall conform to normal plasma spray parameters. The thickness can be achieved by precision spraying or by grinding. The surface finish must be 10 to 15 microinches. The deposited alumina shall have a porosity of 5 to 10%. The base material temperature during alumina deposition shall not exceed 400°F.

ACCEPTANCE TEST

A companion test specimen shall be made from the same base material and coated with alumina in a manner similar to that of the work pieces. The companion specimen shall have the same diameter as the work pieces and a minimum coated length of six inches.

The test shall consist of heating and cooling the companion specimen in a neutral atmosphere. The furnace temperature shall be maintained at 1900 ± 25°F. The specimen shall be heated at a rate of 100°F/Hr., held for a minimum of one hour at 1900°F, and cooled at a rate of 200°F/Hr.

Any visible spalling of the alumina coating shall be considered a failing and the work pieces recoated.

RECOATING AND RETESTING

The alumina sprayed parts that did not meet the acceptance test of their companion test specimen can be recoated by removal of the unapproved coating and recoated with alumina as described in the specifications. In no cases shall the alumina coating exceed 0.020 inches.

Any recoated parts will require a new companion test specimen of non-tested base material to which a duplicate acceptance test shall be applied. The thickness of the alumina coating on the new companion specimen shall now be equal to the new coating on the recoated parts.

PART 4b

Steam-Oxygen Gasification

TABLE OF CONTENTS, PART 4b

LIST OF FIGURES, PART 4b

LIST OF FIGURES, PART 4b
(Continued)

LIST OF TABLES, PART 4b

4b.0 Summary of Steam-Oxygen Gasification

A summary of this work appears in section 4.0.

4b.1 Introduction

4b.1.1 Thermodynamic, Kinetic, and Associated Economic Studies

IGT has obtained a considerable body of experimental information on the hydrogasification of chars and has used this information to develop quantitative correlations to describe how fundamental parameters affect the roles of individual gasification reactions. Unfortunately, however, the experimental conditions studied have not included the combined ranges of temperatures, pressures, and gas compositions anticipated for steam-oxygen gasification.

Although the kinetic correlations developed from IGT data might be extrapolated to estimate behavior in a steam-oxygen system, such an extrapolation is subject to doubt not only because of extrapolated environmental conditions, but also because the gasification of carbon with oxygen may alter the kinetic activity of the solids for other gasification reactions.

It was necessary, therefore, to conduct an experimental program to obtain kinetic information directly pertinent to a steam-oxygen system. Results can be used to evaluate the extrapolations of the previously developed correlations. If necessary, results also can provide a basis for modifications of the correlation to describe gasification kinetics for the steam-oxygen system.

The experimental program was based on developing the necessary information to satisfy three main requirements:

1) Obtain data for developing fundamental kinetic equations to predict carbon gasification rates at conditions anticipated in a steam-oxygen gasifier; a high-pressure, high-temperature thermobalance was selected to obtain the necessary differential rate data.

2) Obtain kinetic data on integral fluidized-bed operation; to obtain this data tests were performed in a 4-inch-diameter balanced-pressure reactor. Operating conditions were varied to study how pressure, temperature, gas composition, and solids residence times affect carbon conversion to carbon oxides and methane.

3) Check and test the applicability of the correlations developed in the thermobalance apparatus for the prediction of behavior in an integral steam-oxygen gasification system. The correlations were checked by operating a fluidized-bed reactor to study the simultaneous feeding of oxygen and steam at operating temperature and pressure. Operation of the reactor also provided mechanical design information necessary for an oxygen-based synthesis gas generator.

As the above studies progressed, and as an improved kinetics model was developed, we were re-evaluating our economic analyses of the steam-oxygen HYGAS system for producing SNG in order to provide guidance in the ongoing research programs.

4b.1.2. Steam-Oxygen Gasifier Development Program

The gasifier development program was directed toward an understanding of the mechanical limitations in operating a steam-oxygen gasifier. Problems associated with backmixing and hot-spotting were studied, because they may be deleterious to the practical operability of such a system. Because sintering is an operating problem, means to avoid sintering of ash were also studied.

Tests were performed in a development unit with a reactor 6 inches in diameter. A reactor this large gives a reasonable test of mixing, and of the tendency for hot spots to form in the bed. Gas backmixing may be deleterious to reaction rates and may result in combustion of a portion of the hydrogen and methane produced. Hot spots may produce a tendency for bed agglomeration and may tend to destroy the reactivity of the char. The effect of backmixing and localized hot zones and reaction rates had to be evaluated. This information was needed for design of the steam-oxygen gasifier.

4b.2 Thermobalance and Kinetic Studies

4b.2.1 Thermobalance Apparatus

The high-pressure high-temperature thermobalance used in this work was designed to obtain reaction rate data on carbon gasification under conditions expected in the synthesis-gas generator. Because the operating temperature of the synthesis-gas generator is considerably higher than the maximum allowable operating temperature of earlier high-pressure thermobalances used at IGT, it was necessary to design a new high-temperature, high-pressure thermobalance capable of operating at these new conditions.

The thermobalance built for this project was designed for operation at pressures up to 1500 psig and temperatures up to 1900°F. The design incorporates a 2-inch-diameter, internal, thin-wall liner which is internally heated and insulated from the pressure shell. A pressure-balance system is used to maintain small pressure differences across the hot internal liner.

Figure 4b-1 is a flow diagram of the unit. This unit is designed to obtain gasification rates of partially gasified chars with gases of the composition that will exist in the synthesis-gas generator.

The thermobalance contains a microforce transducer from which the char sample is suspended into the high-temperature reaction zone. Char sample weight is continuously recorded as the char is gasified. The gasification rate is then calculated from the rate of weight change.

Continuous weighing allows measurement of instantaneous gasification rates at any conversion level within the total range of conversion achieved in a particular test. These "differential rates" are obtained at constant temperature, pressure and gas composition.

The reaction zone is held at the desired temperature by an electric heater, and unit pressure is held constant with a back-pressure regulator. Provisions are made to feed metered quantities of steam and various gas mixtures, in order to achieve the gas composition desired for each test. The exit-gas flow rates are also measured as a check on the feed-gas flow rates.

Figure 4b-2 is a simplified drawing of the reactor assembly. The reactor is internally insulated and contains a 3-zone electric furnace rated for operation at temperatures up to about 2300°F. The outer shell, which operates at only slightly above room temperature, is designed for 1500 psig operation. The design is necessarily somewhat complex because of balanced-pressure operation.

The reactor temperature can be controlled to ±5°F in the range of 1800° to 2000°F. The weight detection device with a rapid response allows for conversion rate measurements within 10 seconds of initial start-up. Basket weights with the char can be measured to an accuracy of ±0.005g with a full-scale reading of 0.5g.

4b.2.2 Experimental Data

Kinetic equations describing char gasification in synthesis gas mixture were developed from data obtained in the thermobalance apparatus. The mathematical derivation of these equations, and the correlation of the experimental data are presented for the temperature range of 1700° to 1900°F, at pressures of 500 and 1000 psig.

Experimental data were obtained for the gasification of partially gasified char at temperatures ranging from 1700° to 1900°F: at pressures of 500 and 1000 psig; and with hydrogen, steam-hydrogen, and synthesis-gas mixtures. A kinetic analysis of the data obtained was made to determine the applicability of the mathematical correlations developed in previous studies predicting gasification rates at the relatively severe conditions anticipated in a commercial-scale oxygasifier.

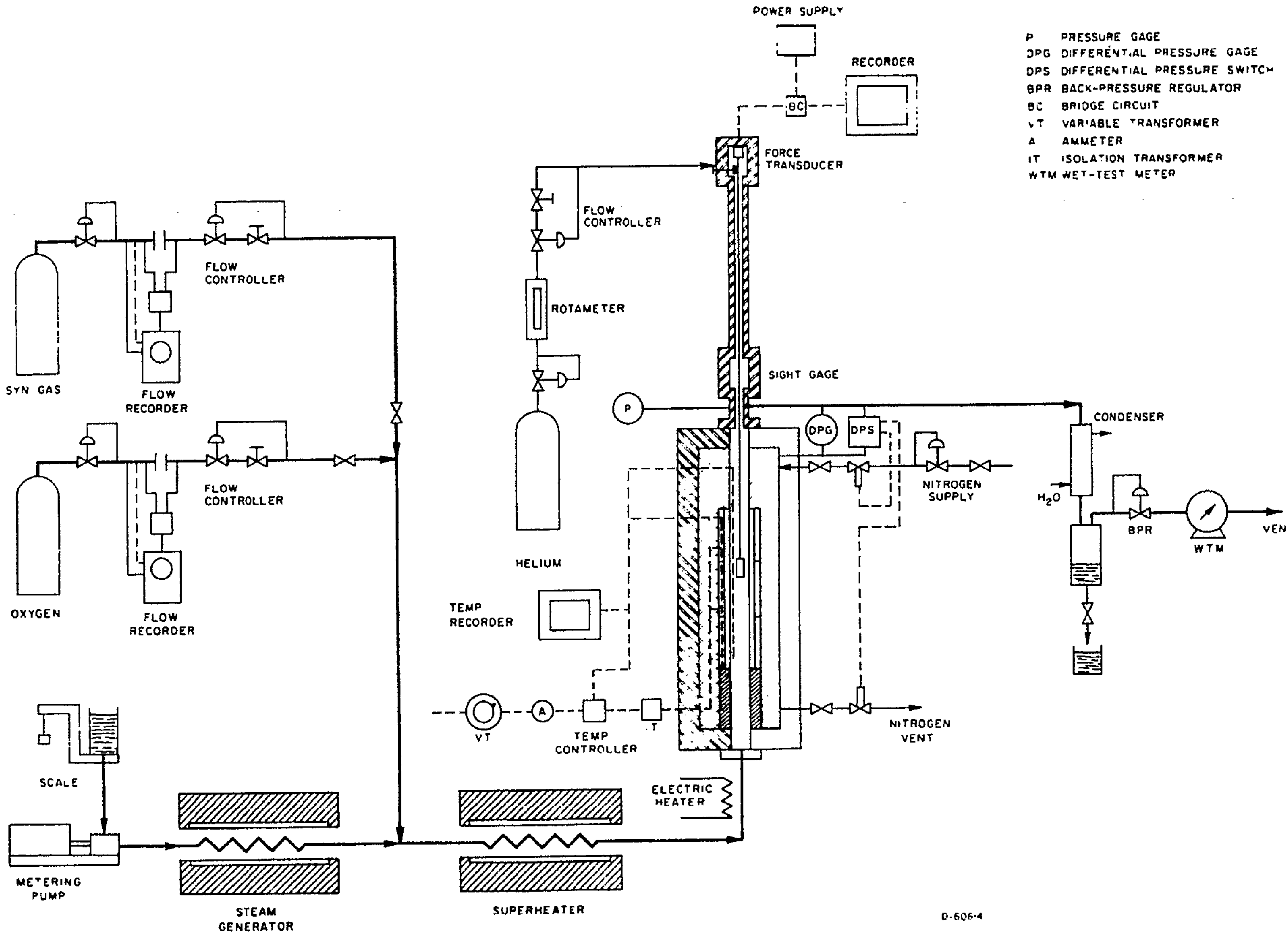


Figure 4b-1. HIGH-TEMPERATURE, HIGH-PRESSURE THERMOBALANCE

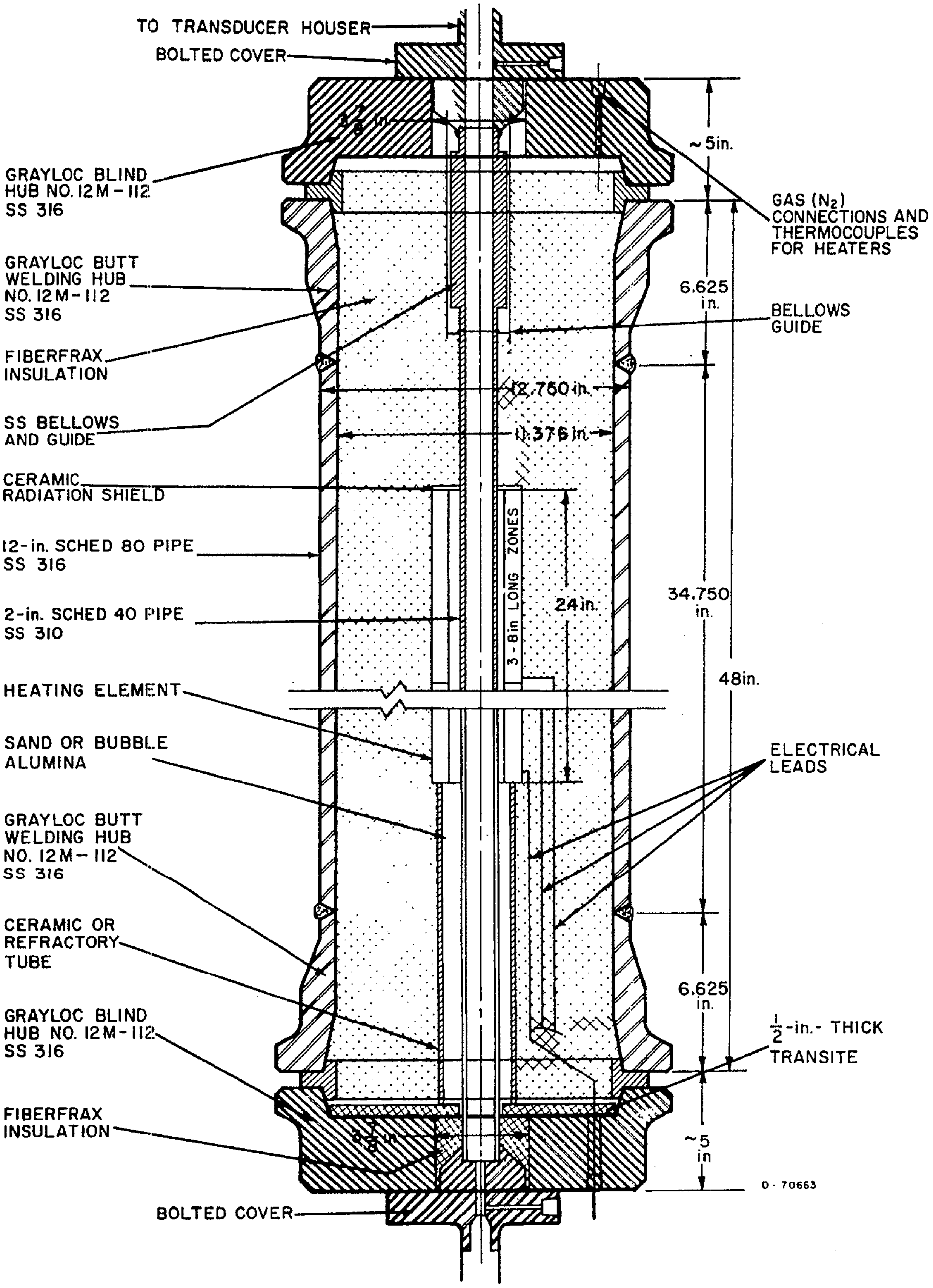


Figure 4b-2. REACTOR BODY FOR HIGH-TEMPERATURE, HIGH-PRESSURE ASSEMBLY

A representative analysis of the partially gasified Ireland mine char used is given in Table 4b-1.

Table 4b-1. TYPICAL CHEMICAL ANALYSIS OF FEED CHAR

Ultimate Analysis (dry), %	
Carbon	74.8
Hydrogen	0.93
Sulfur	1.61
Oxygen	0.12
Nitrogen	0.56
Ash	21.98
Total	100.00

Proximate Analysis, wt %	
Volatile Matter	3.23
Fixed Carbon	74.79
Ash	21.98
Total	100.00

A7506 1563

Weight loss versus time data, obtained in individual tests with this char using the thermobalance, were interpreted in terms of the following correlation:

$$\frac{dX}{dt} = k_T \cdot f_R \, (1-X)^{2/3} \, e^{-\beta X^2}$$

where

X = base carbon conversion fraction

f_R = reactivity factor dependent on particular char used

k_T = overall rate constant dependent on temperature, pressure, and gas composition, min^{-1}

β = kinetic parameter dependent on pressure and gas composition

t = time, min

The dependence of the parameters, k_T and β, in terms of the parameters described above, has been quantitatively defined from results of previous studies. For Ireland mine char, the parameter f_R is equal to unity. The base carbon conversion fraction, X, is defined according to the total amount of carbon present which was not evolved from the parent coal. On this basis, the partially gasified char used in this study has an initial base carbon conversion fraction, X_o, equal to 0.43.