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PULSED COMBUSTION PROCESS FOR BLACK LIQUOR GASIFICATION

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EXECUTIVE SUMMARY

This second annual report summarizes the work accomplished during the period November 1990 through February 1992 for DOE Cooperative Agreement No. DE-FC05-90CE40893. The overall project objective is to field test an energy-efficient, innovative black liquor recovery system at a significant industrial scale. This is intended to demonstrate the maturity of the technology in an industrial environment and serve as an example to the industry of the safer and more energy-efficient processing technique.

The project structure is comprised of three primary activities: process characterization testing, scale-up hardware development, and field testing. The objective of the process characterization testing was to resolve key technical issues regarding the black liquor recovery process that were identified during earlier laboratory verification tests. This was intended to provide a sound engineering data base for the design, construction and testing of a nominal 1.0 TPH integrated black liquor recovery gasifier.

The objective of the scale-up hardware development effort was to ensure that key hardware components, in particular the pulse heater module, would perform reliably and safely in the field.

Finally, the objective of the field test is to develop an industrial data base sufficient to demonstrate the capabilities and performance of the operating system with respect to thermal efficiency, product quality, fuel handling, system control, reliability and cost. These tests are to provide long-term and continuous operating data at a capacity unattainable in the bench-scale apparatus.

The design development and recommissioning of the bench-scale integrated gasification unit along with various process characterization tests conducted were reported in the first annual report. Some additional process characterization tests were performed to improve the overall process efficiency by utilizing the sensible heat of the product gas. Partial drying of the feed material utilizing the sensible heat of the product gas would improve the

overall process efficiency. Two options were tested in the bench-scale unit for pre-drying the feed material. The first option was to inject a portion of the feed black liquor into the freeboard of the gasifier reactor. Test results indicated that a fine atomization of the black liquor feed is required to achieve any considerable drying in the freeboard due to short residence times. Fine atomization of the black liquor requires an additional high pressure pump and also increases the entrainment of the solids from the freeboard. The second option was to compartmentalize or partition the fluid-bed reactor. In this configuration the fluid bed is divided into a cooler compartment and a hot compartment. The cooler compartment is used for drying the feed black liquor and the hot compartment for gasifying the dried black liquor. A test was performed in the bench-scale unit to verify the operability of this concept. The test results indicated that additional detailed design and analysis of the feed system and individual fluidization nozzles for each compartment would be required and could add substantially to the cost and complexity of the process.

The data base gathered during the extensive Phase I bench-scale testing provided significant information essential for the design and development of a scale-up field test unit. However, it was soon realized that a $\frac{1}{2}$ -scale prototype pulse tube heater unit should be developed and tested to ensure that this key hardware component would perform reliably during field service. A 5 MMBtu/hr pulsating tube heater module consisting of 61, 1 $\frac{1}{2}$ -inch diameter, partially shielded tubes arranged in a hexagonal staggered array and spaced on 3-inch centers was fabricated. The previous annual report [1] describes most of the development and testing of this unit. The operation of the prototype 5 MMBtu/hr tube heater over a range of firing rates with low flue gas emissions at low excess air levels was successful and provided confidence in the performance at the scaled-up level.

Testing of the prototype 5 MMBtu/hr heater resulted in incorporation of the following changes in the field test unit:

- Modified gas injectors
- Water jacketed combustion chamber and tube sheet
- Five airovalve configurations
- 72-tube heater bundle

The prototype 61-tube heater module and its performance were evaluated only at the laboratory-scale under simulated conditions during this period. It also became apparent that it was essential that at least one heater module be tested using real black liquor feed at conditions similar to those that would be required at New Bern. This would require numerous other components such as venturi and caustic scrubbers, an impact separator with heat exchanger, a cyclone, a flare, waste heat boilers, mufflers, etc. A cost and performance analysis indicated that a paper mill sludge could be used as a feed material to simulate black liquor without incurring the additional cost for the conversion of the process chemicals to green liquor. Three paper mills showed an interest in hosting the heater performance evaluation tests using their sludge waste. Of the three, namely, Smurfit Newsprint Corporation, Inland Container Corporation (ICC), and Simpson Paper Company, ICC was chosen to be the host site. A 1-ton per hour heater evaluation pilot unit was installed at ICC's recycle paper mill site in Ontario, California. One 72-tube heater bundle was to be used to gasify 1-ton per hour wet sludge with moisture content ranging from 50 to 80 percent. The California Energy Commission provided financial support (cost sharing) of \$500K for the pilot and tests and ICC provided a site and utilities as well as feed.

A 72-tube pulse heater bundle module consisting of a water-jacketed refractory-lined cylindrical combustion chamber was designed and fabricated. Several laboratory test runs were conducted to obtain and study the characteristics of the 72-tube heater module. The heater module was successfully operated over a wide range of firing rates (1.9 to 7.4 MMBtu/hr) with a maximum peak-to-peak pressure of 2.6 psi and a design operating frequency of 60 Hz. Due to relatively high noise levels during the operation of the 72-tube heater bundle, it was decided to design mufflers for the inlet and exhaust ports of the heater. A two-stage muffler was designed and fabricated for both inlet and exhaust plenum which resulted in a 15 to 20 dB noise level reduction at both the inlet and the exhaust plenums. The emissions from the 72 tube heater bundle were, as expected, very low with NO_x emissions between 27 and 40 ppm at 3% O_2 , CO, combustible emissions were undetectable.

After acquiring the required permits and insurance, the installation of the pilot unit for the heater assembly at Inland Container Corporation was initiated and completed in four months. The host company recycles corrugated boxes and currently has a non-hazardous sludge waste product consisting of cellulose paper fibers that are too small to be used in making newsprint. The mill disposes of 50 tons per day of this fibrous sludge waste in a nearby landfill at considerable expense to the mill. Because the MTCI process was also designed to process a wide spectrum of energy-bearing waste and biomass in an environmentally and economically sound manner, the pilot test provided much valuable information on the system behavior and characteristics. Additionally, the pilot unit would establish the industrial-scale operability of the MTCI pulse heater.

As of the preparation of this Annual Report, the pulse heaters have successfully completed all shakedown tests as well as a 500-hour continuous test completed during the month of July but not discussed in this report.

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SECTION 1.0

INTRODUCTION

This report summarizes the work accomplished for the development of a Pulsed Combustion Process for Black Liquor Gasification during the period from November 1990 through February 1992. Based on the extensive bench-scale experimental investigation reported in the previous annual report [1], design development and additional overall process tests were carried out for the field test unit to be tested at Weyerhaeuser's Kraft Pulp Mill in New Bern, North Carolina. Fabrication and procurement of the components for the New Bern system is still in progress.

In order to test the performance of the MTCI pulse combustion heater on a feedstock that could simulate black liquor, a pilot-scale facility was installed at the Inland Container Corporation's Recycle Paper Mill in Ontario, California. The pilot plant is currently in the testing stage and is expected to complete a 500-hour continuous test in July 1992. This report also summarizes the development, commissioning and initial testing of this pilot plant.

The Pulsed Combustion Process for Black Liquor Recovery comprises a pulse-enhanced, indirectly heated, fluidized bed reactor using the principle of steam gasification that effectively recovers the inorganic sodium process chemicals and energy from the black liquor that also contain organic matter (lignin) from the pulping process. The integrated system results in the production of a green liquor product stream that is recycled to the pulping process as well as a high-quality medium-Btu gas that is used to supplement and/or reduce purchased fuel requirements within the mill.

The MTCI indirectly heated gasifier technology is differentiated from existing combustion-based recovery methods by the avoidance of a sodium smelt formation that routinely results in fouling of heat exchange surfaces and corrosion of boiler components. The molten smelt also poses serious safety problems due to smelt-water explosions. Also, the gasification technology

converts organic matter to fuel gas, as opposed to combustion-based processes which generate steam as the sole energy product. This is advantageous since the fuel gas can be combusted in a gas turbine combined cycle system providing overall higher conversion efficiencies as compared to simple steam cycles.

Finally, the Pulsed Combustion Process for Black Liquor Gasification offers the singularly unique ability to separate sulfur from sodium regardless of the chemical nature of the starting liquor. This is significant since it offers an economic and efficient means of recovering process chemicals for a broad range of spent pulping streams (Kraft through sulfite liquors). A more detailed description of the integrated gasification process and its benefits can be found in [2].

In Section 2.0 of this report, key program objectives are highlighted. A detailed listing of project work tasks are found in Section 3.0. Section 4.0 provides a description of the additional tests performed on the bench-scale unit. Section 5.0 discusses the development and testing of a prototype 61-tube heater. Section 6.0 presents the development and testing of the 72-tube heater in the pilot plant operating on a paper mill sludge as for sludge gasification. Section 7.0 gives an overview of the status of the field test of the 72-tube heater, and Section 8.0 presents conclusions and recommendations for completing the project.

SECTION 2.0

PROJECT OBJECTIVES

The overall project objective is to develop an industrial data base sufficient to demonstrate the capabilities and performance of the operating system with respect to thermal efficiency, product quality, fuel handling, system control, reliability and cost. These tests are to provide long-term and continuous operating data at a capacity unattainable in the bench-scale apparatus and at a significant industrial scale. This is intended to demonstrate the maturity of the technology at a scale and in the industrial environment in which it is intended to perform.

The project structure is comprised of three primary activities: process characterization testing, scale-up hardware development, and field testing. The objective of the process characterization testing was to resolve key technical issues regarding the black liquor recovery process that were identified during prior feasibility tests conducted under several projects sponsored by the Weyerhaeuser Company as part of a California Energy Commission award and in part by the DOE, Battelle Pacific Northwest Laboratories. This was intended to provide a sound process data base for the design, construction and testing of a nominal 1.0-TPH system integrated, black liquor recovery gasifier.

The objective of the scale-up hardware development effort was to ensure that key hardware components, in particular the pulse heater module would perform reliably and safely in field tests.

Finally, the immediate objective of the field test is provide long-term and continuous operating data at a capacity and size unattainable in small units.

SECTION 3.0

WORK TASK DESCRIPTION

The following section summarizes the work task description for Phase I and Phase II activities under DOE Contract DE-FC05-90CE40893. Phase I tasks have focused on the collection of process design verification data from bench-scale test equipment, and the translation of this data to the engineering design of a nominal 1.0-TPH field test unit. Phase I tasks were completed and reported in the previous annual report [1].

Phase II tasks comprise a set of activities leading to operational testing of a nominal 1.0-TPH field test gasification system. These activities include key hardware and control development, detailed plant engineering, test plan preparation, equipment procurement, construction and installation, and finally shakedown and field testing. A portion of the Phase II hardware and control development testing has been completed at the time of this report. The results of these Phase II accomplishments are discussed in Section 7.0, "Development Testing."

A detailed description of Phase I and Phase II work tasks follows here.

3.1 PHASE I - PROCESS DESIGN VERIFICATION

3.1.1 TASK I.1: GASIFIER RECOMMISSIONING

The 8-inch process design verification gasification system, laboratory feasibility unit, will be recommissioned. The effort will include modification of the black liquor feed subsystem, fabrication and installation of a gasifier slip-stream scrubber facility, modification of the gas analysis sampling train, and gas chromatograph to extend the range of detectable gas components to include sulfur species and upgrading of the systems controls.

3.1.2 TASK I.2: PROCESS DESIGN VERIFICATION TESTS

The unit will be operated to collect critical design data that will be needed for scaling to the field-test unit.

A. SUBTASK I.2.1: GAS PHASE SULFUR DISTRIBUTION

Steady-state gasification test will be conducted to establish the identity and quantity of sulfur-containing constituents in the product gas stream. A specialized gas chromatograph capable of differentiating a broad spectrum of sulfur species will be employed to accomplish this work. Analysis will be made to quantify the sulfur species contained in the solid products from the gasifier. An overall sulfur elemental balance will then be calculated from both solid phase and gas phase analysis.

B. SUBTASK I.2.2: SCRUBBER VERIFICATION TESTS

A sample gas scrubber subsystem will be constructed and installed. The scrubber will be employed to verify the recovery of green liquor by absorption of H_2S from a product gas slip-stream. The scrubbing solution will consist of an aqueous sodium carbonate solution that simulates the solids dissolution product from the gasifier. The H_2S concentration at the exit of the scrubber will be analyzed to obtain estimates of achievable scrubbing efficiencies. In addition, the scrubbing solution will be analyzed for relevant sulfur compounds. This subtask will provide essential information regarding the basic chemistry of the scrubbing operation, and in particular, the nature of trace sulfur species that may be absorbed in the green liquor solution. In addition, solid samples from the gasifier will be dissolved in a tank and its properties will be characterized. This solution, being representative of the scrubbing solution to be used in the integrated field-test unit, will allow meaningful analysis of the process requirements for handling this stream. Particular attention will be given to the treatment and filtering of carbon from the solution.

C. SUBTASK I.2.3: COMBUSTION OF SIMULATED PRODUCT GAS

Commercial gasification systems may utilize part of the product gas as the pulse combustor fuel source. In contrast, prior laboratory tests have

employed natural gas fuels. Since the combustion properties of these fuels differ, tests are necessary to verify pulse combustor operation on fuel gases with chemical compositions and energy densities similar to that of the product gas.

D. SUBTASK 1.2.4: EVALUATION OF EFFECT OF RECYCLE GAS

Commercial gasification systems will utilize recycle gas to assist in bed fluidization and enhance system thermal efficiency by reducing the amount of steam to the minimum required by the gasification process. In contrast, prior laboratory tests have been conducted without recycle gas by using steam as the sole fluidization medium. The primary difference in these cases relates to the steam partial pressure within the gasifier that impacts the gasification rate and the product gas yield distribution. Thus, a set of tests will be specifically designed to evaluate the effect of steam partial pressure on the gasifier performance.

3.1.3 TASK I.3: DATA REDUCTION AND ANALYSIS

The data collected during Phase I testing will be reduced and summarized. This work will include development of correlations, graphs, plots, and design equations as necessary for scaling to the field test, complete recovery train unit.

3.1.4 TASK I.4: ENGINEERING DESIGN

At the conclusion of the experimental portion of Phase I, an engineering design will be prepared for the 1.0-1PH field test unit. The engineering design will be guided by this data obtained from the experimental program and will include the following preliminary engineering documents:

- Process Flow Diagram
- Heat and Material Balance
- Plot Plan
- Piping Diagram
- Process Equipment Drawings and Specifications

In addition, a budget estimate for the proposed field-test plant will be prepared.

3.2 PHASE II - FIELD UNIT DESIGN, CONSTRUCTION (SHAKEDOWN AND TEST)

3.2.1 TASK II.1: ESTABLISH PERFORMANCE AND CONTROLS DEVELOPMENT

Objectives for system design, performance and operation will be established. Performance and design objectives will be specified for each system and feed to be tested and will include:

- Air/fuel ratio,
- Fuel feed rate,
- Steam injection rates,
- Energy production rate (in millions of Btu/hr) to be achieved at a specific air/fuel ratio, fuel feed rate, and steam injection rate,
- Producer gas production rate and energy content (Btu per standard cubic foot),
- The concentration (ppm_v) and distribution of low to high molecular weight hydrocarbons in the producer gas,
- Producer gas particulate matter concentration and size distribution, and
- Char or ash production rate.

A single module heater bundle of the size that will be used in the field-test unit will be constructed, tested and evaluated. This shall consist of multiple resonance tubes of about sixty. The mechanical design criteria with respect to the differential thermal expansion of the tubes, relationship between tube packing pattern, fluidizing velocity and heat transfer from tubes to the bed, and pulse burner safety controls will be established.

An overall control scheme for the process will be established and a control system will be constructed and tested at the laboratory scale. In the single module heater test rig, sand of different size ranges shall be used for achieving different bed conditions; air shall be employed as fluidizing medium and water shall be used (in place of black liquor) for heat load. Hot operating conditions that are expected in the field-test units between 1100°F to 1200°F shall be established and controlled using the firing rate of the pulse combustor and the feed liquor (water) rate. The control protocol shall be established from these tests for the field-test unit.

3.2.2 TASK II.2: SYSTEM DESIGN

During Phase II, designs will be prepared for the 1.0-TPH black liquor recovery gasifier. The design will include mass and energy balances for the system. In addition, chemical kinetic calculations, subsystem performance sensitivity analysis, environmental impact analysis, safety analysis, and critical materials analysis will be conducted for the overall system and each of the following subsystems:

- System instrumentation and control,
- Fuel feed system,
- Air and stream injection systems,
- Pulse combustor,
- Ash and/or char handling system, and
- Air pollution control system.

3.2.3 TASK II.3: TEST PLAN

A test plan for system testing and evaluation will be evaluated. The plan will describe overall objectives of each major phase of testing, and for each of the subsystems. It will include performance testing over the full operational range of the system. The plan will include a description of each fuel to be tested, each test performed, a protocol for conducting the test, equipment necessary, and data to be obtained.

3.2.4 TASK II.4: FINAL DESIGN

Based on the work completed in Phase I and Phase II, a set of final designs will be developed including materials selection, for the combustor and other support subsystems. A set of working final designs of the system will be prepared that will include the following:

- Blueprints or detailed drawings of the overall system,
- Individual blueprints and materials specifications for each of the major subsystems, and
- Estimated bills of materials for all major subsystems.

3.2.5 TASK II.5: EQUIPMENT PROCUREMENT, CONSTRUCTION AND INSTALLATION

During Phase II, a modular 1.0-TPH integrated black liquor recovery plant will be constructed. The unit will be skid-mounted in transportable pallets for shipment to the mill test site. It will be interfaced in the mill as required. Documentation showing all required local, state, and federal permits, if any, will be obtained for the project.

The gasifier hot section with necessary cyclones and venturi scrubber shall be in one group of skids and the balance of plant consisting of scrubber equipment for sulfur gases shall be in another group of skids.

3.2.6 TASK II.6: SHAKEDOWN TESTING - 1.0-TPH BLACK LIQUOR RECOVERY UNITS

Shakedown testing of the gasifier will be performed in order to establish mechanical integrity and operational reliability of the gasifier on start-ups and shutdowns.

3.2.7 TASK II.7: MANAGEMENT AND REPORTING

This task is devoted to the program's technical direction, in order to maintain the program hardware oriented, and to support reporting functions required by the DOE Uniform Contract Reporting System. Reports will include monthly, quarterly, and annual reports as well as Management Plans and the annual update of such plans, including manpower and other resource

requirements. All projects in the program will be included in the reporting function in addition to the specific requirements of the DOE-sponsored projects.

3.2.8 TASK II.8: MOVE AND INSTALL GASIFIER IN PULP MILL SITE

The test unit will be transported to the host mill site and installed including interconnection of all required utility piping.

3.2.9 TASK II.9: FIELD TESTS

Gasification tests with black liquor will be performed in the 1.0-TPH unit. This effort includes the performance and documentation of all tests necessary to ensure that all components of the facility can and will be operated in a safe and responsible manner prior to achievement of full operational status. An operational test of 24 hours per day, 7 days a week for a mutually agreed upon term (not less than 1 week) will be required in this phase.

This effort includes a planned approach to fully assessing the performance capabilities of the system in accordance with the stated objectives, including (but not limited to) efficiency assessments, process chemistry analysis, system fuel handling, overall system operational flexibility, cost performance, system reliability, and all other information necessary to demonstrate the potential for commercial gasification of black liquor. The participants and DOE will negotiate a mutually agreeable operational schedule for this phase.

3.2.10 TASK II.10: REMOVE FIELD TEST UNIT AND RESTORE HOST SITE

At the successful conclusion of the field-test operation, the Participant shall remove the gasifier facility and restore the host site to as close to the original condition as possible to meet with the host mill manager's satisfaction.

SECTION 4.0

ADDITIONAL BENCH-SCALE TESTS

The design, development and recommissioning of the bench-scale integrated gasification unit along with the various tests conducted were reported in the previous annual report [1]. Additional characterization experiments were conducted with this unit in order to test some options such as freeboard black liquor drying and the partitioning of the gasifier bed. Figure 4-1 shows the integrated bench-scale test unit.

4.1 FREEBOARD DRYING TEST

In the prior Phase I gasification tests [1], it was realized that the raw product gas contained considerable amounts of sensible heat when exiting from the reactor at about 950°F (for a bed temperature of 1150°F). This sensible heat could be effectively utilized for drying and preheating the black liquor by freeboard spray injection (Figure 4-2).

A test was run on January 14, 1991, with a black liquor injector installed at the lower part of the gasifier and another injector installed at the top of the gasifier. A total of 139 pounds of Kraft black liquor from Longview was fed to the gasifier during the 6 hour duration of the test. The average feed rate was 22 lb/hr in which about 10 lb/hr was fed to the top injector and the balance of 12 lb/hr was fed to the injector normally used for all previous tests.

The average temperature of the gasifier bed and exit temperature are listed in Table 4-1 together with the same temperatures recorded in a comparable test. It can be seen that the top feeding did increase the difference between the exit temperature and bed temperature but the increment was not significant. Table 4-1 also shows the product gas analysis.

FIGURE 4-1: BENCH-SCALE TEST RIG

FIGURE 4-2: DRAWING OF THE GASIFIER REACTOR WITH
BLACK LIQUOR INJECTION IN FREEBOARD

TABLE 4-1:
COMPARISON OF GASIFIER TEMPERATURE AT
PARTIAL TOP FEEDING AND NORMAL FEEDING

	<u>PARTIAL (45%) TOP FEEDING (1/14/91)</u>	<u>NORMAL FEEDING (12/6/90)</u>
OPERATION DURATION (hours)	7.5	5.5
AVERAGE BED TEMPERATURE (°F)	1147	1155
PRODUCT GAS TEMPERATURE (°F)	925	941
DIFFERENCE BETWEEN BED TEMPERATURE AND EXIT TEMPERATURE	222	231
PRODUCT GAS ANALYSIS (Dry vol.%)		
H ₂	61.33	64.12
CO	2.29	2.39
CO ₂	30.83	29.26
CH ₄	1.92	1.61
C ₂ H ₄	0.14	0.13
C ₂ H ₆	0.22	0.18
C ₃ H ₆	0.10	0.07
C ₃ H ₈	0.00	0.00
C ₄	0.13	0.07
C ₅	0.01	0.01
H ₂ S	2.96	2.13
CH ₃ SH	<u>0.07</u>	<u>0.03</u>
TOTAL	<u>100.00</u>	<u>100.00</u>

4.2 COMPARTMENTALIZED DRYING TEST

As another alternative to making use of the sensible heat in the product gas was to dry the black liquor feed, it was decided to test a compartmentalized or partitioned fluid-bed reactor. The two-tube reactor was divided into two chambers by vertically inserting a stainless steel plate (Figure 4-3) coated with a 1/8-inch ceramic fiber for insulation. The compartment on the hot side of the tube was used as high-temperature fluid bed for gasification

FIGURE 4-3: COMPARTMENTALIZED DRYING - REACTOR

and the one on the return or cooler section of the U-tube was used as low-temperature fluid bed used for drying the feed.

A test was run on March 22, 1991, to verify the operability of this modified gasifier. When the black liquor feed was started at a bed temperature of 950°F, it was observed that while the cold side temperature remained at approximately 900-1000°F, the hot side temperature kept rising. The feed rate was increased to maintain a hot side bed at approximately 1200°F. The cold side bed temperature decreased to approximately 250°F. The hot side temperature again began increasing. The feed rate was reduced in order to increase the cold side temperature but this further increased the hot side temperature. The test was terminated when the bed temperature rose to 1500°F. The test history is shown in Figure 4-4.

After the reactor cooled down, an inspection of the bed revealed that most of the bed on both sides of the reactor had fused to form hard crusts on the surfaces and granular chunks inside. Even the insulating fiber seemed to have melted to form large chunks. The test clearly showed that the partitioned gasifier cannot be used for drying and gasifying, although it could be used for either one or the other of the above.

It was hypothesized that the partitioning with the heat-insulated plate resulted in a large temperature differential between the two sides. The cold side temperature was reduced significantly because of the evaporation of water in the black liquor feed, whereas the hot side bed did not have sufficient material to be gasified resulting in an increase in hot side temperature. Figure 4-5 shows the temperature profile at 12:00 before the combustor was turned off. At that time, the fluidization was good and no agglomeration seemed to be occurring from the gradually distributed temperature. However, the bed sample taken at this time did have several larger pieces showing that the bed grains started sticking together due to the slow drying process.

The added metal plate also reduced the space between the heater tubes. Some narrow spots between the heater tubes and the metal plate became sites for agglomeration. Once agglomeration started, the fluidization could not be

FIGURE 4-4: COMPARTMENTALIZED REACTOR GASIFICATION TEST HISTORY

FIGURE 4-5: COMPARTMENTALIZED REACTOR GASIFICATION
TEMPERATURE PROFILE AT 12:00

maintained properly and the temperature divergence grew larger. Figure 4-6 shows the temperature profile at 15:00 when operation of the reactor became very difficult to handle and led to the termination of the test.

The reduced reactor cross-section in the cold compartment reduced its ability to dry black liquor. It can be seen from Figure 4-4 at 12:00 that the feed rate was increased which resulted in a decrease of the bed temperature. Further increase in the feed rate caused even faster decline of the bed temperature. When the temperature was too low for rapidly drying the black liquor on the surface of the bed, the bed started to aggregate at the upper part where the temperature was high enough to dry the wet surface so that the bed particles began to agglomerate.

In general, the structure of the partitioned two-tube gasifier presented a dilemma: With a small feed rate, the cold side was able to dry the liquor and form a well-coated bed grain but was not able to supply sufficient bed carbon for gasification in the hot side. On the other hand, a higher feed rate might be able to transport enough carbon to the hot side but not be able to dry the liquor properly. To solve this problem, a two-stage gasifier was suggested and is illustrated in Figure 4-7. This structure may be operated properly but with increased complexity of solid lift mechanics.

FIGURE 4-6: COMPARTMENTALIZED REACTOR GASIFICATION
TEMPERATURE PROFILE AT 3:00

FN = GAS500-C

FIGURE 4-7: COMPARTMENTALIZED REACTOR - SUGGESTED CONFIGURATION

SECTION 5.0

DEVELOPMENT AND TESTING OF A PROTOTYPE 61-TUBE COMBUSTOR HEATER MODULE

5.1 DESIGN AND DEVELOPMENT

The data base gathered during the extensive bench-scale testing provided a significant amount of information for the design and development of the scaled-up field test unit. However, it was realized that a 1/2-scale prototype model of the pulse tube heater should be designed and tested in order to ensure that the key hardware component would perform reliably in service. A program was initiated to design, fabricate and test a heater module with a nominal firing rate of 5×10^6 Btu/hr and capable of processing 1/2 TPH of black liquor solids, which is half the capacity of the proposed field test unit. The previous annual report [1] described most of the developmental design and fabrication activities for this unit but will be briefly summarized here for continuity.

The prototype 5 MMBtu/hr pulsating tube heater module consisted of 61, 1½-inch diameter, partially shielded tubes arranged in a hexagonal staggered array and spaced on 3-inch centers. The tubes were supported on several vertical baffles and longitudinal tie rods. The tube bundle was fabricated by REPCO Engineering and is shown in Figure 5-1. The tube bundle forms the resonating member of the pulsating heater module, and is fully immersed in the fluid bed under operating conditions.

An exploded view of the pulse heater module is shown in Figure 5-2. The pulse heater module comprises four main elements: an air inlet plenum, pulse combustor, tube bundle, and flue gas exit plenum. Air is supplied to the air inlet plenum from a forced draft fan. The air is then aspirated into the pulse combustor through four separate aerovalves. Fuel is injected into the pulse combustor through a series of distributed nozzles surrounding the aerovalve. The combustion products then enter the tube bundle where the heat is transferred to the fluid bed. The cooled combustion gases are collected in a flue gas plenum and vented through a muffler to the stack.

FIGURE 5-1: FULL-SCALE PULSE HEATER MODULE

FIGURE 5-2: EXPLODED VIEW OF PULSE HEATER MODULE

A schematic of the interface between the pulse combustor and the tube sheet with the tube bundle is shown in Figure 5-3.

5.2 TESTING

A series of tests were conducted with the 61-tube prototype heater bundle. The experimental set-up is shown in Figures 5-4 and 5-5. The previous annual report [1] contained the results of a few preliminary tests conducted with this 61-tube set-up. This report discusses the follow-up tests with a different gas injector and other design improvements incorporated thereafter. A continuation of the developmental tests to collect data on the 61-tube heater bundle were conducted with the module operating over a range of firing conditions. A test summary is presented in Table 5-1.

As evident from Table 5-1, the nominal firing rate range (4.65 - 5.73 MMBtu/hr) about the rated 5 MMBtu/hr capacity of the heater was used to test the performance at the design capacity for relatively long test times. Each of the two tests were run for about 3 to 4 hours at the indicated firing rates. The air flow (excess air) was varied by adjusting a fan damper. The back pressure was created by an orifice plate placed in the flue stack to simulate the conditions under actual operation with a waste heat boiler and muffler following the flue gas exhaust from the tube bundle. As seen in Table 5-1, the back pressure varied between 7 and 8 inches of water column.

Although the actual design operating temperature of the gasifier for the field test will be approximately 1100°F, a maximum average bed temperature of approximately 850 to 900°F could be achieved in this prototype test unit over the duration of the operation. However, this temperature was sufficiently close to the actual operating temperature to provide combustion and heat transfer data that could be projected accurately to the design values.

The tube surface temperatures labeled 1 to 6 are at the locations shown in Figure 5-6. The results of the tests show a temperature difference of less than 250°F between the bed and the tubes. That was close to the values predicted by MTCI's simulation models. This temperature difference must be small enough to avoid any hot spots and subsequent bed agglomeration.

FIGURE 5-3: COMBUSTOR TUBE BUNDLE INTERFACE

FIGURE 5-4: EXPERIMENTAL SETUP

FIGURE 5-5: SCHEMATIC OF THE TEST SETUP

TABLE 5-1:

COMBUSTION PERFORMANCE OF THE 61-TUBE PULSE HEATER

TOTAL FIR	EXCESS AIR	AIR		STACK		AVERAGE COMBUS.		TUBE SKIN TEMPERATURE (°F)						TUBE		FLUE GAS ANALYSIS			
		PLENUM	BACK	PLENUM	BACK	BED	CHAMBER	TC#1	TC#2	TC#3	TC#4	TC#5	TC#6	SHEET	STACK	O2	COMB.	CO	NOx
MBtu/hr	(%)	(in WC)	(in WC)	TEMP.	TEMP.	(°F)	(°F)							TEMP (°F)	TEMP (°F)	(%)	(%)	(ppm)	3.3% O2 (ppm)
TEST #120790																			
4.8	10.53	13.0	8.0	870	2392	1000	1000	985	957	940	943	1160	1495	2.0	0.2	13	47.4		
4.8	11.11	13.0	8.0	865	2380	1027	997	1011	956	946	970	1180	1498	2.1	0.2	14	47.6		
4.8	11.70	13.0	7.5	862	2395	1020	885	977	960	930	933	1138	1495	2.2	0.2	22	43.1		
TEST #121290																			
4.65	11.70	13.0	7.0	870	2380	1055	980	1147	1077	885	1060	1282	1470	2.2	0.1	43	38.3		
4.65	12.90	13.0	7.0	855	2382	1050	960	1150	1093	985	1067	1287	1475	2.4	0.1	44	33.1		
4.65	15.38	13.0	7.0	864	2381	1050	975	1135	1062	888	1065	1282	1465	2.3	0	46	39.6		
5.26	8.25	13.0	7.5	892	2415	1085	993	1186	1145	1019	1067	1327	1535	1.6	0.1	-	46.4		
5.26	8.81	13.0	7.5	870	2405	1066	970	1195	1128	1000	1058	1321	1519	1.7	0.1	22	46.6

FIGURE 5-6: THERMOCOUPLE LOCATION (61-TUBE TEST UNIT)

Figure 5-7 shows the combustion performance of the heater module with respect to NO_x emissions (see also Table 5-1). The general trend of the NO_x emission data shows an increasing NO_x value with decreasing excess air. This is to be expected as the NO_x emissions reach a maximum at zero excess air because low excess air results in higher combustion temperature and hence higher thermal NO_x formation. The NO_x values obtained for this heater bundle are considerably lower than existing equivalent capacity combustion systems. The values are expected to be significantly lower when the combustor is fired with the hydrogen-rich product gas instead of the natural gas used for the tests. The values of the combustibles were observed to be significantly low (Table 5-1) at all firing rates and for the entire range of excess air. CO emissions were also observed to be quite low. This is a significant factor for the future sales of the equipment because of the motivation for most paper mills to reduce emissions from their process without expensive post-treatment.

5.3 SOME MAJOR DESIGN PARAMETERS/CHANGES OBTAINED OR INCORPORATED DURING THE PROTOTYPE TESTING

1. The modified gas injector (Figure 5-8) improved the firing rate range to $2.7 - 6.6 \times 10^6$ Btu/hr. This improved design would be incorporated into the field test combustor unit.
2. The combustion chamber and the tube sheet will be water jacketed since the prototype module tests resulted in the center of the heater getting hotter than the periphery of the module, causing the tubes in the center to elongate up to $\frac{1}{2}$ " more than the outer tubes. This deformed the tube sheet somewhat and caused some weld failure. The water-jacketed tube sheet will eliminate this problem.
3. In order to obtain a more uniform radial temperature distribution across the tube sheet and tube bundle as an alternative to water-cooled tube sheet a fifth aerovalve without an injector was installed at the center of the combustor flange. Two tests were run under similar conditions in order to determine the effect of this fifth

FIGURE 5-7: NO_x (@ 3% O_2) vs. EXCESS AIR

FIGURE 5-8: SCHEMATIC OF NEW GAS INJECTOR TIP DESIGN

aerovalve - one without the valve, another with the valve. The results are shown in Table 5-2. As can be seen from the table, the temperature difference between the center and periphery of the tube decreased from approximately 500°F to 100°F. The five-aerovalve configuration also resulted in reduced average tube wall temperatures. The five aerovalve configuration was used for the pilot-scale test combustor unit.

4. The computer simulation for energy and mass balance for the New Bern field test unit indicated the need for about 230 pulse tubes, each with a firing rate of 80 KBtu/hr. The 61-tube prototype had provided valuable information on the design and fabrication of the heater bundles. Based on these activities, it was decided to use three heater bundles, each with 72 tubes, instead of four 61-tube bundles, or one 221-tube bundle. For the given overall diameter, the hexagonal arrangement of pulse tubes within this diameter allowed for 61, 72, and 84 tube units. A 72-tube unit was preferred as it provided sufficient space for refractory and a cooling water jacket around the combustion chamber.

5.4 COMPARTMENTALIZED GASIFIER TESTING

In order to further investigate techniques for maximum utilization of the product gas sensible heat, a compartmentalized reactor configuration was investigated with the prototype 61-tube heat module as an extension of the earlier tests on the bench-scale unit. Theoretical analysis and computer simulations indicated that a considerable reduction in capital cost could be realized with the compartmentalized configuration. Modifications were made to the gasifier vessel, cyclones, combustion plenum, and the stack to experimentally verify the findings. Two different configurations were investigated.

TABLE 5-2:

COMPARISON OF 4 AND 5 AEROVALVE CASES

FIRING RATE (MMBtu/hr)	COMBUSTOR TC#3	TUBE SHEET TEMPERATURE (°F)					TUBE WALL TEMPERATURE (°F)				
		<u>RGTL</u> TC#4	<u>RGTL</u> TC#5	<u>LEFT</u> TC#6	<u>TOP</u> TC#7	<u>MID.</u> TC#8	TC#9	TC#10	TC#11	TC#12	TC#13
TEST: 5 AEROVALVES, 4 AV at 3" throat w/ gas injectors & 1 AV at center location w/2.5" throat w/ 0.15" injection											
4.52	1515	420	455	71	111	199	171	272	330	341	339
3.73	1702	457	553	80	453	635	505	564	573	586	595
4.28	1853	557	577	81	558	782	616	665	686	698	687
4.64	1953	685	797	85	685	827	722	775	798	806	785
5.19	2105	785	892	89	785	911	795	734	847	858	871
5.47	2228	844	967	94	846	999	850	884	901	923	948
7.10											
7.57											
5.44	2095	771	855	89	772	912	793	798	849	866	868
dT (Center-Outers) = 103						Avg. Tube Wall = 341					

TABLE 5-2:

COMPARISON OF 4 AND 5 AEROVALVE CASES
(CONT'D)

FIRING RATE (MMBtu/hr)	COMBUSTOR TC=3	TUBE SHEET TEMPERATURE (°F)					TUBE WALL TEMPERATURE (°F)				
		BOT. TC=4	RGT TC=5	LEFT TC=6	TOP TC=7	MID. TC=8	TC=9	TC=10	TC=11	TC=12	TC=13
TEST: 4 AEROVALVES (4 AV's - 3.25" throat w/ gas injectors)											
3.92	1027	327	448	76	334	372	481	452	468	483	479
4.65	1871	533	675	82	534	1137	713	659	689	703	667
5.19	2014	630	785	84	638	1229	816	733	787	795	777
5.55	2192	804	957	92	807	1397	956	874	923	937	906
6.11	2327	902	1047	97	904	1501	1039	953	973	995	1005
6.47	2367	954	1083	104	959	1540	1056	969	988	1001	1009
6.47	2380	966	1099	112	970	1561	1048	965	989	1004	1010
6.06	2411	977	1114	113	991	1575	1057	972	987	1004	1015
6.06	2425	975	1125	113	999	1571	1046	989	988	1004	1014
0.15											
0.15											
6.23	2382	955	1094	108	965	1550	1049	970	985	1002	1011
TC #6 bad: dT (Center-Outers) = 545						Avg. Tube Wall = 1029					

The first configuration consisted of a two-compartment reactor (see Figure 5-9). The compartment towards the leading edge of the pulse heater tubes would be used as a high-temperature, fluid-bed gasifier. The colder section would be used for feed drying and preheating in a low temperature fluid bed.

A shakedown test was run for this configuration. The test results showed that the design did not perform as expected. The major problem evolved from the mixing of the two bed materials over the partition and bed fluidization. Since the two beds were maintained at two different temperatures, they needed different fluidizing velocity. It was realized that separate fluidization controls are needed which now tends to increase the complexity and cost.

To further investigate the idea, another configuration was tested which included three compartments in the gasifier (Figure 5 10). The two end sections were to be used as low-temperature beds for drying and preheating and the middle one as a high-temperature bed for gasification. A distributed nozzle system was employed to control the fluidization rates of the individual beds. The shakedown tests with this modified gasifier further revealed the implications of such a scheme. Once again, the problem was maintenance of the bed temperatures, especially on the cooler sides. The tests showed that accurate water flow rates need to be maintained on each of the cold sides of the bed.

It is believed that this concept will require a substantial product improvement effort and it will therefore not be included in the New Bern unit.

FIGURE 5-9: TWO COMPARTMENT REACTOR VESSEL:
TEST SETUP

FIGURE 5-10:
THREE COMPARTMENT REACTOR
VESSEL: TEST SETUP

SECTION 6.0

72-TUBE PULSE HEATER DESIGN

Based on the information gathered from the design, development, fabrication and testing of the prototype 61-tube heater bundle as discussed in the previous section, it was decided to manufacture the field test unit heater bundles in a modular form with each module consisting of 72 pulse tubes. A field test heater bundle unit was designed that included a water-jacketed, refractory-lined combustion chamber, water-cooled tube sheets and five aerovalves, each equipped with a gas injector.

6.1 DEVELOPMENT BACKGROUND

An extensive data base from both bench and prototype scales was now available for the pulse combustion heater design. Although the prototype 61-tube heater module was sufficiently close to the 72-tube module to be used in the field test unit, the heater performance was evaluated only at the laboratory-scale under simulated conditions. Moreover, the test was performed only for the heater module immersed in a sand bed but without any feed material to be gasified and resulted in an operating temperature of about 850°F.

The field test unit is intended to operate with black liquor at approximately 1150°F. The system would therefore require numerous other components such as venturi and caustic scrubbers, an impact separator with heat exchanger, a cyclone, a flare, waste heat boilers, mufflers, etc. Moreover, the field unit would require three to four heater modules. In order to determine the reliability of the heater module under conditions simulating more closely the actual operating conditions at New Bern, it was essential that at least one full-size module be field tested under actual high-temperature gasification conditions. In concert with DOE and Weyerhaeuser, it was determined that a paper mill sludge waste would provide a much closer simulation for black liquor processing than the water and sand beds previously used for prototype testing. It was decided to test the module somewhere in the vicinity of the MTCI California facility. Three paper mills were

interested in hosting the gasification pilot plant. Of the three, namely, Smurfit Newsprint Corporation, Inland Container Corporation (ICC), and Simpson Paper Company, ICC agreed to be the host site. A 1-ton per hour gasification pilot was installed at ICC's recycle paper mill site in Ontario, California. One 72-tube heater bundle would be used to gasify 1-ton per hour of wet sludge with a moisture content ranging from 50 to 80 percent.

The gasification of waste sludge differs only slightly from that of black liquor. Sludge gasification is performed at a higher temperature (1300-1500°F) than black liquor (1100-1150°F) a plus for determining reliability. The fluidized bed for black liquor is comprised of Na_2CO_3 . Sludge gasification, on the other hand, is carried out with limestone or sand as the bed material. The low melting temperature of Na_2CO_3 makes it necessary to avoid high-temperatures at the surface of the pulse tubes to prevent smelt formation and subsequent bed agglomeration. Hence, the tube design for black liquor gasification consists of a radiation shield (Figure 6-1) for a portion of the tube length in order to avoid those hot spots. The sludge gasification tube bundle does not require this radiation shield (Figure 6-2) and hence is more convenient to manufacture. It was also possible that good temperature control of the bed and tubes would permit eliminating the radiation shields. It should be noted that the overall performance of the unit will differ only slightly from the earlier prototype, primarily with respect to heat transfer. Therefore, the performance of the new heater bundle for sludge gasification will be well representative of its performance under black liquor gasification conditions. Moreover, the 61-tube prototype heater bundle contained radiation shields, the performance characteristics of which have already been established.

6.2 72-TUBE PULSE HEATER BUNDLE MODULE

The 72-tube pulse heater bundle module (Figures 6-3) consists of a water-jacketed refractory-lined cylindrical combustion chamber. The inner surfaces of the chamber are lined with 2-inch refractory on the cylindrical surface and 3-¼ inch on the flat surface adjacent to the tube sheets. The refractory is temperature cured in a curing oven for over 117 hours and up to 1800°F. The outer cylindrical surface of the chamber and the space between the tube sheets

FIGURE 6-1: HEATER MODULE FOR BLACK LIQUOR GASIFIER
(WITH RADIATION SHIELD)

FIGURE 6-2: HEATER MODULE WITHOUT RADIATION SHIELD

FIGURE 6-3: 72-TUBE HEATER BUNDLE ASSEMBLY

is water-cooled as shown in Figure 6-3. The combustion chamber is flanked on the front side by a gas manifold chamber (Figure 6-4). The manifold chamber consists of five 3.68-inch diameter, 8-inch long aerovalves, each provided with a gas injector with $\frac{1}{4}$ -inch diameter orifice inserted into the base of the chamber which is also refractory-lined on the outer surface. The chamber is provided with an ignition pilot for prefiring and preheating of the combustion chamber. Air is provided by a forced draft fan through a muffled air plenum as shown in Figure 5-2.

The pulse tubes are connected to the tube sheet in a hexagonal arrangement with no pulse tube at the center (Figure 6-5). This design modification was made based on the test with the 61-tube module in which bowing of the tube sheet was postulated to be a result of the center tube operating at a higher temperature than the surrounding tubes. The tailpipes of the pulse tubes are connected to another tube sheet followed by an exhaust plenum.

6.3 LABORATORY TESTING OF THE HEATER MODULE

A series of initial tests was conducted to study the combustion, pulsation and acoustic characteristics of the heater module. There were a number of modifications incorporated during the bundle definition tests at the laboratory and are mentioned here along with the test description.

The tests were conducted by inserting the heater bundle into a pressure test vessel (Figure 6-6). The test vessel is also used for leak testing the tube bundle. The test setup is shown in Figure 6-7. The setup consists of a forced draft fan, air plenum, combustion chamber, heater bundle immersed in water inside a pressure vessel, exhaust plenum, waste heat boiler, muffler and stack. The hot combustion flue gases enter the pulse tubes and heat the water inside the vessel. The water-steam mixture generated is collected in a drum before venting the steam to the atmosphere. The cooled flue gases enter the waste heat boiler through the exhaust plenum where the generated steam is vented to the atmosphere. The flue gases then enter the muffler where the pulsations are further muffled, resulting in further cooling of the gas. The cooled gases are then vented to the atmosphere.

FIGURE 6-4: 72-TUBE HEATER: WATER JACKETED AND REFRACTORY-LINED COMBUSTION CHAMBER AND TUBE SHEET

FIGURE 6-5: HEXAGONAL ARRANGEMENT OF TUBE BUNDLES

FIGURE 6-6: PULSE HEATER AND PRESSURE TEST VESSEL

FIGURE 6-7: SCHEMATIC OF LABORATORY TEST SETUP

The initial test setup did not have a waste heat boiler or a muffler, resulting in loud pulsations. The introduction of the waste heat boiler together with a final muffler design eliminated these acoustic vibrations almost completely as shown by later test results. The description of the waste heat boiler and the muffler are described in the next section.

6.4 TEST RESULTS

Several laboratory test runs were conducted over a period of 3 months to obtain and study the characteristics of the 72-tube heater module. Tables 6-1 through 6-6 show the consolidated results from these tests.

The first shakedown test was run on August 30, 1991 for firing rates ranging from 1.9 to 7.4 million Btu/hr. The peak-to-peak combustion pulsation pressure was observed to be approximately 2.6 psi at approximately 60 Hz frequency. A hand-held decibel meter showed a very high A-weighted sound pressure level of approximately 120 dB (at 3.7×10^6 Btu/hr firing rate) near the exhaust stack. The noise level was higher for higher firing rates. The information is summarized in Table 6-1.

As can be seen from the table, the combustion chamber temperature was well below the calculated adiabatic temperature partly because of the fact that in pulse combustion the gases are only partially combusted and the combustion continues in the tubes. The other reason is the location of the thermocouple in the combustion chamber. It could only be located a few inches away from the refractory and hence could not provide accurate temperature. A sheath thermocouple was used in the next test and a better temperature reading was obtained, as shown in Table 6-2. This test also utilized a stack muffler and the noise level dropped down to about 117 dB at 3.7×10^6 Btu/hr firing rate. An improved muffler design would reduce this even further.

An industry survey revealed that a muffler meeting on our noise reduction requirements was not commercially available due to the temperature and low frequency pressure oscillations of the pulse combustion system. A rigorous design effort was undertaken to design and fabricate one in-house. To reduce the cost of muffler fabrication, a used waste heat boiler (rated 4 MMBtu/hr at

TABLE 6-1: DATA AND RESULTS FOR 8/30/91 TEST RUN

FIRING VALVE POSITION	COMBUSTION CHAMBER TEMPERATURE °F	ADIABATIC FLAME TEMPERATURE °F	PERCENT EXCESS AIR	EXHAUST PIPE TEMPERATURE °F	COMBUSTION CHAMBER DYNAMIC PRESSURE PEAK TO- PEAK PSI	OPERATING FREQUENCY Hz	WATER FLOW METERS		TELEDINE MAX BLUE STACK READINGS		
							WATER JACKET GPM	TEST VESSEL GPM	01 %	001 %	10 %OFF
4.00	1848.00	2010.00	100.05	468.00	0.59	67.00	4.00	8.00	11.00	5.0	330.00
5.00	1560.00	2410.45	73.82	498.00	0.59	67.00	4.00	8.00	9.90	6.0	OFF
6.45	1609.00	2632.74	60.86	520.00	0.59	67.00	4.00	8.00	9.50	6.8	OFF
7.40	1616.00	3010.03	34.97	548.00	0.59	67.00	4.00	8.00	8.90	8.0	OFF

[illegible]

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*WJS = WATER JACKET SECTION
*COOP = COMBUSTION CHAMBER DYNAMIC PRESSURE

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TABLE 6-3: DATA AND RESULTS FOR 12/4/91 TEST RUN

ENGINE DATE TIME	FUELS EXHAUST PLENUM	COMPOSITION Wt-% Wt-% Wt-%	AIR FLOW METERS		TELEPHONE		ACOUSTICS		NOISE	
			TEST VELOCITY (cm)	WATER FLOW (cm)	WAVE LENGTH (cm)	WAVE LENGTH (cm)	CO2 (%)	CO2 (%)	EXHAUST STICK (dB)	EXHAUST PLENUM (dB)
1.98E-06	549	1.767	1.1	5.0	12.5	280.0	1.2	6.2	30	30
	549	1.767	1.1	5.0	12.5	280.0	1.2	6.2	30	30
	549	1.767	1.1	5.0	12.5	280.0	1.2	6.2	30	30
3.71E-06	556	1.926	1.0	5.0	9.3	1000-	0.5	5.5	30	34
	556	1.926	1.0	5.0	9.3	1000-	0.5	5.5	30	34
	556	1.926	1.0	5.0	9.3	1000-	0.5	5.5	30	34
	556	1.926	1.0	5.0	9.3	1000-	0.5	5.5	30	34
5.52E-06	567	2.171	1.0	5.0	13	550	0.2	4.3	39	33
	567	2.171	1.0	5.0	10.7	799	0.4	5.5	37	35
	581	2.174	1.0	5.0	10.3	7.7	0.4	5.5	37	35
7.57E-06	564	2.248	1.0	5.0	5.4	1000+	0.8	8.4	38	38
	561	2.335	1.0	5.0	7.5	1000+	0.4	7.3	101	97
9.91E-06	558	2.108	1.0	5.0	0.5	34	6.4	10.2	39	35
	595	2.259	1.0	5.0	3	20	1.5	9.5	105	35
	700	2.517	1.0	5.0	5.2	14	0.5	8.5	101	98
	597	2.336	1.0	5.0	5.3	3	0.5	8.5	102	101

*PC = PULSE COMBUSTOR

TABLE 6-4: DATA AND RESULTS FOR 12/5/91 TEST RUN

FIRING RATE MMbtu/hr	STATIC PRESSURES			TEMPERATURES (°F)				WATER FLOW GPM		CCOP** PEAK		TELEDYNE MAX. PRESS. (PSI)			PERFORMANCE		NOTES
	AIR PLENUM (IN. HG)	COM. BUSTOR (IN. HG)	EX. HAUST PLENUM (IN. HG)	FLUE 3 PC EXHAUST PLENUM	COMBUSTION CHAMBER REFRACTORY	FLUE 3 WASTE HEAT BOILER EXHAUST	COMBUSTION CHAMBER THERMOWELL	TEST VESSEL (GPM)	WATER JACKET (GPM)	TO PEAK (SEC)	OPER. PRESS. (PSI)	O2 (%)	CO (%)	COMB (%)	CO2 (%)		
1.88	7	4	3	443	857	303	1570	11.0	4.0	2.09	52.6	12.4	4.9	0.0	4.6	1.1	
1.88	9	6	4	451	838	338	1409	-----	---	2.09	52.6	14.7	8.6	0.4	0.4	9.8	
3.71	9	7	3	531	862	344	2050	11.0	4.0	2.09	52.6	9.6	1000-	0.1	6.1	1.8	
3.73	19	13	7	524	844	316	1746	20.0	4.0	2.09	52.6	14.1	9.8	0.1	6.7	1.8	
3.73	20	16	9	518	856	319	1544	20.0	4.0	2.06	53.6	14.1	9.8	0.4	6.7	1.8	
5.59	10.5	8.6	4	606	796	349	2087	20.0	4.0	2.06	57.1	4.5	500	0.6	6.7	1.4	
5.62	17	14	5.5	590	815	355	2240	-----	---	2.79	57.1	8.7	124	0.6	6.9	1.6	
5.63	22	16.6	7.5	573	838	355	2194	20.0	5.0	4.18	57.1	10.6	107	0.4	6.3	1.6	
7.52	10	9.2	2.5	619	833	345	2056	20.0	5.0	2.61	-----	1.2	43	0.1	6.9	1.1	
7.57	19	14	5	558	852	357	2214	-----	---	3.48	-----	4.9	1.8	1.0	6.6	1.4	
7.61	22	17.5	7.5	578	804	878	267	20.0	8.0	4.18	-----	6.9	1.6	0.6	7.6	1.4	
8.91	15	12	4	555	849	347	2113	20.0	8.0	2.96	-----	1.3	1.9	6.8	10.1	1.6	
9.01	18	15.5	6.5	573	847	351	2213	-----	---	4.18	-----	5.6	3	0.1	6.7	1.8	
9.04	23	19	8	565	865	363	2316	-----	---	4.53	-----	4.5	3	1.1	6.8	1.6	

*PC = PULSE COMBUSTOR

**CCOP = COMBUSTION CHAMBER DYNAMIC PRESSURE

TABLE 6-5:
COMPARISON OF NOISE LEVELS
WITH TWO DIFFERENT AEROVALVES

AEROVALVE THROAT DIAMETER = 3.68" (December 4, 1991)				AEROVALVE THROAT DIAMETER = 3.25" (December 4, 1991)			
<u>FIRING RATE (MMBtu/hr)</u>	<u>% O₂</u>	<u>EXHAUST PLENUM (dB)</u>	<u>AIR PLENUM (dB)</u>	<u>FIRING RATE (MMBtu/hr)</u>	<u>% O₂</u>	<u>EXHAUST PLENUM (dB)</u>	<u>AIR PLENUM (dB)</u>
3.71	13.2	94	91	3.73	14.1	108	108
5.62	10.7	99	93	5.63	10.6	116	110
7.75	7.6	101	97	7.57	6.9	116	114
8.91	3	103	95	9.01	2.6	118	109
8.91	5.2	101	98	9.03	4.5	118	111

TABLE 6-6: EMISSIONS DATA FROM THE 72-TUBE HEATER TESTS

FIRING RATE (Btu/hr)	COMBUSTION CHAMBER TEMPERATURE (°F)	TEMP. FLUE @ PULSE COMBUSTOR EXHAUST (°F)	FLUE @ WASTE HEAT BOILER EXHAUST PLENUM (°F)	LAND COMBUSTION FLUE STACK READINGS				PERCENT EXCESS AIR	CORRECTED AT 3% O2 NOX (ppm)
				O2 (%)	CO (ppm)	NOx (ppm)	CO2 (%)		
Dec. 13, 1991									
1.73E+06	753	483	201	13.9	600	2.0	3.6	175.2	5.1
1.74E+05	464	446	233	16.1	1400	1.0	2.5	294.1	3.7
3.39E+06	753	535	246	13.4	700	2.0	3.9	157.8	4.7
3.39E+06	613	513	255	14.8	800	1.0	3.1	213.6	2.9
3.39E+06	-	449	254	16.5	1300	1.0	2.3	328.2	4.0
5.10E+06	-	603	267	8.8	900	17.0	6.3	64.6	25.1
5.10E+06	-	611	267	11.1	1000	14.0	5.2	100.3	25.5
Dec. 19, 1991									
3.37E+06	2283	527	204	9.4	600	29.0	6.1	72.5	45.0
4.25E+06	2224	561	244	10.2	1000	13.0	5.6	84.5	21.7
5.12E+06	2408	625	260	7.8	900	28.0	6.9	52.9	38.2

TABLE 6-6: EMISSIONS DATA FROM THE 72-TUBE HEATER TESTS

(CONT'D)

FIRING RATE (Btu/hr)	SO. CAL GAS CO. ENERAC FLUE GAS READING			CORRECTED AT 3% O ₂			CAL POLY BACHARACH FLUE GAS READINGS			PERCENT EXCESS AIR		CORRECTED AT 3% O ₂	
	O ₂ (%)	NOx (ppm)		PERCENT EXCESS AIR	NOx (ppm)		O ₂ (%)	CO (ppm)	NOx (ppm)			NOx (ppm)	
Dec. 13, 1991													
1.73E+06	13.8	6		171.5	15.0		13.6	476	0		164.5	0.0	
	13.9	6		175.2	15.2		13.6	477	0		164.5	0.0	
	13.8	14		171.5	35.0		13.6	360	1		164.5	2.4	
1.74E+06	16.3	0		310.4	0.0								
	16.3	0		310.4	0.0		15.9	1122	0		279.0	0.0	
	15.1	0		229.1	0.0								
3.39E+06	13.6	4		164.5	9.7								
	14.9	5		218.6	14.8		14.5	698	0		199.7	0.0	
3.39E+06	16.5	0		328.2	0.0								
	16.7	0		347.6	0.0		16.3	1201	0		310.4	0.0	
	9.4	6		72.5	9.3								
3.39E+06	9.4	11		72.5	17.1								
5.10E+06	8.8	22		64.4	32.5								
	8.6	32		62.1	46.5								
5.10E+06							8.6	658	16		62.1	23.2	
							10.9	784	12		96.6	21.4	

150 psig) was also procured to cool the flue gas to about 400°F before it enters the muffler. This serves two purposes: A cooler flue gas would allow the use of less expensive carbon steel for fabrication, and the cooling also results in loss of acoustic energy of the flue gas and thus help to attenuate the noise level.

A test was run on December 4, 1991 to test the performance of the boiler and the muffler. The test data and results are summarized in Table 6-3. As can be seen, the acoustic noise level did attenuate by use of the muffler. Figure 6-8 shows a comparison of the noise levels for almost equivalent firing rate and excess air conditions. It was also observed that the noise level increases with increasing firing rate and/or excess air. Figure 6-9 shows the variation of acoustic noise level as a function of firing rate and excess air.

Another test was run on December 5, 1991 to study the performance of a new aerovalve 3.25 inches in diameter (as against the previous one, 3.68" in diameter). Table 6-4 summarizes the test data and results. Table 6-5 compares the acoustic noise levels for comparable conditions (FR and excess air) and is plotted in Figure 6-10. It is evident that the smaller diameter (3.25") aerovalve performed worse with respect to noise levels.

The tests also showed a very high acoustic noise level at the inlet air plenum side. An air plenum muffler was designed for the same and tested on December 19, 1991. Figure 6-11 shows the reduction in noise level at the air plenum.

EMISSIONS FROM THE PULSE HEATERS

In order to verify the low emissions characteristic of the MTCI pulse combustion heater, measurements were made for emissions of NO_x , CO , SO_2 and combustibles at the flue gas exhaust plenum by specialized analyzers. Three different analyzers were used. MTCI used a Land Combustion NO_x Analyzer; an Enerac Analyzer was provided by Southern California Gas Company (SCGas); and a Bacharach Analyzer was brought to MTCI's Santa Fe Springs laboratory by California Polytechnic Institute's (CalPoly, Pomona) students. The test was

FIGURE 6-8: EFFECT OF BOILER AND STACK MUFFLER
ON ACOUSTIC NOISE LEVEL

FIGURE 6-9: VARIATION OF NOISE LEVEL WITH
FIRING RATE AND EXCESS AIR

FIGURE 6-10: COMPARISON OF NOISE LEVELS
FOR TWO TYPES OF AEROVALVES

FIGURE 6-11: REDUCTION IN NOISE LEVEL
BY AIR PLENUM MUFFLER

also a part of CalPoly's project to test low NO_x combustors. SCGas is the industrial liaison for CalPoly's project.

Table 6-6 shows the emission data obtained during the test conducted on December 13 and December 19, 1991. The December 13, test was conducted with all three NO_x analyzers. The December 19 test utilized only MTCI's Land Combustion Analyzer.

As evident from the table, NO_x emissions from the pulse heater were quite low. The maximum value of NO_x (converted to 3% O₂) was observed to be 45 ppm, much lower than the currently available combustion technologies. The relatively low value of NO_x at low firing rates on December 13 may be attributed to the fact that the air was too much in excess resulting in incomplete combustion. This is also supported by the low combustion chamber temperature observed. However, at higher firing rate (5.10 MMBtu/hr), air was reasonable and the NO_x values measured were more realistic. Whereas the three analyzers showed marked differences in the value of NO_x at low firing rates, the data obtained at high firing rates were very much in agreement. This may also be attributed to the fact that all these instruments have an accuracy of about ± 5 to 10 ppm and, hence, may not accurately detect low NO_x emissions.

SECTION 7.0
PERFORMANCE EVALUATION TEST OF A
72-TUBE PULSE HEATER UNDER
BLACK LIQUOR SIMULATED CONDITIONS

The prototype 61-tube heater module and its performance were previously evaluated only at the laboratory-scale and during this period. It soon became apparent that it was essential that at least one heater module be tested using real black liquor feed at conditions similar to those that would be required at New Bern. This would require numerous other components such as venturi and caustic scrubbers, an impact separator with heat exchanger, a cyclone, a flare, waste heat boilers, mufflers, etc. A cost and performance analysis indicated that a paper mill sludge could be used as a feed material to simulate black liquor without incurring the additional cost for the conversion of the process chemicals to green liquor. The MTCI process was also designed to process a wide spectrum of energy-bearing waste and biomass in an environmentally and economically sound manner.

Three paper mills showed an interest in hosting the heater performance evaluation tests using their sludge waste. Of the three, namely, Smurfit Newsprint Corporation, Inland Container Corporation (ICC), and Simpson Paper Company, ICC was chosen to be the host site. A 1-ton per hour heater evaluation pilot unit was to be installed at ICC's recycle paper mill site in Ontario, California. One 72-tube heater bundle was to be used to gasify 1-ton per hour of wet sludge with a moisture content ranging from 50 to 80 percent.

Inland Container Corporation recycles corrugated boxes and currently has a non-hazardous sludge waste product consisting of cellulose paper fibers that are too small to be used in making newsprint. The mill disposes of 50 tons per day of this fibrous sludge waste in a nearby landfill at considerable expense to the mill. The pilot would establish the industrial scale operability of the MTCI pulse heater in a paper mill environment. The California Energy Commission provided financial support (cost sharing) of \$500K for the pilot

and tests and ICC provided a site and utilities as well as feed and other ancillary participation.

The pilot gasifier was designed to process approximately 20 tons per day of wet sludge with moisture contents ranging from 50 to 80 percent. Table 7-1 shows the chemical analysis of a typical sludge waste from the host paper mill. The sludge consists of cellulose fiber but does not contain any inks or dyes. The chemical analysis detected only two metals: arsenic and lead. After acquiring the required permits and insurance, the installation of the pilot unit for the heater assembly at Inland Container Corporation was initiated and completed in four months.

7.1 PROCESS DESCRIPTION

Figure 7-1 shows the process flow diagram of the pilot facility for the sludge simulation of black liquor. The process consists of a fluid-bed gasifier (R-1) heated by a pulse combustion heater module (H-1) inserted into the fluid-bed gasifier. As previously described, the tube bundle heats the fluid bed indirectly as in a fire-tube boiler. The fluid bed is comprised of either limestone or sand (in actuality, both were used during the test phase) and is fluidized with either steam or recycle product gas or a mixture of the two. In the initial stage, only steam fluidization would be done, though provisions has already been made for recycle gas fluidization. A second blower (B-2) is provided to fluidize the bed with air during start-up.

7.1.1 THE GASIFICATION PROCESS

Sludge is fed to the reactor via a feeder system (X-1, X-2), described later. It is gasified in the fluid bed and the hot particulate-laden product gas exits the reactor at about 1300°F. The product gas first passes through an impact separator-cum-superheater (E-1) where it not only loses a major fraction of the particulates which are fed back to the reactor, but also heats up the fluidizing gas. The cooler product gas then passes through a water-jacketed cyclone (V-1) where most of the solids are removed and collected in a drum (V-2). The product gas exits the cyclone at about 900°F and enters the venturi scrubber (X-3). The latent heat and the particulates from the gas are removed by a jet venturi scrubber (X-3) and a scrubber vessel (V-3). The

TABLE 7-1:
CHEMICAL ANALYSIS OF TYPICAL SLUDGE WASTE
 (FROM HOST PAPER MILL)

<u>ULTIMATE</u>	<u>NEWSPRINT SLUDGE WT. %</u>	<u>CORRUGATED CARDBOARD SLUDGE WT. %</u>
C	42.12	48.60
H	5.65	6.37
N	0.30	0.37
S	1.41	0.30
O (by difference)	34.00	41.56
CL	0.02	0.00
	<u>Btu/lb</u>	<u>Btu/lb</u>
HHV (dry)	7,604	8,863
HHV (wet)	5,239	
<u>PROXIMATE</u>	<u>WT. %</u>	<u>WT. %</u>
VM	34.73	45.70*
Ash	16.50	2.80
Moisture	47.03	49.50
Fixed Carbon (by difference)	1.74	2.00*
<u>TOTAL METALS</u>	<u>mg/kg</u>	
Arsenic	0.41	
Lead	0.57	
All Others	Not Detected	
<u>SEMI-VOLATILE AND VOLATILE ORGANICS</u>	<u>mg/kg</u>	
Xylenes	5.12	
All Others	Not Detected	

* Estimated.

product gas exits the scrubber tank at 120 - 150°F. The gas then scrubbed off hydrogen sulfide with a 10 percent caustic soda in a packed bed column (C-1). The product gas leaving the scrubber (C-1) is nearly moisture- and sulfur-free. A second polishing column (C-2) uses circulating water to further remove any solids particles. The product gas leaving the column (C-2) is used for firing the pulse combustor (H-1) and fluidizing the reactor. The remaining export fuel gas is flared in H-2.

7.1.2 PULSE COMBUSTION HEATER SYSTEM

The heat required for the gasification is supplied indirectly by the pulse combustion heater (H-1). The pulse combustor is fired with natural gas for start-up and recycled product fuel gas at steady state. Combustion air is introduced by a forced draft blower (F-1). The hot flue gases from the heater at 1600°F are cooled to 400°F in a Waste Heat Recovery Steam Generator (WHRSG). The cooled fluid is passed through a two-stage, high efficiency muffler (M-1) before emission into the atmosphere.

7.1.3 FLUIDIZING MEDIA CIRCUIT

Plant steam at 15 psig from the facility is superheated in E-1 to 800°F for bed fluidization. At steady-state condition, a fraction of process gas (split stream after venturi scrubber) is recycled via a steam ejector to superheater (E-1). The superheated steam and recycle process gas mixture is used to fluidize the bed. By doing so, the steam usage is reduced, reducing the heat load in the venturi scrubber circuit.

7.1.4 VENTURI SCRUBBER SYSTEM

The hot gases emerging from the cyclone are cooled and scrubbed of the solid particulate via a water spray jet at the venturi scrubber. Also, most of the steam in the gas condenses out. The condensate and scrubbing water are pumped to an air-cooled fin fan heat exchanger (E-2) before being recycled back to the venturi scrubber. Part of the venturi scrubber water is pumped to a filter canister to knock off any remaining particulates before recycling back to the scrubber. The steam condensed in the venturi scrubber circuit is reinjected from the filter canister.

7.1.5 CAUSTIC-SCRUBBER CIRCUIT

The hydrogen sulfide in the product gas steam is reduced by caustic soda scrubbing in the absorption tower (C-1). Caustic soda available from the plant at 50 percent concentration is diluted to 10 percent concentration before being pumped to the absorption tower. The liquid level in the tower is maintained by continuous recirculation of caustic effluent. Excess effluent is discharged to a discharge tank.

7.1.6 COOLING WATER CYCLE

Cooling water is utilized to remove heat from the following process equipment:

- Pulse Combustor Chamber
- Cyclone (V-1)
- Ducts connecting the cyclone to the impact separator/reactor and the venturi scrubber
- WHRSG

Water is supplied to the above equipment from flash tank (V-7). The heater water/steam mixture exiting the equipment returns to the flash tank for evaporative cooling. The water flow is controlled via natural circulation due to density different between inlet and outlet streams. The height of the flash tank was calculated to be 35 ft. above the base in order to achieve natural circulation.

The steam produced in WHRSG and the flash tank are passed to the flare. In a commercial facility this can be used as process steam or export steam.

7.2 POSSIBLE POINT SOURCES OF EMISSIONS

- Char/ash discharge
- Flue gases
- Flared export product gas

The char/ash discharges from the second cyclone into a local hopper and does not emit any dust. The flue gas emissions consist of NO_x , SO_2 , O_2 , N_2 , CO_2 , and H_2O . Emissions of NO_x are expected to be about 25 ppm at 3 percent O_2 when the pulsed combustor is fired with natural gas and lower when fired with the hydrogen-rich product gas. SO_2 emissions of 9 ppm are anticipated when firing the pulse combustor on product gas. The product gas fuel after passing through the H_2S caustic scrubber contains 50 ppm of S as H_2S . The flared export gas produces emissions of a lower NO_x level due to the hydrogen content of the gas. The flare and flue gas emissions are maximum during start-up (3-6 hrs) when only natural gas is used to fire the pulse combustor. Also, at start-up, all of the product gas is flared and steam only is used to fluidize the reactor bed.

7.3 PROCESS EQUIPMENT DESCRIPTION

A list of the major equipment utilized in the gasification system is shown in the process flow diagram (Figure 7-1) and appears in Table 7-2.

A description of the major component systems follows.

7.3.1 THE SLUDGE FEEDER SYSTEM (X-1 AND X-2)

A schematic diagram of the sludge feeding system is shown in Figure 7-2. It consists of a ground feeder, a first-stage belt conveyor, a second-stage belt conveyor, a metering bin, a 20-inch knife valve, a rotary valve, and finally, a feed screw. The ground level feeder feeds sludge material to the first stage conveyor (at a steeper angle than the first belt). The second-stage belt delivers the sludge to a twin-feed feeder. Sludge travels through the 20-inch knife valve (open during operations) and rotary valve into the injection screw. The injection screw feeds the sludge to the gasifier. A bindicator located at the metering bin controls the feeding rate of the ground feeder. Both conveyor belts operate at all time at constant speed. The feed rate to the gasifier is controlled via a speed controller on the twin-feed feeder.

TABLE 7-2:
LIST OF MAJOR EQUIPMENT

A-1	Agitator	P-3	Caustic Metering Pump
B-1	Fluidizing Blower	P-4	Demister Recycle Pump
B-2	Blower (Recycle Gas)	P-5	Filter Pump
C-1	H ₂ S Scrubber	P-6	Pulse Combustor Cooling Pump
C-2	Demister	P-7	Cyclone Cooling Pump
E-1	Superheater	P-8	Exhaust Stack Cooling Pump
E-2	Air Cooler	R-1	Reactor
E-3	Boiler	V-1	Recovery Cyclone
ED-1	Product Gas Eductor (flare)	V-2	Cyclone Fines Bin
EJ-1	Scrubber Ejector	V-3	Scrubber Tank
EJ-2	Steam Ejector	V-4	Filter Blowdown Tank
F-1	Combustion Air Fan	V-5	Caustic Supply 50%
F-2	Flare Combustion Air Fan	V-6	Caustic Diluter 10%
F-3	Flare Pilot Fan	V-7	Flash Tank
H-1	Pulse Heater	V-8	Demister Caustic Catch
H-2	Flare	V-9	Filter
M-1	Muffler	X-1	Sludge Feeder System
P-1	Venturi Scrubber Pump	X-2	Belt Conveyor
P-2	H ₂ S Scrubber Recycle Pump	X-3	Venturi Scrubber

The feeder is designed for a capacity of 1.5 tph of sludge.

7.3.2 THE GASIFIER/REACTOR (R-1)

The reactor as shown in Figure 7-3 consists of a refractory-lined shell with sparge pipe distribution of air and steam in the bottom. A tube bundle is inserted into the bed and coupled to a pulsed combustion burner for heating the reactor. The process operates in a reducing environment except during start-up when the bed is fluidized with air until the bed temperature is above the dew point of steam. At this point, steam is used to complete the start-up heating and the system air is purged. Sludge feed to the reactor is started when the reactor reaches 1300°F. The reactor produces a hydrogen-rich gas laden with char/ash particulates. The bulk of the solids return to the reactor from the impact separator and reacts further. The gasifier dimensions are approximately 10 x 3 x 10ft³. The gasifier is designed to operate at 15 psig and 1100-1500°F and a throughput of approximately one ton per hour.

FIGURE 7-2: SLUDGE FEEDER SYSTEM

FIGURE 7-3: REACTOR/GASIFIER VESSEL

7.3.3 PULSE COMBUSTION HEATER

Heat is supplied to the fluidized bed reactor by means of a pulsed combustion heater rated 7 million Btu/hr. A schematic diagram of the combustor heater tube bundle was shown in Figure 6-3. The pulsed combustor consists of a forced draft air plenum, refractory-lined and water-jacketed combustion chamber, aerovalves, fuel manifold, interlocked combustion control, pulse resonating 72-tube bundle and exhaust plenum.

The basic components of the pulsed combustor are the aerovalves, the combustion chamber and the tailpipe. The aerovalves act as fluidic diodes and self-aspirate the required air volume into the combustion chamber from the air plenum with a frequency of 50-60 Hz. Fuel gas is supplied to the test unit through a manifold under continuous pressure. Air is supplied via self-aspirating aerovalves from an air plenum. The partially combusted flue gas enters the pulse tube where combustion continues for a fraction of the total tube length. The flue gases then emerge into the exhaust plenum. The pulse combustor is designed to fire with any type of liquid gaseous fuels up to 7.0 MMBtu/hr.

IGNITOR SYSTEM

The combustor is equipped with a spark plug electronic ignitor set to light a pilot flame and the combustor all controlled by an interlocked control panel. The control panel uses a Fire Eye UV sensor to detect the presence of the pilot flame. Solenoid valves control the start-up of pilot and main gas flow to the pulsed combustor. Although the pilot will operate continuously for safety, once the pulse combustor is started up, the ignitor is not required for operation.

7.3.4 IMPACT SEPARATOR AND CYCLONE: SOLID SEPARATIONS SYSTEMS

Most of the particulates are removed from the product gas in the impact separator-cyclone system portion of the system. The impact separator is actually an integral part of the gasifier (Figure 7-3). It also acts as a superheater. The hot product gases pass through the spacing in between the tubes through which the fluidizing steam or recycle gas is passed. A fraction

of the solids separate out from the gas and return to the fluid bed for further reaction or to be taken out as bed overflow. The gases get cooled by indirect heat exchange with the fluidizing steam between entering the cyclone. Most of the solids is removed in the cyclone by centrifugal action. The cyclone is water jacketed in order to further cool the gas and the particulates. The particulates are collected in a drum, whereas the gases leave the cyclone for entry into the venturi scrubber.

The impact separator is designed for a product gas flow rate of 1000 scfm and a heat removal rate of 900 KBtu/hr. The cyclone can handle 1000 scfm of process gas and 460 kBTu/hr of heat removal. The solid loading capacity of the cyclone is 200 lb/hr.

7.3.5 VENTURI SCRUBBER

Figure 7-4 shows the schematic diagram of the venturi scrubber system. Hot product gas enters the venturi where it is cooled by a jet of water. Water vapor in the gas condenses out. The small amount of particles not removed in the cyclone is also scrubbed off. Adequate liquid separation is provided by a separator tank. The scrubbed product gas leaves the tank at 120-150°F with negligible moisture (equivalent to saturated water vapor at the partial pressure in the tank) and particulates. A demister screen at the exit of the scrubber tank (V-3) further removes any entrained droplets. The warm scrubbing water is pumped to a fan-finned cooler (E-2) where the water is cooled down by blowing air across the water tubes. The cooled water then circulates back to the venturi scrubber for the next cycle. The overflow from the venturi is passed through a filter (V-9) to remove any entrained particulates in the water.

7.3.6 CAUSTIC SCRUBBER SYSTEM

Most of the sulfur present in the sludge feed is converted to H₂S during the steam-reforming process. This H₂S must be removed from the product gas before combustion in either the pulse combustor or the flare. The caustic scrubber system uses a 10 percent aqueous NaOH solution to absorb H₂S according to the reaction:

Figure 7-5 shows the schematic of the caustic scrubber column (C-1, Figure 7-1). The column is 16 inches in diameter and 20 feet high and has two sections, each 10 feet long. It is packed with 1½-inch diameter 304 SS Koch brand flexirings to provide intimate gas liquid contact. The gases enter the column at the bottom and exit at the top. The aqueous NaOH enters at the top of the column and exits at the bottom. Another port provides makeup of NaOH. A demister pad at the top of the column removes any entrained droplets from the gas before it leaves the column. The scrubbing efficiency of the column is expected to be 99 percent. A pH value of 10 is maintained constantly for proper operation. The column is designed for a gas flow rate of 250 scfm and caustic flow rate of 7 gpm. The operating temperature lies around 120-150°F.

7.3.7 FLUE GAS WASTE HEAT RECOVERY STEAM GENERATOR

The Cleaver Brooks boiler that was used as the Waste Heat Recovery Steam Generator (WHRSG) at about 1500°F through a 12-inch diameter inner tube at the one end and returns through 62 2.5-inch (OD) diameter tubes of 140-inch length to finally exit the boiler at about 400°F. Water and steam mixture get heated on the shell side of the boiler. The boiler only acts as a heat removal system to cool down the flue gases to about 400°F so that less expensive carbon steel could be used for muffler fabrication, but also cuts down the acoustic energy of the flue gas, resulting in reduced noise level.

The Cleaver Brooks two-pass boiler is rated at 4×10^6 Btu/hr heat transfer rate at 150 psig maximum. The maximum water flow allowed is 3450 lb/hr of steam at 150 psig. The boiler is designed for natural gas firing but is being used as a flue gas boiler. No fuel is fired inside the boiler.

7.3.8 STACK MUFFLER

Because of the strong pulsating flow in the combustion chamber and the pulse tube, the acoustic noise level of the heater system was observed to be tremendous. Even though the introduction of the waste heat boiler reduced the acoustic energy of the flue gas quite a bit, further reduction was necessary

FIGURE 7-5: H2S SCRUBBER

to bring the noise level down to industrial specifications. The performance of this muffler was reported in a previous section.

Figure 7-6 shows the schematic of the exhaust stack muffler. It consists of a two-stage baffled perforated muffling device. The first stage is 12 feet long and the second stage is 6 feet. Both stages consist of a 14-inch diameter inner pipe and 36-inch diameter outer pipe. The first stage consists of a 20-inch long section with 3/8-inch perforation over 40 percent of the surface area. The second stage has a similar perforation but over 40-inch length.

The two stages are separated only across the shell between the tubes. The inner tube runs continuously into both the stages as evident from the figure. The muffler weighs approximately 3320 pounds.

The flue gases enter the muffler at about 500°F and exit at around 300°F. The muffler was observed to attain a transmission loss of about 10-15 dB.

7.3.9 AIR PLENUM MUFFLER

Figure 7-7 shows a schematic of the air plenum/muffler designed to reduce the acoustic emissions from the air inlet plenum. The design is similar to the stack muffler except for the length and diameter of inner and outer pipes and the perforations, as shown in the figure. The muffler was tested at the laboratory and was observed to attain a transmission loss of about 20 dB. The results were reported in Section 6.5.

7.3.10 DATA ACQUISITION AND CONTROL SYSTEM

All the critical parameters required for process operations is continuously monitored from the control panel inside the control room, and also many of the critical parameters are measured locally such as pressure drop across the bed and natural gas flow rate to the pulse combustor. The list of all the parameters monitored and recorded from inside the control room and outside in the field is shown in Appendix A.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
---	---	---	---	---	---	---	---	---	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	-----

FIGURE 7-6: STACK MUFFLER AND EXHAUST

FIGURE 7-7: AIR PLENUM MUFFLER

In addition to the above data acquisition which is recorded manually in the log sheet shown in Appendix A, there is an automatic data logger that was loaned to MTCI by the Weyerhaeuser Paper Company. The data logger monitors and records all the remote temperatures and pressure measurements that are made inside the control room. The data logger sweeps every 5 minutes and data are saved on a disk in ASCII format.

CONTROL PARAMETERS

The critical control parameters are either controlled manually or automatically from the control panel in the control room. These are listed below:

- Fluidization velocity inside the reactor
- Pulse combustor firing rate
- Sludge feed rate to the gasifier
- Combustion air flow rate
- WHRSG back pressure limit

GAS ANALYSIS EQUIPMENT

The instruments used for gas analysis includes two MTI M-200 gas chromatographs, one Tracor 540 gas chromatograph, one Teledyne MAX-5 efficiency monitor, and two Horiba PIR-2000 gas analyzers.

The M-200 gas chromatographs were used for detailed quantitative analyses of the gasifier product gases. Currently, they are configured to measure the concentrations of H_2 , N_2 , O_2 , CO , and CO_2 , methane, ethane, ethylene, propane, propylene, butane, iso-butane, H_2S , and methyl mercaptan. The Model 540 gas chromatograph from Tracor was outfitted with FID and FPD detectors for high sensitivity measurement of trace hydrocarbon and sulfur compounds.

To complement the data provided by the gas chromatograph, three continuous monitors were employed. The Teledyne MAX-5 efficiency monitor measures the concentrations of oxygen, carbon dioxide, carbon monoxide, and total combustible gases. It also calculates the combustion efficiency. The Horiba PIR-2000 gas analyzers are used for continuous monitoring of a single

specified gas component each. One of the units is configured to monitor nitric oxide (NO), another is configured to monitor sulfur dioxide (SO₂) only. The continuous analyzers were used primarily to monitor combustion products from the pulse combustor and incinerator units.

Two IBM-AT compatible computers were equipped for data collection and control of the GCs. The M-200 GC is controlled using EZ Chrom200 software from MTI. A Spectra Physics SP 4400 (ChromJet) was used to record chromatograms from the Tracor 540 GC. A Linseis L-6012 dual-channel chart recorder was also used for real-time recording of chromatograms on a hard copy for M-200.

A. M-200 GAS CHROMATOGRAPHS

Each M-200 has two channels that have separate chromatographic columns and detectors. By combining different types of column, carrier gas and operation conditions (temperature and column pressure) the range of detectable compounds can be optimized. Table 7-3 summarizes the configuration of two of the M-200s and the compounds they can detect.

TABLE 7-3:
CONFIGURATION SUMMARY OF TWO MCI M-200S

GC CHANNEL		CARRIER GAS	COLUMN	DETECTOR	TEMP. (°C)	PRESSURE (psi)	COMPOUNDS
#1	A	Ar	Molecular Sieve 5A	TC	60	10.5	H ₂ , O ₂ , N ₂ , CH ₄ , CO
	B	Ar	HayeSep A	TC	40	15.5	CH ₄ , CO ₂ , ethylene, ethane
#2	A	He	DB-5	TC	35	16.5	propane, SO ₂ and H ₂ O (co-elute) iso-butane, n-butane, methyl mercaptan and HC higher than C ₄
	B	He	HayeSep A	TC	70	18.0	CO ₂ , ethylene, ethane, H ₂ S, COS, propylene, SO ₂ , and H ₂ O

B. TRACOR 540 GAS CHROMATOGRAPH

The Tracor 540 GC is a general purpose gas chromatograph. It features microprocessor control of all temperatures with ten methods stored in protected memory, five level oven temperature programming, built-in diagnostics for error detection, RAM battery backup, etc. The column oven can be heated up to 400°C. Linear program rate up to 40°C/min can be used.

The Tracor 540 GC is equipped with a flame photometric detector (FPD). The detector is specific for detecting sulfur and/or phosphorous compounds. At the same time, the detector is able to provide a signal of flame ionization detection (FID), which responds to all hydrocarbons.

The column installed in the Tracor 540 GC is a J&W megabore (30 m x 0.545 mm) fused silica capillary column. The stationary phase used in the column is GS-Q, a porous polymer stationary phase. This column is able to separate light hydrocarbons up to C8 and common sulfur compounds seen in the fuel industry.

An air-actuated 6-port valve is installed in the GC for gas sampling. Both the action of the valve and the temperature of the valve oven are controlled electronically by the microprocessor program. A sample injection port is also installed for the purpose of calibration and occasional liquid sample analysis.

The detector signal is collected and integrated by a Spectra-Physics SP4400 integrator. The integrator analyzes the chromatogram and print the result and the chromatogram on the ink-jet printer. The collected data can be sent to a PC through a RS-232 serial cable.

C. TELEDYNE MAX-5 EFFICIENCY MONITOR

The MAX-5 efficiency monitor measures the oxygen, carbon monoxide and total combustible compounds directly. It calculates the carbon dioxide and combustion efficiency based on pre-programmed fuel properties. This instrument provides accurate measurement of oxygen and low concentration carbon monoxide (<1000 ppm) in the test gas.

D. LAND COMBUSTION GAS ANALYZER

The land combustor gas analyzer measures O_2 , CO, CO_2 , NO_x , SO_2 , flue gas temperature, and draft. It calculates the carbon dioxide based on pre-programmed fuel properties.

7.4 PLANT LAYOUT AND THE CURRENT STATUS OF THE PILOT PLANT

Figure 7-8 shows a schematic drawing of the plant layout. Figure 7-9 shows a recent photograph of the facility. the plant has been completely commissioned. Currently it is being debugged for leaks, proper pipings and connections, etc. The plant is scheduled to undergo shakedown test within a few weeks. A 500-hour continuous test will follow thereafter.

FIGURE 7-8: SCHEMATIC OF PILOT PLANT LAYOUT

FIGURE 7-9: HEATER PERFORMANCE EVALUATION UNIT
1 TON/HR SYSTEM - INLAND CONTAINER
CORPORATION, ONTARIO, CA (MARCH, 1992)

SECTION 8.0

CONCLUSIONS AND RECOMMENDATIONS

The work accomplished over the past year has resulted in valuable scale-up information with respect to the performance of the heater tube module, system control requirements and system operating parameters. The information gained from the large pilot unit at the Inland Container Corporation's (ICC) Ontario, California recycle paper mill will provide design details and scale-up performance behavior for the core component of the New Bern system, the pulsed heater bundle. This will result in a more effective and less costly installation and field test shakedown period at New Bern and an acceleration of the commercialization of the gasifier into an early market entry position.

All of the lessons learned at ICC: scale-up design, system and component performance, installation procedures and management, system shakedown testing and, finally, realistic system operating parameters at large scale and in an industrial environment with gasifier plant - paper mill mandatory interfaces and plant ES&H.

Additional discussions were held with the DOE and Weyerhaeuser to define a field test that would further accelerate the commercialization of the technology. The recommendations proposed by Weyerhaeuser and endorsed by both the DOE and MTCI were based on their experience in selecting, installing and operating new systems or technologies in their paper mills.

The recommended course of action is as follows:

The Process Validation Test should be extended from the original plan of 600 hours to 1000 hours of continuous operation with recycled product gas to be fired in the combustor utilizing the data obtained during the short-term test period, the 1000-hour continuous operational test should be used to evaluate the performance with respect to the New Bern acceptance criteria. These criteria have not yet been finalized but will include specific performance criteria for:

- Mechanical integrity including corrosion/erosion rates, if test time sufficient to indicate any.
- Steady-state material and energy balances for all stream reduction efficiency.
- Long-term bed fluidization and performance characteristics at steady state.
- Conduct familiarization and training classes for New Bern personnel.
- Identify product (process or mechanical modification) improvement with recommendations as to implementation justified.
- Weyerhaeuser decision to assume operation of facility in accordance with defined specific acceptance criteria.
- Finalize operating, safety and maintenance manuals.

A completely new task was Weyerhaeuser's recommendation for a Process Optimization and Long-Term Reliability Test as an absolutely necessary demonstration to complete the project and enter the commercialization market as well as for securing future orders from Weyerhaeuser. Many of the issues to be resolved here speak to the questions asked concerning the maturity of a technology for commercialization. Although the mechanism for providing definitive and factual responses to these questions with the necessary substantiation (data) is technical, the focus is economic and financial.

The long-term, one year of operations by the mill as well as the determination of how much product can be pumped from the reactor (it was designed for two additional heater bundles) is a very important economic factor. The establishment of long-term reliability, maintainability and availability are also very important economic factors involved in commercializing the technology because on-line time is approaching the point where planned maintenance or outages may be scheduled and the long-term effectiveness of product throughput, yield and energy recovery determined. It will also establish the long-term cost of operating the system.

This is primarily an economic demonstration that should be convincing as to performance in the mill environment by the mill personnel to provide information for purchasers of the Technology.

Some time during the process optimization test period, two additional tube bundles will be fabricated and installed at New Bern to determine the total capacity that can be handled with the gasifier as fabricated for capacity addition. This may require some additional balance of plant, up-sizing of original components or adding some extra balance of plant capacity to handle the additional feedstock quantity.

The above activities as recommended by Weyerhaeuser and strongly endorsed by both the DOE and MTCI are seen as essential to providing a convincing demonstration of the maturity of the MTCI technology for near-term commercialization.

APPENDIX A

TEST PARAMETERS

	A	B	C	D
1	DATA			
2	Lead engineer			
3	Data collector			
4	Project number			
5	Feed material			
6	Time			
7	Outside readings			
8	Orifice delta P on the steam to injector screw			
9	Orifice Static P on the steam to injector screw			
10	Steam purge pressure below the knife valve			
11	Steam purge pressure above the knife valve			
12	Sludge bin refill at time:			
13	Load cell reading time:			
14	Load cell reading #1			
15	Load cell reading #1 before refill			
16	Load cell reading #1 after refill			
17	Load cell reading #2			
18	Load cell reading #2 before refill			
19	Load cell reading #2 after refill			
20	Load cell reading #3			
21	Load cell reading #3 before refill			
22	Load cell reading #3 after refill			
23				
24				
25	FEED RATE			
26				
27	PC rotameter gas flowrate			
28	PC gas rotameter pressure			
29	N.G. pressure at inlet to totalizer			
30	N.G. totalizer			
31	at time:			
32	Orifice Delta P for excitation steam			
33	Orifice static pressure excitation steam			
34	Dilution air flow			
35	Dilution air pressure			
36	PC chamber u tube monametre			
37	Air plenum u tube monametre			
38	Date			
39	Time			
40	COMBUSTION AIR DELTA P INCH WC			
41	Natural gas pressure to startup engine			
42	Startup blower engine rpm ~2500 rpm			
43	Start up engine water temp <160 F			
44	Fluidization air venturi upstream pressure			
45	Fluidization air venturi delta P			
46	Inlet temperature to air coolers			
47	AC-2 inlet temperature			
48	AC-1 return temperature			
49	AC-2 return temperature			
50	Sparge header pressure			

	A	B	C	D
51	PC pilot gas static pressure			
52	Flare pilot static pressure			
53	Demistre column static pressure			
54	H2S scrubber outlet pressure			
55	Bed Delta P			
56	Bed bottom pressure			
57	Bed freeboard pressure			
58	Cyclone recycle eductor orifice delta P			
59	Cyclone recycle eductor orifice static press.			
60	Check the following Pump Outlet Pressures			
61	Venturi Scrubber			
62	H2S Scrubber			
63	Demistre			
64	Filter			
65	Cyclone Delta P			
66	Delta P Filter and filter #			
67	Tail pipe u tube monametre			
68	Water Main totalizer			
69	at time:			
70				
71	Date			
72	Time			
73	Boiler water totalizer			
74	at time:			
75	Flash tank totalizer			
76	at time:			
77	Orifice Delta P on the steam purge to bellows			
78	Orifice Static P on the steam purge to bellows			
79				
80	Check the water level in the following tanks			
81	Waste Heat Boiler			
82	Venturi scrubber tank			
83	Discharge tank			
84	H2S scrubber tank			
85	Demister tank			
86	Weak Caustic tank			
87				
88	PC flue gas analysis			
89	Oxygen			
90	CO			
91	CO2			
92	NOx			
93	SO2			
94	Hydrocarbon			
95				
96	Pulse combustion chamber water jacket totalizer			
97	at time:			
98				
99				
100				

	A	B	C	D
101				
102				
103				
104	Date			
105	Time			
106	Inside Control panel readings			
107	Shen's computer			
108	T1			
109	T2			
110	T3			
111	T4			
112	Average bed temperature			
113	Free board pressure			
114	Orifice pressure			
115	Orifice temperature			
116	Orifice delta P			
117	Bed density delta P			
118	PC chamber temperature			
119	Flare temperature			
120	Natural gas orifice delta P			
121	Upstream N.G. pressure SP			
122	Process gas SP			
123	Process gas delta P			
124	Steam venturi delta P			
125	Steam venturi SP			
126	Fluidization velocity			
127	Steam FCV controller output			
128	Cyclone steam jacket orifice delta P			
129	Tail pipe static pressure			
130	PC static pressure			
131	Air plenum static pressure			
132	Combustion air FCV output			
133	Bed temperature, E&W of reactor			
134	Natural Gas FCV opening			
135	Date			
136	Time			
137	Bed delta P			
138	Bed bottom static pressure			
139	Boiler pressure			
140	Boiler valve opening			
141	Average mid bed temperature			
142	Metering bin speed			
143	TC switch with 40 position			
144	T1 - air plenum			
145	T2 - free board combustor side			
146	T3 - free board exhaust side			
147	T4 - stack exit, WHB <<400 deg F if not check level			
148	T5 - VS exit			
149	T6 - cyclone exit / VS entrance			
150	T7 - Demistre exit			

	A	B	C	D
151	T8 - inlet to cyclone return eductor			
152	T9 - Venturi scrubber splash tank			
153	T10 - Flash tank			
154	T11- Flash tank outlet to flare			
155	T12 - Superheater inlet			
156	T13 - Superheater outlet @ sparge tube header			
157	T14 - Sat. steam entrance to Cyclone after PRV			
158	T15 - Combustor refractory temperature			
159	T16 - Bed backwall by tail pipe			
160	T17 - PC jacket water outlet			
161	T18 - Bed over just above sparge (midway)			
162	T19 - Bed over sparge (midway)			
163	T20 - Not in use			
164	T21 - Not in use			
165	T22 - PC jacket water inlet			
166	T23 - N.G. orifice (main gas)			
167	T24 - Superheated steam orifice (fluidization)			
168	Date			
169	Time			
170	T25 - Ariflow			
171	T26 - PC exit water jacket after belows			
172	T27 - Steam cyclone orifice			
173	T28 - Product gas superheater exit			
174	T29 - Process gas cyclone inlet			
175	T30 - Procoess gas orifice			
176	T31 - Cyclone steam jacket exit			
177	T32 - Flue gas at PC exit, before boiler			
178	T33 - Heat flux probe #1, far side			
179	T34 - Heat flux probe #2, far side			
180	T35 - Heat flux probe #3, near side			
181	T36- steam temp on cyclone recycling eductor			
182				
183				
184				
185				
186	TC Switch with 20 position			
187	TT1- Tube surface temp, top tube, 5" from PC			
188	TT2- Tube surface temp, top tube, 12" away			
189	TT3- Tube surface temp, top tube, 33" away			
190	TT4- Tube surface temp, top tube, 67" away			
191	TT5- Tube surface temp, top tube, 106" away			
192	TT6- Tube surface temp, far side, 5" from PC			
193	TT7- Tube surface temp, far side, 12" away			
194	TT8- Tube surface temp, near side, 5" from PC			
195	TT9- Tube surface temp, near side, 12" away			
196	TT10- Bed temp, far side, PC side, 2" below top tube			
197	TT11- Bed temp, far side, 12" from heat flux 1			
198	TT12- Bed temp, far side, middle, 4" above top tube			
199	TT13- Bed temp, far side, TP end, 8" below top tube			
200	TT14- Bed temp, near side, PC side, 2" below top tube			

	A	B	C	D
201	Date			
202	Time			
203	TT15-Bed temp, near side, 3" from heat flux 3			
204	TT16-Bed temp,near side,middle,8" below top tube			
205	TT17- Bed temp, bottom,11" away from PC end			
206	TT18-Bed temp, bottom, 39" away from PC end			
207	TT19-Bed temp, bottom, 86" away from PC end			
208	TT20-Bed temp, bottom, 108" away from PC end			
209				
210				
211	Pulse combustor peak to peak setting			
212	Pulse combustor peak to peak division			
213	Pulse combustor amplitutde			
214	Pulse combustor frequency			
215				
216	Check the following alarm light mark ON/OFF			
217	Boiler water level lo-lo			
218	Boiler pressure low			
219	Venturi scrubber pump failure			
220	Density meter low level			
221	Delta P for bed low level			
222	Flare temperature low			
223				
224				
225				
226				

END

**DATE
FILMED**

2/25/94