ABSTRACT

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 these units operate a nominal 1600°F (870°C) for optimal sulfur capture. Since this temperature is well below the current combustion turbine combustor outlet operating temperature 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 high temperature gas cleanup equipment and the topping combustor. This paper concentrates on the design and test of the topping combustor. The topping combustor in this cycle must utilize a low heating value syngas 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 hot gas cleanup (HGCU) system. It also contains significant fuel bound nitrogen present as ammonia and other compounds. The fuel-bound nitrogen is significant because it will selectively convert to NOx if the fuel is burned under the highly oxidizing conditions of standard combustion turbine combustors.

The fuel must be burned with the vitiated air from the pressurized fluidized bed combustor (PFBC). Oxidizer has been cleaned of particulates and alkali by HGCU system, and has also been partially depleted in oxygen. The 1600°F (870°C) oxidizer must also be utilized to cool the combustor as much as possible, though a small amount of compressor discharge air at a lower temperature 700°F (about 370°C) may be used.

The application requirements indicate that a rich-quench-lean (RQL) combustor is necessary and the multi-annular swirl burner (MASB) was selected for further development. This paper provides an update on the development and testing of this MASB combustor. Additionally, Westinghouse has been conducting computational fluid dynamic (CFD) and chemical kinetic studies to assist in the design of the combustor and help optimize the operation of the combustor. Results of these models are presented and compared to the test results.

INTRODUCTION

This paper presents the design considerations, features and test results of a low emissions, low heating value gas-fueled topping combustor, that is being developed for application to the "Second Generation Pressurized Fluidized Bed (PFB) Combustion Systems R&D" under the sponsorship of the Department of Energy's Morgantown Energy Technology Center (DOE/METC). This test program is Phase 2 of a three-phase ongoing METC program. Phase I involved the conceptual and economic study (Robertson et al., 1988); Phase 2 addresses subscale testing of components; Phase 3 will cover pilot plant testing of components integrated into one combustion system.

Second generation pressurized fluidized bed (PFBC) combined cycles employ topping combustion to raise the turbine inlet temperature for enhanced cycle efficiency. The cycle has been described in detail in previous papers (Garland, et al., 1991). The concept creates special combustion system
requirements that are very different from requirements of conventional combustion turbine systems. The objective of this work is to develop a durable, efficient, exhibit stable combustion and manageable wall temperatures while providing low emissions. The combustor will burn a low-Btu syngas under normal "coal-fired" conditions. However, for start-up and/or carbonizer outage, it may be necessary to fire a high Btu fuel, i.e., oil or natural gas. Prior testing has shown that the Rich-Quench-Lean Multi-Annular Swirl Burner has excellent potential for meeting these requirements.

Metal wall temperatures can be maintained at reasonable levels, even though most "cooling" is done by 1600°F (870°C) vitiated air. Good pattern factors and combustion efficiencies have been obtained. However, the conversion of fuel bound nitrogen, to NOx simulated in the testing by the addition of NH₃ to the "syngas", was only been demonstrated to be 20% to 30% in pre-1993 tests. Even though this value is considerably better than more conventional burners, it is above that desired for this application. The major objective has been to design a MASB that will achieve lower conversions of the fuel bound nitrogen to NOx. A number of other tasks have been pursued in support of this primary task. These have included CFD and chemical kinetic studies in support of the design of an improved MASB. A modified 14"- (35.6 cm) combustor has been designed, fabricated, and tested. Test results are presented in this paper.

BACKGROUND INFORMATION

The Combustion Turbine

The use of a Circulating Pressurized Fluidized Bed Combustor (CPFBC) as the primary combustion system for a combustion turbine requires provisions for transporting compressor air to the CPFBC and vitiated air/fuel gas back to the turbine. In addition, the topping combustion system must be located in the returning vitiated airflow path. As a result, the conventional fuel system and turbine center section require major changes for the applications.

The currently favored configuration, which utilizes two topping combustor assemblies, one on each side of the unit, is shown in Figure 1. Half of the vitiated air from the CPFBC enters each of the internal plenum chambers in which the topping combustors are mounted. Fuel gas enters the assembly via the fuel nozzles at the head end of the combustor. Combustion occurs, and the products of combustion are ducted into the main shell for distribution to the first-stage turbine vanes.

Compressor discharge air leaves the main shell, flowing around the annular duct into adjacent combustion shells. The air flows around the vitiated air plenums and leaves each combustion assembly via nozzles and is ducted to the CPFBC and carbonizer. (See Figure 1.)

Because the air entering the combustor is at 1600°F (870°C) rather than the 700°F (370°C) usual for combustion turbines, the conventional type of combustor is not suitable. Both emissions and cooling concerns preclude the use of the conventional design. Therefore, a combustor that will meet the requirements of utilizing the higher temperature air for both wall cooling and combustion is required.

Combustor Design

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 is 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 NOx from syngas that contains fuel-bound nitrogen, have high combustion efficiency, produce an acceptable exhaust temperature pattern, exhibit good stability, and be able to light off at cold plant conditions. The Multi-Annular Swirl Burner, based on a design by Dr. J. M. Beér (Beér, 1989) was chosen to meet these requirements.

Test Facility

The topping combustor tests are being conducted at the University of Tennessee Space Institute (UTSI), Tullahoma, Tennessee in the DOE Coal, Oil, or Gas-Fired Flow Facility (CFFF). This facility was designed to accommodate a variety of coal-, oil-, or gas-fired energy conversion equipment.

UTSI modified the existing facility to accommodate the topping combustor and provided all necessary ancillary systems required to conduct the test and obtain data for evaluation. Modifications included the installation of the syngas fuel system with heater, which delivers fuel from tube trailers to the combustor at 1200°F (650°C), establishing required pressure, and perform fuel blending. The fuel gas is a six component mixture of N₂, H₂, CH₄, CO, H₂O and NH₃, that simulates the heating value and flammability limits of carbonizer gas.

Test Rig

The Westinghouse advanced combustor test rig was adapted for use at the UTSI test site. Figure 2 is a longitudinal view of the rig as configured for use in the topping combustor tests.

To simulate actual operating conditions, several modifications and auxiliary systems were required. These items provided: the supply of hot vitiated air; the supply of hot, synthesized fuel gas and/or natural gas and/or fuel oil; and, the ability to dope the fuel with ammonia when firing syngas. The ammonia allowed investigating the effects of fuel bound nitrogen on emissions.

The test facility at UTSI is capable of delivering 20 lb/s (9.1 kg/s) of air at 200 psia (1.4 MPa) and 120°F (50°C). To raise this air to the required 1600°F (870°C) temperature, a distillate oil-fired combustor, referred to as the preheater or the preburner, is placed upstream of the MASB. Directly heating the air through combustion partially depletes the oxygen in the air while adding carbon dioxide, water vapor and NOx. The vitiated air, still high in oxygen content, produced by the preheater simulates the PFB exhaust gases and makes the test conditions more realistic. The high oxygen content is
FIGURE 1. COMBUSTION TURBINE CONCEPTUAL DESIGN

FIGURE 2. TOPPING COMBUSTION AND TEST RIG CONFIGURATION
important as it relates to obtaining high plant efficiency.

Garland and Robertson, 1988.)

Note on Figure 2 that the MASP is held within a series of flanged containment cylinders. In this way, the entering 120°F (50°C) air comes forward to the preheater, where it burns the distillate oil, and is raised to 1600°F (870°C).

Instrumentation and Control

Approximately 200 temperature measurements, over 50 pressure measurements, and measurements relating to flow and emissions were taken during testing.

SUMMARY OF PRE-1993 MASP TESTS TO DATE

The MASP has the desired characteristics for a topping combustor for this application. Three syngas tests and one fuel oil/natural gas test were conducted in the 1990-1991 time frame with 12" (30.5 cm) and 14" (35.6 cm) diameter MASP's at UTSL. These tests have confirmed that the MASP can be successfully cooled with 1600°F (870°C) vitiated air (supplemented with a small amount (5 to 10% of total air flow) of additional cooling air at the hottest locations). The 12" (30.5 cm) combustor demonstrated that good temperature patterns could be obtained at 2100°F (1150°C) firing temperature, and the 14" (35.6 cm) test showed that a uniform 2350°F (1290°C) combustor outlet temperature could be obtained without overheating the materials of construction.

Emissions from the 12" (30.5 cm) and 14" (35.6 cm) MASP tests have shown low CO, and no soot or unburned hydrocarbons have been detected. In a "conventional" oil or natural gas fired combustion turbine combustor, Westinghouse would predict that 85% of the fuel-bound nitrogen would be selectively converted to NOx. The tests to date with the 12" (30.3 cm) and 14" (35.6 cm) MASP's have shown 20% to 30% conversion of the NH₃ added to the syngas to simulate fuel bound nitrogen to NOₓ. This is obviously a significant improvement over conventional combustors, but it is desired to improve further on the NH₃ conversion.

RECENT MASP DESIGN DEVELOPMENT

The MASP has been designed as a combustor specifically for low-Btu, coal-derived fuel gases containing significant fuel bound nitrogen, primarily in the form of NH₃. Other low-NOₓ combustors now being developed have a relatively simpler goal of minimization of thermal NOₓ generation. The MASP must also convert NH₃ to molecular nitrogen.

The MASP approach is to:

- employ a high-residence-time, fuel-rich zone at an optimized temperature such that NH₃ is converted to N₂ rather than to NOₓ.

- establish strong swirl and strong recirculation in the rich zone for flame stabilization, and to ensure that the entire rich zone is utilized for this purpose.

- achieve a rapid quench to fuel lean conditions to minimize the formation of thermal NOₓ after the rich zone.
Westinghouse together with UTSI have conducted significant computer modeling, both with computational fluid dynamic (CFD) codes and with chemical kinetics codes. Output from this analysis has been factored into the latest designs of the MASB, particularly with respect to the primary (fuel-rich) zone. CFD modeling of the redesigned configuration shown in Figure 3 shows that this new design will have significant recirculation in the primary zone, Figure 4. This has been strongly supported by cold flow visualizations taken in conjunction with calibration of the device to control primary to secondary air flow.

Westinghouse has performed chemical kinetic studies under conditions as close as possible to those planned for the next series of tests. Basically, the equivalent of 5 ms of backmixing followed by 40 ms of plug flow (as shown in Figure 5) could yield NOx levels below 20 ppm when corrected to 15% O2. The CFD model and the cold flow work indicate that significant recirculation (backmixing) should occur with the redesigned fuel-rich zone.

During the past year, significant MASB design improvements have been made with the objective of improving the flame pattern in the combustor, and thereby achieving improved low NOx performance. The effectiveness of these improvements is to be demonstrated in a two stage test program. In the first (reported below in this paper), 14" (35.6 cm) MASB test conducted in June 1993, the goal was to demonstrate that a redesigned fuel nozzle assembly (Figure 6) could achieve the rich zone environment control, the flame stability, and oxidant distribution control needed for this application.

In the next stage (planned for 1994), a full-scale 18" (45.7 cm) MASB will be tested. Lessons learned in the 14" (35.6) MASB tests will be incorporated into a full-scale 18" (45.7 cm) MASB. In addition, the 18" (45.7 cm) design will have a greater rich zone residence time for improvement of low-NOx performance, higher pressure drop downstream swirlers, and on-line oxidant flow control.

Control of the Rich Zone Environment

Kinetic studies, using the Chemkin kinetic code with a data base of 100 elementary reactions, have been used to develop the theoretical basis of the rich zone design. Figures 5 and 7 are resulting theoretical curves illustrating the principles, and provide ultimate performance targets.

Figure 5 shows that there is an optimum calculated temperature, about 2900°F (1590°C), for the case of a fuel containing 0.4 wt % NH3. At lower temperatures, NH3 survives the rich zone. At higher temperatures, NO is generated in the lean zone.

Figure 7 shows that increased residence time in the rich zone improves performance. The progression in rich zone residence from prior 14" (35.6 cm) MASB to the new, redesigned 14" (35.6 cm) MASB, to the designed 18" (45.7 cm) MASB is also shown.

Flame Stabilization

Also shown in Figure 7 is the effect of having a strong recirculation zone. Prior MASB embodiments have had insufficient recirculation, and operated close to the upper curve. The new MASB design is intended to achieve performance as close as practical to the lower, "strong
so Q C
Total NOx from combustor
- Syngas containing fuel-bound nitrogen
- Normalized to 0.5 ± 0.2, dry
- 2540 F combustor outlet temperature
- 5 ms exit = 35 ms plug flow

FIGURE 5. RICH ZONE KINETICS

recirculation" curve in this figure. Strong recirculation is
defined here as having a 5 ms equivalent residence time prior
to plug flow. This is believed to be an achievable goal.

Early mixing of fuel and oxidant are intended in the new
nozzle design, in which swirling high velocity slot jets of fuel
and oxidant meet. Figure 8 shows the geometry of this
injection design.

The flame is stabilized and recirculation kept intense by the
use of strong swirl. The swirl number, the ratio of angular
momentum to the product of axial momentum and exit radius,
is 0.9 (our target swirl number is between 0.6 and 1.0). In
addition, the use of a blunt body and a divergent cone section
provide recirculating wake regions.

CFD modeling using the KIVA-II (Amsden, et al., 1989)
shows that recirculation is being obtained with the new fuel-
rich MASB design. Figure 4 shows a plot of the axial velocity
contours. Note that the low velocity contour (indicated by the
letter "L" on the plots) is negative. This indicates that
recirculation is occurring.

Oxidant Distribution Control

Control of the rich zone temperature and stoichiometry
requires that the oxidant (vitiated air) be distributed properly
between the primary (rich) zone, and quench (lean) zone.

For the June 1993, 14" (35.6 cm) MASB tests, the quench
dilution swirlers were substantially obstructed (80 to 90%) to
increase pressure drop so that sufficient oxidant is forced to
enter the upstream end of the combustor. In addition, a
variable orifice assembly was designed into the fuel nozzle
assembly. This consists of two six-hole orifice plates, one of

FIGURE 6. NEW FUEL NOZZLE ASSEMBLY

which can be rotated to control the degree of overlap of the
orifices. For the 14" (35.6 cm) MASB test, this will be pre-set
between tests, according to calibration, as necessary to set the
fraction of oxidant entering the rich zone at the required level.

For the 18" (45.7 cm) test, an actuator is being designed to
allow on-line adjustment.

14" MASB TEST

Test Plan

The major test objective was to determine the fuel-bound
nitrogen (simulated by NH₃) conversion to NOx over a range
of conditions. Therefore, the test matrix included predicted
ammonia injection levels for the dry or paste feed at most
points. Only a few points without ammonia injection were run,
primarily to determine a baseline. Most data will be presented
in terms of NH₃ conversion to NOx. However, since there
may be an interest in the absolute NOx levels, Figure 9 shows
a plot of NOx in ppmv corrected to 15% oxygen. These levels
would be considered excellent for a coal fired plant. It must be
noted that the NOx generated in the preburner has been
deducted, along with other corrections for dilution. Thus any
NOx entering the MASB must be added to these values, i.e.,
the NOx exiting the PFBC in the second-generation PFBC
cycle. Although not shown on the plot, the 0.1318% NH₃
corresponds to a conversion rate of 17%, and the 0.2742%
point corresponds to a 9.3% conversion. This exceeds our goal
of 10% to 12% conversion at 0.27 wt% ammonia levels. Thus,
our goal of proving the redesign of the rich zone was
Old 14 - New 14 - 18 -

- Syngas containing fuel-bound nitrogen
- Normalized to 15% O2, dry
- 2350 F combustor outlet temperature
- 2900 F rich zone temperature

No recirculation

Strong recirculation

FIGURE 7. RICH ZONE NOX KINETICS

FIGURE 8. NEW NOZZLE INJECTION DESIGN
successful. Figure 10 shows a comparison of a previous test completed in 1991 vs. the most recent test in June of 1993 with the redesigned MASB.

The test plan is shown in Table 1 and addressed the following operational conditions:

- Main emphasis upon feed conditions - composition, 1600°F (870°C) air preheat, 0.13 weight percent ammonia in the syngas, 150 psia (1.0 MPa), and 16% (dry volumetric) oxygen entering the MASB. This corresponds as closely as possible to the latest predictions provided to Westinghouse by FWDC. Other test points represent variations from this base condition.
- Reduced MASB Vitiated Air Inlet Temperature to evaluate an off-design condition.
- Variable Oxygen Levels in the vitiated air to determine the effect on emissions and performance.
- Reduced Residence Time within the rich zone to evaluate performance (by varying pressure).
- Reduced pressure to see if we could detect a pressure effect upon NOx emissions.
- Remainder of fuel at Dry feed conditions, similar to the Paste feed tests except for closest syngas composition and 0.17 weight percent ammonia.

One of the items noted in preburner tests conducted in Fall 1992 was that leakage was occurring around the two sets of spring clips, located at the end of the preburner at the end of the MASB. The preburner spring clip was removed entirely and replaced by an expansion joint, thus eliminating this leakage entirely. The downstream spring clip could not be handled so simply, however, since access was not possible (due to assembly procedures), thermal expansion was several inches, and the temperature was too high for normal expansion joint materials. However, the downstream spring clip "seal" was significantly improved compared to previous tests. This was accomplished by changing the material specification (to a more flexible material), improving the curvature of the spring clip leaves, and adding nichrome foil between the spring clip leaves.

During initial testing on June 23, it was found that, although the leakage area was significantly reduced, the MASB pressure drop had been (intentionally) increased in order to improve flow control. Thus, even though the leakage area was substantially reduced, the leakage was still higher than expected. With syngas combustion, the leakage was about 30%. It should be noted that the leakage flow is not large, but in this particular test, the total oxidizing air flow was low, thus increasing the percentage of leakage.
### TABLE 1 - TEST PLAN

**TEST PLAN FOR 14" COMBUSTOR TEST - DRY AND PASTE FEED**

<table>
<thead>
<tr>
<th>Point</th>
<th>PB Exit Temp, °F</th>
<th>PB Inlet Pres, psia</th>
<th>Syngas Comp.</th>
<th>Syngas Flow</th>
<th>Wt % NH3 in Syngas</th>
<th>PB Exit O2, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1600</td>
<td>150</td>
<td>PASTE</td>
<td>0.9</td>
<td>0.13</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>1600</td>
<td>150</td>
<td>PASTE</td>
<td>0.9</td>
<td>0.13</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>150</td>
<td>PASTE</td>
<td>0.9</td>
<td>0.13</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>1400</td>
<td>150</td>
<td>PASTE</td>
<td>0.9</td>
<td>0.13</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>1600</td>
<td>120</td>
<td>PASTE</td>
<td>0.9</td>
<td>0.13</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>1600</td>
<td>150</td>
<td>DRY</td>
<td>0.74</td>
<td>0.17</td>
<td>16</td>
</tr>
<tr>
<td>7</td>
<td>1600</td>
<td>150</td>
<td>DRY</td>
<td>0.74</td>
<td>0.17</td>
<td>16</td>
</tr>
<tr>
<td>8</td>
<td>1600</td>
<td>150</td>
<td>DRY</td>
<td>0.74</td>
<td>0.17</td>
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<td>9</td>
<td>1500</td>
<td>150</td>
<td>DRY</td>
<td>0.74</td>
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<tr>
<td>10</td>
<td>1400</td>
<td>150</td>
<td>DRY</td>
<td>0.74</td>
<td>0.17</td>
<td>16</td>
</tr>
<tr>
<td>11</td>
<td>1600</td>
<td>120</td>
<td>DRY</td>
<td>0.74</td>
<td>0.17</td>
<td>16</td>
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<tr>
<td>12</td>
<td>1600</td>
<td>150</td>
<td>DRY</td>
<td>0.74</td>
<td>0.17</td>
<td>10</td>
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<tr>
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<td>150</td>
<td>DRY</td>
<td>0.74</td>
<td>0.00</td>
<td>16</td>
</tr>
</tbody>
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**FIGURE 11. AMMONIA CONVERSION VS. % OXYGEN - PASTE FEED**

![Graph showing ammonia conversion vs. percent oxygen from preburner](https://example.com/graph.jpg)
The test matrix that was followed for the test on June 24 is shown in Table 1, though a number of additional points mentioned in this report were also conducted on both the 23rd and 24th. Basically, since most interest was in ammonia conversion, we conducted most tests with ammonia flow. The base pressure was 150 psia (1.0 MPa), but one point with each gas composition was taken at a lower pressure to see if we could discern a pressure effect on NOx.

Figure 11 shows the effect of ammonia conversion versus percentage of oxygen in the vitiated air entering the MASB for paste feed, and Figure 12 shows the same for the predicted dry coal feed syngas composition. Both dry feed and the paste feed syngas conversion increases with decreased oxygen. Note, however, that the data point at 9.01% (Figure 11) is below the recommended range of operation and corresponded to a calculated rich zone equilibrium temperature of 2500°F (1370°C), well below the optimum temperature.

The main interest in this test was to confirm the predicted percent conversion of NH₃ to NOx. The new 14" (35.6 cm) nozzle was designed to improve recirculation and to operate within a temperature range of 2900°F (1590°C) ± 100°F (50°C). Prior to, and following the test a flow check was conducted of the MASB. This information was used to calculate the flow through the MASB in the previous plots. Most rich zone temperatures were between 3000°F (1650°C) and 3300°F (1820°C), with some as low as 2500°F (1370°C).

Adequate data was taken to account for leakage, but these calculations could not be done on line. In spite of this, the bulk of the NH₃ percent conversions to NOx were between the low teens to low twenties, compared to 20% to 30% conversion rates in previous tests.

Figure 13 shows ammonia conversion versus preheater exit temperature for the paste feed simulation, and Figure 14 shows the same for the dry feed simulation. Both plots show that ammonia conversion decreases with increased preheat temperature.

The highest conversion rate was 30%. This point corresponded to an unusually low NOx level out of the preburner. Since this NOx level enters the calculation when we "deduct" the entering NOx to calculate conversion, a high conversion results. The second highest point, 29%, occurred...
FIGURE 14. AMMONIA CONVERSION VS. PREHEAT TEMPERATURE - DRY FEED

FIGURE 15. PREDICTED AND ACTUAL PASTE FEED NOX LEVELS
with a 2500°F (1370°C) rich zone temperature, well below the optimum temperature. The best point (7%) occurred with the paste feed at twice the predicted ammonia level (.26% by weight in the syngas.)

Carbon monoxide emissions were near zero at all points of the test with syngas firing. Even though some carbon monoxide was produced in the preburner, it was usually below the limits of detection of the gas analyzers (less than 5 PPM) when exiting the MASB. Even when we tried to lower the preburner O₂ exit concentration to 9% and the preburner CO varied up to 5000 PPM, essentially no CO exited the MASB. This also indicates that combustion efficiency was essentially 100%.

The only identified material distress occurred on the downstream side of the quench flow deflector. This was located at a weld, and was a worsening of a condition noted prior to the test. This was a high thermal gradient area in an uncooled “non-commercial” designed test piece. Changes had already been made in the 18” (45.7 cm) MASB design to avoid this particular problem.

ACKNOWLEDGEMENTS

The topping combustor development work is being performed by Westinghouse through FWDC and DOE/METC. Mr. A. Robertson is the Project Manager at FWDC and Mr. Don Bonk is the Project Manager at DOE/METC. The design work for the combustor was performed in consultation with Dr. János Beér, Professor of Chemical Fuel Engineering at MIT.

REFERENCES


