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DEVELOPMENT OF TOPPING COMBUSTOR FOR ADVANCED CONCEPT PRESSURIZED FLUIDIZED-BED COMBUSTION

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7.1 Development of Topping Combustor for Advanced Concept Pressurized Fluidized Bed Combustion

CONTRACT INFORMATION

Contract Number	DE-AC21-86MC21023
Contractor	Westinghouse Electric Corporation 4400 Alafaya Trail Orlando, Florida 32826-2399 (407) 281-2000
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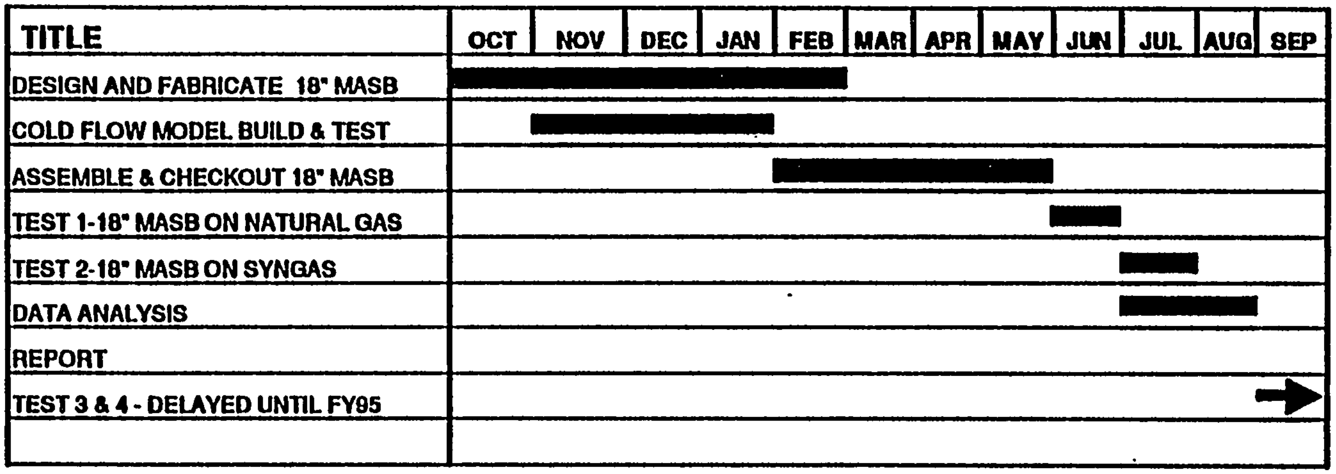
METC Project Manager	Donald L. Bonk
Period of Performance	June 1, 1988 to December 31, 1994 (Phase II)
Schedule and Milestones	
	FY94 Program Schedule

OBJECTIVES

The objective of this program is to develop a topping combustor to operate in a Second-Generation Pressurized Fluidized Bed (PFBC) Combined Cycle power generation system. The combustor must be able to:

- Lightoff with a high heating value fuel and compressor discharge air to heat the fluidized bed(s) and provide power for PFBC and carbonizer off-line.
- Operate with 1600°F (870°C) oxygen depleted air from the PFBC and high heating value fuel to handle carbonizer off-line conditions.
- Ramp up to 100% carbonizer syngas firing (normal operation) by firing a blend of decreasing high heating value fuel and increasing low heating value syngas.
- Utilize the vitiated air, at temperatures up to 1600°F (870°C) for as much cooling of the metal combustor as possible, thus minimizing



FY94 Program Schedule

the compressor bypass air needed for combustor cooling.

- Provide an acceptable exit temperature pattern at the desired burner outlet temperature (BOT).
- Minimize the conversion of fuel bound nitrogen (FBN) present in the syngas to NO_x.
- Have acceptably high combustion efficiency, and low emissions of carbon monoxide, UHC, etc.

BACKGROUND INFORMATION

A project team consisting of Foster Wheeler Development Corporation, Westinghouse Electric Corporation, Gilbert/Commonwealth, and the Institute of Gas Technology, are developing a Second Generation Pressurized Fluidized Bed System. Foster Wheeler is developing a carbonizer (a partial gasifier) and a pressurized fluidized bed combustor. Both of these units operate at a nominal 1600°F (870°C) for optimal sulfur retention.

Since this temperature is well below the current combustion turbine burner outlet temperature (BOT) operation of 2350°F (1290° C), to reach commercialization, a topping combustor and hot gas cleanup (HGCU) equipment must be developed. Westinghouse is participating in the development of the HGCU equipment (reported elsewhere at this conference) and the topping combustor. Work performed on the topping combustor since the last contractor's review meeting (Domeracki, et al. 1993) is presented in this paper.

This paper updates only one part of a multi-phase program. This test program is part of Phase II of a three-phase ongoing DOE/METC program. Phase I involved the conceptual and economic study (Robertson et al., 1988); Phase II addresses subscale testing of components; Phase III will cover pilot plant testing of components integrated into one combustion system.

PROJECT DESCRIPTION

The topping combustor in this cycle must utilize a low heating value syngas produced from the carbonizer at approximately 1600°F (870°C) and 150 to 210 psi (1.0 to 1.4 MPa).

The syngas entering the topping combustor has been previously cleaned of particulates and alkali by the HGCU equipment. In addition to the combustible materials (primarily CO, H_2 and CH_4) it also contains significant fuel bound nitrogen (FBN) from the coal present as ammonia (NH_3) and other compounds. This FBN is significant because it will selectively convert to NO_x in the highly oxidizing conditions of standard combustion turbine combustors.

The hot syngas must be burned with the vitiated (partially burned) air from the pressurized fluidized bed combustor (PFBC). This air is at 1600°F (870°C) and still contains sufficient oxygen for combustion and has been cleaned of particulates and alkali in a separate HGCU system. To obtain optimum efficiency, the 1600°F air must also be utilized to cool the metal combustor surfaces to as great an extent as possible, though a small amount of compressor discharge air at a lower temperature, 700°F (370°C) will also be needed for combustor rich zone cooling.

These application requirements indicate that a specially designed rich-quench-lean (RQL) combustor be used and Westinghouse has selected the Multi-Annular Swirl Burner (MASB, Beér, 1965& to 1969&) for further development for this application.

In selecting a combustor design that will withstand the conditions expected in the topping application, the effective utilization of the 1600°F (870°C) air could satisfy the wall cooling challenge by maintaining a cooling air layer of substantial thickness. Thick layers of cooling air at the leading edge of each inlet section are easily achieved if the combustor is made up of concentric annular passages. In addition to wall cooling considerations, the burner must inhibit the formation of NO_x from syngas that contains FBN, have high combustion efficiency, produce an acceptable exhaust temperature pattern, exhibit good stability, and be able to light off at cold plant conditions. The MASB has demonstrated that it can meet all of these requirements.

This paper reports the results of tests of a 14" diameter topping combustor with a modified fuel-rich zone conducted in June 1993, design of an 18" diameter topping combustor to be tested in June 1994 and afterwards, and results of a 50% scale cold flow model which has been built and tested.

RESULTS

June 1993 14" Diameter Test Results

In June 1993 a test was performed at the University of Tennessee Space Institute (UTSI) with a modified 14" diameter MASB. This test was considered to be very successful, as will be shown in the following data and text.

The "old" MASB, which had been utilized in pre-1993 tests (Figure 1) was modified, as shown in Figure 2. This design was described in the 1993 contractors review, (Domeracki, 1993). Essentially the new design increased the residence time in the fuel-rich zone, obtained backmixing and a controlled reaction temperature in the fuel rich zone, and tested the most recent "Wilsonville" paste feed composition. If sufficient fuel remained (which it did) we were to also test the "Wilsonville" dry feed compositions. These compositions, as predicted and as tested, are shown in Tables 1 & 2.

Table 1. Wilsonville Paste Syngas Composition

	Volume Predicted	Percent as Tested
CO	14.31	14.31
H_2O	11.44	11.44
CO_2	9.44	0
H_2	15.48	15.48
CH_4	2.15	2.15
N_2	46.45	56.45
NH_3	.17	.17

Table 2. Wilsonville Dry Syngas Composition

	Volume Predicted	Percent as Tested
CO	17.22	17.22
H_2O	9.17	9.17
CO_2	7.82	0
H_2	18.01	18.01
CH_4	2.62	2.62
N_2	44.42	52.76
NH_3	.23	.23

The main interest was to confirm the predicted NH_3 to NO_x conversion. The new 14" nozzle (Figure 2) was designed to improve recirculation and to have the rich zone operate within a temperature range of 2900°F +/- 100°F. Due to higher than anticipated leakage around the MASB (i.e., lower than measured oxidizer flow through the MASB), most calculated (allowing for

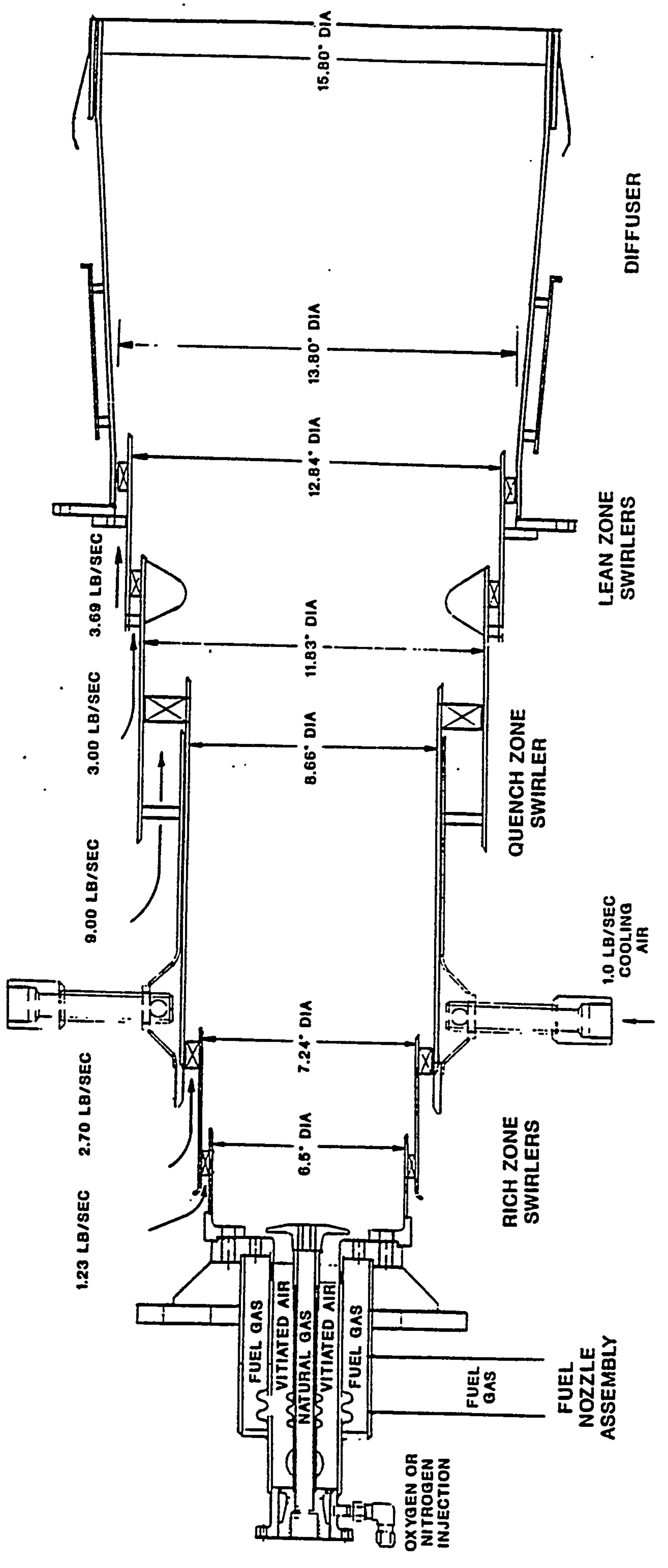


Figure 1. Old 14" MASB Design

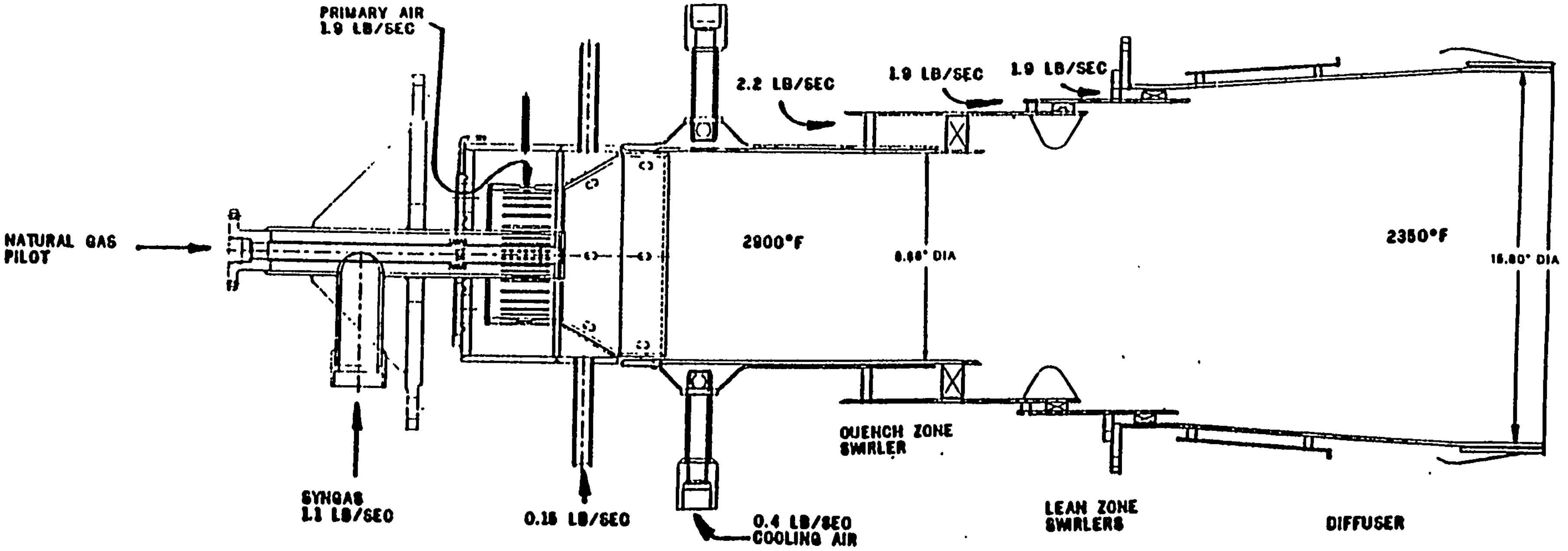


Figure 2. New 14" MASB Design

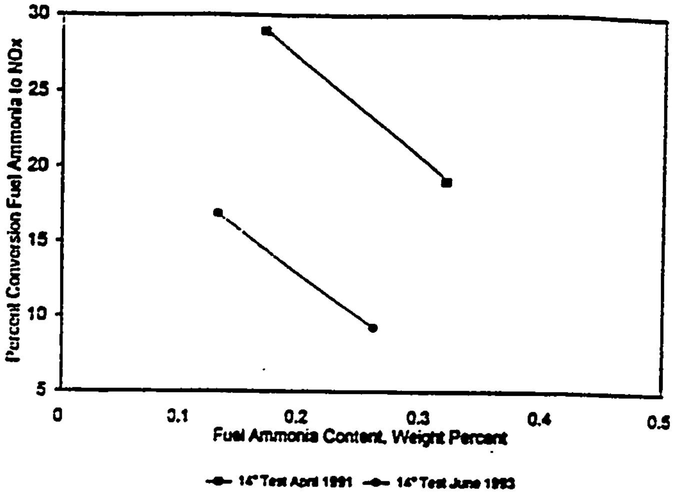


Figure 3. Comparison of 1991 and 1993 14" MASB Ammonia Conversion

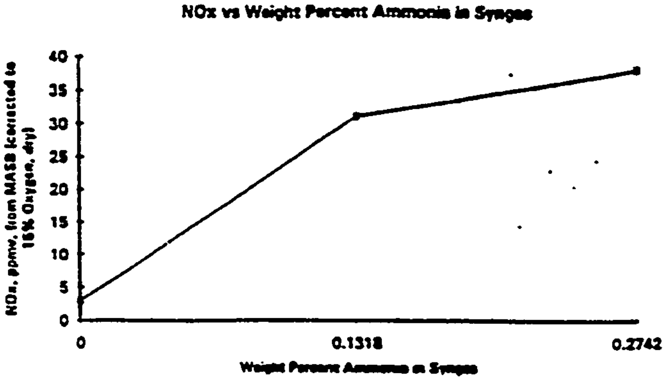


Figure 4. NOx vs Weight Percent Ammonia in Syngas

leakage) rich zone temperatures were between 3000°F and 3300°F. Thus, in spite of running at this off design condition, the bulk of the NH_3 conversions to NO_X were about 10 to 20 percent (Figure 3). Figure 3 shows that this was significantly better than previous test results at similar conditions. This was within our target range of expected results and thus demonstrated that our objective of demonstrating that our methodology for the redesign of the rich zone was acceptable and on the conservative side.

Carbon monoxide emissions were near zero at all points of the test with syngas firing. Even though the oil-fired direct heated preheater generated some carbonmonoxide, it was usually below detection limits of the gas analyzers at the MASB exit.

Modifications for 14" Test

A fuel blending station was added at UTSI, so that the cost of syngas (which had been bought premixed) could be lowered, the run time extended, and any desired composition of syngas could be produced by on-line adjustment. Prior computational fluid dynamics (CFD) and chemical kinetic computations had indicated that the previously utilized syngas entrance temperature of 800°F (425°C) at UTSI was not sufficiently high to rapidly initiate the desired reactions (Domeracki, 1993). Therefore, the syngas heater at UTSI was modified to provide 1200°F (650°C) syngas to the MASB.

Most of the results presented in this section represent percent conversion of ammonia to NO_X. However, Figure 4 shows three data points taken over a few minutes of time. All conditions were held constant except for the weight percent ammonia in the syngas. Two things should be noted from this plot:

First, with no ammonia in the syngas, very little NO_X was formed. The 3ppm plotted cannot be assumed to be an absolute value, since the preheater was generating approximately one order

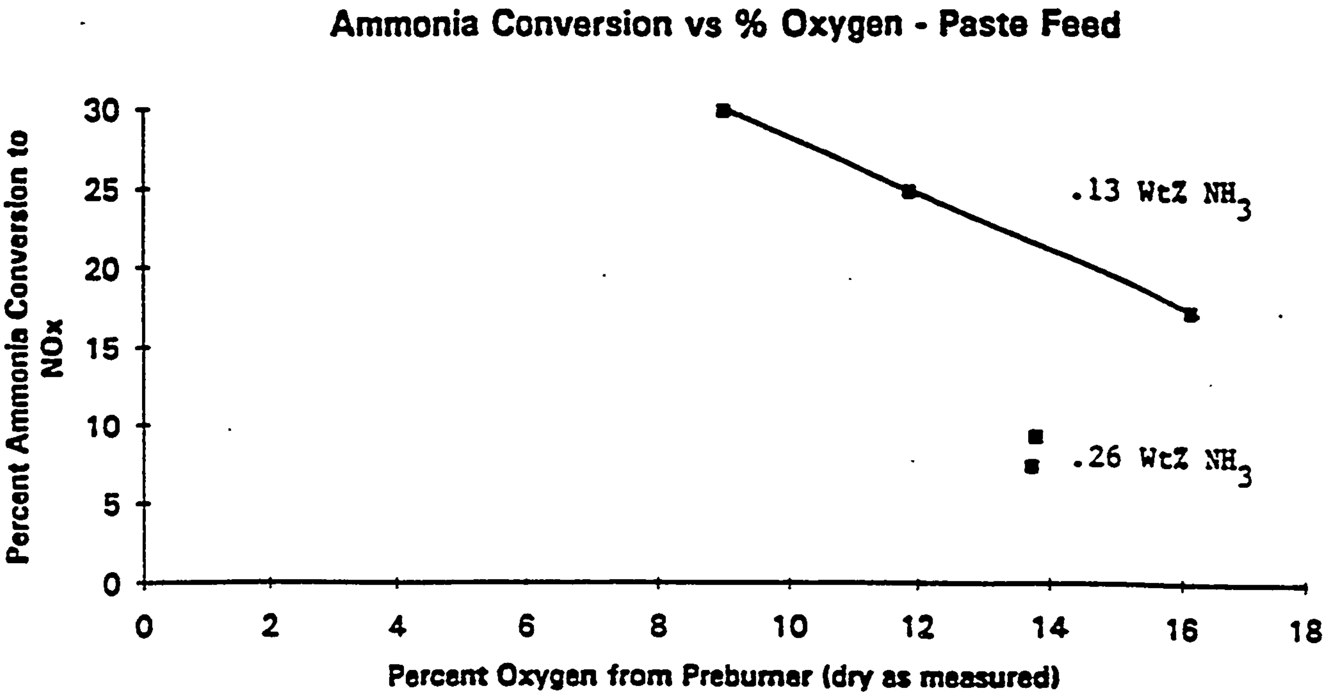


Figure 5. Ammonia Conversion vs % Oxygen - Paste Feed

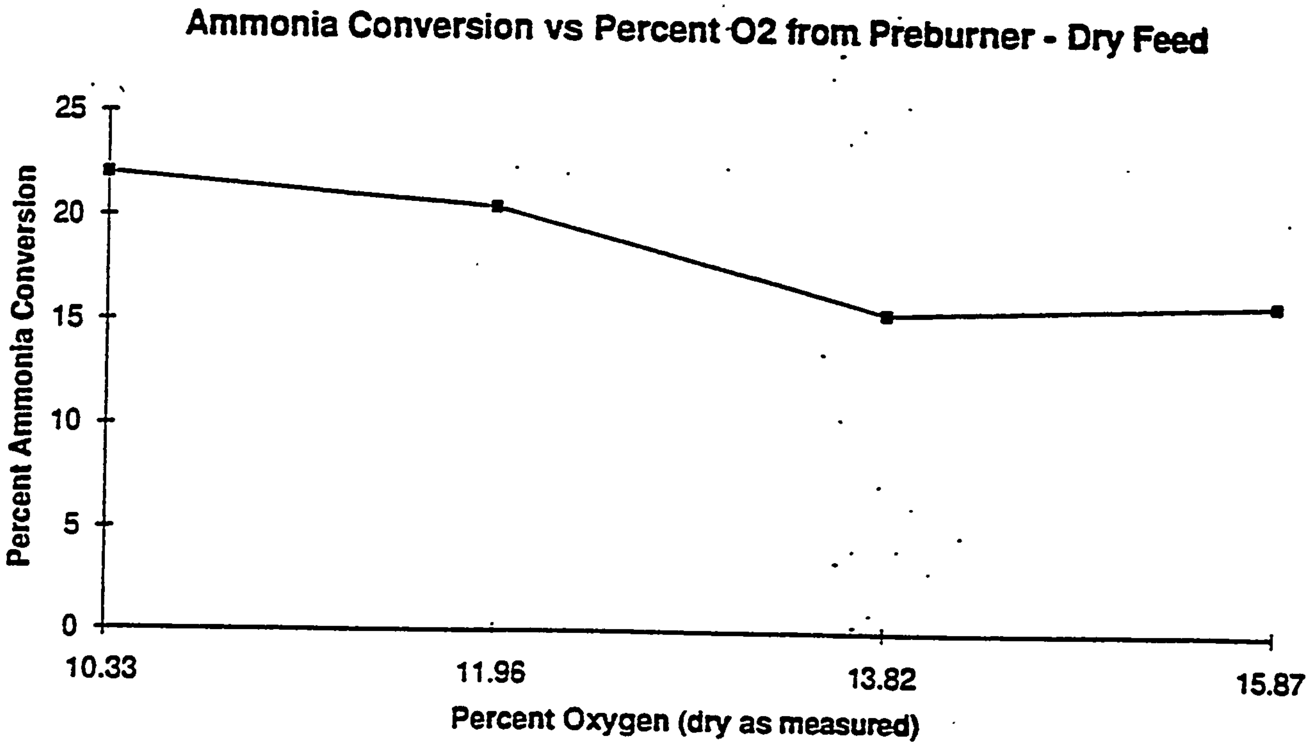


Figure 6. Ammonia Conversion vs % Oxygen - Dry Feed

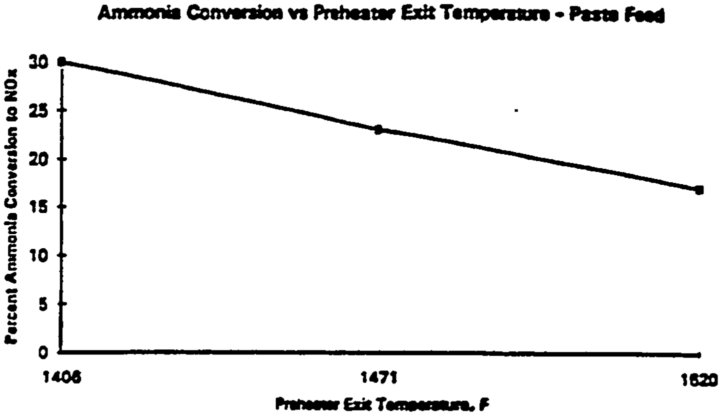


Figure 7. Ammonia Conversion vs Preheat Temperature - Dry Feed

of magnitude more NO_x, and this value is calculated by difference between two much larger numbers, (i.e. NO_x - NO_x in). Still, the combined thermal and prompt NO_x formed is extremely low.

Second, between 0.13 weight percent NH_3 and 0.27 weight percent, the slope is relatively flat. Thus the absolute NO_x emissions from the MASB is relatively insensitive to ammonia content, as our analysis predicts.

Figures 5 and 6 show that the percent ammonia conversion is an inverse function of oxygen content from the preburner. Figures 7 and 8 show that the percent ammonia conversion decreases with increasing preburner exit temperature. Both of these can be explained by the higher inlet oxygen or higher inlet vitiated air temperature which will initiate the NH_3 to N_2 conversion in a shorter period of time. With corrections made for higher than expected leakage of the oxidizer, corresponding with higher than expected rich zone temperature, the calculated flame temperature in the rich zone was higher than desired in most tests. However, even with the hotter than desired temperatures, the NH_3 conversion was equal to or below our design predictions. Thus we conclude that our design simulation technique is acceptable, though conservative.

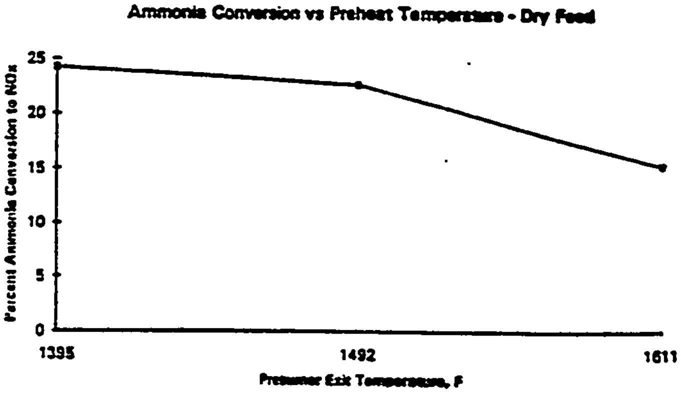


Figure 8. Ammonia Conversion vs Preheat Temperature - Dry Feed

Cold Flow Model Pattern Verification

A half scale cold flow model with similar Reynolds number and velocity profiles as the hot 18 inch MASB at full pressure was tested to verify the flow characteristics required and expected. Table 3 compares the hot 18 inch and the cold model MASBs.

Extensive mapping of the flow pattern in the MASB was performed using a two-dimensional flow probe (United Sensor model W-187), which measures yaw angle, static pressure, and dynamic pressure, giving the direction (in the tangential/axial plane) and magnitude of flow velocity as a function of axial and radial positions.

Figure 9 is a map of the resulting axial velocities. The results verified CFD modeling projections and the existence of desired flow patterns. The following significant features are apparent:

1. A strong donut-shaped recirculation region was confirmed in the wake of the bluff body end of the fuel swirler. This extends about one third of the way down the rich zone cylinder. The existence of this recirculation is essential for backmixing of free radicals to initiate combustion early so the whole rich zone residence time is available for the relatively slow conversion of NH_3 to N_2.
2. There is an absolute boundary (location C to C_2) between the rich and quench zones through which no reverse flow occurs, thereby guaranteeing the existence of fuel rich combustion.
3. Swirl was very strong (100 to 200 ft/sec tangential velocity), for good stabilization.
4. Axial velocities are also high near the wall for necessary effective wall cooling.

Design of the 18-Inch MASB

The 18-inch MASB (Figure 10) is intended to be a full-scale prototype of a single basket, incorporating all commercially required features. Therefore, the 18-inch MASB has been designed to accomplish the following four major technology advancements with respect to the 14 inch MASB.

1. Scale up from half-scale (in terms of mass flow) to full-scale.

   The 18-inch MASB is the same scale as planned for the Wilsonville Pilot Facility. Future applications to commercial combustion turbines would feature a multiple number of cans of this design. Table 4 shows the typical achieved conditions in the 14 inch MASB test, the planned operating conditions for the 18-inch MASB, and the conditions expected for the Wilsonville MASB.

   The rich zone diameter for the 14-inch MASB was 8.5 inches, whereas for the 18-inch MASB, this diameter is 14 inches. All fuel nozzle end dimensions are a direct geometric scale up.

2. Optimize combustor rich zone performance for better conversion of NH_3 to N_2.

   Although very good NO_x performance was achieved in the 14-inch testing, analysis indicates that better performance is possible. Table 5 shows the effects of rich zone equivalence ratio and residence time on NO_x generation in the MASB. The first line represents 14-inch achieved performance. These calculations were made using a Westinghouse combustion chemical kinetic data base with the Sandia Chemkin-II chemical kinetics modeling program.

   Table 5 shows that if the rich zone stoichiometry is too lean substantial NO_x is generated in the rich zone itself. If too rich, then NH_3 survives the rich zone to be converted to NO_x in the downstream lean regions. An optimum occurs in the 1.4 to 1.5 equivalence ratio range, as shown in Table 5. Also, performance is better with increased residence time.

   Consequently, an increase in residence time to 40 msec from 25 msec, by increasing length, and an increase in fuel equivalence ratio to 1.4 from 1.2 are goals of the 18-inch design and test plan.

18 Inch MASB Design Cold Model Results

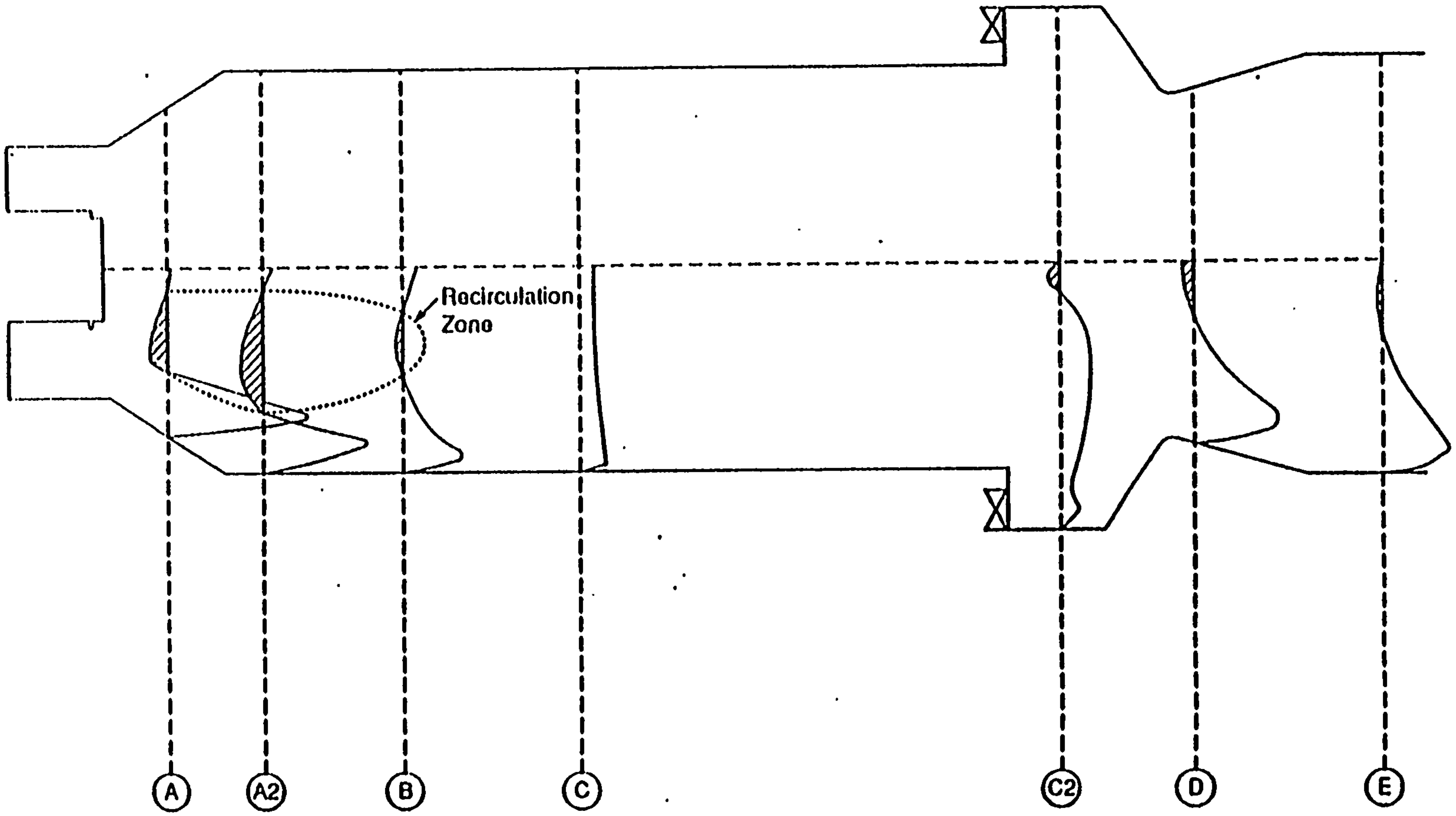


Figure 9. 18 Inch MASB Design Cold Model Results

Table 3. Similarity of Hot 18-Inch MASB and Cold Model

	18-Inch Hot MASB	Cold Model
Rich zone:		
Diameter, in.	14.5	7.0
Length, in.	27.9	13.5
Temperature, F	2900	70
Pressure, psia	160	16.2
Gas density, lbm/ft3	0.124	0.082
Gas velocity, ft/sec	55	52
Gas viscosity, lbm/ft-sec	0.00004	0.000012
Reynolds No.	206,000	206,000
Quench zone:		
Diameter, in.	12.0	5.8
Length, in.	6.9	3.6
Temperature, F	2850	70
Pressure, atm	160	16.2
Gas density, lbm/ft3	0.126	0.082
Gas velocity, ft/sec	120	114
Gas viscosity, lbm/ft-sec	0.00004	0.000012
Reynolds No.	380,000	380,000

3. Incorporate and demonstrate natural gas firing capability in both vitiated air and compressor air.

The design features the capability for natural gas firing via a central dual fuel burner as shown in Figure 10 and magnified in Figure 11. A modified Pabst burner is utilized for natural gas combustion. Design natural gas consumption rates are 0.2 lb/sec for vitiated air firing and 0.4 lb/sec for compressor air firing. When doing so, steam (1 lb per lb natural gas) is injected through the syngas swirlers, both to keep it purged and to moderate rich zone temperature. Since this is a rich/lean combustor, the steam is not needed for NO_X reduction. A specially designed axial ignitor rod is used. These technologies are now to be demonstrated.

4. Incorporate improved mechanical designs.

A number of hardware mechanical improvements have been incorporated.

- The convergent-divergent flow deflector in the quench zone (see Figure 2) is now directly cooled by the incoming dilution section vitiated air in contract to the uncooled 14 inch flow vitiated air, in contrast to the uncooled 14-inch deflector where some thermal distress occurred. Also, a thermal barrier coating is now applied to all internal surfaces.

18 Inch MASB Design

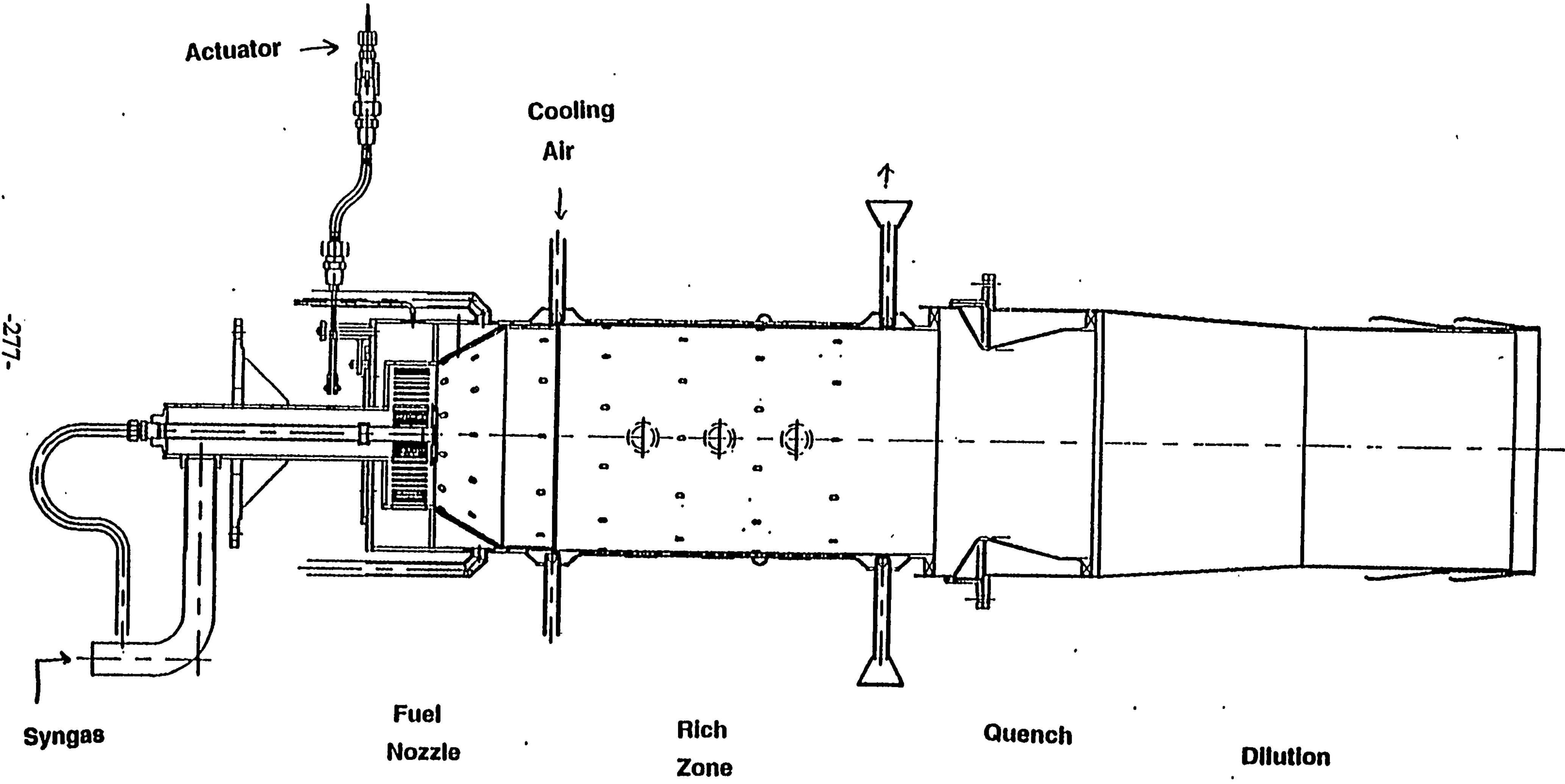


Figure 10. 18 Inch MASB Design

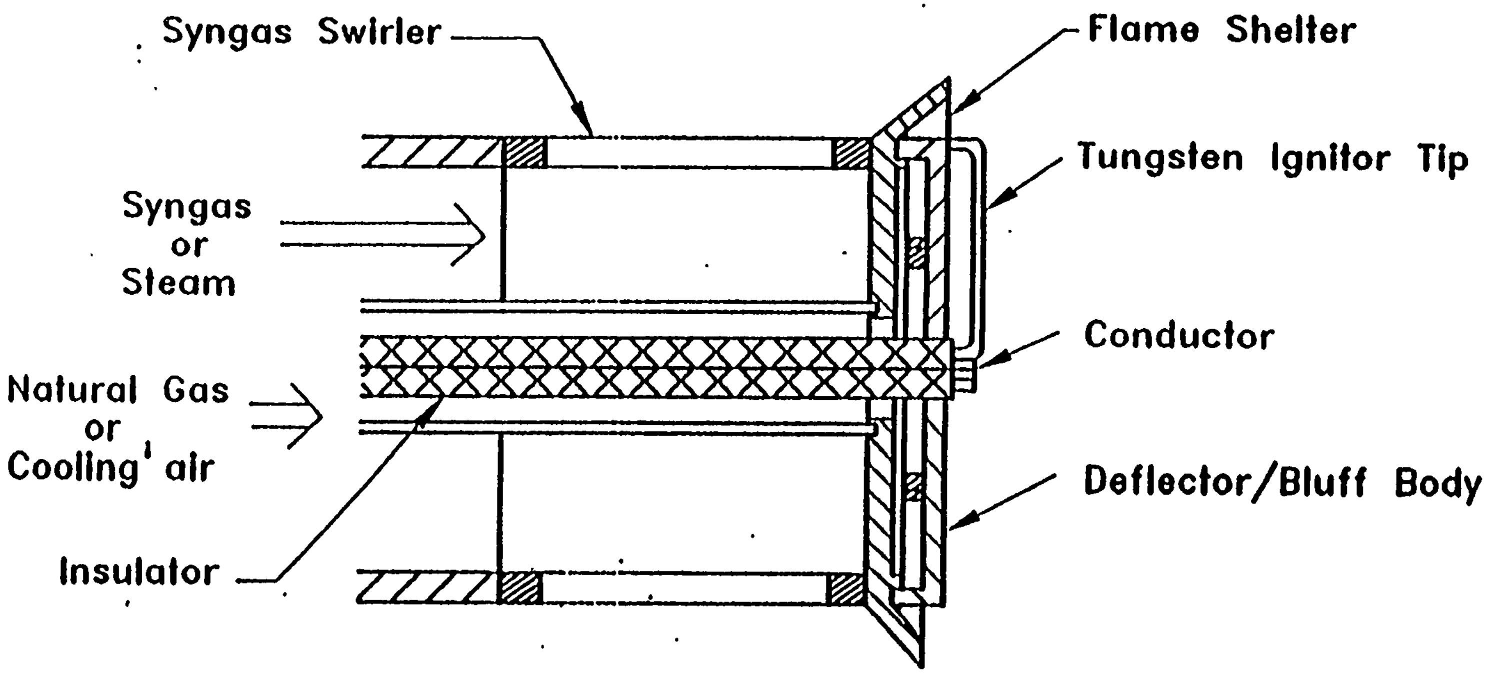

Syngas Swirler
Syngas
or
Steam
Natural Gas
or
Cooling' air
Insulator
Flame Shelter
Tungsten Ignitor Tip
Conductor
Deflector/Bluff Body

Figure 11.

Table 4. Scale up of the MASB

	UTSI 14"	UTSI 18"	Wilsonville 18"
Syngas			
Temperature, xF	1200	1200	1600
Vitiated air			
Temperature, xF	1600	1600	1470
Pressure, atm (abs)	10	7.3	10
Rich zone velocity, ft/sec	45	55	55
Rich zone res. time, msec	28	45	43
Pressure drop, psid	2.8	2.8	2.5
Temperatures, xF			
Rich zone	3100	2750	2800
Quench zone	2650	2850	2850
Exit	2250	2350	2100
Turbine inlet			1977
Flows, lb/sec			
Syngas	0.7	2.6	3.3
Primary vit. air	0.9	2.0	4.3
Quench vit. air	0.4	3.2	6.8
Dilution vit. air	2.2	6.4	9.0
Cooling air	0.9	0.8	5.0

Table 5. Theoretical Fuel NO_x Formation vs. Rich Zone Parameters

Case	Equivalence ratio	Res. time,	NH_3 from rich zone, ppmv	NO_x from rich zone, ppmv	Fuel NO_x from MASB, ppmv
1	1.2	25	15	150	36
1	1.2	45	14	132	32
2	1.5	25	61	17	18
2	1.5	45	33	14	12
3	1.7	25	317	12	57
3	1.7	45	199	12	38
4	2.0	25	725	10	109
4	2.0	45	514	10	78