University of Illinois at Urbana-Champaign's GATE Center for Advanced Automotive Bio-Fuel Combustion Engines

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University of Illinois at Urbana-Champaign

This presentation does not contain any proprietary or confidential information

Outline

- Goals and Objectives
- Address Previous Review Comments
- Barriers – Research and Educational Challenges
- Educational and Research Approach
- Accomplishments – Performance measures
- Collaborations – Interactions and Technology Transfer
- Publications
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- Summary

Goals - Expected Benefits

- A successful GATE Center is envisioned that will:
  - educate scholars and engineers who will develop the emerging bio-fuel technologies in the automotive field, thus serving a crucial societal need.
  - provide high quality research in a novel field of automotive science by addressing the critical current issues of bio-fuel automotive fuel application: emissions, novel injection and combustion processes, compatibility with current automotive practice.

- The knowledge obtained by the Center can have a significant impact on the commercialization of bio-fuels and bio-fuel engines, and enable the U.S. to achieve the FCVT program goal of saving 4 to 6 million barrels of oil per day, reducing greenhouse gas emissions by 50%, and enabling U.S. manufacturers to be competitive in the global market.

Objectives

1. Set up a comprehensive syllabus that will enrich the technical expertise of graduate students of thermal/automotive sciences in agricultural/biological issues related to biofuels and vice-versa.

2. Provide a channel through which well established theoretical, computational, and experimental methodologies can be focused so that the potential of biofuels for automotive combustion is fully explored.

3. Develop state-of-the-art techniques for automotive R&D with a particular emphasis on laser diagnostics, modeling, and multi-dimensional computations.

4. Establish a mutually beneficial strong link with both the automotive and agricultural industry.

Address Previous Review Comments

- "Some information was given on the technical progress being achieved by the program, but it wasn't clear how this relates to the students' work." "A clearer connection to overall objectives would have been helpful."
  - This has been made clearer in this presentation.
- "There was relatively little in terms of interactions, and the program should seek more direct external interactions to help direct their work." "The presenter should elaborate more fully on the program's specific lab/industry technology exchanges in future reviews."
  - The interactions were established and have been strengthened, and will be described in this presentation.
- "The GATE center would end up being completely swamped by the Energy Biosciences Institute (EBI)"
  - The objectives of EBI and the GATE center are different.
- "Students need to understand regulatory context of emissions too, since this is the main research driver."
  - This is included in the Bio-Energy Seminar and some related courses.
- "Needs more focus on DOE objectives for building workforce"
  - Seven students graduated and more are recruited and trained.

Barriers –Educational and Research Challenges

- Bio- vs. -fuels: Currently an educational disconnect. "Bio-" students (Agricultural/ Biological) do not know much about fuels and "-fuel" students (Mechanical/ Automotive) do not know much about "bio-". Still highly skilled "bio-fuel" engineers educated in a comprehensive manner are urgently needed.

- Biofuel automotive combustion with high efficiency and low emissions is not a direct extrapolation of current automotive practices. Novel fuel injection and combustion techniques have to be devised.

- Biofuel properties relevant to automotive combustion remain an almost uncharted area. As novel renewable fuels emerge (butanol, ethylesters) high-quality data on their properties and the dependence of these properties on engine operational conditions are necessary.

Overall Approach

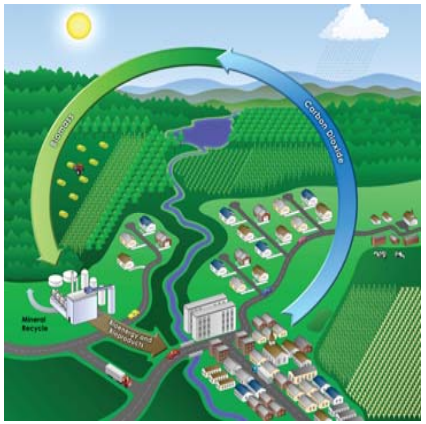
Establish a high-quality interdisciplinary program at the M.S. and the Ph.D. level that will bridge the current educational disconnect between mechanical and biological aspects of biofuel technology and will integrate educational initiatives and collaborative research projects

- An interdisciplinary curriculum that provides comprehensive, advanced training on automotive biofuel combustion to students that approach the subject both from both Mechanical Engineering and Agricultural/Biological Engineering backgrounds has been set up.

- Seminal research projects of current interest have been identified by the PIs and have been assigned to GATE fellows The input of the Industrial Advisory Board will be crucial for the determination of future research directions.

- Industrial internships that will constitute a required program component.

Core Competencies for GATE



AUTOMOTIVE TECHNOLOGY: *Fundamentals of Engines* **Components; Engine Cycles; Power and Efficiency; Fuel Systems and Control; Intake and Exhaust Systems…**

Technology and Combustion

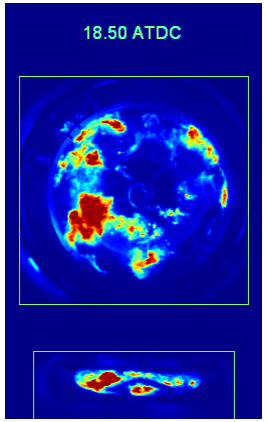
Technology and Environment

SYSTEMS AND MODELING: *Studies, Analysis, Modeling and Integration for overall* **Technical Workability, Energy Efficiency, Life-Cycle Analysis, Environmental Compatibility**

Combustion and Environment

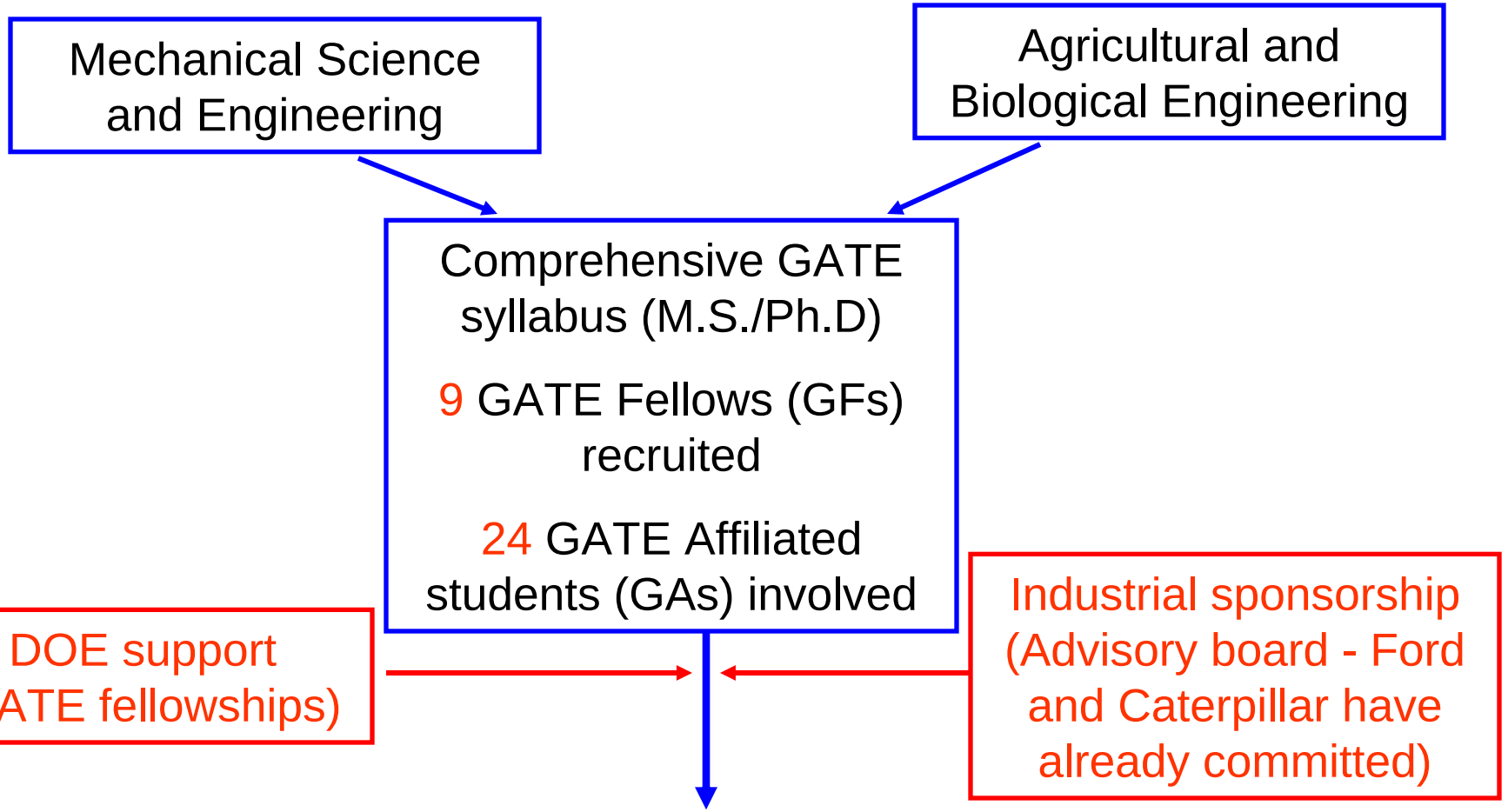
COMBUSTION: *Fundamentals of Combustion Processes* **Thermodynamics, Heat Transfer…**

ENVIRONMENT: *Impact of Engines and Fuels on the Surroundings including* **Exhaust Emissions, Biofuel Utilization…**



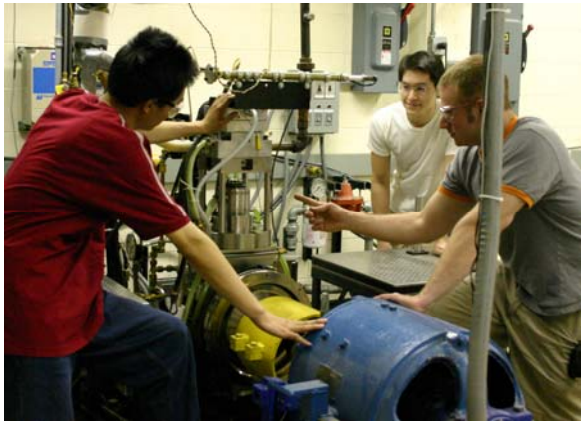
Research Domains for GATE

- Biofuels and Properties
- Fuel Injection Control and Optimization
- Electrospray Systems for Fuels
- Fuel Injection, Ignition, Combustion and Emissions Modeling
- Engine Performance and Emissions Evaluation
- In-Cylinder Diagnostics
- Emissions Reducing Technologies


Mechanical Science and Engineering
Agricultural and Biological Engineering
Comprehensive GATE syllabus (M.S./Ph.D)
9 GATE Fellows (GFs) recruited
24 GATE Affiliated students (GAs) involved
DOE support (GATE fellowships)
Industrial sponsorship (Advisory board - Ford and Caterpillar have already committed)
Highly skilled UIUC graduates who can lead industrial application of bio-fuel engine technology

Specific educational accomplishments

- Nine students supported by GATE scholarships.
- Established a combined Mechanical/ Agricultural Syllabus that will lead to GATE Certificate.
- Established a graduate seminar class with presentations from GATE scholars and 18 invited speakers.
- Established two new courses *(ME 598: Laser diagnostics for thermal and fluids engineering, ABE 436 Renewable Energy Systems)* that were offered by Center and ABE faculty.
- Center faculty membership of departmental and campus Energy Committees
- Activity presentation at the College of Engineering Advisory Board



Automotive Bio-fuel Combustion Syllabus

The GATE program on "Advanced Automotive Bio-Fuel Combustion Engines" is a three-semester long, 15-credit-hours program. 3 credit hours (1 per semester) are given by the seminar class on Automotive Bioenergy. 12 credit hours are completed by taking one 4 hour course from each of the following groups.

Fundamentals

- ME 404 – Intermediate Thermodynamics
- ME 501 – Combustion Fundamentals
- ABE 436 – Renewable Energy Systems

Core Specialty

- ME 403 – Internal Combustion Engines
- ABE 466 – Engineering Off-road Vehicles

Electives

- ME 503 Modeling/Design of Internal Combustion Engines
- ME 598 Laser Diagnostics for Thermal/Fluids Engineering
- ABE 488 Bioprocessing Grains for Fuels
- ABE 498 Processing of Biomass
- NPRE 498 The Hydrogen Economy and Fuel Cells

"Automotive Bio-energy" Seminar Series – Student participation and placement

- All 24 students involved in the program so far participated in the seminar class ME 598: "*Automotive Bio-energy*". The students were required to investigate a wide range of bio-fuel related issues (mechanical, agricultural, chemical, economical, legal) and give half-hour presentations. The students include 3 women and 2 Native Americans.
- Weekly sessions with typically two student presenters. Students supported on GATE fellowships gave 1 hour-long presentations of their research.
- Invited speakers (18 total): Rolf Reitz (Wisconsin), J. Suryawanshi (IIT), V. Singh (UIUC), Y. Zhang (UIUC), A.C. Fernandez-Pello (Berkeley), M.Wu (Argonne), R. Watson (World Bank), W. Chang (MIT), D. Ruan (Chongqing), S. Kong (IowaSU), G. Knothe (USDA), F. Dryer (Princeton), C. Cadou (Maryland), Y. Jiang (HSU), X. Zhang (UIUC), D. Assanis (Michigan), D. Rosner (Yale), and S. Shuai (Tsinghua).
- Student placement (7 students): T. Fang – Faculty, MAE Dept. N.C. State Univ., D.S. Elegant – Sargent and Lundy LLC, J. McCrady and V. Stringer - Ph.D. Graduate School, UIUC, S. J. Wenzel - Gamma Tech. Inc., J. Beasley – Cummins, R. P. Buchanan - ETEL Motion Tech. Inc.

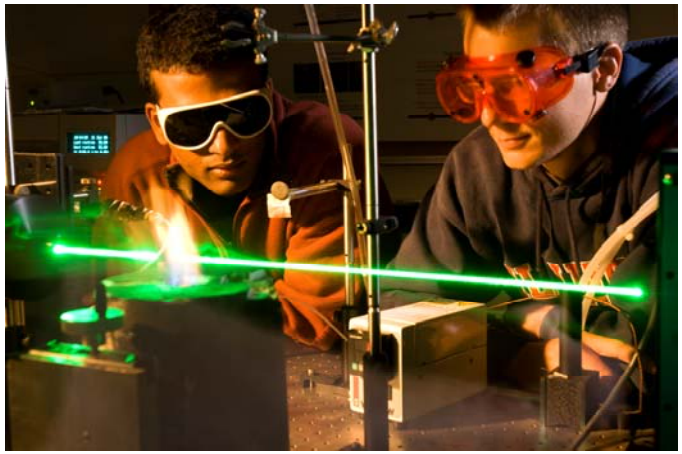
New Course Developed: ME 598 Laser Diagnostics for Thermal and Fluids Engineering

- Laser diagnostics an indispensable tool for the study of advanced bio-fuel combustion. However students of both agricultural and mechanical engineering lack knowledge of the necessary fundamentals. A class offered by a co-PI (D.C. Kyritsis) in order to address this gap.

- Laser Diagnostics are particularly important for bio-fuels. E.g. acetone which is a major component of the novel bio-fuel baelene is a strong fluorescer. So is OH which is significant for radical combustion.

- Students split in groups of five and performed three experiments together with the instructor (flame shadowgraph, LIF in mixing layer, Raman in counterflow) and wrote paper-like reports.

- Attended by 10 graduate students.

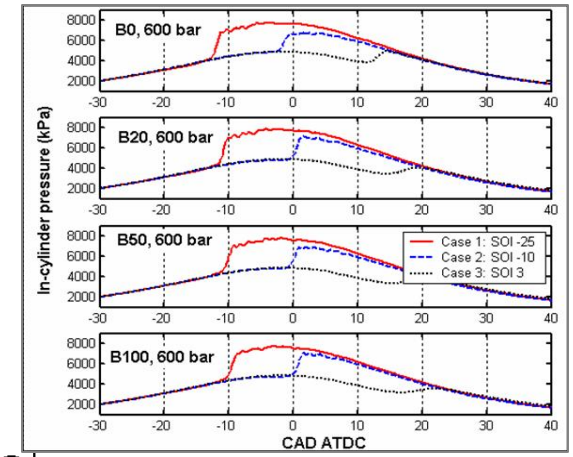


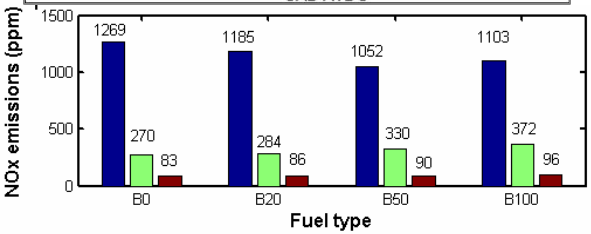
ABE 436 Renewable Energy Systems

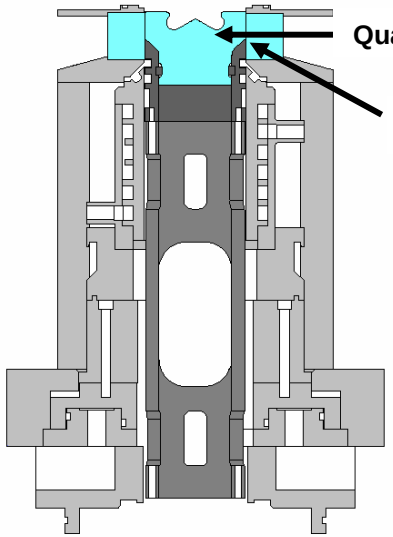
- Comprehensive overview of renewable energy sources and applications, including solar, geothermal, wind, and biomass
- Environmental consequences of energy conversion including how renewable energy can reduce air pollution and global climate change are explored and quantified
- Capstone group project encompasses the design of a system for collecting and converting renewable energy into thermal or electrical energy
- Topics covered in biomass and bioenergy include: bioenergy sources, photosynthetic processes, combustion of biomass, anaerobic digestion, alcoholic fermentation, thermal pyrolysis and gasification, ethanol and biodiesel production and utilization

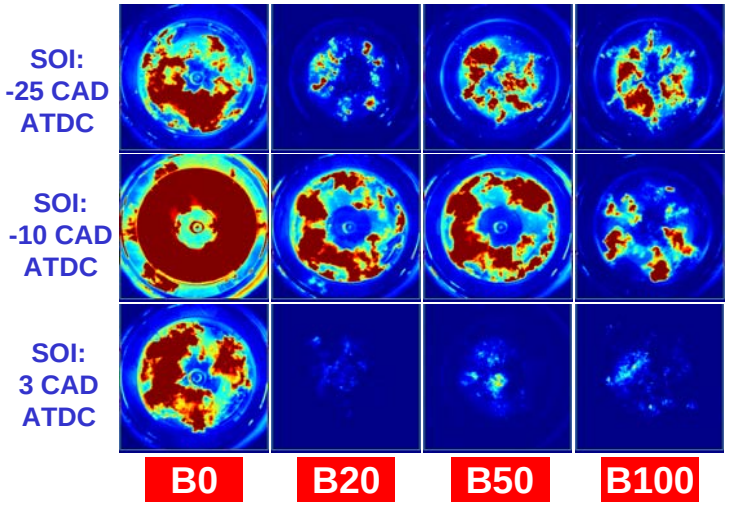
GATE Fellows Research - Low-Temperature Biodiesel Combustion

- Longer ignition delay for higher biodiesel content due to higher boiling temperature of biodiesel than low sulfur diesel
- Simultaneous reduction of soot and NOx is observed for late injection strategy for all the fuel blends compared with conventional injection strategy
- NOx emissions increase with biodiesel content for conventional and late injection strategy
- Biodiesel fuel reduces flame luminosity with less soot formation.





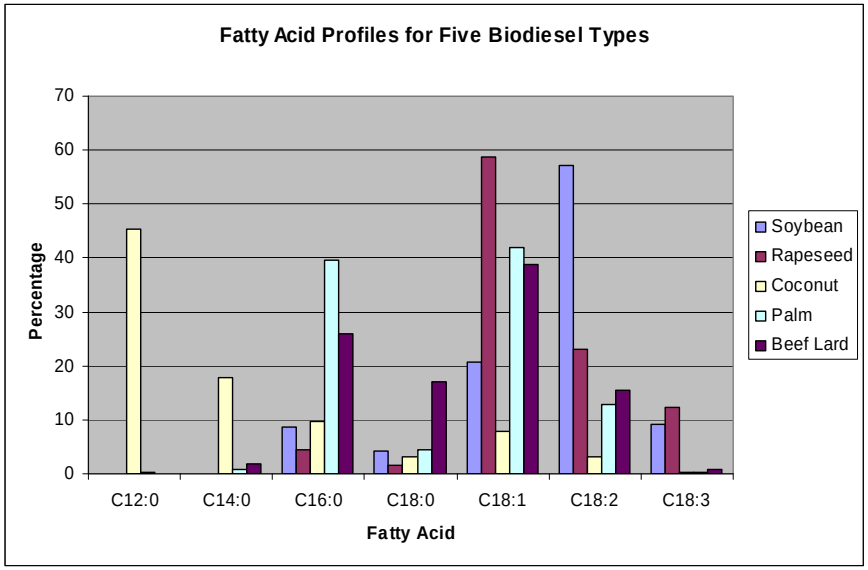




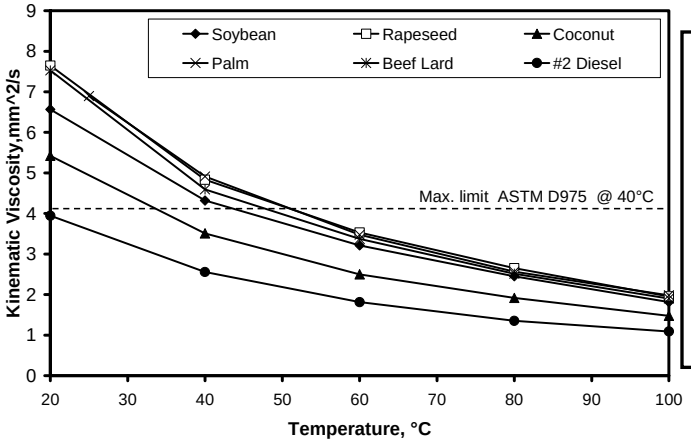
Biodiesel combustion with multiple injection strategy

- Multiple injection strategy can help to alter the combustion mode from diffusion flame combustion to premixed combustion by increasing the time interval between the two injections
- Results show that less soot emission for biodiesel fuel or biodiesel blends is due to less soot formation in the early stage of combustion and stronger soot oxidation in late cycle combustion
- Multiple injection can achieve simultaneous reduction of soot and NOx emissions for biodiesel fuel or blends

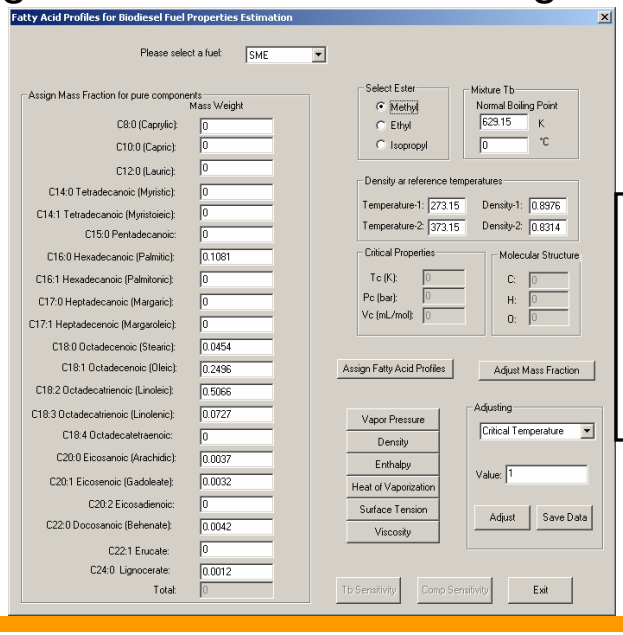
Biodiesel Property Measurement and Computation for Combustion Modeling



- Measured properties of biodiesel produced from source materials with a broad range of fatty acid compositions
- Updated computational models for estimating viscosity, surface tension, density, thermal conductivity for LTC engine combustion modeling

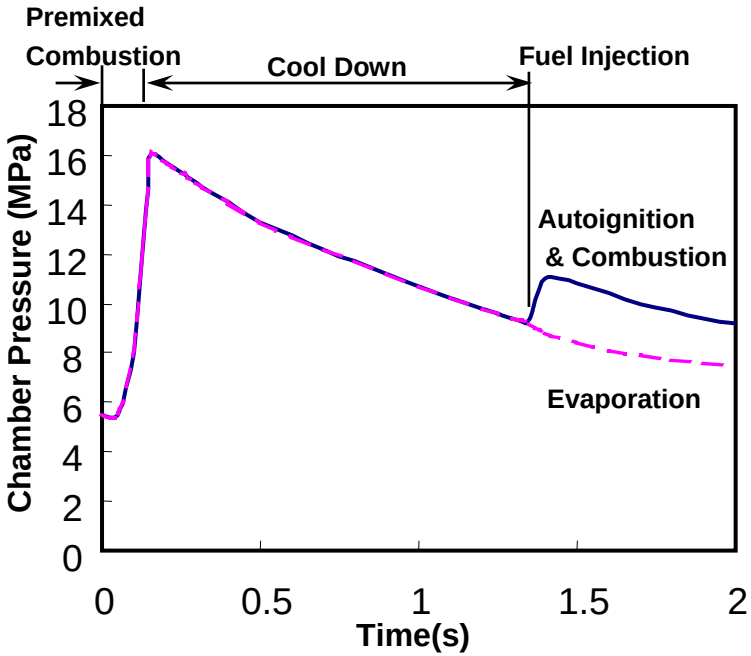


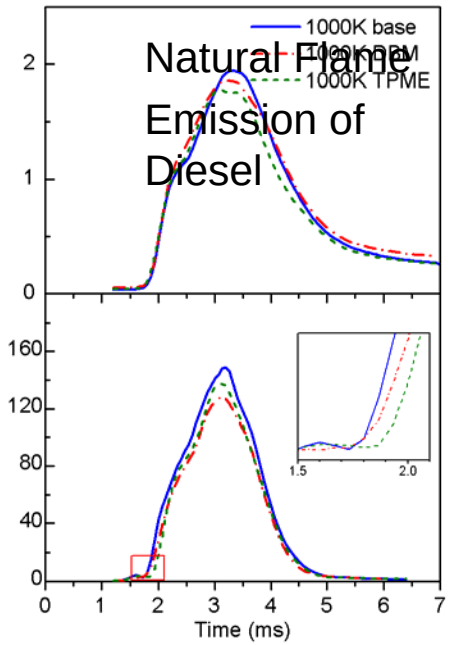
Kinematic Viscosity of Biodiesel from five different source materials



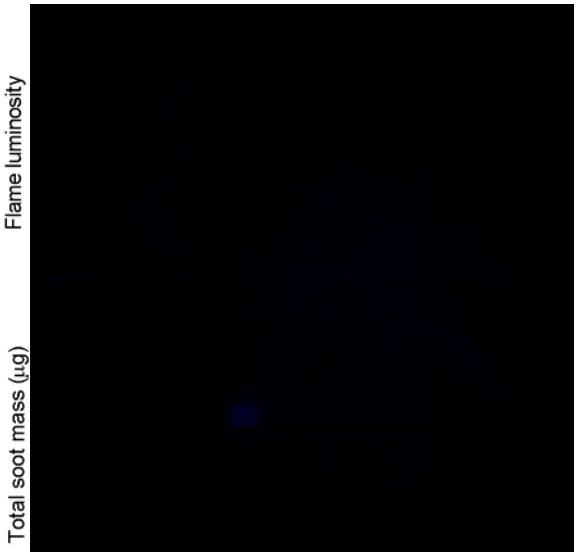
BDProp Program for computing biodiesel fuel properties

Bio-Diesel Spray and Combustion Diagnostics in Chamber

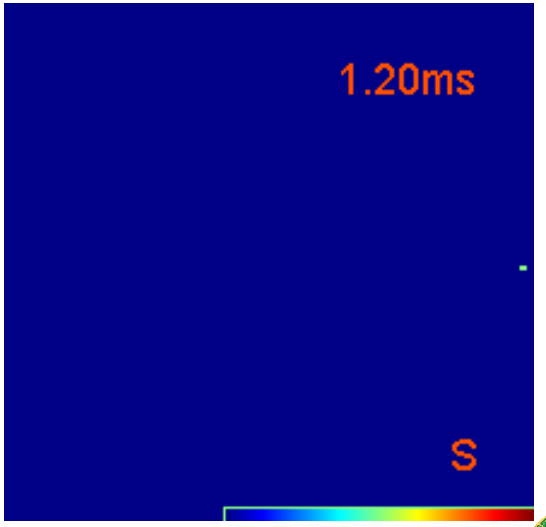




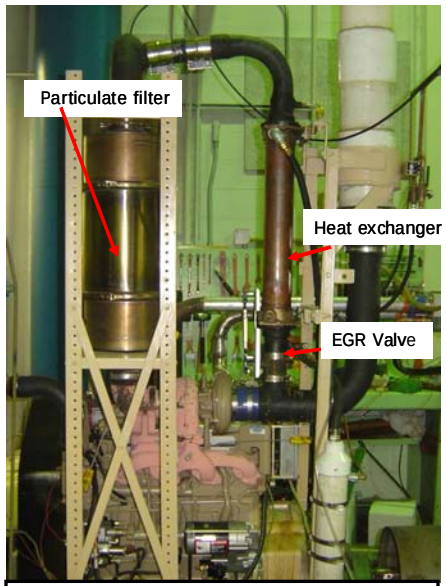
Natural Flame Emission of Diesel



Forward Illumination Light Extinction (FILE) Measurement of Soot

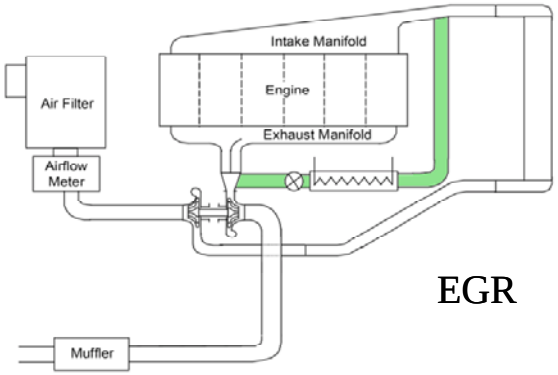


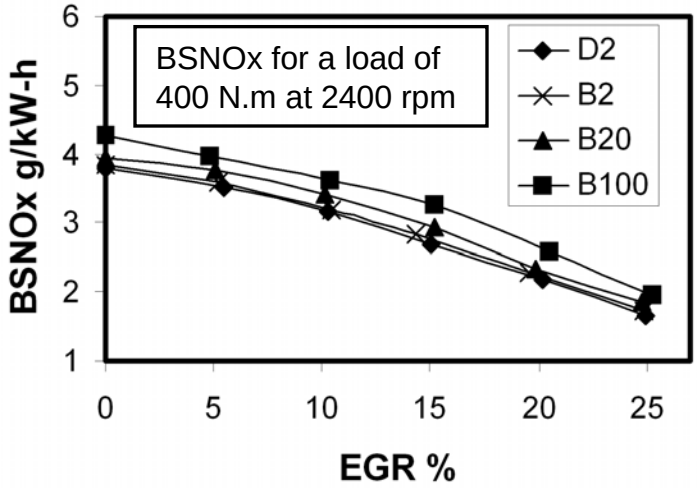
Combined impact of biodiesel and exhaust gas recirculation on NOx emissions



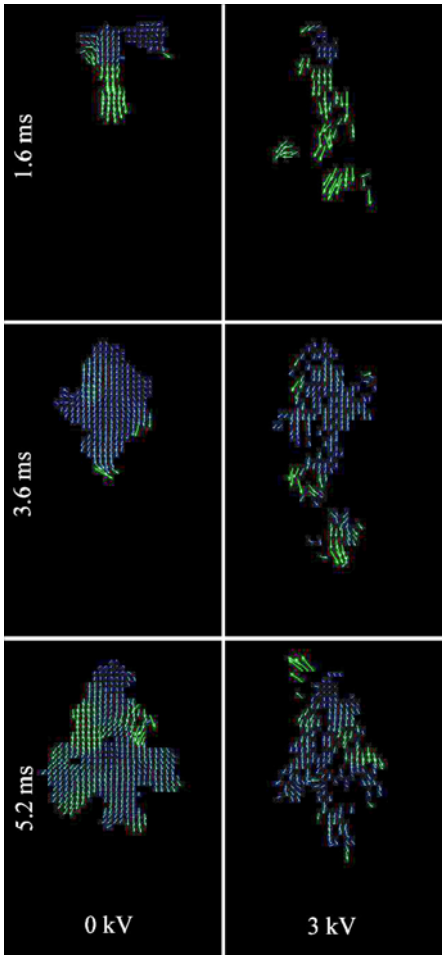
Clean low pressure loop EGR system used in the study

- Designed and implemented EGR system and NOx measurement unit on EPA Tier 2 emissions compliant turbocharged and intercooled engine
- Evaluated NOx emissions engine performance with varying amounts of EGR and with different biofuel blends of biodiesel
- Determined potential sources which contribute to differences in NOx emission trends produced between D2 and biodiesel when used with EGR
- Determined approximate EGR rates to use in conjunction with different biofuel blends of biodiesel to achieve similar NOx emissions as D2 combustion



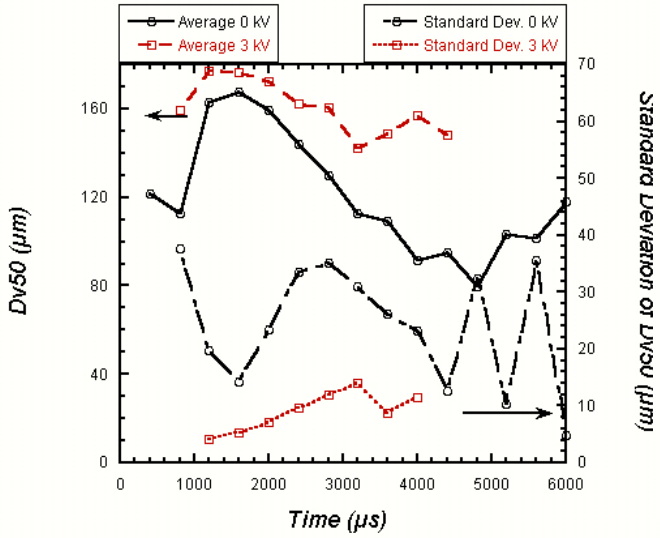


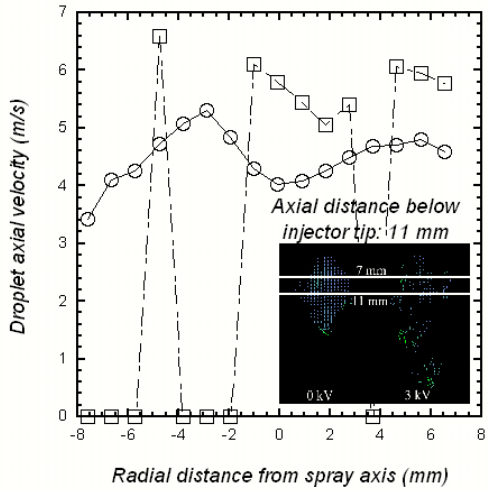
Electrostatic effects on bio-fuel injection



PIV measurements in charged vs. non-charged gasoline sprays.

- Electrostatic field causes velocity fields that would normally be observed at higher injection pressures and increases repeatability of droplet size.
- Because of their polar molecules, alcohols (ethanol, butanol) have increased conductivity and can act as conductivity enhancers. **Novel feature of bio-fuels. The possibility emerges of electrostatically assisted biofuel injectors.**



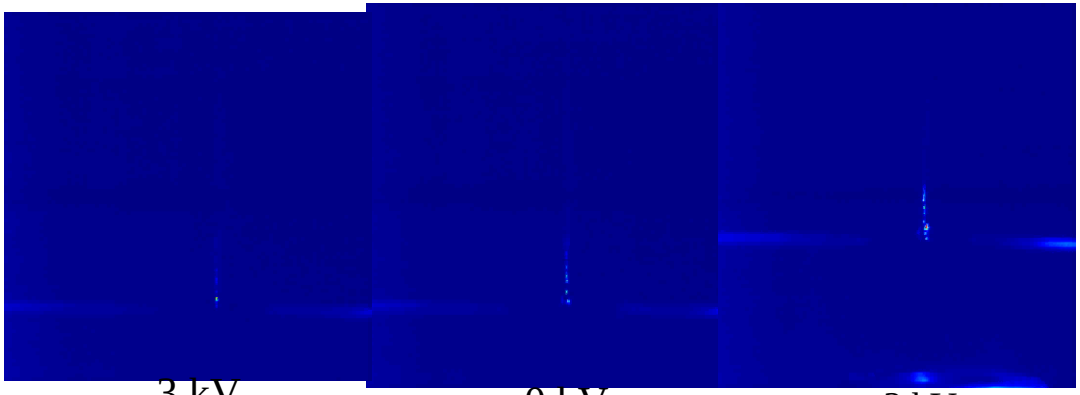


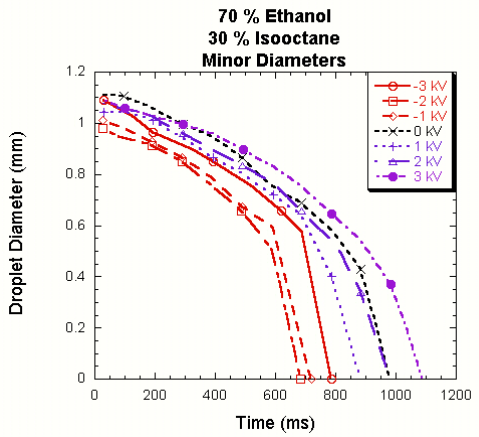
Electrostatic effects on bio-fuel combustion

- The electrostatic force can be used in order to drastically affect morphology of ethanol-containing gasoline blends. **This is a particular bio-fuel characteristic because of the significantly increased conductivity of alcohols compared to hydrocarbons.**

- Possibility for in-cylinder control of combustion through electrostatic fields. Appropriate charging of the droplet was shown to expedite the burning time of individual droplets. High voltage already exists in the combustion chamber (in the spark plug of spark-ignited engines). It could be used for combustion control.

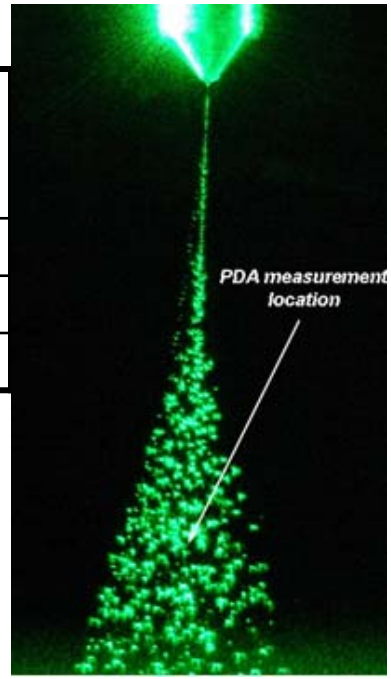
- Coupling with up-stream technologies: What is the optimum fuel composition for the application of this technology?



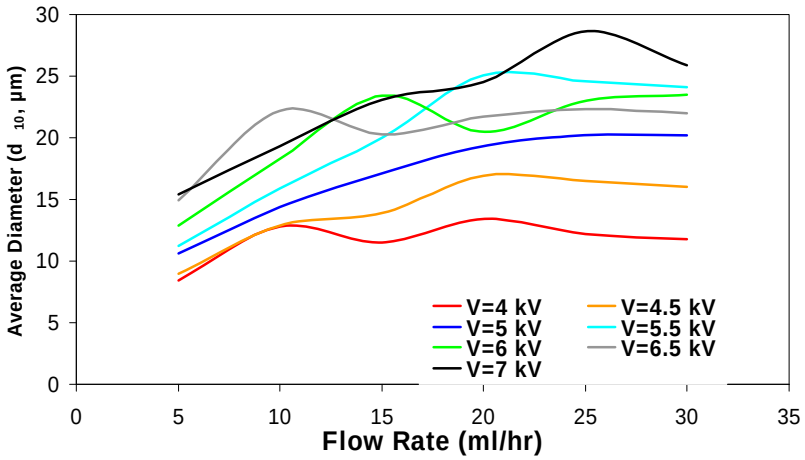


Butanol e-sprays

Fuel	Energy density (MJ/kg)	Stoich. A/F ratio	Heat of vaporiz. (MJ/kg)	Density (g/cm^3)	R-octane Rating	Kin. Viscosity (cSt)
Gasoline	44.9	14.0	0.36	0.712	91-99	0.4-0.8
Ethanol	24.8	9.0	0.92	0.789	130	1.52
Butanol	36.4	11.2	0.43	0.802	96	3.64



- Butanol is a novel biofuel that can combine production from renewable sources (*clostridium bejernickii – Blaschek et al.)* with an energy density and octane rating comparable to gasoline.
- Preliminary work has shown the electrosprays of the two fuels to be qualitatively different, with butanol electrosprays producing a much wider range of droplet sizes.
- Coupling with bio-fuel production: E-sprays of mixtures of ethanol-butanol-acetone (baelene)



Performance measures - Progress towards objectives

- Performance measures
  - Comparison with proposed milestones
  - Student participation and evaluation (coursework, publications, presentations)
  - Research productivity (publications, presentations)
- The project is on time with respect to completion of milestone I.
  - Center activities widely publicized and first generation of GATE fellows recruited.
  - Curriculum established, proposed new classes offered.
  - Co-PI involvement in Energy Biosciences Institute (focus on bio-energy production) offers great opportunities for collaboration and strengthening the objectives of the Center especially with regard to evaluating downstream biofuel utilization and how it is impacted by upstream production.
- 24 students involved in the seminar series, 10 enrolled in new class, numbers above campus averages. Student evaluations instrumental in one of the co-PI's being awarded the Everitt award, the highest distinction for teaching in the college of Engineering.
- 16 archival publications and 28 conference papers by the 3 co-PIs and the 9 supported students in the first year.

Collaborations – Interactions and Technology Transfer

- The co-PIs and students have been active participants and presenters of GATE activities in the following forums:
  - At the DOE HCCI Working Group Meetings held twice a year at Sandia National Laboratory and in Detroit at the USCAR. This forum includes representatives from most of the engine, vehicle OEMs, and oil companies in the U.S.: Ford, GM, Chrysler, CAT, Cummins, John Deere, International, DDC, BP, Exxon, Shell, Chevron… as well as representatives from the major engine research centers at universities in the U.S.: UIUC, Univ. of Michigan, Univ. of Wisconsin-Madison, MIT, Stanford and UC Berkeley
  - Energy Biosciences Institute (BP), Shell, Ford, Caterpillar, Cummins and John Deere forms the base of the Center's Advisory Board, and more partners will be invited.
  - Five-day course organized annually by the National Soybean research laboratory attended by representatives from ADM, Cargill, Monsanto and other key companies in the area of biomass/crop production and processing
  - SAE Congress, American Society of Agricultural and Biological Engineers Annual International conferences, Combustion Institute Meetings, and ILASS conferences

Collaborations – Interactions and Technology Transfer (cont.)

- Interactions with industry via GATE student internships at the Caterpillar Simulation Center at UIUC, Caterpillar Tech. Center, ADM, and Sargent and Lundy LLC.
- Collaborations have been established with the University of Lecce, Italy, on electrostatic atomization and the National Technical University of Athens, Greece on E-diesel mixtures.
- Deere & Company will be establishing a Research Center in the Research Park of the Univ. of Illinois this spring 2008 and one of the key areas of research will be engine combustion modeling. This decision was influenced by PIs' presentations made to the Company
- Participation in on-campus initiatives via College of Engineering and of Agricultural, Consumer and Environmental Sciences to develop graduate options related to bio-energy and sustainability that will include the GATE Center
- Technology transfer: ORBITEC (Madison, WI) – electrostatically assisted charged injector – STTR proposal put together to ARO; VW Europe – electrostatically charged sprays; Caterpillar – bio-diesel property code; DDC – LTC engine technology.

Publications of GATE students – presentations (I)

Co-PIs and GATE-supported students have co-authored 16 archival publications and presented 28 conference papers during the first year of the program.

Archival publications:

Agathou, M. S., J. W. Powell, C. F. Lee, and D. C. Kyritsis, "Preliminary Experimental Study of Butanol Electrosprays for Power Generation" SAE Paper No. 2007-24-002.

Anderson, E. K., A. P. Carlucci, A. de Risi, and D. C. Kyritsis, "Synopsis of Experimentally Determined Effects of Electrostatic Charge on Gasoline Sprays," *Energy Conversion and Management,* 48, 2769-2774, 2007.

Anderson, E. K., A. P. Carlucci, A. de Risi, and D. C. Kyritsis, "Experimental Investigation of the Possibility of Automotive Gasoline Spray Manipulation through Electrostatic Field," *International Journal of Vehicle Design*, 45, 61-79, 2007.

Anderson, E. K., A. P. Carlucci, A. de Risi, and D. C. Kyritsis, "Electrostatic Effects on Gasoline Direct Injection in Atmospheric Ambiance," *Atomization and Sprays*, 17, 289-313, 2007.

Fang, T., R. E. Coverdill, C. F. Lee, and R. A. White, "Combustion and Soot Visualization of Low Temperature Combustion within an HSDI Diesel Engine Using Multiple Injection Strategy," SAE Paper No. 2006-01-007.

Fang, T., R. E. Coverdill, C. F. Lee, and R. A. White, "Smokeless Combustion Within a Small-bore HSDI Diesel Engine Using a Narrow Angle Injector," SAE Paper No. 2007-01-0203 - Accepted for publication to *Journal of Engine*, 2007.

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Kyritsis D. C., "Innovative Combustion Technologies: Modelling and Experimentation - Editorial" *International Journal Alternative Propulsion*, 1, 133-134, 2007.

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Activities for the upcoming fiscal year

- Increase Center visibility in and outside Campus
  - Connect with the emerging UIUC BS/MS program on Energy Systems
  - Finalize GATE Certificate arrangements
  - Increase industrial contacts, and strengthen the function of the Industrial Advisory Board
  - Involvement with Formula SAE and SAE Mini Baja teams
  - Strengthen collaboration with the Energy Biosciences Institute
- Further improve web infra-structure
  - Downloadable research software link for GATE personnel
  - Record of past seminar presentations as a future resource
  - Depository of research results
- Conduct research in emerging biofuel technologies
  - Investigate properties and engine processes of baelene and baelene-containing mixtures
  - Investigate the possibility of “upstream” savings in biofuel production through appropriate tuning of “downstream” technologies

Summary

- The GATE Center on Advanced Automotive Bio-Fuel Combustion Engines supported the research of 9 students and involved 24 in an interdisciplinary curriculum that offered instruction on agricultural, biological, chemical, mechanical and economical aspects of emerging bio-fuel and engine technologies. Four students placed in industry, and three in academia (Obj. 1-4).

- Industrial and institutional collaborations have been established through faculty participation in various forums and through student internships and tech. transfer. Key forums include the DOE HCCI Working Group, the BP Energy Biosciences Institute, National Soybean Research Laboratory, companies such as Shell, Ford, Caterpillar, Cummins, and John Deere, and professional conferences (Obj. 4)

- A syllabus that will lead to a GATE certificate was established along with core competencies and domains, and two new classes were introduced, one on Renewable Energy Systems and one on Laser Diagnostics (Obj. 1).

- The research activity of GATE Fellows involved state-of-the-art laser diagnostics, multi-dimensional modeling, and bio-fuel characterization and prediction methodology, and the students and PIs produced 16 archival publications and 28 conference presentations on biofuel research (Obj. 2,3,4).