

## **Final Report**

# **Technical, Environmental and Economic Feasibility of Bio-Oil in New Hampshire's North Country**

partially funded by the New Hampshire Industrial Research Center (NHIRC)

NHIRC Project Manager: Mr. Henry Mullaney, Executive Director

UNH Project Numbers: 14B316 UDKEIF or ABAN-URI-BO43

UNH Project Director: Dr. Ihab H. Farag  
Hamel Professor of Innovation and Technology  
Chemical Engineering Dept.  
University of New Hampshire  
Durham, NH 03824-3591  
Phone: 603-862-2313, Fax: 603-862-3747  
e-mail: Ihab.Farag@unh.edu  
www.unh.edu/p2/ihf

Project Engineers/Bio-Oil Team Members:

Caitlin E. LaClaire & Christopher J. Barrett  
Chemical Engineering Department  
Kingsbury Hall  
University of New Hampshire  
Durham, NH 03824-3591  
Phone: 603-862-4395  
e-mail: claclair@cisunix.unh.edu  
cbarrett@cisunix.unh.edu

Project Period: December 15, 2001 to August 31, 2002

# Technical, Environmental and Economic Feasibility of Bio-Oil in New Hampshire's North Country

## Table of Contents

Abstract .....	4
Acknowledgment .....	4
Executive Summary.....	5
1. Project Motivation.....	8
2. Goals, Objectives, Approach, Scope.....	9
2.1 Goals/Objectives.....	9
2.2 Approach/Scope.....	9
(Phase 1 and Phase 2)	
<b>Phase One</b>	
3. Social Analysis.....	11
3.1 Social Considerations.....	11
3.2 UNH Bio-Oil Team.....	12
Formation	
4. Technical Analysis.....	14
4.1 Current Biofuels.....	14
4.2 Fast Pyrolysis Technologies.....	14
4.3 Fast Pyrolysis Companies: Ensyn vs. DynaMotive.....	16
4.4 DynaMotive Technology For Northern NH.....	17
4.5 BioTherm Process.....	18
4.5.1 Process in General	
4.5.2 Feedstock Preparation, Storage, and Feed System	
4.5.3 Pyrolysis Reactor	
4.5.4 Cyclone	
4.5.5 Bio-Oil Quench and Storage System	
4.5.6 Electrostatic Precipitator	
4.6 Bio-Oil Chemical Composition.....	25
4.7 Bio-Oil Physical Characteristics.....	26
4.8 Improvements in Bio-Oil.....	27
4.9 Bio-Oil in Perspective: Comparison to Petroleum Fuel....	29
4.10 Volume and Yield of Bio-Oil from Various Size Plants...	31

5. Environmental and Health Analysis.....	32
5.1 Toxicity and Health Hazards.....	32
5.2 Aging, Storage, and Corrosiveness.....	32
5.3 Biodegradability.....	33
5.4 Emissions and Wastes Associated with Bio-Oil Production and Combustion.....	33
6. Economic Analysis.....	35
6.1 Cole Hill, DynaMotive, & UNH Economic Analyses.....	35
6.2 Bio-Oil For Residential Home Heating.....	52
<b>Phase Two</b>	
7. End-Use markets.....	55
7.1 Power Generation.....	55
7.2 Residential and Industrial Heating.....	57
7.3 Green Substitute in Asphalt Paving.....	57
7.4 Coal Dust Suppression.....	58
7.5 Vehicular Application.....	58
7.6 Green Chemicals.....	58
7.7 Char Market.....	59
7.8 Community Outreach.....	59
8. Conclusions, Recommendations, & Future Steps.....	60
9. References.....	62
Note: the referencing system will be: ( <sup>Reference #</sup> Author or Company, page)	
10. Appendices.....	65
A1. Sample Calculations.....	65
A2. MSDS DynaMotive.....	66
A3. No. 6 Oil MSDS.....	70
A4. No. 2 Oil MSDS.....	78
A5. Co-Firing Lab Results.....	83
A6. Optical Activity.....	85
A7. FAQ.....	86

# Technical, Environmental and Economic Feasibility of Bio-Oil in New Hampshire's North Country

Ihab H. Farag, Caitlin E. LaClair & Christopher J. Barrett, Chemical Engineering Dept, University of New Hampshire (UNH), Durham, NH 03824-3591, USA, phone: +1-603 862 2313, fax: +1-603 862 3747, e\_ mail: [Ihab.Farag@unh.edu](mailto:Ihab.Farag@unh.edu)

## **Abstract**

The University of New Hampshire has been researching the technical, environmental and economic feasibility of a Bio-Oil facility in New Hampshire and exploring end-use markets for the product. Interest in this process for New Hampshire stems from the available low-quality wood chips, labor, and need for an innovative technology using low-grade wood chips or small diameter wood that will help maintain healthy forests.

Bio-Oil is a liquid produced by fast pyrolysis (or thermolysis) of low-grade wood. Although there are several fast pyrolysis processes, two, fluidized bed and circulating fluid beds are the most developed and well understood. The social advantages of a Bio-Oil facility are that it would help the economy by creating jobs and another market for low-grade wood chips in New Hampshire. Environmentally, creating Bio-Oil generates little wastes, and when used as a fuel, it produces less emissions than petroleum fuels. Some of the obstacles to Bio-Oil are that it is highly acidic, immiscible with petroleum fuels, and difficult to store without aging.

The Bio-Oil production economics are affected by the low-grade wood chips cost, which we took to be \$18/ton, and by the plant size. Our study show that the approximate cost for Bio-Oil from a 440 US ton wet wood/day is \$0.89/gal or \$0.16/Mbtu (million Btu), while that of a 110 US ton wet wood/day plant is \$1.21/gal or \$0.216/Mbtu. These production costs include a payment plan for capital cost. Economically this makes Bio-Oil about twice as expensive as number two fuel oil when it comes to producing heat or electricity. This is because Bio-Oil has about half the heating value of number two fuel oil. This had led UNH to look more into non-energy uses for Bio-Oil, which all require further validation or development.

The technology to process low-grade wood chips and produce Bio-Oil is not new; however, the Bio-Oil industry is in its infancy. There are many challenges to commercialization, e.g., scale-up, quality of product, the specification of Bio-Oil standards, and cost reduction. As such, more thorough environmental, economic, end-use market, and competitive risk analyses are necessary for New Hampshire.

## **Acknowledgment**

This work was partially funded by a grant from the New Hampshire Industrial Research Center (NHIRC), which the authors would like to acknowledge. For more details, please visit our website: <http://www.unh.edu/p2/biooil/>.

# Technical, Environmental and Economic Feasibility of Bio-Oil in New Hampshire's North Country

Ihab H. Farag, Caitlin E. LaClair & Christopher J. Barrett, Chemical Engineering Dept, University of New Hampshire (UNH), Durham, NH 03824-3591, USA, phone: +1-603 862 2313, fax: +1-603 862 3747, e\_ mail: [Ihab.Farag@unh.edu](mailto:Ihab.Farag@unh.edu)

## Executive Summary

The UNH Bio-Oil team has partnered with several organizations to research the technology to convert low-grade wood to Bio-Oil and explore the feasibility of a Bio-Oil facility in New Hampshire. This technology has been sought as a result of the declining end-use markets for low-grade wood chips, in New Hampshire, and particularly in the North Country. With three of the eight wood-fired power plants already decommissioned, and five more that will be closed by 2006-2008, a strong market for New Hampshire's low-grade wood chips is critical for New Hampshire. Labor and wood are available in New Hampshire, as well as a need for a technology that will boost NH's economy. In the first phase of the project, beginning in December 2001, the UNH Bio-Oil team researched the economic, environmental, and technical feasibility of a facility in NH. Phase two, starting in May 2002, was the exploration of end-use markets for Bio-Oil. The UNH team has made several presentations to educate the public about fast pyrolysis and Bio-Oil throughout the duration of the project.

Bio-Oil is created using a fast pyrolysis process, which involves heating small biomass particles without oxygen to temperatures ranging from 400-800°C- depending on which type of fast pyrolysis is used. Resulting from this process are char and gases. The char is collected and can be sold or combusted to contribute heat to the process. Some of the gases can be condensed to Bio-Oil, and the remaining, non-condensable gases, can be used for process heat. Bio-Oil is an acidic, viscous, water-soluble liquid that has a dark brown color and a pungent smoky odor. A common application for Bio-Oil is as a fuel. Another is to extract chemicals for food flavoring. There are four companies involved in the production of Bio-Oil using fast pyrolysis; they include DynaMotive, Ensyn, Pyrovac International, and Renewable Oil International. The two leading fast pyrolysis companies that use Bio-Oil for these applications are DynaMotive and Ensyn.

Ensyn's focus is on using the chemicals from Bio-Oil for food flavoring. However, the company did try co-firing Bio-Oil with coal at Manitowoc Public Utilities in Red Arrow, Minnesota. DynaMotive, on the other hand, puts an emphasis on using Bio-Oil as a green fuel, generating power from specialized turbines and using it as a petroleum replacement in boilers and kilns. Two other companies producing Bio-Oil include Pyrovac International and ROI. Of the four companies, all to some degree are based in Canada, Ensyn is the only one that has commercial applications.

As the UNH Bio-Oil team began researching fast pyrolysis, a review of Ensyn and DynaMotive’s technology was in progress. DynaMotive had the technology that more appropriately fit New Hampshire’s needs. Thus, while this report covers Bio-Oil and fast pyrolysis in general, the focus is on DynaMotive’s process and product, with the economic analysis performed on a facility utilizing the DynaMotive technology.

The following is a table of the properties of DynaMotive’s Bio-Oil from a feedstock most similar to the low-grade wood chips in New Hampshire.

**Table 0.1: DynaMotive Bio-Oil Properties** (<sup>10</sup> DynaMotive, 3)

<b>Bio-Oil Properties</b>	<b>Pine/Spruce 53% wood + 47% bark</b>
PH	2.4
Water Content wt%	23.4
Lignin Content wt%	24.9
Solids Content wt%	<0.10
Ash Content wt%	<0.02
Density	
kg/L (SI units)	1.19
lb <sub>m</sub> /ft <sup>3</sup> (English units)	74
Calorific Value:	
MJ/kg (SI units)	16.4
Btu/lb <sub>m</sub> (English units)	7051
Kinematic Viscosity cSt	
@ 20°C	78
@ 80°C	4.4

From some of the properties shown, it becomes apparent that Bio-Oil has many challenges. The obstacles result from Bio-Oil’s properties and lack of a well-established industry for the product. Bio-Oil’s acidity, immiscibility in petroleum fuels, and increase of viscosity over time leads to obstacles in developing cost effective systems, or minimal changes to existing systems when using Bio-Oil as a fuel. In this application, Bio-Oil has about half the heating value of number two and produces half the NO<sub>x</sub>, no SO<sub>x</sub>, and is considered CO<sub>2</sub> neutral. As a fuel, Bio-Oil’s uses include power generation, replacement for petroleum fuels in boilers and kilns. Future fuel applications may include home heating or an additive for gasoline and diesel with the use of emulsifying agents.

Another barrier to the development of the Bio-Oil industry in New Hampshire is the production cost of Bio-Oil. The study found that Bio-Oil should cost approximately \$0.89/gal to \$1.21/gal to produce with a payment plan for capital cost included. The range in cost is due to the plant size ranging from a 110 wet wood US ton/day to a 440 wet wood US ton/day facility. Economically this makes Bio-Oil about twice as expensive as number two oil for producing heat or electricity since it has about half of the energy content of fossil fuels. These numbers were for a woodchip cost of \$18/ton. Should a feedstock be available at half that price or less then Bio-Oil, much like the wood-fired plants, becomes more competitive for these purposes. This had led UNH to look more into non-energy uses for Bio-Oil, which all require further validation or development.

Although power generation was explored by UNH, the objective for Phase Two of the project, the end-use market study, was to focus on non-energy producing end-use markets. Some of these markets include a green substitute for use in asphalt emulsions and dust suppressor and Btu enhancer for coal piles. Tests must be done to determine Bio-Oil's ability to adhere to aggregate in order to find if further study should be pursued. At this time, a dust suppressor is not a feasible role for Bio-Oil, due to its solubility in water and the hazards that may result from leaching of the Bio-Oil into the ground water. Optical activity, found by UNH College of Engineering and Physical Science Dean, Dr. Arthur Greenberg, has indicated that solvents, pharmaceuticals, or food products may be obtained from Bio-Oil. Other applications identified by fast pyrolysis companies include activated carbon from the char, fertilizers, resins, and other valuable chemicals.

With more resources, UNH would be able to continue to explore the possibility of using Bio-Oil for asphalt paving and the potential of optically active green chemicals. Many possible applications for Bio-Oil exist, and further research would help identify the most feasible market for New Hampshire.

There are many possible applications for Bio-Oil and further research will be needed to find the most profitable market for NH that is environmentally acceptable. Some of the specific areas that the UNH Bio-Oil team has identified include:

- Environmental testing:
  - Biodegradation rates and spill management
  - Exploration of fate of toxics such as lead and mercury
- Competitive risk analysis
- End-Use market analysis
- Possibility of a Government Incentive Program
- Re-evaluation of Bio-Oil companies
  - Which best fits NH.(DynaMotive, Ensyn, ROI, Pyrovac Int.)?
- Improvements in economic analysis
  - Grinding Cost
  - Energy Use
    - Natural gas and Electricity

Fast pyrolysis has proven itself to be a technically viable technology for the 0 to 45 ton per day plant size range. Scaling up of fluidized beds has been historically difficult, but DynaMotive and Ensyn have made claims and guarantees that they can do so. In regard to environmental feasibility, fast pyrolysis is promising in regard to NO<sub>x</sub>, SO<sub>x</sub>, and CO<sub>2</sub>, but not all the tests in regard to mercury, lead, and dioxin or the effects of a spill have been done. Economically it is too early to tell if Bio-Oil is feasible due to the need for more research in regard to all the possible end-use markets that Bio-Oil can be used for and the possible feedstocks available in the state.

## **1.0 Introduction: Project Motivation**

The University of New Hampshire College of Engineering and Physical Sciences (UNH-CEPS) is studying the feasibility of introducing Bio-Oil, a liquid derived from the pyrolysis of low-grade wood. UNH is collaborating with the Business Enterprise Development Council (BEDCO), Public Service of New Hampshire (PSNH), the New Hampshire Industrial Research Center (NH IRC), New Hampshire Small Business Development Center (SBDC), N.H. Department of Environmental Services (NH DES), N.H. Department of Transportation (NH DOT), N.H. Department of Resources and Economic Development (DRED), and other state and federal agencies.

The study was motivated by the declining consumption of the low-grade wood market in northern NH. The decrease in usage was caused by the closing(s) of the Berlin/Gorham pulp and paper mills along with the future closing of the five remaining wood-fired power plants in NH. A 2002 DRED report has shown the low-grade wood market to be a 'critical cornerstone' to NH's third largest manufacturing economy, the forest industry (<sup>3</sup>DRED, pg8). Alternative consumptions for low-grade wood are being sought out and early estimates have shown Bio-Oil to hold promise.

This comprehensive report will examine the economic, environmental, and social viability of implementing a Bio-Oil facility in northern NH. It will review the fast pyrolysis technologies and companies that produce Bio-Oil, the background history of Bio-Oil and the northern NH low-grade wood market, the physical properties of Bio-Oil, and end-use markets for Bio-Oil. The study should act as a guide for future New Hampshire Bio-Oil development. This report is envisioned to be dynamic, with more material added as research progresses.

## **2.0 Goals/Objectives/Approach/Scope**

### **2.1 Goals/Objectives**

The goal of the UNH Bio-Oil Project is to support the revitalization of the New Hampshire North Country by researching a new technology that might boost the economy in this region. The project has been carried out in several phases. The objective of phase one, which took place from December 2001 to May 2002, was to do a technical, environmental, and economic feasibility study of a Bio-Oil facility and develop an economic model for a Bio-Oil plant in Northern New Hampshire. The objective of phase two, from May 2002 to the present, is to research possible end-uses of Bio-Oil. Collaboration with involved organizations has been fundamental in developing a plan of action for each phase of the project.

### **2.2 Approach/Scope (Phase 1 & Phase 2)**

#### **2.2.1 Phase 1.**

The scope of phase one was to gather technical, environmental, and economic information pertaining to Bio-Oil in general. For each of these three topics, the following procedures were taken:

##### *Technical Analysis*

Patents on the production of bio-fuels produced by two companies, DynaMotive and Ensyn, were collected and reviewed. The technical papers published by the companies as well as other sources on fast pyrolysis and Bio-Oil production were obtained. Technical papers from DynaMotive (references <sup>8,9,10</sup>) and Ensyn (reference <sup>17</sup>) can be found on their websites (references <sup>1 & 2</sup>). It should be noted that Bio-Oil is the generic name for the fuel. Each company producing the product calls it by a slightly different name, such as Bio-Oil or bio-oil (<sup>12</sup>Brady, 23). In this report, it will be consistently referred to as Bio-Oil.

##### *Environmental Analysis*

The characteristics and properties of general Bio-Oil, and more specifically, DynaMotive's Bio-Oil were reviewed in as much detail as possible. Since one of the primary uses for Bio-Oil is as a fuel in power generation, most environmental information was found in this capacity. To this end, one of the UNH Bio-Oil Team's partners conducted tests on Bio-Oil to explore the possibility of co-firing Bio-Oil with oil. The data obtained from the lab tests can be found in Appendix A5 and is discussed in section 5.0. DynaMotive and CANMET performed emission testing during the summer of 2002; UNH is still trying to obtain the results of these tests. Once received it will be possible to compare the environmental impacts of burning Bio-Oil to wood and fossil fuels.

##### *Economic Analysis*

Using data from DynaMotive, previous economic analyses, as well as figures that pertain to New Hampshire, an analysis of the cost to produce Bio-Oil from various size

plants was determined for NH. Assumptions and data used to complete the analysis can be found in the economic analysis section (section 6) of this report.

### **2.2.2 Phase 2.**

The scope of the second phase of the project is to explore possible end-use markets and work to educate the public about Bio-Oil. The highly competitive nature of the electric market in NH led the UNH Bio-Oil team to research other non-power generating avenues. Some of the most recent activities on which we have been focusing include:

#### *Green Substitution in Asphalt Paving*

Resin-like qualities of stickiness were displayed in the UNH Bio-Oil Team's partner's tests when the heavier layer of Bio-Oil was separated out and heated. These qualities resemble those of asphalt binders, thus the possibility of using Bio-Oil as a substitute for petroleum products in asphalt emulsions is being explored. Because of the volatile organic compounds released by some petroleum products, the process has been modified, with a trade-off for the quality of the paving. By exploring economic and environmental feasibility of Bio-Oil for this application, a higher quality, more environmentally friendly asphalt paving may be in the future. A meeting with the New Hampshire Department of Transportation and UNH asphalt expert, assistant professor Jo Daniel, has initiated the research into this venue.

#### *Coal Dust Suppression*

Another market that may be feasible for Bio-Oil is coal dust suppression. The current product used to coat coal piles is a plasticizer that is biodegradable and does not contaminate ground water. Research would have to be done to make a Bio-Oil product that coats and enhances Btu value without leaching into the ground. Research focusing on making Bio-Oil immiscible in water, testing the strength of its polymerization reactions, as well as ensuring that it meets environmental and physical requirements is required.

#### *Community Outreach Programs*

The UNH Bio-Oil team is committed to bringing knowledge of the Bio-Oil technology to the public eye. To that end, the Bio-Oil team has initiated a web site at [www.unh.edu/p2/biooil](http://www.unh.edu/p2/biooil). The team has also made presentations to high school students participating in the pre-engineering program, "Project Lead the Way," in May 2002. On June 5<sup>th</sup>, the team presented at the Coatings, Composites, and Green Chemistry Conference. On July 17<sup>th</sup>, Caitlin and Chris gave a presentation at the NH Pollution Prevention Program Mid-Summer Meeting. Most recently, the UNH Bio-Oil project was the subject of Governor Jean Shaheen's press conference on July 23, 2002. As a result, the research being done at UNH has been highlighted in five newspaper articles in the UNH and seacoast community and on NHPR public radio station. Details of these articles are available on the Bio-Oil web page aforementioned. The UNH Bio-Oil team will also work to develop a Bio-Oil community outreach program.

## **3.0 Phase One: Social Analysis**

### **3.1 Social Considerations**

The two greatest markets for low-grade wood, pulp and paper manufacturing and wood-fired power plants, account for two-thirds to three-fourths of NH's low-grade wood market (<sup>6</sup>Hammond). However, these markets are currently faltering in New Hampshire with the result being a decline in the low-grade wood market. When the demand for low-grade wood in New Hampshire is high, forests can be maintained such that more high quality sawlogs are produced and sustainable forestry can be practiced (<sup>3</sup>DRED, pg5). Low-grade wood is the portion of trees that cannot be used for high quality lumber, such as bark and small branches. Additionally, the success of the NH sawmill industry is intimately connected to the low-grade wood market and depends on its ability to sell or landfill the 400,000 – 600,000 tons of residue produced per year (<sup>3</sup>DRED, pg19). The pulp and paper industries of New Hampshire utilize about 2.8 million tons of local low-grade wood each year, and until it was recently closed, the Berlin-Gorham mills have used over 40% of that total (<sup>3</sup>DRED, pg5). Despite the re-opening of the mills under Nexfor-Fraser, the pulp and paper industry in New Hampshire is not projected to increase dramatically in the near future (<sup>3</sup>DRED, pg7).

Eight wood-fired power plants were constructed in New Hampshire in the 1980's. Together they consumed a total of 1.56 million tons of low-grade wood chips. These plants were encouraged after the energy crisis of the 1970's as a renewable and diversified source of electricity. Of the eight plants constructed, five currently remain in operation. However, these plants are endangered. The NH Power Utilities Commission (PUC) allowed the rate orders of Whitefield Power and Light and Bio Energy in Hopkinton to expire in fall 2001. This means that contracts ensuring the plants' operation are no longer in effect (<sup>3</sup>DRED, pg6). In addition, laws that dictate the price at which the Public Service of New Hampshire (PSNH) must buy electricity from the remaining plants are due to expire between 2006 and 2008 at which time these facilities are likely to be closed (<sup>3</sup>DRED, pg6). When this occurs, another 1.14 million tons of wood chips per year, the amount used by the five operating facilities will no longer be consumed (<sup>3</sup>DRED, pg6).

In DRED's 2002 project to identify and implement alternatives to sustain the wood-fired electricity generating industry in New Hampshire, fourteen markets were identified to determine if they would be able to expand or provide a new use for low-grade wood. The fourteen markets included: pulp and paper manufacturing, fuel pellets, wood chip export, small-scale gasification, process heat/ co-location, ethanol and biochemicals, co-firing wood with PSNH Merrimack coal-fired electricity plant, firewood, animal bedding, landscaping mulch, densified logs, lumber from small diameter material, and solid wood composites (oriented strand board (OSB) and medium density fiberboard (MDF) (<sup>3</sup>DRED, pg 20). After initial economic screening, the six markets more thoroughly explored included: OSB, MDF, ethanol and biochemicals, wood chip export, co-firing with coal, and pulp and paper manufacturing. The results of the analysis showed that medium density fiberboard presented the most economically viable market for expanding the usage of large quantities of low-grade wood (<sup>3</sup>DRED, pg 21). Thus a full feasibility analysis was conducted on that market. Results showed that

the facility modeled for New Hampshire would use 420,000 tons of wood annually. However, a plant of this size would still not generate the expected internal rate of return expected in industry, thus the facility would not interest an investor in New Hampshire. (<sup>3</sup>DRED, pg22).

With the markets that were initially identified exhausted as viable alternatives to wood-fired electricity in New Hampshire, DRED asserted the conclusion that “in the foreseeable future, no other market exists to replace wood-fired electricity as an outlet to consume low-grade wood in New Hampshire (<sup>3</sup>DRED, pg23).” The alternative markets studied are not sufficient to sustain New Hampshire’s low-grade wood usage, yet a market for low-grade wood is vital for the state’s economy. Thus, DRED’s next phase advocated the sustained operation of the wood-fired power plants through laws and legislative incentives.

Previous legislative action to protect the low-grade wood market from being bought out have taken place in the mid 1990’s. Some of the policies include: the New Hampshire Forest Resource Plan (1996) Good Forestry in the Granite State (1997), the Final Report of Governor Shaheen’s Forest Industry Task Force (1997) and the legislation regarding the state’s wood to energy facilities. (<sup>3</sup>DRED, pg19)

In spite of efforts to sustain NH’s market for low-grade wood, the projected closing of the five wood-fired electric plants along with most recently closed wood-fired plant (mid 2002) would still result in 1.3 million tons per year of unused low-grade wood. The social impact is a direct loss of 125 jobs (<sup>3</sup>DRED, pg28), an indirect loss of 412 jobs (<sup>6</sup>Hammond), and an economic impact of \$96 million a year. At times when the Berlin-Gorham paper mill is closed, another 1.3 million tons per year will be unused with similar losses in jobs and economic impact (<sup>3</sup>DRED, pg30). For the preservation of NH’s economy and jobs, industrial uses for low-grade wood chips are essential. One of the previously unexplored markets for low-grade wood consumption is fast pyrolysis technology. This process uses low-grade wood to generate a product called Bio-Oil that may be used for applications ranging from heating fuel to green chemicals.

### **3.2 UNH Bio-Oil Team Formation: *Partnership for Success***

In response to the NH North Country’s economic and social situation, the NH Industrial Research Center (NH IRC) recognized the need for an innovative technology using low-grade and small diameter wood chips in Northern New Hampshire. Henry Mullaney, Executive Director of NH IRC, was asked in July 2001 for possible industrial applications for low-grade wood besides paper, wood pellets, and fiberboard (<sup>5</sup>Mullaney). It was suggested that a fast pyrolysis process could be used to convert low-grade or small diameter wood to a liquid fuel or source of green chemicals. Dr. Ihab Farag, professor, University of New Hampshire (UNH) Chemical Engineering Department, was recruited to contribute to the technical, environmental, and economic analysis of the feasibility of the plant. Recognizing the importance of partnerships and collaborative effort, Dr. Farag contacted Dennis Cote, of the Business Enterprise Development Council (BEDCO). Cote joined the project with the objective to make the Whitefield plant more competitive through synergies with a bio-fuel plant (<sup>5</sup>Mullaney). Dr. Farag also invited Ron Tetu, from Public Service of NH (PSNH), to bring expertise in the technical risks due to

potential scale-up problems, and economic risks because of the dynamic and changing situation regarding electric rates, oil prices, and scrap wood prices and availability. The core Bio-Oil Team is a cooperative group consisting of the Business Enterprise Development Council (BEDCO), Public Service of New Hampshire (PSNH), UNH, and NH IRC. The core group has had several meetings in which various research tasks have been identified and accomplished, the first of these taking place January 25, 2002. Since that time, several organizations have provided invaluable resources. These important organizations include: the Department of Resources and Economic Development (DRED), the US Department of Energy (US DOE), the Governor's Office of Energy and Community Services (ECS), the Small Business Development Council (SBDC), the NH Department of Environmental Services (NH DES), and the NH Department of Transportation (NH DOT).

## **4.0 Phase One: Technical Analysis**

### **4.1 Current Biofuels**

There are a number of technologies that have been developed to convert biomass to other usable products.

Bioethanol is a biofuel made in a process similar to brewing beer. Starches or cellulosic crops are converted to sugars, which then ferment into alcohol. The ethanol is then distilled further to achieve the final product. Ethanol is used to increase octane and decrease the emissions of burning gasoline. Ethanol is the most widely used biofuel as it can be successfully used in any engine that uses gasoline (<sup>12</sup>Brady, 8).

Biomethanol is another type of biofuel with similar chemical and physical properties to bioethanol. However, to achieve high yields of methanol from biomass (thus biomethanol), a process similar to that used for the production of methanol from coal is used. Methanol is not yet suitable to be used as a stand alone, or neat fuel, however, it is currently used as 85% of a gasoline/methanol mix. It is also used to make methyl-tert-butyl-ether (MTBE) an additive for gasoline in the late 1990's (<sup>12</sup>Brady, 8).

Another form of biofuel unlike methanol or ethanol is biodiesel. This fuel is not an alcohol; it is an ester. Biodiesel is made through a process called transesterification, where fatty acids are combined with ethanol or methanol in the presence of a catalyst like potassium hydroxide. It is most typically used as a fuel additive in 20% blends with gasoline. The United States produces about 30 million gallons of biodiesel per year using recycled cooking and soy oils. The fuel is most commonly used in marinas, tourist boats and launches (<sup>12</sup>Brady, 9). Stefan Czernik, US representative of the Pyrolysis Network (PyNe), has stated that 'biodiesel is a better fuel than Bio-Oil' due to higher energy content and miscibility with gasoline, 'but is twice as expensive.' (<sup>47</sup>Czernik)

Unique from all of the previously mentioned biofuels is Bio-Oil. Bio-Oil, is an oxygenated compound containing carbonyls, carboxyls, and phenolics, and is soluble in water. It is made by the degradation of biomass in the absence of oxygen by a process called fast pyrolysis, which will be further explored in the following sections.

### **4.2 Fast Pyrolysis Technologies**

Pyrolysis dates back to ancient Egyptian times, where tar for caulking boats and an embalming agent were made from pyrolysis. Since then the process had been improved and is widely used in charcoal and coke production. In the 1980's, scientists found that the liquid yield of pyrolysis could be increased in fast pyrolysis, where the biomass is indirectly heated and condensed rapidly. (<sup>50</sup>Renewable Oil International)

Several fast pyrolysis reactor technologies exist today. Some include ablative reactors, entrained flow reactors, rotating core reactors, vacuum pyrolysis reactors, circulating fluidized bed reactors, and deep bubbling fluidized bed reactors. Ablative pyrolysis is a process in which particles of biomass rub against the wall of a heated tube as they degrade. The process is limited by the rate of heat supplied to the reactor, rather than the rate of heat absorption by the particles, as in fluid bed reactors. This means that the biomass particle size can be larger than in fluid bed reactors. The entrained flow reactor, known as the Egemin Process, has been used commercially. However, heat transfer rates from the gaseous heat carrier to the biomass solids were difficult to attain,

so the facility is no longer in operation (<sup>12</sup>Brady, 26). The rotating core reactor, invented at the University of Twente, operates a transported bed reactor, with the transport affected by centrifugal force. A technology currently under development is vacuum pyrolysis. In this technology, the heating rate is slower than in the other technologies mentioned, however, liquid yield and quality is high. The process takes place at about 450° C and about 2 psi. Circulating fluid beds and deep bubbling fluid beds are both technologies that operate under atmospheric pressure and temperatures ranging from about 450°C to 800°C.

Although several fast pyrolysis companies reached near-commercial status in the 1990's (<sup>4</sup>Oasmaa, pg2), two, Ensyn and DynaMotive, have become dominant in North America. Both technologies use renewable biomass, organic residues such as forest (e.g. sawdust, bark) or agricultural wastes (e.g., bagasse) as the process feedstock (<sup>1</sup>DynaMotive.com). Ensyn, with a patented Rapid Thermal Processing (RTP), emphasizes the use of additional chemicals obtained from the process for food smoking and has had commercial plants in the United States and Europe (<sup>2</sup>Ensyn.com). DynaMotive, with the patented BioTherm Process (<sup>7</sup>Patent # 5853548), emphasizes the development and commercialization of environmentally friendly energy systems, based on fuels produced from biomass (<sup>1</sup>DynaMotive.com).

A third smaller contender in North America is Renewable Oil International that has a pending patent. They currently have a one kilogram per hour bench scale plant for research and development and a five ton per day demonstration plant in Alabama under construction facility for chicken litter. The plants are built in modules that are prefabricated and shipped to site for final assembly. Design features allow for the plant to be moved should the biomass dry up in the area. (<sup>50b</sup> Fransham)

Another known Bio-Oil company is Pyrovac that uses vacuum pyrolysis in Quebec (Patent # 6042696). Pyrovac has operated a demonstration plant at 72 tonne/hr at the beginning of 2000, but has had limited progress over the last two years due to a key partner being bought out. When a company was found to replace the withdrawn partner, the rest of the stakeholders decided not to continue funding on the large facility. The researchers were then forced to return to their pilot plant of 1.2 tonne/day to try to iron out minor problems with the larger facility. (<sup>56</sup> Roy)

**Table 4.2 – Operating Pyrolysis Units in the World**

Type of Bed	Size in Dry Tons	Location or Company
Fluidized Beds	400 kg/h = 11 US tons/day	DynaMotive
	250 kg/h = 6.6 US tons/day	Wellman, UK
	20 kg/h = 0.5 tons/day	RTI
	Many other research units	
Circulating Fluidized Beds	1500 kg/h = 40 tons/day	Red Arrow, WI & Ensyn
	1700 kg/h = 45 tons/day	Red Arrow, WI & Ensyn
	20 kg/h = 0.5 tons/day	VTT (Ensyn)
Rotating Cone	120 kg/h = 3.2 tons/day	BTG (Netherlands)
Vacuum	3500 kg/h = 93 tons/day	Pyrovac
Other Types	350 kg/h = 9.3 tons/day	Fortum, Finland

(<sup>47</sup>Czernik)(<sup>49</sup>Boulard)

### **4.3 Fast Pyrolysis Companies: Ensyn vs. DynaMotive**

In the energy crisis of the 1970's, the United State's government encouraged renewable alternatives to fossil fuels (<sup>4</sup>Oasmaa, 2). Biomass played a large role during that time; in New Hampshire, it was the feedstock for the eight wood-fired electricity generating plants established. In other parts of the country, and even the world, biomass was used as the feedstock for the fast pyrolysis process, which was also being chartered during this time. Although slow pyrolysis products were the mainstays of the chemical industry until about the 1950's, several companies have recently been researching the value of chemicals and fuels obtained from the fast pyrolysis process, (<sup>15</sup>Reed, 2001).

Ensyn Group Inc. (EGI) has two primary business objectives: to develop industrial applications for its core technology, Rapid Thermal Processing or (RTP), and to exploit these applications commercially. RTP is a patented process that transforms carbon-based feedstocks, either wood biomass or petroleum hydrocarbons, to more valuable chemical and fuel products (<sup>2</sup><http://www.ensyn.com>). Ensyn's first commercial plant was developed in 1984. From that time to 1996, four commercial plants have been in operation, one in Ontario, Canada, and the remaining three in Wisconsin, USA, with a 45 dry ton per day plant built in 2002 (<sup>2</sup><http://www.ensyn.com> & <sup>49</sup>Boulard). The Wisconsin plant most widely represented Red Arrow's, because it supplied Bio-Oil to be co-fired with coal at Manitowoc Public Utilities in 1996. Ensyn claims a successful month long commercial demonstration to produce electricity. Bio-Oil was co-fired for about 370 hours at a level of about 5% of the total fuel input to the boiler with the primary fuel being coal (<sup>17</sup>Sturlz, 8). Although the program was intended to endure for one year, it was terminated due to Red Arrow's own Bio-Oil fuel use increased to the extent that no surplus was available for Manitowoc Public Utilities (<sup>17</sup>Sturlz, 9). When asked by Dr. Farag in an e-mail, Manitowoc Public Utilities expressed that the performance of the Bio-Oil was poor and the co-firing would not be repeated (<sup>18</sup>Jones). Despite Ensyn's track record of commercialization, the co-firing of Bio-Oil with coal at Manitowoc Public Utilities in Red Arrow, Wisconsin, showed that Ensyn did not produce the Bio-Oil with the quality and properties needed for long-term success in co-firing. Ensyn views Bio-Oil fuel as an economical alternative because it is subsidized by higher value Bio-Oil chemicals. However, the natural chemicals are the main products, and the Bio-Oil fuel is a byproduct (<sup>16</sup>Grahm, 2001).

DynaMotive, incorporated in 1991, while interested in the fast pyrolysis chemical products that can be obtained from fast pyrolysis, focuses primarily on the development and commercialization of environmentally friendly energy systems, based on fuels produced from biomass. The completion and construction of a 10 dry tonne (~18 wet tonne) wood chip per day Bio-Oil pilot plant located at BC Research Inc. in Vancouver BC has been DynaMotive's largest scale operation to date; and was officially commissioned and launched on March 8, 2001. The 10 dry metric tonne/day plant produces 1,465 gallons per day or 14,550 pounds per day of Bio-Oil. Construction and engineering drawings for a 100 tonne woodchip per day, 2.5MWe electricity plant have been completed and the plant is scheduled to be built in the United Kingdom once an investor is found. For comparison purposes, the maximum heating value of a ten US ton per day wood plant (10 tons of 5% moisture, pine/spruce mix = 8384 Btu/lb (<sup>33</sup>Engalichev, 6)) is 1940 Btu/s, or 2.05 MWt. The maximum heating value of the

produced Bio-Oil (10 tons of 5% moisture, pine/spruce mix = 6.6 tons (due to 66% yield) of 7100 Btu/lb Bio-Oil (<sup>1</sup>DynaMotive.com)) is equal to 1085 Btu/s or 1.14 MWt. By maximum heating value we are examining all the possible heat given off (100% efficiency). See Appendix A1 for sample calculations.

DynaMotive is planning to use this same design to commission a 200 tonne per day plant in the Canadian forestry industry by the fourth quarter of 2002 and a 400 tonne per day plant capable of producing 20 MWe of electricity in 2003 in the US coal industry (<sup>1a</sup>www.dynamotive.com).

#### **4.4 DynaMotive Technology for Northern NH**

The advantages of DynaMotive's technology, BEDCO's research into fast pyrolysis companies, and DynaMotive's reputation with the bio-mass Pyrolysis Network (PyNe) led BEDCO to sign a memoranda of understanding (MOU) with DynaMotive in November 2001 and the UNH Bio-Oil Team to focus on DynaMotive (<sup>5</sup>Mullaney). BEDCO's original objective was to make Whitefield Power & Electric Plant more competitive through synergies with a biofuel plant. In addition to the advantages of DynaMotive's technology, the feedback received from Manitowoc Public Utilities in response to co-firing with Ensyn's Bio-Oil also supported DynaMotive as the company of choice.

Another push towards DynaMotive was their patented BioTherm technology. A comparison between DynaMotive's BioTherm Technology and Ensyn's Rapid Thermal Processing (RTP) shows advantages of the BioTherm Process. Ensyn's 25 ton dried wood per day (50 US ton/day wet wood) and their 35 ton dried wood per day (70 US ton/day wet wood) units located at Red Arrow, WI, U.S.A. are used for the production of food flavoring chemicals (liquid smoke) and are not configured for fuel production (<sup>19</sup>Radlein & <sup>2b</sup>Ensyn). The Ensyn process uses a circulating fluid bed, whereas DynaMotive uses a bubbling bed process (<sup>19</sup>Radlein). Several drawbacks to circulating fluid beds have been identified. As stated in the DynaMotive's Bio-Therm patent, "a disadvantage of many rapid pyrolysis systems like shallow fluid beds, circulating fluid beds, entrained flow reactors, etc. is the large amount of carrier gas required to maintain short contact times. This gas represents increased capital and operating costs and incurs a penalty of loss of thermal efficiency (<sup>19</sup>Radlein)"

Higher temperatures, above 600°C, result in Polynuclear Aromatic Hydrocarbons (PAH), which are considered carcinogenic. Reactor bed temperatures for the Ensyn process, are described to be between 350°C and 800°C in Ensyn's US patent number 5,961,786 (<sup>51</sup>Freel, 7). However, in a more recent presentation by Ensyn, the bed reactor temperature was told to be between 400-600 °C. DynaMotive's process from 450-500°C, takes place below 600°C (<sup>11</sup>Stone, 12).

Table 4.4.a shows a comparison between the quality of Bio-Oil produced by Ensyn and that produced by DynaMotive. The viscosity, PAH, and solids content is much higher in the Bio-Oil produced by Ensyn than in that produced by DynaMotive in 2000. Although Ensyn's Bio-Oil from 2000 shows a poor quality, a due diligence report by Ensyn Inc. from June 2001 showed improvement in the Bio-Oil. This can be seen in the last column of table 4.4.a.

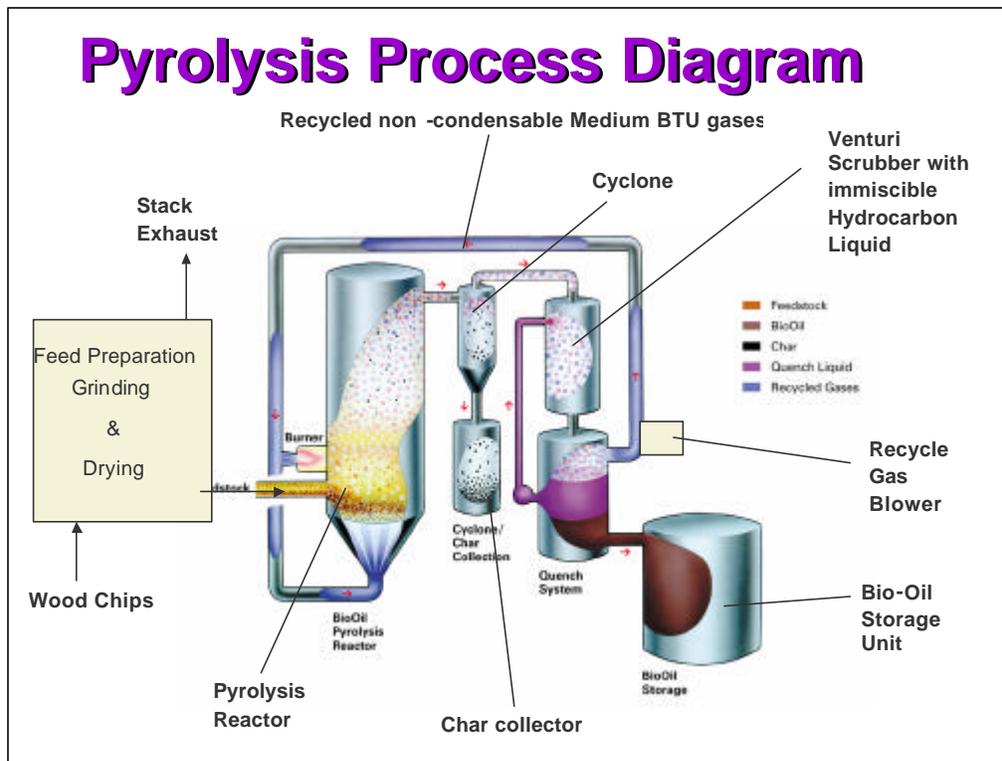
**Table 4.4.a Results from PyNe 2000 Tests of Bio-Oil**

	DynaMotive 2000	Ensyn 2000	Ensyn 2001
Viscosity (cSt 20 °C)	101	1823	10-150 @ 50°C
Viscosity (cSt 40 °C)	30	235	
Polynuclear Aromatic Hydrocarbons (ppm)	8.0	334.1	unknown
Water Insoluble materials (wt%)	27.8	55.1	unknown
Solids Content (wt%)	0.10	0.42	<0.10

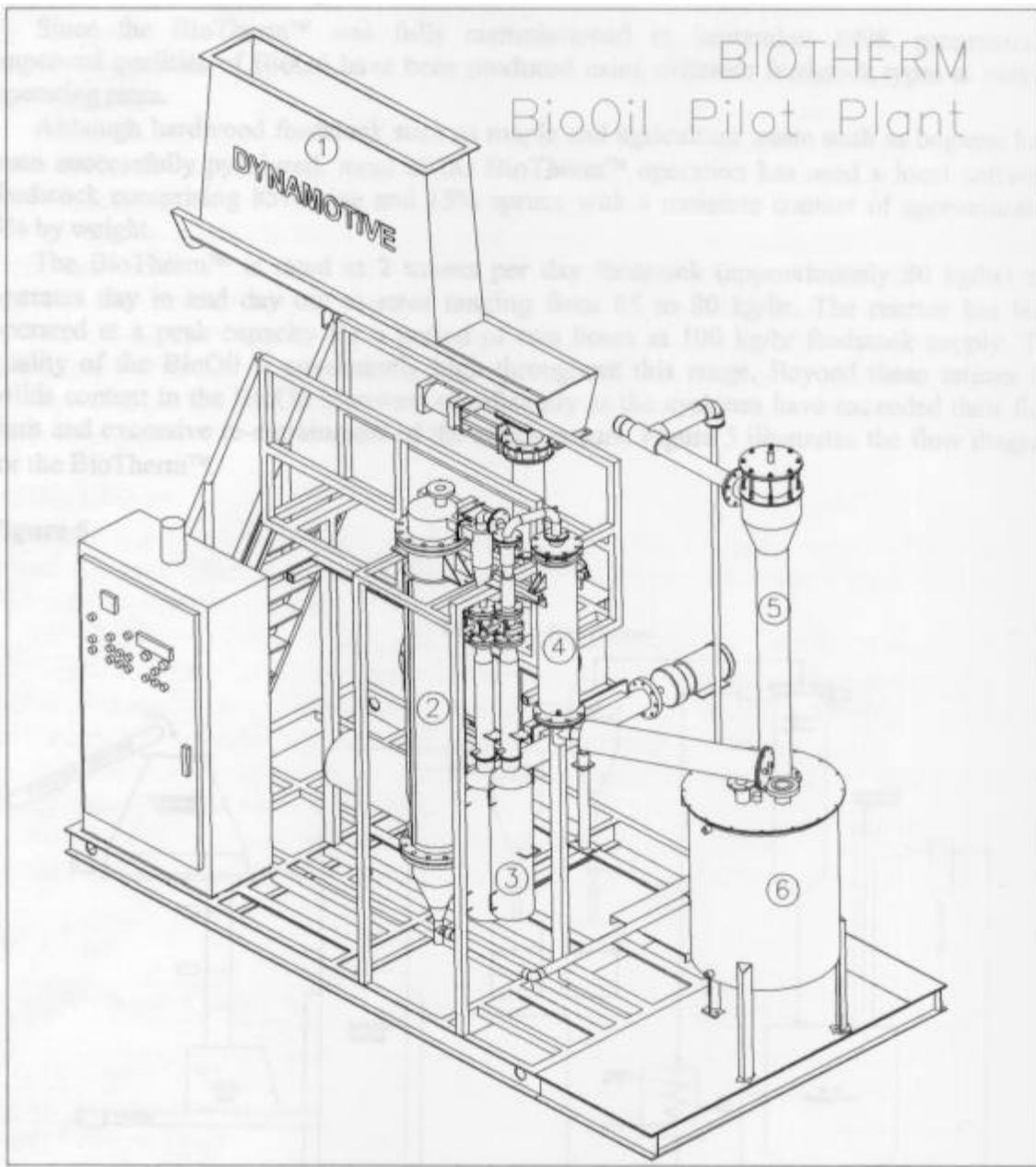
(<sup>19</sup>Radlein)

Higher attrition and reactor erosion rates result due to high gas velocities required in a circulating fluid bed. Process power requirements due to high re-circulation gas rates add costs to the operation and the process is intrinsically complex due to the sand circulation requirements to accommodate given biomass feed rates (<sup>19</sup>Radlein). Although quantitative statements about power requirements and the complexity of Ensyn's process without energy and material balances is not possible, the Bio-Therm process has been carefully designed to minimize the gas throughput in order to reduce power requirements. In DynaMotive's Bio-Therm Process a mass ratio of recycle gas to biomass feed is as low as 1:1 and as high as 2:1. (<sup>19</sup>Radlein & <sup>7</sup>Piskorz, 11) From this information, DynaMotive's bubbling-bed technology appears to avoid several of the complications of the circulating bed technologies.

#### **4.5 BioTherm Process**



**Figure 4.5a: Simplified Process Diagram** (<sup>1</sup> www.dynamotive.com)



(<sup>8</sup>DynaMotive, 6)

**Figure 4.5b – Detailed 3D Model of DynaMotive’s 2 metric tonne/day BioTherm Pilot Plant**

### **4.5.1 Process in General**

Although the fast pyrolysis process that DynaMotive uses is more accurately called thermolysis, the two terms are used interchangeably. Since ‘pyro’ means fire in Greek and ‘thermo’ means heat, thermolysis more closely describes the process, which involves heating biomass through indirect heat. The term ‘fast’ refers to the residence time of the biomass in the reactor. Slow pyrolysis produces more solid char, while fast pyrolysis yields more gas and liquid. The reactor design, temperature, and residence time determine the yields of the products and to some extent, their qualities.

(<sup>22</sup>[www.wgtuk.com/ukDefinitionPyr.html](http://www.wgtuk.com/ukDefinitionPyr.html))

In the fast pyrolysis process, indirect heat, followed by cooling, is used to convert biomass at 400-800°C into CO<sub>2</sub>, CO, and CH<sub>4</sub> gases (medium heating value gases), Bio-Oil liquids, and solid char. A simplified diagram of the process is shown in Figure 4.5a. The conversion of wood chips to Bio-Oil occurs in the absence of oxygen in the pyrolysis reactor shown in the figure. Oxygen is excluded to prevent the biomass or its products from combusting. Gasification is different from fast pyrolysis, or thermolysis, because it is a combustion process in which enough oxygen, through air, is supplied for the carbon and hydrogen in the fuel to form a rich mixture of CO and hydrogen in the product gas (<sup>33</sup>Mathur, 19). The product gas from gasification will contain up to 60% nitrogen and have a lower heating value of 107 to 484 Btu/ft<sup>3</sup> whereas the heating value of fast pyrolysis gases range from 484 to 807 Btu/ft<sup>3</sup> (<sup>23</sup>[www.wgtuk.com/ukDefinitionGas.html](http://www.wgtuk.com/ukDefinitionGas.html)).

The products exit the pyrolysis reactor (item 2 on Figure 4.5b) in a gas state that includes vapors, aerosols, and a suspension of small solid particles. A cyclone (above item 3 on Figure 4.5b) separates most of the solid particles from the vapors, where they are then deposited to the char collector (item 3 on Figure 4.5b). The gases are then condensed in a quench system (item 4 on Figure 4.5b), which converts most of the vapor into liquid Bio-Oil. The non-condensable gas is then recycled back to the reactor to the separate combustion chamber for indirect heating (<sup>9</sup>Thambuaj, 1-2).

DynaMotive Technologies owns a specific fast pyrolysis technology patented by its business partner Resource Transforms International (RTI). Resource Transformation International is a spinoff company from the University of Waterloo in Ontario, Canada. (<sup>12</sup>Brady, 23) This fast pyrolysis process is described in the patent #5,853,548, titled, “Energy Efficient Liquefaction of Biomaterials by Thermolysis”(<sup>9</sup>Thambuaj, 1).

Feedstock for the DynaMotive fast pyrolysis process can be any biomass waste material ranging from agricultural wastes to wood by-products. Fifty biomass feedstocks have been successfully tested to date. (<sup>12</sup>Brady, 24) Over the last couple years DynaMotive has been focusing on wood waste (white wood and bark) and sugarcane as its feedstocks. Wood derived feedstocks produce the highest yields with approximately 72 weight (wt) % Bio-Oil, 15 wt % solid char, and 13 wt % non-condensable gases obtained from feedstock with less than 10% wt moisture content. (<sup>8</sup>DynaMotive, 3) The non-condensable gases are recycled to supply 75% of the energy needed in the process, while the Bio-Oil and char can be sold as commercial products (<sup>1</sup>[DynaMotive.com/biooil](http://DynaMotive.com/biooil)).

DynaMotive has had three BioTherm pilot plants. A 0.4 metric tonne/day plant was built in 1995 and experimented with until 1997. The next generation of pilot plant was built in 1997 and was a 0.5 tonne per day facility. The 1997 plant was upgraded in

1998 to a 2 tonne/day plant (pictured in Figure 4.5b) and was used for research up until 2001. The third plant 10 tonne per day was constructed in May of 2001 and has been running since. (<sup>8</sup>DynaMotive, 2)

For both pilot plants, DynaMotive has been testing the maximum capacity that the reactors can achieve. In 1999, the 2 tonne per day facility was found to process up to 2.64 tonne per day before product quality decreased significantly. Above this upper limit the solids content of the Bio-Oil increases dramatically due to the volume of gas and solid particles exceeding the flow limit of the cyclones in the process. (<sup>8</sup>DynaMotive, 7) In July 2002 this process was repeated with DynaMotive's 10 tonne/day facility and the upper limit was found to be approximately 15 tonne/day. (<sup>20</sup>Stewart).

The 2 tonne/day facility can reach steady-state operation from a cold start in two hours. Once the char removal storage tanks become full, the feed has to be stopped while the storage tanks are switched. (<sup>8</sup>DynaMotive, 8)

The core aspects of the DynaMotive technology are explained below from information released and from their patents. As DynaMotive is continuously improving their pilot plant, some of the information presented may not be up to date (<sup>8</sup>DynaMotive, 8).

#### **4.5.2 Feedstock Preparation, Storage, and Feed System.**

(Storage & Feed System –see Item 1 in Figure 4.5b)

In New Hampshire, low-grade-wood chips have a moisture content of approximately 45% by weight (<sup>24</sup>Wells). In order to prepare the low-grade wood chips, they must be dried and ground to the correct size. Although DynaMotive's patent from 1998 showed that the particle size must be 3mm or less in diameter (<sup>7</sup>Piskorz,11), more recent literature suggests that wood is ground to about one millimeter in diameter (<sup>12</sup>Brady, 24). A 1999 DynaMotive technical paper shows that wood was dried to 4.6 wt % moisture for tests (<sup>8</sup>DynaMotive, 9). It is generally stated that wood be dried to less than 10 wt % moisture. Small particle size allows for fast heat transfer rates, (<sup>12</sup>Brady,24) while reducing the water content in the feedstock decreases the amount of water in the Bio-Oil. (<sup>10</sup>DynaMotive, 3).

Dried and ground feedstock is stored in a hopper near the pyrolysis reactor. It is metered using a variable screw-feeder to a constant speed screw-feeder that transfers it rapidly to the thermolysis reactor (<sup>7</sup>Piskorz, 11). These three steps take place before the feed enters the pyrolysis reactor, and can be seen labeled in Figure 4.5a.

#### **4.5.4 Pyrolysis Reactor**

(See Item 2 in Figure 4.5b)

A bubbling fluidized bed pyrolysis reactor is used to convert the prepared wood chips into three components: small particles of solid char (aerosols), condensable gases, and non-condensable gases (<sup>8</sup>DynaMotive, 5). Silica sand is used as the inert material inside the reactor, which can withstand temperatures up to 1500°C and aids in heat transfer (<sup>7</sup>Piskorz, 11). As Figures 4.5.4a, b, & c show below, the greatest yield for DynaMotive's reactor is approximately 480°C from 1999 results. The temperature range of DynaMotive's reactor is usually set for 450° to 500°C (<sup>8</sup>DynaMotive, 4). Operating

below 400°C in the reactor will quickly result in the Bio-Oil clogging pipes due to its nature of depositing on surfaces (<sup>8</sup>DynaMotive, 8). Transfer lines are also maintained above 380°C to prevent clogging caused by condensation (<sup>7</sup>Piskorz, 13). One important specification of the reactor is that the height to width ratio must be greater than one (<sup>10</sup>DynaMotive, 2).

The bed is heated indirectly by flue gases in the jacket of the reactor to temperatures from 700° to 1000°C (<sup>7</sup>Piskorz, 13). The total heat requirement, including radiation and stack gas losses, amounts to 2.5 MJ per kilogram of Bio-Oil produced. DynaMotive claims that up to seventy-five percent of the energy required by the pyrolysis process can be supplied through the recycled non-condensable gases (<sup>1</sup>Dynamotive.com/biooil). Usually though the total heat required from an external source such as natural gas is 1.0 MJ/kg of Bio-Oil. (<sup>9</sup>Thamburaj, 2). These gases are combusted to supply indirect heat to the sand in the reactor. The exhaust gas from the burner is then sent through a gas-to-gas heat exchanger that preheats the recycled non-condensable gas (<sup>8</sup>DynaMotive, 5). Some of the recycled gases are sent to the natural gas burner, while another portion is sent through the reactor again to aid the fluidization (<sup>8</sup>DynaMotive, 5). The mass ratio of gas to biomass is less than 2:1 (<sup>7</sup>Piskorz, 11). Nitrogen gas is also added to the reactor to act as a fluidizing gas (<sup>11</sup>Stone, 30). Oxygen is not added to the reactor in order to prevent combustion from occurring (<sup>8</sup>DynaMotive,5).

Modifications to the fast pyrolysis process have taken place between the time that the BioTherm Process was patented in 1998 and the present in regard to reaction time (how long it takes for the low-grade wood chips to decompose into gases and char particles) and temperature. DynaMotive's patent from 1998 claims that their invention operates at 375° to 450°C with a reaction time of 1 to 60 seconds. (<sup>7</sup>Piskorz, 3) In 2001, DynaMotive claims that their reaction temperature is 450° to 500°C with a reaction time of a 'few seconds'. (<sup>10</sup>DynaMotive, 2) These differences suggest that DynaMotive has made improvements to their process since 1998.

Another area that may have changed due to the changes in reaction temperature and reaction time is gas residence time (how long the gas formed from the reaction stays in the reactor). In 1998, when DynaMotive received their patent, it was stated that conventional fast pyrolysis processes have vapor residence times on the order of 1 second, while their process achieved better results with gas residence times on the order of 2 to 25 seconds (<sup>7</sup>Piskorz, 6). The longer residence time allows for greater ease in scaling-up the system, since conventional fluidized beds with short residence times are notorious for causing scale-up problems. (<sup>7</sup>Piskorz, 11)

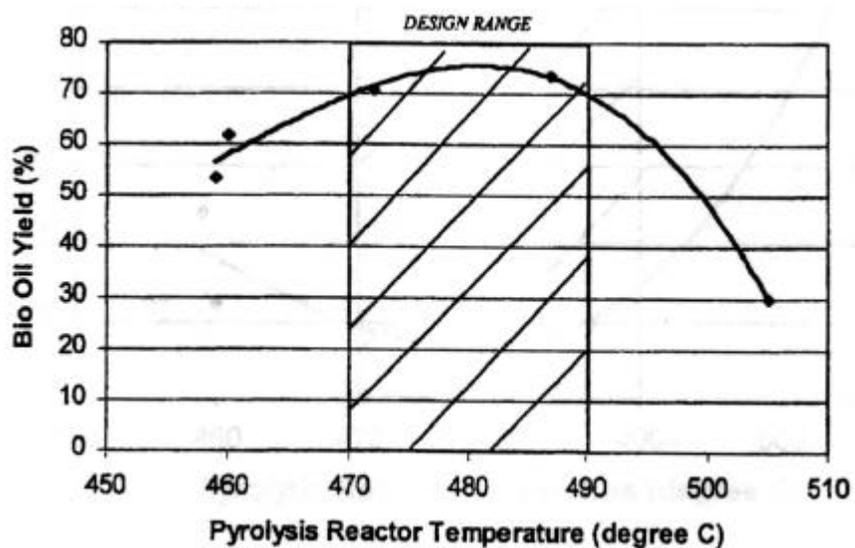


Figure 4.5.4a – Bio-Oil Yields due to Varying Temperature (DynaMotive, 3)

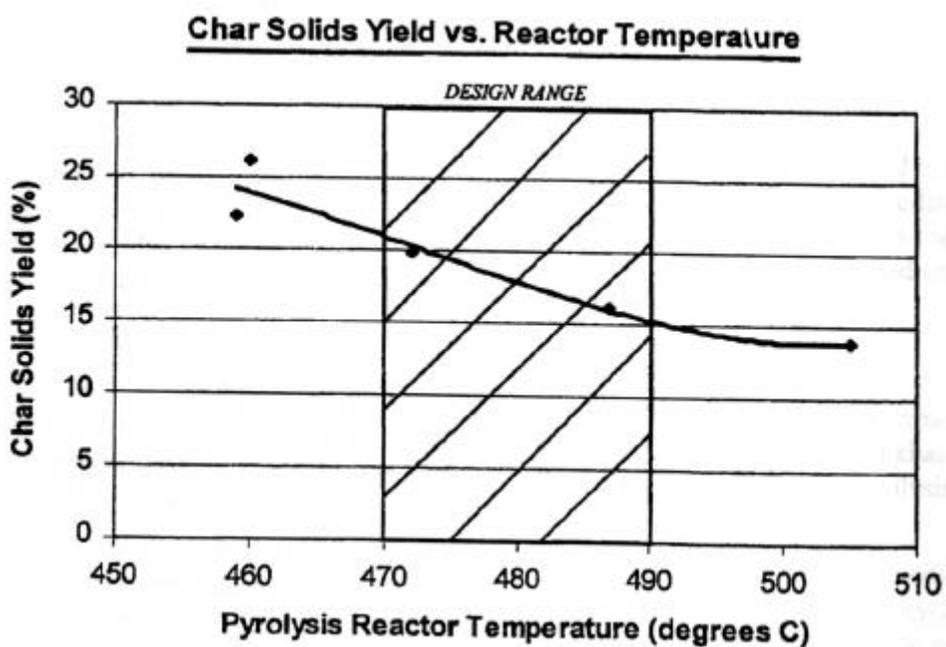
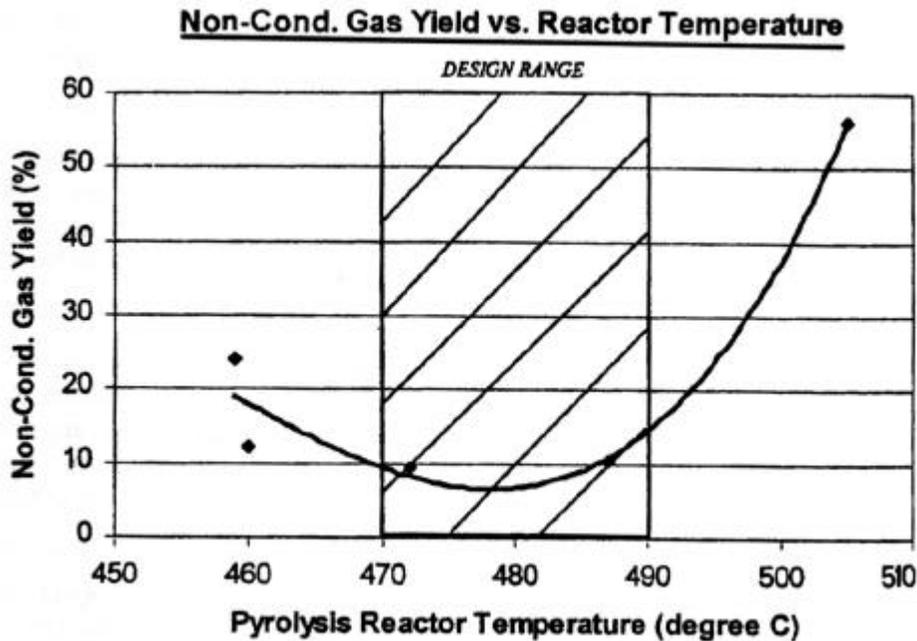


Figure 4.5.4b – Char Yields due to Varying Temperature (DynaMotive, 4)



**Figure 4.5.4c – Non-Condensable Gas Yields due to Varying Temperature**  
 (<sup>8</sup>DynaMotive, 4)

#### **4.5.5 Cyclone**

(See Item 3 in Figure 4.5b)

A cyclone is a cone like apparatus that uses centrifugal force to keep heavier particles against the wall. Gravity then pulls the solid particles downward to a collection tank, while the gases move in a pattern much like a tornado or cyclone out of the top of the equipment. DynaMotive’s 1998 patent indicates the use of only one cyclone to remove char particles from the effluent (<sup>7</sup>Piskorz, 11). However, in 1999, DynaMotive added a second cyclone, which dramatically decreased the solids weight percent in the Bio-Oil (<sup>8</sup>DynaMotive, 5 & 8). This was an important improvement for cleaner and more efficient combustion of the Bio-Oil. The change in quality of the Bio-Oil can be seen in table 1.4 in section 4.8 of this report. Since then, DynaMotive has tried many different particle removal combinations including a cyclone followed by an electrostatic precipitator or a bag houses to remove char particles effectively (<sup>20</sup>Stewart).

#### **4.5.6 Bio-Oil Quench and Storage System**

(See Item 4 in Figure 4.5b)

When the cleaned gases exit the cyclone unit, they must be cooled to form the Bio-Oil and non-condensable, recyclable product gases. This prevents further reactions from taking place (<sup>10</sup>DynaMotive, 2). The most detrimental reaction for Bio-Oil as a fuel is secondary cracking, which decreases the liquid fuel’s yield (<sup>28</sup>SciTecLibrary.com, 5). In 1999, DynaMotive used a Bio-Oil immiscible liquid to quench the gases. At this time,

Bio-Oil was separated from the immiscible quench liquid in the product tank before being transferred to other storage containers. The immiscible liquid was then decanted from the tank, cooled in a heat exchanger, and recycled for reuse (<sup>8</sup>DynaMotive, 5).

To simplify the process, the company started using previously made and cooled Bio-Oil to quench the gases. The quenching process uses direct contact heat transfer, spraying Bio-Oil below 50°C that was cooled in a heat exchanger onto the gases to condense Bio-Oil (<sup>20</sup>Stewart). Since DynaMotive's switch to using previously made Bio-Oil as the quenching agent the separation process is no longer needed and the product tank acts as a storage unit.

#### **4.5.7 Electostatic Precipitator**

(See Item 5 in Figure 4.5b)

After the quenching process, the non-condensable gases and any Bio-Oil particles leftover are sent through an electrostatic precipitator (ESP). The ESP uses electric charges to first charge unwanted aerosol particles and then trap them using an oppositely charged plate. The cleaner, non-condensable gas is then recycled back to the fluidized bed (<sup>12</sup>Brady, 24). In 1999, the excess low to medium Btu value gases consisting primarily of CO<sub>2</sub>, CO, and CH<sub>4</sub> to be incinerated in a flare, but are now recycled by a compressor to the reactor burner to decrease the amount of natural gas required (<sup>8</sup>DynaMotive, 8 & <sup>7</sup>Piskorz, 12).

#### **4.6 Bio-Oil Chemical Composition**

Bio-Oil is a dark brown, free flowing liquid with a pungent smoky odor. A mixture of oxygenated compounds, it contains various chemical functional groups such as carbonyls, carboxyls, and phenolics. Bio-Oil is made up of the following constituents: 20-25% water, 25-30% water insoluble pyrolytic lignin, 5-12% organic acids, 5-10% non-polar hydrocarbons, 5-10% anhydrosugars and 10-25% of other oxygenated compounds (<sup>10</sup>DynaMotive, 3). The compositions of Bio-Oil from three feedstocks are listed in Table 4.6a. The first, bagasse, is the outer stalk that remains after the juice has been obtained from sugar cane. The next feedstock, Pine/Spruce 53% wood and 47% bark refers to a mixture containing only the two types of tree, with 53% coming from wood and 47% coming from bark. Finally, Pine/Spruce 100% all the wood comes from Pine and Spruce, and that no bark is included.

**Table 4.6a: Bio-Oil Composition** (<sup>10</sup>DynaMotive, 4)

<b>Biomass Feedstock</b>	<b>Bagasse</b>	<b>Pine/Spruce 53% wood + 47% bark</b>	<b>Pine/Spruce 100% wood</b>
Bio-Oil Concentrations wt%			
Water	20.8	24.3	23.3
Lignin	23.5	24.9	24.7
Cellobiosan	-	1.9	2.3
Glyoxal	2.2	1.9	2.3
Hydroxyacetaldehyde	10.2	10.2	9.4
Levogluconan	3.0	6.3	7.3
Formaldehyde	3.4	3.0	3.4
Formic acid	5.7	3.7	4.6
Acetic acid	6.6	4.2	4.5
Acetol	5.8	4.8	6.6
Unlisted	18.8	14.8	11.6
Total	100	100	100

#### **4.7 Bio-Oil Physical Characteristics**

Like chemical composition, the physical properties of Bio-Oil also vary depending on the feedstock. Table 4.7a, lists the properties of Bio-Oil produced by DynaMotive’s pilot plant. Of the three different feedstocks, the pine/spruce and bark feed is most similar to the low-grade wood chips in New Hampshire and those that DynaMotive uses at their 10 tonne per day facility in Vancouver, B.C. Canada. The pilot plant is currently using a 60% white wood and 40% bark mix (<sup>20</sup>Stuart).

**Table 4.7a: DynaMotive Bio-Oil Properties** (<sup>10</sup>DynaMotive, 3)

<b>Biomass Feedstock</b>	<b>Bagasse</b>	<b>Pine/Spruce 53% wood + 47% bark</b>	<b>Pine/Spruce 100% wood</b>
Moisture wt%	2.1	3.5	2.4
Ash Content wt%	2.9	2.6	0.42
<b>Bio-Oil Properties</b>	<b>Bagasse</b>	<b>Pine/Spruce 53% wood + 47% bark</b>	<b>Pine/Spruce 100% wood</b>
pH	2.6	2.4	2.3
Water Content wt%	20.8	23.4	23.3
Lignin Content wt%	23.5	24.9	24.7
Solids Content wt%	<0.10	<0.10	<0.10
Ash Content wt%	<0.02	<0.02	<0.02
Density kg/L (lb <sub>m</sub> /ft <sup>3</sup> )	1.20 (75)	1.19 (74)	1.20 (75)
Calorific Value: MJ/kg Btu/lb <sub>m</sub>	15.4 6621	16.4 7051	16.6 7137
Kinematic Viscosity, cSt @ 20°C @ 80°C	57 4.0	78 4.4	73 4.3

Some of the characteristics listed in Table 4.7a, such as the water content, solids content, and viscosity create issues when using the Bio-Oil as a fuel. Although the water content (hydrophilic) lowers NOx, and improves Bio-Oil's flow characteristics, it also means that Bio-Oil is immiscible in petroleum fuels (hydrophobic), and lowers the heating value of the fuel. The solids entrained in the Bio-Oil principally contain fine char particles that are not removed by the cyclones. The ash content in these solids ranges from 2% to 20%, depending on the ash content of the feedstock (<sup>10</sup>DynaMotive, 3). Solids content in the Bio-Oil must be less than 0.1% or there is a possibility of injector blockage or turbine erosion (<sup>4</sup>Osamaa, 1). The viscosity of Bio-Oil may become problematic as the Bio-Oil is stored over time, as unfavorable reactions take place that make the liquid too viscous to be a viable fuel. To address some of the obstacles of using Bio-Oil as a fuel, efforts to modify and improve the quality of Bio-Oil have been made.

#### **4.8 Improvements in Bio-Oil**

Since the BioTherm technology was fully commissioned in September 1998, the quality of Bio-Oil has been improved. A variety of feed stock types at varying operating rates have also been tested to improve the process and determine ideal feedstock characteristics (<sup>8</sup>DynaMotive, 7).

Most of DynaMotive's operation has used a local softwood feedstock comprising 85% pine and 15% spruce with a moisture content of approximately 5% wt after drying (<sup>8</sup> DynaMotive, 7). Table 4.8.a compares the properties of the Bio-Oil produced in the BioTherm pilot plant compared to that produced by the same process, but in a significantly smaller unit located at RTI's facility, labeled as RTI #28. As can be seen, the chemical constituent concentrations are very similar for the two different reactors when operated at the same bed temperature (<sup>8</sup>DynaMotive, 9).

**Table 4.8.a Bio-Oil Chemical Composition Changes (<sup>8</sup>DynaMotive, 9 & <sup>1</sup>DynaMotive.com)**

	Oct 98 BioTherm	June 99 BioTherm	RTI #28 Pre-2000	BioTherm July 2002
Feedstock Characteristics	Pine/Spruce	Pine/Spruce	Pine/Spruce	Pine/Spruce 53 % wood 47 % bark
Moisture Content, wt%	4.6	4.6	4.6	
Ash Content, wt %	0.25	0.25	0.25	
Particle Size	<1.2mm	< 1.2mm	< 1.2mm	
Feed Rate kg/hr	50	65	15.8	
Temperature °C	475	475	473	
Component	Weight %			
Water	25.0	20.7	22.4	23.4
Lignin	24.0	27.0	27.0	24.9
Cellobiosan	-	2.6	0.7	1.9

	Oct 98 BioTherm	June 99 BioTherm	RTI #28 Pre-2000	BioTherm July 2002
Glyoxal	-	2.4	0.4	1.9
Methylglyoxal	-	-	1.2	-
Hydroxyacetaldehyde	7.3	7.3	6.3	10.2
Levogluconan	5.2	6.7	6.4	6.3
Formaldehyde	3.9	3.2	3.9	3.0
Formic acid	3.3	3.6	3.1	3.7
Acetic acid	4.1	3.2	3.5	4.2
Acetol	6.0	5.5	6.0	4.8
Methanol	2.0	0.3	0.5	-

Table 4.8.b shows the improvements in the quality of Bio-Oil produced from October 1998 to July 2002. Important changes were a decrease in solids content and a reduction of viscosity. As can be seen, the solids in the Bio-Oil have been reduced significantly to levels of approximately 0.1% by weight. The ash content in these solids ranges from 2% to 8%, depending on the ash content of the feedstock (<sup>8</sup>DynaMotive, 9). These characteristics make Bio-Oil better suited for combustion.

**Table 4.8.b: Bio-Oil Quality Improvements** (<sup>8</sup>DynaMotive, 8 & <sup>1</sup>DynaMotive.com)

Bio-Oil Production Date	October 1998	June 1999	July 2002
Water Content wt%	25.0	20.7	23.4
Lignin Content wt%	24.0	27.0	24.9
Solids Content wt%	0.37	0.11	<0.10
PH	2.4	2.2	2.4
Density: g/L lb <sub>m</sub> /ft <sup>3</sup>	1.19	1.20	1.19
Calorific Value: MJ/kg BTU/lb	16.8 7,225	17.9 7,700	16.4 7,051
Kinematic Viscosity, cSt 20°C 40°C 50°C 60°C 80°C	62 - 12 cSt@50°C - -	112 30 - 11 -	40 - - - 6 cSt@80°C

Although the acidic nature of Bio-Oil was not drastically changed from 1998 to 2002, processes are being developed to raise the pH, making the liquid non-corrosive. In a report done by the Alaskan company, Huskywood, the BDM Process for blending Bio-Oil is described as a process that produces a stable, non-corrosive, and easy to ignite fuel. CANMET Energy Technology Centre (CETC) of Natural Resources Canada has developed the process. The process uses surfactants to change Bio-Oil from a liquid

immiscible in hydrocarbons to one that can be blended to 5-30% blends with hydrocarbons. The drawback of this process is the high-energy requirement (<sup>4</sup>Oasmaa,13).

Because of the reduced efficiency of scaling up cyclones, filtration has been tried as a means to reduce the solids content in Bio-Oil with little success. However, hot vapor filtration provided more favorable results. In this experiment, filters were operated between 400-420°C, temperatures high enough to avoid condensation. Although the yield of Bio-Oil was only 50-55%, the ash content was less than 0.01% and alkali content was less than ten parts per million (ppm), which also helped decrease viscosity and its increase rate during storage. Although cracking did take place, which reduced the yield of Bio-Oil, by reducing the size of the molecules in the Bio-Oil, the viscosity was reduced and the combustion chemistry was improved. Although the results of this experiment seem favorable to the quality of Bio-Oil, new developments are needed to use this technology for long-term, continuous processing (<sup>4</sup>Oasmaa, 11).

Solvent addition to Bio-Oil is another method of homogenizing and reducing the viscosity of Bio-Oil. Experiments showed that the addition of methanol to Bio-Oil showed stabilization of the product. The rate of viscosity increase for a Bio-Oil with a 10%wt addition of methanol was almost 20 times less than for Bio-Oil alone. Researchers suggest that the solvent addition reduces viscosity in three ways. First, the Bio-Oil is physically diluted without affecting the chemical reaction rates. Second, the reaction rates are reduced by molecular dilution or by changing the Bio-Oil's microstructure. Finally, the chemical reactions between the solvent and the Bio-Oil prevent reactions that increase hydrocarbon chain growth. The reactions taking place between Bio-Oil and solvents are esterification and acetalization, and although the reactions are not thermodynamically favored, they progress significantly in appropriate conditions. In addition to decreasing viscosity and the aging rate, other changes such as reduced acidity, improved volatility, heating value, and miscibility with diesel fuel results (<sup>4</sup>Oasmaa, 12).

#### **4.9 Bio-Oil in Perspective: Comparison to Petroleum Fuels**

A first generation fuel system and combustion system were designed and tested by DynaMotive and Orenda Aerospace Corporation, demonstrating the capability to operate a 2.5 MW industrial gas turbine on Bio-Oil. These tests showed that Bio-Oil can be used with comparative results to diesel. Although CO and particulate emissions were higher than diesel, tests showed that NO<sub>x</sub> emissions were about half that from diesel fuel and the SO<sub>2</sub> emission levels were too low to be detected by the instrumentation (<sup>10</sup>DynaMotive, 5). Table 4.9a shows a comparison of properties of Bio-Oil and diesel fuel. As can be seen, the heating value of Bio-Oil is about half that of diesel fuel. Another important difference is the viscosity, Bio-Oil is much more viscous than diesel fuel. Problematic for standard materials that are used with diesel fuel is the low pH of Bio-Oil. One of the greatest differences between Bio-Oil and diesel, or any hydrocarbon fuel, is the water content. Bio-Oil contains over 20% water by weight, making it hydrophilic and immiscible in hydrocarbon fuels which contain less than 5% water and solids by volume combined. Alkali content in Bio-Oil can result in hot corrosion. This occurs because the metals listed in the table, sodium and potassium, form low melting

temperature compounds that stick to the hot gas path components, reacting to erode them. This obstacle, however, can be overcome with the use of fuel additive that react with the metals so they do not liquefy (<sup>10</sup>DynaMotive, 6).

**Table 4.9a: Typical Properties of Bio-Oil Compared to Diesel Fuel** (<sup>10</sup>DynaMotive, 5)

	Bio-Oil	Diesel
Calorific Value MJ/kg	15-20	42
Btu/lb <sub>m</sub>	6,450- 8,600	18,060
Kinematic Viscosity @ 20°C	~78	2-4
Acidity	2.3-3.3	5
Water %	20-25 wt	0.05 vol (combined)
Solids %	<0.1 wt	
Ash	<0.02	0.01
Alkali (Na + K) ppm	5-100	<1

The density of Bio-Oil is high, approximately 1.2 kg/liter versus the 0.87 kg/liter of number two fuel. On a volumetric basis Bio-Oil has 55% of the energy content of diesel oil and 40% on a weight basis (<sup>10</sup>DynaMotive, 3). Table 4.9b shows the properties of Bio-Oil compared to light and heavy fuel oil. Although Bio-Oil has approximately half of the heating value of light or heavy fuel oil on an equal volume basis, its viscosity, ash, sulfur, nitrogen content, and NOx emission are less than that of heavy fuel oil. Bio-Oil's advantages over fuel oil are that it releases almost no SOx and 50% less NOx emissions in gas turbines. Bio-Oil has a lower pour point than both heavy and light fuel oils (<sup>1</sup>DynaMotive.com/whatisbiooil).

**Table 4.9b: Typical Properties of Bio-Oil Compared to Light & Heavy Fuel Oil** (<sup>1</sup>DynaMotive.com/whatisbiooil)

	BioTherm Bio-Oil	Light Fuel Oil	Heavy Fuel Oil
Heating Value: MJ/kg	16.5	42.3	40.9
BTU/lb <sub>m</sub>	7100	18200	17600
Viscosity, cSt @50°C	7	4	50
@80°C	4	2	41
Ash wt%	<0.02	<0.01	0.03
Sulphur wt%	Trace	0.15 to 0.5	0.5 to 3
Nitrogen wt%	Trace	0	0.3
Pour Point °C	-33	-15	-18
Turbine NOx g/MJ	<0.07	1.4	N/A
Turbine SOx g/MJ	0	0.28	N/A

#### **4.10 Volume and Yield of Bio-Oil from Various Size Plants**

Table 4.10a – Volume & Yield of Products

Tons wet wood processed per day (45% moisture content)	100 metric tpd wet wood (60 metric tpd dried wood) [110.2 US tpd wet wood (66.12 US tpd dried wood)]	200 metric tpd wet wood (120 metric tpd dried wood) [220.5 US tpd wet wood (132 US tpd dried wood)]	400 metric tpd wet wood (240 metric tpd dried wood) [440.9 US tpd wet wood (264.54 US tpd dried wood)]
US Tons wet wood per year (45% moisture)	36,376 tons	72,752 tons	145,505 tons
US Tons dried wood per year (8.3% moisture content)	21,826 tons (20,007 tons bone dry wood and 1,819 tons water)	43,651 tons	87,303 tons
Yield Char (US tons/yr)	4,583	9,167	18,334
Yield Non-condensable gases (US tons/yr)	2,837	5,675	11,349
Yield Bio-Oil (US tons/yr)	14,405	28,810	57,620
Yield Bio-Oil (gallons/yr)	2,900,986	5,801,972	11,603,945

Note: In Table 4.10a, the yields of Bio-Oil, char, and gas are taken to be respectively 66%, 21%, and 13%. The DynaMotive website claims yields of 60-75% Bio-Oil, 15-25% char, and 10-20% gas. The yields for this analysis were chosen as values approximately in the middle. (<sup>11</sup>Stone, 1)

## **5.0 Phase One: Environmental & Health Analysis**

### **5.1 Toxicity and Health Hazards**

A Material Data Safety Sheet (MSDS) has been developed by DynaMotive and can be found in appendix A2. After being reviewed by the IEA Pyrolysis group, Bio-Oil was found to be irritating to the eyes (and possibly causing irreversible damage), respiratory system, and skin. The most severe damage is done by Bio-Oils produced at temperatures greater than 600°C, which can have mutagenic effects (<sup>4</sup>Oasmaa, 13). Bio-Oil produced by the DynaMotive process is not considered mutagenic or carcinogenic (<sup>12</sup>Brady, 29).

Although Bio-Oil is handled with the same precautions that number six fuel oil is handled at the DynaMotive 10 tonne wood chip per day pilot facility (<sup>20</sup>Stuart). An obstacle for the Bio-Oil's assimilation into current systems is its high acidity. The Environmental Protection Agency considers materials with pH less than 2 hazardous because of corrosiveness (<sup>29</sup>[www.orcbs.msu.edu/newhazard/wastemanualdocs/05classification.html](http://www.orcbs.msu.edu/newhazard/wastemanualdocs/05classification.html)). Bio-Oil's pH is not typically lower than 2, however, being that pH can decrease during storage and that the pH is close to two, it might be considered a hazardous chemical. Environmental specialist, Ron Tetu from PSNH, commented on the feasibility of burning Bio-Oil in conventional burners. He asserted that the Bio-Oil is too acidic for the piping and fuel lines of normal materials and if a spill occurred, it could be considered a hazardous waste because of its corrosiveness (<sup>30</sup>Ron Tetu).

### **5.2 Aging, Storage, and Corrosiveness**

Because of Bio-Oil's acidic nature, it is corrosive to common materials such as carbon steel and aluminum (<sup>4</sup>Oasmaa, 13). Phase separation results from reactions such as polymerization, in which larger molecules are formed, and etherification and esterification, in which water is a by-product. Larger molecules formed from polymerization reactions form a tar like bottom layer, and the top layer is acidic and has a high water content.

The viscosity of Bio-Oil also increases with aging and temperature increase. For example, viscosity of a hardwood Bio-Oil doubled after a yearlong storage at room temperature. At 60°C, the time for the viscosity to double took one week, and at 80°C, it took only one day (<sup>4</sup>Oasmaa,7). Figure 5.2.a, below, shows the increase of viscosity with time in centistokes. The source for this data was obtained from J.P. Diebold's, [A Review of the Chemical and Physical Mechanisms of the Storage Stability of Fast Pyrolysis Bio-Oils](#), which is detailed in the reference section.

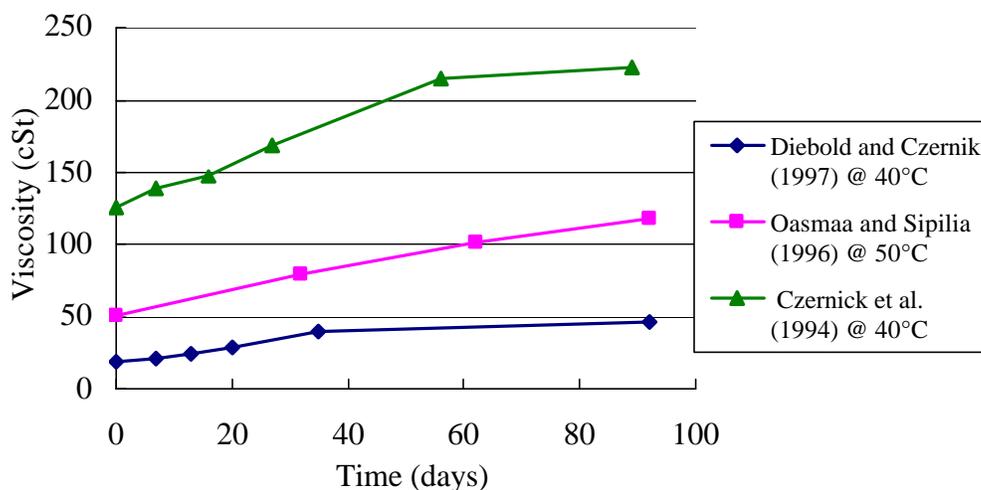


Figure 5.2.a: Viscosity Increase with Time of Bio-Oils

Another property that makes Bio-Oil difficult to store is its high oxygen content. Bio-Oil contains up to 30% oxygen, whereas hydrocarbon fuels contain less than 1% (<sup>12</sup>Brady, 29). This difference implies the lack of miscibility of Bio-Oil in hydrocarbon fuels; Bio-Oil is hydrophilic whereas hydrocarbon fuel is hydrophobic. The oxygen content in Bio-Oil also lends to oxidation reactions, and the liquid must be kept in a vacuum container to prevent this process (<sup>12</sup>Brady, 29).

Due to the properties of Bio-Oil, it must be stored in an air-free environment in resistant materials at room temperature or below (<sup>4</sup>Oasmaa, 13). Material selection is critical for all components wetted by Bio-Oil. Typically, 300 series stainless steels are acceptable metallic materials and high-density polyethylene (HDPE) or fluorinated HDPE for polymers. (<sup>10</sup>DynaMotive, 6). Copper and its alloys can also be used for pumping Bio-Oil with minimal abrasive particles at low velocities and moderate temperatures (<sup>4</sup>Oasmaa, 14).

### **5.3 Biodegradability**

In their paper, Fuel Oil Quality of Bio-mass Pyrolysis Oils- State of the Art for End-Users, Czernick and Oasmaa state that pyrolysis oils are biodegradable in both the aquatic and soil environment. This information was referenced from Determination of Biodegradation Rates of Bio-Oil by Respirometry, by Piskorz and Radlein. This topic is important for developing environmental protocol in the case of storage, handling, and spill management.

### **5.4 Emissions & Wastes Associated with Bio-Oil Production & Combustion**

The production of Bio-Oil is a contained process that generates little waste. Biomass is fed to the fluidized bed reactor, and gases are recycled in the process. The effluent from the reactor consists of recycle gas, product vapors, aerosols, and char particles (<sup>7</sup>Piskorz, 12). The char is collected and can be sold a product or burned to dry the feedstock. The vapors are quenched using cooled Bio-Oil and stored for further use.

The aerosols, collected in a demister are cleaned to yield a medium heating value gas containing CO<sub>2</sub>, CO, and CH<sub>4</sub>, which are recycled as the fluidizing gas. Some of this gas is combusted along with a supplemental fuel such as propane or natural gas to heat the fluidized bed (<sup>7</sup>Piskorz, 12). The 10 tonne per day pilot plant in Vancouver, BC, Canada, has a flare that can be used to combust gases if needed as a safety device. Since 2001, when the plant commenced operation, the flare has been used twice (<sup>20</sup>Stuart). Tests on the emissions from the flare are currently unknown.

The metals reportedly found in Bio-Oil include potassium and sodium, which comprise 5-100 ppm of Bio-Oil. When Bio-Oil is used as a fuel, these metals can cause hot erosion. However, additives to the fuel can be used to react with the metals to prevent them from liquefying. The fate of some of the metals, such as lead and mercury, has not been studied, but are likely to appear in the char. (<sup>47</sup>Czernik) The national average for lead content of wood is 20 ppm and mercury is assumed to be about 10 ppb (<sup>48</sup>Peavy). Thus for a 440 ton/day plant, it must be known that 17.6 pound or about 2.9 tons annually, would be on site or transferred from the site. Also, for the estimated mercury content, about 2.9 pounds will be on or transferred from the site annually. The implications of these metals must be considered.

Although the scope of this project tries to examine non-power generating uses of Bio-Oil, DynaMotive's primary use for the product has been as a liquid alternative to replace fossil fuel. To that end, the bulk of the research on the environmental impact of Bio-Oil has been related to its combustion. When combusted, Bio-Oil does not produce some of the emissions associated with fossil fuels. Bio-Oil is CO<sub>2</sub> and greenhouse gas neutral because it is derived from organic waste (<sup>12</sup>Brady, 29). A more complete definition of greenhouse gas neutral can be found in the frequently asked question section, Appendix A8. Because Bio-Oil combusts below the temperature at which sulfur oxides are produced, it produces no SO<sub>x</sub> emissions, thus is not subject to SO<sub>x</sub> taxes (<sup>12</sup>Brady, 28). The water content in Bio-Oil, although disadvantageous in that it reduces the heating value of the fuel and poses obstacles for mixing with diesel, is beneficial in that it helps to lower thermal NO<sub>x</sub> (<sup>10</sup>DynaMotive, 6). In fact, Bio-Oil produces about half as much NO<sub>x</sub> as number two fuel oil per energy unit produced when combusted in gas turbines (<sup>10</sup>DynaMotive, 6). Not only can solids in Bio-Oil clog equipment, but they also cause sticking of close tolerance surfaces. This can result in particulate emissions because of the long residence time required to fully combust. For this reason, it is important that the solids level in the Bio-Oil is controlled to be less than 0.1 wt % (<sup>10</sup>DynaMotive, 6).

## **6.0 Phase One: Economic Analysis**

### **6.1 Economic Results**

The economic study has been updated many times over the course of this eight-month investigation. In the beginning we considered signing a non-disclosure agreement with DynaMotive in order to critique their economic analysis, but chose not to after finding that should we sign we wouldn't be able to share our results without DynaMotive's approval. The sources of helpful information in this process include the 2002 DRED report<sup>3</sup> which gave us the cost of low-grade wood chips at \$18/ton, which has been verified by Whitefield Power and Light (WPL). WPL, a wood-fired power plant in NH that uses low-grade wood chips, stated that the NH wood chips have a moisture content of 44 to 46% (<sup>24</sup>Wells). The DynaMotive patent<sup>7</sup> and website<sup>1</sup> aided in understanding the fast pyrolysis process in regards to areas for operating costs and product conversions. The Stone & Webster Due Diligence Report<sup>11</sup> clarified the operating costs even further. Connections with Huskywood LLC<sup>12 & 13</sup>, an Alaskan consulting company studying Bio-Oil, and BEDCO<sup>14</sup>, a northern NH development group, shared information that DynaMotive's non-disclosure agreement allowed. The only item left for the economic analysis is the cost of grinding per ton of low-grade wood chips. This information will probably be found from one of the wood fired plants in NH.

#### **Table 6.1.A Capital Cost of a DynaMotive Bio-Oil Plant**

Note: Cost includes cost of feed preparation equipment, site planning, preparation, and construction. Does not include cost of land, since community would welcome facility. A metric ton is 2,204.62 lbs, while a US ton is 2,000 lbs.

Size in Wet Wood Chips (tons/day)	Cost (\$) for General DynaMotive Plant
100 metric tonne/day (110.2 US ton/day)	~6.6 million
200 metric tonne/day (220.5 US ton/day)	~8.8 million
400 metric tonne/day (440.9 US ton/day)	~14.3 million
For Every 100 tonne/day can purchase 2.5 MWe turbine for:	
100 tonne/day + 1 turbine = 2.5 MWe	~8.3 million
200 tonne/day + 2 turbines = 5 MWe	~12.2 million
400 tonne/day + 4 turbines = 10 MWe	~21.1 million

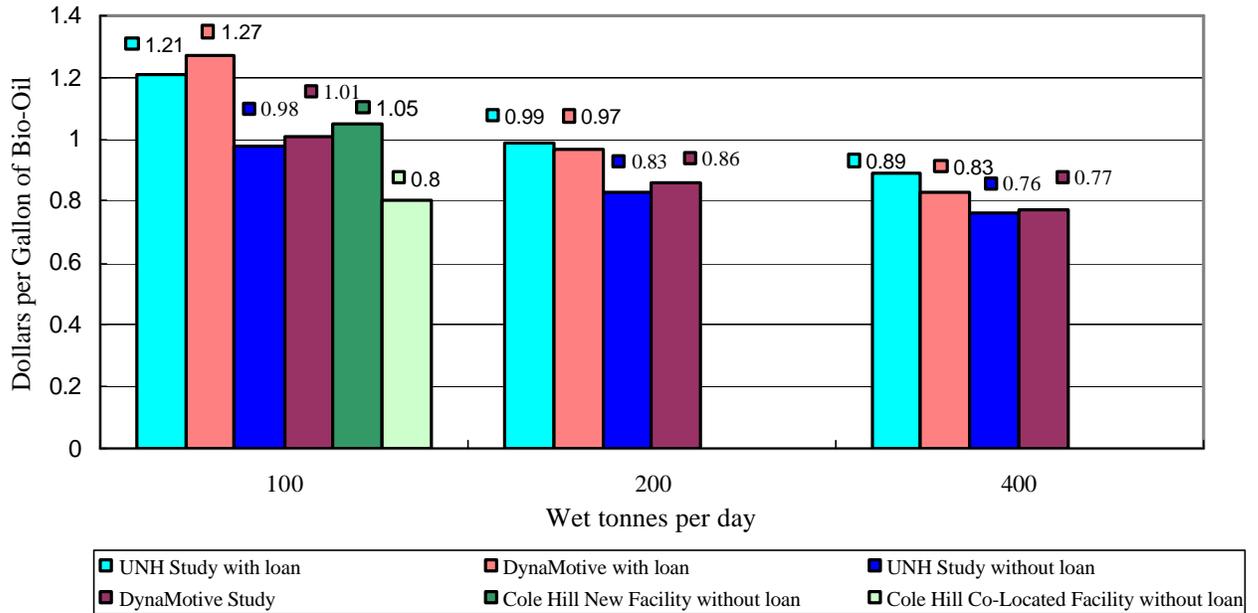
(<sup>35</sup>Stewart, 6)

The capital plant costs shown in Table 6.1.A were stated during a February meeting and have been increased by a 5-10% safety factor for planning/construction problems. The capital cost includes all equipment, including feed preparation, planning, and construction. The cost does not include the cost of land or site preparation. The offer is a turnkey package, meaning that they will guarantee to build an operating facility for that price. The plants with turbine packages have some left over Bio-Oil, which could be used for research or alternative markets.

**Table 6.1.B Dollar per Gallon Cost to Produce Bio-Oil**

Note: This is the cost for the plant to produce the Bio-Oil, the cost would be raised an unknown amount for the profit desired by the plant and allowed for in the market. The UNH study calculated the loan payments through the PMT function in Microsoft EXCEL, which is based on constant payments and a constant interest rate. The loan was set to be paid off in 10 years and had 8% interest. It is unknown what payment plan DynaMotive used to reach their cost per gallon with the capital cost included.

<b>Cole Hill Associates / BEDCO Study*</b>		
Size of Plant in wet weight per day	Cost per Gallon Capital Cost Not included	Cost per Gallon Capital Cost Included
100 metric tonne/day (110.2 US ton/day)	\$0.80 to \$1.05*	-
200 metric tonne/day (220.5 US ton/day)	-	-
400 metric tonne/day (440.9 US ton/day)	-	-
<b>DynaMotive Study**</b>		
Size of Plant in wet tons per day	Cost per Gallon Capital Cost Not included	Cost per Gallon Capital Cost Included
100 metric tonne/day (110.2 US ton/day)	~\$1.01**	~\$1.27**
200 metric tonne/day (220.5 US ton/day)	~\$0.86**	~\$0.97**
400 metric tonne/day (440.9 US ton/day)	\$0.77**	~\$0.83**
<b>University of New Hampshire Study***</b>		
Size of Plant in wet tons per day	Cost per Gallon Capital Cost Not included	Cost per Gallon Capital Cost Included
100 metric tonne/day (110.2 US ton/day)	\$0.98***	\$1.21***
200 metric tonne/day (220.5 US ton/day)	\$0.83***	\$0.99***
400 metric tonne/day (440.9 US ton/day)	\$0.76***	\$0.89***



**Figure 6.1.A – Bar Chart for Dollar per Gallon Production Cost of Bio-Oil**

When a study mentions ‘with loan’ it means that the capital cost of the plant was not paid in full at the beginning and that some form of payment plan is used to account for the capital cost. Both of the Cole Hill studies are ‘without loan.’

**Table 6.1.C.1 - Cost to Produce Bio-Oil per Therm at 80% Combustion Efficiency**

Note: A Therm is a 100,000 Btu. To convert \$/gal to \$/Therm, take \$/gal divide by density (lb/gal), divide by lower heating value (Btu/lb), multiple by 100,000 Btu's, and divide by 0.80 for a 80% heating efficiency.

Density of Bio-Oil used for Calculation	9.931 lb/gal = 1.19 kg/L	
Lower Heating Value	7057 Btu/lb = 16.4 MJ/kg	
<b>Cole Hill Associates / BEDCO Study*</b>		
Size of Plant in wet weight per day	Cost per Therm Capital Cost Not included	Cost per Therm Capital Cost Included
100 metric tonne/day (110.2 US ton/day)	\$1.43 to \$1.88	-
200 metric tonne/day (220.5 US ton/day)	-	-
400 metric tonne/day (440.9 US ton/day)	-	-
<b>DynaMotive Study**</b>		
Size of Plant in wet weight per day	Cost per Therm Capital Cost Not included	Cost per Therm Capital Cost Included
100 metric tonne/day (110.2 US ton/day)	~\$1.80	~\$2.26
200 metric tonne/day (220.5 US ton/day)	~\$1.53	~\$1.73
400 metric tonne/day (440.9 US ton/day)	\$1.37	~\$1.48
<b>University of New Hampshire Study***</b>		
Size of Plant in wet weight per day	Cost per Therm Capital Cost Not included	Cost per Therm Capital Cost Included
100 metric tonne/day (110.2 US ton/day)	\$1.75	\$2.16
200 metric tonne/day (220.5 US ton/day)	\$1.48	\$1.77
400 metric tonne/day (440.9 US ton/day)	\$1.36	\$1.59

**Table 6.1.C.2 - NH Market Fuel Costs per Therm Comparison**

Note: All numbers in this table are from the NH Governor's Office of Energy & Community Services July 3, 2002 Fuel Cost Comparison Report.

Fuel Type	Oil	Kerosene	Propane	Natural Gas	Electric	Wood
Cost per Unit	\$1.084 /gal	1.394 /gal	1.402 /gal	0.6898 /therm	0.11427 /kWh	185 cord
Btu per Unit	138,000 /gal	134,000 /gal	91,000 /gal	100,000 /therm	3412 /kWh	24,000,000 cord
Heating System Efficiency	80%	80%	80%	80%	100%	60%
Cost per Therm	\$0.98 /therm	\$1.30 /therm	\$1.93 /therm	\$0.86 /therm	\$3.35 /therm	\$1.28 /therm

(<sup>36</sup>NH ECS)

As shown from Table 6.1.C.1, Bio-Oil's cost per therm to produce ranges from \$1.36 to \$2.26 depending on the analysis and size of the plant. The other fuel's costs

were market value, meaning that the Bio-Oil's final cost would be higher due to the Bio-Oil company's desire for profit.

**\*Cole Hill Associates / BEDCO Study:**

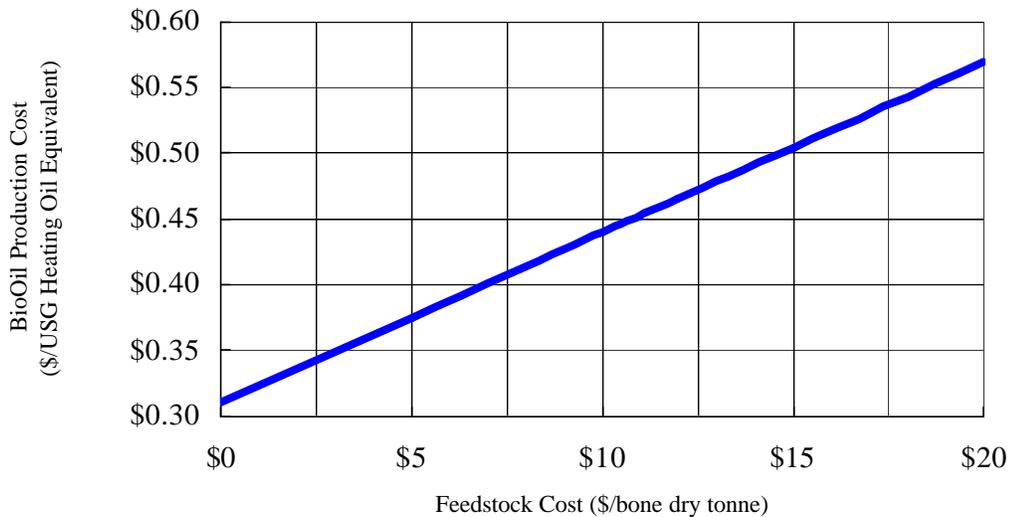
The Cole Hill Associates & BEDCO study had the following details:

- 1.) No char revenue.
- 2.) Portion of char used to dry low-grade wood chips.
- 3.) Capital cost of the plant is paid completely in the beginning, such that interest does not have to be paid.
- 4.) Feedstock is 100% hardwood chips received at 50% moisture and a cost of \$18/ US wet ton.
- 5.) Electricity purchased at \$0.065/kWh for electrostatic precipitator, pumps, compressors, etc.
- 6.) No royalties, just licensing fees in original payment
- 7.) No cost of land or property taxes, since town should want facility to be built in their region.
- 8.) 30% overhead for employees
- 9.) Maintenance at 10% of capital cost of facility
- 10.) 5 cents/gallon transportation cost
- 11.) 90% of operating year, operation during 330 days a year, 24 hours a day.

The \$0.80/gal cost is for a Bio-Oil 100 US ton per day facility co-located with a wood-fired plant, while the \$1.05/gal cost is for a new 100 US ton per day facility.  
(<sup>20</sup>Stewart)&(<sup>35</sup>Stewart)

**\*\* DynaMotive Study:**

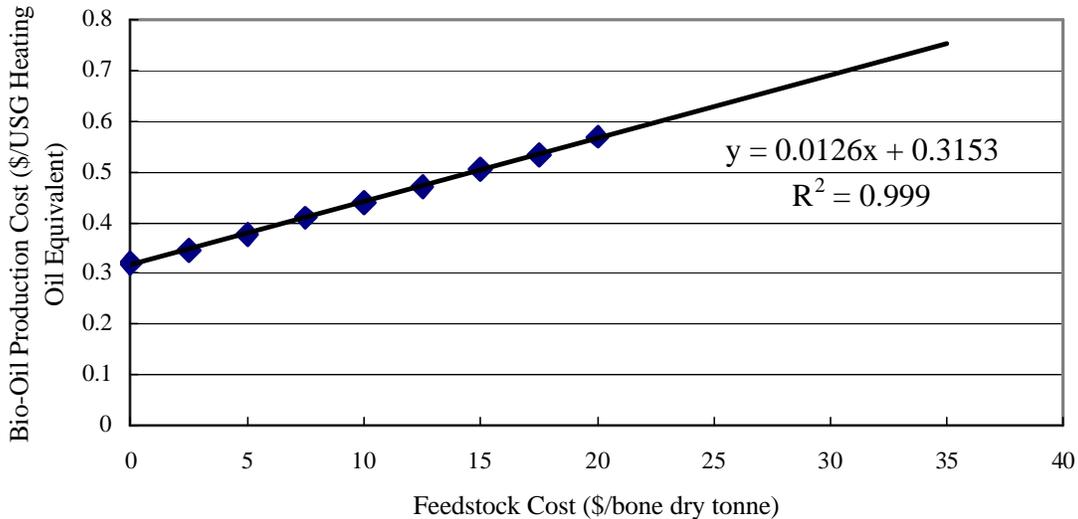
The following chart is from a DynaMotive presentation given in Alaska.



**Figure 6.1.B DynaMotive's Dollar per Gallon Results**

Figure 6.1.B was taken from a DynaMotive presentation for an Alaskan Feasibility Study. The information is based on a 400 metric tonne/day plant in Western Canada.<sup>(13Brady)</sup>

In NH, wet wood at 45% moisture costs \$18/ US ton (<sup>24Wells</sup>), meaning that a bone dry ton (0% moisture) costs  $\$18/(0.55) = \$32.73/\text{US dry ton}$ . The DynaMotive chart uses metric tons meaning that  $\$32.73/\text{US dry ton}$  equals  $\$36.08/\text{metric tonne}$ . Since this value is off DynaMotive’s linear graph, extrapolation was required.



**Figure 6.1.C – Adjusted DynaMotive Economic Model showing Heating Oil Energy Equivalent Bio-Oil Production Cost vs. Feedstock Cost.**

When the appropriate feedstock cost ( $x = \$36.08/\text{metric tonne}$ ) is plugged in to the equation shown in Figure 6.1.C, the result is a cost per gallon for production of \$0.77 by DynaMotive’s analysis of a Western Canada plant using our cost of feedstock.

To obtain the DynaMotive values for a 100 and 200 tonne/day, the cost relationships for a previous DynaMotive study for a co-located facility were modeled with the newer 400 metric tonne/day day cost of \$0.77/gal. The co-located facility under question would be a combination of a Bio-Oil facility along with a NH wood-fired plant sharing the same facilities. The numbers presented are in the following table. Note that these numbers were from February of 2002 and it is highly possible that they have been updated, but our assumption is that the basic pattern between them will remain the same.

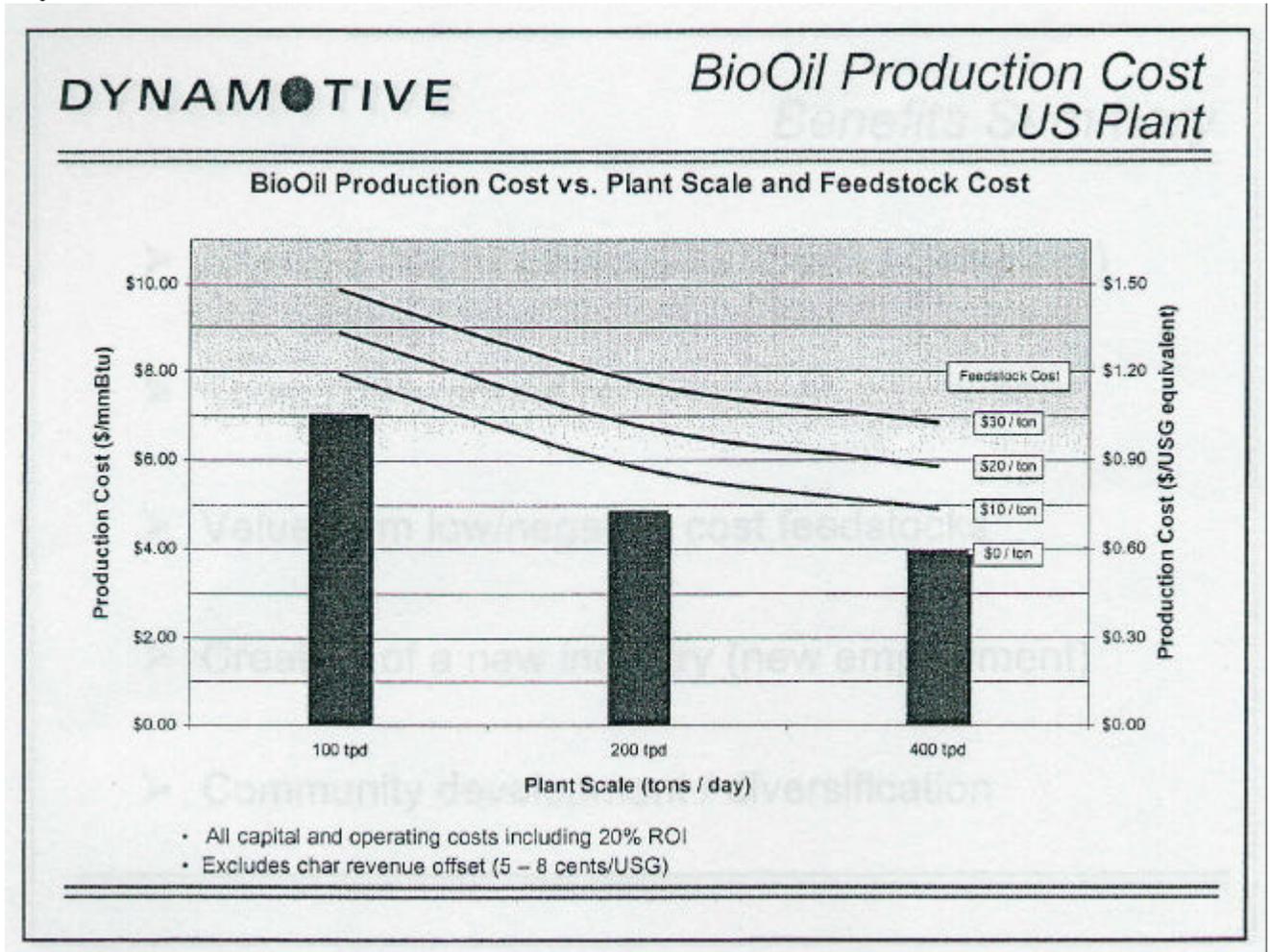
**Table 6.1.D – Modeling of DynaMotive Dollar per Gallon (DPG) Economics Applied to New Hampshire**

Note: Assuming Wood cost of 18/wet ton and 45% moisture content.

Size of Facility in Wet tons & (Dried tons 8.33% moisture)	February 2002 DPG (Co-Located Facility) ( <sup>35</sup> Stewart, 17)	ΔDPG (Change in Dollar per Gallon)	July 2002 Modeled DPG Numbers (Stand alone facility)
100 metric tonne/day (60 metric dry tonne/day)	\$0.63/gal	-	\$1.01/gal
200 metric tonne/day (120 metric dry tonne/day)	\$0.48/gal	\$0.15	\$0.86/gal
300 metric tonne/day (180 metric dry tonne/day)	\$0.42/gal	\$0.06	\$0.80/gal
400 metric tonne/day (240 metric dry tonne/day)	\$0.39/gal	\$0.03	\$0.77/gal****

\*\*\*\*The 400 metric tonne/day value was found from Figures 6.1.B & 6.1.C above, while the rest of the July 2002 modeled numbers were found using the change in dollar per gallon, ΔDPG, off the base 400 metric tonne/day value. Example...\$0.77/gal + \$0.03 = \$0.80/gal, etc. The assumptions that DynaMotive took for their original economic values and the projected ones are unknown.

**\*\*Second Economic Analysis of DynaMotive Information – Includes Capital Cost Payment Plan**



(<sup>53</sup>Kingston)

**Figure 6.1.D - Economic Analysis by DynaMotive for US Plant.**

It is assumed that the feedstock cost shown on the figure is for wet tons (~45 to 50% moisture) and the plant scale is with wet tons due to discussions with BEDCO that the DynaMotive cost per gallon was in the range of 85 cents and up. This would mean that the wet wood feedstock cost would be \$18/US ton and that the dollar per gallon cost for Bio-Oil for a 440 ton/day plant (= 400 tonne/day) would be approximately 85 cents. Otherwise the cost for dry wood would be \$32.73/ US ton and the Bio-Oil would cost approximately \$1.00 for a 440 ton/day plant (=400 tonne/day). Comparison is for 440 US ton/day plants because all other economic analysis was based on metric values, i.e. for 100, 200, & 400 metric tonne/day plants (=110, 220, & 440 US ton/day plants respectively).

**Table 6.1.E DynaMotive Economic Summary of Figure 6.1.D**

Plant Size in wet metric tons and (US tons)	Approximate Dollars per Gallon
100 tonne/day (110 ton/day)	~1.27
200 tonne/day (220 ton/day)	~0.97
400 tonne/day (440 ton/day)	~0.83

Figure 6.1.D states that, “all capital and operating costs including 20% ROI,” suggesting that the dollar per gallon cost includes payments for capital cost.

**\*\*\* University of New Hampshire Study:**

The University of New Hampshire study had the following details:

- 1.) Analysis done for two situations, one where capital cost of the plant is paid completely in the beginning, such that interest does not have to be paid. The second situation is where a loan is taken out that is paid over 10 years at 8%. Equal payments are due at the end of each annual period.
- 2.) Assume that the char is used for drying and not used for making charcoal briquettes or activated carbon, which NH both have to import.
- 3.) Assumed that the transfer of heat energy to the low-grade wood from the char is at least 34% efficient. Otherwise, not enough char exists for drying.
- 4.) Even though the wood chip piles would be dried to some extent by the weather during the warmer months, it will be assumed that this does not occur. It is unknown how much the sitting process actually dries the wood.
- 5.) The heat capacity of wood varies depending on the type of the wood and its moisture content. We assumed that the heat capacity given will be that of bone dry wood (approximately 1.76 to 2.5 kJ/kg°C).
- 6.) Feedstock includes bark, hardwood, and softwood received at 45% moisture and a cost of \$18/ton. (<sup>37</sup>York)
- 7.) The yields of Bio-Oil, char, and gas are taken to be respectively 66%, 21%, and 13%. These are the median values shown by Stone & Webster’s tests. (<sup>11</sup>Stone, 1)
- 8.) Electricity purchased at \$0.065/kWh for electrostatic precipitator, pumps, compressors, etc.
- 9.) No royalties, just licensing fees in original payment
- 10.) No cost of land or property taxes, since town should want facility to be built in their region.
- 11.) 30% overhead for employees
- 12.) Maintenance at 10% of capital cost of facility
- 13.) 5 cents/gallon transportation cost
- 14.) Cost to grind the 2-inch wood chips to approximately 0.04 inches is assumed to be \$5/ton.
- 15.) Cost of nitrogen and miscellaneous chemicals was taken from the <sup>11</sup> Stone and Webster Report and scaled up linearly.

- 16.) The amount of natural gas needed was calculated from a DynaMotive figure that a MJ of energy was needed for each kg of Bio-Oil. (<sup>8</sup>DynaMotive, 3) The cost of natural gas was taken from the NH Governor's Office of Energy and Community Services webpage for July 2002. (<sup>36</sup>NH ECS)
- 17.) The amount of electricity used for each size plant was provided by a source that has asked to remain anonymous.
- 18.) The cost of non-production labor (excepting the position for accountant, bookkeeper, and purchasing), non-production utilities, and supplies & services were linearly scaled down from values given for the ~700 ton/day wood-fired plants in NH. (<sup>3</sup>DRED, 12)
- 19.) The cost of water for usage in heat exchangers, potable water, sewage, etc was determined from the Stone & Webster analysis and scaled up linearly. The value given for a 25 tonne/day plant seemed high and was taken for a 100 tonne/day plant (<sup>11</sup>Stone, 30).
- 20.) About total 10 workers are required for a 100 tonne/day plant, 14 total workers are required for a 200 tonne/day plant, and 19 workers are required for a 400 tonne/day facility. This information comes from modeling numbers given in a DynaMotive presentation. (<sup>53</sup>Kingston)
- 21.) The cost of petroleum products based on Table 6.1.c.2, prices for July 2002.

## **Operating Costs:**

### **6.1.1.) Wood Chip Purchasing Cost**

Cost of the low-grade wood chips available in NH range from \$18 to \$20/wet US ton. The low-grade wood is comprised of soft woods and hard woods, where soft woods have less BTU content. (<sup>38</sup>Bartlett) The 2002 DRED report shows that the cost to cut, skid, chip, and truck the low-grade wood chips to the logger in NH is \$16/wet ton. Landowners are paid \$0.50 to \$1.50 per wet ton for whole tree chips. (<sup>3</sup>DRED, 88) The combination of these two prices makes the total cost to the logger around \$16.50 to \$17.50 per wet ton. The logger then has to make some profit, meaning that the cost of low-grade wood chips will not decrease significantly without government aid or technological advances in preparing woodchips.

The average price of wood at the Whitefield Light and Power wood fired plant has been \$18.83/wet ton from 1996 to 2000 with a variance of \$14 to \$19. (<sup>3</sup>DRED, 89)

**Table 6.1.F – Wood Chip Purchasing Costs**

Wet Wood Plant Size	100 metric tonne/day = 110.231 US ton/day	200 metric tonne/day = 220.462 US ton/day	400 metric tonne/day = 440.924 US ton/day
Days a Year of Operation	330 days/yr, 90% of year.		
Hours a Day	24 hours a day		
Operating Hours a Year.	7920 hrs/yr		
Annual Wet Feedstock Processed	36,376 wet US tons/yr	72,752 wet US tons/yr	145,505 wet US tons/yr
Cost of Feedstock per ton	\$18/wet US ton		
Cost of Feedstock per Year	\$654,772/yr	\$1,309,544/yr	\$2,619,089/yr

Table 6.1.F, above, shows the amount of wet tons of wood used in a year and the annual cost taking the cost of wood at \$18/ wet ton and a plant operating for 24 hours a day, 330 days a year.

**6.1.2.) Cost of Grinding the Low-Grade Wood Chips**

At present the cost of grinding the low-grade from the delivered 2-inch diameter to 3mm (0.12 inches) or 1mm (0.04 inches) is unknown. (<sup>37</sup>York) The cost to chip the wood chips to the 2-inch diameter from branches and stumps is \$4/ton (<sup>3</sup>DRED, 89), so the cost to grind the 2-inch wood chips to approximately 0.04 inches is assumed to be \$5/ton.

**Table 6.1.G – Cost of Grinding**

Wet Wood Plant Size	100 metric tonne/day	200 metric tonne/day	400 metric tonne/day
Cost of Grinding per ton from 2 inch to 0.04 inch diameter	\$5/wet ton		
Cost of Grinding per year	\$181,881/yr	\$363,762/yr	\$727,525/yr

**6.1.3.) Cost of Drying the Low-Grade Wood Chips**

At the wood-fired plants, the wood chips are often dried during the warmer months by letting the piles sit for at least 30 days and preferably four to six weeks. In the winter months the outdoor drying does not work well due to the snow and low

temperatures. (<sup>37</sup>York) The piles are rotated periodically to prevent fermenting. (<sup>38</sup>Bartlett)

A Bio-Oil facility would most likely use a similar system of using outdoor/indoor pile drying first and then drying the woodchips further with indirect heating from electric heating or combustion of a fuel. The possibility of using waste heat or excess heat from the pyrolysis reactor or heat exchangers also exists. As stated earlier the wood arrives at 45% moisture content and must be below 10% moisture content before entering the pyrolysis reactor.

For the purposes of the economic analysis the char created in the process will be burned to supply the heat required to dry the low-grade wood. The following calculations will show that as long as the burning of the char is at least 34% efficient in energy transfer that enough char exists to dry all the wood to the required moisture content.

Should it be possible to chip the low-grade wood chips at 45% moisture content before drying them, the increased surface area would increase drying rates. Once the wood chips are chipped to a 1mm (0.04 inch) diameter, the material should be stored inside to avoid the wind blowing the small wood pieces around.

**Table 6.1.H – Heat & Material Properties**

Heat Capacity of Water (Felder & Rousseau, 637)	89.732 kWh/ton°C = 4.188 kJ/kg°C = 85.113 Btu/lb°F
Heat of Evaporation for the Water (Felder, 634)	569.22 kWh/ton = 2258.67 kJ/kg = 971.9 Btu/lb
Heat Capacity of Wood*	0.4435 to 0.63 kWh/ton = 1.76 to 2.5 kJ/kg°C = 0.4207 to 0.5976 Btu/lb°F

\*Note: The heat capacity of wood varies depending on the type of the wood and its moisture content. We assumed that the heat capacity given will be that of bone dry wood. This will overestimate the heat needed because the less water that is in the wood the lower the heat capacity will be. Hence we are using a higher heat capacity than bone dry wood would have. To counter this overestimate the lower value on the heat capacity range will be used. (<sup>40</sup>Univ. of Minnesota)

To estimate the heat required to dry the wood, the water and wood will be warmed from 15°C (59°F) to 100°C (212°F) and then all the water will be evaporated. This will be a conservative estimate since the moisture content of the wood only has to be less than 10%.

**Table 6.1.I – Drying Heat Requirements**

Note to find any of the heat requirements multiply the heat capacity or heat of evaporation (Table 6.1.H) times the amount of substance of interest.

Wet Wood Plant Size	100 tonne/day	200 tonne/day	400 tonne/day
Tons of Water in wood per year assuming 45% moisture content	16,369 tons/yr	32,739 tons/yr	65,477 tons/yr
Tons of Bone Dry Wood per year	20,007 tons/yr	40,014 tons/yr	80,028 tons/yr
Energy to Heat the Water (15° to 100°C) (kWh)	1,468,850 kWh	2,937,701 kWh	5,875,401 kWh
Heat to Evaporate the Water (kWh)	9,317,735 kWh	18,635,470 kWh	37,270,940 kWh
Heat for the Wood (15° to 100°C) (kWh)	8,873 kWh	17,746 kWh	35,492 kWh
Total Heat Requirement	10,795,458 kWh	21,590,917 kWh	43,181,833 kWh

Assume that the char is used for drying and not used for making charcoal briquettes or activated carbon, which NH both have to import. (<sup>41</sup>Newell) The total heat requirement from Table 6.1.I is then compared with the amount of energy available from the char in Table 6.1.J.

**Table 6.1.J – Drying with Char**

Higher Heating Value of Char (MJ/ton)	25,038 MJ/ton = 27.6 MJ/kg( <sup>11</sup> Stone, 10)		
Wet Wood Plant Size	100 tonne/day	200 tonne/day	400 tonne/day
Tons of Char Created	4,583 tons/yr	9,167 tons/yr	18,334 tons/yr
Total Energy from Char Available	114,585,125 MJ/yr	229,170,249 MJ/yr	458,340,498 MJ/yr
Char left if 100% efficient heat transfer for drying	66% (3,029 tons/yr)	66% (6,058 tons/yr)	66% (12,116 tons/yr)
Char left if 50 % efficient heat transfer for drying	16% (737 tons/yr)	16% (1,475 tons/yr)	16% (2,949 tons/yr)
Char left if 34% heat transfer for drying	0.1% (4 tons/yr)	0.1% (8 tons/yr)	0.1% (16 tons/yr)

Note: The yields of Bio-Oil, char, and gas are taken to be respectively 66%, 21%, and 13%. The DynaMotive website claims yields of 60-75% Bio-Oil, 15-25% char, and 10-20% gas. The yields for this economic analysis were chosen as values approximately in the middle of those provided. (<sup>11</sup>Stone, 1)

#### 6.1.4.) Utility Costs

**Table 6.1.K – Utility Operating Costs**

Wet Wood Plant Size	100 tonne/day	200 tonne/day	400 tonne/day
Amount of Electricity Used per operating hour	550 kWh/hr	962 kWh/hr	1788 kWh/hr
Operating Hours a Year.	7920 hrs/yr		
Electricity @ \$0.065/kWh	\$283,140/yr	\$495,238/yr	\$920,462/yr
Nitrogen	\$80,000/yr	\$160,000/yr	\$320,000/yr
Miscellaneous Chemicals	\$120,000/yr	\$240,000/yr	\$480,000/yr
Amount of Natural Gas Needed (MJ/yr)	13,068,000 MJ	26,136,000 MJ	52,272,000 MJ
Natural Gas @ (\$0.00675/MJ)	\$88,214/yr	\$176,428/yr	\$352,856/yr

The amount of electricity used for each size plant was provided by a source that has asked to remain anonymous. (<sup>39</sup>Anonymous) The cost of the electricity was chosen after examining the New England Average Monthly Electricity Prices from 1999 to 2001 distributed by ISO New England. The average electricity price over this period was \$0.039/kWh, with the maximum being \$0.0728/kWh and the minimum being \$0.0239/kWh. A conservative value of \$0.065/kWh was chosen for this study. (<sup>4</sup>DRED, 50)

In the Stone & Webster Economic Analysis, nitrogen is shown to cost \$20,000/yr for a 24 ton per day Bio-Oil plant. The cost of nitrogen for larger plants was reached by linearly scaling up the cost of a smaller plant. (i.e. 24 tonne/day\*4= ~100 tonne/day & \$20k\*4= \$80k) The exact amount of nitrogen used to provide fluidization in the bed is unknown and because of this the Stone & Webster values were scaled up. The nitrogen would most likely be trucked to any plant built in northern NH.

The same method was used to calculate the miscellaneous chemicals used in the process. Miscellaneous chemicals were priced at \$30,000/yr for a 24 tonne/day plant. The known miscellaneous chemicals include the special sand that is used in the reactor bed and possibly the quench fluid. The Stone & Webster report was released in the 1999 era when DynaMotive was still using quench fluid. Since then they use previously created Bio-Oil to quench the Bio-Oil gas vapors. (<sup>20</sup>Stewart) Therefore, the cost of the miscellaneous chemicals could possibly be less and our estimate is conservative.

The amount of natural gas used in the process was calculated through a 2001 DynaMotive claim that 1.0 MJ of energy from an external fuel source out of a total 2.5 MJ is needed per kg of Bio-Oil. (<sup>10</sup>DynaMotive, 3) DynaMotive also claims that the non-condensable gases are recycled to supply 75% of the energy needed in the process on their 2002 website. (<sup>1</sup>DynaMotive.com/biooil). The two claims are not in unison due to  $(2.5-1.0)/2.5 = 60\%$  of the energy supplied. In the interest of being conservative the 1.0 MJ/kg of Bio-Oil method was used.

### 6.1.5.) Non-Production Utilities & Labor

**Table 6.1.L – Non-Production Costs**

Wet Wood Plant Size	700 ton/day wood-fired plant	110.231 US ton/day	220.462 US ton/day	440.924 US ton/day
Additional Non-Production Labor (loaded)	\$281,250/yr	\$44,196/yr (1 employee)	\$88,393/yr (2 employees)	\$176,786/yr (4 employees)
Utilities (non-production)	\$125,000/yr	\$19,643/yr	\$39,286/yr	\$78,571/yr
Supplies & Services	\$400,000/yr	\$62,857/yr	\$125,714/yr	\$251,429/yr
Heat Exchanger Water, Potable Water & Sewage	Not Available	\$10,000/yr	\$20,000/yr	\$40,000/yr

The non-production costs for the roughly 700 US ton/day wood-fired plant were taken from the 2002 DRED report. The figures for the 110 US ton/day, 220 ton/day, and 440 ton/day are just fractions (110/700, 220/700, and 440/700) the cost of the 700 ton/day plant. The potable water & sewage estimates were modeled off the Stone & Webster analysis.

### 6.1.6.) Labor Costs:

**Table 6.1.M – Labor Costs**

100 tonne/day Workers	Base Pay \$/yr	Fully-Loaded Pay (30% overhead)
1. Manager	\$80,000	\$104,000
2. Supervisor	\$60,000	\$78,000
3. Shift Breaker	\$35,000	\$45,500
4. 2 <sup>nd</sup> Shift Breaker	\$35,000	\$45,500
5. Field Operator	\$35,000	\$45,500
6. 2 <sup>nd</sup> Field Operator	\$35,000	\$45,500
7. Forklift Operator	\$25,000	\$32,500
8. 2 <sup>nd</sup> Forklift Operator	\$25,000	\$32,500
9. Accountant, Bookkeeper, & Purchasing	\$45,000	\$58,500
	Total for 100 tonne/day	\$487,500/yr
12 employees (factor 1.333 * 100 tonne/day labor)	Total for 200 tonne/day	\$649,984/yr
15 employees (factor 1.666 * 100 tonne/day labor)	Total for 400 tonne/day	\$812,468/yr

About total 10 workers are required for a 100 tonne/day plant, 14 total workers are required for a 200 tonne/day plant, and 19 workers are required for a 400 tonne/day

facility. This information comes from modeling numbers given in a DynaMotive presentation. (<sup>53</sup>Kingston) Table 6.1.M shows a majority of production labor and other non-production labor is shown in Table 6.1.L.

For comparison purposes, a 700 US ton/day wood-fired facility has a total of 21 employees with 16 devoted to production and 5 to non-production. The labor cost for said wood-fired plant is \$975,000/yr.

**6.1.7) Maintenance**

Yearly maintenance costs are estimated to be 10% of the capital cost of the plant and include maintenance labor. (<sup>54</sup>Ulrich)

**Table 6.1.N -Maintenance**

Wet Wood Plant Size	100 tonne/day	200 tonne/day	400 tonne/day
Maintenance Cost	\$660,000/yr	\$880,000	\$1,430,000/yr

**6.1.8.) Transportation of the Bio-Oil**

Transportation is estimated at \$0.05/gal for liquid oil. (<sup>20</sup>Stewart)

**Table 6.1.O -Transportation**

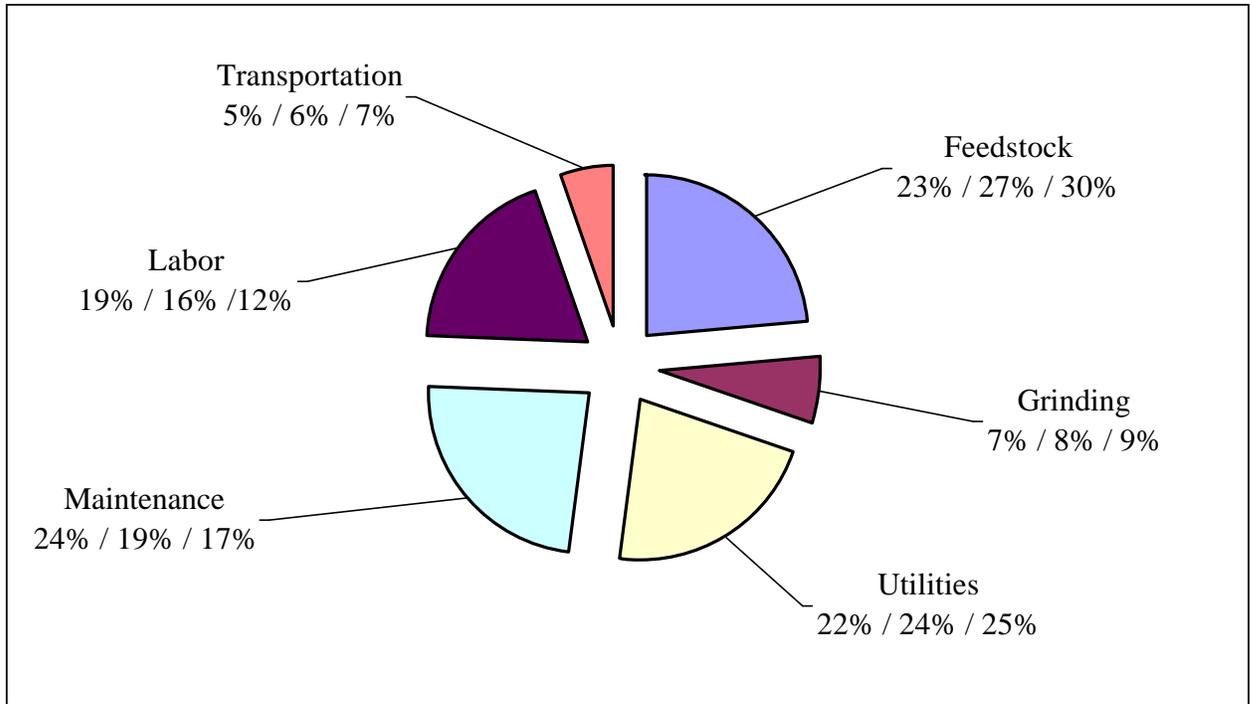
Wet Wood Plant Size	100 tonne/day (110.231 US tons/day)	200 tonne/day (220.462 US tons/day)	400 tonne/day (440.924 US tons/day)
Bio-Oil Produced (gallons/day)	8,790.9 gals/day	17,581.7 gals/day	35,163.5 gals/day
Bio-Oil Produced (gallons/year)	2,900,986 gal/yr	5,801,972 gal/yr	11,603,945 gal/yr
Gallons Produced / US ton of wet wood (& per tonne)	79.75 gals/US ton = 1.9 bbl/US ton* (87.9 gals/metric ton)		
Cost for Transportation	\$145,049/yr	\$290,099/yr	\$580,197/yr

\* A barrel (bbl) is defined as 42 gallons. (<sup>25</sup>McCabe, 1063)

### 6.1.9.) Total Operating & Capital Costs

**Table 6.1.P - Operating Costs**

Wet Wood Plant Size	100 tonne/day (110.231 ton/day)	200 tonne/day (220.462 ton/day)	400 tonne/day (440.924 ton/day)
Feedstock Cost	\$654,772	\$1,309,544	\$2,619,089
Grinding Cost	\$181,881	\$363,762	\$727,525
Electricity for process	\$283,140	\$495,238	\$920,462
Nitrogen	\$80,000	\$160,000	\$320,000
Miscellaneous Chemicals	\$120,000	\$240,000	\$480,000
Natural Gas	\$88,214	\$176,428	\$352,856
Labor	\$487,500	\$649,984	\$812,468
Maintenance	\$660,000	\$880,000	\$1,430,000
Additional Non-Production Labor	\$44,196	\$88,393	\$176,786
Utilities (non-production) + potable water	\$19,643	\$39,286	\$78,571
Potable water, Heat Exchanger water, sewage.	\$10,000	\$20,000	\$40,000
Supplies & Services	\$62,857	\$125,714	\$251,429
Transportation	\$145,049	\$290,099	\$580,197
<b>Total Annual Operating Cost</b>	<b>\$2,837,252/yr</b>	<b>\$4,838,448/yr</b>	<b>\$8,789,383/yr</b>
Gallons Produced	2,900,986	5,801,972	11,603,945
Dollars per Gallon Capital Cost Payment Plan Not Included	\$0.98/gal	\$0.83/gal	\$0.76/gal
Capital Cost	\$6,600,000	\$8,800,000	\$14,300,000
Annual Loan Payment (equal amounts, payback period of 10 years at 8%)	\$684,441/yr	\$912,588	\$1,482,956
<b>Total Annual Operating Cost with Loan Payments</b>	<b>\$3,521,693/yr</b>	<b>\$5,751,036/yr</b>	<b>\$10,272,339/yr</b>
Dollars per Gallon with Capital Cost Payment Plan	\$1.21/gal	\$0.99/gal	\$0.89/gal



**Figure 6.1.E – Pie Chart of Operational Costs in Percent for 100 / 200 / 400 tonne/day Plants Respectively**

## **6.2 Bio-Oil for Residential Home Heating**

Bio-Oil for residential heating is still in the future. However, in order to translate the volume of Bio-Oil that could be produced in New Hampshire into meaningful numbers, the homes that could be heated using Bio-Oil as a replacement for number two fuel oil was determined.

Converting this 1.3 million tons of wet wood chips annually into Bio-Oil translates to being able to heat between 49-71% of all, or one and a half times as many homes currently using number two fuel in the three northern most counties: Grafton, Coos, and Carroll. This amounts to heating between about 48,123-69,205 housing units. This was determined using information from the NH Governor’s Office of Energy & Community Services web page (<sup>26</sup>NH ECS Web Page) and calculations from UNH’s economic analysis about the yield of Bio-Oil from various size plants.

Table 6.2.a shows the number of housing units in the three most northern counties, as well as the number of housing units in New Hampshire (<http://quickfacts.census.gov/qfd/states/33000.html>) as well as the number of units in each county and the state using number two fuel oil. The units using number two fuel oil were determined from the fraction of energy consumed from number two fuel oil in NH. On the Governor’s Office of Energy and Community Services Energy Facts for 2002, two total energy consumption figures were given for residential home heating. Depending on which figure more accurately reflects New Hampshire, the fraction of homes using number two ranges from 32% to 46% of the total energy residentially consumed in New Hampshire. This same fraction is assumed to hold in the three northern

most counties. Both cases are considered in determining the number of homes that could convert from number two fuel oil to Bio-Oil if the technology was available.

**Table 6.2.a: Number of Housing Units for Three Northern Counties and New Hampshire's Total**

County	# of Units	If 32% of NH using #2	If 46% of NH Using #2
Carroll	37,750	12,080	17,365
Coos	19,623	6,279	9,026
Grafton	43,729	13,993	20,115
3 Counties Total	98,102	31,392	45,127
NH Total	547,024	175,047	251,631
% of NH represented by 3 Northern Counties	18%		

The facts about number two fuel usage for residential use in New Hampshire can be seen in Table 6.2.b, below:

**Table 6.2.b: Residential Annual Use of #2 and Energy from #2**

#2 Annual Residential Use in NH :	Value
Barrels, million bbl/yr (42 gal/bbl)	4.555
Million Gallons, million gal/yr	$4.555 \times 42 = 191.3$
TBtu/yr (HV #2 = 0.14 TBtu/Mgal)	$191.3 \times 0.14 = 26.8$

From the number of homes in NH using number two fuel oil, and the given energy content of the total amount of number two fuel used, the energy requirement for each housing unit was determined as can be seen in table 6.2.c.

**Table 6.2.c: Energy Required per Housing Unit Using Number Two Fuel**

Energy Required per housing unit annually	If 32% of NH using #2	If 46% of NH Using #2
Million Btu/unit-yr	$26.8 \times 10^{12} / 175,047 = 153$	$26.8 \times 10^{12} / 251,631 = 107$

Table 6.2.d shows the volume of Bio-Oil and energy content of Bio-Oil for three different capacity plants and how much Bio-Oil would be produced from 1.3 million tons of low-grade wood chips annually.

**Table 6.2.d. Bio-Oil Information**

	100 metric tpd	200 metric tpd	400 metric tpd
Bio-Oil Yield, gal/yr	2,901,000	5,802,000	11,604,000
Bio-Oil plants to use 1.3 million tons wood per year	36	18	9
Bio-Oil from 1.3 million tons wood annually, million gal/yr	103.6		
Bio-Oil Heating Value, Btu/gal	70,083		
Total TBtu Available from 1.3 million tons wood, TBtu/yr	7.3		

Table 6.2.e shows the number of homes that could replace number two fuel with Bio-Oil.

**Table 6.2.e: Number of Units and Percentage of NH and Northern Counties Possibly Replaced by Bio-Oil**

	If 32% of NH using #2	If 46% of NH Using #2
Number of units that could be replaced by Bio-Oil	$7.3 * 10^{12} / 153 * 10^6 =$ 47,700	$7.3 * 10^{12} / 107 * 10^6 =$ 68,200
Units replaced using #2 in NH	$47,700 / 175,047 =$ 27%	$68,200 / 251,631 =$ 27%
Units replaced in 3 northern counties using #2 (Carroll, Coos, and Grafton)	$47,700 / 31,392 =$ 151%	$68,200 / 45,127 =$ 151%
Percentage of ALL homes in 3 northern counties	$47,700 / 98,102 =$ 47%	$68,200 / 98,102 =$ 70%
Percentage of ALL homes in NH	$47,700 / 547,024 =$ 9%	$68,200 / 547,024 =$ 12%

This shows that the wood that becomes available when the wood fired power plants close would produce enough Bio-Oil to replace number two fuel in all of the homes in the northern three counties currently using number two, and still be able to heat about another 17,000 housing units.

## **7.0 Phase Two: End-Use Markets**

### **7.1 Power Generation**

One of the common applications for Bio-Oil is as a fuel for electric power generation. Organizations testing Bio-Oil in engines include Wartsila Diesel, in Finland, Onnrod Diesel in Great Britain, and Orenda in Canada. DynaMotive has worked closely with their business partner, Orenda Aerospace Corporation, a Magellan Aerospace Company, to develop the 2.5 MW OGT2500, an industrial gas turbine (<sup>10</sup>DynaMotive, 6). This turbine has been specially designed to use Bio-Oil, rather than the conventional number two or number six fuel oil. The turnkey package, using Bio-Oil offered by Orenda, is comprised of a 100 tonne per day plant with a 2.5 MWe turbine.

One of the alterations to the turbine includes changing the fuel system and nozzle to handle a higher flow rate. Since the heating value is about half that of number two fuel, the flow rate must be doubled to achieve the same power. Because of Bio-Oil's high viscosity, the efficiency of fuel atomization is also an issue that must be addressed to achieve complete combustion. The Bio-Oil turbine engine is designed for proper atomization, thus attaining complete combustion and reducing CO emissions. (<sup>10</sup>DynaMotive, 6). Also, the ash content of Bio-Oil is addressed by creation of a turbine wash system that allows turbine cleaning without any downtime (<sup>10</sup>DynaMotive, 6). The current gas turbine by Orenda starts on diesel fuel, since Bio-Oil has poor ignition characteristics. Then after the warm-up period, the diesel is phased out and replaced with 100% Bio-Oil (<sup>10</sup>DynaMotive, 7). In addition to gas turbines, DynaMotive has more recently been exploring the use of Bio-Oil in the industrial fuels market. Through work with the Canadian federal department of Natural Resources (NRCan) CANMET Energy Technology Centre (CETC) in Ottawa, Ontario, a burner nozzle design for stable Bio-Oil fuel combustion has been developed. This has created opportunities for applications for Bio-Oil to replace natural gas, diesel and other fossil fuels in the industrial boilers and kilns (<sup>1</sup>Dynamotive.com/biooilapplications).

Alterations to conventional systems must be made if Bio-Oil is combusted alone. In the case of co-firing, retrofitting is also likely to be necessary. Co-firing with coal, as previously discussed, was attempted by Manitowoc Public Utilities in 1996. The utility retrofitted a Wicks boiler to allow for the co-fire (<sup>57</sup>Sturzl). In systems using liquid fuel such as diesel or number two or six, modifications would also be necessary. Because crude Bio-Oil is insoluble with petroleum fuels, it is not possible to mix the fuels before combustion without emulsification, which is currently under research, and would be cost intensive (<sup>4</sup>Oasmaa).

The Bio-Oil Team's efforts to explore co-firing showed that proper storage and preparation needs to occur for Bio-Oil testing and combustion. For example Bio-Oil like other fossil fuels is not suggested to sit unattended for six months and then used or tested. The problem that the UNH Bio-Oil Team now faces is that to do more research on Bio-Oil, additional samples must be obtained. In order to get additional samples, approval from DynaMotive on what the Bio-Oil will be used for is needed. In order to move forward with PSNH or another electric provider in the region, testing by a third party source is needed. DynaMotive's tests with CANFOR in August were emission studies (soon to be published), but may not meet all the requirements that an electric provider is looking for.

In general DynaMotive Bio-Oil is technically and environmentally feasible for power generation. (<sup>53</sup>Kingston) The only question that remains is...is it economically feasible? The answer depends on the cost of the feedstock. It can be logically deduced that if the wood-fired electric power plants in NH are faltering and they only have to pay approximately \$18/ wet ton for low-grade wood and the Bio-Oil plant has to pay the same amount along with the cost for grinding and drying the wood-chips and supplying energy to the pyrolysis reactor; then the Bio-Oil plant should also falter at that price. The 2002 DRED study figured that a production cost of approximately \$0.0542/kWh for a wood-fired plant (700 US ton/day) to produce electricity (<sup>3</sup>DRED, 13), while DynaMotive claims approximately \$8.50/mmBtu=\$0.029/kWh (100 tonne/day) to \$5.50/mmBtu= \$0.019/kWh (400 tonne/day). (See Figure 6.1.D with \$18/ US ton feedstock cost) The production cost for DynaMotive can be lowered to \$4.00/mmBtu=\$0.014/kWh (400 tonne/day) with a zero cost of feedstock. If DynaMotive's claims are true then Bio-Oil is cost competitive with oil and even more so since the NH legislature has passed bills that allow renewable fuel power plants to sell electricity at \$0.048/kWh when the market price is below that value. (<sup>20</sup>Stuart) More research is needed into the Orenda turbine to find out how much Bio-Oil is needed to be combusted per MW of electricity made. It is known that somewhere around a 100 tonne/day plant is needed per turbine, but it was mentioned that there would be extra Bio-Oil off this plant that could be used for testing or other markets. It is also not completely certain whether they meant a 100 tonne/day wet or dry plant. To recap, DynaMotive's claims on energy production are cost competitive, but the wood fired plants which run a simpler process are not according to DRED. Should a Bio-Oil facility be co-located and possibly co-owned with a saw mill that produces low-grade wood waste then the most cost effective Bio-Oil will result. Further information on the emission tests done on the Orenda turbines in August 2002 and the required amounts of Bio-Oil per turbine is required before a final analysis can be made on the feasibility of Bio-Oil for power generation in NH. Although the end-use market study of Bio-Oil is in its infancy, some of the end-uses explored by the UNH Bio-Oil team are described in the following sections.

### **7.1.1 "Green Power" Generation: New Plants**

Currently a turnkey package (guaranteed to be built to operate properly and at a given cost) is advertised for a 100 ton per day plant with a 2.5 MWe turbine. The implication of this end-use is to provide electricity to northern NH after the remaining wood fired plants close. One 400 tonne/day plant could provide electricity for 7,000 households year around (DynaMotive-Green Fuels to the World-Promotional CD, 2002).

### **7.1.2 Greener Power Generation: Co-Firing of Existing Plants**

Previous tests that were done by a UNH Bio-Oil Team partner under legislated fossil fuel standards show that Bio-Oil is too acidic for co-firing with other fossil fuels. Tests were done with a sixth month old sample that DynaMotive claimed was not properly prepared since phase separation had occurred. Further research is needed to study the effect of pH on transportation and co-firing. DynaMotive affiliates have done these studies as well. The aim of co-firing current facilities with Bio-Oil is to improve emissions from NH power plants.

## **7.2 Residential and Industrial Heating**

### **7.2.1 Residential Heating**

As shown in section 6.2, enough Bio-Oil can be produced from 1.3 million tons of low-grade wood chips to heat between 49-71% of all, or one and a half times as many homes currently using number two fuel in the three northern most counties: Grafton, Coos, and Carroll. This amounts to heating between about 48,123-69,205 housing units. DynaMotive claims that one 400 tonne/day plant can heat 14,000 homes. (DynaMotive-Green Fuels to the World-Promotional CD, 2002) However, because Bio-Oil's heating value is only about half that of number two fuel, even though the gallon for gallon cost is similar, about two times the volume of Bio-Oil would be needed to supply the energy that is provided by number two fuel oil. The current unrefined Bio-Oil is presently too acidic to be used in existing residential boilers, meaning that the Bio-Oil would have to be processed or stainless steel (a stronger material) used. Research to modify the nozzle/burner to ensure efficient firing is also necessary. Although using Bio-Oil as a residential heating fuel is not currently realistic, the volume of Bio-Oil that could be produced from the 1.3 million tons of low-grade wood chips that will no longer be consumed by the wood-fired plants could heat 150% of the homes in Coos, Carrol, and Grafton counties.

### **7.2.2 Industrial Heating: Fuel substitute for forest companies, district heating, or process heat.**

DynaMotive has been working with the Canadian department of Natural Resources (NRCan) and CANMET and succeeded in developing an industrial burner nozzle design. They hope to replace natural gas, diesel, and other fossil fuels in industrial boilers and kilns. Lime kiln tests have already occurred as of last 2001. Other potential industrial heating uses include fuel substitution for district heating and process heat for sawmills, pulp mills, and greenhouses. (<sup>1</sup>[dynamotive.com/biooil/industrialfuels.html](http://dynamotive.com/biooil/industrialfuels.html)) DynaMotive states that the Bio-Oil from a 400 tonne/day plant could replace the natural gas used in four saw mills. The size of the sawmills was not mentioned. (DynaMotive-Green Fuels to the World-Promotional CD, 2002)

## **7.3 Green Substitute in Asphalt Paving**

One of the goals of the project is to find a suitable end-use market for Bio-Oil. Although DynaMotive's first objectives are to use the fuel for electricity generation and heating, many other possibilities exist. One option is to explore is the use of Bio-Oil to replace some or all of the petroleum products in asphalt emulsions. In the past, volatile organic compounds (VOC's) released into the atmosphere by air striping asphalt paving were an environmental concern. Since then, the most commonly used process has changed to reduce VOC's. However, by exploring economic and environmental feasibility of Bio-Oil in this application, a higher quality, more environmentally friendly asphalt paving may be in the future.

The vision for Bio-Oil's application in the asphalt industry stemmed from the results of the UNH Bio-Oil Team's partner, in which the Bio-Oil became resin-like when heated and dried. The UNH Bio-Oil Team began researching asphalt emulsions and

planned a meeting with Dr. Jo Daniel, civil engineering assistant professor and expert in the asphalt field. Dr. Daniel suggested that the area of asphalt pavement where Bio-Oil might have application is asphalt emulsion (<sup>55</sup>Daniel). An asphalt emulsion is a combination of asphalt cement combines with water and an emulsifying agent mixed with aggregate. A meeting with Dr. Daniel and the NH Department of Transportation has initiated the effort to determine the feasibility of Bio-Oil in this capacity. The conclusion of that meeting was that the Bio-Oil must be tested for stickiness. This is the most basic requirement for the binder. Dr. Daniel's lab equipment would be able to determine the potential of Bio-Oil for use in an emulsion. If the Bio-Oil withstands temperature, load, and loading rate tests, then further work will determine its promise as a green replacement for asphalt binders. Once more Bio-Oil is obtained then testing can begin to see if Bio-Oil has the qualities required for asphalt paving purposes.

#### **7.4 Coal Dust Suppression**

Another market being looked into for Bio-Oil is coal dust suppression. The current product that PSNH uses to coat coal piles is a 'plasticizer' that is biodegradable and does not settle into the lagoon. Because of Bio-Oil's acidity and water solubility, research would have to be done to make a Bio-Oil product that forms a seal on the coal pile, so the dust will not fly off. The product has to be a non-pollutant to the bottom ash, after burning the coal, and can not leach into the lagoon or settling ponds. The research would focus on making Bio-Oil immiscible in water along and making sure it satisfies the environmental and physical requirements.

#### **7.5 Vehicular Applications**

Research that is required to use Bio-Oil in vehicular applications is more long term. The goal would be to use Bio-Oil as an additive in diesel or gasoline as an additive to reduce emissions. The challenge is that crude (unrefined) Bio-Oil does not currently mix with fossil fuels and an inexpensive method has not been found. A method called the BDM Process where Bio-Oil is mixed with diesel has been developed that is 'stable, non-corrosive, and easy to ignite', but the price to develop it is not shared. (<sup>12</sup>Brady, 30) DynaMotive is also considering the use of surfactants that emulsify Bio-Oil with liquid fossil fuels. The benefit of emulsifying Bio-Oil with fossil fuels is the possibility of a gasoline additive to reduce emissions.

#### **7.6 Green Chemicals**

Both DynaMotive and Ensyn are interested in the green chemicals that can be obtained from Bio-Oil. Some possibilities include flavor chemicals, octane enhancers, solvents, resins, varnishes, brightening agents for paper production, pharmaceutical synthesis, pesticide synthesis, specialty plastics, and slow release fertilizers (<sup>1</sup>DynaMotive). Dean Arthur Greenberg, of the College of Engineering and Physical Sciences, found right-handedness in Bio-Oil. This optical activity suggests that Bio-Oil may be useful in pharmaceutical or handed solvent applications. The results of Dean Greenberg's work can be found in Appendix A7. For more green chemical applications visit reference one and two.

## **7.7 Char Market**

The by-product of Bio-Oil, char, can be sold as charcoal briquettes or refined to make activated carbon. In a feasibility study by Huskywood, the selling price is suggested to be \$20-\$25 per ton (<sup>12</sup>Brady, 3). The char can also be combusted in order to supply energy for drying wood chips at the Bio-Oil facility. In Figure 6.1.D, DynaMotive claims that selling the char reduces the price of the Bio-Oil by 5 to 8 cents per gallon, suggesting that they have found a more economical method of drying the wood that does not need to use the char.

## **7.8 Community Outreach**

To further the end-use market study the UNH Bio-Oil Team has been educating the public about the Bio-Oil project through several initiatives. In May, 2002, the Bio-Oil Team shared a poster presentation with high school students taking part in a “Project Lead the Way” field trip. Project Lead the Way is a program offered to high school students interested engineering sciences.

More recently, Governor Jean Shaheen visited UNH for a press conference in which she spoke about the benefits of energy diversification. The UNH Bio-Oil project was featured and the possible benefits that Bio-Oil could afford New Hampshire were outlined for the public. The UNH Bio-Oil Team is also taking part in the Pollution Prevention Program. As part of this program, the team has presented to interns in the NH Pollution Prevention Internship program, the NH DES, and the US EPA in July and September of 2002.

## **8.0 Phase Two: Conclusions, Recommendations, & Future Steps**

New Hampshire is the second most forested state in the nation, and as such, relies on the low-grade wood market as a critical cornerstone of its economy. However, as earlier mentioned, the low-grade wood market is facing challenges due to the previous instability of the paper mill in Berlin-Gorham and the closing of the five remaining wood fired power plants by 2006-2008. In support of the initiative to explore technologies that will keep the low-grade wood market strong and provide an economic boost to New Hampshire, the UNH Bio-Oil Team formed to explore fast pyrolysis technology. The project has included an economic, technical, environmental, and social feasibility analysis of a facility in New Hampshire, and explored some end-use markets.

The technology of fast pyrolysis involves heating biomass to between 400-800°C in the absence of oxygen for a few seconds. There are several types of fast pyrolysis including vacuum, ablative, circulating bed, and fluidized bed pyrolysis. The most well known methods of fast pyrolysis are circulating bed and fluidized bed, and the two companies using these technologies are Ensyn and DynaMotive, respectively. Ensyn's technology is focused on extracting chemicals for food flavoring, and DynaMotive's focus is on using Bio-Oil as a fuel to generate electricity and use as a replacement for conventional fuels in boilers and kilns

Environmentally, Bio-Oil as a fuel compares positively to petroleum fuels. However, it has half the heating value of number two fuel on a volume basis. Because Bio-Oil's viscosity increases with time, the liquid must be stored in airtight, room temperature conditions. Another obstacle to Bio-Oil is its acidic nature. With a pH of 2-2.5, it is considered a hazardous material for corrosiveness by US EPA standards. With a national average of 20 ppm of lead in wood, the implications that metals have on plant permitting is important to consider. Toxic metals such as lead and mercury are destined to the char, however, studies on the fate of these metals have not been conducted. Although biodegradation rates have been studied, an environmental risk analysis would be beneficial in developing protocol for a spill in the soil or aquatic environment. To address some of the obstacles of the fuel, processes are being developed to improve the quality of Bio-Oils. Hot filtration to remove char is one method of improving Bio-Oil's performance as a fuel. Emulsifying agents are also being developed to make Bio-Oil miscible with petroleum fuels. If retrofitting is not necessary to co-burn Bio-Oil with conventional fuels, assimilation of Bio-Oil might help to develop a more prominent Bio-Oil industry. The barrier to more rapid development, as in many cases, is cost.

The UNH economic analysis found the production cost of Bio-Oil to be approximately \$0.89/gal (440 US ton/day) to \$1.21/gal (110 US ton/day) with a payment plan for capital cost included (see table 6.1.P). It is worth noting that all three independent economic analysis performed by UNH, Cole Hill Associates, and DynaMotive end up with very similar values. When comparing Bio-Oil to petroleum fuel oil, it takes about two gallons of Bio-Oil to deliver the same energy content of one gallon of petroleum fuel. Although a system is not yet available that uses Bio-Oil for residential heating, Bio-Oil will be compared to home heating fuel for illustration purposes. A household using about 1,100 gallons of heating fuel annually would pay about \$1,190 to heat the home annually. That same household would have to use about 2,200 gallons of Bio-Oil for equivalent heating, which would cost a total of between \$1,830 and \$2,790.

As can be seen from the numbers above, electric generation and heating uses for Bio-Oil using \$18/ wet ton low-grade wood is not economical. However, regulations or legislation that economically aids alternate fuels, raises taxes for the emission of NO<sub>x</sub> and SO<sub>x</sub>, creates taxes for CO<sub>2</sub> emissions, or requires that a certain portion of energy production comes from alternate fuels might make Bio-Oil economically feasible. If a different type of feedstock became available at half or less than the current price of low-grade wood chips in NH, then Bio-Oil would be more competitive for the end-uses described. However, this scenario might not aid the low-grade wood market of northern NH.

The non-energy uses for Bio-Oil are at different stages of development from commercialized food smoking to the researching of a Bio-Oil / diesel mixture. Once further funding and more Bio-Oil is obtained, UNH will be able to continue to explore the possibility of using Bio-Oil for asphalt paving and optically active green chemicals. Further market analysis and research is needed and might be completed by the NH Governor's Office of Energy and Community Services in their feasibility study of Bio-Oil from October 2002 to March 2003.

In conclusion, fast pyrolysis has proven itself to be a technically viable technology for the 0 to 45 ton per day plant size range. Scaling up of fluidized beds has been historically difficult, but DynaMotive and Ensyn have made claims and guarantees that they can do so. In regard to environmental feasibility, fast pyrolysis is promising in regard to NO<sub>x</sub>, SO<sub>x</sub>, and CO<sub>2</sub>, but not all the tests in regard to mercury, lead, and dioxin or the effects of a spill have been done. Economically it is too early to tell if Bio-Oil is feasible due to the need for more research in regard to all the possible end-use markets that Bio-Oil can be used for and the possible feedstocks available in the state. Both cost reduction and the setting of Bio-Oil standards will aid in its development.

There are many possible applications for Bio-Oil and further research will be needed to find the most profitable market for NH that is environmentally acceptable. Some of the specific areas that the UNH Bio-Oil team has identified include:

- Environmental testing:
  - Biodegradation rates and spill management
  - Exploration of fate of toxics such as lead and mercury
- Competitive risk analysis
- End-Use market analysis
- Possibility of a Government Incentive Program
- Re-evaluation of Bio-Oil companies
  - Which best fits NH.(DynaMotive, Ensyn, ROI, Pyrovac Int.)?
- Improvements in economic analysis
  - Grinding Cost
  - Energy Use
    - Natural gas and Electricity

"Congress continues to give away billions of dollars every year to the fossil fuel industry. The oil, gas, and coal industries receive approximately \$3 billion in subsidies every year - at the expense of taxpayers' pocketbooks. Congress needs to direct more of its efforts on supporting the technologies of the future, not the policies of the past."

– <sup>56</sup>Jeanne Shaheen, NH Governor, 7/23/200

## **9.0 - References**

Note: the referencing system will be: (<sup>Reference #</sup> Author or Company, page). The reference number is the first number shown 1.) to 55.).

- 1.) DynaMotive Energy Systems Corporation Website, [www.dynamotive.com](http://www.dynamotive.com)
  - a. [www.dynamotive.com/biooil/milestones.html](http://www.dynamotive.com/biooil/milestones.html)
  - b. [www.dynamotive.com/biooil/markets.html](http://www.dynamotive.com/biooil/markets.html)
- 2.) Ensyn Group Inc., [www.ensyn.com](http://www.ensyn.com)
  - a. <http://www.ensyn.com/who/ensyn.htm>
- 3.) NH Department of Resources and Economic Development; Identifying and Implementing Alternatives to Sustain the Wood-fired Electricity Generating Industry of New Hampshire”, January 2002.
- 4.) Oasmaa, Anja; Czernik, Stefan; Fuel Oil Quality of Biomass Pyrolysis Oils – State of the Art for the End-Users; VTT Bioenergy Program & NREL Biomass Power Program
- 5.) Mullaney, Henry; Personal Communication; NH Industrial Research Center, [hm@mmr.mv.com](mailto:hm@mmr.mv.com), 603-862-0126
- 6.) Hammond, Pat; “PSNH Plan could make Deep Cut on Woodsmen”, Union Leader, Sept. 9, 2001.
- 7.) Piskorz, Jan; Majerski, Piotr; Radlein, Desmond; United States Patent # 5,853,548 , Dec. 29, 1998.
- 8.) DynaMotive Energy Systems Corporation; BioTherm™ A System for Continuous Quality, Fast Pyrolysis BioOil; Fourth Biomass Conference of the Americas, Oakland, California, September 1999.
- 9.) Thambuaj, R.; DynaMotive Energy Systems Corporation; Fast Pyrolysis of Biomass for Green Power Generation; First World Conference and Exhibition on Biomass for Energy and Industry, 2000.
- 10.) DynaMotive Energy Systems Corporation; Fast Pyrolysis of Bagasse to Produce BioOil Fuel for Power Generation; Sugar Conference, 2001.
- 11.) Stone & Webster Canada Ltd.; Due Diligence Report: Bio-Oil Refinery Project; 1999.  
[Includes Economic Analysis for 96 tpd DynaMotive bagasse plant in Brazil. Since 1999 the process has improved.]
- 12.) Brady, Terry; Fast Pyrolysis: Wood to Gas, Bio-Oil and Fuel-Grade Char; Huskywood LLC, Jan. 2002.  
[A Preliminary Economic Analysis for Southeast Alaska]
- 13.) Huskywood, LLC; DynaMotive Energy Systems PowerPoint presentation in Juneau Alaska, March 2002.
- 14.) BEDCO (Cote, Dennis; Hardy, Jay; Stewart, Gerald); Personal Communication; Q1 & Q2 of 2002.
- 15.) Reed, Tom; BioC:Bio-Oil, Past and Future...April, 2001.  
<http://www.repp.org/discussion/bioconversion/200104/sg00001.html>
- 16.) Grahm, Robert, Ph.D. President and CEO of Ensyn; April, 2001.  
<http://www.repp.org/discussion/bioconversion/200104/sg00001.html>

- 17.) Sturlz, Ray, The Commercial Co-Firing of RTP Bio-Oil at the Manitowoc Public Utilities Power Generating Station. Manitowoc Public Utilities. June 1997. Pg 8.
- 18.) Jones, Red, MPU. Co-Firing of Bio-Oil. March 2002. E-mail Correspondence to Dr. Farag.
- 19.) Radlein, D. Some Comparisons Between the DynaMotive and Ensyn Processes. Resource Transforms International Ltd. Waterloo, Ontario. From a correspondence between Henry Mullaney and Rudolpho Guido-Oct, 2001.
- 20.) Personal Communication- Gerald Stuart July 15, 2002.
- 21.) [www.pyne.co.uk](http://www.pyne.co.uk) , Pyrolysis Network. (2002)
- 22.) Waste Gas Technology, [www.wgtuk.com/ukDefinitionPyr.html](http://www.wgtuk.com/ukDefinitionPyr.html) (2002)
- 23.) Waste Gas Technology, [www.wgtuk.com/ukDefintionGas.html](http://www.wgtuk.com/ukDefintionGas.html) (2002)
- 24.) Wells, Joanne, Whitefield Power & Light of NH employee, Personal Communication, July 2002.
- 25.) McCabe, Warren, and Julian Smith. Unit Operations of Chemical Engineering. 6<sup>th</sup> Edition. McGraw-Hill, Boston. 2001. Pg. 1063
- 26.) NH Governor's Office of Energy and Community Services Energy Facts 2002, [www.state.nh.us/governor/energycomm/prices/pricejuly0302.html](http://www.state.nh.us/governor/energycomm/prices/pricejuly0302.html)
- 27.) <http://quickfacts.census.gov/qfd/states/33000.html>
- 28.) [www.sciteclibrary.com](http://www.sciteclibrary.com) June 12, 2000.
- 29.) [www.orcbs.msu.edu/newhazard/wastemanualdocs/05classification.html](http://www.orcbs.msu.edu/newhazard/wastemanualdocs/05classification.html)
- 30.) Tetu, Ron. Bio-Oil Sample: E-mail to Dr. Ihab Farag. Thursday, May 2, 2002.
- 31.) Communication with Dr. Jo Daniel. Thursday, June 27,2002.
- 32.) Maker, Timothy. The Northeast Regional Biomass Program: Wood-Chip Heating System- A Guide for Institutional and Commercial Biomass Installations. Energy Efficiency Associates. Vermont. 1994.
- 33.) Engalichev, N and V.K. Mathur. Wood Power: Its Promises & Problems. University of New Hampshire. 1980.
- 34.) Mullaney, Henry. E-mail Response to Questions on Bio-Oil Briefing. August 13, 2002.
- 35.) Stewart, Gerald; Bio-Oil: Feasibility Study, February 5, 2002.
- 36.) NH Governor's Office of Energy and Community Services: Fuel Price Data, July 2002.  
<http://www.state.nh.us/governor/energycomm/images/fuelscost.pdf>
- 37.) York, Doug, Whitefield Power & Light of NH employee, Personal Communication, July 2002.
- 38.) Bartlett, Jay, Whitefield Power & Light of NH employee, Personal Communication, July 2002.
- 39.) Anonymous, Source familiar with DynaMotive process that asked to remain anonymous, July 2002.
- 40.) University of Minnesota webpage, July 2002,  
<http://www.physics.umn.edu/groups/phised/Research/CRP/on-lineArchive/creeh.html>

- 41.) Newell, Jon, Engineering Technician at the University of New Hampshire, Personal Communication, July 2002.
- 42.) Felder, Richard; Rousseau, Ronald; Elementary Principles of Chemical Processes, Third Edition, John Wiley & Sons, Inc., New York, 2000.
- 43.) US Census Bureau, NH State & County Quick Facts, <http://quickfacts.census.gov/qfd/states/33000.html>
- 44.) NH Governor's Office of Energy and Community Services, Energy Facts 2002, <http://www.state.nh.us/governor/energycomm/images/factsheet.pdf>
- 45.) Greenberg, Arthur; Dean of the University of New Hampshire's College of Engineering and Physical Sciences & Professor of Chemistry, Personal Communication & Presentation, June 2002.
- 46.) Pyrocyling by Pyrovac International Inc. [http://www.enviroaccess.ca/fiches\\_4/F4-03-95a.html](http://www.enviroaccess.ca/fiches_4/F4-03-95a.html)
- 47.) Czernik, Stephen; US representative of the Pyrolysis Network, Personal Communication & Presentation, August 16, 2002.
- 48.) Peavy, Dwight; EPA, Personal Communication from July 17<sup>th</sup> NH Pollution Prevention presentations.
- 49.) Boulard, Dave; Ensyn, Personal Communication & Presentation, August 16, 2002.
- 50.) Renewable Oil International's webpage, August 2002, <http://www.renewableoil.com/pages/history.html>
- 51.) Freel, Barry A. and Graham, Robert G. Apparatus for a Circulating Bed Transport Fast Pyrolysis Reactor System. US Patent Number 5,961,786. June 15, 1998.
- 52.) J.P. Diebold. A Review of the Chemical and Physical Mechanisms of the Storage Stability of Fast Pyrolysis Bio-Oils. Thermalchemie, Inc. Lakewood, Colorado. January 2000.
- 53.) Kingston, Andrew; Guido, Rodolfo; DynaMotive, Personal Communication & Presentation, August 16, 2002.
- 54.) Ulrich, Gael D.; A Guide to Chemical Engineering Design and Economics; John Wiley & Sons, 1984.
- 55.) Daniel, Jo; Civil Engineering Prof. at UNH, Personal Communication, July 2002.
- 56.) Shaheen, Jeanne; Shaheen Calls For Smart, Forward-Looking Energy Policy; 7 23, 2002; [http://www.shaheen.org/index.asp?Type=B\\_BASIC&SEC={26BAAE1F-2370-4921-A650-76110724C32B}&DE={EF31BB00-097A-4F02-9229-2F8A4B603D36}](http://www.shaheen.org/index.asp?Type=B_BASIC&SEC={26BAAE1F-2370-4921-A650-76110724C32B}&DE={EF31BB00-097A-4F02-9229-2F8A4B603D36})

## **10.0 Appendices**

### **Appendix A1 Sample Calculations**

For comparison purposes, the maximum heating value of a ten US ton per day wood plant (10 tons of 5% moisture, pine/spruce mix = 8384 Btu/lb (<sup>51</sup> Engalichev, 6)) Spruce, Pine (mid height) has an average heating value of 8,825 Btu/lb when it is bone dry. Multiply this value by 0.95 to achieve a 5% moisture content heating value (=8384 Btu/lb)

$$8384 \text{ Btu/lb} * (2000 \text{ lb/ton}) * (10 \text{ tons/day}) * (1 \text{ day/24hrs}) * (1 \text{ hr/60min}) * (1 \text{ min/60sec}) = 1940 \text{ Btu/sec}$$

$$1940 \text{ Btu/sec} * (1 \text{ W}/(9.486 * 10^{-4} \text{ Btu/sec})) * (1 \text{ MW}/(10^6 \text{ W})) = 2.05 \text{ MWt} \quad (\text{t is for thermal})$$

Same process for Bio-Oil except use 7100 Btu/lb for heating value and 6.6 tons/day instead of 10 tons/day due to the 66% yield.

By maximum heating value we are examining all the possible heat given off (100% efficiency).

## **Appendix A2: Material Safety Data Sheets from DynaMotive**

### **Section I. Product Identification and Use**

Manufacturer:	DynaMotive Technologies Corporation 105 - 1700 West 75 <sup>th</sup> Avenue Vancouver, B.C. V6P 6G2	Emergency Phone Numbers: (604)267-6000 CANUTEC (613)996-6666
Product Name:	BioOil	
Synonyms:	Pyrolysis oil, biomass pyrolysis oil	
UN number:	UN1993	
TDG Shipping Name:	Flammable Liquid N.O.S. (lignin solution)	
TDG Classification/Packing group:	Class 3.3, Packing Group III	
Use:	Applications as a liquid fuel or raw material for industrial processes	

### **Section II. Ingredients**

Water:	25%
Lignins:	25%
Other Oxygenated Compounds	50%

### **Section III. Physical Data**

Physical State:	liquid
Appearance:	dark brown liquid
Odour:	charred odour
Odour Threshold:	not applicable
Vapour Pressure:	not available
Vapour Density:	not available
Evaporation Rate:	not available
Boiling Point:	not available
Freezing Point:	not available
pH:	2.2 to 3.5
Specific gravity:	1.1 to 1.25
Coefficient of Water/Oil Distribution:	not available

### **Section IV. Fire or Explosion Hazard**

Conditions of flammability: WHMIS Class B, Division 3. Combustible liquid.  
Flammable at extremely high temperatures. May react with strong oxidants.

Extinguishing media: water, foam, dry chemical. Fire fighters should wear self-contained breathing apparatus.

Flash point/method: 44°C/PMCT

UEL: not available

LEL: not available

Auto-ignition temperature: not available

Hazardous Combustion Products: CO<sub>x</sub>

Explosion Data - sensitivity to mechanical impact: no  
- sensitivity to static discharge: no

### **Section V. Reactivity Data**

Conditions of Instability: normally stable

Incompatibilities: oxidizers

Conditions of Reactivity: temperatures above 160°C may generate highly flammable acetone

Hazardous Decomposition Products: acetone, carbon dioxide, carbon monoxide

### **Section VI. Toxicological Properties/Health Hazard Data**

Route of Entry:

Skin contact: may irritate

Skin absorption: no information available

Eye contact: may irritate

Inhalation: may irritate

Ingestion: may irritate

LC<sub>50</sub>: not available

LD<sub>50</sub>: not available

Exposure limits: not established

Effects of Acute Exposure: Coughing or mild breathing difficulties may result. If ingested, large doses may irritate the gastrointestinal tract

Effects of Chronic Exposure: no information available

Irritancy: no experimental information available

Sensitizing capability: no information available

Carcinogenicity: no information available

Reproductive toxicity: no information available

Teratogenicity: no information available

Mutagenicity: no information available

Toxicologically Synergistic Products: no information available

## Section VII. First Aid Measures

**Skin:** flush the contact area with lukewarm running water for at least 15 minutes. Remove contaminated clothing, taking care not to spread the chemical. If contamination is extensive, remove the clothing under running water. Discard or decontaminate clothing before use. Unless contact has been slight, seek medical attention. Seek medical attention if irritation persists.

**Eye:** flush the contaminated eye(s) for at least 15 minutes with lukewarm running water, holding the eyelids open. Take care not to rinse contaminated water into the non-affected eye. Always seek medical attention for accidents involving the eyes.

**Inhalation:** Take proper precautions to ensure your own safety before attempting rescue. Remove source of contamination or move victim to fresh air. If breathing has stopped, trained personnel should begin artificial respiration, or if the heart has stopped, cardiopulmonary resuscitation (CPR) immediately. Seek medical attention.

**Ingestion:** Never give anything by mouth if victim is rapidly losing consciousness, or is unconscious or convulsing. Rinse mouth thoroughly with water. Do not induce vomiting. Have victim drink 200 to 400 mL of water to dilute. If breathing has stopped, trained personnel should begin artificial respiration, or if the heart has stopped, cardiopulmonary resuscitation (CPR) immediately.

## Section VIII. Preventive Measures

**Engineering Controls:** Engineering control measures to reduce hazardous exposures are preferred. Methods include mechanical ventilation (dilution and local exhaust), control of personnel exposure, control of process conditions and process modification. Administrative controls and personal protective equipment may also be required.

**Personal protective equipment:**

**Gloves:** neoprene, latex or equivalent

**Respiratory protection:** fume hood or NIOSH/MSHA approved organic vapor respirator as appropriate

**Eye protection:** chemical safety goggles

**Clothing:** plastic apron, sleeves and boots as appropriate

**Storage Requirements:** Store in suitable labeled containers. Keep containers tightly closed when not in use and when empty. Protect from damage. Store in a cool, dry, well ventilated area, out of direct sunlight. Store away from oxidants.

**Handling Procedures and Equipment:** Follow routine safe handling procedures.

Leak or Spill Cleanup: Before dealing with spills take necessary protective measures, inform others to keep at a safe distance and shut off all possible sources of ignition when the oil is at temperatures above 160°C. Mix with sand, transfer carefully to container and arrange removal by disposal company. Wash site of spill thoroughly with water.

Disposal: Follow all federal, provincial and local regulations for disposal. Use only licensed disposal and waste hauling companies. Disposal of small amounts of spilled material may be handled as described under "Leak or Spill Cleanup". Large spills must be dealt with separately and must be handled by qualified disposal companies.

Special Shipping Information: Follow all TDG regulations and see classification in Section I.

### **Section IX. Preparation Information**

Prepared by: DynaMotive Technologies Corporation, 105 - 1700 West 75<sup>th</sup> Avenue, Vancouver, B.C. V6P 6G2, phone 604-267-6000.

Date: April 3, 2000.

**Appendix A3: Number 6 Fuel Oil MSDS**

MATERIAL SAFETY DATA SHEET EQUILON MSDS: 52432E-03 01/04/99 SHELL NO. 6 FUEL OIL-THIRD PARTY STORAGE TELEPHONE NUMBER: 24 HOUR EMERGENCY ASSISTANCE GENERAL MSDS ASSISTANCE EQUIVA SERVICES: 877-276-7283 877-276-7285 CHEMTREC: 800-424-9300 NAME AND ADDRESS EQUILON ENTERPRISES LLC PRODUCT STEWARDSHIP P.O. BOX 674414 HOUSTON, TX 77267-4414

---

SECTION I NAME

---

PRODUCT: SHELL NO. 6 FUEL OIL-THIRD PARTY STORAGE CHEM NAME: MIXTURE (SEE SECTION II-A) CHEM FAMILY: PETROLEUM HYDROCARBON; INDUSTRIAL FUEL SHELL CODE: 41009 HEALTH HAZARD: 3 FIRE HAZARD: 2 REACTIVITY: 0

---

SECTION II-A PRODUCT/INGREDIENT

---

NO. COMPOSITION CAS NO. PERCENT --- ----- P SHELL NO. 6 FUEL OIL-THIRD PARTY STORAGE MIXTURE 100 1 VACUUM TOWER BOTTOMS 64741-56-6 VAR. 2 CATALYTICALLY CRACKED LIGHT GAS OIL 64741-59-9 VAR. 3 CATALYTICALLY CRACKED CLARIFIED OIL 64741-62-4 VAR. 4 HYDROGEN SULFIDE (H<sub>2</sub>S) 7783-06-4 <0.04

---

SECTION II-B ACUTE TOXICITY DATA

---

NO. ACUTE ORAL LD50 ACUTE DERMAL LD50 ACUTE INHALATION LC50 --- -  
----- P NOT AVAILABLE

---

SECTION III HEALTH INFORMATION

---

THE HEALTH EFFECTS NOTED BELOW ARE CONSISTENT WITH REQUIREMENTS UNDER THE OSHA HAZARD COMMUNICATION STANDARD (29 CFR 1910.1200). EYE CONTACT: BASED ON ESSENTIALLY SIMILAR COMPONENT TESTING, PRODUCT IS PRESUMED TO BE MINIMALLY IRRITATING TO THE EYES. CONTACT WITH HOT PRODUCT MAY RESULT IN THERMAL BURNS. SKIN CONTACT: BASED ON ESSENTIALLY SIMILAR COMPONENT TESTING, PRODUCT IS MODERATELY IRRITATING AND TOXIC UPON REPEATED SKIN CONTACT. ABSORPTION THROUGH SKIN MAY RESULT IN LIVER DAMAGE. REPEATED CONTACT MAY ALSO RESULT IN VARIOUS SKIN DISORDERS SUCH AS DERMATITIS, FOLLICULITIS, OIL ACNE, OR SKIN TUMORS. CONTACT WITH HOT PRODUCT MAY RESULT IN THERMAL BURNS. INHALATION: WARNING - HYDROGEN SULFIDE (H<sub>2</sub>S) AND OTHER HAZARDOUS VAPORS MAY EVOLVE AND COLLECT IN THE HEADSPACE OF STORAGE TANKS OR OTHER ENCLOSED VESSELS. HYDROGEN SULFIDE IS AN EXTREMELY FLAMMABLE, HIGHLY TOXIC GAS.

IN THE ABSENCE OF H<sub>2</sub>S, INHALATION OF VAPORS, MISTS OR FUMES (GENERATED AT HIGH TEMPERATURES) MAY CAUSE IRRITATION TO THE NOSE, THROAT AND RESPIRATORY TRACT. (SEE SECTION VI FOR FURTHER INFORMATION). INGESTION: BASED ON ESSENTIALLY SIMILAR COMPONENT TESTING, PRODUCT IS PRESUMED TO BE MODERATELY TOXIC AND MAY BE HARMFUL IF SWALLOWED; MAY PRODUCE LIVER DAMAGE. SIGNS AND SYMPTOMS: H<sub>2</sub>S TOXICITY MAY BE EVIDENCED BY A RAPID LOSS OF CONSCIOUSNESS; DEATH MAY FOLLOW QUICKLY. IRRITATION AS NOTED ABOVE. LIVER DAMAGE MAY BE EVIDENCED BY LOSS OF APPETITE, JAUNDICE (YELLOWISH SKIN COLOR) AND SOMETIMES PAIN THE UPPER ABDOMEN ON THE RIGHT SIDE. AGGRAVATED MEDICAL CONDITIONS: PREEXISTING SKIN DISORDERS MAY BE AGGRAVATED BY EXPOSURE TO THIS PRODUCT. IMPAIRED LIVER FUNCTION(S) FROM PREEXISTING DISORDERS MAY BE AGGRAVATED BY EXPOSURE TO THIS PRODUCT. PREEXISTING SKIN OR LUNG ALLERGIES MAY INCREASE THE CHANCE OF DEVELOPING INCREASED ALLERGY SYMPTOMS FROM EXPOSURE TO THIS PRODUCT. OTHER HEALTH EFFECTS: THE INTERNATIONAL AGENCY FOR RESEARCH ON CANCER (IARC) HAS DETERMINED THERE IS SUFFICIENT EVIDENCE FOR THE CARCINOGENICITY OF CATALYTICALLY CRACKED OILS. IARC HAS DETERMINED THAT RESIDUAL FUELS ARE POSSIBLY CARCINOGENIC TO HUMANS. HANDLING PROCEDURES AND SAFETY PRECAUTIONS IN THE MSDS SHOULD BE FOLLOWED TO MINIMIZE EMPLOYEE'S EXPOSURE.

---

#### SECTION IV OCCUPATIONAL EXPOSURE LIMITS

---

COMP	OSHA	ACGIH	NO.	PEL/TWA	PEL/CEILING	TLV/TWA	TLV/STEL	OTHER
--	-----	-----	-----	-----	-----	-----	-----	-----
				P 0.2	MG/M <sup>3</sup> *	0.2	MG/M <sup>3</sup> *	4 10 PPM 10 PPM 15 PPM 15 PPM ** 4 - HYDROGEN SULFIDE (300 PPM IDLH). * PARTICULATE POLYCYCLIC AROMATIC HYDROCARBONS, AS BENZENE SOLUBLES. **OSHA PEL/STEL.

---

#### SECTION V EMERGENCY AND FIRST AID PROCEDURES

---

EYE CONTACT: FLUSH EYES WITH PLENTY OF WATER FOR 15 MINUTES WHILE HOLDING EYELIDS OPEN. GET MEDICAL ATTENTION. SKIN CONTACT: REMOVE CONTAMINATED CLOTHING/SHOES AND WIPE EXCESS FROM SKIN. FLUSH SKIN WITH WATER. FOLLOW BY WASHING WITH SOAP AND WATER. IF IRRITATION OCCURS, GET MEDICAL ATTENTION. DO NOT REUSE CLOTHING UNTIL CLEANED. IF CONTACT WITH HOT PRODUCT OCCURS IMMEDIATELY FLUSH WITH COOL WATER FOR 15 MINUTES. CAREFULLY REMOVE CLOTHING; IF CLOTHING IS STUCK TO A BURN AREA DO NOT PULL IT OFF, BUT CUT AROUND IT. COVER BURN AREA WITH A CLEAN MATERIAL. GET MEDICAL ATTENTION IMMEDIATELY. INHALATION: WARNING: EFFECTS FROM OVEREXPOSURE MAY BE DELAYED. ACT QUICKLY! UNCONSCIOUS VICTIMS CAN DIE IF NOT

REMOVED FROM CONTAMINATED AREA AS SOON AS POSSIBLE. PUT ON NIOSH APPROVED AIR-SUPPLIED PRESSURE DEMAND RESPIRATOR BEFORE ENTERING CONTAMINATED AREA. MOVE VICTIM TO FRESH AIR. GIVE ARTIFICIAL RESPIRATION IF NOT BREATHING. GET MEDICAL ATTENTION AS SOON AS POSSIBLE. KEEP VICTIM QUIET AND WARM. VAPORIZATION OF H<sub>2</sub>S THAT HAS BEEN TRAPPED IN CLOTHING CAN BE DANGEROUS TO RESCUERS. MAINTAIN PROTECTION TO AVOID CONTAMINATION FROM VICTIM TO RESCUER. INGESTION: DO NOT GIVE LIQUIDS IF VICTIM IS UNCONSCIOUS OR VERY DROWSY. OTHERWISE, GIVE NO MORE THAN 2 GLASSES OF WATER AND INDUCE VOMITING BY GIVING 30CC (2 TABLESPOONS) SYRUP OF IPECAC.\* IF IPECAC IS UNAVAILABLE, GIVE 2 GLASSES OF WATER AND INDUCE VOMITING BY TOUCHING FINGER TO BACK OF VICTIM'S THROAT. KEEP VICTIM'S HEAD BELOW HIPS WHILE VOMITING. GET MEDICAL ATTENTION. NOTE TO PHYSICIAN: \*IF VICTIM IS A CHILD, GIVE NO MORE THAN 1 GLASS OF WATER AND 15CC (1 TABLESPOON) SYRUP OF IPECAC. IF SYMPTOMS SUCH AS LOSS OF GAG REFLEX, CONVULSIONS OR UNCONSCIOUSNESS OCCUR BEFORE EMESIS, GASTRIC LAVAGE SHOULD BE CONSIDERED FOLLOWING INTUBATION WITH A CUFFED ENDOTRACHEAL TUBE.

---

#### SECTION VI SUPPLEMENTAL HEALTH INFORMATION

---

REPEATED DERMAL APPLICATION OF COMPONENT 3 (30 MG/KG/DAY FOR 13 WEEKS) IN RATS RESULTED IN ANEMIA, DISORDERS OF THE LIVER, BONE MARROW AND LYMPHOID TISSUES. AT DOSES OF 200 MG/KG/DAY MORTALITY WAS 100 PERCENT WITH 3 WEEKS. H<sub>2</sub>S IS IRRITATING TO THE EYES AND RESPIRATORY TRACT AT LOW CONCENTRATIONS. 0.02 PPM - ODOR THRESHOLD. 10 PPM - EYE IRRITATION. 100 PPM - HEADACHE, DIZZINESS, VOMITING, COUGHING. 200-300 PPM - EYE INFLAMMATION, RESPIRATORY TRACT IRRITATION AFTER 1 HOUR EXPOSURE. 300-700 PPM - LOSS OF CONSCIOUSNESS OR POSSIBLY DEATH IN 30 MIN. TO AN HOUR. 700-900 PPM - RAPID LOSS OF CONSCIOUSNESS; DEATH CAN RESULT. >1000 PPM - UNCONSCIOUSNESS IN SECONDS; DEATH IN MINUTES UNLESS VICTIM IS REMOVED FROM CONTAMINATED AREA AND BREATHING IS RESTORED. DO NOT DEPEND ON SENSE OF SMELL FOR WARNING. H<sub>2</sub>S CAUSES RAPID OLFACTORY FATIGUE (DEADENS SENSE OF SMELL). THERE IS NO EVIDENCE THAT H<sub>2</sub>S WILL ACCUMULATE IN THE BODY TISSUE AFTER REPEATED EXPOSURE.

---

#### SECTION VII PHYSICAL DATA

---

BOILING POINT (DEG F): SPECIFIC GRAVITY (H<sub>2</sub>O = 1): VAPOR PRESSURE (MM HG): >662 >1 NOT AVAILABLE MELTING POINT (DEG F): SOLUBILITY IN WATER: VAPOR DENSITY (AIR = 1): 45 (POUR POINT) NEGLIGIBLE NOT AVAILABLE EVAPORATION RATE (NORMAL BUTYL ACETATE = 1): NOT AVAILABLE APPEARANCE AND ODOR: BLACK OIL; STRONG

HYDROCARBON OR ROTTEN EGG ODOR. PHYS/CHEM PROPERTIES: SEE ABOVE FOR DETAILS

---

#### SECTION VIII FIRE AND EXPLOSION HAZARDS

---

FLASH POINT AND METHOD: 150 DEG. F (PMCC) MIN. FLAMMABLE  
LIMITS/PERCENT VOLUME IN AIR: LOWER: N/AV HIGHER: N/AV  
EXTINGUISHING MEDIA: USE WATER FOG, FOAM, DRY CHEMICAL OR CO<sub>2</sub>.  
SPECIAL FIRE FIGHTING PROCEDURES AND PRECAUTIONS: CAUTION.  
COMBUSTIBLE. DO NOT ENTER CONFINED FIRE SPACE WITHOUT FULL  
BUNKER GEAR (HELMET WITH FACE SHIELD, BUNKER COATS, GLOVES  
AND RUBBER BOOTS), INCLUDING A POSITIVE PRESSURE NIOSH  
APPROVED SELF-CONTAINED BREATHING APPARATUS. COOL FIRE  
EXPOSED CONTAINERS WITH WATER. UNUSUAL FIRE AND EXPLOSION  
HAZARDS: SULFUR OXIDES AND HYDROGEN SULFIDE, BOTH OF WHICH  
ARE TOXIC, MAY BE RELEASED UPON COMBUSTION.

---

#### SECTION IX REACTIVITY

---

STABILITY: STABLE HAZARDOUS POLYMERIZATION WILL NOT OCCUR  
CONDITIONS AND MATERIALS TO AVOID: AVOID HEAT, FLAME AND  
CONTACT WITH STRONG OXIDIZING AGENTS. HAZARDOUS  
DECOMPOSITION PRODUCTS: THERMAL DECOMPOSITION PRODUCTS ARE  
HIGHLY DEPENDENT ON THE COMBUSTION CONDITIONS. A COMPLEX  
MIXTURE OF AIRBORNE SOLID, LIQUID, PARTICULATES AND GASES WILL  
EVOLVE WHEN THIS MATERIAL UNDERGOES PYROLYSIS OR COMBUSTION.  
CARBON MONOXIDE, SULFUR OXIDE, HYDROGEN SULFIDE AND OTHER  
UNIDENTIFIED ORGANIC COMPOUNDS MAY BE FORMED UPON  
COMBUSTION.

---

#### SECTION X EMPLOYEE PROTECTION

---

RESPIRATORY PROTECTION: USE NIOSH APPROVED RESPIRATORY  
PROTECTION AS REQUIRED TO PREVENT OVEREXPOSURE TO OIL MIST,  
VAPOR, OR FUMES AND H<sub>2</sub>S. DO NOT ENTER STORAGE COMPARTMENTS  
UNLESS EQUIPPED WITH A NIOSH APPROVED SELF-CONTAINED  
BREATHING APPARATUS WITH A FULL FACEPIECE OPERATED IN A  
POSITIVE PRESSURE MODE. PROTECTIVE CLOTHING AVOID CONTACT  
WITH EYES. WEAR SAFETY GLASSES OR GOGGLES AS APPROPRIATE.  
AVOID CONTACT WITH SKIN. WEAR CHEMICAL-RESISTANT GLOVES AND  
OTHER CLOTHING AS REQUIRED TO PREVENT CONTACT. ADDITIONAL  
PROTECTIVE MEASURES: USE EXPLOSION-PROOF VENTILATION AS  
REQUIRED TO CONTROL OIL MIST CONCENTRATIONS.

---

#### SECTION XI ENVIRONMENTAL PROTECTION

---

SPILL OR LEAK PROCEDURES: CAUTION. COMBUSTIBLE. \*\*\* LARGE SPILLS  
\*\*\* ELIMINATE POTENTIAL SOURCES OF IGNITION. WEAR APPROPRIATE  
RESPIRATOR AND OTHER PROTECTIVE CLOTHING. SHUT OFF SOURCE OF  
LEAK ONLY IF SAFE TO DO SO. DIKE AND CONTAIN. REMOVE WITH  
VACUUM TRUCKS OR PUMP TO STORAGE/SALVAGE VESSELS. SOAK UP  
RESIDUE WITH AN ABSORBENT SUCH AS CLAY, SAND, OR OTHER  
SUITABLE MATERIAL; PLACE IN NON-LEAKING CONTAINERS AND SEAL  
TIGHTLY FOR PROPER DISPOSAL. FLUSH AREA WITH WATER TO REMOVE  
TRACE RESIDUE; DISPOSE OF FLUSH SOLUTION AS ABOVE. \*\*\* SMALL  
SPILLS \*\*\* TAKE UP WITH AN ABSORBENT MATERIAL AND PLACE IN NON-  
LEAKING CONTAINERS FOR PROPER DISPOSAL.

---

## SECTION XII SPECIAL PRECAUTIONS

---

KEEP LIQUID AND VAPOR AWAY FROM HEAT, SPARKS AND FLAME.  
SURFACES THAT ARE SUFFICIENTLY HOT MAY IGNITE EVEN LIQUID  
PRODUCT IN THE ABSENCE OF SPARKS OR FLAME. EXTINGUISH PILOT  
LIGHTS, CIGARETTES AND TURN OFF OTHER SOURCES OF IGNITION PRIOR  
TO USE AND UNTIL ALL VAPORS ARE GONE. CONTAINERS, EVEN THOSE  
THAT HAVE BEEN EMPTIED, CAN CONTAIN EXPLOSIVE VAPORS. DO NOT  
CUT, DRILL, GRIND, WELD OR PERFORM SIMILAR OPERATIONS ON OR  
NEAR CONTAINERS. WASH WITH SOAP AND WATER BEFORE EATING,  
DRINKING, SMOKING OR USING TOILET FACILITIES. LAUNDRY  
CONTAMINATED CLOTHING BEFORE REUSE. DISCARD CONTAMINATED  
LEATHER ARTICLES THAT CANNOT BE DECONTAMINATED.

---

## SECTION XIII TRANSPORTATION REQUIREMENTS

---

DEPARTMENT OF TRANSPORTATION CLASSIFICATION: COMBUSTIBLE  
LIQUID, III DOT PROPER SHIPPING NAME:FUEL OIL NA 1993 OTHER  
REQUIREMENTS: NOT APPLICABLE

---

## SECTION XIV OTHER REGULATORY CONTROLS

---

THE COMPONENTS OF THIS PRODUCT ARE LISTED ON THE EPA/TSCA  
INVENTORY OF CHEMICAL SUBSTANCES. PROTECTION OF STRATOSPHERIC  
OZONE (PURSUANT TO SECTION 611 OF THE CLEAN AIR ACT AMENDMENTS  
OF 1990): PER 40 CFR PART 82, THIS PRODUCT DOES NOT CONTAIN NOR  
WAS IT DIRECTLY MANUFACTURED WITH ANY CLASS I OR CLASS II OZONE  
DEPLETING SUBSTANCES. IN ACCORDANCE WITH SARA TITLE III, SECTION  
313, THE ENVIRONMENTAL DATA SHEET (EDS) SHOULD ALWAYS BE  
COPIED AND SENT WITH THE MSDS.

---

## SECTION XV STATE REGULATORY INFORMATION

---

THE FOLLOWING CHEMICALS ARE SPECIFICALLY LISTED BY INDIVIDUAL

STATES; OTHER PRODUCT SPECIFIC HEALTH AND SAFETY DATA IN OTHER SECTIONS OF THE MSDS MAY ALSO BE APPLICABLE FOR STATE REQUIREMENTS. FOR DETAILS ON YOUR REGULATORY REQUIREMENTS YOU SHOULD CONTACT THE APPROPRIATE AGENCY IN YOUR STATE. STATE LISTED COMPONENT CAS NO PERCENT STATE CODE

---

HYDROGEN SULFIDE 7783-06-4 0.04 MA SOOTS, TARS, AND CERTAIN 64741-56-6 0-100 CA65C MINERAL OILS SOOTS, TARS, AND CERTAIN 64741-62-4 0-100 CA65C MINERAL OILS SOOTS, TARS, AND CERTAIN 64741-59-9 0-100 CA65C MINERAL OILS CA = CALIFORNIA HAZ. SUBST. LIST; CA65C, CA65R, CA65C/R = CALIFORNIA SAFE DRINKING WATER AND TOXICS ENFORCEMENT ACT OF 1986 OR PROPOSITION 65 LIST; CT = CONNECTICUT TOXIC. SUBST. LIST; FL = FLORIDA SUBST. LIST; IL = ILLINOIS TOX. SUBST. LIST; LA = LOUISIANA HAZ. SUBST. LIST; MA = MASSACHUSETTS SUBST. LIST; ME = MAINE HAZ. SUBST. LIST; MN = MINNESOTA HAZ. SUBST. LIST; NJ = NEW JERSEY HAZ. SUBST. LIST; PA = PENNSYLVANIA HAZ. SUBST. LIST; RI = RHODE ISLAND HAZ. SUBST. LIST. CALIFORNIA PROPOSITION 65 FOOTNOTE: CA65C = THE CHEMICAL IDENTIFIED WITH THIS CODE IS KNOWN TO THE STATE OF CALIFORNIA TO CAUSE CANCER. CA65R = THE CHEMICAL IDENTIFIED WITH THIS CODE IS KNOWN TO THE STATE OF CALIFORNIA TO CAUSE BIRTH DEFECTS OR OTHER REPRODUCTIVE HARM. CA65C/R = THE CHEMICAL IDENTIFIED WITH THIS CODE IS KNOWN TO THE STATE OF CALIFORNIA TO CAUSE BOTH CANCER AND BIRTH DEFECTS OR OTHER REPRODUCTIVE HARM.

---

#### SECTION XVI SPECIAL NOTES

---

THIS MSDS REVISION HAS CHANGES IN SECTION XV - STATE REGULATORY INFORMATION

---

THE INFORMATION CONTAINED IN THIS DATA SHEET IS BASED ON THE DATA AVAILABLE TO US AT THIS TIME, AND IS BELIEVED TO BE ACCURATE BASED UPON THAT DATA. IT IS PROVIDED INDEPENDENTLY OF ANY SALE OF THE PRODUCT, FOR PURPOSE OF HAZARD COMMUNICATION. IT IS NOT INTENDED TO CONSTITUTE PRODUCT PERFORMANCE INFORMATION, AND NO EXPRESS OR IMPLIED WARRANTY OF ANY KIND IS MADE WITH RESPECT TO THE PRODUCT, UNDERLYING DATA OR THE INFORMATION CONTAINED HEREIN. YOU ARE URGED TO OBTAIN DATA SHEETS FOR ALL PRODUCTS YOU BUY, PROCESS, USE OR DISTRIBUTE, AND ARE ENCOURAGED TO ADVISE THOSE WHO MAY COME IN CONTACT WITH SUCH PRODUCTS OF THE INFORMATION CONTAINED HEREIN. TO DETERMINE THE APPLICABILITY OR EFFECT OF ANY LAW OR REGULATION WITH RESPECT TO THE PRODUCT, YOU SHOULD CONSULT WITH YOUR LEGAL ADVISOR OR THE APPROPRIATE GOVERNMENT AGENCY. WE WILL NOT PROVIDE ADVICE ON SUCH MATTERS, OR BE RESPONSIBLE FOR ANY INJURY FROM THE USE OF THE PRODUCT DESCRIBED HEREIN. THE

UNDERLYING DATA, AND THE INFORMATION PROVIDED HEREIN AS A RESULT OF THAT DATA, IS THE PROPERTY OF EQUIVA SERVICES, LLC AND IS NOT TO BE THE SUBJECT OF SALE OR EXCHANGE WITHOUT THE EXPRESS WRITTEN CONSENT OF EQUIVA SERVICES, LLC.

---

ENVIRONMENTAL DATA SHEET EQUILON EDS: 52432E SHELL NO. 6 FUEL OIL-THIRD PARTY STORAGE TELEPHONE NUMBER: 24 HOUR EMERGENCY ASSISTANCE GENERAL MSDS ASSISTANCE EQUIVA SERVICES: 877-276-7283 877-276-7285 CHEMTREC: 800-424-9300 NAME AND ADDRESS EQUILON ENTERPRISES PRODUCT STEWARDSHIP P.O. BOX 674414 HOUSTON, TX 77267-4414 PRODUCT CODE: 41009

---

SECTION I PRODUCT COMPOSITION

---

NO. COMPOSITION CAS PERCENT

---

=====

P SHELL NO. 6 FUEL OIL-THIRD PARTY STORAGE MIXTURE 100 1 VACUUM TOWER BOTTOMS 64741-56-6 VAR. 2 CATALYTICALLY CRACKED LIGHT GAS OIL 64741-59-9 VAR. 3 CATALYTICALLY CRACKED CLARIFIED OIL 64741-62-4 VAR. 4 HYDROGEN SULFIDE 7783-06-4 <0.04\* \* BASED ON MAXIMUM ALLOWABLE CONTAINER HEADSPACE CONCENTRATION

---

SECTION II SARA TITLE III INFORMATION

---

NO. EHS RQ EHS TPQ SEC-313 313 CATEGORY 311/312 CATEGORY (\*1) (\*2) (\*3) (\*4) (\*5)

---

=====

P H-1, H-2, P-3 4 100 500

---

\*1 = REPORTABLE QUANTITY OF EXTREMELY HAZARDOUS SUBSTANCE, SEC 302 \*2 = THRESHOLD PLANNING QUANTITY, EXTREMELY HAZARDOUS SUBSTANCE, SEC 302 \*3 = TOXIC CHEMICAL, SEC 313 \*4 = CATEGORY AS REQUIRED BY SEC 313 (40 CFR 372.65 C), MUST BE USED ON TOXIC RELEASE INVENTORY FORM \*5 = CATEGORY (FOR AGGREGATE REPORTING REQUIREMENTS UNDER SARA 311, 312) HEALTH: H-1 = IMMEDIATE (ACUTE) HEALTH HAZARD H-2 = DELAYED (CHRONIC) HEALTH HAZARD PHYSICAL: P-3 = FIRE HAZARD P-4 = SUDDEN RELEASE OF PRESSURE HAZARD P-5 = REACTIVE HAZARD

---

SECTION III ENVIRONMENTAL RELEASE INFORMATION

---

UNDER EPA-CWA THIS PRODUCT IS CONSIDERED AN OIL AND CONTAINS A COMPONENT DESIGNATED AS A HAZARDOUS SUBSTANCE UNDER SECTION 311. SPILLS INTO OR LEADING TO WATERS THAT CAUSE A SHEEN MUST BE REPORTED TO THE NATIONAL RESPONSE CENTER, 800-424-8802. EPA - COMPREHENSIVE ENVIRONMENTAL RESPONSE,

COMPENSATION AND LIABILITY ACT. UNDER EPA-CERCLA ("SUPERFUND") RELEASES TO AIR, LAND OR WATER WHICH EXCEED THE REPORTABLE QUANTITY MUST BE REPORTED TO THE NATIONAL RESPONSE CENTER, 800-424-8802. THE REPORTABLE QUANTITY (RQ) FOR THIS PRODUCT UNDER CWA HAZARDOUS SUBSTANCE LIST AND CERCLA IS 250,000 LBS., WHICH IS BASED ON THE PRESENCE OF COMPONENT 4, HYDROGEN SULFIDE.

---

SECTION IV RCRA INFORMATION

---

PLACE IN AN APPROPRIATE DISPOSAL FACILITY IN COMPLIANCE WITH LOCAL REGULATIONS.

---

THE INFORMATION CONTAINED IN THIS DATA SHEET IS BASED ON THE DATA AVAILABLE TO US AT THIS TIME, AND IS BELIEVED TO BE ACCURATE BASED UPON THAT DATA. IT IS PROVIDED INDEPENDENTLY OF ANY SALE OF THE PRODUCT, FOR PURPOSE OF HAZARD COMMUNICATION. IT IS NOT INTENDED TO CONSTITUTE PRODUCT PERFORMANCE INFORMATION, AND NO EXPRESS OR IMPLIED WARRANTY OF ANY KIND IS MADE WITH RESPECT TO THE PRODUCT, UNDERLYING DATA OR THE INFORMATION CONTAINED HEREIN. YOU ARE URGED TO OBTAIN DATA SHEETS FOR ALL PRODUCTS YOU BUY, PROCESS, USE OR DISTRIBUTE, AND ARE ENCOURAGED TO ADVISE THOSE WHO MAY COME IN CONTACT WITH SUCH PRODUCTS OF THE INFORMATION CONTAINED HEREIN. TO DETERMINE THE APPLICABILITY OR EFFECT OF ANY LAW OR REGULATION WITH RESPECT TO THE PRODUCT, YOU SHOULD CONSULT WITH YOUR LEGAL ADVISOR OR THE APPROPRIATE GOVERNMENT AGENCY. WE WILL NOT PROVIDE ADVICE ON SUCH MATTERS, OR BE RESPONSIBLE FOR ANY INJURY FROM THE USE OF THE PRODUCT DESCRIBED HEREIN. THE UNDERLYING DATA, AND THE INFORMATION PROVIDED HEREIN AS A RESULT OF THAT DATA, IS THE PROPERTY OF EQUIVA SERVICES, LLC AND IS NOT TO BE THE SUBJECT OF SALE OR EXCHANGE WITHOUT THE EXPRESS WRITTEN CONSENT OF EQUIVA SERVICES, LLC.

**Appendix A4: Number two Fuel Oil MSDS**

=====  
MSDS Safety Information  
=====

FSC: 9140 NIIN: 00-247-4365 MSDS Date: 09/07/1993 MSDS Num: BTHTD Tech Review: 02/09/1995 Product ID: FUEL OIL,2 Responsible Party Cage: 4N717 Name: AMERADA HESS CORP Address: 1 HESS PLAZA City: WOODBRIDGE NJ 07095 US Info Phone Number: 201-750-6000 Emergency Phone Number: 201-750-6000/800-424-9300(CHEMTREC)  
=====

I. Contractor Summary  
=====

Cage: 4N717 Name: AMERADA HESS CORP Address: 1 HESS PLAZA City: WOODBRIDGE NJ 07095-1229 US Phone: 908-750-6000, CHEMTREC 800-424-9300  
=====

II. Item Description Information  
=====

Item Name: FUEL OIL,BURNER Specification Number: VV-F-815 Type/Grade/Class: GR II Unit of Issue: GL UI Container Qty: X  
=====

III. Ingredients  
=====

Cas: 68476-30-2 RTECS #: LS8930000 Name: NO. 2 FUEL OIL % by Wt: 100 Other REC Limits: 5 MG/M3 OIL MIST OSHA PEL: 5 MG/M3 AS OIL MIST ACGIH TLV: 5 MG/M3 AS OIL MIST Ozone Depleting Chemical: N ----- Cas: 91-20-3 RTECS #: QJ0525000 Name: NAPHTHALENE (SARA 313) (CERCLA) % by Wt: <2 Other REC Limits: NONE RECOMMENDED OSHA PEL: 10 PPM ACGIH TLV: 10 PPM/15 STEL; 9495 EPA Rpt Qty: 100 LBS DOT Rpt Qty: 100 LBS Ozone Depleting Chemical: N  
=====

IV. Health Hazards Data  
=====

LD50 LC50 Mixture: LD50 (ORAL, RAT) IS 14000 MG/KG. Route Of Entry Inds - Inhalation: YES Skin: YES Ingestion: NO Carcinogenicity Inds - NTP: NO IARC: NO OSHA: NO Effects of Exposure: TARGET ORGANS:EYE, SKIN, RESPIRATORY & GI TRACTS. ACUTE- MAY CAUSE IRRITATION OF EYES, SKIN, RESPIRATOR & GI TRACTS. INGESTION MAY CAUSE HARMFUL CNS EFFECTS. PROLONGED INHALATION OF HIGH VAPOR CONCENT RATIONS MAY CAUSE DIZZINESS, HEADACHE &DEGENERATIVE CHANGES TO LIVER, KIDNEYS & BONE MARROW. CHRONIC- DERMATITIS. Explanation Of Carcinogenicity: NIOSH(BASED ON TESTS ON MICE & RATS) RECOMMENDS THAT WHOLE DIESEL EXHAUST BE REGARDED AS A POTENTIAL CARCINOGEN. Signs And Symptions Of Overexposure: EYES, SKIN, RESPIRATORY AND GASTROINTESTINAL TRACTS IRRITATION; HEADACHE, DIZZINESS, NAUSEA, VOMITING, EXCITATION, DROWSINESS, RESPIRATORY ARREST, COMA, DEATH, EYE REDNESS, TEARNING AND BLURRED VISION ;

SKIN CRACKING, ALLERGIC REACTION, POISONING FROM ABSORPTION  
Medical Cond Aggravated By Exposure: MAY AGGRAVATE PRE-EXISTING  
DERMATITIS. First Aid: GET MEDICAL HELP IF SYMPTOMS PERSIST.  
INHALED:REMOVE TO FRESH AIR. PROVIDE CPR/OXYGEN IF NEEDED.  
EYES:FLUSH WITH WATER FOR 15 MINUTES, HOLDING EYELIDS OPEN.  
SKIN:WASH WITH SOAP & WATER. ORAL:DO NOT IN DUCE VOMITING. IF  
CONSCIOUS, RINSE MOUTH WITH WATER & DRINK 1-2 GLASSES OF  
WATER/MILK. SEEK IMMEDIATE MEDICAL ATTENTION. IF SPONTANEOUS  
VOMITING OCCURS, MONITOR FOR BREATHING DIFFICULTY.

=====

#### V. Handling and Disposal

=====

Spill Release Procedures: WEAR PROTECTIVE EQUIPMENT. ELIMINATE  
SOURCES OF IGNITION. VENTILATE AREA. CONTAIN SPILL. PICK UP SPILL  
WITH NON-FLAMMABLE ABSORBENT SUCH AS SAND, EARTH/USE PUMP  
(EXPLOSION PROOF). GROUND ALL HANDLING EQUIPMENTS. PREVENT  
LIQUID FROM ENTERING SEWERS. Neutralizing Agent: NOT RELEVANT Waste  
Disposal Methods: MAXIMIZE PRODUCT RECOVERY FOR REUSE OR  
RECYCLING. CONTAMINATED MATERIALS MAY BE CLASSIFIED AS RCRA  
HAZARDOUS DUE TO THE LOW FLASH POINT. WASTE MAY BE  
INCINERATED. OBSERVE ALL LOCAL, STATE AND FEDERAL REGULATIONS.  
Handling And Storage Precautions: STORE IN COOL (<100F), WELL-VENTILATED  
AREA, AWAY FROM HEAT, FLAMES, SPARKS, HOT SURFACES &  
INCOMPATIBLE MATERIALS. BOND & GROUND CONTAINERS. Other  
Precautions: "EMPTY" CONTAINERS RETAIN RESIDUE AND CAN BE  
DANGEROUS. DO NOT PRESSURIZE, CUT, WELD, BRAZE, SOLDER, DRILL OR  
EXPOSE SUCH CONTAINERS TO HEAT, FLAME, SPARKS. THEY MAY  
EXPLODE AND CAUSE INJURY/DEATH. KEEP OUT OF REACH OF CHILDREN.

=====

#### VI. Fire and Explosion Hazard Information

=====

Flash Point Method: PMCC Flash Point Text: 100F,38C Autoignition Temp Text: 495F  
Lower Limits: 0.6 Upper Limits: 7.5 Extinguishing Media: FOAM, DRY CHEMICAL,  
CARBON DIOXIDE, HALON, WATER SPRAY. USE WATER SPRAY TO COOL  
FIRE-EXPOSED CONTAINERS AND STRUCTURES. Fire Fighting Procedures:  
WEAR FULL PROTECTIVE CLOTHING AND NIOSH-APPROVED SELF-  
CONTAINED BREATHING APPARATUS WITH FULL FACEPIECE OPERATED IN  
THE POSITIVE PRESSURE MODE. Unusual Fire/Explosion Hazard: VAPOR IS  
HEAVIER THAN AIR AND CAN TRAVEL CONSIDERABLE DISTANCE TO A  
SOURCE OF IGNITION AND FLASH BACK. CONTAINERS MAY RUPTURE DUE  
TO VAPOR PRESSURE BUILDUP.

=====

#### VII. Control Measures

=====

Respiratory Protection: NOT REQUIRED IN WELL VENTILATED AREAS. IN  
CONFINED SPACES, NIOSH-APPROVED SELF-CONTAINED BREATHING

APPARATUS IS REQUIRED. Ventilation: MECHANICAL (GENERAL AND/OR LOCAL EXHAUST, EXPLOSION-PROOF) VENTILATION TO MAINTAIN EXPOSURE BELOW TLV(S). Protective Gloves: NEOPRENE, NITRILE RECOMMENDED Eye Protection: CHEMICAL SAFETY GOGGLES RECOMMENDED Other Protective Equipment: EYE WASH STATION, SAFETY SHOWER, BARRIER CREAMS SPECIFIC FOR PETROLEUM-BASED MATERIALS, PROTECTIVE CLOTHING Work Hygienic Practices: DO NOT TAKE INTERNALLY. AVOID SKIN CONTACT. WASH SKIN AFTER USING PRODUCT. AVOID BREATHING VAPORS. Supplemental Safety and Health: FORMULA CHANGED. FOR PREVIOUS FORMULATION, SEE PNI A, SAME NSN.

=====  
VIII. Physical/Chemical Properties  
=====

HCC: F4 NRC/State LIC No: NOT RELEVANT B.P. Text: 340F - 700F Vapor Pres: 0.5 @ 70F Vapor Density: >1 Spec Gravity: 0.86 @ 60F Viscosity: 33-38SUS@100F Evaporation Rate & Reference: VARY WITH CONDITIONS Solubility in Water: NEGLIGIBLE Appearance and Odor: CLEAR BLUE LIQUID, MILD PETROLEUM DISTILLATE ODOR Percent Volatiles by Volume: 100

=====  
IX. Reactivity Data  
=====

Stability Indicator: YES Stability Condition To Avoid: HIGH TEMPERATURES, OPEN FLAMES, WELDING, SMOKING AND IGNITION SOURCES. Materials To Avoid: STRONG OXIDIZING AGENTS Hazardous Decomposition Products: CARBON MONOXIDE, CARBON DIOXIDE, AND REACTIVE HYDROCARBONS (SMOKE). Hazardous Polymerization Indicator: NO Conditions To Avoid Polymerization: NOT RELEVANT

=====  
X. Toxicological Information  
=====

=====  
XI. Ecological Information  
=====

=====  
XII. MSDS Transport Information  
=====

=====  
XIII. Regulatory Information  
=====

=====  
XIV. Other Information  
=====

=====  
XV. Transportation Information  
=====

Responsible Party Cage: 4N717 Trans ID NO: 60946 Product ID: FUEL OIL,2 MSDS

Prepared Date: 09/07/1993 Review Date: 02/09/1995 Article W/O MSDS: N Tech Entry  
NOS Shipping Nm: ALIPHATIC PETROLEUM HYDROCARBONS Multiple KIT  
Number: 0 Unit Of Issue: GL Container QTY: X Additional Data: PROPER SHIPPING  
NAME (FUEL NO 2), PER MSDS.

=====  
XVI. Detail DOT Information

=====  
Code: GOD Symbols: D DOT Proper Shipping Name: FUEL OIL DOT PSN Modifier:  
(NO. 1, 2, 4, 5 OR 6) Hazard Class: 3 UN ID Num: NA1993 DOT Packaging Group: III  
Label: FLAMMABLE LIQUID Special Provision: B1 Packaging Exception: 150 Non  
Bulk Pack: 203 Bulk Pack: 242 Max Qty Pass: 60 L Max Qty Cargo: 220 L Vessel Stow  
Req: A

=====  
XVII. Detail IMO Information

=====  
IMO PSN Code: LMH IMO Proper Shipping Name: PETROLEUM DISTILLATES,  
N.O.S. o IMDG Page Number: 3375 UN Number: 1268 UN Hazard Class: 3.3 IMO  
Packaging Group: III Subsidiary Risk Label: - EMS Number: 3-07 MED First Aid Guide  
NUM: 311

=====  
XVIII. Detail IATA Information

=====  
IATA UN ID Num: 1268 IATA Proper Shipping Name: PETROLEUM DISTILLATES,  
N.O.S. IATA UN Class: 3 IATA Label: FLAMMABLE LIQUID UN Packing Group: III  
Packing Note Passenger: 309 Max Quant Pass: 60L Max Quant Cargo: 220L Packaging  
Note Cargo: 310

=====  
XIX. Detail AFI Information

=====  
AFI Proper Shipping Name: PETROLEUM DISTILLATES, N.O.S. AFI Hazard Class: 3  
AFI UN ID NUM: UN1268 AFI Packing Group: III Special Provisions: P5 Back Pack  
Reference: A7.3

=====  
XX. HAZCOM Label

=====  
Product ID: FUEL OIL,2 Cage: 4N717 Company Name: AMERADA HESS CORP  
Street: 1 HESS PLAZA City: WOODBRIDGE NJ Zipcode: 07095-1229 US Health  
Emergency Phone: 201-750-6000/800-424-9300(CHEMTREC) Date Of Label Review:  
02/09/1995 MFG Label NO: NOT RELEVANT Label Date: 02/09/1995 Eye Protection  
IND: YES Skin Protection IND: YES Signal Word: WARNING Respiratory Protection  
IND: YES Health Hazard: Moderate Contact Hazard: Slight Fire Hazard: Moderate  
Reactivity Hazard: None Hazard And Precautions: TARGET ORGANS:EYE, SKIN,  
RESPIRATORY & GI TRACTS. ACUTE- MAY CAUSE IRRITATION OF EYES,  
SKIN, RESPIRATOR & GI TRACTS. INGESTION MAY CAUSE HARMFUL CNS  
EFFECTS. INHALATION OF HIGH VAPOR CONCENTRATIONS MA Y CAUSE  
DEGENERATIVE CHANGES TO LIVER, KIDNEYS & BONE MARROW.

CHRONIC- DERMATITIS. STORE IN COOL, WELL-VENTILATED AREA, AWAY FROM SPARKS & INCOMPATIBLES. PICK UP SPILL WITH NON-FLAMMABLE ABSORBENT SUCH AS SAND. FIRST AID- GET MEDICAL HELP IF SYMPTOMS PERSIST. INHALED:REMOVE TO FRESH AIR. PROVIDE CPR/OXYGEN IF NEEDED. EYES:FLUSH WITH WATER FOR 15 MINUTES, HOLDING EYELIDS OPEN. SKIN:WASH WITH SOAP & WATER. ORAL:DO NOT INDUCE VOMITING. CALL DOCTOR.

=====  
Disclaimer (provided with this information by the compiling agencies): This information is formulated for use by elements of the Department of Defense. The United States of America in no manner whatsoever expressly or implied warrants, states, or intends said information to have any application, use or viability by or to any person or persons outside the Department of Defense nor any person or persons contracting with any instrumentality of the United States of America and disclaims all liability for such use. Any person utilizing this instruction who is not a military or civilian employee of the United States of America should seek competent professional advice to verify and assume responsibility for the suitability of this information to their particular situation regardless of similarity to a corresponding Department of Defense or other government situation.

**Appendix A5: Lab Test Results From UNH Bio-Oil Team Partner**

Sample Description: Work Order: 02-0585

Sample Type: Date Completed: 4/27/02

Source ID: Dynamotive Corp., Fuel Date Received: 4/8/02

Date Taken: 4/4/02

Barge Name: Barge Number:

Terminal Name: Tank:

---

Sample No. 1805

<b>Parameter</b>	<b>Results</b>	<b>ASTM Methods</b>
Al-Aluminum Total ppm	<1.0	ASTM D-3605
Ash, From Petroleum %	0.19	ASTM D-482
BTU/Lb	See Note	ASTM D-240
Calcium ppm	<1.0	ASTM D-365
Carbon, %	41.1	ASTM D-5291
CU-Corrosion	1a	ASTM D-130
Fe-Iron Total ppm	221.6	EPA 200.7
Flash Point, °F	152	ASTM D-93
Hydrogen, %	7.80	ASTM D-5291
K-Potassium Total ppm	<1.0	EPA 200.7
Lead ppm	<0.05	ASTM D-3605
Mg-Magnesium Total ppm	<0.05	EPA 200.7
Mn-Magnesium Total ppm	<1.0	EPA 200.7
Na-Sodium Total ppm	<1.0	EPA 200.7
Nitrogen, %	0.05	ASTM D-5291
Specific Gravity	1.65	ASTM D-287
Sulfur, in Petroleum %	0.01	ASTM D-1552
Viscosity, Kinematic @ 40°C	25.23	
Water and Sed. % (by volume)	70	ASTM D-1796
Zn-Zinc Total ppm	<0.10	EPA 200.7

---

When DynaMotive became aware of these testing results, they were frustrated that we had not consulted them first. They claim that before testing a sample that has been stored for a significant amount of time that the sample should be stirred and heated. The stirring and heating return the Bio-Oil to a suspension of uniform concentrations. If

a sample is allowed to sit for six months, such as the sample tested above, and then tested; two layers will exist. The top layer will contain most of the water and acids, while the bottom layer contains the heavier species in the Bio-Oil.

The conclusions from the above tests were that the pH of the sample (upper layer) were too acidic for co-firing in boiler system. The testing continued further on the bottom layer and was found too viscous and sticky to be combusted. The testers had a hard time removing the Bio-Oil (bottom layer) from their equipment and complained bitterly about it.

The results have led the UNH Bio-Oil Team to search for an additional third party to do more testing on a properly prepared sample of Bio-Oil.

## Appendix A6: Optical Activity Results

Dean Arthur Greenberg's research team developed the optical rotation data.

State of the Oil: Thick dark brown liquid with a lot of suspended particles

Stock Solution: 1:4 (5ml of Oil in 20ml of Acetone)

This stock solution is very dark and optical rotation measurement is not possible. Hence, the following dilutions were made.

Path length 10 cm

$\lambda = 589 \text{ nm}$

S. No.	Concentration	Optical Rotation		
		In Chloroform	In Acetone	In Acetonitrile
1.	1:20	+0.005	-0.063	-0.058
2.	2:20	+0.008	-0.107	-0.092
3.	3:20	----	-0.168	-0.122
4.	4:20	+0.033	-0.195	-0.144
5.	5:20	----	-0.220	-0.170
6.	6:20	+0.056	-0.243	-0.196
7.	7:20	----	-0.299	-0.213
8.	8:20	+0.075	-0.330	-0.246
9.	10:20	-0.092	----	----
10.	11:20	-0.095	----	----
11.	12:20	-0.096	----	----
Optical Rotation Data				
1.	Organic Bases		-0.072	
2.	Organic Acids		+1.632	
3.	Neutral Fraction		-0.003	
4.	Activated Charcoal Filtered Bio-Oil		-0.015	

(<sup>45</sup> Greenberg)

The conclusions reached by the University of New Hampshire's Dean Greenberg where that the Bio-Oil displays significant optical activity. He theorizes that optically inactive material can be removed with activated charcoal cleaning. Bio-Oil has the potential to be a relatively cheap optically active solvent with interesting uses in pharmaceuticals, flavors, etc. The university is looking for \$5,000 with overhead to continue this research. (<sup>45</sup> Greenberg)

## **Appendix A7. Frequently Asked Questions**

### **A.- If Bio-Oil were used for residential heating...**

The UNH Bio-Oil study found that if the quantity of wood available after the closing of NH's wood fired power plants was converted to Bio-Oil, enough Bio-Oil would be created to heat one and a half times the number of the homes *currently using number two fuel oil* in Coos, Carroll, and Grafton counties. That equates to between about 48,000 to 69,000 homes that could replace the no. 2 fuel oil they use with Bio-Oil, if the home heating system was available.

### **B.- The justification used by Alaska to use Bio-Oil for home heating. Does this apply to NH? Did they do any economic estimates in Alaska about this?**

The interest in using Bio-Oil for home heating in Alaska stemmed from two realities. Alaska uses a relatively high percentage of the distillate used in the United States for a relatively small percentage of the population. Also, forest residue is available in that area, as it is in New Hampshire. From the preliminary economic analysis for Bio-Oil in Southeast Alaska, it was determined that if Bio-Oil's cost was less than a dollar, it would be feasible to use the fuel for home heating. This was determined based on the statement by the author of the report that the average cost of heating fuel is \$1.80 per gallon and that 1.5 times the volume of petroleum fuel would be needed to supply energy required.

### **C.- The economic disadvantage, as of now, assuming the Bio-Oil to be \$1.20. How many gallons of Bio-Oil will an average home use?**

Because the heating value of Bio-Oil is about half that of no. 2 fuel, about twice as much Bio-Oil would be needed to heat a home. In order to supply the Btu's needed for a home, 2160 gallons of Bio-Oil are needed annually.

### **D.- The challenges to be researched: material of construction, furnace retrofitting, bio-oil storage, corrosiveness due to pH?**

Due to the properties of Bio-Oil, it must be stored in an air-free environment in resistant materials at room temperature or below (<sup>4</sup> Oasmaa, 13). Material selection is critical for all components wetted by Bio-Oil. Typically, 300 series stainless steels are acceptable metallic materials and high-density polyethylene (HDPE) or fluorinated HDPE for polymers. (<sup>10</sup> DynaMotive, 6). Copper and its alloys can also be used for pumping Bio-Oil with minimal abrasive particles at low velocities and moderate temperatures (<sup>4</sup> Oasmaa, 14).

### **E.- Are there other universities or research organizations that are studying this application? Has it been tried anywhere?**

The closest research to study the application of Bio-Oil in heating systems is taking place in Canada, DynaMotive and CANFOR are working convert boilers and kilns to Bio-Oil.

## **F.- Need to identify partners for this type of research**

Obvious partners include the companies already producing and studying Bio-Oil such as DynaMotive, Ensyn, Renewable Oil International, and Pyrovac. These companies will lead to other entities that have interest in the market. PyNe, the Pyrolysis Network, would also aid in identifying partners.

## **G1 -Explain''carbon-dioxide-neutral'' to a lay person. Did you come across a simple definition?**

UNH Bio-Oil Team Explanation:

Although burning Bio-Oil does produce carbon dioxide, the same source from which the Bio-Oil was produced (plant matter) will use carbon dioxide for growth. Thus no net gain of carbon dioxide in the atmosphere takes place.

This decreases global warming because, unlike burning fossil fuels, which take a long time to form, trees are renewable and mean that there is a lesser net gain of carbon dioxide into the atmosphere. Carbon dioxide is one of the pollutants responsible for global warming because it traps heat in the atmosphere.

BioEnergy Information Network Explanation:

“Burning biomass efficiently results in little or no net emission of carbon dioxide to the atmosphere, since the bioenergy crop plants actually took up an equal amount of carbon dioxide from the air when they grew. However, burning conventional fossil fuels such as gasoline, oil, coal or natural gas results in an increase in carbon dioxide in the atmosphere, the major greenhouse gas which is thought to be responsible for global climate change. Some nitrogen oxides inevitably result from biomass burning (as with all combustion processes) but these are comparable to emissions from natural wildfires, and generally lower than those from burning fossil fuels. Utilization of biomass residues which would have otherwise been dumped in landfills (e.g. urban and industrial residues) greatly reduces greenhouse gas emissions by preventing the formation of methane.”

(<http://bioenergy.ornl.gov/faqs/index.html#overview1>)

## **How does this help in Global Warming?**

Greenhouse gases are naturally occurring and synthetic gaseous substances that form a protective blanket around the Earth, keeping it warm enough to sustain life. They include water vapor (H<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), ozone (O<sub>3</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) - and synthetic substances, such as chlorofluorocarbons (CFCs).

Just like a greenhouse where plants grow, the gases allow sunlight to pass through them from above and warm the surface of the Earth. The Earth and its atmosphere give off their warmth in the form of infrared radiation, but greenhouse gases absorb the infrared rays much like a blanket traps heat to warm the planet.

(<http://www.api.org/globalclimate/thescience.htm>)

The question that has been of much debate is whether the increasing warming of the earth is due to greenhouse gases, part of a natural cycle, or both. If greenhouse gases are part of the problem then the amount of them in the atmosphere increases the effect. A carbon dioxide neutral fuel means that there is no net gain of burning that substance to the

atmosphere and that is how Bio-Oil aids in slowing global warming. Since Bio-Oil is made from only part of the carbon absorbing tree (low grade wood chips), it is estimated that a net loss of carbon occurs from the atmosphere through the tree and bio-oil system assuming that the rest of the tree is not combusted.

**G2.- You are comparing Bio-Oil to fossil fuel in making this statement?**

The two do not have to be compared, but Bio-Oil is an example of CO<sub>2</sub> neutral, while fossil fuels are not.

**G3.- So, the tree consumes CO<sub>2</sub> to produce O<sub>2</sub>, then when you cut the tree and burn it you use O<sub>2</sub> to produce about the same amount of CO<sub>2</sub>. Is this correct?**

Assuming that the whole tree is burned then the answer is yes. Remember though that Bio-Oil is made from waste wood, which otherwise would have just decayed on the ground. When plants and animals decompose, carbon is released into the air and soil. Not all of the carbon going into the soil stays there and goes into the air as CO<sub>2</sub>. ([http://www.exxonmobil.com/news/publications/c\\_winter00\\_lamp/c\\_co2.html](http://www.exxonmobil.com/news/publications/c_winter00_lamp/c_co2.html)). This means that if the wood chips are burned or turned into Bio-Oil and then burned, they will release CO<sub>2</sub>, while if they are allowed to decay they also release CO<sub>2</sub>, though in a smaller amount. Also remember that only a fraction of the tree is the low grade wood, the rest of the tree is used for everything from paper products, cosmetics, pharmaceuticals, baby foods, beverages, furniture, insecticides, flavoring, to colognes amongst others ([http://www.nbforestry.com/e/dyk/index\\_b.htm](http://www.nbforestry.com/e/dyk/index_b.htm)). Therefore, all the carbon in the tree from CO<sub>2</sub> ends up in these products and the low-grade wood chips that are used to create Bio-Oil (which can be combusted).

“Wood, however, differs from the fossil fuels such as oil and gas because it is a renewable fuel. As a tree grows, it absorbs carbon dioxide from the air and stores it in the wood as carbon. This carbon makes up about half of the weight of wood. When wood is burned, carbon dioxide is released again to the atmosphere. The same amount of carbon dioxide would be released if the tree died and were left to rot on the forest floor. Our forests can be a perpetual source of fuel provided they are cared for and managed properly.”-Natural Resources Canada  
([http://www.nrcan.gc.ca/es/erb/reed/wood/02\\_e.html](http://www.nrcan.gc.ca/es/erb/reed/wood/02_e.html))

**G4.- If yes, then the fossil fuels will have advantage. You do not have to cut trees, and the CO<sub>2</sub> emitted from Fossil fuel burning will be assimilated by the trees to give you O<sub>2</sub>. What is wrong with this argument?**

The answer to the last question was not a complete yes, since the low-grade wood chips are only the leftover parts of the tree (bark, small branches) and would otherwise decompose into some CO<sub>2</sub> anyway.

Even if the answer was yes, the latest statement about fossil fuels having an advantage in regard to CO<sub>2</sub> emissions is wrong. Concentrate on the cycle of a fossil fuel product versus a Bio-Oil product.

Hundreds of millions of years ago plants and animals died and have decomposed to create the present day crude oil, coal, and natural gas. The crude oil is then pumped out of the ground, imported to the United States through fuel tankers, sent to a refinery,

distilled into everything from gasoline, #2 oil, #6 oil, to tar. Coal is mined and natural gas is mined/pumped. If the fossil fuel is used for combustion then it releases its carbon into CO<sub>2</sub> and CO.

Trees on the other hand grow using CO<sub>2</sub>, water, and nutrients in the soil. The nutrients in the soil come from decomposed plants and animals. The trees often live anywhere from around 20 to 150 years before being cut down. Logging then transports the trees/wood to the appropriate refineries for their end-use. End-use can range from furniture, paper products, solvents, to heating. The low-grade wood is either left in the forest, sent to a paper and pulp mill, combusted, or sent through fast pyrolysis unit to make Bio-Oil. Bio-Oil can also be made from the sawdust left over from sawmills. If the Bio-Oil is combusted it releases CO<sub>2</sub> as well.

The comparison was supposed to look at why fossil fuels do not have an advantage in CO<sub>2</sub> over trees in regard to combusting fuel from each source. The reason why the CO<sub>2</sub> from trees is better is because the CO<sub>2</sub> comes from a waste source that would release part of the CO<sub>2</sub> anyway. Fossil fuels and their carbon can remain undisturbed for additional hundreds of millions of years without releasing CO<sub>2</sub> into the atmosphere.

**G5.- If you burn 1 gal of no. 2 fuel oil and 1 gal of Bio-Oil do you get the same amount of CO<sub>2</sub>? If yes, then to obtain the same Btus to heat your home you will be producing twice as much CO<sub>2</sub>?**

Bio-Oil is approximately 50% C elemental. We have not found information on gasoline yet. We will need emission tests for both to truly know answer. Though if energy content of a fuel comes from the number of CO<sub>2</sub>, and hence H<sub>2</sub>O for the reaction that can be created this means that if Bio-Oil has half the energy content of say #2 fuel oil that it should have half the carbon. Therefore, when Bio-Oil is burned, it produces the same amount of CO<sub>2</sub> per Btu generated. .

**G6.- You will need twice as large a Bio-Oil tank?**

Due to the energy content being half that of #2, you will need either twice the size of a storage tank or the delivery Bio-Oil truck will have to visit you twice as often.

**G7.- What other "fuels" are called "CO<sub>2</sub> neutral"? Is the same explanation you provided apply to all "CO<sub>2</sub>-neutral" fuels?**

Any fuels made from biomass are considered CO<sub>2</sub> neutral. Ethanol, methanol, biodiesel, Bio-Oil. Ethanol and methanol may interchange with Bio-ethanol and Bio-methanol. Same explanation for CO<sub>2</sub> neutral fuels is given in earlier question G1.

**H.- I'm wondering if bio-oil could be used in a home furnace as heating oil?**

Yes. With the appropriate furnace system and materials of construction.

**I.- Will any of your research at UNH be exploring this (home heating) as a market for bio-oil?**

The UNH Bio-Oil team has looked into this area. See section 6.2 and 7.0 of the report.

**J.- I don't have a clue what chemical changes take place with bio-oil if it sits around for a while, but I understand that might be a problem.**

Around 6 months or earlier, the product separates out into a lighter and heavier layer. To restore the fuel to its original state, stirring is required and heating helps. Many petroleum companies do not recommend storing petroleum diesel for more than six months. ([www.biodiesel.org/pdf\\_files/Myths\\_Facts.PDF](http://www.biodiesel.org/pdf_files/Myths_Facts.PDF))

**K.- Where is Bio-Oil being actually used anywhere in the world? Is it currently used as a fuel? as a source of chemicals?**

Outside of the United States, Bio-Oil is being, or has been produced in Italy, Greece, Canada, Finland, Spain, the Netherlands, and Great Britain. The only place in the United States where Bio-Oil has been produced by fast pyrolysis is Red Arrow, Wisconsin, by a company called Ensyn. Mostly the application involves using the Bio-Oil either for power generation or researching the valuable chemicals contained in it. For example, Ensyn uses some of the chemicals for food smoking flavor. In Finland, Canada, and Great Britain, the Bio-Oil was used to test Diesel, Gas Turbine, and Diesel engines, respectively.

(source= SciTechLibrary - Analytical Reviews)

**- Someone claims that Bio-Oil is used in Australia. Did you come across anything on this?**

No. The previous source listed only the stated countries working on fast pyrolysis methods of producing Bio-Oil. However, it is possible and it would be appreciated if this person gave the source of information as it may be helpful for our work.

**- What is happening at Keene State College with Biodiesel?**

Keene, NH and Keene State College have started a pilot program to test biodiesel in their diesel fleet. Keene State College's fleet of maintenance vehicles used to be supplied with a 500 gallon diesel tank that now contains bio-diesel. Four mower/snowplows, a loader, and the trash truck have been running on biodiesel from June 2002 to present (August 2002). Diesel engines can run on bio-diesel without any conversions. Keene State claims that biodiesel has no adverse effect on engines and helps clean them out. Biodiesel reduces the emissions of carbon dioxide by 78% in comparison to diesel. It is biodegradable and does not have carcinogens. The problem with biodiesel is that it freezes at a higher temperature than diesel, meaning that in the winter time a 20% biodiesel to 80% diesel mixture is required (called B20). Biodiesel also has a drawback in cost at about 15 to 20 cents more per gallon than petroleum diesel with the B20 mixture and a cost of \$1.25 to 2.25/gal for 100% biodiesel.

- [http://www.afdc.doe.gov/pdfs/Biodiesel\\_fs.pdf](http://www.afdc.doe.gov/pdfs/Biodiesel_fs.pdf)

- [http://www.keene.edu/newsevents/default.cfm?Type=NewsDetail&News\\_ID=184](http://www.keene.edu/newsevents/default.cfm?Type=NewsDetail&News_ID=184)

The energy content of biodiesel is close to that of diesel fuel. (<sup>47</sup> Czernik)

**L.- If these Bio-Oil plants were to go on-line here in NH will NH be ahead of other places? How far ahead will we be?**

If the Bio-Oil plants go online, they will be the first commercial plants established under DynaMotive, third to sixth commercial plant under Ensyn, and the second state (first was Wisconsin) in the United States to use commercial Bio-Oil. The process, fast pyrolysis, should be noted as different from slow pyrolysis. Slow pyrolysis has been used for many years to produce charcoal with some leftover bio-oil produced.

**M.- Are all Bio-Oils the same?**

No. Bio-Oil is like soda. Soda can be caffeinated or decaffeinated, diet or regular, clear, orange, green, dark, and relatively healthy or relatively unhealthy. Bio-Oil varies too it can vary in acidity, viscosity, how much energy it gives off when burned, how environmentally friendly it is, etc. Bio-Oil varies because of what it is made from (wood, grass, sugarcane, etc) and how it is made (each company has their own design). Companies also improve their designs over time, which changes their Bio-Oil.

**N.- What is the status of commercialization of Bio-Oil Technology?**

Bio-Oil commercialization has been attempted in one of the fifty United States: Wisconsin. Five commercial plants were established in Wisconsin, one in Red Arrow, which processed 30 dry tons per day, and another in Northern Wisconsin which processed 70 green tons per day. The plant in Red Arrow supplied Manitowoc Public Utilities with residual Bio-Oil after the chemicals needed for value added chemical markets were taken off (<sup>17</sup>Sturlz, 2)&(http://www.ensyn.com/info/11122000.htm)& (49 Bouldard).

**O.- What is unique about NH, other than the job market situation in the North Country?**

New Hampshire is the second most forested state in the country, and has an economy that relies heavily on a strong wood market. What is unique about Northern New England is that it is the most forested region of the country, with an abundance of low-grade wood (<sup>34</sup>Mullaney).

**P.- What is unique about the UNH study, and the economic model?**

The goal of this report was to centralize and provide easy, comprehensive access to information about the fast pyrolysis process and the need for a strong low-grade wood market in New Hampshire. The unique situation in New Hampshire, and a Bio-Oil facility's effect on New Hampshire, environmentally and socially, was analyzed. Additionally, the economic analysis done by the UNH Bio-Oil Team is independent of any completed previously. The UNH Bio-Oil Team has made contacts with experts in the Bio-Oil field, conducted some chemistry research on Bio-Oil's optical activity and will be conducting tests on Bio-Oil's possible use in the asphalt industry, worked closely with PSNH to explore the possibility of co-firing, met with experts in other fields to explore possible end-use markets, and done several public outreach presentations on Bio-Oil and the situation in Northern New Hampshire.

What was unique about the UNH study was that it was done independently, and without bias (<sup>34</sup>Mullaney).

**Q.- How is the product market UNH is considering different from what the NH DRED study did?**

None of the markets that NH DRED explored were considered in the UNH Bio-Oil study. The fourteen markets considered for low grade wood by NH DRED included: pulp and paper manufacturing, fuel pellets, wood chip export, small-scale gasification, process heat/ co-location, ethanol and bio-chemicals, co-firing wood with PSNH Merrimack coal-fired electricity plant, firewood, animal bedding, landscaping mulch, densified logs, lumber from small diameter material, and solid wood composites (oriented strand board (OSB) and medium density fiberboard (MDF) (<sup>3</sup> DRED, pg 20). The only end-use market studied in great detail was MDF. On the other hand, the UNH Bio-Oil Team has explored one market for low-grade wood chips: Bio-Oil, which was not considered by NH DRED. The end-use market for the wood-chips was set: Bio-Oil, the UNH Bio-Oil Team then began studying end-use markets for the Bio-Oil.

**R.- Is co-location of the Bio-Oil facility in NH important? Does UNH have any economics on this? Would you co-locate with an existing biomass energy plant? Would you co-locate with a paper mill?**

The UNH economic study considers a new facility. However, according to the Cole Hill Associate economic study, co-location saves \$0.15-\$0.20 per gallon of Bio-Oil. However, because the co-location considered was with a wood fired power plant, and they will be shut down by the year 2006-2008, co-locating with an existing biomass energy plant is unlikely. Co- location with a paper mill has not yet been considered.

**S.- Are you aware of "due Diligence"? Would you describe what UNH is doing as a first step of a "due diligence" report?**

The UNH Bio-Oil study had some qualities of a due diligence report. The economics of a Bio-Oil Facility in New Hampshire was considered, as well as the potential impacts, socially and environmentally, that a facility would incur. However, the report is more general to Bio-Oil and the fast pyrolysis process than a due diligence of DynaMotive would be (and has been done by Stone and Webster). A due diligence report would be expected to review financial records, physical assets, and business prospects, which was not done by UNH as a result of refraining from signing a non-disclosure agreement with DynaMotive.

**T.- What is the no. 1 priority for Bio-Oil in NH and in New England?**

Highest priority: green chemistry R&D using bio-oil as a chemical feedstock.  
Second: low cost ways to reduce pH and to allow bio-oil to be mixed with fuel oil or diesel (<sup>34</sup>Mullaney).

**U.- If the state is willing to provide a small incentive to stimulate the market growth for Bio-Oil production in NH, what would you suggest?**

Possible incentive: no taxes on diesel fuel with at least 5% bio-oil until market develops. Another possible incentive is state payment for conversion of home furnaces that convert to bio-oil, and guaranteed price of \$1 per gallon to low-income households (<sup>34</sup>Mullaney).

**V.- What companies are you aware of that produce Bio-Oil and have a patented technology?**

- ❑ DynaMotive, patent number 5,853,548
- ❑ Ensyn, patent number 5,961,786
- ❑ Renewable Oil International, patent pending
- ❑ Pyrovac International Inc., patent number 6042696

**W.- Please discuss the impact of “economies of scale” for the Bio-oil technology - is bigger better?**

Generally yes. As the plant size increases, the Bio-Oil becomes less expensive per gallon. However, the end-use market for the Bio-Oil must also be taken into consideration. If no market is available for the quantity of Bio-Oil produced from a 400 ton per day plant, but a 200 ton per day plant will sell all Bio-Oil produced, the better choice is the size plant that will satisfy the market demand. Also depending on the end-use market's value, the Bio-Oil produced could be profitable at say \$1.20/gal for green chemicals, but not for power generation.

Also under consideration is that fluidized beds are known to be difficult to scale up and the largest known is approximately 45 dry tons per day in Wisconsin. For that reason it is suggested that turnkey packages are signed with the company of choice and that new plants that are built around the world should be monitored.

**X.- What is the potential economic impact of future Bio-Oil production - in jobs created and energy displacement?**

The answer to this question depends on how many Bio-Oil plants are constructed and the capacity of each plant. If enough Bio-Oil plants to convert all of wood chips used by the wood-fired power plants, 1.3 million tons, were to be constructed, then about 125 direct jobs would be created. However, the energy displacement is dependent on the end-use market used for the Bio-Oil and the capacity of the Bio-Oil plants.

Before the most recently closed wood-fired plant (Mid 2002), the remaining six plants used 1.3 million tons per year of low-grade wood. With all six closed (one has already closed) there will be a direct loss of 125 jobs (<sup>3</sup> DRED, pg28), an indirect loss of 412 jobs (<sup>6</sup> Hammond), and an economic impact of \$96 million a year. (<sup>3</sup> DRED, pg30) it is expected that Bio-Oil facilities using that much low-grade wood would reverse this trend.

**Y. - What is the potential to produce multiple products from a single production facility, e.g., the biorefinery concept?**

There is potential to use Bio-Oil for higher value chemicals and use the residual Bio-Oil for combustion. If the facility was available, part of all of the Bio-Oil could be refined on site. In this regard, the UNH Bio-Oil study figured a transportation cost into the economic analysis of a Bio-Oil facility. Thus, off-site refinement would not change the projected cost of the Bio-Oil.

**Z.- Please discuss, in general terms, the environmental challenges and benefits associated with a Bio-Oil product.**

The benefits associated with Bio-Oil are currently known for the combustion application.

- Bio-Oil produces about 50% of the NO<sub>x</sub> and no SO<sub>x</sub> emissions,
- Bio-Oil is CO<sub>2</sub> neutral.
- Bio-Oil is produced from a renewable source.

Environmental benefits in other applications are yet to be known. For example, the advantages of using Bio-Oil as a fuel additive might be proved when technology for emulsifying the Bio-Oil into hydrocarbon fuels becomes readily available. The environmental benefits for Bio-Oil in other applications such as a replacement in asphalt emulsions are also unknown.

The challenges of Bio-Oil, in general, are that it is not soluble with conventional hydrocarbon fuels, and therefore, co-firing becomes less feasible, as retrofitting is necessary. The Bio-Oil's acidic nature also implies standard materials used may have to be replaced with stainless steel or other materials that can withstand low pH. Other challenges of Bio-Oil are the metals, sodium and potassium, that are present in the ash, some of which is found in the Bio-Oil. These metals can cause hot corrosion if the ash content in the Bio-Oil is too high. Finally, a challenge which the UNH Bio-Oil Team was unable to find literature is the destination of metals such as lead and mercury that are present in the wood. Stephen Czernik claims that these heavy metals are found primarily in the char. (<sup>47</sup> Czernik)

**AA.- What are the downstream research needs? How will future research reduce production costs and/or help to build markets for Bio-Oil and co-products?**

Dean Arthur Greenberg, from UNH, has found optical activity in Bio-Oil that suggests that it may have value for pharmaceuticals or handed solvents. Research into using Bio-Oil for green chemicals could add value to Bio-Oil and provide markets for the product. Future research to emulsify Bio-Oil safely and cost effectively into diesel or gasoline might help to build markets for Bio-Oil. As research continues more applications for Bio-Oil are found or become more realistic in regard to environmental and economic considerations.

**AB. - What is the single most important step that either federal or state government can take to support the commercialization of Bio-Oil?**

The UNH Bio-Oil study has aimed to educate interested parties about the work that has already been done on Bio-Oil, provide a general economic model for a plant in New Hampshire, and suggest several possible end-use markets for Bio-Oil in addition to energy generation or boiler combustion. Because most of the research has been done in Canada, some of the issues and regulations in the United States have not been explicitly addressed. To that end, some of the areas that still need to be addressed on the state and federal level include:

1. Environmental Hazards-
  - a. What are the dangers if a truck is overturned and a Bio-Oil spill should occur on land or water?
  - b. Where is the final destination of lead and mercury in the wood, and what permits, if any will be required as a result of this?
  - c. Further studies into the health effects of exposure to Bio-Oil or Bio-Oil products.
2. Markets analysis for each end-use
3. Emission Testing of Bio-Oil combustion
4. Further economic analysis comparing each pyrolysis company
5. Economic comparisons to gasification and other biomass programs (ethanol, biodiesel, etc).
6. Further consideration of legislation that aids alternative fuels.
7. Confirming of company data on their product specifications.