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Executive Summary

Biomass and black liquor gasification have been viewed by the forest products industry as important and beneficial technologies for nearly three decades. The U.S. Department of Energy and the industry have committed substantial resources to the development and demonstration of these technologies over this time period.

By the early 1990s, the results of these efforts appeared to be bringing both biomass and black liquor technologies to the point of commercial reality. Weyerhaeuser has been an industrial leader in the promotion of gasification throughout the period. The company has piloted black liquor technologies at its mill in New Bern, North Carolina, and operated the world's first commercial black liquor gasification unit at that facility.

The industry vision of the powerhouse of the future will necessitate both black liquor and wood residual gasification; and in the early 1990s, Weyerhaeuser proposed and received a grant from the Department of Energy to look at the feasibility of a wood residual gasifier—also at the New Bern facility. The results of that study, published in June 1995, indicated that in an electric power value situation of $0.05/kWh and above, a biomass gasification combined cycle project could potentially be attractive.

A further DOE grant was pursued, a biomass gasification technology was chosen, and the design and economics of both a New Bern specific and a generic gasification facility were developed, which is the subject of this report.

The project began in late 1996. It was originally envisioned to have a 12–18 month life with a goal of producing a design and engineering estimate for proceeding to construction and operation at either the New Bern facility or another facility, to be selected either inside or outside of Weyerhaeuser. The technology of choice was the Battelle/FERCO Low Inlet Velocity Gasification (LIVG) technology. It was selected because it operates at close to atmospheric pressure, produces a medium as opposed to a low Btu gas, is somewhat forgiving of variability in feedstock, and was believed to have the possibility of lower capital cost than other competing technologies.

The economic equation for an application at New Bern was driven by the belief that:

- A new power boiler would soon be necessary
- The opportunity to export power at prices in excess of $0.05/kWh would likely be in place for the foreseeable future
- Oil, on which the mill depends for its non-recovery fuel, would remain in excess of $20/bbl and trend upward at a higher rate than inflation
- The demonstration facility being built by FERCO at Burlington, Vermont, would provide the database for reducing capital costs and understanding both process performance and operating economics

Since the initiation of the project in late 1996, the Burlington facility has been significantly delayed as a result of both technical and program funding issues. The price of oil to the New Bern facility has fluctuated widely, and the process of electrical deregulation has created uncertainty with respect to power prices. In addition, in order to meet the powerhouse demands of the New Bern mill, a new power boiler has been installed. A detailed discussion of the unique factors surrounding a project at New Bern is found beginning on page § 8–21.

All of this resulted in eliminating biomass gasification as an option for New Bern in the near future. Therefore, to capture the greatest value possible from the extensive work already undertaken in this project, the scope of work was altered—with the concurrence of the DOE—to focus on the process design, operating economics and public policy factors that would support a commercially viable biomass gasification project.

This report looks at the realities of raw material availability in eastern North Carolina and concludes that sufficient material is available for the size project considered here (236,200 BDT/year) at an average price of $18/BDT. Further, producing an energy crop while utilizing nutrients from municipal wastewater was investigated with preliminary conclusions that such application could, in fact, be feasible and does potentially increase fiber production on a site of the kind investigated.

The gasification island design and cost is dealt with in depth, with the significant finding that feedstock drying technology integration is perhaps the most important capital and operating cost opportunity for design optimization. Further, a steam as opposed to a flue gas dryer, may be uniquely suited for integration with the gasification technology considered.

The integration of the gasifier island with a pulp mill is dealt with in detail using the New Bern facility as a real-life example. Nth Plant, Next Plant and Generic Nth Plant capital cost estimates are reported.

Utilization of medium Btu syngas from biomass is discussed with a conclusion that the impact of firing this gas in either a boiler or a lime kiln should be modest, with potential for positive environmental implications.

Finally, the last two sections of the report deal with the economic and public policy factors that would support the initial construction and operation of the first few gasification facilities and later support the sustainability of the technology as broadly applied across the industry. It appears from this analysis that the conclusion of the 1995 report—namely, that at a power value of $0.05/kWh or more with reasonable wood costs of $20/BDT or less and fossil fuel replacement value of $3.00/Btu or more—a mature gasification technology is likely to be economically sustainable given that a facility considering this technology is at the point of needing to replace or significantly upgrade existing powerhouse facilities.

A discussion of the relationship of this work to that reported in 1995 begins on page § 8-18. It should be pointed out that in the 1995 study the concept included export power sales and therefore was significantly more influenced by power value than the current effort.

Given the current state of development, the report concludes that to nurture the technology to maturity and get the first full commercial units in place will require:

- unique site characteristics of very low raw material costs, fossil fuel prices in excess of $3.00/MBtu and power values in excess of $0.05/kWh; and/or
- significant public policy changes on the order of a $0.50/MBtu or greater fuel gas tax credit, a $25/ton avoided atmospheric carbon emissions credit, or some similar policy.

An example of conditions that would produce favorable economics is found on page § 8-17, where a $24/bbl oil price escalating at 1% real, biomass cost of $8/BDT and a $0.06/kWh power cost results in ROIs above 20%.

The study strengthens the belief that the perceived benefits of the Battelle/FERCO technology—given a successful demonstration at the Burlington, VT, facility—are real. It is hoped that this study provides the design and economic basis for a demonstration project that has the site characteristics essential for commercial success and will enhance and improve the efficiency of such project development.

Weyerhaeuser would like to recognize with special thanks the Department of Energy for their financial support of this project, FERCO for the cooperation and essential information provided, Bechtel and Stone & Webster Corporation for the professionalism of their engineering services and NREL—particularly, Dr. Ralph Overend—for his willingness to review and provide insight.

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Section 1

Background and Introduction

1.0 Background and Introduction

1.1 Putting Gasification in Context

According to the Combined Heat & Power Association, on average two-thirds of the fuel used to make electricity in the U.S. is wasted. The average efficiency of power generation has remained around 33% since 1960. By utilizing the emerging technologies of gasification combined cycle, this percentage can be increased to levels of 70% and above.

Combined heat and power technologies have been practiced in the forest products industry for several decades, and this industry is currently the largest producer of energy from biomass in the world. By combining the efficiency gains offered by biomass gasification combined cycle with the renewable energy available through wood residuals and spent pulping liquors, the forest products industry has by far the greatest early opportunity to significantly impact the National goals of less dependence on foreign oil and reduced carbon emissions while at the same time increasing the industry's global competitiveness. In addition, BGCC technologies applied to spent pulping liquors also have benefits associated with pulp yield and quality. It is for these reasons that for many years the industry has had an interest in the development, commercialization and deployment of BGCC technologies.

1.2 Brief History of Gasification Interest in the Forest Products Industry

The gasification of carbonaceous feedstocks has been practiced successfully for well over 40 years. Beginning in the early 1970's, the forest products industry began to intensively study the potential opportunity of applying gasification technologies to its wood residuals, spent pulping liquors and solid wastes. This interest was driven by the realization that the technologies that had been in use for many years were inefficient, capitally intensive and had both safety and environmental issues. A landmark conference was undertaken in Sweden in 1976 where the world's alternatives to the processing of Kraft black liquor were discussed and the most promising selected for further development. At about this same time, the U.S. Department of Energy began to actively support research in the area of spent liquor and wood residual gasification. This industry/government partnership has evolved the most promising technologies to the point of large scale demonstrations.

1.3 Summary of Recent Weyerhaeuser Activities in Gasification

Weyerhaeuser's interest in gasification dates back to the mid-1970s, during which time technologists within the company evolved their own bubbling bed gasification concept and design. Near the end of the Carter administration in 1980, the company applied for and received a significant grant from the DOE in the gasification area. This grant was for the purpose of installing the Weyerhaeuser-designed gasifier on a lime kiln at its Everett, Washington, pulp mill.

As a result of a withdrawal of funds by the incoming Reagan administration, the project was never completed. However, the interest in gasification within Weyerhaeuser continued.

In the early to mid 1980s, several studies were made focused on applying gasification technology in a number of the company's mills—including the evaluation of coal gasification at the Weyerhaeuser mill in Plymouth, North Carolina, biomass gasification at the Weyerhaeuser mill in Valliant, Oklahoma, and a study of the use of biomass gasification at the Weyerhaeuser mill in Springfield, Oregon. Although the results of these studies were encouraging, it was concluded that the technology was not sufficiently developed to effect a low-risk implementation.

In the late 1980s, the company turned its attention to black liquor gasification and worked with MTCI in the development of a novel black liquor technology. This effort ultimately resulted in a pilot plant being built and operated at the Weyerhaeuser New Bern, North Carolina, mill in 1994. The pilot plant was evolved from 1994–1995 and was operated successfully for a brief period of time in late 1995.

At about the same time, the decision was made to construct a unit at the New Bern mill using a different black liquor technology. This technology, offered by Kvaerner Chemrec, was built and started operation in December of 1996. It is an atmospheric pressure technology designed for the purpose of providing incremental pulping capacity to the mill. The unit has been operated intermittently since that time, and a considerable amount of knowledge has been gained about the chemistry and physics of the operation as well as the materials of construction and refractories that will survive in the harsh environments created by black liquor.

1.4 Opportunity at the New Bern Mill

Since 1991, the New Bern mill has been unable to utilize internally-generated hog fuel in its power boiler and has operated with the use of #6 oil. Consequently, there has been significant motivation to find an economically sustainable alternative to the use of oil in the power boiler and the lime kiln. As a result, Weyerhaeuser responded to the NREL Request for Proposals (LOI number RCA-3-13326) in July, 1993. The company also responded to a DOE Request for Proposals (DE-NPO2-93CH10566) in October, 1993; and most recently to the DOE program solicitation DE-PS36-95GO10052 aimed at biomass power for rural development. The company was fortunate to receive DOE grants in two of these attempts and has been working with the DOE on projects aimed at the New Bern mill opportunity since receiving the first grant in May of 1994.

The first of these studies—which was carried out with Stone & Webster Engineering, Amoco Oil, EPRI and Carolina Power & Light as partners—concluded that at export power prices in excess of 4–5¢/kWh, a biomass gasification combined cycle plant at a facility like New Bern should be economically attractive. It was this result that motivated the company to apply for the second grant, which was awarded in October, 1996. It is this project, entitled Biomass Gasification Combined Cycle, that is the subject of this report.

1.5 Current DOE/Weyerhaeuser Project

The technology of choice in this work has been the Battelle/FERCO Low Inlet Velocity gasification technology that is being demonstrated in a utility application in Burlington, Vermont. The reasons for choosing this technology included a belief that it would be more forgiving of feedstock variability, the unit operates without pressurization, it provides a medium as opposed to a low heating value gas and was anticipated to be lower in capital than many alternatives—particularly those that required pressurization. A significant part of the present work has been to verify whether or not these lower capital expectations were justified.

The Biomass Gasification Combined Cycle project had an original completion date of September, 1997, but was highly dependent on the information being developed at the Burlington demonstration facility. As a result of significant delays in the Burlington project, four time extensions were requested and approved. During this time period, the drivers that initially made the project look economically sustainable at New Bern underwent significant change. For example, the mill became significantly more thermally efficient and, until very recently, the anticipated price of oil has been much lower than the early economics assumed.

As a result of these and other factors, it was determined in the fist quarter of 1999 that an early implementation of the technology was unlikely at the New Bern location. Consequently, a scope change was negotiated with the DOE that basically refocused the project on process improvements and capital cost reduction opportunities and eliminated the tasks associated with a detailed engineering cost estimate for implementation at New Bern. Even though the decision was made not to implement a biomass application at New Bern in the short term, interest in developing both biomass and black liquor gasification combined cycle technologies for use in other Weyerhaeuser locations remains strong.

1.6 The Formation and Purpose of the Forest Products Industry Gasification Initiative

The development of the Forest Products Industry technology vision in 1994 and its further refinement resulted in gasification combined cycle technologies being identified as a very high priority for the industry. In 1998, Weyerhaeuser joined forces with Georgia Pacific and Champion International to evolve an alliance of the industry entitled the Forest Products Industry Gasification Initiative. This initiative is broadly supported across the entire industry and recently Gaylord Container has joined the alliance as another potential host company for the early deployment of these technologies. This initiative is being overseen by the Agenda 2020 Chief Technology Officers Committee.

The motivation behind this initiative is the belief that the industry needs at least three different technologies in at least three different applications in order to take full advantage of a window of opportunity in the capital cycle, which is commencing now and will continue for the next 15–20 years. The goal that the alliance and Weyerhaeuser has in this initiative is to bring biomass and black liquor gasification combined cycle technologies to a stage of development that they will be available to the industry as commercially viable choices. If proven, these technologies offer great potential for improved capital effectiveness, energy efficiency, environmental performance, global competitiveness and safety. These advantages will be gained from:

- the ability to increase electrical power production capability by up to 300%;
- providing the potential to positively impact green house gas emissions by over 30 million metric tons of carbon per year;

- making available these technology options early enough for the majority of the U.S. forest products industry to utilize them in normal capital replacement decisions; and
- providing U.S. facilities with significantly more effective and efficient powerhouses compared to currently growing segments of the global industry, such as southeast Asia.

The three projects **originally** proposed were:

- Champion's Courtland, Alabama mill to demonstrate a full-scale pressurized, oxygen-based Kraft black liquor gasification system,
- Georgia Pacific's Big Island, Virginia mill to demonstrate semi-chem caustic/carbonate liquor gasification, and
- Weyerhaeuser's New Bern, North Carolina mill to demonstrate gasification of residual biomass.

Each of the three projects utilizes a different gasification technology in a different application. Choosing one technology over another to demonstrate on a sequential basis would result in a significant delay getting the technology to the marketplace for use by all segments of the industry. The combination of these three projects ensures that the broadest range of the pulp and paper industry will benefit from the proposed demonstrations. Each of the applications may be used separately, or may be combined for the highest level of benefits. Demonstrating them in different mill configurations ensures that, if proven, the technology will find broad market acceptance in a wide range of facilities in the industry—be it for replacement of current technology or for incremental new capacity.

Because of the age of the industry's powerhouses, these technologies need to be demonstrated in parallel if they are to be available in time for broad application across the industry. Due to the diversity of the industry's needs, no one technology can provide a full solution. Though the three technologies differ, there are fundamental issues of chemistry and physics that are common across each project. This can reinforce the robustness of the projects, reduce the risk of failure, and—in the event of a project delay or diminished success—provide an adaptable alternative.

By working through the American Forest & Paper Association and with lobbyists from the involved companies, a line item in the Federal budget has been established to fund the initiative. In FY 1999, $2M was provided to launch the gasification initiative. $14M has been appropriated in the current fiscal year, and a similar or larger amount is anticipated for FY 2001. Additional funds are available for basic research projects to support the success of the large-scale demonstrations. Among the areas being pursued are materials and corrosion issues, gas cleaning and the basic chemistry and physics of gasification.

After a decade of building a partnership to bring biomass and black liquor gasification to commercial reality, the players and the funding appear to be falling into place. However, the big steps of design and construction of the large-scale demonstration facilities remains.

1.7 The Organization of This Report

This report focuses on the potential application of the Battelle/FERCO residual gasification technology at the Weyerhaeuser mill in New Bern, North Carolina. It reports the results of studies carried out by Weyerhaeuser and Bechtel on the gasifier's cost and performance, taking into account process improvements over the design being implemented in Burlington. The report begins by discussing the results of a raw material availability study around Weyerhaeuser's facilities in Eastern North Carolina. These raw material availability studies included the possibility of utilizing nutrients from waste water for the purpose of growing an energy crop.

This section is followed by discussions of the gasifier island design and cost, and its integration into a pulp mill operating environment. The utilization of medium Btu gas from the Battelle/FERCO technology in a lime kiln was studied, and is included as well.

Weyerhaeuser worked with Stone & Webster Engineering Corporation to look at the integration of the technology, specifically into the New Bern mill, but also more generically to enhance the understanding of how the technology can be used in any similar pulp mill application. A conventional technology alternative—existing power boiler relifing—will be presented as a point of comparison for the gasification technology.

This report will discuss the site characteristics and public policy considerations that will be necessary to provide sustainable economics to the first few projects. Conclusions of this work will be discussed and the detailed economic analysis carried out will be reported, giving emphasis to the major leverage points to achieve economic sustainability in future applications. From the beginning, it has been a strong belief that any project implemented must have economic sustainability.

Although the gasification project conceived at New Bern will not be built in the immediate future, it is hoped and believed that the results reported here will encourage and enhance the ability to find an appropriate location where the learnings and the process improvements that resulted from this project can find an early application. Biomass and black liquor gasification combined cycle technologies are among the very few defining technology needs for a sustainable future for this industry and must be developed so the industry has them available as commercial choices.

Section 2

Raw Material Availability

2.0 Raw Material Availability

2.1 Scope and Objectives

Weyerhaeuser first looked at the economics and availability of wood and processing residuals for use in a gasification facility in the mid-nineties. The results of this study were described in a report to the Department of Energy in June, 1995, as part of the "New Bern Biomass to Energy Project Phase 1 Feasibility Study". The work reported here uses this prior study as a basis and updates the results.

The objectives of this work included developing a description of the fuel supply and the fuel costs for the biomass gasification options being proposed for New Bern. To address both existing and potential supplies, six strategies were developed to account for alternative sources, future costs, and environmental benefits. The strategies have been developed sufficiently to address real costs and benefits, in dollars, fuel supply, and sustainable forest management practices.

2.2 Approach

Availability and costs for volume from Weyerhaeuser forests and facilities were obtained from historical records and knowledgeable people in the company who have the responsibility for managing the forests and supplying the raw material for the mills. Information on plantation growth and economics was backed up by strategic planners and researchers who utilized computer runs on Weyerhaeuser's proprietary financial models. These models rely on extensive information collected and verified over many years on volume, growth and field operations. Estimates for items such as harvesting, collecting, transporting, site prepping, and planting were based on data from actual experience modified for the specific situation. Cost, volume, and growth estimates were generally modified towards optimism in an attempt to include a particular component such as biomass from plantations or from short rotation forestry. However, when it was apparent that inclusion of the component was not feasible, conservative estimates (those tending to reduce the quantity) were used to identify the quantity actually available for use in an energy facility.

Data for residual material potentially available from external sources was obtained primarily from resource bulletins published by the Southeastern Forest Experiment Station, United States Department of Agriculture (Resource Bulletins SE-111, SE-113, SE-120, & SE-142). The Forest Experiment Station researchers and writers of the bulletins were especially helpful in interpreting the data in the bulletins and in making a special run to collate the mill residual data on a county-by-county basis. The quantity in each county was roughly proportioned on the basis of each county's area within mileage circles around New Bern to determine transportation cost and availability.

The forest residue quantity available from lands not owned by Weyerhaeuser was determined on a county-by-county basis. A recoverable residual biomass to merchantable growing stock ratio was determined on a full state basis since this was the lowest level that individual biomass component information was available (Resource Bulletin SE-142). This ratio was then applied to the merchantable growing stock for each county (from Resource Bulletins

SE-111 & SE-113) to determine the recoverable residual by county. In addition, several Weyerhaeuser people knowledgeable about raw materials assessed the quantity information on each component of forest biomass from the bulletin and estimated the amount of each component that would be recoverable and the portion of forests that would be accessible. This was compared with Weyerhaeuser experience and found to be conservatively low.

The data on residual material available from wood product facilities was examined in great detail and in several different ways. In the final analysis, the primary data source for the quantity generated and potentially available was again the Southeastern Forest Experiment Station bulletins. The bulletins contain information on mill residuals from mill surveys conducted every two years on all wood product facilities in the state. The amount available by county was proportioned on a mileage circle basis.

Since the data produced by the above approach indicated a significant volume (160,000 BDT) of mill residuals generated within 40 miles, a more direct and detailed study was conducted. Weyerhaeuser Raw Material Managers directly contacted more than 80 mills (chip mills, pulp mills and sawmills) out to 160 miles to obtain the material type each mill was willing to market and the associated volume and price. The mileage to each mill was determined and the mileage related transportation cost was added to arrive at total costs.

2.3 Findings

There is sufficient biomass fuel available from the feedstock system surrounding New Bern to satisfy the feedstock needs of the gasification facility described in this report—236,200 bone dry tons (BDT) per year—at an average cost of $18 per BDT. This biomass is made up of Weyerhaeuser mill residuals and woods residuals from the final harvest of natural stands and plantations and is all within a 60 mile transportation radius of New Bern (Figures 2-1 and 2-2). A requirement of 390,000 BDT raises the average cost to ~$23 per BDT, increases the transportation distance to about 80 miles and adds woods residuals from non-Weyerhaeuser lands and more non-Weyerhaeuser mills. More volume would be available beyond 80 miles, but this was not pursued because of the scope of this project

The fuel for a New Bern facility could be sourced entirely from mill residuals. The 236,200 BDT of fuel required represents ~60% of the residual fuel that has been identified (Table 2-1). The least costly and most readily committed components are the residuals available from the New Bern and Greenville sawmill, pulp mill and chip mill. These amount to 146,000 BDT.

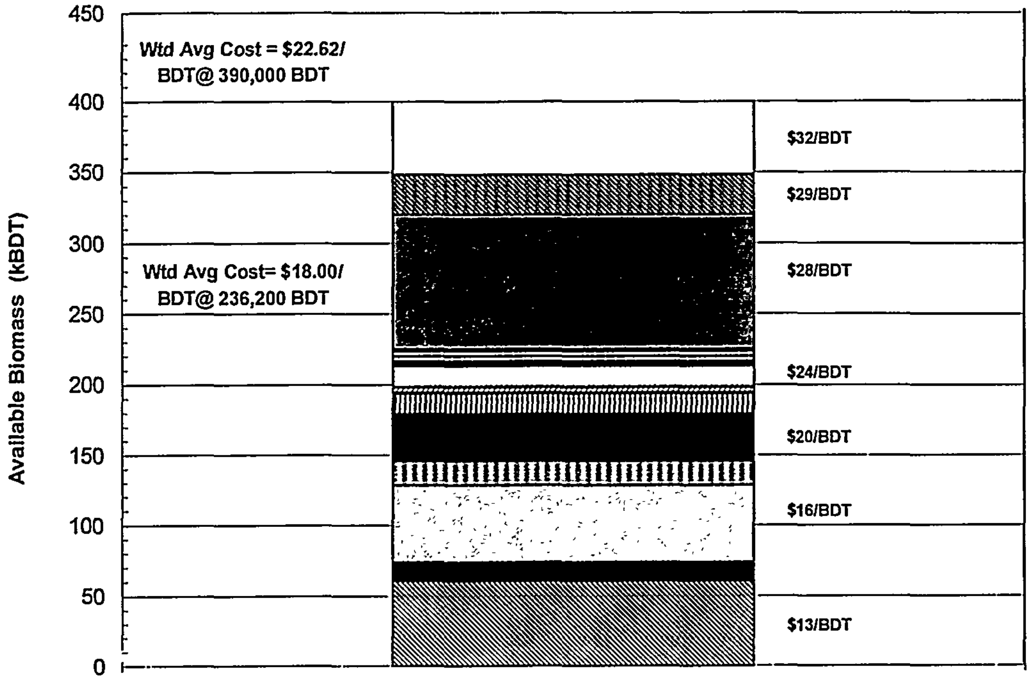

Figure 2-1: Residual Biomass Fuel Resources

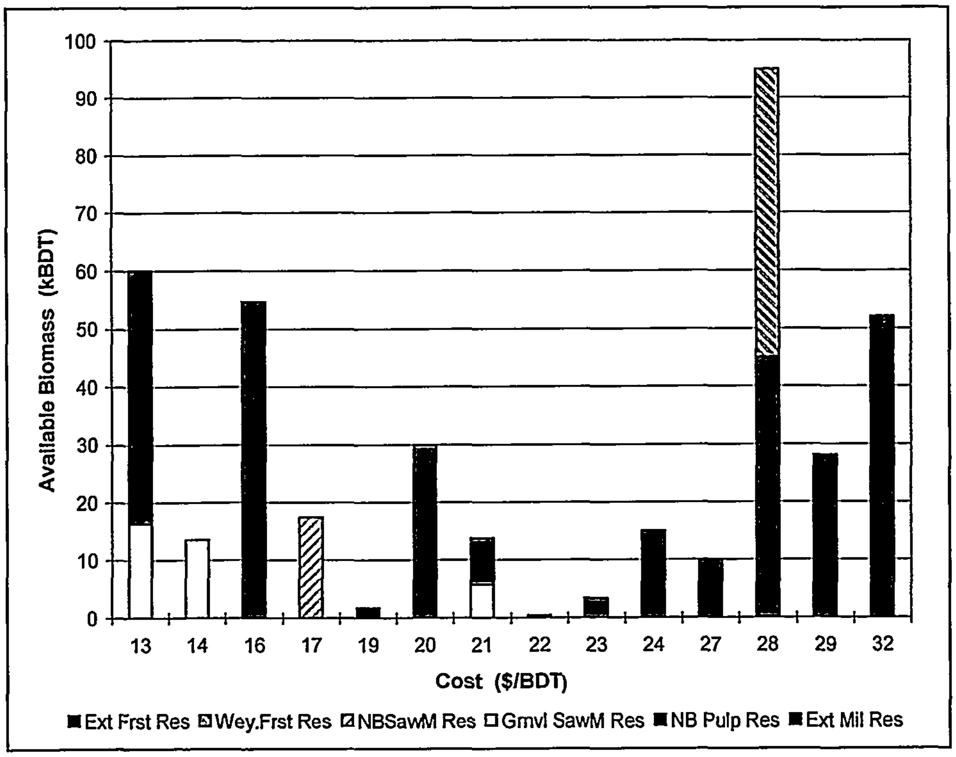

Figure 2-2: Total Biomass Fuel Resource

	Weyerhaeuser Operations				Non-Weyerhaeuser Operations			
		Mill Residuals						
Fuel Cost ($/BDT)	Final Harvest Residuals	New Bern Sawmill	New Bern Pulp Mill	Greenville Sawmill	Final Harvest Residuals	Mill Residuals	Total Residual Fuel	Accm. Residual Fuel
13			43.8	16.3			60	60
14				13.6			14	74
16			54.7				55	128
17		17.5					48	146
19						1.8	2	148
20						30.0	30	178
21				5.7		8.1	14	192
22						0.4	0	192
23						3.4	3	195
24						15.0	15	210
27						10.0	10	220
28	50.0				45.0	3.4	98	319
29						24.6	25	343
32						52.0	52	395
Source Total	50	18	99	36	45	149	395	

Table 2-1: Total Biomass Fuel Resource (kBDT/year)

With the above information, six potential strategies were evaluated as possible approaches for supplying the needed biomass for the projects. These strategies are summarized below.

2.4 Supply Strategies

2.4.1 Capture existing volumes of residuals available to Weyerhaeuser that are available at hog fuel (or lower) values

Weyerhaeuser Mill Residuals

Weyerhaeuser processes predominantly pine into bleached market pulp and lumber at the New Bern, Greenville and Plymouth locations.

The New Bern pulp mill, New Bern sawmill and Greenville sawmill generate 146,000 BDT per year of bark, sawdust, screenings and hogged waste wood at values of $13 to $17/BDT delivered to New Bern (Table 2-2). Greenville furnishes about 30,000 BDT of residual material. At the present time, most of this material is sold to Craven Hydraco, a private electricity generating facility utilizing wood residuals, with some small portion going to the Plymouth wood waste boiler on a supplemental basis.

Fuel Cost ($/BDT)	Mill Residuals (kBDT)		
	New Bern Sawmill	New Bern Pulp Mill	Greenville Sawmill
12.80		43.8	
13.10			16.3
13.70			13.6
15.60		54.7	
16.70	17.5		
Total	18	99	30

Table 2-2: Weyerhaeuser Mill Residuals by Fuel Cost

The wood products facilities at New Bern and Greenville also generate about 10,000 BDT of dry planer shavings. This material was not included as a source for fuel because of its very high value ($40 to $50/BDT) as poultry bedding and furnish for engineered panels.

The obvious benefit of using the mill residuals as fuel is the large volume of low-value material already owned by Weyerhaeuser and—in the case of New Bern—already on site. The handling costs are the only incremental costs, and the existing value is what other people are willing to pay for fuel less transportation cost. Using this source of material for a new New Bern power plant provides a dedicated Weyerhaeuser supplier/consumer; a reliable flow of fuel; an opportunity to reduce current handling, marketing, and disposal costs; and the opportunity to add value to existing products.

Non-Weyerhaeuser Plant Residuals

Based on the mill surveys conducted by the Southeast Forest Experiment Station and an internal study conducted by Weyerhaeuser, there is over 160,000 BDT of mill residuals within a 40 mile radius of New Bern (Figure 2-3 and Figure 2-4).

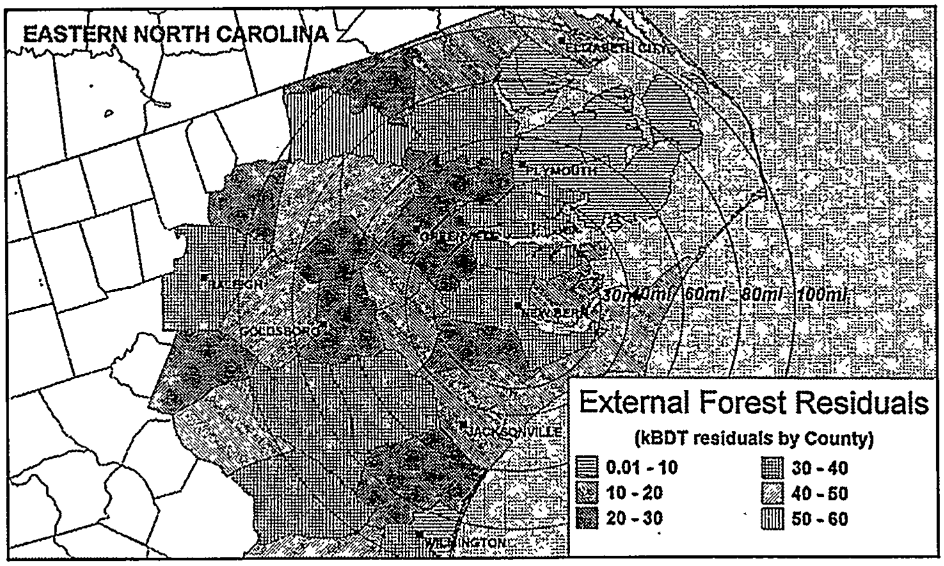

Figure 2-3: Map of External Forest Residuals

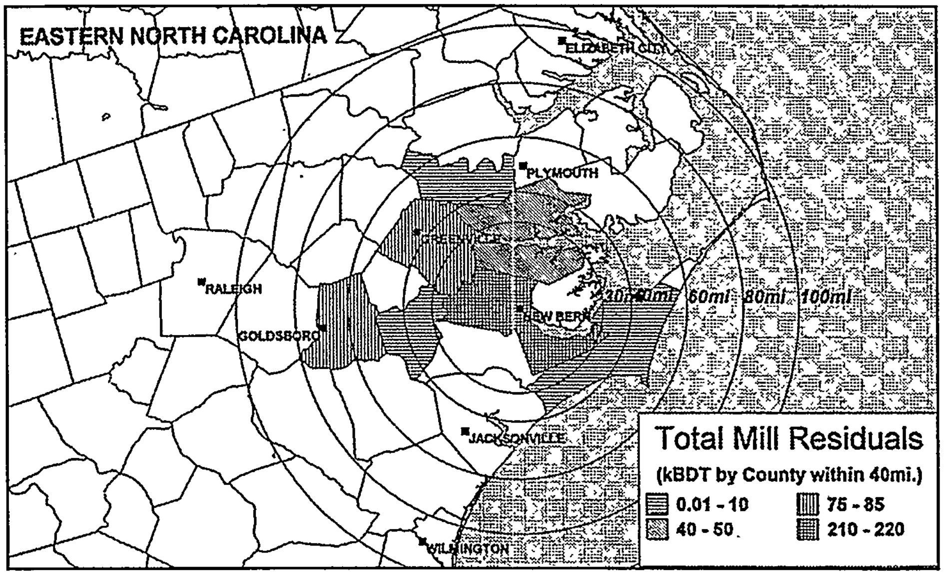

Figure 2-4: Map of Total Mill Residuals

The direct contact by the raw material managers to the 82 mills identified over 450,000 BDT (not including the planer shavings) of bark, sawdust, and hog fuel that the mills had available to market at a maximum price of $35/BDT. The weighted average price for all 450,000 BDT would be $24/BDT. A large portion of this was already being sold to others. Because of proximity to New Bern and the associated lower transportation costs, it is highly likely that a large portion of the 160,000 BDT of mill residuals within a 40 mile radius currently being utilized by others would be available to a New Bern facility. Since Weyerhaeuser mills and woods residuals are providing 193,000 BDT of the 262,000 requirement, there should be little problem in obtaining the remaining 69,000 BDT from this source at their market prices. Volumes from each mill range from 400 BDT to 30,000 BDT and costs from $19 to $27 (Table 2-3).

Residual Product	Volume Produced (kBDT)	Price ($/BDT)
Hog Fuel	1.8	$19
Bark	30.0	$20
Bark	2.4	$21
Bark	5.7	$21
Hog Fuel	0.4	$22
Hog Fuel	3.4	$23
Screenings	15.0	$24
Sawdust	2.5	$27
Sawdust	7.5	$27
Bark	3.4	$29
Mix	24.6	$29
Mix	52.0	$32
Total	149	

Table 2-3: Non-Weyerhaeuser Mill Residuals ($/BDT)

Continued efficiency improvements in wood product plants and increases in residual uses could somewhat reduce the amount available from wood product mill facilities in the 2000 and beyond time frame. However, having to take more volume from the next highest cost mill residual increment would only increase the average cost by $1 to $2/BDT.

Poultry House Waste

Dry planer shavings from Weyerhaeuser and other sawmills are being purchased at a high value ($30 to $34/BDT) and utilized as bedding material in the burgeoning North Carolina poultry business. After use, the material is reclaimed from the poultry houses and some of it is spread on farm fields as mulch and fertilizer. One of the larger users, Goldsboro Milling, uses approximately 90,000 tons of shavings annually to which the poultry adds about 25,000 tons. Today, there is a cost to Goldsboro Milling to reclaim, load, haul and spread the material in the fields as well as a problem with winter time disposals when the fields are too wet to spread. Goldsboro is very interested in alternative disposals, and it was assumed that this material would be available for the cost of transportation or $8 to $12/BDT. Since it was not known if the fuel facility could handle this material, it was not included in the following summaries.

Summary

Mill residuals from Weyerhaeuser mills are an obvious first choice for fuel as they are readily available, can be committed to internal use and for the most part are the lowest cost. Residuals from external mills are the next obvious choice because of their attractive prices and large quantity available on the market . The use of poultry house residuals could reduce the average cost of fuel.

2.4.2 *Incorporate mill residuals that currently are going to landfill or lagoon disposal sites at a net cost and long-term liability to the Company.*

New Bern Pulp currently sends sludge (23,850 wet tons) to an old landfill as 10-15% solids at about a $4.00/T handling cost (est.). New landfill space would have a much higher cost. Probability of permitting additional landfill construction beyond the current space is difficult and would require significant capital.

The landfill and the treatment lagoons at New Bern have many tons of material that could be recovered as a fuel source. The lagoons may have to be dredged in the near future with expensive disposal alternatives. Combustion under controlled temperature is a potential remediation process. Plymouth has a system in place to dry dredged sludge for burning, but does not have the capacity to dry and burn all their lagoon sludge if further clean up is required. A system designed with the temperature requirements of sludge burning at New Bern could be a desirable home for this material. The mill residuals included in this discussion are generally not net contributors to an energy balance due to their high moisture levels (85% to 90% moisture content). However, the use by the energy facility would have a significant benefit to the mill site in the form of reduced operating cost for disposal. There may be qualities that discourage their use as a fuel source. However, these residuals are part of the current manufacturing process and do have costs and limited options for disposal. Use in an energy system would capture some benefit from materials that are currently direct costs. Landfill or lagoon storage have been low cost options, but creation of new space will continue to increase in cost with significant regulatory barriers that may prevent long term continuation without changes and significant costs. Thermal conversion in a gasifier or combustion system may be an attractive alternative.

Summary

Requires suitable drying technology, regulatory driven, some risk, and not a significant Btu source.

2.4.3 *Capture existing and/or potential woods residual chips from final harvest and plantation thinning, that are available at hog fuel prices plus transportation.*

Non-Weyerhaeuser Forest Residuals

Every four to six years the Southeastern Forest Experiment Station of the U.S. Forest Service conducts a survey of the North Carolina standing forest inventory and operational logging sites. Based on the 1996 analysis of the 1989 survey (no later survey was available at the time of this study), 8% of the merchantable growing stock (6% softwood, 10% hardwood) in harvested areas is left in the woods as logging residue. In addition, unmerchantable material, composed primarily of small stems—1" to 5" dbh (diameter at breast height)—and tops and limbs, but with a portion of salvageable dead trees, rough trees and partially rotten trees, is not currently recovered. The total unmerchantable material is an increment about 25% greater than the merchantable growing stock for softwood and about 55% greater than the merchantable growing stock for hardwood.

After several knowledgeable people assessed each unmerchantable component for recoverability, it was determined that approximately 40% of the unmerchantable pine and 35% of the unmerchantable hardwood would be recoverable from those stands selected for residual harvest. It was also assumed that residual recovery would not be attempted on 50% of the stands due to small stand size, inaccessibility, operability constraints, low volume per acre, and a future shift from natural stands to more plantations for Weyerhaeuser and other large forest products companies. The increment to the merchantable growing stock removal amounts to 16% (about 7 BDT/acre) for softwood and 31% (about 13 BDT/acre) for hardwood. Residual availability was determined for each county and then each county was proportioned on the basis of map area and portions assigned to specific mileage zones around New Bern. Residual availability and costs were determined for mileage zones from 40 to 100 miles in 20 mile increments (Table 2-4).

Distance from New Bern (miles)	**30**	**40**	**60**	**80**	**100**
Material Available (kBDT)	92	58	122	157	209
Recovery Cost ($/BDT)	$20	$20	$20	$20	$20
Transportation Cost ($/BDT)	$7	$8	$11	$14	$17
Total Cost ($/BDT)	**$27**	**$28**	**$31**	**$34**	**$37**

Table 2-4: Non-Weyerhaeuser Forest Residuals by Distance from New Bern

Recovery of forest logging residuals at the time of final harvest for roundwood is already a significant and reliable source of biomass fuel for the Weyerhaeuser wood residue boilers in Plymouth. Its contribution has ranged from 10% to 35% of the Plymouth wood fuel source over the last eight years. Although higher in cost than the mill residual increment by up to $10/BDT within the same transportation zones, it is available in significant quantities within a 100 mile hauling distance of New Bern.

For more than 8 years, Weyerhaeuser has experienced a residual recovery of 10 to 15 BDT/acre on natural pine stands. Logging contractors have developed efficient systems for residual recovery over the more than 8 years of producing fuel for Weyerhaeuser. They are now realizing incremental harvest costs which range from $18 to $22/BDT with transportation and handling costs an additional $8 to $15/BDT with hauling distances up to 70 miles.

With the significant volume available as shown above and based on Weyerhaeuser experience, there should be no problem producing 100,000 BDT per year. Four chipping contractors would be able to produce 100,000 to 120,000 BDT per year with most coming within 50 miles of New Bern at a delivered cost of $28.30/BDT.

The lower costs of regeneration behind harvest operations utilizing a woods chipper to remove more biomass provides a competitive advantage for purchase of stumpage from some small private landowners. While this type of advantage may be difficult to assign a value to, as competition for timber increases it may be the difference in being competitive for this timber stumpage.

Weyerhaeuser Natural Stands and Plantation Final Harvest

Merchantable volume from final harvest of natural stands is decreasing as the natural stands are depleted and residual volume per acre also reduces from the current 16 BDT per acre to 12 BDT per acre by 2008. Merchantable volume from final harvest of plantations will continue to increase until about the year 2004, and then level off at that amount into the foreseeable future. Based on projected quantities of limbs and tops and the residual recovery results from early plantation harvests, there appears to be 3 to 5 BDT/acre of residual biomass available for fuel. This is composed of non-merchantable stems, hardwood in-growth, pine tops and large limbs, landing scraps, long butts and lily pads.

Because of more intensive management, future plantations will have less non-merchantable material and hardwood in-growth resulting in a decrease of residuals to 2 to 4 BDT/acre. It was estimated that at least 50,000 BDT/ year could be recovered from natural and plantation stands (Table 2-5). With an identified need and improved values, this could be increased slightly through the use of harvesting heads which could cut off the stem at or slightly below ground level. Residual harvest costs will be about the same as for the non-Weyerhaeuser forest residuals at $28.30/BDT.

Harvest Year	Plantation Residuals	Natural Stand Residuals	Total Residuals
2000	46	82	129
2001	70	61	131
2002	59	41	100
2003	56	41	97
2004	76	10	86
2005	80	3	83
2006	76	17	93
2007	83	2	86
2008	93	7	100
2009	83	9	92
2010	101	7	108

Table 2-5: Weyerhaeuser Forest Residuals – kBDT

First Thinning

Market conditions will dictate the stocking level of future plantations in North Carolina. Depending on the value of chips and fuel at first thinning in relation to the value of diameter at final harvest, there may be some options to increase chip and/or fuel harvest removals in the first thin. However, higher expected future demand for chips from already planted plantations is expected to shift the existing first thinning activity from fuel production to pulp and paper chip production for export and domestic sales.

Although the total volume for fuel from this source will decrease, if these operations utilize woods chipping with flail debarking about 5 tons/acre of flailed bark, limbs and tops can be recovered for fuel as a by-product of the chips at a recovery (grind and load) cost of approximately $25/BDT and average transportation cost of $8 to $12/BDT. This could provide about 20,000 BDT of residual fuel annually during the 1998 to 2006 time frame (Table 2-6) but is above the cost of the other alternatives.

First thinning on already planted more heavily stocked plantations is expected to be completed by 2006 when the wider spacing and fewer trees of the new regime will start to be thinned and overall removal volume and residual volume will be significantly reduced. The new planting regime would only yield about 1 to 2 tons/acre of residuals from thinning; and because of low volume (requires coverage of up to 24 acres for each truckload), could only be applied to the highest volume stands (assumed to be applicable to 40% of available stands),which would make it costly to recover. This would only provide 5,000 to 8,000 BDT per year.

Harvest Year	Biomass (kBDT)	
	20% Available Flail & Chip	Produced on 60% of Stds
2000	30	18
2001	29	17
2002	28	17
2003	37	22
2004	26	16
2005	36	21
2006	31	19
	10% Available Flail & Chip	Produced on 40% of Stds
2007	16	6
2008	16	6

Table 2-6: First Thinning Residuals

North Carolina operations are also considering an alternative to the woods chipping approach for first thinning in both time frames, which removes the thinning material in roundwood log form from the forest and processes the stems at a chip plant. This would still recover the bark at the chip plant; but since the chipping or grinding process would need to be brought to the woods specifically for the small increment of fuel from the limbs and tops (less than 1 ton/acre or more than 24 acres required per truckload), the costs would probably be prohibitive for either of the above plantation time frames.

Second Thinning Residuals

If second thinning is conducted in the future, cut-to-length harvesters will be utilized for second thinning. This process removes the limbs and tops and leaves them at the stump while recovering all of the stem to the terminal bud. Recovering these limbs and tops would be more difficult than first thinning or final harvest residuals recovery because, in addition to being a very low volume (less than 1 BDT/acre), the harvest costs would be considerably higher since they would have to be independently collected at the stump and transported to roadside. This would make the costs considerably higher ($5 - $7/BDT) than any of the alternative biomass fuel options and would also require incremental fertilization to offset the limbs and tops nutrient contribution.

Site Preparation Residuals

The initial V-shear operation produces a roll of biomass on each side of the blade, even with a fairly clean logging job. This material consists of stump lily pads, non-merchantable stems, understory, and soil litter. After the V-shear pass for slash disposal behind final harvest, a flail-type chipper on a Hydro-ax with a collection system (silage chopper concept), could be used to collect the residual biomass. However, there is a value in this material to the long-term organic matter levels on mineral soils. In addition, there is a question about how much of this shearing will be done long term if the EPA/Corps continues their present direction. Given the regulatory risk, soil organic matter impact, harvesting cost, and other options, this should not rank very high on the list of biomass options.

Summary

Though not the lowest cost, the woods residual component from final harvest is a large source of biomass fuel. Based on the conservative assumptions above, there is about 209,000 BDT of non-Weyerhaeuser forest residuals available within 100 miles of New Bern. Weyerhaeuser forest residuals account for about 50,000 BDT more. Residual volumes from thinning are very low and have a high cost. Because of the low volume of material available from thinning and the mechanical systems being utilized, the costs of recovering residuals are not currently competitive.

2.4.4: Grow biomass by maximizing pine volumes per acre without giving up solid wood values, and trying to hold costs to hog fuel values plus transportation.

Pine Inter-row Planting

The most cost effective (most tons of biomass produced) approach to increase available biomass would be to plant more trees, make more frequent thinning entries, leave more trees at each entry, lengthen the rotation and forego some diameter growth. An option to achieve this is to plant an additional row of pine between the rows of the existing current prescription and then remove all of the trees in the extra row plus some in the normal rows to reach the desired 200 trees per acre after thinning. If the final harvest values are assumed to be unaffected by this additional row—even though current forest growth and financial models indicate that the smaller trees would be worth less—then the incremental site preparation cost must be offset by the value of the additional material removed in the thinning. In order to earn 8% real after tax on the additional site preparation and planting investment, the thinning material must have a value of $90/BDT if thinned at 14 years and $120/BDT if thinned at 10 years (Table 2-7, Option 1).

Thin Age	10	11	12	13	14
Option 1: All merchantable and residuals to fuel Required Fuel Value for viable economics	$120	$100	$95	$90	$90
Option 2: Assumed 10% higher final stand value; all thinning material to fuel Required Fuel Value for viable economics		$50	$45	$45	$45
Option 3: Option 2 with 80% of bole from thinning to chips; 20% of bole to fuel Required Fuel Value for viable economics	$85	$50	$40	$35	$35

Table 2-7: Inter-row Planting – 450 to 800 trees/acre

There is a possibility that the loss of value from having a smaller log (due to the heavier initial stocking) might be offset by a benefit from the smaller low value juvenile log core and smaller limbs/knots. If a higher final harvest stand value of about 10% is assumed, then—since the thinning provides an offsetting benefit—the total required return for thinning and the resulting fuel value can be reduced by 50% (Table 2-7, Option 2). This requires a high fuel value of $45 to $60/BDT. However, if 80% of the material is allocated to the higher value of chips (with a chip price of $50/BDT), the fuel would only need a value of $35 to $40/BDT for ages 14 to 12 respectively.

The incremental costs of almost doubling the site preparation and planting costs for the current values of fuel—or even optimistically high future values—do not appear to be warranted for the harvest of fuel alone. However, if chip prices for pulp and paper increase significantly (above $50/BDT) and if an increase in final harvest values can be validated, a higher planting level with subsequent thinning for chips and fuel could be justified.

Early fertilization on responsive stands has been shown to provide the option to increase first thinnings removal at age 12 by 3-4 BDT and still leave larger diameters on crop trees. While this approach does not minimize DOS (unpruned, low value core), the combination of values from a single lift prune, chip harvest, and growing to a larger final diameter may be a net benefit.

Summary

Biologically feasible; low volumes, high plantation establishment and carrying costs.

2.4.5 *Grow maximum pine/hardwood biomass per acre trying to hold costs to hog fuel plus transportation*

Hardwood Sprouting Between Rows

The next increment of volume would come from a strategy that intentionally grew biomass fuel as opposed to using residuals from other processes. A low-investment approach within the existing solid-wood strategy could use the current bed spacing to advantage. Most of Weyerhaeuser's sites have an understory component of Red Maple, Pepperbush, Sweetgum, Bay, etc. that is not killed with the V-streaking. This is heavier in natural stands, but plantations can have a significant component. With early thinning, more thinning entries, and wider row spacing, the understory is heavier. North Carolina has not used brush control like the rest of the South. However, brush control between rows might be needed to reduce competition with the pine; but would only be done if the competition level was severe. Energy harvest could replace a brush control on these sites. One of the options for this brush control would be a mechanical chopping or mowing, which would replace part of the harvesting cost of an energy operation.

Seeding between the rows is an option, but most of the native species would have a prohibitive seed cost compared to planting. The plantation would then be fertilized, bedded and planted with weed control directly on the top of the bed. The materials between rows could be re-harvested just before second thinning or final harvest, or when volume justified with a yet to be developed silage chopper concept. This regrowth material would be Sweetgum, Red Maple, Pepperbush, and Switchcane.

The harvest costs associated with this biomass harvest would be higher than standard round wood harvest or woods chipping costs. There is an additional cost associated with this strategy that is less apparent. The understory material has a higher concentration of nutrients than pine bark and stem wood. The nutrient concentration increases with increases in the percentage of leaves and non-woody material. Most of eastern North Carolina has soils that are nutrient limited, with much of the available nutrient supply tied up in vegetation. Natural additions to the nutrient pool are limited and would not compensate for removals associated with intensive biomass harvesting of the understory. Thus, nutrient replacement is essential to insure long-term sustainability of this type of system.

An option for this nutrient replacement is to spread the residual ash from the biomass boiler back across the harvested acres. Research done internally by Weyerhaeuser has shown the costs and values associated with this process. Estimated application costs are less than costs of new landfill space, so replacement of nutrient removals from biomass harvesting could be limited to nitrogen and phosphorus replacement. There is always the potential for new harvest technologies that would separate leaves and other small pieces from the larger pieces and return these to the forest floor with a resulting reduction in nitrogen and phosphorus replacement cost.

There are values associated with soil organic matter related to water movement, soil structure, root penetration, slow release of nutrients, maintenance of microbial populations, and nutrient retention in the upper soil profile that are extremely difficult to quantify. A conceptual example is the comparison of an old field plantation with a stand on a woods site. The woods site may or may not exhibit the greater productivity of pine, but the greater ecosystem diversity and buffering capacity results in a greater total productivity. The old field site is more comparable to row crop agriculture in relation to the requirement of nutrient additions in excess of removals to maintain long-term productivity potential.

Another issue in this type of system is the amount of traffic over the soil with heavy harvesting equipment. Rutting and compaction seriously impact the surface rooting volume of most soils and subsequent tree growth. Amelioration during site preparation can alleviate some impacts.

Hardwood Inter-Row Planting

The next increment of volume (and cost) would be to plant Sweetgum or Red Maple in a row between the rows of pines. A nitrogen-fixing tree species that was not very competitive with the pine crop trees would be desirable for this use. However, there is not a native species available. Wax Myrtle is an aborescent shrub that has some potential. Black Locust has been used in mine reclamation for this purpose, but is not native or particularly adapted to eastern North Carolina. This row would be chipped at first thinning entry and resprouting encouraged. The sprouts could be harvested whenever volume justified reentry. The incremental costs associated with this approach are primarily the planting stock and planting labor.

Summary

Biologically feasible; high risk, low volumes, high plantation establishment and carrying costs and high harvest costs with current harvest technology.

2.4.6 Dedicated Short Rotation Plantation

Weyerhaeuser foresters believe that for the Eastern North Carolina region the lowest cost fast growth tree crop to grow is a Loblolly Pine plantation. With the addition of sludge as discussed in the next section, it was assumed that the site index could be increased to an 85. For a harvest age of 10 years, it appears that 800 trees per acre initial planting is a good balance between site preparation, planting, and harvesting costs and maximum biomass growth. As above with Strategy 2.4.4, it is assumed that the harvested material must have a value high enough to earn 8% real after tax on the site preparation and planting investment. Based on projections of growth and volume and expected planting, site preparation and harvesting cost, fuel value would have to reach about $50/BDT in order to achieve the required return (Table 2-8, Option 1, Alternative A). If site preparation and planting costs could be reduced by about 20%, then fuel values would only have to reach about $45/BDT (Table 2-8, Option 1, Alternative B). If they could be dramatically reduced by 75%, fuel values would only have to be $30/BDT (Table 2-8, Option 1, Alternative C).

Alternative	A	B	C
Site Index	85	85	85
Initial Trees (trees/acre)	800	800	800
Final Harvest Age	10	10	10
Site Preparation & Planting Cost	Normal	80%	25%
Option 1: All Merchantable and Residuals to Fuel			
Total Required Return ($/BDT)	$50	$45	$30
Option 2: Merchantable to Chips and Residuals to Fuel			
Fuel price to return 8% on site preparation ($/BDT)	$60	$30	

Table 2-8: Short Rotation Pine Plantation

Though it would reduce the amount of biomass for fuel, a more feasible though still optimistic alternative would be to harvest for fuel and for pulp and chips. Fuel costs would only have to reach $30/acre with a 20% reduction in site preparation and planting costs (Table 2-8, Option 2, Alternative B).

The above scenarios all assume an optimistically low harvest and transport cost and a relatively high chip price for a very high site with no incremental cost for the application of sludge to achieve the high productivity site.

Section 3

Energy Crop Possibilities

3.0 Energy Crop Possibilities

3.1 Background

Economic constraints and value of alternative products have limited wood production for energy purposes in intensive plantation regimes. A potential opportunity was identified which included the growing of high-value saw timber with municipal wastewater in intensively managed plantations and to produce significant amounts of wood for energy in the process.

The Neuse River has a documented history of nutrient related water quality problems that are linked to effluent discharges from various sources. Municipal treatment plants are recognized as primary point source contributions. Recent limits restricting nitrogen loading in sewer plant permits makes alternatives to point source discharge more attractive. Published research shows that land application of treated municipal and industrial wastewater on forestland has been utilized successfully at various locations in the South for up to 30 years. Land application is one of the most cost-effective and environmentally-sound processes for the recycling of wastewater. Limited availability of well-drained soils and rising land cost, coupled with increased growth and the need for greater wastewater treatment capability, have caused a decline in land application.

Eastern North Carolina is dominated by hydric soils with seasonally high water tables. Under current State guidelines, these soils are not generally permitted for land application. Weyerhaeuser and other forest landowners have established loblolly pine plantations of upland hydric soils throughout the coastal plain using water management and drainage systems to reduce the periods of high water tables. In the Neuse Basin, Weyerhaeuser owns over 200,000 acres with a total of about 570,000 acres in eastern North Carolina. Including private landowners and other industry, about 60% of North Carolina's coastal plain is covered with managed forests. Weyerhaeuser Company and many private landowners are interested in production of high-value sawtimber, but are limited by markets for early thinnings. Energy wood market opportunities coupled with the nutrient values of wastewater would support an intensive plantation management regime that would meet these objectives.

In managed plantations, the extensive root system and accumulation of organic matter promotes and enhances infiltration, percolation, and denitrification of wastewater in the soil. Loblolly pine provides rainfall interception, evaporation, and transpiration during the entire year. All of these factors significantly reduce the surface water runoff potential. Nutrient uptake by fine roots in the surface soil is rapid under most conditions. Denitrification, a primary process in nitrogen reduction, can also occur in these wet forest soils. Soil micro-organisms change nitrate-nitrogen in shallow groundwater to gaseous nitrogen. (Amatya, D., Gilliam, J.W., Skaggs, R.W., and Blanton, C.D.; 1996)

The North Carolina State Forest Nutrition Cooperative has documented loblolly pine growth increases of 30% with 200 pounds of nitrogen and 25 pounds of phosphorus fertilizer per acre. Recent efforts are focused on nitrogen dosage/frequency studies in younger stands. Results from the SETRES site in Scotland County have shown the substantial increases in growth associated with frequent, complete fertilization and irrigation on a droughty site.

Treated wastewater nutrient analyses are very low, with application rates usually limited by hydraulic loading rather than nutrient levels. However, cumulative applications should produce growth response. "Managed pine forests in the coastal plain grow on nutrient deficient soils and, thus, are effective nutrient sinks." (Gilliam, J.W.; 1995).

Research efforts over the last 30 years have provided excellent data on loblolly pine water and nutrient use, and this demonstration project considers several specific questions. The impact of land application of water during the peak growing season that typically has a moisture deficit is evaluated. The project was designed to quantify the water and nutrient balance for the selected site, and tree growth and nutrient uptake provided permitting and management guidance. Data was used to validate the utility of DRAINMOD (Skaggs, 1978) and NUTREM (NCSFNC, 1998) as models to predict water and nutrient balances, respectively, on potential land application sites in the Neuse River basin and eastern North Carolina.

3.2 Objectives

1) Determine the feasibility of seasonal fertigation of mid-rotation loblolly pine on hydric soils in eastern North Carolina as a technology to increase production of wood for energy as a co-product of a sawtimber rotation.
2) Quantify the nutrient and water balances with different amounts of water to assess the potential for nutrient movement off the site.
3) Evaluate the utility of the water balance model DRAINMOD and the nutrient model NUTREM for prediction of water and nutrient balances.
4) Demonstrate the potential for low-cost, mobile systems.

3.3 Approach

The demonstration project used simulated wastewater, based on the five-year average analysis for the City of New Bern's effluent. A specially formulated liquid fertilizer was injected into irrigation water as it was applied. By mixing the nutrient concentrations to the same analysis in every application, the variation in nutrient contents often seen in long-term wastewater application studies was controlled. For an operational system, dischargers would haul or pipe the treated effluent to permitted forestlands. The project also demonstrated multiple application technologies suitable for non-dedicated forest sites. The mobile systems (i.e., irrigation hose or traveler system) are lower cost and more adaptable to normal forestry activities than traditional fixed riser systems.

3.3.1 Field Study

The site is located on a Company-owned 12-year-old loblolly pine plantation. It represents a large percentage of Company land ownership on drained hydric soil—specifically, a Pantego fine sandy loam. The property lies within the Neuse River basin in Craven County off NC 1005 near the Craven County Landfill at Tuscarora.

3.3.2 Treatments

A minimum application period was proposed from May–October (6 months) based on the growing season of loblolly pine with peak leaf area in August. The June–October hurricane season of 1995 and 1996 produced a higher than average rainfall resulting in a worst case scenario.

In order to answer both how much and how often wastewater can be applied, the treatments consisted of:

- **High Volume** (4 in. every other month from May to Oct. = 12 in./year)
- **High Frequency** (2 in. every month from May to Oct. = 12 in./year)
- **Constant Wetting** (maintains water table at 12 in. below soil surface)
- **Control** (average rainfall last 5 years is May–2.72 in., June–3.66 in., July–5.88 in., August–6.64 in., September–6.80 in., and October–4.49 in.)

3.3.3 Application Systems

A traditional "fixed" spray irrigation system would be cost-prohibitive for the frequency and duration of application being considered. Therefore, low-cost and highly mobile delivery systems were utilized. These included:

1) **Modified surface application**, in which the water is distributed through surface pipes. Advantages of this system include limited disturbance to the soil and plant roots and decreased human exposure due to no aerosol production.
2) **Traditional reel system**, used in agricultural land application. The water pressure was decreased dramatically so the tree bark would not be injured. The "gun" trolley is slowly retracted down the third (cut) row while supplying water to the four rows on either side.

The two delivery systems mentioned above were combined with the four treatments for a total of eight regimes in order to determine the best silvicultural practice, in terms of both economic and environmental standards.

3.3.4 Plot Layout

Schematics of the plot layouts are seen in Figures 3-1 and 3-2. Operational third row select thinning with an average of 150 residual trees/acre was the uniform pretreatment. The first delivery system, shown in Figure 3-1, utilizes irrigation hoses in the middle three cut rows to supply water to the trees on each side. The water pressure and hose construction were calculated such that the water would be as evenly distributed as possible.

Figure 3-2 shows the second delivery system using the third (cut) row as the distribution path. In an agricultural setting, the gun can shoot water in a 120' radius. This approach was modified for forest application by decreasing the pressure and using a diffuse nozzle, resulting in water flows of approximately 40' in all directions. This wets four rows of trees on each side of the reel device.

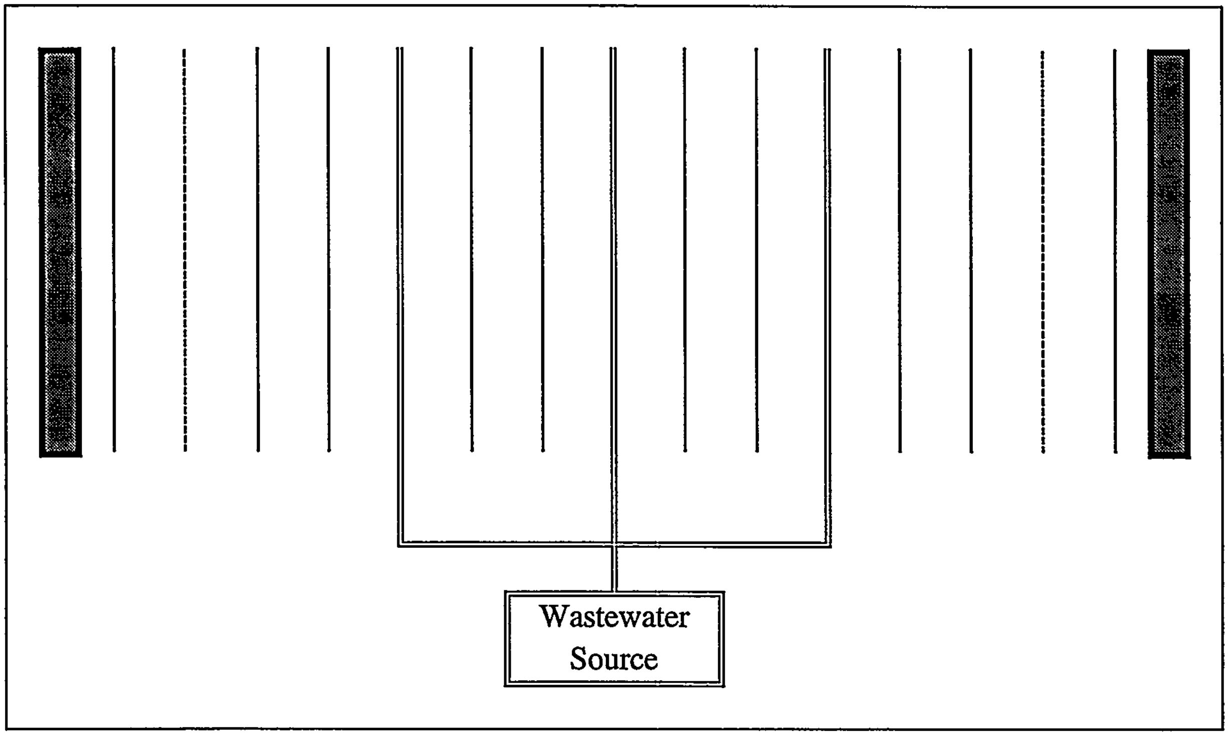

Figure 3-1: Schematic of Irrigation Hose Application Method.

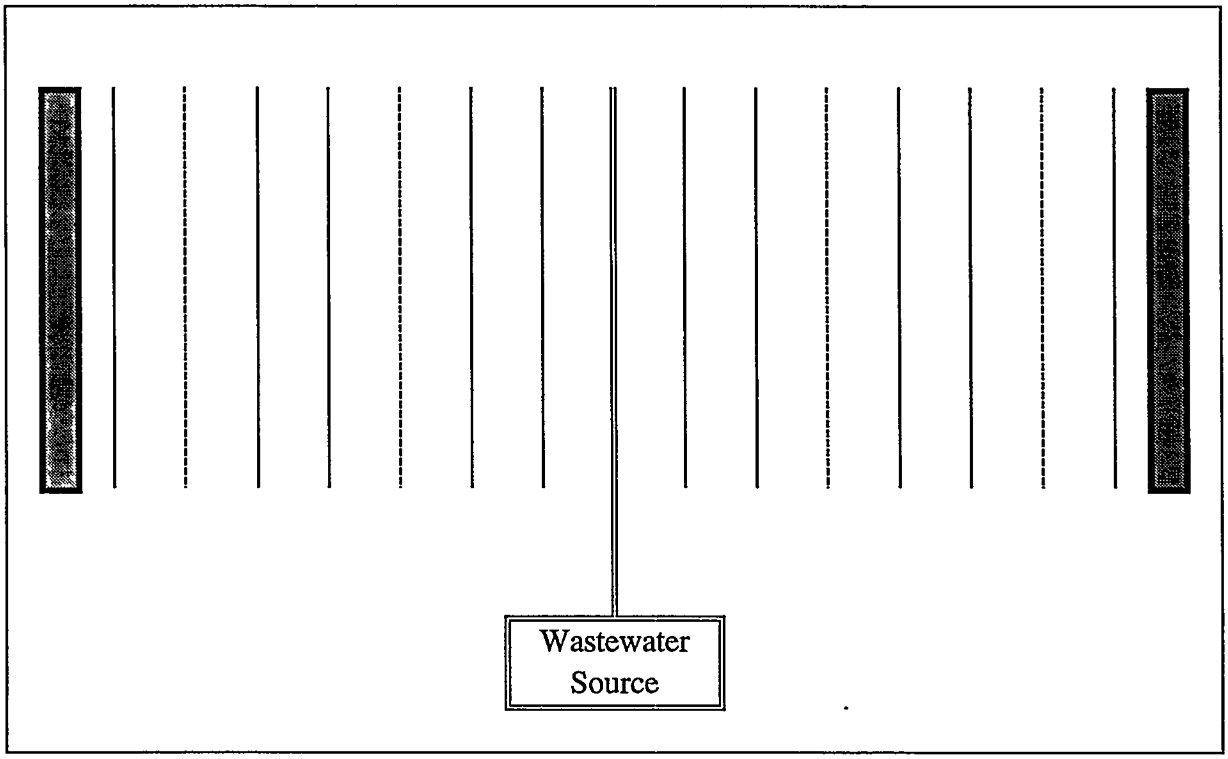

Figure 3-2: Schematic of Reel Rain Traveler Irrigation System.

3.3.5 Monitoring

The two main objectives of the comprehensive monitoring regime are:

1) to insure that unacceptable levels of nutrients, particularly nitrate, do not occur downstream; and
2) to obtain data representative of the nutrient and hydrologic cycles of the site to compare with the NCSFNC nutrient use model and DRAINMOD as the basis for the hydrologic model.

A complete characterization of the soil—including but not limited to organic matter, pH, CEC, soil moisture, soil nutrients, permeability, and bulk density—was accomplished prior to application and at yearly increments. Soil nutrient constituents include nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), sulfur (S), zinc (Zn), Manganese (Mn), iron (Fe), copper (Cu), and boron (B).

The application method delivery systems were located in separate ditch cuts. Any drainage of surface water from the study site was limited by water control structures with downstream sampling to monitor any nutrient loss from the site.

Surface and ground water table levels were monitored along two transects in both ditch cuts. Additionally, ground water monitoring wells were placed at different depths in the soil profile of each plot to measure nutrient concentrations in the soil water.

The outlet riser had a Stevens water level recorder to provide a continuous measurement of water level. Additionally, a Sigma water sampler was used to sample surface water during periods of flow for nutrient analysis.

Loblolly and understory foliage were sampled for weight and nutrient concentrations. Litter traps were used to collect monthly litterfall and estimate leaf area. Tree diameter was measured monthly during the spray season with annual height and diameter recorded at the end of the growing season.

A Davis GroWeather station was placed at the site to record weather data. The high variability of weather patterns and the importance of accuracy dictated this necessity. Additionally, manual rain gauges were strategically placed to act as a check on the electronic gauge and to determine variability across the site.

Statistical Analysis Software (SAS, 1997) was used to analyze relationships between tree growth, various nutrient concentrations, water level, treatment level, and application method. The general linear model procedure was used to test for significant differences among treatments. Duncan multiple range tests were used to separate means by treatment level and application method.

The effluent from the City of New Bern WWTP was analyzed over a period of five years. Average nutrient concentrations over that time were used to simulate a fertilizer with those same characteristics. The fertilizer was manufactured by Encee Chemical, Inc. and is comprised of 4.87% N, 1.30% P_2O_5, 5.05% K_2O, 80 ppm Cu, and 122 ppm Zn. It has a pH of 1.62 and a density of 1.144 g/ml. It is diluted at a rate of 1 to 3225 to produce a fertigant with the approximate concentration of 15 ppm N, 9.61 ppm NH_3, 1.76 ppm P, 13 ppm K, 25 ppb Cu, and 38 ppb Zn.

3.4 Results

3.4.1 Tree Measurements

Covariance analysis was used to account for the pretreatment bias in initial tree measurements. Table 3-1-A shows simple height and diameter means for each treatment level and application method. The coefficient of determination, R^2, is very high. This signifies that the variation in measurements is accounted for by the model variables; i.e., treatment level, application method and initial measurements. All of the measurements are the greatest in the constant wetting (6 in/mo) treatment and are followed by control, high volume (4 in/2 mo), and high frequency (2 in/mo). The trees in the outer four rows, receiving less fertigation water, were significantly larger in height and diameter than those in the inner four rows.

	Measurement Date						
	Jan-98	Aug-98	Sep-98	Oct-98	Jan-99	Jun-99	Aug-99
Height							
R^2	0.23	*	*	*	0.93	*	*
Treatment Level							
High Frequency (2in/mo)	36.59 d	*	*	*	40.26 d	*	*
High Volume (4in/2mo)	38.53 c	*	*	*	41.78 c	*	*
Constant Wetting (6in/mo)	42.92 a	*	*	*	46.11 a	*	*
Control	41.08 b	*	*	*	44.17 b	*	*
Application Method							
Irrigation Hose	40.26 a	*	*	*	43.36 a	*	*
Reel Rain Traveler	38.95 b	*	*	*	42.42 b	*	*
Tree Row							
Inner	38.29 a	*	*	*	42.14 b	*	*
Outer	39.61 a	*	*	*	42.91 a	*	*
Diameter							
R^2	0.04	0.99	0.99	0.99	0.99	0.98	0.97
Treatment Level							
High Frequency (2in/mo)	8.42 b	8.96 c	9.01 c	9.04 c	8.98 c	9.38 c	9.50 c
High Volume (4in/2mo)	8.41 b	8.97 c	9.01 c	9.06 c	9.02 c	9.40 c	9.54 c
Constant Wetting (6in/mo)	8.96 a	9.48 a	9.52 a	9.56 a	9.50 a	9.88 a	10.00 a
Control	8.63 ab	9.20 b	9.25 b	9.31 b	9.26 b	9.67 b	9.79 b
Application Method							
Irrigation Hose	8.80 a	9.34 a	9.39 a	9.44 a	9.40 a	9.78 a	9.90 a
Reel Rain Traveler	8.40 b	8.96 b	9.00 b	9.04 b	8.98 b	9.38 b	9.51 b
Tree Row							
Inner	8.12 a	8.71 b	8.66 b	8.69 b	8.65 b	9.05 b	9.19 b
Outer	8.62 a	9.16 a	9.21 a	9.26 a	9.21 a	9.60 a	9.72 a
* No measurements were taken.		Means with the same letter are not significantly different.					

Table 3-1-A: Loblolly pine measurements of height (ft) and dbh (in) by treatment level and application

Table 3-1-B shows the growth of the trees over the 19-month period. Again, covariance analysis was used. The R^2 was very low; however, it is increasing over time for diameter. Interestingly, height and diameter growth show significantly different patterns. Height growth is greatest in the high frequency (2 in/mo) plots while the control plots exhibit greater diameter growth. Additionally, the inner tree rows show greater height growth while the outer rows exhibit greater diameter growth. Tree spacing was not taken into account.

	Measurement Date						
	Jan-98	Aug-98	Sep-98	Oct-98	Jan-99	Jun-99	Aug-99
Height							
R^2	0	*	*	*	0.06	*	*
Treatment Level							
High Frequency (2in/mo)	0	*	*	*	3.63 a	*	*
High Volume (4in/2mo)	0	*	*	*	3.28 b	*	*
Constant Wetting (6in/mo)	0	*	*	*	3.21 b	*	*
Control	0	*	*	*	3.09 b	*	*
Application Method							
Irrigation Hose	0	*	*	*	3.07 b	*	*
Reel Rain Traveler	0	*	*	*	3.55 a	*	*
Tree Row							
Inner	0	*	*	*	3.86 a	*	*
Outer	0	*	*	*	3.29 b	*	*
Diameter							
R^2	0	0.08	0.14	0.17	0.17	0.17	0.18
Treatment Level							
High Frequency (2in/mo)	0	0.53 a	0.58 ab	0.62 bc	0.56 b	0.96 bc	1.08 b
High Volume (4in/2mo)	0	0.57 a	0.60 a	0.65 ab	0.59 b	1.00 ab	1.15 a
Constant Wetting (6in/mo)	0	0.53 a	0.56 b	0.60 c	0.55 b	0.93 c	1.06 b
Control	0	0.57 a	0.62 a	0.68 a	0.64 a	1.04 a	1.16 a
Application Method							
Irrigation Hose	0	0.53 a	0.58 a	0.64 a	0.59 a	0.98 a	1.11 a
Reel Rain Traveler	0	0.56 a	0.60 a	0.63 a	0.58 a	0.98 a	1.11 a
Tree Row							
Inner	0	0.59 a	0.53 b	0.56 b	0.53 b	0.92 a	1.06 a
Outer	0	0.55 a	0.60 a	0.64 a	0.59 a	0.99 a	1.11 a
* No measurements were taken.		Means with the same letter are not significantly different.					

Table 3-1-B: Loblolly pine growth as measured by change in height (ft) and dbh (in) and presented by treatment level and application method on Craven 26 fertigation study.

Tree volume measurements and volume growth are represented by D^2H (ft^3) and are presented in Table 3-1-C. While the covariance analysis accounts for the pretreatment bias, it is not removed. Therefore, percent growth is also shown. These results demonstrate that high frequency (2 in/mo) and high volume (4 in/2 mo) had greater percent growth than the control. The constant wetting (6 in/mo) treatment level has a significantly lower impact on percent growth. The reel rain traveler had significantly higher percent growth than the irrigation hose method. While outer tree rows had greater growth, inner tree rows had greater percent growth.

	Jan-98	Jan-99	Growth	% Growth
R^2	0.08	0.98	0.60	n/a
Treatment Level				
High Frequency (2in/mo)	20.1 c	25.0 b	4.83 b	124
High Volume (4in/2mo)	20.7 c	25.7 c	4.90 b	124
Constant Wetting (6in/mo)	26.0 a	31.3 a	5.41 a	120
Control	23.5 b	25.0 d	5.47 a	123
Application Method				
Irrigation Hose	23.9 a	29.2 a	5.24 a	122
Reel Rain Traveler	21.1 b	26.0 b	5.04 a	123
Tree Row				
Inner	19.0 b	23.7 b	4.62 b	124
Outer	22.6 a	27.8 a	5.17 a	123

Table 3-1-C: Loblolly pine measurements and growth by D^2H (ft3) on Craven 26 fertigation study.

3.4.2 Pine Foliage

Loblolly pine foliage was sampled Fall, 1997, prior to application and again Fall, 1998. Nutrient content data is presented in Table 3-2. The coefficient of determination, adjusted R^2, ranged from 0.41 for Mn to 0.98 for B. There were no significant differences among treatment level or application methods for N, P, K, Mg, Ca, B, Zn, Mn, Fe, or Cu. Boron (B), Zn, and Fe increased significantly from Fall, 1997, to Fall, 1998.

	N	P	K	Mg	Ca
	g				
R^2	0.56	0.80	0.50	0.72	0.57
Treatment Level					
High Frequency (2in/mo)	0.32 a	0.02 a	0.10 a	0.01 a	0.02 a
High Volume (4in/2mo)	0.33 a	0.03 a	0.11 a	0.02 a	0.02 a
Constant Wetting (6in/mo)	0.30 a	0.02 a	0.11 a	0.01 a	0.02 a
Control	0.32 a	0.03 a	0.11 a	0.01 a	0.02 a
Application Method					
Irrigation Hose	0.31 a	0.02 a	0.11 a	0.01 a	0.02 a
Reel Rain Traveler	0.32 a	0.02 a	0.10 a	0.01 a	0.02 a
Season					
Fall 1997	0.30 a	0.02 a	0.10 a	0.01 a	0.02 a
Fall 1998	0.34 a	0.03 a	0.12 a	0.02 a	0.02 a
	B	Zn	Mn	Fe	Cu
	g				
R^2	0.98	0.62	0.41	0.76	0.67
Treatment Level					
High Frequency (2in/mo)	0.08 a	0.05 a	0.09 a	0.10 a	0.01 a
High Volume (4in/2mo)	0.08 a	0.05 a	0.09 a	0.11 a	0.01 a
Constant Wetting (6in/mo)	0.08 a	0.05 a	0.08 a	0.10 a	0.01 a
Control	0.09 a	0.05 a	0.08 a	0.11 a	0.02 a
Application Method					
Irrigation Hose	0.08 a	0.05 a	0.08 a	0.11 a	0.01 a
Reel Rain Traveler	0.08 a	0.05 a	0.08 a	0.10 a	0.01 a
Season					
Fall 1997	0.02 b	0.04 b	0.09 a	0.08 b	0.01 b
Fall 1998	0.15 a	0.06 a	0.08 a	0.12 a	0.02 b
Means with the same letter are not significantly different.					

Table 3-2: Loblolly pine foliar nutrient content on Craven 26 fertigation study

3.4.3 Litter

Loblolly pine litter data is presented in Table 3-3-A. The R^2 ranges from 0.56 for Cu to 0.91 for B. Potassium (K), S, and Na vary with treatment level. Potassium was highest in the constant wetting (6 in/mo) plots. Sulfer (S) and Na were greatest in the control plots.

Other litter includes hardwoods, bushes and forbs. Its nutrient content data is presented in Table 3-3-B. Copper (Cu) varied with treatment level. It was greatest in the constant wetting (6 in/mo) plots. All of the nutrients were greatest in the irrigation hose plots.

	N	P	K	S	Mg	Ca	Na
	g						
R^2	0.81	0.85	0.74	0.79	0.82	0.83	0.86
Treatment Level							
High Frequency (2in/mo)	1.18 a	0.09 a	0.22 ab	0.09 ab	0.08 a	0.29 a	0.04 ab
High Volume (4in/2mo)	0.95 a	0.07 a	0.20 b	0.07 b	0.08 a	0.27 a	0.03 b
Constant Wetting (6in/mo)	1.16 a	0.09 a	0.26 a	0.11 ab	0.08 a	0.32 a	0.04 ab
Control	1.26 a	0.10 a	0.25 ab	0.12 a	0.08 a	0.31 a	0.04 a
Application Method							
Irrigation Hose	1.00 b	0.07 b	0.22 a	0.09 a	0.07 b	0.26 b	0.03 b
Reel Rain Traveler	1.28 a	0.10 a	0.25 a	0.11 a	0.09 a	0.33 a	0.04 a
		B	Zn	Mn	Fe	Cu	Al
		g					
R^2		0.91	0.77	0.75	0.59	0.56	0.78
Treatment Level							
High Frequency (2in/mo)		0.55 a	0.22 a	0.51 a	0.97 a	0.14 a	5.16 a
High Volume (4in/2mo)		0.48 a	0.19 a	0.48 a	1.37 a	0.13 a	4.99 a
Constant Wetting (6in/mo)		0.51 a	0.25 a	0.51 a	1.27 a	0.18 a	5.59 a
Control		0.52 a	0.25 a	0.56 a	1.27 a	0.18 a	5.69 a
Application Method							
Irrigation Hose		0.48 a	0.20 b	0.47 a	1.03 b	0.16 a	4.63 b
Reel Rain Traveler		0.55 a	0.26 a	0.56 a	1.41 a	0.16 a	6.09 a
Means with the same letter are not significantly different.							

Table 3-3-A: Loblolly pine litter nutrient content on Craven 26 fertigation study

	N	P	K	S	Mg	Ca	Na
	%						
R^2	0.71	0.56	0.29	0.35	0.73	0.75	0.46
Treatment Level							
High Frequency (2in/mo)	1.33 b	0.07 a	0.24 a	0.11 a	0.24 b	0.84 c	0.04 a
High Volume (4in/2mo)	1.46 ab	0.10 a	0.44 a	0.16 a	0.26 b	0.89 bc	0.05 a
Constant Wetting (6in/mo)	1.52 ab	0.10 a	0.29 a	0.14 a	0.27 b	1.05 ab	0.05 a
Control	1.55 a	0.08 a	0.25 a	0.14 a	0.32 a	1.09 a	0.05 a
Application Method							
Irrigation Hose	1.45 a	0.08 a	0.27 a	0.12 a	0.28 a	0.95 a	0.05 a
Reel Rain Traveler	1.48 a	0.10 a	0.34 a	0.14 a	0.26 a	0.97 a	0.05 a
Sampling Date							
Sep-98	1.78 a	0.14 a	0.19 b	0.18 a	0.18 c	0.50 d	0.05 a
Oct-98	1.83 a	0.09 ab	0.36 ab	0.13 ab	0.28 b	0.89 bc	0.05 a
Nov-98	1.17 c	0.12 a	0.65 a	0.17 a	0.37 a	1.25 a	0.05 a
Dec-98	1.17 c	0.06 b	0.29 ab	0.09 b	0.32 a	1.22 a	0.05 ab
Jan-99	1.35 bc	0.06 b	0.13 b	0.12 ab	0.27 a	1.09 ab	0.03 b
Mar-99	1.52 b	0.05 b	0.21 ab	0.10 ab	0.21 a	0.81 c	0.05 ab
		B	Zn	Mn	Fe	Cu	Al
		ppm					
R^2		0.92	0.66	0.65	0.44	0.54	0.48
Treatment Level							
High Frequency (2in/mo)		64.31 a	37.12 b	210.33 ab	148.10 ab	33.05 a	244.30 a
High Volume (4in/2mo)		66.72 a	40.86 b	157.92 b	219.48 a	23.65 a	225.00 a
Constant Wetting (6in/mo)		64.33 a	59.65 a	220.12 ab	185.89 ab	37.30 a	287.00 a
Control		68.05 a	56.62 a	253.82 a	119.89 b	45.36 a	246.00 a
Application Method							
Irrigation Hose		67.58 a	50.96 a	240.77 a	160.47 a	36.82 a	234.75 a
Reel Rain Traveler		63.95 a	45.70 a	177.13 b	178.67 a	32.32 a	267.47 a
Sampling Date							
Sep-98		36.63 c	34.25 b	95.50 d	107.38 b	14.88 c	281.25 a
Oct-98		18.71 d	50.57 a	162.14 cd	224.86 a	31.71 bc	191.14 a
Nov-98		86.38 b	51.50 a	282.75 a	203.38 ab	14.25 c	238.63 a
Dec-98		97.63 ab	60.38 a	274.00 a	134.13 ab	21.25 c	248.63 a
Jan-99		106.38 a	65.13 a	254.88 ab	230.25 a	69.38 a	286.38 a
Mar-99		43.23 c	28.79 b	182.55 bc	123.19 ab	55.87 ab	*
* No measurements were taken.		Means with the same letter are not significantly different.					

Table 3-3-B: Other litter nutrient concentration on Craven 26 fertigation study

3.4.4 Soils

Soil samples were collected Spring 1998 and Spring 1999. Except for P, soil parameters were well accounted for by the model and produced reasonably high R^2. Table 3-4 shows that K, Mg, Ca, Na, pH, and CEC significantly increased by the second sampling date. Manganese (Mn) and Cu significantly decreased over that year. There are no significant differences among treatment level or application method for any of the constituents analyzed.

	P	K	Mg	Ca	Na	S	Zn	Mn	Cu
	ppm								
R^2	0.31	0.84	0.96	0.89	0.93	0.56	0.63	0.78	0.68
Treatment Level									
High Frequency (2in/mo)	33.10 a	78.91 a	140.41 a	1271.5 a	11.50 a	41.15 a	4.03 a	61.08 a	4.35 a
High Volume (4in/2mo)	29.85 a	57.88 a	124.09 a	778.1 a	17.25 a	48.85 a	3.55 a	41.83 a	1.69 a
Constant Wetting (6in/mo)	25.50 a	78.94 a	98.24 a	541.8 a	11.50 a	41.25 a	7.40 a	34.61 a	1.84 a
Control	39.95 a	63.08 a	113.00 a	825.0 a	11.50 a	36.05 a	14.58 a	27.28 a	2.16 a
Application Method									
Irrigation Hose	24.15 a	49.98 a	121.61 a	784.0 a	14.38 a	41.40 a	1.62 a	22.77 a	2.12 a
Reel Rain Traveler	39.75 a	89.42 a	116.26 a	924.1 a	11.50 a	42.25 a	13.16 a	59.64 a	2.90 a
Season									
Spring 1998	33.75 a	20.88 b	19.63 b	38.8 b	0.00 b	37.00 a	14.42 a	80.40 a	4.08 a
Spring 1999	30.15 a	118.53 a	218.24 a	1669.4 a	25.88 a	46.65 a	0.36 a	2.00 b	0.94 b
	OM	pH	CEC						
	%		meq/100g						
R^2	0.53	0.76	0.94						
Treatment Level									
High Frequency (2in/mo)	9.95 a	4.05 a	11.03 a						
High Volume (4in/2mo)	9.95 a	4.05 a	8.00 a						
Constant Wetting (6in/mo)	9.85 a	4.15 a	6.80 a						
Control	9.56 a	4.05 a	8.30 a						
Application Method									
Irrigation Hose	9.76 a	4.06 a	8.38 a						
Reel Rain Traveler	9.90 a	4.09 a	8.69 a						
Season									
Spring 1998	9.90 a	4.00 b	1.75 b						
Spring 1999	9.76 a	4.15 a	15.31 a	Means with the same letter are not significantly different.					

Table 3-4: Soil nutrient concentrations on Craven 26 fertigation study

3.4.5 Surface Water

Surface water analyses are presented in Table 3-5. Total nitrogen and total phosphate were not well accounted for by the model. However, they are greatest in the high frequency (2 in/mo) plots. The high frequency (2 in/mo) plots also had significantly higher ammonium-N along with the outlet riser. Ammonium-N was highest in the irrigation hose plots. Nitrate-N was highest in the constant wetting (6 in/mo) plots but significantly diluted at the outlet riser. Nitrate-N was greatest in the traveler plots.

	NH_4-N	TKN	NO_3/NO_2-N	TPO$_4$
	ppm			
R^2	0.81	0.37	0.85	0.36
Treatment Level				
High Frequency (2in/mo)	0.06 a	0.81 a	0.13 ab	0.07 a
High Volume (4in/2mo)	0.04 b	0.65 a	0.11 bc	0.05 ab
Constant Wetting (6in/mo)	0.04 b	0.69 a	0.15 a	0.05 b
Control	0.04 b	0.30 b	0.13 ab	0.04 b
Outlet	0.06 a	0.60 ab	0.09 c	0.04 b
Application Method				
Irrigation Hose	0.06 a	0.71 a	0.11 b	0.05 a
Reel Rain Traveler	0.04 b	0.57 a	0.15 a	0.05 a
Means with the same letter are not significantly different.				

Table 3-5: Surface (riser) water nutrient concentration on Craven 26 fertigation study

3.4.6 Ground Water

The ground water nutrient concentrations are presented in Table 3-6. Again, total nitrogen and total phosphate were not particularly well accounted for by the model. Total N was greatest at a depth of 2 feet. Ammonium-N was highest in the high frequency (2 in/mo) plots, the traveler plots, and at a depth of 4 feet. Nitrate-N was highest in plots treated with high volume (4 in/2 mo), constant wetting (6 in/mo), high frequency (2 in/mo), and control, in that order. Nitrate-N was highest in the irrigation hose plots and at depths of 2 and 3 feet.

	NH_4-N	TKN	NO_3/NO_2-N	TPO$_4$
	ppm			
R^2	0.86	0.51	0.87	0.51
Treatment Level				
High Frequency (2in/mo)	0.09 a	0.82 a	2.21 b	0.10 a
High Volume (4in/2mo)	0.07 b	1.08 a	3.60 a	0.14 a
Constant Wetting (6in/mo)	0.05 c	0.97 a	3.41 a	0.08 a
Control	0.04 c	0.63 a	0.65 c	0.09 a
Application Method				
Irrigation Hose	0.05 b	1.00 a	3.09 a	0.11 a
Reel Rain Traveler	0.07 a	0.74 a	1.88 b	0.10 a
Depth				
2 feet	0.04 b	1.31 a	3.25 a	0.13 a
3 feet	0.06 ab	0.83 b	2.98 a	0.11 a
4 feet	0.07 a	0.64 b	1.68 b	0.08 a
Means with the same letter are not significantly different.				

Table 3-6: Ground (well) water nutrient concentration on Craven 26 fertigation study

3.4.7 Understory Vegetation

Understory vegetation sampling results were divided into grasses and forbs and are presented in Tables 3-7-A and 3-7-B, respectively. The model did not produce reasonable R^2 for any of the nutrients. Nitrogen (N), Mg, Na, Zn, and Mn had significant differences among treatments for grass. They were highest in the high frequency (2 in/mo) plots and lowest in the constant wetting (6 in/mo) plots. There were no significant differences in nutrient content for the forbs.

	N	S	P	K	Mg	Ca	Na
	g						
R^2	0.29	0.27	0.23	0.35	0.3	0.22	0.37
Treatment Level							
High Frequency (2in/mo)	1.69 a	0.20 a	0.11 a	1.01 a	0.39 a	0.59 a	0.33 a
High Volume (4in/2mo)	1.03 ab	0.14 a	0.08 a	0.77 a	0.17 ab	0.35 a	0.14 ab
Constant Wetting (6in/mo)	0.25 b	0.02 a	0.02 a	0.13 a	0.03 b	0.09 a	0.03 b
Control	1.11 ab	0.14 a	0.09 a	0.54 a	0.13 ab	0.20 a	0.16 ab
Application Method							
Irrigation Hose	0.95 a	0.11 a	0.08 a	0.53 a	0.20 a	0.31 a	0.15 a
Reel Rain Traveler	1.05 a	0.13 a	0.07 a	0.68 a	0.13 a	0.28 a	0.16 a
		B	Zn	Mn	Fe	Cu	Al
		g					
R^2		0.26	0.36	0.32	0.23	0.36	0.22
Treatment Level							
High Frequency (2in/mo)		1.02 a	0.74 a	1.49 a	3.07 a	0.12 a	3.48 a
High Volume (4in/2mo)		0.83 a	0.37 ab	1.19 ab	1.47 a	0.10 a	1.95 a
Constant Wetting (6in/mo)		0.16 a	0.11 b	0.18 b	0.88 a	0.02 a	0.68 a
Control		0.71 a	0.32 ab	0.68 ab	0.84 a	0.05 a	3.23 a
Application Method							
Irrigation Hose		0.62 a	0.36 a	0.84 a	1.44 a	0.06 a	1.73 a
Reel Rain Traveler		0.72 a	0.39 a	0.89 a	1.59 a	0.09 a	2.98 a
	Means with the same letter are not significantly different.						

Table 3-7-A: Understory grass vegetation nutrient content on Craven 26 fertigation study

	N	S	P	K	Mg	Ca	Na
	%						
R^2	0.30	0.38	0.47	0.60	0.31	0.22	0.41
Treatment Level							
High Frequency (2in/mo)	1.07 a	0.12 a	0.07 ab	0.66 ab	0.22 a	0.33 a	0.22 a
High Volume (4in/2mo)	1.03 a	0.12 a	0.08 ab	0.66 ab	0.15 ab	0.28 a	0.14 ab
Constant Wetting (6in/mo)	1.24 a	0.13 a	0.13 a	0.98 a	0.12 ab	0.38 a	0.16 ab
Control	0.93 a	0.11 a	0.06 b	0.57 b	0.11 b	0.17 a	0.12 b
Application Method							
Irrigation Hose	1.12 a	0.13 a	0.10 a	0.77 a	0.17 a	0.31 a	0.18 a
Reel Rain Traveler	1.00 a	0.11 a	0.07 a	0.65 a	0.12 a	0.27 a	0.13 b
	B	B	Zn	Mn	Fe	Cu	Al
	ppm	ppm					
R^2	0.22	0.22	0.59	0.34	0.43	0.54	0.34
Treatment Level							
High Frequency (2in/mo)	63.17 a	63.17 a	44.50 b	96.17 a	168.7 b	7.67 b	210.83 a
High Volume (4in/2mo)	89.29 a	89.29 a	34.86 b	98.57 a	113.0 b	10.71 ab	165.86 a
Constant Wetting (6in/mo)	82.00 a	82.00 a	81.29 a	97.00 a	907.9 a	21.71 a	232.00 a
Control	61.57 a	61.57 a	26.71 b	66.71 a	80.1 b	6.14 b	230.00 a
Application Method							
Irrigation Hose	73.60 a	73.60 a	56.67 a	96.67 a	463.7 a	13.80 a	203.67 a
Reel Rain Traveler	75.42 a	75.42 a	34.75 a	80.25 a	146.9 a	9.08 a	217.08 a
	Means with the same letter are not significantly different.						

Table 3-7-B: Understory grass vegetation nutrient concentration on Craven 26 fertigation study

3.5 Discussion

The impact of wastewater application on tree growth is not fully understood. One year of data on this trial is not sufficient to determine its total effect. However, using percent growth on the control plots as a base line, initial trends can be identified. The constant wetting (6 in/mo) treatment has a significantly negative impact. It appears that the high frequency (2 in/mo) and high volume (4 in/2 mo) treatments caused a slight increase in percent growth over the control treatment.

Overall, foliar nutrient contents were not significantly affected by wastewater application. Of the nutrients that increased from 1997 to 1998, only P and Cu were added. The other nutrients were either provided by the soil or availability increased with a change in soil pH. With continued application, these values would probably increase over time—particularly in the higher treatment levels. Pine litter nutrient contents will most likely continue the similar trend of increasing for the higher treatment levels.

Soil nutrient concentrations show potential leaching or runoff situations for P, Ca, Mn, and Cu in the constant wetting (6 in/mo) and high volume (4 in/2 mo) treatment regimes. The pH appears to be increasing with increasing treatment levels.

3.6 Key Results

The limited time of tree response is not adequate to make definitive statements. The statistical differences in some of the parameters are surprising; but the effects of the hurricane events, particularly on the constant wetting treatment, may confound the trends.

The pine foliage nutrients do not show strong differences in content or concentrations between treatments. Trends and some specific comparisons do indicate that foliar nutrients are increasing with the nutrient additions. The seasonal comparison and the litter trends reinforce this trend.

Soil nutrient values show seasonal significant increases, although treatment differences are not yet significant.

The understory grass nutrient concentration and content values reflect the differences in nutrient additions. The constant treatment shows increases (significant and non-significant) in nitrogen, sulfur, phosphorus, potassium calcium, sodium, zinc, iron, and magnesium.

Ground water nutrient concentrations of nitrogen forms have significant increases associated with treatments. These trends are also visible at the outlet risers, although NO3/N has the most differences and trends.

3.7 Conclusions

The early results from this demonstration trial are beginning to show trends that reflect the treatment differences. This is somewhat unexpected at this stage.

The trends would indicate that tree growth could be increased using nutrients supplied by wastewater. The range of treatments appears to be adequate to cover the range from complete retention of nutrients to some leakage into surface water.

Continued monitoring of this fertigation project is needed to meet the original goal to quantify the effects of wastewater application on loblolly pine to produce additional energy wood as a co-product of a saw timber rotation.

3.8 Literature Cited

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Section 4

Gasifier Island Design & Cost

4.0 Gasifier Island Design & Cost

This section discusses the design and cost of a gasification island for integration into a market pulp mill. The Weyerhaeuser mill at New Bern, North Carolina, is used as the focus of the study. The technology utilized is Battelle's dual-bed Low Inlet Velocity Gasification (LIVG) process, licensed by Future Energy Resource Corporation (FERCO).

The FERCO gasifier would be used to gasify the waste biomass typically available on and around the facility as described in Section 2. It would be used to generate sufficient medium Btu gas to reduce the quantity of No. 6 fuel oil used in the kiln and power boilers.

In support of this activity, Nexant (a Bechtel Technology and Consulting Company) was asked to develop a conceptual design, including capital cost estimates, that would concentrate on the design, constructability, and capital costs associated with the gasification island. It was agreed that this evaluation would be accomplished in two phases.

The first phase was completed in mid-1999 and covered the design and capital cost estimate for a generic greenfield commercial-size gasification facility. The technology was assumed to be mature or "Nth plant" in order to determine the commercial feasibility of the technology. Significant effort was expended on examining the impact of operating parameters, such as gasifier feed moisture, on overall plant performance. Based on these results, a plant configuration was established and a "Class 40" capital cost estimate was prepared. (A further clarification of "Class 40" is found on page § 4–4, 4.2.5)

The second phase also examined the impact of key operating parameters but included their effect on capital cost as well as on performance of the gasification island. Since the capital costs developed in the first phase had illustrated the considerable impact the dryer has on the overall plant cost, the second phase included the evaluation of drying options. Also included was an estimate of the capital cost for a first-of-a-kind, or "next plant" cost, as compared to the "Nth plant" costs developed during the first phase. Where possible, the revised work also incorporated information from FERCO's demonstration plant in Burlington, Vermont, to fine tune some of the chemistry, throughput, and operational issues that have not been demonstrated to date at the larger scale. Unfortunately, this was limited due to restricted operation of the Burlington plant during this phase.

The results from Bechtel's work on Phase 2 have been incorporated into an overall conceptual design and cost estimate by Stone & Webster Engineering Corporation (SWEC). This estimate will include BOP elements and interface to the existing onsite facilities at the New Bern site and is reported in Section 5.

4.1 Approach to Cost/Performance Analysis

The work carried out under Phase 2 built on the results and findings from Phase 1. Because of the critical nature that the choice of dryer type and the operating parameters have on the Gasifier Island, a significant amount of effort in Phase 2 was directed to determining the optimum dryer configuration. Since a steam dryer was used in Phase 1, sufficient information was available to carry out the steam dryer portion of the analysis. Therefore, the initial work in Phase 2 was directed at determining the size, configuration, operating conditions, and capital cost for a rotary dryer operating off heat from the combustor flue gas. Included in this analysis was a determination of what downstream equipment would be required to clean the wet flue gas leaving the dryer.

Typical operating conditions for the rotary dryer under various design scenarios were provided by M-E-C Company. This data was introduced into the gasifier process model to provide performance data that more closely reflected actual operating practice. The process portion of the model for the steam dryer/gasifier system was unchanged except to add the option of using a constant steam flow to the gasifier. Both models were enhanced to be able to provide scaled capital costs using the costs developed in Phase 1 as a basis.

4.2 New Bern Mill Specifications & Design Basis

The key general and economic criteria used to develop the design of the gasifier island are described below.

4.2.1 General Criteria

The general study criteria are as follows:

- Designs are based on FERCO's dual-bed LIVG biomass gasification process developed by Battelle
- Plant is a grassroots facility
- Design of the gasifier island components emphasize minimizing capital cost wherever prudent
- Nth plant perspective was used in the base design
- Product gas from the gasifier was assumed to be used to replace No. 6 fuel oil in existing boilers and kiln

4.2.2 Site-related Conditions

The study site is located at Weyerhaeuser's New Bern Mill facility in North Carolina. The site is clear and level with no unusual problems due to soil conditions; however, 60-foot pile foundations are assumed required based on previous work at the site.

4.2.3 Meteorological Data

Annual average ambient air conditions assumed for material balances, thermal efficiencies, and equipment sizing are:

Dry bulb temperature	60°F
Atmospheric pressure	14.7 psia

4.2.4 Technical Data.

The technical data used include:

- The plant capacity is 420 million Btu/hr of product gas, as set by the size of the fuel feed dryer
- The design biomass feed is a combination of hogged fuel, wood residuals, and sludges; a representative analysis is presented in Tables 4–1 through 4–3.
- Gasifier yields are based on Battelle data from their 8- and 10-inch diameter pilot plant gasifier operations. Typical product gas analysis used for this study is presented in Table 4–4

Heating value, HHV = 8,800 Btu/lb. (dry basis)

Component	Weight %
Moisture	50.0
Carbon	25.1
Hydrogen	2.7
Nitrogen	0.1
Oxygen	20.1
Ash	2.0
Total	100.0

Table 4–1: Design Biomass Feed Analysis

Size Fraction	Weight %
+ 29 mm	7.9
29 - 22 mm	14.6
22 - 16 mm	23.0
16 - 10 mm	26.3
10 - 5 mm	15.9
Pan	12.3
Total	100.0

Table 4–2: Design Biomass Size, Williams Classification

Component	Weight %
Chips	22.5
Chip fines	6.5
Forest residue	71.0
Total	100.0

Table 4–3: Design Biomass Source Distribution

Component	Dry Gas (N_2 Free)	Contribution to Heating Value
	Volume %	Btu/SCF
H_2	17.5	56.9
CO	50.4	161.9
CO_2	9.4	---
CH_4	15.5	156.9
C_2H_4	6.1	97.8
C_2H_6	1.1	19.5
Calculated Heating Value = 493.0		

Table 4–4: Typical Product Gas Analysis, Dry Basis

- The level of product gas cleaning is consistent with use in a distributed gas system typically found at pulp and paper facilities. This includes bulk solids removal and scrubbing residual tar leaving the tar cracker. The design temperature of the product gas leaving the gasifier island is 125°F, as agreed between SWEC, Weyerhaeuser, and Nexant. While this temperature minimizes the size of the product gas compressor, a more detailed analysis would likely show that a higher temperature would provide an economic optimum between the product gas cleanup system and product gas compressor.
- All heat and material balances are based on a feed with 50 percent moisture.
- Sand is delivered to the site by truck equipped with self-contained pneumatic unloading equipment. Fresh sand is nominally 50 mesh and free of oversize and fine dust.
- Tar yield is 1.0% of dry wood based on Battelle report, May 1988.
- Sparing philosophy: Online spares for rotating equipment at critical locations with severe duty conditions.
- Plant steam level is 850 psig/825°F.
- Extraction steam from the turbine generator is at 155 psig, while exhaust is at 55 psig.

4.2.5 Capital Cost Criteria.

The estimating approach and the engineering information provided to support the estimate are generally consistent with an EPRI Class II, Preliminary Estimate, as defined in EPRI's *Technical Assessment Guide*, (EPRI TR-102275-VIR7, Volume 1: Rev. 7, June 1993). Based on early discussions with Weyerhaeuser, it was agreed that this level of detail is consistent with Weyerhaeuser's Class 40 evaluation. Cost data are based on a January 1999 price level.

4.2.6 Qualifications

The capital cost estimate was developed based on the following qualifications:

- Nth plant perspective was used.
- All major foundations rest on piles. Allowed pre-cast concrete piles with average length – 60 LF.
- A 120 foot long pipe/utility bridge is provided to link the Fuel Dryer and Gasification equipment with the rest of the plant.
- All pipe runs and electrical cables to/from unit are above ground.
- Price levels are generally 1st Quarter-1999. There is no milestone schedule, so no allowance for price/wage escalation has been provided. Project duration would probably be about 24 months.

- Engineering, Procurement, and other management/administration costs ("Home Office Cost") have been estimated as a percentage of the constructed cost of the plant. The percentage used is typical for process plants in this cost range and does not allow for additional effort associated with incorporating new technology and lessons learned from the demonstration plant into the design for a commercial plant.

4.2.7 Direct Field Material Costs

Direct field material costs are for permanent physical plant facilities including equipment, material, and freight. The local sales tax is excluded.

4.2.8 Direct Field Labor Costs

The components of direct field labor costs are labor manhours and the composite labor wage rate.

Manual labor average "all-in" wage rate ($21.50) was used. There is no allowance for travel or per diem for manual labor, because the construction peak is expected to be less than 100 people.

4.2.9 Direct Subcontract Costs

Direct subcontract costs are those for equipment, materials, and services furnished by the subcontractors, including installation labor costs and related indirect field costs.

Major items that were estimated as subcontract costs include:

- Dryer assembly
- Refractory
- Insulation, painting, and personnel protection

4.2.10 Indirect Field and Home Office Engineering Costs

Indirect field costs are costs that cannot be directly identified with any construction operation related to specific plant facilities but they support the general construction operation.

Based on previous experience at the New Bern Mill, the ratio of indirect to direct manual hours is typically less than 10% of the contractor's work; 20% has been used in order to allow for the cost of scaffolding and cleanup. Construction indirect material costs were estimated at $8/manual hour, which is also consistent with the previous jobs at New Bern.

Field nonmanual hours were estimated as 20% of manual hours. The average cost of $25 per hour was used for nonmanual labor while the combination of nonmanual travel, relocation, and per diem was estimated at $2.25/nonmanual hour.

Home office engineering manhours and other home office services are accounted for by Bechtel through the addition of 15% of the Field Costs based on historical data for plants of this size. No special allowances were provided for New Technology for the base estimate. Also included is 5% of the Total Field Cost and 5% of the Engineering Cost to cover contractor's fee.

4.3 Plant Description

A brief description of the major systems is provided below. The basic system closely follows the configuration developed by Battelle and employed by FERCO at the Burlington Demonstration Facility. A process flow diagram for the commercial application of the LIVG process used for this evaluation is shown in Figure 4-1, Figure 4-2, and Figure 4-3. The material balance associated with these figures is presented in Table 4-5 (three sheets).

4.3.1 Fuel Feed and Drying Systems

Raw wood residuals from the storage yard are reclaimed and transported to a drying plant surge bin, which is included in the BOP. This system is discussed in Section 5. The raw feed is transported to the steam dryer by a rotary feeder and screw conveyor. A knife gate is installed between the rotary feeder and the surge bin to permit isolation of the surge bin from down-stream equipment.

During the passage through the screw conveyor, the wet chips are preheated by waste steam coming from down-stream equipment. The screw conveyor delivers the warmed wet wood residuals to the first of 16 internal drying cells within the Niro steam dryer.

The Niro Steam Drying System is provided as a package that includes:

- Dryer feed end rotary valve
- Dryer feed screw conveyor
- Steam dryer
- Dryer discharge screw conveyor
- Dryer discharge end rotary valve
- Dryer discharge end knife gate
- Flash vessel
- Flash vessel discharge rotary feeder

The Niro dryer uses superheated IP steam as the source of heat. IP steam at approximately 309 psig and 464°F is supplied to the dryer from the flue gas HRSG in the gasification section. The condensate from the IP steam (which never contacts the wood residuals and thus remains clean) is recovered and is pumped back to the flue gas HRSG.

The steam used to dry the wood is actually the steam released from the wood that has been superheated in the central exchanger and recirculated within the dryer by a circulating fan located at the bottom of the dryer. Excess steam is released at the top of the dryer through a pressure control system nominally set at 40 psig. At steady state, the quantity of process steam leaving the dryer equals the amount of water evaporated from the wet wood residuals. A predetermined amount of the process steam is sent to the Gasifier where it serves to fluidize the solids and control sand flow in the L valve. The remaining steam is condensed and sent to water treatment using partially heated cooling water from the product gas scrubber cooler.

A screw conveyor collects the dried wood residuals from the dryer. A rotary valve, similar in construction to the feed end valve, delivers the solids at atmospheric pressure to a combination flash vessel and cyclone collector to separate solids from the gases, mainly steam.

During normal operation, the dried solids are transported by a reversible screw conveyor and high angle conveyor to a live-bottom surge bin containing six discharge screws. A collecting screw gathers the dried wood and transports it to the rotary valve, which feeds the wood residuals to a water-cooled screw that, in turn, feeds the gasifier. The screw feeder is installed in a declined position of about 15 degrees to assist flow of dried feed into the gasifier.

This reversible screw conveyor permits diversion of wood residuals to either the gasifier or the dried wood storage. The dried wood storage bin is a Flo-Matic® bin with about 4 hours capacity at full feed rates. When required, a reclaim conveyor returns the wood chips to the high angle conveyor and live-bottom surge bin for use in the gasifier.

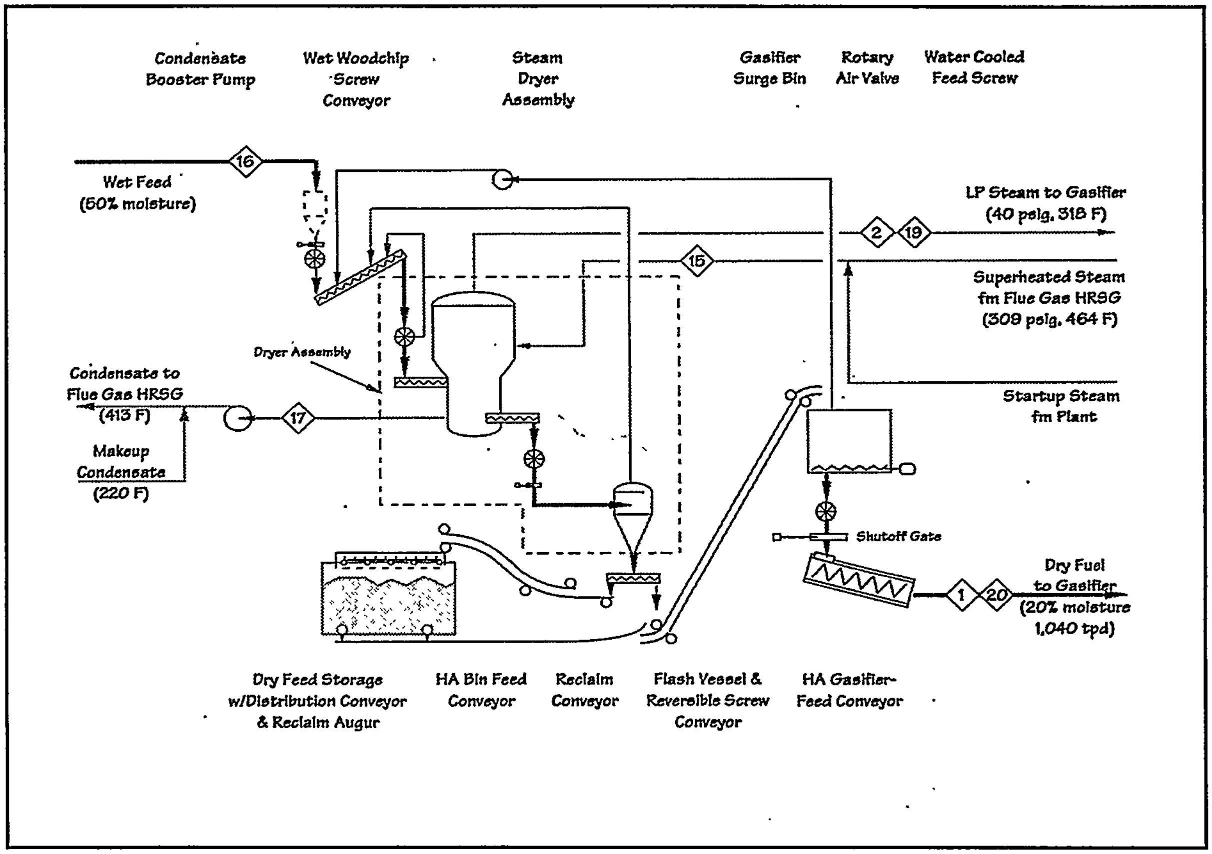

Figure 4–1: Feed Preparation

4.3.2 Gasifier/Combustor System

The process configuration for the gasifier and combustor systems closely resembles the system being demonstrated at the Burlington facility. A dual bed system is used with both a gasifier and combustor. Biomass entering the gasifier is heated to pyrolysis temperatures (nominally 1500°F) with hot sand from the combustor. The gasifier is an entrained bed design with steam providing the motive force at the bottom of the vessel.

The partially cooled sand is separated from the product gas in a cyclone and is returned to the bottom of the combustor along with unconverted wood in the form of char. Air is provided by high-pressure blowers to fluidize the combustor and provide oxygen for the char combustion. Combusting the char reheats the sand to about 1800°F, which is separated from the hot flue gas in a cyclone and returned to the gasifier, thereby completing the circuit.

Although the basic elements are the same, several modifications were made to simplify the system, reduce capital cost, or take into account some of the operating experience gained at the Burlington facility. Following the system more or less from beginning to end, the changes include:

- The external startup burners used at Burlington have been replaced with burners close coupled to the Gasifier and Combustor windboxes. The burners have been sized to provide sufficient heat to heat the incoming air to 1500°F for faster startup.
- The current study assumed that a dashpot/L-valve and a J-valve can be used to control solids circulation in the gasifier–combustor loop. The J-valve system would be similar to those used in CFB boilers. There is currently some concern on the integrity of such a seal since it will have to maintain a seal between product gas and flue gas with low levels of oxygen. However, for the Nth plant it has been assumed that these concerns will be overcome and the simpler and less expensive J-valve system will be acceptable practice.
- The secondary combustor cyclone at Burlington has been removed. Currently CFB boilers operate with a heat recovery system following a single cyclone and the LIVG process should be able to do the same. The only difference is the high level of quartz sand which is more erosive than coal ash; but based on discussions with HRSG vendor Deltak, it is believed that these difficulties can be overcome through proper design, materials, and reduced velocities.
- A HRSG replaces the quench system used at Burlington. It is assumed that the HRSG would be configured similar to the back end of a CFB boiler running top to bottom where any sand knocked out of the flue gas would be collected. In CFBs this is typically only about 5-10%, with the bulk of the solids continuing with the flue gas to an ESP. If the solids prove too much for the ESP, the secondary cyclone will have to be added back in.
- Since the HRSG uses only a portion of the heat in the flue gas, a combustor air heater has been added down stream of the HRSG to recover the remaining heat.

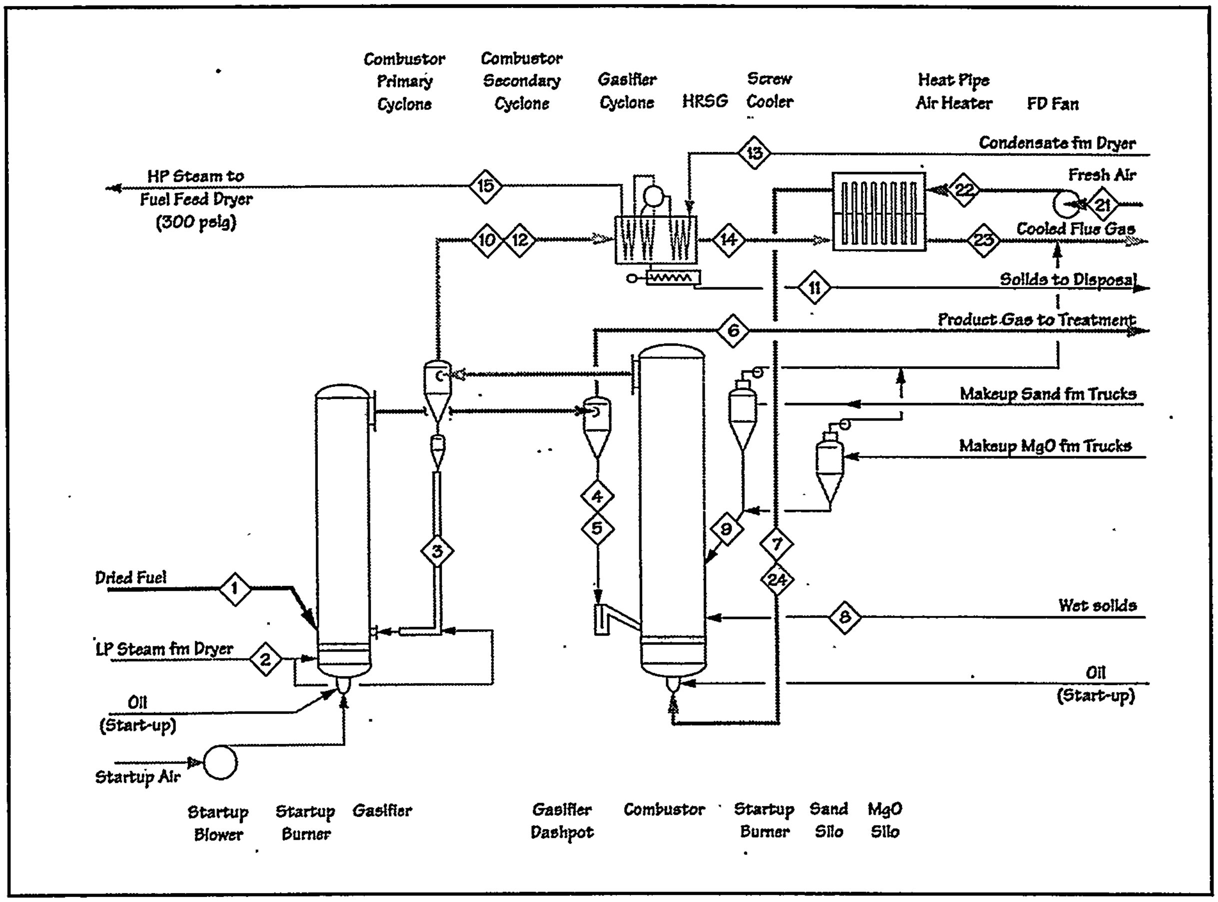

Figure 4–2: Gasification/Combustion

4.3.3 *Product Gas Clean-up System*

The product gas leaving the gasifier cyclone is sent directly to a tar cracker designed by Battelle. Battelle indicates that roughly 90% of the tar will be cracked to carbon monoxide and hydrogen. For the purpose of this work, it has been assumed that sufficient tar will be cracked to prevent problems in the scrubbing system and downstream equipment.

A product gas HRSG replaces the product gas quench system installed at Burlington to recover the heat and reduce the temperature to 300°F prior to entering the scrubber system. Steam is generated at plant conditions and added to the HP steam header.

Since it is not clear what the makeup of the gas stream leaving the tar cracker might be, the scrubbing system provided is essentially the same as the one used at Burlington. However, it is believed that in the commercial application a simpler system may be used to remove particulates (sand, ash, and carbon) and condense out the majority of the water. This would most likely be in the form of a Venturi scrubber without the column. Without the tar phase, the settling and recirculation tanks could also be simplified.

For Phase 2, the gas leaving the scrubber is cooled to 125°F as requested by SWEC to minimize the power required by the product gas compressor. Unfortunately, at 125°F the duty on the scrubber cooler is about 50 percent greater than the close temperature approach which means that the size—and hence, cost—are increased several fold. While it was agreed to use the lower temperature for this phase, any future work should determine what temperature would provide an economic optimum between the two systems. While not determined, based on discussions with SWEC it is expected that this will be in the range of 135°F to 145°F.

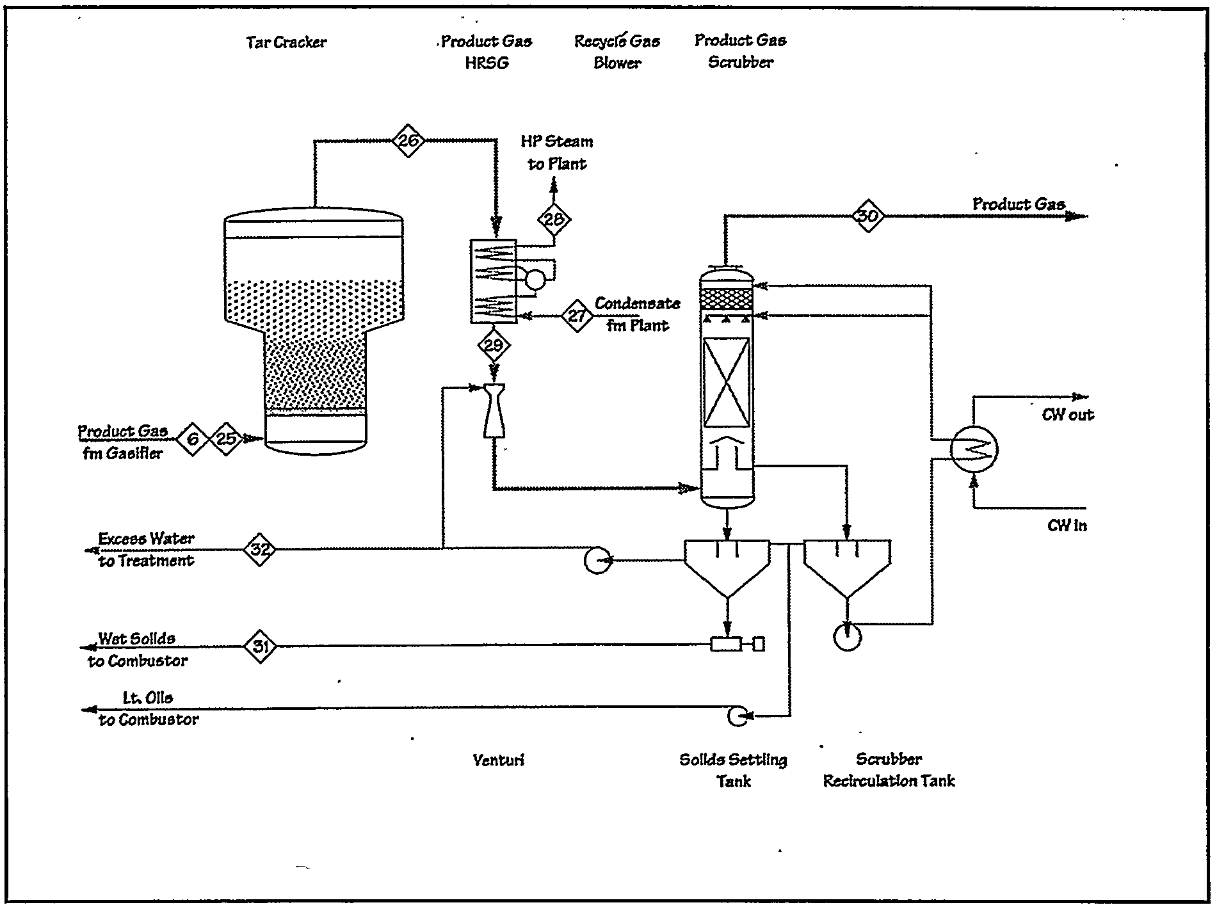

Figure 4–3: Product Gas Clean-up

Table 4-5

Major Process Flow Streams - Weyerhaeuser / LIVG Gasifier

Moisture in Feed = 20% with Controlled Steam to Gasifier

	Stream No.	1		2		3		4		5	
Stream		Biomass to Gasifier		Steam to Gasifier		Sand to Gasifier		Sand fm Gasifier		Char fm Gasifier	
		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
	Carbon	40.16%	35,754							78.91%	10,485
	Hydrogen	4.32%	3,846							4.77%	634
	Oxygen	32.16%	28,632								
	Nitrogen	0.16%	142							1.07%	142
	Sulfur										
Solids	Ash	3.20%	2,849			100.00%	936,627	100.00%	936,627	15.25%	2,026
lb/h	Moisture	20.00%	17,806								
	CaCO3										
	MgCO3										
	CaO										
	MgO										
	CaS										
	CaSO4										
	CH4										
	C2H4										
	C2H6										
	C3H8										
	CO										
Gases	H2										
lb/h	CO2										
	H2O			100.00%	35,000						
	O2										
	N2										
	H2S										
	COS										
	SO2										
	C6H6										
	Argon										
	NH3										
	NO2										
	Total Flow, lb/h	100.00%	89,029	100.00%	35,000	100.00%	936,627	100.00%	936,627	100.00%	13,287
	M/H				1,943						
	MW				18.02						
	Pressure, psia		23.45		23.45		17.70		20.45		20.45
	Temperature, °F		213.00		317.66		1,880.01		1,580.01		1,580.01
	Temperature, °C		100.56		158.70		1,026.67		860.00		860.00
	Sens. Heat, MM Btu/hr		4.80		41.03		487.00		401.00		5.88
	Lat. Heat, MM Btu/hr				(36.96)						
	LHV, Btu/lb		6,418.76								13,082.83
	HHV, Btu/lb		7,040.00								13,535.04
	LHV, MM Btu/hr		571.45								173.84
	HHV, MM Btu/hr		626.76								179.84
Total Energy,	LHV		576.25		4.06		487.00		401.00		179.72
MM Btu/h,	HHV		631.56		41.03		487.00		401.00		185.73
	HHV Btu/lb		7,093.90		1,172.20						13,977.80

6		7		8		9		10		11	
al Product Gas		Air to Combustor		Recycle Sludge		Makeup Sand		Flue Gas fm Comb		Ash fm Comb	
wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
4%	374			1.42%	18					2.00%	105
3%	32										
0%	111										
0%	1										
4%	823			65.72%	823	80.00%	1,834			89.26%	4,683
				32.86%	411						
6%	6,051										
8%	3,855										
0%	668										
0%	30,459										
6%	734										
8%	12,710	0.05%	86					20.84%	38,186		
0%	54,924	0.61%	1,047					3.89%	7,127		
		23.05%	39,562					3.73%	6,826		
		76.29%	130,940					71.54%	131,082		
0%	110,741	100.00%	171,635	100.00%	1,252	100.00%	2,293	100.00%	183,221	100.00%	5,247
29	5,326		5,971						6,156		
60	20.79		28.75						29.76		
	20.45		20.70		20.45		17.70		17.70		25
	1,580.01		456.51		125.00		100.00		1,880.01		1,880.01
	860.00		235.84		51.67		37.78		1,026.67		1,026.67
	134.23		17.85		0.02		0.03		100.15		2.45
	(58.02)		(1.11)		0.42				(7.55)		
	3,636.98				192.65						281.52
	3,888.71				192.65						281.52
	402.76				0.24						1.48
	430.64				0.24						1.48
	478.98		16.74		0.26		0.03		92.60		3.93
	564.87		17.85		0.68		0.03		100.15		3.93
	5,100.83		103.99		544.12		14.00		546.60		

Flue Gas HRSG

Stream No.		12		13		14		15	
		Flue Gas to HRSG		Cond to HRSG		Flue Gas fm HRSG		Steam fm HRSG	
Stream		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
	Carbon								
	Hydrogen								
	Oxygen								
	Nitrogen								
	Sulfur								
Solids	Ash								
lb/h	Moisture			100.00%	81,449				
	CaCO3								
	MgCO3								
	CaO								
	MgO								
	CaS								
	CaSO4								
	CH4								
	C2H4								
	C2H6								
	C3H8								
	CO								
Gases	H2								
lb/h	CO2	20.84%	38,186			20.84%	38,186		
	H2O	3.89%	7,127			3.89%	7,127	100.00%	81,449
	O2	3.73%	6,826			3.73%	6,826		
	N2	71.54%	131,082			71.54%	131,082		
	H2S								
	COS								
	SO2								
	C6H6								
	Argon								
	NH3								
	NO2								
	Total Flow, lb/h	100.00%	183,221	100.00%	81,449	100.00%	183,221	100.00%	81,449
	M/H		6,156		4,521		6,156		4,521
	MW		29.76		18.02		29.76		18.02
	Pressure, psia		16.70		343.39		16.20		323.39
	Temperature, °F		1,880.01		413.02		563.08		464.00
	Temperature, °C		1,026.67		211.68		295.04		240.00
	Sens. Heat, MM Btu/hr		100.16		29.49		30.95		98.70
	Lat. Heat, MM Btu/hr		(7.56)		(84.10)		(7.56)		(83.72)
	LHV, Btu/lb								
	HHV, Btu/lb								
	LHV, MM Btu/hr								
	HHV, MM Btu/hr								
Total Energy,	LHV		92.60		(54.61)		23.39		14.98
MM Btu/h,	HHV		100.16		29.49		30.95		98.70
	HHV Btu/lb		546.66		362.09		168.92		1,211.84

Biomass Dryer										FD Fan	
16		17		18		19		20		21	
omass Feed		Cond fm Dryer		HP Stm to LP Stm		LP Stm fm Dryer		Dried Biomass		Air to FD Fan	
wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
0%	35,754							40.16%	35,754		
0%	3,846							4.32%	3,846		
0%	28,632							32.16%	28,632		
0%	142							0.16%	142		
0%	2,849							3.20%	2,849		
0%	71,223	100.00%	81,008					20.00%	17,806		
										0.05%	86
				100.00%	441	100.00%	53,858			0.61%	1,047
										23.05%	39,562
										76.29%	130,940
0%	142,446	100.00%	81,008	100.00%	441	100.00%	53,858	100.00%	89,029	100.00%	171,635
	1,709		4,497		24		2,990				5,971
			18.02		18.02		18.02				28.75
	15.70		321.39		54.38		54.38		22.70		14.70
	60.00		413.02		317.66		317.66		213.00		60.00
	15.56		211.68		158.70		158.70		100.56		15.56
	0.09				0.51		62.68		5.93		1.15
					(0.46)		(56.43)				(1.11)
	3,614.22								6,418.76		
	4,400.00								7,040.00		
	514.83								571.45		
	626.76								626.76		
	514.92				0.05		6.25		577.39		0.04
	626.85				0.51		62.68		632.70		1.15
5	4,400.65				1,163.83		1,163.83	66.64	7,106.64		6.70

		Air Heater						Tar Cracker		
	Stream No.	22		23		24		25		26
Stream		Cold Air to Air Htr		Flue Gas fm Air Htr		Hot Air fm Air Htr		FG to Tar Crack		Prod Gas to
		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt
	Carbon							0.32%	355	
	Hydrogen							0.03%	30	
	Oxygen							0.10%	111	
	Nitrogen							0.00%	1	
	Sulfur									
Solids lb/h	Ash							0.74%	823	
	Moisture									
	CaCO3									
	MgCO3									
	CaO									
	MgO									
	CaS									
	CaSO4									
	CH4							5.46%	6,051	5.46%
	C2H4							3.48%	3,855	3.48%
	C2H6							0.60%	668	0.60%
	C3H8									
	CO							27.50%	30,459	28.75%
Gases lb/h	H2							0.66%	734	0.69%
	CO2	0.05%	86	20.84%	38,186		86	11.48%	12,710	10.64%
	H2O	0.61%	1,047	3.89%	7,127	100.00%	1,047	49.60%	54,924	49.60%
	O2	23.05%	39,562	3.73%	6,826		39,562			
	N2	76.29%	130,940	71.54%	131,082		130,940			0.00%
	H2S									
	COS									
	SO2									
	C6H6							0.02%	21	0.02%
	Argon									
	NH3									
	NO2									
	Total Flow, lb/h	100.00%	171,635	100.00%	183,221	100.00%	171,635	100.00%	110,741	99.24%
	M/H		5,971		6,156		5,971		5,326	
	MW		28.75		29.76		28.75		20.79	
	Pressure, psia		25.00		15.70		24.50		19.45	
	Temperature, °F		162.40		300.00		456.51		1,580.01	
	Temperature, °C		72.44		148.89		235.84		860.00	
	Sens. Heat, MM Btu/hr		5.42		18.52		17.85		133.72	
	Lat. Heat, MM Btu/hr		(1.11)		(7.55)		(1.11)		(58.02)	
	LHV, Btu/lb								3,632.51	
	HHV, Btu/lb								3,884.23	
	LHV, MM Btu/hr								202.76	
	HHV, MM Btu/hr								216.81	
Total Energy, MM Btu/h,	LHV		4.32		10.97		16.74		278.46	
	HHV		5.42		18.52		17.85		350.53	
	HHV Btu/lb		31.60		101.10		104.00		3,165.29	

	Fuel Gas HRSG				Fuel Gas Scrubber							
	27		28		29		30		31		32	
G	BFW to HRSG		SH Stm fm HRSG		Prod Gas to Scrubber		Fuel Gas Product		Sludge to Comb		Water to Treatment	
lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
18					0.02%	18			1.42%	18		
823					0.74%	823			65.72%	823		
	100.00%	55,769							32.86%	411		
,051					5.46%	6,051	9.92%	6,051				
,855					3.48%	3,855	6.32%	3,855				
668					0.60%	668	1.10%	668				
,836					28.75%	31,836	52.20%	31,836				
764					0.69%	764	1.25%	764				
,781					10.64%	11,781	19.32%	11,781				
,924			100.00%	55,769	49.60%	54,924	9.86%	6,014				48,499
1					0.00%	1	0.00%	1				
21					0.02%	21	0.03%	21				
,741	100.00%	55,769	100.00%	55,769	100.00%	110,741	100.00%	60,990	100.00%	1,252		48,499
,369				3,096		5,369		2,654				2,692
0.63		18.02		18.02		20.63		22.98				18.02
6.95		869.70		864.70		16.45		15.45		27.70		50.00
0.58		150.00		950.00		300.00		125.00		125.00		100.00
4.76		65.56		510.00		148.89		51.67		51.67		37.78
5.63		4.52		76.91		68.42		7.72				51.72
3.03)		(57.59)		(53.41)		(58.03)		(6.36)				(50.86)
0.17						3,574.95		6,485.09				
4.50						3,829.28		6,946.89				
2.63						395.90		395.53				
6.82						424.06		423.69				
0.23		(53.06)		23.51		406.29		396.89				0.86
2.45		4.52		76.91		492.48		431.41				51.72
1.16		81.12		1,379.13		4,447.15		7,073.46				1,066.35

4.4 Significant Findings

The LIVG technology, when applied in a commercial setting, is a highly integrated process. As such, changes made in one part of the process can have profound effects on other parts of the system that don't appear to have any obvious connection. This section summarizes some of the more significant findings observed during this study.

4.4.1 Dryer Type

Two dryer types were examined: a steam dryer and a more conventional rotary dryer that uses hot flue gas as the drying medium. Within each of these types, two alternatives were included.

The steam dryer produces process steam that can be used directly in the gasifier for fluidization. However, if uncontrolled, the amount of steam is governed by the amount of water removed from the biomass feed. Therefore, the more the wood is dried, the more steam is available for the gasifier. It happens that when the wood is dried to 35% moisture content, the amount of steam produced is very close to the amount required by the dryer. However, if the wood feed is dried beyond 35%, the amount generated by the dryer is in excess of the amount of fluidizing medium needed in the gasifier. Therefore, the use of both an uncontrolled and controlled level of steam flow from the dryer to the gasifier was examined. In the controlled case, the excess steam was condensed with the water going to the plant water treatment facility.

The rotary dryer was also examined under two scenarios. While steam is the medium of choice at the Burlington demonstration facility and was used for the steam dryer option, recycled product gas can also be used. A blower is required to recycle the gas, but this is offset by the elimination of drawing steam from the plant steam system.

An examination of performance, capital cost and environmental impact for these four options revealed that a steam dryer is still the preferred system over the rotary dryer. Between the two steam dryer options, both had almost identical overall efficiency when the usable heat in the product flue gas is accounted for. However, a controlled steam flow requires slightly smaller equipment due to the lower throughput, and, therefore, has a lower capital requirement.

Environmental considerations are also an important factor in choosing a dryer. During the drying, a number of organic compounds are generated. In the case of the steam dryer, these compounds leave with the process steam and are either sent to the gasifier (where they are either destroyed or join the product gas) or they are condensed and sent to the existing waste water treatment facility.

The rotary dryer system is different. The flue gas used in the dryer will contain fine sand particles. These will continue with the flue gas through the dryer where the flue gas will pick up other pollutants that are generated within the dryer. The pollutants expected in the gases exiting the dryer are shown below with their respective sources:

- Total Particulate Matter (PM): wood dust from the dryer with sand and ash from the combustor flue gases

- Particulate Matter less than 10 microns in aerodynamic diameter (PM-10): wood dust from the dryer with sand and ash from the combustor flue gas
- VOCs: From initial pyrolysis of wood residuals inside the dryer
- Condensable PM: From initial pyrolysis of wood residuals inside the dryer
- NOx : From the combustor flue gas

It is difficult to estimate exactly what level of contaminants will be present, but it appears certain that the level of pollutants will exceed the annual allotment. This means gas cleanup equipment will be required. In addition to the cyclones and multiclones supplied with the dryer, the gas cleaning section includes a Wet Electrostatic Precipitator for particulate control and Regenerative Thermal Oxidizer for reduction of VOCs and condensable PM. This adds both capital and operating cost to the rotary dryer option. It is likely that the plant availability will be reduced, although to what degree was not determined.

4.4.2 Plant Size

As part of the current study, Weyerhaeuser prepared data on the projected steam demand by month for the New Bern facility. The results showed that the demand ranged from an equivalent product gas production rate of about 500 M Btu/hr in the summer up to about 800 M Btu/hr in the winter. It was agreed early in this phase of the study that a single train configuration was desirable to minimize the $/Btu capital cost and that the plant size would be set by the large practical size for such a configuration. It was quickly determined that for both types of dryers, a production level of 420 M Btu/hr of product gas is the maximum level that a single dryer can provide.

The steam dryer is a Niro Size 10, which is the largest machine currently offered. The Niro dryers come in finite sizes, much as do gas turbines. Therefore, it is not possible to incrementally increase the size of the dryer; and multiple dryers would be required for gas production rates beyond the capability of the Size 10 system. A maximum gas production level of 420 M Btu/hr was determined for the Size 10 system based on information provided by Niro during Phase 1.

Although rotary dryers can be made to fit the situation, the 15 ft diameter by 96 ft long dryer suggested by M-E-C is beyond the size of any dryer currently built. They do, however, believe it is a minor extension from existing technology. The majority of dryers offered for large jobs are 13 ft in diameter to allow shop fabrication and overland transportation, although a few 14 ft machines have been built successfully. Having to go to two units for either type of dryer would significantly increase the cost.

It should be noted that the dryer isn't the only equipment that is reaching its size limit. Although it is believed the gasifier and combustor could be sized for much higher flow rates, some consideration would have to be given to using multiples of some of the supporting equipment, such as the cyclone separators. If the system had to be much larger, a double set of cyclones would likely be required to maintain high cyclone efficiency and height constraints in the gasifier system. The high-pressure feed blowers are also near the maximum sizes available for this kind of duty.

4.4.3 Feed Moisture

Several operating parameters were examined during both phases of the study; however, the impact of feed moisture on the operation and capital cost of the gasifier island for the four systems dominated the current studies. As in Phase 1, the feed moisture was varied from 20 percent moisture up to 35 percent by 5 percent increments. Much of this work was an update of performance evaluations made during Phase 1. However, the addition of a steam dryer using controlled steam to the gasifier provided a fourth option that turned out to have several benefits.

Before comparing all four systems, it is worth looking at the two steam dryer options and a couple of key variables. Figures 4-4 and 4-5 provide information on the impact of moisture content on the steam flow to the gasifier and sand circulation rates for these two systems. Figure 4-4 shows that almost twice as much steam is sent to the gasifier at the 20% feed moisture level for the uncontrolled scenario. This extra steam puts a higher heat demand on the gasifier, which means that the gasifier operates at a slightly lower temperature to make more char to provide the extra energy to heat the steam. This increase in heat requirement is reflected in Figure 4-5, which shows the relative sand circulation rates. While the sand circulation is only 10 percent lower when the feed is dried to 20% moisture, a 10 percent reduction in sand flow will translate to a 10 percent reduction in sand loss and the reduced flow is indicative of the corresponding reduction in size of the equipment in the gasifier system for the controlled steam case.

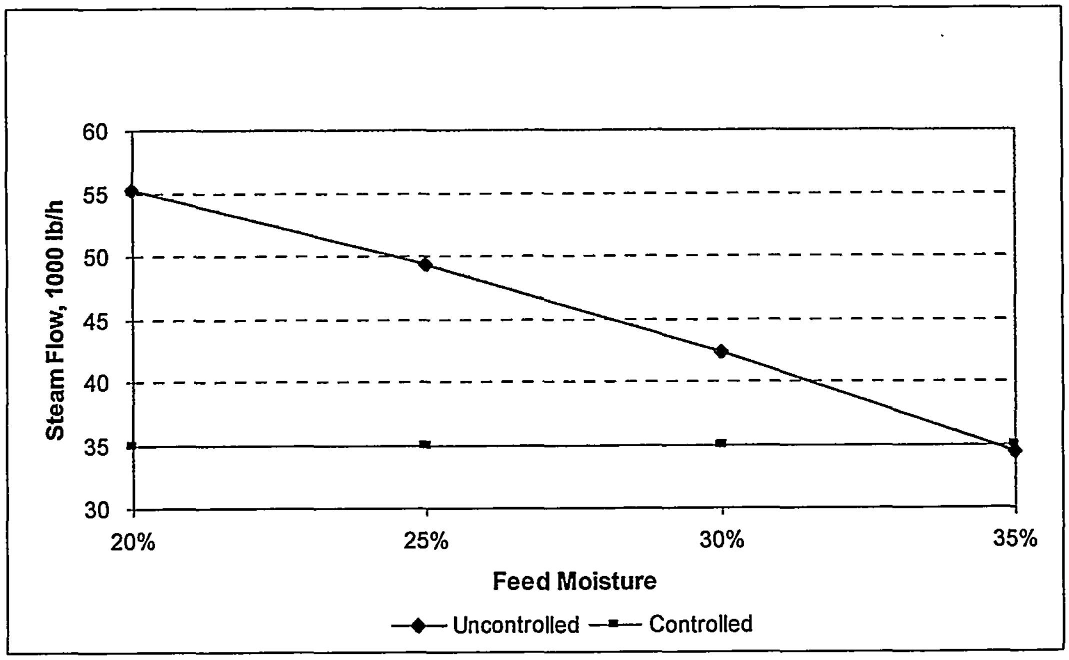

Figure 4–4: Steam to Gasifier

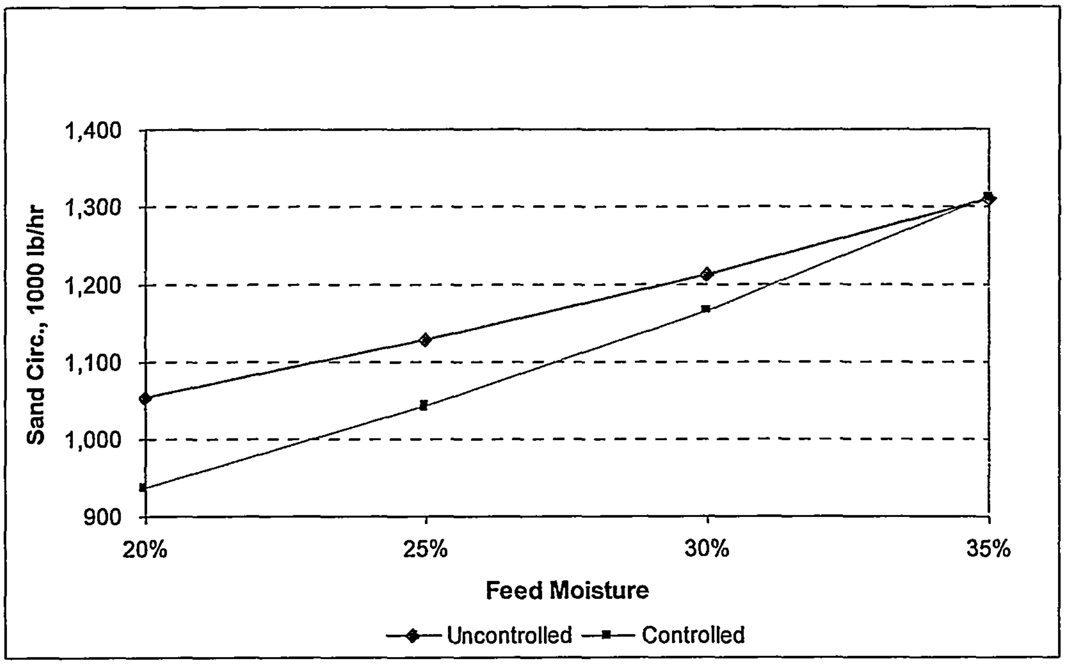

Figure 4-5: Sand Circulation

Figures 4–6 and 4–7 provide a comparison of system efficiency for all four systems evaluated. Figure 4–6 is an update of the cold gas efficiency determinations made during Phase 1, with the addition of the new steam dryer case. Cold gas efficiency is determined from the fraction of chemical heat available in the wood feed to the gasifier that is transposed to chemical heat in the product gas. It does not account for enthalpy changes or recovery. Figure 4–6 continues to show that reducing the level of moisture in the feed benefits the cold gas efficiency.

Steam is generated in the Product Gas HRSG, which is added to the plant steam production. Since the product gas will be used for steam generation it makes sense to combine these two sources to determine the true overall efficiency of the gasifier island. Figure 4–7 provides an insight into the overall energy efficiency for the four systems when this extra heat from the Product Gas HRSG is accounted for. The first thing that is noticed is that the degree of change in performance between 20% and 35% moisture is much less dramatic. It should be noted that this graph does not account for capital costs that still favor a lower feed moisture. The other thing it shows is that the two steam cases are essentially identical and that both have a considerable advantage over the two rotary dryer cases—especially rotary dryer with steam feed to the gasifier.

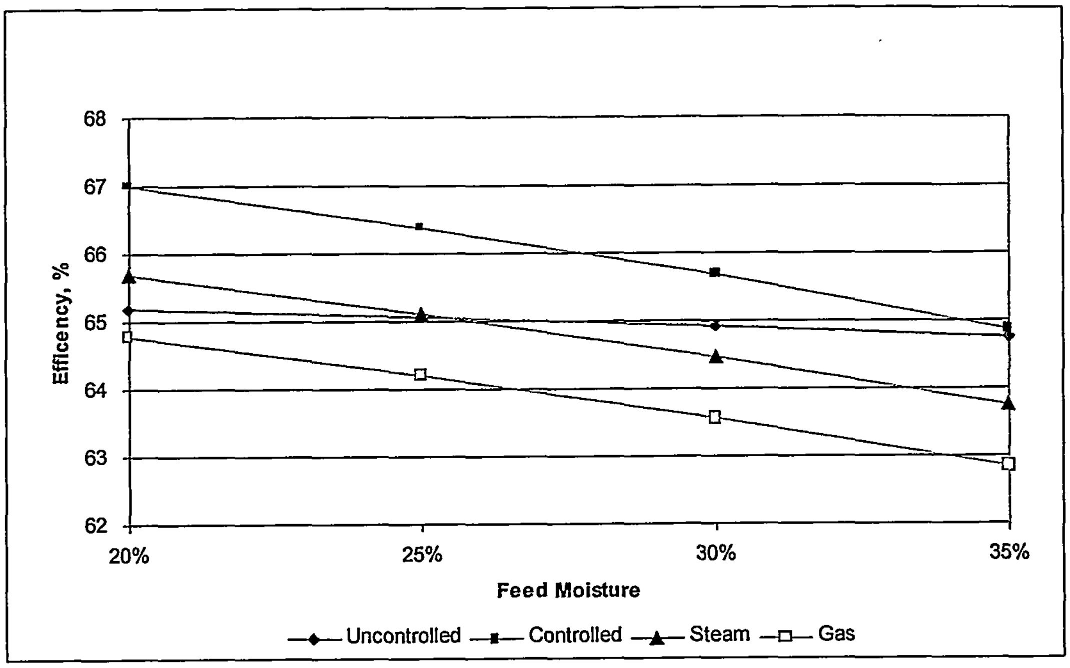

Figure 4-6: Cold Gas Efficiency

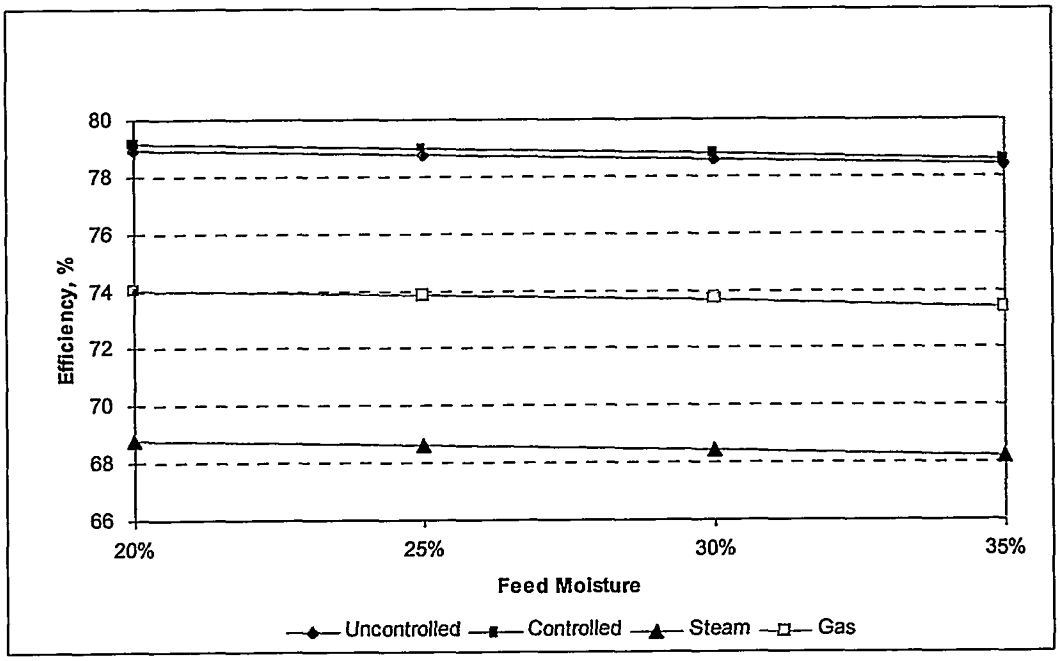

Figure 4-7: Overall Efficiency

4.5 Implications to Future Designs

It appears based on the work carried out during Phase 1 and Phase 2 that the steam dryer offers the best match for the LIVG system. The current level of evaluation is as detailed as can be made with the available data. If the LIVG process is to be considered further, the following information would have to be available:

- Process data from the Burlington Demonstration Facility including:
    - Plant operation parameters while feeding typical New Bern feed compositions
    - Confirmation of product gas composition leaving the gasifier
    - Tar properties and amounts
    - Confirmation of pyrolysis algorithms used in the process models
- Detailed data on the performance and design of the tar cracker
- Detailed information on sand attrition rates and cyclone performance, especially on the gasifier
- Information from the Burlington Demonstration Facility on preferred method and equipment for feeding fuel to the gasifier
- Information from the Burlington Demonstration Facility regarding preferred methods for controlling solids circulation in the gasifier–combustor loop
- Confirmation that the New Bern fuel composition could be handled in the Niro steam dryer
- Confirmation of the steam dryer's capabilities and operating conditions based on testing with New Bern feedstock

Based on details related to the tar cracker, a simplification of the product scrubbing system may be possible. This would reduce both capital and complexity of the current system. A new product cleanup system may also offer opportunities in improving the plant layout, and would certainly reduce the floor space required.

Future designs should provide for additional optimization between the gasifier island and the BOP. Most evident is the determination of the optimum product gas temperature leaving the gasifier island, but there may be some savings or optimization in other areas such as the fuel feed interface and the use and generation of water, steam, and power.

4.6 Areas of Significant Impact on Economics

A detailed discussion of capital costs is presented in Sections 4.7, 4.8, and 4.9. This section provides a discussion of how the capital cost and operating costs were impacted by the choices made in the equipment and operating conditions.

4.6.1 Drying Technology Integration

Despite the large cost of the dryer system, current work indicated that the actual difference in capital cost between the various dryer cases was minimal, and that most of the gains were in operation, complexity (availability), and environmental aspects. The stream dryer is a much simpler system which integrates extremely well between the dryer and the gasifier/combustor. The combustor provides all the superheated steam required by the dryer and the dryer provides the necessary fluidizing steam for the gasifier.

4.6.2 Fluidizing Gas Selection

Fluidization gas selection is considered to be an application-specific design parameter. The availability of process steam at the conditions required by the gasifier is too opportune to ignore in the current case where a steam dryer is used. However, if pilot testing of the New Bern fuel in the Niro dryer test facility proves disappointing and a rotary dryer has to be used, then it appears that recycling product gas to fluidize the gasifier offers the best option.

An examination of the overall efficiency in Figure 4-7 shows that the efficiency using recycled product gas is more than 5 percent higher. Although the actual plant size would not be significantly different when using product gas vs. steam fluidization, the fact that in the steam case the gasifier would have to draw from the plant steam system for fluidization steam means that additional oil would have to be used to make up this amount with a corresponding increase in plant operating cost.

4.6.3 Dryer Product Moisture

The effect of dryer product moisture was examined again in Phase 2. As discussed in Section 4.4.3, the results gained during the Phase 2 work supported the findings from Phase 1 that the best option is to dry the feed to a 20% moisture level. Plant performance is maximized and plant capital cost is minimized at the 20% moisture level. Plant performance is improved because less moisture has to be evaporated in the gasifier. The capital cost is reduced because the savings in the fuel handling, gasifier, and product cleanup systems outweigh the additional capital required for the dryer, which in the steam dryer case is essentially zero.

4.6.4 Capital and Operating Cost Tradeoffs

In most plants one weighs spending additional capital to obtain reductions in operating expenses. In this regard, the LIVG process is somewhat unique—at least when looking at the gasifier island as an entity unto itself. In this regard, reducing the feed moisture from 35% to 20% reduces both the capital requirements and the operating expenses since the performance is improved, which means less material has to be processed.

A tradeoff study was carried out between the two types of dryers; and as discussed in Section 4.6.1, the difference in capital was not the deciding factor. In this case, the rotary dryer, even with the flue gas cleaning facilities, appeared to be marginally less cost than the steam dryer but the operating cost was higher. However, the overriding issue was the environmental considerations and the added complexity.

4.7 Capital Cost Estimating Approach

Two cost estimates for the gasifier island were developed for Phase 2 of the study—an update of the Nth plant cost developed as part of Phase 1, and a modified version of the same estimate that reflects potential costs for a first-of-a-kind, or "next plant" scenario.

The Nth plant costs prepared for Phase 2 reflect local conditions at Weyerhaeuser's New Bern facility. Since the labor rates used for Phase 1 were also developed based on New Bern conditions, this allowed the costs for Phase 2 to be scaled directly from the Phase 1 results. There were two new pieces of equipment in the gasifier island for the new design—a live-bottom bin for the dry fuel feed to the gasifier and a steam condenser for the excess steam from the dryer. The equipment cost for the bin was developed using in-house data and verbal quotes from vendors. The condenser costs was scaled from condenser quotes obtained as part of other studies.

The "next plant" cost was developed using methodology used by EPRI. This methodology includes two elements—a reexamination of each major piece of equipment to determine if a change in the equipment size, configuration, or sparing philosophy used for the Nth plant is warranted, and the addition of a process contingency.

Contingency is applied to an estimate to denote the level of confidence in the values ascribed to the finite elements of the particular estimate. The amount of contingency is the estimator's judgment of the cost applied to the complete estimate to yield the most probable total cost or the cost at some specified probability of underrun/overrun. The addition of the contingency value does not improve the overall accuracy of the estimate, but rather reduces the probability of overrun to the desired level. The contingency applied in this study is based on achieving approximately a 50 percent probability of overrun.

Upon further review of previous Bechtel estimates on similar technologies, it was determined that the project contingency for the Nth plant could be reduced from 20% (used in Phase 1) down to 15% and still meet this goal. For the "next plant", however, a value of 25% was considered more in line with past experience.

Process contingency provides an allowance based on process uncertainties or lack of commercial demonstration, i.e., risk. It allows for additional expenditures typically experienced during initial operation, which can include the modification or replacement of equipment not meeting design expectations. An estimate of process contingency is accomplished by examining every subsystem or piece of major equipment in the estimate and assigning a contingency that reflects the level of confidence in the design and operating knowledge of that system. The composite is added as a lump sum to the Total Field Cost along with the Engineering & Head Office and Project Contingency to give the Total Plant Cost. A weighted process contingency of about 12% of the Total Field Cost has been estimated and added for the "next plant" scenario. Process contingency is not included for the Nth plant estimate since it is assumed the design has been proven and startup will be routine.

4.8 Detailed Capital Costs

A comparison of the revised estimate for Phase 2 and the original estimate for Phase 1 by system is presented in Table 4-6. An examination of the two total columns provides the following information:

- The Total Plant Cost remained essentially the same.
- The combination of higher plant capacity and change of design basis from uncontrolled to controlled steam to the gasifier affected the three main process areas differently.
  - The capital requirements for the Fuel Handling area increased by about 7%. This increase can be attributed to three changes from the original plant: the dry fuel feed bin has been upgraded from a simple cone to a live bottom storage; the conveyor system entering and leaving the bin has been changed to reflect the

change in bin type; and a process steam condenser has been added to reflect the change in operation to a controlled steam basis.

  - Despite the 5% increase in plant capacity, the cost of the gasification island decreased by a little over 1% due to the reduced steam injection into the gasifier under the controlled steam flow design.
  - Although the tar cracker and scrubber also experienced a slight decrease in cost, cooling the product gas to 125°F required a much larger cooler and an increase in the size of the recirculation tanks under the scrubber. The result is a net increase of almost 5%.

The miscellaneous elements, including bulks, were adjusted to reflect to the changes in the major equipment and subsystems.

A capital cost estimate for the first-of-a-kind or "next plant" is presented in Table 4-7. This table also includes in the attached notes, a delineation of the philosophy used in developing the process contingency or equipment modifications made for each line item. Some of the more significant additions include:

- Per Niro's suggestion, an extra $1 million has been added to the dryer cost for the first unit.
- A round-robin conveying system has been added to the fuel handling system to reduce the possibility of feed interruptions to the gasifier. The round-robin system allowed the use of a smaller feed bin since it is maintained full.
- The gasifier is provided with two fuel feed systems, also to increase availability.
- A 20% process contingency has been added for both the gasifier and combustor in case data from Burlington indicates more residence time is required.
- Solids removal from the gas streams is critical so an allowance for secondary cyclones has been added for both the gasifier and combustor systems.
- A 50% process contingency has been allowed for all ceramic-lined pipe to reflect the limited data available regarding potential erosion issues.
- A 50% process contingency has also been provided for the tar cracker due to the limited data available.

The overall process contingency is slightly over 12%. When compared to the Nth plant in Table 4-6, the results presented in Table 4-7 indicate the Total Plant Cost for the "next plant" will be 25-30% higher.

On the surface, these figures appear low based on experience with other projects that show process contingencies in the range of 15-20% and a Total Capital Cost that is 30-40% higher for first-of-a-kind plants. However, it should be noted (as it was during Phase 1) that over half of the equipment cost is tied up in four items—the dryer, the two HRSGs, and the air preheater. Although some process contingency has been allowed for each of these items, the level of confidence in these commercially demonstrated systems, is higher than those systems typically associated with demonstration projects, such as the gasifier, combustor and tar cracker systems. This heavy weighting of capital in more conventional equipment has lessened the penalty expected with a normal first-of-a-kind project.

4.9 Capital Cost Result Summary

The Total Capital Cost of $36 million appears to be in line with previous estimates made by Princeton's Dr. Eric Larson, NREL, and others.

One of the original goals set forth by Weyerhaeuser was for Nexant to determine whether significant savings in capital could be gained by improving the design or operation of the gasifier island. Under these guidelines, Nexant has attempted to optimize the design based on the available process data by incorporating a steam dryer (which appears to be uniquely suited to the LIVG process) and by simplifying the equipment where prudent. Nexant has also spent some time studying the effect various operating conditions have on plant performance and the size of the equipment.

As a result of these studies, it is believed that the current combination of using a steam dryer with controlled steam to the gasifier offers the best option for the gasifier island. This is reflected, in part, by the lack of increase in the capital cost despite the 5% increase in throughput and the addition of some new equipment.

However, none of these improvements has yielded the significant improvement in the capital costs hoped for at the onset of the study. This is largely due to the phenomenon discussed in Section 4.8 that a large percentage of the equipment cost is tied up in items that are less sensitive to changes in gasifier operation. Doubling the capacity of the gasifier—if that were possible—would only offer savings of a few hundred thousand dollars at most, or less than 1% of the total capital. Conversely, should the current data on the gasifier prove to be optimistic, increasing the size of the gasifier should not have a significant penalty on the Total Plant Cost. The impact on operating economics, however, could be significant.

During Phase 1, several alternate configurations were considered for constructing the gasifier/combustor portion of the LIVG system, including:

- Stacking the major vessels
- Incorporating the cyclones within the major vessels as done for some systems in the petrochemical industry
- Bottom supporting the major vessels instead of top hanging as done at Burlington

Although a detailed examination was not made, a preliminary evaluation indicated that none of these alternatives appeared to offer any advantage over the current configuration.

	Equipment	Bulks	Labor	SC	Total	Phase 1 Total
Fuel Handling						
Dryer Feed Screw	45	-	2	-	47	46
Steam Dryer Assembly	-	-	-	6,000	6,000	6,000
Process Steam Condenser	141	-	3	-	144	
Transfer Conveyor	815	-	36	-	851	701
Dried Wood Chip Storage	480	-	81	-	561	457
Feed Bin	214	-	19	-	233	21
Rotary Air Lock	321	-	8	-	329	354
Water Cooled Feed Screw	51	-	3	-	54	53
Subtotal					8,219	7,631
Gasifier/Combustor						
Gasifier	162	-	8	195	365	405
Gasifier Hot Gas Line	58	-	8	66	132	149
Gasifier Cyclone	136	-	6	242	384	425
Gasifier Dashpot	70	-	1	98	169	168
Combustor L Valve	14	-	5	55	74	75
Air Blower	530	-	56	-	586	600
Combustor	212	-	11	237	460	467
Combustor Hot Gas Lines	103	-	13	78	194	198
Combustor Primary Cyclone	167	-	7	410	584	592
Combustor J Valve	22	-	7	86	115	118
Combustor Secondary Cyclone	-	-	-	-	-	0
Sand Cooler	10	-	1	-	11	16
Sand Silos	54	-	3	-	57	53
Magnesium Oxide Storage	7	-	-	-	7	21
Expansion Joints	1,067	-	30	-	1,097	1,111
Misc. Ceramic Pipe	146	-	24	601	771	780
Flue Gas HRSG	2,062	-	14	-	2,076	1,964
Heat Pipe Air Heater	659	-	25	-	684	748
Subtotal					7,766	7,889
Product Gas Cleanup						
Tar Cracker	118	-	6	554	678	755
Product Gas HRSG	1,702	-	11	-	1,713	1,742
Venturi	19	-	4	-	23	24
Scrubber	193	-	13.	-	206	186
Scrubber Cooler	196	-	5	-	201	34
Skimmer Settling Tank	71	-	9	-	80	71
Scrubber Recirculation Tank	64	-	3	-	67	27
Flare	32	-	2	-	34	37
Subtotal					3,002	2,874
Misc						
Civil/Structural	-	1,151	556	-	1,707	1,680
Piping	-	1,071	691	-	1,762	1,645
Electrical	-	233	78	-	311	293
Insulation	-	-	-	158	158	150
I&C	-	1,392	70	-	1,462	1,365
Subtotal					5,400	5,133
Total Direct Cost					24,387	23,527
Indirects					1,728	1,613
Total Field Cost					26,115	25,140
Engr. & Head Office					5,484	5,280
Contingency @15%					4,740	6,145
Total plant cost					36,339	36,565
Piping					319	304
Total plant cost including catalyst					36,339	36,869

Table 4–6: Total Plant Cost for an Nth Plant (New Bern) by System (January 1999 k$)

	Equipment		Labor	SC	Total
Fuel Handling					
Dryer Feed Screw	45	-	2	-	47
Steam Dryer Assembly	-	-	-	7,000	7,000 [a]
Process Steam Condenser	141	-	3	-	144
Transfer Conveyors	1,226	-	54	-	1,280 [b]
Dried Wood Chip Storage	480	-	81	-	561
Feed Bin	127	-	11	-	138 [c]
Rotary Air Lock	432	-	11	-	443 [d]
Water Cooled Feed Screw	90	-	5	-	95 [d]
Subtotal					9,708
Gasifier/Combustor					
Gasifier	162	-	8	195	365 [e]
Gasifier Hot Gas Line	58	-	8	66	132 [f]
Gasifier Cyclone	136	-	6	242	384 [g]
Gasifier Dashpot	70	-	1	98	169 [f]
Combustor L Valve	14	-	5	55	74 [f]
Air Blower	530	-	56	0	586
Combustor	212	-	11	237	460 [e]
Combustor Hot Gas Lines	103	-	13	78	194 [f]
Combustor Primary Cyclone	167	-	7	410	584 [h]
Combustor J Valve	22	-	7	86	115 [f]
Combustor Secondary Cyclone	-	-	-	-	- [i]
Sand Cooler	-	-	-	-	- [j]
Sand Silos	88	-	4	-	92 [k]
Magnesium Oxide Storage	11	-	1	-	12 [l]
Expansion Joints	1,067	-	30	-	1,097
Misc. Ceramic Pipe	146	-	24	601	771 [m]
Flue Gas HRSG	2,062	-	14	-	2,076 [n]
Heat Pipe Air Heater	659	-	25	-	684 [n]
Subtotal					7,795
Product Gas Cleanup					
Tar Cracker	118	-	6	554	678 [o]
Product Gas HRSG	1,702	-	11	-	1,713 [p]
Venturi	19	-	4	-	23 [f]
Scrubber	193	-	13	-	206 [q]
Scrubber Cooler	196	-	5	-	201 [f]
Skimmer Settling Tank	71	-	9	-	80 [q]
Scrubber Recirculation Tank	64	-	3	-	67 [f]
Flare	32	-	2	-	34
Subtotal					3,002
Misc					
Civil/Structural	-	1,284	620	-	1,904 [r]
Piping	-	1,192	769	-	1,961
Electrical	-	255	85	-	340
Insulation	-	-	-	176	176
I&C	-	1,576	118	-	1,694 [s]
Subtotal					6,075
Total Direct Cost					26,580
Indirects					1,989
Total Field Cost					28,569
Engr. & Head Office					5,999
Contingency @25%					8,642
Process Contingency					3,550
Total plant cost					46,760
Electrical					319
Total plant cost including catalyst					47,079

Table 4–7: Total Plant Cost for First-of-a-Kind Plant (New Bern) (1999 k$)

Notes for Table 4-7

	Process Contingency	Comments
a)	10%	Niro suggested a cost of $700M for the first plant, in addition, some allowance is given for likely redesign or specification of the flash vessel
b)	0%	Provided for round-robin conveying system
c)	0%	Bin for first-of-a-kind is 1/3 the size since we've added the round-robin conveyor system
d)	0%	Two feed systems provided
e)	205	Should data from Burlington indicate additional residence time is required
f)	50%	Process Contingency
g)	100%	In case a secondary cyclone is required to further reduce solids to the tar cracker and scrubber
h)	100%	No process contingency is allowed but later more detailed analysis may show a second cyclone to be more cost effective than the enhancements that might be necessary to handle the solids loading in the ESP
i)	0%	Not used, but see note under Primary Cyclone
j)	0%	Included as part of OBP
k)	0%	Doubled the size of sand silo in the event of higher than predicted sand usage
l)	0%	Doubled the size of MgO silo in the event of higher than predicted MgO usage
m)	50%	Process Contingency – This assumes sufficient data is obtained from Burlington to allow for proper design of critical lines, including specification of refractory
n)	10%	To allow for potential rework related either to erosion in unexpected places and/or modifications to solids removal system
o)	50%	Untested design, so final design may be larger or more complex than used here
p)	15%	To allow for potential rework related either to erosion in unexpected places and/or modifications to solids removal system
q)	10%	Process Contingency – This assumes sufficient data is obtained from Burlington to allow for proper design
r)		Additional allowance put in to account for higher structure in case gasifier or combustor become taller
s)		Provided for additional instrumentation plus 50% additional labor for on-site modifications during startup