Calcium Oxide Chemical Looping with CO2 Capture for the Power Industry

Ninth Annual Carbon Capture and Sequestration Conference
May 10-13, 2010 in Pittsburgh, Pennsylvania, USA

Authors: Herbert E. Andrus, Jr., herbert.e.andrus@power.alstom.com
ALSTOM Power Inc., 2000 Day Hill Rd Windsor, CT 06095

Paul R.Thibeault, paul.r.thibeault@power.alstom.com
ALSTOM Power Inc., 2000 Day Hill Rd Windsor, CT 06095

John H. Chiu, john.h.chiu@power.alstom.com
ALSTOM Power Inc., 2000 Day Hill Rd Windsor, CT 06095

Bruce W. Lani, Bruce.Lani@NETL.DOE.GOV
US DOE, NETL, 626 Cochrans Mill Rd., Pittsburgh, PA

Abstract

Chemical looping has a potential for economical CO_2 Capture in coal-fired power plants. This process uses calcium oxides as oxygen carriers to transport oxygen from air to the fuel, which has the potential to capture CO_2 from new and existing coal-fired power plants while maintaining high plant power generation efficiency. This new power plant concept is based on a hybrid combustion-gasification process utilizing high temperature chemical and thermal looping technology. The chemical and thermal looping technology could also be potentially configured as a hybrid combustion-gasification process producing a syngas or hydrogen for various applications while also producing a separate stream of CO_2 for use or sequestration.

The process is being developed with funding from the US DOE National Energy Technology Laboratory's (NETL) Existing Plants Program. Development of the process has progressed through three phases and is currently in Phase IV, which will concentrate on designing, building and testing a 3 MWth prototype of the chemical looping process that will integrate all of the equipment and systems required to operate the facility. The prototype facility will be located in Windsor Ct. Operation of the facility will be used to characterize performance and develop design information for future plants.

Work in Phase I and Phase II validated the chemistry required for the chemical looping process, while work in Phase III investigated the solids transport mechanisms and design requirements. In Phase IV, preliminary design of prototype has been done including engineering, environmental permitting and general arrangements. Final design is underway and procurement is ongoing.

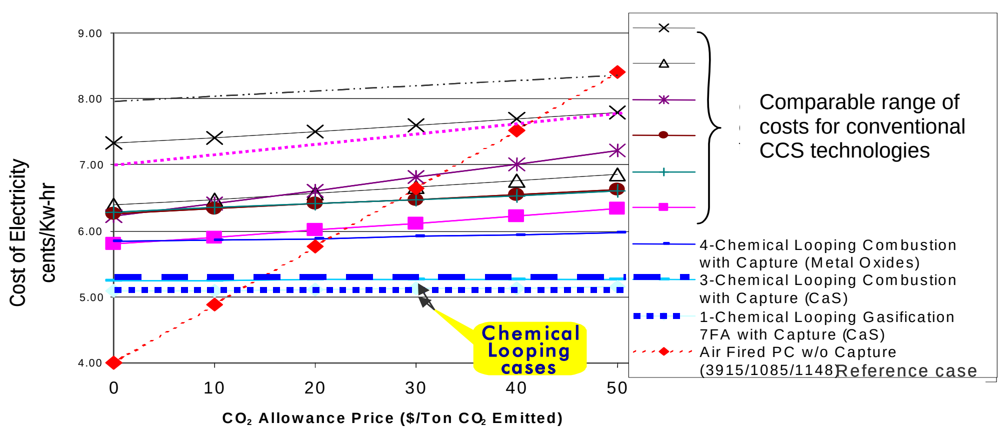
Background

Alstom has been working to develop and commercialize a novel chemical looping combustion process that is well suited for capturing nearly all of the CO_2 from existing or new pulverized-coal-fired (PC) and circulating fluidized bed (CFB) power plants with a cost of electricity increase of less than 20% compared with current coal-fired power plants. This process has been developed through pilot plant scale (10 lb/hr coal). The company was awarded a project (known as Phase IVA) to design, build and test a prototype version of this process (1000 lb/hr of coal). The purpose of the prototype is to to provide the information necessary for a reliable future commercial-size demonstration.

The project to design, build, and test a chemical looping prototype plant is part of an ongoing, US DOE sponsored, multiphase development program aimed at commercializing this chemical looping process. Phase I of the program developed and tested a high efficiency chemical looping combustion process with CO_2 separation and/or syngas production from coal with the calcium sulfide (CaS) / calcium sulfate ($CaSO_4$) loop at a small-scale process development unit (PDU) facility. Phase II of the program developed the lime (CaO) / calcium carbonate ($CaCO_3$) loop, for integration with the hybrid combustion-gasification loop from Phase I, and demonstrated the feasibility of hydrogen production from the combined loops in tests at the PDU. Phase III studied process control, solids transport and scale-up. All milestones for Phase I, II and III were successfully completed on time and on budget.

Alstom's commercial plant concepts, expected performance and economics have been described in previous papers (References 1 and 2). Figures 1 and 2 show that the chemical looping process economics are favorable. Figure 1 shows the cost of electricity of new capacity coal-fired power plants as a function of CO_2 allowance cost employing various CO_2 capture technologies including IGCC, oxy-firing with advanced O_2 technology, advanced post-combustion CO_2 scrubbing technologies and chemical looping alternatives. All of the studies were on the same basis as shown in the figure. The three chemical looping cases have the lowest potential cost of electricity (COE).

Figure 1 New Capacity Economics

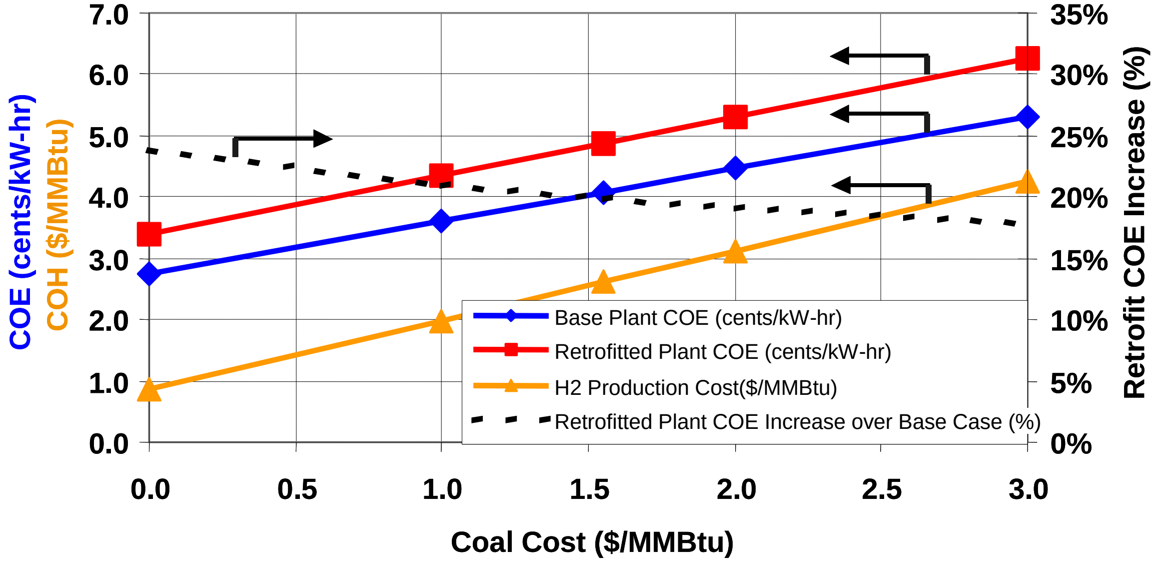


Basis:

- Plant size 400 MWe
- Steam conditions 3915 psia/1085 degF/1148 degF/2.5in Hga
- Cost basis 2006, $US
- Coal cost 1.5 $/MMBtu
- Levelized capital charge 13.8%
- Capacity factor 85%

Figure 2 shows the COE for retrofitted coal-fired power plants as a function of coal cost. The chemical looping facility produces CO_2-free hydrogen that is burned in an existing coal-fired boiler to produce the full original power at about a 20% increase in the COE as compared with the original COE.

Figure 2 Retrofit Economics



The economic potential is favorable. Phases I, II and III developed and tested the concept in a small PDU/pilot facility (about 10 lb/hr of coal). Phase IVA will construct and test the concept in a prototype plant (about 1000 lb/hr of coal). Successful completion of Phase IVA will be a major step forward to meet Alstom's overall objective of commercializing this low cost, high performance, environmentally clean, coal-fired power technology for capturing nearly all of the CO_2 from either existing or new coal-fired power plants.

Phase IVA is progressing. Alstom is completing the final engineering. The building and testing of the prototype will continue through 2010 and 2011. The facility includes all of the equipment that is required to operate the chemical looping plant in a fully integrated manner with all major systems in service. Because of its small scale relative to a commercial-size, coal-fired, chemical looping power plant, the prototype will have operating and performance limitations not applicable to commercial-size units. The principal limitations are as follows:

1. The unit will have height limitations because of zoning requirements. This means that the operating pressure of the Reducer will be about ½ to 1/3 of the commercial unit (i.e. 2 to 3 atmospheres absolute (ata) vs. 6 to 7 ata),
2. Heat loss through the vessel walls will be about 5% to 10% of the Coal HHV for the prototype vs. < 1% for a commercial-sized unit,
3. There will be no heat recuperation between the exit hot gas streams and incoming air as compared with the commercial-sized plants. The commercial plants will make nearly full use of the sensible energy of the exit gas stream by employing an air heater.

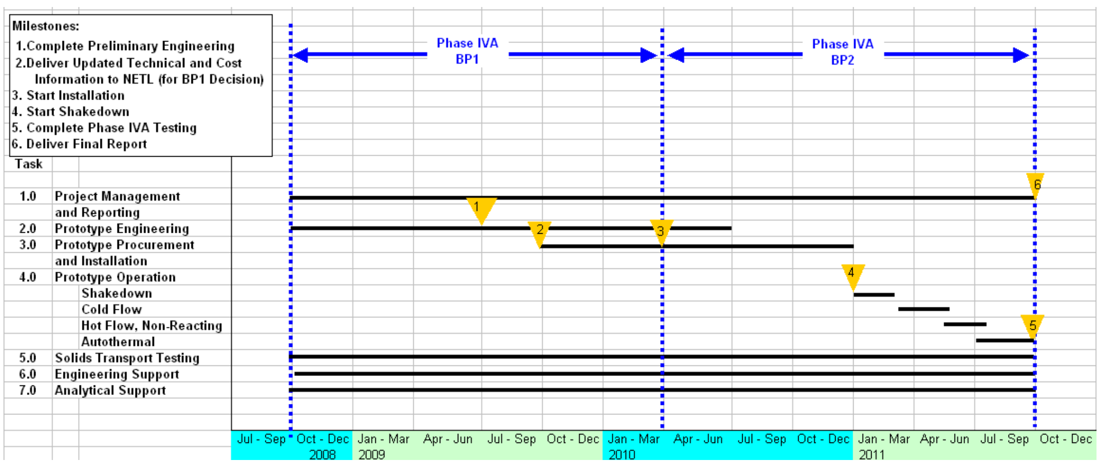
These limitations will not affect the ability of the prototype to achieve fully integrated, auto-thermal operation as required for scale-up to a commercial-sized demonstration. The limitations will, however, affect the CO_2 capture performance and gas making performance of the prototype resulting in less efficiency than will be achievable with a commercial-sized unit.

These limitations will be accounted for with the help of chemical looping process models. The process models are used to estimate the performance of the prototype. Modeling assumptions will be corrected based on prototype test results and then the model will be usable for scale up to commercial-sized units without the restrictions encountered by the prototype. This approach was successfully employed by Alstom in previous designs.

Data from the design, construction, and testing of the prototype will be used to characterize environmental performance, identify and address technical risks, reassess commercial plant economics, and develop design information for a demonstration plant planned to follow the proposed prototype. The objective of the prototype program is to learn how to operate the prototype, test the prototype to get the data required, apply the lessons learned to the commercial design and economics and plan for a future demonstration plant.

The schedule for Phase IVA is shown in Figure 3, which shows the milestones for Budget Periods 1 and 2.

Figure 3 Phase IVA Schedule



WORK COMPLETED IN Phase IVA

Alstom updated the information required for NEPA and submitted it to the U.S. Department of Energy (DOE) on October 18, 2009. Based on this information the US DOE concluded that no Environmental Assessment is required for this project.

Additionally, Alstom has completed the permitting work with the State of Connecticut Department of Environmental Protection (CT DEP). The CT DEP has concluded that no Air Permit is required for the prototype Facility to be built and tested during Budget Period 2. This successfully concludes all of the enabling environmental permitting actions for this project.

A design of the prototype plant (1000 lb/hr of coal) was completed based on the results of Phases I, II and III. It was designed to include all of the equipment necessary to test the chemical looping concept in the combustion mode and in the gasification mode. It includes a reducer and an oxidizer as well as the required transport lines. The product gas will be combined with the oxidizer exit gas stream and then burned in an existing fuel burning Test Facility, called the Industrial Scale Burner Facility (ISBF). After leaving the ISBF the exit gas will be cooled and then exhausted through an existing baghouse, particulate/SO_2 scrubber and stack.

The following design tasks were completed:

- Development of process flow diagram (PFD) and material balance,
- Heat loss calculations on prototype design,
- Heat-up rate calculations for a 1000 lb/hr prototype,
- Review and analysis of solids transport information from Phase III,
- Sizing of critical solids transport control equipment,
- Design of the prototype reactors,
- Safety requirements review,
- Development of control concept ,
- Development of piping and instrumentation diagram (P&ID),
- Plot plans, equipment and general arrangement,
- Specifications for facilities, fabricated equipment and vendor equipment,
- Quotes were procured

The prototype design that resulted from the work described above resulted in a design in which the prototype was standalone design with a separate building from the existing equipment at Alstom's facility. This design was reported in the previous papers (References 1 and 2)

Additional engineering was done to modify the prototype design to fit the prototype into an existing Alstom facility called the Multi-use Test Facility (MTF) and to use as much of the MTF equipment as possible. With this design the entire MTF equipment is used, and the MTF vessel itself is used as the oxidizer vessel for the prototype. The following additional engineering items were accomplished.

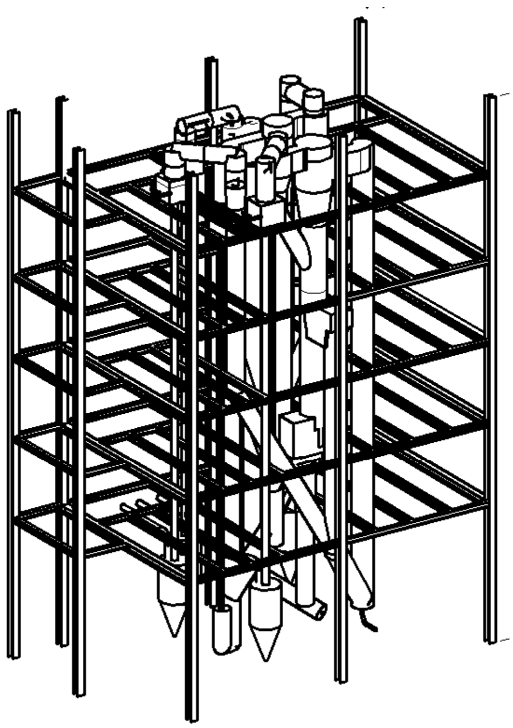
- The process flow diagram (PFD) was modified for the MTF design.
- A refractory liner was designed to fit in the existing MTF to reduce the MTF inner diameter to the size needed for the oxidizer.
- The solids transport control system for the MTF was modified,
- Heat-up rate calculations were reworked,
- Revised plot plans, equipment and general arrangement drawings
- An engineering study was done to determine if the existing MTF structure can support the extra weight,
- An engineering study of vessel and piping support methods was started.
- Engineering of the refractory installation was started.
- Revised specifications for facilities, fabricated equipment and vendor equipment,
- Revised quotes were procured

In support of the prototype design, cold flow transport testing is required. The configuration of the prototype is different in some respects from the configuration of the previously tested Pilot Plant. Accordingly, construction and testing of a cold flow model (CFM) of the prototype is required to study solids transport in the prototype configuration. The retrofitted prototype will be simulated in a small scale cold flow model.

Standalone Prototype Design

The original prototype concept was to build a separate building to house the prototype. The preliminary costs estimates indicated that this was feasible. However, after better design information was developed, it became apparent that the cost of a separate facility was too high. The original design as described in previous papers (References 1 and 2) is shown in Figure 4.

Figure 4 - Prototype Arrangement Isometric (Standalone Design)



Integrating the Prototype into the MTF

A revised prototype design was developed using the existing MTF facility. In this concept the existing MTF vessel is used as the oxidizer in the chemical looping system. All of the existing MTF equipment is used and all of the new equipment for the reducer and crossover lines is fit into the existing structure that houses the MTF.

The following modifications will be made to the standalone prototype design.

- The existing MTF vessel will be used as the oxidizer. A new refractory liner will be installed inside the old one to reduce the inner diameter of the MTF to the diameter needed by the oxidizer. All of the MTF equipment will be retained and used as much as possible. The MTF cyclone, feed system, heat exchangers, fans and gas cleanup system will be used.

- The first Calciner (Calciner 1) will be designed into the system to leave room in the arrangement. Calciner 1 will not be installed until Phase IV B, since the hot testing in Phase IVA will only include the auto-thermal test run of 40 hours. When the project proceeds to Phase IVB, Calciner 1 will be installed. In place of Calciner 1, a crossover line from the reducer bottom to the oxidizer will be used.

- The support structure and foundation for the MTF, as originally designed, can handle the extra weight of the new chemical looping vessels.

Revised Process Flow Diagram

A revised process flow diagram is shown in Figure 5. The PFD is color coded to indicate which equipment exists and which will be added to the existing MTF. The equipment drawn in blue represents existing MTF equipment and the equipment drawn in red indicates the new equipment. A green box is drawn around the Calciner 1 equipment to indicate that this will be installed later. For Phase IVA, Calciner 1 will be replaced by a crossover line directly from the reducer to the oxidizer.

Revised Prototype arrangement

The revised prototype arrangement is shown in Figures 6, 7 and 8. Figure 6 shows how the new equipment will fit into the existing MTF structure. The arrangements presented here include the future addition of Calciner 1 and its associated equipment. The equipment is a tight fit but manageable. The equipment is packed close together for another reason. Crossover pipes needed to be minimized in length. The further apart the equipment is, the smaller the angle the crossover lines can be. Crossover solids flow is enhanced by steep crossover lines. Figure 7 shows the equipment arrangement without the steel structure and identifies the components. Figure 8 shows the equipment arrangement in a top view.

The prototype installation in the MTF is located close to the ISBF facility which will be used to burn the product gas and clean the flue gas.

Table 8 Lists the revised prototype equipment and Weights.

Acknowledgement

Alstom would like to thank the many people at the US DOE NETL for their sponsorship and help with this work.

Figure 5 Revised Prototype Process Flow Diagram using MTF

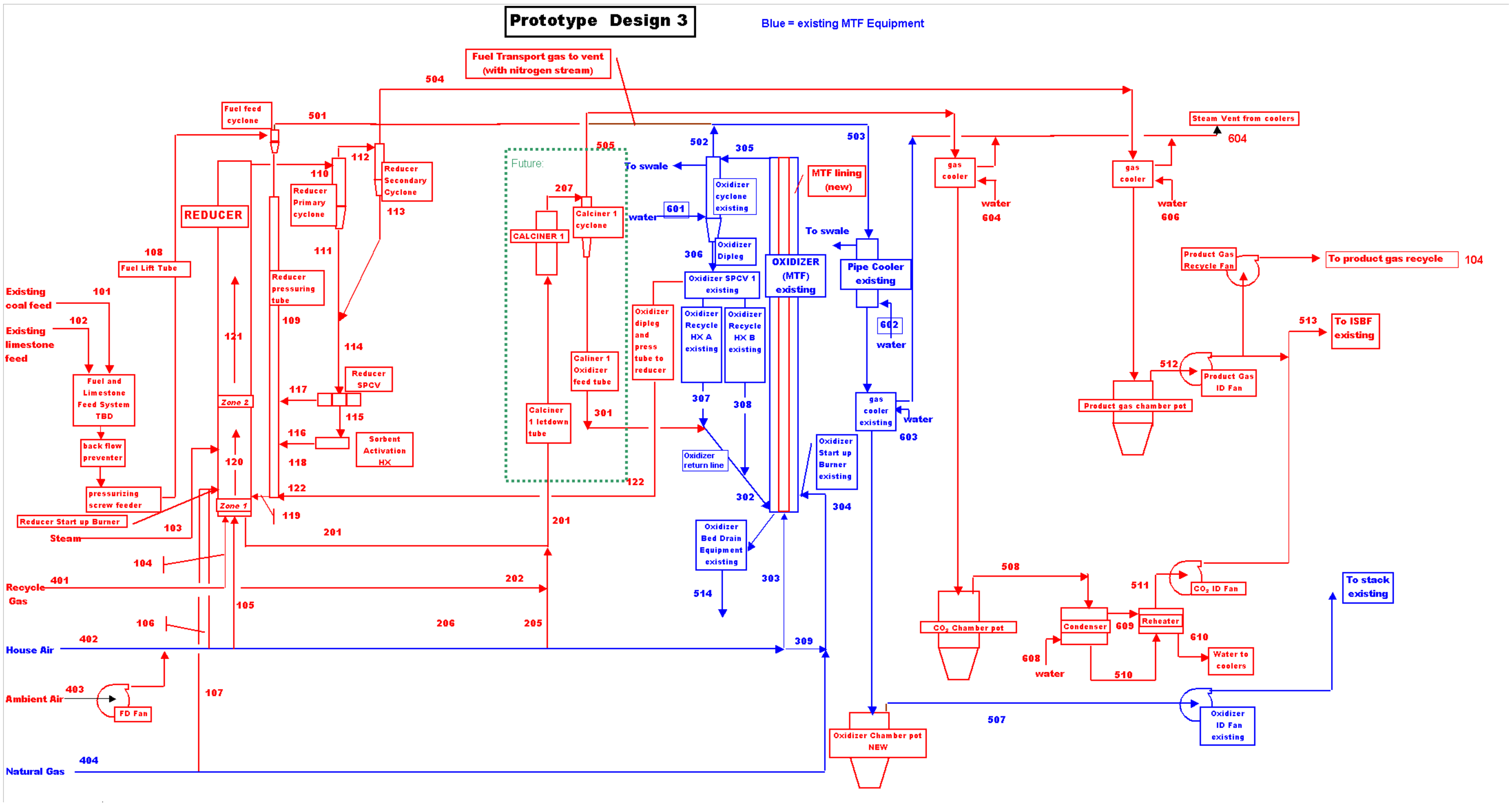
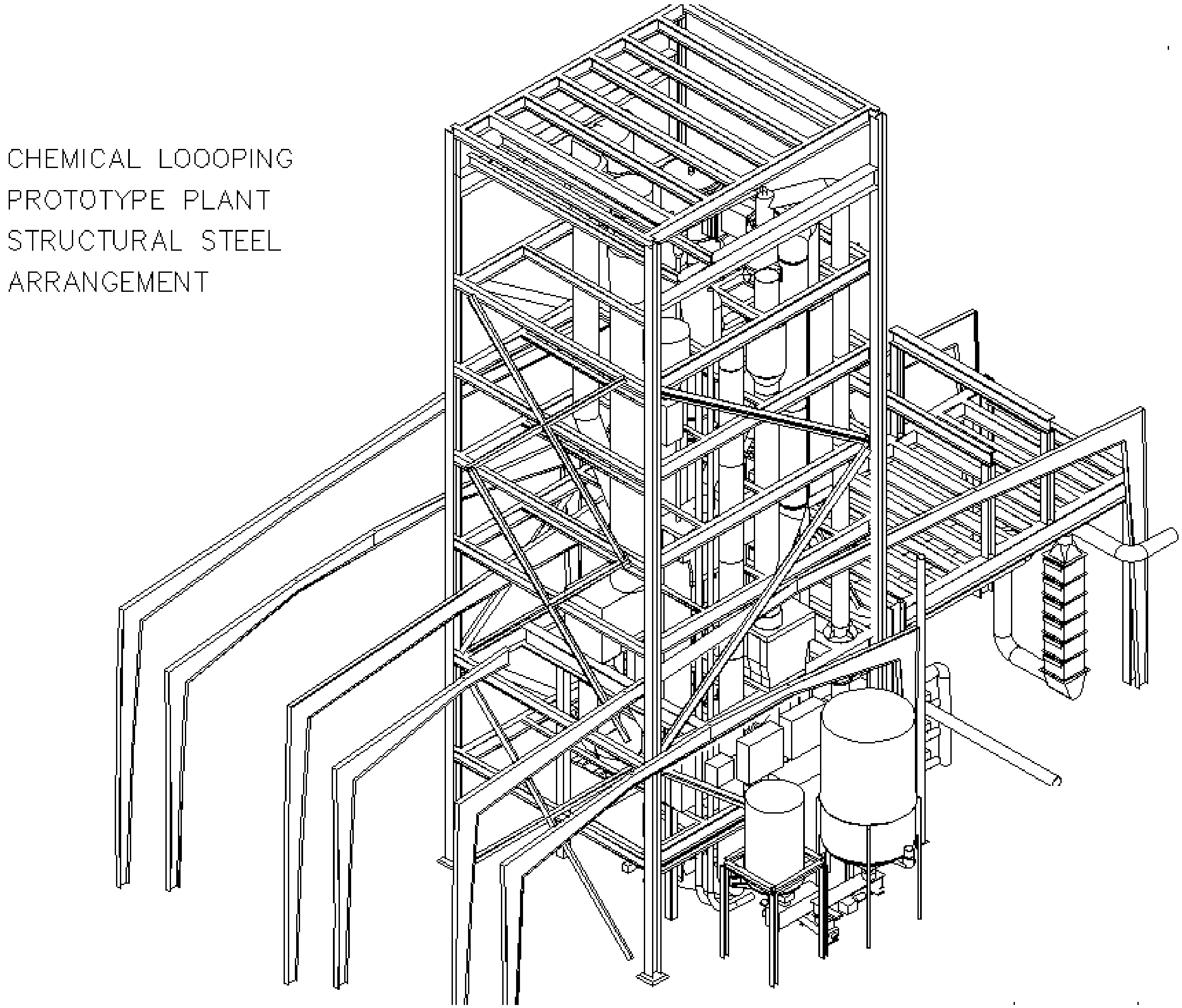


Figure 6 – Revised Prototype – Isometric View in Existing Steel



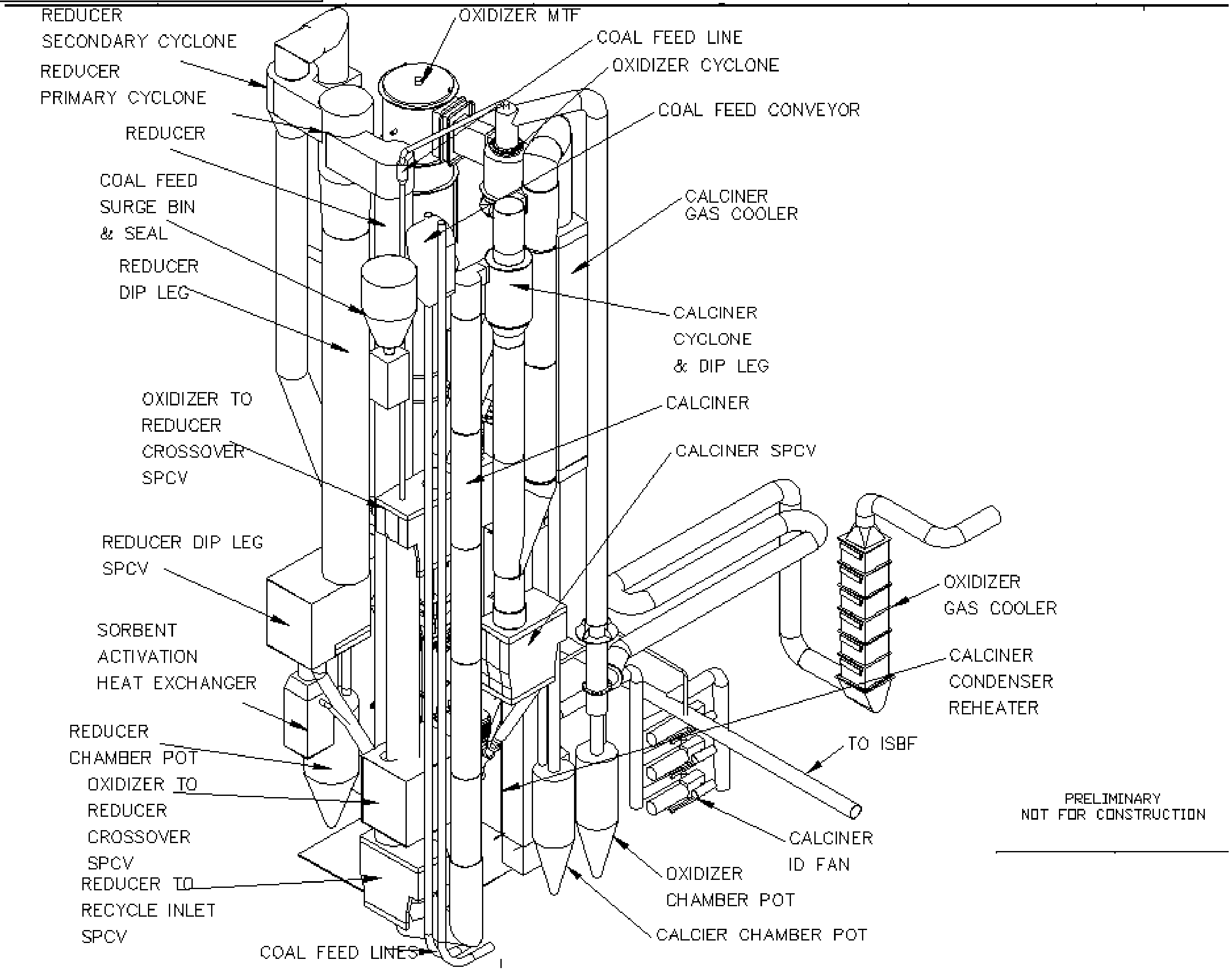
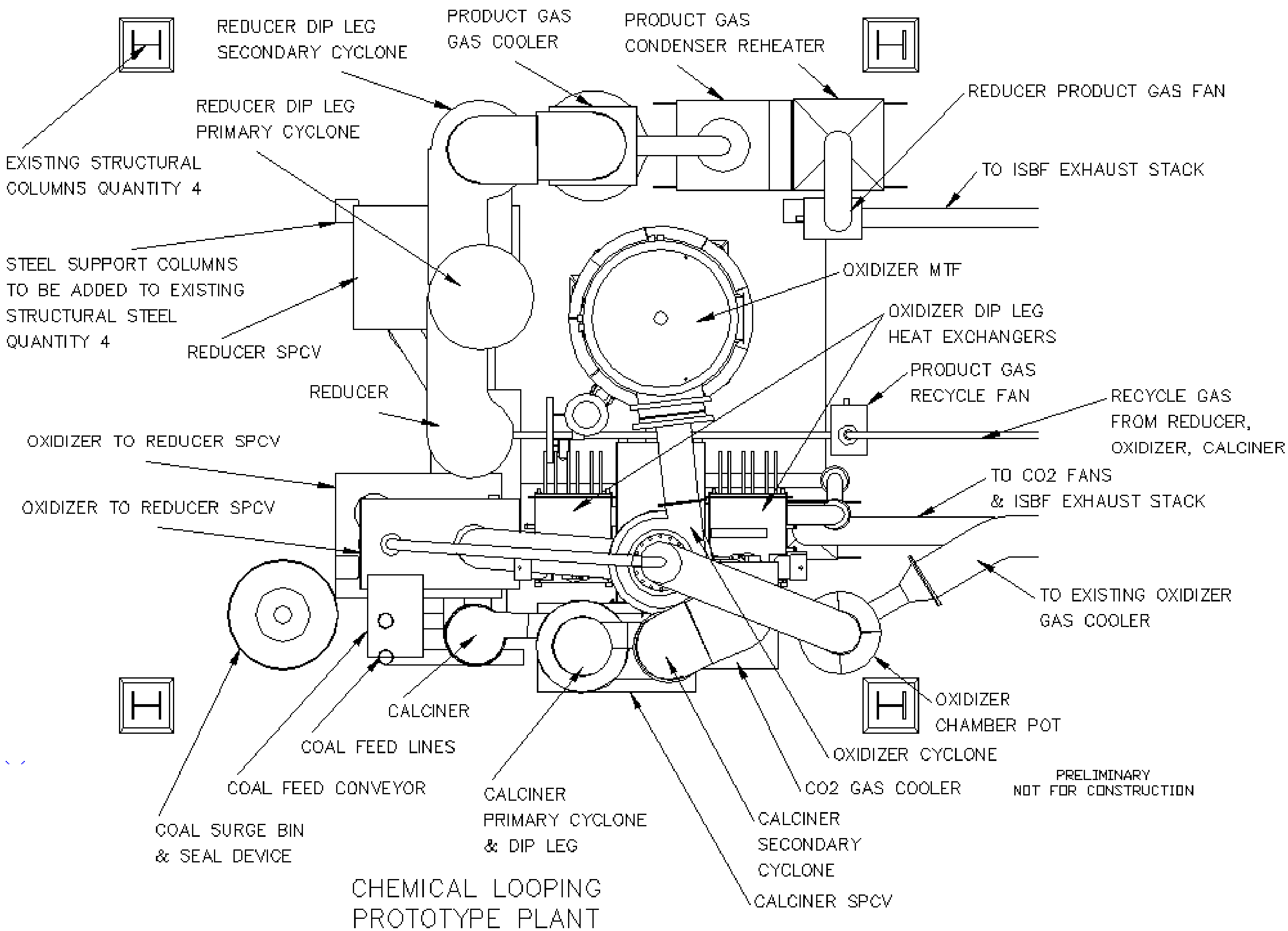


Figure 7 – Revised Prototype –Isometric View - Components

Figure 8 – Revised Prototype Design Using MTF – Top View



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