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# Commissioning an Engineering Scale Coal Gasifier

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MD Bearden

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July 2010



**Pacific Northwest**  
NATIONAL LABORATORY

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Pacific Northwest National Laboratory  
Richland, Washington 99352



## Abstract

This report explains the development, commissioning, and testing of an engineering scale slagging coal gasifier at PNNL. The initial objective of this project was to commission the gasifier with zero safety incidents. The commissioning work was primarily an empirical study that required an engineering design approach. After bringing the gasifier on-line, tests were conducted to assess the impact of various operating parameters on the synthesis gas (syngas) product composition. The long-term intent of this project is to produce syngas product for use by internal Pacific Northwest National Laboratory (PNNL) researchers in catalyst, materials, and instrumentation development.

Future work on the project will focus on improving the reliability and performance of the gasifier, with a goal of continuous operation for greater than 4 hours using coal feedstock. In addition, alternate designs that allow for increased flexibility regarding the fuel sources that can be used for syngas production is desired. Continued modifications to the fuel feed system will be pursued to address these goals. Alternative feed mechanisms such as a coal/methanol slurry are being considered.



## Acknowledgments

The authors gratefully acknowledge the financial assistance of a Laboratory Directed Research and Development (LDRD) project from Pacific Northwest National Laboratory<sup>1</sup> (PNNL). All research herein was performed at the Integrated Environmental Technologies (InEnTec) facility in Richland, WA.

James Cabe was the project manager and a source of great knowledge and guidance. Stanley L. Owsley Jr., Mark D. Bearden, Robert J. Robertus, Mike Dodson, and Michael L. Elliott were instrumental in the initial design and construction effort.

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## Acronyms and Abbreviations

°C	Degrees Celsius
°F	Degrees Fahrenheit
$\Delta H^\circ$	Standard enthalpy change of reaction (units of joules). The enthalpy change that occurs in a system when one mole of reactant is transformed by a chemical reaction at 1 bar and 25°C. Positive values indicate endothermic reactions, which require a continuous supply of energy from the surroundings to be sustained. Negative values indicate exothermic reactions, which release energy to the surroundings.
$\tau$	Residence time (a.k.a. space time, units of seconds); the time necessary to process one reactor volume of reactant based on entrance conditions. The residence time can be thought of as the average time feedstock molecules spend in the gasifier.
ASTM	American Society for Testing and Materials
BTU	British thermal units
CGE	Cold gas efficiency
CH <sub>3</sub> OH	Methanol (often abbreviated MeOH)
DOE	U.S. Department of Energy
InEnTec	Integrated Environmental Technologies
k	Thermal conductivity in Btu-ft/hr-ft <sup>2</sup> -°F
LDRD	Laboratory Directed Research and Development
PEM	Plasma enhanced melter
PLC	Programmable Logic Controller
PNNL	Pacific Northwest National Laboratory
PPE	Personal protective equipment
psia	Pounds (force) per square inch, absolute
psig	Pounds (force) per square inch, gauge
QA	Quality Assurance
Scfm	Standard cubic feet per minute
Slpm	Standard liters per minute
SNG	Substitute natural gas
SOP	Standard operating procedure
Syngas	Syngas is also known as synthesis gas. It is the name given to a gas mixture that contains varying amounts of carbon monoxide and hydrogen.
TRC	Thermal residence chamber
WGS	Water-gas shift



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# 1.0 Introduction

## 1.1 The PNNL Coal Gasifier

The theory of coal gasification is not described in this document. A separate PNNL issued document addresses these issues [17].

PNNL's gasifier at Integrated Environmental Technologies (InEnTec) is a small entrained flow slagging gasifier of nominally 10 lb/hr of pulverized coal feed. Oxygen vapor from liquid dewars is used as the oxidant. The primary purposes of this gasifier are to 1) produce an internal slag layer to determine if its thickness could be determined by millimeter wave technology and 2) to produce syngas from coal for catalyst and materials testing. Thus the gasifier is not designed for fundamental studies of coal gasification.

The gasification vessel and associated equipment is designed for operation to 250 psig. However, limitations of the coal feed system, oxygen supply, syngas processing capability and safety concerns have limited operation to near atmospheric pressure.

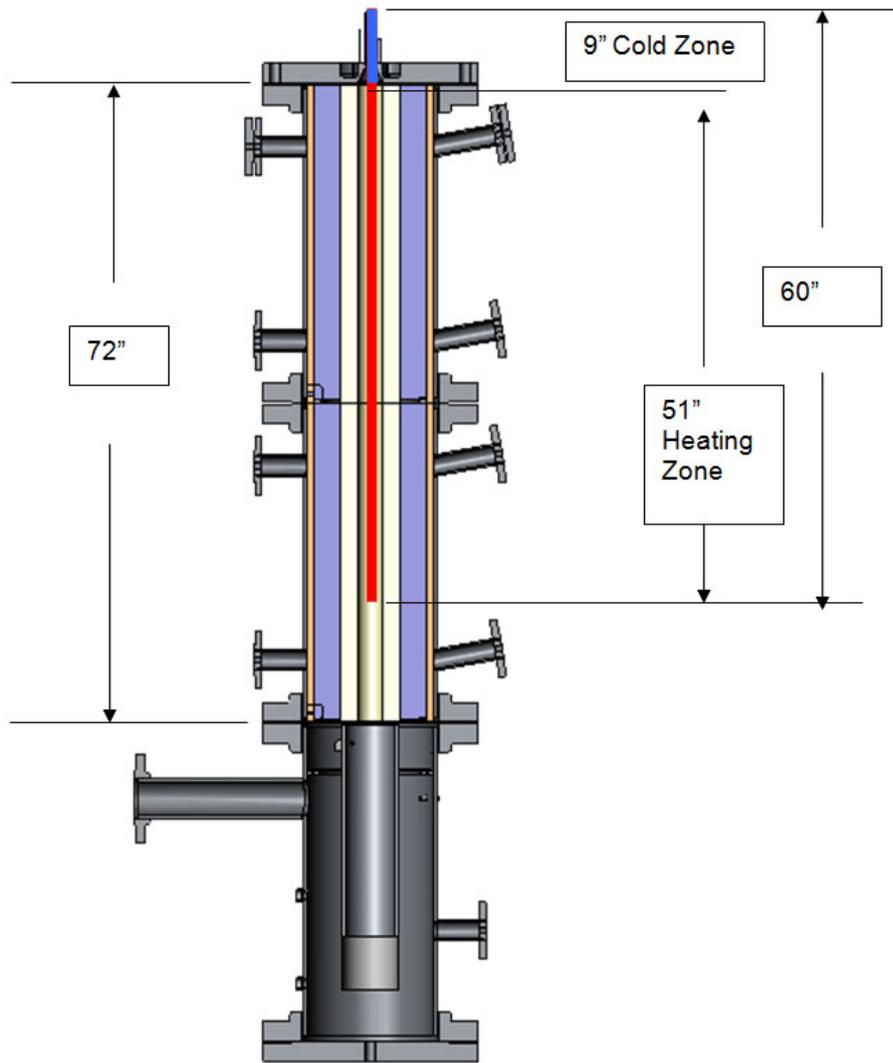
In an entrained flow gasifier, finely ground coal feedstock particles undergo thermal decomposition, partial combustion, and reaction with steam and other gas components as they are dragged along with the self generated gas stream in co-current flow.

Dry, pulverized solid coal is fed from a small nitrogen purged screw feeder and a liquid fuel (methanol) are fed to a burner located at the top of the gasifier vessel by a hopper system with nitrogen push gas and a pump, respectively (see Figure 1.1). The burner serves to establish good mixing between the fuel(s) and the oxygen, so that the gasification reactions take place in a dense cloud of very fine particles. (Methanol provides a reliable feed source that serves to attenuate temperature fluctuation in the gasifier caused by variability of the instantaneous coal feed rate from the hopper system.)



**Figure 1.1.** Burner

Below the burner, the gasifier vessel 3, 16" pipe flanged spool pieces bolted together to form a vessel approximately 9' tall (see Figure 1.2). The first two segments of the gasifier are lined with concentric layers of ceramic fiber blanket insulation, castable insulating refractory, and an interior dense castable ring, leaving an internal, empty cylindrical chamber in the center. The insulation and refractory layers protect the gasifier walls from high temperature and prevent excessive heat loss. The cylindrical chamber is designed to provide residence time for the coal to gasify and gas reactants to approach equilibrium at 250 psig and 2,500°F.



**Figure 1.2.** Gasifier Vessel

The gasifier is designed to react the coal feed at 2,500°F which is above the melting point of the coal ash. The molten ash, composed primarily of silica and alumina minerals (slag) form a highly viscous layer on the inner wall of the gasifier, with liquid slag being solidified and then removed at the bottom of the gasifier. The ash fluid temperature estimated for the Pocahontas coal used in the PNNL gasifier is 2,201°F [6]. The Pocahontas coal used is a low sulfur seam coal from West Virginia. The coal was ground extremely fine for greater reactivity and conversion. For a certificate of analysis of the coal fed to the PNNL gasifier refer to Appendix A.

In the third section, water is sprayed through nozzles into the gas stream to rapidly lower its temperature and stop reaction.





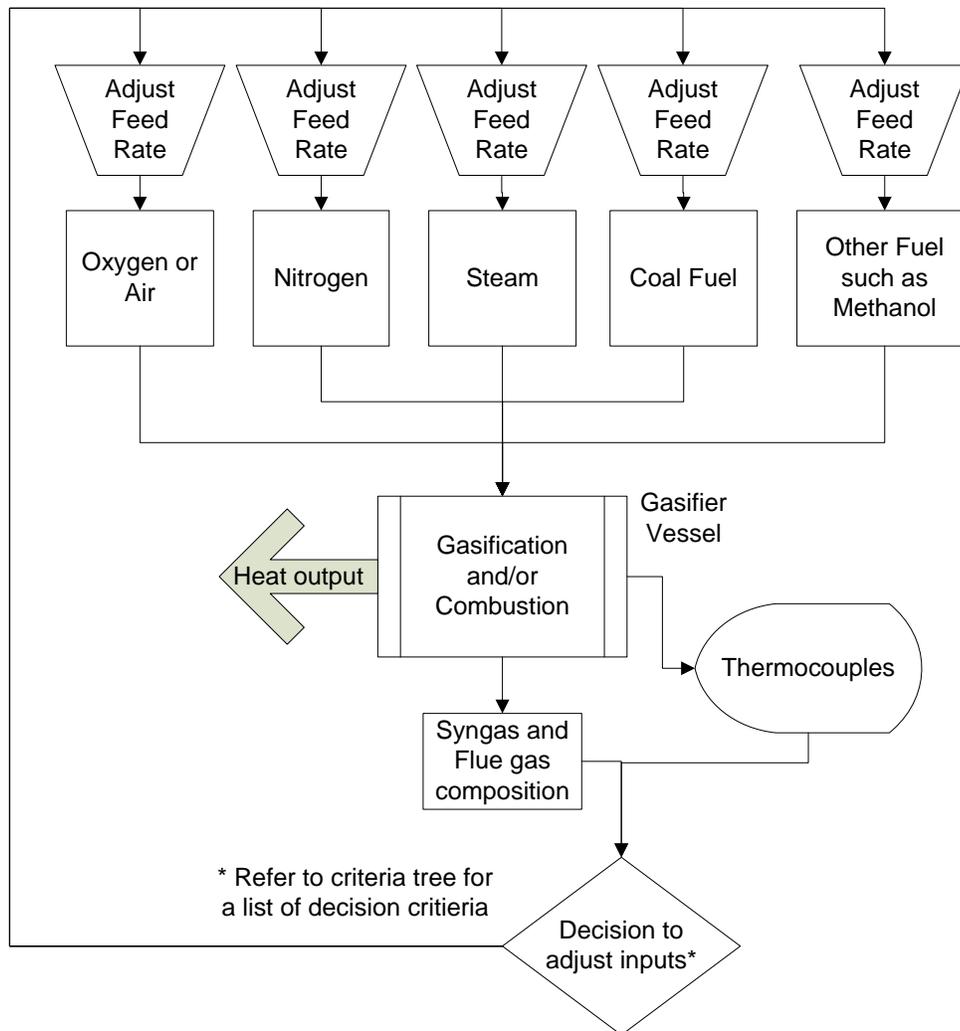
**Figure 1.3.** PNNL's Engineering Scale Gasifier

## 1.2 Project Goals

The primary goals of this gasification project were to safely commission the gasifier and to provide internal PNNL customers with syngas. This project was not funded to significantly advance the science of commercial gasification, but rather to serve as a research and development effort aimed at enhancing PNNL's internal capabilities with respect to operating a small-scale gasifier. Success was defined by completion of the following milestones:

- Develop and maintain a standard operating procedure (SOP) [18] and safe operating practices
- Start up the gasifier on methanol ( $\text{CH}_3\text{OH}$ )
- Transition to a higher energy density fuel (diesel)
- Transition to coal feed
- Develop sustainable run procedures and capability
- Align future efforts with research objectives/projects at PNNL
- Produce syngas for internal PNNL customers.

The technical goals of this project include maximizing the conversion of carbon from the solid to gas phase, running the gasifier continuously for a length of four hours or more, and being able to fine-tune the inputs/operating conditions of the gasifier to achieve a desired syngas composition. Figure 1.4 is the process flow chart showing the inputs and outputs of the gasifier.



**Figure 1.4. Flow Chart**

The following conditions are monitored during gasifier operation:

1. Gasifier Internal Temperature. If the temperature read by any thermocouple exceeds 1,425°C (2,600°F) an alarm is set off. A temperature exceeding 1,510°C (2,750°F) initiates the emergency stop system (ESTOP), which instantaneously stops fuel and oxygen from entering the gasifier.
2. Syngas Oxygen (O<sub>2</sub>) Content. If the continuous oxygen meter registers more than 1.0% O<sub>2</sub> in the exiting syngas outlet stream for a period of time that exceeds the expected lag time between syngas sample and measurement, ESTOP is initiated. (Normal syngas O<sub>2</sub> content is from 0.1 to 0.3%).
3. Syngas Hydrogen (H<sub>2</sub>) Content. Altered by adjusting fuel and oxygen inputs.
4. Syngas CO to (CO + CO<sub>2</sub>) Ratio. Altered by adjusting fuel and oxygen inputs.
5. Syngas CO to H<sub>2</sub> Ratio. Altered by adjusting fuel and oxygen inputs.
6. Gasifier Heat Ramp. The rate the gasifier bore heats up should not to exceed 150°C/hr.

7. Gasifier Pressure and Delta Pressure. ESTOP is initiated if pressure in the gasifier exceeds 5 psig. Normal gasifier operation requires the pressure to be below the high-high set point of 2 psig. The gasifier's delta pressure (inlet to outlet) is not to exceed 1.5 psig. (A 1 psig pressure is maintained at the coal fuel hopper.)
8. Fuel to O<sub>2</sub> Ratio. Sub-stoichiometric for gasification.
9. For additional conditions, refer to the alarm response section of the SOP[18].

PNNL leases space at Integrated Environmental Technologies (InEnTec). Figure 1.2 shows the gasifier located in the InEnTec facility in Richland, WA. Facility information can be found on the InEnTec website [10].

### **1.3 Environmental Impact**

Before constructing a gasifier facility, PNNL considered the environmental impact. The syngas product stream from the PNNL gasifier is sent through existing equipment maintained by InEnTec for treatment of syngas produced by their plasma enhanced melter (PEM) waste-to-energy technology. The analytics was performed by InEntec's NOVA instrument (figure 1.5). The syngas is quenched with water at the bottom of the gasifier vessel. InEnTec disposes of the quench water via approved regulatory disposal paths. Next, the syngas passes through a thermal residence chamber (TRC), which is a refractory-lined empty steel vessel. The TRC provides additional cooling for the syngas. The syngas exits the TRC and moves into a packed column scrubber (figure 1.6), which removes acid gases (CO<sub>2</sub> and H<sub>2</sub>S) and particulates. After passing through the scrubber, the gas is directed through a high efficiency particulate air (HEPA) filter. The cleaned syngas is then released to the atmosphere through a stack.



**Figure 1.5.** InEnTec's NOVA



**Figure 1.6.** InEnTec's Scrubber



## 2.0 Design Parameters, Testing, and Results

An entrained flow slagging gasifier was developed, commissioned, and tested. This chapter addresses the system design, the engineering design approach, testing, and results.

### 2.1 Project QA and Safety

A standard quality assurance process was implemented and followed during the gasifier commissioning. First, a hazard assessment was conducted to assess physical and chemical hazards to which lab employees may be exposed. Based on the hazard assessment the required personal protective equipment (PPE) was determined and a standard operating procedure was developed, maintained, and followed. Appropriate PPE includes such items as safety goggles, Nomex or Tyvek suits, appropriate gloves, and dust masks when working with the pulverized coal.

Implementation of system changes were documented on system logs; a sample system log is provided in Appendix A. When non-conformance issues were discovered, immediate corrective action was taken to mitigate potential hazards. Lessons learned were documented and discussed with the project team to prevent future occurrences. An example of this was the observance of audible deflagrations during one of the runs. This led to the design of alternative feed systems including a slurry feed system discussed in Chapter 5.

### 2.2 Engineering Design Approach

An engineering design approach was applied to commissioning the gasifier. This approach focused on the coordination of all the individual tasks, activities, and technical disciplines to develop a total system. This methodology involves the understanding of the problem statement, identification of objectives and requirements, concept selection, system creation, system operation, and life cycle management.

Before any experimentation could be performed, the incomplete engineering scale coal gasifier required system completion. To achieve mechanical and electrical system completion, the project team created and completed system check-out and mechanical logs. These logs helped track the process of equipment modification, addition, elimination, and testing. The team followed engineering best practices including peer review and quality assurance measures. When appropriate, certain subsystems were independently developed and bench tested prior to connecting them together in a cohesive system. This approach allowed parallel development and thorough pre-testing of each subsystem as well as simultaneous procurement of parts. All components were organized into a system/subsystem list as follows:

- Purge system
  - Gas supply (provided by InEnTec facility)
  - Nitrogen to head
  - Nitrogen to coal hopper
  - Manual stop valve

- Oxygen system
  - Gas supply (provided by InEnTec facility)
  - Manual stop valve
  - Inlet/outlet pressure
  - Dwyer meter
  - Block valve
  - Injection tubing and/or nozzles
- Water systems
  - Cold water supply to head
  - Filter for head water
  - Flow valve
  - Cold water supply to basin
  - Filter for basin water
  - Spray nozzles for basin
- Structure/Frame
  - Cages
  - Safety structure
- Gasifier
  - Steel vessel
  - Flanges and sealing surfaces
  - Refractories and BTU-BLOCK
  - Bolting
  - Insulation
- Feed systems
  - Containers
  - Filters
  - Drawdown tube
  - Pumps
  - Valving (isolation and check)
  - Nozzles
- Instrumentation (run via programmable logic controller (PLC) see Figure 2.1)
  - Steam, oxygen, and coal block valves

- Slag basin fill and discharge valves
- Oxygen flow control valve
- Off-gas analyzers including the NOVA (gas analyzer at InEnTec <http://www.novaanalytic.com/brand.html> )
- Emergency-stop
- Water basin level switches
- Thermocouples
- Pressure sensors
- Fuel feed control

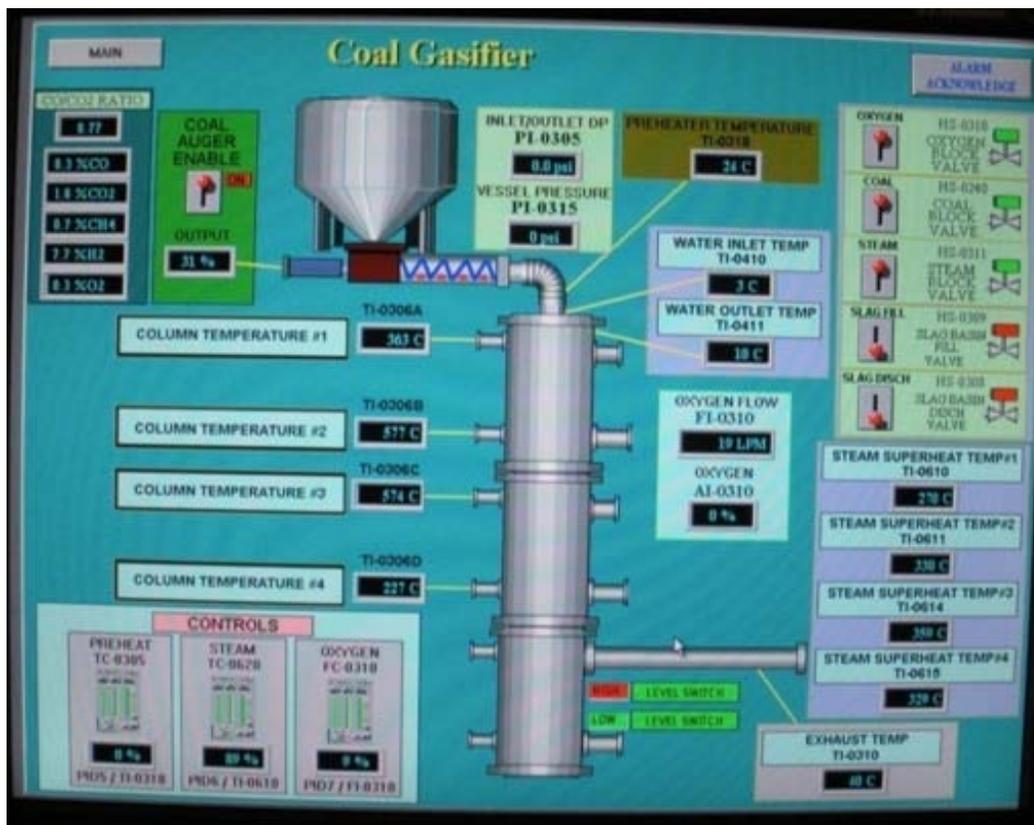


Figure 2.1. PLC Screen

## 2.3 Heat Flux Modeling

Thermal modeling of the gasifier vessel takes into account the various thermal conductivity values (K), various heat transfer rates (units of Btu/hr), heat transfer rates per unit area (units of Btu/hr-ft<sup>2</sup>), and internal heat generation as calculated by the AspenPlus®<sup>1</sup> program. AspenPlus is one of the many software tools that are used to simulate the material and energy balances for the chemical process

<sup>1</sup> AspenPlus is a registered trademark of AspenTech Incorporated.

industry. Dr. Robertus of PNNL was instrumental in the initial calculations. Acceptable operating temperatures are material specific and are provided in data sheets from the vendors. Table 2.1 lists the materials of construction along with their limiting operating temperatures.

**Table 2.1. Limiting Operating Temperatures**

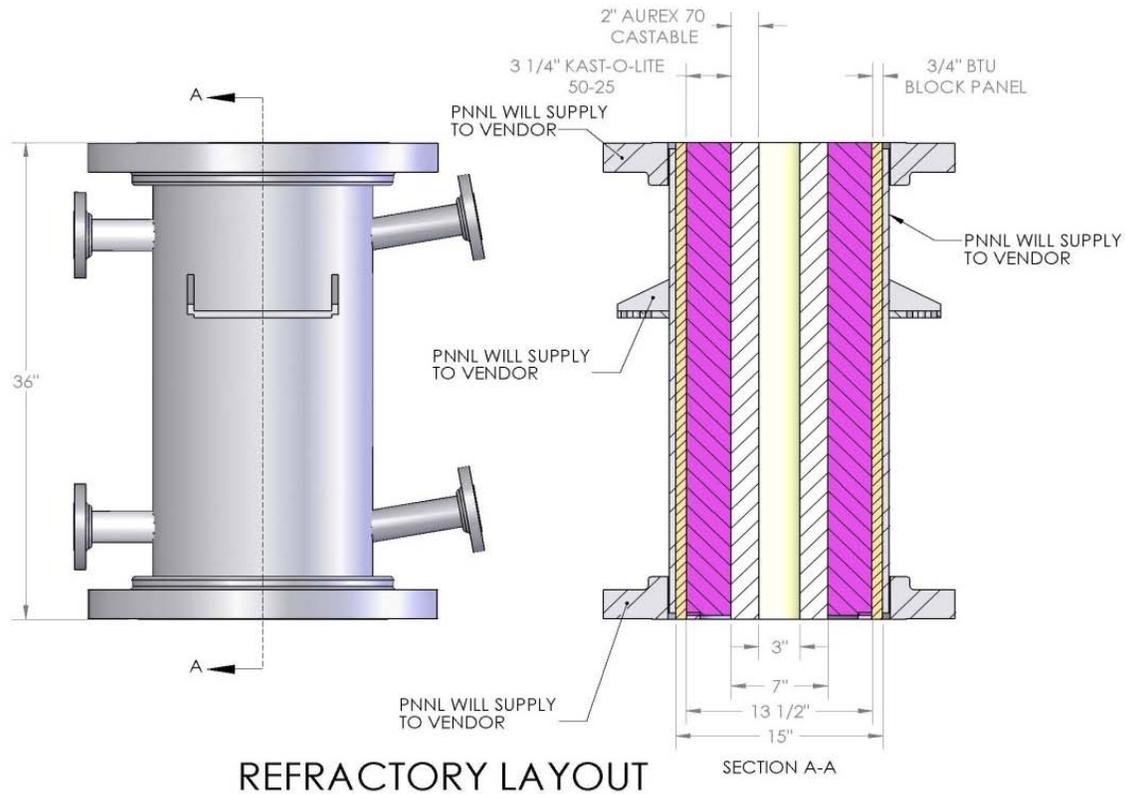
<b>Material</b>	<b>Maximum Recommended Service Temperature</b>
Aurex 70	1,816°C / 3,300°F
Kast-O-Lite 50-25	1,371°C / 2,500°F
BTU-block	649°C / 1,200°F

In the original gasifier, KS-4V-Plus (<http://www.empire-refractory.com/catalog/ks-4v-plus.htm>) was installed; however, after flame impingement damaged the liner, it was replaced with Aurex 70. Aurex 70 has a higher heat tolerance.

The operating pressures are driven by the internal reactions and are observed by pressure sensors. To calculate the internal heat generation, Aspen modeling was performed by senior PNNL staff using AspenPlus version 2006.5. The Aspen combustion databank was used for these heat load predictions and a flow chart is displayed in Appendix F. The modeling approach assumes RGIBBS equilibrium reactors were used, which minimize Gibbs free energy (i.e., stoichiometric equations are not required and equilibrium is determined from the free energy). Additional simplifying assumptions include an atmospheric operating pressure at sea level (14.696 psia), a constant feed temperature of 15.5°C (60°F), and that ionization can occur in combustion flames or gases at high temperature. Resulting flame temperatures were calculated to be 2,628°C (4,762°F) without ionization and 2,479°C (4,494°F) with ionization. In the case of ionization, the resulting flame burns at such a temperature as to strip electrons from many compounds, producing positively charged ions and electrons and reducing the energy available to increase the temperature. The energy from this reaction center is radiated away in all directions with the most lost to the quench section where water spray reduces the temperature to near ambient. Additional energy radiates to the refractory walls where it is conducted through the refractory and vessel wall layers and ultimately to the ambient air surrounding the gasifier shell.

The Harbison-Walker website [8] provides a heat flux modeling capability. This website employs the American Society for Testing and Materials (ASTM) C680-08 [1] standards of practice to provide the algorithms and calculation methodologies for predicting the heat loss or gain and surface temperatures of certain thermal insulation systems that can attain one-dimensional, steady- or quasi-steady-state heat transfer conditions in field operations. This practice is based on the assumption that the thermal insulation systems can be well defined in rectangular, cylindrical or spherical coordinate systems and that the insulation systems are composed of homogeneous, uniformly dimensioned materials that reduce heat flow between two different temperature conditions. ASTM C680-08 also specifies that qualified personnel familiar with insulation-systems design and analysis should resolve the applicability of the methodologies to real systems. The range and quality of the physical and thermal property data of the materials comprising the thermal insulation system limit the calculation accuracy. PNNL consulted the Harbison-Walker website to determine predicted temperatures of each layer of the gasifier under various conditions. The website tool includes material properties for the materials of construction used in PNNL's engineering scale gasifier. The Harbison-Walker website tool also allowed PNNL staff to create scenarios where various thicknesses of the spool piece walls could be varied thus resulting in different

thermal profiles. The hypothetical thermal profiles allowed staff to determine minimum thicknesses of the individual constituents that are necessary to maintain safe operating temperatures. Figure 2.2 shows the refractory layout in a cross section of a typical spool piece (note: dimensions shown have changed in the latest modified design).



**Figure 2.2.** Spool Piece Cross Section

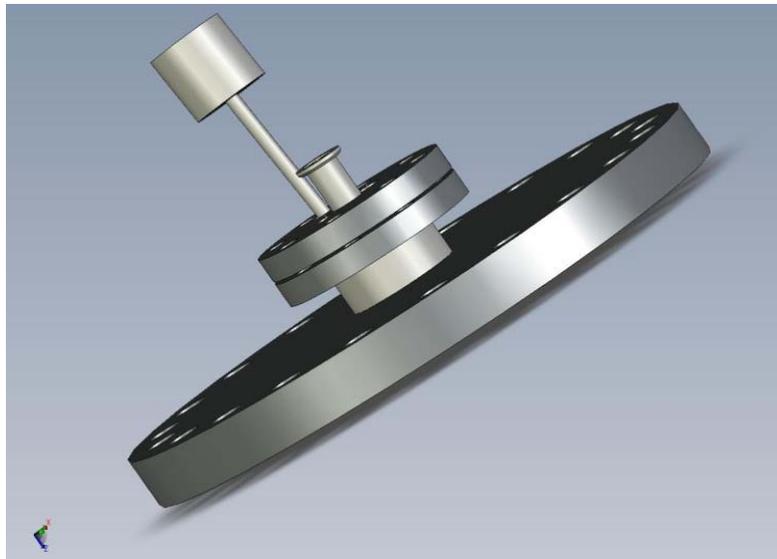
## 2.4 Fuel Feed Design

Many feed designs were considered to deliver both the coal and the methanol and many driving parameters were considered in the head design. Such parameters included the dynamics of mixing feed constituents. Feed dynamics involve velocities, residence time, chemical reactions, and the target percent of carbon conversion. Residence time (also known as space time, denoted by the symbol  $\tau$  is the time necessary to process one reactor volume of reactant based on entrance conditions. In the case of a gasifier, the residence time can be thought of as the average time feedstock molecules spend in the gasifier. Residence time is related to the volume ( $V$ ) and the volumetric flow rate ( $v$ ) in the mathematical relation:

$$\tau = \frac{V}{v} \quad (2.1)$$

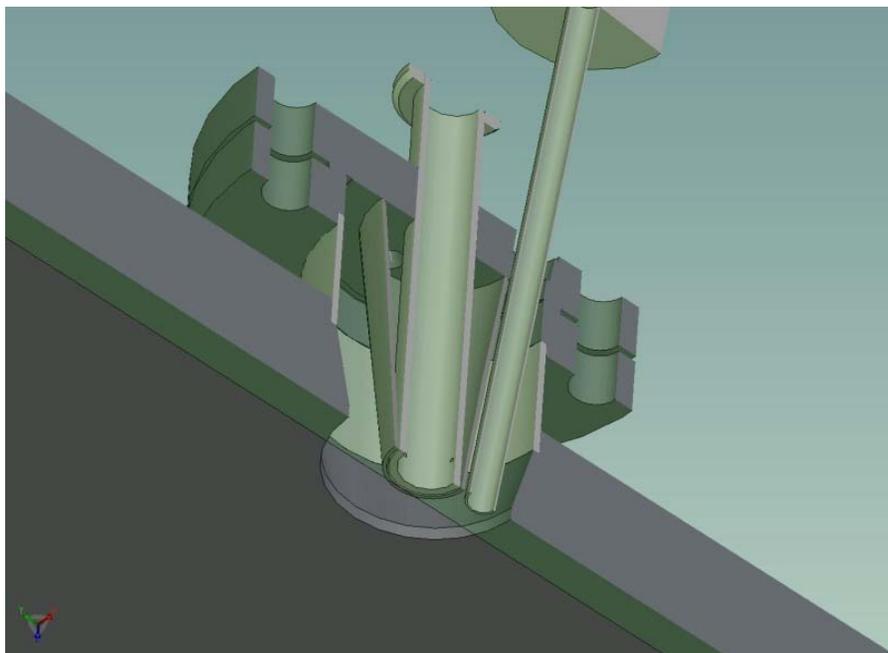
Previous modeling based on a vessel pressurized at 150 psig predicted a 2 second residence time. Experimentation at near atmospheric conditions suggests a residence time of less than a half second. The





**Figure 2.4.** Burner Redesign Concept

Figure 2.5 is a cut away view of the redesigned burner head. The oxygen, nitrogen, and steam were injected into the annular space between the inner coal feed tube and the reducer.

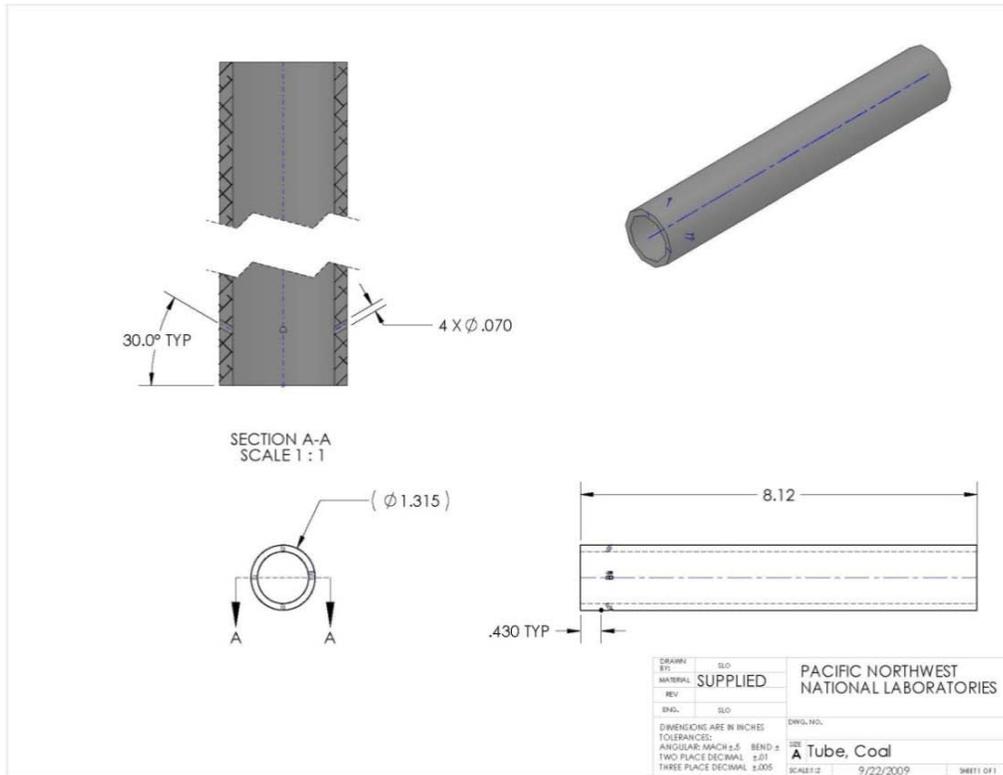


**Figure 2.5.** New Burner Three Dimensional Cutaway

Figure 2.6 shows the first iteration of the coal tube. After several trial runs, steam was eliminated from the feed process. It was difficult to keep the steam in the vapor phase and was determined that the attenuating quality of steam addition was not necessary to control the reactions.

The initial process of heating up the gasifier bore involves inserting an electric heating rod and gradually heating the bore over a 24-hour period. Once the top two thermocouples in the bore exceed

600°C (1,112°F), the heating rod is removed. Methanol is then injected at a controlled rate until the temperature of the first two thermocouples exceeds 1,000°C (1,832°F). At this point, varying rates of coal and methanol are fed into the gasifier.



**Figure 2.6.** First Iteration Coal Tube

Figure 2.7 shows the installation of the methanol fuel post. The first run involving coal feed resulted in a plug in the coal feed tube. Figure 2.12 shows one of the coal plugs. More nitrogen was added in an attempt to apply motive energy.

Prior to running the new head design, a series of bench top tests (Figure 2.8) were performed to simulate the coal feed with the forced jet mixing provided by the four holes shown in Figure 2.6. Effective mixing was observed using a silica sand substitute for coal; however the mixture tended to form eddies. This indicated that some of the coal was being drawn back up toward the outside of the reducer thereby increasing the surrounding feed head temperature. Based on bench testing of the fuel spray (Figure 2.9 and Figure 2.10), gas injection, and coal feed, the burner was insulated to protect it from extreme temperatures. Insulation was wrapped around the burner, as shown in Figure 2.11, but coal still plugged the opening as a result of the processes of coal devolatilization, softening, and swelling within the burner head. A 1-lb check valve was added to the coal hopper using nitrogen to prevent backpressure and syngas leaks. Coal plugging was still encountered. When the nitrogen feed rate was increased another problem was encountered. If the worst case flame temperature of 2,628°C (4,762°F) was actually reached and the oxygen force from the 0.07-inch diameter nozzles forced the flame front to the extreme sides of the bore, the maximum service temperature of 1,371°C (2,500°F) would clearly have been

exceeded leading to the damage to the castable shown in Figure 2.13 and Figure 2.14. It is also believed that at least two of the nozzle holes were plugged thereby doubling the nozzle velocity of the remaining two holes.



**Figure 2.7.** Initial Burner Redesign for Dual Fuel Feed



**Figure 2.8.** Burner Head Bench Testing



**Figure 2.9.** Nozzle Spray Testing in Clear Tube



**Figure 2.10.** Nozzle Spray Pattern Observed



**Figure 2.11.** Insulated Burner



**Figure 2.12.** Sample Coal Plug



**Figure 2.13.** Damaged Castable



**Figure 2.14.** Burner Removed

A total of 9 methanol runs were performed to date. Two diesel runs were attempted before deciding to return to methanol. Dry coal was fed into the gasifier on five occasions. For the initial runs, the first iteration coal tube (Figure 2.6) was used. In the 5<sup>th</sup> and most successful run, the feed holes were relocated to the extreme bottom of the coal feed tube, where the reducer is welded on. The four relocated nozzle holes were increased to a diameter of 3/32 inch and pointed vertically down, parallel to the gasifier walls.

Figure 2.15 shows the most recent burner head design after a methanol and coal run.



**Figure 2.15.** Burner Head after Coal Run in February 2010

## 2.5 Sensitivity Analysis

A sensitivity analysis was performed during a methanol run. Additional sensitivity analysis will be performed during the future gasifier run including coal runs. Sufficient runs have been performed to date to establish an effective heat up procedure. In general, the procedure involves ramping up heat in the gasifier no more than 150°C (302°F) per hour by observing thermocouple readings. The goal is to gradually feed less methanol and more coal. Ultimately a 100% coal feed is desired. The highest mass ratio of methanol to coal reached to date is 0.27 at steady state. Chemical composition and empirical evidence indicate that as the coal feed ratio increases, the carbon content increases, and as the methanol feed ratio increases, the hydrogen content increases. One percent adjustments are made to the input parameters approximately every five minutes. The procedures were designed to keep the gasifier below stoichiometry for combustion. The following steps outline the process to reach stable conditions where sensitivity studies can be performed. Refer to Table 2.2 for feed rate unit conversions.

- Heat up bore to about 600°C (1,112°F) with heating rod
- Install the burner head and start feeding 40% methanol fuel and 20% oxygen
- After a gradual ramp up in temperature, a 36% methanol fuel and 24% oxygen ratio is where coal can be introduced at about 8%.
- Eventually the methanol fuel should be 26%, oxygen 26%, and coal 14%
- Begin sensitivity analysis.

The percent inputs refer to the PLC controls. Units of scfm refer to standard cubic feet per minute, and slpm refers to standard liters per minute.

**Table 2.2.** Fuel Input Conversion Quick Reference

<b>Methanol Fuel Feed</b>			
<b>% Flow</b>	<b>ml/min</b>	<b>lb/hr</b>	<b>scfm</b>
25	72	7.5	2.04
50	140	14.7	3.96
75	210	22.1	5.95
100	280	28.6	7.93
<b>Oxygen Feed</b>			
<b>% Flow</b>	<b>slpm</b>		
25	50		
50	100		
100	203		
<b>Coal Feed</b>			
<b>% Output</b>	<b>lb/hr</b>		
10	6.6		
20	12.6		
30	18.6		

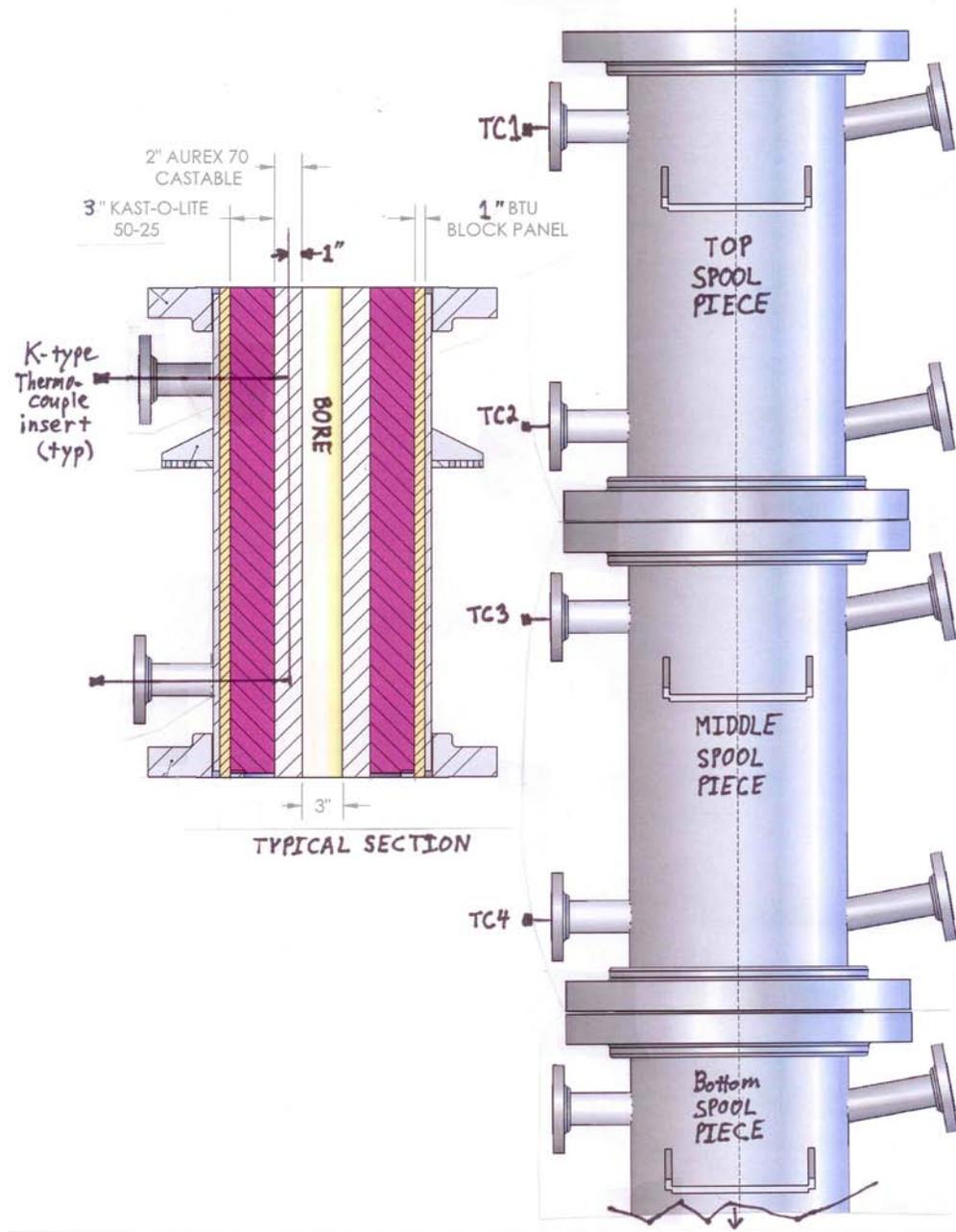
The uncertainty of all the instruments reading the various inputs and outputs must be considered before experimentation can begin. To the extent possible each instrument was calibrated and checked for accuracy and precision. Accuracy is important because it refers to the agreement between a measurement and the true or correct value. Precision is also important because it refers to the repeatability of measurement.

Table 2.3 shows the accuracy of each of the parameter data recording instruments used, and the operating range for which it is valid.

**Table 2.3.** Instrumentation Uncertainty/Parameter Accuracy

<b>Instrumentation</b>	<b>Uncertainty / Parameter Accuracy</b>	<b>Valid in This Operating Range</b>
K-Type Thermocouples	+/- 0.1 °C	-200 to 1,250 °C
Methanol pump	+/- 0.18 lb/hr	8 to 12 lb/hr
Coal auger	+/- 0.6 lb/hr	6 to 12 lb/hr
Oxygen feed	+/- 1 Liters per minute	40 to 80 Liters per minute
Nitrogen feed	+/- 0.1 scfm	1 to 2.5 scfm
Syngas readings from InEnTec's NOVA instrument	+/- 0.2 %	Any

Figure 2.16 shows the locations of the thermocouples. They are referred to as TC1, TC2, TC3, and TC4. The tip of each thermocouple was installed 1-inch from the inside surface of the gasifier bore.



**Figure 2.16.** Thermocouple Locations

Appendix L relates the oxygen flow percentage reading from the PLC to a slpm flow rate. Appendix M relates the methanol flow percent reading from the PLC to a lb/hr rate. Appendix N relates the coal flow percent reading from the PLC to a lb/hr rate. The oxygen, methanol, and coal are assumed to be at standard temperature and pressure. Appendix O contains the results of the sensitivity analysis for a methanol run in February 2010. In this run, methanol was fed until the gasifier temperatures were high enough to begin feeding coal. Section 3.2 contains a discussion and picture of the coal plug that stopped the coal feed after about 20 minutes.

The output syngas readings are measured and displayed by the NOVA instrument on a percent volume basis. The NOVA instrument is maintained and calibrated by the InEnTec facility. Moisture is removed by a wet scrubber before it goes to the NOVA. Previous to, and including this last sensitivity run, the flow meter on the NOVA was not functional. Although the flow meter has been repaired, the percentage of gas measured by NOVA is vented separately and not measured as part of gas going through flow meter. Currently there is no capability to measure the caloric value of the syngas. With the specific setup and instrumentation available at this gasifier an elemental mass balance is not possible. There are many factors that prevent an exact measure of the carbon conversion and syngas production. In the future, PNNL will develop the capability to quantify the carbon content captured in the water bath. An accurate measure of the calorific content of the syngas is also needed. In the future PNNL plans to bottle the syngas for internal customers. When gas bottling occurs it will be feasible to send a sample to be tested for its caloric value.

Table O-1A reports the fuel sensitivity data for 1-% incremental increases in methanol fuel. All other inputs remained constant. The nitrogen feed was held at 1.2 scfm, and the oxygen was constant at 18%. Table O-1B shows the net change in each of the syngas constituents over the entire 20 minute test. Table O-1C shows the gasifier temperature profile for which this test is valid. Figure O-1 plots the output syngas data from Table N-1A with time in minutes on the x-axis and volume % on the y-axis. Figure O-2 plots the output syngas ratio data from Table O-1A with time in minutes on the x-axis, and volume % on the y-axis. In both Figure O-1 and O-2, a step function showing the methanol % input is overlaid to show the discrete points in time where adjustments were made to the methanol input. The actual methanol percent values are printed next to each change in the step function for clarity.

Table O-2A reports the fuel sensitivity data for 1-% incremental increases in oxygen flow. All other inputs remained constant. The nitrogen feed was held at 1.2 scfm, and the methanol was constant at 24%. Table O-2B shows the net change in each of the syngas constituents over the entire 15 minute test. Table O-2C shows the gasifier temperature profile for which this test is valid. Figure O-3 plots the output syngas data from Table O-2A with time in minutes on the x-axis, and volume % on the y-axis. Figure O-4 plots the output syngas ratio data from table O-2A with time in minutes on the x-axis and volume % on the y-axis. In both Figure O-3 and O-4, a step function showing the oxygen % input is overlaid to show the discrete points in time where adjustments were made to the methanol input. The actual oxygen percent values are printed next to each change in the step function for clarity.

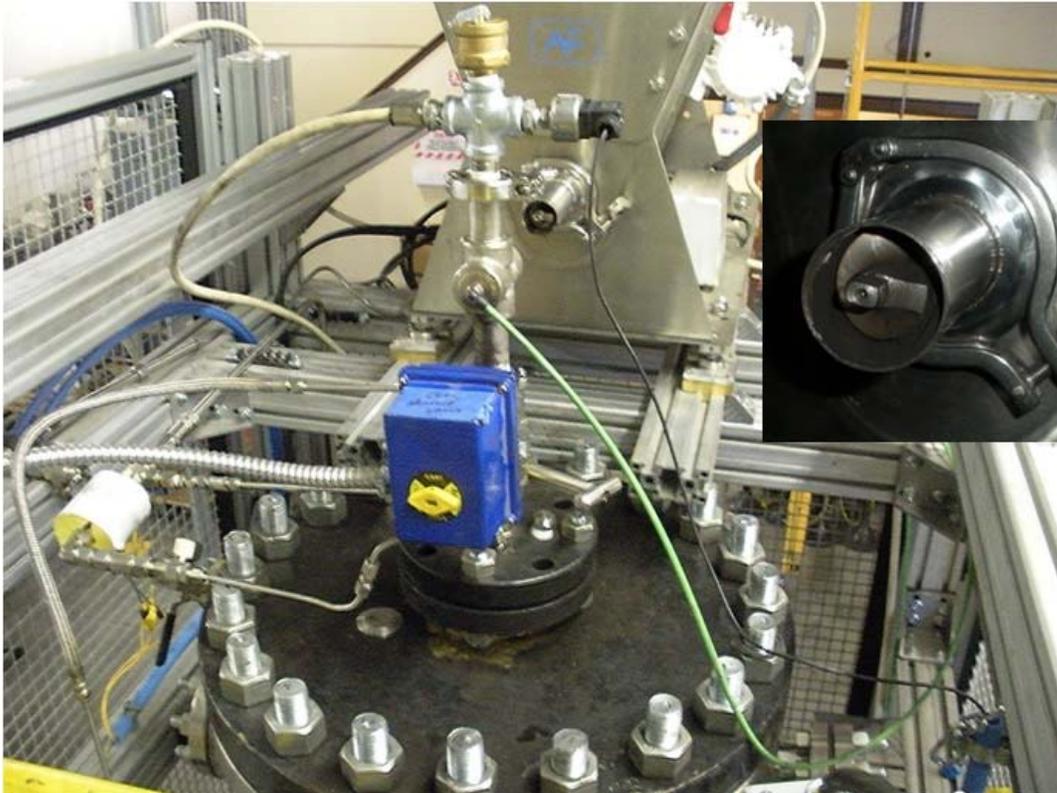
Several conclusions can be drawn from the sensitivity analysis data in Appendix O

A given percentage change in methanol has more of an impact on the output syngas composition than the same percentage change in oxygen. When the methanol is increased the fuel to oxygen mixture becomes fuel rich, and the CO to (CO+CO<sub>2</sub>) ratio increases, thus indicating more incomplete combustion in the gasifier. A higher CO to (CO+CO<sub>2</sub>) ratio is desirable when the intended output is a syngas with high combustible content. The CO to H<sub>2</sub> ratio is an indication of the formation of free radicals and cannot be used directly to predict quantitatively the calorific value of the syngas generated.

## 3.0 Technical Challenges

### 3.1 Fuel Feed

The current pulverized coal auger feed design does not deliver a consistent feed rate because the coal powder has a tendency to clump. Additionally at low speed corresponding to low flow rates, the feeder is observed to jump. Bucket and stop watch calibration have shown that on average the feeder is reasonably reliable. Figure 3.1 shows the top of the gasifier including a close-up of the coal auger scroll feed. An alternative slurry feed system under consideration has been designed to replace the current dry coal delivery system. Modifications to dry feed are currently being pursued before consideration of slurry feed.



**Figure 3.1.** Coal Auger Scroll Feed

Diesel fuel was evaluated as an alternative to methanol because of its higher energy content. Gasifying with diesel fuel presented many problems. During testing, sufficient oxygen was not supplied resulting in incomplete combustion of the diesel. The water basin became contaminated with diesel and created a dirty cleanup and disposal scenario. Additionally, diesel has much higher viscosity than methanol, thus making it a less attractive candidate for slurry feed. The syngas composition is significantly more affected by feeding diesel than to methanol. Thus methanol is preferred for start up and normal operation of the gasifier.

## 3.2 Gasifier Temperatures

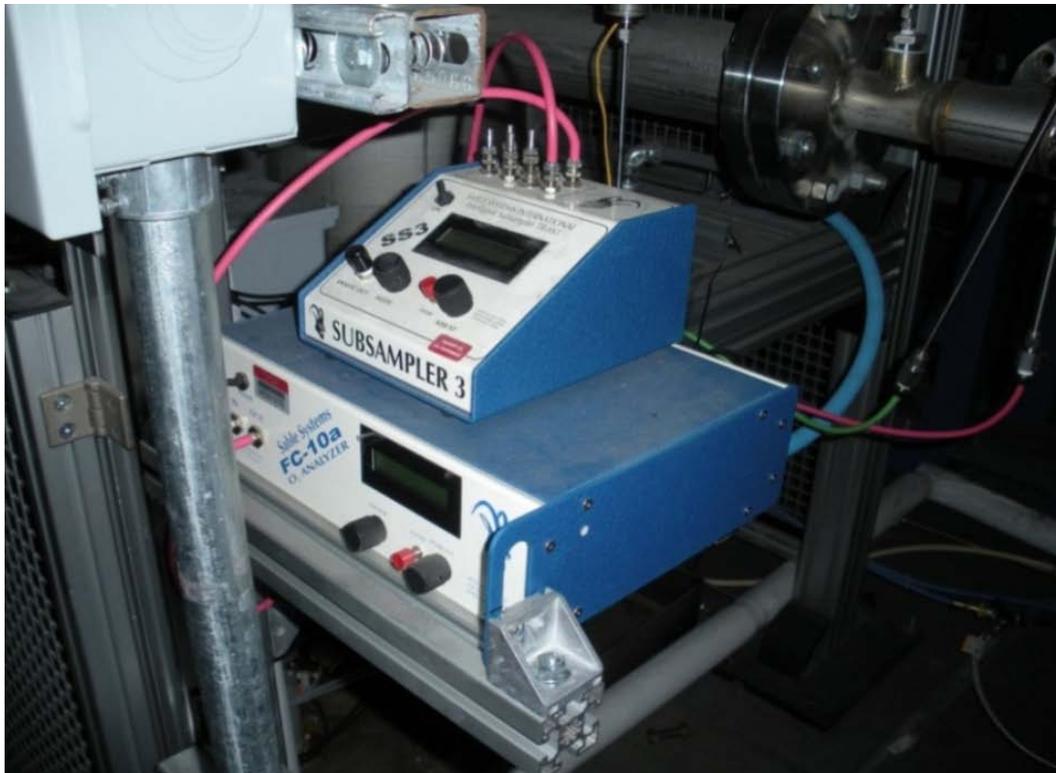
Another unexpected problem is evidenced by the large temperature fluxuations shown in Appendix C. Sudden changes in temperature can cause unacceptable thermal expansion and contraction leading to cracking of the gasifier vessel. Appendix C also shows five times where analytics caused issues. Sensors were tripped due to high oxygen levels causing delays in the continuity of fuel feed. This is evidence of incomplete mixing. Figure 3.2 shows how the bore became plugged from coal build up half-way down the gasifier. This problem is also a temperature delta problem, which causes the slag to cool too rapidly before encountering the water bath at the bottom of the gasifier.



**Figure 3.2.** Bore Plugged up February 2010

## 3.3 Syngas Analysis

Initially, a Sable Systems oxygen analyzer (Figure 3.3) was purchased for sampling and analyzing the off-gas stream for oxygen content. The gas traps installed to filter the syngas prior to the Sable sub-sampler became plugged too frequently to be relied on for the critical oxygen alarms. After testing and experimentation, it was determined that the NOVA instrument provided by InEnTec would be used to measure syngas composition. Oxygen high alarms were provided by the NOVA system because the lag time was significantly less than the Sable system.



**Figure 3.3.** Sable Oxygen Analyzer

Figure 3.4 shows the path of the off-gas stream from the gasifier.



**Figure 3.4.** Off-Gas Stream



## 4.0 Lessons Learned

In the process of encountering the technical challenges of running the gasifier, many lessons were learned. One challenge encountered at InEnTec was limited facility space. If future funding allows, a larger space will be used to facilitate easier access to the gasifier. Another important lesson learned was that gasifying with methanol is preferable to diesel in this application for reasons described in Chapter 3. Also, the challenges of technology scaling became evident. The predictions for full scale operation do not easily translate to engineering scale. Relying on the upper pressure gauge to determine the basin water level was a temporary solution to the fouled limit switches. More reliable water level sensors will be installed for future runs.

The original refractory liner was rated for lower temperatures than the intended operation of the gasifier. New material was purchased, and new spool pieces were fabricated.

The current feed system and gasifier setup does not allow for sustained run time. The feed system must be continually modified and improved to allow longer run times.

Predicted results from analytical models must ultimately be validated with experimentation. A cost benefit analysis must be performed when determine whether analytical modeling is justified prior to experimentation. When a limited budget is involved, the risk of damaging equipment must be weighed against the time and cost of extensive modeling and engineering analysis.



## 5.0 Conclusions and Recommendations for Future Work

At the conclusion of commissioning, proof of principle was achieved for a modified burner that delivers coal and methanol to the gasifier (see Figure 1.1). Bench testing for fuel constituent mixing was completed, followed by successful demonstration in the gasifier vessel itself. As the project progresses, future gasifier runs will be prioritized and aligned with PNNL research objectives. These primary future objectives include providing syngas to researchers by pressurizing and bottling samples and by ensuring syngas composition is appropriate for customer needs.

Increased residence time for the fuel is needed. By observing the amount of particulate in the water we know there is still a lot of fixed carbon in the quench solids. A material balance suggests only about 30% of the carbon that is fed into the gasifier is accounted for in the syngas. This calculation is inexact due to current feed rate and syngas measurements. The possibility of increasing the bore size on the upper two spool pieces has been considered. Increasing the feed path length by way of swirling may be achieved by a fuel feed design modification. The possibility of installing a fire eye has been left open pending sufficient need and budget. To facilitate a reliable and consistent feed rate, a slurry feed capability was also considered.

In the current configuration, the engineering scale gasifier does not support highly pressurized operation. Future testing of a bench top setup will evaluate delivery of coal methanol slurry into an atmospheric gasifier. When diesel was under consideration as a fuel source, a slurry sample was sent to Moyno Industrial for analysis [15]; Appendix H shows the test results. When methanol was ultimately chosen for the slurry feed, the results from Appendix H were consulted to size a pump. Methanol's specific gravity is less than diesel, and there was no time to wait for another analysis before a pump was ordered. Appendix I shows viscosity in centipoise on the y-axis and velocity in ft/sec on the x-axis. Basic velocity calculations were performed for the new head design resulting in a maximum anticipated feed rate of 12 pounds an hour. The resultant velocity of the slurry through the 0.25-inch feed line and the 0.03-inch diameter fuel post is 0.0011 ft/sec and 10.9 ft/sec, respectively. These values lie on the extreme ends of the Moyno viscosity curve, shown in Appendix H. The pump ordered has nitrile o-rings and is chemically compatible with methanol, as defined in [13].

Appendix D depicts the thermal profile of the four thermocouples versus time in hours and minutes. One of the ongoing design goals is to move the flame front further down in the vessel. When this is achieved, the temperature profile of thermocouple 1 and 2 will more closely match. Future burner designs aim to move the thermal energy further down the gasifier.

Additional sensitivity runs need to be performed to better understand the affects that a given change in the input has on the output syngas composition. Sensitivity data similar to appendix O must be gathered for changes in all input parameters, and preferably during longer duration tests.



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## **Appendix A**

### **Sample System Completion Log Sheet**





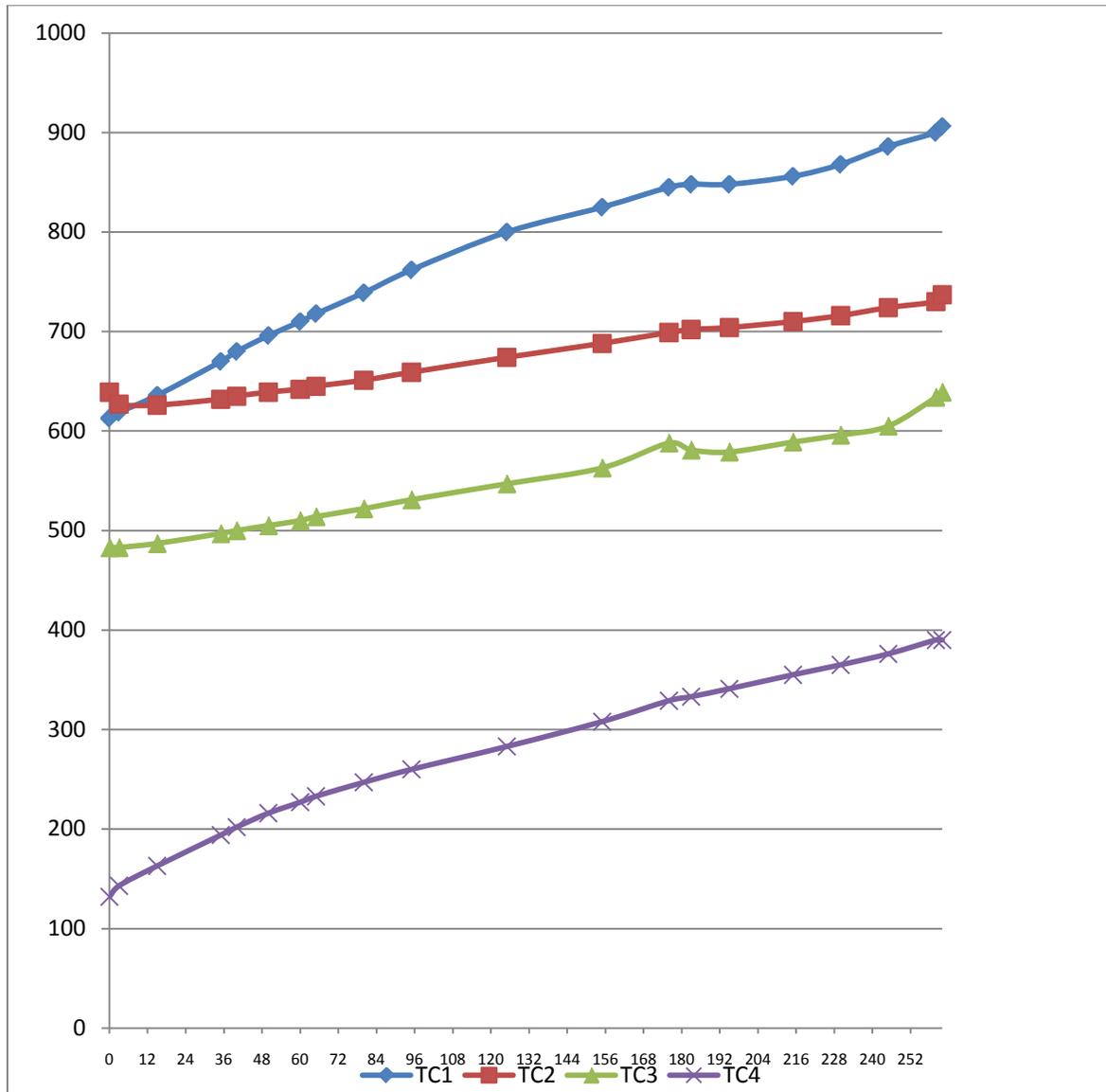


## **Appendix B**

### **Thermocouple Temperatures with Methanol Fuel**



## Appendix B – Termocouple Temperatures with Methanol Fuel



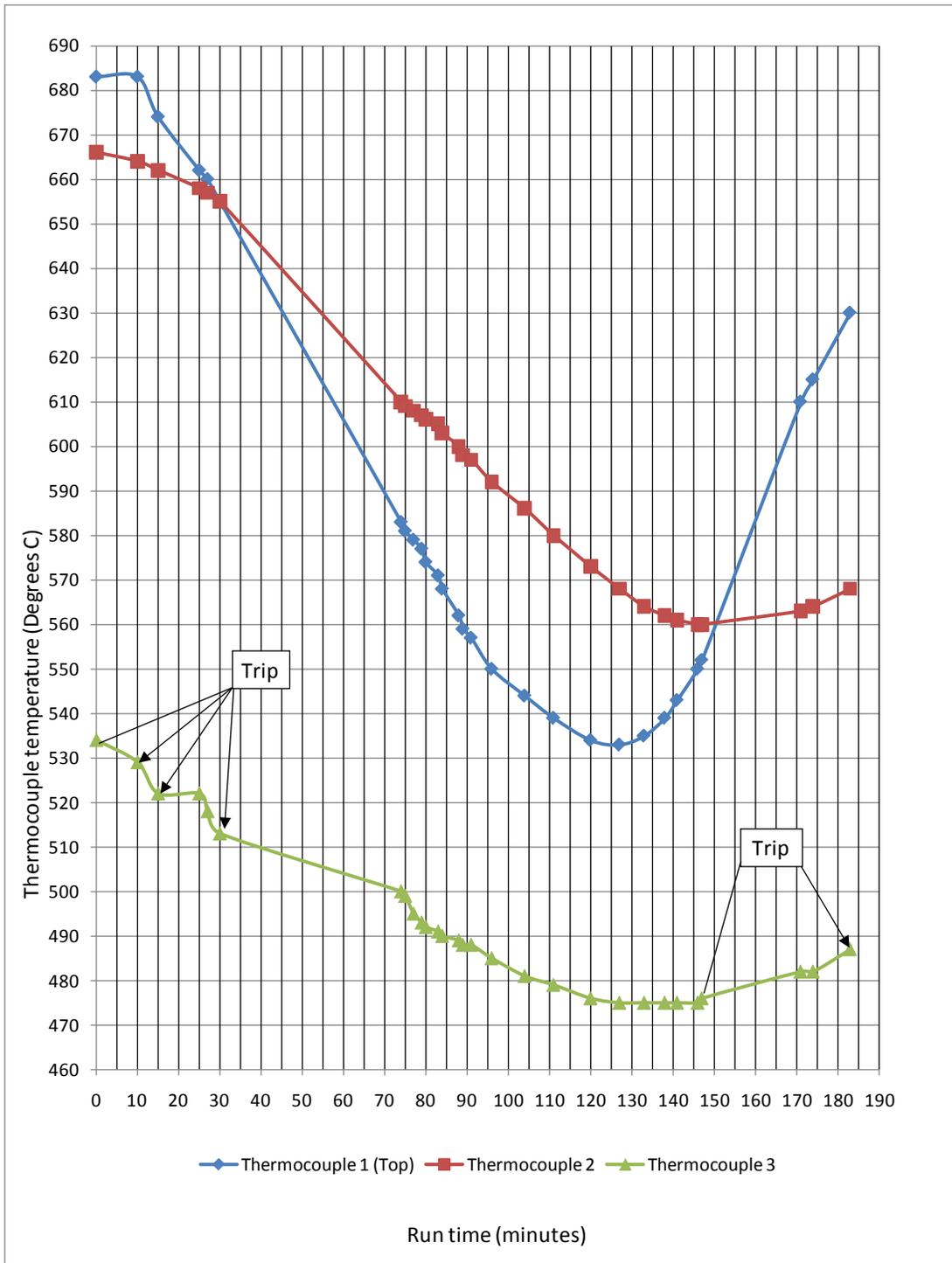


## **Appendix C**

### **Thermocouple Temperatures with First Diesel Run**



# Appendix C – Thermocouple Temperatures with First Diesel Run



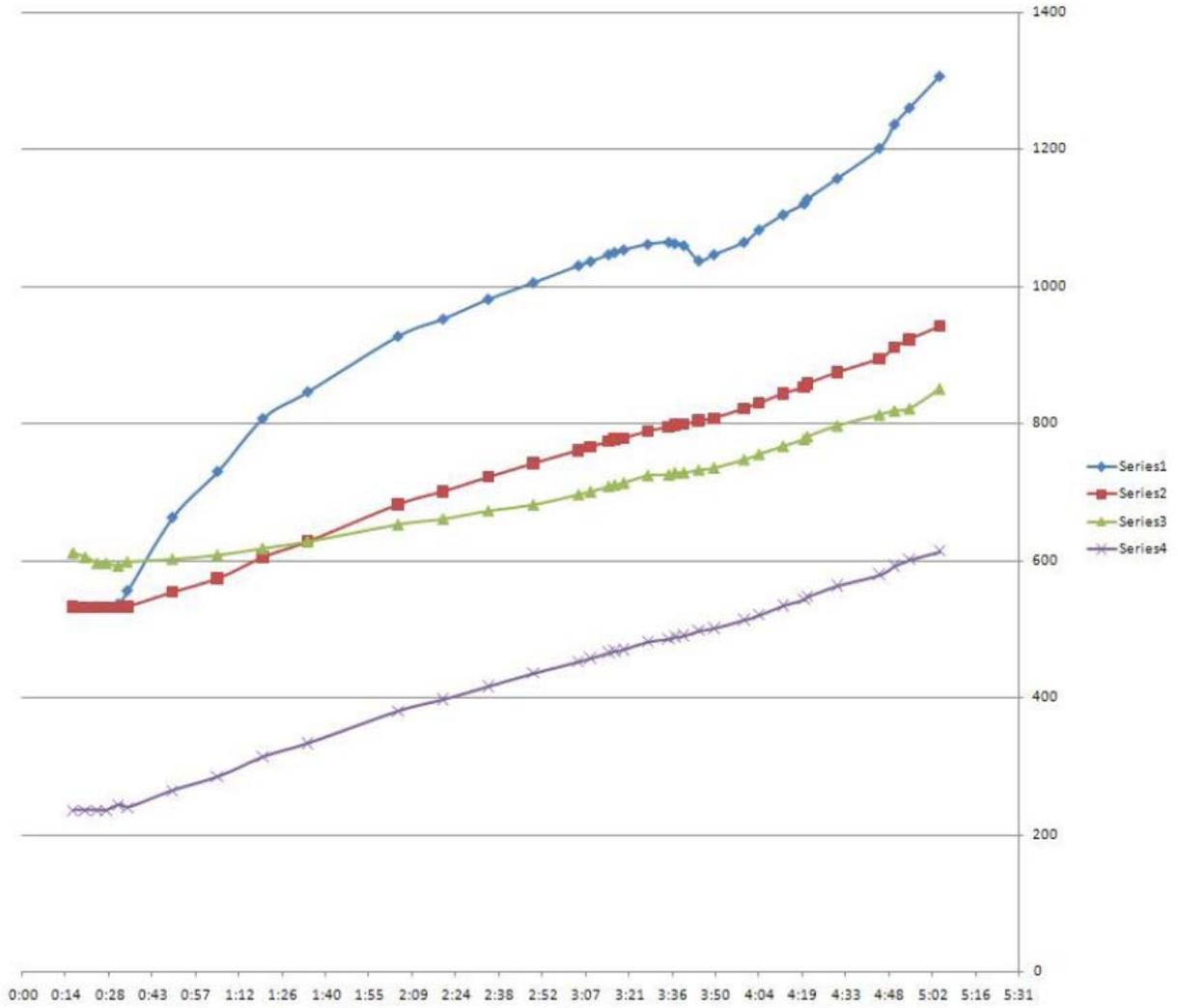


## **Appendix D**

### **First Successful Coal Run**



# Appendix D – First Successful Coal Run



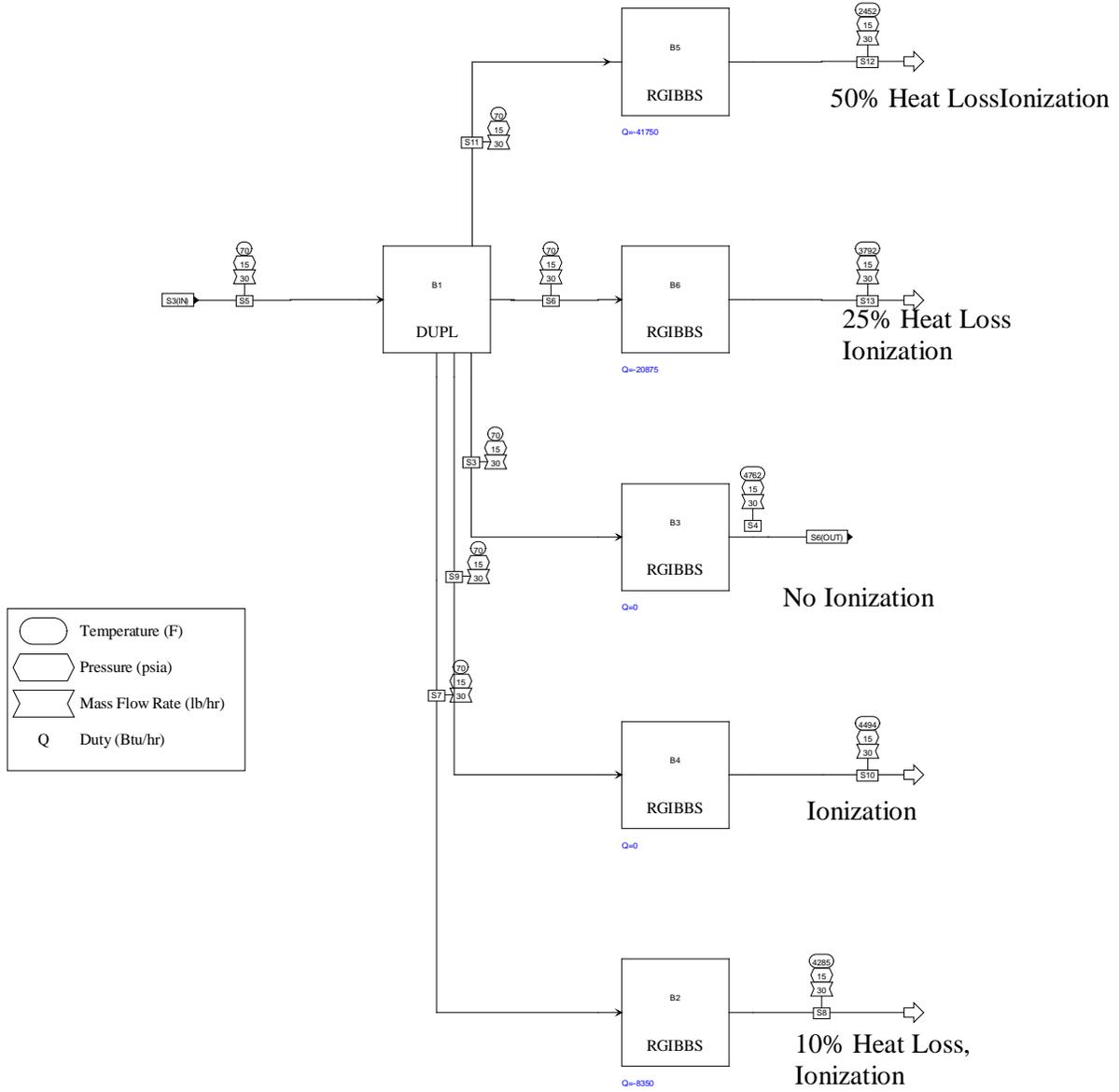


## **Appendix E**

### **Aspen Model Flow Chart**



# Appendix E – Aspen Model Flow Chart





## **Appendix F**

### **Harbison-Walker Calculations**



# Appendix F – Harbison-Walker Calculations

Harbison-Walker Refractories Company



Customer:	<b>PNNL</b>	Date:	<b>Sep 18, 2009</b>
Vessel Type:	<b>gasifier</b>	Shell Geometry:	<b>Vertical Cylinder</b>
Hydrogen Atmosphere:	<b>0%</b>	Thermal Dimensions:	<b>Outside Diameter: 1.33 (ft)</b>

Hot Face Temp (°F)	Material	Thickness (in)	K-Value	Mean Temp (°F)	Resistivity
2539	Aurex 70 Castable (est.)	2.00	59.49	2520	0.1147
2500	KAST-O-LITE 50-25 * <b>**WARNING**</b>	3.00	2.39	2149	2.0754
1799	BTU-Block Panel	1.00	0.24	1006	4.6887
213	304 Stainless	0.50	105.88	212	0.0049
Heat Flux: <b>338.12</b>		Shell Temp: <b>212</b>			
Ambient Temp: <b>75</b>		Wind Velocity: <b>0.00</b>			
Vessel Temp: <b>2539</b>		Cold Face Emmissivity: <b>0.91</b>			

**Manufacturer's Suggested Maximum Service Temperature Is Being Exceeded.**

The Values Shown Here Were Calculated Based on the Method Prescribed in ASTM C680



**Appendix G**  
**Certificate of Analysis**



# Appendix G – Certificate of Analysis



August 16 2007

**Client:** BATTELLE  
 PACIFIC NORTHWEST NATIONAL LABORATORY  
 P.O. Box 999 MS-K5-22  
 Richland, WA 99354

**Attn:** Michael G. Dodson

**Project:**

**Date Received:** August 14, 2007

## Certificate of Analysis

Analyses	Method	units	1	# 131	# 132
			DA07-7482	DA07-7483	DA07-7484
<b>Proximate Analysis</b>					
Moisture	D3172-89	%	0.52	0.51	0.50
Volatile Matter		%	16.55	16.55	17.30
Fixed Carbon		%	72.60	72.64	71.88
Ash		%	10.86	10.81	10.81
<b>Ultimate</b>					
Carbon	D3176-89	%	79.17	78.74	79.53
Hydrogen		%	4.32	4.06	4.06
Nitrogen		%	1.57	1.60	1.58
Oxygen		%	4.10	4.50	3.94
Sulfur		%	0.583	0.618	0.590

2-3 Day Rush

**Notes:**

Values reported on an Moisture Free basis

  
 Ralph V. Poulsen, Lab Director

3860 S. Palo Verde Rd.  
 Suite 303  
 Tucson, AZ 85714  
 520.623.3381

Page 1 of 1

Rpt-7482 Battelle Dodson,  
 8/16/2007



## **Appendix H**

### **Moyno Results**



# Appendix H – Moyno Results

H.1 Page 1

**MATERIAL  
CHARACTERISTICS &  
COMPATIBILITY**

**MOYNO INDUSTRIAL  
PRODUCTS**

PRELIMINARY TEST INFORMATION			
CUSTOMER:	BATTELLE PACIFIC NW NATIONAL LA AUTH. NO.:	5118	
MATERIAL:	DIESEL FUEL		
DATE:	3/17/2009	TEMP:	70 F
MATERIAL CHARACTERISTICS			
SPECIFIC GRAVITY:	1.05		
PH:			
ABRASION:	0		
VISCOSITY	.001 ft/sec.: 0	.1ft/sec.: 0	
ELASTOMER	FINAL RATINGS		
NITRILE	RM100		1
NATURAL	RM200		4
FDA EPDM	RM300		4
FKM	RMS20		1
	0		#DIV/0!
	0		#DIV/0!
RATING SPECIFICATIONS			
	1- SATISFACTORY		
	2- FAIR		
	3- DOUBTFUL		
	4- UNSATISFACTORY		
NOTES:			
Above ratings are subjective guidelines, and can not encompass all performance conditions. These ratings are to be used as reference only. Chemical capability is the responsibility of the end user.			
APPLICATIONS ENGINEER:	DATE:		
TECHNICIAN SIGNATURE:	DATE:	17-Mar-09	

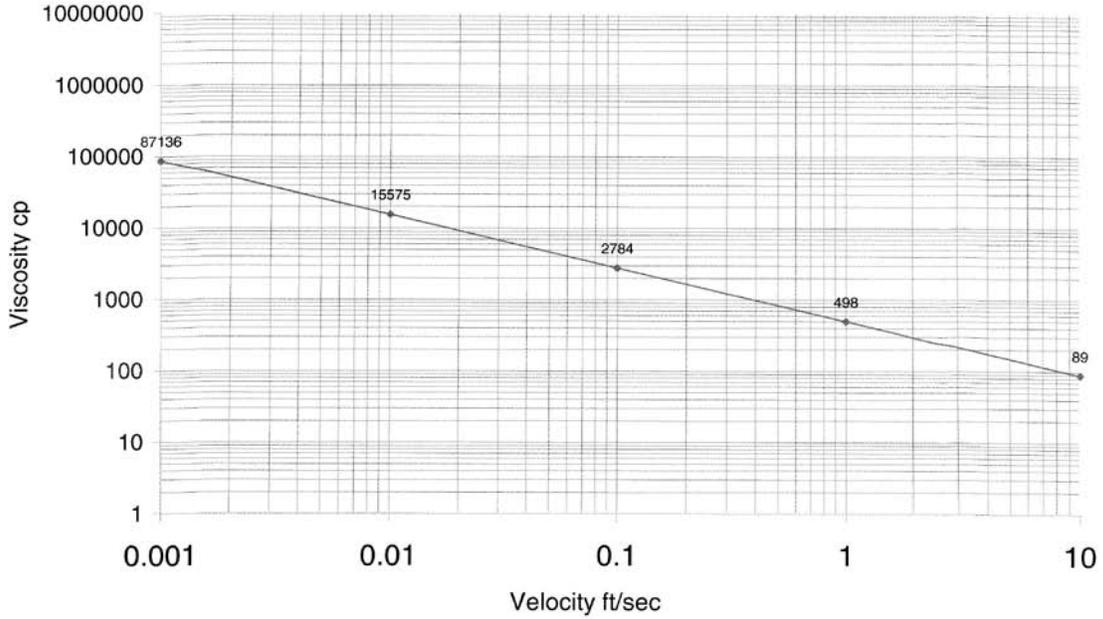
MATCHR1 3-17-95

## H.2 Page 2



Company Name: PACIFIC NW NATIONAL LA  
Sample Name: DIESEL FUEL

Test #: 5118  
Date: 3/10/09 2:21 PM



Temp Deg F: 70

Specific Gravity: 1.05

## **Appendix I**

### **Aurex 70 Castable Data Sheets**



# Appendix I – Aurex 70 Data Sheets

## I.1 Page 1

### AUREX® 70 CASTABLE



#### Product Data

10/04 4286

**Description:** Chrome-Alumina Castable Based on AUREX® and NOVACON® Technology

- Features:**
- Excellent corrosion resistance.
  - Contains a spall inhibitor for improved resistance to thermal shock.
- Uses:**
- Special applications where excellent resistance to slag, spalling, and chemical corrosion is required, such as incineration, coal gasification, and carbon black production.

#### Chemical Analysis: Approximate (Calcined Basis)

Chromium Oxide (Cr <sub>2</sub> O <sub>3</sub> )	68.5%
Alumina (Al <sub>2</sub> O <sub>3</sub> )	26.7%
Silica (SiO <sub>2</sub> )	2.4%
Iron Oxide (Fe <sub>2</sub> O <sub>3</sub> )	0.2%
Phosphorus Pentoxide (P <sub>2</sub> O <sub>5</sub> )	0.2%
Lime (CaO)	0.1%
Magnesia (MgO)	0.10%
Alkalies (Na <sub>2</sub> O+K <sub>2</sub> O)	0.3%
Other Oxides	1.6%

#### Physical Data (Typical)

Maximum Service Temperature	3,300°F (1816°C)
Material Required	218 lb/ft <sup>3</sup> (3.49 g/cm <sup>3</sup> )
Bulk Density	lb/ft <sup>3</sup> (g/cm <sup>3</sup> )
After 230°F (110°C)	220 (3.52)
After 2810°F (1543°C)	220 (3.52)
Modulus of Rupture	lb/in. <sup>2</sup> (MPa)
After 230°F (110°C)	200 (1.4)
After 2810°F (1543°C)	700 (4.8)
Cold Crushing Strength	lb/in. <sup>2</sup> (MPa)
After 230°F (110°C)	610 (4.2)
After 2810°F (1543°C)	4,650 (32.1)
Permanent Linear Change	
After 2810°F (1543°C)	0.0%
After 3300°F (1816°C)	+0.2%

Note: The data given above are based on averages of the results of a small number of test specimens made in the laboratory. Variation from the above data may occur in individual tests and in large-scale plant production. The test data cannot be taken as minimum or maximum values for specification purposes. ASTM test procedures used when applicable.

**AUREX® 70 CASTABLE**



Product Data

Mixing and Using Information (Water calculated at 8.337 lb/gallon)	55 lb bag	1000 lb bag	1500 lb bag
Water Required—Vibration Casting (Weight 5.0%)			
Pounds	2.8	50	75
Gallons	0.3	6.0	9.0
Liters	1.2	22.7	34.0
For detailed mixing and using instructions, contact your ANH representative or visit <a href="http://www.anhrefractories.com">www.anhrefractories.com</a> .			
Heatup/Dryout Schedule			
See ANH Dryout Schedule 11—NOVACON PRODUCTS.			
Installation Guidelines			
See ANH Installation Guidelines LCC-3—Low Cement Castables—Standard.			
Shelf Life (Under Proper Storage Conditions)		90 days	

## **Appendix J**

### **KAST-O-LITE Data Sheets**



# Appendix J – KAST-O-LITE Data Sheets

## J.1 Page 1

### KAST-O-LITE® 50-25



#### Product Data

1/09, 5925

**Description:** 2500°F Low-Density Insulating Castable

- Features:**
- Lightweight, super duty, hydraulic-setting castable.
  - High strength, insulating product.
  - Provides low thermal conductivity.
  - Can be installed by pouring or gunning.

- Uses:**
- Backup behind dense refractory.
  - Duct work for hot air and exhaust.

**Chemical Analysis:** Approximate (Calcined Basis)

Silica (SiO <sub>2</sub> )	34.9%
Alumina (Al <sub>2</sub> O <sub>3</sub> )	48.0%
Iron Oxide (Fe <sub>2</sub> O <sub>3</sub> )	1.6%
Titania (TiO <sub>2</sub> )	1.4%
Lime (CaO)	12.2%
Magnesia (MgO)	0.3%
Alkalies (Na <sub>2</sub> O+K <sub>2</sub> O)	1.6%

Physical Data (Typical)	Conventional Cast/Poured	Gunned
Maximum Service Temperature	2500°F (1370°C)	2500°F (1370°C)
Material Required	58 lb/ft <sup>3</sup> (0.93 g/cm <sup>3</sup> )	76 lb/ft <sup>3</sup> (1.22 g/cm <sup>3</sup> )
Bulk Density	lb/ft <sup>3</sup> (g/cm <sup>3</sup> )	lb/ft <sup>3</sup> (g/cm <sup>3</sup> )
After 220°F (105°C)	62 (0.99)	81 (1.30)
After 1500°F (815°C)	58 (0.93)	76 (1.22)
Modulus of Rupture	lb/in. <sup>2</sup> (MPa)	lb/in. <sup>2</sup> (MPa)
After 220°F (105°C)	200 (1.4)	400 (2.8)
After 2000°F (1095°C)	100 (0.7)	300 (2.1)
After 2500°F (1370°C)	300 (2.1)	500 (3.5)
Cold Crushing Strength	lb/in. <sup>2</sup> (MPa)	lb/in. <sup>2</sup> (MPa)
After 220°F (105°C)	650 (4.5)	800 (5.5)
After 2000°F (1095°C)	125 (0.9)	500 (3.5)
After 2500°F (1370°C)	600 (4.1)	1,200 (8.3)
Permanent Linear Change		
After 220°F (105°C)	None	None
After 2000°F (1095°C)	-0.4%	-0.1%
After 2500°F (1370°C)	+1.3%	+2.5%
Thermal Conductivity	Btu-in/hr-ft <sup>2</sup> °F (W/m °C)	
At 400°F (205°C)	1.7 (0.25)	N/A
At 800°F (425°C)	1.8 (0.26)	
At 1200°F (650°C)	1.9 (0.27)	
At 1600°F (870°C)	2.1 (0.30)	
At 2000°F (1095°C)	2.5 (0.36)	

Note: The test data shown are based on average results on production samples and are subject to normal variation on individual tests. The test data cannot be taken as minimum or maximum values for specification purposes. ASTM test procedures used when applicable.

KAST-O-LITE® 50-25			
Product Data			
Mixing and Using Instructions (Water calculated at 8.337 lb/gallon)	55 lb bag	1000 lb bag	1500 lb bag
<b>Water Required—Hand Casting (Weight 45.0%)</b>			
Pounds	24.8	450.0	675.0
Gallons	3.0	54.0	81.0
Liters	11.2	203.9	305.9
<b>Water Required—Predampening for Gunning (Weight 13.0%)</b>			
Pounds	7.2	130.0	195.0
Gallons	0.9	15.6	23.4
Liters	3.2	58.9	88.4
For detailed mixing and using instructions, contact your ANH representative or visit <a href="http://www.anhrefractories.com">www.anhrefractories.com</a> .			
<b>Heatup/Dryout Schedule</b>			
See ANH Dryout Schedule 3—Standard Insulating Castables and Gunning Castables.			
<b>Installation Guidelines</b>			
See ANH Installation Guidelines IC-3—Insulating Castables—Castable/Gunnable.			
<b>Shelf Life (Under Proper Storage Conditions)</b>		365 days	



## **Appendix K**

### **BTU-BLOCK Data Sheets**



# Appendix K – BTU-BLOCK Data Sheets

## K.1 Page 1

### Thermal Ceramics **BTU-BLOCK Panel 1208/16**

Product Information



BTU-BLOCK products are a family of microporous insulation designed for use in high temperature industrial applications. Microporous insulation is a very high thermal efficiency material which has a thermal conductivity less than that of still air. These materials, consisting of fine diameter heat resistant particles, reinforcement fibers and high temperature radiation blockers, address the primary modes of heat transfer in a novel way compared to traditional refractories. These components are appropriately sized and configured to create a microporous structure. This structure limits the number and movements of air particles, and creates a material of exceptionally low thermal conductivity. At elevated temperatures, the radiation blockers are employed to minimize radiation heat transfer by again proper sizing and distribution.

- **Minimizing heat loss** relates simply to energy saving, or reheat issues. For example, steel ladles containing back-up microporous insulation have substantially less solidified steel remaining in the ladle after the casting process is complete.
- **Consistency of operating temperature**, which results in a more consistent final product or an easier process to regulate and control.
- **Minimum space requirements** for an equivalent temperature drop across the insulation component, microporous material may need as little as  $\frac{1}{4}$  the thickness compared to traditional fibrous material (at elevated temperatures).

BTU-BLOCK Panel consists of BTU-BLOCK Board encapsulated in a high temperature textile. The exterior fabric maximizes the strength of the panel while providing a lightweight, low thermal conductivity finished product. The textile also offers mechanical protection, flexural strength and an excellent substrate for bonding the panels to walls or other insulation. These panels are easily cut to shape, however the cut edge should be sealed if the part is to undergo any movement.

Standard BTU-BLOCK Panel 1208/16 consists of a 1200°F (649°C) rated outer textile, while the core has a continuous use limit of 1800°F (982°C). By substituting a higher temperature cloth, such as a silica or quartz cloth, the use limit of the entire composite can be increased to 1800°F (982°C).

Degradation of the textile may not be a concern after initial installation depending on the application.

#### Features

- Extremely low thermal conductivity and heat loss
- High compressive strength
- Fiberglass encapsulation provides flexural strength and surface for bonding (1200°F [649°C] use limit)
- Special facing allows use limit up to 1800°F (982°C)

#### Applications

- OEM
- High temperature industrial
- Fire protection
- Vending machines
- Appliances

#### Physical Characteristics

Core density, pcf ( $kg/m^3$ )	16 (256)
Standard panel size, in (cm)	24 x 36 (60 x 90)
Standard thicknesses, in (cm)	$\frac{1}{2}$ - 2 (1.25, 5.1)

Note: Parts may be supplied in custom shapes and sizes to meet customer requirements.

## BTU-BLOCK Panel 1208/16

Product Information

**Physical Properties**

Continuous use limit, up to °F (°C)	
Panel core	1800°F (982°C)
Glass cloth	1200°F (649°C)
Specialty fabric	1800°F (982°C)
Fired linear shrinkage, % (ASTM C 356) 24 hrs	
@ 1000°F (538°C)	0.3
@ 1500°F (815°C)	0.6
@ 1750°F (954°C)	1.0

**Thermal Conductivity, Btu·in./hr·ft<sup>2</sup>·°F (w/m·k) ASTM C 201**

Mean temperature	
@ 500°F	0.18 (0.02)
@ 1000°F	0.23 (0.03)
@ 1500°F	0.31 (0.04)

**Compression Resistance, ASTM C 165**

Deformation 16 pcf material, psi (Mpa)	
10%	173 (1.19)
20%	315 (2.17)
30%	458 (3.16)
40%	641 (4.42)

The values given herein are typical average values obtained in accordance with accepted test methods and are subject to normal manufacturing variations. They are supplied as a technical service and are subject to change without notice. Therefore, the data contained herein should not be used for specification purposes. Check with your Thermal Ceramics office to obtain current information.

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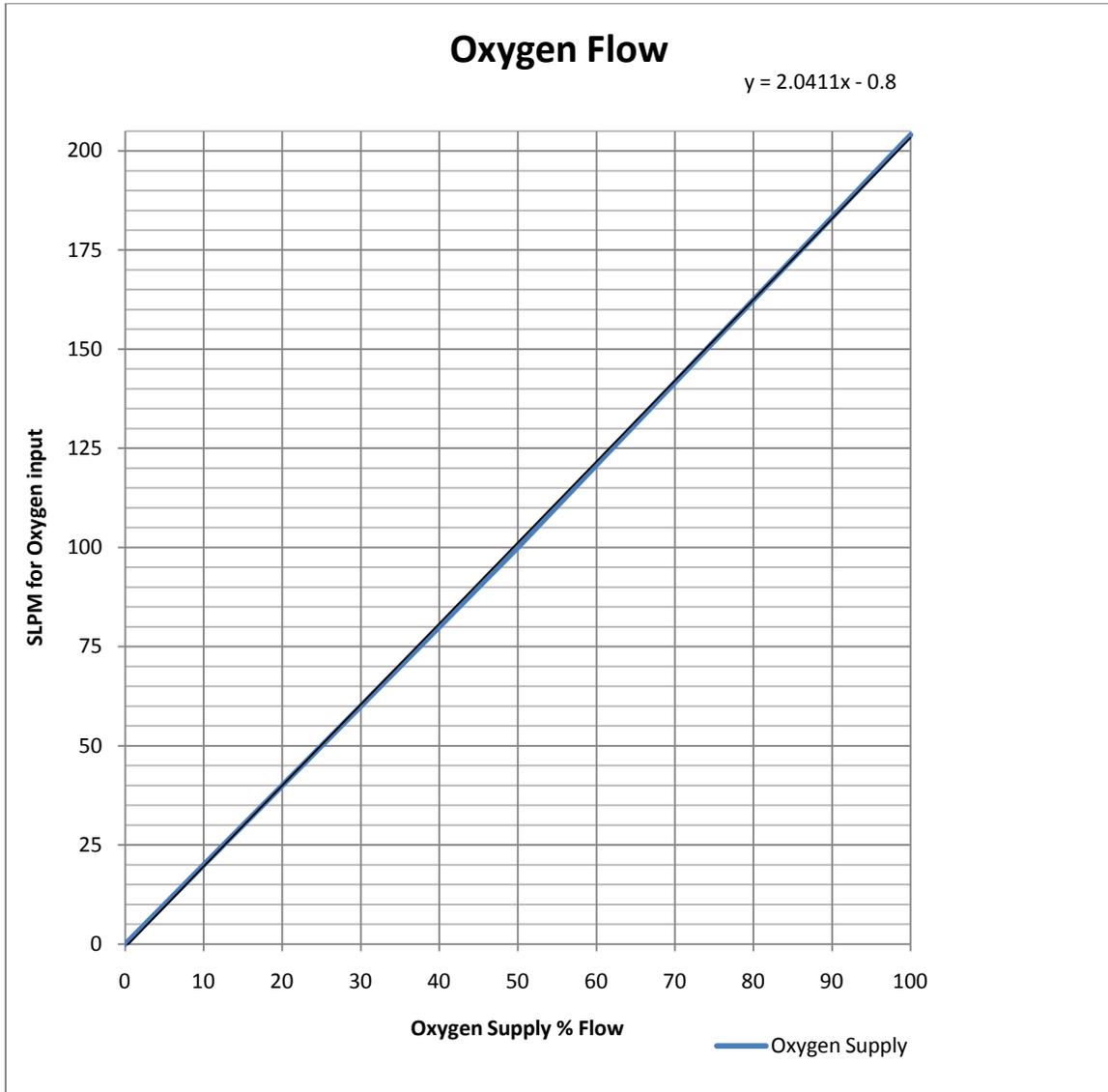
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## **Appendix L**

### **Oxygen Flow Calibration Curve**



## Appendix L – Oxygen Flow Calibration Curve



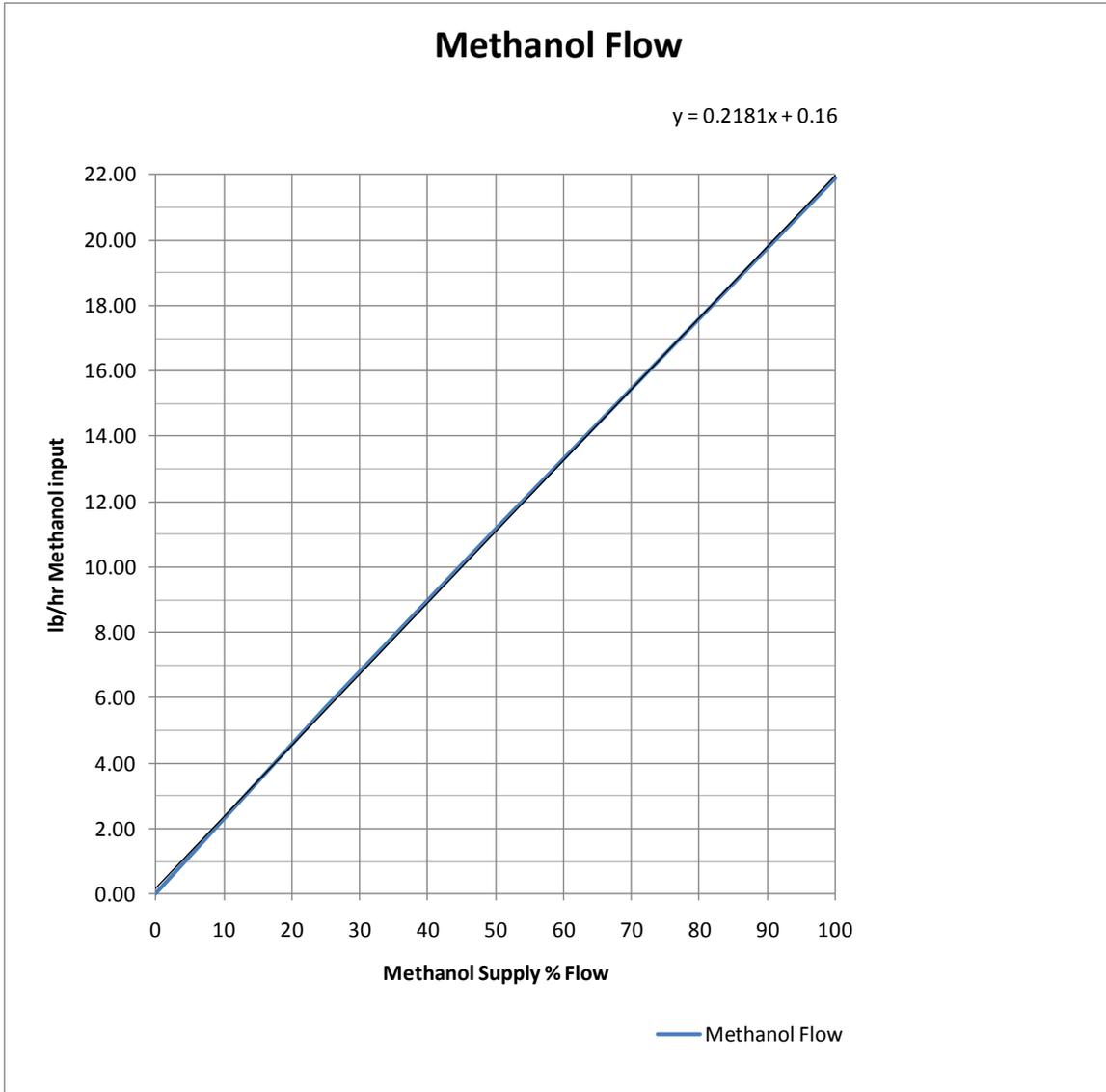


## **Appendix M**

### **Methanol Pump Calibration Curve**



# Appendix M – Methanol Pump Calibration Curve



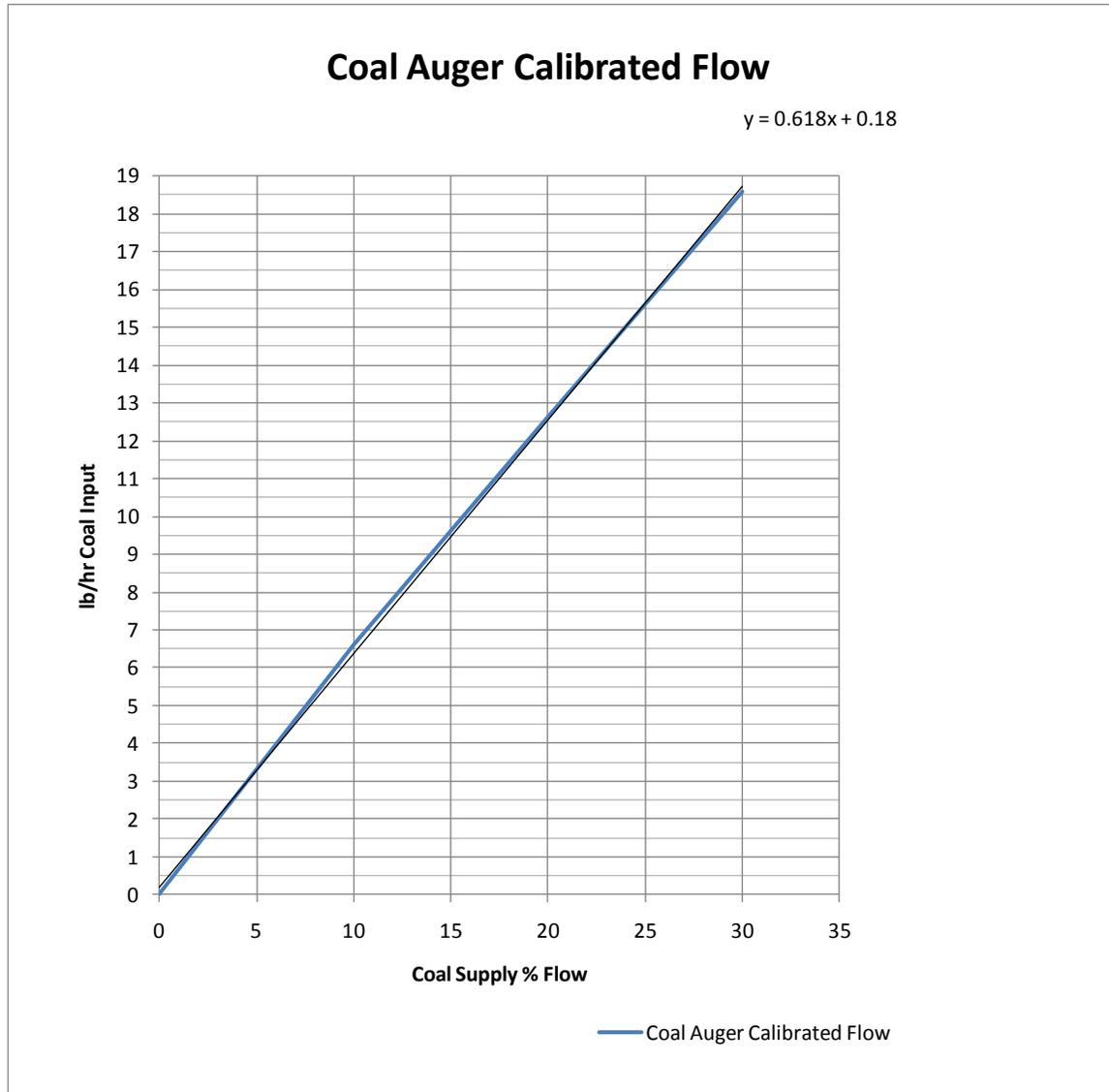


## **Appendix N**

### **Coal Auger Calibrated Flow Curve**



## Appendix N – Coal Auger Calibrated Flow Curve





## **Appendix O**

### **Sensitivity Analysis for Methanol Input Change**



## Appendix O – Sensitivity for Methanol Input Change

**Table O.1.** E85 (Methanol Substitute) Fuel Sensitivity Data

Time interval	Input	Output Syngas					Output syngas ratios		
Minutes	E85 Fuel %	CO %	CO <sub>2</sub> %	CH <sub>4</sub> %	H <sub>2</sub> %	inert constituent %	CO/(CO+CO <sub>2</sub> ) % ratio	CO/H <sub>2</sub> % ratio	
0	20	9.7	25.8	20	7.4	37.1	0.27	1.31	
5	21	10.5	25.4	19.5	8.4	36.2	0.29	1.25	
10	22	12.5	23.7	20	10	33.8	0.35	1.25	
15	23	15	22.4	18.9	12	31.7	0.40	1.25	
20	24	17.5	20.4	18.4	14	29.7	0.46	1.25	

**Table O.2.** E85 (methanol substitute) Fuel Sensitivity Summary

Time interval	Total input change	Output syngas change					Output syngas ratio changes		
Minutes	E85 Fuel %	CO %	CO <sub>2</sub> %	CH <sub>4</sub> %	H <sub>2</sub> %	inert constituent %	CO/(CO+CO <sub>2</sub> ) % ratio	CO/H <sub>2</sub> % ratio	
20	4	7.8	-5.4	-1.6	6.6	-7.4	0.189	-0.061	

**Table O.3.** E85 (methanol substitute) Fuel Sensitivity Temperature Profile

Time interval	Thermocouple Output Temperature (degrees Celsius)			
Minutes	TC 1	TC 2	TC 3	TC 4
0	943	715	493	264
5	951	719	491	268
10	965	723	492	272
15	975	724	494	275
20	984	727	492	278

**Table O.4. Oxygen Input Sensitivity Data**

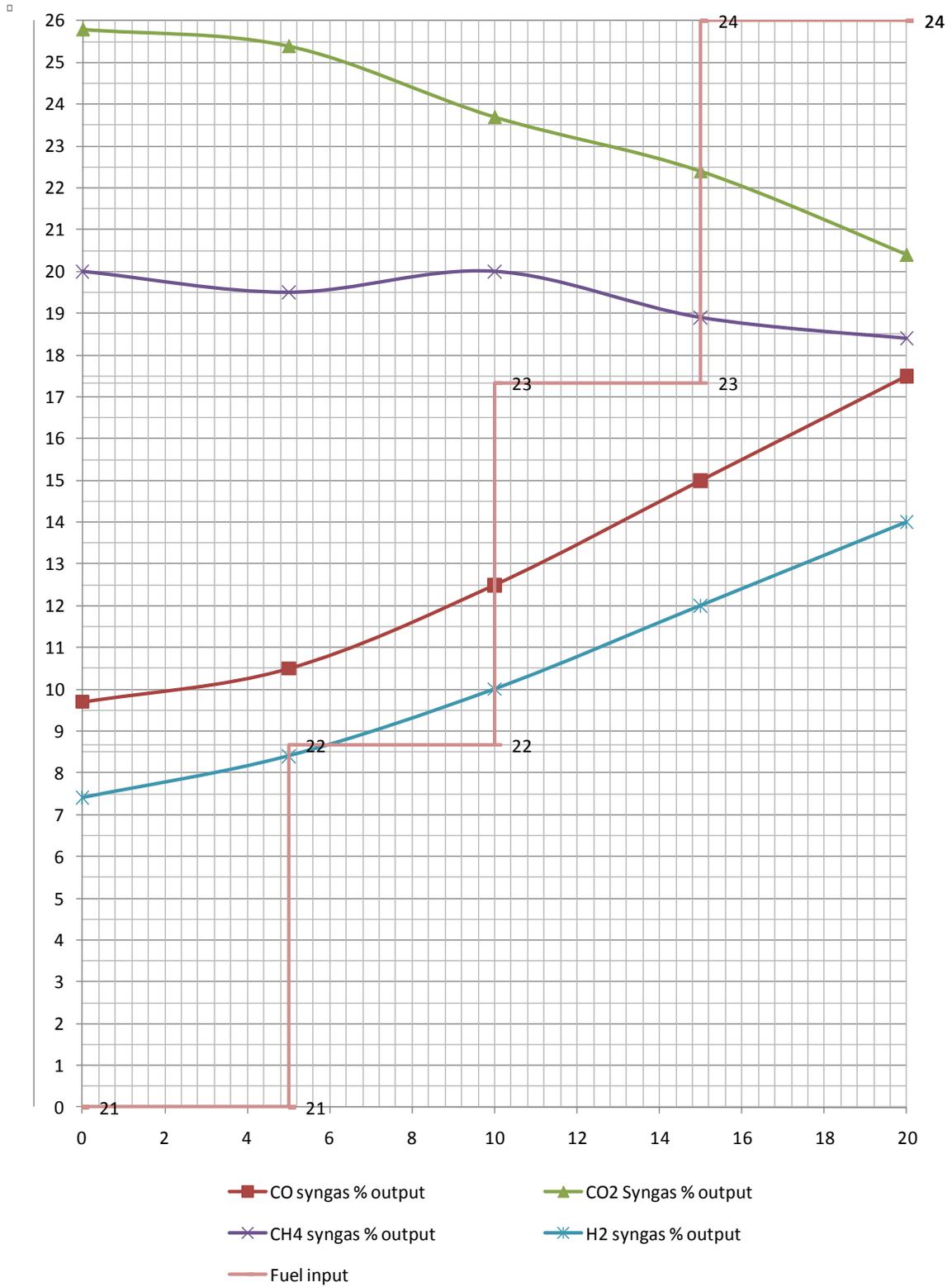
<b>Time interval</b>	<b>Input</b>	<b>Output Syngas</b>					<b>Output syngas ratios</b>	
<b>Minutes</b>	<b>Oxygen %</b>	<b>CO %</b>	<b>CO<sub>2</sub> %</b>	<b>CH<sub>4</sub> %</b>	<b>H<sub>2</sub> %</b>	<b>inert constituent %</b>	<b>CO/(CO+CO<sub>2</sub>) % ratio</b>	<b>CO/H<sub>2</sub> % ratio</b>
0	18	17.5	20.4	18.4	14	29.7	0.46	1.25
5	19	18.6	19.2	18.9	15	28.3	0.49	1.24
10	20	19.1	18.9	18.2	15.5	28.3	0.50	1.23
15	20	20	19.1	15.7	16.3	28.9	0.51	1.23

**Table O.5. Oxygen Input Sensitivity Summary**

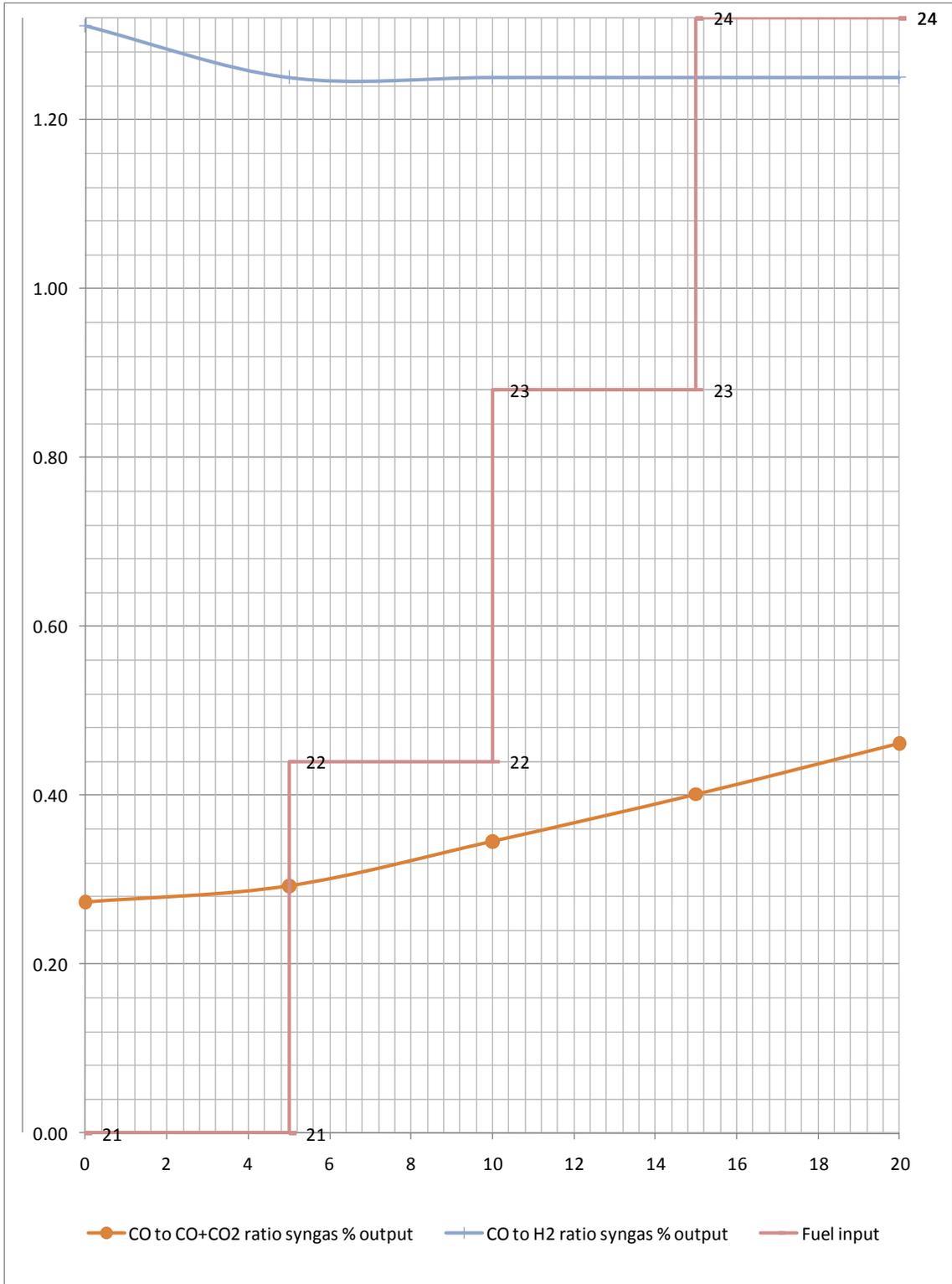
<b>Time interval</b>	<b>Total input change</b>	<b>Output syngas change</b>					<b>Output syngas ratio changes</b>	
<b>Minutes</b>	<b>Oxygen %</b>	<b>CO %</b>	<b>CO<sub>2</sub> %</b>	<b>CH<sub>4</sub> %</b>	<b>H<sub>2</sub> %</b>	<b>inert constituent %</b>	<b>CO/(CO+CO<sub>2</sub>) % ratio</b>	<b>CO/H<sub>2</sub> % ratio</b>
15	2	2.5	-1.3	-2.7	2.3	-0.8	0.050	-0.023

**Table O.6. Oxygen Input Sensitivity Temperature Profile**

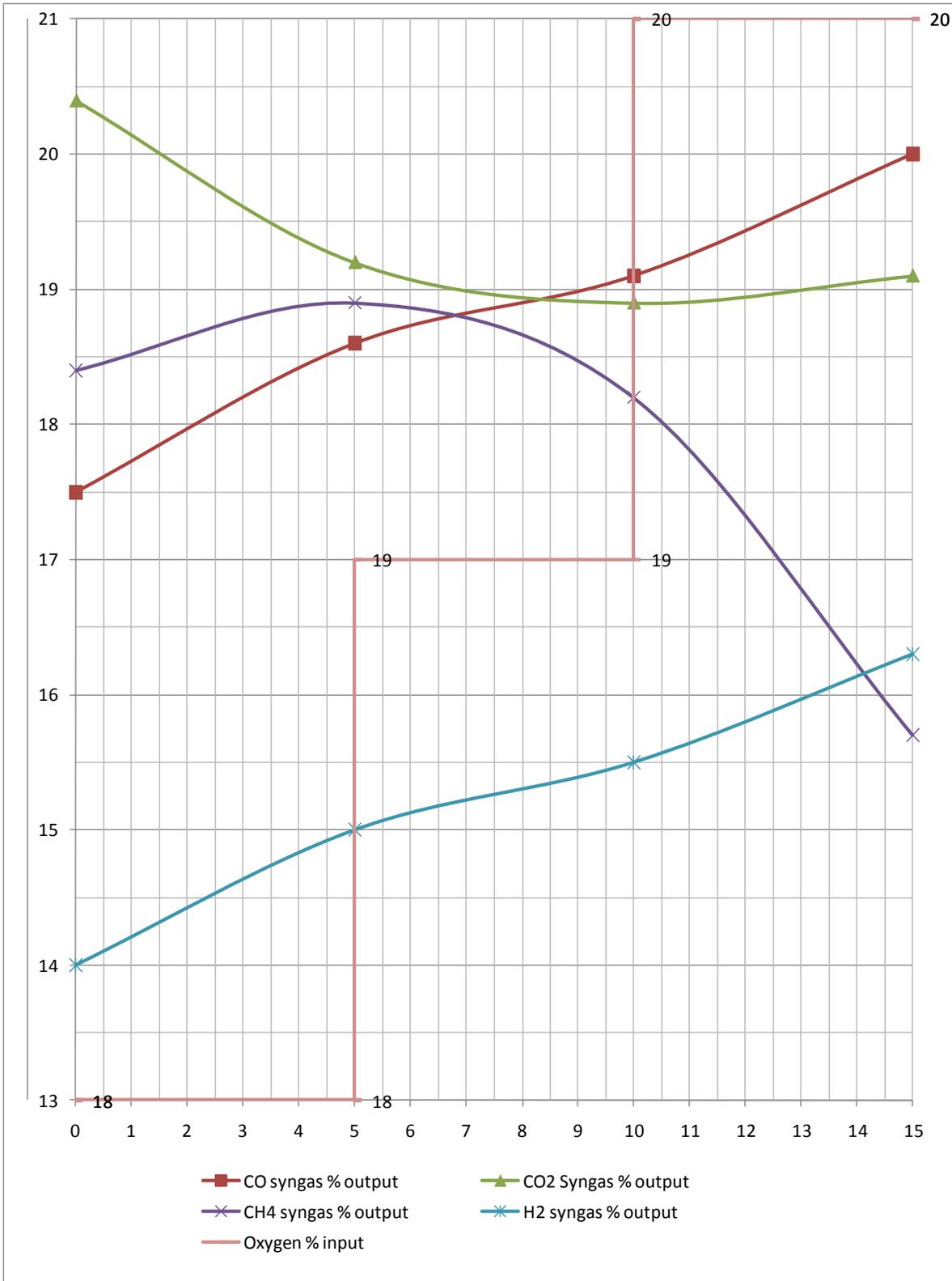
<b>Time interval</b>	<b>Thermocouple Output Temperature (degrees Celsius)</b>			
<b>Minutes</b>	<b>TC 1</b>	<b>TC 2</b>	<b>TC 3</b>	<b>TC 4</b>
0	984	727	492	278
5	993	730	491	282
10	1001	730	489	284
15	1014	732	489	287



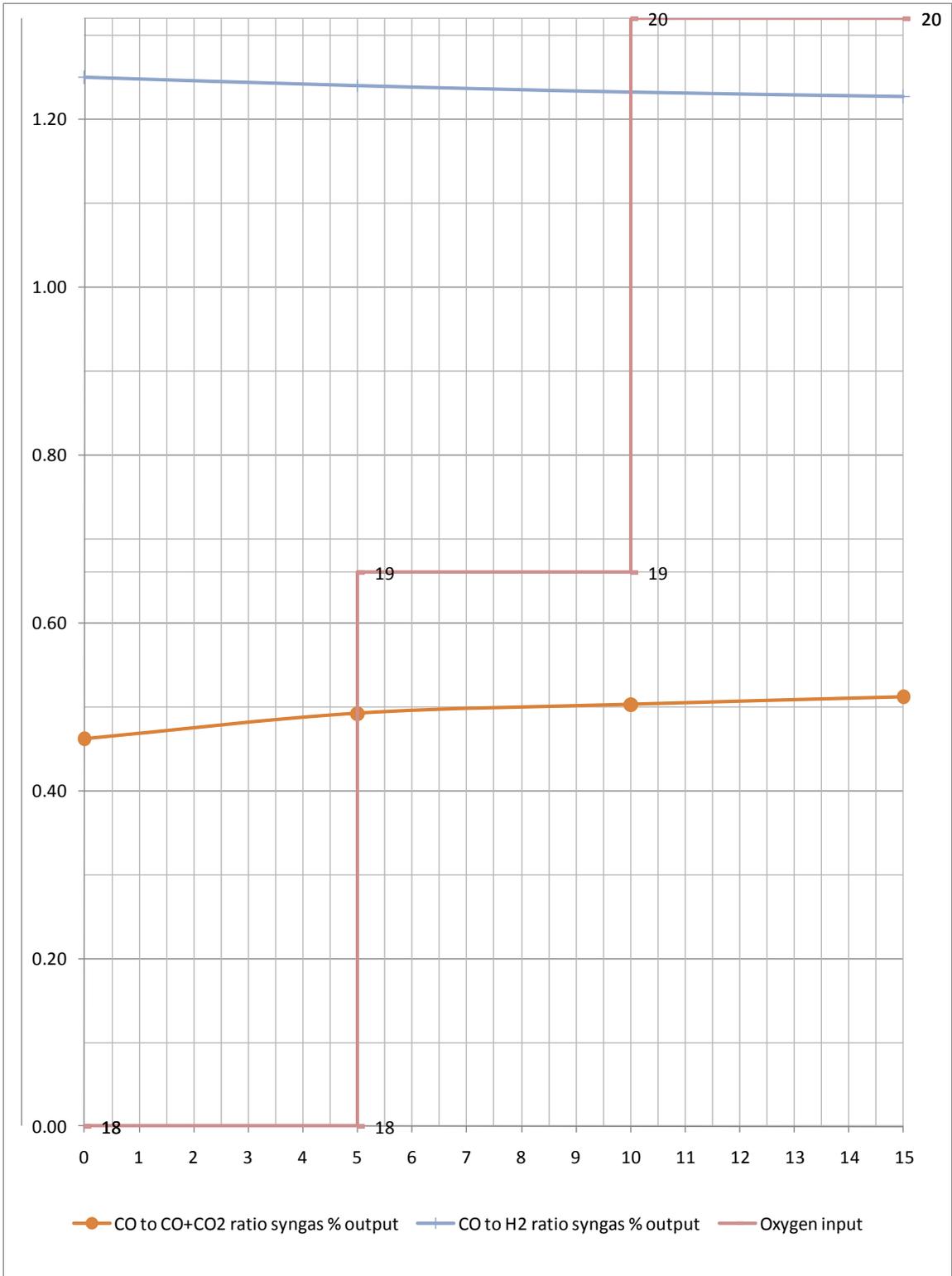
**Figure O.1.** Methanol Input Change versus Syngas Output



**Figure O.2.** Methanol Input Change versus Syngas Ratio Output



**Figure O.3.** Oxygen Input Change versus Syngas Output



**Figure O.4.** Oxygen Input Change versus Syngas Ratio Output

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