DOE/MC/26288 -- 5132
(DE96004355)

Sonic Enhanced Ash Agglomeration and Sulfur Capture

Quarterly Report
April - June 1995

August 1995

Work Performed Under Contract No.: DE-AC21-89MC26288

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Manufacturing and Technology Conversion International, Inc.
Columbia, Maryland

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DOE/MC/26288 – 5132 **SONIC ENHANCED ASH AGGLOMERATION AND SULFUR CAPTURE** **USDOE**

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August 1995

PREFACE

This 24th Quarterly Technical Progress Report presents the results of work accomplished during the period March 27, 1995 through June 30, 1995 under Contract No. DE-AC21-88MC26288 entitled "Sonic Enhanced Ash Agglomeration and Sulfur Capture."

During this reporting period, the slagging mode of operation for the pulse coal combustor was again revisited on the basis of progress being made with refractory life and integrity. A slagging design for the test facility was generated and analyzed. Configurations for both retrofit and Greenfield applications were also developed and analyzed. Preliminary designs were generated for a modified PDU that would be used for evaluating the system's ability to meet the new performance goal of one-tenth the New Source Performance Standards.

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SECTION 1.0

INTRODUCTION

1.1 PROJECT DESCRIPTION AND WORK STATUS

A major concern with the utilization of coal in directly fired gas turbines is the control of particulate emissions and reduction of sulfur dioxide, and alkali vapor from combustion of coal, upstream of the gas turbine. Much research and development has been sponsored on methods for particulate emissions control and the direct injection of calcium-based sorbents to reduce SO_2 emission levels. The results of this research and development indicate that both acoustic agglomeration of particulates and direct injection of sorbents have the potential to become a significant emissions control strategy.

The Sonic Enhanced Ash Agglomeration and Sulfur Capture program focuses upon the application of an MTCI proprietary invention (Patent No. 5,197,399) for simultaneously enhancing sulfur capture and particulate agglomeration of the combustor effluent. This application can be adapted as either a "hot flue gas cleanup" subsystem for the current concepts for combustor islands or as an alternative primary pulse combustor island in which slagging, sulfur capture, particulate agglomeration and control, and alkali gettering as well as NO_x control processes become an integral part of the pulse combustion process.

The goal of the program is to support the DOE mission in developing coal-fired combustion gas turbines. In particular, the MTCI proprietary process for bimodal ash agglomeration and simultaneous sulfur capture will be evaluated and developed. The technology embodiment of the invention provides for the use of standard grind, moderately beneficiated coal and WEM for firing the gas turbine with efficient sulfur capture and particulate emission control upstream of the turbine. The process also accommodates injection of alkali gettering material if necessary. This is aimed at utilization of relatively inexpensive coal fuels, thus realizing the primary benefit being sought by direct firing of coal in such gas turbine systems. The proposed technology provides for practical, reliable, and capital (and O&M) cost-effective means of protection for the gas turbine from impurities in the coal combustor effluent.

1.2 PROGRAM OBJECTIVES

The major objective of the Phase I test program is to confirm the feasibility of the MTCI bimodal particle size approach to enhance particulate control by acoustic ash agglomeration. An ancillary objective of the Phase I effort is to demonstrate and confirm the feasibility of an acoustic field to enhance sulfur capture by increasing sorbent reactivity. Phase I tests are designed to cover the frequency range between 50 and 1400 Hz, establish monomodal baseline performance as a benchmark from which to measure the degree of enhancement expected from the bimodal approach, and, finally, to confirm the effectiveness of low-frequency fields over high-frequency fields for realistic particulate streams.

The program will demonstrate the effectiveness of a unique approach which uses a bimodal distribution composed of large sorbent particles and fine fly ash particles to enhance ash agglomeration and sulfur capture at conditions found in direct coal-fired turbines. Under the impact of high-intensity sound waves, sorbent reactivity and utilization, it is theorized, will increase while agglomerates of fly ash and sorbents are formed which are readily collected in commercial cyclones. The work will extend the concept from the demonstration of feasibility (Phase I), through proof-of-concept (Phase II) to the construction (Phase III) of a coal-fired pulsed combustor with in-furnace sorbent injection. For Phase I, Pennsylvania State University will conduct studies for enhanced sulfur capture in The Combustion Laboratory and agglomeration tests in the High Intensity Acoustic Laboratory.

1.3 SUMMARY STATUS FOR THE PERIOD

During this reporting period, the slagging mode of operation for the pulse coal combustor was again revisited on the basis of progress being made with refractory life and integrity. A slagging design for the test facility was generated and analyzed. Configurations for both retrofit and Greenfield applications were also developed and analyzed. Preliminary designs were generated for a modified PDU that would be used for evaluating the system's ability to meet the new performance goal of one-tenth the New Source Performance Standards.

SECTION 2.0

TECHNICAL DISCUSSION OF THE WORK ACCOMPLISHED DURING THE REPORTING PERIOD

2.1 TASK 2: ADDITIONAL TEST FACILITY MODIFICATIONS AND SHAKEDOWN TESTING

Until the early part of this reporting period, a non-slagging mode of operation for the pulse coal combustor was being actively pursued due to reported mechanical problems experienced in slagging coal gasifiers and combustors. These were concerns regarding refractory integrity, extended refractory life, and slag handling at elevated pressure. On the other hand, non-slagging mode of operation also caused concern on account of serious limitations such as: (i) lower (~ 50 Btu/scf) than desired ($\geq$ 100 Btu/scf) heating value of fuel gas generated, and (ii) difficulty in designing for sufficient heat loss to control combustion zone temperature and avoid slagging. The low fuel gas heating value was unacceptable to DOE/METC. Therefore, the slagging option was revisited. Literature in the public domain on slagging gasifiers and refractory selection were reviewed. In the conventional slagging gasifiers, the slag region corresponds to an active zone with gas-solids mixing, combustion, and slag tapping, all occurring above the hearth plate. Tuyere design and the ability to keep the slag tapping process functioning is critical. The art is to retain the solids within the gasifier and yet allow the liquid slag to drain through the tap hole at the desired rate. In the MTCI pulse combustor-hot gas cleanup island, the slag region would correspond to an active and a passive zone. In the active zone, combustion and slag formation take place and the slag is tapped from the passive zone. Consequently, the slag removal process/hardware design is comparatively simple with essentially the only requirement that the slag tap hole not be allowed to freeze shut. Preliminary conversations with refractory vendors indicated that refractories suitable for aggressive environments such as in this application are available. Therefore, a slagging design was generated and computations were performed.

A schematic of the pulse coal combustor-hot gas cleanup island for power generation is shown in Figure 1 and a process flow diagram in Figure 2. In Figure 1, CHFS denotes coal handling and feed system, SHFS stands for sorbent handling and feed system, SHS connotes slag handling system, and AGHFS stands for alkali getterer handling and feed system.

This configuration is flexible enough for adaptation to both Greenfield and retrofit applications. For the Greenfield application, all the coal will be pulverized and routed to the pulse combustor and hot-gas cleanup section. The atmospheric fluidized bed sulfater/combustor (AFBSC) would primarily serve to sulfate the calcium sulfide collected from the hot-gas cleanup section (HGCU) and also burnout the carbon in the char collected from the hot-gas cleanup section. The pulse combustor hot- gas cleanup section is anticipated to convert between 80 and 90 percent of carbon in the coal. The fluidized bed sulfater/combustor will incorporate tube surfaces to heat the compressed air supplying the second-stage burner. This is done to increase the heat input to the gas cycle. For the retrofit application, the raw coal could be crushed and classified with the coarse coal being fed to the fluidized bed sulfater/combustor and the fine coal pulverized and routed to the pulse combustor - hot-gas cleanup (PC-HGCU) section. The AFBSC would incorporate tube banks to generate steam. The fuel split between AFBSC and the pulse combustor-HGCU will depend on the steam cycle specifications and the total power demand for the retrofit application. The larger the difference between the total power generation required and the steam cycle power generation capacity, the larger the size and fuel input rate to the PC-HGCU. Optionally, wastes could be either co-fired or substituted for the coarse coal routed to the AFBSC.

The clean low Btu gas generated in the PC-HGCU is expected to have a heating value on the order of 100 + Btu/scf. This value is comparable to that reported for low Btu gases generated in IGCC and second-generation PFBC.

There are several benefits associated with the slagging mode of operation. First, the heating value of the fuel gas generated is higher (100 + Btu/scf) and facilitates the use of topping burner concepts being developed under other DOE/METC sponsored programs. Second, the pulse combustor design is not heat transfer

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limited and consequently, scale-up is less of a problem. Third, the higher peak combustion chamber temperature (~ 3000°F) permits the use of higher compressed air inlet temperatures (on the order of 700°F) with less concern about aerovalve diodicity and heat loss. Finally, more heat is retained in a topping gas cycle and less heat is rejected to the steam and this improves the overall plant efficiency.

In pulse combustion, one of the critical design parameters is tailpipe inlet diameter. While pulse combustors for non-slagging mode of operation can be designed with small (1.5 inches or larger) tailpipe inlet diameter, pulse combustors for slagging mode of operation cannot be designed with a small tailpipe inlet diameter due to the propensity for plugging. The larger this diameter (6 inches or more), the less likelihood this is for plugging. A design simulation was performed to examine the tailpipe inlet diameter requirement as a function of pulse combustor firing rate. This simulation was carried out for a system pressure of 12 atm. Figure 3 shows the results. A tailpipe inlet diameter of 6 inches calls for a pulse combustor firing rate on the order of 80 MMBtu/hr. This together with the nominal design criteria of 40 percent/ 60 percent split in firing rate between pulse combustor and reburn zone suggests a total firing rate of about 200 MMBtu/hr. This is a fairly large size unit and definitely too big for a process development unit (PDU). Therefore, a smaller tailpipe inlet diameter needs to be selected for the PDU. One advantage of the slagging design is that a 12-inch tailpipe inlet diameter is capable of firing about 330 MMBtu/hr in the pulse combustor and about 825 MMBtu/hr total. This could translate into a 100 MW_e unit in the combined-cycle format for greenfield application. Consequently, large modules (100 - 400 MW_e size) with single tailpipes are feasible and this is very encouraging from the standpoint of design, fabrication, and economics.

The initial objective of this program is to demonstrate the pulse combustor technology and meet the target goals but the final objective is to integrate the system with a gas turbine and perform system qualification tests. Therefore, commercially available small gas turbine specifications were reviewed (Ref. Gas Turbine World, The 1990 Handbook, Vol. 12) to select the appropriate size for the combustor island PDU. The gas turbine specifications and the tailpipe inlet

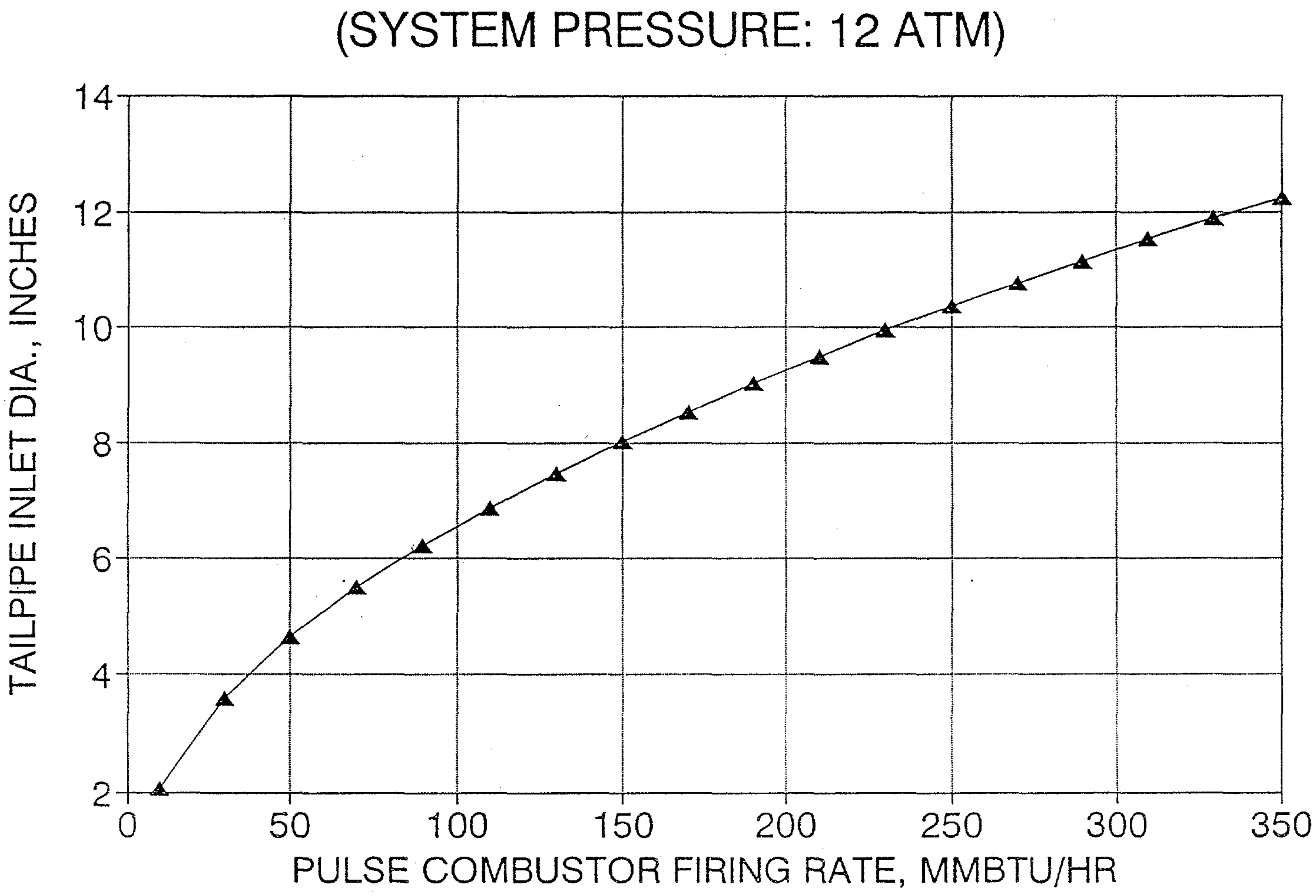

FIGURE 3: TAILPIPE INLET DIAMETER vs. FIRING RATE

diameter estimate for two different turbine sizes are given in **Table 1**. The tailpipe inlet diameter required turns out to be about 2.5 inches and 3.6 inches for the Solar Turbines Incorporated Saturn and Centaur Type-H gas turbines, respectively. For slagging mode of operation, 2.5 inches diameter is rather small (there is potential for plugging) and therefore the Saturn size unit is not suitable. The tailpipe inlet diameter for the Centaur Type-H unit is still not as large as desired (about 6 inches) but is a reasonable compromise based on tailpipe inlet diameter and total firing rate. As stated earlier, total firing rate for a 6-inch tailpipe inlet diameter is on the order of 200 MMBtu/hr and a unit of that size would require a budget far exceeding that currently in place. Table 1 also lists candidate gas turbines from other manufacturers which may be used as prime mover for this PDU. Of course, not all of these gas turbines may be amenable for hook-up to an off-base combustor and this fact could shorten the list of suitable candidates. The net power output of this system in a greenfield mode of operation is estimated to be on the order of 5 MW_e.

Computer calculations were performed to generate a PDU design to interface with the Solar Centaur Type-H gas turbine. The design system pressure was 9.3 atm and the nominal total firing rate was 55 MMBtu/hr. The design fuel was Pittsburgh No. 8 bituminous coal and the design sorbent was Annville limestone. The pulse combustor/reburn zone firing rate split was 40 percent/60 percent. **Table 2** provides a summary of design data for the unit. The projected heating value of the fuel gas generated by the pulse combustor-hot gas cleanup section is about 106 Btu/scf. The unit will be designed and fabricated to operate at 9.3 atm. However, due to existing coal and sorbent feed system and gas compressor throughput limitations, it is planned to conduct the initial series of tests at a system pressure of 2.33 atm. The run summary for this case is provided in **Table 3**. The total firing rate now is 13.75 MMBtu/hr with 5.5 MMBtu/hr firing with pulse combustor and the rest in the reburn zone.

TABLE 1:

PULSE COMBUSTOR TAILPIPE INLET DIAMETER ESTIMATE FOR INTERFACING DIFFERENT GAS TURBINES

	PRESSURE RATIO	MW_e	HEAT RATE MMBtu/mwh	FIRING RATE		SYSTEM PRESSURE (atm)	FINAL (WITH SLAG) TP THROAT DIA., Inch	GREENFIELD NET POWER OUT, MW_e
				GAS MMBtu/hr	COAL MMBtu/hr			
SOLAR SATURN	6.70	1.08	14.79	15.97	18.79	6.70	2.69	
SOLAR CENTAUR TYPE-H	9.30	3.88	12.20	47.34	55.69	9.30	3.64	5.22
ALLISON 501-KB5	15.10	3.81	11.84	45.09	53.04	15.10		4.97
CENTRAX CX350-KB5	9.30	3.73	12.26	45.76	53.83	9.30		5.05
DEUTZ MWM-GASTNK CA 139	9.30	3.65	12.05	43.98	51.74	9.30		4.85
DRESSER-RAND DR-990	12.60	4.22	11.78	49.71	58.48	12.60		5.49
FIATAVIO LM500	14.00	3.85	11.12	42.81	50.37	14.00		4.72
HITACHI ZOSEM GT10-5	9.30	3.66	11.30	41.30	48.59	9.30		4.56
ISHIKAWAJIMA IM400-6	9.30	3.61	12.04	43.46	51.13	9.30		4.80
KAWASAKI MIT-13	9.00	2.89	14.23	41.12	48.38	9.00		4.54
MITSUI ENG. & SHPBLDG. SB15	11.00	2.84	12.19	34.62	40.73	11.00		3.82
NUOVO P-T MS1002R	8.30	4.61	10.50	48.38	56.92	8.30		5.34
RUSTON TYPHOON	12.80	3.90	11.31	44.16	51.95	12.80		4.87
STEWART & STVNSN. TG-501-KB5	9.30	3.69	12.02	44.38	52.21	9.30		4.90
U.S. TURBINE UST3800	9.30	3.71	12.33	45.76	53.84	9.30		5.05

TABLE 2:

RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND FOR PDU-SCALE SCREENING TESTS

-- GREENFIELD MODE OF OPERATION --

NOTE: ONE (PC+HGCU+HC) FEED ONE TOPPING BURNER & ONE AFB SULFATER; HOWEVER SULFATER WILL NOT BE ONLINE FOR THIS STUDY

	100% LOAD
TOTAL FIRING RATE,MMBTU/HR	55.00
FUEL	PITT NO.8
NO. OF PULSE COMB/HGCU/HC SECTNS	1
NO. OF TOPPING BURNERS	1
NO. OF AFB SULFATERS	1
PC FIRING RATE,MMBTU/HR	22.00 EACH
REBURN FIRING RATE,MMBTU/HR	33.00 EACH
TOPPING BURNER FIRING RATE,MMBTU/HR	33.65 EACH
TOTAL COAL FEED RATE,LB/HR	3,908
TOTAL SORBENT FEED RATE,LB/HR	307
REBURN SORB FEED RATE,LB/HR	248 EACH
SULFATER SORB FEED RATE,LB/HR	59 EACH
TRANSPORT AIR MASS RATIO	1
TRANSPORT AIR TEMPERATURE,F	150
COMPRESSED AIR FLOW RATE,LB/HR	91,262
- PULSE COAL COMBUSTOR	13,853 EACH
- HOT GAS CLEANUP SECTION	0 EACH
- COAL FEED SYSTEM	2,736 EACH
- SORBENT FEED SYSTEM	248 EACH
- SULFATER	0 EACH
- SULFATER HX SECTION	19,646 EACH
- TOPPING PULSE COMBUSTOR	54,773 EACH
- INSTRUMENTATION	7
AMBIENT AIR,LB/HR	
- COAL TRANSPORT	0
- SORBENT TRANSPORT TO SULFATER	59 EACH
AMBIENT AIR PRESSURE,PSIA	14.70
AMBIENT AIR TEMPERATURE,F	59
RELATIVE HUMIDITY	60%
INSTRUMENTATION AIR,LB/HR	7 EACH
INSTRUMENTATION AIR PRESSURE,PSIA	182
INSTRUMENTATION AIR TEMPERATURE,F	59
FORCED DRAFT FAN FOR SULFATER:	
- AIR FLOW RATE,LB/HR	8,207
- EXIT AIR PRESSURE,PSIA	16.73
STOICHIOMETRY	
- PULSE COAL COMBUSTOR	90.0%
- HOT GAS CLEANUP SECTION (HGCS)	39.3%
- TOPPING BURNER	
- SULFATER	
MEAN TEMPERATURE,F	
- PULSE COAL COMBUSTOR	3,356
- HOT GAS CLEANUP SECTION	2,616
- TOPPING BURNER	2,250
- SULFATER	1,550
MEAN PRESSURE,PSIA	
- PULSE COAL COMBUSTOR	136.71
- HOT GAS CLEANUP SECTION	136.21
- TOPPING BURNER	135.21

TABLE 2:

RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND FOR PDU-SCALE SCREENING TESTS

(CONT'D)

- SULFATER	15.60	
SORBENT CA/S MOLAR FEED RATIO		
- HOT GAS CLEANUP SECTION	1.50	
- SULFATER	1.50	
FLUE GAS MASS FLOW RATE,LB/HR		
- HOT GAS CLEANUP SECTION EXIT	21,419 EACH	
- HOT CYCLONE EXIT	20,595 EACH	
- TOPPING BURNER EXIT	95,013 EACH	
- SULFATER EXIT	8,732 EACH	
SOLIDS MASS FLOW RATE,LB/HR		
- HGCS DRAIN	90 EACH	
- HOT CYCLONE	824 EACH	
- SULFATER BED DRAIN	104 EACH	
- SULFATER CYCLONE CATCH	313 EACH	
FLUE GAS PRESSURE,PSIA		
- HOT GAS CLEANUP SECTION EXIT	135.71	
- HOT CYCLONE EXIT	135.01	
- TOPPING BURNER EXIT	134.71	
- SULFATER EXIT	14.60	
FLUE GAS TEMPERATURE,F		
- HOT GAS CLEANUP SECTION EXIT	1,715	
- HOT CYCLONE EXIT	1,695	
- TOPPING BURNER EXIT	2,100	
- SULFATER EXIT	1,550	
FLUE GAS COMPOSITION		
- HOT CYCLONE EXIT		PPMV
-- OXYGEN, VOL. %	0.00	
-- CARBON DIOXIDE, VOL. %	4.04	
-- NITROGEN, VOL. %	56.56	
-- CARBON MONOXIDE, VOL. %	23.80	
-- HYDROGEN, VOL. %	10.18	
-- HYDROGEN SULFIDE, VOL. % (PPMV)	0.01	79
-- WATER VAPOR, VOL. %	5.38	
-- HYDROGEN CHLORIDE, VOL. % (PPMV)	0.00	0
-- AMMONIA, VOL. % (PPMV)	0.12	1,196
-- PARTICULATES,PPMW	7	
-- HHV,BTU/LB	1,634	106
- TOPPING BURNER EXIT		BTU/SCF
-- OXYGEN, VOL. %	12.01	
-- CARBON DIOXIDE, VOL. %	6.87	
-- NITROGEN, VOL. %	75.58	
-- CARBON MONOXIDE, VOL. %	0.00	29
-- SULFUR DIOXIDE, VOL. %	0.00	20
-- WATER VAPOR, VOL. %	5.53	
-- HYDROGEN CHLORIDE, VOL. % (PPMV)	0.00	0
-- NITROGEN OXIDE- NO, VOL. % (PPMV)	0.00	30
-- PARTICULATES,PPMW	2	
- SULFATER EXIT		
-- OXYGEN, VOL. %	3.91	
-- CARBON DIOXIDE, VOL. %	13.21	
-- NITROGEN, VOL. %	75.97	
-- CARBON MONOXIDE, VOL. %	0.03	326
-- SULFUR DIOXIDE, VOL. %	0.01	75
-- WATER VAPOR, VOL. %	6.87	
-- HYDROGEN CHLORIDE, VOL. % (PPMV)	0.00	0
-- NITROGEN OXIDE- NO, VOL. % (PPMV)	0.01	76
-- PARTICULATES,PPMW	2	
SOLIDS COMPOSITION		

TABLE 2:

RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND FOR PDU-SCALE SCREENING TESTS

(CONT'D)

- HGCS DRAIN			
-- CARBON, WT. %	6.96		
-- ASH, WT. %	92.58		
- HOT CYCLONE			
-- OXYGEN, WT. %	3.48		
-- CARBON, WT. %	56.41		
-- NITROGEN, WT. %	0.97		
-- HYDROGEN, WT. %	3.54		
-- SULFUR, WT. %	5.58		
-- ASH, WT. %	30.02		
- SULFATER			
-- OXYGEN, WT. %	0.14		
-- CARBON, WT. %	2.26		
-- NITROGEN, WT. %	0.04		
-- HYDROGEN, WT. %	0.14		
-- SULFUR, WT. %	10.85		
-- ASH, WT. %	86.58		
PULSE COMBUSTION ISLAND :			
COMBUSTION EFFICIENCY,%	99.54		
SULFUR CAPTURE EFFICIENCY,%	94.28		
NOX EMISSIONS,LB/MMBTU	0.06		
SO2 EMISSIONS,LB/MMBTU	0.10		
PARTICULATES EMISSIONS,LB/MMBTU			
-- TOTAL	0.0030		
-- TOPPING COMBUSTOR EXIT	0.0026		
-- SULFATER EXIT	0.0003		
CO EMISSIONS,LB/MMBTU	0.10		
HCL EMISSIONS,LB/MMBTU	0.00		
MATERIALS IN	104,260		
MATERIALS OUT	104,260		
MATERIALS BALANCE	100.00%	(0)	-0.000
ENERGY IN	6.6015E+07		
ENERGY OUT	6.6010E+07		
ENERGY BALANCE	99.99%	4,971	0.318

TABLE 3:

RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND FOR PDU-SCALE SCREENING TESTS

-- GREENFIELD MODE OF OPERATION --

NOTE: ONE (PC+HGCU+HC) FEED ONE TOPPING BURNER & ONE AFB SULFATER; HOWEVER SULFATER WILL NOT BE ONLINE FOR THIS STUDY

	100% LOAD
TOTAL FIRING RATE,MMBTU/HR	13.75
FUEL	PITT NO.8
NO. OF PULSE COMB/HGCU/HC SECTNS	1
NO. OF TOPPING BURNERS	1
NO. OF AFB SULFATERS	1
PC FIRING RATE,MMBTU/HR	5.50 EACH
REBURN FIRING RATE,MMBTU/HR	8.25 EACH
TOPPING BURNER FIRING RATE,MMBTU/HR	8.42 EACH
TOTAL COAL FEED RATE,LB/HR	977
TOTAL SORBENT FEED RATE,LB/HR	77
REBURN SORB FEED RATE,LB/HR	62 EACH
SULFATER SORB FEED RATE,LB/HR	15 EACH
TRANSPORT AIR MASS RATIO	1
TRANSPORT AIR TEMPERATURE,F	150
COMPRESSED AIR FLOW RATE,LB/HR	20,070
- PULSE COAL COMBUSTOR	3,463 EACH
- HOT GAS CLEANUP SECTION	0 EACH
- COAL FEED SYSTEM	684 EACH
- SORBENT FEED SYSTEM	62 EACH
- SULFATER	0 EACH
- SULFATER HX SECTION	4,463 EACH
- TOPPING PULSE COMBUSTOR	11,396 EACH
- INSTRUMENTATION	2
AMBIENT AIR,LB/HR	
- COAL TRANSPORT	0
- SORBENT TRANSPORT TO SULFATER	15 EACH
AMBIENT AIR PRESSURE,PSIA	14.70
AMBIENT AIR TEMPERATURE,F	59
RELATIVE HUMIDITY	60%
INSTRUMENTATION AIR,LB/HR	2 EACH
INSTRUMENTATION AIR PRESSURE,PSIA	45
INSTRUMENTATION AIR TEMPERATURE,F	59
FORCED DRAFT FAN FOR SULFATER:	
- AIR FLOW RATE,LB/HR	2,052
- EXIT AIR PRESSURE,PSIA	16.73
STOICHIOMETRY	
- PULSE COAL COMBUSTOR	90.0%
- HOT GAS CLEANUP SECTION (HGCS)	39.3%
- TOPPING BURNER	
- SULFATER	
MEAN TEMPERATURE,F	
- PULSE COAL COMBUSTOR	3,196
- HOT GAS CLEANUP SECTION	2,281
- TOPPING BURNER	2,250
- SULFATER	1,550
MEAN PRESSURE,PSIA	
- PULSE COAL COMBUSTOR	34.18
- HOT GAS CLEANUP SECTION	33.68
- TOPPING BURNER	32.68

TABLE 3:

RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND FOR PDU-SCALE SCREENING TESTS

(CONT'D)

- SULFATER	15.60	
SORBENT CA/S MOLAR FEED RATIO		
- HOT GAS CLEANUP SECTION	1.50	
- SULFATER	1.50	
FLUE GAS MASS FLOW RATE,LB/HR		
- HOT GAS CLEANUP SECTION EXIT	5,615 EACH	
- HOT CYCLONE EXIT	5,409 EACH	
- TOPPING BURNER EXIT	21,268 EACH	
- SULFATER EXIT	2,183 EACH	
SOLIDS MASS FLOW RATE,LB/HR		
- HGCS DRAIN	23 EACH	
- HOT CYCLONE	206 EACH	
- SULFATER BED DRAIN	26 EACH	
- SULFATER CYCLONE CATCH	78 EACH	
FLUE GAS PRESSURE,PSIA		
- HOT GAS CLEANUP SECTION EXIT	33.18	
- HOT CYCLONE EXIT	32.48	
- TOPPING BURNER EXIT	32.18	
- SULFATER EXIT	14.60	
FLUE GAS TEMPERATURE,F		
- HOT GAS CLEANUP SECTION EXIT	1,273	
- HOT CYCLONE EXIT	1,253	
- TOPPING BURNER EXIT	2,100	
- SULFATER EXIT	1,550	
FLUE GAS COMPOSITION		
- HOT CYCLONE EXIT		PPMV
-- OXYGEN, VOL. %	0.00	
-- CARBON DIOXIDE, VOL. %	7.09	
-- NITROGEN, VOL. %	52.78	
-- CARBON MONOXIDE, VOL. %	18.89	
-- HYDROGEN, VOL. %	12.82	
-- HYDROGEN SULFIDE, VOL. % (PPMV)	0.01	74
-- WATER VAPOR, VOL. %	8.38	
-- HYDROGEN CHLORIDE, VOL. % (PPMV)	0.00	0
-- AMMONIA, VOL. % (PPMV)	0.11	1,117
-- PARTICULATES,PPMW	6	
-- HHV,BTU/LB	1,556	99
- TOPPING BURNER EXIT		BTU/SCF
-- OXYGEN, VOL. %	10.68	
-- CARBON DIOXIDE, VOL. %	7.63	
-- NITROGEN, VOL. %	73.84	
-- CARBON MONOXIDE, VOL. %	0.00	28
-- SULFUR DIOXIDE, VOL. %	0.00	22
-- WATER VAPOR, VOL. %	7.83	
-- HYDROGEN CHLORIDE, VOL. % (PPMV)	0.00	0
-- NITROGEN OXIDE- NO, VOL. % (PPMV)	0.00	33
-- PARTICULATES,PPMW	2	
- SULFATER EXIT		
-- OXYGEN, VOL. %	3.91	
-- CARBON DIOXIDE, VOL. %	13.21	
-- NITROGEN, VOL. %	75.97	
-- CARBON MONOXIDE, VOL. %	0.03	326
-- SULFUR DIOXIDE, VOL. %	0.01	75
-- WATER VAPOR, VOL. %	6.87	
-- HYDROGEN CHLORIDE, VOL. % (PPMV)	0.00	0
-- NITROGEN OXIDE- NO, VOL. % (PPMV)	0.01	76
-- PARTICULATES,PPMW	2	
SOLIDS COMPOSITION		

TABLE 3:

RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND FOR PDU-SCALE SCREENING TESTS

(CONT'D)

- HGCS DRAIN			
-- CARBON, WT. %	6.96		
-- ASH, WT. %	92.58		
- HOT CYCLONE			
-- OXYGEN, WT. %	3.48		
-- CARBON, WT. %	56.41		
-- NITROGEN, WT. %	0.97		
-- HYDROGEN, WT. %	3.54		
-- SULFUR, WT. %	5.58		
-- ASH, WT. %	30.02		
- SULFATER			
-- OXYGEN, WT. %	0.14		
-- CARBON, WT. %	2.26		
-- NITROGEN, WT. %	0.04		
-- HYDROGEN, WT. %	0.14		
-- SULFUR, WT. %	10.85		
-- ASH, WT. %	86.58		
PULSE COMBUSTION ISLAND :			
COMBUSTION EFFICIENCY,%	99.54		
SULFUR CAPTURE EFFICIENCY,%	94.28		
NOX EMISSIONS,LB/MMBTU	0.06		
SO2 EMISSIONS,LB/MMBTU	0.10		
PARTICULATES EMISSIONS,LB/MMBTU			
-- TOTAL	0.0030		
-- TOPPING COMBUSTOR EXIT	0.0026		
-- SULFATER EXIT	0.0003		
CO EMISSIONS,LB/MMBTU	0.09		
HCL EMISSIONS,LB/MMBTU	0.00		
MATERIALS IN	23,580		
MATERIALS OUT	23,580		
MATERIALS BALANCE	100.00%	(0)	-0.000
ENERGY IN	1.5698E+07		
ENERGY OUT	1.5692E+07		
ENERGY BALANCE	99.97%	5,448	1.394

Figure 4 shows a schematic of the bimodal system that needs to be tested to properly evaluate the performance and advantages of the pulse combustor island. This setup includes the pulse combustor-hot gas cleanup section, primary and secondary cyclones, duct burner (topping burner), air preheater (to simulate normal air compressor outlet temperature), heat exchanger (to cool the flue gases down below 600°F to be compatible with the pressure letdown valve seals), pressure letdown valve, baghouse, coal and sorbent feed systems, air compressor and steam circuit. This configuration will help evaluate the systems for meeting 1/10th NSPS and gas turbine tolerance criteria. A cost estimate was made to fabricate and build this system and it was found that the existing budget was inadequate to do so. With additional simplification and component reuse to cut costs and stay within budget, the configuration shown in **Figure 5** was arrived at. The significant departures from Figure 4 are the deletion of the duct burner, the use of an existing heat exchanger, and the incorporation of a flare-cum-air preheater. This arrangement will aid in determining the fuel gas composition and the particulate loading in the fuel gas stream and the operating and performance characteristics of the pulse combustor-HGCU system. The unit shown in Figure 5 can be modified to that shown in Figure 4 at a later date to more completely evaluate this advanced concept.

Figures 6 through 10 show preliminary design drawings of the PDU. The pulse combustor for the PDU is shown in **Figure 6**. The combustor is refractory-lined (high density-single layer) and water-jacketed to control the heat loss and maintain slagging conditions. As the unit size becomes larger, the surface area-to-volume ratio decreases and the refractory thickness required decreases. For combustors firing 100 MMBtu/hr or higher, it is projected that there would be no need for refractory-lining. Upon initial coal firing, a layer of slag (¼ to ½ inch) would coat the metal, solidify, and form a protective layer. The combustion chamber is provided with parts for pilot burner, flame detection, temperature and pressure (static and dynamic) measurements. A draw pipe is provided in the water jacket to drain water in freezing weather if the unit will be non-operative. A flue gas annulus around the tailpipe water jacket is incorporated to facilitate proper tailpipe-resonance chamber acoustic interface. A radiant shield around the water jacket is provided near the tailpipe exit to minimize heat losses from the flue gas.

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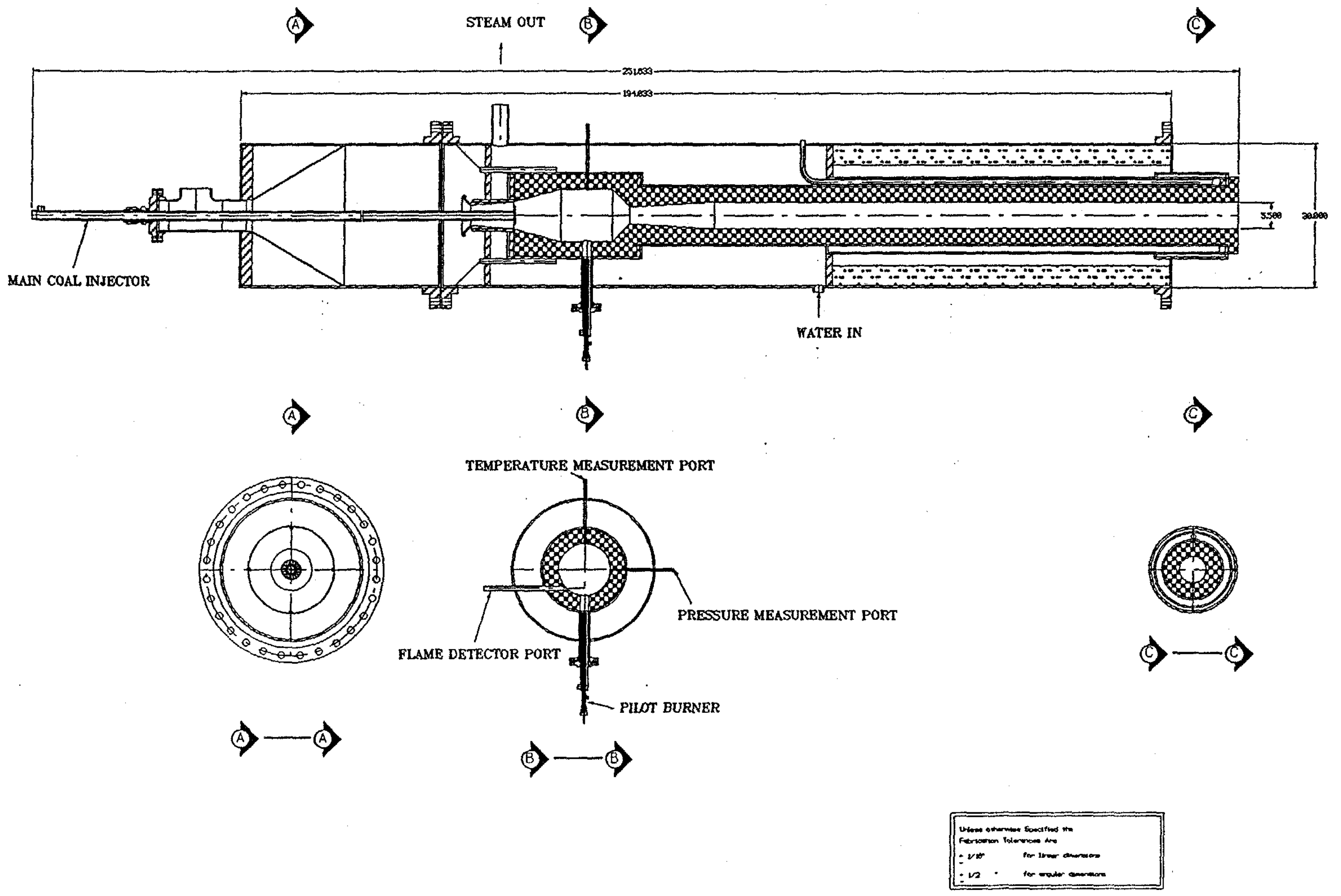


FIGURE 6: PULSE COMBUSTOR FOR PDU

Figure 7 shows the pulse combustor-hot gas cleanup section for the PDU. The HGCU section comprises a U-bend and a straight section. The flue gas exits the tailpipe and flows through the U-bend section first and then the straight vertical section. Slag is anticipated to predominantly flow along the bottom side of the first half of the U-bend into the slag top hole and then into the slag quench bath. A hot gas draw-off port is provided below the tap hole to facilitate flue gas-slag co-flow through the tap hole (to minimize solidification of slag near the tap hole), and also to vent the steam generated in the slag quench operation. By using a steam eductor, the hot gases will be drawn off the slag topping/quenching zone. A double lock hopper arrangement is employed to depressurize the glassy frit generated by the slag quench and discharge the same. Multiple injection parts are provided to vary the location of injection of reburn coal, sorbent, and recycle solids from the primary cyclone catch. A fluidized bed section is provided in the second half of the U-bend section but below the straight vertical section to collect relatively big agglomerates, if any, fluidize with steam to promote carbon conversion and to withdraw the solids once again through a double lock hopper arrangement. The HGCU section is designed to provide a gas residence time on the order of 5 seconds. The overall height of the PDU above ground level is on the order of 70 ft. The fuel gas and solids leaving the HGCU pass through a primary and secondary cyclone to capture particulates on their way to the heat exchanger.

Figure 8 shows the slag handling section. It incorporates a man-hole and a hand-hole for internal access, if needed. Auxiliary burner parts (two in quantity) are provided to melt the slag and facilitate its flow in case of accidental slag solidification in the slag tap hole. A sight port is also provided near the tap hole to facilitate visual inspections.

Figure 9 shows the elevation and plan views of the PDU. The PDU requires a footprint of about 20 ft. x 12 ft. and is between 60 and 70 ft. tall. Figure 10 shows the layout of the system. It shows the location of the auxiliaries such as compressors, feed systems, flare, etc. Preliminary structural support design has been performed and will be shown to an outside consultant for review and approval. The existing concrete pad outside the building may not be adequate as

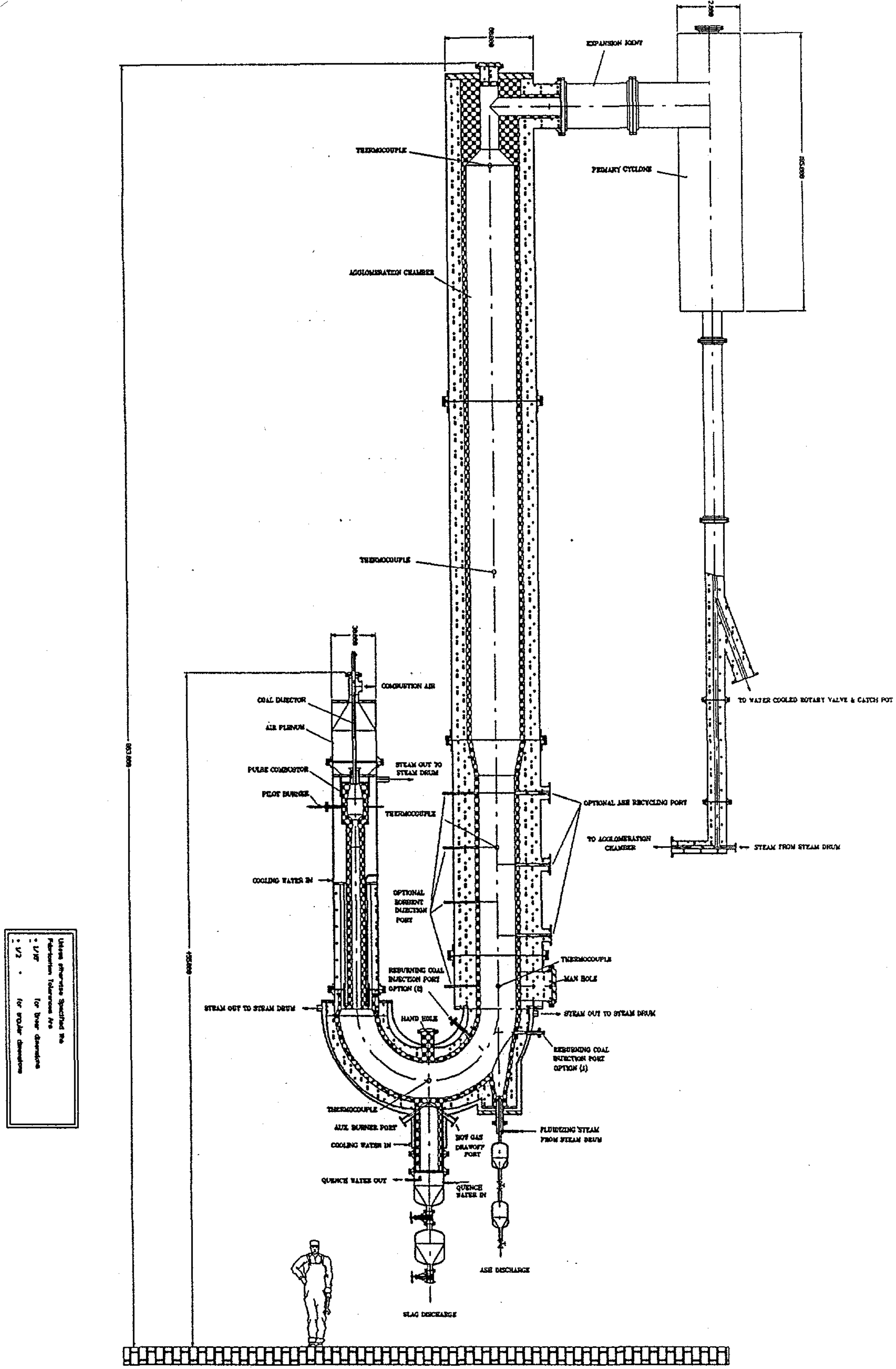
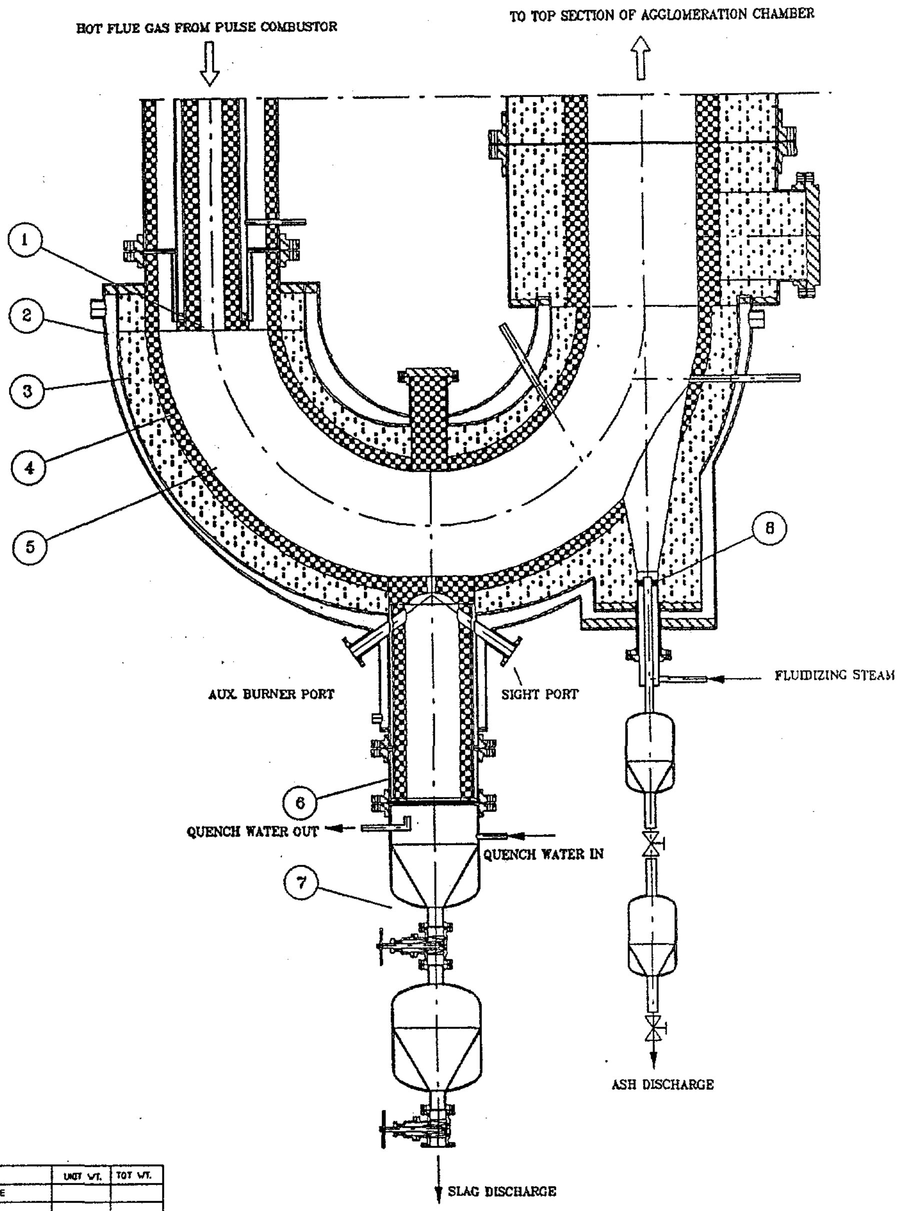


FIGURE 7: PULSE COMBUSTOR - HGCU FOR PDU



Unless otherwise Specified the
Fabrication Tolerances Are
± 1/16" for linear dimensions
± 1/2 ° for angular dimensions

ITEM	QTY	DWG NO.	DESCRIPTION	UNIT WT.	TOT WT.
1	1		PULSE COMBUSOR TAILPIPE		
2	1		WATER JACKET		
3	1		LOW DENSITY REFRACTORY		
4	1		HIGH DENSITY REFACTORY		
5	1		AGGLOMERATION CHAMBER		
6	1		QUENCH VESSEL		
7	1		LOCK VESSEL		
8	1		STEAM DISTRIBUTOR		
9					
				TOTAL WT.	

FIGURE 8: SLAG HANDLING SECTION FOR PDU

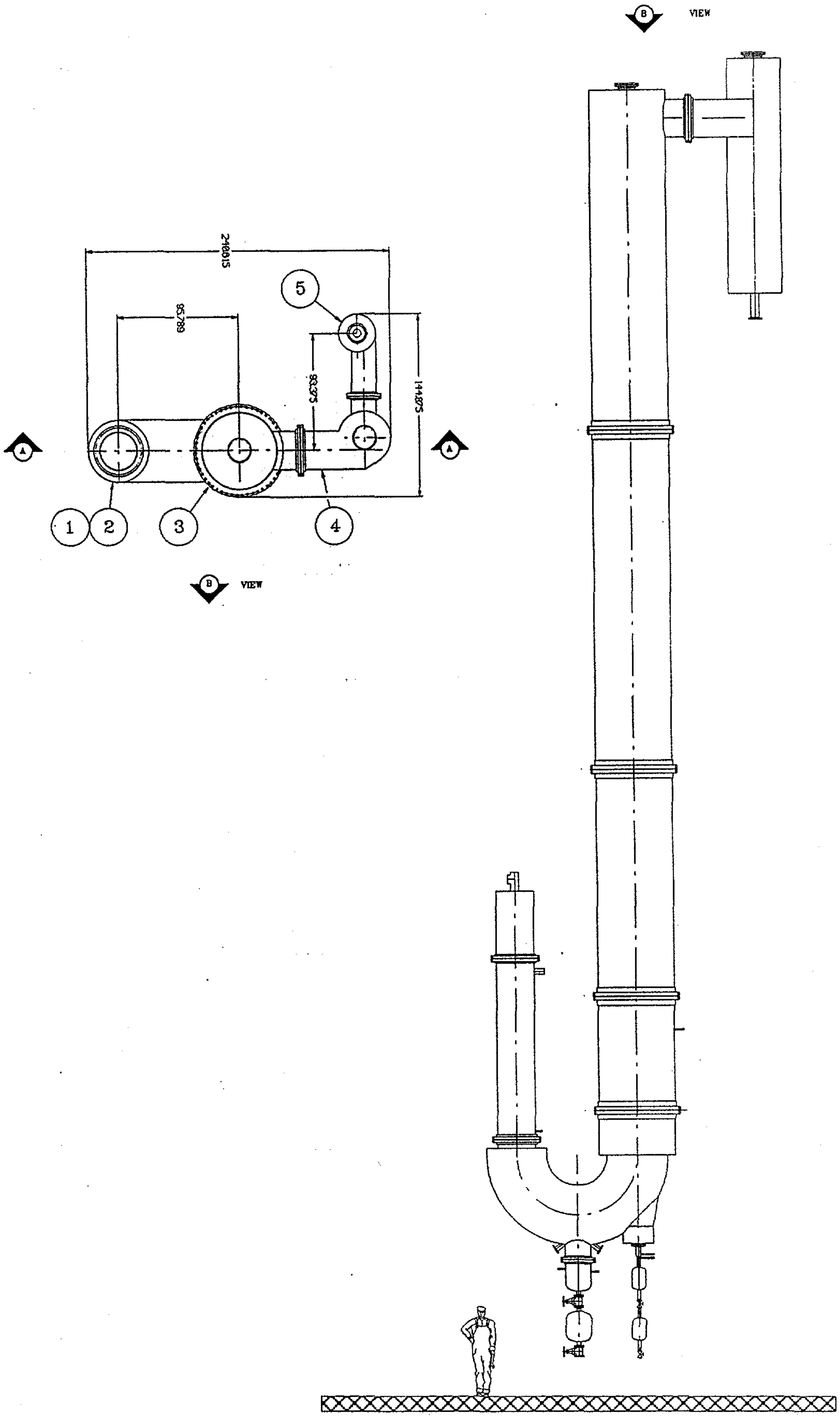


FIGURE 9: ELEVATION AND PLAN VIEWS OF PDU

ITEM	QTY	DWG NO.	DESCRIPTION	UNIT WT.	TOT WT.
1	1		AIR PLENUM		0.2435 TON
2	1		PULSE COMBUSTOR		.34 TON
3	1		AGGLOMERATION CHAMBER		4.37 TON
4	1		PRIMARY CYCLONE		5.5 TON
5	1		SECONDARY CYCLONE		1.6 TON
6	1		HEAT EXCHANGER		
7	1		STEAM DRUM		
8	1		FLARE BURNER		
9	1		FLARE FD FAN		
10	1		COAL SPLITTER		
11	1		COAL SILO AND FEEDER		
12	1		SORBENT SILO AND FEEDER		
13	1		BUCKET ELEVATOR		
14	1		RECEIVING HOPPER		
15	1		AIR COMPRESSOR		
16	1		CONTROL ROOM		
17	1		CONTROL PANEL		
18	1		GAS COMPRESSOR		
19	1		CATCH POT		
20	1		SLAG HANDLING SYSTEM		
21	1		STEAM / REBURN COAL INJECTION		
22	1		ASH DISCHARGE SYSTEM		
				TOTAL WT.	

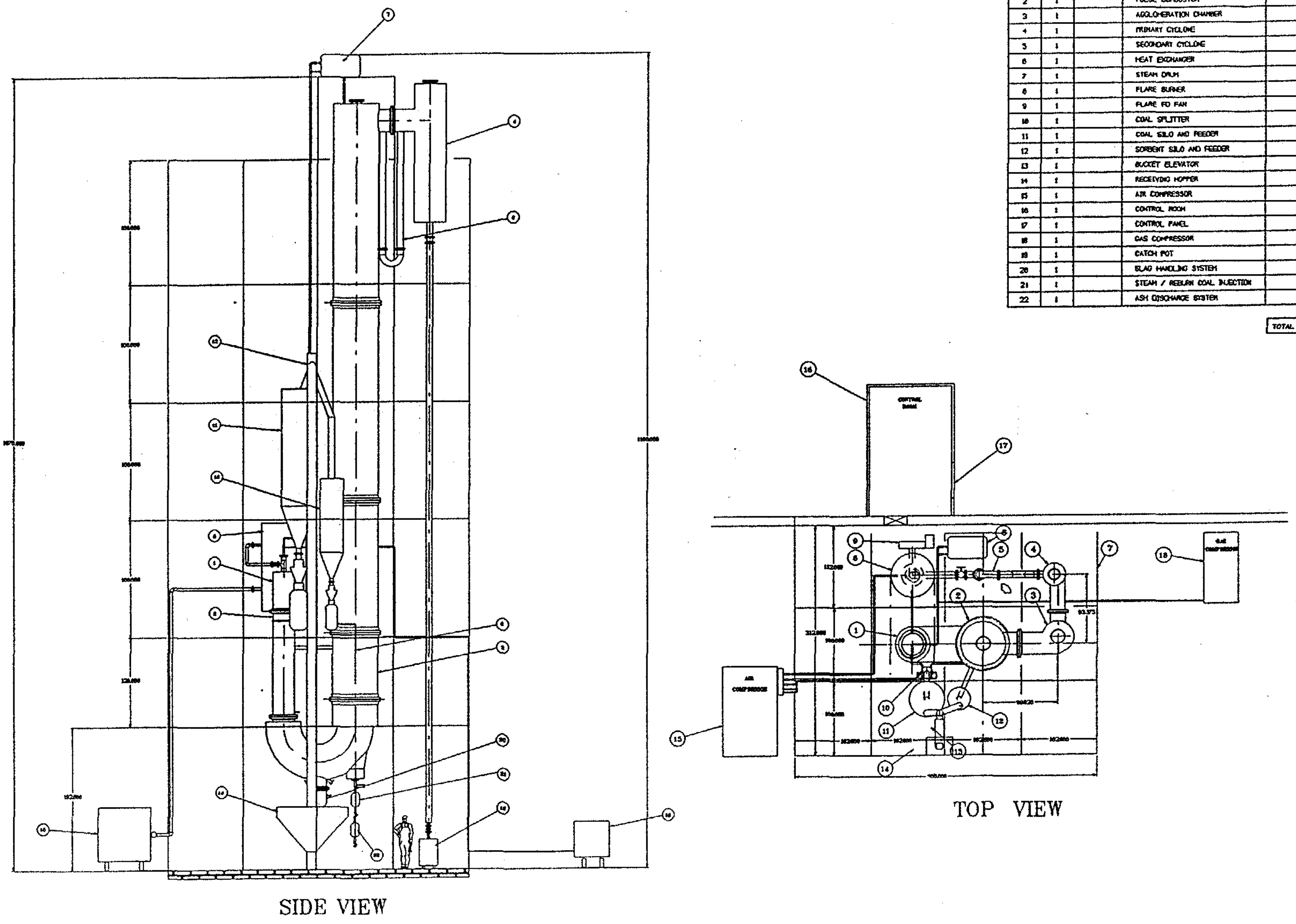


FIGURE 10: PDU LAYOUT

is to withstand the total load. Additional reinforcement will probably be needed.

Figure 11 shows a preliminary process and instrumentation diagram (P&ID) for the PDU. The system will include purge, ignition verification and main fuel start-up protocols, safety interlocks, and instrumentation and control corrections for monitoring and operational safety. The system will be manually controlled with automatic shutdown in case of alarm activation. The hardware from the dismantled bimodal unit will be reused as far as possible with additional hardware and software procured as needed.

A preliminary commercialization plan was submitted at a project review meeting held at DOE/METC on June 23, 1995.

Construction of the new control room behind the concrete pad is in progress. Air, water, and gas access lines have been installed for hook-up. Procurement of materials is underway. The fabrication of the U-bend section has started.

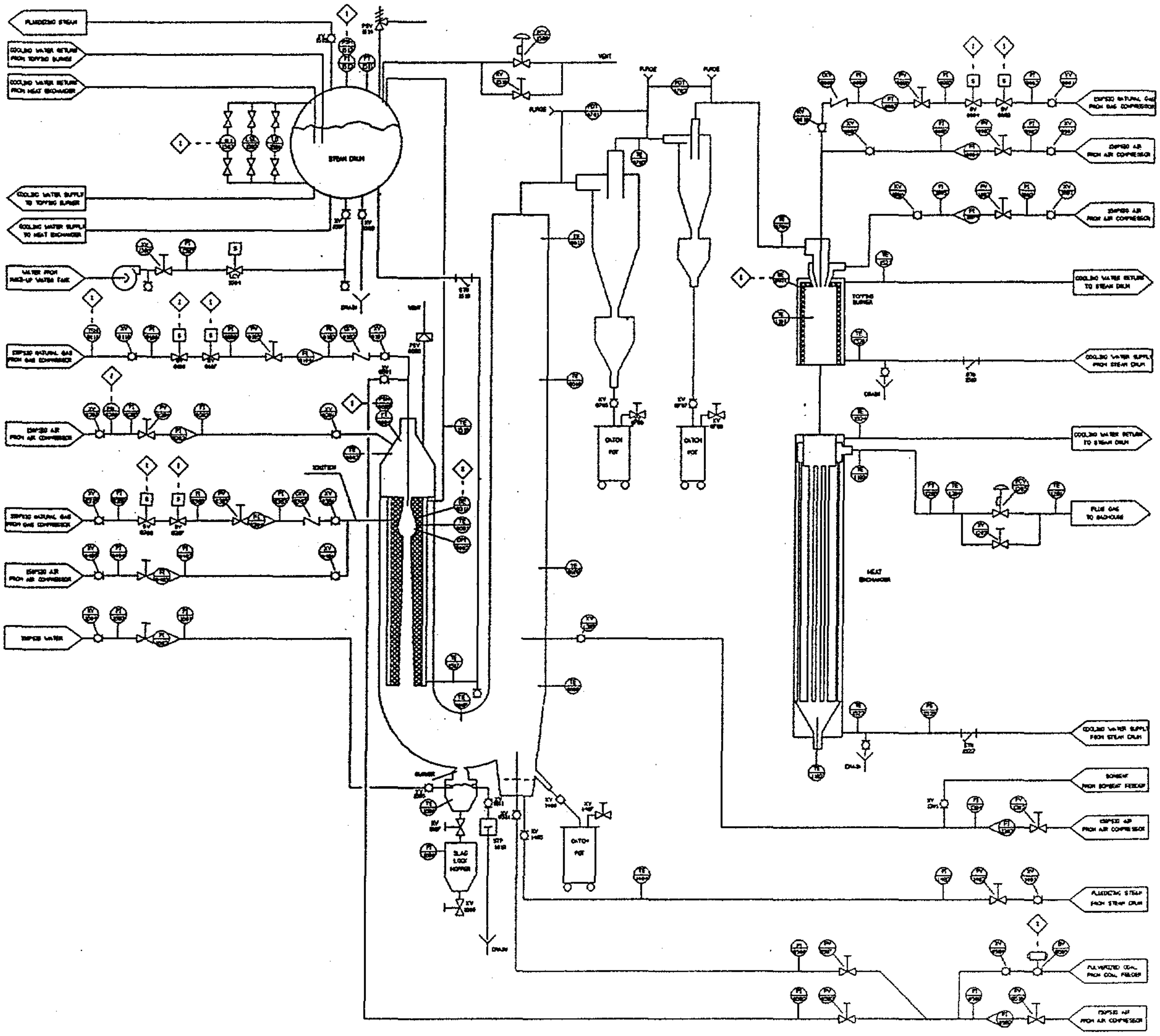


FIGURE 11: PRELIMINARY P&ID FOR THE PDU

2.2 PENN STATE UNIVERSITY

The species conservation equation for SO_2 is given by *Equation 1.*

$$\bar{\rho}\tilde{u}\left(\frac{\partial \tilde{Y}_i}{\partial x}\right) + \bar{\rho}\tilde{v}\left(\frac{\partial \tilde{Y}_i}{\partial r}\right) - \frac{\partial}{\partial x}\left(\tilde{D}^y \frac{\partial \tilde{Y}_i}{\partial x}\right) - \frac{1}{r}\frac{\partial}{\partial r}\left(r\tilde{D}^y \frac{\partial \tilde{Y}_i}{\partial r}\right) = \overline{W}_i \qquad (1)$$

Essentially, the sum of the convective and diffusive terms equals the net source term for the species under consideration. The net source term consists of both the source from the burning coal particles and the sink from the take-up of SO_2 by the sorbent. The source terms were obtained from combustion model while the sink terms were obtained by tracking the sorbent particles after injection in a Lagrangian fashion through the combustor. As the sorbent particles moved through each cell, the sink terms for each cell were calculated and stored. The species transport equation given in (1) was then solved with the source and sink terms to arrive at the concentrations of SO_2 with sorbent injection. The boundary condition used at the outlet is given in *Equation 2.* The combustor geometry and the numerical grid are the same as were used in the previous reports.

$$\frac{\partial^3 \tilde{Y}_i}{\partial x^3} = 0 \qquad (2)$$

The results of the simulations using the conditions and the equations mentioned above are shown in Figures 12 through 16. The exit shown in the figures is at x=5.6m. Since PCGC-2 cannot compute backflow into the agglomeration tube surrounding the pulse combustor, the exit is assumed to be at the right. However, it is felt that sulfur dioxide concentrations calculated at the new exit will not be significantly different from the concentrations at the exit as measured by MTCI. Figure 12 shows the concentrations without any sorbent. Figures 13 through 15 show concentrations in the combustor using 45 microns, 10 microns and 5 microns, respectively. As is seen very clearly from the comparative graph in Figure 16, the concentrations in the combustor decrease drastically as the particle size is decreased. For 45 micron sorbent sizes, we observe an exit concentration of ~320 ppm, for 10 micron sizes a concentration of ~150 ppm, while for 5 micron sizes the concentration is zero nearly everywhere, thus showing that almost all of the sulfur dioxide present is captured for

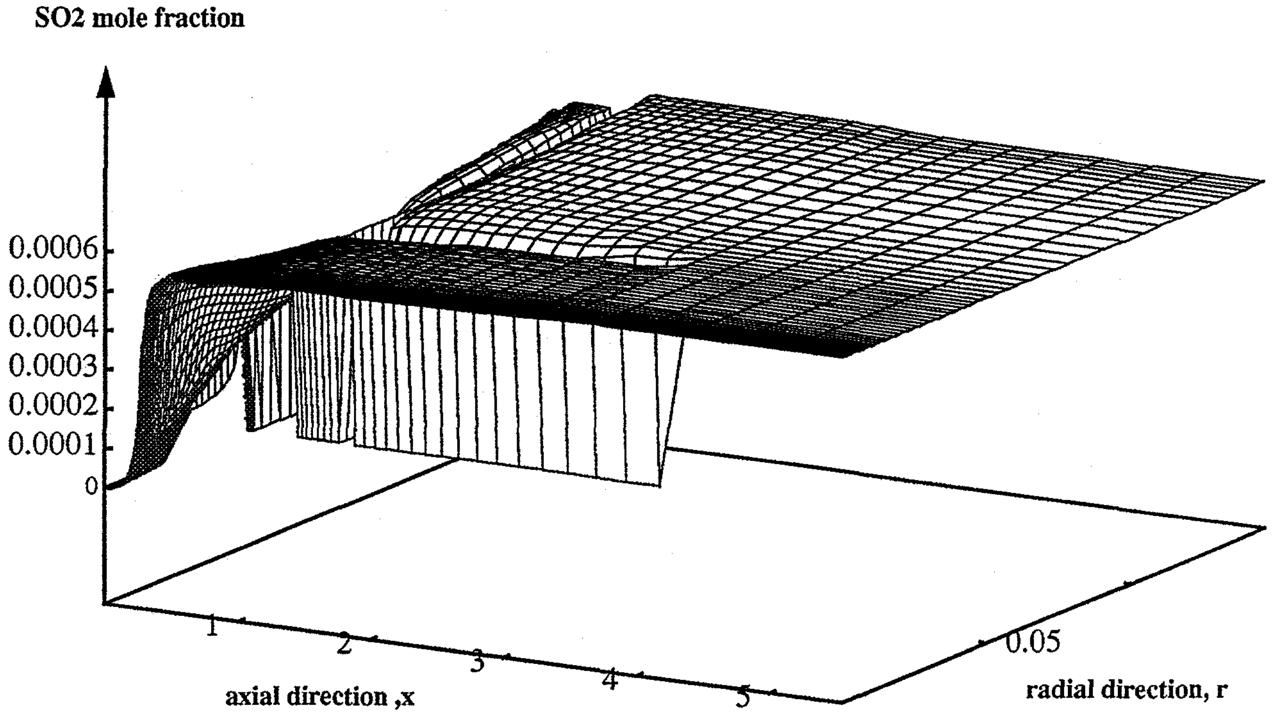


FIGURE 12: SO_2 CONCENTRATIONS IN COMBUSTOR WITHOUT SORBENT

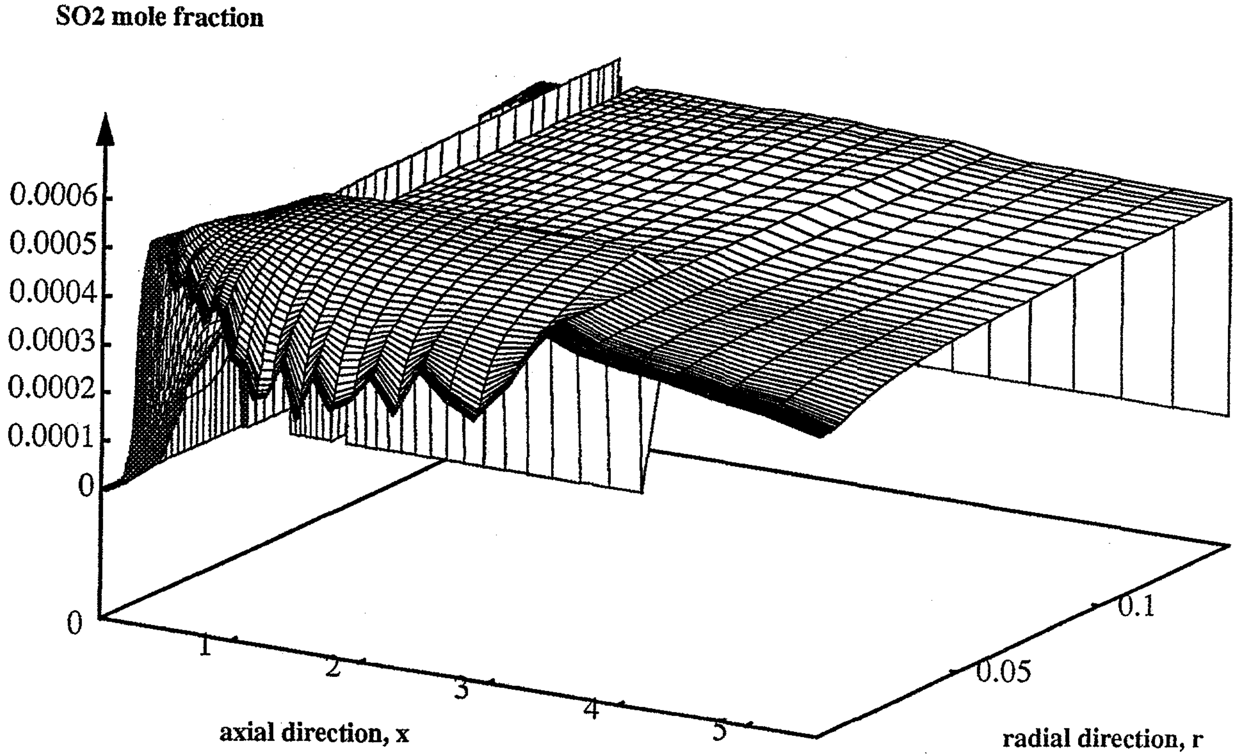


FIGURE 13: SO_2 CONCENTRATIONS IN COMBUSTOR USING 45 μM SIZE SORBENT (MMD)

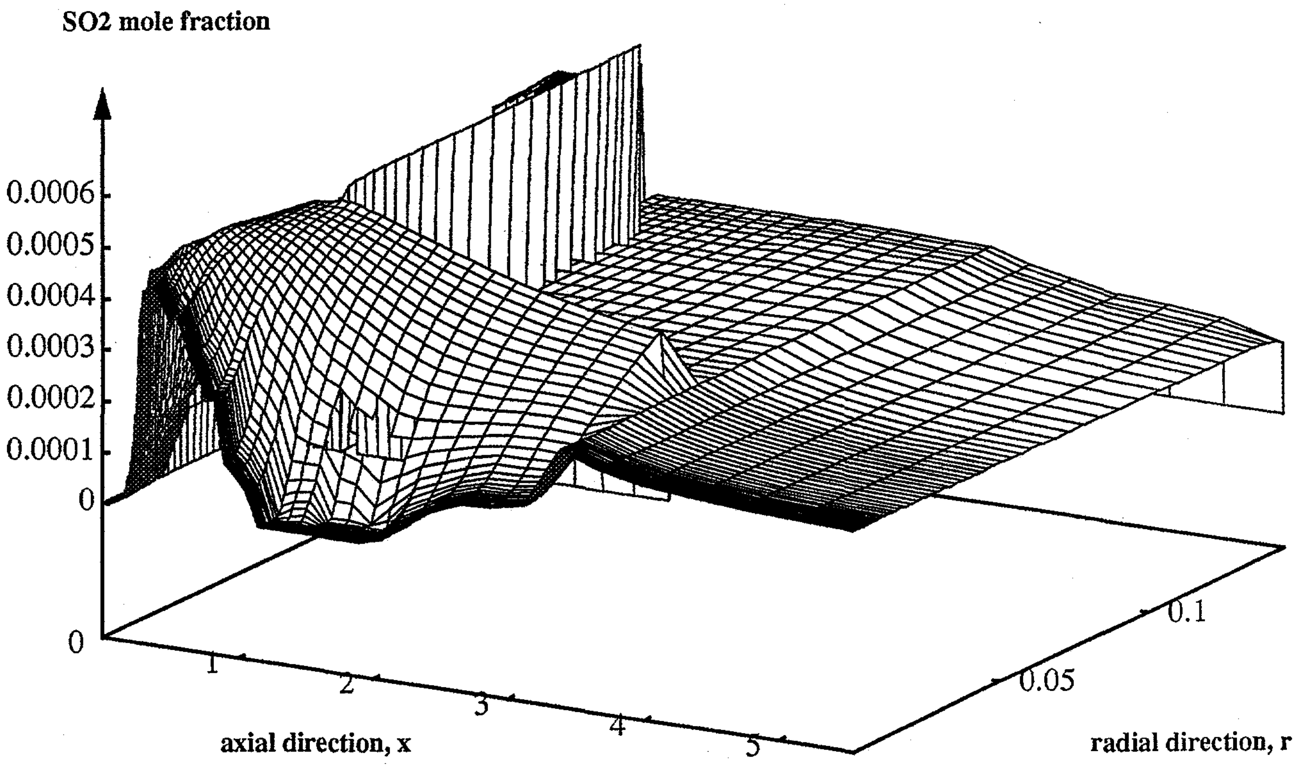


FIGURE 14: SO_2 CONCENTRATIONS USING 10 μM SIZE SORBENT (MMD)

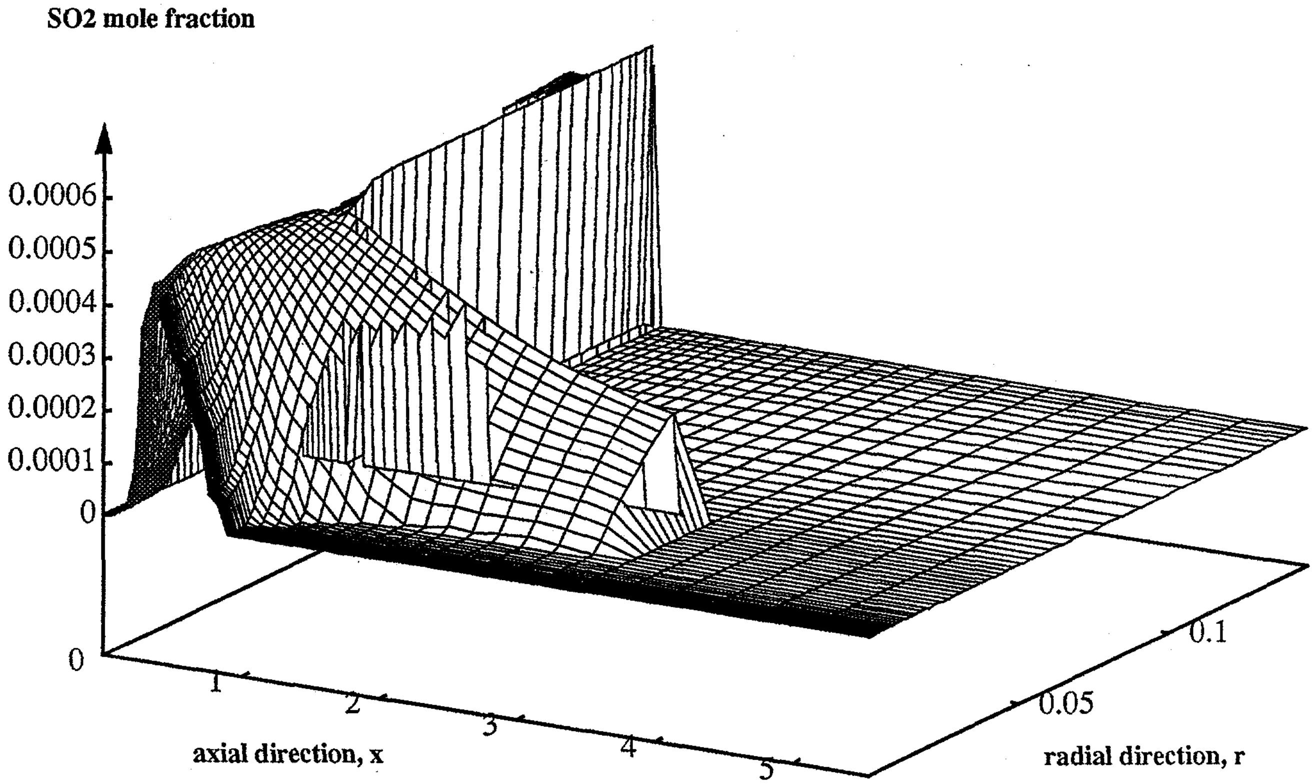


FIGURE 15: SO_2 CONCENTRATIONS USING 5 μM SIZE SORBENT (MMD)

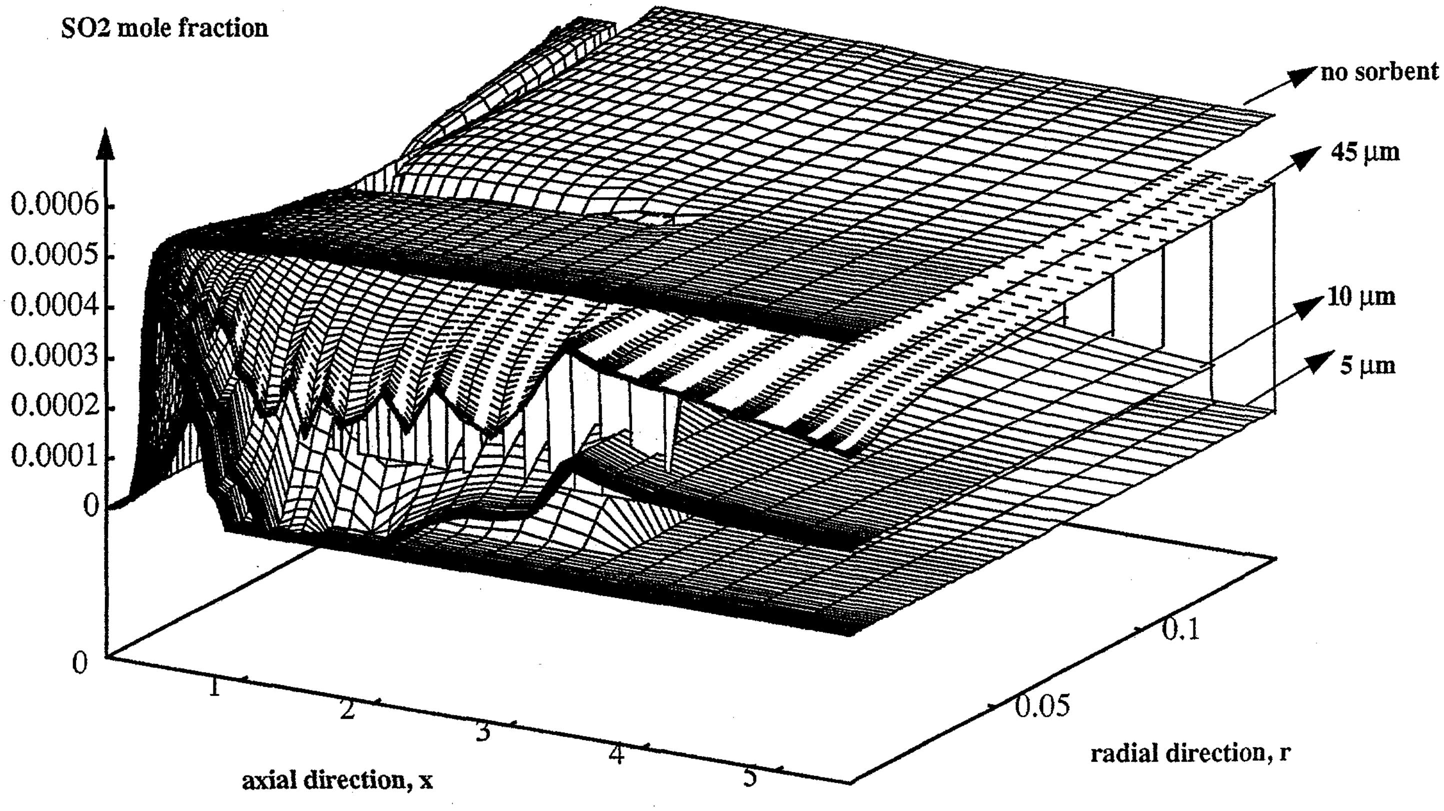


FIGURE 16: COMPARISON OF SO_2 CONCENTRATION WITH DIFFERENT SORBENT SIZES

that particular sorbent size. Figure 16 shows that smaller sorbent particle sizes capture more sulfur dioxide as compared to larger sizes. A diameter of 45 microns was chosen, since this was the mean mass diameter calculated from the MTCI data for the sorbent. Compared to MTCI results of about 54 ppm using sorbent injection, it is felt that a variety of reasons (some of which have not been modeled currently) could be responsible for the different results obtained from the simulations. First, the sorbent model cannot account for the presence of MgO along with the limestone, i.e., the model assumes that the sorbent is 100 percent calcium carbonate. Furthermore, dolomitic limestones, such as the one used in the MTCI experiment, are known to breakup/disintegrate and produce very small fragments. Such a phenomenon would definitely increase the rate of sulfur capture but would not be predicted by the model since it does not take into account the question of particle breakup. Hence, a series of simulations for different sorbent sizes were run for 10 micron as well as 5 micron sizes. It is felt that the effective particle size distribution will lie somewhere between 5 to 20 microns to obtain the MTCI results of sulfur dioxide capture.

Figure 17 shows the extent of sulfation of a single isolated grain, a purely hypothetical concept, for different temperatures and residence times. The sorbent particles are themselves composed of many such grains, overlapping each other and forming a porous structure. However, it is instructive to look at the grain sulfation process in order to estimate what the absolute maximum extent of sulfation is for any particle given a temperature and residence time. As is seen in the figure, the sulfation extent increases with increasing residence time. However, an optimum temperature is also observed for the extent of sulfation. The only resistance considered here is the diffusion through the product layer of $CaSO_4$ formed around the grain as the reaction proceeds. In the real problem, of course, additional resistances appear due to pore diffusion (consisting of Knudsen and bulk diffusion) and external mass transfer. These resistances have been neglected while analyzing a single grain.

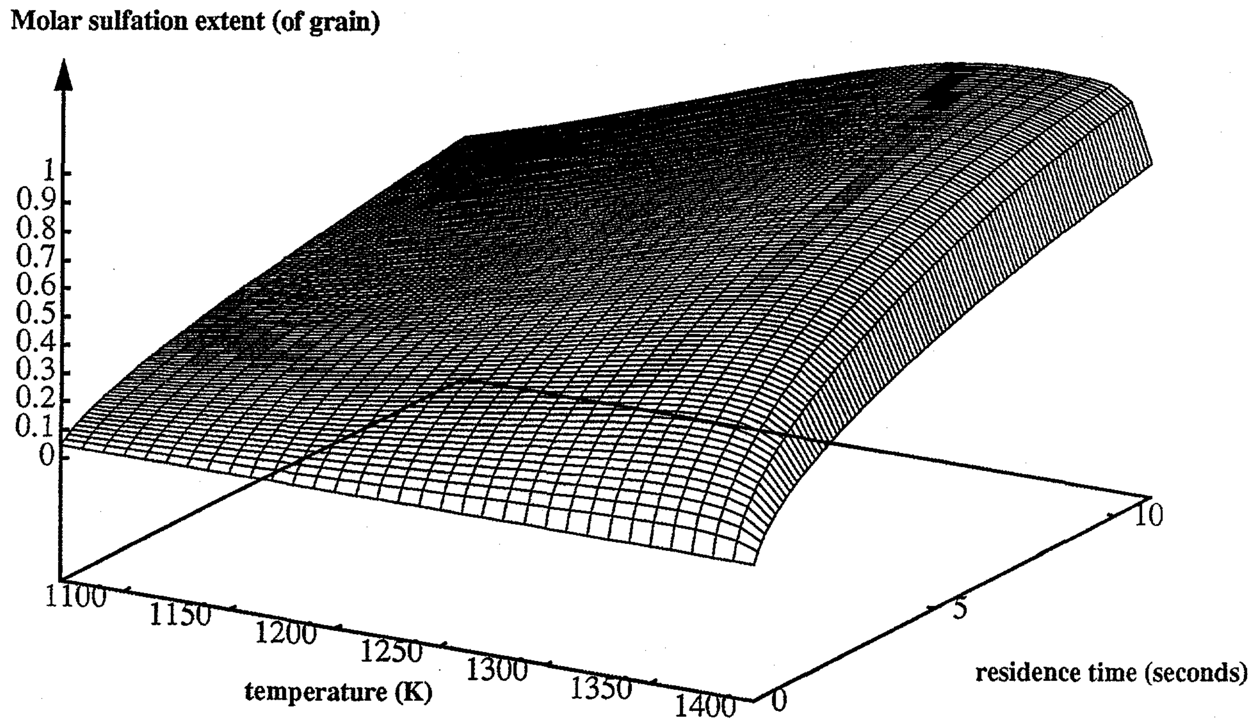


FIGURE 17: MAXIMUM GRAIN SULFATION EXTENTS FOR DIFFERENT TEMPERATURES AND DIFFERENT RESIDENCE TIMES
(FOR ISOLATED GRAINS, A PURELY HYPOTHETICAL CONCEPT)

The conditions used for the test run were:

Firing Rate:	Total-(MMBtu/hr)	2.42 (709.2 KW)
	% Coal	70.1
	% Natural Gas	29.9
Pressure:		44.7 psia (3 atm)
Excess Air:		9.9%
Temperature of Walls:		300°F (422 K)
Sorbent Loading:		22.5 lb/hr

The species conservation equation for SO_2 is the same as the one used in previous reports. Also, the boundary conditions used are the same. The only essential difference is the residence time of the sorbent particles. Since PCGC-2 cannot compute backflow, the domain has been extended so that the effective residence time is increased so as to adequately simulate the conditions present in the MTCI test combustor/agglomeration tube.

Figure 18 shows the concentration field in the combustor without any sorbent. At the exit of the combustor, a concentration of ~696 ppm is observed. The current run is for a different case than the previous reports. The conditions for the current run were also taken from MTCI test data and are provided elsewhere in this report. Figure 19 shows the concentration field in the combustor using 10 micron sorbent particles. It can be seen that the average exit concentration is ~95 ppm which is comparable to the MTCI result of 54 ppm. Figure 20 shows the molar extent of sulfation of the sorbent particles for each of the ten different trajectories used (for 10 micron particles). Very high extents of sulfation are observed because of the long residence time. Figures 21 through 24 show radial variation of the SO_2 concentration at different axial locations for three different sorbent sizes. Three diameters have been chosen: 45 microns, 10 microns and 6 microns. Figure 21 shows the concentration at x=0.1 m. There is not much evidence of capture at this stage since the concentrations are approximately the same with or without sorbent. Figure 22 shows the concentration at x=1.0 m, Figure 23 at x=~3 m, Figure 24 at x=5.66 m, and Figure 25 at x=8.146 m (the exit, taking into account the extended domain). Figure 25 shows that at the exit, concentrations of about ~696 ppm are observed

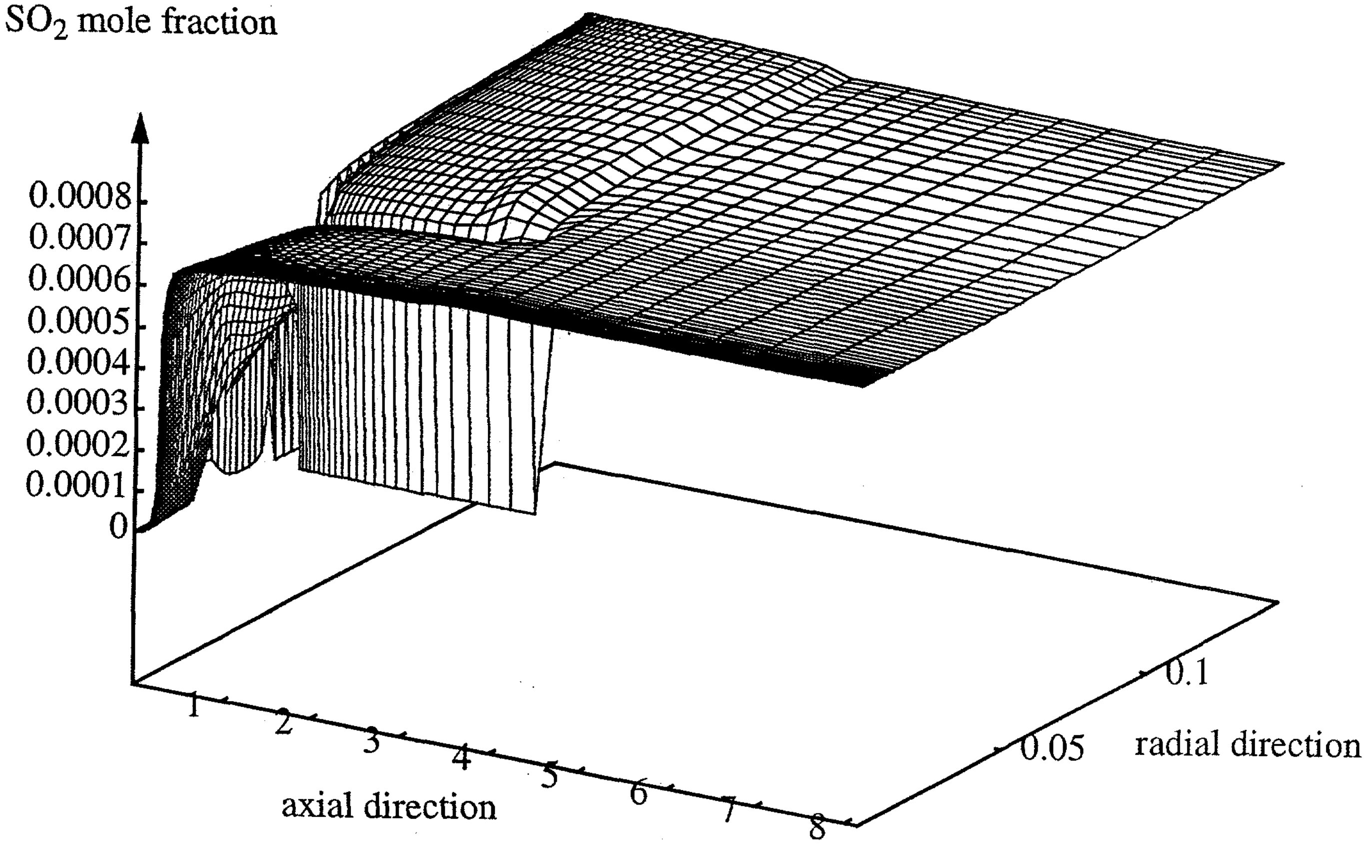


FIGURE 18: SO_2 CONCENTRATIONS WITHOUT SORBENT IN COMBUSTOR (DOMAIN HAS BEEN EXTENDED TO INCREASE RESIDENCE TIME)

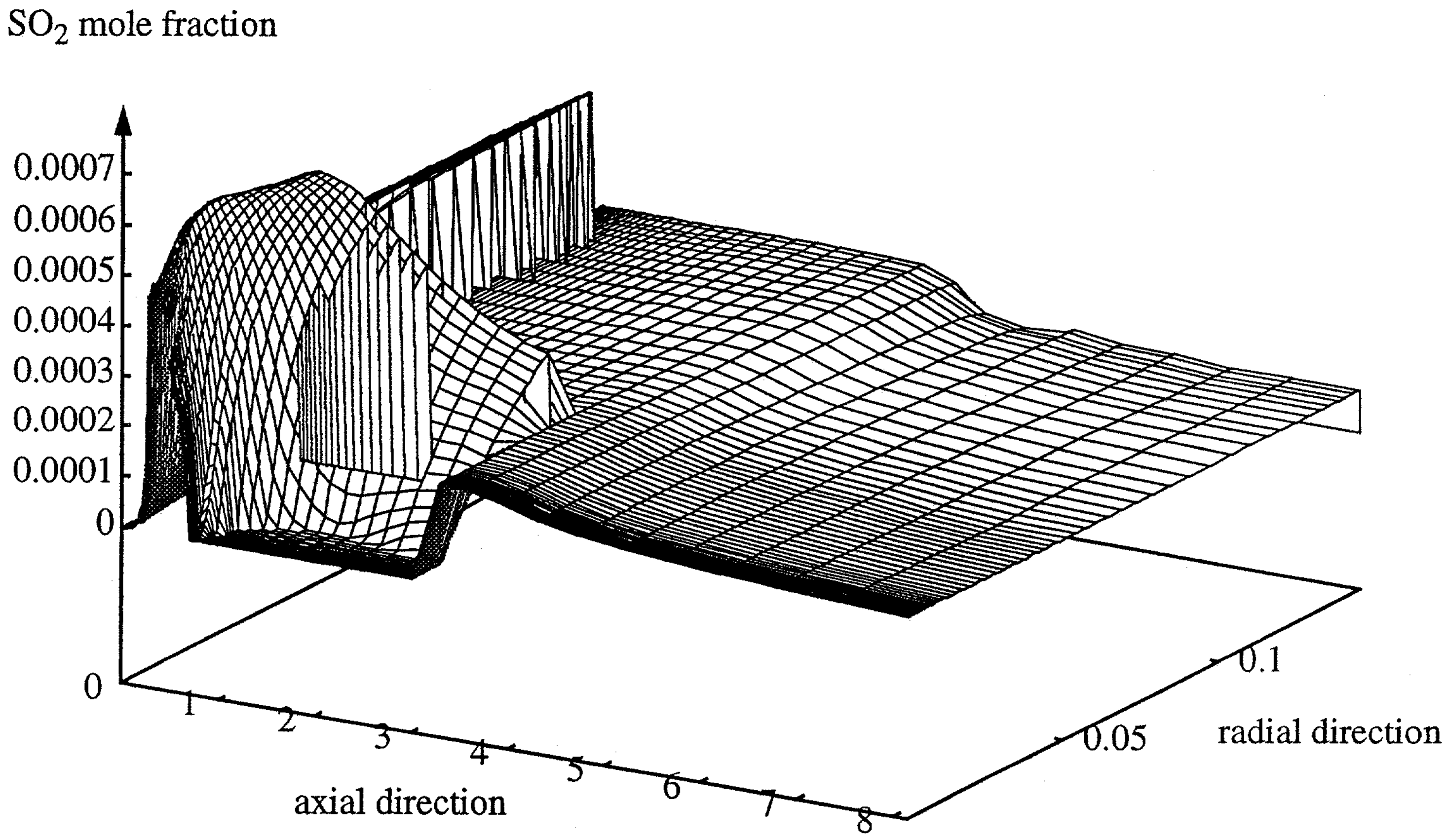


FIGURE 19: SO_2 CONCENTRATIONS IN COMBUSTOR USING 10 μM SORBENT PARTICLES (WITH EXTENDED DOMAIN)

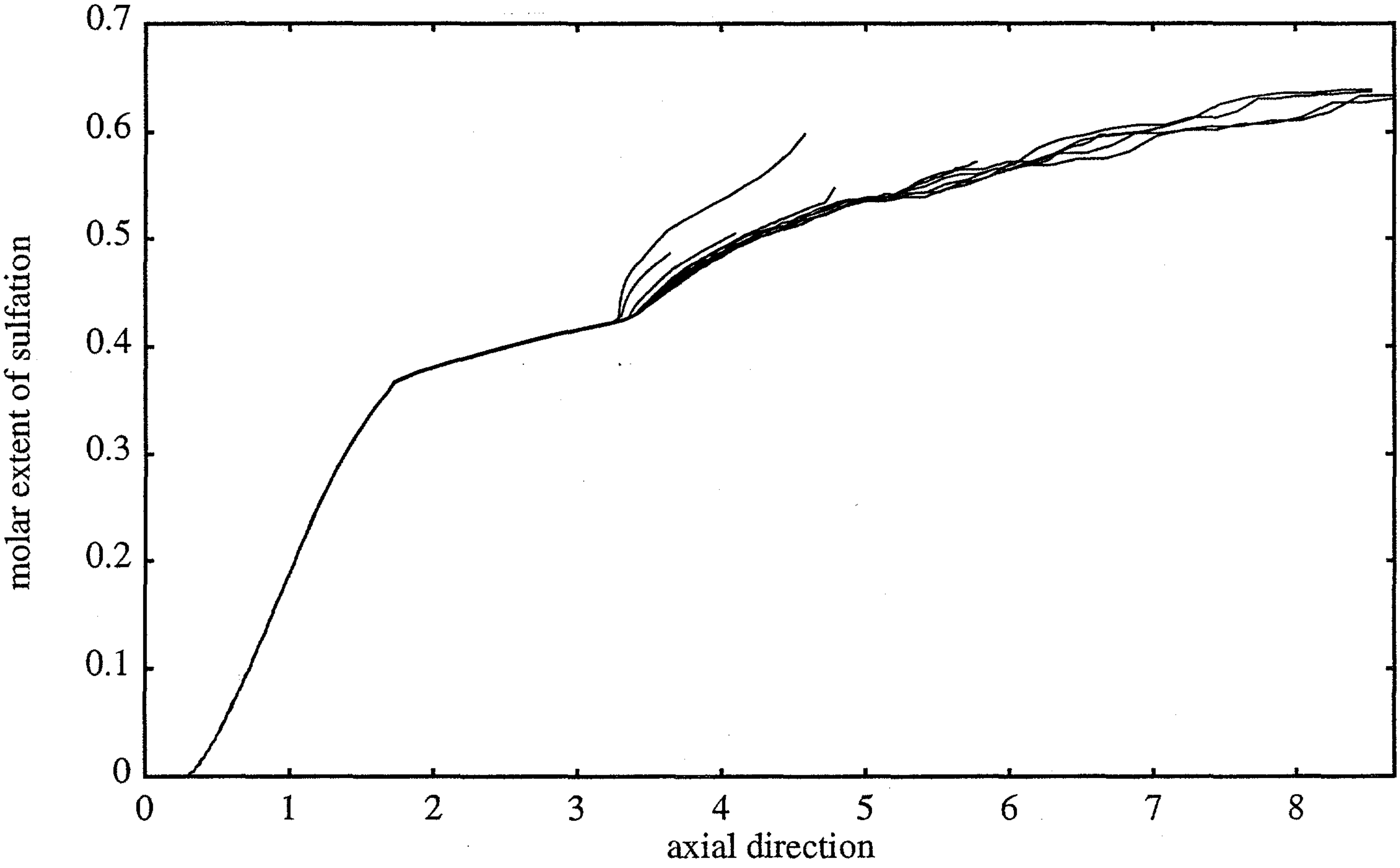


FIGURE 20: MOLAR EXTENT OF SULFATION OF INDIVIDUAL PARTICLES (10 TRAJECTORIES) (10 μM PARTICLE SIZE)

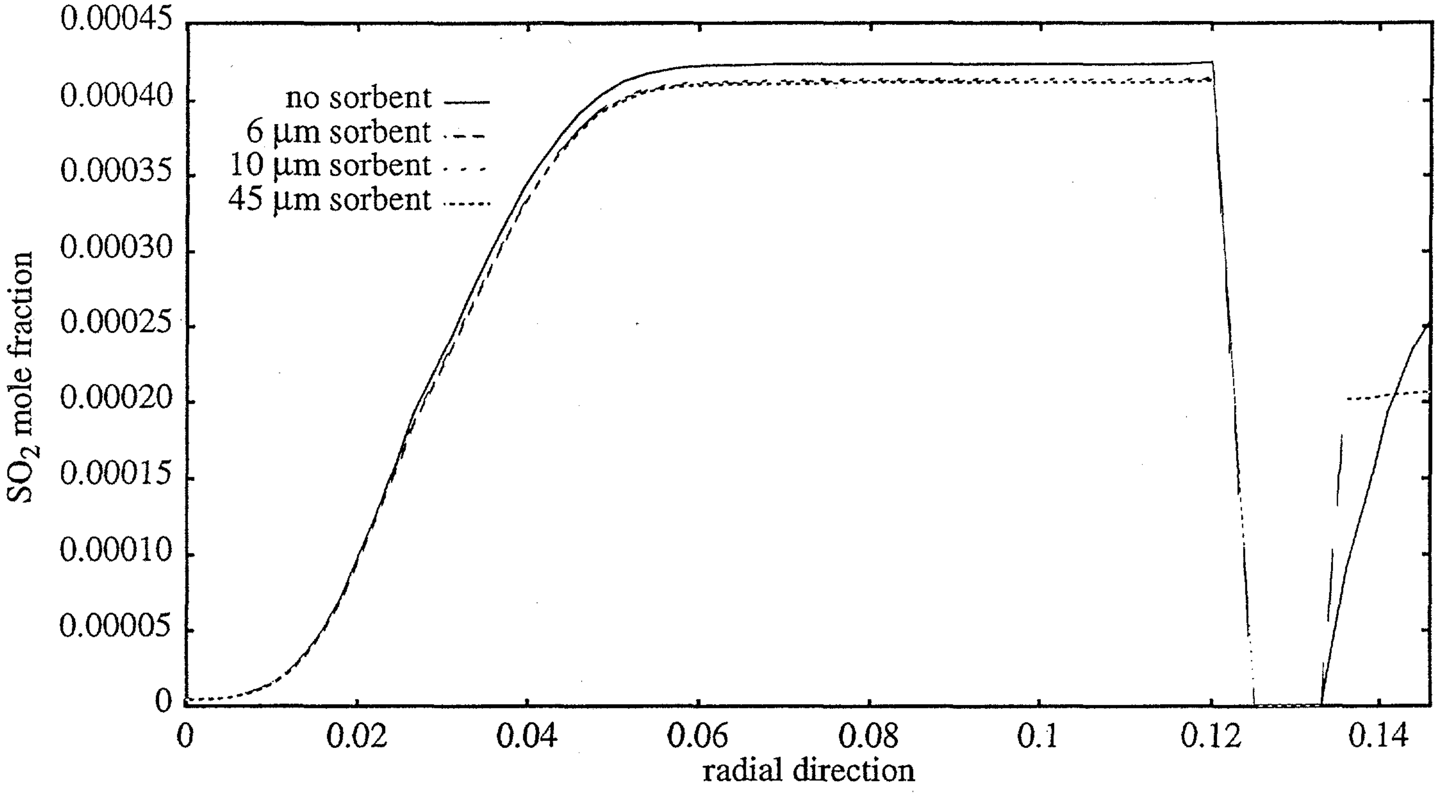


FIGURE 21: RADIAL VARIATION OF SO_2 CONCENTRATION AT x=0.1 M

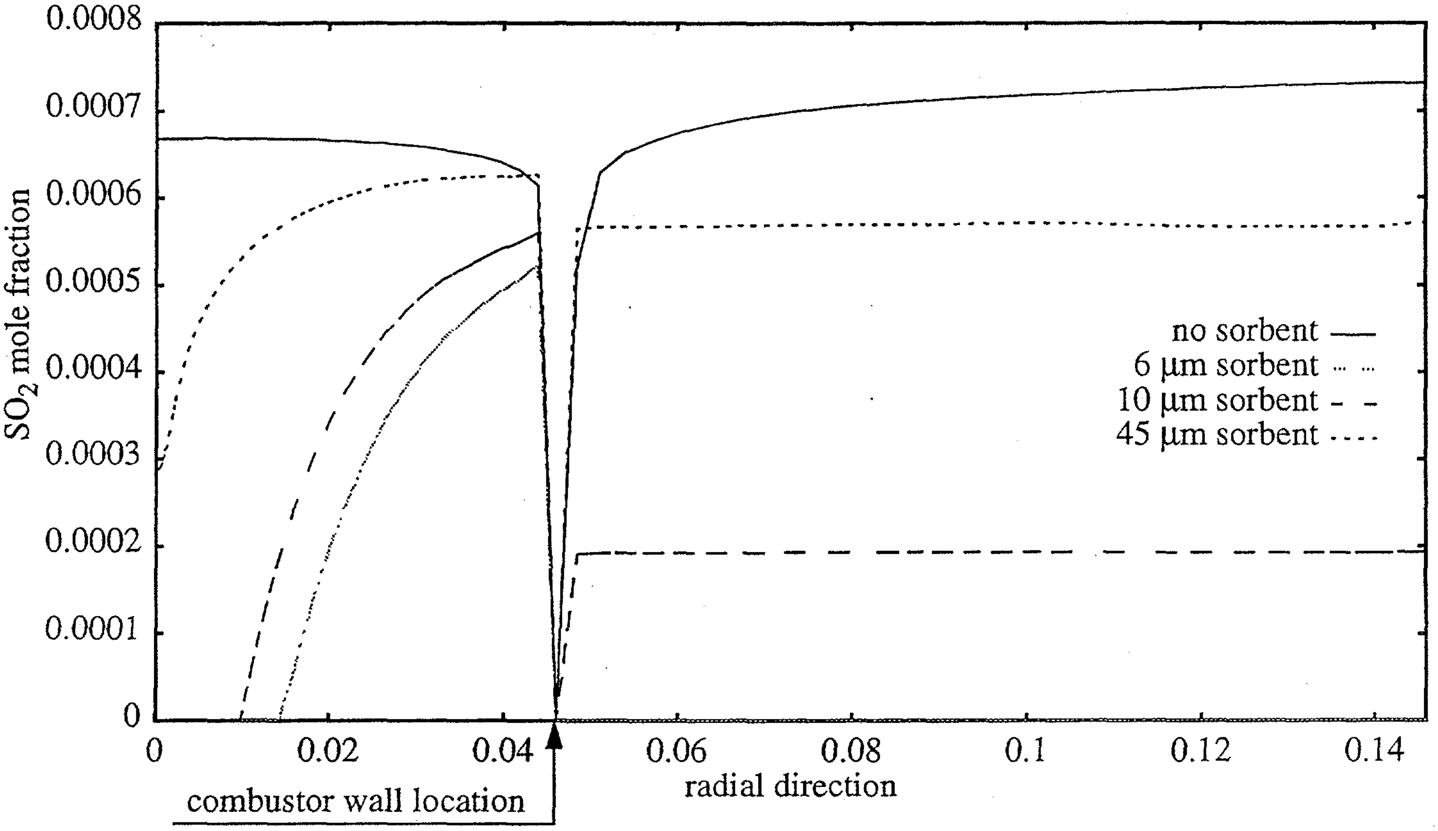


FIGURE 22: RADIAL VARIATION OF SO_2 CONCENTRATION AT x=1.006 M

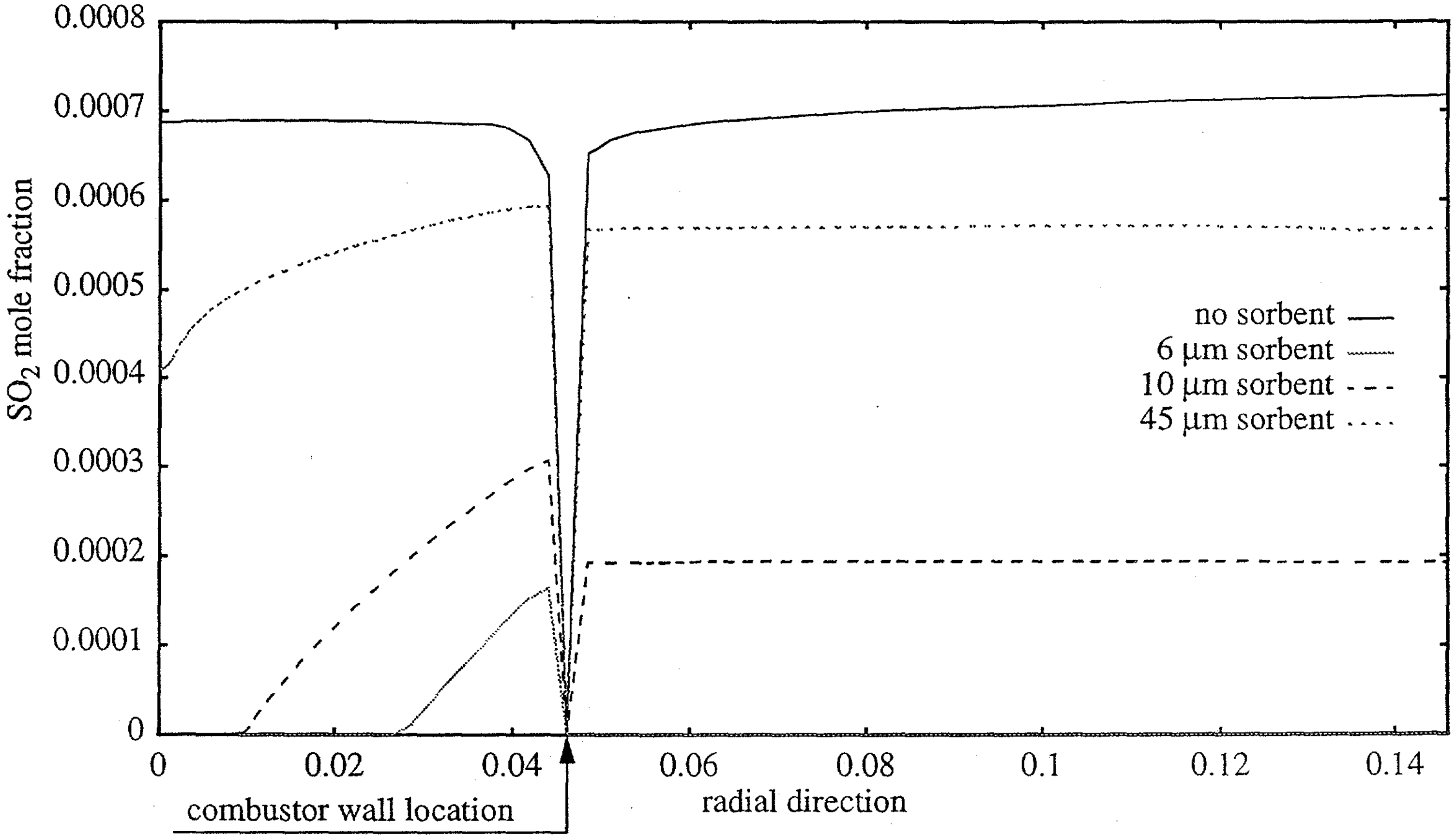


FIGURE 23: RADIAL VARIATION OF SO_2 CONCENTRATION AT x=2.998 M

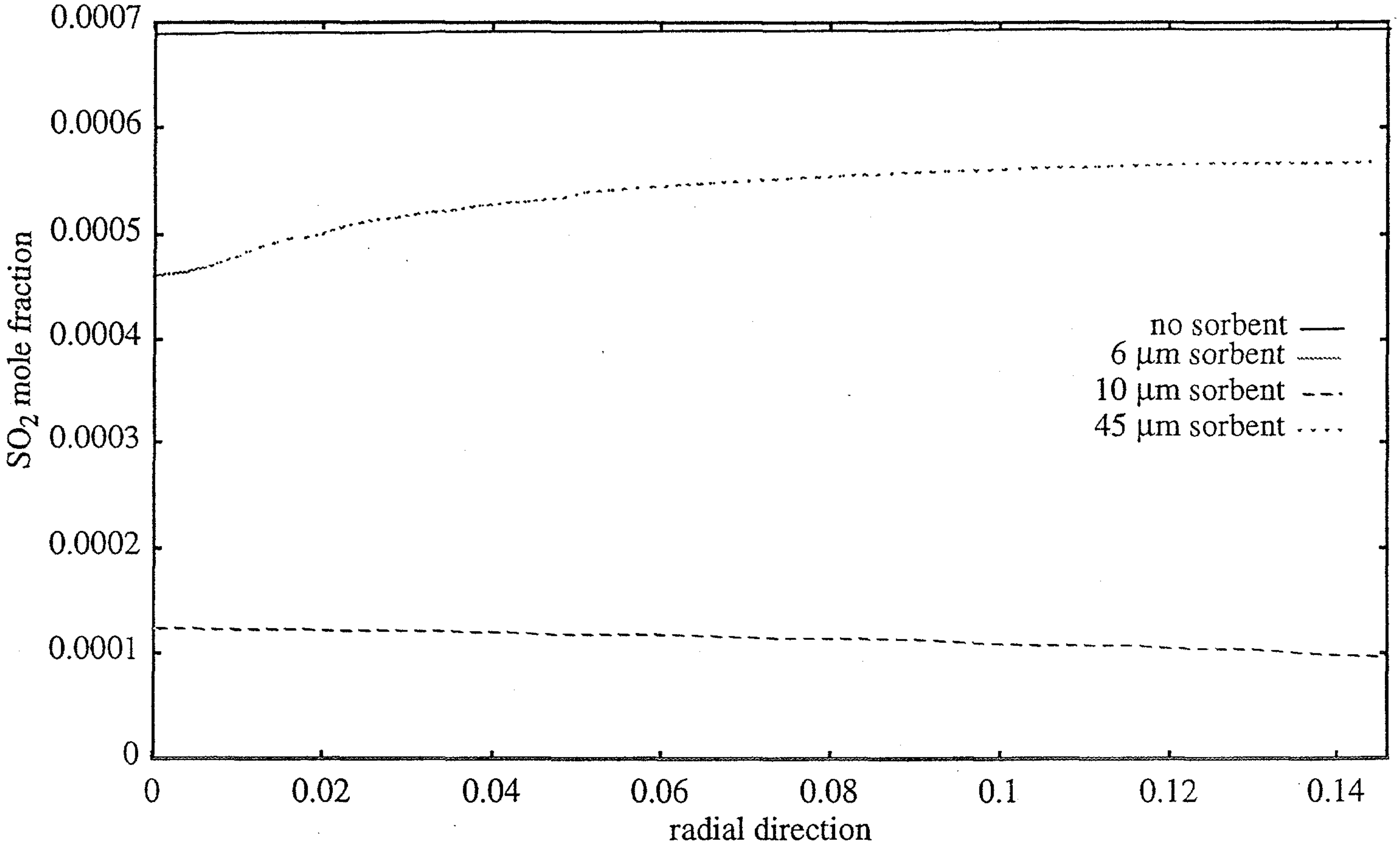


FIGURE 24: RADIAL VARIATION OF SO_2 CONCENTRATION AT x=5.664 M

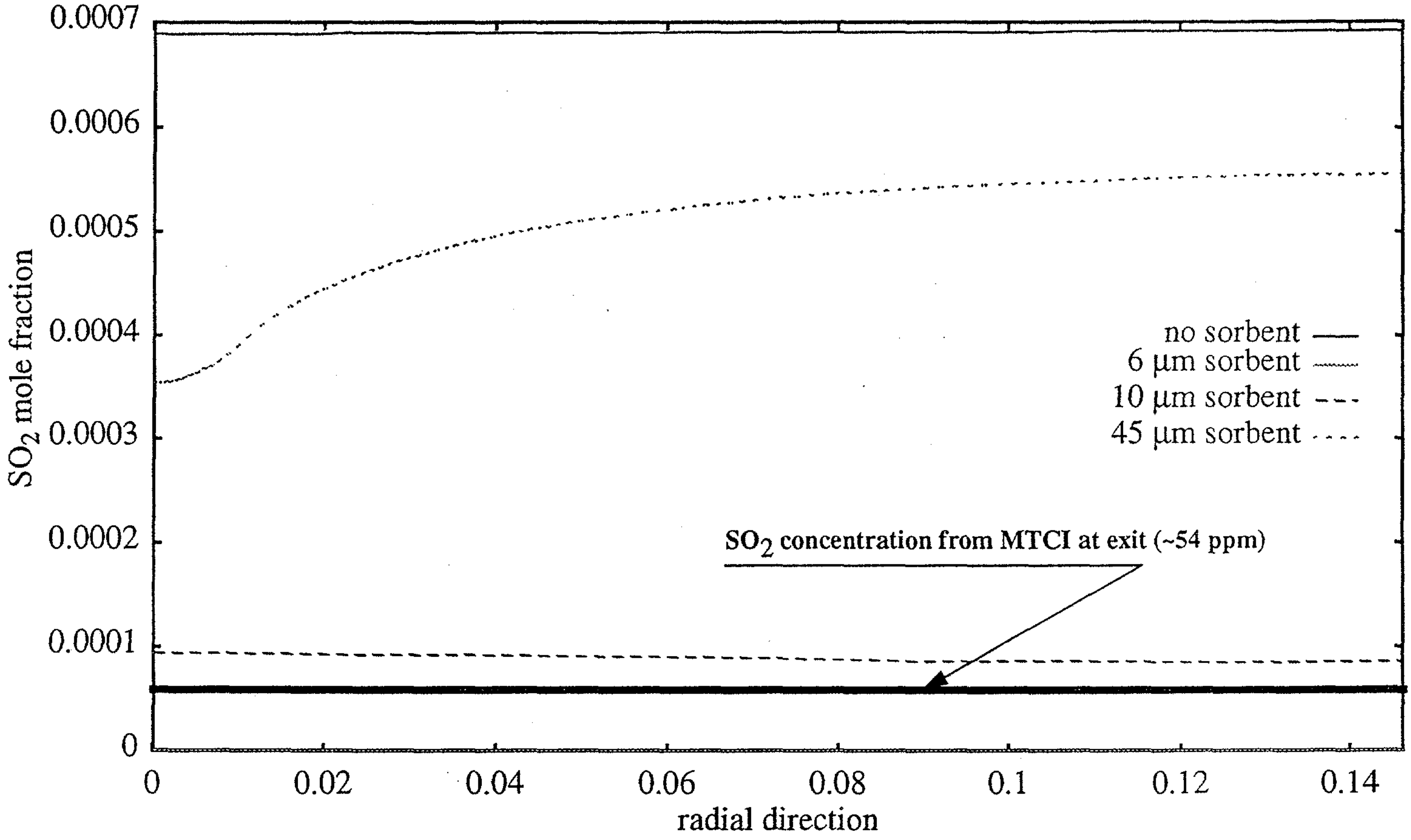


FIGURE 25: RADIAL VARIATION OF SO_2 CONCENTRATION AT THE EXIT (x=8.146 M)

without sorbent, ~500 ppm with 45 micron sorbent, ~95 micron with 10 micron sorbent, and zero with 6 micron sorbent. From this, the effective particle size distribution within the sorbent is very likely 8 to 10 microns. Significant capture occurs in the agglomeration tube in addition to the combustion chamber.

The conditions used for the simulation (taken from MTCI data) were:

Firing Rate:	Total-(MMBtu/hr)	2.16
	Coal, %	78.4
	Methane, %	21.6
Sorbent Feeding Rate:		22.5 lb/hr
	Type:	C&CD (Calcined and Classified Dolofil)
Pressure, psia:		45.4 (~3 atm)
Excess Air, %:		13.5
Emissions Data (from MTCI):		54 ppm with sorbent

The sorbent particle model has been implemented in PCGC-2 and is being subject to minor revisions. Work has been started on the agglomeration model for the behavior of sorbent particles when subject to a high intensity acoustic field. Since tracking each individual particle is computationally impossible given current levels of computing technology, a statistical representation would be more feasible. However, the relative merit of different statistical approaches is in itself a moot issue. Tracking of particles can be done in one of two ways, either: 1) deterministic, or 2) stochastic. The deterministic Lagrangian tracking of particles in an otherwise Eulerian field was first suggested by Crowe and co-workers(1) in their now well-known PSI-Cell (Particle-Source-In Cell) technique, whereby the paths of the particles could be modeled as a delta function spike with zero variance. However, this approach, which has been the method of choice so far for tracking the coal particles (and more recently the sorbent) has problems because it relies on an Eulerian transport equation that calculates the particle number density field inside the combustor in order to calculate the turbulent particle diffusivity from a gradient diffusion hypothesis and an arbitrary choice of the so-called Schmidt. number. A stochastic representation on the other hand is weighed down by the fact that a large number of particle trajectories have to be computed in order to get a sufficiently smooth representation of the particle number density. This approach has been outlined by Gosman and Ioannides.(2)

Other alternatives have been proposed which involve using the stochastic model of Gosman and Ioannides(2) for groups of particles in combination with accounting for diffusion of particles within the group. A significant amount of bookkeeping becomes necessary in such a technique. The relative positions of particles within a group at any time is random because of the turbulent gas velocity field. Therefore, movement of the particles w.r.t the center of the group is almost like a random walk. Theoretical considerations and experimental data suggest that this kind of particle dispersion can be closely represented by a normal Gaussian distribution.

At this stage, we are still looking into simple solutions which can be easily programmed within the limitations of the existing code structure, yet give reasonable particle number distributions for comparison with experimental data/ previous numerical studies in a reasonable amount of time.

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1) Crowe, C.T., M.P. Sharma, and D.E. Stock, "The Particle-Source-In Cell (PSI-Cell) Model for Gas-Droplet Flows," *Journal of Fluids Engineering*, Vol. 99, pp. 325-332.

2) Gosman, A.D., and E. Ioannides, "Aspects of Computer Simulation of Liquid-Fueled Combustors," AIAA Paper 81-0323, 1981.

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To maximize the compression ratio in a high mass flow ratio ejector, one should change its design to multiple ejectors in series. The reason is the non-linearity of compression ratio with mass flow ratio. Increasing the mass flow ratio produces diminishing returns on the compression ratio. The Air Force Arnold Engineering Development Center uses many types of ejectors; for example, for high altitude rocket testing. They published their research on "Theoretical Optimization of Staged Ejectors," Part I in 1966 and Part II in 1968. John Loth was the author although the work was done by many engineers. The optimum configuration turned out to be only slightly different from equal mass flow ratio in each ejector with equal compression ratio (r) in each ejector. Then the overall compression ratio is r^n; n are the number of stages. Two or three stages are usually used. In rare cases such as the AEDC Low Density Plasma Arc facility, five steam ejectors were used.

We can therefore increase the compression ratio of a pulsed combustor along the same technique as in staged ejectors. As the natural frequency of combustion is mainly controlled by the speed of sound and the length of the unit, each stage will pulse at the same frequency. When placed in series the pulse from the upstream unit will control the phase shift between successive stages. The recently developed vortex-type aerovalve is already turning the flow by 90 degrees. This makes placing each combustor side by side a logical arrangement. Due to the decrease in diodicity by feeding the downstream unit with vitiated air, the number of stages may be limited. There are several arrangements which should be considered each for their own special merits.

SECTION 3.0

PLANS FOR NEXT PERIOD

- Continue procurement, design and fabrication.
- Pursue commercialization leads.