# ENGINEERING DEVELOPMENT OF ADVANCED COAL-FIRED

# LOW-EMISSION BOILER SYSTEMS - TECHNICAL PROGRESS REPORT NO. 17

QUARTERLY TECHNICAL PROGRESS REPORT

OCTOBER 1, 1996 - DECEMBER 31, 1996

PRINCIPAL AUTHORS: John W. Regan, David J. Bender
James P. Clark, James D. Wesnor

JANUARY 1997

CONTRACT DE-AC22-92PC92159

ABB POWER PLANT LABORATORIES
COMBUSTION ENGINEERING, INC.

2000 DAY HILL ROAD

P.O. BOX 500

WINDSOR, CONNECTICUT 06095-0500

## DISCLAIMER



## LIMITED RIGHTS NOTICE



## PATENT STATUS

Cleared by Chicago OIPC February 4, 1997.

.

## ABSTRACT

This report describes the work performed between October 1 and December 31, 1996 by the ABB team on U.S. Department of Energy project "Engineering Development of Advanced Coal-Fired Low-Emission Boiler Systems" (LEBS), which is part of the DOE's Combustion 2000 Program.

The overall objective of the LEBS Project is to dramatically improve environmental performance of future coal-fired power plants without adversely impacting efficiency or the cost of electricity. Near-term technologies, *i.e.*, advanced technologies that are partially developed, will be used to reduce $NO_X$ and $SO_2$ emissions to one-sixth current NSPS limits and particulates to one-third current NSPS limits.

# EXECUTIVE SUMMARY

The Project is under budget and generally on schedule. The current status is shown in the Milestone Schedule Status Report included as Appendix A. All Phase II reports were issued as scheduled. All project plans were updated in October (an annual requirement) and again in December (due to the addition of four months to the Phase III schedule.)

Technology transfer activities included delivering a technical paper at the 96 IJPGC (Appendix B) and submitting a paper abstract for the '97 CSTA Conference.

Task 12 work was completed and the Phase II Report was submitted.

Task 13 Work on optimizing the Kalina heat balance with the vapor generator design continued. Performance-type specifications were prepared for the three key CGU systems: vapor generator, turbine/generator, and NID system.

Task 14 The design basis for the revised POC Test Facility design was established, and approximately 65% of the technical work associated with revising the preliminary design package was completed. Drafts have now been completed for the four major permit applications required for the POCTF project, and one of these four (the air permit) has been finalized and submitted to the state.

Plans for the next reporting period include completing work on the revised POCTF preliminary design and continuing work on the revised CGU design and the POCTF test plan.

# INTRODUCTION

The Pittsburgh Energy Technology center of the U.S. Department of Energy (DOE) has contracted with Combustion Engineering, Inc. (ABB CE) to perform work on the "Engineering Development of Advanced Coal-Fired Low-Emission Boiler Systems" Project and has authorized ABB CE to complete Phase I on a cost-reimbursable basis and Phases II and III on a cost-share basis.

The overall objective of the Project is the expedited commercialization of advanced coal-fired low-emission boiler systems. The specified primary objectives are:

| | Preferred Performance | Minimum Performance |
|---|---|---|
| $NO_X$ Emissions, lb/million Btu | 0.1 | 0.2 |
| *$SO_2$ Emissions, lb/million Btu | 0.1 | 0.2 |
| Particulate Emissions, lb/million Btu | 0.01 | 0.015 |
| Net Plant (HHV) Efficiency, % | 42 | 38 |

*3 lb S/million Btu in the coal

The specific secondary objectives are:

- Improved ash disposability.
- Reduced waste generation.
- Reduced air toxics emissions.

The final deliverables are a design data base that will allow future coal-fired power plants to meet the stated objectives and a preliminary design of a Commercial Generation Unit.

The work in Phase I covered a 24-month period and included system analysis, RD&T Plan formulation, component definition, and preliminary Commercial Generating Unit (CGU) design.

The work in Phase II covered a 24-month period and included preliminary Proof-of-Concept Test Facility (POCTF) design and subsystem testing.

Phase III will cover a 6-month period beginning October 1, 1996 and will produce a revised CGU design and a revised POCTF design, cost estimate and a test plan.

Phase IV, the final Phase, will cover a 36-month period and will include POCTF detailed design, construction, testing, and evaluation.

The project is being managed by ABB CE as the contractor and the work is being accomplished and/or guided by this contractor, the DOE Contracting Officer's Representative (COR) and the following team members:

Subcontractors and Suppliers

- ABB Combustion Engineering Systems (ABBES)
- ABB Environment Systems, Inc. (ABBES)
- Raytheon Engineers and Constructors, Inc. (RE&C)

Consultants

- Dr. Janos Beér, MIT
- Dr. Jon McGowan, U. of Mass.

Advisors

- Association of Edison Illuminating Companies - Power Generation Committee (AEIC)
- Advanced Energy Systems Corporation (AES)
- Black Beauty Coal Company
- Electric Power Research Institute (EPRI)
- Illinois Clean Coal Institute (ICCI)
- Peridot Chemicals, Inc.
- Richmond Power & Light (RP&L)
- Southern Company Services, Inc. (SCS)

**RESULTS AND DISCUSSION**

## TASK 1 - PROJECT PLANNING AND MANAGEMENT

The Project is under budget and generally on schedule. The current status is shown in the Milestone Schedule Status Report included as Appendix A. All work in Task 1 and all Task 1 deliverables for the reporting period were competed on schedule. All Phase II and quarterly reports and all monthly Status, Summary, Milestone Schedule Status, and Cost Management reports were submitted on schedule.

The following plans were updated and issued on October 4, 1996.

- Milestone Plan
- Cost Plan
- QA/QC Plan
- Notice of Energy R&D
- Management Plan

These plans were updated again on December 6, 1996 to reflect the change in the Phase III end date from March 31, 1997 to July 31, 1997.

Technology transfer activities consisted of the following:

- A paper titled "ABB's LEBS Technologies" was delivered at the 1996 International Joint Power Generation Conference (96 IJPGC). See Appendix B.
- ABB chaired a technical session at the 96 IJPGC titled "Systems Development Under DOE's Combustion 2000 Program". The Vice Chairman was from DOE.
- An abstract of a paper titled "ABB's LEBS Technologies: Practical Solutions for Controlling Air Emissions and Increasing Efficiency" was submitted for the 22nd International Technical Conference on Coal Utilization and Fuel Systems. The abstract was accepted.

## TASK 13 - REVISED COMMERCIAL GENERATING UNIT DESIGN

To guide the development of the major equipment packages for the conceptual revised design of the commercial generating unit (CGU), performance-type specifications were prepared for the following:

- Vapor Generator System,
- Turbine/Generator System,
- New Integrated Desulfurization (NID) System.

The intent of these specifications is not to dictate the details of the process or the equipment design/fabrication for each system, which is the subject of on-going development work. Rather, the primary purpose of these documents is to define consistent design criteria to insure proper interface of each system with the overall plant configuration, and to define scope-of-supply and terminal points.

## TASK 12 - PHASE II REPORT

The Phase II Report was issued early in the reporting period. See Appendix C for a summary of the report.

## TASK 14 - POC TEST FACILITY REVISED DESIGN AND PLAN

### <u>Subtask 14.1:</u> Revised Engineering Design of the POC Test Facility

*Design Basis*

The basis for the revised POCTF design is a new Kalina heat balance that incorporates 34 heat exchangers, rather than the 50-exchanger set used in the original (Task 8) design. In addition, a number of project-optimization design changes were developed at a project review meeting in mid-November, were subsequently reviewed with RP&L, and have been adopted for inclusion in the revised preliminary design.

The revised Kalina heat balance is shown on Drawing No. 96800-D-200101-SK, and the design changes are summarized in Table 14-1.

*Preliminary Design*

The first step in revising the preliminary design package was to modify the process flow diagrams:

- Gas-side heat balance,
- Turbine heat balance,
- Water balance,
- Ammonia balance.

The first of these diagrams is presented on Drawing No. 96800-D-200102-SK for the performance coal (Black Beauty). The major process changes that have been incorporated in this diagram are the switch from pressurized mills to suction-type mills, and minor changes in the gas flows/temperatures through the vapor generator as a result of design changes to this component. The balance of the gas-side configuration reflects the original design.

The P&ID's for the power cycle (*e.g*., Kalina system) were first revised to reflect the new Kalina (or turbine) heat balance, including the reduced number of heat exchangers, new pumping configurations, and associated piping/instrumentation changes. These P&ID's are a set of 12 diagrams, of which one (Condensate System) is shown in Drawings No. 96800-D-211103-SK and -211104-SK.

The P&ID's for the auxiliary mechanical systems were also revised to incorporate the variety of changes specified in Table 14-1. As an example, the Ammonia Blowdown & Recovery System is shown in Drawing No. 96800-D-211126-SK. In contrast to the original system in which waste ammonia was reprocessed and recycled into the power system, the new arrangement follows the approach successfully implemented at the Kalina facility in Canoga Park. Here, all discharges of working fluid from the power cycle are collected in a blowdown tank containing an initial charge of water and equipped with a spray system for capture of ammonia vapor. The ammonia solution is allowed to build up to a weak concentration of 12-15%, at which time a portion of the inventory is transferred to the adjacent waste tank for off-site processing, and fresh water is added to the blowdown tank.

The new plant general arrangements are shown in the plot plan, Drawing No. 96800-E-150101-SK. The primary changes that occur in this perspective are the heat exchanger building and some of the yard facilities. Due to the reduced number of Kalina heat exchangers, the plan area required for the heat exchanger building is reduced by 30-35%. In addition, the heat exchanger arrangement has been optimized to reduce piping, to consolidate the pumping stations, and to provide a facility that is more easily operated and maintained. The revision of the blowdown & ammonia recovery system has also reduced some of the equipment located in the yard and reconfigured the waste tankage arrangements.

All calculations associated with the revised mechanical and power systems have been, or are being, updated. These revisions include, for example, equipment size and performance for individual systems, pipe sizing and pressure drop, high energy piping flexibility, and tabulation of working fluid inventory.

The revisions made to the project have reduced the size of the electrical distribution system. The revised electrical single-line diagram is shown on Drawing No. 96800-E-SLD-101-SK. The electrical equipment requirements have been revised to reflect the power/mechanical system changes (reduced quantity of switchgear and MCC's), and revised estimates have been developed for electrical bulk material quantities (cabling, terminations, raceway), lighting and grounding. The electrical load list has been similarly revised, with a resulting reduction in the estimated unit 1 auxiliary load from 7,250 kW to 5,980 kW.

The primary structural changes in the project are the heat exchanger building and various yard foundations. The calculations of structural requirements for this building have been revised, including a new foundation plan (caissons and floor slab) and steel framing. Similarly, the foundations and containment for the fresh and waste ammonia tanks have been revised. All material quantities have been re-estimated, reflecting the design changes.

The reduction in the complexity of the Kalina cycle also reduces the instrumentation and control requirements. The revised I&C requirements that have been developed include:

- instrument count,
- control valve count and re-sizing, and
- I/O count.

Both instrument and control valve requirements have been reduced due to the reduced number of heat exchangers and associated piping.  In turn, these changes result in a reduced I/O count for the control system, and thus a smaller (*e.g.*, reduced capacity) control system requirement.

*Licensing*

A significant number of  POCTF project licensing activities were completed in the present reporting period.

1. The air permit was revised to incorporate review comments, was forwarded to RP&L, and has been signed and submitted to the state by RP&L.

2. The draft of the risk management plan was completed and distributed for ABB/RP&L comment.

3. The draft of the NPDES permit amendment was completed and distributed for ABB/RP&L comment.

4. The draft of the Title V permit amendment was completed and distributed for ABB/RP&L comment.

These four permits constitute the major permits required for the project.

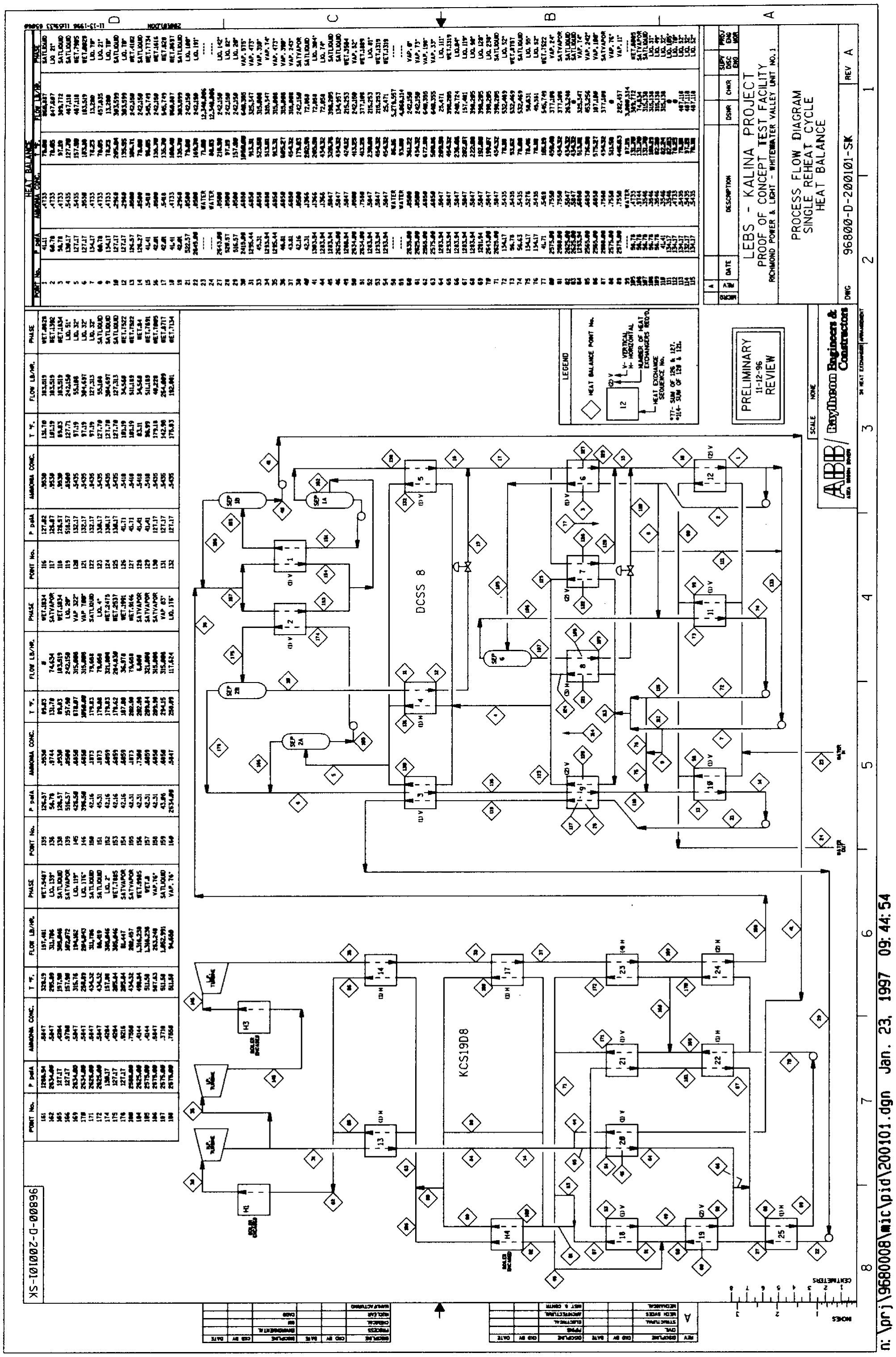
**TABLE 14-1**
**POCTF DESIGN CHANGES**

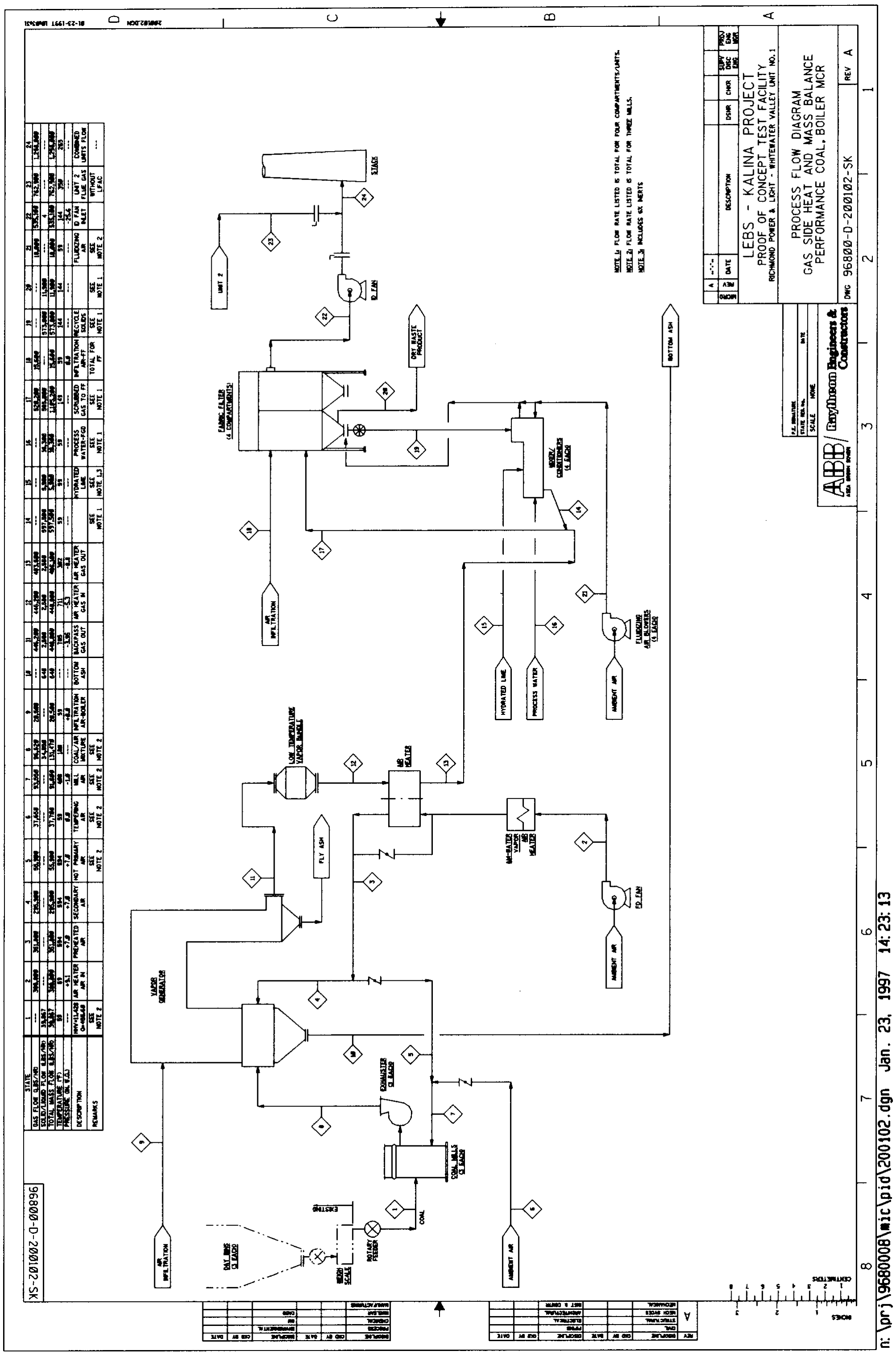
| | Original Design | Revised Design |
|---|---|---|
| 1. | 50 Kalina HX's | 34 Kalina HX's |
| 2. | Ammonia recovery system with ammonia recycle | Waste aqua-ammonia trucked offsite |
| 3. | Redundant power cycle pumps (2x50% or 2x100%) | All pumps single-position (1x100%) |
| 4. | New cooling tower with lower cold water temperature/segregated from unit 2 | Reuse existing cooling tower and pump inlet flume |
| 5. | Air sootblowing with dedicated compressed air system | Steam sootblowing with (larger) oil-fired auxiliary boiler / unit 2 steam |
| 6. | All new service/instrument air system | Augment existing system |
| 7. | Full-flow condensate filter | Partial-flow condensate filter |
| 8. | Indoor heat exchanger installation | Outdoor heat exchanger installation (?) |
| 9. | Brick siding on heat exchanger building | Insulated metal siding |
| 10. | Dummy louvres in building walls for HX bundle removal | Removable metal panels |
| 11. | Oil-fired auxiliary boiler | Reboiler heated with Kalina cycle fluid (?) |

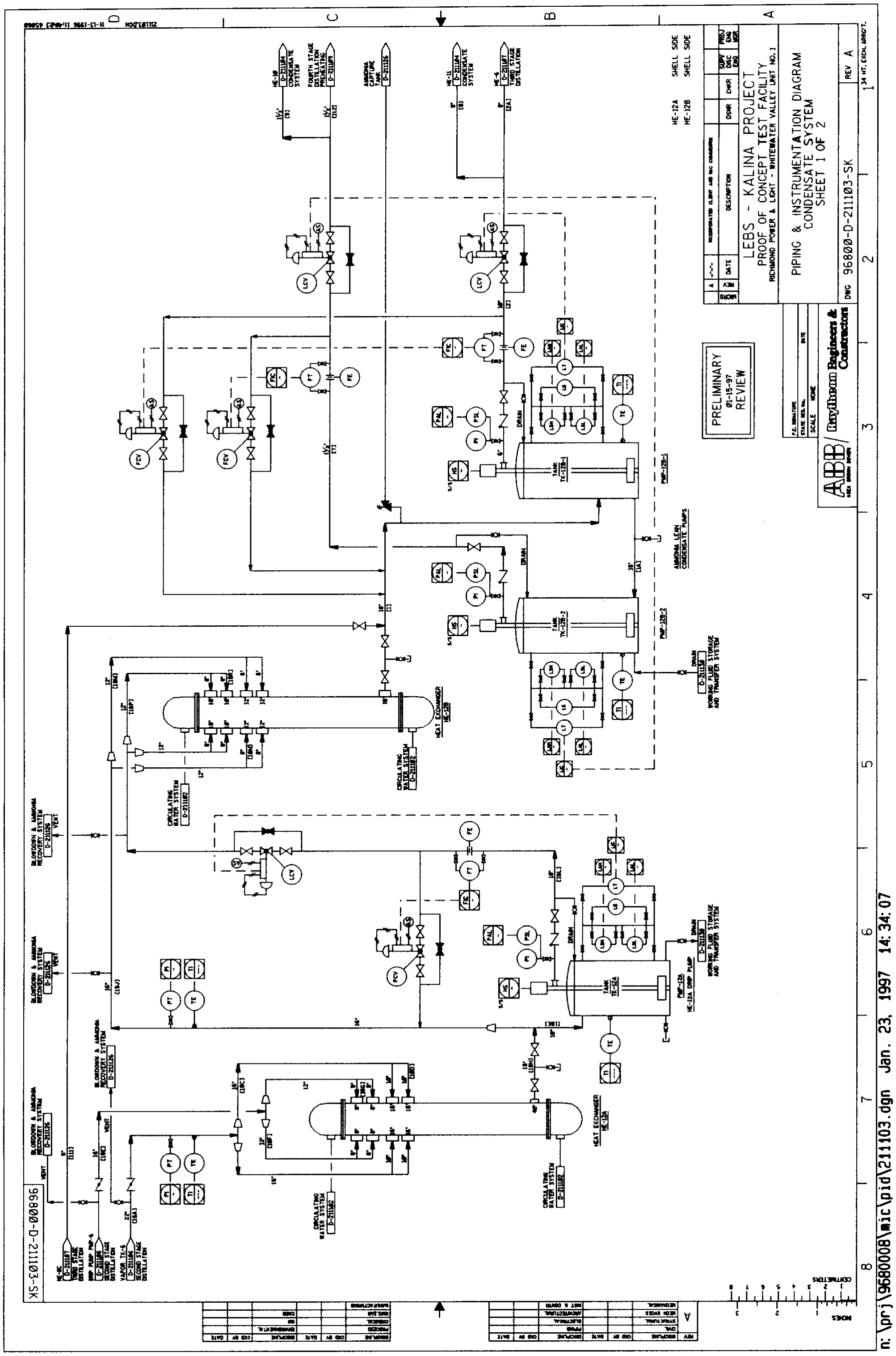
**TABLE 14-1**
**(Cont'd)**

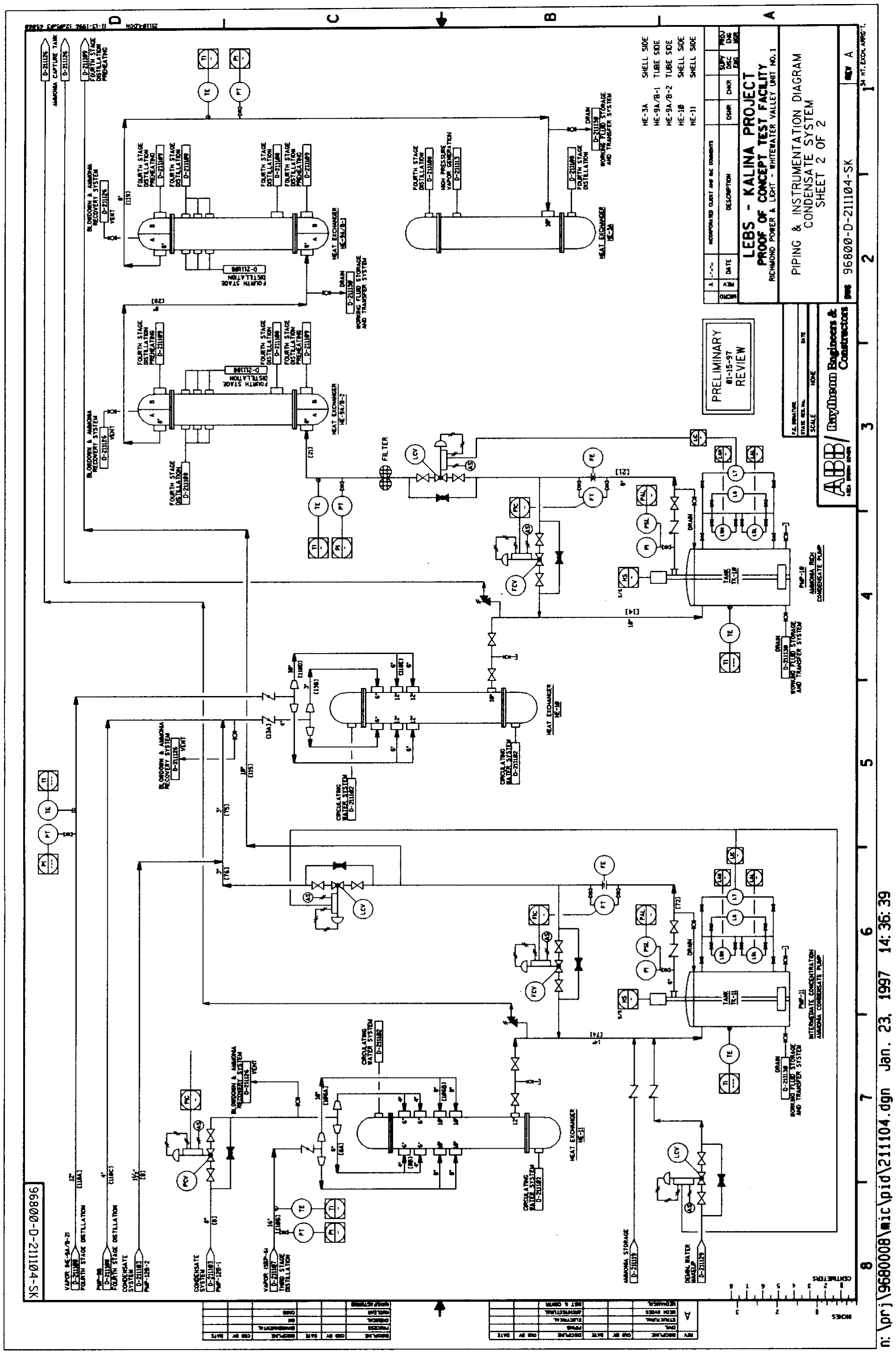
| | | |
|---|---|---|
| 12. | Low-velocity (large dia.) power cycle piping | Increase flow velocities (smaller pipe dia.) where practical |
| 13. | Reline existing circulating water piping | Use piping as-is. |
| 14. | Anhydrous ammonia storage tank @ 18,000 gal. / 3x50% vaporizers | Reduced storage capacity / 2x50% vaporizers |
| 15. | Ammonia blowdown tank @ 500,000 gal capacity / heat traced | 176,00 gal. capacity / bare |
| 16. | New plant elevator | Revise sootblower arrangements to eliminate interference with existing elevator |
| 17. | Pressurized pulverizers with new feeders, bunker mods & primary air system | Exhauster mills with rotary feeders, re-use existing weigh scales, no bunker mods. |

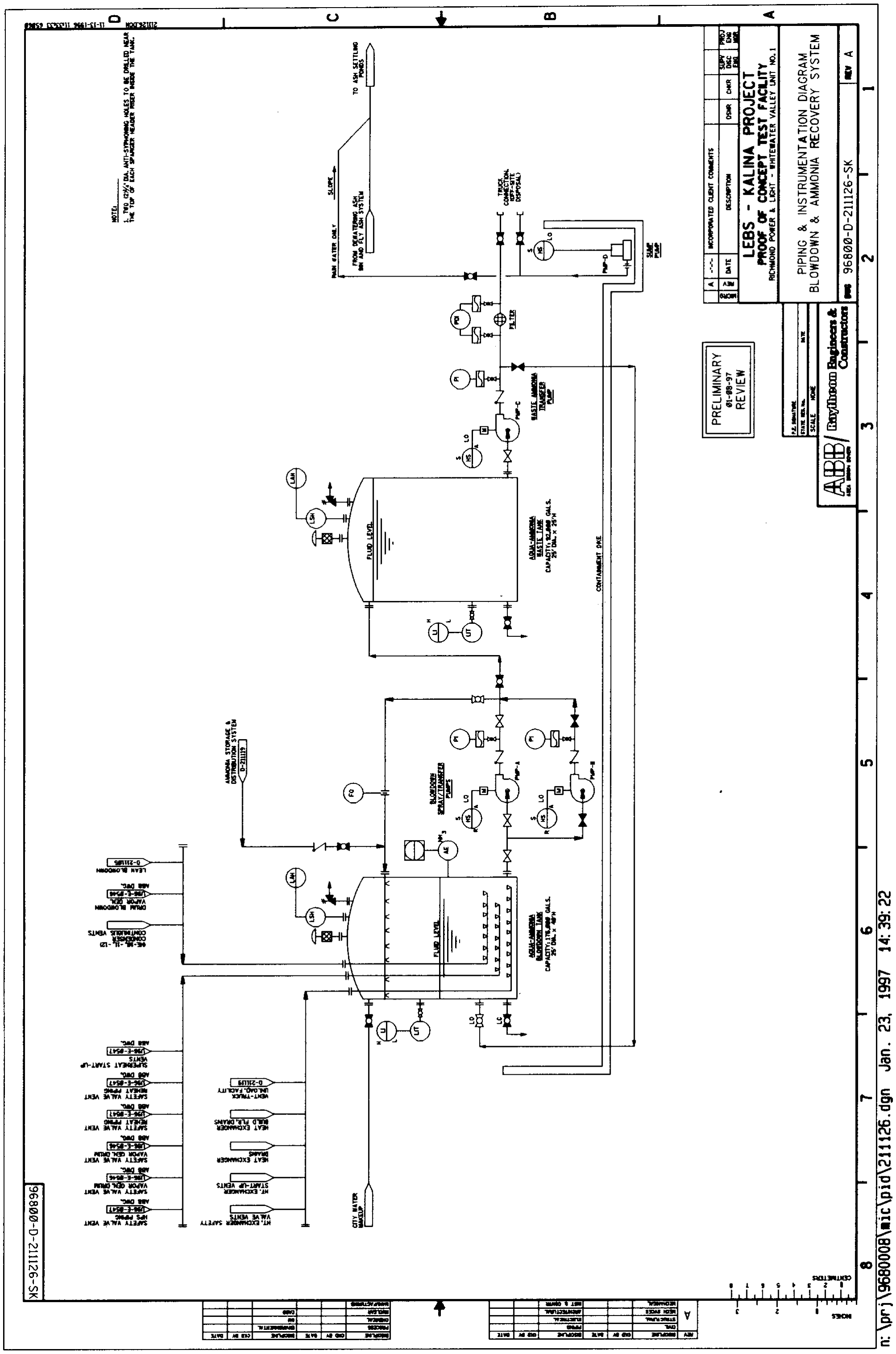
**Note:** Those revised items followed by a (?) are under evaluation but have not been adopted for inclusion in the project.

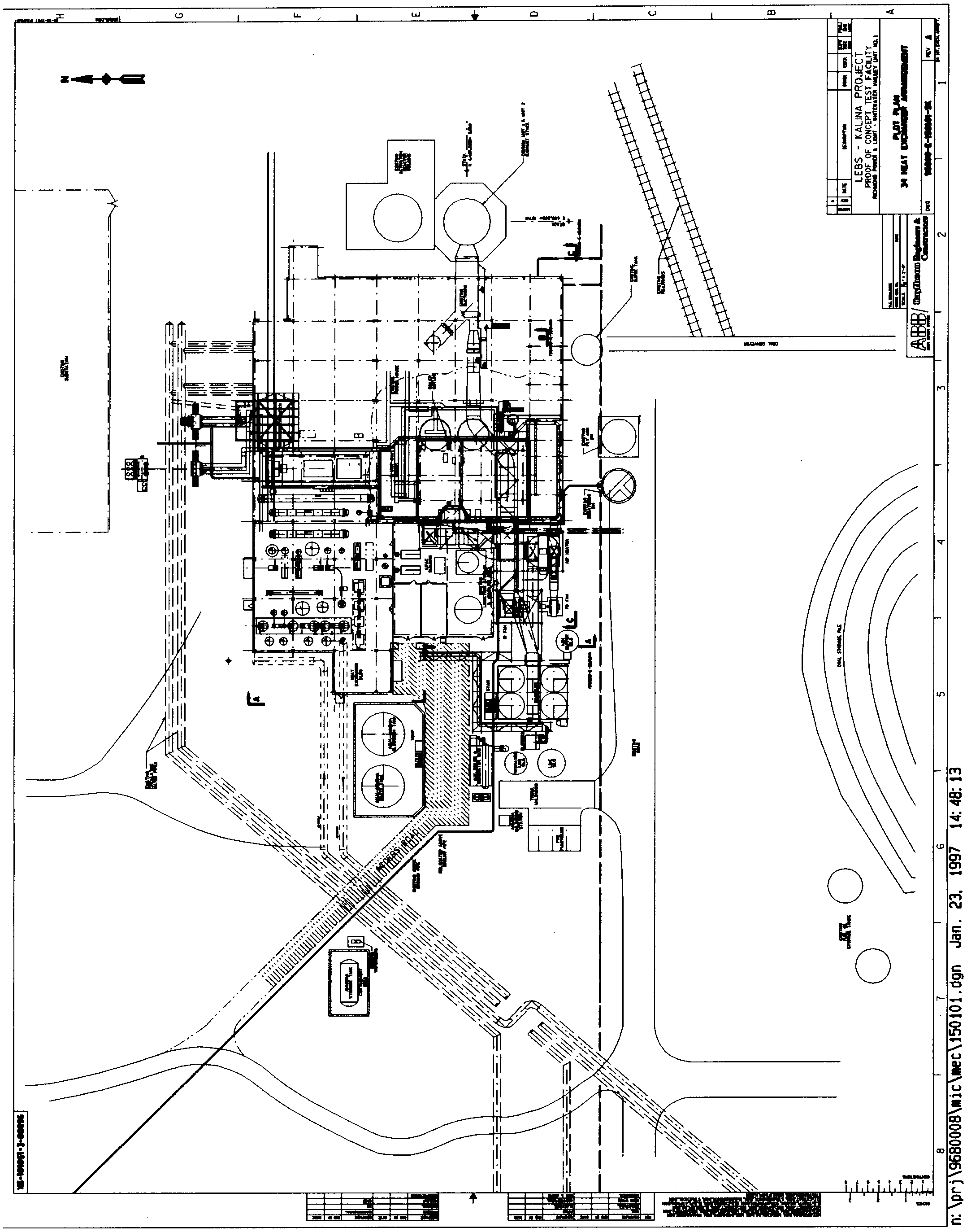

LEBS - KALINA PROJECT
PROOF OF CONCEPT TEST FACILITY
RICHMOND POWER & LIGHT - WHITEWATER VALLEY UNIT NO.1
PROCESS FLOW DIAGRAM
SINGLE REHEAT CYCLE
HEAT BALANCE
96800-D-200101-SK
PRELIMINARY
11-12-96
REVIEW
DCSS 8
KCS19D8
HEAT BALANCE
LEGEND
Raytheon Engineers & Constructors
n:\prj\9680008\mic\pid\200101.dgn Jan. 23, 1997 09:44:54

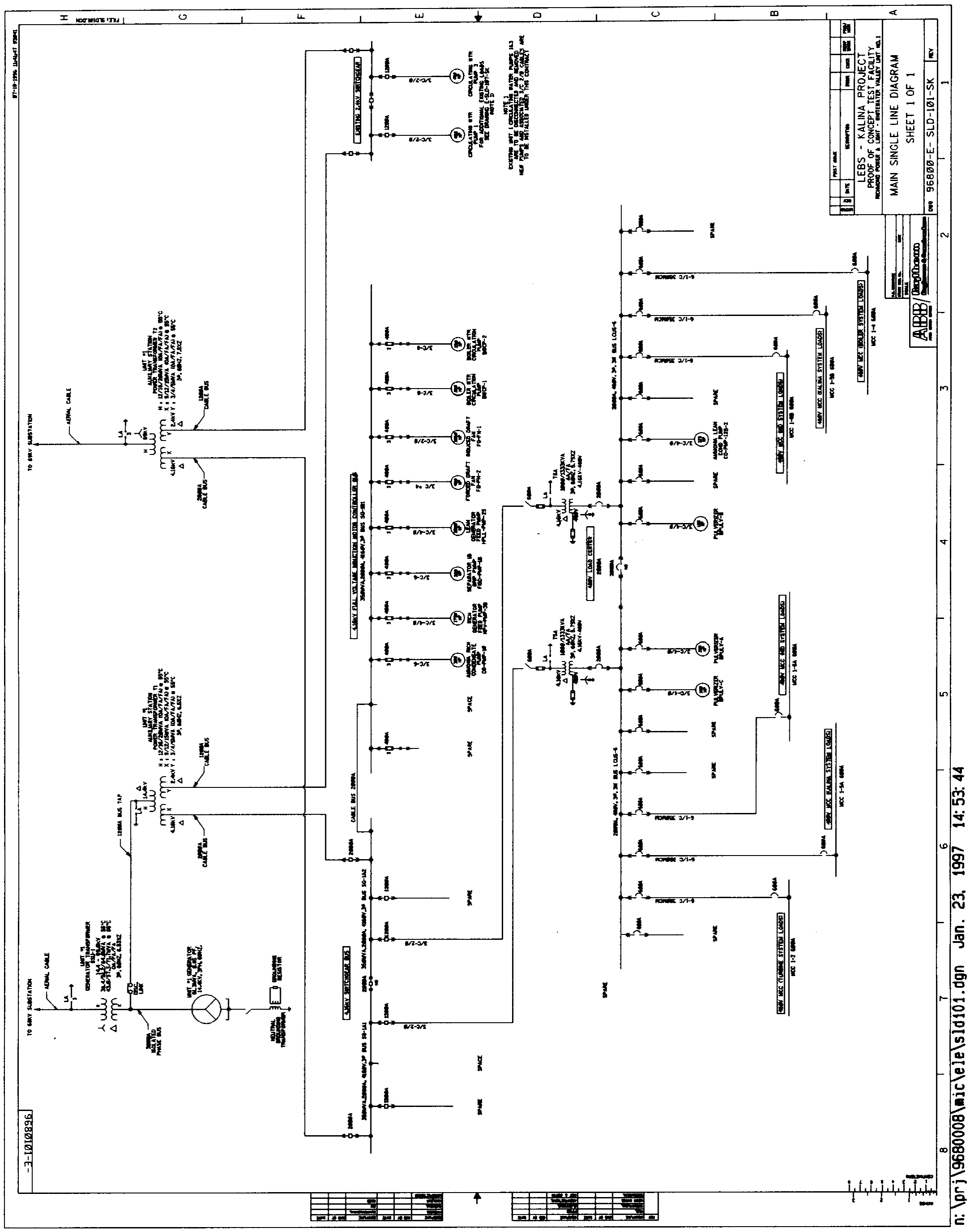

LEBS - KALINA PROJECT
PROOF OF CONCEPT TEST FACILITY
RICHMOND POWER & LIGHT - WHITEWATER VALLEY UNIT NO.1
PROCESS FLOW DIAGRAM
GAS SIDE HEAT AND MASS BALANCE
PERFORMANCE COAL, BOILER MCR
DWG 96800-D-200102-SK
REV A
n:\prj\9680008\mic\pid\200102.dgn Jan. 23, 1997 14:23:13


PIPING & INSTRUMENTATION DIAGRAM
CONDENSATE SYSTEM
SHEET 1 OF 2
LEBS - KALINA PROJECT
PROOF OF CONCEPT TEST FACILITY
RICHMOND POWER & LIGHT - WHITEWATER VALLEY UNIT NO. 1
DWG 96800-D-211103-SK
REV A
PRELIMINARY
01-15-97
REVIEW
HEAT EXCHANGER HE-12A
HEAT EXCHANGER HE-12B
96800-D-211103-SK
n:\prj\9680008\mic\pid\211103.dgn Jan. 23, 1997 14:34:07


LEBS - KALINA PROJECT
PROOF OF CONCEPT TEST FACILITY
RICHMOND POWER & LIGHT - WHITEWATER VALLEY UNIT NO.1
PIPING & INSTRUMENTATION DIAGRAM
CONDENSATE SYSTEM
SHEET 2 OF 2
96800-D-211104-SK
PRELIMINARY
01-15-97
REVIEW
n:\prj\9680008\mic\pid\211104.dgn Jan. 23, 1997 14:36:39


LEBS - KALINA PROJECT
PROOF OF CONCEPT TEST FACILITY
PIPING & INSTRUMENTATION DIAGRAM
BLOWDOWN & AMMONIA RECOVERY SYSTEM
96800-D-211126-SK
PRELIMINARY
01-08-97
REVIEW
n:\prj\9680008\mic\pid\211126.dgn Jan. 23, 1997 14:39:22


LEBS - KALINA PROJECT
PROOF OF CONCEPT TEST FACILITY
PLOT PLAN
n:\prj\9680008\mic\mec\150101.dgn Jan. 23, 1997 14:48:13


LEBS - KALINA PROJECT
PROOF OF CONCEPT TEST FACILITY
MAIN SINGLE LINE DIAGRAM
SHEET 1 OF 1
96800-E-SLD-101-SK
n:\prj\9680008\mic\ele\sld101.dgn Jan. 23, 1997 14:53:44

**<u>Subtask 14.2</u>** **POC Test Plan**

Work on the POC Test Plan was initiated during the latter part of the Quarter. Initial discussions were held toward establishing Test Plan preparation schedules and responsibilities.

During the next Quarter, test objectives and requirements will be established toward developing a preliminary overall plan for demonstration testing of the integrated Low-Emission Boiler System. The Test Plan will address, at a minimum: measurement and control requirements; data requirements to permit scale-up to commercial-size units; and plans to achieve environmental compliance while maintaining unit operating capacity.

## TASK 15 - PHASE III REPORT

No activity during this reporting period.

## CONCLUSION

Phase II was completed satisfactorily, on schedule and under budget.

Phase III is in progress, on (the new) schedule and is projected to be at or under budget.

## PLANS FOR NEXT QUARTER

Task 1

- Deliver a paper at the 22nd International Technical Conference on Coal Utilization & Fuel Systems.

Task 13

- Work will be started on the revised Commercial Generating Unit plant design, following the completion of the Kalina heat balance optimization and development of key system packages.

Task 14

- Technical work will be completed on Subtask 14.1, POC Test Facility Revised Design. The Subtask 14.1 technical results will be documented by revising the existing POCTF preliminary design report (issued in October 1996). Work will continue on the licensing effort per the current plan.
- Work will continue on Subtask 14.2 - POC Test Plan.

APPENDIX A - 2 pages

DOE F1332.3 X
(11-84)

U.S. DEPARTMENT OF ENERGY

**MILESTONE SCHEDULE** ☐PLAN ☒STATUS REPORT

FORM APPROVED
OMB 1901-1400

1. TITLE
Engineering Development of Advanced Coal-Fired Low-Emission Boiler Systems - Phases II & III

2. REPORTING PERIOD
October 1, 1994 - September 30, 1996

3. IDENTIFICATION NUMBER
DE-AC22-92PC92159

4. PARTICIPANT NAME AND ADDRESS
Combustion Engineering, Inc.
P.O. Box 500
Windsor, CT 06095-0500

5. START DATE
October 1, 1994

6. COMPLETION DATE
March 31, 1997

9. DURATION: FY95 (OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG SEPT), FY96 (OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG SEPT)

| 7. ELEMENT CODE | 8. REPORTING ELEMENT | 10. PERCENT COMPLETE a. Plan | b. Actual |
|---|---|---|---|
| | PHASE II | | |
| 1.0 | Prj Mgt | 80 | 80 |
| 7.0 | Comp Dev | 100 | 100 |
| 8.0 | POCTF | | |
| 8.1 | Site Sel | 100 | 100 |
| 8.2 | Pre Dsn | 100 | 100 |
| 9.0 | Subsyst | | |
| 9.1 | Design | 100 | 100 |
| 9.2 | Plan | 100 | 100 |
| 10.0 | Constr | 100 | 100 |
| 11.0 | Subsyst | | |
| 11.1 | Oper | 100 | 100 |
| 11.2 | Test Ev | 100 | 100 |
| 11.3 | Dsn Ev | 100 | 100 |
| 12.0 | Draft Report | 100 | 88 |

11. SIGNATURE OF PARTICIPANT'S PROJECT MANAGER AND DATE

DOE F1332.3 X
(11-84)

U.S. DEPARTMENT OF ENERGY

**MILESTONE SCHEDULE ☐ PLAN ☒ STATUS REPORT**

FORM APPROVED
OMB 1901-1400

1. TITLE
Engineering Development of Advanced Coal-Fired Low-Emission Boiler Systems - Phases II & III

2. REPORTING PERIOD
October 1, 1994 - September 30, 1996

3. IDENTIFICATION NUMBER
DE-AC22-92PC92159

4. PARTICIPANT NAME AND ADDRESS
Combustion Engineering, Inc.
P.O. Box 500
Windsor, CT 06095-0500

5. START DATE
October 1, 1994

6. COMPLETION DATE
July 31, 1997

| 7. ELEMENT CODE | 8. REPORTING ELEMENT | 9. DURATION FY97 | | | | | | | | | | FY | FY | 10. PERCENT COMPLETE a. Plan | b. Actual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PHASE III | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | | | | |
| 1.0 | Prj Mgt | | | | | | | | | | | | | 79 | 79 |
| 13.0 | CGU Dsn | | | | | | | | | | | | | 23 | 10 |
| 14.0 | POCTF | | | | | | | | | | | | | | |
| 14.1 | Rev Dsn | | | | | | | | | | | | | 24 | 15 |
| 14.2 | Test Plan | | | | | | | | | | | | | 41 | 2 |
| 15.0 | Report | | | | | | | | | | | | | 0 | 0 |

11. SIGNATURE OF PARTICIPANT'S PROJECT MANAGER AND DATE

APPENDIX B - 8 Pages

# ABB's LEBS TECHNOLOGIES

**John W. Regan**
**Robert J. vonHein**
ABB Power Plant Laboratories
Combustion Engineering, Inc.
Windsor, Connecticut

**Michael J. Davidson**
ABB CE Utility Power Boilers
Combustion Engineering, Inc.
Windsor, Connecticut

**James D. Wesnor**
ABB Environmental Systems
Knoxville, Tennessee

**David J. Bender**
Raytheon Engineers & Constructors, Inc.
Philadelphia, Pennsylvania

**ABSTRACT**

This paper describes the work by the ABB team on the U.S. Department of Energy (DOE) project "Engineering Development of Advanced Coal-Fired Low-Emission Boiler Systems" (LEBS) which is part of the DOE's Combustion 2000 Program. The objectives of the LEBS project are to dramatically improve environmental performance of future pulverized coal-fired power plants, to increase their efficiency and to reduce their cost of electricity using near-term technologies, *i.e*., advanced technologies that are partially developed. The overall objective is to expedite commercialization of the technologies that are developed under LEBS.

The technologies being developed by the ABB team are expected to meet all the project objectives, *i.e*., to reduce emissions of $NO_X$, $SO_2$ and particulates to one-third to one-sixth NSPS limits while reducing the cost of electricity and increasing net station (HHV) efficiency to 45 percent. The results to date and future work are described in the paper.

**INTRODUCTION**

Phase I consisted of selection of candidate technologies, creation of an preliminary 400 MWe unit design and preparation of an RD&T Plan for Phases II and III. The Phase II work consists of: Component Optimization, Proof-of-Concept Test Facility (POCTF) Preliminary Design and Subsystem Testing. The major Phase II activities are: in-furnace $NO_X$ reduction, catalytic filter optimization, and POCTF design/licensing with a Kalina cycle. The activities and results to date are described below. (The work on in-furnace $NO_X$ reduction is the only one completed as of this writing.)

**IN-FURNACE $NO_X$ REDUCTION**

**Introduction.** The team selected ABB's TFS 2000™ firing system, which has been demonstrated to provide $NO_X$ emissions of 0.2 pounds/MM Btu in prior laboratory and full scale, retrofit, utility boiler applications The objective of recent development work was to reduce this value to 0.1 lb/MM Btu while maintaining the fly ash carbon content <5% for high sulfur, mid-western and eastern bituminous coals. In addition, the lower furnace heat absorption profiles and convective pass heat flux distribution were to remain similar to or improved over the existing system. Specific features of this system include the use of concentric firing system (CFS) air nozzles, where the main windbox secondary air jets are introduced at a larger firing circle than the fuel jets; close coupled overfire air (CCOFA) for improved carbon burnout; and multi-staged separated overfire air (SOFA) to provide for complete combustion while maintaining an optimum global stoichiometry history for $NO_X$ control. In addition, the TFS 2000™ firing system includes flame attachment coal nozzle tips for rapid fuel ignition and a pulverizer configured with a DYNAMIC™ Classifier to produce fine coal to minimize carbon losses under these staged combustion conditions.

Potential enhancements to the TFS 2000™ firing system focused on optimizing the introduction of the air and fuel within the primary windbox zone to provide additional horizontal and vertical staging. These enhancements were based on controlling the combustion of the coal in a more local sub-stoichiometric environment. That is, in addition to the global staging currently applied, improved $NO_X$ reduction was sought by controlling and optimizing the mixing of the fuel and air locally through vertical and horizontal staging techniques. The approach used in the development and evaluation of the various firing system concepts included an integrated approach of kinetic and computational modeling, small scale experimental testing in a Fundamental Scale Burner Facility (FSBF), and larger scale combustion testing in a Boiler Simulation Facility (BSF). These techniques were applied to better understand the mechanisms governing in-furnace $NO_X$ reduction and to identify potential enhancements to the TFS 2000™ firing system.

**Pilot Scale Combustion Testing.** The BSF is a pilot scale test furnace, nominally rated at 50 MM Btu/hour (5 MWe) for coal firing, that reliably duplicates the combustion characteristics of a tangentially-fired utility boiler. All major aspects of a typical tangentially-fired utility boiler are duplicated in the BSF including a v-shaped hopper for bottom ash collection, the use of multiple burner elevations, and an arch with subsequent backpass convective "superheat," "reheat," and "economizer" surfaces. Selective refractory lining over atmospheric pressure "waterwalls" allows the matching of the residence time/temperature history of large scale utility boilers, including the horizontal furnace outlet plane (HFOP) gas temperature. The BSF is fully instrumented to monitor the combustion process. Instruments for measuring coal feed rate, primary and individual secondary air mass flow rates, outlet emissions ($O_2$, $CO_2$, CO, $SO_2$, NO, and $NO_X$), and convective pass heat flux distribution are tied into a combined DCS/data acquisition system to allow for control and logging of these and other important operational parameters. The coal utilized was the high sulfur, medium volatile, bituminous Viking coal from Montgomery, Indiana.

Prior to the initiation of $NO_X$ control subsystem testing, the firing system for the BSF was modified to take advantage of current and previous R&D project findings. First, ABB's Aerotip™ coal nozzle tip design was utilized as the base from which the BSF coal nozzles were constructed. The Aerotip™ design embodies improved aerodynamic features which support the test program need for a low $NO_X$ coal nozzle tip through its control over near field stoichiometry. In addition, the main windboxes were designed to accommodate a range of vertical and horizontal air and coal staging scenarios. The design of the secondary air nozzles was based on the need to maintain proper jet momenta, while having sufficient flexibility to test variations in vertical and horizontal air staging. Excess coal nozzle capacity was incorporated to allow the testing of various coal staging scenarios, including two-corner coal firing. With this foundation, each of the "base" (*i.e.*, benchmark) firing system designs tested, including the TFS 2000™ firing system, was able to incorporate the results of the prior chemical kinetic modeling and small scale (FSBF) combustion testing with respect to main windbox vertical air staging.

Various "conventional" global air staging techniques were tested in order to benchmark their $NO_X$ reduction potential on the test fuel. This work included investigations of close coupled overfire air (CCOFA), upper and lower (single) elevations of separated overfire air (SOFA), and an implementation of TFS 2000™ technology. All of the various overfire air configurations utilized the same main windbox arrangement, and all were performed with high fineness (90% - 200 mesh) coal grind. A summary of the results from testing various overfire air configurations are given in Figure 1. As anticipated, the implementation of global air staging results in a significant reduction in furnace outlet $NO_X$ emissions. Beginning with $NO_X$ emissions of 0.52 pounds/MM Btu with a typical "baseline" (post-NSPS) firing system arrangement, $NO_X$ reductions continued to a low of 0.13 pounds/MM Btu for an "optimized" TFS 2000™ firing system arrangement (Note: similar 0.13 pounds/MM Btu outlet $NO_X$ emissions were obtained with the upper SOFA only, but this was at slightly degraded carbon in the fly ash performance). The "optimized" TFS 2000™ system incorporates improvements to the bulk stoichiometry history. In all, a 75% reduction in $NO_X$ from baseline levels was achieved with the "optimized" TFS 2000™ system. As expected, carbon in the fly ash increased as the global staging was increased, but remained below the limit of 5%.

Having benchmarked the effects of global staging on firing system performance, both vertical and horizontal staging techniques within the main firing zone were subsequently tested. The objectives of this work were to confirm the results of prior main windbox vertical air staging work, and to further reduce outlet $NO_X$ emissions from the previously demonstrated "best" level of 0.13 pounds/MM Btu. As such, these methodologies were applied in concert with the "optimized" TFS 2000™ firing system, keeping the global stoichiometry history constant to allow meaningful comparisons.

First, vertical air staging within the main windbox was independently varied to demonstrate its effect on $NO_X$ formation at this large pilot scale. Results from this testing, given in Figure 2, show that significant variation in $NO_X$ emissions occur as main windbox vertical air staging is changed. This result confirms that the main windbox vertical stoichiometry history is an important contributor to overall $NO_X$ formation, even with significant levels of global air staging. Overall, $NO_X$ emissions increased when variations to the main windbox vertical stoichiometry build-up were applied to the previously "optimized" TFS 2000™ arrangement. This result is, however, expected since the "optimized" TFS 2000™ system incorporates the results of prior chemical kinetic modeling and small scale combustion test vertical air staging work into the configuration of its main windbox as noted above.

Next, horizontal staging, used to control the horizontal "build-up" of stoichiometry (corner to corner) within the main burner zone, was evaluated. This was accomplished by biasing the fuel and air between one or more of the four corners. Tested subsets of this technique are two corner firing, where all of the air and fuel are injected through two of four corners in a tangential arrangement, and opposed corner firing where the coal is injected from two corners, and the air from the remaining two. In general, independent implementation of horizontal staging techniques resulted in neutral to degraded $NO_X$ emissions performance over that of the "optimized" TFS 2000™ firing system. This is seen in Figure 3. These results

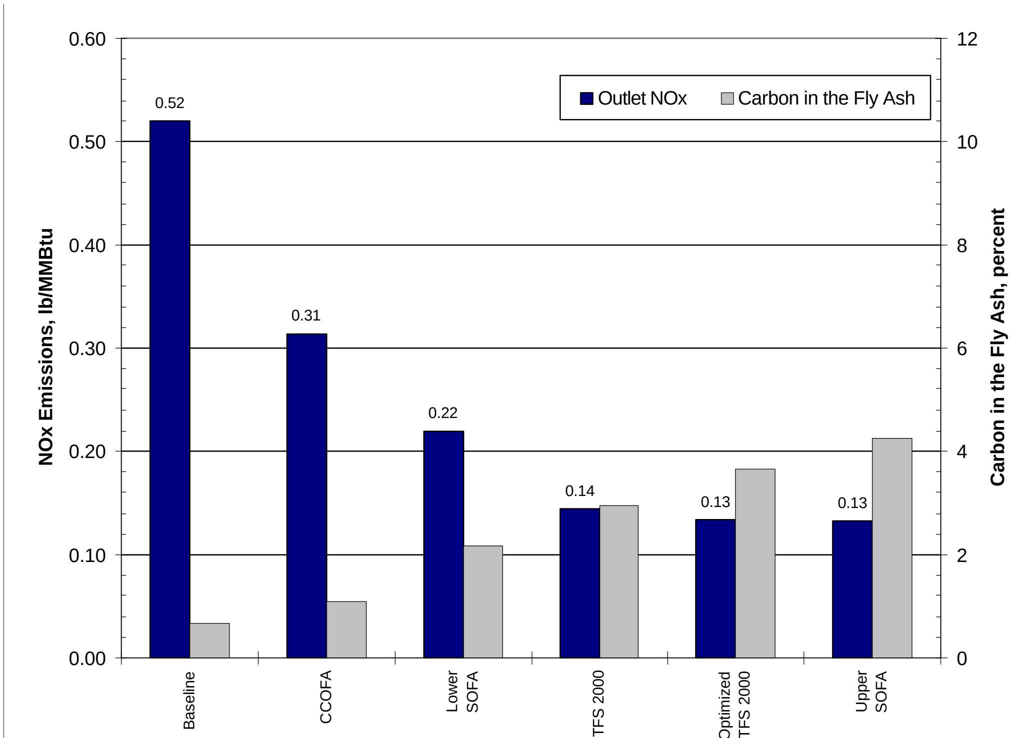



Figure 1 Global Staging

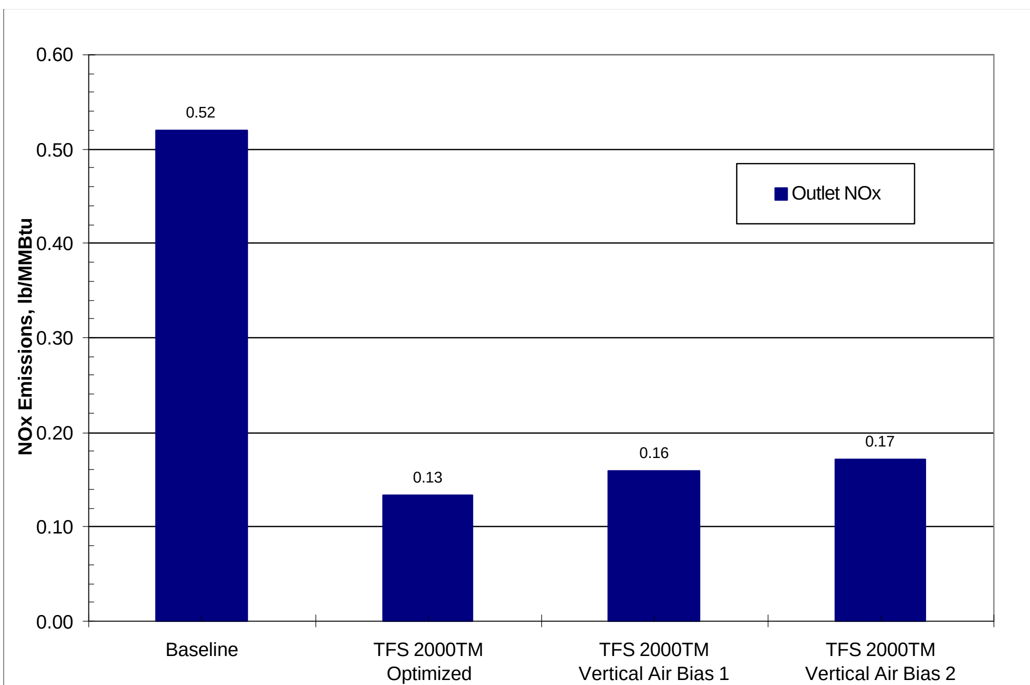



Figure 2 Effects of Vertical Staging on NOx

demonstrate that, similar to the prior vertical staging experiments, outlet $NO_X$ emissions can be affected by horizontal fuel and air distributions. However, these results also demonstrate that the global time - stoichiometry history (*i.e*., the TFS 2000™ stoichiometry profile) dominates the $NO_X$ formation and reduction processes at these levels of global air staging.

Finally, several configurations which applied integrated vertical and horizontal staging techniques as a means of "optimizing" the stoichiometry of combustion within the main windbox were evaluated. Integrated vertical and horizontally staged firing systems were extensively evaluated using CFD modeling prior to the BSF tests. In contrast to their independent performance, Figure 4 shows that when suitably combined, an integrated vertical and horizontal staging strategy offers a small, but consistent improvement to the $NO_X$ emissions performance. At a $NO_X$ emission level of 0.11 pounds/MM Btu, the "best" integrated system ("Integrated Config. 6") produced a greater than 10% reduction in $NO_X$ over the previously "optimized" TFS 2000™ system. Carbon loss results (not shown) were similar for the two firing systems.

Additional pilot scale testing of potential $NO_X$ control subsystems in the BSF has been recently completed and results are being analyzed. The objective of this testing was to confirm the performance of the integrated vertical and horizontal staging technique, focusing on the repeatability of the present test results, while generating design information for this and other promising firing system concepts for eventual full scale utility boiler application.

## CATALYTIC FILTER OPTIMIZATION

**Introduction.** The principal goal of the Catalytic Filter Optimization activities is the acquisition of initial field test data, which will be used for a larger field demonstration. These activities include the determination of feasible and reasonable operating conditions for the catalytic filter system. Data collected through testing focused on particulate and $NO_X$ removal efficiencies as well as filter draft loss.

The goals of this task are listed below in order of priority. It is desirable that these goals be achieved simultaneously.

- Particulate emissions of less than 0.005 lb/MMBtu
- Maximum filter clean-side draft loss of 8 inches w.g. at 4 ft/min at 775°F
- Operation with a Filter Face Velocity (FFV) of at least 4 ft/min at 650°F
- Minimum of 80 % $NO_X$ removal efficiency
- Ammonia slip of less than 15 ppm

Information gained from demonstration and evaluation will address the following issues:

- Confirm filter particulate removal efficiency.
- Determine the tubesheet differential pressure (filter draft loss) as a function of face velocity, cleaning cycle characteristics, operating time, and other parameters.
- Determine the $NO_X$ reduction efficiency as a function of flue gas composition ($NO_X$ inlet concentration, $NH_3$ stoichiometry, particulate removal), and flue gas temperature. Of further interest is the determination of the requirements to maintain the catalytic conversion efficiency.

**Approach.** The approach used is to test the catalytic filter system with four filter modules on a 100 ACFM (165 $m^3$/hr) slipstream at Richmond Power & Light's Whitewater Valley Station Unit 2, a 66 MWe pulverized coal-fired boiler. CeraMem manufactured the ceramic filter modules and Engelhard applied the $NO_X$ reduction catalyst. At this writing, an initial 500-hour test has been concluded, in which both particulate removal and $NO_X$ reduction were investigated.

**Preliminary Results.** *The tubesheet differential pressure* (filter draft loss) is considered an essential element to the success of the catalytic filter. For the first 500-hour test, the initial tubesheet differential pressure was approximately 16 inches w.g. (FFV=4 ft/min, T= 650°F). The filter permeance, a parameter inversely proportional to tubesheet differential pressure and independent of filter face velocity and process temperature, decreased through the first 150 hours of operation, as shown in Figure 5. This decrease indicated that the filter tubesheet differential pressure increased at constant process conditions, an effect that is typical of all ceramic particulate filters. This decrease in permeance or increase in tubesheet differential pressure is caused by the smaller particulate (less than 0.5μ diameter) becoming permanently lodged in the filter substrate. For all ceramic particulate filters, the filter permeance should stabilize at some point, indicating that essentially the pores that are able to become "plugged" have been, and that the filter is being cleaned efficiently. At this point, the tubesheet differential pressure will remain constant at constant process conditions. In the case of the initial 500-hour test, the tubesheet differential pressure rose to approximately 23-24 inches w.g. (FFV=4, T=650°F) after approximately 200 hours of operation and was stable for the remainder of the test.

Upon conclusion of the 500-hour test, the system was opened and the filter modules were inspected. Visual inspection showed that the filters were being cleaned effectively, with no particulate buildup being detected and no plugged channels being found. Subsequent analysis of the catalytic filters indicate that catalyst addition was responsible for approximately 75 % of the tubesheet differential pressure.

*Particulate removal* for this filter system was expected to be near absolute. In previous laboratory testing outlet emissions from the filter could not be detected using a laser light-scattering measurement system, indicating that removal efficiency exceeded 99.99994%. In the 500-hour test, two outlet particulate samples were taken, with results indicating a removal efficiency of 99.93% which is below the expected value. Upon completion of the 500-hour test, the unit was opened and the tubesheet and vessel inspected. Lack of particulate matter on the "clean-side" of the tubesheet, particularly in cracks and crevices, tends to indicate that particulate matter was not passing through the filters and that the sampling results were reflective of material that had been left in the ducts when the system was being bypassed.

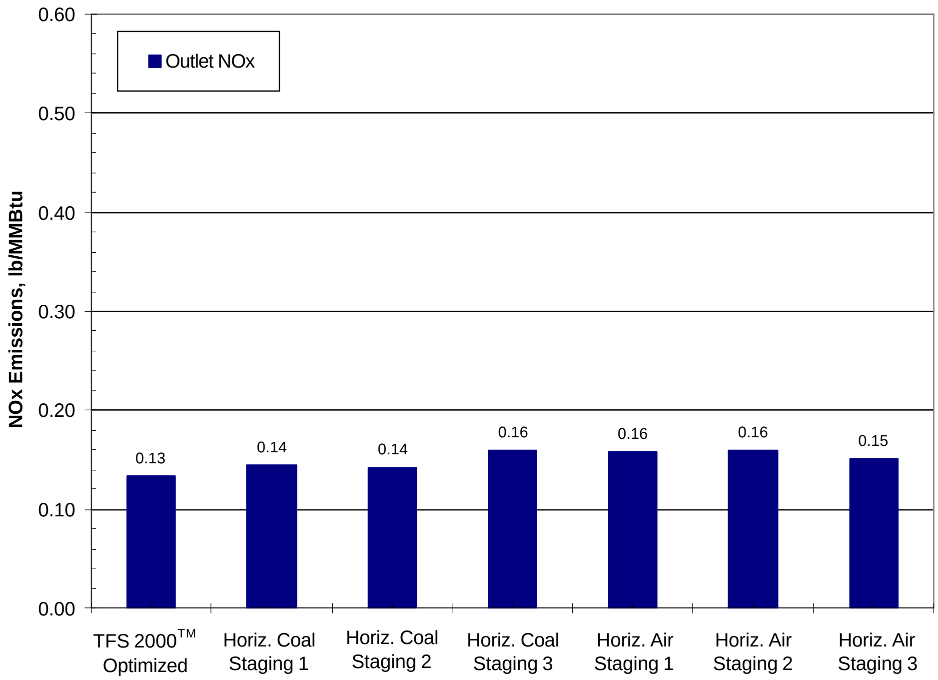


Figure 3 Effects of Horizontal Staging on NOx

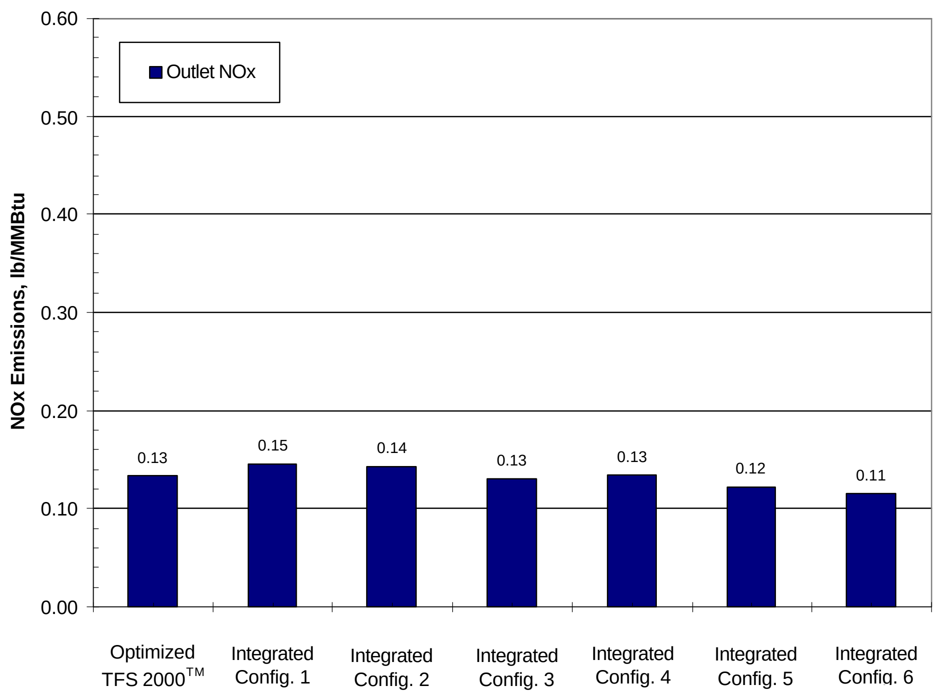


Figure 4 Effects of Integrated Staging on NOx

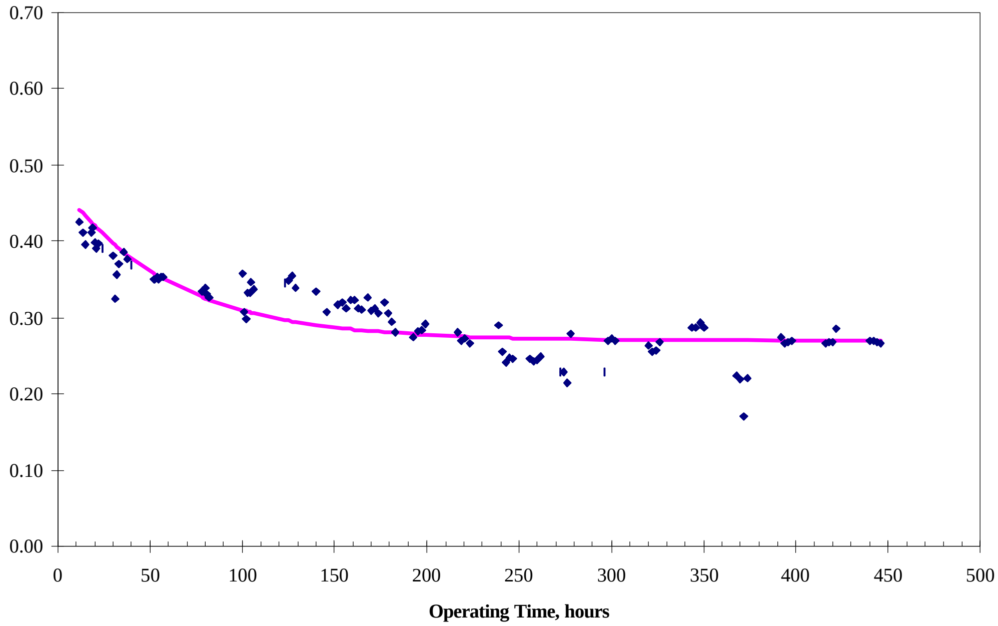



**Figure 5 - Filter Permeance vs. Operating Time**

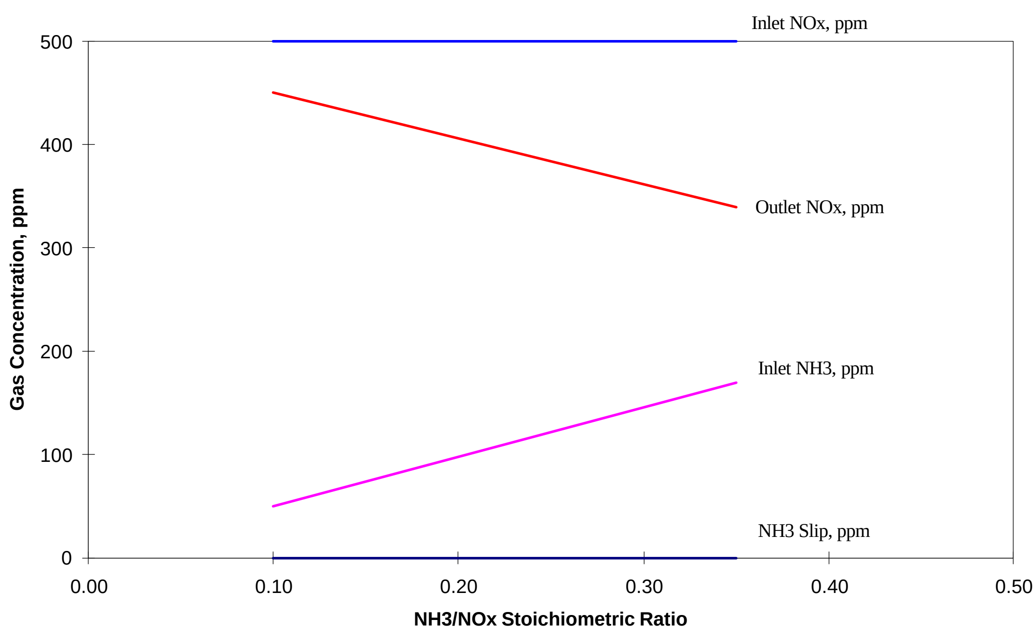



**Figure 6 - NOx Reduction**

*$NO_X$ Reduction Efficiency* testing was initiated after approximately 350 hours of operation. Ammonia was injected into the system to facilitate the $NO_X$ reduction reaction. Inlet and outlet ammonia sampling was conducted to quantify ammonia injection rates and ammonia slip, while $NO_X$ inlet and outlet concentrations were determined using two ThermoElectron Model 10 $NO_X$ CEMs. Due to vendor problems that are beyond the scope of the paper, maximum injection stoichiometry was limited to 0.4 (maximum ammonia concentration in the inlet flue gas was approximately 200 ppm). Preliminary results indicate that the catalyst made efficient use of the ammonia, as shown in Figure 6. The ammonia was fully accounted for in the $NO_X$ reduction reaction, and sampling and analysis found less than 3 ppm in the outlet flue gas in all samples.

**Future Tests.** It is unlikely that an advancement in catalyst deposition technology will be made that will achieve an initial tubesheet pressure differential of less than 8 inches w.g. within the 100 ACFM Test time frame. A second 500-hour test will be conducted to gather engineering data on the performance of a non-catalytic filter system. Catalyst development is continuing in a parallel program, with the hope of being able to achieve project goals by completion of Phase II.

## POCTF DESIGN AND LICENSING WITH A KALINA CYCLE

**Introduction.** The centerpiece of the LEBS project is Phase IV which will undertake the design, construction and test operation of a proof-of-concept test facility (POCTF). These final-phase activities will provide the design and operating database critical to commercialization of the LEBS technologies. At present, the team is developing a site-specific preliminary design for their POCTF, and has project licensing in progress.

**Project Description.** The team was fortunate in obtaining a commitment for an outstanding host site for the POCTF. Richmond (Indiana) Power & Light Co. (RP&L) has offered to host the project at their Whitewater Valley station. RP&L has a history of successful involvement in technology demonstration programs, including one of the earliest low $NO_X$ burner installations, a LIMB installation, and a Clean Coal Technology project.

The Whitewater Valley plant is composed of two coal-fired, non-reheat units, with nominal ratings of 33 MWe (Unit 1) and 66 MWe (Unit 2). Unit 1 will be modified to accept the LEBS technology package. This unit is approximately 40 years old, and incorporates a 900F/900 psig steam cycle with a steam capacity of 325,000 lb/hr. The POCTF project will involve a major restructuring of the unit, that entails the replacement of the complete power system (boiler, turbine-generator, feedwater heaters, power piping) with a new Kalina-based power system, and addition of the LEBS flue gas cleanup system. The project will use the plant infrastructure to the maximum extent practical, including coal handling, heat rejection, ash handling, powerhouse structures, and auxiliary systems. Although the project is being implemented as a test facility, RP&L intends to use the unit for long-term production service following completion of the LEBS project. This criterion, therefore, has a dominant effect on specification and design of the equipment and the facility. The approach taken in establishing the size of the modified unit has been to maximize its generating capacity, consistent with making maximum use of existing plant infrastructure. Key plant performance parameters are summarized in Table I.

By leveraging the significant improvement in heat rate offered by the Kalina cycle with a modest 10% increase in coal heat input, the unit output will be increased a substantial 43% to about 48 MWe, with a corresponding 23% decrease in heat rate. At the projected net unit heat rate of about 9,200 Btu/kWh, the modified Whitewater Valley Unit 1 will be the most efficient coal-fired unit of its size in the U.S. The planned project, in fact, compares favorably to the best coal-fired unit heat rate reported in the USA in 1994 of 8,889 Btu/kWh (annual average) for a 660 MW supercritical unit.

**Equipment.** Because the Kalina cycle optimizes at different thermodynamic conditions than a steam cycle, and because of the change in working fluid and the increase in generating capacity, the complete steam side of the power cycle is to be removed and replaced. Equipment to be replaced includes the boiler and auxiliaries, turbine-generator and auxiliaries, condenser, condensate system and feedwater system. The size of the unit has been selected such that the new vapor generator will fit in the existing boiler support-steel cavity, and the new turbine-generator will fit the existing turbine pedestal (after pedestal modification). The fact that the Kalina cycle regenerates substantially more heat than a steam cycle results in a significant increase in the number of regenerative heaters, such that a turbine hall addition will be required to house this new equipment.

The vapor generator, or boiler, design for the POCTF is a single reheat, drum type with pumped circulation for cooling furnace wall evaporative tubes. The Kalina cycle, with its higher rate of heat regeneration, requires less evaporation but more superheater and reheater duty in the vapor generator. Thus, in addition to pendant and horizontal superheater and reheater surfaces, in the preliminary design portions of the upper furnace walls are used for superheating and reheating the working fluid. The design of these sections is the same as conventional radiant wall reheater designs. The vapor generator looks very much like a large utility unit designed for a Rankine cycle.

Turbine design performance for a Rankine or Kalina cycle is very similar. Ammonia has a molecular weight very close to that of pure water, (17 vs. 18). This allows the use of current designs for turbine blading and turbine shell to be used in a Kalina cycle. One major difference in the turbine, when used in a Kalina cycle, is that the turbine is changed to a back pressure configuration. In doing so, there is no need for the large low pressure section and vacuum system which are required in the Rankine cycle. This provides a capital cost saving as well as improved system efficiency.

Table I - UNIT 1 PERFORMANCE PARAMETERS
(Preliminary)

| | | Existing | POCTF | Change |
|---|---|---|---|---|
| Coal Heat Input | MM Btu/hr | 400 | 440 | + 10% |
| Cooling Tower Load | MM Btu/hr | 216 | 215 | |
| Generator Output | MWe | 35.6 | 54.6 | |
| Auxiliary Load | MWe | 2.2 | 6.7 | |
| Net Unit Generation | MWe | 33.4 | 47.9 | + 43% |
| Net Unit Heat Rate | Btu/kWh | 12,000 | 9,186 | - 23% |

In addition, the inclusion of the LEBS flue gas emissions control features dictates removal of the gas side power cycle systems. The replacement systems will include the low $NO_X$ firing technology described previously, a new draft system, and a flue gas cleanup system. At present, two alternative processes are being evaluated for flue gas cleanup: the $SNO_X$™ hot process and an advanced dry-scrubbing process.

Control requirements associated with the Kalina power cycle, and the fact that Unit 1 still has its original control system, dictate that the project will include installation of a new unit-wide distributed control system. The increase in auxiliary power consumption associated with the modified unit also requires that the station service transformers for Unit 1 (unit auxiliary and startup) be replaced with larger capacity units, and substantial new power distribution capability be added.

**Licensing.** A licensing plan and schedule have been developed for the project that has identified the need to obtain twelve individual environmental/safety permits and approvals. The project will result in large reductions of all the regulated air emissions from Unit 1. Thus, approvals for the air permits are expected to be relatively straight forward. Unique to this power project, however, is the significant ammonia inventory required for operation of the Kalina cycle. The presence of this material on site will require the development of plans to deal with a potential accidental ammonia release.

## CONCLUSIONS AND FUTURE WORK

Testing of the low-$NO_X$ firing system has been completed. The work remaining is analysis of data from the second week of testing in the BSF. The $NO_X$ emission target of 0.1 lb/MM Btu with <5% carbon in the fly ash was achieved in the BSF (actually 0.11 lb). However, at this time it cannot be predicted with certainty that 0.1 lb/MM Btu will be achieved in commercial size systems. There presently is no further LEBS firing system development work planned prior to construction of the POCTF.

The preliminary results of the catalytic filter field testing were very encouraging regarding particulate emissions and $NO_X$ reduction. However, measured gas draft loss was excessive. Since approximately 75% of the draft loss is attributed to the catalyst, testing will continue with a non-catalytic filter system while catalyst deposition technology is reviewed. Also, since it is possible that the catalytic filter draft loss situation may not be resolved within the POCTF schedule, an alternative technology will be evaluated.

The POCTF preliminary design work will be completed within the project schedule. A full release for detailed engineering, manufacturing, *etc*. is expected in mid to late 1997.

## REFERENCES


1. Regan, J.W., et al, "ABB's LEBS Activities - A Status Report", First Joint Power & Fuel Systems Contractors Conference, Pittsburgh, PA, 1996


* * * * * * * * * *


Acknowledgment: A large number of people representing the US Department of Energy - Pittsburgh Energy Technology Center, the author's companies and advisors to the project have contributed to the work described in the paper. Any attempt to list all of their names risks omitting one or more. However, their contributions are deeply appreciated and they are hereby acknowledged and thanked sincerely.

APPENDIX C - 25 pages

**PHASE II REPORT**

**VOLUME I - EXECUTIVE SUMMARY AND DESCRIPTION OF WORK PERFORMED**

**IN TASKS 7 THROUGH 11**

ENGINEERING DEVELOPMENT OF ADVANCED COAL-FIRED

LOW-EMISSION BOILER SYSTEMS

FOR

U.S. DEPARTMENT OF ENERGY

PITTSBURGH ENERGY TECHNOLOGY CENTER

CONTRACT DE-AC22-92PC92159

PRINCIPAL INVESTIGATORS:

David J. Bender
Charles Q. Maney
Robert J. von Hein
James D. Wesnor

PROJECT DIRECTOR:

John W. Regan

SUBMITTED BY:

ABB POWER PLANT LABORATORIES

COMBUSTION ENGINEERING, INC.

2000 DAY HILL ROAD

P.O. BOX 500

WINDSOR, CT  06095-0500

October 1996

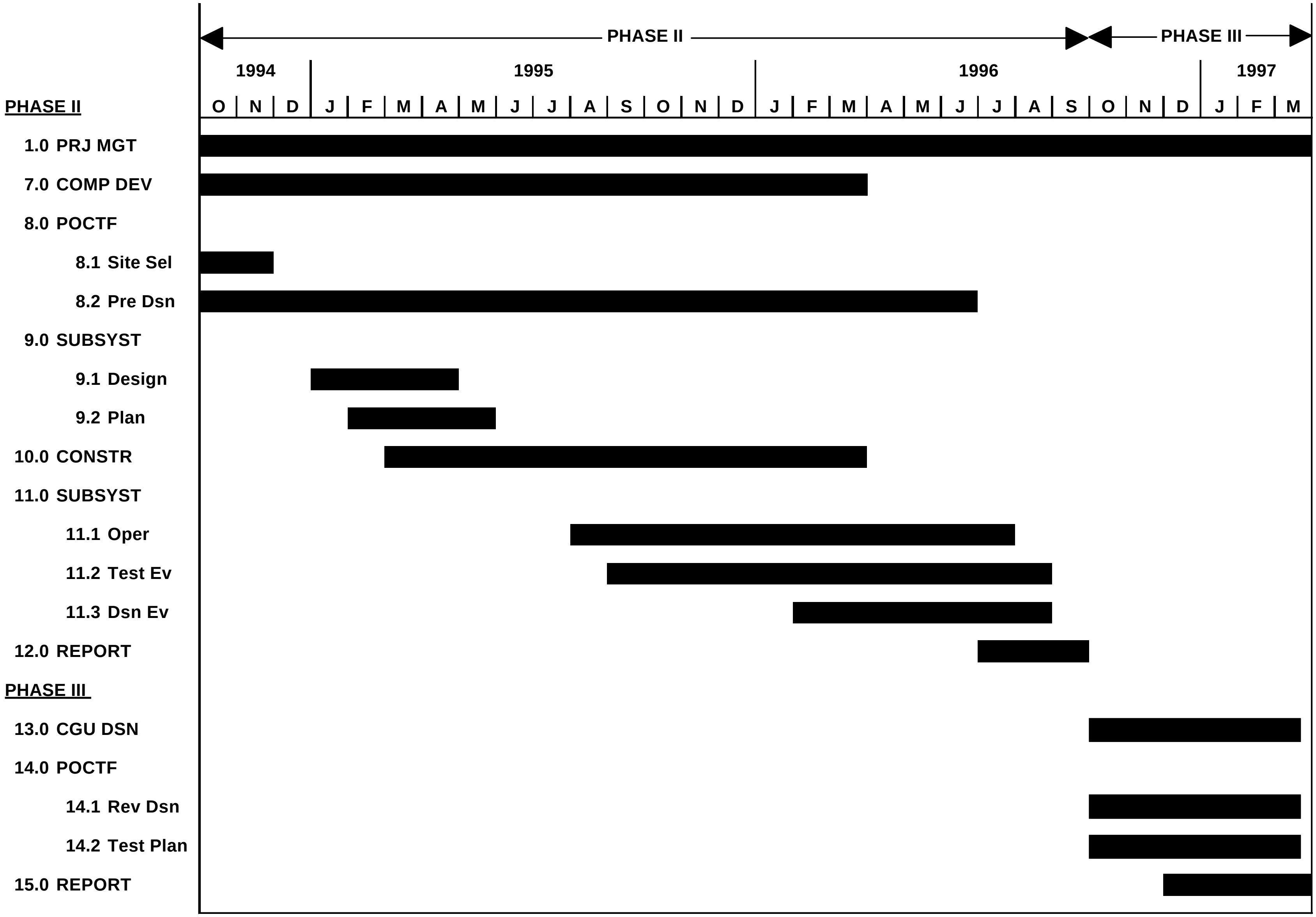
## 1.0 SUMMARY

This report describes the work by the ABB team in Phase II of the U.S. Department of Energy (DOE) project "Engineering Development of Advanced Coal-Fired Low-Emission Boiler Systems" (LEBS) which is part of the DOE's Combustion 2000 Program. The objectives of the LEBS project are to dramatically improve environmental performance of future pulverized coal-fired power plants, to increase their efficiency and to reduce their cost of electricity using near-term technologies, *i.e.*, advanced technologies that are partially developed or are already commercial. The overall objective is to expedite commercialization of the technologies that are developed under LEBS. The final deliverables are a design data base that will allow future coal-fired power plants to meet the stated objectives and a preliminary design of a Commercial Generation Unit (CGU). The schedule for Phases II and III is shown in Figure 1.0-1 and the work in Tasks 8-11 is summarized below and is described in detail in the body of this document.

The major activities in Phase II were:

Task 7 - Component development and optimization of technologies selected in Phase I. This work centered around the low-$NO_X$ firing system, ABB's TFS 2000™, and the CeraMem filter, a component required in the $SNO_X$™ Hot Process.

Figure 1.0-1 **PROJECT MILESTONE SCHEDULE - PHASE II & PHASE III**



Task 8 - The preliminary design and licensing of the Proof-of-Concept Test Facility (POCTF) for the site selected in Phase I - Richmond (Indiana) Power & Light (RP&L).

Tasks 9 through 11 - Larger scale testing of the low-$NO_X$ firing system and the CeraMem filter.

Midway through Phase II ABB acquired the rights to Kalina cycle technology for direct fired, *e.g.*, pulverized coal, applications. Following discussions with the DOE and RP&L, it was decided to change from the advanced supercritical Rankine cycle selected in Phase I to a Kalina cycle for both the POCTF and the CGU. As with the Rankine cycle, the boiler, turbine/generator and related power cycle auxiliaries are being developed outside of the LEBS project.

The other significant change in ABB's LEBS technologies was from the SNOX Hot Process to ABB's advanced dry scrubber called NID (New Integrated Desulfurization). The change was made because Task 7 testing indicated that the catalyzed CeraMem filter, while having the potential to be commercially viable, would not be developed in time to satisfy the LEBS schedule.

**Task 7**

Low-$NO_X$ Firing System

The foundation of the $NO_X$ Control Subsystem for the LEBS boiler design is ABB's TFS 2000™ firing system, which encompasses sub-stoichiometric combustion in the main firing zone for reduced $NO_X$ formation, with subsequent injection of close coupled overfire air (CCOFA) and multiple levels of separate overfire air (SOFA) to provide for complete combustion while maintaining an optimim global stoichiometry history. Near field stoichiometry control is accomplished through the use of advanced, anti-deposition, low-$NO_X$ Aerotip™ coal nozzle fuel admission assemblies. Also included in this design is the use of Concentric Firing Circle (CFS) secondary air for reduced waterwall corrosion potential. Finally, a pulverizer equipped with a Dynamic™ Classifier is included to produce fine coal to minimize carbon losses under staged combustion.

The primary objective of Task 7 was to conduct research, development, and testing in support of Subsystem Test Operation and Evaluation (Task 11), the Revised Commercial Generating Unit design (Task 13), and the revised Proof-of-Concept Test Facility design (Task 14). The work consisted of engineering analysis, experimental research and computational modeling designed to address various key technical aspects associated with the TFS 2000™ firing system, and is summarized below.

*Computational Modeling:* Kinetic modeling and computational fluid dynamic (CFD) modeling were used in the development and evaluation of firing system enhancements, based on controlling the combustion of the coal in a more local sub-stoichiometric environment, on potential $NO_X$ reduction and boiler performance. A one-dimensional chemical reaction kinetic model was used to evaluate the potential effects of vertical staging within the main burner zone (MBZ.) Screening and development of new, novel variations employing horizontal staging in the MBZ was accomplished using 3-dimensional CFD modeling.

Results from chemical kinetic modeling indicate that, although the MBZ stoichiometry is the primary factor influencing overall $NO_X$ emissions, the stoichiometric build up in the MBZ can have a notable influence on $NO_X$ emissions. Results from the CFD modeling suggest that firing configurations employing two-corner firing for horizontal staging are viable when applied to the BSF geometry. These model predictions further suggest that horizontal staging through the use of a helical firing arrangement should result in boiler performance resembling that of the standard TFS 2000™ firing system.

*Corrosion Tests:* The sub-stoichiometric environment associated with deeply staged low-$NO_X$ pulverized-coal firing can result in relatively high concentrations of total reduced sulfur species (TRS) and unburned carbon at boiler waterwalls, resulting in conditions that are more conducive to corrosion attack. To develop a better understanding of these effects, ABB Power Plant Laboratories conducted bench-scale corrosion studies under simulated staged combustion conditions and short-term exposure under combustion conditions in ABB's Boiler Simulation Facility. The effects of sulfur content on corrosion, with and without carbonaceous deposits, were systematically evaluated.

A proper firing system design can minimize localized reducing environments and unburned carbon at furnace walls. Key parameters influencing corrosion potential are the amount and form of reduced sulfur, unburned carbon content in the particulate arriving at waterwalls, and local heat transfer conditions. Increased TRS resulted in increased metal recession rates. Increased TRS and CO reflect increases in carbon and sulfur concentrations in the particulate arriving at waterwalls, thereby increasing the susceptibility for wastage due to a reducing micro-climate effect. Under heat transfer conditions, a localized high temperature exacerbated wastage rates under either oxidizing or reducing gases. From a material standpoint, SA-213 grade T-11 steel was most susceptible to high-temperature sulfidation with a larger wastage rate than 310 SS, while chromized T-11 was superior.

*Advanced Firing Systems:* A series of combustion tests were carried out in ABB's Fundamental Scale Burner Facility (FSBF), firing an Illinois No. 6 coal at a nominal rate of 6 MBtu/hr. Initial testing focused on benchmarking global staging arrangements. Tests were also performed to evaluate firing system concepts for suppressing $NO_X$ formation by controlling the stoichiometry history in the MBZ. These concepts were: 1) advanced fuel staging utilizing strategic distributions of coal feed rates; and 2) vertical windbox staging using air and coal nozzles strategically distributed within the MBZ.

Results indicated that with global staging, there is an optimum main burner zone stoichiometry at which the lowest $NO_X$ emissions are achieved. The largest $NO_X$ reduction occurs over a short bulk residence time, with diminishing returns in overall $NO_X$ reduction as the sub-stoichiometric residence times are increased. Investigations into the fundamentals of coal reburn processes show that the reburn efficiency decreases as inlet $NO_X$ emissions decrease. For already staged low-$NO_X$ firing systems, this may mitigate the effectiveness of classical reburn techniques. Results from the advanced staged firing systems showed biasing fuel to the lower elevations of the MBZ did not perform better than the standard TFS 2000™ firing system. However, vertical windbox staging does influence outlet $NO_X$ emissions, with increased $NO_X$ emissions resulting when peak MBZ stoichiometries were above 1.0.

*Pulverizer Technology:* Staged combustion conditions required for achieving low-$NO_X$ emissions tend to run counter to those that are favorable for good coal combustion. Controlling the proper coal particle size distribution becomes a more critical factor, as it has obvious effects on facilitating better carbon burnout. Work was performed in ABB's Pulverizer Development Facility (PDF) using a commercially available 3-journal 32-inch shallow bowl mill equipped with state-of-the-art pulverizer components to evaluate the influence of design characteristics on pulverizer performance in terms of mill power consumption, throughput and product size produced.

Results showed that the Dynamic™ classifier provides greater flexibility with respect to the desired fuel size than static classifiers, and require significantly less throughput reduction to achieve very fine products. Test results comparing the standard roll design to the proposed chamfered design showed that no advantage would be provided by the latter. However, an independent collaboration between ABB and a commercial customer concerning reduction of pulverizer vibration has resulted in the development of a new standard grinding roll design. This new design reduces vibration and has also been found to reduce pulverizer power requirements by 10-15%, and is recommended for the POCTF. Air flow requirements for pulverizing are dictated by the need to dry and convey the coal though the pulverizer, and it was seen that too little air can be detrimental to pulverizer performance. Since a pulverizer body redesign to accommodate lower air flow is not feasible at this time, recommendations for air flow must be those for a conventional design, typically 1.5 pounds of air for every pound of coal feed.

Flue Gas Treatment

The air pollution abatement system initially recommended for the POCTF was the $SNO_X$ Hot Process. The process requires use of a catalytic CeraMem filter for $NO_X$ reduction and particulate control. The filter, commonly referred to as $CeraNO_X$, was the key technical obstacle towards successful application of the technology. The remaining components of the $SNO_X$ Hot Process have been demonstrated at the Clean Coal Technology Demonstration Facility at Ohio Edison Niles Station and at commercial scale at the NEFO Power Station in Denmark.

Concerns for the CeraNO$_X$ system centered primarily on regeneration (*i.e.*, on-line cleaning of the filter) and filter draft loss. As the NO$_X$ emission target could be met by the burner system alone, subsystem NO$_X$ reduction and $NH_3$ stoichiometry were secondary issues.

Task 7 results, from testing conducted on a 150 ACFM slipstream unit, indicated that the filter could be cleaned effectively. However, filter draft loss was exceedingly high. Phase I technical and economic analysis indicated that for the CeraNO$_X$ system to be viable, filter draft loss should be less than 12 inches w.c. at process conditions. Task 7 results indicated that the CeraNO$_X$ draft loss would approach 24 inches w.c. at process conditions, and was due in large part to the catalyst application to the filter. Draft loss of the filter alone would approach 8 inches w.c. at process conditions. It was concluded, based on Task 7 results, that the CeraNO$_X$ filter, which has the potential to be effective, was not sufficiently developed for it to be recommended for the POCTF design at this time. Therefore, the Task 11 testing was deleted.

Recently ABB Environmental Systems had developed outside of the LEBS project an advanced desulfurization system, called NID, and recommended study of this system as an alternate to the SNO$_X$ Hot Process. The NID process will meet the most stringent LEBS environmental performance objectives. In addition, the NID process is attractive to the project goals due to good integration into the Kalina thermal scheme and the high potential for commercialization. This system is described in the body of this report.

**Task 8**

The scope of the task consists of the selection of a suitable host site, and the development of a preliminary engineering design for the proof-of-concept test facility (POCTF). The purpose of the POCTF is *not* to demonstrate a low-emission boiler system, but rather to develop the technology base required for the design, construction, and operation of initial commercial LEBS-based electric generating plants. The design of the POCTF is required to reflect the technical characteristics of a Commercial Generating Unit design that incorporates the LEBS technologies, and includes those components and subsystems that require POCTF testing prior to commercial use.

The ABB team was fortunate in obtaining an outstanding host site for the POCTF. Richmond (Indiana) Power & Light Co. (RP&L) has commited to host the project at their Whitewater Valley (WV) Station. RP&L has a history of succesful involvement in technology demonstration programs, including one of the earliest low $NO_X$ burner installations, a LIMB installation, and a Clean Coal Technology project. The POCTF will be a repowering of WV-Unit 1.

*Plant Arrangement:* The POCTF project will involve a major restructuring of Unit 1, that entails the replacement of the complete power system (boiler, turbine-generator, feedwater heaters, power piping) with a new Kalina-based power system, and addition of a new flue gas treatment system. The project will use the plant infrastructure to the maximum extent practical however, including coal handling, heat rejection, ash handling, powerhouse structures, and auxiliary systems. Although the project is being implemented as a test facility, RP&L intends to use the unit for long-term production service following completion of the LEBS program. This criteria therefore has a dominant effect on specification and design of the equipment and the facility. The proposed equipment arrangement is shown in Figure 1.0-2.

The size of the proposed unit was selected such that the new vapor generator will fit in the existing boiler support-steel cavity, and the new turbine-generator will fit the existing turbine pedestal (after pedestal modification). The fact that the Kalina cycle regenerates substantially more heat than a steam cycle results in a significant increase in the number of regenerative heaters, such that a turbine hall addition is required to house this new equipment.

In addition, the inclusion of the LEBS flue gas emissions control features dictates removal of the gas-side power cycle systems. The replacement systems will include low $NO_X$ firing technology (TFS 2000™), a new draft system, and an advanced dry-scrubbing flue gas treatment system (NID).

The fact that Unit 1 still retains its original control system, and the unique control requirements associated with the Kalina power cycle, dictate that the project will include installation of a new unit-wide distributed control system. The large increment in auxiliary power consumption associated with the modified unit also requires that the

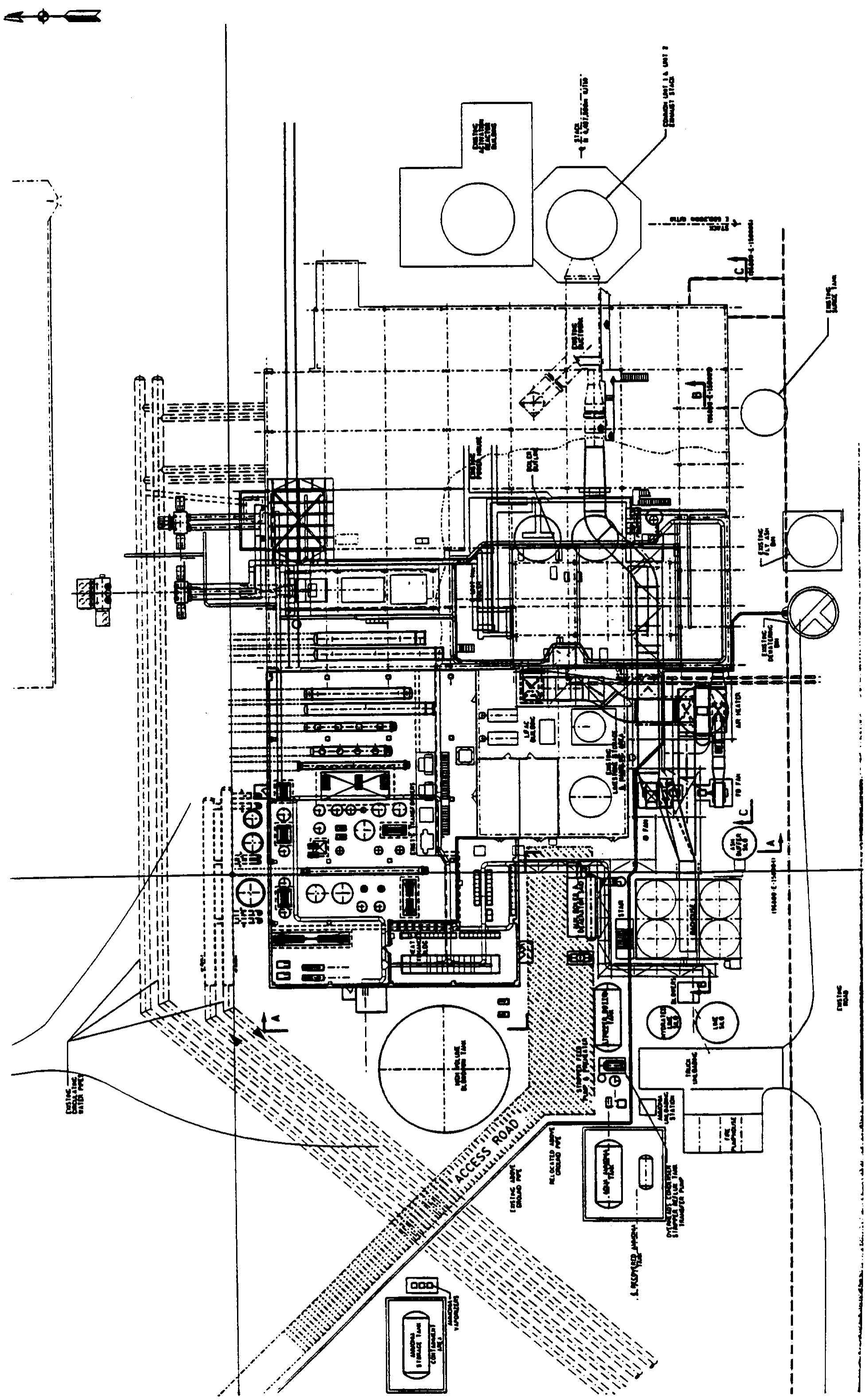



Figure 1.0-2 POCTF Plot Plan

station service transformers for Unit 1 (unit auxiliary and startup) be replaced with larger capacity units, and substantial new power distribution capability be added.

*Plant Performance:* The approach taken in establishing the size of the modified unit has been to maximize its generating capacity, consistent with making maximum use of existing plant infrastructure. Key plant performance parameters, for the existing unit and the POCTF, are compared in Table 1.0-1. By leveraging the significant improvement in heat rate offered by the Kalina cycle with a modest increase in coal heat input, the unit output will be increased a substantial 42% to about 47 MWe, with a corresponding 20% decrease in heat rate.

**TABLE 1.0-1**

**COMPARISON OF**
**UNIT 1 PERFORMANCE PARAMETERS**

| Thermal | | Existing | POCTF | Change |
|---|---|---|---|---|
| Coal Heat Input | MBtu/hr | 400 | 455 | + 14% |
| Cooling Tower Load | MBtu/hr | 216 | 215 | |
| Generator Output | MWe | 35.6 | 54.6 | |
| Auxiliary Load | MWe | 2.2 | 7.2 | |
| Net Unit Generation | MWe | 33.4 | 47.4 | + 42% |
| Net Unit Heat Rate | Btu/kWh | 12,000 | 9,610 | - 20% |
| Environmental | | | | |
| $SO_2$ | lb/MBtu | 6.0 / 1.6(*) | 0.1 - 0.2 | |
| $NO_X$ | lb/MBtu | - / 0.5(*) | 0.1 - 0.2 | |
| Particulates | lb/MBtu | 0.19/ 0.19(*) | 0.01 | |

(*) pre/post Phase II Clean Air Act Amendments (2000)

To identify the overall facility configuration and quantify key process flow variables, the following process flow diagrams were developed:

- gas-side heat balance, (Figure 3.2.1-1, page 3-9)
- NID process mass balance, (Figure 3.2.3-1, page 3-19)
- turbine heat balance, (Figure 3.2.4.2-1, pages 3-24 and 3.25)
- water balance, and (Figure 3.2.5-1, page 3-28.)
- ammonia balance.

The firing system incorporates a conventional coal feed system, with an advanced pulverizer and a highly-staged air admission arrangement, to achieve ultra-low $NO_X$ levels leaving the furnace. The gas-side of the vapor generator is conventional in design. (See Figure 3.5.2-1 on page 3-56.) The flue gas, after final heat recovery in the air heater, is ducted to the NID (New Integrated Desulfurization) gas treatment system, where sulfur oxides and particulates are removed. The NID system uses a dry scrubber-type process, in which both gas/sorbent contacting and solids removal are accomplished within a baghouse and its associated ductwork.

The POCTF uses a Kalina cycle for the power system. The Kalina cycle is a Rankine-type thermodynamic cycle that uses a binary mixture of ammonia and water as the working fluid. The turbine heat balance (Figure 3.2.4.2-1 on pages 3-24 and 3-25) depicts the basic Kalina cycle configuration and quantifies the thermodynamic state points and flow variables throughout the cycle. The Kalina cycle represented in the diagram was developed specifically for the POCTF application, and is denoted as Kalina Cycle System 19 (KCS19). The cycle is based on a single-reheat configuration with turbine throttle conditions of 2400 psig / 1050F and reheat to 1050F. A single turbine extraction, at the discharge of the HP staging, is used. In contrast to a steam cycle, the low pressure turbine exhausts at elevated conditions of 35 psia / 583F. Condensation also occurs above ambient pressure, at 29.4, 44.4 and 95.6 psia, and provides a saturated condensate temperature of 62F.

The primary technical parameters for the facility, that characterize its design and performance, are listed in Table 1.0-2. The design-basis values of primary plant emission rates are included. It is emphasized that these are not guarantee values, nor are they values for which the facility will be licensed; rather, they are target values and they provide the design basis for the associated systems and equipment.

*Project Schedule:* The schedule has been developed around the following key elements: an authorization-to-proceed with Phase IV on, or about, October 1, 1997, and the start of work on-site about three months later, in early January, 1998.

The initial work on-site will be demolition, with a start in January 1998 and lasting a duration of six months. An overall demolition/construction period of about 24 months is planned, with construction completing around the end of 1999. Facility commissioning will continue through the first quarter of 2000. The formal POC testing and evaluation task is scheduled for the following six months, completing the end of September, 2000.

*Licensing*: A licensing plan and schedule has been developed for the project that has identified the need to obtain twelve individual environmental/safety permits and approvals. The project will result in large reductions of all the regulated air emissions from Unit 1, and thus approvals for the air permits are expected to be relatively straight forward. Unique to this power project, however, is the significant ammonia inventory required for operation of the Kalina cycle. The presence of this material on site will require the development of plans to deal with a potential accidental ammonia release.

The licensing schedule is based on obtaining all approvals by October 1997, the expected start date for Phase IV. At present, contact has been established with the Indiana Department of Environmental Management (IDEM), IDEM has been throughly briefed on the proposed project, and preparation of the long-lead permit applications is in progress.

## TABLE 1.0-2
## PLANT TECHNICAL SUMMARY

### Power Cycle and Plant Performance

| | | |
|---|---|---|
| Net Generation Capacity | (kW) | 47,350 |
| Gross Generation Capacity | (kW) | 54,590 |
| Auxiliary Power | (kW) | 7,250 |
| | | |
| Main Flow @ Turbine Throttle | | |
| Flow Rate | (lb/hr) | 640,000 |
| Ammonia Proportion | (wt%) | 68.5 |
| Temperature | (F) | 1050 |
| Pressure | (psig) | 2400 |
| Hot Reheat Flow @ Turbine | | |
| Flow Rate | (lb/hr) | 302,300 |
| Ammonia Proportion | (wt%) | 68.5 |
| Temperature | (F) | 1050 |
| Pressure | (psig) | 338 |
| | | |
| Vapor Generator | | |
| Firing Rate | (MBtu/hr) | 455 |
| Efficiency | (%) | 87.7 |
| | | |
| Heat Rate | | |
| Unit Turbine Cycle | (Btu/kWh) | 7,310 |
| Net Unit | (Btu/kWh) | 9,610 |
| | | |
| Operation | | |
| Type | | Baseload |
| Expected Capacity Factor | (%) | 80 (min.) |

### Coal Quality (Performance Coal)

| | | |
|---|---|---|
| Coal Name | | Black Beauty |
| Classification | | Bituminous |
| Higher Heating Value | (Btu/lb) | 11,428 |
| Short Proximate Analysis | | |
| Moisture | (wt%) | 13.0 |
| Ash | (wt%) | 8.1 |
| Sulfur | (wt%) | 3.4 |
| $SO_2$ Content | (lb/MBtu) | 6.00 |

**TABLE 1.0-2**
**(Cont'd)**

**Selected Equipment Options**

| | |
|---|---|
| Coal Handling (existing) | Truck Delivery |
| Power Cycle | Kalina |
| Working Fluid | Ammonia/Water |
| Vapor Generator | Drum Type |
| Firing System | Tangential |
| Feed Pump Drive | Motor |
| Air Heater | Rotary-Regenerative |
| Emissions Control | |
| $NO_X$ | Combustion-Based |
| $SO_2$ | NID Process |
| Particulate | Pulse-Jet Fabric Filter |
| Turbine | 2-Casing w/ Reducing Gear |
| Cooling Tower (existing) | Wet, Mechanical Draft |

**Flue Gas Flow Characteristics**

| | | |
|---|---|---|
| Final Tube Bundle (LTVB) Outlet | | |
| Temperature | (F) | 746 |
| Excess Air Level | (%) | 20.0 |
| Air Heater Outlet | | |
| Temperature | (F) | 321 |
| Excess Air Level (equivalent) | (%) | 31.8 |
| Volumetric Flow | (ACFM) | 165,000 |
| NID Outlet | | |
| Temperature | (F) | 144 |
| Volumetric Flow | (ACFM) | 147,500 |

**Material Flow Rates**

| | | |
|---|---|---|
| Coal | (ton/hr) | 19.91 |
| Lime (pebble) | (lb/hr) | 4,608 |
| FGD Waste Solids | (lb/hr) | 11,930 |
| Bottom Ash (dry) | (lb/hr) | 666 |
| Makeup River Water | (gpd) | 965,000 |
| Wastewater Discharge | (gpd) | 363,000 |

**TABLE 1.0-2**
**(Cont'd)**

| | | |
|---|---|---|
| **Airborne Emissions** | | |
| $SO_2$ (98.3% Removal) | (lb/MBtu) | 0.1-0.2 |
| $NO_X$ | (lb/MBtu) | 0.1-0.2 |
| Particulates | (lb/MBtu) | 0.01-0.005 |
| **Waste Solids** (Ash + FGD) | | |
| Mass Rate | (ton/hr) | 6.30 |
| Specific Rate | (lb/kWh) | 0.266 |
| **Water Discharge** | | |
| Volume Rate | (gpd) | 363,000 |
| Specific Rate | (gal/kWh) | 0.319 |

**Tasks 9, 10 and 11**

Low-$NO_X$ Firing System

Combustion testing was performed in ABB Power Plant Laboratories' 50 MBtu/hr Boiler Simulation Facility (BSF) to support the development of a low-$NO_X$ firing system for the LEBS Proof-of-Concept Test Facility (POCTF) and Commercial Generating Unit (CGU) designs. Through in-furnace combustion control, the specific goals of the low-$NO_X$ firing system were:

- 0.1 lb/MBtu outlet $NO_X$ emissions
- carbon in the fly ash below 5%
- acceptable boiler thermal performance

As previously noted, the TFS 2000™ firing system was chosen as the foundation for the LEBS low-$NO_X$ firing system design. In-furnace combustion process modification of this system focused on the optimization of localized sub-stoichiometric combustion in the main burner zone. Three enhancement strategies were identified and developed through CFD modeling and small scale combustion testing:

- Main windbox vertical staging: the control of the combustion process in the vertical direction, at each corner of the furnace.
- Horizontal windbox staging: the control of the combustion process at a given elevation within the main windbox.
- Integrated horizontal and vertical staging: the combination of vertical and horizontal staging techniques, an example of which is the helical arrangement with alternating elevations of two-corner coal firing.

Two coals were fired during the BSF combustion testing. The primary test fuel was the high sulfur, mid-western bituminous Viking coal from Montgomery, Indiana, which is presently fired at the proposed site for the POCTF, and is representative of the class of high sulfur bituminous coals specified for use under the LEBS project. The second test coal, the Ashland coal, is a low sulfur, eastern bituminous coal from West Virginia. This coal was selected as a lower reactivity, higher $NO_X$ potential fuel, as compared to the Viking coal. Both coals were fired at a fineness of 90% < 200 mesh, consistent with the TFS 2000™ firing system.

BSF combustion testing produced outlet $NO_X$ emissions of 0.1 lb/MBtu with acceptable carbon in the flyash (<5%) and acceptable thermal performance. This performance demonstrates $NO_X$ emissions reductions of 70% to 80% from the post-NSPS baseline levels are possible for an enhanced TFS 2000™ firing system configuration. Major process influences on the overall $NO_X$ emissions were:

- Global stoichiometry was found to have the single largest influence on furnace outlet $NO_X$ emissions for all firing system configurations. Greater than 45% of the achieved $NO_X$ reductions from a post-NSPS baseline configuration were directly related to the level of global air staging, irrespective of the overfire air elevation, or main burner zone firing system configuration.
- For all applications of overfire air, there is a consistent relationship between outlet $NO_X$ emissions and bulk main burner zone stoichiometry. Specifically, there is an optimum MBZ bulk stoichiometry for which $NO_X$ is a minimum. Outlet $NO_X$ emissions increase as this stoichiometry increases or decreases.

- Enhancing the performance of existing tangential firing systems through vertical and horizontal staging in the primary windboxes provides a small improvement in $NO_X$ emissions at an optimum main burner zone stoichiometry.
- Increasing the bulk, staged residence time at an optimum MBZ stoichiometry provided up to an additional 30% reduction in $NO_X$ from post-NSPS baseline levels over that found for stoichiometry adjustment alone.
- Carbon in the fly ash (CIFA) levels have a consistent variance with stoichiometry and staged residence time. For all configurations tested, CIFA increased with decreases to the bulk MBZ stoichiometry or increases in staged residence times. However, CIFA was below 5% for each of the tested configurations on the Viking coal.
- The use of two elevations of separate overfire air provides additional flexibility with respect to the tuning and optimization of boiler performance, as compared to single elevation overfire air systems. By providing increased control over the bulk gas residence time - stoichiometry history, $NO_X$ emissions can be optimized with respect to carbon loss and/or boiler thermal performance as fuels or loads are changed.
- Boiler thermal performance was shown to be favorably affected by global and local stoichiometry histories. At the optimum bulk MBZ stoichiometry for minimum $NO_X$, heat fluxes were shown to be more uniform and more similar to the baseline (no SOFA) furnace configuration.

As a result of the BSF combustion testing and subsequent analysis, the best available solution to in-furnace $NO_X$ emissions reduction is a TFS 2000™ firing system which incorporates separated overfire air, near-field $NO_X$ reduction coal nozzles, and is optimized with respect to the local staging within the main windbox region. With the comprehensive performance data compiled in this test program, it is possible to optimize the furnace configuration for a wide range of unit sizes. As a result of this work, $NO_X$ emissions, carbon in the fly ash and heat flux are well documented with respect to main burner zone stoichiometry and overfire air configuration.  This information provides a valuable engineering data set for the scale-up of the “optimized” low-$NO_X$ firing system for the Proof-of-Concept Test Facility and Commercial Generating Unit.

Flue Gas Treatment

Deleted.  See Task 7 above.