5. CONCLUSIONS AND RECOMMENDATIONS

Based on the long term (>1000 hr) cross flow filter testing and evaluations conducted in this program, the following conclusions and recommendations are offered:

- The extended testing (>1000 hr) accomplished in this program using simulator facilities has confirmed the cross flow filter high collection efficiency on ash type material meeting both current emission and turbine tolerance requirements. Prior to this testing, long term filter performance was extrapolated based on short term test results. Integral to achieving this high performance level was the development of an improved, long term, high temperature, ceramic dust seal for seating and fixing the cross flow filter element.

- Improved cross flow filter durability to steady state filtrations and pulse cleaning was demonstrated. The increase in base material strength of the filter matrix and the improvements made in the filter mount and dust seal system were primary factors in achieving this improvement. However, improvements to filter fracture toughness may yet be needed to achieve filter durability to thermal process transients that can occur during plant upsets. Detecting and eliminating weak plate bonding and/or critical flaws developed during filter manufacturing will be essential to achieve this goal. Alternate filter manufacturing techniques that produce truly monolithic structures should be pursued.

- The alumina/mullite oxide matrix currently used for the cross flow filter appears suitable for a wide range of process gas conditions typical of Advanced Fossil Power Generation Systems. The gas environment of the simulator facilities used in the current testing program does not however reproduce all process gas conditions representative of actual coal fired plants. Field based material studies are being utilized for this purpose.

- Comparison of results show that the high temperature high pressure PFBC simulator facilities used in this program was effective in reproducing filtration conditions representative of actual plant operation. In addition, the simulator facilities are effective tools to reproduce filter thermal and mechanical stressing that is typical of actual plant operations. Such testing is an important dimension to evaluating long term filter durability issues. Thermal transient testing should be an integral part of any and all future hot gas filter development programs.

- Gasifier simulation testing using hot inert gas and injected char produced only similar plant trends regarding filter operating characteristics. Better simulation may be achieved if reducing gas conditions could be utilized and operated at actual temperature and pressure conditions of the gasifier applications. It appears important that both a temperature and gas density effect be included in the gasifier simulation testing.

Appendices

CONTENTS

		Page
Appendix A	PFBC Simulator Process and Mechanical Drawings.......	A-1
Appendix B	High Temperature, High Pressure (HTHP) Ceramic Filter Test Facility Process and Design Description.........	B-1
Appendix C	Analysis, Design and Qualification of the Eductor Jet Pump System for the Recirculation Gas Test Loop..	C-1
Appendix D	Pressure Drop Traces from PFBC Simulator Filter Test WRTX-9 and WRTX-11.............................	D-1
Appendix E	Assessment of Cross Flow Filter Mounting Design......	E-1
Appendix F	Pressure Drop and Gas Temperature Traces Recorded During PFBC Plant Thermal Transient Testing WRTX-76, WRTX-77, WRTX-78, WRTX-81 (WRTX-80, and WRTX-84).....	F-1
Appendix G	Pressure Drop Traces from PFBC Simulator Filter Tests WRTX-76, WRTX-77, WRTX-78 and WRTX-21 Steady State Operation...............................	G-1
Appendix H	Filter Pressure Drop Traces from Selected Test Periods During Gasifier Simulator Testing............	H-1
Appendix I	1. Characterization of the Ash and Char Fines Used in Simulator Testing.......................	I-1
	2. Characterization of Alumina/Mullite Filters Exposed in the Westinghouse PFBC Durability Test Facility..................................	I-1
Appendix J	Description of Cross Flow Filter Durability During PFBC Simulator Thermal Transient Testing.............	J-1
Appendix K	Property Characterization - Room Temperature.........	K-1
Appendix L	Hot Strength Characterization of the 1300 Hour, HTHP Tested Ceramic Cross Flow Filter................	L-1

APPENDIX A

PFBC SIMULATOR PROCESS AND MECHANICAL DRAWINGS

Figure 1 (Dwg 2D27878)	Schematic of HTHP PFBC Simulator
Figure 2 (Dwg 1301J68)	PFBC Simulator Process and Instrumentation Diagram - sheet 1
Figure 3 (Dwg 1301J67)	PFBC Simulator Process and Instrumentation Diagram - sheet 2
Figure 4 (Sketch)	PFBC Simulator General Assembly
Figure 5 (Dwg 1503E74)	Dust Collection Vessel
Figure 6 (Sketch)	Layout of Tubesheet for Two Filter Holders
Figure 7 (Dwg 2235D75)	Modified PFBC Simulator Filter Stack Weldment
Figure 8 (Dwg 2235D83)	Modified PFBC Simulator Top Half Liner Weld
Figure 9 (Dwg 2235D84)	Modified PFBC Simulator Liner Collar Weld
Figure 10 (Dwg 2235D74)	Modified PFBC Simulator Spool Transition Detail
Figure 11 (Dwg 2235D85)	Modified PFBC Simulator Piping Weldments
Figure 12 (Dwg 2235D89)	Modified PFBC Simulator Liner Pipe Weldments

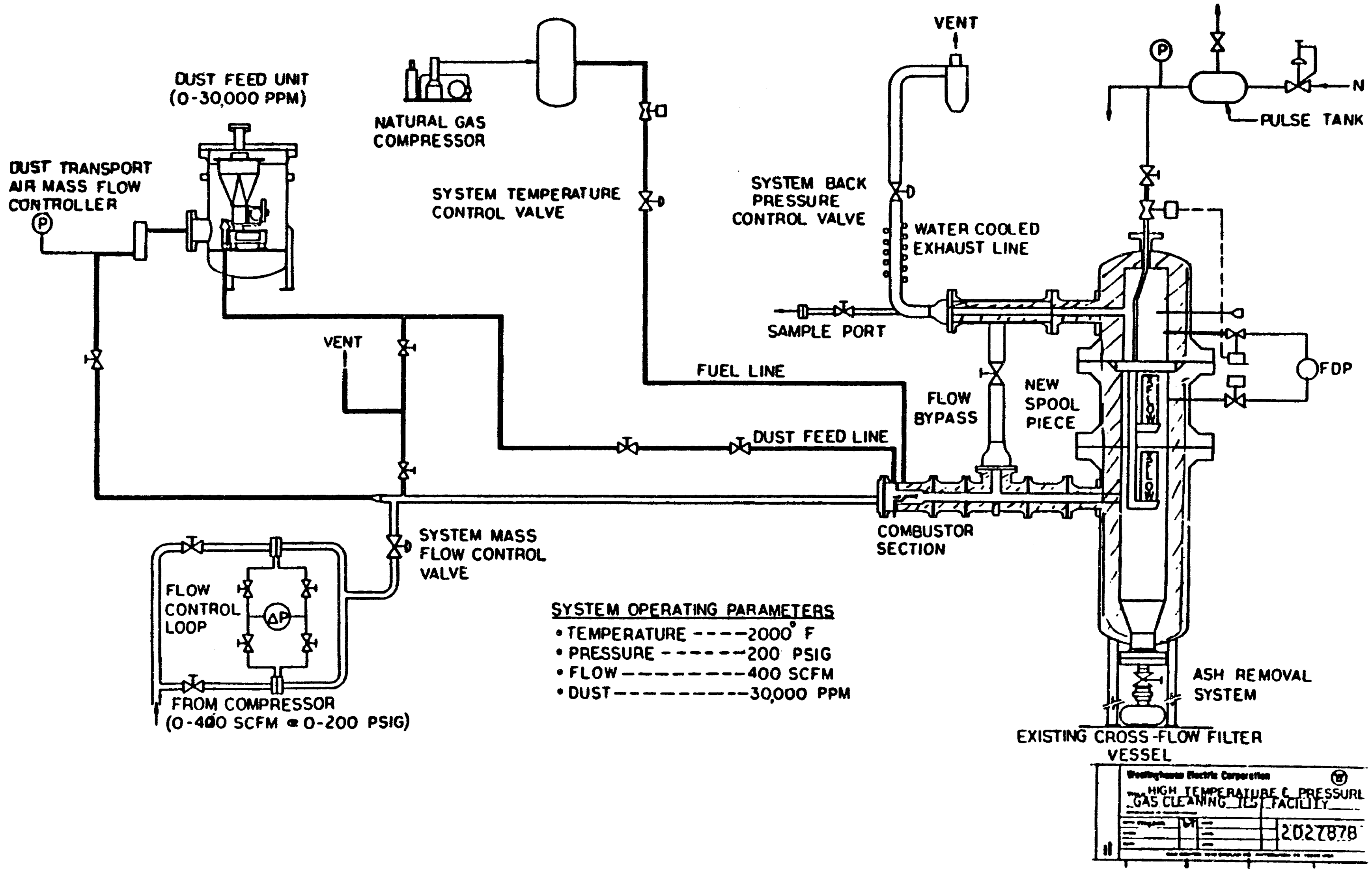


Figure A.1 - Westinghouse HTHP Simulator for PFBC Filter Testing - Schematic

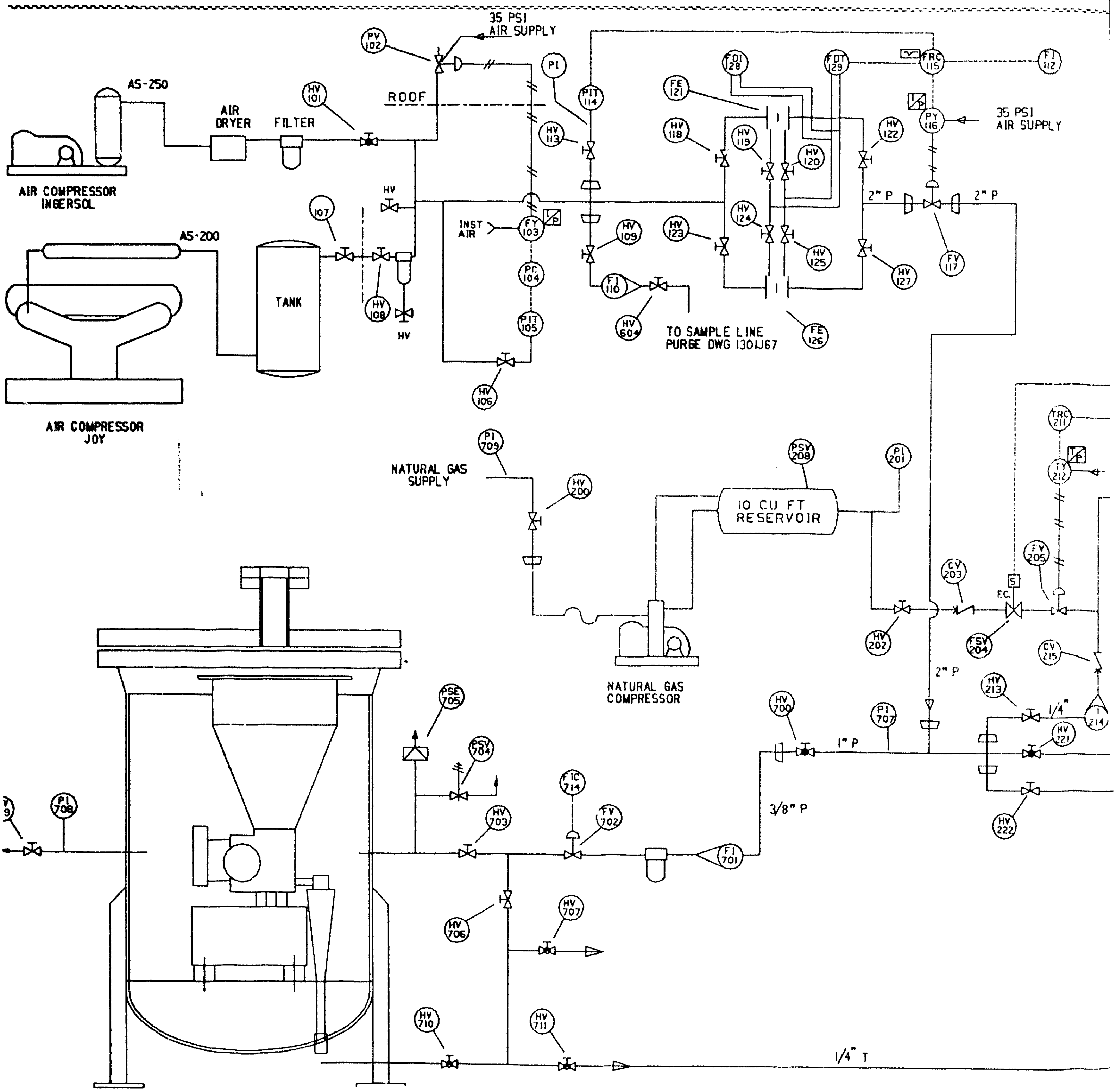
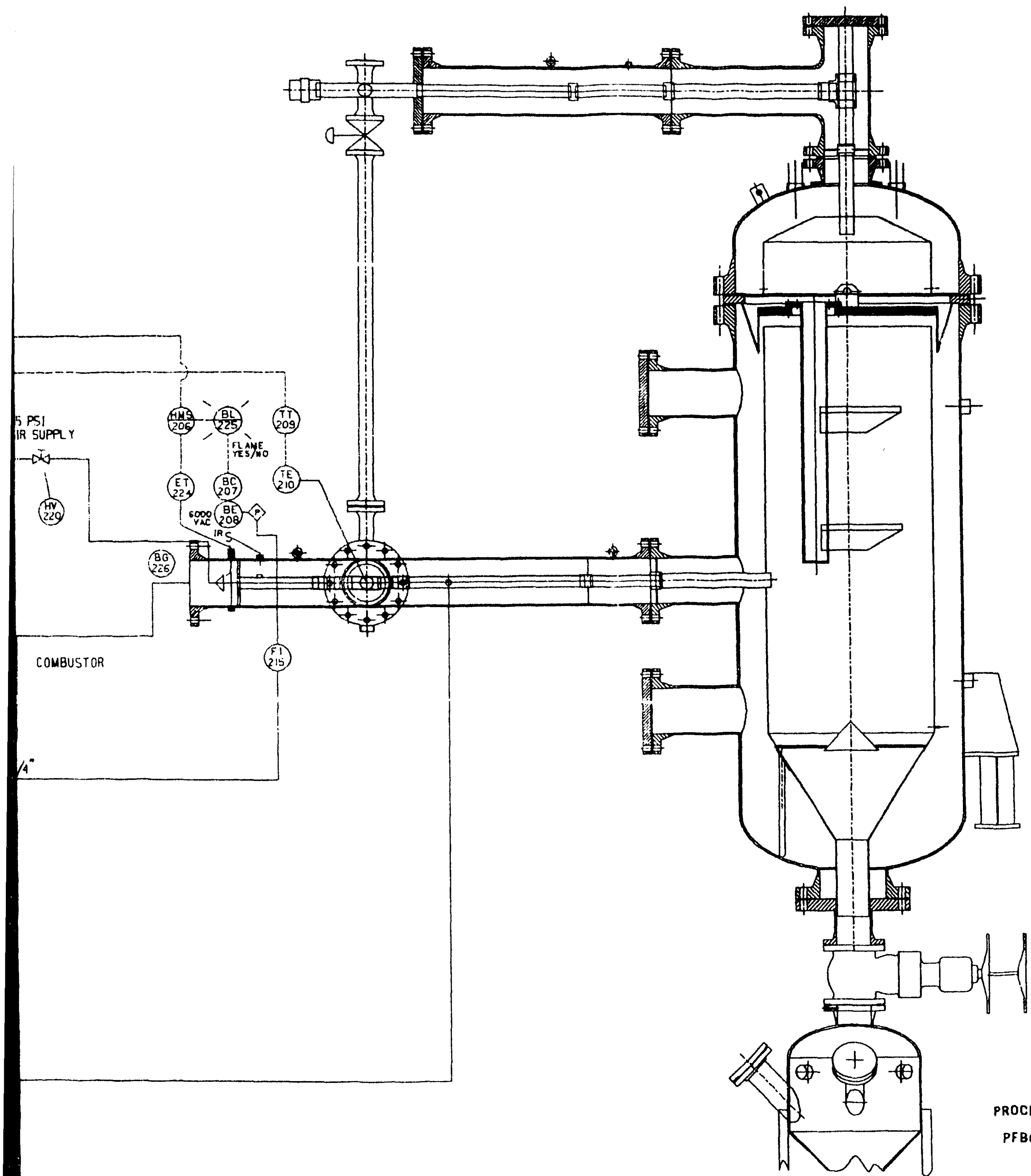


Figure A.2 - PFBC Simulator Process and Instrumentation Diagram - Sheet 1

DUST FEEDER



PROCESS AND INSTRUMENTATION
PFBC SIMULATOR

13C

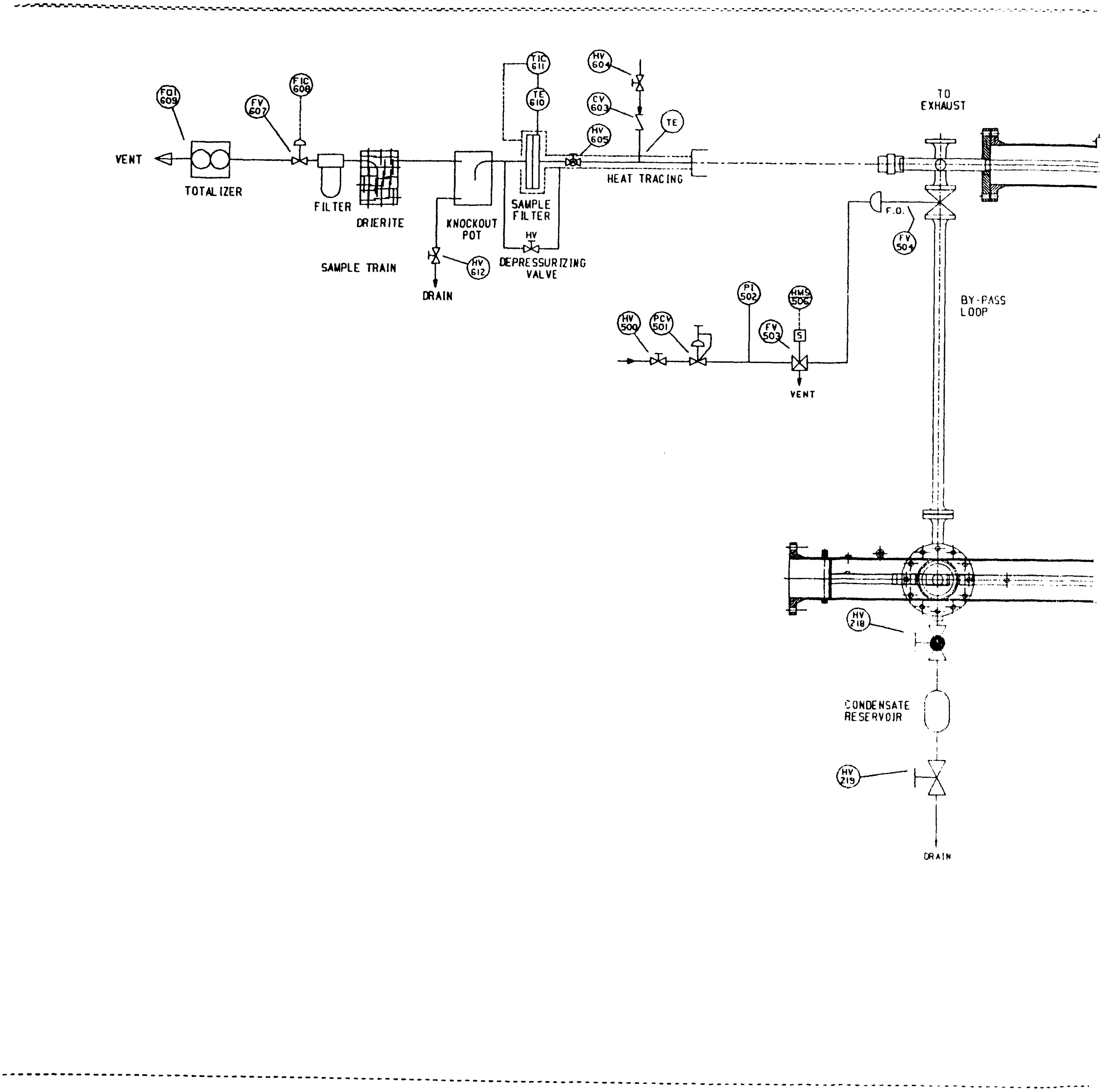
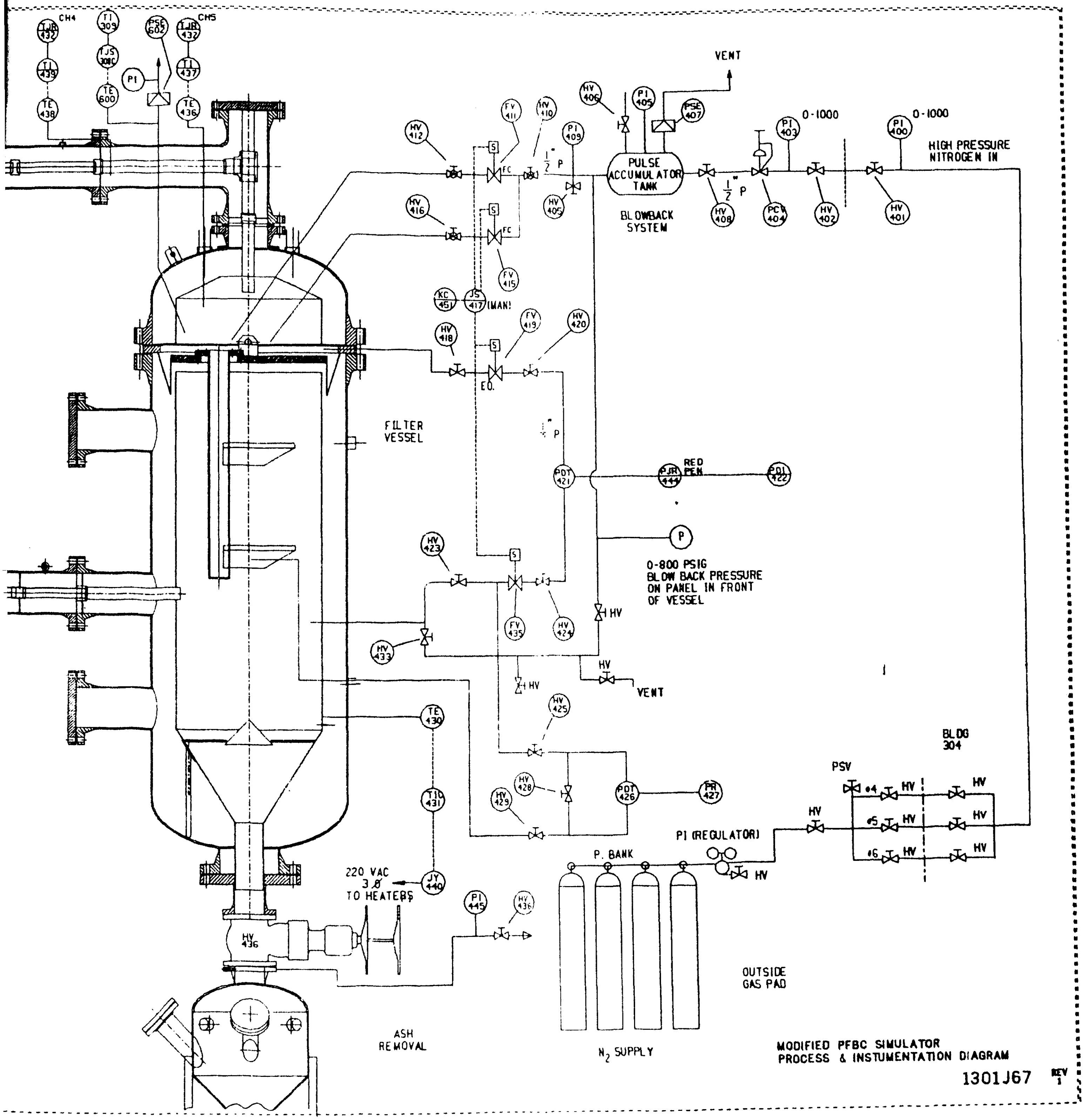


Figure A.3 - PFBC Simulator Process and Instrumentation Diagram - Sheet 2



MODIFIED PFBC SIMULATOR
PROCESS & INSTUMENTATION DIAGRAM

1301J67 REV 1

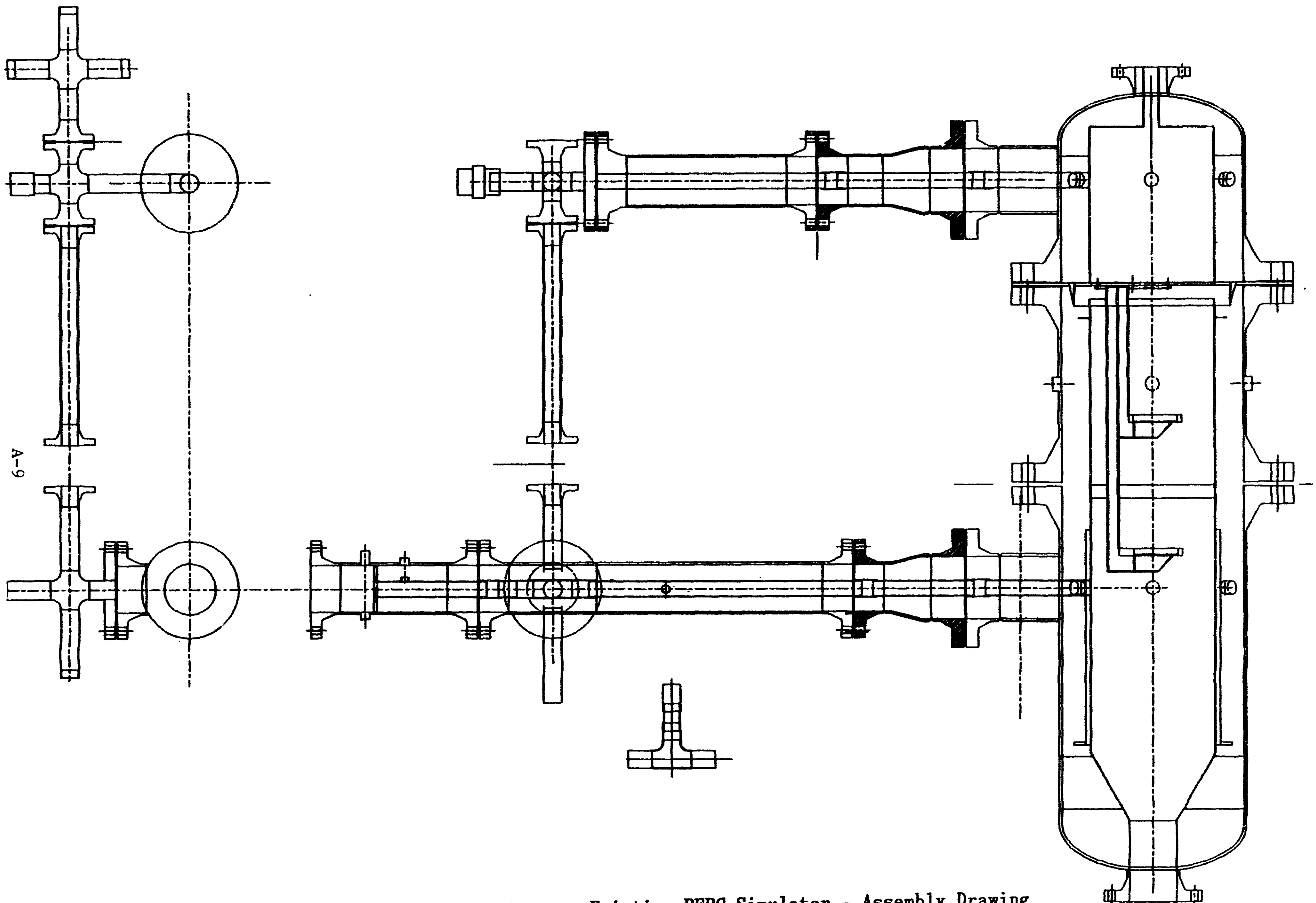


Figure A.4 - Modifications to Existing PFBC Simulator - Assembly Drawing

4th Qtr.

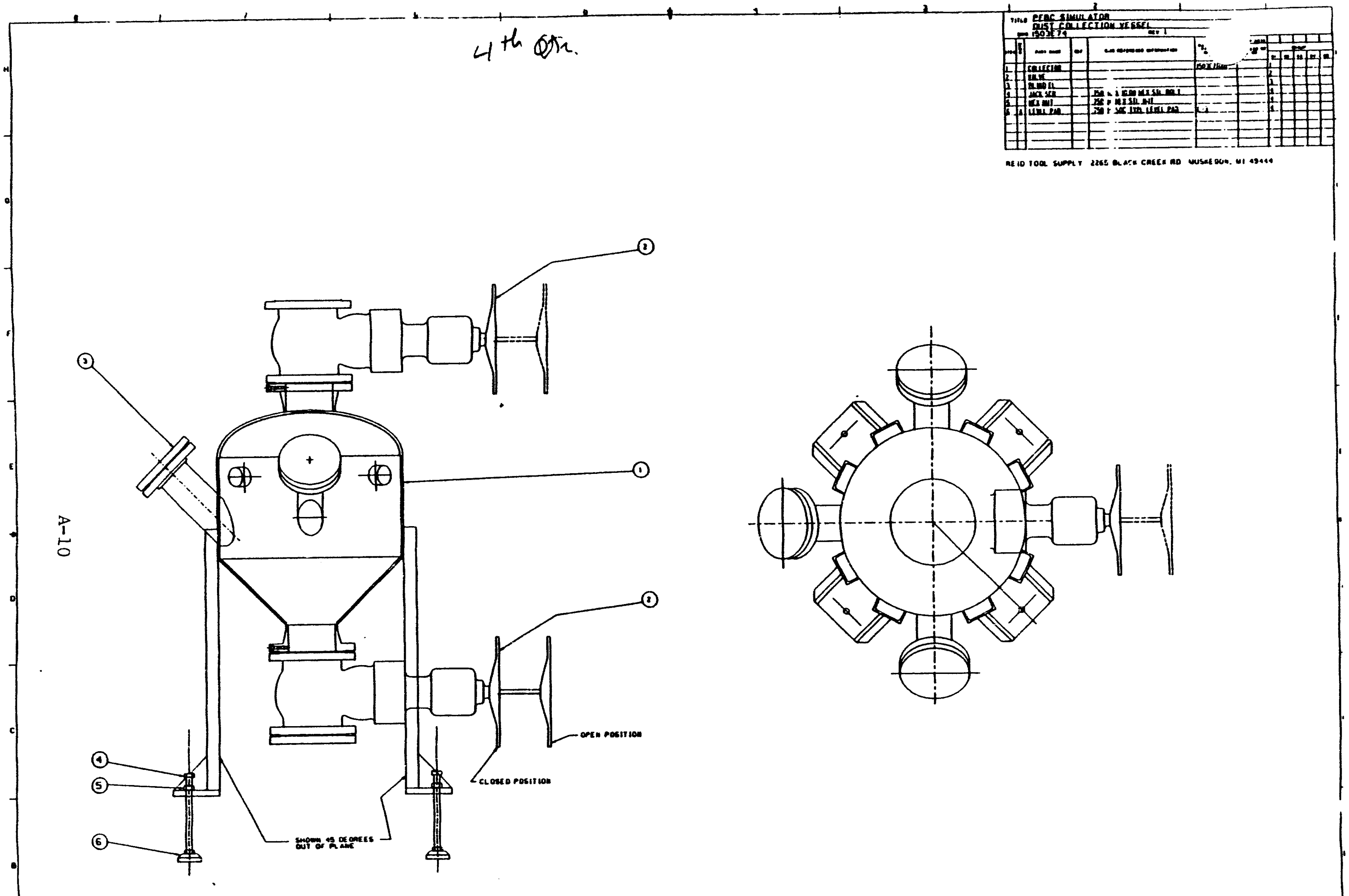
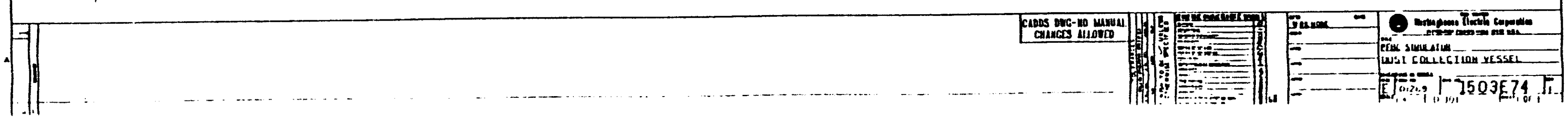


Figure A.5 - Dust Collection Vessel for New PFBC Simulator



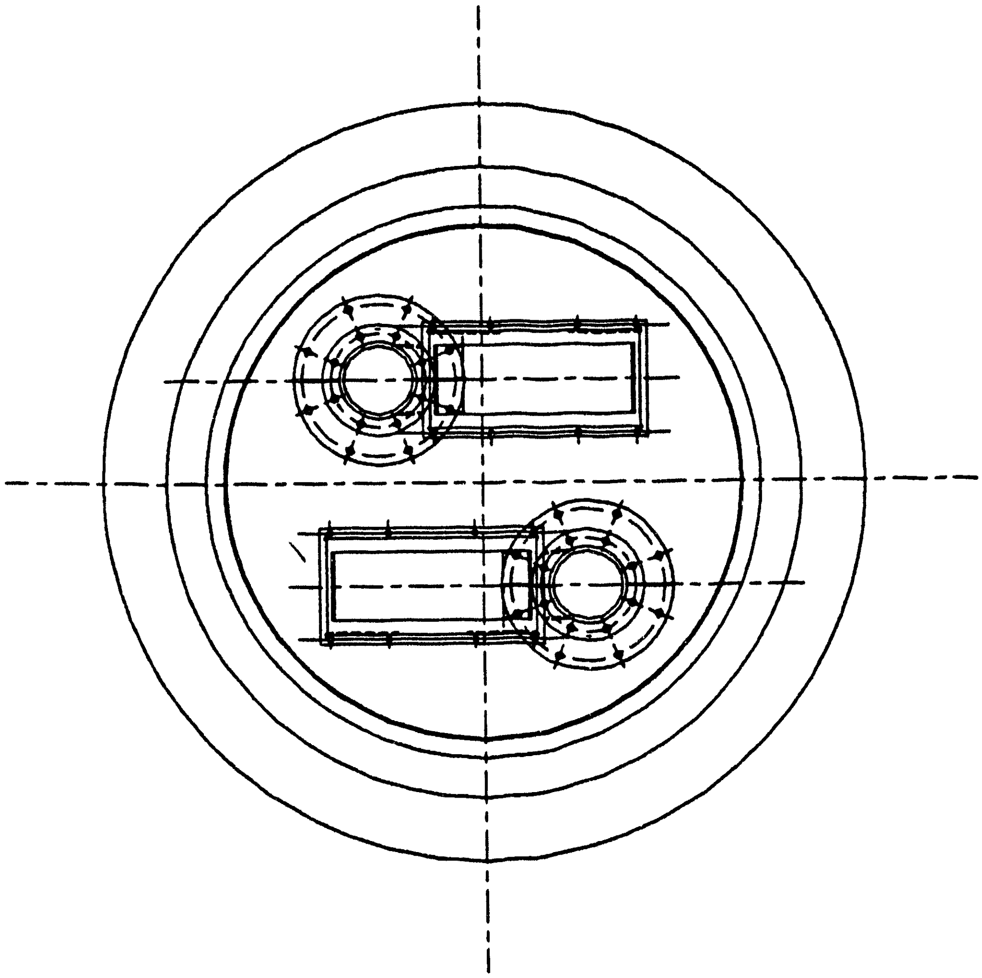


Figure A.6 - Layout of Tubesheet to Accommodate Two Filter Holders

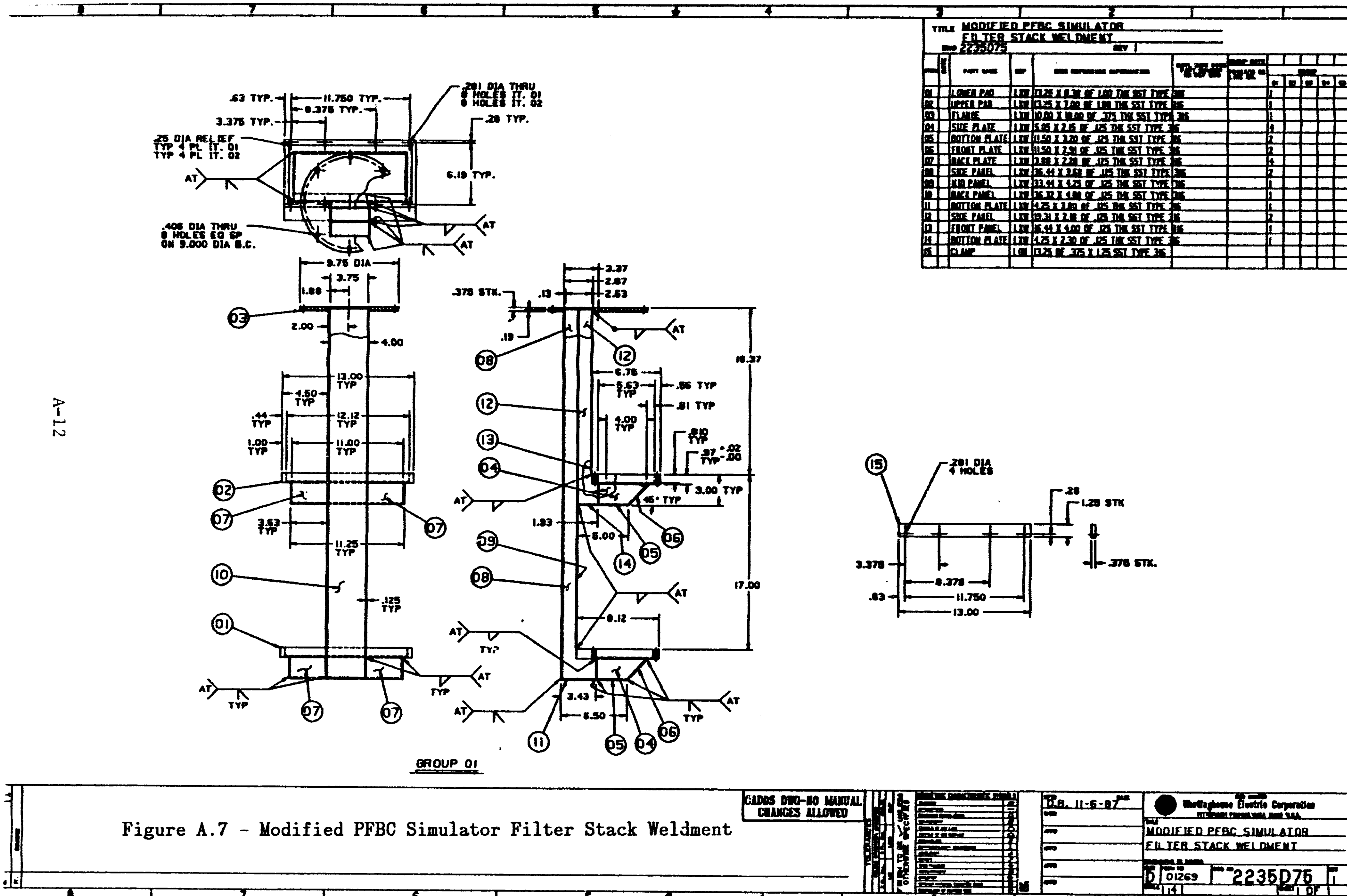


Figure A.7 - Modified PFBC Simulator Filter Stack Weldment

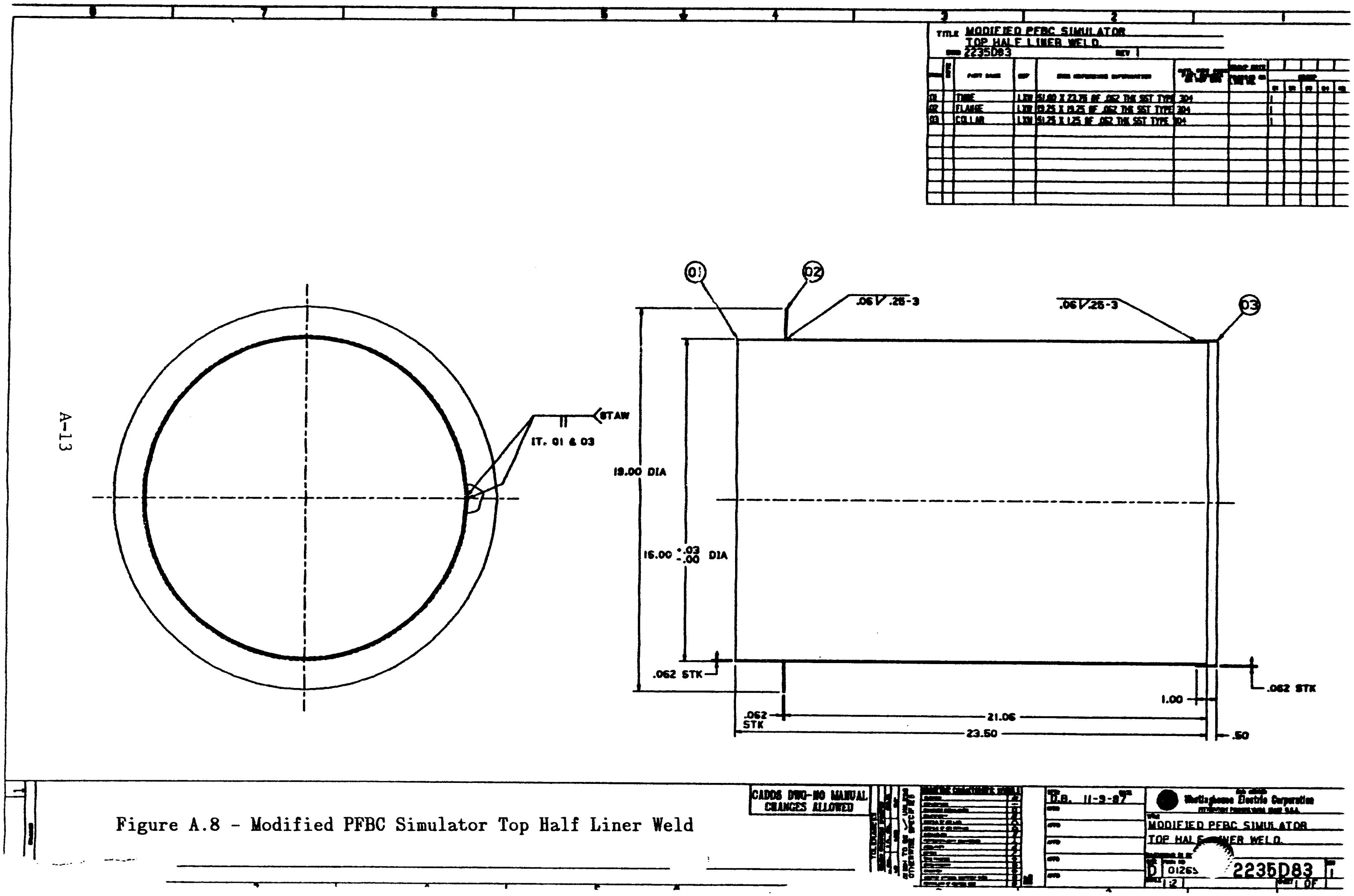


Figure A.8 - Modified PFBC Simulator Top Half Liner Weld

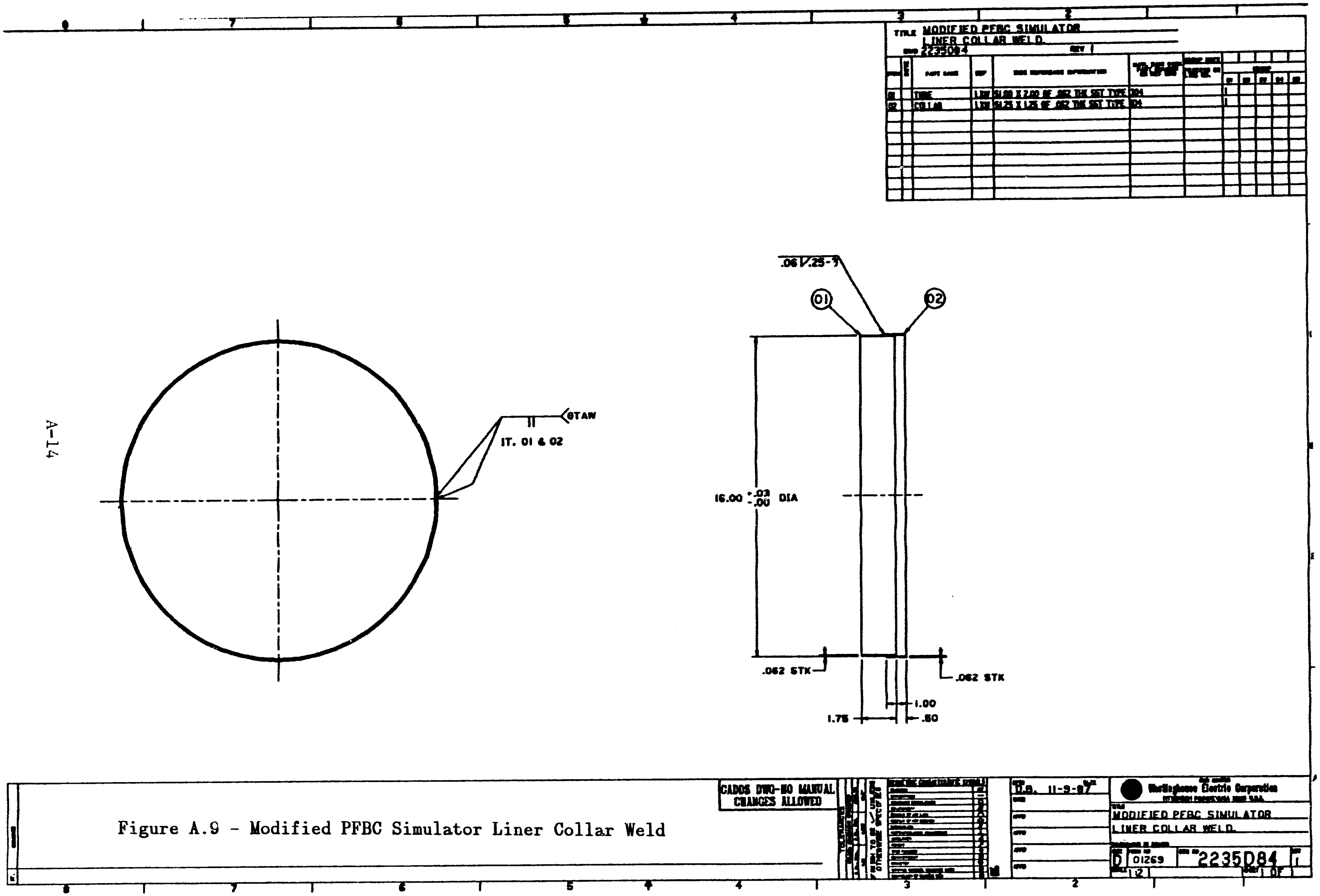


Figure A.9 - Modified PFBC Simulator Liner Collar Weld

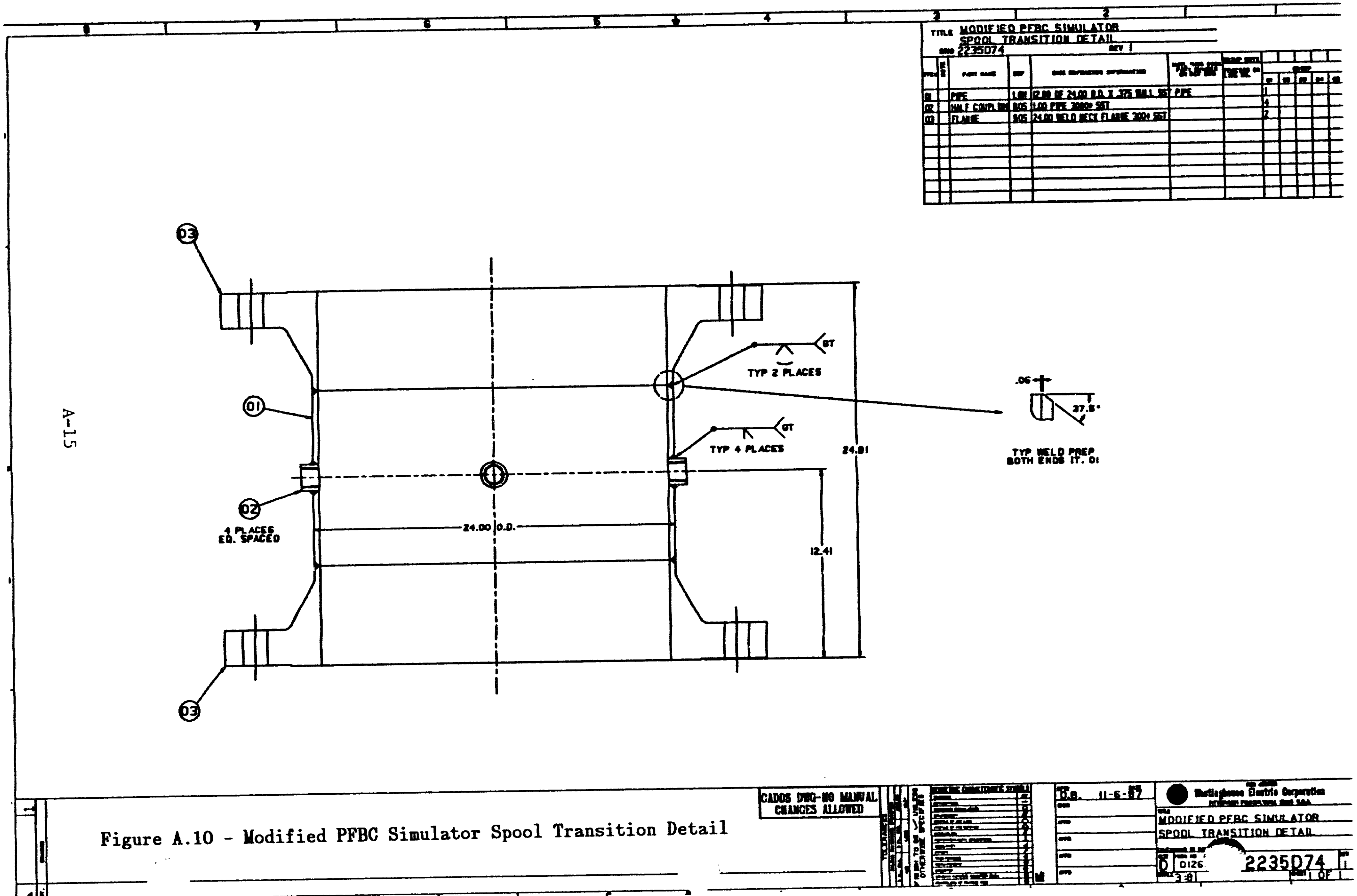


Figure A.10 - Modified PFBC Simulator Spool Transition Detail

TITLE MODIFIED PFBC SIMULATOR PIPING WELDMENTS

DWG 2235D85 REV 1

		PART NAME									
01	A	HALF NIPPLE	DOS	6.00 OF 2.375 OD X .154 WALL SST PIPE TYPE 316			2	2	3		
02		PIPE	DOS	10.75 OF 2.375 OD X .154 WALL SST PIPE TYPE 316			1				
03		PIPE	DOS	3.38 OF 2.375 OD X .154 WALL SST PIPE TYPE 316			1				1
04		CROSS	DOS	2 IN X .154 WALL SST CROSS TYPE 316			1	1	1		
05		FLANGE	DOS	2 IN 300# WEL NECK FLANGE SST TYPE 316			2	1	1	2	
06		TEE	DOS	2 IN X .154 WALL SST TEE TYPE 316			1				1
07		FLANGE	DOS	6 IN 300# BLIND FLANGE SST TYPE 316			1	1			
08		PIPE	DOS	3.62 OF 2.375 OD X .154 WALL SST PIPE TYPE 316				1			
09		PIPE	DOS	8.44 OF 2.375 OD X .154 WALL SST PIPE TYPE 316				1			
10		PIPE	DOS	4.12 OF 2.375 OD X .154 WALL SST PIPE TYPE 316					1		
11		PIPE	DOS	22.62 OF 2.375 OD X .154 WALL SST PIPE TYPE 316						1	
12		TUBE	DOS	3.88 OF 2.00 OD X .035 WALL SST TUBE TYPE 304							1
13		TUBE	DOS	2.81 OF 2.00 OD X .035 WALL SST TUBE TYPE 304							1

A- ONE 12.00 NIPPLE MAKES TWO HALF NIPPLES

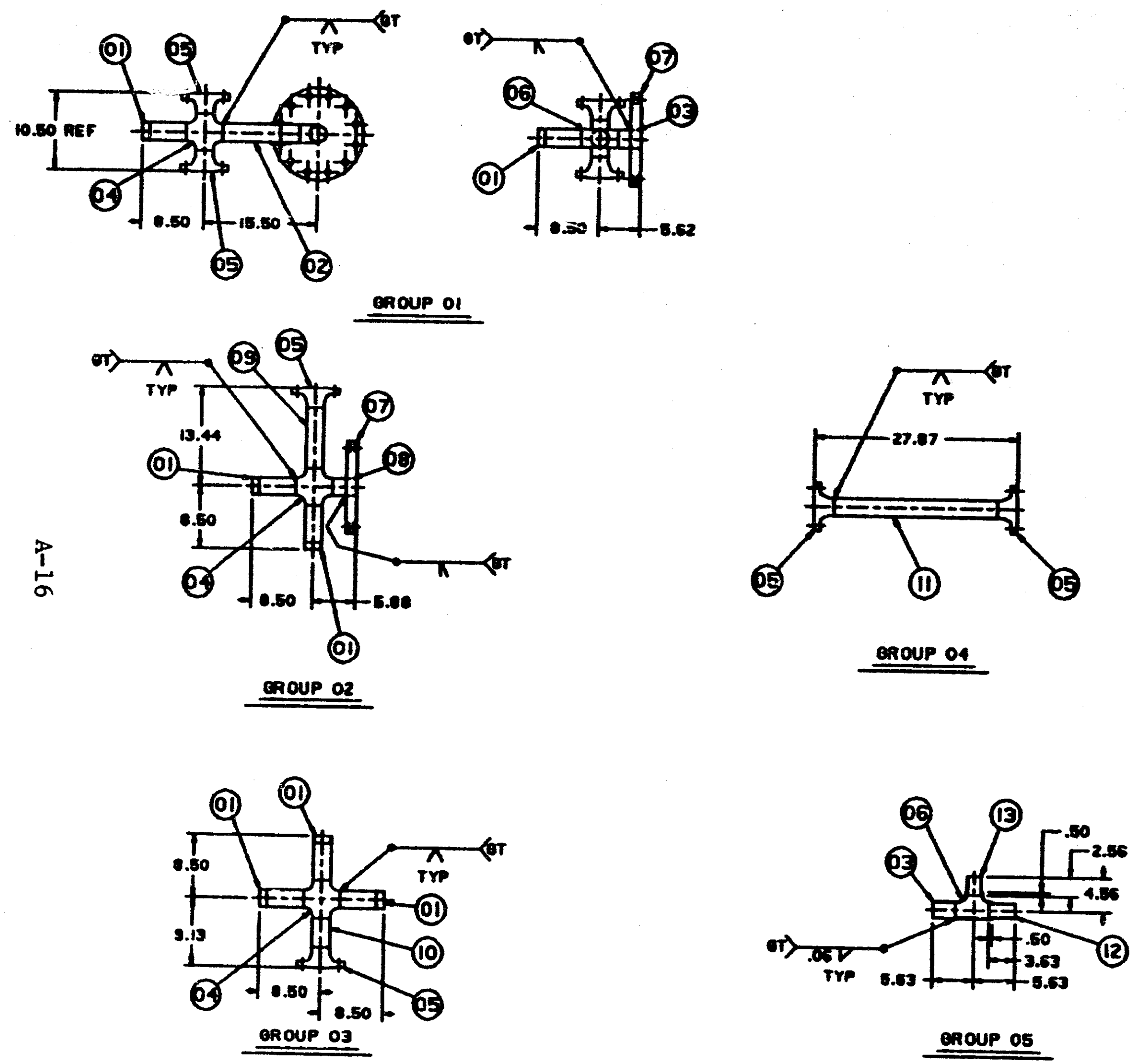


Figure A.11 - Modified PFBC Simulator Piping Weldments

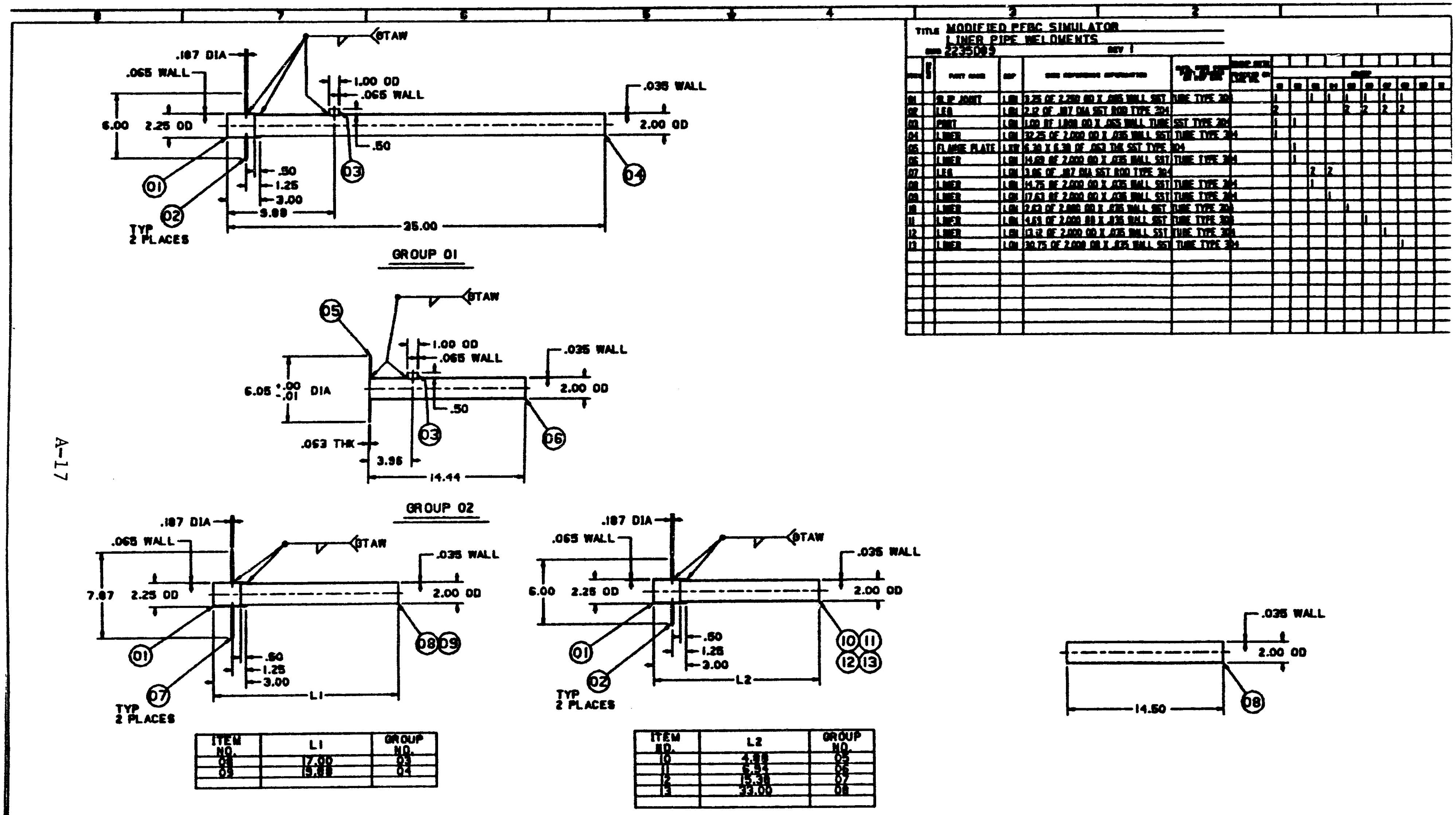
CADDS DWG-NO MANUAL CHANGES ALLOWED

D.B. 11-10-87

Westinghouse Electric Corporation

MODIFIED PFBC SIMULATOR PIPING WELDMENTS

D 2235D85 1 OF 1



TITLE MODIFIED PFBC SIMULATOR LINER PIPE WELDMENTS
2235D89 REV 1

	PART NAME													
01	SLIP JOINT	[illegible]	3.25 OF 2.250 OD X .065 WALL SST	TUBE TYPE 304	1		1	1	1	1	1	1		
02	LEG	[illegible]	2.12 OF .187 DIA SST ROD TYPE 304		2				2	2	2	2		
03	PORT	[illegible]	1.00 OF 1.000 OD X .065 WALL TUBE	SST TYPE 304	1	1								
04	LINER	[illegible]	32.25 OF 2.000 OD X .035 WALL SST	TUBE TYPE 304	1									
05	FLANGE PLATE	[illegible]	6.30 X 6.30 OF .063 THK SST TYPE	304		1								
06	LINER	[illegible]	14.69 OF 2.000 OD X .035 WALL SST	TUBE TYPE 304		1								
07	LEG	[illegible]	3.06 OF .187 DIA SST ROD TYPE 304				2	2						
08	LINER	[illegible]	14.75 OF 2.000 OD X .035 WALL SST	TUBE TYPE 304			1							
09	LINER	[illegible]	17.63 OF 2.000 OD X .035 WALL SST	TUBE TYPE 304				1						
10	LINER	[illegible]	2.63 OF 2.000 OD X .035 WALL SST	TUBE TYPE 304					1					
11	LINER	[illegible]	4.63 OF 2.000 OD X .035 WALL SST	TUBE TYPE 304						1				
12	LINER	[illegible]	13.12 OF 2.000 OD X .035 WALL SST	TUBE TYPE 304							1			
13	LINER	[illegible]	30.75 OF 2.000 OD X .035 WALL SST	TUBE TYPE 304								1		

ITEM NO.	L1	GROUP NO.
08	17.00	03
09	19.88	04

ITEM NO.	L2	GROUP NO.
10	4.88	05
11	6.94	06
12	15.38	07
13	33.00	08

CADDS DWG-NO MANUAL CHANGES ALLOWED

Westinghouse Electric Corporation

MODIFIED PFBC SIMULATOR LINER PIPE WELDMENTS

D 01269 2235D89 1

Figure A.12 - Modified PFBC Simulator Liner Pipe Weldments

APPENDIX B

HIGH TEMPERATURE, HIGH PRESSURE (HTHP) CERAMIC FILTER TEST FACILITY PROCESS AND DESIGN DESCRIPTION

HTHP Ceramic Filter Test Facility and Process Description

1. Introduction

This document describes the test facility and process to be used for investigating the long-term durability of the ceramic cross flow filter, per DOE Contract No. DE-AC21-87MC24022. The test plan that will be conducted in this facility provides for efficient and economic long-term durability tests under simulated reducing gas (similar to coal gasifier product gas) and simulated pressurized fluidized bed combustion (PFBC) conditions.

The objective of this work is to assess the long-term mechanical integrity and stability of components and materials used in the construction of the ceramic cross flow filter as well as the stability of filtration properties over time. This objective will be met by conduct of the test plan, which provides for 2000 hours of testing under both simulated reducing gas and PFBC conditions. The reducing gas and PFBC tests will be carried out in parallel with four test segments of at least 500 continuous hours each at steady-state conditions.

The experimental test facilities consist of a new gasifier simulator test loop plus an existing PFBC simulator test loop that will be upgraded. This document will describe both systems in terms of gas supply, particulate injection, ceramic cross flow filter, process instrumentation and control devices, and piping and vessel design.

These systems will be installed in a new hot gas cleaning laboratory that Westinghouse is currently constructing. The preliminary equipment lay-out and floor plan for the new laboratory is shown in Figure B.1. This facility will have a floor area of approximately 2045 ft^2 and will enable both systems to be operated simultaneously. The filter loops will be in an area with usable head space to approximately 20 feet. An isometric drawing of the area is shown in Figure B.2. An overhead X-Y, 2 ton hoist will provide full coverage for assembly and disassembly of the test systems. This laboratory provides a large, flexible site for the conduct of hot gas cleaning programs.

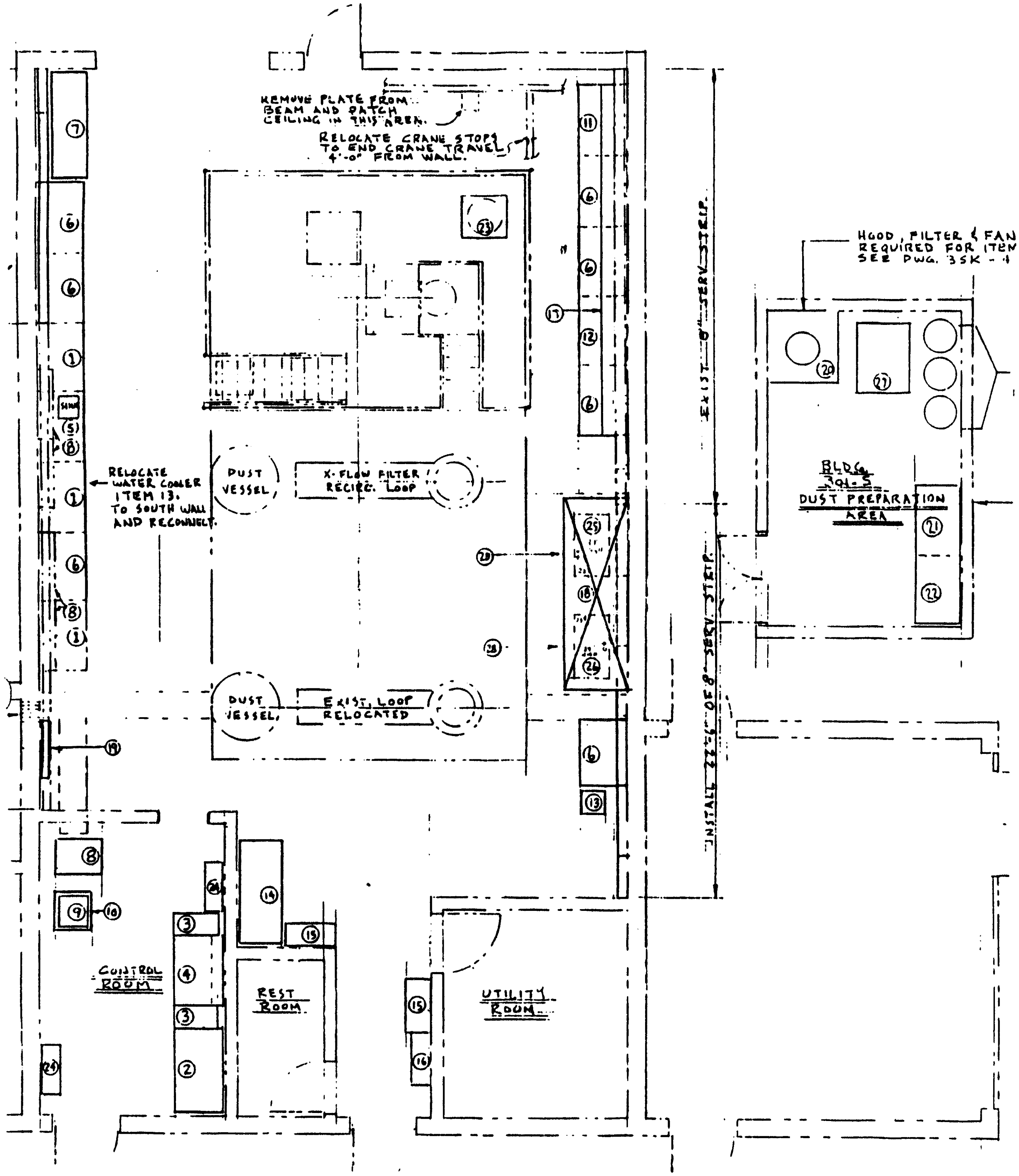
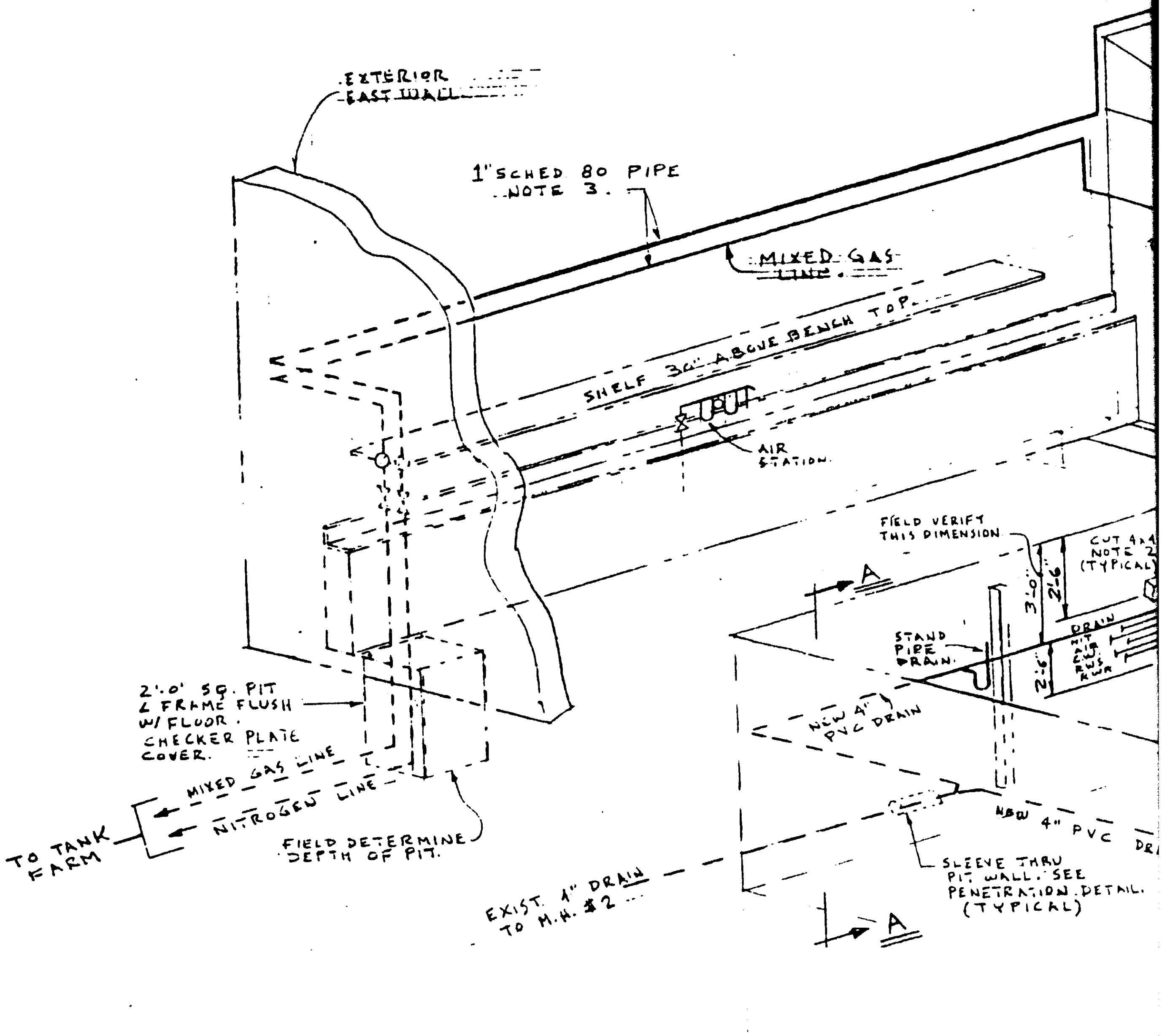


Figure B.1 - Facility Floor Plan


EXTERIOR EAST WALL
1"SCHED 80 PIPE NOTE 3.
MIXED GAS LINE.
SHELF 36" ABOVE BENCH TOP.
AIR STATION.
FIELD VERIFY THIS DIMENSION
CUT 4x4 NOTE 2 (TYPICAL)
A
3'-0"
2'-6"
2'-6"
STAND PIPE DRAIN.
NEW 4" PVC DRAIN
2'-0" SQ. PIT
L FRAME FLUSH W/ FLOOR.
CHECKER PLATE COVER.
MIXED GAS LINE
NITROGEN LINE
TO TANK FARM
FIELD DETERMINE DEPTH OF PIT.
NEW 4" PVC DR
SLEEVE THRU PIT WALL. SEE PENETRATION DETAIL. (TYPICAL)
EXIST. 4" DRAIN TO M.H. #2
A

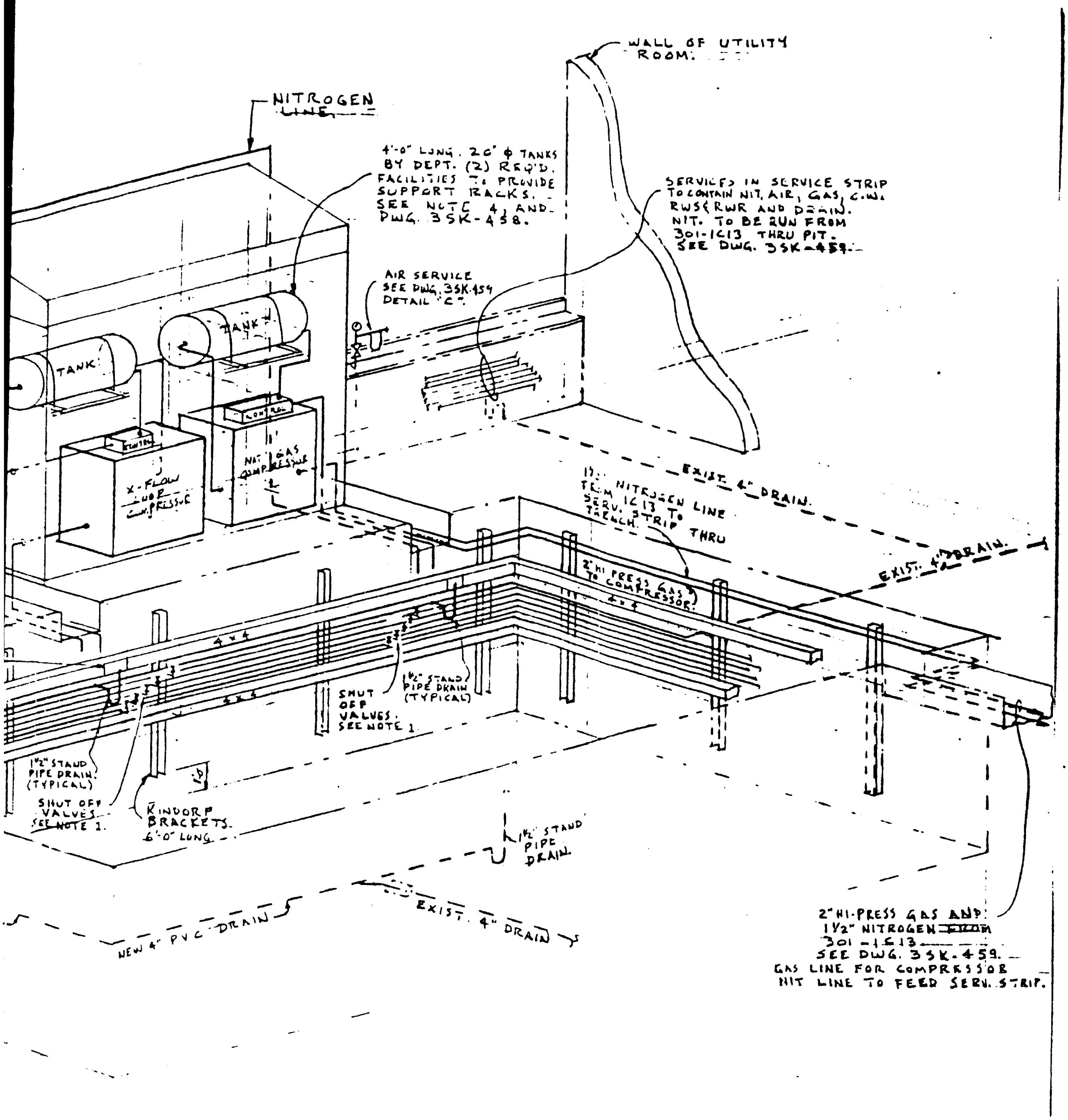


Figure B.2 – Isometric of Facility

2. Gasifier Simulator Test Loop

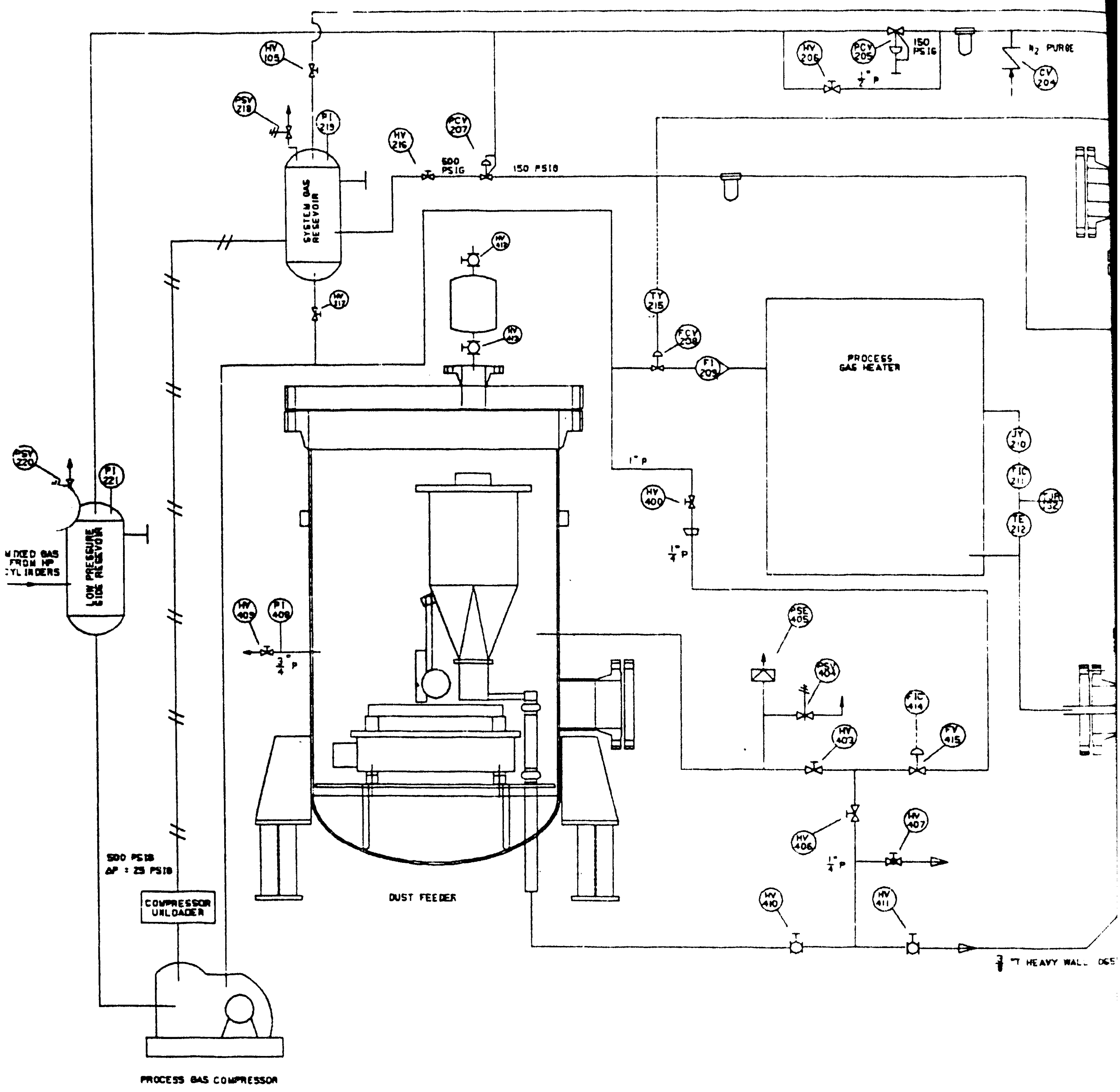
2.1 General Description and Operating Basis

The gasifier simulator test loop will be designed and built following the general arrangement shown in Figure B.3 to provide the necessary gas flow at the desired pressure and temperature. This system will consist of a closed recirculating loop so that a fixed gas composition can be maintained. The gas supply for this system will be provided by pre-mixing a simulated reducing gas with the following composition:

Nitrogen	64%
Carbon Monoxide	23%
Carbon Dioxide	13%

The test loop will be operated to provide approximately 100 actual cubic feet per minute (acfm) at 150 psig and 1500°F, through the cross flow filters installed in the filter vessel. With two filter elements installed, this flow will provide a filter face velocity of approximately 7 feet per minute. After the gas stream passes through the filters, the total flow is determined by measuring the pressure drop through a venturi which along with the system pressure and temperature, are used to calculate the total mass flow in a mass flow controller.

Approximately 10 percent of the gas flow will be used as high pressure motive gas for an eductor that will recirculate the system gas to maintain flow through the filter. The design basis for the eductor is given in Appendix C. The eductor flow is removed from the system after the mass flow venturi, cooled, and then recompressed to 500 psig. This high pressure gas is then heated to above 1500°F in a process gas heater before being reinjected into the eductor nozzle, causing the balance of the gas flow to recombine with the motive gas. A metered dust flow will be added to this stream before it enters the filter vessel. The dust (char) laden gas enters the test vessel at a point below the filter mounts. A dust removal system will allow on-line removal of the collected dust from the filter vessel so that long-term test can be conducted without interruption.


HV 105
PSV 218
PI 219
HV 216
500 PSIG
PCV 207
150 PSIG
SYSTEM GAS RESEVOIR
HV 217
HV 206
PCV 205
150 PSIG
1/2" P
N_2 PURGE
CV 204
HV 412
HV 413
TY 215
FCV 208
FI 209
PROCESS GAS HEATER
JY 210
FIC 211
TE 212
1" P
HV 400
1/4" P
PSV 220
PI 221
MIXED GAS FROM HP CYLINDERS
LOW PRESSURE SIDE RESEVOIR
HV 409
PI 408
3/4" P
PSE 405
PSV 404
FIC 414
HV 403
FV 415
HV 406
HV 407
1/4" P
500 PSIG
ΔP = 25 PSIG
COMPRESSOR UNLOADER
DUST FEEDER
HV 410
HV 411
PROCESS GAS COMPRESSOR

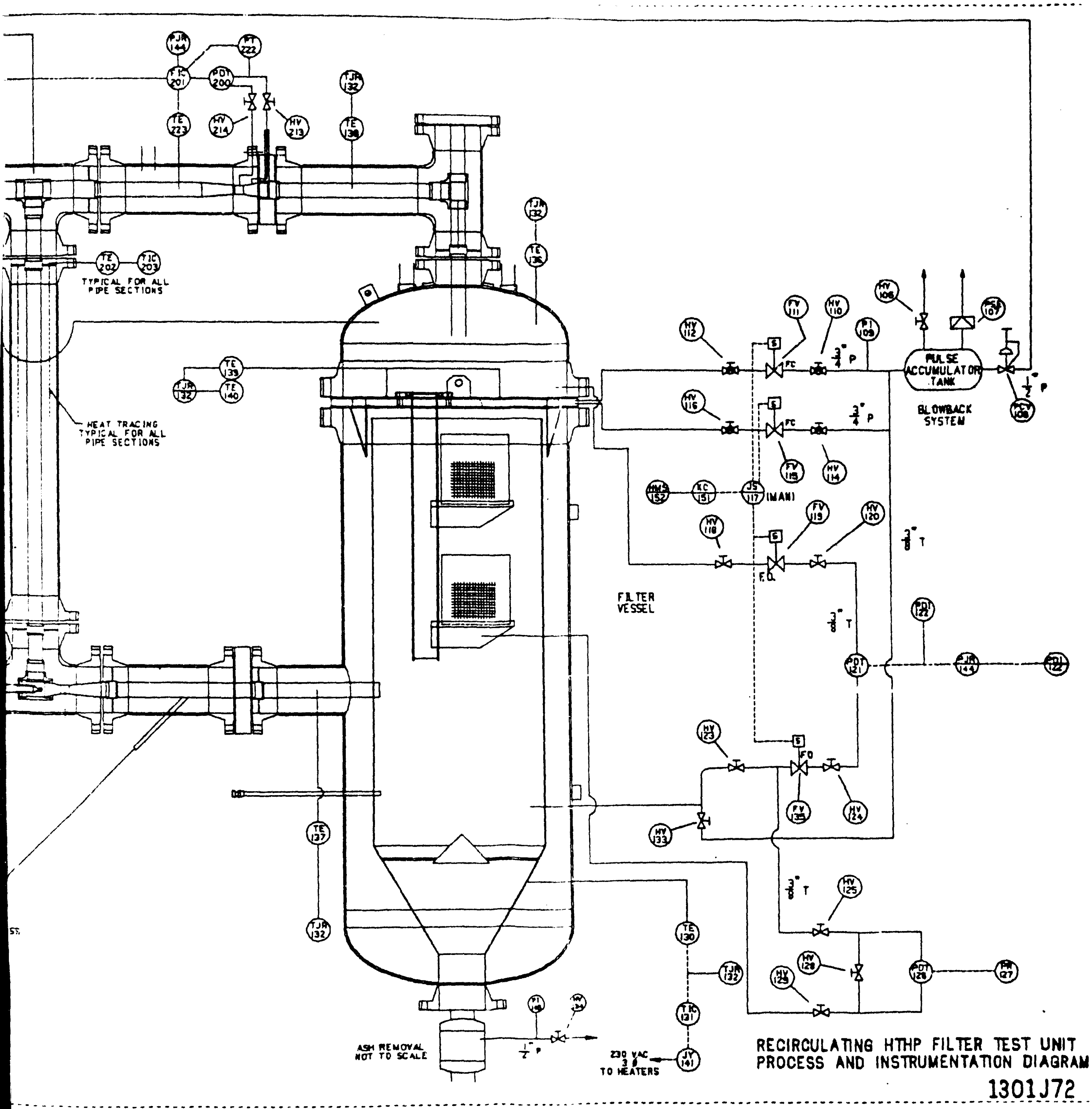


Figure B.3 – Recirculating HTHP Filter Test Unit

Electrical heaters will provide internal heat tracing of all the insulated piping and the filter vessel to maintain the desired operating temperature.

A blow-back system using the simulated reducing gas from the high pressure compressor will be used to clean the filters on-line. The use of that gas as the blow-back medium will maintain the gas composition in the closed loop system.

A full complement of instrumentation will be available to automatically control the operation of the system and to collect data.

A detailed description of the subsystems and process is provided in the following sections.

2.2 Piping and Vessel Design

2.2.1 Piping and Vessel Specification

The piping and device pressure housings will be refractory lined carbon steel pipe sections so that the pressure boundaries remain at relatively low temperature. Figure B.3 shows the general arrangement of the vessel, piping and filter internals. Figures B.4 through B.7 show the design drawings for vessel and piping components.

A 2-1/2 inch diameter stainless steel liner is used to separate the process gas stream from the refractory material (e.g., Fiberfrax or castable ceramic). The pressure boundary will be 8 inch diameter carbon steel schedule 40 pipe with 300 series flanges. The filter vessel will be a 40 inch diameter ASME coded pressure vessel designed for 350 psig maximum working pressure. The filter vessel will have an internal straight section formed by a 30 inch diameter, 316 stainless steel liner, from the tube sheet used to support the filters to the start of a discharge cone section, of approximately 6 feet. This provides adequate volume for positioning the filters to be tested and enough flexibility to test a wide variety of configurations.

2.2.2 Heat Tracing

The heat tracing for the system will be provided by two different styles of Watlow Electric heaters. All of the pipe liners

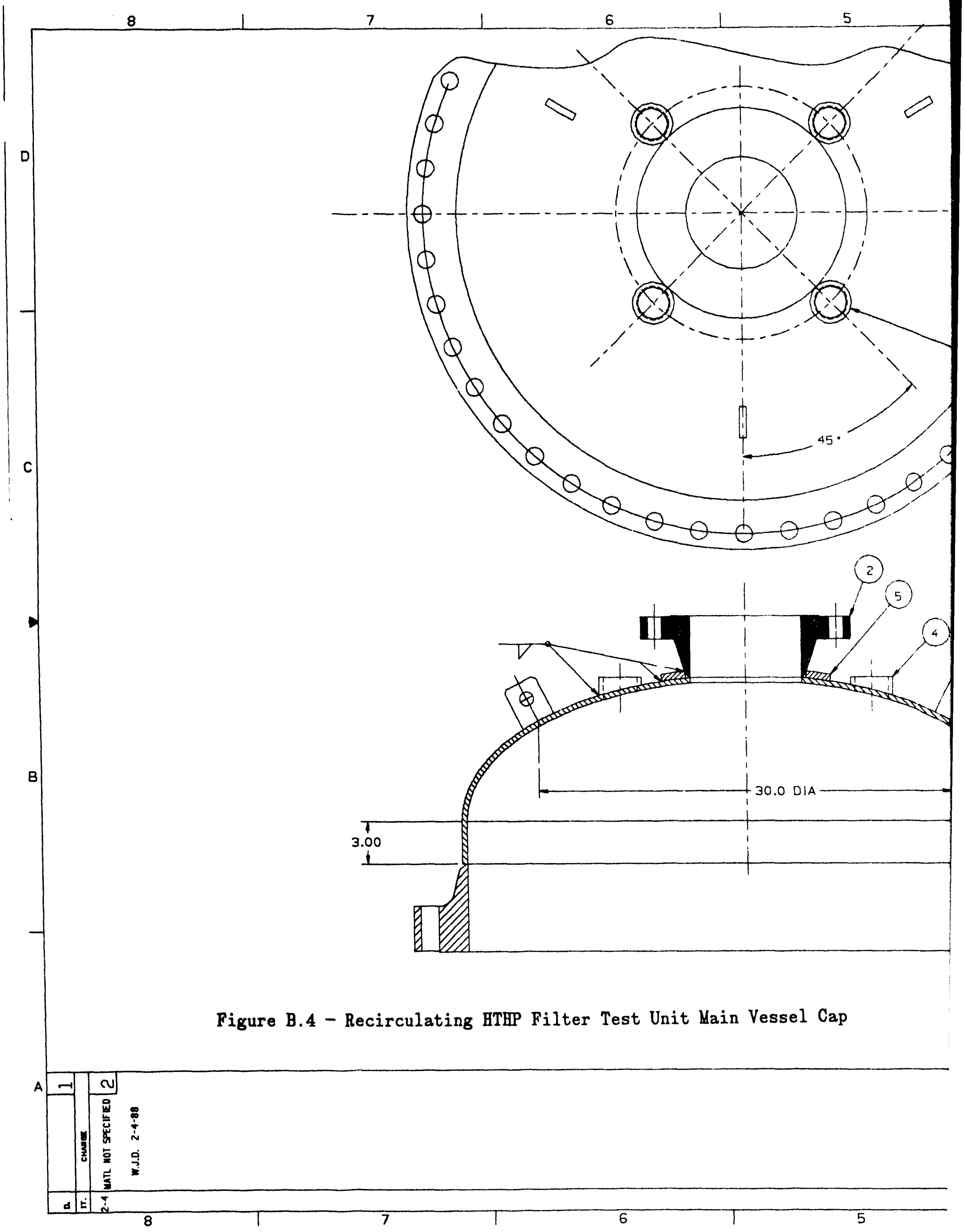
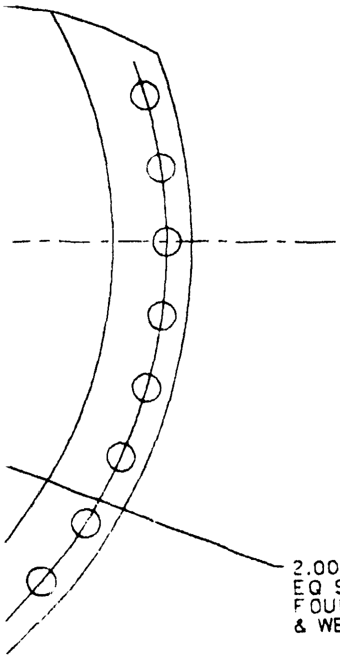


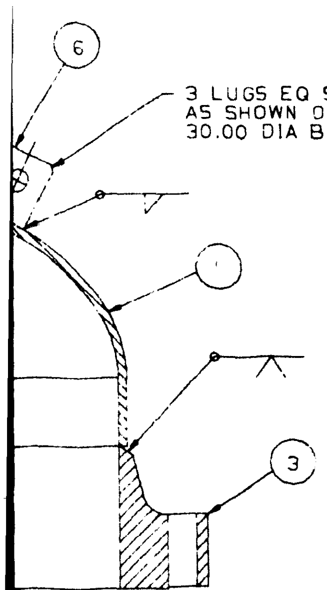
Figure B.4 – Recirculating HTHP Filter Test Unit Main Vessel Cap

TITLE RECIRCULATING HTHP FILTER TEST UNIT
MAIN VESSEL CAP
DWG 2236D44 REV 2

ITEM	NOTE	PART NAME	DEF	SIZE REFERENCE INFORMATION	MATL SIZE CODE PART NUMBER OR REF DWG	GROUP NOTE PROCESS OR LINE NO.	GROUP 01	02	03	04	05
1		CAP		40.00 I.D. .375 THK 2:1 ELLIPTICAL HEAD		STL	1				
2		WELD NECK		8.00 300 LB WELD NECK FLANGE		STL	1				
3		FLANGE		350# WELD NECK PRESSURE VESSEL FLANGE		STL	1				
4		HALF CPLG		2.00 NPT 3000# HALF CPLG		STL	4				
5		REINF PAD		12.00 DIA OF .50 THK		STL	1				
6		LIFT LUG		FROM .500 THK BAR		STL	3				

NOTE: REINFORCING PAD IT. 5 TO BE ROLLED TO FIT IT. 1 BEFORE WELDING.





DESIGN SPECS:

1. DESIGN CONDITIONS 350 PSIG - 650° F
2. CONSTRUCTION - FUSION WELDED - DYE PENETRANT TEST ROOT PASS AND FINAL PASS.
3. CODE REQUIREMENTS - ASME SECT VIII
4. WELDERS QUALIFIED PER ASME CODE SECT IX
5. TESTING - 500 PSI HYDROSTATIC COMPLETE ASSY.
6. STAMPING - PER CODE.

CADDS DWG-NO MANUAL CHANGES ALLOWED

TOLERANCES UNLESS OTHERWISE SPECIFIED
FINISH TO BE ✓ UNLESS OTHERWISE SPECIFIED
GEOMETRIC CHARACTERISTIC SYMBOLS

DFTR W. DILMORE DATE
CHKR
APPD
APPD
APPD
APPD

R&D CENTER
Westinghouse Electric Corporation
PITTSBURGH PENNSYLVANIA 15235 U.S.A.

TITLE RECIRCULATING HTHP FILTER TEST UNIT
MAIN VESSEL CAP

DIMENSIONS IN INCHES

SIZE	FSCM NO	DWG NO	REV
D	01269	2236D44	2

SCALE 1:2 D.301 SHEET 1 OF 1

DESIGN SPECS:

1. DESIGN CONDITIONS 350 PSIG - 650° F
2. CONSTRUCTION - FUSION WELDED - DYE PENETRANT TEST ROOT PASS AND FINAL PASS.
3. CODE REQUIREMENTS - ASME SECT VIII
4. WELDERS QUALIFIED PER ASME CODE SECT IX
5. TESTING - 500 PSI HYDROSTATIC COMPLETE ASSY.
6. STAMPING - PER CODE.

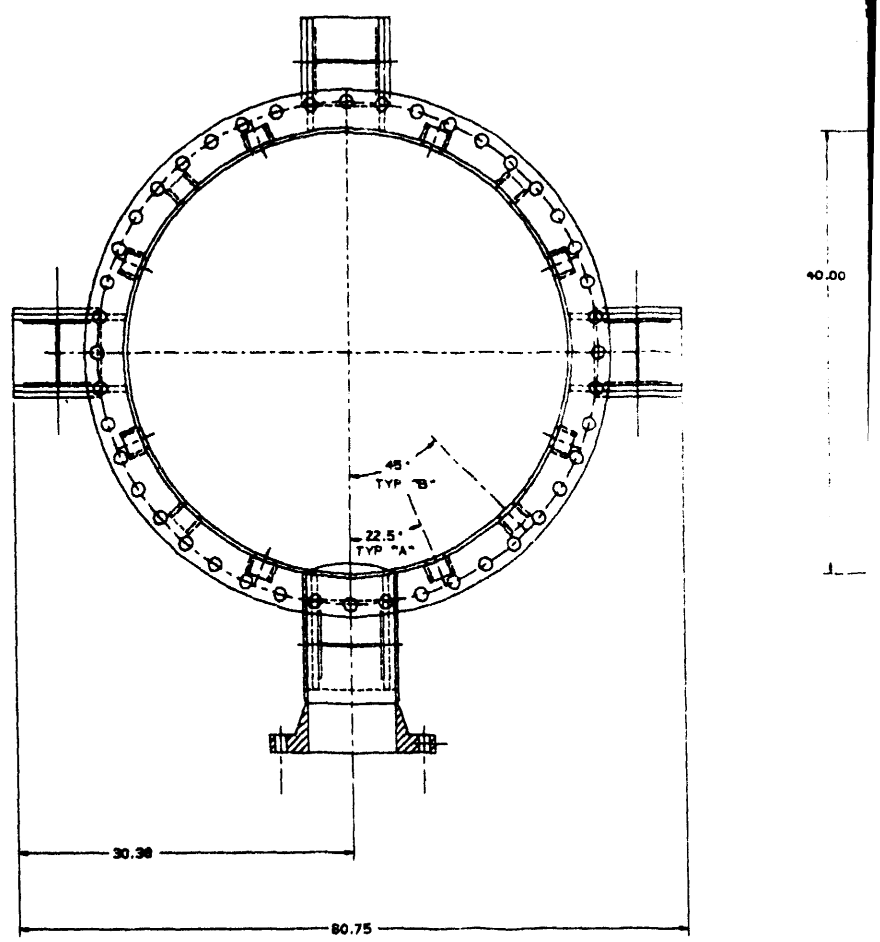


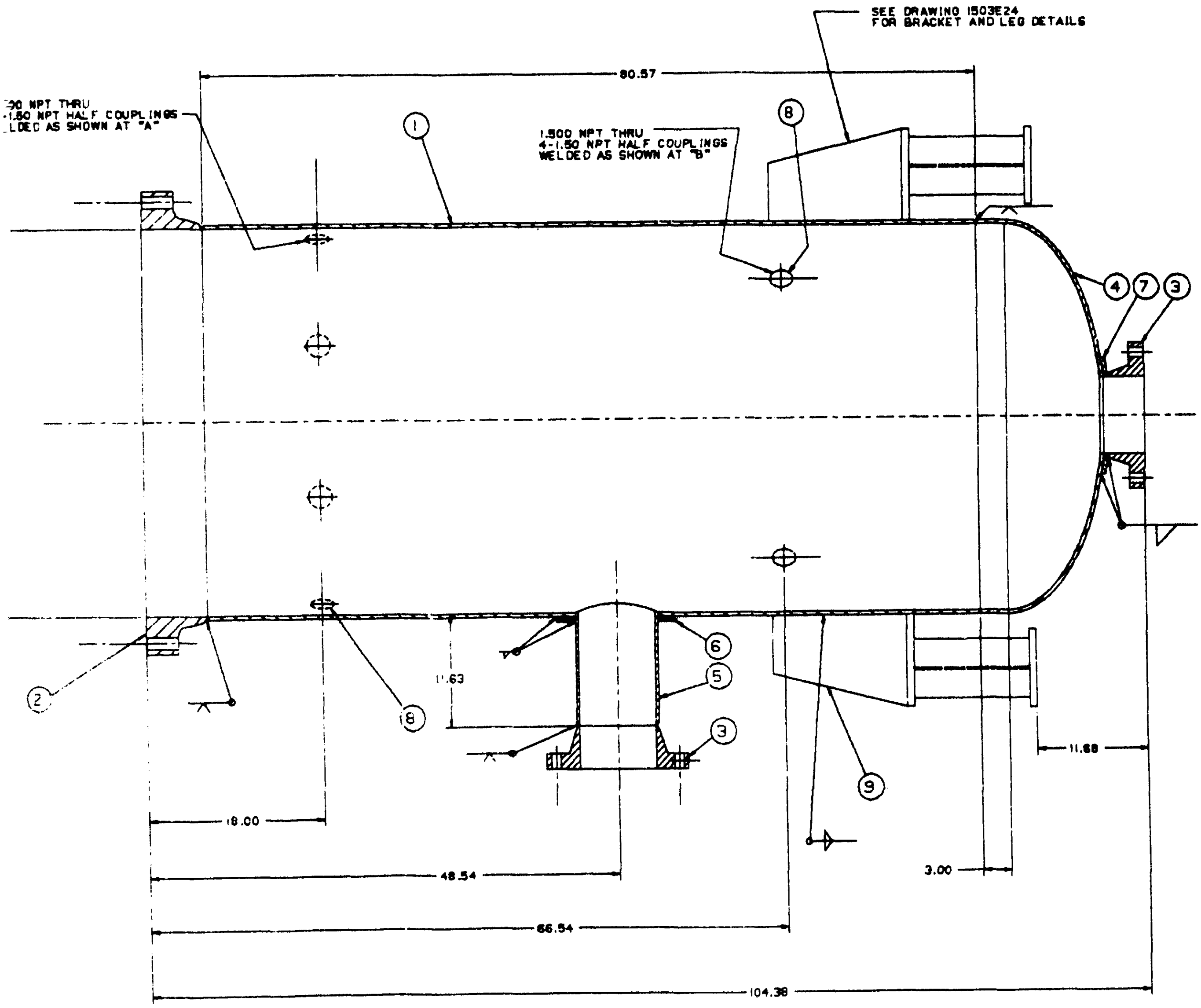
Figure B.5 – Recirculating HTHP Filter Test Uni

TITLE RECIRCULATING HTHP FILTER TEST UNIT
MAIN VESSEL
DWG 1503E22 REV 1

ITEM	NOTE	PART NAME	REF	SIZE REFERENCE INFORMATION	[illegible]	[illegible]					
1		PIPE		81.00 OF 40.00 I.D. .375 WALL PIPE		STL	1				
2		WELD NECK		40.00 DIA 350 LB. PRES. VESSEL FLANGE		STL	1				
3		WELD NECK		8.00 DIA 300 LB. WELD NECK FLANGE		STL	2				
4		ELL HEAD		40.00 I.D. .375 WALL 2:1 ELL HEAD		STL	1				
5		PIPE		MAKE FROM 8.00 STD WALL PIPE		STL	1				
6		REINF PAD		MAKE FROM .50 THK		STL	1				
7		REINF PAD		MAKE FROM .50 THK		STL	1				
8		COUPLING		1.50 NPT 3000# HALF COUPLING		STL	12				
9		LEG ASSY			1503E24802		4				

NOTE:

1. REINFORCING PADS ITS 6 AND 7 ARE TO BE ROLLED TO FIT BEFORE WELDING.



Main Vessel

CADDS DWG-NO MANUAL CHANGES ALLOWED

Westinghouse Electric Corporation

RECIRCULATING HTHP FILTER TEST UNIT
MAIN VESSEL

E 01269 1503E22 1

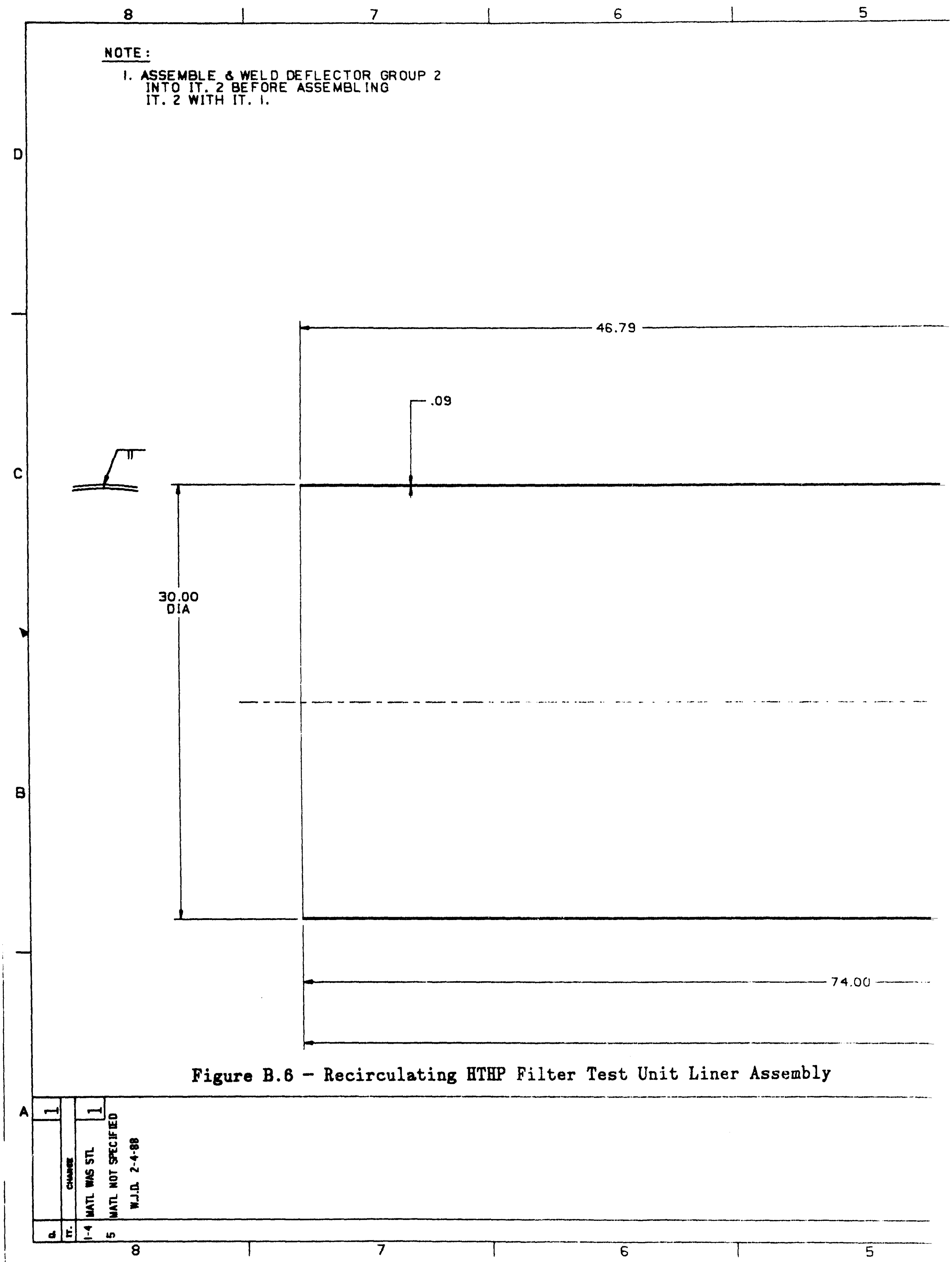
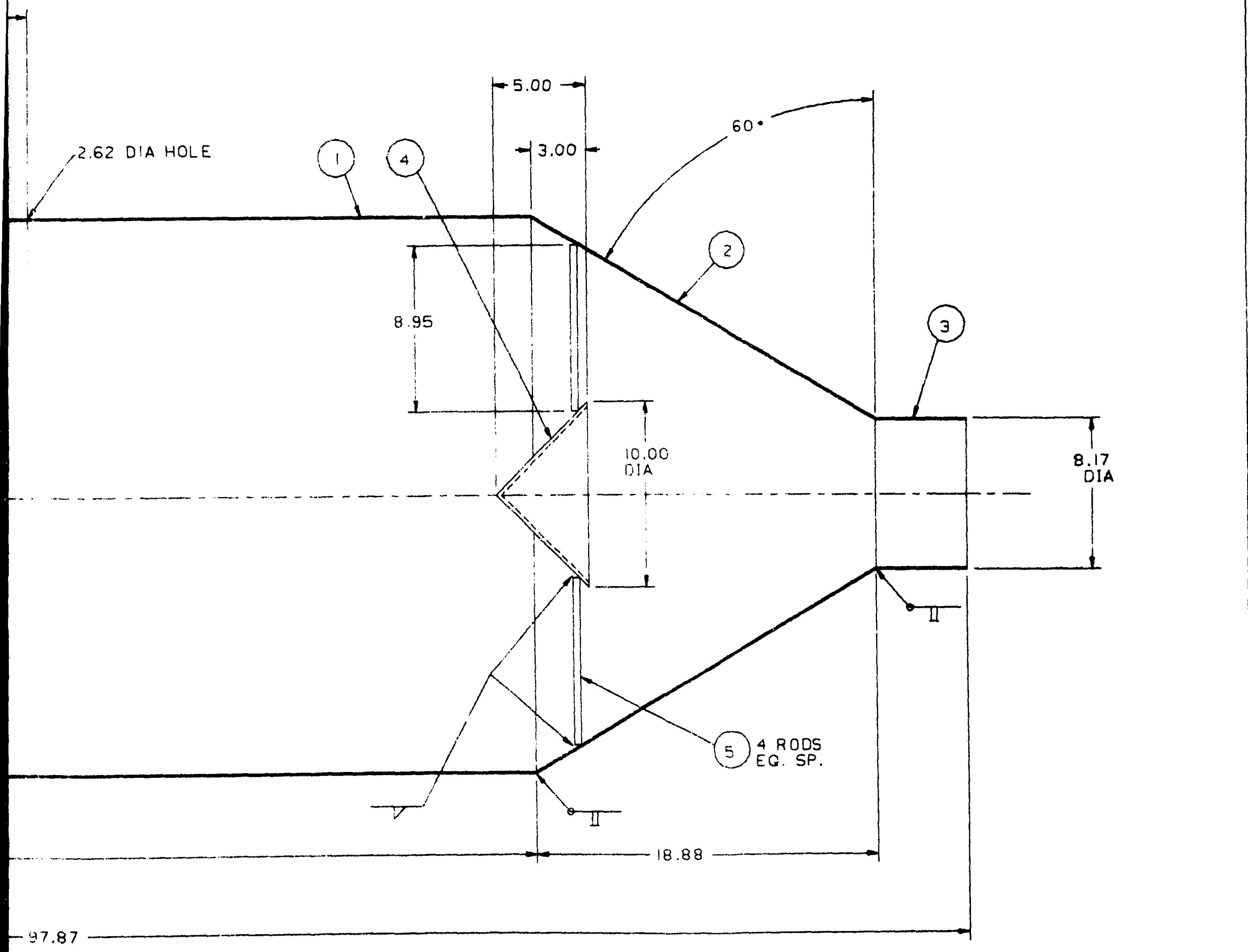


Figure B.6 - Recirculating HTHP Filter Test Unit Liner Assembly

TITLE RECIRCULATING HTHP FILTER TEST UNIT
LINER ASSY
DWG 2236D47 REV 2

ITEM	NOTE	PART NAME	DEF	SIZE REFERENCE INFORMATION	MATL SIZE CODE PART NUMBER OR REF DWG	GROUP NOTE PROCESS OR LINE NO.	GROUP 01	02	03	04	05
1		LINER		ROLL FROM .093 THK	SST 310		1	1			
2		CONE		ROLL FROM .093 THK	SST 310		1	1			
3		LINER		ROLL FROM .093 THK	SST 310		1	1			
4		DEFLECTOR		ROLL FROM .093 THK	SST 310			1			
5		SUPPORT		.375 DIA SST ROD	SST 310			4			



CADDS DWG-NO MANUAL CHANGES ALLOWED

TOLERANCES UNLESS OTHERWISE SPECIFIED

FINISH TO BE ✓ UNLESS OTHERWISE SPECIFIED

GEOMETRIC CHARACTERISTIC SYMBOLS

DFTR W.DILMORE DATE

CHKR

APPD

APPD

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APPD

R&D CENTER
Westinghouse Electric Corporation
PITTSBURGH PENNSYLVANIA 15235 U.S.A.

TITLE RECIRCULATING HTHP FILTER TEST UNIT
LINER ASSY

DIMENSIONS IN INCHES

SIZE D FSCM NO 01269 DWG NO 2236D47 REV 2

SCALE 1:4 D.301 SHEET 1 OF 1

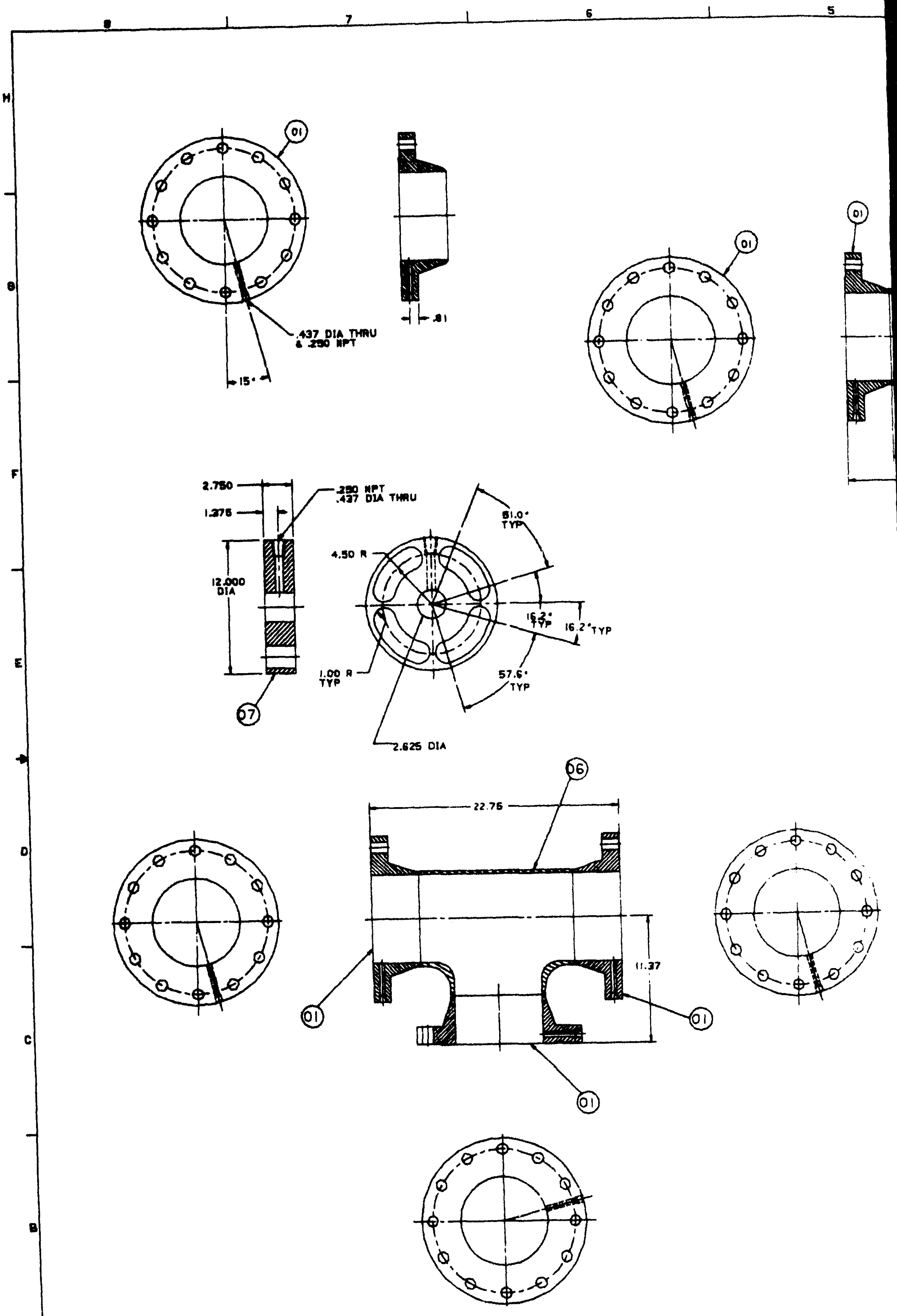
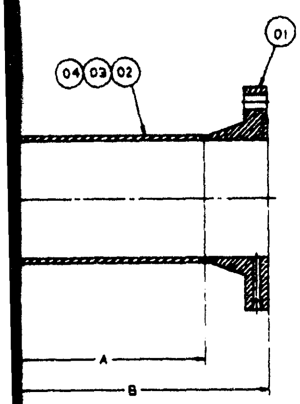
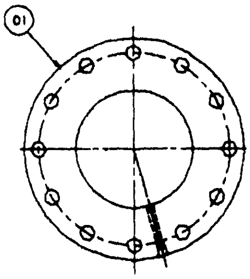


Figure B.7 – Recirculating HTHP Filter Test Unit Recirculating Pip

	A	B
1	18.50	27.25
2	54.12	62.88
3	13.88	22.62



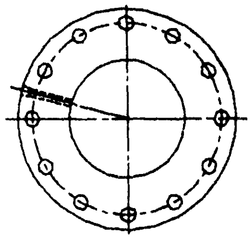


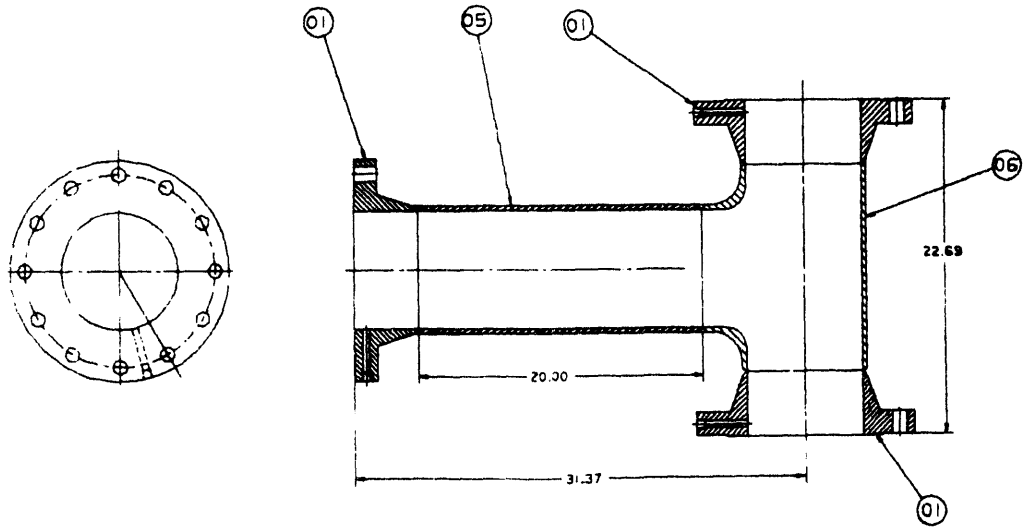
TITLE RECIRCULATING HTHP FILTER TEST UNIT
RECIRCULATING PIPE
DWG 1503E28 REV 2

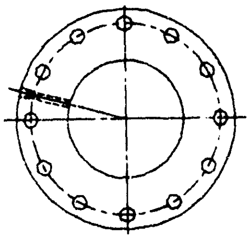
ITEM		PART NAME		REFERENCE INFORMATION	MATL		GROUP				
1		WELD FLANGE		8.00 300# WELD NECK FLANGE	STL		2	2	2	3	3
2		PIPE		MAKE FROM 8.00 STD STL PIPE	STL		1				
3		PIPE		MAKE FROM 8.00 STD STL PIPE	STL			1			
4		PIPE		MAKE FROM 8.00 STD STL PIPE	STL				1		
5		PIPE		MAKE FROM 8.00 STD STL PIPE	STL					1	
6		WELD TEE		8.00 300# WELD TEE	STL					1	1
7		INS FLANGE		12.00 DIA OF 3.00 THK SST	SST 310						
8		INS FLANGE		12.00 DIA OF 3.00 THK SST	SST 310						

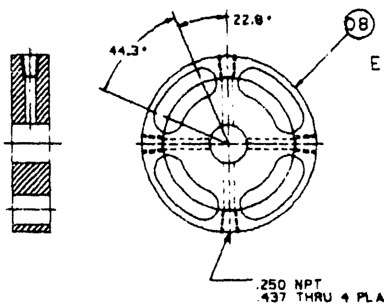
DESIGN SPECS:

1. DESIGN CONDITIONS 350 PSIG - 650° F
2. CONSTRUCTION - FUSION WELDED - DYE PENETRANT TEST ROOT PASS AND FINAL PASS.
3. CODE REQUIREMENTS - ASME SECT VIII
4. WELDERS QUALIFIED PER ASME CODE SECT IX
5. TESTING - 500 PSI HYDROSTATIC COMPLETE ASSY.
6. STAMPING - PER CODE.









SAME AS IT 7
EXCEPT AS SHOWN

CADDS DWG-NO MANUAL CHANGES ALLOWED

DFTR B. DR.MORE 1-15-88

Westinghouse Electric Corporation

TITLE RECIRCULATING HTHP FILTER TEST UNIT
RECIRCULATING PIPE

SIZE E | FSCM NO 01269 | DWG NO 1503E28 | REV 2

SCALE 0.301

will use 1/8 inch diameter cable heaters and the filter vessel will use single ended Firebars. Both types have an Inconel 600 sheath and use internal type K thermocouples to control the element temperature and provide for a more reliable operation.

The cable heaters will have a 60 inch heated length and a 5 inch unheated length. Each heated section will be able to supply approximately 600 watts. They will be wrapped around the internal liners to provide approximately 600 watts/foot. Each heater will be controlled independently with digital temperature controllers, Omron Model E5CS-R1KJX-F. This will provide the most reliable level of control for these heaters, since each heater could see different duty cycles to maintain the operating temperature.

The Firebars will have a 60 inch heated length and a 6 inch unheated length. Each heater will be able to supply approximately 1200 watts. Ten heaters will be banded to the filter vessel liner to supply a total of approximately 12 kw. They will all be connected in parallel and use one digital temperature controller, a Watlow Series 910. The thermocouple from one of the heaters will be used for the control temperature, and the other thermocouples will be connected to a switch and a digital readout, a Watlow Model 873, so each heater temperature can be monitored.

2.3 Process Gas Circuit and Equipment

2.3.1 Process Gas Compressor

The process gas will be compressed from below 150 psig to 475/500 psig with a 15 HP single stage, oil free, vertical, air cooled, Corken Model D491AM9FBA-103 gas compressor. It will be capable of providing approximately 84 SCFM when operating continuously at 400 RPM. The system requirements at this time indicate that only approximately one half of this flow would be needed. Therefore, the compressor will be provided with a pneumatic valve unloader that will allow constant speed regulation. The unloader will be adjusted for a maximum of 500 psig, at which point the unloader opens the discharge valves. Using a 25 psig differential, when the system gas reservoir pressure drops to 475 psig the unloader closes the discharge valves and allows the compressor to operate until the 500 psig pressure is recovered.

A 10 cubic foot gas receiver (Figure B.8), the low pressure side reservoir at below 150 psig, will be used on the inlet (suction) side of the compressor (see Figure B.3 for the process and instrumentation diagram, P&ID, for the interconnections and instrumentation designations). This reservoir is where the mixed gas from high pressure tanks will be introduced for the initial charging of the system, and also where the side stream from the test loop will be returned. (See Section 2.3.2 for the description of the flow and pressure control strategy.) The required system gas flows will be drawn from the 500 psig system gas reservoir, a 10 cubic gas receiver vessel, on the discharge side of the compressor. Both of these receivers will be ASME coded vessels with the appropriate pressure safety relief valves and pressure gages.

The system flows include the gas going to the process gas heater through the flow control valve, FCV 208; to the dust feed system, through flow valve FV 415; to the pressure control regulator, PCV 207; and to the filter blow back system, via the pressure control regulator, PCV 108, to the pulse accumulator tank. (See Section 2.2.2, 2.3, and 2.6 for additional details on these subsystems.)

2.3.2 Flow and Pressure Control

The total mass flow through the filters will be calculated in a mass flow controller, FIC 201, using the pressure drop, PDT 200, through the venturi located in the clean gas outlet pipe, the system pressure from PT 222, and the system temperature from TE 223. This flow is compared against the set point (approximately 1500 pounds/hour for 100 acfm) and the controller output adjusts the flow control valve FCV 208 accordingly. The flow of high pressure (500 psig) gas through FCV 208 is indicated on flow indicator FI 209, approximately 150 pounds/hour, before it enters the process gas heater (described in Section 2.2.3) where it will be heated to approximately 1550°F. When

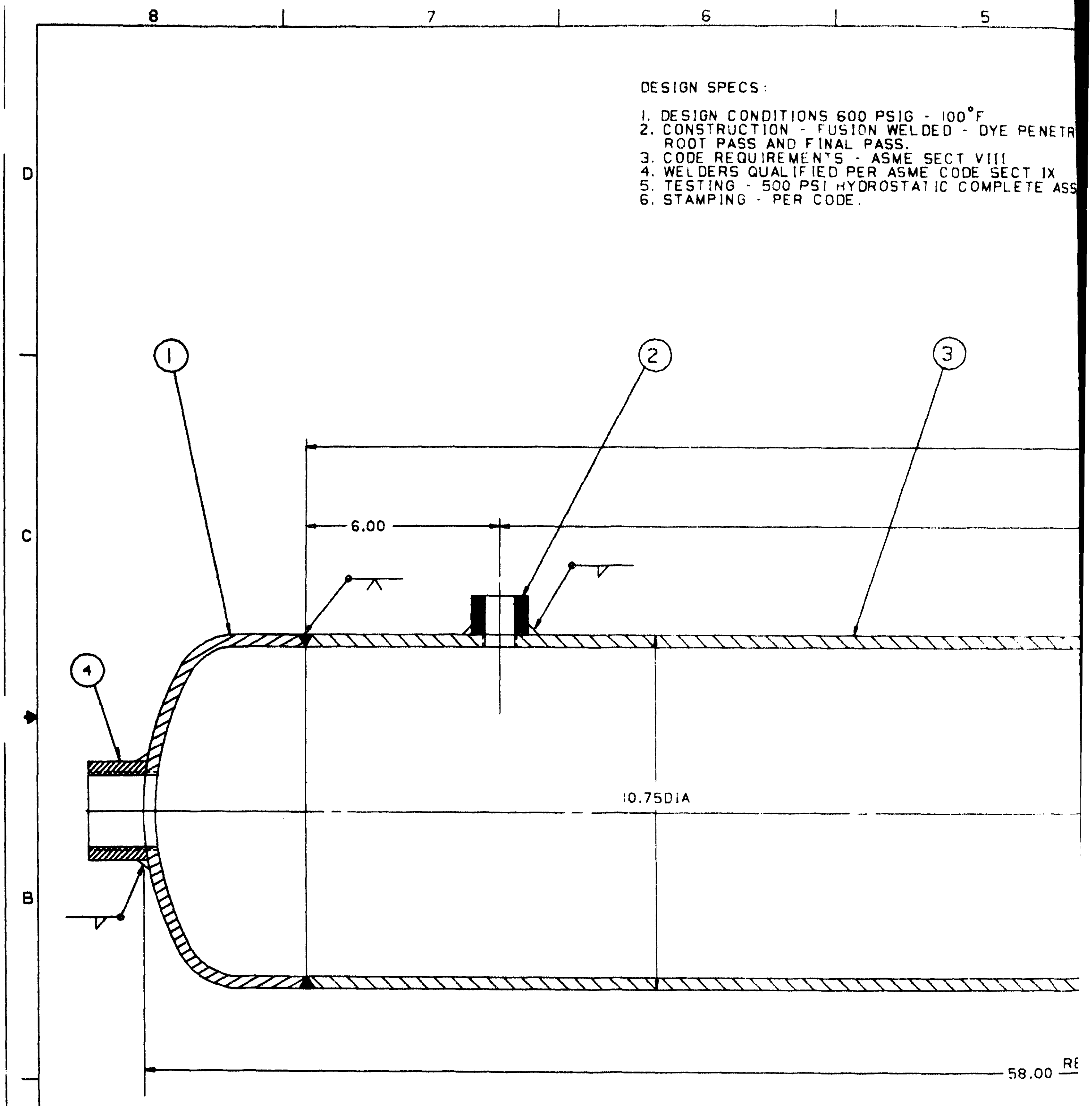
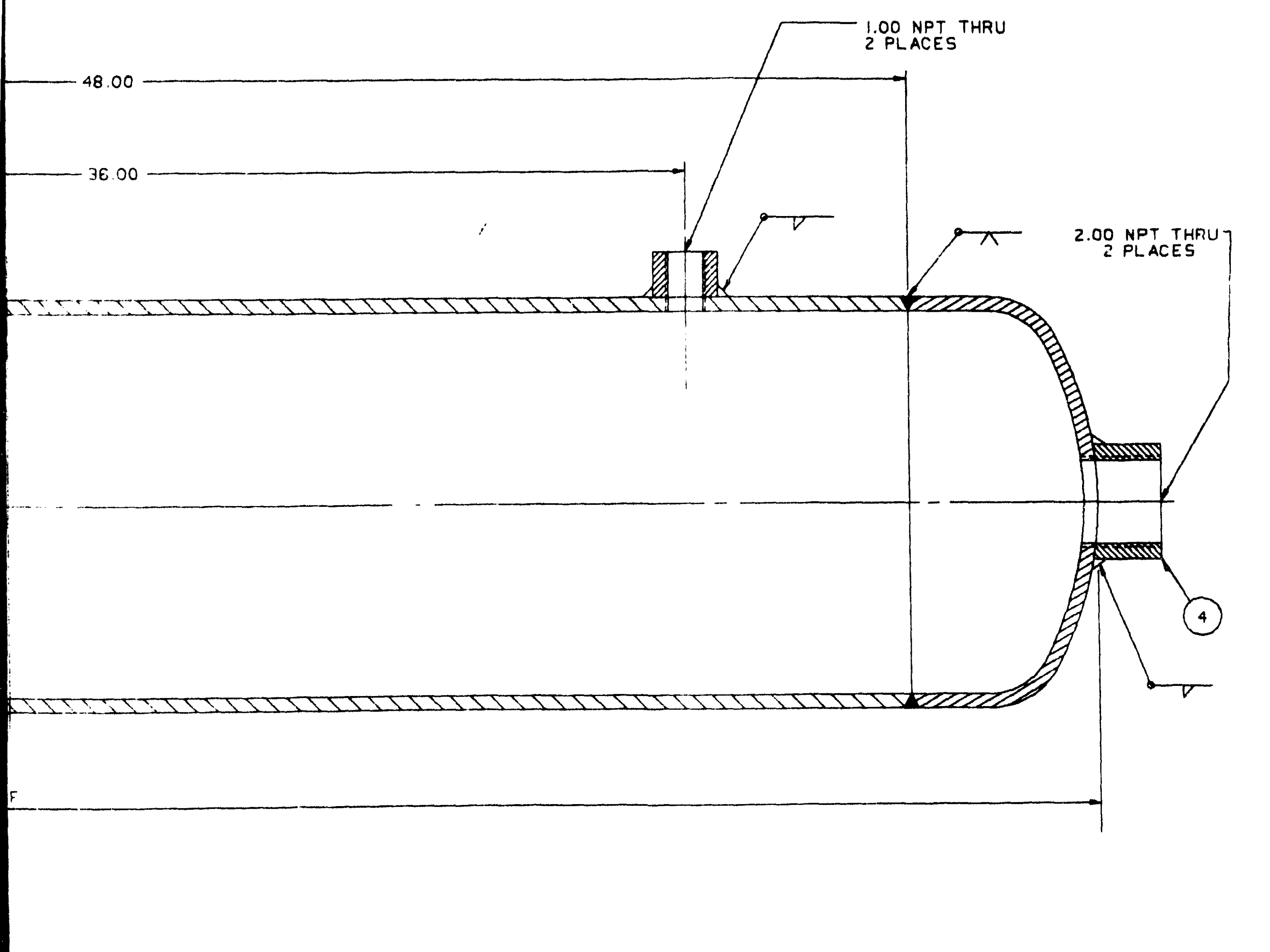


Figure B.8 – Recirculating HTHP Filter Test Unit Accumulator Tank

TITLE RECIRCULATING HTHP FILTER TEST UNIT
ACCUMULATOR TANK
DWG 2236D46 REV 1

ITEM	NOTE	PART NAME	DEF	SIZE REFERENCE INFORMATION	MATL SIZE CODE PART NUMBER OR REF DWG	GROUP NOTE PROCESS OR LINE NO.	GROUP 01	02	03	04	05
1		CAP		10.00 STD WT WELD CAP	STL	ASTM A234	2				
2		HALF COUP		1.00 NPT HALF COUPLING	STL		2				
3		PIPE		48.00 OF 10.00 STD PIPE	STL	ANSI B36.10	1				
4		HALF CPLG		2.00 N.P.T. HALF CPLG	STL		2				

NT TEST



CADDS DWG-NO MANUAL CHANGES ALLOWED

TOLERANCES UNLESS OTHERWISE SPECIFIED

FINISH TO BE ✓ UNLESS OTHERWISE SPECIFIED

GEOMETRIC CHARACTERISTIC SYMBOLS

DFTR DATE
CHKR
APPD
APPD
APPD

R&D CENTER
Westinghouse Electric Corporation
PITTSBURGH PENNSYLVANIA 15235 U.S.A.

TITLE RECIRCULATING HTHP FILTER TEST UNIT
ACCUMULATOR TANK

DIMENSIONS IN INCHES

SIZE	FSCM NO	DWG NO	REV
D	01269	2236D46	1
SCALE 1:2		D.301	SHEET 1 OF 1

the heated gas leaves the heater it will pass through a heat traced and insulated pipe to the test loop where it enters through a small diameter nozzle to act as the motive gas for the recirculating eductor. This causes approximately 90% of the total flow to be recirculated through the test loop. The remaining 10% will be taken out after the flow measuring venturi and cooled before it passes through the back pressure regulator, PCV 205 or the hand valve, HV 206. These help to maintain the system pressure at 150 psig. The gas then goes to the low pressure side reservoir before it is recompressed to 500 psig.

The system pressure is also maintained by pressure control valve PCV 207. This will be set at 150 psig and be supplied from the system gas reservoir that is at 500 psig. PCV 207 will be equipped with a vent set at 160 psig that will allow any system over pressure to be directed to the low pressure side reservoir. The filter vessel will also have a pressure relief valve to insure that the maximum working pressure (350 psig) is not exceeded.

2.3.3 Process Gas Heater

The process gas heater will be a vertical, cylindrical, electrically heated radiant tube furnace, approximately 52 inches diameter by 80 inches high, supplied by Armstrong Engineering Associates. Heat input to the furnace will be 24 kw, supplied by 80/20 Ni/Cr rod heaters. The gas will be contained and heated in a 1 inch double extra heavy Incoloy 800H helically wound pipe coil, 68 feet long inside the furnace. The coil will be designed for 550 psig at 1600°F. The pressure drop through the coil will be less than 10 psi. Figure B.9 shows the initial drawing of the heater.

A thermocouple on the exit side of the heater, TE 212, provides the actual temperature of the gas stream to the temperature controller, TIC 211, that compares this to the set point temperature (e.g., 1550°F) and adjusts the electrical power to the heating elements in the heater accordingly.

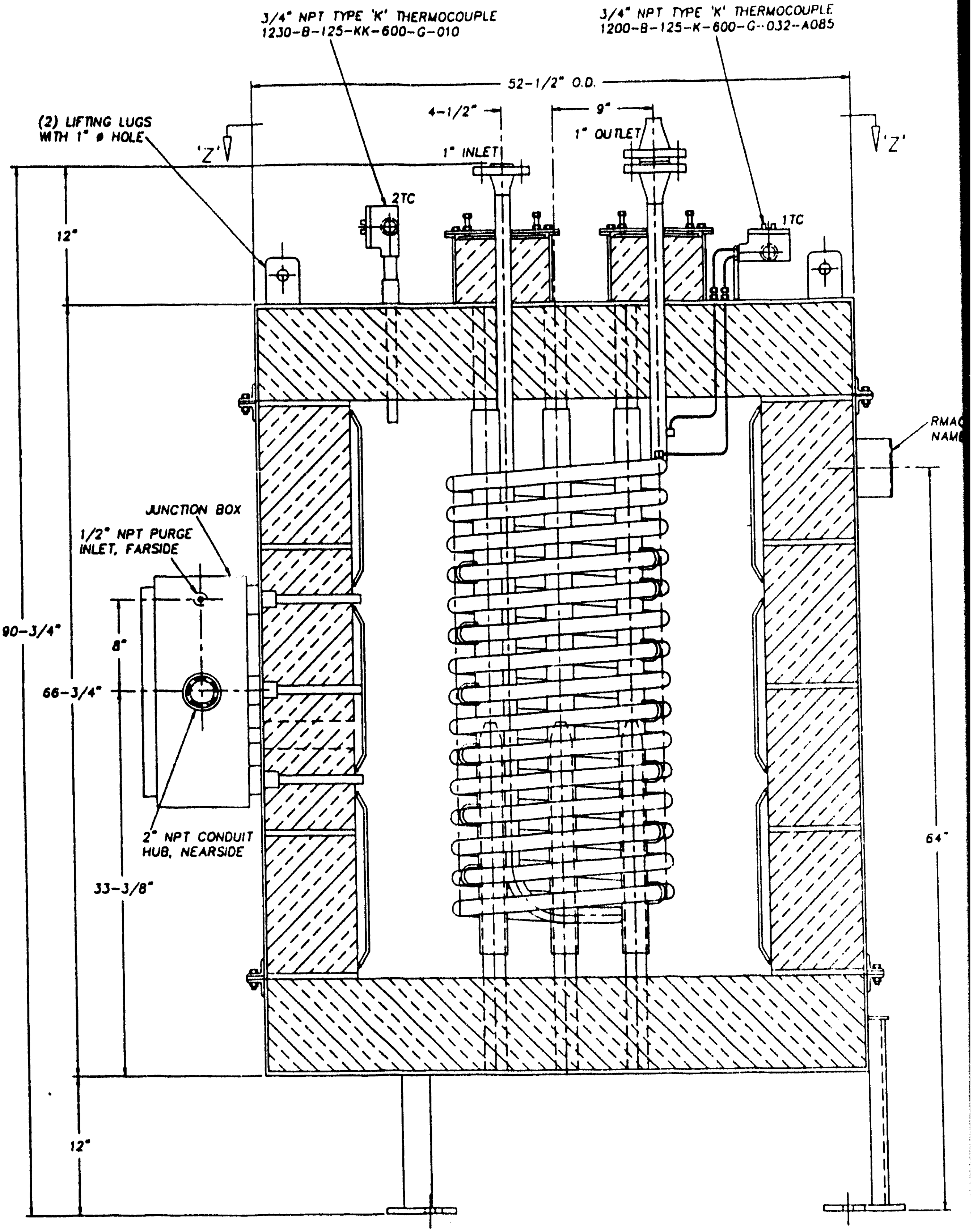
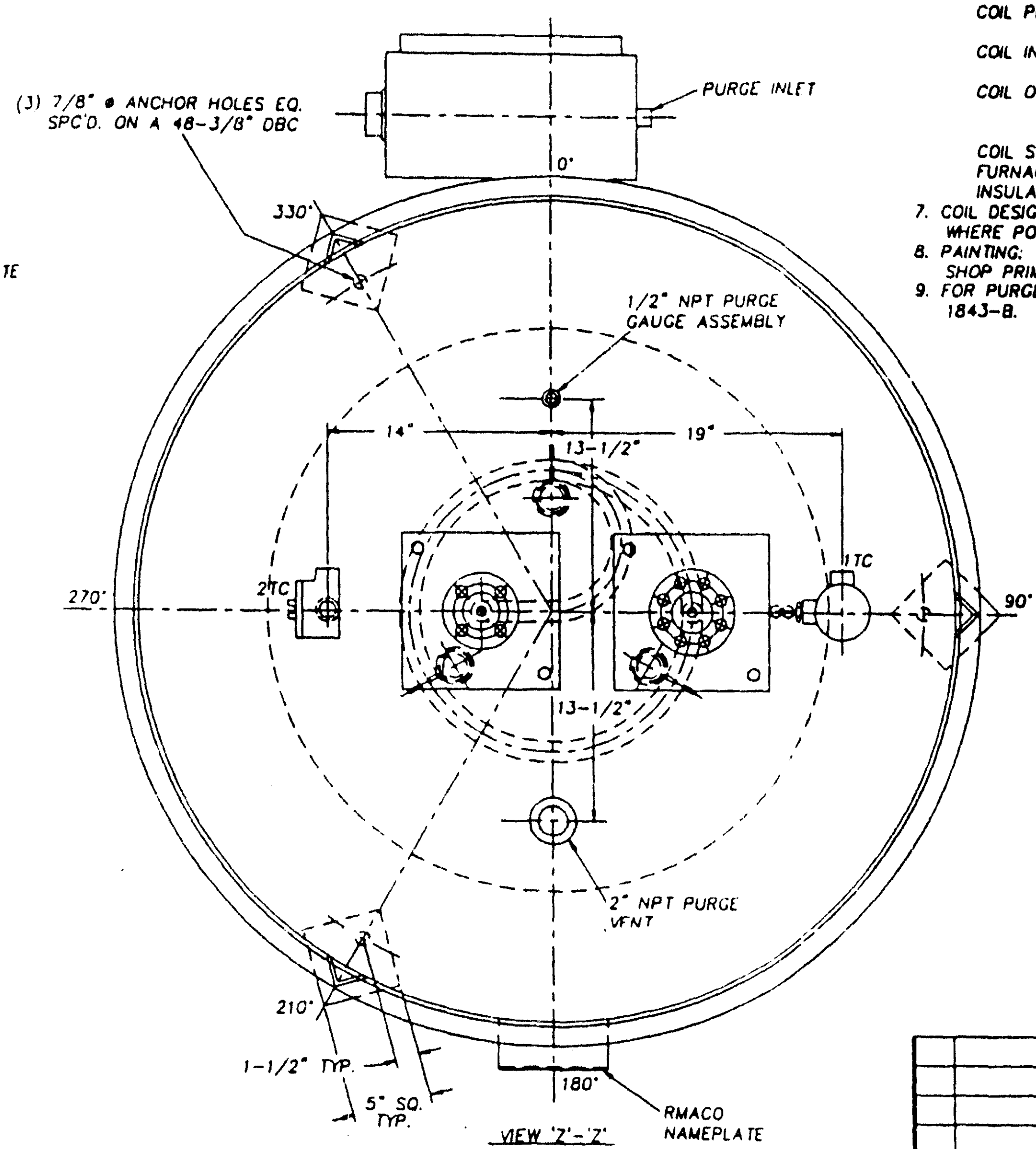


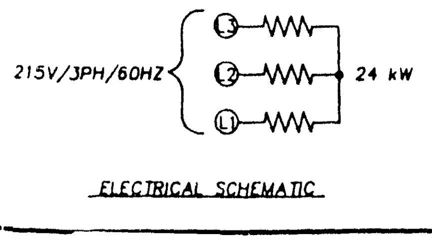
Figure B.9 – Process Gas Heater Drawing

NOTES.
1. ELECTRICAL CLASSIFICATION: CL 1, GRP. B, DIV. 2
   FURNACE TO BE MANUALLY PURGED TO NFPA 496, TYPE 'Z' TO MAKE IT SUITABLE FOR USE IN CL 1, GRP. B, DIV. 2 AREA.
2. ELECTRIC POWER: 215 V., 3 PH., 60 HZ.
3. DESIGN DATA:
   DESIGN PRESS. COIL: 550 PSIG
   TEST PRESS. COIL: 11138 PSIG
   TEST PRESS. COIL OUTLET FLG: 9157 PSIG
   TEST PRESS. COIL INLET FLG: 2160 PSIG
   DESIGN TEMP. COIL: 1600°F. (EXCEPT INLET FLANGE 800°F)
4. UNIT WEIGHT: EMPTY 2550 LBS.
5. FURNACE TO BE SHIPPED ASSEMBLED AS SHOWN PURGE ITEMS/PIPING WILL BE PACKED SEPARATELY FOR SHIPMENT.
6. MATERIALS OF CONSTRUCTION:
   COIL PIPE-1" IPS SCH. XXH SMLSS. SB-407 ALLOY 800H
   COIL INLET FLG.-1" ANSI 600# WNRTJ SB-564 ALLOY 800
   COIL OUTLET FLG.-1" PC-4S XXS WN MALE W/ FEMALE COMPANION FLANGE SB-564 ALLOY 800H
   COIL SUPPORTS-INCONEL 600
   FURNACE SHELL & SUPTS.-CARBON STEEL
   INSULATION-8" TK. X 10 LB. CERAMIC FIBER
7. COIL DESIGNED TO ASME CODE SECTION VIII, DIV. 1 WHERE POSSIBLE, NO STAMP REQUIRED.
8. PAINTING: WIREBRUSH & PAINT (1) COAT OF 180° SHOP PRIMER.
9. FOR PURGE SCHEMATIC PLEASE REFER TO DWG. 1843-B.

ATE



VIEW 'Z'-'Z'



ELECTRICAL SCHEMATIC

Cust. P.O. No: 34-82692-EY

Tag No: C9816

No. Required: ONE

"This drawing, and the information and know-how thereon, is the confidential property of Richard M. Armstrong Co. and may not be used or reproduced for any reason without the written permission of the Richard M. Armstrong Co. Return of this drawing must be made to the Richard M. Armstrong Co. upon request."

REVISIONS	DATE

52" DIA. ELECTRIC RADIANT GAS HEATER

WESTINGHOUSE ELECTRIC CORP. PITTSBURGH, PA.

RICHARD M. ARMSTRONG CO.
WEST CHESTER, PA.

REFERENCE DRAWINGS: 1843-B; 10477-D

TEMPLATE MADE

DRAWN BY	BROOKS	ORDER NO.	DRAWING NO.
DATE	25JAN88		CAD
CHECKED	WAV	A8733345	10476-D
DATE	2 FEB 88		

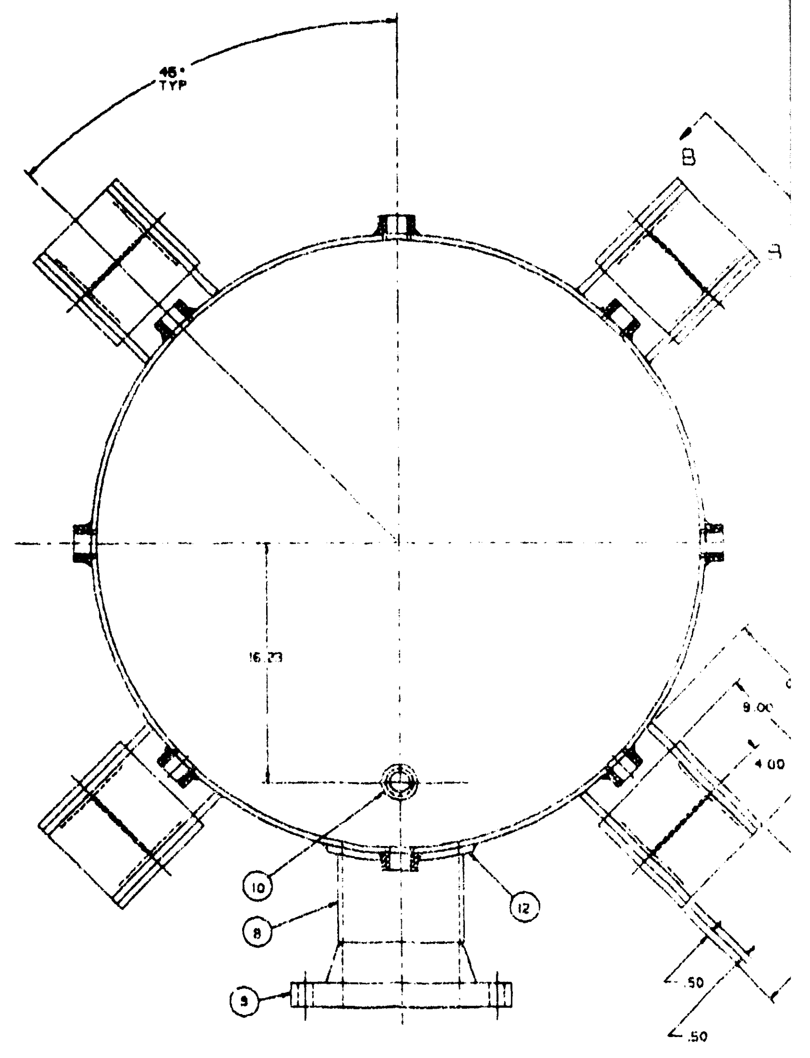
2.4 Dust Feed/Metering

Dust feed to the system will consist of redispersed and sized char, metered into the system by a Westinghouse developed powder feeder system. The dust metering and injection system currently used at the test facility also represents the product of an evolutionary process, as the problem of metering small amounts of fine powders into high-pressure systems has proven to be a formidable one. Westinghouse recently invested a significant amount of capital in the design, fabrication, installation and proof-testing of a system that delivers a wide range of powder feed rates accurately and smoothly to the high-pressure system. The dust feed system is currently capable of providing an on-line read-out of the powder and transport gas mass flow rates. This is of great value in the analysis of the performance of a test device. This highly accurate powder feed system consists of a K-TRON "loss in weight" powder feeder with a twin screw feed barrel for uniform powder feeding, Model LWF 20 with a capacity of 10,000 grams/hour. The device is enclosed in a pressure vessel sized to house the feeder and its hopper, Figure B.10. This vessel is an ASME coded vessel with a pressure relief valve to insure that the maximum working pressure (350 psig) is not exceeded. A small amount of pressurized motive gas, controlled by flow valve FV 415 and flow controller FIC 414, will be used to entrain the metered char into the test loop, as shown in Figure B.3. The particle dust loading will be between 2000 and 4000 parts per million by weight and have a mean mass particle diameter between 5 and 10 microns. It will be injected into the main gas stream downstream of the eductor or into the filter vessel directly.

Two sources of char are currently being considered: the cyclone catch from the KRW fluidized bed gasifier and from an appropriate location downstream of the Texaco entrained bed gasifier. The decision on which one to be used will be made prior to testing, based on the program directions at that time.

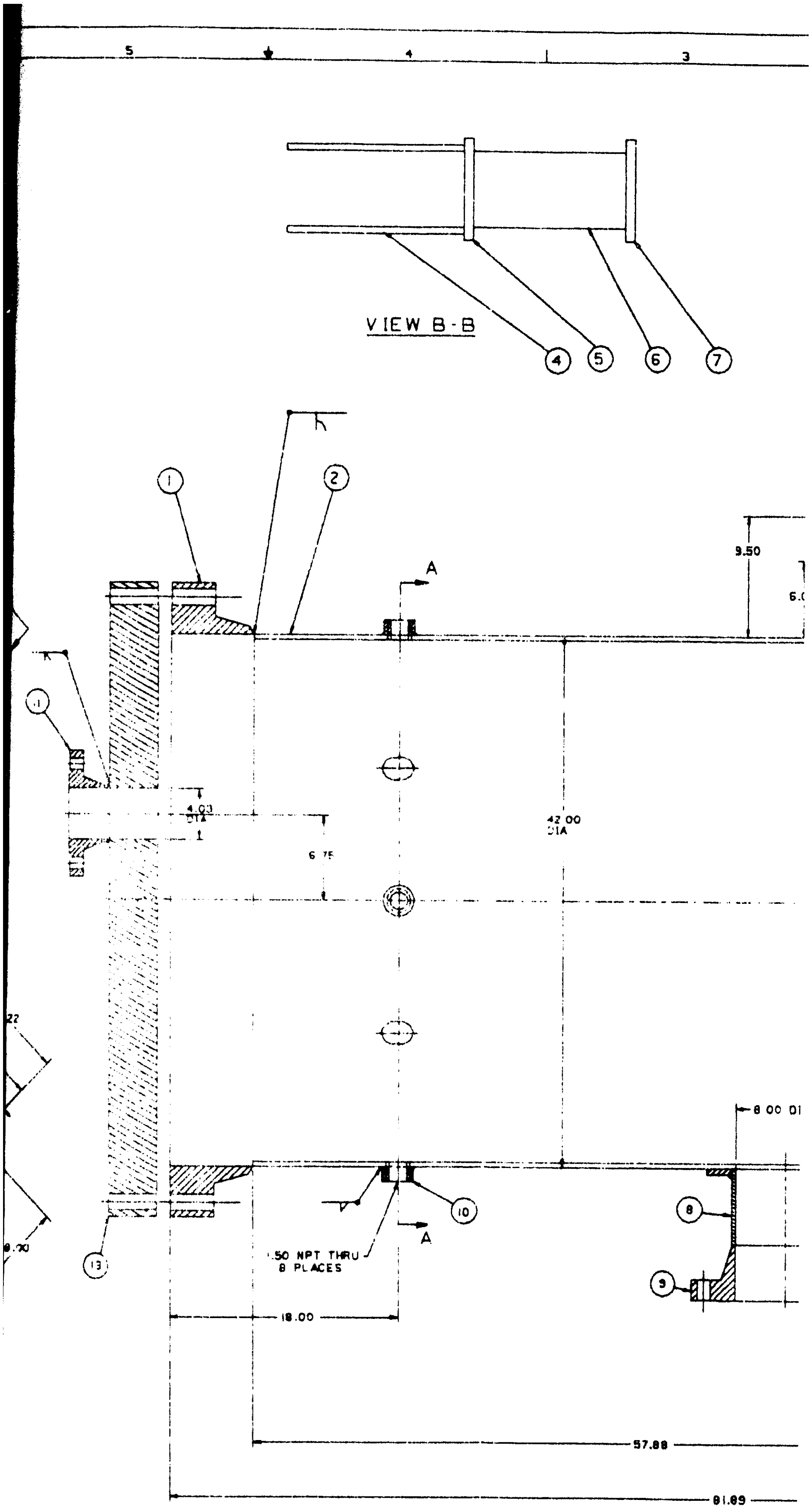
DESIGN SPECS:

1. DESIGN CONDITIONS 350 PSIG - 650° F
2. CONSTRUCTION - FUSION WELDED - DYE PENETRANT TEST ROOT PASS AND FINAL PASS.
3. CODE REQUIREMENTS ASME SECT VIII
4. WELDERS QUALIFIED PER ASME CODE SECT IX
5. TESTING - 500 PSI HYDROSTATIC COMPLETE ASSY.
6. STAMPING - PER CODE

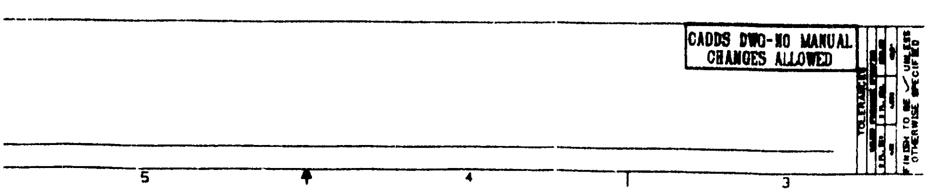


SECTION A-A

Figure B.10 – Recirculating HTHP Filter Test Unit D-



st Feeder Vessel



2.5 Dust Removal (TBD)

Two options were evaluated for removing the dust collected in the filter vessel. Figure B.11 shows these options. On the right side of the figure, a large collection vessel is attached directly to the filter vessel. The vessel would hold the char injected for one 500 hour test. At the end of the test, the char would be recycled for the next test.

The other option is shown on the left side of the figure. This option uses a small (e.g., 3 ft^3) collection hopper that would hold approximately 1 day's worth of operation. A large valve would then be closed to isolate the hopper and the hopper would be depressurized. The hopper would be disconnected and another one would be connected. The filled hopper would be moved to the dust feeder vessel location and used to refill the dust feeder hopper.

The small vessel option would add less volume to the system, but requires a high temperature valve to isolate the system during hopper changes. Additional design of this part of the system is in progress.

2.6 Filter System

The following deals with the actual filter elements, support structure and cleaning system.

2.6.1 Filter Elements

The ceramic cross flow filters that will be tested in this program will be of the "commercial" scale filter designs manufactured by Coors. Each filter will be nominally 12 x 12 x 4 in. and have approximately 7 ft^2 of active filter area. Currently the most favorable design parameters for the cross flow filter include the following:

Pore Size	70-100μ
Porosity	45-50%
Back Wall Thickness	65 mils
Mid Rib Design	
• corner radius	110 mils
• rib height	150 mils
• slip coated ribs	

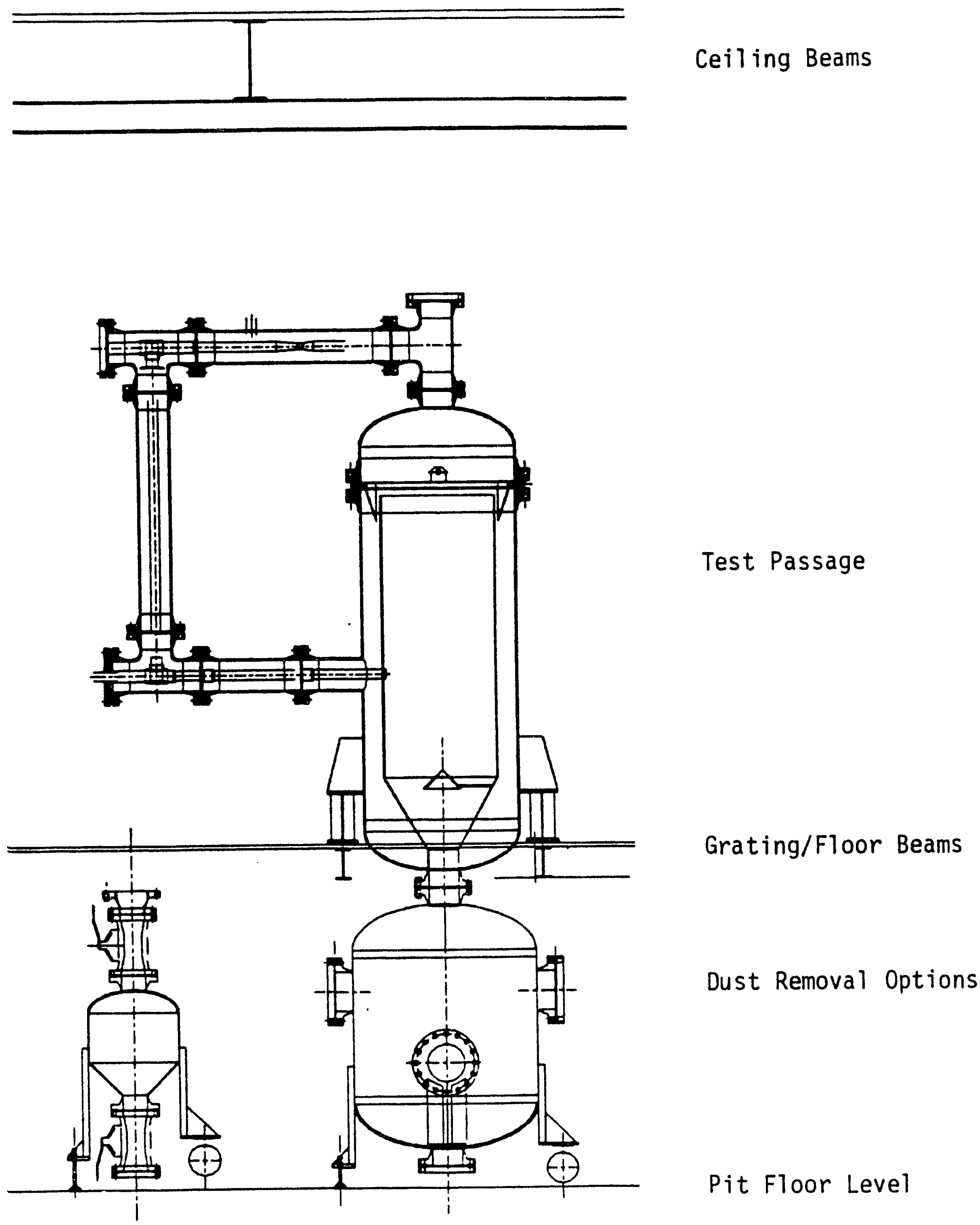


Figure B.11 - Dust Removal Options

Optimization of the firing cycle is currently under way and it appears that the full manufacturing process will require a bisque fire, a primary fire and a final high fire. In related cross flow filter development programs, progress is being made in the evolution of more rugged filter elements, so the exact filter specification is not certain at this point; however, the best filter design available at the time of testing will be used.

2.6.2 Filter Mount and Support Structure

The filter elements will be mounted in a filter holder that is designed to hold two filters, as shown in Figure B.12. The filter mounting assembly consists of a clean gas plenum chamber, made from 4 inch, schedule 40, type 316 stainless steel pipe, and the two horizontal flange mounts for the filter elements. The flange mounts are welded to the clean gas plenum to insure a dust tight seal. The filter elements are gasketed with a high temperature ceramic gasketing material called Interam made by 3M Company. The filter elements have a flange designed into the base and the mount has a corresponding recess for the filter flange. Metal bars are bolted to the mount to clamp the filter flange in place, with the Interam gasketing providing the seal.

Two filter plenums can be mounted on the tube sheet, as shown in Figure B.13. This allows up to four filter elements to be tested at one time. A split-ring flange design is used to fasten the filter holders to the tube sheet. This design prevents the bolts from being in tension at the operating temperature.

The overall arrangement of the tube sheet assembly is shown in Figure B.14. The tube sheet plate, Figure B.15, supports the filter plenum mount and serves as the dirty gas to clean gas barrier across the pressure vessel. The cylindrical and cone section form a bellow type expansion section that is used to support the assembly and accommodate vertical and radial thermal growth. The assembly is supported from a ring section that clamps between the main vessel flange. The ring section is sealed by two (top-bottom) flexitallic gaskets that also permits slight rotational motion of the ring section. The cylinder and

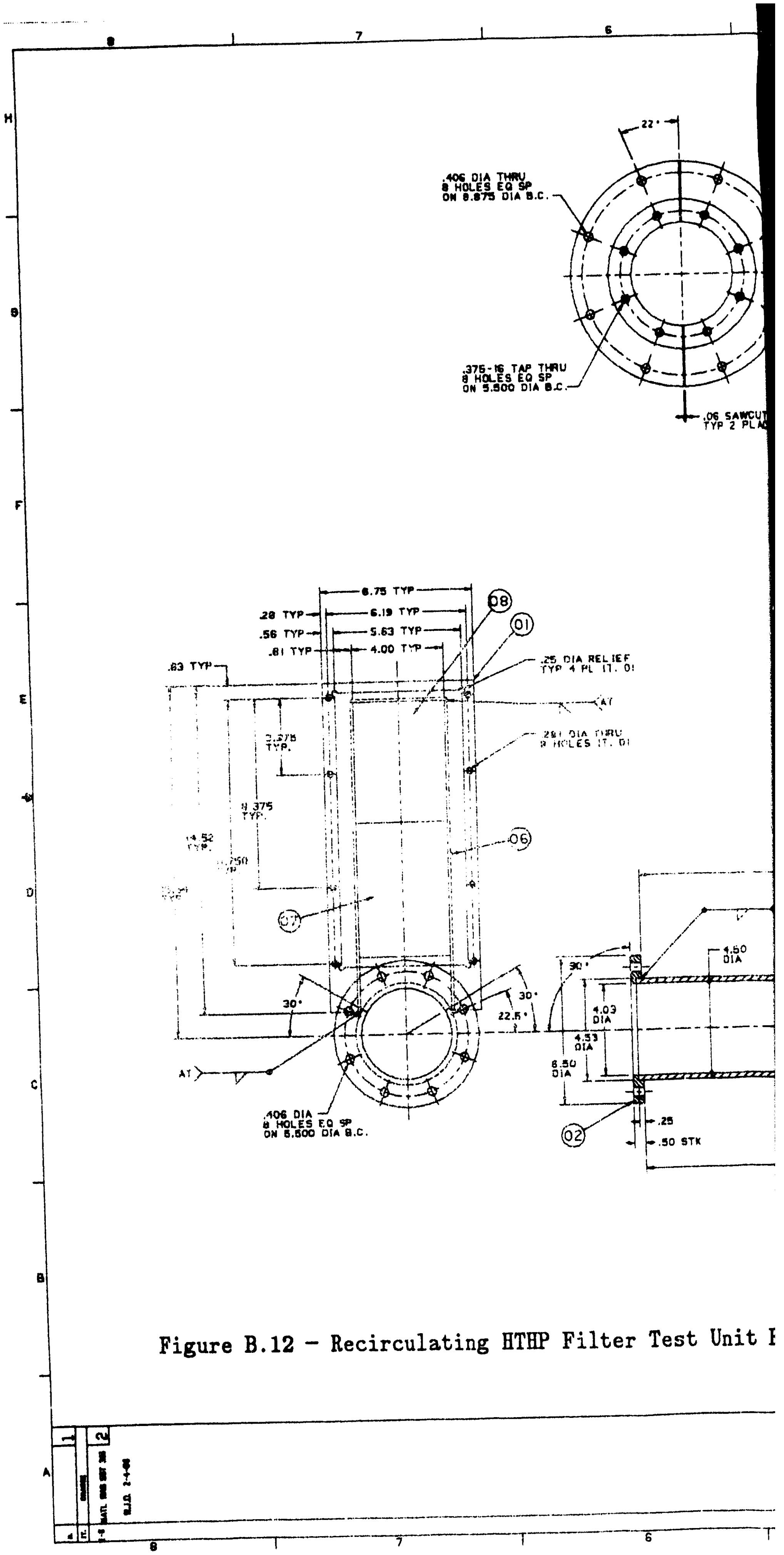
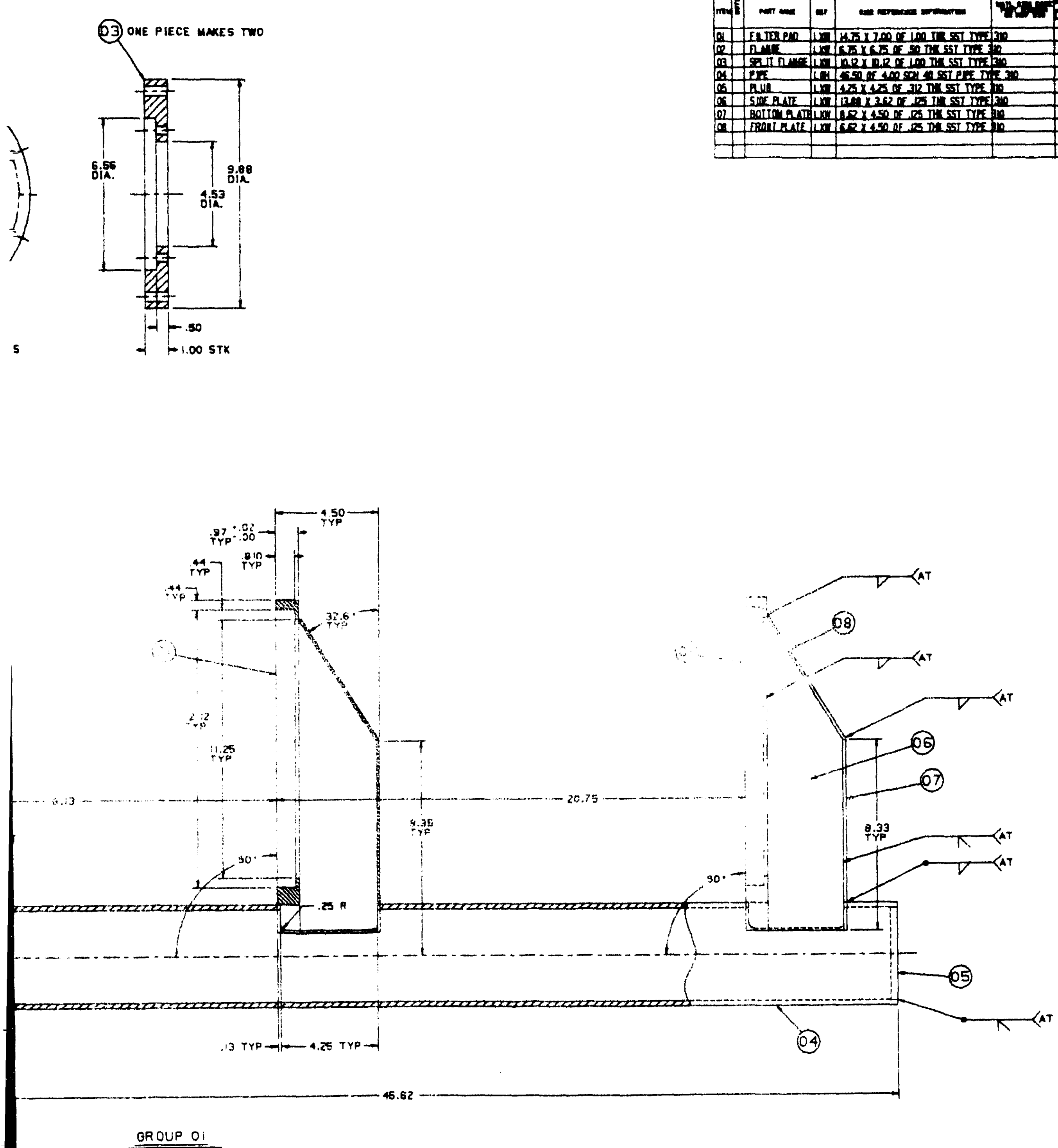


Figure B.12 - Recirculating HTHP Filter Test Unit F

TITLE RECIRCULATING HTHP FILTER TEST UNIT
FILTER HOLDER
DWG 1503E26 REV 2

ITEM	NOTE	PART NAME	REF	SIZE REFERENCE INFORMATION			01	02	03	04	05
01		FILTER PAD	LXIII	14.75 X 7.00 OF 1.00 THK SST TYPE 310			2				
02		FLANGE	LXIV	6.75 X 6.75 OF .50 THK SST TYPE 310			1				
03		SPLIT FLANGE	LXIV	10.12 X 10.12 OF 1.00 THK SST TYPE 310			—				
04		PIPE	LBH	46.50 OF 4.00 SCH 40 SST PIPE TYPE 310			1				
05		PLUG	LXIV	4.25 X 4.25 OF .312 THK SST TYPE 310			1				
06		SIDE PLATE	LXIV	13.88 X 3.62 OF .125 THK SST TYPE 310			4				
07		BOTTOM PLATE	LXIV	8.62 X 4.50 OF .125 THK SST TYPE 310			2				
08		FRONT PLATE	LXIV	6.62 X 4.50 OF .125 THK SST TYPE 310			2				



ter Holder

CADDS DWG-NO MANUAL CHANGES ALLOWED

TOLERANCES

FINISH TO BE ✓ UNLESS OTHERWISE SPECIFIED

DFTR D.BAKER DATE 1-14-88

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Westinghouse Electric Corporation

TITLE RECIRCULATING HTHP FILTER TEST UNIT
FILTER HOLDER

SIZE E FSCM NO 01269 DWG NO 1503E26 REV 2

SCALE 1/2 D.301 SHEET 1 OF 1

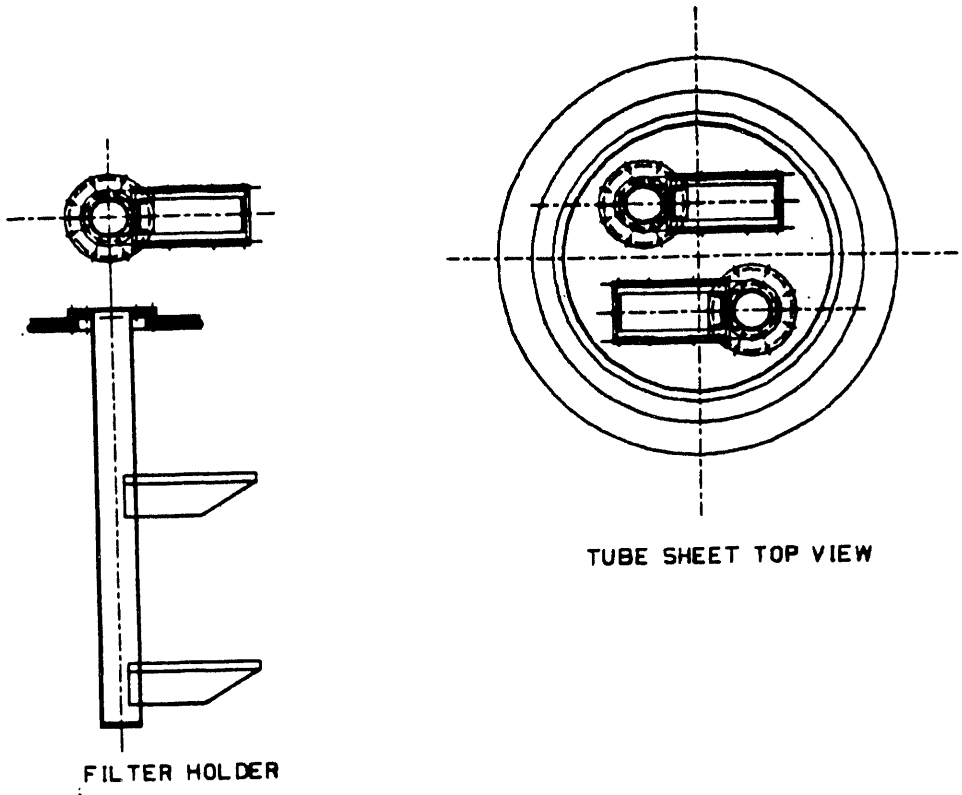


Figure B.13 – Filter Holder and Tube Sheet Layout

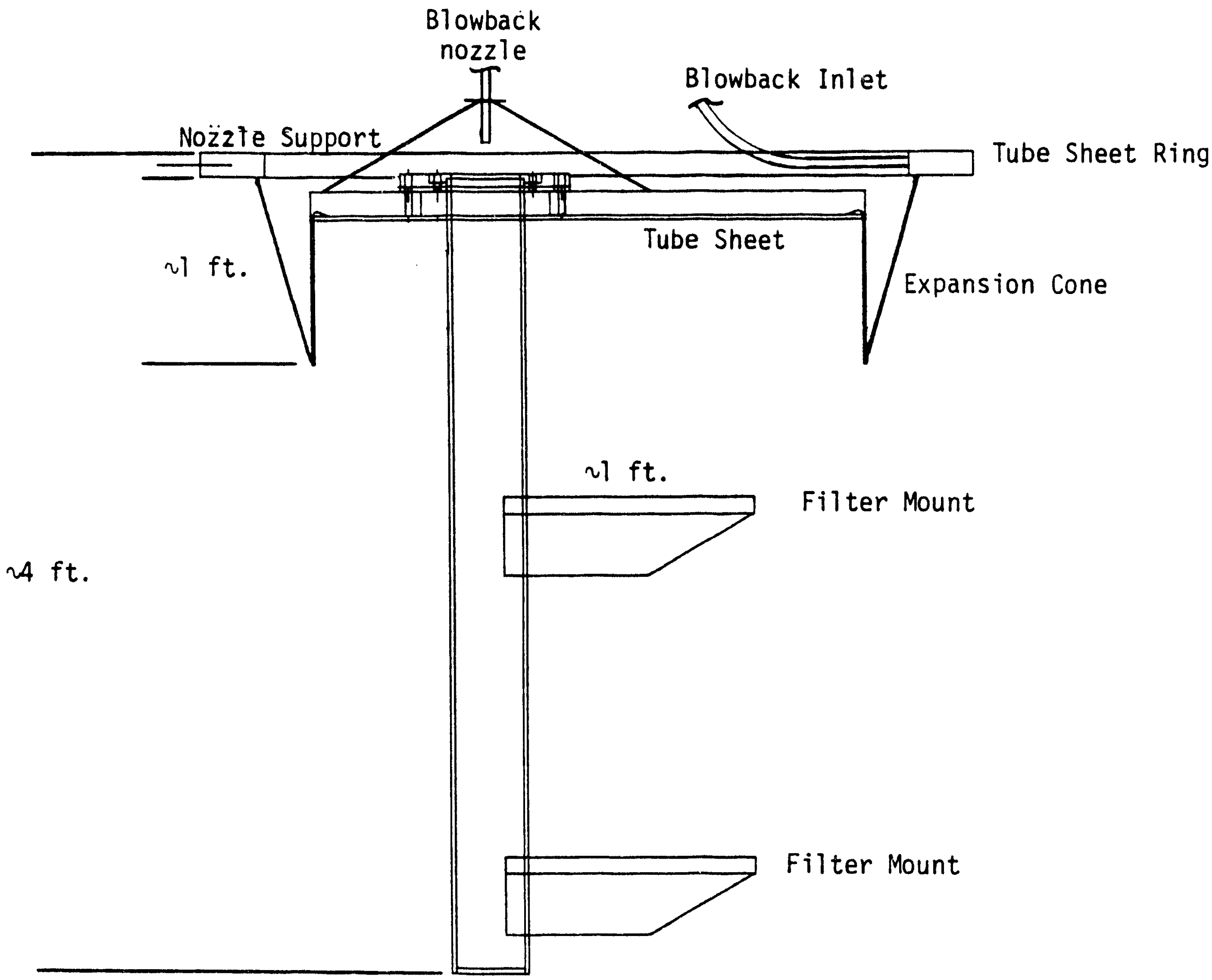


Figure B.14 – Tube Sheet and Filter Holder Assembly

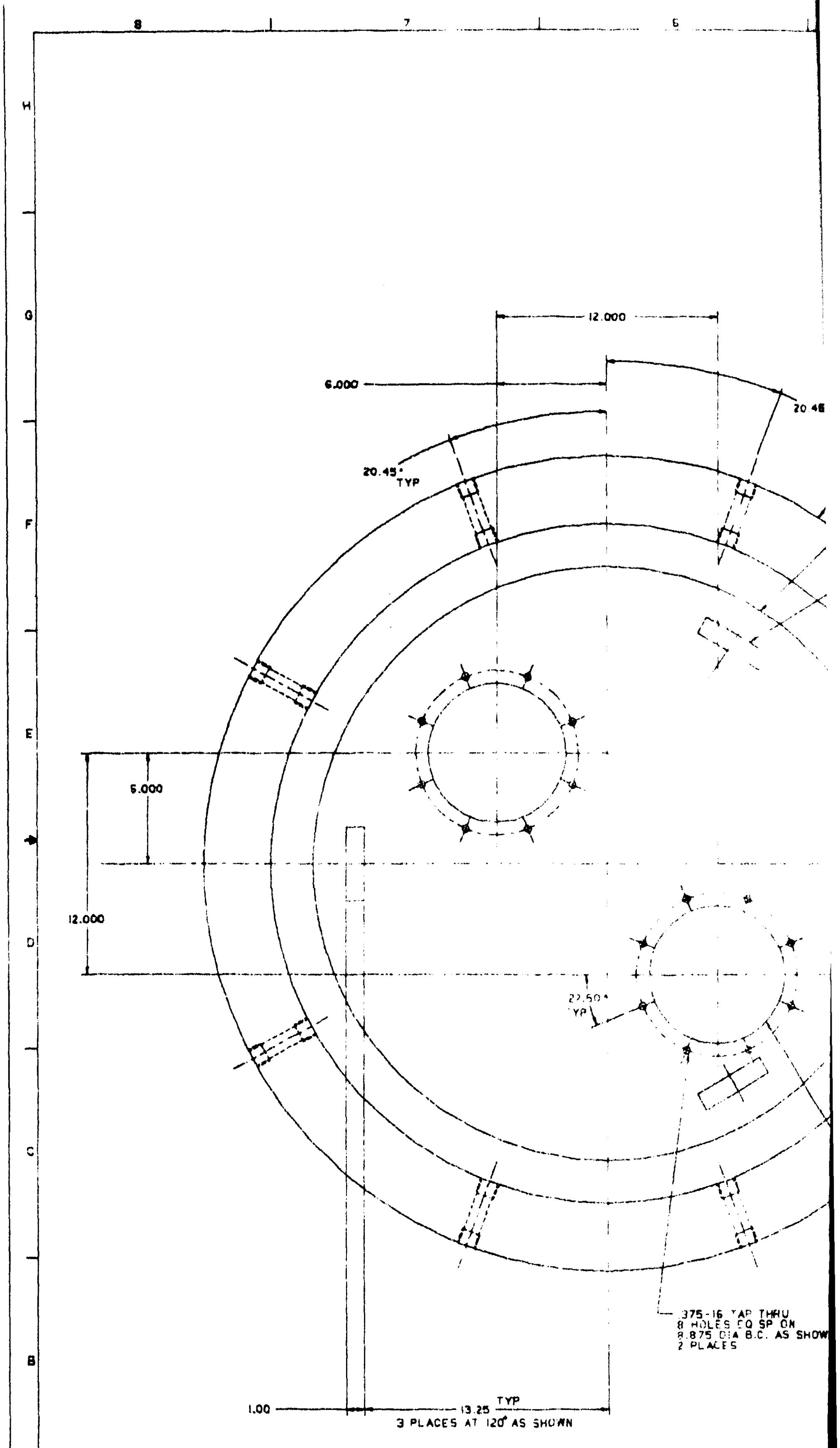
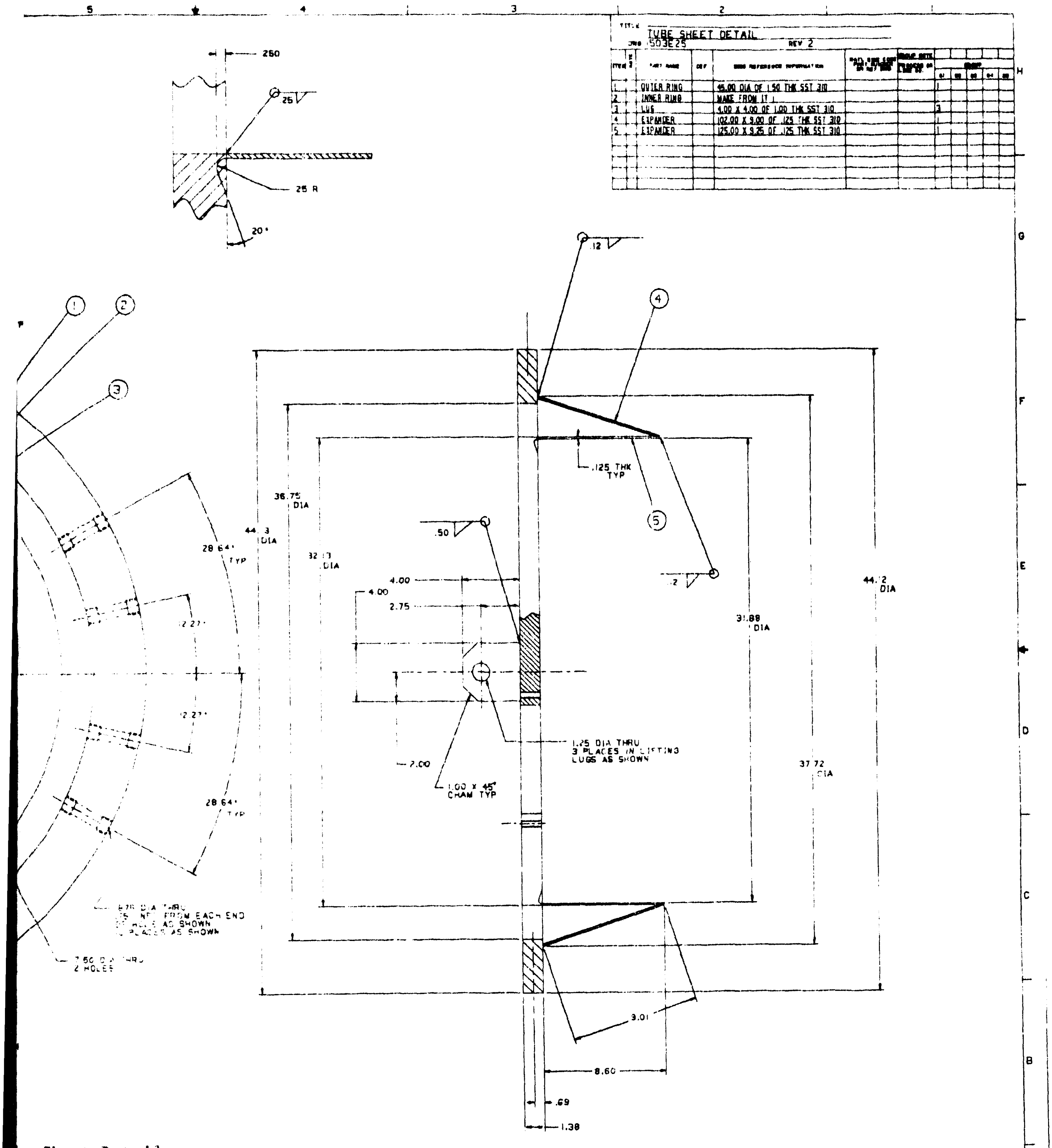


Figure B.15 - Recirculating HTHP Filter Test Unit Tu



ITEM	PART NAME	REFERENCE INFORMATION	QTY
1	OUTER RING	45.00 DIA OF 1.50 THK SST 310	1
2	INNER RING	MAKE FROM IT 1	1
3	LUG	4.00 X 4.00 OF 1.00 THK SST 310	3
4	EXPANDER	102.00 X 9.00 OF .125 THK SST 310	1
5	EXPANDER	125.00 X 9.25 OF .125 THK SST 310	1

be Sheet Details

cone sections are insulated with a blanket refractory to reduce temperature and temperature gradients through critical sections of the assembly. The tube sheet design is premised on a similar system that has been used successfully at larger scale and at higher operating temperatures.

The tube sheet outer ring section is also fitted with 3/4 inch pipe penetrations to bring the pulse jet cleaning pipes into the filter plenum, as described in the next section. These penetrations can also be used for other instrumentation access points, such as temperature and pressure.

2.6.3 Pulse Jet Cleaning

Pulse jet cleaning of the cross flow filters will be accomplished using high pressure (500 psig) system gas from the system gas reservoir. System gas will be used in order to maintain the gas composition. The gas will be held in a pressure regulated pulse accumulator tank at 300 to 500 psig. Fast acting, 1/2 inch pipe size solenoid valves (FV 111 and FV 115) will be actuated with an electronic timer (KC 151), with a typical "ON" time of 0.1 second. The solenoid valves will have a block valve (HV 110 and HV 112, and HV 114 and HV 116) on either side so they can be changed during operation in case of a failure. The gas is delivered through a 3/8 to 1/2 inch tube nozzle into the filter plenum, as shown in Figure 2.5. This reverse flow of gas removes the collected dust from the filter. The blow back sequence can be initiated manually (with HMS 152) or automatically when the filter pressure drop reaches a predetermined level or on a timed basis.

The blow back sequence also closes two solenoid valves (FV 119 and FV 135) to isolate the filter pressure drop transmitter, PDT 121. This transmitter gives the pressure drop versus time reading used to determine when the filter should be cleaned and the effectiveness of the blow back pulse.

During a blow back pulse, the pressure rise in the filter plenum can be measured with a fast response differential pressure transducer, PDT 126, and it can be recorded on a high speed strip chart recorder, PR 127. This can be used to determine the long term effectiveness of the blow back pulse in relation to the degree of cleaning seen on the filter at the end of a test segment.

2.7 Material Specifications

The gasifier simulator test loop will be constructed of the following materials:

Item	Material
Filter test vessel	Carbon steel (coded for 350 psig @ 650°F)
Pressure piping	Carbon steel (coded for 350 psig @ 650°F)
Filter test vessel liner	316 stainless steel
Filter holders	316 stainless steel
Tube sheet and expansion cone	TBD
Pipe liners	316 stainless steel
Vessel insulation	Fiberfrax blanket
Piping insulation	Fiberfrax blanket
Dust feed vessel	Carbon steel (coded for 350 psig @ 650°F)
Dust removal vessel	Carbon steel (coded for 350 psig @ 650°F)
Process gas heater piping	Incoloy 800H (designed for 550 psig @ 1600°F)

The selection of 316 stainless steel was made as a result of discussions with material specialists at the R&D Center on stress, strain, and creep, given the operating conditions and test duration and gas composition expected in the test system.

2.8 Data Acquisition

The data acquisition for the test passage will be primarily accomplished with a Molytek Model 3702 data logger. This unit has 32 input channels and 12 alarm output relays. It has chart paper to print out data at set intervals and a RS-232 output that can be connected to a computer directly or transmitted via telephone wires. This allows immediate access to the data as it is generated and also permits storing data for later analysis.

The system pressure and temperature and filter pressure drop will be recorded continuously on a three pen strip chart recorder, Capp model P100M. The filter pressure drop is used to determine when to clean the filters with a reverse pressure pulse, and how well the filter was cleaned. Since the system pressure and temperature affect this value, all three are recorded simultaneously so they can be compared easily.

APPENDIX C

ANALYSIS, DESIGN AND QUALIFICATION OF THE EDUCTOR JET PUMP SYSTEM FOR THE RECIRCULATION GAS TEST LOOP

1. INTRODUCTION

The objective of the work under DOE Contract No. DE-AC21-87MC24022 (Long-Term Durability Testing of Ceramic Cross Flow Filters) is to assess the mechanical integrity and stability of components and materials of the filter, as well as the stability of filtration properties over long time spans of use. This assessment will be done by testing the filters under both pressurized air-blown gasification and pressurized fluidized bed combustion (PFBC) conditions.

The gasification tests will be performed in a new gasifier simulator, the general arrangement of which is shown in Figure C.1.1, being designed by Westinghouse. The system is to consist of a closed recirculation loop so that a fixed gas composition can be maintained. The plan is for approximately 10% of the total gas flow to be used as high pressure motive gas for an eductor that recirculates the system gas and provides the pumping needed to maintain flow through the filter. Since only a small amount of gas is to be mechanically pumped, this design greatly reduces requirements for mechanical gas compression, as well as for the necessary cooling and reheating before and after compression.

This concept relies heavily on the presumed ability of an eductor system to operate with a high entrained-to-motive gas flow ratio. Verification of this capability was needed early in the facility design exercise. Consequently, we performed several studies which are discussed in this report. First, the existing analytical model of the recirculation loop fluid dynamics was improved to include more rigorous treatments of the reversible and irreversible pressure losses in the flow loop and of the compressible flow mechanics of the eductor nozzle gas. Second, the existing hot gas filtration test facility was used to

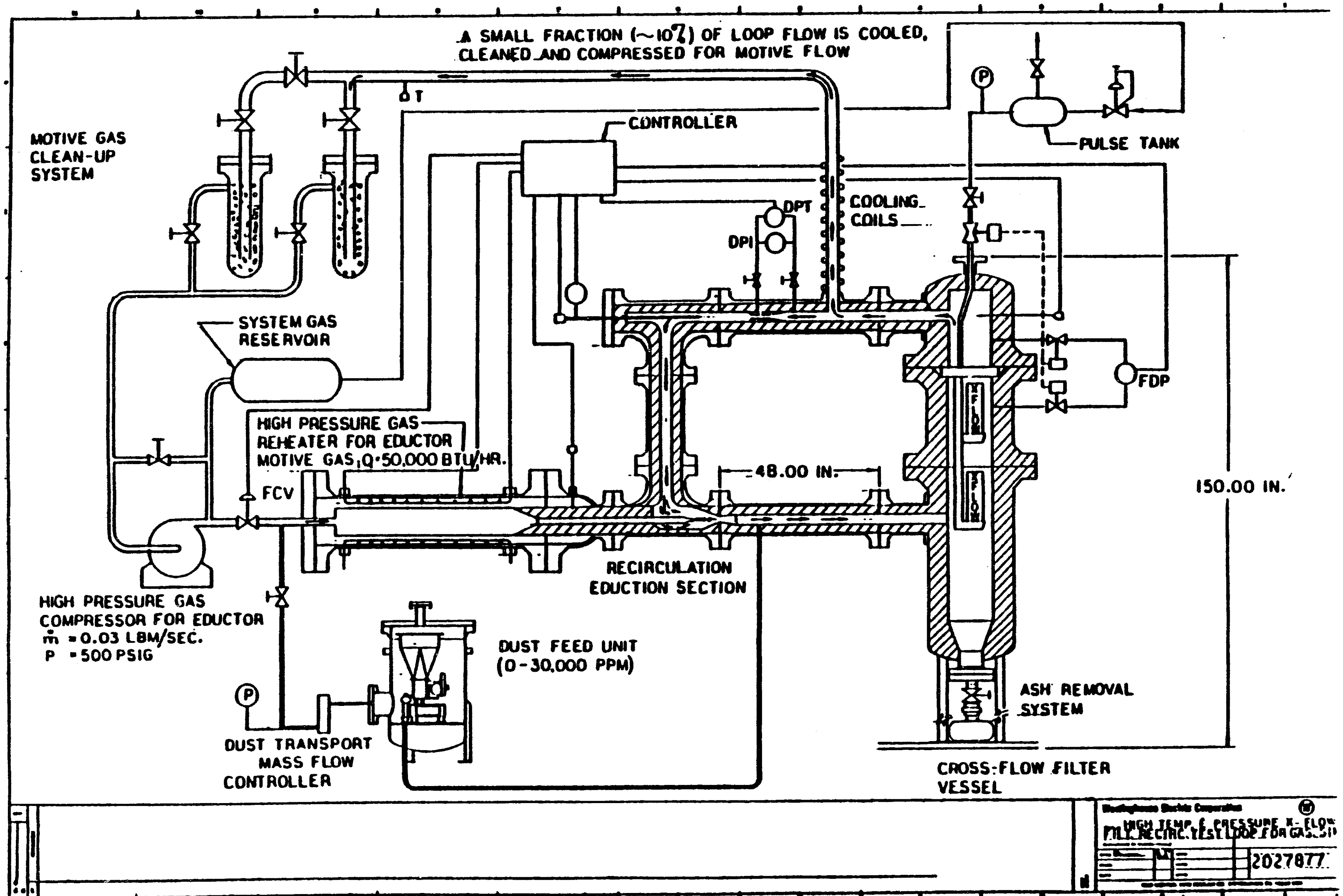


Figure C.1.1 - HTHP Gasifier Simulator for Cross Flow Filter Testing perform cold flow eductor-driven recirculation tests to validate the analytical model. Third, the model was used to project performance of the gasifier simulator recirculation system, and to evaluate eductor system design details.

2. CONCLUSIONS

1. The eductor-driven recirculation model has been demonstrated to be an effective tool for predicting recirculation rates.

2. The hot gas eductor recirculation concept is practical, and should work with reasonable motive to total gas flow rate ratios.

3. Eductor design details have been chosen based on the model results.

3. EDUCTOR RECIRCULATION MODEL

3.1 DETAILED MODEL DESCRIPTION

The gas recirculation analytical model was developed prior to this program and used as the basis of a rigorous BASIC computer program for examination of recirculation system design parameters. At the heart of the model were mass, momentum, and energy balances for the eductor, based on filter blowback modelling that had been performed earlier[1]. Given a set of design parameters, the model calculates steady-state entrained and total recirculation flows. Different sets of parameters may be tested to see what combination meets system design requirements. Table C.3.1 summarizes input design parameters. The model treats a constant diameter nozzle as a special case of a converging/diverging nozzle (exit diameter equals throat diameter).

For a given set of input parameters, the model performs the following steps:

1. Determine flow rate, pressure, and temperature of gas exiting eductor nozzle. The desired flow may or may not be possible given available pressure from the motive-gas supply compressor and nozzle dimensions. Also, flow through the nozzle may fall into any of several flow regimes, depending on throat velocity and system pressure at the discharge. To sort out these possibilities, the following possible states are investigated with the use of compressible flow relations[2], in the order given, until one is found to be possible for the given target motive gas flow rate and the maximum available motive pressure:

TABLE C.3.1 - DESIGN PARAMETERS AND UNITS

	ENTRAINED GAS
P1	Pressure, atm
T1	Temperature, °F
	MOTIVE GAS
P2M*	Maximum stagnation pressure (maximum compressor discharge pressure), atm
T2S*	Stagnation temperature (temperature in nozzle feed tube), °F
W2T*	Desired flow (lb/sec)
MW	Molecular weight
CP	Heat Capacity, Btu/lb °F
K	Ratio of specific heats
	EDUCTOR SYSTEM GEOMETRY
D1	Inside diameter of eductor entrained gas inlet, in.
D2*	Nozzle exit inside diameter, in.
DT*	Nozzle throat inside diameter, in.
D2O	Nozzle outside diameter, in.
D3*	Eductor diffuser inside diameter, in.
	SYSTEM GEOMETRY
DP	Inside diameter of main recirculating gas piping, in.
**	Lengths of various main gas recirculation flow path component, in.
	FILTER
RW	Resistance coefficient, /ft
AF	Filtration area, ft^2
	TOTAL FLOW MEASUREMENT (VENTURI OR ORIFICE)
DOR	Throat or orifice diameter, in.
CD	Discharge coefficient
F	Ratio of permanent to measured pressure loss

*Prompted input, others must be changed within program.

**Various symbols particular to the specific design.

1a. Assume motive gas flow equals target value and subsonic flow through nozzle throat. This is not possible if the resulting throat Mach number is greater than one, or if the resulting stagnation pressure at the throat is greater than the available pressure.

1b. Assume motive gas flow equals target value, sonic flow through the nozzle throat, and supersonic flow throughout the diverging section. This is not possible if the system pressure (into which the nozzle discharges) is greater than the resulting maximum allowable pressure outside the nozzle required to avoid shock in the converging nozzle[3], or if the resulting stagnation pressure at the throat is greater than the available pressure.

1c. Assume motive gas flow equals target value, sonic flow through the nozzle throat, and that a normal shock occurs in the diverging section. This is not possible if the resulting stagnation pressure at the throat is greater than the available pressure.

1d. Assume stagnation pressure at the throat equals the maximum available pressure, and subsonic flow through nozzle throat. This is not possible if the resulting throat Mach number is greater than one.

1e. Assume stagnation pressure at the throat equals the maximum available pressure, sonic flow through the nozzle throat, and supersonic flow throughout the nozzle diverging section. This is not possible if the system pressure (into which the nozzle discharges) is greater than the resulting maximum allowable pressure outside the nozzle required to avoid shock in the converging nozzle.

1f. Assume stagnation pressure at the throat equals the maximum available pressure, sonic flow through nozzle throat and a normal shock in the diverging section.

Note that states 1a through 1c represent the situation where a valve is used between the motive gas compressor and the nozzle, to let down the pressure and control the flow rate. States 1d through 1f represent the situation where this valve is wide open, and maximum flow is occurring. States 1b, 1c, 1e, and 1f represent "choked" flow through the nozzle. The result of step 1 is that the flow rate, pressure, and temperature of gas issuing from the nozzle are known.

2. Guess total (entrained plus motive) flow to equal motive flow.

3. Guess mixture temperature.

4. Guess mixture pressure equal to entrained pressure.

5. Determine pressure drop around filter test loop. The loop pressure drop includes the following irreversible pressure loss components:

- friction loss in eductor
- expansion from eductor diffuser to main piping
- friction loss in piping into filter test vessel
- expansion into test vessel
- loss across filter
- contraction out of filter vessel
- outlet piping friction loss
- irreversible component of venturi or orifice pressure drop
- contraction of entrained gas into eductor suction end

  and the following two reversible components (accounting for velocity changes due to area changes):
- total gas flow between eductor diffuser and main piping into splitter tee (where gas is drawn off for compression to become motive gas)
- entrained gas flow between splitter tee and eductor suction area

6. Estimate mixture pressure as entrained pressure plus loop pressure drop.

7. Estimate mixture velocity from a momentum balance on the entrainment zone, accounting for pressures and velocities in each of the three streams: motive gas, entrained gas, and mixed gas. Then determine

the mixed gas density from the velocity and flow rate, and the mixed gas temperature from the density and pressure.

8. Estimate the mixed gas temperature from an energy balance on the entrainment zone, accounting for temperatures and velocities in each of the three streams.

9. Compare estimated mixture temperatures from previous two steps. If they are close, go to step 10. Otherwise, a numerical procedure is used to re-estimate a total mixture flow rate that will reduce the difference between these two estimated temperatures. The mixture temperature and mixture pressure are assumed to be those given by steps 8 and 6, respectively, and calculations resume with step 5. (It has been found that when convergence on mixture temperature is achieved, convergence on mixture pressure will also have occurred.)

10. Print recirculation loop performance parameters.

3.2 APPROXIMATE MOMENTUM BALANCE

In an eductor with a straight (i.e., not converging/diverging) sleeve, the momentum balance is

$$(W_3^2/S_3\,\rho_3) + P_3S_3g_c = (W_1^2/S_1\,\rho_1) + P_1S_1g_c + (W_2^2/S_2\rho_2) + P_2S_2g_c + P_1(S_3-S_1-S_2)g_c \qquad (3\text{-}1)$$

where the variables are:

W = Gas flow rate, lb_m/sec
S = Flow area, ft^2
P = Pressure, lb_f/ft^2
ρ = Gas density, lb_m/ft^3
g_c = Conversion constant, 32.174 $lb_m\text{-}ft/(lb_f\text{-}sec^2)$

and the subscripts are:

1 = Entrained gas
2 = Motive gas
3 = Combined (entrained plus motive) gas

Note that S_1, S_2, and S_3 are areas referring to the eductor inside diameter minus the nozzle outside diameter, the nozzle exit inside diameter, and the eductor inside diameter, respectively.

If the momentum contributions of the entrained and combined gas streams are assumed to be small, then Equation 3.1 simplifies to:

$$(P_3-P_1)S_3g_c = (W_2^2/S_2\rho_2) + (P_2-P_1)S_2g_c \tag{3-2}$$

At steady state, the eductor pressure gain (P_3-P_1), will equal the pressure drop around the loop. This pressure difference will therefore increase with increasing total gas flow rate around the loop, and will decrease with increasing sleeve i.d., since that would offer less resistance to flow. If the sleeve inside diameter is less than the balance-of-loop pipe i.d., then these proportionalities are roughly approximated by:

$$(P_3-P_1) = K\rho_3W_3^2/\sqrt{S_3- S_n} \tag{3-3}$$

where K = a proportionality constant

S_n = area based on outside diameter of nozzle, ft^2

Combining Equations 3.2 and 3.3 gives an indication of how the loop pressure drop will depend on major eductor parameters, as indicated in Equation 3.4:

$$W_3= \left(\frac{\sqrt{S_3 - S_n}}{K\rho_3\ S_3\ g_c} \left[\frac{W_2^2}{S_2\rho_2} + (P_2 - P_1)\ S_2g_c \right] \right)^{1/2} \tag{3-4}$$

Note that when the sleeve i.d. is considerably larger than the nozzle o.d., the total flow rate through the loop varies inversely with approximately the square root of the sleeve i.d. (or with approximately the fourth root of the area S_3). This explains the predictions and experimental data concerning the effect of sleeve diameter in the following sections. Note also that when the sleeve i.d. is smaller and approaches the nozzle o.d., Equation 3.4 predicts that the flow rate will fall with decreasing sleeve i.d. -flow is being choked off by the narrowing annulus around the nozzle.

This simplified model is presented for help in understanding qualitative effects. In subsequent calculations the detailed eductor recirculation model was used. The detailed model differs from the simplified version in that the pressure drop relationship corresponding to Equation 3.3 is replaced by a much more rigorous treatment of all actual sources of pressure losses and gains in the loop, and in that the momentum balance of Equation 3.1 is not simplified to the form of Equation 3.2.

4. COLD-FLOW RECIRCULATION TESTS

4.1 SYSTEM DESCRIPTION

The existing high-temperature, high-pressure test facility was modified to accommodate a sequence of recirculation verification tests. Figure 4.1 shows the modified system configuration. The combustor, inlet gas, exhaust gas, and bypass piping were replaced with standard 2 inch pipe. An eductor was designed and fabricated for causing recirculation. As shown in Figures C.4.1 and C.4.2, the eductor nozzle was fabricated from a piece of 0.5 inch tubing, with one end plugged to give an opening of 0.15 inches. An eductor sleeve with an inside diameter of about 1 inch was fabricated and installed. The purpose of this sleeve was to maximize conversion of motive gas kinetic energy into pressure energy so as to drive the combined gas through the flow resistances around the loop. This is explained by derivation of an approximate momentum balance as described in Section 3.2. Design dimensions were selected based upon preliminary parametric studies using the existing rigorous eductor recirculation model described above.

The system was operated at room temperature because there was no provision for pre-heating the eductor gas. Nevertheless, the resulting experiments, as described in the next section, were a valid test of the rigorous recirculation loop model, since that model's critical assumptions are not related to temperature. The system was run pressurized, however, since exhaust flow was still controlled by the back-pressure regulator.

The effectiveness of recirculation, as determined by the ratio of total flow to motive flow, is very sensitive to the flow resistance around the loop. This particular cold-flow test configuration has relatively high flow resistance, the major components of which are:

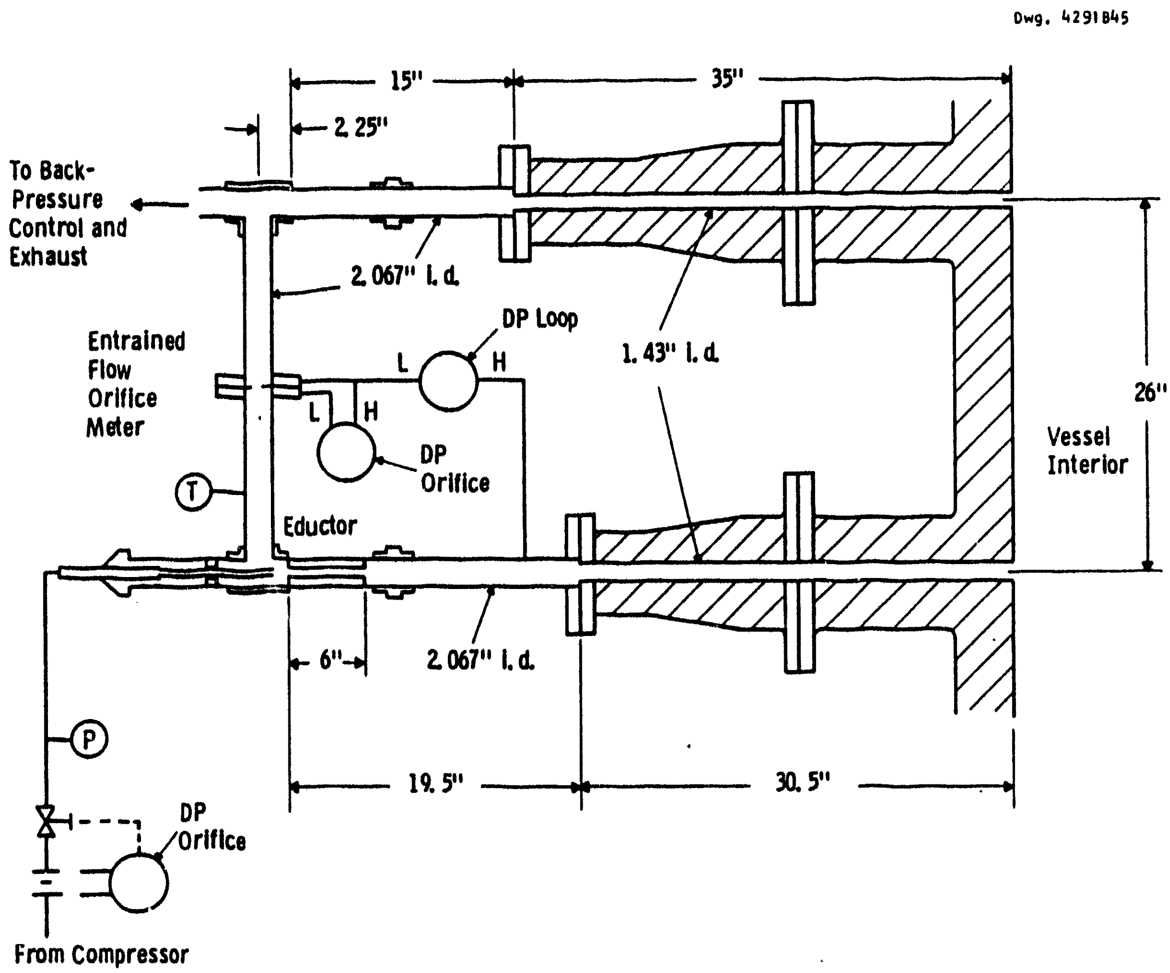


Figure C.4.1 - Test Facility Modification for Cold Flow Recirculation

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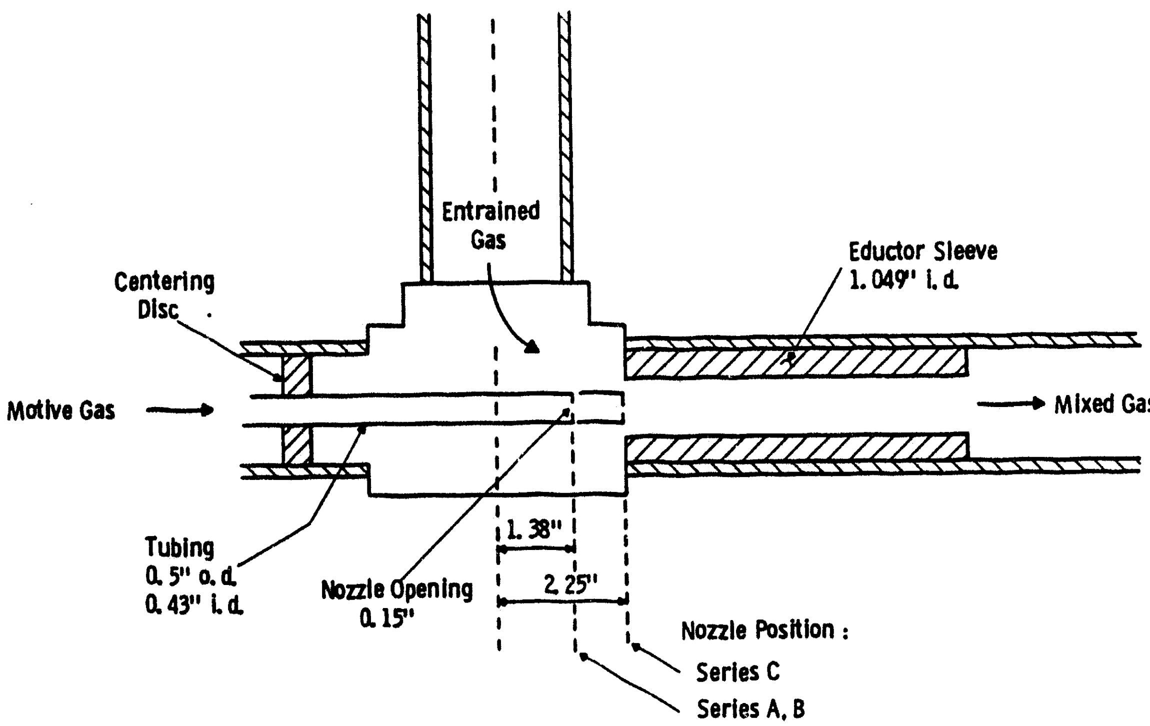

Figure C.4.2 - Eductor Detail

1. expansion from eductor sleeve to main pipe
2. contraction from main pipe into vessel inlet nozzle
3. expansion into vessel
4. contraction into vessel outlet nozzle
5. expansion into main pipe
6. flow through orifice flow meter (permanent loss component)
7. contraction into eductor sleeve

The cold flow test loop was set up by a quick and inexpensive modification to an existing facility not intended for eductor-driven recirculation operation. Consequently, the magnitudes of the flow resistances in this loop are relatively large. The high-temperature loop, on the other hand, was designed to minimize these resistances: resistances 2 and 5 from the preceding list were eliminated, by making the vessel nozzle i.d.'s the same as the rest of the piping; resistances 1 and 7 were greatly reduced, by using a venturi-shaped eductor sleeve; and resistance 6 was reduced by using venturi flow meter rather than an orifice meter. Because [illegible] already high total resistance in the cold flow tests, it was decid[illegible] to further increase resistance by the use of a filter in the test vessel. However, a filter is assumed to be in place for the application of the model to the hot system.

4.2 TEST RESULTS

Three series of tests were run to verify model performance. In Series A, summarized in Table C.4.1, a 1.0 inch orifice was used to measure entrained gas flow rate in the position shown in Figure C.4.1, and the motive gas nozzle was inserted as shown in Figure C.4.2. The eductor sleeve shown in both Figures was not used, i.e., the eductor throat had the same i.d. as the general piping, 2.067 inches. "Actual" entrained flow rates were measured with the orifice meter and "predicted" entrained flow rates are from the detailed eductor recirculation model given the system dimensions, pressure, and motive gas flow rate as shown. In general, the actual and predicted values

TABLE C.4.1 - RECIRCULATION TEST RESULTS - SERIES A

Orifice Diameter, in.	1.0							
Sleeve	Not used							
Test No.	1	2	3	4	5	6	7	8
Motive Gas Flow, lb/hr	60	100	150	200	250	280	280	200
System Pressure, atm (abs)	1.68	2.02	2.63	3.31	4.06	4.54	6.71	6.85
ΔP Orifice, in Water								
Actual	4.4	6.0	8.2	11.0	13.5	15.5	13.5	8.0
Predicted	2.2	4.9	8.1	11.1	14.0	15.7	13.4	7.3
ΔP Loop, in Water								
Actual	4.0	5.0	6.0	9.0	10.0	11.0	10.0	7.0
Predicted	2.0	4.1	6.6	8.9	11.2	12.6	10.0	5.4
Entrained Flow, lb/hr								
Actual	181	234	311	405	497	563	638	497
Predicted	128	212	309	407	506	567	636	475
Ratio (Actual/ Predicted)	1.41	1.11	1.01	1.00	0.98	0.99	1.00	1.05
Flow Ratio (Total/ Motive)								
Actual	4.0	3.3	3.1	3.0	3.0	3.0	3.3	3.5
Predicted	3.1	3.1	3.1	3.0	3.0	3.0	3.3	3.4

agreed well, except at the lowest flow rate, where orifice pressure drops could have easily been in error enough to explain the difference. At the bottom of Table C.5.1, the actual and predicted ratios of total gas flow (motive to entrained) to motive gas flow are shown, and it is seen that a typical such ratio is about 3.0. The important point is that the model was able to accurately predict eductor performance. An essential element in this model capability is that the flow resistance characteristics of the recirculation loop are rigorously and accurately modeled, as shown by the close agreement between measured and predicted loop pressure drop values in the cases where actual and predicted flow rates agreed well.

Series B tests differed from those in Series A only in that the sleeve was inserted into the eductor, thus reducing the throat i.d. to 1.049 inches. This change was expected to increase eductor performance, for the reasons discussed in Section 3.2, and it did, as shown in Table C.4.2. The achieved ratios of total to motive gas flow rates were increased to about 4.0 (from 3.0 without the sleeve). This represents a 50 percent increase in entrained flow rate over the no-sleeve case. As is also shown in Table C.4.2, the model predicted performance reasonably well, usually under-predicting entrained flow by a few percent.

The series C tests were also performed with the sleeve in place, but with a 1.4 inch orifice in use instead of the 1.0 inch orifice in prior tests. The motive gas nozzle was also inserted so as to be flush with the start of the sleeve. The results are shown in Table C.4.3. The achieved ratios of total to motive gas flow rates increased further, to about 5.0, representing about a 25 % additional increase in entrained flow relative to Series B. The reason for this is the important but small decrease in resistance to flow recirculation caused by the small decrease in permanent pressure drop across the orifice. A permanent pressure loss in the case of the 1 inch orifice is about 77 % of the actual measured value listed in Table C.4.2 or C.4.3, and for the 1.4 inch orifice, it is about 54 % of the value in Table C.4.3. It can readily be seen that the permanent pressure drops for the smaller orifice were similar in magnitude to the overall loop pressure drops.

TABLE C.4.2 - RECIRCULATION TEST RESULTS - SERIES B

Orifice Diameter, in.	1.0							
Sleeve	Used							
Test No.	1	2	3	4	5	6	7	8
Motive Gas Flow, lb/hr	60	100	150	200	250	280	280	200
System Pressure, atm (abs)	1.68	2.02	2.56	3.04	3.72	4.54	6.71	6.92
ΔP Orifice, in Water								
Actual	11.0	14.0	20.0	25.0	32.0	35.0	32.0	19.0
Predicted	6.6	13.8	22.1	30.6	38.6	42.3	35.5	19.3
ΔP Loop, in Water								
Actual	6.6	8.9	12.0	15.0	18.5	20.5	16.0	8.9
Predicted	4.0	8.2	13.3	18.5	23.2	25.1	20.3	10.9
Entrained Flow, lb/hr								
Actual	289	356	481	586	732	846	984	769
Predicted	224	354	506	648	804	930	1036	775
Ratio (Actual/Predicted)	1.29	1.01	0.95	0.90	0.91	0.91	0.95	0.99
Flow Ratio (Total/Motive)								
Actual	5.8	4.6	4.2	3.9	3.9	4.0	4.5	4.8
Predicted	4.7	4.5	4.4	4.2	4.2	4.3	4.7	4.9

TABLE C.4.3 - RECIRCULATION TEST RESULTS - SERIES C

Orifice Diameter, in.	1.4							
Sleeve	Used							
Test No.	1	2	3	4	5	6	7	8
Motive Gas Flow, lb/hr	60	100	150	200	250	280	280	200
System Pressure, atm (abs)	1.75	2.02	2.70	3.38	4.2	4.67	6.85	6.78
ΔP Orifice, in Water								
Actual	3.1	4.5	6.5	8.2	10.8	12.0	10.0	6.5
Predicted	2.1	4.5	7.1	9.7	12.2	13.7	11.4	6.4
ΔP Loop, in Water								
Actual	8.0	11.0	15.0	20.0	24.0	26.0	21.0	15.0
Predicted	5.3	11.3	17.7	24.2	30.3	34.0	27.7	15.4
Entrained Flow, lb/hr								
Actual	334	433	603	758	968	1076	1194	955
Predicted	275	433	630	824	1029	1150	1275	948
Ratio (Actual/ Predicted)	1.21	1.00	0.96	0.92	0.94	0.94	0.94	1.01
Flow Ratio (Total/ Motive)								
Actual	6.6	5.3	5.0	4.8	4.9	4.8	5.3	5.8
Predicted	5.6	5.3	5.2	5.1	5.1	5.1	5.6	5.7

From these test sequences we learned that:

- the analytical model is able to predict eductor-induced recirculation rates quite accurately and can therefore be used for parametric design studies
- the dimensional design envisioned for the eductor, including its throat, is appropriate
- it is very important to minimize flow resistance to get high recirculation ratios.

5. DURABILITY TEST SYSTEM PERFORMANCE PROJECTIONS

The eductor recirculation model was used to project performance in the planned gasification simulator loop. The results have been used to fine-tune design details for optimizing recirculation performance.

5.1 SYSTEM DESCRIPTION

Figure C.5.1 shows the configuration of the planned recirculation loop, with dimensions applicable to the pressure drop calculations in the eductor recirculation model. Figure C.5.2 shows a possible set of dimensional details for the eductor nozzle and sleeve. The dimensions in Figure C.5.2 may be considered adjustable parameters, since they can be easily changed via replacement of the component.

Not shown in Figure C.5.1, but important with regard to recirculation performance, is the feed of dust and transport gas to the system. Transport gas is supplied by the same compressor as is the eductor motive gas. Whereas the motive gas from the compressor is reheated to near system temperature prior to injection, the transport gas is not heated, but is passed through the dust feed system and thence to the system. The entry point will be somewhere in the horizontal line between the eductor and the vessel inlet, and is assumed to be a piece of 3/8 inch tubing inserted into the center of the main gas flow path, and bent to point downstream.

The recirculation flow loop and model have the following pressure drop and flow resistance components:

1. wall friction in eductor sleeve, corrected to account for variable diameter
2. irreversible expansion loss from eductor sleeve
3. reversible gain due to velocity gain from eductor sleeve to main pipe

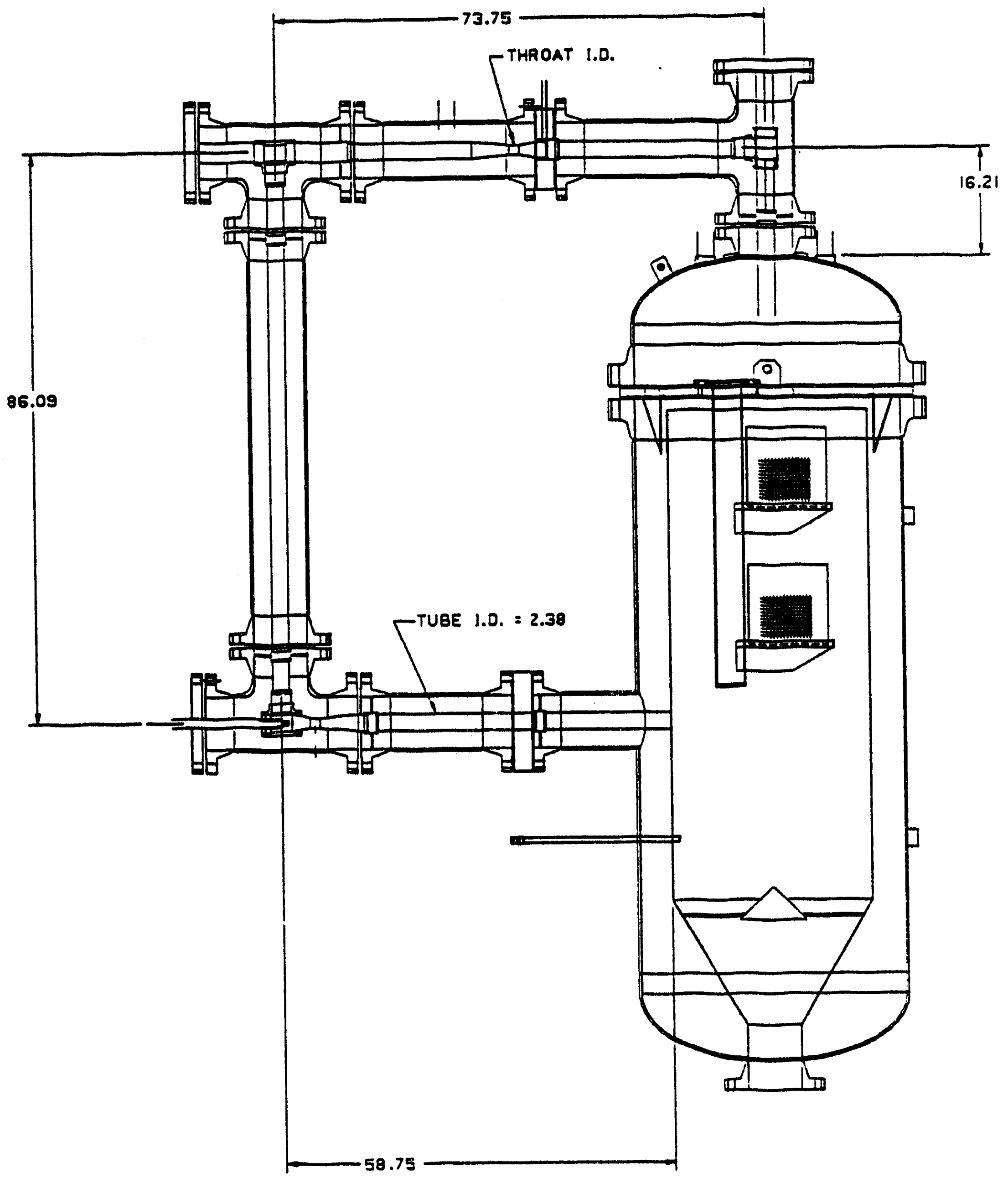

Figure C.5.1 - High Temperature Recirculation Loop

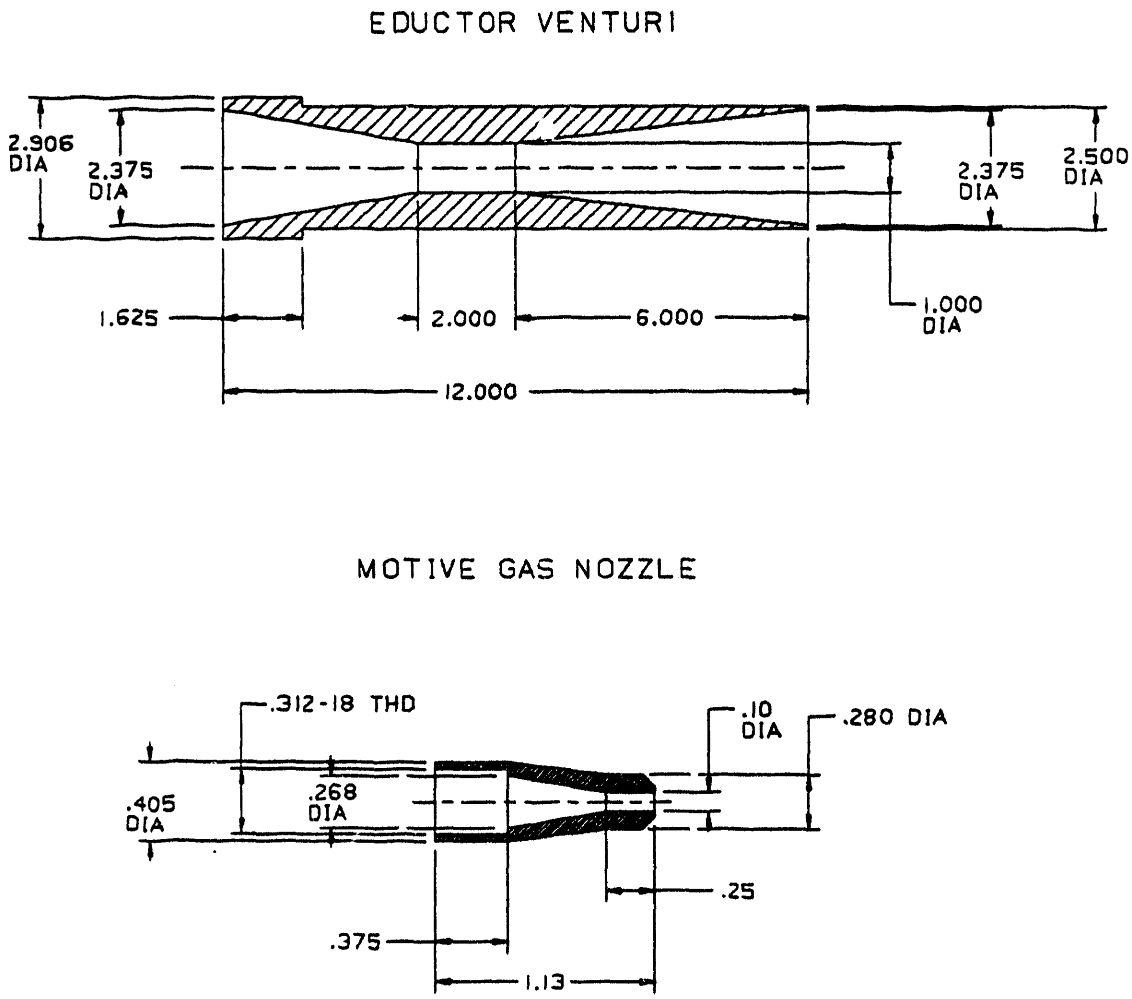

Figure C.5.2 - Eductor Component Details.

4. flow through horizontal pipe after eductor
5. friction loss passing dust injection nozzle
6. loss or gain due to mixing with dust transport gas
7. flow through horizontal pipe entering vessel
8. expansion into vessel
9. loss across filter
10. contraction out of vessel
11. flow through vertical pipe upward out of vessel
12. flow through tee used as elbow
13. flow through upper horizontal run
14. irreversible component of loss across venturi flow meter
15. flow though tee dividing total flow into recirculating flow heading back to eductor and flow to compressor
16. reversible gain due to velocity change from inlet pipe to vessel to after flow branching at tee in item 15
17. flow through vertical run downward toward eductor
18. flow through eductor tee used as elbow
19. contraction to get around motive gas nozzle
20. flow through the short horizontal run between the tee and eductor sleeve
21. contraction into sleeve
22. reversible loss of recirculating gas due to velocity change from downward vertical pipe to inside throat of eductor sleeve

5.2 PROJECTED PERFORMANCE

The target flow rate of gas through the filter is 0.35 lb/sec (1260 lb/hr). It is desired to keep the motive gas flow rate at not much more than a tenth of this. The system operating pressure and temperature are 10 atm and 1550°F, respectively. The dimensions (other than nozzle orifice diameter) shown in Figures C.5.1 and C.5.2 are assumed, as are the following additional parameters:

motive gas temperature	1400°F
maximum available motive gas pressure	30 atm (abs)
flow rate of dust transport gas	0.01 lb/s
temperature of transport gas	100°F
venturi throat diameter	1.25 inch

Based upon previous filter testing, the filter pressure drop immediately after a successful blow back pulse is assumed to be

$$\Delta P = R_W \mu v \tag{5-1}$$

where ΔP = pressure drop, $lb_m/(ft\text{-}sec^2)$
R_W = resistance coefficient, ft^{-1}
μ = gas viscosity, $lb_m/(ft\text{-}sec)$
v = superficial gas velocity (face velocity) through filter, ft/sec

The actual filter pressure drop is assumed to be given by a multiple of the clean pressure drop from Equation 5.1. In the worst case, this filter pressure drop multiple is assumed to be 2.0.

Table C.5.1 summarizes the effects of motive gas flow rate and nozzle orifice size (nozzle not converging/diverging) on total gas flow through the filter given the above assumptions, including the pressure drop multiplier of 2.0. The "nozzle" pressure shown in the table is that in the nozzle prior to the nozzle orifice. Essentially, the motive gas flow rate is controlled by a valve after the compressor and before

TABLE C.5.1 - EFFECT OF NOZZLE ORIFICE SIZE ON EDUCTOR PERFORMANCE

Nozzle Diameter, In.	Motive Flow, lb/s	Total Flow, lb/s	Nozzle Pressure, atm	Exit Pressure, atm	Motive Gas Mach No.	Pressure Gain, psi
0.215	0.035	0.107	10.6	10.0	0.31	0.70
	0.070	0.296	12.6	10.0	0.61	2.47
	0.080	0.353	13.5	10.0	0.69	3.15
0.15	0.035	0.185	12.8	10.0	0.62	1.46
	0.040	0.223	13.7	10.0	0.71	1.87
	0.050	0.301	15.9	10.0	0.87	2.82
	0.057	0.356	17.9	10.0	0.98	3.57
0.12	0.035	0.248	17.2	10.0	0.94	2.24
	0.040	0.294	19.6	10.7	1.0	2.84
	0.045	0.337	22.0	12.0	1.0	3.45
	0.047	0.353	23.0	12.5	1.0	3.70
0.10	0.035	0.296	24.7	13.4	1.0	2.94
	0.040	0.339	28.2	15.4	1.0	3.57
	0.042	0.355	29.6	16.1	1.0	3.82
0.095	0.035	0.306	27.4	14.9	1.0	3.11
	0.0383*	0.335	30.0	16.3	1.0	3.53
0.090	0.0344*	0.310	30.0	16.3	1.0	3.19

Filter pressure drop multiplier = 2.0.

*Maximum possible flow, given 30 atm pressure limit.

the heater, and the nozzle pressure increases as the valve is opened. In the case of sonic flow through the orifice, the velocity is a constant at a given temperature, while the total flow will be proportional to this nozzle pressure. The actual pressure of the gas exiting the system ("exit" pressure in Table C.5.1) will be the system pressure (10 atm) for sub-sonic flow, and a constant fraction, given by the critical pressure ratio, of the nozzle pressure for sonic flow. As shown in this table, larger nozzle orifice sizes (.215 and .15 inches) require higher than desirable motive gas flow rates to achieve the needed total gas flow rate at this degree of filter resistance. The 0.10 inch nozzle requires a motive flow of 12% of the total gas flow. Smaller nozzles cannot achieve the total flow, because the flow rate of motive gas through the nozzle orifice is limited to critical flow at the maximum available motive gas pressure. Based on Table C.5.1, a nozzle orifice diameter of 0.10 inches has been selected.

The question arose as to whether using a converging/diverging nozzle could result in improved eductor performance, as measured by the ratio of entrained to motive gas flow rates. Such a nozzle could allow supersonic flow at the nozzle exit, at the expense of pressure of the exiting gas. Since both velocity and pressure are important in the momentum balance that determines entrained flow rate, there must be a tradeoff with using converging/diverging nozzles. Table C.5.2 looks at the effect of such nozzles relative to straight nozzles, in the vicinity of the selected 0.10 inch straight nozzle. It can be seen that very slight divergences have very slight beneficial effects. Divergences that increase the exit diameter to 10% more than the nozzle throat diameter have a deleterious effect, i.e., the resulting fall in pressure of the exiting gas is much more important than the increased diameter. We conclude that the straight nozzle is appropriate for this system.

Another important design parameter is the diameter of the sleeve of the eductor. A sleeve diameter of 1.0 inches, as shown in Figure 5.2, was assumed for the Table C.5.1 calculations. Table C.5.3 shows

TABLE C.5.2 - BEHAVIOR OF CONVERGING/DIVERGING NOZZLES

Throat Diameter, In.	Exit Diameter, In.	Motive Flow, lb/s	Total Flow, lb/s	Nozzle Pressure, atm	Exit Pressure, atm	Exit Mach No.	Exit Velocity ft/s
0.10	0.10	0.035	0.330	24.7	13.4	1.0	1867
	0.101	0.035	0.331	24.7	11.1	1.16	2114
	0.105	0.035	0.330	24.7	8.4	1.37	2414
	0.11	0.035	0.327	24.7	6.9	1.53	2628
	0.12	0.035	0.316	24.7	4.7	1.77	2910
	0.15	0.035	0.248	24.7	2.1	2.25	3380
	0.20	0.035	0.141	24.7	10.0	0.36*	710
0.12	0.12	0.045	0.373	22.0	12.0	1.0	1867
	0.121	0.045	0.373	22.0	10.1	1.14	2092
	0.125		0.372	22.0	7.9	1.33	2367
	0.13	0.045	0.368	22.0	6.4	1.48	2566
0.08	0.08	0.0272	0.296	30.0	16.3	1.0-	1867
	0.084	0.0272	0.298	30.0	10.3	1.37	2414
	0.088	0.0272	0.297	30.0	8.1	1.53	2629

Filter pressure drop multiplier = 1.5.

*Normal shock in diverging section.

TABLE C.5.3 - EFFECT OF SLEEVE DIAMETER

Nozzle Diameter, In.	Motive Flow, lb/s	Sleeve Diameter, in.	Total Flow, lb/s	Pressure Gain, psi
0.10	0.035	2.38	0.109	0.54
		2.0	0.147	0.76
		1.5	0.233	1.30
		1.2	0.300	2.00
		1.1	0.319	2.40
		1.0	0.330	3.01
		0.9	0.329	3.97
		0.8	0.311	5.56
		0.7	0.271	8.18
		0.6	0.208	12.1
		0.5	0.125	16.2

Filter pressure drop multiplier = 1.5.

how this sleeve diameter is expected to affect total flow rate, based upon the detailed eductor recirculation model. There is an optimum sleeve diameter of 1.0 inch at which total recirculation flow rate is highest. This effect can be understood in terms of the conversion of motive gas momentum into the product of pressure and flow area, as demonstrated in the cold flow study, and as explained in Section 3.2.

Table C.5.4 shows how total flow rate varies with motive gas flow rate in this case, as well as how motive gas flow rates would have to be varied as filter flow resistance varies, in order to keep a constant total gas flow rate. If the filter pressure drop multiplier were to vary between 1 and 2 during a test (i.e., blowback would be triggered at a multiple of 2.0) then the motive gas would vary from 0.033 to 0.042 lb/sec during each period between blowback events, assuming a single filter module. Motive gas flow will be controlled by automatically reading the pressure drop across the venturi flow meter and automatically adjusting the motive gas flow control valve (and hence the nozzle pressure) to keep that pressure drop constant.

If the motive gas preheater does not deliver gas at the vendor-promised temperature, there will be an effect on eductor performance as shown in Table C.5.5. Slightly higher motive gas flow rates will be required if the motive gas temperature is only 1200°F. This is because sonic velocity varies directly with the square root of the absolute temperature.

The magnitudes of the pressure drop terms listed in Section 5.1 are listed in Table C.5.6, for the case of a straight 0.10 inch nozzle orifice, a 1.0 inch sleeve, an average filter pressure drop multiplier of 1.5, and a motive gas flow rate of 0.38 lb/sec at 1400°F.

TABLE C.5.4 - EFFECT OF FILTER RESISTANCE AND MOTIVE GAS FLOW RATE ON TOTAL GAS FLOW RATE

Filter ΔP Multiplier	Motive Flow, lb/s	Total Flow, lb/s	Pressure Gain, psi	Filter ΔP, in. H_2O	Flow Meter ΔP, in. H_2O	Nozzle Pressure, atm
* 2.0	0.042	0.355	3.82	60.4	23.9	29.6
1.5	0.042	0.392	3.91	50.1	29.2	29.6
1.0	0.042	0.436	4.03	37.1	36.0	29.6
0.5	0.042	0.485	4.22	20.7	44.7	29.6
2.0	0.038	0.322	3.32	54.9	19.7	26.8
* 1.5	0.038	0.358	3.39	45.8	24.3	26.8
1.0	0.038	0.400	3.50	34.1	30.4	26.8
0.5	0.038	0.449	3.67	19.1	38.3	26.8
2.0	0.033	0.277	2.69	47.4	14.7	23.3
1.5	0.033	0.311	2.75	39.9	18.5	23.3
* 1.0	0.033	0.352	2.84	30.1	23.6	23.3
0.5	0.033	0.399	2.98	17.1	30.4	23.3
2.0	0.029	0.239	2.19	40.9	10.9	20.5
1.5	0.029	0.271	2.23	34.8	14.0	20.5
1.0	0.029	0.309	2.30	26.5	18.3	20.5
* 0.5	0.029	0.356	2.42	15.2	24.1	20.5

*Locus of operating points.

TABLE C.5.5 - EFFECT OF MOTIVE GAS TEMPERATURE

Filter ΔP Multiplier	Temperature, °F	Motive Flow, lb/s	Total Flow, lb/s	Nozzle Pressure, atm	Exit Velocity, ft/s	Exit Mach No.
2.0	1400	0.042	0.355	29.6	1867	1
	1200	0.042	0.338	28.0	1764	1
	1200	0.044	0.354	29.3	1764	1
1.0	1400	0.033	0.352	23.3	1867	1
	1200	0.033	0.335	22.0	1764	1
	1200	0.035	0.354	23.3	1764	1

TABLE C.5.6 - MAGNITUDES OF FLOW RESISTANCES AT NOMINAL CONDITIONS

Loss Component	Pressure Loss, in. H_2O
1. Eductor Sleeve	4.9
2. Irreversible Expansion From Eductor Sleeve	11.6
3. Reversible, From Eductor Sleeve to Main Pipe	-55.6
4. Horizontal Pipe After Eductor	0.3
5. Passing Dust Injection Nozzle	0.6
6. Mixing With Dust Transport Gas	-0.1
7. Horizontal Pipe Entering Vessel	0.4
8. Expansion Into Vessel	1.9
9. Across Filter	45.8
10. Contraction Out of Vessel	1.0
11. Vertical Pipe From Vessel	0.4
12. Tee	0.7
13. Upper Horizontal Run	1.4
14. Irreversible Component Across Flow Meter	3.7
15. Tee Dividing Flow	0.7
16. Reversible, From Vessel Inlet Pipe to After Branching in Tee in Item 15	-0.5
17. Vertical Run Downward to Eductor	1.2
18. Eductor Tee	0.5
19. Contraction Around Nozzle	0.5
20. Short Horizontal Run Before Eductor Sleeve	0.1
21. Contraction Into Sleeve	8.5
22. Reversible, From Downward Vertical Pipe to Inside Throat of Eductor Sleeve	65.8
Total Pressure Loss (= Pressure Rise Due to Eductor)	93.8

6. REFERENCES

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2. A. G. Hansen, Fluid Mechanics. New York: John Wiley & Sons, 1967, Chapter 7.

3. Ibid, pp. 252-256.