Title: Optimization of acetic acid production during conversion of hybrid poplar to jet fuel by screening of water soluble streams using Raman Spectroscopy and detoxification.

Proposal Year: 2015-16
Proposal Type: Renewal

Principal Investigators: Renata Bura, UW, SEFS (206) 616-2179
Brian Marquardt, UW, APL (206) 685-0112
Rick Gustafson, UW, SEFS (206) 543-2790

Research Personnel: Chang Dou UW, SEFS PhD Student

Executive Summary

To be viable, future biorefineries will require new sensors and control systems to measure, in real time, the progress of fermentation. Research at CPAC has already resulted in new approaches to processes, and sensors for biorefineries. Examples include a revolutionary and unique Raman spectroscopy analytical method to monitor fermentation of sugar to ethanol processes in real time. The results from this study have recently been published in "Biofuels for Bioethanol" and "Pure and Applied Chemistry" (Ewanick et al., 2013, 2014) and CPAC was one of the financial sponsors for the study. **For 2015 we propose taking advantage of the Raman spectroscopy method and apply it to optimization of acetic acid production during conversion of hybrid poplar to jet fuel. We propose to develop screening method to quantify lignin induced fluorescence (LIF) in sugars streams prior to fermentation and to test different detoxification methods for florescent compounds removal prior to fermentation.** Application of Raman spectroscopy will allow us to optimize sugars to acetic acid titer during fermentation by *M. thermoacetica*. At CPAC we have unique technology (operational Raman probes with the chemometric models) (Prof. Marquardt), expertise in the field of biomass to biofuels and biochemicals conversion (Prof. Bura), modeling and process kinetics (Prof. Gustafson), instrumentation (Prof. Marquardt), facilities (lab scale and pilot scale biomass to biofuels and biochemicals facilities) and graduate students to successfully complete the project. It should be noted that many of the laboratory facilities for the proposed research were funded by DOE grants (DE-EE0000405 and DE-EE0003155) and that the proposed work builds on these grants to carry out essential basic research.

Objectives

The overarching goal of this project is to optimize acetic acid production during conversion of hybrid poplar to jet fuel by using Raman spectroscopy. **The first objective of this research is to determine how the background signal caused by lignin induced fluorescence can affect the acetate signal, specifically the signal to noise ratio (SNR) and the limit of detection (LOD) and to expand fundamental understanding of limitations governing fermentation of sugars by *M. thermoacetica* process with the ultimate goal of overcome those limitations. The second objective is to develop methods to reduce the concentration of fluorescent compounds prior to fermentation.** This research project will be coordinated with research currently being supported by the College of the Environment, the United States Department of Agriculture and the Department of Energy, to provide a comprehensive program for development of advanced sensor for biorefinery processes.

Budget:

$30,000 is requested for the current funding period. The bulk of the requested CPAC funding will be for Graduate Students support (6 months), and various research supplies.

Background

Production of lignocellulosic bioproducts will grow significantly over the next decade. In order to be competitive with fossil-based fuels and chemicals, maintaining cost-effectiveness will be critical. The majority of research in reducing operating costs of biofuels and biochemical has focused on finding cheaper feedstocks, developing more efficient and robust microorganisms, process integration, and/or co-product utilization. Development of robust sensors for lignocellulosic biorefineries is as critical as the research for developing the processes themselves, but has received little or no attention. Process improvements (feedstock pretreatment, microorganisms, enzymes, etc.) will likely reduce costs in the future, but in both the short and long term, improving the efficiency of existing operations will have the greatest effect on overall process economics.

Meeting the United States goal of producing 20 billion gallons of renewable fuel by 2022 will require the construction of approximately 200 new biorefineries each with a capacity of 100 million gallons per year. These biorefineries will process approximately 1 million tons of biomass per year and will cost on the order of $500 million to construct. This will be a commodity industry (high volume with low profit margins) using a highly variable feedstock – biomass.

Currently, our labs are working on conversion of hybrid poplar to jet fuels via a process which is similar to that proposed by ZeaChem, as shown in Figure 1. Poplar feedstock is loaded from a chip pile to a pre-processing unit operation to homogenize the feedstock. The biomass is then steam exploded to release some sugars and to enable enzymatic hydrolysis. During enzymatic hydrolysis, all the carbohydrates are converted to simple sugars which are then fermented with an acetogen (*M. thermoacetica***)** to produce acetic acid. In the proposed process, acetic acid is converted to cellulosic jet fuel by a series of chemical reactions: reduction to ethanol, dehydration to ethylene, oligomerization and hydrogen treat to jet fuel (Figure 1).

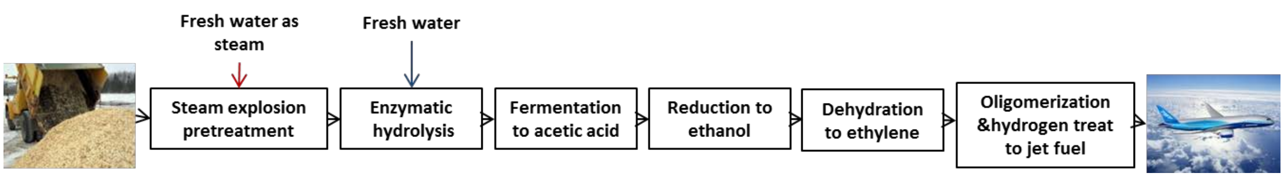

Figure 1. Hybrid poplar to cellulosic jet fuel - a general process flow diagram.

The proposed poplar to jet fuel process will require good conversion yields and operation near optimal conditions to be profitable. The rapid, complete and efficient conversion of lignocellulosic sugars during fermentation to acetic acid by *M. thermoacetica*, however, remains a challenging goal, despite intensive research. ASPEN biorefinery simulations in our laboratory show that an acetic acid titer of 50g/L is required for an economically feasible process. High yields and optimal conditions for fermentation of five and six carbon sugars to acetic acid requires rapid chemical analysis that can follow the progress of conversion in real time; enabling global optimization of the biorefinery to achieve its production and efficiency goals. Thus, the overarching goal of this project is to optimize acetic acid production during conversion of hybrid poplar to jet fuel by using Raman spectroscopy.

The major challenge in utilizing Raman spectroscopy in the presence of organic compounds, such as lignin, is fluorescence interference background signal that can reduce, if not completely mask Raman scattering. The exact cause of laser-induced fluorescence (LIF) from lignin is not completely understood. In order to overcome the effects of LIF, both chemometric data analysis and physical treatments have been employed. Previous studies have shown that the pretreatment methods prior to bioconversion affect the background of Raman spectra of the hydrolysate, and subsequently the quantitation of monosaccharides and other metabolites. However, thermochemical pretreatment of lignocellulosic biomass can lead to inhibitory compounds such as furans, phenolic compounds and soluble lignin components for fermentation. Prior to fermentation, detoxification steps can be used to remove these inhibitive compounds created by the degradation of lignocellulosic compounds in pretreatment. In addition, recently we have learned that high concentration of phenolic compounds in sugars streams prior to fermentation (higher that 3g/L) inhibit sugars to acetic acid fermentation by *M.*

thermoacetica. Thus, by employing Raman we can develop screening method to quantify lignin induced fluorescence (LIF) prior to fermentation. Thus, we can evaluate how good sugars streams are for fermentation and Raman analysis. For the sugars streams with high concentration of inhibitors we will test different detoxification methods such as overliming and activated carbon treatment to remove inhibitory compounds thus improving fermentation yields and the quality of Raman data.

Significance

How significant is the biomass to drop-in fuel market in the Pacific Northeast? The commercialization goal for ZeaChem is to produce 400 million gallons of renewable, 100% infrastructure compatible (drop-in) fuel per year in the Pacific Northwest. The company envisions approximately five 80 million gallons capacity biorefineries strategically located near population centers with high fuel demands. ZeaChem biorefineries will produce gasoline, diesel, or jet fuel in an optimal ratio to meet market demands. There is a strong market pull from airlines and the military to produce renewable jet fuel. Accordingly, this market demand will result in much of the 400 million gallons total capacity being allocated to jet fuel.

The potential economic impact and financial risk for the envisioned biorefinery network is enormous. Each biorefinery will cost on the order of $600 million and produce $280 million of product each year. It will be essential that the biorefineries operate at capacity with optimal process yields to be profitable. The capital cost requirements and stringent yield requirements necessitate comprehensive process instrumentation and advanced control strategies. Online Raman sensors can provide the feedback measurements necessary for high yield sugars to acetic acid fermentation by *M. thermoacetica*.

Progress to Date

Significant progress has been made in main research area of this project. We have shown that glucose and ethanol in a lignocellulosic fermentation can be accurately monitored by a 785 nm Raman spectroscopy instrument and novel immersion probe, even in the presence of an elevated background thought to be caused by lignin-derived compounds. Chemometric techniques were used to reduce the background before generating calibration models for glucose and ethanol concentration. The models have shown very good correlation between the real-time Raman spectra and the offline HPLC validation. The results from study were published (Ewanick et al., 2013, 2014) and CPAC was one of the financial sponsors for the study.

Since there is not published data on conversion of sugars from pretreated lignocellulosic biomass to acetic acid, we have just completed a systematic study of lignocellulosic sugars to acetic acid fermentation by *Moorella thermoacetica* (strain ATCC 39073). Five different hydrolysates obtained after steam pretreatment of lignocellulosic biomass were selected. These hydrolysates as well as their corresponding synthetic sugar models were studied in batch fermentations. The bacterial strain (ATCC 39073) can effectively ferment xylose and glucose in steam exploded hydrolysates from switchgrass, forest residues, wheat straw, sugarcane straw and sugarcane bagasse to acetic acid. The highest acetic acid yield obtained was in steam pretreated sugarcane straw hydrolysate with 71% of theoretical yield. In sugarcane straw hydrolysate, consumption of xylose and glucose was faster than their corresponding synthetic sugar model. It was also observed that *M. thermoacetica* can tolerate process derived inhibitory compounds from steam explosion pretreatment. This strain is capable of fermenting glucose and xylose in the presence of total phenolics up to 3 g/L. Furthermore, this microorganism metabolizes hydroxymethylfurfural and furfural (up to 0.28 and 0.9 g/L, respectively). The results will be presented at the 37th Symposium on Biotechnology for Fuels and Chemicals in San Diego (CA) in May 2015 and submitted for publication in Journal of Industrial Biotechnology and Microbiology.

Research Plan

The first objective of this research is to determine how the background signal caused by LIF can affect the acetate signal, specifically the signal to noise ratio (SNR) and the limit of detection (LOD) and to expand fundamental understanding of limitations governing fermentation of sugars by *M. thermoacetica* process with the ultimate goal of overcome those limitations.

We will monitor the progress of fermentation of steam pretreated hydrolysates from switchgrass, wheat straw, sugarcane bagasse, and sugarcanes straw. The reactions will take place in a controlled bioreactor using a novel Raman immersion probe inserted in a fast loop parallel sampling system. Chemometric analysis of the reactants (arabinose, glucose, galactose, xylose and mannose) and products (acetic acid) will be done using Principal Component Analysis (PCA) of the Raman spectra and a Partial Least Squares (PLS) model will be developed and validated using HPLC data.

In order to determine the effect of LIF on the acetate Raman signal, the signal to noise ratio (SNR) will be calculated for lignocellulosic hydrolysate from wheat straw, switchgrass, sugarcane straw, and sugarcane bagasse. The biomass samples will be pretreated using steam explosion as described above. After pretreatment, each sample will be spiked to 20 g L^{-1} of acetate and the pH was adjusted to 6.8 using 5M NaOH. The acetate C-C stretching band at 928 cm^{-1} will be used by selecting the spectral range in 900–950 cm^{-1}. The SNR will be calculated as follows,

$$SNR = \frac{S}{\lambda\sigma}$$

where S is the peak intensity of a Raman spectrum of interest, σ is the root mean square error between the a high-SNR sample and a low-SNR reference, and λ is a scaling coefficient obtained by dividing the sum of all the intensity values in the reference Raman spectrum by that in the corresponding low-SNR Raman spectrum. This method for the SNR calculation will be used because it directly compares fluorescence free pure spectra with the signal affected by LIF over a particular region of interest.

The limit of detection (LOD) can be defined as the minimum analyte concentration that is detectable with a certain degree of confidence [73]. Typically the LOD is calculated after taking several samples at various concentrations as well as instrument blank samples and developing calibration curves. In this study, an approximation of the LOD will be used based on SNR calculations without developing calibration curves. The LOD will be calculated from the SNR as follows,

$$LOD = 3\frac{X_{20}}{SNR}$$

where X_{20} is the concentration of the samples spiked with acetate.

The second objective is to develop methods to reduce concentration of fluorescent compounds in hydrolyzates prior to fermentation. After the initial analysis of the raw and spiked hydrolysates, overliming and activated carbon treatment will be performed on sugarcane straw hydrolysate to determine its effects on the Raman signal.

During overliming three target pH conditions will be assessed: a low level condition (target pH 9), a medium level (target pH 10), and a high level (target pH 11). For each target condition the reaction will be stirred at 50^{o}C for 30 minutes as described in the methods above. In addition we will use activated carbon treatment as a detoxification method. To reduce the toxic compounds concentration in the hydrolysate and to improve the acetic acid yield and volumetric productivity, lignocellulosic hydrolysate collected after steam pretreatment of sugarcane straw will be treated with activated charcoal. The pH of the hydrolysate will be adjusted to 1.8 prior to being treated with activated charcoal. Powdered activated charcoal will be mixed with hydrolysate at 3% (w/v) and incubated at 40° C for 24 hours.

After detoxification, the cleaned hydrolysates will be analyzed for sugars (glucose, xylose, galactose, mannose, and arabinose), furans and phenolic compounds (5-hydroxymethylfurfural, furfural, acetic acid, and lignin degradation products). The detoxified sugarcane straw hydrolysates will be subsequently spiked with acetate to 20 g L^{-1}, and the SNR and LOD will be calculated for each corresponding detoxification condition. This allowed the SNR and LOD to be used as a screening method for detoxification prior to fermentation. Detoxified and original hydrolyzates will be fermented by *M. thermoacetica* in a 1 L BioFlow 115 bioreactor with a working volume of 500 mL. The bioreactor is equipped with a with a Rushton impellor that will be operated 400 rpm in order to ensure a homogenous mixture and agitation

Anticipated Annual Accomplishments

The results from this unique study supported by CPAC will provide economically optimum fermentation conditions for conversion of hybrid poplar to jet fuel. Thus, ultimately we will be able to use Raman spectroscopy to track carbohydrate and metabolite concentrations during continuous fermentation to obtain high conversion yields and operate near optimal conditions, enhancing profitability. The findings from this research would be applicable to any type of infrastructure-compatible fuel since the majority of drop-in fuels will be produced from lignocellulosic biomass derived sugars via pretreatment, enzymatic hydrolysis, fermentation and chemical conversion process.

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Ewanick, S., Thompson, W., Marquardt, B., and Bura, R, (2013), Real-time understanding of lignocellulosic bioethanol fermentation by Raman spectroscopy, Biotechnology for Biofuels, *6*, 28-33

Ewanick, S., Schmitt, E., Gustafson, R., and Bura, R, (2014), Use of Raman spectroscopy for continuous monitoring and control of lignocellulosic biorefinery processes, Pure and Applied Chemistry

Curriculum Vitae

Renata Bura

Denman Professor in Bioresource Science Engineering
Associate Professor in Natural Products Chemistry
University of Washington

a.Professional Preparation

- Postdoctoral Fellow, Forestry, University of British Columbia, Vancouver, Canada, 2004-2006
- Ph.D., Forestry, University of British Columbia, Vancouver, Canada, 2004
- M.A.Sc., Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Canada, 2000
- B.Sc., (Honours) Department of Applied Chemistry and Biology, Ryerson University, Toronto, Canada, 1997

b. Appointments

- Associate Professor in Natural Products Chemistry, University of Washington, Seattle, WA, 2012-Present
- Denman Professor in Bioresource Science Engineering, University of Washington, Seattle, WA, 2007-Present
- Assistant Professor in Natural Products Chemistry, University of Washington, Seattle, WA, 2006-2012

c.Publications:

i. Five publications most closely related to the proposed project

1. Ewanick, S., Thompson, W., Marquardt, B., and **Bura, R,** (2013), Real-time understanding of lignocellulosic bioethanol fermentation by Raman spectroscopy, Biotechnology for Biofuels, *6*, 28-33
2. Vajzovic, A., **Bura, R.**, Kohlmeier, K., and Doty L.S., (2012) Novel endophytic yeast *Rhodotorula mucilaginosa* strain PTD3 II: production of xylitol and ethanol in the presence of inhibitors, Journal of Industrial Microbiology and Biotechnology 39(10) 1453-1463.
3. **Bura, R.,** Vajzovic, A., and Doty, L.S., (2012) Novel endophytic yeast *Rhodotorula mucilaginosa* strain PTD3 I: production of xylitol and ethanol, Journal of Industrial Microbiology and Biotechnology, 7, 1003-1011.
4. Schmitt, E., **Bura, R.,** Gustafson, R., Cooper, J., and Vajzovic, A., (2012) Converting lignocellulosic solid waste into ethanol for the State of Washington: an investigation of treatment technologies and environmental impacts, Bioresource Technology, *104*, 400-409.
5. **Bura, R,** Ewanick, S., and Gustafson R., (2012) Assessment of *Arundo donax* (Giant reed) as feedstock for conversion to ethanol, TAPPI Journal, 11(4), 59-66

ii. Other significant publications

1. Öhgren, K., Bura, R., Lesnicki, G., Saddler, J.N., and Zacchi, G., (2007) SSF versus SHF for steam-pretreated corn stover. Process Biochemistry, 42 (5): 834-839
2. Öhgren, K., Bura, R., Saddler, J.N., and Zacchi, G., (2007) Effect of hemicellulose and lignin removal on enzymatic hydrolysis of steam pretreated corn stover. Bioresource Technology, 98: 2503-2510
3. Berlin, A., Gilkes, N., Kilburn, D., Maximenko, V., Bura, R., Markov, A., Sinitsyn, A., and Saddler, J.N., (2006) Evaluation of cellulase preparation for hydrolysis of hardwood substrates. Applied Biochemistry and Biotechnology, 129-132: 528-545

4. Mabee, W., Gregg, D., Arato, C., Berlin, A, Bura, R., Gilkes, N., Mirochnik, O., Pan, X., Pye, K., and Saddler, J.N., (2006) Updates on softwood-to-ethanol process development. Applied Biochemistry and Biotechnology, 129-132: 129-132
5. Bura, R., Bothast, R.J., Mansfield, S.D., and Saddler, J.N., (2003) Optimization of SO_2-catalysed steam explosion of corn fibre for ethanol production. Applied Biochemistry and Biotechnology, 105: 319-335
6. Bura, R., Mansfield, S.D., Saddler, J.N., and Bothast, R.J., (2002) SO_2-catalysed steam explosion of corn fibre for ethanol production. Applied Biochemistry and Biotechnology, 98-100: 59-72

d. Synergistic activities

Prof. Bura started mentoring women during her graduate work at the UBC. She participated in "Women in Science Program" where she mentored 5 female high school students and gave lectures about bioenergy and sustainable energy at local high schools. Prof. Bura has been a mentor in Woman in Science and Engineering Program at the UW since 2006. In 2012 she participated in the week long UW STEM-bridge program where she hosted 10 female freshmen engineering students in her Bioenergy Lab. She also participated in the National Women in Technology Sharing Online (WitsOn) program; an exciting, 6 weeks, online pilot program to support female undergraduates pursuing degrees in science, technology, engineering, and math (STEM).

e. Collaborators and other affiliations

i. Collaborators (present and within 4 years)

Ch. E. Wyman (University of California); Y.Y. Lee (University of Auburn); J.N. Saddler (UBC, Canada); M. Holtzapple, (Texas, A&M); B. Dale (UM); H. Lee (UofG, Canada) M. Ladisch (Purdue University); N. Mosier (Purdue University); R. Elander (NREL); T. Eggman (NREL); S.L. Doty (UW); G. Zacchi (University of Lund, Sweden); R. Chandra (UBC, Canada); S. Mansfield (UBC, Canada); R. Gustafson (UW); W. McKean (UW); S.L. Doty (UW); Dr. K. Gill (WSU); J. Cooper (UW); B. Marquardt (UW); R. Synovec (UW) and N. Holmes (UW)

ii. Graduate and Postdoctoral Adviser

S. N. Liss (UofT, Canada)
A. Allen (UofT, Canada)
J. Saddler (UBC, Canada)

iii. Thesis adviser and Postgraduate-Scholar Sponsor (5 years)

Mandana Ehsanipour (Ph.D), Shannon Ewanick (Ph.D), Azra Vajzovic (Ph.D), Rodrigo Morales (Ph.D), Lisa Lai (Ph.D), Shannon Ewanick (MS), Dexter Lam (MS), Tina Konrad (MS)

NAME **Brian J. Marquardt, Ph.D.** Applied Physics Laboratory University of Washington Seattle, WA 98105	**POSITION TITLE** Senior Research Engineer

Education/Training

INSTITUTION AND LOCATION	**FIELD OF STUDY**	**DEGREE**	**YEARS**
Ripon College	Chemistry	A.B.	1993
University of South Carolina	Analytical Chemistry	Ph.D.	1997
University of Washington	Analytical Chemistry	*Post-Doc*	1998-1999

Appointments

2007-present Senior Res. Engineer, University of Washington, Applied Physics Lab

2000-2006 Senior Research Scientist, University of Washington, CPAC

1998-1999 Post-doc, University of Washington, CPAC

1993-1997 Research Assistant, University of South Carolina

Publications – 5 Most Relevant

1. K. R. Mann, J. R. Burney, K. A. McGee, B. J. Marquardt, "Crystalline Oxygen Sensors that Contain Ruthenium Complexes," *JACS*, **129(49)**, 15092, **2007**.
2. N. K. Afseth, B.J. Marquardt, and J.P. Wold, "A Chromatographic Approach for Fluorescence Rejection in Raman Analysis," *Appl. Spectrosc*, **61(12)**, 1283, **2007**.
3. A. E. Moe, S. Marx, N. Banani, M. Liu, B. Marquardt, and D. M. Wilson, "Improvements in LED-based Fluorescence Analysis Systems," *Sensors and Actuators B*, **111-112**, 230, **2005**.
4. S. M. Drew, J. E. Mann, B. J. Marquardt, K. R. Mann, "A Humidity Sensor Based on Vapoluminescent Platinum(II) Double Salt Materials," *Sensors and Actuators (B),* **B97(2-3)**, 307, **2004**.
5. B.J. Marquardt*, T. Le and L.W. Burgess, "Demonstration of a High-Precision Optical Probe for Effective Sampling of Solids by Raman Spectroscopy," SPIE Proceedings, **Vol. 4469**, 465, **2001**.

Other Publications

6. B. J. Marquardt, "Application of On-Line Raman Spectroscopy to Characterize and Optimize a Continuous Microreactor," (Eds) Koch, M.V.; VandenBussche, K.M.; and Chrisman, R.W., *Micro Instrumentation for High Throughput Experimentation and Process Intensification – a Tool for PAT*, Wiley-VCH, Chapter 9.2, **2007**.
7. B. K. Dable, B. J. Marquardt,* "Characterization and Quantitation o a Tertiary Mixture of Salts by Raman Spectroscopy in Simulated Hydrothermal Vent Fluid," *App. Spectrosc*, **60(7)**, 773, **2006**.
8. N. K. Afseth, V.H. Segtnan, B.J. Marquardt, and J.P. Wold, "Raman and Near Infrared Spectroscopy for Quantification of Fat Composition in a Complex Food Model System," *Appl. Spectrosc*, **59(11)**, 1324,
9. B. K. Dable, K. S. Booksh, B. J. Marquardt*," Rapid Multivariate Curve Resolution Applied to Near Real-Time Process Monitoring with HPLC/Raman Data," *Anal. Chimica Acta*, 544(1-2), 71, **2005**.

10. J. P. Wold, B. J. Marquardt, B. K. Dable, D. Robb, B. Hatlen, " Rapid quantification of carotenoids and fat in Atlantic salmon (Salmo salar L.) by Raman spectroscopy and chemometrics," *Appl. Spectrosc.,* **58(4)**, 395, **2004**.

Synergistic Activities

- Developed a research program aimed at designing, optimizing and implementing optical sensors for on-line/*in-situ* analysis of industrial and environmental processes and applications
- the program includes training of undergrads, grads and post-docs to develop skills in optics, lasers, various spectroscopic techniques and general measurement science
- the program emphasis of on-line measurement science has had an impact on how and where optical sensors are implemented in the laboratory, in the field and in industry
- Instructor, developer and advisor for FDA Process Analytical Technology (PAT) training course and certification program for reviewers and inspectors
- Organizer and chair for technical sessions at various national technical meetings (IFPAC, FACSS, ACS)

Collaborators & Other Affiliations

Marvin Lilley, Professor, Oceanography, Univ. of Washington
Deborah Kelly, Professor, Oceanography, Univ. of Washington
Karl Booksh, Professor, Chemistry, University of Delaware
Deirdre Meldrum, Professor and Dean, Electrical Engineering, Arizona State Univ.
S. Michael Angel, Professor, Chemistry, University of South Carolina
Mary Lidstrom, Professor, Chemical Engineering, Univ. of Washington
Kent Mann, Professor, Chemistry University of Minnesota
Rob Synovec, Professor, Chemistry Univ. of Washington
David Veltkamp, Senior Research Scientist, Chemistry, Univ. of Washington
Melvin Koch, Director, Center for Process Analytical Chemistry, Univ. Of Washington
Jens Petter Wold, Research Scientist, Food Research Institute of Norway

Publications, Seminars and Professional Service:

30 publications, 16 since 2004 (not including In Press and submitted); 86 Invited seminars; 94 Submitted Technical Presentations (not including invited), 15 Sessions Organized at National Meetings, Process Section Chair for FACSS, Coblentz and IFPAC Board member.

Thesis Advisor and Postgraduate – Scholar Sponsor

Brian K. Dable – Post-Doctoral

Graduate Student's = 2

Post doc's = 1

Professor Richard Gustafson

EDUCATION: B.S. (Wood and Fiber Science) 1977, University of Washington
Ph.D. (Chemical Engineering) 1982, University of Washington

PROFESSIONAL EXPERIENCE:

1982-1986 Development Scientist, Union Carbide Corp. (Now Amoco Performance products), Parma, Ohio. Research and development to produce higher performance carbon fibers.

1986-1990 Assistant Professor of Paper Science and Engineering, University of Washington, Seattle, Washington

1990-1995 Associate Professor of Paper Science and Engineering, University of Washington, Seattle, Washington

1993–2006 Denman Professor of Paper Science and Engineering

1995–PRESENT Professor of Bioresource Science and Engineering, University of Washington, Seattle, Washington

1997–2003 Chair of Management and Engineering Division, University of Washington, Seattle, Washington

Managed department of 14 faculty. Responsible for setting strategic directions of the department as well as managing budgets and departmental support staff. Developed improved methodologies to assess faculty performance and implemented comprehensive work plans. Responsible for accreditation of three the undergraduate curriculum.

2003-2006 Faculty Chair, College of Forest Resources, University of Washington

Managed merger of two departments resulting in a large department of 40 faculty. Merger required reallocation of support staff, integrating seven undergraduate curricula into two, and developing new operating procedures and principles for the merged department. Nine faculty were hired (or in the process of being hired) while serving as chair.

2006-PRESENT Denman Endowed Chair in Bioresource Science and Engineering.

Provides leadership to develop bioresource education and research programs at the University of Washington. This includes building new laboratories, hiring new faculty, developing a biofuels and bio-based product research program, and starting new Bioresource Science and Engineering graduate and undergraduate programs.

RECENT PUBLICATIONS

1. Budsberg, E., M. Rastogi, M. E. Puettmann, J. Caputo, S. Balogh, T. A. Volk, R. Gustafson, and L. Johnson. 2012. Life-cycle assessment for the production of bioethanol from willow biomass crops via biochemical conversion. Forest Prod. J. **62**(4):305–313
2. Bura, R, Ewanick, S., and Gustafson R., 2012. "Assessment of *Arundo donax* (Giant reed) as feedstock for conversion to ethanol", *Tappi Journal*, ***11***(4), 59-66
3. Schmitt, E., Bura, R., Gustafson, R., Cooper, J., and Vajzovic, A., 2011. Converting lignocellulosic solid waste into ethanol for the State of Washington: an investigation of treatment technologies and environmental impacts, Bioresource Technology ***104***, 400-409.
4. Lippke, Bruce; Gustafson, Richard; Venditti, Richard; et al: "Sustainable Biofuel Contributions to Carbon Mitigation and Energy Independence", *Forests* **2011**, *2*(4), 861-874
5. Gustafson, Richard and Raffaelli, Natalia, Washington State Pulp and Paper Mill Boilers: Current and Potential Renewable Energy Production Final Report", Washington Department of Ecology Report 09-07-048, 2009, http://www.ecy.wa.gov/biblio/0907048.html
6. Rayal, Gaurav; Qiao, Ming; Gustafson, Richard; "On the Nature of Single Fiber Kappa Distrbutions", *Tappi Journal, v 8, n3, 26-31, 2009.*
7. Amundson, Charles and Gustafson, Richard, "A paper forming simulation based on fibre and floc deposition", *Appita Journal, v 62, n3, 194-200, 2009*

8. Gustafson, Richard; Rayal, Gaurav; Ming, Qiao; Mao, Jinliang;, "On the Nature of Single Fiber Kappa Distributions", Tappi Journal, v 8, n3, 26-31, 2009.
9. Gustafson, R.R., et al. "Method and apparatus for assaying wood pulp fibers", U.S Patent# 7,537,732, Awarded May 26, 2009.
10. Qiao, Ming; Gustafson, Richard; "Influence of Fiber Scale Heterogeneity on Softwood Kraft Pulp Kappa Uniformity"; Journal of Pulp and Paper Science, 33(4): 227-232 (2007)

SYNERGISTIC ACTIVITIES

Project Director – Advanced Hardwood Biofuels – Northwest. A $40million USDA funded project to develop a regional biofuels industry. Project has significant programs in feedstock development, conversion processes, sustainability assessment, extension, and education. Responsible for overall management of project and LCA portion of the research.

Several biofuels research projects:

- Development of methods to produce ethanol for municipal solid waste
- Development of novel membranes for separations in biorefineries
- LCA of woody biomass to fuels. Research supported by US Forest Service and DOE to develop comprehensive life cycle assessment of producing ethanol from woody biomass, including forest residuals and plantation grown hardwoods. Responsible for coordination of "conversion" LCA research and for final integration of the all the LCA analysis. Process and LCA models developed in these projects may be directly used in proposed research.
- Development of novel sensor and control systems for cellulosic ethanol production.

COLLABORATORS

Collaborators and Co-Editors

Dwight Anderson (Weyerhaeuser)	Jerry Seidler (Univ. of Washington)
Carsten Bruckner (ParAllele Bioscience)	Erik Strom (Systematix Inc.)
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Chavonda Jacobs-Young (USDA)	Paul Watson (Paprican)
Bill Fuller (Weyerhaeuser)	Jerry Ward (BP)
Dan Swartz (Univ. of Washington)	Joyce Cooper (Univ. of Washington)
Dave Sjoding(Wash State Energy)	Peter Moulton (Wash State Energy Coordinator)

Graduate Advisor
Charles Sleicher – retired

Thesis Advisor Advised 9 PhD, 19 MS – advisees last 5 years:
C. Sarvanakish (PhD) – Chulongkorn Univ. Vivek Srivastava (MS)
Saket Kumar(PhD) – Booz Allen. Jeff Mathews (PhD) – Quaker Oats
Gaurav Rayal (MS) – BP Chemicals. Ming Qiao (PhD) – Viren