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Alliance Research Center

High-Solids Black Liquor Firing in Pulp and Paper Industry Kraft Recovery Boilers

Phase I: Final Report

Volume I — Executive Summary

PREPARED FOR:

The United States Department of Energy

UNDER CONTRACT NO. DE-FC36-94G010002, AMENDMENT M001

SUBMITTED BY:

The Babcock & Wilcox Company

RESEARCH AND DEVELOPMENT DIVISION
ALLIANCE, OHIO 44601

NOVEMBER 1995

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OVERVIEW

1.1 Objectives

This project, conducted under The United States Department of Energy (DOE) Cooperative Agreement DE-FC36-94G010002-M001, is a multiple-phase effort to develop technologies to improve high-solids black liquor firing in pulp mill recovery boilers.

The objectives of this project phase are to:

- Develop a preliminary design of a recovery furnace simulator (RFS). This includes evaluating high-solids black liquor property data, and scaling and numerical modeling necessary to support the design.
- Evaluate the economics of high-solids advanced combustion.
- Delineate a project concept for evaluating candidate technologies to improve chemical recovery including planning future tests, identifying industry interests, estimating the cost of future project phases, and charting the overall path forward for the project.

Subsequent project phases are to construct a pilot-scale test facility, develop an advanced recovery design, test the design at the pilot scale, and demonstrate the advanced design in a first-of-a-kind commercial unit or prototype.

1.2 Report Structure

This report is presented in two volumes, the executive summary and the project technical results. This volume, the executive summary, provides pulp and paper industry background, presents key results from Phase I and delineates development plans and means. The second volume (project technical results) includes a technical summary of the Phase I results, a full description of technical work completed in this phase, and Appendixes A through J which provide detailed descriptions, results, and product documents of the major areas of investigation. A copy of the technical paper, *Recovery Furnace Simulator - Design and Modeling*, which summarizes much of the Phase I technical results, is included in Appendix J. Some of the information provided in Volume II is redundant to Volume I to make the two volumes more independent.

1.3 Major Results

The primary technical result of this phase was to develop a preliminary design of the RFS. The work completed demonstrates that a 6-million-Btu/hr test apparatus would adequately simulate the chemical processes present in an industrial recovery boiler. Available black liquor properties data were evaluated and found adequate for the RFS preliminary design. In addition, tests to start up and characterize the RFS were planned in enough detail to assure that the design is adequate for the application and to estimate the facility costs. Two major paper companies provided letters of support for the project, and potential suppliers have been identified for all key components and services required to go forward with the project.

The cost to complete the design and build and start up the RFS were closely estimated. Budgetary estimates were updated for the later project phases that address testing and development of a high-solids advanced combustion system. Within this report, high-solids advanced combustion refers to a significant modification of the Tomlison recovery boiler technology (particularly the lower furnace, air system, and black liquor system) to accommodate firing black liquor at up to 85%+ solids and with increased throughput (compared to current commercial designs).

A confidential advanced combustor design concept was included in the proposal for this project. Assuming the project moves forward along that technical path, that concept (and potentially others) would be evaluated using numerical modeling; then a selected concept would be tested in the RFS during a later phase of the project.

The economics of high-solids advanced combustion technology were evaluated based on a commercialization strategy of combining high-solids advanced combustion with low-odor conversion in existing process recovery boilers. That evaluation shows that high-solids advanced combustion is economically justified; however, site-specific parameters significantly affect this result.

1.4 Recommended Direction

The future direction of the program was evaluated in view of a current assessment of industry interests in recovery technology and considering trends affecting the industry. This assessment included consideration of proprietary company marketing data based on confidential customer interviews collected outside this contract. Recently published technical results on black liquor high-solids firing and gasification were also considered. The resulting conclusion is that high-solids advanced combustion technology is a viable technology that may be economically justified in many cases.

However, there is growing industry interest in black liquor gasification as a potential technology to augment (and later displace) recovery boiler technology. Therefore, the recommended direction of this program is to consider black liquor gasification as the leading candidate technology competing with advanced combustion to improve black liquor processing. Considering this result, the recommended next steps are:

To conduct an interim phase to evaluate gasification as an alternative development path for the balance of the project.

At the conclusion of that interim phase, select a path forward considering three options:

- Proceed with development of high-solids advanced combustion.
- Proceed with development of black liquor gasification.
- Pursue neither technology as described in this report.

2

BACKGROUND

2.1 Pulp and Paper Industry

The paper industry is a stable, major industry and a major employer in the U.S. It is also a major exporter and is recognized as a world leader in this field. The industry is a major consumer of energy but also has the highest rate of self-generated energy.[1] This industry is very capital intensive due to the complex and substantial production equipment required. It has also incurred substantial costs to meet established emission-reduction goals ahead of schedule and to increase the use of recycle fiber.[2]

The North American paper industry is currently the dominant segment of the industry in the world, with 45% of the worldwide pulp production capacity and 35% of the paper and paperboard capacity.[3] (See the box, U.S. Paper Industry — World Position, Employment, Investment, and Geographic Distribution for more details.)

2.2 Recovery Process

This project is primarily concerned with pulp production from virgin wood fiber via the kraft (or sulfate) process. Pulp production from recycled material within the industry and from postconsumer sources is significant and continues to increase. However, the impact of recycling on this project is limited to its effect of competing with the kraft process for production capacity and its impact of increasing mill demand for electricity due to the power requirements related to recycle production.

The kraft process, which includes chemical recovery processes addressed by this project, remains the primary means of virgin pulp production and accounts for more than two-thirds of all U.S. production. Wood fiber is overwhelmingly the fiber source for U. S. virgin pulp.[3] (See the box, *The Kraft Process* for more details.)

2.3 Four Major Trends Affecting Chemical Recovery

The U.S. paper industry is recognized as a technological leader, and is the major producer of pulp and paper products in the world. Means to reduce costs, including purchased energy costs, and maintain or improve the environmental acceptability of pulp and paper manufacturing processes are of continuing interest within the industry. Four major trends that impact the industry's interest in improving recovery processes include:

- **Emissions.** More stringent control of all emissions is anticipated. Process improvements will need to consider means to reduce airborne emissions.[7] Also, mill closure will impact liquor composition and disposal of noncondensible gases from liquor concentration and pulping processes.
- **Mill Energy Requirements.** Electrical demands compared to steam demands will increase for both pulp and integrated (mills that produce pulp and paper products) mills due to the increases in environmental control equipment and the increased use of recycle fiber.[7,8]
- **Age of Equipment.** There is a significant base of installed pulp production equipment in the U.S. Between the years 2000 and 2020, a significant segment of this capacity will require replacement or upgrade.[9,10]
- **Capacity.** Process changes will increase the load on the recovery plant.[7,11] Due to economies of

U.S. Paper Industry — World Position, Employment, Investment, and Geographic Distribution

World Position. While the majority of the domestic paper industry production, approximately 92%, is consumed in the U.S., the industry is also a major exporter. In recent years, exports and imports in this industry have approximately balanced, with a small trade deficit in these products being typical. The top five importers of U.S. paper and applied products in 1992 were Canada, Mexico, Japan, Germany, and South Korea.[1] These five trading partners collectively imported more than 50% of the U.S. exports of these products.[1] Canada was the leading exporter of paper and allied products to the U.S., supplying approximately 75% of these products imported by the U.S. in 1992.[1] U.S. and North American production is compared with other world regions in Table 1.

The U.S. currently operates 16% of the pulp mills in the world but produces approximately 35% of the world's pulp.[2] The U.S. once was clearly the technological leader in pulp and paper. However, Canada and the Scandinavian countries are now challenging that position.[2] Also, increased pressure from low-cost producers in emerging countries, including Chile, Indonesia, and Brazil[2], is a reality. Major market growth is expected in these low-producer-cost regions that will produce a significant export market for new recovery equipment suppliers.

Table 1. U.S. PULP AND PAPER PRODUCTION COMPARED WITH OTHER WORLD REGIONS* (1993, in thousands of tons)

Region	*Paper/Board*	*Pulp*
North America	94,091	79,966
U. S.	76,577	57,069
Europe (East & West)	74,760	38,338
Asia	65,819	30,742
Latin America, Africa, and Australia	16,945	14,065

* Adapted from Reference 4.

Employment. The industry is a major employer, with 620,000 employees total in the U.S.[1] These are typically high-paying jobs. The average earnings in paper and allied products in 1993 was $13.92/hour for all production workers and $19.15/hour for pulp production workers.[1] This compares with a national average of $11.76/hour for all U.S. manufacturing production.[5] Although the industry experiences periods of decline, total employment by the industry has been reasonably stable since 1987, and its compounded annual growth rate, based on value of shipments, has been 1.2% over that period.[1]

Investment. The industry is one of the country's most capital-intensive manufacturing industry.[2] It is ranked second in total capital expenditures by the U.S. Census Bureau[1] and invests approximately $120,000 per employee — more than twice the average for U.S. manufacturers.[2] Capital expenditure by the industry ranged from $5.7 billion to $10.8 billion, averaging $8.6 billion, between 1987 and 1991.[1] Approximately 40% of the capital spending for the period of 1994 to 1996+ is expected to be invested in the wood yard and pulp mill.[4] The recovery process, which this project addresses, is a major part of the pulp mill equipment investment.

Geographic Distribution. While much of the pulp and paper industry capacity is located in the south, the industry is also quite geographically diverse, with 351 pulp mills and 605 paper/paperboard mills located throughout the country.[4] The distribution by major region, in number of mills and production in 1000 tons, is shown in Table 2.

Table 2. NUMBER AND PRODUCTION OF U.S. PULP AND PAPER MILLS BY REGION (Production from 1992 in thousands of tons; adapted from Ref. 4)

Region	*States*	*Pulp Mills*	*Paper/Board Mills*	*Pulp*	*Paper/Board*
West	AK, AZ, CA, CO, HI, ID, MT, NM, OR, WA	63	76	10,310	12,858
Midwest	IL, IN, IA, KS, MI, MN, MO, OH, WI	75	158	5,154	16,867
Northeast	CT, ME, MA, NH, NJ, NY, PA, VT	54	187	4,901	12,339
South	AL, AR, DE, FL, GA, KY, LA, MD, MS, NC, OK, SC, TN, TX, VA, WV	159	184	48,335	49,563
Totals		351	605	68,700	91,627

scale, recovery capacity is more often installed in large increments. However, smaller capacity increases could offer an advantage for part of the U.S. mills due to site-specific needs.

2.4 Advancing Recovery Technology

Phase I of this project focused on high-solids advanced combustion as a potential means to improve chemical recovery processes. However, black liquor gasification is the leading technology competing with high-solids advanced combustion to achieve the same end. In the paragraphs that follow, we examine how high-solids black liquor concentration, advanced combustion, and black liquor gasification would each improve chemical recovery in the kraft process.

High-Solids Black Liquor Concentration

Current processing of black liquor in the recovery plant involves concentrating the liquor from its relatively weak concentration as received from the washing process, typically less than 20% solids (recoverable inorganics and combustible material), to a suitable level for combustion — typically 65% to 75% solids. This is accomplished with relatively low-pressure steam in multiple-effect evaporators.

In older facilities, the liquor is concentrated to more modest levels, 40% to 50%, in multiple-effect evaporators and is then concentrated to firing levels in direct-contract evaporators (DCEs) that use the flue gas exiting the boiler as the heat source. DCEs also liberate sulfur compounds that are discharged with the flue gas.

In either system, with or without the DCE, the concentrated liquor is sprayed into a recovery boiler where the remaining water in the liquor is evaporated in the combustion zone. This results in additional gas volume that must be handled by all downstream equipment. Also, the heat used to evaporate the remaining water in the liquor could otherwise be used to produce steam for electric power production. This has promoted industry interest in firing recovery boilers at increased solids levels. To do so, the evaporator technology has evolved to supply higher-solids liquor.

The current evaporator technology has the ability to support concentration to approximately 80% solids and may be pushed higher. As the solids levels increase, the liquor properties, most notably viscosity, change significantly. Evaluation of black liquor properties indicates that operating (firing) at higher liquor temperatures should adequately control liquor viscosity for handling and atomization by the spray nozzles. However, viscosity is expected to set the upper limit of liquor solids level that is achievable in this project.

Advanced Combustion

Phase I of this project focused on preliminary design of an RFS to evaluate advanced combustion using high-solids firing. The advanced combustor would fire at liquor solids levels of 85%+. The upper limit will be set by the economic and practical limitations for liquor handling. In addition, this approach would include significant modification to the lower furnace to increase the quantity of material processed for a given furnace size (i.e., increase hearth heat input rate). As a result, advanced combustion would offer the advantage of increased liquor processing for similar recovery boiler size. This would reduce capital costs and increase high-pressure steam production per unit of liquor processed, while operating at the same or lower emissions per unit of liquor processed. This technology could also be integrated with low-odor conversions and capacity upgrades for older DCE units. Major results from Phase I addressing the first steps to develop this technology are discussed in Section 3.

Black Liquor Gasification

This is an emerging technology for black liquor processing that is an alternative to advanced combustion. In this process, the black liquor is heated under reducing conditions in a gasifier vessel or reactor to produce a fuel gas. There are several variations of black liquor gasification under development or proposed worldwide. These may be considered in two broad categories of high-temperature and low-temperature processes.[9] The high-temperature processes recover the inorganic materials in a molten state, similar to the smelt produced by a recovery boiler.[9] The low-temperature gasifiers

The Kraft Process (adapted from Reference 6)

The kraft process flow diagram (see Figure 1) shows the typical relationship of the recovery boiler to the overall pulp and paper mill. The kraft process starts with feeding wood chips (or nonwood fibrous material) to the digester. The chips are cooked under pressure in white liquor or cooking liquor (an aqueous chemical solution of sodium hydroxide and sodium sulfide) in the digester.

After cooking, pulp is separated from the residual liquor (black liquor) in the washers. Following washing, the pulp is screened and cleaned to remove knots and shives and to produce fiber for use in the final pulp and paper products.

The weak black liquor rinsed from the pulp in the washers is an aqueous solution containing wood lignins, organic material, and inorganic compounds oxidized in the cooking process. Typically, the combined organic and inorganic mixture is present at a 13% to 17% concentration of solids in weak black liquor. The kraft cycle processes the black liquor through a series of operations, including evaporation, combustion of organic materials, reduction of the spent inorganic compounds, and reconstitution of the white liquor.

The weak black liquor is concentrated in the multiple-effect evaporators (and concentrators in systems that combust at higher solids). The concentrated black liquor that results is introduced into the recovery boiler furnace along with combustion air. Inside the furnace, the residual water is evaporated, while the organic material is combusted and the oxidized inorganic material is chemically reduced, primarily in a bed on the furnace floor. The molten inorganic chemicals (or smelt) in the bed are discharged to a tank and dissolved to form green liquor (containing the active chemicals sodium carbonate and sodium sulfide).

Within the furnace of the recovery boiler, organic compounds in the black liquor are combusted in parallel with the reduction of sulfur compounds to form smelt. The boiler uses the energy released by the combustion to produce steam from feedwater. The steam can be introduced to a turbine generator to produce electrical energy for the pulp and paper mill. Steam extracted from the turbine at low pressure is used for process requirements such as cooking wood chips, evaporating water from black liquor, recovery furnace air heating, and drying the pulp or paper products.

The green liquor, noted previously, is further processed to generate white liquor for reuse in the pulping process. In addition to the active chemicals, the green liquor contains impurities from the smelt or dregs, that are removed in the green liquor clarifier. The dregs are pumped out of the clarifier as a concentrated slurry and the clarified green liquor is pumped to the slaker. The dregs are typically water washed before landfill disposal, producing a water wash liquid, or weak wash, containing the recovered sodium chemicals. The sodium chemicals are then recovered by using the weak wash to dissolve the smelt coming from the recovery boiler to produce green liquor.

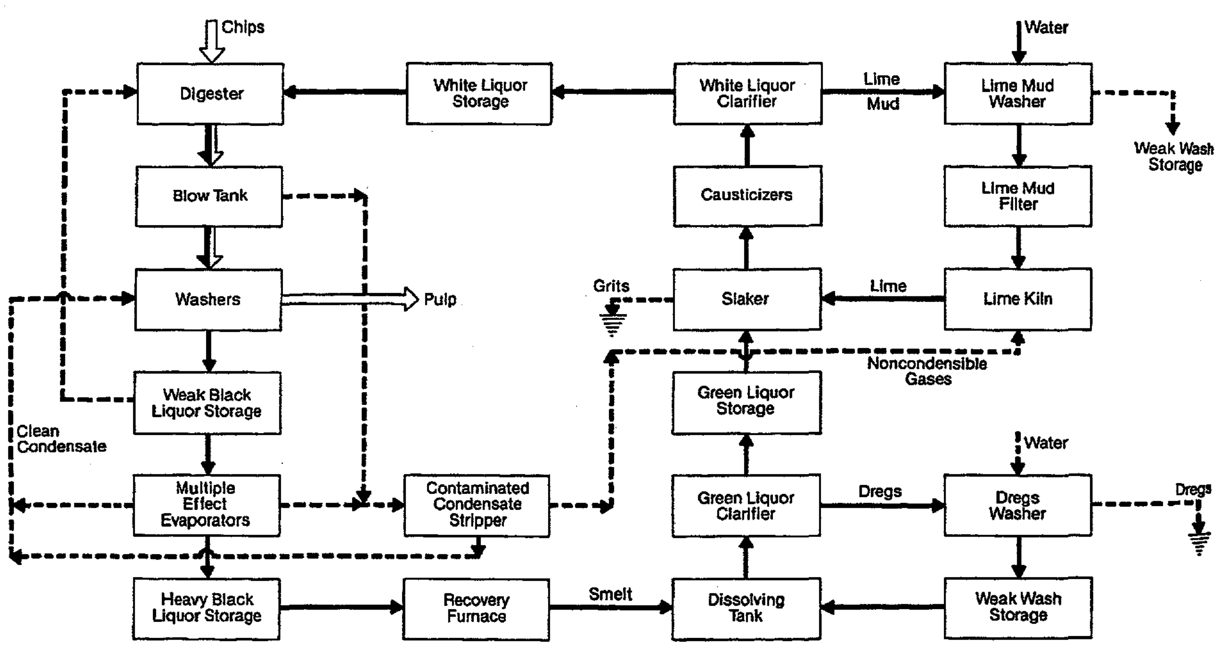

Figure 1. Kraft process diagram (Ref. 6).

Kraft Process (Continued)

Clarified green liquor and lime are continuously fed to a slaker where the lime is converted into calcium hydroxide. The liquor from the slaker flows to the causticizing plant that converts sodium carbonate into active sodium hydroxide. The calcium carbonate formed in the conversion reaction precipitates in the causticizing operation to form a suspended lime mud. The causticizing product is clarified to remove the lime mud and produce clear white liquor for cooking. The lime mud is then washed and filtered to obtain the desired consistency for feed to the kiln. The lime kiln calcines the washed lime mud feed into lime and carbon dioxide. The calcined lime is then slaked as previously described. The combination of these process steps, slaking, causticizing, and calcination, is referred to as recausticization.

operate so that the material is recovered as a dry solid.[9] The composition and resulting heating value of the product fuel gas are determined by the gasifier process chosen.

Independent of this contract, the Babcock and Wilcox Company (B&W) has examined black liquor gasification and determined that low-temperature gasification shows promise for satisfying the process requirements and achieving a cost advantage. Possible process designs considered include direct pyrolysis, carbon dioxide gasification, steam gasification, and air-blown gasification.

The process selected offers an adequate heating value in the product gas, avoids some potential operational problems, and is predicted to achieve acceptable carbon conversion. Black liquor gasification will involve cooling the product gas to allow low-temperature gas cleanup and recovery of sulfur. This introduces the need for a heat recovery boiler downstream of the gasifier.

As a result, gasification, which can accommodate a range of solids in the black liquor supply, could also benefit from using high-solids black liquor. With a higher-solids black liquor supply, more of the sensible heat in the hot product gas would be available to generate high-pressure steam in the heat recovery boiler instead of evaporating the remaining water in the incoming liquor. As was the case with advanced combustion, if the incoming black liquor is higher in solids and, therefore, lower in water, the volume of the product gas is reduced by the amount of water vapor that would not be evaporated within the gasifier. This reduces the required size and resulting cost of the downstream equipment to process the gas.

High-solids concentration may not be the most economic approach for all installations, so the flexibility of the design to accommodate liquor over a range of solids remains an advantage of B&W's conceptual gasifier design for retrofit or incremental capacity increases in exiting mills.

3

PHASE I RESULTS

3.1 Recovery Furnace Simulator (RFS)

Preliminary Design

A major result of Phase I of this project was development of a preliminary design for a pilot-scale RFS. The RFS design is suitable for developing advanced combustion technology using high-solids black liquor. The base-design firing rate, 6 million Btu/hr, is high enough to make scaling issues manageable as demonstrated by prior company experience in simulating combustion chemistry and emissions in fossil fuel test facilities. The general arrangement of the resulting design is shown in Figure 2. Some key features of the RFS design are:

- A design scaled to simulate a commercial unit.
- Refractory lining of the furnace to control heat release and enable gas temperature control to simulate a commercial unit.
- Auxiliary gas burners for startup and combustion support at difficult operating conditions.
- A three-level air system (primary, secondary, and tertiary) similar to commercial designs, but with greater operating flexibility in air distribution and temperature control and a design suitable for modification to alternative staged-combustion approaches.
- A single liquor gun and a single smelt spout for simple operation.
- Natural convection, atmospheric pressure, cooling circuits to simplify operation and future modifications.

A schematic block diagram of the facility design is shown in Figure 3. Facility design features include:

- Simple gas cleanup using a boiling-water heat exchanger (BWHX) to cool the gas, followed by a baghouse to collect particulate. The design is planned to meet all local emission requirements.
- Flexible liquor handling and processing to support the range of testing and a liquor receiving system to meet local environmental requirements.
- A smelt-handling system based on proven technology that is designed to minimize the volume of material handled.
- Use of an existing structure and existing equipment for auxiliary systems where possible.

RFS Scaling

This design was developed using scaling techniques described in Volume II to simulate a modern recovery boiler. The scaling criteria used were:

- Simulate the gas side time/temperature profile of a commercial recovery boiler and convection pass.
- Select the liquor nozzle and gun height to achieve liquor droplet carry-over to the convection pass and liquor drop drying similar to a commercial unit.
- Size the secondary and tertiary air ports to achieve jet penetration similar to a commercial unit.
- Size the primary air ports based on commercial practice for small commercial units.

Modeling to Support Preliminary Design

Numerical modeling was used to evaluate design options and compare RFS simulation results with a

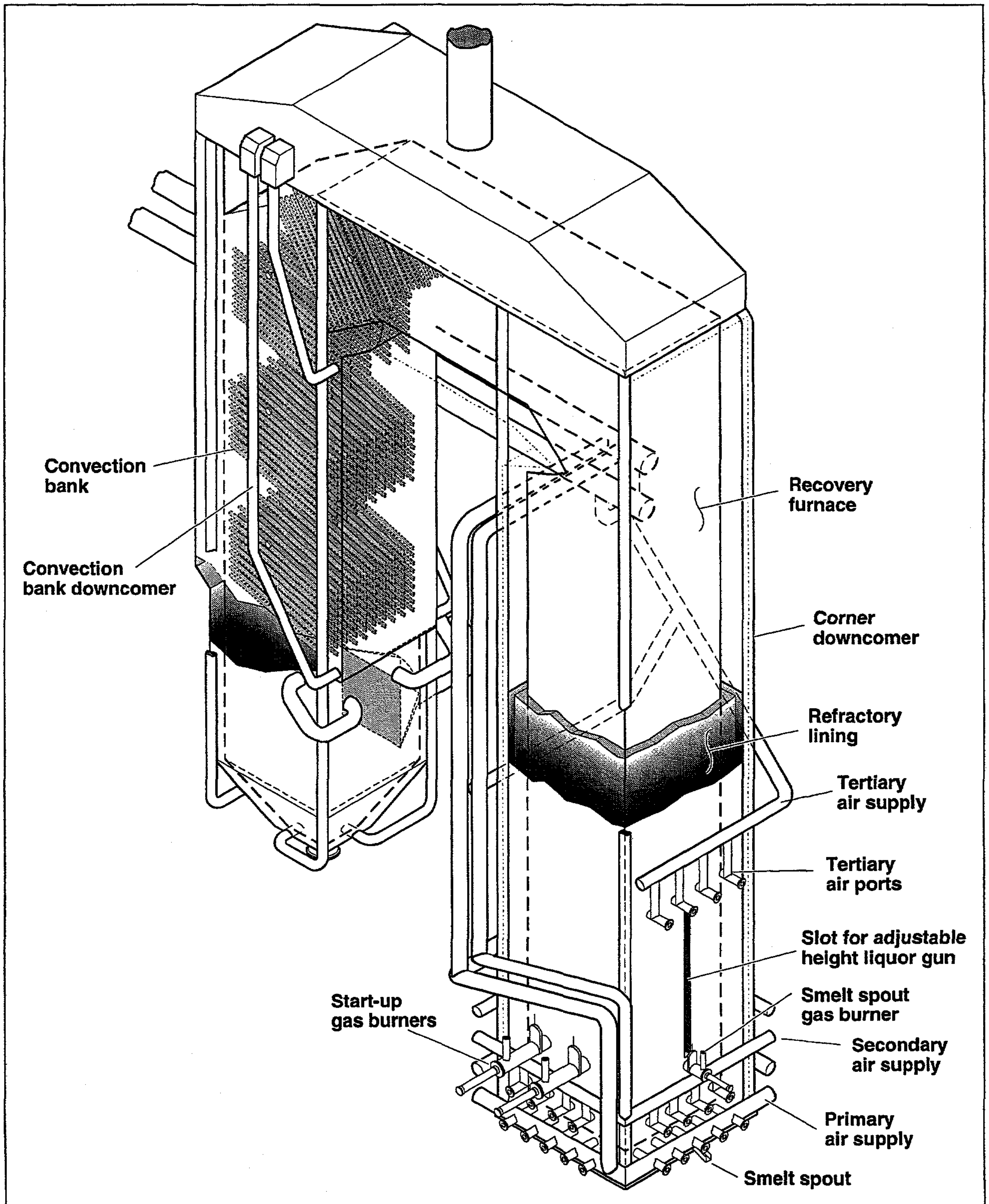

Figure 2. Recovery furnace simulator (RFS) general arrangement.

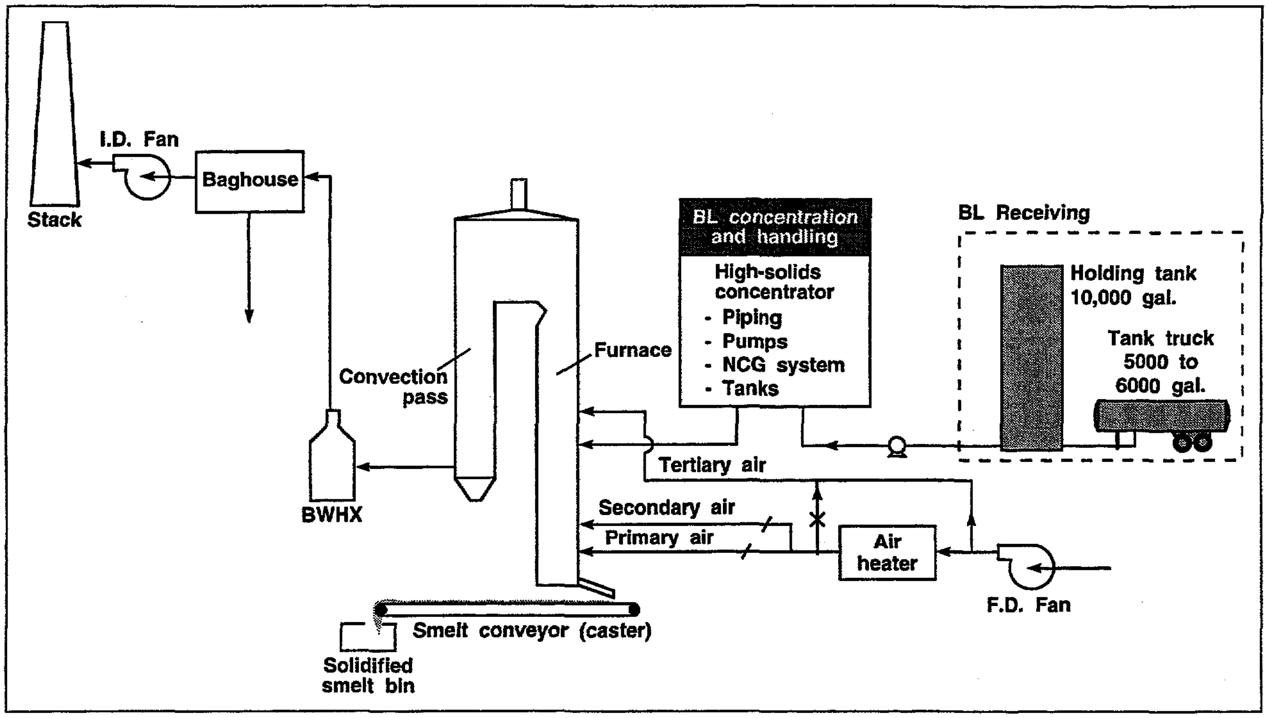

Figure 3. Schematic block diagram of RFS process flow.

reference commercial unit to demonstrate scaling. Overall, the numerical modeling results demonstrate that the RFS design would be well suited to simulate black liquor combustion and for supporting advanced combustion development. The key results show that:

- The gas side time/temperature profile in the RFS simulates a modern commercial design.
- Air jet penetration and mixing in the RFS simulates a modern commercial design.
- Black liquor distribution in the RFS simulates a modern commercial design; that is, for the liquor constituents considered (water, volatiles, char, and inorganics) the "fate" of those constituents as a function of normalized drop size is similar in the RFS and a reference commercial unit.

  [*The fate of the constituents considered is where the constituents are evolved (i.e., in flight, on the char bed, on the walls, or exiting the furnace with the flue gas). Evolved refers to water being evaporated, volatiles being burned, char being burned, and inorganics deposited. The normalized drop size is the drop size divided by the mass median drop size for the spray distribution produced by the liquor gun.*]

- Oxygen levels in the RFS upper and lower furnace are similar to commercial design.
- Liquor spray in the RFS entrained the combustion gases in the spray direction — a phenomena not evident in the commercial design. As a result, alternate spray nozzles were considered, and a nozzle to minimize this effect was identified. However, it was not possible to eliminate this effect, so this will be a limitation of the RFS simulation of commercial designs.

Additional work is planned during detailed design in Phase II of the project to take advantage of improvements in numerical models that are expected be available by that time.

The key results of the preliminary design, scaling methodology, and numerical modeling were presented at the 1995 International Chemical Recovery Conference. The technical paper, *Recovery Furnace Simulator - Design and Modeling*, which was included in the preprints for that conference, describes these results and is included in Appendix J, of Volume II of this report.

3.2 High-Solids Property Data and Related Test Plans

This project phase included a review and evaluation of high-solids black liquor property data. The existing data for viscosity, surface tension, density, and boiling point elevation were reviewed. These data were determined to be adequate for preliminary design of the RFS and to assure that the design will accommodate high-solids conditions. Property data needs, specific to the liquor that will be used in the test program, were identified and test plans prepared to obtain these data.

In addition to the liquor property data, the test program will also evaluate atomizers (liquor spray nozzles or liquor guns), and use single drop tests to determine liquor combustion parameters. The atomizer evaluation will ensure that the preliminary atomizer selection, based on engineering evaluation of suppliers' water spray data, is adequate. These tests will also support changes in the atomizer selection or size if necessary. The drop combustion testing will quantify liquor drying, devolatilization, and char-burning rates to support the final design.

3.3 RFS Test Planning

Test planning for startup and characterization of the RFS was developed in sufficient detail to assure that the RFS preliminary design is adequate to support the tests needs. The planned tests and their purposes are:

Shakedown Tests. These tests commission the RFS and will sequentially move the system from startup to full, stable operation at the base design heat input (6 million Btu/hr). The tests will also provide the preliminary data to guide the balance of the test program.

Baseline Characterization Tests. These tests evaluate RFS operation at steady-state conditions, near the design heat input (6 million Btu/hr) and black liquor solids conditions (65% solids). These tests will also investigate variations in operating parameters at the design heat input and black liquor solids.

High-Solids Liquor in Base Unit. These tests push the operating bounds of the base unit configuration higher than commercial solids level at near the design heat input rate. Subsequent tests would then push to the highest feasible heat input rate with higher flows of high-solids liquor. The results will provide the baseline from which to develop the advanced combustor and against which to compare its performance.

The advanced combustor design will be developed in the Phase III of the project; tests to evaluate the advanced combustor are planned as part of that development.

3.4 Industry and Supplier Interest

This project has the potential to significantly benefit the U.S. pulp and paper industry. Through our ongoing efforts to maintain contact with our customers in this industry, B&W has continued to evaluate interest in this area of development. International Paper Company and Boise Cascade Corporation have provided letters of support for the project and expressed interest in possible participation by providing a host site in the last phase of the project.

These companies are ranked first and fourteenth among North American paper products companies, based on 1993 sales. In addition, International Paper Company operates the largest number of recovery boilers in the world. A leading paper company with a kraft pulp mill in relatively close proximity to B&W's Alliance Research Center, where the RFS will be located, also expressed its willingness to participate as the liquor supplier for the project.

B&W has been well received by potential suppliers of all major components and services required for this project. As an example, leading black liquor concentrator manufacturers have expressed interest in supplying the concentrator for this project. In addition, leading researchers at the University of Florida and the Institute of Paper Science and Technology have expressed their willingness to apply the talents of their staff and their specialized laboratory facilities to provide the unique liquor analysis services required for the project.

3.5 Economic Justification

The economics of high-solids advanced combustion technology were evaluated based upon it being commercialized as part of the low-odor conversion of existing DCE recovery boilers in the U.S. There are 88 such candidate boilers (operating in the U.S. as of January, 1995) that process approximately 160 million pounds of liquor solids per day. The economic analyses demonstrated that if a representative unit were converted to low-odor operation for environmental reasons, high-solids advanced combustion technology could produce a significant cost savings and economically justify the conversion. However, this would depend upon plant-specific limitations.

These limitations include being capable of utilizing the additional steam and electrical power and the ability to upgrade the black liquor concentrator system in a way that produces the necessary steam economy. Naturally, if the added steam and electrical power capacity could not be fully utilized for a given unit cost effectively, or the target concentrator steam economy could not be achieved, the attractiveness of the investment would diminish. The payback period becomes more attractive if both the steam economy and the added capacity are achieved when firing liquor at higher solids levels.

If high-solids advanced combustion technology is developed, it would also become available for new boiler designs. U.S. pulp and paper chemical recovery capacity is expected to grow at less than 1.0% per year capacity in the next two decades and an average of one or two older units per year will be replaced during that period based on a 40-year boiler life.[10] Significant capacity growth outside the U.S., particularly in South America and the Pacific Rim of Asia, is also expected during the period.[10] Thus, these technological advances will also be an advantage to assure that U.S. suppliers of recovery boilers and associated equipment remain viable competitors for this growing export market.

The impact of high-solid advanced combustion technology on the new capacity and replacement segment was not evaluated. However, its utilization in new equipment for this segment would produce additional savings for the industry and increase the rate of self generation, further reducing the industry's dependence on purchased fuel.

4

DEVELOPMENT PLANS AND MEANS

As noted previously, B&W evaluated black liquor gasification, independent of this contract as an alternative to recovery boiler technology. Industry interest in black liquor gasification is evident in industry positions presented in DOE and AF&PA publications.[2,7] B&W's on-going marketing contacts have also confirmed a continuing industry interest in pursuing this technology as an alternative to the process recovery boiler technology.[10] The more likely near-term applications are small gasification units for incremental capacity increases.

The potential also exists to later develop larger, pressurized units, that are integrated with gas turbines to displace new or replacement recovery boiler capacity.[2] As a result, B&W recommends adjusting the path for future development accordingly. This shift would consider black liquor gasification as the leading candidate technology to provide an alternate means of high-solids black liquor combustion for pulp and paper mills.

4.1 Evaluating Alternatives

The benefits of using high-solids black liquor in both advanced combustion and gasification were described previously. However, gasification is a significantly different technology. Therefore, an interim program phase, Phase Ia, is recommended to evaluate this technology to a similar level as was completed for advanced combustion during Phase I. Then, based on the results of the two evaluations, a single technology would be selected for further development. Gasification work previously completed by B&W will provide a starting point for Phase Ia. Results from that work include:

- Gasifier conceptual design.
- Preliminary evaluation of industry needs.
- Preliminary functional specification for the commercial conceptual design.

The prior work also identified the need for engineering and reaction rate data at gasifier conditions. These data will ensure adequate sizing of the gasifier equipment for a pilot unit if this technology is pursued. Therefore, the results that would be sought from the proposed recommended Phase Ia include:

- Engineering and reaction rate data adequate to size the pilot gasifier test unit.
- Functional specification and preliminary design of the pilot gasifier test unit.
- Cost estimate to complete the program assuming gasification is the technology pursued in subsequent phases.
- A preliminary test outline to support developing a commercial first-of-a-kind (FOAK) unit.
- Economic justification of gasification considering industry needs for incremental capacity increases, replacement capacity, and new capacity.

4.2 Decision Point

After completing Phases I and Ia, there would be sufficient technical and economic data for selecting a path forward; that is, advanced combustion, gasification, or neither technology. Assuming that one of the two technologies is selected to move forward, then the research path forward is somewhat analogous for either case.

4.3 Pilot Facility

Phase II of the program would be to design, construct, and commission a pilot facility. The recommended capacity of the pilot facility (based on liquor processing rates) for either the recovery furnace simulator or the pilot gasifier is approximately the same. Phase I has demonstrated that this scale is adequate for simulating a modern recovery boiler design. This capacity would also represent a reasonable scale compared to the units that would be the first commercial application of gasifier technology.

Pilot facilities for either technology would include significantly more operational flexibility than required for commercial units to permit adequate investigation of key variables. The pilot facility would also simulate the key features needed to develop the commercial design but would use considerably simplified designs for either technology pursued. These simplified designs would contain cost, facilitate operation, and permit easy modification to accommodate developmental changes. In Phase III the pilot facility would be used to conduct tests that would provide engineering data needed to support a commercial design.

4.4 Commercialization

The resulting technology from this program, either high-solids advanced combustion or black liquor gasification, would be demonstrated in a FOAK installation in Phase IV. This FOAK installation in an operating mill would be tested to document its performance. This demonstration would be the first commercial installation and would provide broad visibility of the technology within the industry.

High-solids advanced combustion and black liquor gasification ultimately achieve the same end — extracting energy from combustible material in black liquor and recovery of the inorganic materials for reuse. However, the path to commercialize these technologies is expected to have significant differences.

Advanced combustion compliments upgrades currently offered for existing recovery boilers. These include low-odor conversion of direct-contact evaporator (DCE) units, furnace rebuilds, and upgrades to increase capacity. The FOAK installation would target a conversion and upgrade of an existing boiler with the addition of the advanced combustion technology.

There is a significant number of older recovery boilers that may utilize these upgrades. This would provide a major avenue for introducing the technology to the industry. Advanced combustion technology would also be available for integration into new recovery boilers from the proposal stage forward. This would address boiler replacement and new capacity applications.

Black liquor gasification is an emerging technology. The proposed initial designs would operate at atmospheric pressure to deliver low-heating-value gas that would displace purchased fuel in existing mills. These units would be used to eliminate recovery capacity shortfalls similar to those that might be addressed by recovery boiler upgrades. Black liquor gasifiers could offer the advantages of providing added capacity when an upgrade of an existing boiler is impractical and potentially reduce downtime during installation compared with boiler upgrades. The technology will need to evolve to larger capacity and integration with combustion turbines to displace the large recovery boilers for new or replacement capacity. The time frame for this evolution to occur has been suggested to be 10 - 20 years.[8]

B&W is a recognized industry leader and is uniquely positioned to commercialize either technology domestically as the major supplier of the installed chemical recovery boiler capacity in the U.S. The company not only supplies recovery boilers in the U.S. and Canada but, as a leading international supplier, is well positioned to extend any technology developed to increase the export market as well. The company has the engineering, manufacturing, construction, and service capabilities to address the full life cycle of either technology. Either technology would be an extension of B&W's existing capabilities in recovery boilers and turnkey installations for the pulp and paper industry.

As noted previously, high-solids concentration of black liquor is generally a benefit with either technology if it can be implemented cost effectively at the specific mill being considered. This requires high-solids liquor concentrators. The black liquor concentrator suppliers being considered to support a pilot facility are also leading, recognized domestic suppliers of that equipment.

4.5 Estimated Costs, Schedule, and Industry Investment

As part of Phase I, the costs to complete the program were estimated based on the recommended program direction and the schedule to do so. Estimates for Phases Ia, II, III, and IV are provided in Table 3, and the overall schedule for major tasks is shown in Figure 4. The estimate for Phase Ia includes the labor and materials costs to complete the workscope described previously. The Phase II estimate is based on an engineering estimate to complete the detailed design, construction, and startup of the RFS pilot facility. The Phase III and Phase IV estimates are budgetary estimates and are based on advanced combustion being the technology pursued. Cost shares and final pricing would vary based on the specific business arrangements pursued. These will be provided in separate proposals to DOE as needed.

Table 3. ESTIMATED COSTS FOR PROJECT PHASES Ia, II, III, AND IV (In Thousands of Dollars)

Description	*Phase Ia*	*Phase II*	*Phase III*	*Phase IV*
Direct Cost (Labor + Material)	455	7,625	3,700	20,800
Indirect Cost (G&A + COM*)	107	1,700	1,175	7,200
Total Cost	562	9,325	4,875	28,000

* COM - Cost of money

The following general notes apply to these estimated costs:

- Escalation of 5% per year is used throughout to adjust for inflation.
- G&A and COM rates are assumed at current levels.
- The results shown are based on estimates for the detailed design and construction of the RFS at ARC as described in this report. Phase Ia is included, assuming it would be executed to provide input for the decision of whether to pursue advanced combustion or gasification in future phases. Phases II - IV assume that advanced combustion is the technology selected after Phase Ia.
- The Phase IV budgetary cost is that used for a representative unit in the economic justification and includes the cost of low-odor conversion of the representative unit.
- Gasification would impose similar costs except that the demonstration unit may be a smaller unit and is not a retrofit, so Phase IV costs would be lower. Note that the Phase IV advanced combustion costs would also be lower for conversion of a smaller unit.

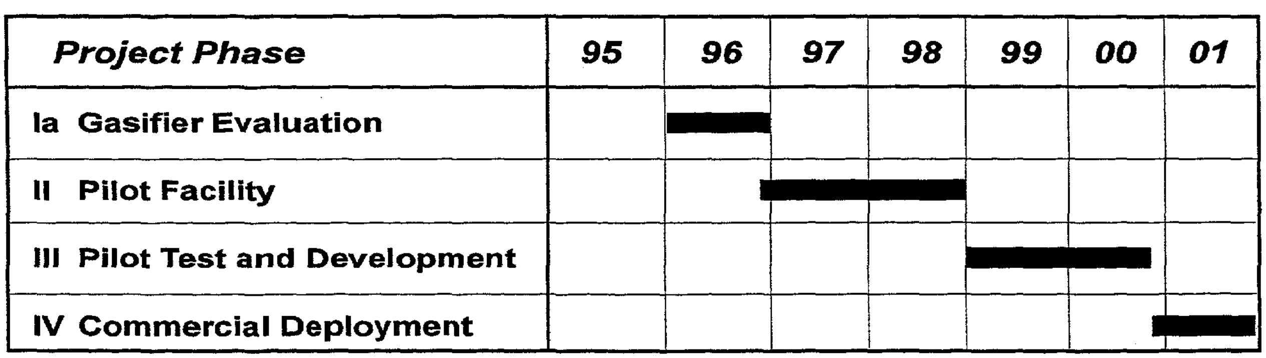

Figure 4. Schedule for project Phases Ia, II, III, and IV.

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