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Abstract

The underlying goal of this project was to provide multi-disciplinary engineering training for graduate students in the area of internal combustion engines, specifically in direct injection compression ignition engines. The program was designed to educate highly qualified engineers and scientists that will seek to overcome technological barriers preventing the development and production of cost-effective high-efficiency vehicles for the U.S. market. Further, these highly qualified engineers and scientists will foster an educational process to train a future workforce of automotive engineering professionals who are knowledgeable about and have experience in developing and commercializing critical advanced automotive technologies.

Eight objectives were defined to accomplish this goal:

1. Develop an interdisciplinary internal combustion engine curriculum emphasizing direct injected combustion ignited diesel engines.
2. Encourage and promote interdisciplinary interaction of the faculty.
3. Offer a Ph.D. degree in internal combustion engines based upon an interdisciplinary curriculum.
4. Promote strong interaction with industry, develop a sense of responsibility with industry and pursue a self sustaining program.
5. Establish collaborative arrangements and network universities active in internal combustion engine study.
6. Further Enhance a First Class educational facility.
7. Establish 'off-campus' M.S. and Ph.D. engine programs of study at various industrial sites.
8. Extend and Enhance the Graduate Experience.

Executive Summary

The Interdisciplinary Center for Advanced Propulsion (ICAP) was formed at Michigan Tech to be the umbrella organization for the GATE Program activities and to make specific progress on the following project objectives.

1. Develop an Interdisciplinary Curriculum in Engines: The introductory course in I. C. Engines is now routinely taught by an interdisciplinary team. A total of seven faculty members from five academic departments (Mechanical Engineering, Electrical Engineering, Chemical Engineering, Materials and Metallurgical Engineering, and the School of Technology) participate in this effort.

2. Interdisciplinary Interaction of Faculty: In addition to faculty members team teaching the Engines course, a culture of collaborative work has been instilled in our research efforts.

3. Establish a Ph.D. degree in Engines: This program was approved by the university in 2001. However it has not gained traction in the graduate program. We have found that students routinely choose the traditional Ph.D. programs in their departments.

4. Promote Interaction with Industry: The original objective was to establish an Industrial Advisory Board specific to I.C. Engines research. This did not happen. However the Center has been able to access the Departments' industrial advisory boards with great success. For example the Mechanical Engineering Advisory Board has 12 representatives from automotive and engine manufacturing companies.

5. Establish collaborative arrangements with Universities: ICAP faculty established a joint Center in Engines with UW-Madison and U-Minnesota sponsored by the Army Research Office.

6.Establish off-campus MS and PhD programs with industry: Distance programs have been created and are managed by the MTU Extended University Programs Department. The Center is leveraging those programs. MS programs exist with Ford, GM, and Harley-Davidson. A PhD program exists with Ford; Anand Gandhi completed his PhD at Ford in April 2005. Tom Wagoner has just started a PhD program at Ford.

7. Enhance Facilities: ICAP was headquartered in approximately 2000 sq. feet of newly re-modeled office space in 1999. The space is shared by both faculty members and graduate students in close proximity. Four dynamometer cells have been renovated during the period of the project, including two diesel cells, a spark ignited engine cell, a hydrogen engine cell. This new equipment is largely devoted to research in alternate and renewable fuels.

8. Enhance Graduate Experience: A goal of 25% of ICAP students enrolled from undergraduate programs other than mechanical was developed. That target was met with the initial DOE GATE funding. However, as the Center activities expanded to include

more faculty and other sources of funding we have not been able to maintain that success. Mechanical engineering remains the dominant source of students.

Efforts were made to attract women students particularly through the use of engine based independent study projects and undergraduate research projects in the senior year. Currently 3 out of 8 undergraduate researchers in ICAP are female.

Project Summary

Faculty members in the Department of Mechanical Engineering-Engineering Mechanics have been involved with teaching and research in engines for many years. Student interest in these courses has always been very good. Sixty to eighty students are enrolled in the first engines course each year. Interaction with industries in the automotive and diesel engine arena has been and continues to be strong.

The Interdisciplinary Center for Advanced Propulsion (ICAP) as proposed for the GATE Program was established at Michigan Tech to take the next step forward. This Center is steered toward advanced study in direct-injected internal combustion engines, including emission control technology. This Center is focused on graduate education but extends to the senior level as well since this is where interest in one's career most often develops. Eight objectives were proposed that capture the essence of the DOE GATE Program. The Department, College, and University have been strongly supportive of the Center. The ICAP faculty members have coalesced to focus their activities toward collaborative and interdisciplinary work.

OBJECTIVE 1. Develop an interdisciplinary internal combustion engine curriculum emphasizing direct-injected combustion-ignited diesel engines.

The GATE Program came at an opportune time. MTU committed to change from the academic quarter system to the more common semester system in the year 2000. Faculty members at MTU were involved with planning this repackaging as this unfolded. This massive curricular reform served to enhance the creative design of engines related coursework with interdisciplinary networking across departmental lines. This program allowed the area of internal combustion engine study to exploit a surge of interdisciplinary activity in such areas as combustion, emissions chemistry, control, design, materials, and manufacture.

ME 450 Internal Combustion Engines (now designated as MEEM 4220) - The first course in engines now contains the necessary components to convey most pertinent topics in engine basics, including materials and manufacture, as well as CIDI specific material in a cross disciplinary approach (e.g., spray formation, kinetics, manufacture, fuels, alternate fuels, emissions, materials, etc.). The introductory course in I. C. Engines is now routinely taught by an interdisciplinary team. A total of seven faculty members from five academic departments (Mechanical Engineering, Electrical Engineering, Chemical Engineering, Materials and Metallurgical Engineering, and the School of Technology) have participated in this effort.

Additional engine courses that have been developed and taught as a part of the GATE program include: ME451 Internal Combustion Engines 2, ME453 Automotive Engineering Laboratory 1, and ME 590 I.C. Engines Seminar.

OBJECTIVE 2. Encourage and promote interdisciplinary interaction of the faculty.

There is a growing need for faculty to be knowledgeable not only in their specialized area of research but in interdisciplinary areas as well. For example, a metallurgist must understand the basics of tribology in the engine environment, an electrical engineer teaching controls must understand the basics of combustion chemistry and engine emissions, and a mechanical engineer must understand the nuances of organic chemistry and chemical kinetics of combustion. To reach this level of interdisciplinary competence participating faculty were selected to participate in the center 1) based upon prior experience with combustion engine design, 2) creativity and innovative accomplishments, and 3) willingness to participate in additional study of internal combustion engine propulsion.

Faculty members have participated in team-teaching both regular programs of study and also short (modular) courses offered for the MTU Enterprise Program:

MEEM 4220 I.C. Engines – This course has the largest component of interdisciplinary team-teaching in the ME-EM degree program. As described under Objective 1.

ME 590 I.C. Engines Seminar – This course was a graduate seminar course that included guest lectures from various GATE program faculty.

MTU Enterprise Program – A 16 credit program that is half project-based and half coursework. The courses are delivered in one-credit modules that include topics ranging from a technical introduction to the project to business, communications, and team work. GATE faculty have delivered I.C. Engine lectures to the Clean Snowmobile Enterprise, and the Challenge-X Enterprise.

In addition to faculty members team-teaching courses, a culture of collaborative work has been instilled in our research efforts. Faculty members participating in this project represent a spectrum of full, associate and assistant levels at varied stages in their careers. This flexibility in a rather traditional system is possible because of the character of the institution; sixty percent of the student body (and hence faculty) are enrolled in engineering.

Further, applied research and fundamental research are equally valued because of the strong industrial interaction of MTU faculty. Almost all of the research proposals submitted by ICAP faculty, including industrially sponsored research now involve collaboration of two or more faculty members.

OBJECTIVE 3. Offer a Ph.D. degree in internal combustion engines.

Historically, study in a specialized area such as internal combustion engines has been accomplished through traditional departmental Ph.D. programs. This has pretty

much limited engine Ph.D. graduates to mechanical engineering departments. Although flexibility of the Ph.D. degree can be accomplished through major and minor requirements, most students and faculty perceive the degree to be mechanical engineering in nature due to traditional departmental boundaries.

Rapid advances in scientific knowledge and technological development often require the blending of expertise from several academic departments to solve problems. The role of the individual scientist trained and working alone in a specific discipline is rapidly being replaced by a scientific team that brings individuals with different backgrounds and expertise together in a multidisciplinary approach. In recognition of this changing way in which science and engineering research is increasingly being done. The College of Engineering developed a "Ph.D. in Engineering" degree program that draws on faculty from several traditional science and engineering academic departments and focuses on several nontraditional engineering specialties. Thus, each department offers a traditional departmental Ph.D. degree program and the College administrates a Ph.D. at the College level which is based upon interdisciplinary study and monitored by faculty that comprise an interdisciplinary thrust area.

The mechanism for establishing a Ph.D. thrust area program in internal combustion engines was in place. The faculty constituting the engines Ph.D. thrust area resided in five of the traditional engineering and science departments. This multi-departmental group was charged with administration of the doctoral program in accordance with the University's rules and regulations for graduate students and this multi-departmental group had the same degree of autonomy as that of an academic department in regulating its own programs.

Unlike traditional departmental programs, state approval involving months (or years) of political dialog was not required. ICAP defined an acceptable program of study and was approved by the Dean of Engineering, the MTU Faculty Senate, the Graduate Faculty, and the Provost. Unexpectedly though, it has not gained traction in the graduate program. We have found that students routinely choose the traditional Ph.D. programs in their departments instead of the non-traditional Ph.D. in engines.

OBJECTIVE 4. Promote strong interaction with industry and pursue a self-sustaining program.

Strong interaction with industry has been an essential component of this project. At the onset of ICAP, interaction has been cultivated and encouraged to meet the underlying mission of the program. This interaction has involved (travel, telephone contact, correspondence, progress reporting, etc.) with key industrial representatives at both the technical and executive level. It was proposed that this interaction would also involve active participation of industrial representatives on an advisory board. Finally, this interaction has involved co-advising of students and projects under the ICAP program. The advantages that have ensued from this support include 1) the mutual benefits of research and development, 2) an opportunity to actively participate in curriculum development at a major engineering institution, 3) the visibility of

contribution among peers of competing industries, and most important, 4) the talent pool with which to train, recruit, and employ.

It was originally proposed that an Industrial Advisory Board would be formed consisting of seven to ten representatives from industry to promote a strong interaction with industry. The members of this board were expected to be at significant leadership levels in management control of both personnel and the technical aspects engine research and development. It became evident very early that the existing IAB's for each Department had extensive representation from the automotive industry, engine manufacturers and suppliers. For example, the Mechanical Engineering Department has 12 such representatives from companies that include Ford, GM, DaimlerChrysler, Caterpillar, John Deere, Visteon, Bosch, Dow, Navistar International Truck and Engine Corp., American Axle, Dana, and Denso International.

ICAP has had excellent access to these boards, presenting our activities to them at meetings twice per year, and receiving critical input from the members of these boards. Several research projects have resulted from these interactions and continue to develop. Industrial and government sponsored engine research at ICAP include projects with: Army Research Office, NASA, State of Michigan, U.S. Department of Energy, U.S. Department of Education, Auto Liv N.A., Caterpillar, Cummins, Detroit Diesel Corporation, Dow Automotive, EMP, Ford Motor Company, General Motors, Harley-Davison, International Truck and Engine, John Deere, Johnson-Mathey, Motorola, Polaris, R. W. Fernstrum, and Visteon. The research funding for the engine faculty and their collaborators for the last three years equaled $1.9M. No GATE funds were used for the purchase of equipment or lab construction in these programs.

OBJECTIVE 5. Establish collaborative relationships with universities active in internal combustion engine studies.

There are several universities with notable engine research programs across the country. For instance, Michigan Technological University, the University of Wisconsin-Madison, the University of Michigan, Michigan State University and Wayne State University all have recognized engine research programs and all are located within proximity of each other. There are others as well. It would be of mutual benefit to the national interest to develop a productive network of creative talent at these and other universities that promotes advancement of technology in internal combustion engine study and research.

The GATE program has been a catalyst for collaborative work at Michigan Tech. Prior to the GATE program the engine faculty worked almost exclusively as sole investigators on their projects. The formation of ICAP was the first formal effort by the engine faculty to organize and work together as intended in the original proposal. This new working relationship has made it possible to establish significant collaborative efforts with other universities. One visible example of this collaboration was the establishment of a joint "Center of Excellence for Propulsion Systems" by the ICAP

faculty with UW-Madison and U-Minnesota sponsored by the Army Research Office. The work was related to compression-ignition and direct-injection diesel engines. The three areas of focus were Transient Engine Experiments, Engine Simulation and Powertrain Modeling, and Combustion and Emission Characterization. A description of the ARO program follows:

The Transient Engine Experiments thrust was aimed at developing a better understanding of transient engine behavior and the possibilities for engine optimization in 'real-time' while under transient operation. Many of the most difficult engine operating regimes and environments involve rapid transients (from idle to full-load), but there has been little focus on the transient behavior as other than a set of quasi-steady conditions. In part, this may be due to the lack of ability to run controlled transient tests and make appropriate transient measurements. This thrust was aimed at developing a rapid transient dynamometer and applying these capabilities.

The Engine Simulation and Powertrain Modeling thrust built on the extensive experience in the ERC in modeling both detailed in-cylinder processes as well as the experience of the Powertrain Control Research Laboratory (PCRL), also at the University of Wisconsin-Madison, in larger scale powertrain system modeling. The projects executed by this thrust represented new efforts aimed at making the 'research' based models more robust and more accessible for design and evaluation of engine and powertrain systems. This work also involved increased integration of engine and powertrain models to the advantage of both. The collaborations between MTU, UW, and University of Minnesota (UMN) was beyond the scope of most nearer-term focus projects currently underway, so it represented an area of new work for university-based long-range development projects.

The Combustion and Emission Characterization thrust studied in significant detail the characteristics of engine emissions, principally from diesels. While the Army had some initial interest in emissions because of their potential detection signatures, there were other reasons for interest in this topic. One of these was the recognition that emissions are a major limiter of commercial engine performance; to the extent that the Army is supplied with commercial engines or engines which rely on commercial engine technology, the compromises that favor emissions reduction at the expense of performance were considered detrimental to Army needs. The long term goal of this work is that an improved understanding of emissions generation will then provide the basis for emissions reduction methods that are less detrimental to engine performance than current and planned methods. No GATE funds were used for the purchase of equipment or construction in this program.

OBJECTIVE 6. Establish off-campus M.S. and Ph.D. engine programs of study at various industrial sites.

The College of Engineering and ME-EM Department at Michigan Tech have long recognized the fact that many employees in industry cannot easily leave their career or family responsibilities to pursue the advanced degree. To address this issue, the

Department has established both a distance M.S. and Ph.D. graduate program that is flexible to serve the needs of highly motivated and exceptionally qualified industry employees and provide the opportunity for these individuals to obtain advanced degrees while still working. This program is specifically designed to be an engineering science degree requiring a traditional thesis or dissertation in contrast to the more typical 'night school' graduate program found in major metropolitan areas.

The off campus M.S. and Ph.D. programs are largely focused on the automotive and engine industry. Students from industry, once admitted to the program, establish an advisory committee. The committee will consist of at least two MTU graduate faculty and two adjunct professors from industry. A key element of any student's graduate program is the direct interaction between the student and their advisor. To facilitate student-faculty interaction, MTU faculty are encouraged to spend three to six months in residence at the participating industry while advising and directing the students research and making contributions to the industry. Expenses are to be covered by the participating industry. The student is expected to establish a short term residence at MTU for the necessary examinations (qualifying, comprehensive, and final defense).

Ten on-campus graduate students have been supported by GATE funds and have graduated. Thirteen Distance Learning students have graduated under the program described above. In addition, DOD funds were solicited under the GAANN program and used to support ICAP students. Seven students have graduated under that program. A complete summary of these students who have been supported and graduated during the performance period (names, thesis titles, and enrollment status) is provided in Appendix A.

OBJECTIVE 7. Further Enhance a First Class Educational Facility.

Through the years, the educational facilities devoted to the study of internal combustion engines at Michigan Tech have developed to a comfortable level. 'High Tech' classrooms with large screen overhead and computer projection have been used to deliver lecture material to students studying internal combustion engines. Laboratory facilities (dynamometer facilities, a laser diagnostics and optics facility, and a combustion laboratory) have been used for both research and instruction in a collaborative manner and have helped to bring research into the classroom at both graduate and undergraduate levels.

The ME-EM building, an eleven story structure of approximately 78000 square feet, was re-modeled at about the time ICAP was formed. Several floors were re-modeled and ICAP was housed in one of these floors. ICAP faculty and graduate students are housed in approximately 2000 sq. feet of this newly re-modeled office space. During the period of this project four dynamometer cells have been renovated during the period of the project, including two diesel cells, a spark ignited engine cell, and a hydrogen engine cell. These renovations have allowed ICAP to begin work on alternate and renewable fuels including ethanol, bio-diesel, hydrogen, and hydrogen enhanced gasoline. A new initiative is being developed around bio-fuels derived from woody biomass. No GATE

funds were used for the purchase of equipment or construction in this re-modeling program.

OBJECTIVE 8. Extend and Enhance the Graduate Experience.

The graduate experience for most students in any subject can be a transforming experience. A good portion of entering graduate students are fresh from their undergraduate program with limited interdisciplinary experiences. The mission of ICAP is to be truly interdisciplinary. Students enrolled in ICAP have the opportunity to interact not only with professors who may be outside of the student's major but with students from other disciplines as well. ICAP maintains an effort to recruit students from all engineering disciplines into the program. Our students have backgrounds in electrical engineering, chemical engineering, mechanical engineering, and metallurgical engineering. ICAP strove initially for a minimum of 25% of students from backgrounds other than mechanical engineering. That target was met with the initial DOE GATE funding. However, as the Center activities expanded to include more faculty and other sources of funding we have not been able to maintain that success. Mechanical engineering remains the dominant source of students.

Efforts are made continually to attract women students, particularly through the use of engine based independent study projects and undergraduate research projects in the senior year. Currently, 3 of 8 undergraduate researchers in ICAP are female. We still find it very difficult to enroll these women into a graduate engine's program. We have supplemented the GATE funding with NSF Fellowship offers that include a $30K stipend. Even with that level of funding, we find our women students will accept an offer from industry in preference to graduate school.

Perhaps we should consider a collaboration between DOE, industry, and universities that promotes graduate education and employment for underrepresented groups as a package.

APPENDIX A ICAP Program - Student Summary

Distance Learning Students

Barrett	Eric	A Comparison of Electric Power Assist Steering with Hydraulic Power Assist Steering for Automotive Applications	MS	Mech Engrg	21-Dec-02
Black	Matthew	Evaluation and Diagnosis of Steering Column Vibration	MS	Mech Engrg	11-May-02
Esper	Gregory	A Comparative Study of Hydrogen Carriers for Fuel Cell Electric Vehicles	MS	Mech Engrg	20-May-00
Frait	Steve	Parameter Effects in Magnetic Speed Sensing Through an Interposed Rotating Element	MS	Mech Engrg	20-Dec-03
Goodhall	Shane	Investigating Deflection in a Seat Integrated Restraint System	MS	Mech Engrg	10-Aug-02
Hagemeyer	Catherine	The Classification and Applications of Problem Solving Quality Tools	MS	Mech Engrg	10-May-03
Hutchins	Douglas	Energy Generation in a Nickel-Metal Hydride Battery	MS	Mech Engrg	23-Dec-00
Kenny	Patrick	The Influence of Laminar Flame Speed on Cyclic Combustion Variability During the Engine Warm-Up Period	MS	Mech Engrg	21-Dec-02
King	*Kevin*	*(course work)*	*MS*	Mech Engrg	*9-Feb-05*
Lichtenberg	Glen	Quality Improvement of a Manual Transmission Input Shaft Radial Lip Sealing System: Failure Analysis, Design and Manufacturing Assessment	MS	Mech Engrg	10-May-03
Pariseau	David	Development of a Computational Fluid Dynamics Model for Assessment of Lubricant Performance in a Manual Transmission Gear Mesh	MS	Mech Engrg	10-Aug-02
Plotkin	Charles	Continuously Variable Transmission Degradation Test for Customer Satisfaction Attributes	MS	Mech Engrg	10-May-03
Wilbur	Don	Automatic Transmission, Static Engagement Design Improvement Using a Systems Engineering Design Approach	MS	Mech Engrg	17-Dec-05

GATE Students

Diemer	Paul	Investigation of Engine Noise Induced by Vibrational Force Transmitted at the Crankshaft and Engine Block Interface	MS	Mech Engrg	11-Aug-01
Hilbert	David	Hydrocarbon Emission Sources in a Direct Injected Two-Stroke Engine	MS	Mech Engrg	22-Dec-01
Horstman	David	On-site Dimethyl Ether Generation for Pilot Injection and Enhanced Ignition in	MS	Mech Engrg	21-Dec-02

		Natural Gas Fueled Compression Ignition Engines			
Inal	Mehmet	Thermal Loading and Surface Temperature Analysis of the Piston of a Small HSDI Diesel Engine	PHD	Mech Engrg	13-Aug-05
Mathews	Benjamin	A Computational Fluid Dynamics Model to Predict the Workpiece Temperature During Cylinder Boring	MS	Mech Engrg	18-Aug-00
Nelson	Alan	Sulfation of Ceria-Zirconia Model Automotive Emissions Control Catalysts	PHD	Chem Engrg	12-May-01
Singh	Paramjot	An Experimental Study of Active Regeneration of an Active Regeneration of an Advanced Catalyzed Particulate Filter by Diesel Fuel Injection Upstream of an Oxidation Catalyst	MS	Mech Engrg	17-Dec-05
Stalsberg-Zarling	Krista	An Investigation of Vapor Generation from Artificial Cavities with Applications to Fuel Rail System	MS	Mech Engrg	12-May-01
Stocker	Robert	Experimental Study of Direct Injection Fuel Sprays Under HCCI Conditions	MS	Mech Engrg	17-Dec-05
Vande Kemp	John	Nozzle Spray Penetration of the Diesel Injection Process at Reduced Temperatures	MS	Mech Engrg	12-May-01

GAANN Students

Henning	Christopher	Natural Gas Compression Ignition Engine withPilot Injection of Dimethyl Ether (DME)	MS	Mech Engrg	7-Aug-04
Horstman	*David*	On-site Dimethyl Ether Generation for Pilot Injection and Enhanced Ignition in Natural Gas Fueled Compression Ignition Engines	*MS*	Mech Engrg	*21-Dec-02*
Miers	Scott	Identification and Characterization of Impingement Signatures in a High Speed Diesel Engine using Piston Surface Temperature Measurements	PHD	Mech Engrg	18-Dec-04
Miller	Kenneth	n/a Course Work	MS	Mech Engrg	20-Dec-03
Parolini	Jason	On the Kinetics and Mechanical Properties of Austempered Gray Iron	MS	Matls Sci & Engrg	20-Dec-03
Rosso	Paul	A Variable Displacement Engine with IndependentlyControllable Stroke Length and Compression Ratio	MS	Mech Engrg	13-Aug-05
Stocker	*Robert*	Experimental Study of Direct Injection Fuel Sprays UnderHCCI Conditions	*MS*	Mech Engrg	*17-Dec-05*