Technology Transitions Case Study
Combustion Research Facility (CRF)

CRF: Pioneering Science and Technology Transition Approaches

Established as the first Department of Energy (DOE) user facility in the 1970s and designated as a DOE collaborative research facility in 2008, the Combustion Research Facility (CRF) at Sandia National Laboratories (SNL) has served as a national and international leader in combustion science and technology for more than 30 years. Within the CRF, staff and visiting researchers have greatly expanded the fundamental knowledge of combustion processes, pioneering research into new science and applied concepts—while at the same time helping the automotive industry to produce cleaner, more efficient vehicles.

To develop this improved understanding of combustion science, the CRF develops advanced, laser-based diagnostics and other techniques that are then applied both to studies of combustion fundamentals, and to investigations of engine-combustion processes through the use of optically accessible engines and other specialized experimental hardware that simulates realistic engine conditions. As new engine data emerge, the understanding gained by basic-science researchers on combustion fundamentals or laser spectroscopy in flames is often used by the more-applied researchers in their data analysis and interpretation to create new conceptual frameworks of the physics underlying engine-combustion processes. Findings and frameworks are shared and transitioned to other applied researchers and industry stakeholders in many ways, including in-depth discussions, influential papers in academic and applied journals, and presentations at widely attended events. In some cases, the work can be distilled into freely available models that accurately reflect combustion phenomena—and yet are sufficiently condensed for practical use by industry, to help them create proprietary innovations that enhance transportation engines.

Foundational DOE Sponsorship

The flow of knowledge and ideas between scientific and applied researchers reflects the two missions of the CRF, which in turn stem from the two major sources of CRF funding. Specifically, the Basic Energy Science (BES) Program within the Office of Science directs the CRF to do excellent science, while the Vehicle Technologies Office within the Office of Energy Efficiency and Renewable Energy (EERE) directs the CRF to create results that can be more immediately useful to industry.

The core of the CRF's success is founded in the synergy created by these two missions. Focusing on the much-needed science fundamentals from the perspective of delivering applicable results has been central to the continued value of the CRF. To this end, the CRF has approached its science undertakings with an eye to meeting industry's needs and pioneered methods for bridging the transfer of knowledge and technologies across the spectrum of activities required to generate innovation. Learning from its experiences, the CRF has created and continues to enhance principles for collaborations—which can take many forms, such as consortia like the Advanced Engine Combustion (AEC) Consortium; close collaborations both internally with other CRF researchers and with researchers from outside

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organizations, including visiting researchers who come to the CRF for weeks, months, or years; and Work for Other (WFO) Agreements and Cooperative Research and Development Agreements (CRADAs) that enable the CRF to conduct focused research to meet DOE and partner needs.

Creating an effective program that produces results also requires strong relationships with DOE program managers. Through ongoing communication, the CRF is able to listen to and share perspectives on how building and applying scientific knowledge can fulfill the needs and goals of both DOE and industry. With this understanding, CRF and DOE managers are well prepared to engage in strategic planning that advances science and technology in ways that allow industry to achieve the critical national goal of progressing toward a clean, efficient, and low-carbon transportation system.

To focus more specifically on how the CRF ensures its continued impact on industry, it is helpful to understand some of the forms that impact can have, the principles that the CRF follows for engaging with industry, the different engagement models the CRF has employed, and the best practices developed at the facility.

Impact

The success of the CRF may have been best summarized by a top U.S. automotive industry executive, who maintained that every vehicle being built today is cleaner and more efficient due to work done at the CRF. A quantitative perspective on the benefits of the CRF's work is available from a 2010 report[1]—prepared by Albert N. Link at the University of North Carolina at Greensboro with funding from EERE—that estimated the benefits of DOE investments in vehicle technologies.

Examining just two CRF research areas—laser and optical diagnostics and combustion modeling for heavy-duty vehicles—the study found that the DOE investment achieved total economic and health benefits of $70.2 billion (in 2008 dollars) from 1995–2007 by reducing the diesel fuel consumption of heavy-duty trucks by 17.6 billion gallons over this period. In addition, the study credited the DOE investment in the CRF with reducing U.S. crude oil imports by 1% during the study period and creating a knowledge base supporting more than a dozen important technologies, including fuel injection, homogenous charge compression ignition combustion processes, exhaust gas recirculation, and low-emissions diesel fuel formulations.

Evidence of impact is embodied in the knowledge and models the CRF has transferred to industry, as well as in the influence of CRF publications. In addition, awards demonstrate the value that peers have placed on the CRF's work. Each of these areas is discussed below.

New Knowledge and Models

Science-based Understanding of Key Diesel-Engine Combustion Processes

Realizing that a more detailed understanding of the physics underlying combustion and emissions formation in heavy-duty vehicle diesel engines was a prerequisite to meeting stringent standards for nitrogen oxides (NO_X) and soot, industry leader Cummins entered into a CRADA with the CRF, Lawrence

[1] Link, Albert N. May 2010. Retrospective Benefit-Cost Evaluation of U.S. DOE Vehicle Combustion Engine R&D Investments: Impacts of a Cluster of Energy Technologies. University of North Carolina at Greensboro.
http://www1.eere.energy.gov/analysis/pdfs/advanced_combustion_report.pdf

Livermore National Laboratory (LLNL), and Los Alamos National Laboratory (LANL) in late 1993. Under this CRADA, which later grew to include General Motors (GM), Caterpillar, and Detroit Diesel, the CRF conducted in-depth measurements over several years, using advanced laser diagnostics applied in a new-generation optically accessible engine.

This effort yielded highly significant results. Specifically, a series of increasingly refined measurements—augmented by close collaborations with scientists supported under DOE's BES program—allowed CRF researchers to revolutionize the existing physical understanding of fuel/air mixing and NO_X and soot formation in diesel engines and to reduce this information to a tractable physical description.

Guided by this new understanding, researchers at LANL and the University of Wisconsin improved computational fluid dynamic (CFD) models and developed new submodels that enabled the numerical simulations to match the CRF's experimental data. Armed with these new models, quantitative experimental data, and a much more accurate understanding of combustion, automakers developed, refined, and validated their proprietary computational models for engine design to produce cleaner and better performing engines.

As an additional testament to the long-term value of this work and the methods used to obtain the experimental data, the optical engine built by the CRF researchers for this work has remained in use for 22 years, providing measurements and data that continue to enhance understanding of combustion physics today.

Understanding Supercritical Fuel Mixing

Under the high temperature and pressure (supercritical) conditions present within the cylinder of a diesel engine, liquid and gas molecules behave in unconventional ways. The CRF's computational experts have developed a theoretical model that captures the physics of fuel/air mixing processes under supercritical conditions, and images from CRF experiments have shown the mixing behavior predicted by the models. These findings can help engine makers redesign fuel-injection and fuel-air mixing strategies to achieve better engine emissions and efficiency.

In-cylinder Carbon Monoxide Emissions Control

Controlling emissions within the engine cylinder is more effective and cost-efficient than mitigating emissions with after-treatment in the exhaust system. In addition, emissions of some species, and particularly of carbon monoxide (CO), occur because of incomplete combustion and can therefore signify a substantial efficiency loss. To help industry understand the in-cylinder sources of CO emissions, CRF researchers performed time-resolved laser-sheet imaging that showed the evolution of the in-cylinder CO distribution. Using quantitative spectroscopic information developed under the Basic Energy Science program at the CRF, they were able to reduce the images acquired to provide accurate measurements of the in-cylinder CO concentration. Comparison to tailpipe CO measurements taken using well-established methods verified the optical measurements and gave the industry confidence to use the optical measurements to validate their proprietary models and ultimately to decrease engine emissions.

First All Computationally Designed Diesel Engine

In 2007, Cummins produced the world's first all-computationally designed diesel engine, eliminating the traditional test and build approach. The new design approach—developed by Cummins based on knowledge from a multi-institution collaboration led by the CRF—reduced by about 10% the time and cost of producing a new more robust, fuel-efficient engine that met all expectations for performance and emissions. First marketed in 2007, the Cummins ISB series 6.7 liter diesel engine now powers more than 200,000 Dodge Ram heavy-duty pickup trucks. Further, all new U.S. engines today are designed in large part with computer simulation, a development that is helping U.S. industry reduce product development cycles and costs.

Presentations and Publications

CRF researchers publish dozens of papers every year, targeting academic and scientific researchers via the scientific press and more-applied researchers and industry stakeholders in relevant industry association journals. These articles—along with presentations offered at conferences such as the International Combustion Symposium (the largest event for combustion science in the world, held biannually), the SAE International Congress (the largest event in the world for engine-combustion research, held annually), and many other events for both fundamental and applied research—allow the CRF to disseminate its findings to others in like-minded research and applied pursuits.

One indication of the quality of the CRF research is the high rate of citations of its papers. Rough estimates indicate that the nearly 600 papers published by CRF researchers between 2009 and 2014 are referenced in thousands of citations.

Awards

CRF scientists have been recognized with the highest awards in their fields, including the Gold Medal of the Combustion Institute and the Broida Prize of the American Physical Society. Since the CRF's inception, six CRF researchers have been designated as SAE Fellows, and CRF researchers have won the SAE's prestigious Horning Memorial Award seven times—honors that are unmatched by any other institution.

Principles for Industry Impact

To create such impact, the CRF follows specific principles:

- **Build foundational scientific understanding:** As noted, the CRF has been focused on generating basic knowledge about combustion for more than three decades. Although much has been learned, several interrelated factors—including the complexity of modeling combustion processes, ever-more stringent regulation of vehicle efficiency and emissions, and the need to understand the interaction of engines with future fuels—strengthen the mandate to continue the search for increasingly in-depth understanding of combustion and engine science.
- **Focus on industry needs, including emerging challenges:** Through deliberate and ongoing partnerships with industry, the CRF seeks to focus its research toward helping industry face its toughest challenges and develop technological solutions to enable each new generation of clean

engines. Thanks to trust earned through decades of effective working relationships and a track record of meeting objectives, the communications include a solid feedback loop from industrial partners, which allows the CRF—working with DOE program managers—to adjust goals, programs, and deliverables as needed to maintain their relevance.

- **Deliver valued results:** Beyond delivering new knowledge, CRF researchers seek to package that knowledge into forms that industry can use to further their own development processes by creating proprietary solutions and intellectual property (IP). Whenever possible, the knowledge is delivered as computational models, considered the most succinct form of encapsulating the most relevant knowledge of a process. Key models delivered by the CRF, in addition to the supercritical mixing models discussed above, include better turbulence models, soot and NOx formation and oxidation models, and models for spray flame entrainment, mixing, and combustion under conventional sub-critical conditions.
- **Deliver pre-competitive results:** Industry has consistently expected the CRF to deliver results at the pre-competitive stage by providing the science base or fundamental understanding, leaving industry free to compete by drawing upon this understanding to develop propriety products. Thus, while the CRF has been a source of often unique breakthroughs, it has created relatively fewer patents than similar organizations, opting instead to meet DOE goals and industry needs by delivering knowledge and tools at an upstream development phase. This strategy has in fact proven extremely successful.

  This said, some evidence suggests that when the CRF does create patents, they can be highly influential. The May 2010 cost benefit report cited earlier [Link 2010] noted that, based on citation averages and patent families filed since 1999, each of the combustion patent families associated with DOE investments is linked to an average of 2.35 subsequent patent families owned by a set of leading companies. As such, DOE places second in patent influence only to Nissan, whose combustion patent families filed since 1999 are each linked to an average of 2.67 later patent families of the leading companies.

- **Work collaboratively on projects with mission importance:** Much of the benefit delivered from the CRF can be traced directly to an intense pursuit of collaboration—a strategy that dates back to the CRF's inception as a DOE user research facility. However, the CRF operates differently from typical user facilities, which provide staff scientist support and access to major equipment and facilities for users with research proposals judged sound by their peers. Instead, the CRF accepts collaboration only on research topics of interest to the CRF mission, as well as to the partner. In recognition of this unique operating model, DOE changed the CRF's designation from user facility to collaborative research facility in 2008. The section below on engagement approaches discusses the different avenues that the CRF has taken to maximize the value of its collaborations.

Approaches to Engagement

To maximize its ability to collaborate effectively and deliver on its objectives, the CRF engages with others in several ways, as described below.

Consortia

The CRF has initiated and leads several consortia with industry stakeholders and other research centers. The focus of these consortia is to accelerate research and obtain more accurate results by coordinating either DOE-funded research with U.S. industry or research being carried out across the globe. The tables below summarize the goals, types of partners, and working arrangements of three current consortia.

Advanced Engine Combustion Consortium (AEC)

Dates of Operation	Initiated by the CRF in 2003 and renewed until 2018 through a MOU agreed upon by all partners
Goals	**Current goals:** • Working at the pre-competitive stage, coordinate DOE-funded engine-combustion research with U.S. industry to provide the science and knowledge basis for the next generation of clean, high-efficiency light- and heavy-duty engines running on conventional and future fuels • Advance models for engine design to advance further proprietary work conducted outside of the AEC **Target combustion strategies:** • Advanced dilute-burn gasoline engines (e.g. boosted, spray-guided GDI) • Advanced clean, diesel combustion (e.g., multiple injections, high EGR) • Low-temperature combustion (LTC) (e.g., HCCI, PCCI, PPCI) • Alternative liquid hydrocarbon, natural gas, renewable fuels, and hydrogen
Membership	• **Auto Industry:** Caterpillar, Chrysler, Cummins, Detroit Diesel, Ford, ElectroMotive, GM, John Deere, Mack Trucks, PACCAR, Volvo • **Energy Companies:** BP, Chevron, ExxonMobil, GE Global Research, Shell Global Solutions, • **National labs:** Argonne National Laboratory, Lawrence Livermore National Laboratory, NREL, Los Alamos National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, Sandia National Laboratories • **Universities (participants, but not MOU signatories):** Clemson University, Massachusetts Institute of Technology, Michigan State University, Michigan Technological University, New Hampshire University, Pennsylvania State University, Stanford University, University of California, Berkeley, University of Connecticut, University of Michigan, University of Vermont, University of Wisconsin, Wayne State University, Yale University
Significant Achievement	Maintains the relevancy of DOE research by providing a forum for communicating research results to members in a timely manner and gaining feedback from industry
Organizational Structure	• Memorandum of Understanding (MOU), led by the CRF; each MOU member has a single vote • Biannual review meetings to share latest research results and partner needs • Maintain AEC efforts at the precompetitive stage; IP based on this work is performed by members outside the scope of the MOU • Additional work through WFOs and CRADAs between specific partners is handled by those partners, and IP management is determined in those agreements. • Governance and planning conducted via a business meeting held with the biannual review meeting. DOE investment decisions ultimately reside with DOE program managers. • Consideration of new members determined by existing partners, and new partners require the unanimous approval of the existing MOU membership
Member Roles	**Industry:** • Actively participate in biannual program review meetings • Provide constructive feedback on research progress and direction • Make presentations on industry needs and non-proprietary in-house research • At their discretion, provide technical assistance and hardware to facilitate research **National laboratory and university researchers:** • Actively participate in the biannual program review meetings • Present latest research • Listen to and respond to industry feedback

Engine Combustion Network (ECN)

Dates of Operation	Initiated by the CRF in 2011
Goals	**Goals:** • Coordinate international research to provide the science and knowledge basis for the next generation of clean, high-efficiency light- and heavy-duty engines running on conventional and future fuels • Advance models for engine design **Current Focus** • Establish an internet library of well-documented experiments that are appropriate for model validation and the advancement of scientific understanding of combustion at conditions specific to engines • Provide a framework for collaborative comparisons of measured and modeled results • Identify priorities for further experimental and computational research
Membership	Multiple partners, including automotive companies, research labs, and universities from specialized facilities around the world; current participants follow: **Experimental Participants:** • *United States:* Argonne National Laboratory, Caterpillar, General Motors, Michigan Technological University, Pennsylvania State University, Purdue University, Sandia National Laboratories, University of Massachusetts • *International:* Aachen University, Germany; Chalmers University of Technology, Sweden; CMT, Spain; Eindhoven University, Netherlands; IFP Energies Nouvelles, France; Meiji University, Japan; Seoul University, South Korea **Modeling Participants:** • *United States:* Argonne National Laboratory, Sandia National Laboratories, University of Wisconsin • *International:* CMT, Spain; Eindhoven University, Netherlands; Politecnico Di Milano, Italy; University of Cambridge, U.K.; University of New South Wales, Australia
Significant Achievement	Generates collective results far beyond what any single institution could achieve by linking and coordinating research efforts from multiple partners with different capabilities
Organizational Structure	• Voluntary participation • Led by the CRF
Member Roles	**Experimental participants:** • Conduct experiments on a set of identical fuel injectors to improve the understanding of injector-produced fuel sprays, spray mixing and spray-combustion processes in engines, and to provide a database for modeling these sprays. **Modeling participants:** • Use the experimental data to validate and improve models to predict the behavior of fuel sprays and spray-combustion in engines.

Turbulent Nonpremixed Flame Workshop (TNF)

Dates of Operation	**Initiated by the CRF in 1996**
Goals	**Goal:** • Understand fundamental issues of turbulence-chemistry interactions in gaseous flames **Objectives:** • Provide an effective framework for comparison of measured and modeled results • Establish a series of benchmark experiments and calculations that cover a progression in geometric and chemical kinetic complexity across a range of combustion modes and regimes • Understand the capabilities and limitations of various combustion models and submodels • Identify priorities for further collaborative research
Dates of Operation	• Since July 1996, 12 international workshops with invited session coordinators presenting collaboratively generated information on selected topics
Participants	• Each workshop typically attracts 80–100 experimental and computational researchers in turbulent combustion from 13 countries with expertise in a variety of areas, including velocity measurements, scalar measurements, computational methods, turbulence modeling, chemical kinetics, reduced mechanisms, mixing models, direct and large-eddy simulation, radiation, and combustion theory • *Main participating institutions:* Cambridge University, Cornell University, Delft University of Technology, DLR-Stuttgart, Ecole Centrale Paris, Hanyang University, Imperial College of London, Aachen University, Ohio State University, Princeton University, Purdue University, Sandia National Laboratories, SINTEF, Stanford University, Stuttgart University, Sydney University, Technical University of Darmstadt, University of Adelaide, University of California, Berkeley, University of California, San Diego, University of Duisburg-Essen, University of Melbourne, University of New South Wales, University of Southern Queensland, University of Texas at Austin, University of Toronto
Significant Achievements	Pursues collective research strategies that generate basic science knowledge far beyond the scope of any single organization. Tangible results include a TNF library that includes: • Multi-scalar and velocity data from several flows and flames that carry through a progression in complexity of the chemistry and the flow field • Research on flames of simple hydrocarbon fuels (methane, natural gas, and methanol), that include modeling challenges, such as local extinction and re-ignition, detached or lifted reaction zones, auto-ignition, flow recirculation, and swirl • Workshop proceedings available via the Internet
Organizational Structure	Voluntary collaboration with participants
Participant Roles	• Contribute to development of a collective research strategy • Present and share results

Co-location of Researchers Critical to impact

A major asset of the CRF is co-location of applied and fundamental researchers, a strategy that encourages collaboration and creates strong synergism between basic science and applied efforts. The CRF expands on the benefits of proximity by hosting more than 100 visiting researchers every year from around the world. These visitors, who work at the CRF from periods of weeks to years, include industrial collaborators, postdocs, university faculty and graduate students, high school teachers, and national laboratory and government researchers. Flexibility of the period and longevity of visits fosters relationships that maximize the value of the CRF. For example, some CRF visitors have returned to the CRF multiple times over 20 years to pursue ongoing projects, while a researcher from Cummins worked at the CRF for a continuous three-year period.

Working side-by-side with CRF staff, visiting researchers help develop new research methods and approaches and conduct experiments that benefit from the unique facilities and techniques available at the CRF. In turn, the visitors boost CRF capabilities by sharing developments and unique knowledge from their home institutions that stimulate progress and new approaches to CRF projects.

Industry-Sponsored Research

CRADAs and Work for Others (WFO) Agreements allow the CRF to conduct focused research on proprietary projects in areas important to a DOE mission with funding or significant in-kind support from partners outside of government. Such partners share in project strategy development and receive regular, in-depth information on their respective projects to enable them to stay current on the research and continue to play a role in project strategy. Agreement terms may protect proprietary information and can protect designated project-generated information for up to five years before public disclosure.

CRF has worked under sponsored research agreements with many in the engine industry, including General Motors, Ford, Chrysler, Toyota, Caterpillar, Cummins, Detroit Diesel, International, and John Deere. In addition, Chevron has funded an ongoing project for many years, and other energy companies, such as ExxonMobil, Shell, ConocoPhillips, and BP, are exploring options for working with the CRF on various combustion experiments of interest.

As discussed above, one of the most significant CRF CRADAs, formed with Cummins, laid the foundation for a new understanding of diesel combustion that has changed the way engineers think about and model the combustion process and led to the first entirely computer-designed engine.

Engagement Best Practices

From lessons learned through years of working with industry partners, the CRF has developed the following best practices for engaging in ways that produce impact:

- **Deliver precompetitive results:** On numerous occasions in different types of collaborative forums, industry has expressly stated that the CRF should focus on creating fundamental knowledge that industry can then carry forward to create IP and proprietary designs. This approach allows deep and open information-sharing, that results in trusted relationships between the CRF and its partners.
- **Engage in impactful research topics:** Strong communication with industry allows CRF researchers to gain intimate understanding of their needs and identify important research topics that impact the industry. For example, from Ford, the CRF has understood the importance of accounting for not only engine emissions and efficiency, but also for factors, most notably noise, that drive consumer acceptance. Further, the OEMs have helped direct research towards emerging concepts, such as low-temperature combustion and the mega-knock phenomena that arises in modern boosted, down-sized engine designs. The CRF is also responding to an industry-expressed need for research on advanced ignition systems.

- **Develop strong connections:** The deep level of discussions and information-sharing possible with close relationships help steer the CRF's research toward highly valued and relevant results and—perhaps more important—generates mutual trust that facilitates further information-sharing. The benefits of close connections can accrue to individual companies, as well as to the CRF and the industry as a whole. For example, by taking the step of donating fuel injectors to the ECN experimental partners for their studies, Bosch gained detailed information on their product from research facilities around the world.
- **Share information:** The CRF makes a concerted effort to share its information and results. During projects, CRF researchers schedule regular meetings with partners to discuss progress, data, developments, and issues. Partners thus have access to findings before they can be published in publically available journals. As noted above, the CRF publishes extensively and presents at meetings that are well attended by industry. Further, because of the importance it places on information sharing, the CRF often organizes sessions at industry-attended events, such as the SAE Congress, the SAE Powertrain, Fuels and Lubricants Meeting, and the International Combustion Symposium.

Moving Forward

As pressures for cleaner, more efficient, and low-carbon transportation intensify, so does the need to direct research in areas that can accelerate development of vehicles that can contribute to a sustainable energy future. The CRF will therefore continue to examine, expand, and enhance its collaboration processes to maintain its relevance to industry. This strong engagement with industry will be balanced with an equally focused partnership with DOE program managers and others who are helping to shape national research agendas toward the achievement of critical overarching goals.