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Linkages from DOE's Vehicle Technologies R&D in Advanced Combustion to More Efficient, Cleaner-Burning Engines

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Acknowledgments

This report uses bibliometric analysis to trace linkages from knowledge outputs of Advanced Combustion Engine research and development (ACE R&D) by the Vehicle Technologies Program (VTP) of the U.S. Department of Energy, to downstream innovations in diesel engines and other areas. The report is prepared for DOE under Purchase Order No. 933589 of Sandia National Laboratories (SNL) in Albuquerque, New Mexico, USA. SNL is operated by Sandia Corporation, a subsidiary of Lockheed Martin Corporation.

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Rosalie Ruegg of TIA Consulting, Inc., led the study and was joined by Patrick Thomas of 1790 Analytics, LLC, as co-researcher and report co-author. Laura LaMonica of LaMonica Associates provided assistance with the publication citation analysis.

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Any errors remain solely the authors' responsibility.

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Executive Summary

This report uses bibliometric analysis, supported by interview and review of documents and databases, to trace linkages from knowledge outputs resulting from DOE's advances in vehicle engine combustion to downstream innovations in commercial diesel engines and other areas. This analysis covers the period from 1974 through 2008 (and in some cases to early 2009).

Background

DOE's advances in vehicle engine combustion have been achieved by a cooperative effort of two operations: Advanced Combustion Engine R&D (ACE R&D), which comprises one of the Subprograms within the Vehicle Technologies Program (VTP) of DOE's Office of Energy Efficiency and Renewable Energy (EERE); and DOE's Combustion Research Facility (CRF), at Sandia National Laboratories (SNL) in Livermore, California, which is part of the Office of Science.

DOE was authorized by Congress to begin active R&D on vehicle technologies through the Electric and Hybrid Vehicle Research, Development, and Demonstration Act (Public Law 94-413) of 1976. The CRF was formed in 1978, as part of DOE's mission, and began operations in 1981, with the intent of developing the most advanced possible diagnostic systems for combustion applications.

ACE R&D has focused on laser diagnostics and optical engine technologies, combustion modeling, combustion and emission control, and solid state energy conversion. The goal has been the development of high-efficiency clean combustion and emission control technologies for both passenger and commercial vehicles. This goal is important because increasing the efficiency of internal combustion engines is one of the most cost-effective approaches to reducing the petroleum consumption of the nation's fleet of vehicles in the near-to-mid-term. Using advanced internal combustion engines in hybrid electric vehicles will enable even greater fuel savings benefits. The internal combustion engine is expected to continue to dominate the transportation market for a number of years, as alternatives continue to enter commercial markets.

Study Purpose

In response to congressional and administrative directives for program evaluation, as well as to program management needs, this study provides an evaluation of knowledge outputs attributable to DOE's ACE R&D Subprogram in cooperation with the CRF (hereafter referred to simply as ACE R&D). Specifically, it examines the extent to which the knowledge outputs of DOE's combustion engine research are linked to downstream advances in vehicle engines, as well as to innovations in other industries.

Study Methods

The study uses bibliometric and supporting methods to determine if there are identifiable and measurable linkages between outputs of ACE R&D and subsequent developments both within

and outside the area of combustion technology. The study is designed to address a series of questions (see Table 2-1) to identify linkages and the organizations and technologies that are involved. As background to formulating the questions, the study reviewed the ACE R&D Subprogram's mission, goals, strategies, activities, and outputs to ascertain program logic.

As for many federal civilian applied research programs, knowledge embodied in patents and publications are important explicit outputs of ACE R&D. The study's primary analysis tools—bibliometric methods, namely patent and publication analyses—offer the advantage of enabling an objective, quantitative analysis of prominent, explicit outputs of ACE R&D. When looking for connections between knowledge creation in an applied research program and downstream commercial developments, patents are of particular interest because they are considered close to commercial application. Patent citation analysis has been used extensively in other studies of technological change.

Backward patent tracing is used by the study to assess the extent of linkage of combustion innovations by companies in the vehicle and engine industries back to ACE-funded research. Forward patent tracing is used to assess the broader downstream influence of ACE-funded research. Both the backward and forward patent tracing are performed at two levels: (1) the organizational level, and (2) the individual patent level. These dual tracing approaches both provide a comparative assessment of ACE R&D's influence relative to that of other organizations, and identify particularly noteworthy inventions.

Publications are also of interest as knowledge outputs of ACE R&D and as a mechanism linking the research to downstream developments in vehicle engines, and possibly to other areas. Analyses of authorship/co-authorship reveal collaboration on publications as a means of research dissemination, and analyses of publication citations reveal who was accessing the publications, when, and to what extent.

Other important outputs of ACE R&D include models and computer code; test data; research tools; research prototypes; trained technologists; and stimulation of interest, innovation, and understanding by others in the field of advanced combustion. To some extent, these outputs are reflected in the outputs of patents and publications (such as user manuals accompanying models and computer code, publications on test data, and contractor reports accompanying prototype development). However, some are tacit knowledge outputs, such as those embodied in humans (human capital). Tacit knowledge outputs are both extremely important and difficult to capture in evaluation metrics. These outputs are explored using document/database review and, to a limited extent, interview with DOE staff.

Findings

ACE R&D has generated a knowledge base that has supported advances in clean-burning, efficient engines—including heavy-duty diesel engines, and further advances in spectrometry, a technique used in materials analysis.

An overview of patenting in engine combustion revealed the following:

- Among the knowledge outputs of ACE R&D over the period 1975 to early 2009 are 109 patent families (i.e., groups of patents based on the same invention) containing a total of 166 individual patents (127 U.S. patents, 14 European Patent Office (EPO) patents, and 25 patent applications filed with the World Intellectual Property Organization (WIPO))—with most of these filed since 1999.
- These 109 DOE-attributed advanced combustion patent families are assigned to multiple organizations, including DOE national laboratories, universities, and companies.
- In comparison, 22,103 patent families related to combustion technology were identified as assigned to 10 vehicle and engine companies with the most patents in engine combustion from 1974 through 2008 (referred to in the study as "the 10 leading innovative companies"). The 10 companies are Ford, General Motors, Chrysler (Daimler-Chrysler during part of the period covered), Toyota, Honda, Nissan, Caterpillar, Delphi, Denso, and Fiat.
- The 109 DOE-attributed patent set represents less than 1% of the total number of combustion patent families of the 10 leading companies.
- ACE R&D was aimed at overcoming specific persistent and challenging technical barriers within a mature industry. The solution required special facilities and concentrated R&D to advance the understanding of in-engine combustion processes. The result has been a small, recent, and rapidly developing and highly focused DOE-attributed patent portfolio in advanced combustion technology.
- The 10 leading innovative vehicle and engine companies have filed most of their priority patents in the United States, followed by Japan.

The study's backward patent tracing at the organizational level revealed that the patents of the leading innovative vehicle and engine companies traced back relatively strongly to the earlier DOE advanced combustion patents.

Findings from the backward patent citation analysis include the following:

- Many combustion patents of the leading innovative vehicle and engine companies link back to earlier DOE advanced combustion patent families (This analysis compared average citations per patent of DOE since 1999 with those of the 10 leading innovative companies over the same period.)
- Caterpillar, Ford, and Chrysler are three leading innovative vehicle and engine companies whose combustion patent portfolios have built particularly extensively on the DOE-funded advanced combustion research.

The study's forward patent tracing at the organizational level showed that DOE advanced combustion patents were linked not only to combustion patents of the 10 leading innovative vehicle and engine companies, but also to combustion patents of other companies, and to non-combustion patents of organizations in other fields.

These conclusions were supported by the following findings:

- The DOE-attributed combustion patents are connected through citations to engine combustion technologies developed by other important vehicle and engine companies (not among the 10 vehicle and engine companies with the most patents in combustion) including Cummins, Bosch, and Hitachi.
- Three organizations outside the vehicle and engine fields—Thermo Electron Corporation, Sionex Corporation, and Charles Stark Draper Laboratory—all have ion moblity spectrometry patents linked to a non-combustion technology developed at SNL and Lawrence Livermore National Laboratory (LLNL) as a tool for in-engine research.
- The most dominant areas of influence of the DOE-attributed advanced combustion patents, identified using the International Patent Classifications (IPCs), are "internal combustion engines", "engine fuel supply", and "engine exhaust apparatus." "Separation of materials" is another area of influence.

Over a relatively short period (1986-2008) DOE funded the development of more than a dozen high-impact combustion technologies. Furthermore, multiple high-impact technologies developed by others are linked to earlier DOE-funded advanced combustion research.

The most noteworthy patents include the following:

- DOE-attributed "advanced combustion" patent families describing improved fuel injection techniques, cylinder-to-cylinder balancing, Homogeneous Charge Compression Ignition (HCCI), Exhaust Gas Recirculation (EGR), and other methods of engine control and exhaust emissions reduction are deemed influential due to their linkages to large numbers of subsequent combustion patent families of the 10 leading vehicle and engine companies.
- DOE-attributed "other" patent families describing a method for allowing multiple fuels to be supplied to an engine, and "staged direct fuel injection for diesel engines" are also considered influential due to their linkages to large numbers of subsequent combustion patent families of leading companies.
- A General Motors patent describing fuel injection for spark-ignited direct injection engines; several very recent Caterpillar patents describing various advanced combustion engine techniques; and a Ford patent describing methods for reducing NO_x emissions are noteworthy for being among those with the most citation links back to DOE-attributed combustion patent families.
- A Ford patent describing a method for transitioning between HCCI and spark ignition operation; patents assigned to Toyota, Ford, Chrysler, and Caterpillar describing EGR technologies; a patent assigned to Toyota describing a fuel injection system enabling the use of lower octane fuel; and a patent assigned to Nissan describing variable valve control for combustion engines are noteworthy because they are highly cited combustion patent families that are linked to earlier DOE-attributed combustion patent families.

- Engine and combustion patents owned by Hitachi and by Cummins; and spectrometry patents owned by the National Research Council of Canada, by Draper Labs, and by Thermo Electron are noteworthy as highly cited patents of non-vehicle/non-engine organizations that are linked to earlier DOE-attributed advanced combustion patent families.
- Also noteworthy are the following highly cited DOE-attributed patents resulting from ACE R&D: a patent developed by LLNL and assigned to the University of California describing an HCCI engine; patents assigned to Caterpillar describing a fuel injection technique and an exhaust catalyst specifically designed for use with lean burn engines; an ion mobility spectrometry patent assigned to SNL; two patents developed by Argonne National Laboratory and assigned to the University of Chicago describing a method for decreasing emissions by introducing oxygen or nitrogen into the engine intake; and patents assigned to Lockheed Martin describing additives for diesel fuel designed to reduce emissions and methods for removing particulates from fuel injectors.

Of the DOE-contributed publications in advanced combustion topics, 112 were identified by performing a search of advanced combustion-related keywords using the DOE Office of Scientific and Technical Information (OSTI) database.

Findings from the analysis of these publications include the following:

- The KIVA Code has received extensive citing. This multi-dimensional model and computer code, developed by researchers at Los Alamos National Laboratory, is used to provide 3D simulation of the in-cylinder processes of an advanced diesel engine.
- In addition to multiple citations of DOE KIVA-related publications by companies active in engine design and manufacture, citations by other organizations indicate the use of the KIVA Code in studies of fluid-particle interaction defined more broadly, and even for modeling medical bio-sprays for upper airways of humans.

DOE-funded R&D in advanced combustion is disseminated directly to automotive engineers working in commercial applications.

Findings, based on a focused search of publications of the Society of Automotive Engineers International (SAE) include the following:

- Contributions by DOE national laboratory researchers in advanced combustion accounted for about 10% of the papers appearing in the two series of SAE special publications examined, as well as in two recent issues of a relevant SAE journal.
- Analysis of the affiliations of those citing the DOE-contributed SAE papers showed that the results of DOE combustion research are reaching companies, and also universities, government laboratories, and a variety of applied institutions, such as national and state environmental and health offices.

In addition to its explicit knowledge outputs such as patents, publications, models and code, research prototypes, and test data, ACE R&D has contributed to more-difficult-to-quantify tacit knowledge in the field of advanced combustion research.

- The R&D partnerships and Cooperative Research and Development Agreements (CRADAs) with companies established by ACE R&D have resulted in numerous interactions – formal and informal – between ACE R&D researchers and those in vehicle and engine companies.
- The Program's funding of combustion research, particularly the funding of special university centers for combustion research, has created group of trained technologists in the field.
- ACE R&D has fostered the development of an informal R&D network in the field of advanced combustion through which researchers from various sectors and organizations are working toward efficient, clean-burning vehicle engines.

1. Introduction

This report uses bibliometric analysis, supported by interview and document and database review, to trace linkages from knowledge outputs of the U.S. Department of Energy's (DOE) combustion engine research to downstream innovations in vehicle engines and other areas of application. The analysis covers the period from 1974 through 2008 (and in some cases to early 2009).[1]

DOE conducts research and development (R&D) to increase the engine combustion efficiency of passenger and commercial vehicles, while also reducing emissions. Within DOE's Office of Energy Efficiency and Renewable Energy (EERE) this function is carried out by the Vehicle Technologies Program's Advanced Combustion Engine Research and Development Subprogram (ACE R&D). Within DOE's Office of Science, there is the support of special facilities at the Sandia National Laboratories' Combustion Research Facility (CRF) used to conduct combustion research. DOE's combustion engine research is a cooperative effort by ACE R&D and CRF.

It was recognized in the 1970s that a better understanding of the fundamentals of in-engine combustion processes was required to make substantial improvements in combustion efficiency. This in turn would require mounting a comprehensive, long-term combustion engine R&D program, and the development of special facilities in which to conduct combustion diagnostic experiments and validate models. It would also require the development of state-of-the art research tools. To that end, the Combustion Research Facility (CRF) was established in 1978, at Sandia National Laboratories (SNL) in Livermore, California, by the DOE Office of Basic Energy Sciences (now the DOE Office of Science). CRF operations began in 1981, with the goal of developing advanced diagnostic systems for combustion applications.

DOE began active R&D on vehicle technologies in 1976, as authorized by Congress through the Electric and Hybrid Vehicle Research, Development, and Demonstration Act (Public Law 94-413).[2,3] In 2001 the Vehicle Technologies Program (VTP) was created within EERE, and ACE R&D became the part of VTP to carry forward applied advanced combustion engine research. Thus, the ACE R&D effort began with attention to fundamental combustion research, and later, when the fundamentals were better understood and enabling research technologies had been developed, the effort expanded to applied combustion research.

This joint research effort of ACE R&D and CRF has increased understanding of engine combustion processes and resulted in a number of knowledge outputs. Hereafter, for ease of exposition, reference to the DOE cooperative research effort is referenced simply as "ACE R&D."

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[1] A series of federal responses were made to the oil embargo in the early 1970s, including establishment of the Energy Research and Development Administration (ERDA) in 1974, and, in 1977, creation of DOE, and transfer of ERDA's mission to DOE. EERE was formed in 2001, and its predecessor, the Office of Conservation and Solar Energy, was created in 1978.

[2] Link (2010), p. ES-2.

[3] Ibid.

This study examines how the outputs of ACE R&D have moved to downstream technical and commercial advances in combustion engines and beyond. The study uses bibliometric methods to trace from the explicit ACE R&D outputs of patents and publications to downstream innovations in engine performance and to other developments. Bibliometric methods are supplemented by other methods to extend the assessment to a limited extent to other important ACE R&D knowledge outputs, such as computer codes, laboratory prototypes, and human capital. The study is responsive to both congressional and administrative directives for evaluation of federal programs. It also serves the needs of DOE program managers and other stakeholders.

Comparisons of the creation and dissemination of DOE's outputs in the field with those of other organizations help to assess the role DOE has played in advancing engine combustion. Moreover, documenting these linkages has lent support to a parallel benefit-cost study (Link 2010), by documenting evidence of attribution of benefits to DOE. The parallel benefit-cost study, which was retrospective through 2007, found that DOE investments in ACE R&D have yielded dollar benefits much greater than expenditures, taking into account only a portion of the benefits, but all of the costs.[4]

1.1 Background: DOE's Advanced Combustion Engine Research and Development Subprogram (ACE R&D)[5]

The ACE R&D in the Office of Energy Efficiency and Renewable Energy (EERE) is one of eight Subprograms that make up VTP.

EERE's ACE R&D encompasses the following four research areas:

1. Laser Diagnostic and Optical Engine Technologies
2. Combustion Modeling
3. Emission Control Technologies
4. Solid State Energy Conversion

Through its four research areas and specific strategies, ACE R&D aims to improve the fuel economy of passenger vehicles (cars and light trucks) and commercial vehicles (medium-duty

[4] Link (2010) found net present value benefits of $23.1 billion and a benefit-to-cost ratio of 53 to 1. These results are based on use of a 7% discount rate, total costs of the ACE R&D Subprogram and cooperative use of CRF resources between 1986 and 2007, and benefits of just two of four research areas over the same period, namely (1) laser diagnostic and optical engine technologies and (2) combustion modeling for heavy-duty diesel engines. The internal rate of return was 63%.

[5] This overview is based on DOE program information found at DOE's EERE, VTP, and ACE R&D websites as of late 2010, including a brochure on the ACE R&D Subprogram, and DOE annual reports. It should be noted that future reorganizations may change the number and names of programs, subprograms, and research areas.

and commercial trucks) by increasing the efficiency of their engines, while also reducing the emissions they generate.

The ACE R&D in EERE employs collaborative partnerships with vehicle and engine manufacturers, suppliers, national laboratories, and universities. It works under the umbrella of broader federal initiatives for improvements in vehicle transportation, such as the FreedomCAR and Fuels Partnership for passenger vehicle applications and the 21st Century Truck Partnership for commercial vehicle applications, both established in the early 2000s. These collaborative relationships are depicted in Figure 5-1.

The focus on improving internal combustion engines reflects the fact that these engines are expected to continue to dominate the passenger and commercial vehicle markets for years to come—both used alone and in combination with electric engines in hybrid and plug-in hybrid vehicles. More than 230 million cars and light trucks consume three quarters of U.S. highway transportation fuel, most of which is gasoline. Moreover, though they account for fewer than 5% of highway vehicles, medium-duty and commercial vehicles consume a quarter of the fuel used. Although the internal combustion engine is a mature technology, it offers opportunities for additional major improvements in energy efficiency and emissions reductions. It is thought that by incorporating the latest advanced technologies into internal combustion engines, the United States can cut its transportation fuel use by 20-40%, other factors being the same.[6]

Figure 1-1 shows a timeline of selected developments in the history of DOE's combustion research efforts from 1973/74 to 2009. Table 1-1 shows annual appropriations for EERE's ACE R&D and CRF used to carry out DOE research in advanced combustion from 1986 through 2008, the period for which cost data for both ACE R&D in EERE and CRF are available.[7] The combined annual appropriations for the ACE R&D Subprogram and CRF research totaled $981 million (in inflation adjusted, but undiscounted, 2008 dollars). A step-up in funding for ACE R&D is apparent beginning in 1999.

1.2 Report Organization

The report is presented in an executive summary, five chapters, and two appendices.

Chapter 2 provides an overview of the bibliometric evaluation methodology. It explains why patent analysis is particularly effective for tracing knowledge outputs from a federal civilian applied research program to its downstream applications.

Chapter 3 presents the results of a patent analysis. Appendix A supplements Chapter 3 with details on construction of key patent data needed for the analysis, and Appendix B lists the individual DOE-attributed patents used in the study.

[6]DOE/EERE/Vehicle Technologies Program, "Advancing New Vehicle Technologies and Fuels," www.eere.energy.gov/library/pdfs/48096_eere_vehicles_fsr3.pdf.
[7]Link (2010), p. 3-4. Note that the CRF was established in 1978 and became operational in 1981, and energy R&D on vehicle technologies began in 1976.

Chapter 4 presents the results of a publication analysis. Several sets of publications are analyzed.

Chapter 5 depicts relationships among DOE and other organizations that have been instrumental in DOE's creation and dissemination of advanced combustion outputs.

A list of references concludes the report.

Figure 1-1. Timeline of Select Notable Events in the History of DOE's Advanced Combustion Research Efforts

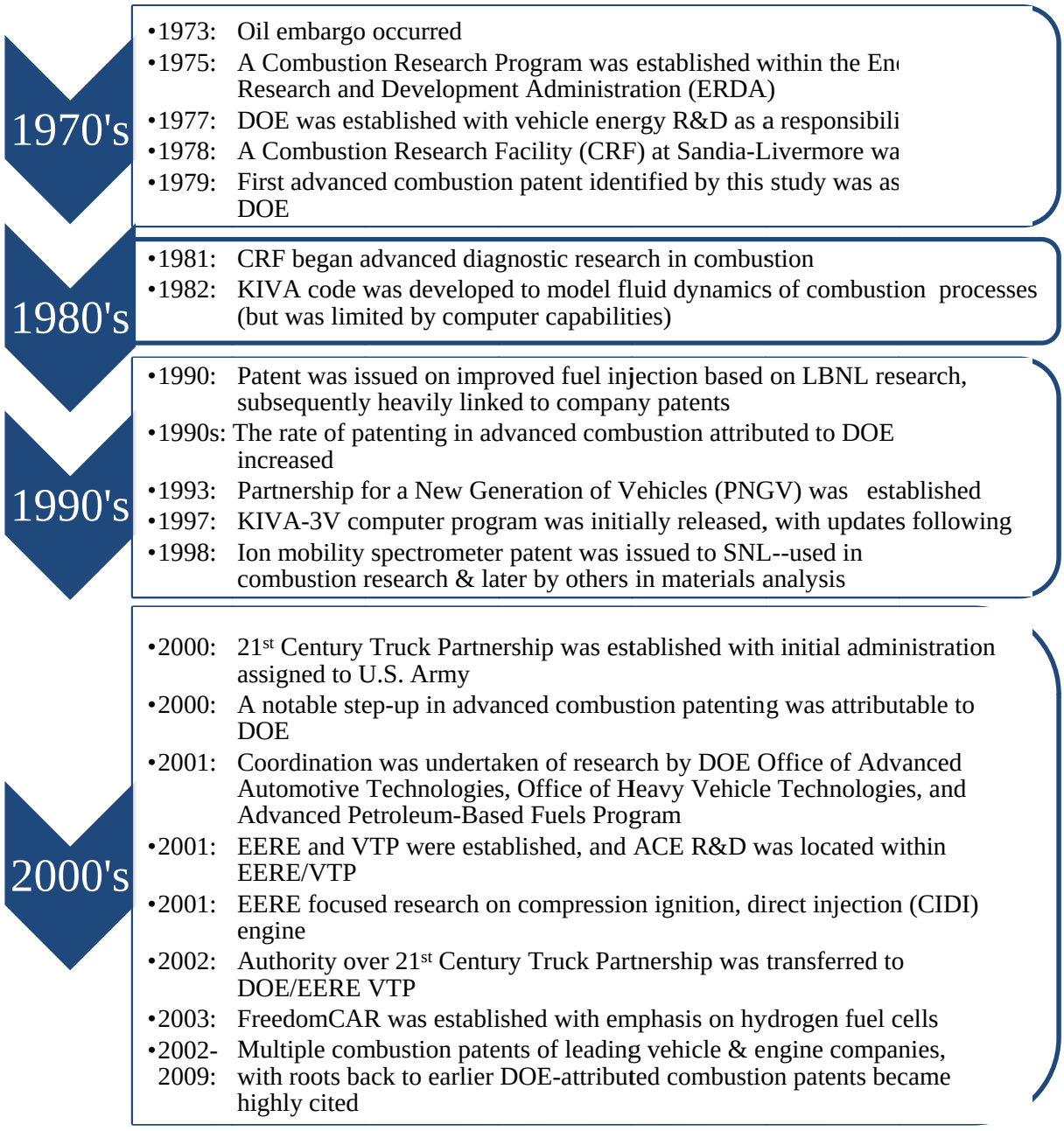


Table 1-1. Annual Appropriations for ACE R&D and the CRF

Year	ACE R&D Subprogram Budget (millions $2008)	Office of Science Budgets for Cross-Cutting Combustion Research within the CRF (millions $2008)	Total (millions $2008)
1986	$27.402	$5.602	$33.004
1987	$29.005	$5.930	$34.935
1988	$27.785	$5.680	$33.465
1989	$26.525	$5.423	$31.948
1990	$25.929	$5.588	$31.517
1991	$22.869	$6.240	$29.109
1992	$23.611	$6.223	$29.834
1993	$20.550	$6.073	$26.623
1994	$17.587	$5.665	$23.252
1995	$13.890	$5.549	$19.439
1996	$21.574	$6.154	$27.728
1997	$24.714	$6.743	$31.457
1998	$23.239	$6.547	$29.786
1999	$46.230	$6.281	$52.511
2000	$57.211	$5.796	$63.007
2001	$62.475	$6.538	$69.013
2002	$55.538	$6.332	$61.870
2003	$63.714	$6.842	$70.556
2004	$59.119	$6.605	$65.724
2005	$52.593	$6.983	$59.576
2006	$42.649	$6.567	$49.216
2007	$49.379	$7.811	$57.190
2008	$43.443	$6.755	$50.198
Total	$837.031	$143.927	$980.958

Source: EERE-provided annual appropriation data as reported in Link (2010).
Note: CRF construction data for 1978-1980 are omitted because they were not available.

2. Study Methodology

The program logic of the ACE R&D Subprogram in EERE informed the structuring of the evaluation study by positing goals of the Subprogram, how it was expected to work, and its intended outputs and outcomes. After establishing this background, a series of evaluative questions were formulated to be addressed by the study. Table 2-1 lists the set of questions and matches each question with the specific evaluation approach used by the study to address it.

Table 2-1. Study Questions and Evaluation Methods Used to Address Them

Study Question	Method Used
Did the results of ACE R&D reach a downstream audience well positioned to take the research results into commercial development?	Bibliometrics: Backward patent tracing from combustion patents of vehicle and engine companies leading in combustion innovation.
How does the influence of the body of ACE R&D patents compare with that of others in the field?	Bibliometrics: Comparing organizations based on the extent of citing of their bodies of combustion engine patents by others.
Which ACE R&D-attributed patents have had notable influence on subsequent combustion innovations?	Bibliometrics: Backward patent tracing at the individual patent level.
Which combustion patents of vehicle and engine companies have the most citation links back to ACE R&D-attributed patents?	Bibliometrics: Backward patent tracing at the individual patent level.
What high-impact patents of vehicle and engine companies have links back to ACE R&D-attributed patents?	Bibliometrics: Backward patent tracing at the individual patent level.
Are there indications of influence of ACE R&D research results extending beyond vehicle and engine companies?	Bibliometrics: Forward patent tracing.
What have been the principal downstream innovations in all fields and by all organizations linked to ACE R&D?	Bibliometrics: Forward patent tracing at the individual patent level.
To what extent have co-authoring and citing of ACE R&D publications provided paths of knowledge dissemination?	Bibliometrics: Analysis of publication authoring/co-authoring and citations, based on publication samples.
What other modes of transferring the results of ACE R&D to others were found?	Document and database review and interview.

The bibliometric methods of patent and publication citation analyses featured in the study's evaluation are among multiple evaluation methods[8] that are useful for assessing R&D programs. These methods are particularly applicable to tracing the dissemination of outputs of civilian research programs, such as ACE R&D, because patents and publications tend to be among the outputs of these programs. Bibliometric evaluation methods provide objectively derived, quantitative measures of knowledge creation and dissemination. They help to identify the extent to which patents and publications are used, by whom, and for what. Because patent and publication outputs are generally a principal mechanism by which further downstream developments of applied research programs are enabled and program goals accomplished, bibliometric evaluation approaches enable one to address the larger question: "Are the resulting outputs being accessed by those positioned to take them into intended downstream application?"—i.e., is there evidence that the program/sub-program is linked to desired outcomes? It also enables one to address the more specific questions listed in Table 2-1.

Thus, the methodological focus of this study is straightforward: the influence of patents and publications resulting from ACE R&D funding is assessed. The assessment includes patents directly assigned to DOE and the laboratories, and those deemed attributable to ACE R&D funding but assigned to companies and universities and other organizations. The publication analysis includes co-authoring analysis and citation analysis, and is applied to a sample of DOE conference and technical reports in advanced combustion, as well as to a sample of publications contributed by DOE researchers to industry publications.

The study also acknowledges and provides a brief treatment of outputs other than patents and publications from ACE R&D. These include models and computer software, test data, demonstrations, and prototypes, as well as tacit forms of knowledge such as human capital gains.

2.1 Why Emphasize Patent Analysis?

Patents are of particular interest in tracing from outputs of an applied research program, such as ACE R&D, to downstream innovations and commercialized technologies, because patents are considered close to application. The use of patents as indicators of invention, and patent citation analysis as indicative of technology diffusion reflects a central role of patents in the innovation system. Indeed, patent citation analysis has been used extensively in the study of technological change.[9]

A patent discloses to society how an invention is practiced, in return for the right during a limited period of time to exclude others from using the patented invention without the patent assignee's permission. The front page of a patent document contains a list of references to "prior art." Prior

[8] For a directory of evaluation methods commonly used for evaluating R&D programs and illustrations of their uses, see Ruegg and Jordan (2008).

[9] For an account of the usefulness of patents and citations data as a window on the process of technological change and the "knowledge economy," and as a research tool for tracing links across inventions, see Jaffe and Trajtenberg (2005).

art in patent law refers to all information that previously has been made available publicly that might be relevant to a patent's claim of originality and, hence, its validity. Prior art may be in the form of previous patents, or published items such as scientific papers, technical disclosures, trade magazines, and other forms of relevant information.

Patent citation analysis is based on the idea that the prior art referenced by a patent has had some influence on the development of that later patent. The prior art is thus regarded as part of the foundation for the later development. In the patent analysis presented in this report, the idea is that the downstream technologies represented by patents that cite earlier ACE R&D-attributed patents have built in some way on the knowledge base generated by DOE-funded R&D.

An additional premise of the study is that highly cited patents (i.e., patents cited by many later patents) tend to contain technological information of particular importance. A patent that forms the basis for many new innovations tends to be cited frequently by later patents. Although it is not true to say that every highly cited patent is important, or that every infrequently cited patent is unimportant, research studies have shown a correlation between the rate of citations of a patent and its technological importance.[10]

Patent analysis has been employed in other studies of the historical linkages from research funded by DOE/EERE programs/subprograms to downstream technological developments. These include studies of energy storage for vehicles, wind energy, geothermal energy, and solar photovoltaic energy.[11]

2.2 Forward and Backward Patent Tracing

Two main approaches to patent analysis are used in this study—forward patent tracing and backward patent tracing. Forward patent tracing takes a broad look at downstream linkages of a starting group of DOE-attributed patents. Backward patent tracing focuses specifically on linkages from patents of targeted industry groups back to patents attributable to DOE.

2.2.1 Forward Patent Tracing

The idea of forward tracing is to take a given body of research, and to trace the influence of this research upon subsequent technological developments. In the context of the current analysis, forward patent tracing starts by identifying all advanced combustion patent families resulting from ACE R&D. The influence of these patent families on subsequent generations of technologies as revealed by citations is then assessed. This tracing is not restricted to later combustion patents. In recognition that the influence of a body of research may extend beyond its immediate targeted technology area(s), the forward patent tracing element of this project

[10] For background on the use of patent citation analysis to identify important technological information , including a summary of validation studies supporting the use of patent citation analysis, see Breitzman and Mogee (1999) and Chapter 3 of Thomas (1999).

[11] See Ruegg and Thomas (2008, 2009, 2010A, and 2010B) for other historical tracing studies of DOE's energy efficiency and renewable energy programs and subprograms.

determines the broader influence of DOE-funded advanced combustion patents on combustion technology and on all other technologies.

2.2.2 Backward Patent Tracing

The idea of backward tracing is to start with the downstream intended (targeted) area of ACE R&D, and determine if this area did, in fact, build on the earlier DOE-attributed advanced combustion patents. In the context of this project, the idea of backward patent tracing is to trace back from combustion patent families owned by the leading innovative vehicle and engine companies to assess the extent to which they link back to the DOE-attributed advanced combustion patents. (See Section 2.5 for an explanation of how the leading innovative companies were identified.)

By tracing from combustion patent families of leading innovative vehicle and engine companies back to the set of DOE-attributed advanced combustion patent families, it is possible to determine the extent to which later company innovations built on the earlier DOE-funded research. Furthermore, comparing the extent of the linkage of these companies' combustion patent families to earlier DOE-attributed combustion patent families, versus the linkages back to other organizations, provides an indication of the relative importance of DOE in establishing a knowledge base in engine combustion on which other organizations have built.

2.3 Extensions of the Analysis

The simplest form of U.S. patent tracing is based on a single generation of citation links between U.S. patents. Such a study identifies U.S. patents that cite, or are cited by, a given set of U.S. patents as prior art. This study extends the patent analysis in three ways: (1) it adds a second generation of citation links; (2) it searches for citations beyond the U.S. Patent System; and (3) it organizes patents into patent families to avoid counting the same invention multiple times.

2.3.1 Tracing Multiple Generations of Citation Links

The analysis adds a second generation of citation links. This means that the study traces forward through two generations of citations, starting from DOE-attributed combustion patents, and backward through two generations starting from the combustion patents of leading innovative vehicle and engine companies.

The idea behind adding this second generation of citations is that federal agencies such as DOE often support scientific research that is more basic than applied. It may take time and multiple generations of patents for the results of this more basic research to be used in an applied technology. The impact of the more basic research may not therefore be reflected in a study based on referencing a single generation of prior art. Introducing a second generation of citations provides greater access to the indirect links between basic and applied research and technology development.

That said, adding additional generations may bring in patents with little connection to the starting set, and, hence, should be limited. A potential problem with continuing to add generations of citations is a problem common to many networks, whether these networks consist of people, institutions, or scientific documents, as in this case. This problem is that, if one uses enough generations of links, eventually almost every node in the network will be linked. The most famous example of this is the idea that every person is within six links of any other person in the world. By the same logic, if one takes a starting set of patents, and extends the network of prior art references far enough, eventually almost all earlier patents will be linked to this starting set. Based on previous experience, using two generations of citation links is appropriate for tracing studies such as this. Adding any further generations may bring in too many patents with little connection to the starting patent sets.

2.3.2 Extending the Analysis beyond the U.S. Patent System

This study extends the analysis by looking beyond the U.S. patent system. It includes patents from the European Patent Office (EPO) and patent applications filed with the World Intellectual Property Organization (WIPO). The analysis thus allows for a wide variety of possible linkages between DOE-funded advanced combustion research and subsequent technological developments in and outside of the United States.

2.3.3 Constructing Patent Families based on the "Priority Application"

Because organizations often file for protection of their inventions across multiple patent systems, and also may apply for a series of patents in the same country based on the same underlying invention, there may be multiple patent documents for the same invention. In the case of this project, for example, one or more U.S., EPO, and WIPO patents resulted from a single invention.

To avoid counting the same invention multiple times, it is necessary to construct patent families. A patent family contains all of the patents, patent applications, continuations, and divisionals that result from the same original patent application (which is the "priority document"). A patent family may include patents/applications from multiple countries, and also multiple patents/applications from the same country.

The priority document need not necessarily be a U.S., EPO, or WIPO application. For example, a Japanese patent application may result in U.S., EPO, and WIPO patents/applications, which are grouped in the same patent family because they share the same Japanese priority document.

To construct patent families, fuzzy matching algorithms were used, along with a small amount of manual matching. The study constructed combustion patent families for patents attributed to DOE, combustion patent families for the leading innovative vehicle and engine companies, and also patent families for all of the patents linked through citations to DOE.

2.4 Constructing a Data Set of DOE-Attributed Advanced Combustion Patent Families

A data set of DOE-attributed advanced combustion patent families is needed as the starting point of the forward tracing analysis. It is also needed as the end point for the backward tracing analysis. This data-construction step is described here and in Appendix A-I, and the resulting list of patents is provided in Appendix B.

2.4.1 Challenges to Constructing the Data Set

With adequate record keeping in support of evaluation, a database of DOE-attributed combustion patents would be available to begin the forward tracing analysis. However, if complete records are unavailable—as in this case—the analysis must supplement and validate the data set of DOE-attributable patents, prior to grouping them into patent families.

Identifying these patents tends to be more difficult than identifying patents funded by companies. When a company funds internal research, any patented inventions emerging from this research are likely to be assigned to the company itself. To construct a patent set for a company, one simply has to identify all patents assigned to the company, along with all of its subsidiaries, acquisitions, etc.

In contrast, a federal agency such as DOE may fund research in a variety of organizations. For example, DOE funds a number of laboratories and research centers. Patents emerging from these laboratories and research centers may be assigned to DOE, or they may be assigned to the organization that manages the laboratories or research centers. For example, patents from SNL may be assigned to Lockheed Martin, while Lawrence Livermore National Laboratory (LLNL) patents may be assigned to the University of California. A further complication is that DOE not only funds research in these laboratories and research centers. It also funds research carried out by private companies, universities, and other organizations. When this research results in patented inventions, these patents are usually assigned to the company, university, or other organization carrying out the research, rather than to DOE. At the time of the research, all parties involved—the company, university, and government research coordinator—likely know that the patents result at least in part from DOE-funded research. But with the passage of time, awareness of this connection may be lost unless formally recorded.

2.4.2 Identifying the Population of All DOE-Attributable Patents

To identify patents resulting from DOE-funded advanced combustion research, the study started with the following data sources to identify the larger population of DOE-funded patents:

(1) OSTI Database—the first source used was a database provided by DOE's Office of Scientific & Technical Information (OSTI) for use in DOE-related projects. This database contains information on research grants provided by DOE since its inception. It also links these grants to the organizations or DOE centers carrying out the research, the sponsor organization within DOE, and the U.S. patents that resulted from these DOE grants.

(2) Patents assigned to DOE—the study identified a number of U.S. patents assigned to DOE that were not in the OSTI database because they have been issued since the latest version of that database. These patents were added to the list of DOE-attributed patents.

(3) Patents with DOE Government Interest—a U.S. patent has on its front page a section entitled 'Government Interest' that details the rights that the government has in a particular invention. The study identified all patents that refer to 'Department of Energy' or 'DOE' in their Government Interest field, along with patents that refer to government contracts beginning with DE- or ENG-, since these abbreviations denote DOE grants. Patents in this set that were not already in the OSTI database, and were not assigned to DOE, were added to the list of DOE-attributed patents.

The DOE patent database constructed from these three sources contains a total of 19,642 US patents issued between January 1976 and March 2009.

2.4.3 Identifying DOE-Attributed Patent Families Related to Combustion

The next step was to identify candidate DOE-attributed patents that are related to combustion from the larger population. A candidate list was developed by applying a patent filter to the larger population and by reviewing DOE annual reviews. The candidate list was narrowed by review by DOE experts to those resulting from DOE-funded research. Any equivalent patents resulting from the same inventions were identified and patent families constructed.

Identifying DOE-Attributed Combustion Patents by Applying a Filter: The study constructed and applied a patent filter to search within the above generated population database to identify candidate DOE-attributed patents related to advanced combustion. As a starting point for the filter, the study identified a set of U.S. Patent Office Classifications (POCs) and International Patent Classifications (IPCs) related to engine combustion. The search was restricted to patents in these IPCs and POCs. Restricting the search by patent classification reduces the chance of including irrelevant patents that use the same terms, especially the same acronyms. For example, EGR is not only used as an acronym for exhaust gas recirculation, it is also used for terms such as early growth response and enhanced gas recovery. Both broad IPCs and POCs that relate to combustion technology in general, and specific IPCs and POCs that relate to combustion technologies of particular interest were used in the patent filter. DOE patents in the specific IPCs and POCs were considered for inclusion in the analysis without any keyword restriction. However, patents in the broad IPCs and POCs had to use at least one of a list of keywords or phrases to be considered for inclusion. The IPCs and POCs are listed in Appendix A, Table A-1, and keywords/phases are listed in Appendix A, Table A-2.

Identifying DOE-Attributed Combustion Patents Based on Document Review: In addition to using a patent filter, the study also identified candidate DOE-attributed patents related to advanced combustion patents by reviewing DOE annual reports. These reports detail the history of DOE funding in advanced combustion, and identify a number of specific advanced combustion patent filings as being funded by DOE. In some cases, actual patent numbers were provided in the reports, while in other cases, the information was incomplete, and had to be filled in by matching inventor names, titles, and filing dates based on the information provided. Patents

identified based on document review were added to the candidate set of DOE-attributed advanced combustion patents.

Narrowing the Candidate List by Expert DOE Review: The final step in identifying the list of DOE-attributed advanced combustion patents was to provide the list of candidate patents identified using the patent filter and document review to DOE experts for advice. These "experts" were DOE scientists and program managers in advanced combustion. They provided feedback as to which of the candidate patents should be included in the final set, which should be deleted, and whether any additional patents should be added. Many of the patents recommended for deletion were concerned with exhaust gas treatment, since this was considered to be beyond the scope of the analysis. At the request of program managers, the analysis focused on 'in-cylinder' combustion technologies. A total of 119 advanced combustion U.S. patents were attributed to DOE funding.

Identifying Patent Equivalents and Constructing Patent Families: An additional 18 U.S. patents were identified as being continuations, continuations-in-part, or divisionals of the 119 U.S. patents, for a total of 127 U.S. patents. An additional 14 EPO patents, and 25 WIPO patents were identified as related to the original 119 U.S. patents. Thus, a total of 166 advanced combustion patents, identified as DOE-attributed, were identified. These 166 patents were then grouped into 109 distinct patent families. A list of the individual patents can be found in Appendix B.

2.5 Constructing a Data Set of Leading Innovative Vehicle and Engine Companies and Their Combustion Patent Families

For the backward patent tracing element of the analysis, the study began by constructing a list of leading innovative vehicle and engine companies. Specifically, the study defined the leading innovative vehicle and engine manufacturers as those with the largest number of U.S. patents granted since 1992, including patents assigned to all company subsidiaries and acquisitions. It then took the top 10 such companies as a group of feasible size to use for the backward patent tracing analysis. The 10 companies are Honda, Denso, Toyota, Ford, General Motors, Daimler, Delphi, Nissan, Caterpillar, and Fiat. [12] These companies were considered most likely to adopt new engine inventions and to engage in further innovation based on those inventions.

A possible criticism for basing the list of companies on U.S. patents is that it may skew the analysis towards U.S. companies. However, more than half of the companies identified in this manner are non-U.S. based, with the three most prolific patenting companies being Japanese. This presence of foreign firms reflects the fact that large companies, irrespective of their locations, tend to patent extensively in the United States, due to the importance of protecting

[12] These companies are variously referred to hereafter as "10 leading innovative vehicle and engine companies" or simply "leading vehicle and engine companies." The selection is based on patent portfolio size, and is not a reflection of number of vehicles sold or revenues, profits, or other criteria. A fuller description would be "leading vehicle and engine companies in patenting," but this is a cumbersome description to use throughout. Hence, the shorter terms are used interchangeably with the longer term.

their inventions in this very large market. Hence, the analysis selection approach does not appear to introduce a significant bias toward U.S. companies.

The study then used a patent filter to identify all U.S., EPO, and WIPO combustion patents assigned to each of the ten companies. This filter was a modified version of the filter used to identify DOE-attributed advanced combustion patents (shown in Appendix A-I), and is described further in Appendix A-II. The modification was made because the backward tracing element of the study is designed to determine DOE's impact on all combustion technologies owned by leading companies, not just on specific advanced combustion technologies. For example, if a DOE-attributed patent describing an HCCI engine is cited by a subsequent Honda patent describing engine control, this link should be identified in the backward tracing analysis, even if the Honda patent does not make specific reference to a term such as HCCI. Again, patents were removed that used terms related to exhaust gas treatment (such as catalyst, particulate trap, and after-treatment) since, as noted above, patents describing these technologies were considered by DOE program managers to be beyond the scope of the desired analysis.

As a result of this process, the study identified 18,091 U.S. patents, 4,358 EPO patents, and 1,556 WIPO patents that are related to combustion technology and are owned by the 10 leading vehicle and engine companies. This set of all U.S., EPO, and WIPO combustion patents/applications owned by the leading vehicle and engine companies were then grouped into 22,103 patent families using the approach described earlier.

2.6 Publication Co-Authoring and Citation Analyses

As a major output of research organizations, publications are of interest as a linkage mechanism. In bibliometric theory, citations of scientific papers by other papers in a field are generally considered to acknowledge scientific and intellectual debts, whereas, citations of patents by other patents are taken to acknowledge technological debts, and citations of publications by patents are considered to acknowledge the intellectual debt of a technology to the science base on which it draws.[13] Thus, analysis of publications offers a supplementary approach to patent analysis for identifying linkages from DOE's advanced combustion research to downstream developments in and outside the area of vehicle engine combustion, particularly those by commercial firms.

Co-authoring of the publications by DOE researchers with researchers from other organizations may indicate collaboration and linkages of DOE researchers with those involved in downstream technology development, commercialization, and applications. Citations of publications resulting from DOE's advanced combustion research show paths of knowledge flow and suggest areas of influence.

The publication citation search is facilitated by the use of a publication citation database and search engine. For an extended period, the U.S.-based firm Thomson Scientific (formerly the Institute for Scientific Information [ISI]) was the principal entity facilitating publication citation analysis. However, today there are a growing number of publication citation databases and

[13] See Martin (2005), Chapter 4.

search tools, such as Scopus, CiteSeer, and Google Scholar, which provide comprehensive coverage beyond the major journals, including, for example, conference proceedings, book chapters, dissertations, and research reports.[14] For this study's publication-to-publication citation analysis, conference papers and research reports were prominent, and Google Scholar was used because it included these kinds of publications in its search capability.[15] A comparison of alternative publication search tools rated Google Scholar among the best.[16]

2.6.1 Identifying Two Sets of Publications for Analysis

A challenge to this part of the study was identifying DOE-attributed advanced combustion publications that were within scope, including DOE-funded papers that were published in industry publications, but not always included in DOE's database of publications. To this end, two sets of publications were separately identified and used in the study: (1) a set of DOE-sponsored publications on advanced combustion included in the DOE Office of Scientific and Technical Information (OSTI) database of DOE-sponsored publications and found by keyword search; and (2) a set of papers by DOE researchers included in combustion-related publications of the Society of Automotive Engineers (SAE).

OSTI-Drawn Set of Publications: The first set was drawn from the OSTI database of DOE-sponsored publications, using keywords designed to pick up only advanced combustion publications within scope of the analysis. A set of 112 DOE publications in advanced combustion was identified by this search. It is recognized that this number substantially understates the body of DOE publications in advanced combustion, because not all relevant publications contain the keywords in their titles or abstracts. At the same time, the approach had the advantage of likely identifying only publications within scope of the analysis. All of the publications in the OSTI-drawn set identified in this way are used in the analysis (after adjusting for duplicates).

SAE Papers Contributed by DOE Researchers: The second set of publications was identified by searching two special publication series and a SAE journal for contributions by DOE authors. The resulting set of SAE papers was developed in response to discussions with DOE researchers who emphasized the importance of publications of SAE and other industry organizations as effective routes of dissemination of DOE combustion research findings to industry. DOE researchers noted that these industry publications might be under-represented in the OSTI database.

It should be noted that the set of publications drawn from the OSTI database based on keywords was found to include nine DOE-contributed papers published in SAE publications, all with dates between 1998 and 2003. In contrast, the papers drawn directly from the SAE publications were more recent. The inclusion in the analysis of a set of papers specifically drawn from SAE

[14] Meho (2007) p. 32.
[15] Harzing & Wal (2008) also make the point that Google Scholar provides a more complete listing of publications beyond journals.
[16] Meho (2007), pp. 31-36, and Meho & Yang (2007).

publications is intended to highlight how industry publications disseminate DOE research papers directly to companies concerned with advances in engine combustion.

2.7 Study Limitations

Historical tracing can be expected to miss connections worthy of inclusion. Many factors go into producing a commercially successful innovation and not all of these factors will likely be captured even if multiple methods of tracing are used.

In historical tracing, documentation of linkages across time does not prove ultimate cause and effect; neither does it provide a dollar measure of the economic benefits of such linkages. Documentation of linkages between program outputs and downstream developments does, however, provide strong evidence of relationships and connections, and is a step toward establishing cause and effect.

Interview has limitations. For example, the person interviewed may not be aware of a connection, may not know the specifics, may believe a connection exists when it actually does not, and may have reasons to provide biased information. Significant events may be overlooked, forgotten, or misunderstood, especially if a long period of time has elapsed between the event and the interview. The number of interviews for this study was limited by resources and time. In any case, the results are generally anecdotal rather than statistical. Interviews with other experts and additional experts may have revealed different perspectives and information.

A review of documents, while useful for compiling supplemental evidence, is generally unreliable for developing a full picture of linkages. Some relevant events are reported in documents; some are not. Some documents are preserved; others are not. Available documents tend to provide only partial coverage of long and complex paths over which linkages occur.

While some databases are available, others that are needed may not be available. When some of the necessary data must be constructed after the fact, relying on historical documents and staff memory, there is the risk that relevant data may not be found or may be incorrectly remembered. An additional limitation is that some kinds of data tend to be confidential. For example, detailed information on licensing of patents by DOE may be restricted at the request of licensees. Some databases are too resource-intensive to construct, confidentiality issues notwithstanding. For example, relevant licensing data are dispersed among many companies that hold intellectual property based on research funded by DOE. Tracing such licensing activity among companies is resource intensive, in addition to entailing data that is typically considered proprietary and confidential. The study did not trace licensing activity despite this being a potentially important pathway of knowledge dissemination.

With respect to the patent and publication analyses, there are several limitations. One limitation is that not all knowledge outputs of significance are embodied in patents and publications. Furthermore, some of the DOE strategies for advancing technology and fostering markets are by their nature not reflected in patent or publication data. Flows of information along informal lines,

information transferred by reverse engineering, information that is placed in the public domain with access by all, information transfers that are held confidential, and tacit knowledge flows through the movement of people across organizations are among the research results not captured by patents and publications.

Other limitations are that not all patents and publications are equal; not all citations are equal; not all patents lead to commercial implementation; not all citations mean that a patent or publication was actually used; and not all patents and publications reveal their source(s) of support. Lack of comprehensive databases in support of evaluation may result in an understatement of the number of patents and publications identified as attributable to DOE-funded R&D. The publication citation analysis may suffer from citing errors due to imperfect citation search tools.[17] Self-citations, reciprocal citing by friends and colleagues, ceremonial citations whereby an author cites an authority in the field without actually consulting the relevant work, and negative citations used to point out incorrect results may also limit the usefulness of patent data.[18]

Using multiple tracing methods to produce multiple lines of evidence of linkages is a way to overcome the limitations of a single method. Linkages may be found by one method that are missed by others.

[17] Harzing (2008).
[18] Meho (2007), pp. 33-35.

3. Patent Analysis

This chapter uses patent analysis to trace linkages between DOE's advanced combustion R&D and subsequent developments in vehicle engine technology, as well as in other areas. First, for context, the chapter provides an overview of patenting in vehicle engine combustion. Next, the chapter examines issues of age and size of the DOE-attributed patent portfolio, how these issues are handled in the analysis, and their implications. It then presents the results of the backward and forward patent tracing.

Highlights of the patent analysis include the following: advanced combustion patent families attributed to DOE numbered 109, most of which were filed since 1999; and combustion patent families of the 10 most innovative vehicle and engine companies numbered 22,103. The relatively small number of DOE-attributed combustion patent families and recent average issue date is reflective of the fact that ACE R&D was aimed at overcoming specific persistent and challenging technical barriers within a mature industry.

The study's backward patent tracing found that combustion patenting of the 10 leading innovative companies built substantially on the set of earlier DOE-attributed advanced combustion patent families. An analysis of the leading companies' combustion patent portfolios revealed that the portfolios of Caterpillar, Ford, and Chrysler built particularly extensively on the DOE-funded advanced combustion research.

The study's forward patent tracing found linkages from the DOE-attributed patent families in combustion to related combustion technologies developed not only by the 10 leading innovative companies but also by other important companies in the field, including Cummins, Bosch, and Hitachi. Forward patent tracing also revealed linkages from DOE-funded advanced combustion research to company innovations in ion mobility spectrometry. The tracing of individual patents showed that over a relatively short period DOE funded the development of more than a dozen high-impact combustion technologies.

3.1 Overview of Patenting in Vehicle Engine Combustion

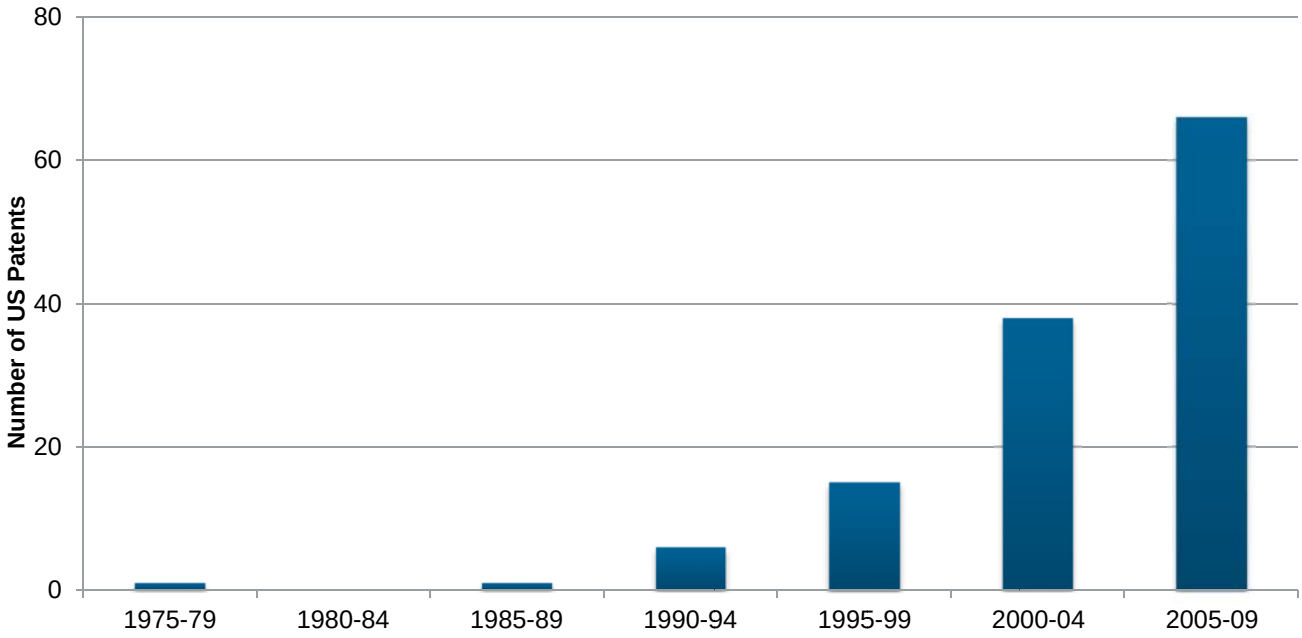
The overview of patenting is presented in three parts. The first is an overview of trends over time in U.S. combustion patenting in attributed to DOE. The second is an organizational comparison of combustion patenting. The third is a country comparison based on where the leading innovative companies filed their priority patents.

3.1.1 Trend in Advanced Combustion Patenting Attributed to DOE

Figure 3-1 shows the trend in U.S.-issued advanced combustion patents attributed to DOE funding, using 5-year intervals from 1975 through the first quarter of 2009. As the figure shows, there was low activity in the 1970s and 1980s, slightly more activity in the 1990s, and a dramatic increase in activity after the period ending in 1999. Indeed, more DOE-attributed U.S. advanced

combustion patents were granted in the five years between 2005 and early 2009 than were granted in the previous 30 years.

Figure 3-1. Number of U.S.-Issued Advanced Combustion Patents Attributed to DOE, 1975-early 2009

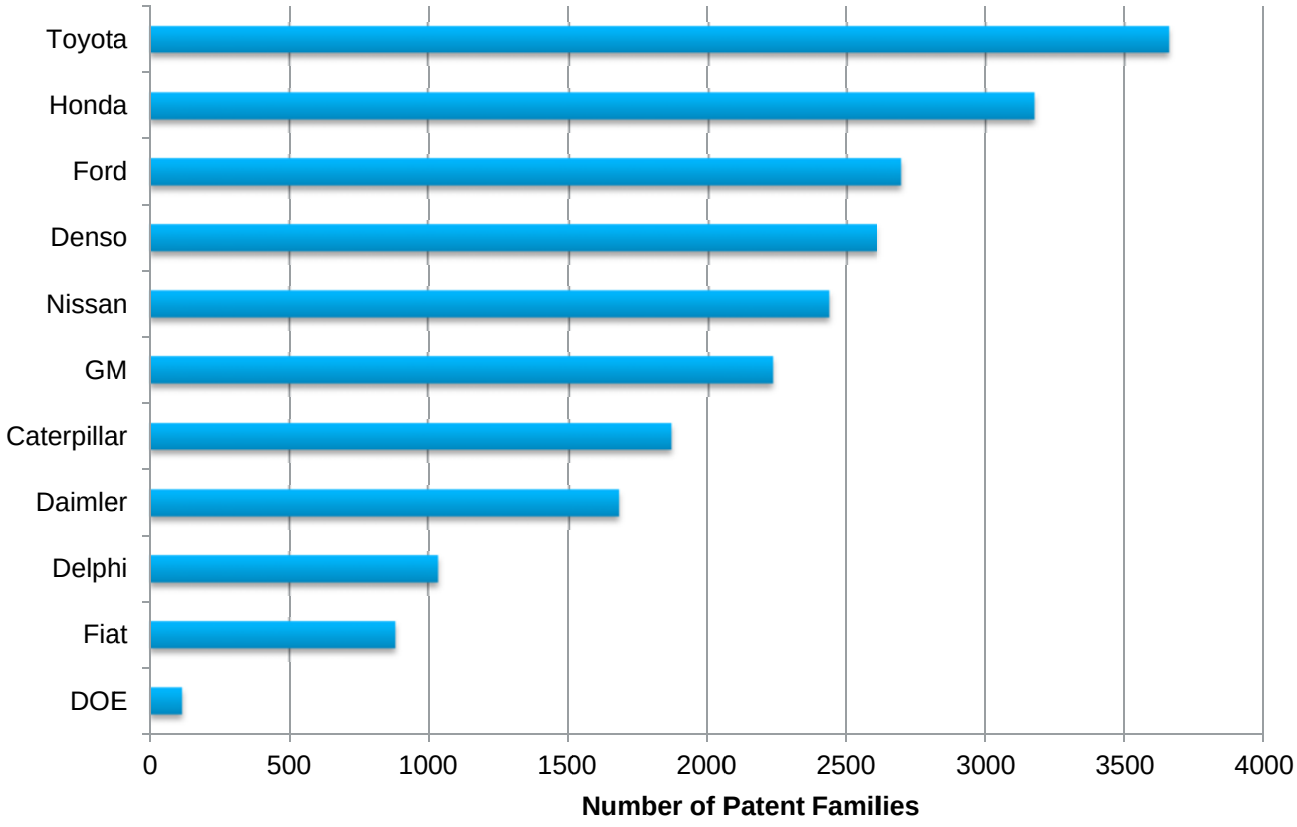


Note: the data extend through the first quarter of 2009.

3.1.2 Organizational Comparison of Combustion Patenting

It is instructive to place the DOE-attributable patenting in advanced combustion in the wider context of patenting by other organizations in this technology area. Figure 3-2 compares the number of advanced engine combustion patent families attributable to DOE to all combustion patent families assigned to the 10 leading vehicle and engine companies through 2008. (These 10 companies and their combustion patents were identified for purposes of conducting the study's backward patent tracing analysis, as explained in Section 2.5 and Appendix A-II.) DOE ranks last in Figure 3-2.

Figure 3-2. Comparison of the Number of Engine Combustion Patent Families Attributed to the Leading Vehicle and Engine Companies and to DOE[19]



Toyota has the largest engine combustion portfolio, containing 3,658 patent families, followed by Honda (3,179 families), Ford (2,696 families) and Denso (2,609 families). Each of the 10 companies has more than 1,000 patent families in combustion technology, except for Fiat (874 families). By comparison, the number of DOE-attributed advanced combustion patent families is 109 families.

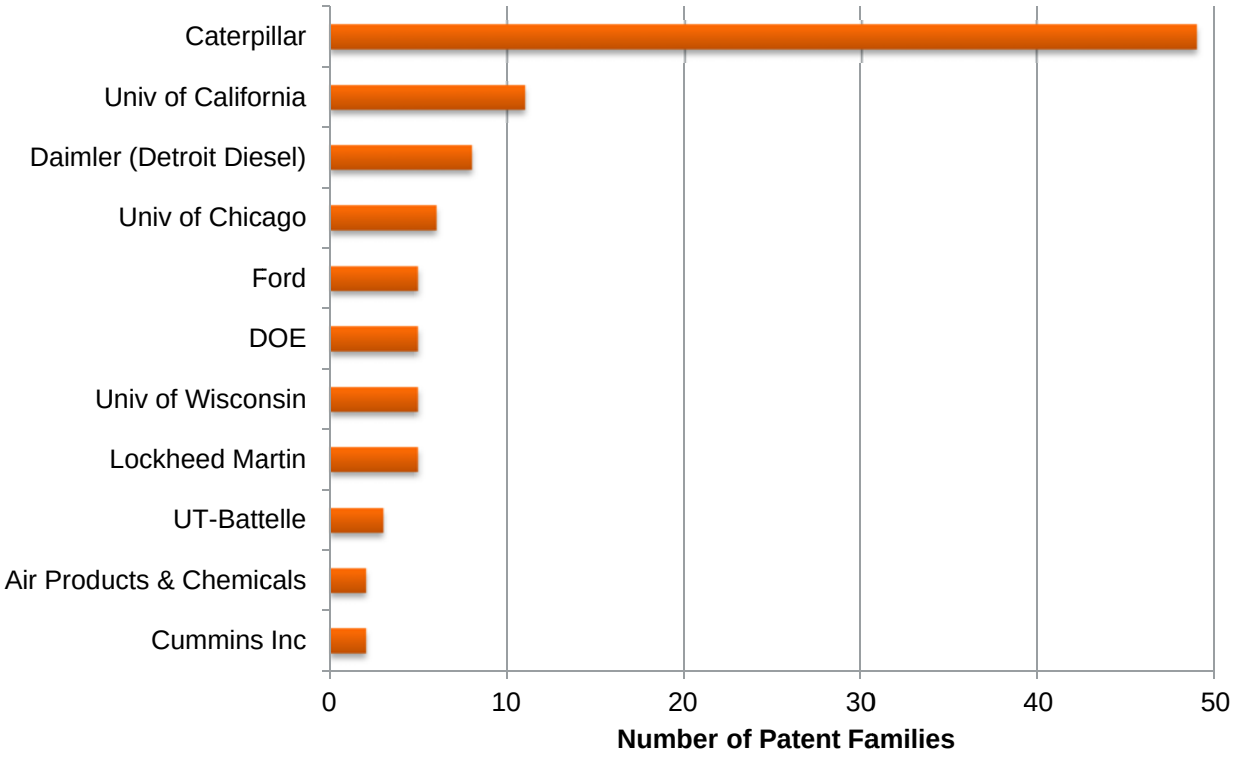
When comparing DOE with the leading vehicle and engine companies, it should be noted that the number of patent families for DOE is derived somewhat differently than the patent family counts for the other organizations in Figure 3-2. Specifically, DOE's 109 patent families are those **attributed** to research funded by DOE, not just those **assigned** to DOE. That is, DOE funded underlying research that led to the generation of the 109 patent families.

There is a degree of overlap between DOE-attributed patents and those of the leading companies. Figure 3-3 suggests the extent of the overlap. It shows assignees in declining order of the number of DOE-attributed advanced combustion patent families assigned to each company. Caterpillar has the largest number assigned (49), and the University of California has the next largest number (11). Caterpillar, with its 49 DOE-attributed patent families; Detroit Diesel (part of

[19] The counts of patent families for the 10 companies cover all their combustion patents through 2008, and for DOE from 1975-early 2009.

Daimler), with its eight DOE-attributed advanced combustion patent families; and Ford, with its five DOE-attributed patent families, are among both the 10 leading vehicle and engine companies and organizations assigned DOE-attributed patents. The degree of overlap is not extensive even for Caterpillar, which has nearly 2,000 combustion patent families, 49 of which are attributed to DOE-funded research. (The degree of overlap is dealt with further in the analysis contained in Section 3.3.)

Figure 3-3. Assignees of DOE-Attributed Advanced Combustion Patent Families, by Number of Patent Families Assigned

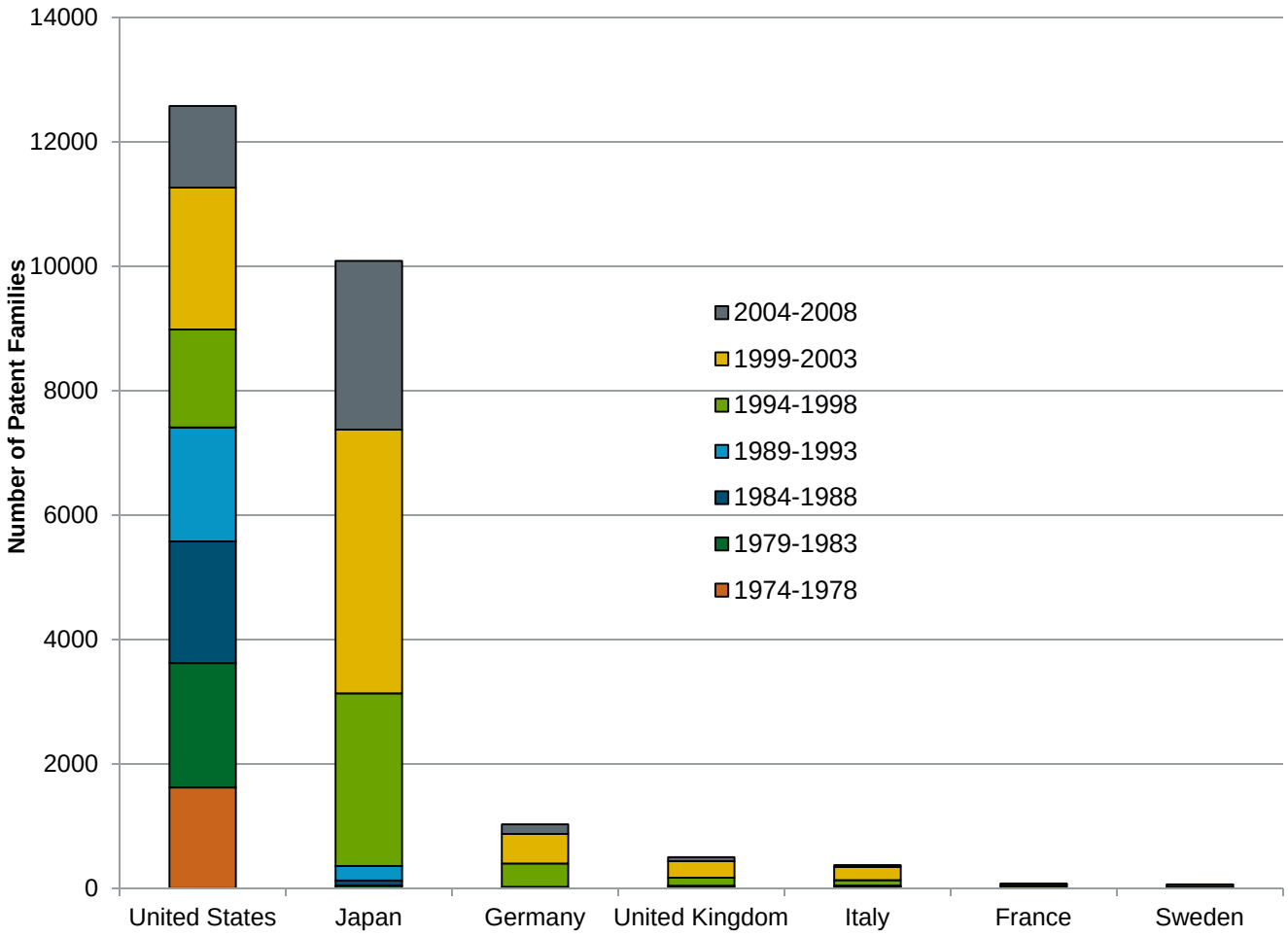


3.1.3 Country Comparisons Based on Where the Priority-Patent is Filed

The 10 leading vehicle and engine companies have filed most of their priority combustion patents in the United States, followed by Japan. The countries in Figure 3-4 represent the nationality of the priority document, i.e., where the first filing was made for a combustion invention. This is generally, but not always, the home country of the applicant.

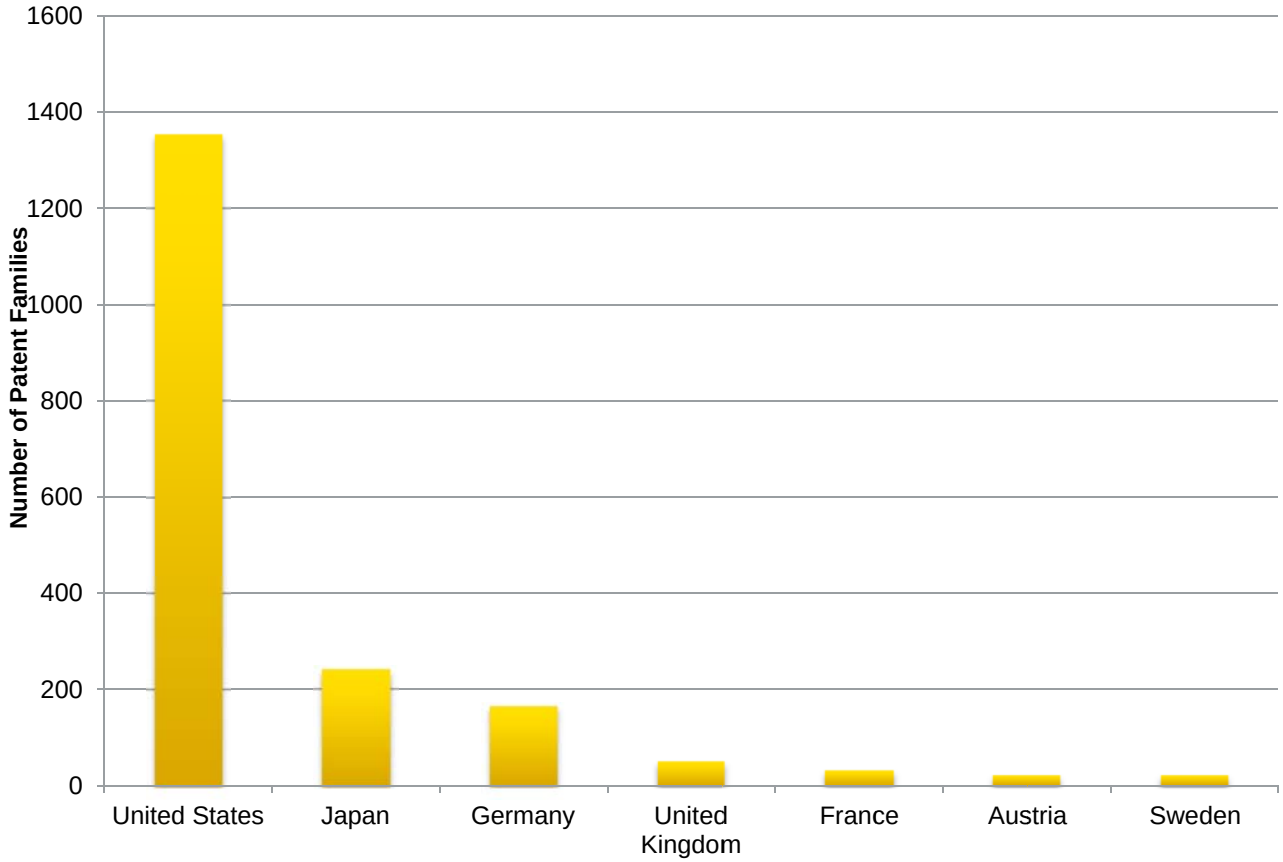
The division of the country bars into five-year intervals shows that filings of priority combustion patents in the United States have been fairly even over the seven intervals since 1974. In contrast, filings of priority combustion patents in Japan were few or insignificant before 1994, and the numbers have jumped over the three most recent time intervals. Priority filings in the other EPO and WIPO countries have been far below those in the United States and Japan.

Figure 3-4. Number of Combustion Patent Families of 10 Leading Vehicle and Engine Companies by Country of Priority Filing and Priority Year



Most of the impact of DOE-attributed advanced combustion patents has been on subsequent technologies developed in the United States. This is shown by Figure 3-5, which covers all patent families citing DOE-attributed advanced combustion patents, not just those in combustion, and shows the country of their priority filing. The number of all patent families linked to DOE-attributed advanced combustion patent families is far greater in the United States than elsewhere.

Figure 3-5. Number of All Patent Families Linked to DOE-Attributed Advanced Combustion Patent Families by Country of Priority Filing



3.1.4 Highlights of Patenting Trends

The assessment of DOE-attributed advanced energy combustion patents identified 109 patent families (i.e., groups of patents based on the same invention) containing a total of 166 individual patents. Most of these patents were filed since 1999. The 109 DOE-attributed advanced combustion patent families are assigned to multiple organizations, including companies, universities, DOE laboratories, and managers of DOE laboratories. Assignees include companies prominent in engine technology, including Caterpillar Inc., Detroit Diesel Corporation, Cummins Inc., Honeywell International Inc., and Ford Motor Company.

To test for linkages backward from combustion patents of leading vehicle and engine companies, the study identified 22,103 patent families related to combustion technology and assigned to the 10 most innovative vehicle and engine companies as indicated by their patenting intensity. These 10 companies are listed in order of their number of combustion patent families in Figure 3-2. Compared with the body of combustion patent families produced by these 10 companies, the DOE-attributed combustion patent set of 109 is quite small. The comparatively small number of DOE-attributed combustion patent families and the relatively recent average issue date are

reflective of the fact that ACE R&D was aimed at overcoming specific persistent and challenging technical barriers within a mature industry. Solutions required special facilities and concentrated R&D (such as the CRF and diagnostics research) to advance the understanding of in-engine combustion processes. The result has been a small, but rapidly developing and highly focused DOE-attributed patent portfolio in advanced combustion technology.

3.2 Results of Backward Patent Tracing at the Organization Level

The backward tracing analysis at the organization level is designed to help answer three principal questions:

- Did DOE's funded research in engine combustion form a foundation for further developments in combustion technology?
- How did DOE's influence on engine combustion compare with that of other organizations?
- Did DOE's funded research in engine combustion reach a downstream audience well positioned to take the research results into commercial development for improved vehicle engine performance?

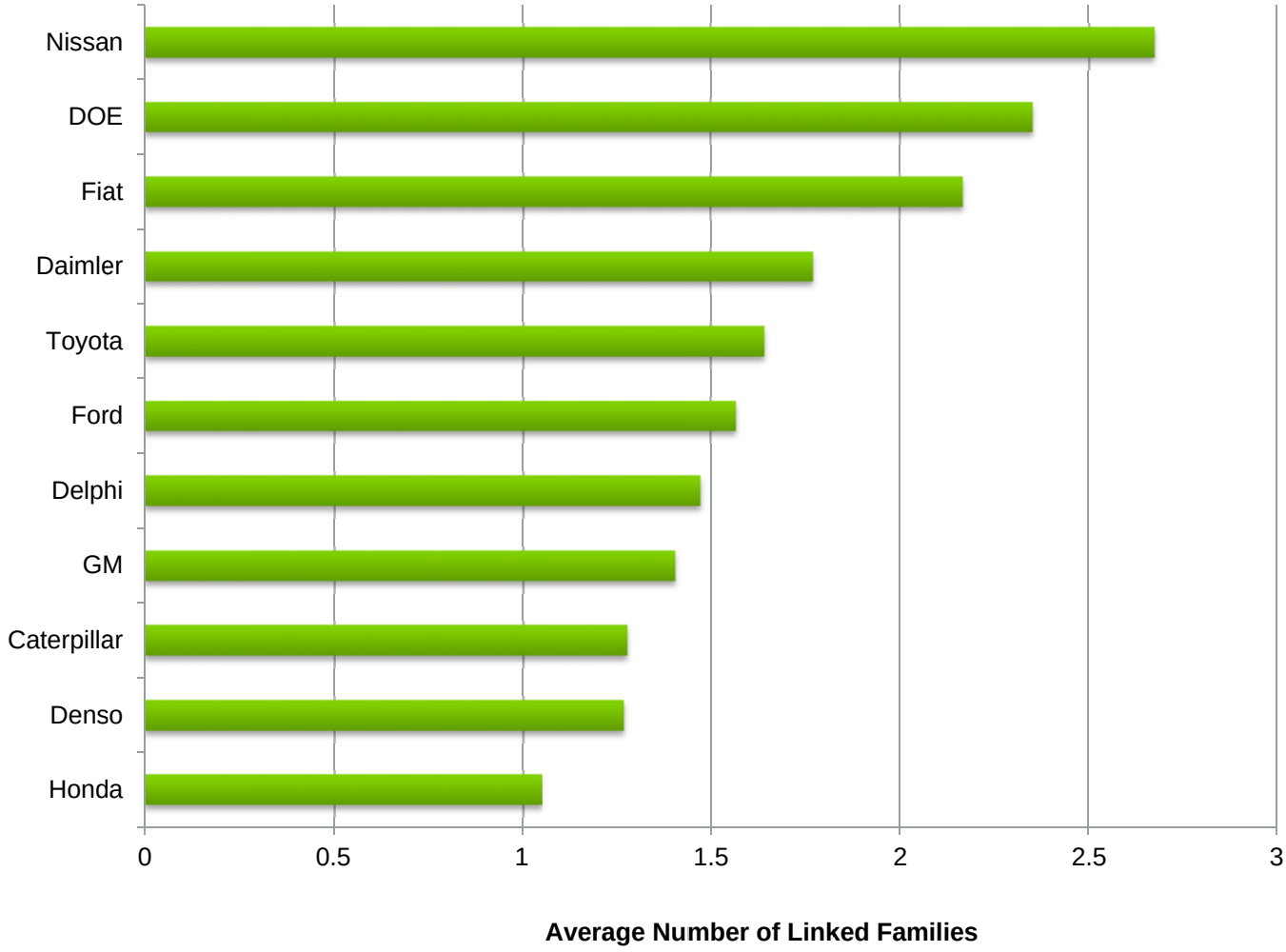
3.2.1 Influence of DOE-Funded Combustion Research on Combustion Innovation Compared with that of Leading Vehicle and Engine Companies

For an analysis of comparative influence, it is necessary to adjust for the vast differences in number and age of combustion patent families of DOE and those of the 10 leading vehicle and engine companies. Namely, the relatively recent surge in the number of patents in the DOE-attributed combustion patent portfolio means that these patents will be expected to have received fewer citations than the older combustion patents of the companies. Further, because the combustion patent portfolios of the companies are overwhelmingly larger than that of DOE, there are vastly more company patents available for citing as prior art, compared with the relatively few DOE-attributed patents available to be cited as prior art. For example, a patent filed in 1993 by Toyota will have been preceded by many earlier combustion patents owned by Toyota and its competitors. These earlier patents were therefore available to be cited as prior art by the Toyota patent. At the same time, there were only six DOE-attributed advanced combustion patent families issued earlier than 1993. To overcome the patent portfolio age biasing effect, this analysis is limited to patent families filed since 1999. To overcome the portfolio size biasing effects, the average (mean) number of citations per patent is used rather than the absolute numbers of citations.

Based on citation averages per patent family filed since 1999, Figure 3-6 shows the 10 leading vehicle and engine companies, plus DOE, listed in declining order of the influence of their

combustion patent families[20] DOE is second from the top in the list. Each of its combustion patents families filed since 1999 is linked to an average of 2.35 subsequent combustion patent families of the leading companies. The average number of linked combustion patent families is second only to that of Nissan, which has an average of 2.67 subsequent combustion patent families linked to each of its combustion patent families. Thus, the comparative rates of average citing suggest that DOE's patents in advanced combustion have, on average, been cited more by other combustion patents than have those of nearly all of the leading vehicle and engine companies, excepting Nissan.

Figure 3-6. Leading Vehicle and Engine Companies and DOE Listed in Declining Order of the Average Number of Citations of their Combustion Patent Families



Note: Based on average (mean) citations per patent issued since 1999, by the leading companies.

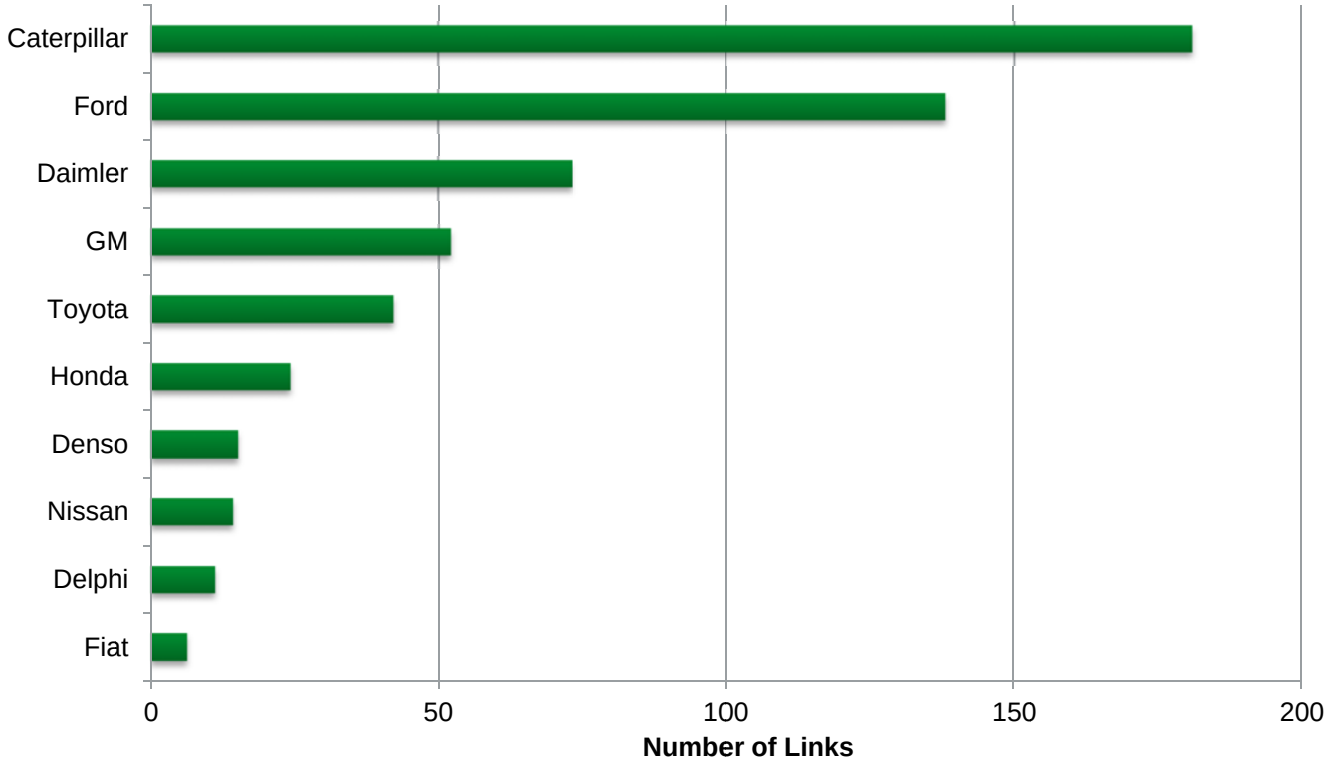
[20] This is not to imply that only these companies were the targeted audience of DOE's research. Rather they provide a manageable group for testing the hypothesis that DOE's research reached leading innovative companies in the field of engine combustion.

3.2.2 Linkage of Combustion Patent Families of Leading Companies to Earlier DOE-Attributed Patent Families

The next illustration, Figure 3-7, shows which of the leading companies have combustion patent portfolios that have built particularly extensively on the DOE-funded advanced combustion research. It shows the **total** number of citation links between each of the companies' subsequent combustion patent portfolios and the DOE-attributed combustion patent families. Note that this figure takes into account both how many of each company's patent families are linked to earlier DOE-attributed patents, and the number of times each family is linked. This analysis does not constrain the analysis to patents issued post 1999, however, because most of the DOE-patent families are recent, most of the patents families citing them will also be recent.

Caterpillar is at the head of Figure 3-7 with 181 citation linkages to earlier DOE combustion patent families. It has 111 combustion patent families (not separately shown) linked to earlier DOE-attributed advanced combustion patents, and these 111 Caterpillar patent families are linked a total of 181 times. Ford, Chrysler (referenced as Daimler in Figure 3-7), and GM follow—all with patent families linked more than 50 times to earlier DOE combustion patent families. This finding supports the conclusion that ACE R&D has been successful in having the results of its research taken up by leaders of innovation in the vehicle and engine industries who are well positioned to take the advances into commercial development.

Figure 3-7. Leading Companies in Declining Order of the Number of Links between Their Combustion Patent Families and Earlier DOE-Attributed Advanced Combustion Patent Families



As noted in Section 3.1.2, the presence at the head of the figure of Caterpillar, Ford, and Chrysler—each funded by DOE to carry out advanced combustion research—is emphatically not caused simply by DOE-attributed patents of these companies citing earlier DOE-attributed patents. Only 19 of the 111 Caterpillar patent families linked to earlier DOE-attributed patents are themselves attributed to DOE funding. Only six of Chrysler's 55 families linked to earlier DOE-attributed families are themselves attributed to DOE funding, and none of Ford's 95 families shown linked to earlier DOE-attributed patents are themselves attributed to DOE funding.[21] This finding suggests that DOE-funded advanced combustion research helped these companies form a foundation of scientific and engineering knowledge on which they continued to build, substantially beyond the development of technologies specifically funded by DOE.

3.2.3 Highlights of Findings from Backward Tracing at the Organization Level

Adjusting for the huge differences in size and age of the company portfolios of combustion patents as compared with the set attributed to DOE, the study found that based on patents filed since 1999, the DOE-attributed combustion patents were cited on average by 2.35 combustion patent families owned by the 10 leading vehicle and engine companies. Average citing of the DOE-attributed combustion patents was second only to the average citing of Nissan combustion patents by these companies, with 2.67 links on average. An analysis of the leading companies' combustion patent portfolios revealed Caterpillar, Ford, and Chrysler as those leading companies whose portfolios built particularly extensively on the DOE-funded advanced combustion research.

3.3 Results of Forward Tracing at the Organization Level

The forward tracing analysis is designed to assess the broader influence of ACE R&D in and outside the area of combustion technology. The tracing starts with the DOE-attributed 109 advanced combustion patent families and assesses where their influence is found, without limit to technology or industry area, and without constraining the analysis to post 1999 patents. This section addresses the following two questions:

- Who, beyond the 10 leading vehicle and engine companies, used the DOE-funded advanced combustion research results?

- Are there indications of influences of ACE R&D research results extending beyond engine combustion, and, if so, in what topic areas?

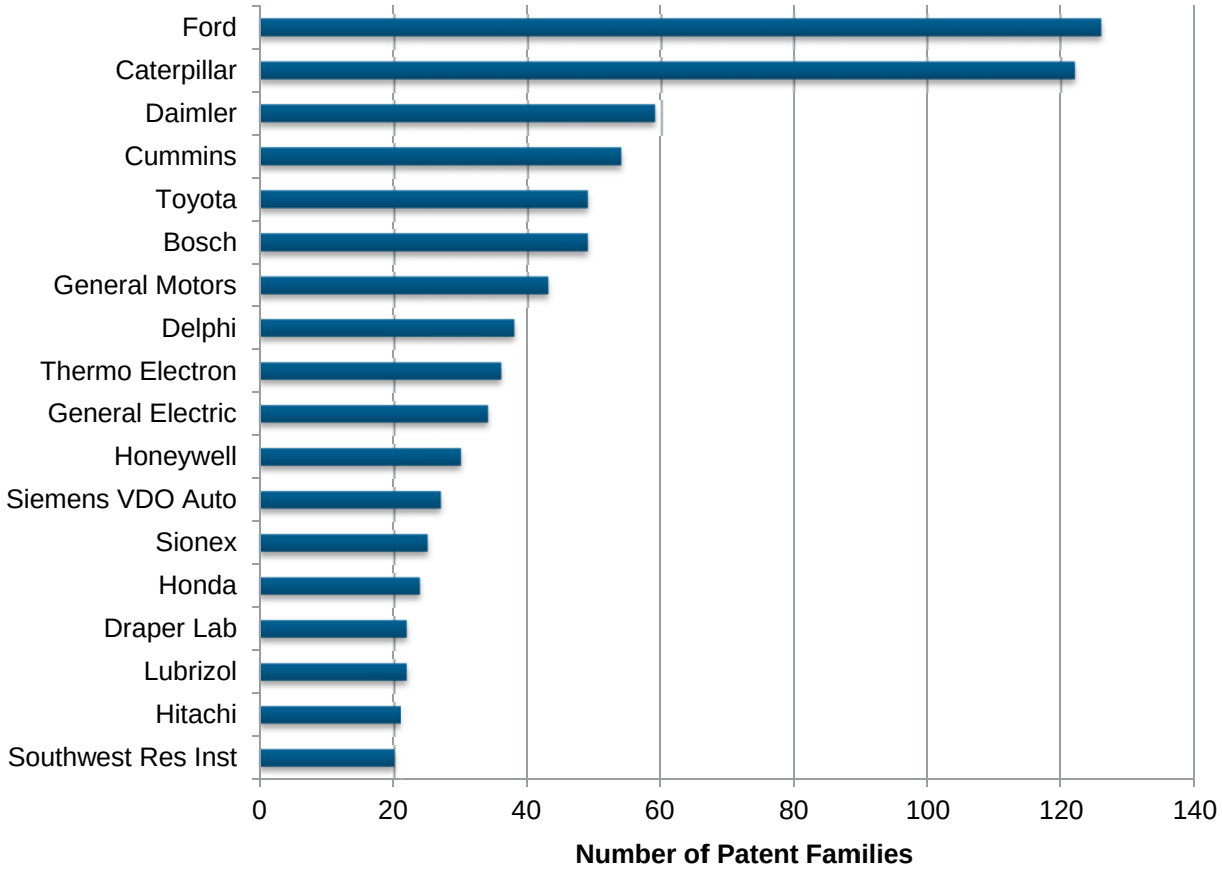
[21] This finding also implies that the DOE-attributed advanced combustion patents assigned to these companies did not necessarily cite earlier DOE-attributed patents in advanced combustion. For example, Caterpillar had 49 DOE-attributed advanced combustion patents, but only 19 of these cited earlier DOE-attributed advanced combustion patents.

3.3.1 Organizations in All Areas Most Influenced by DOE-Funded Advanced Combustion Research

The organizations with the largest number of patent families linked to earlier DOE-attributed combustion patent families are listed in declining order in Figure 3-8. This list is based on all patent families from all technology areas and all organizations. It includes most but not all of the 10 leading vehicle and engine companies that were used in the backward tracing component of the study (i.e., some of the 10 were not high enough on this list to be shown when compared against all organizations).

Forward tracing at the organizational level suggests that much of the impact of DOE-attributed combustion patents has been on companies developing technologies related to engines in general, and combustion in particular. Ford and Caterpillar, two of the 10 leading vehicle and engine companies used in the backward tracing analysis, are at the head of Figure 3-8, with 126 and 122 patent families, respectively, linked to the earlier DOE-attributed advanced combustion patents. Chrysler (referenced as Daimler in Figure 3-8), Toyota, GM, and Delphi also have prominent positions in the list.

Figure 3-8. Organizations from All Sectors with the Largest Number of their Patent Families Linked to DOE-Attributed Advanced Combustion Patent Families



There are two additional companies near the head of Figure 3-8 that are not among the companies included in the backward tracing analysis, but are innovators in engine technologies. One is Cummins, a global leader in the design and manufacture of engines and related technologies, including fuel systems, controls, air handling, filtration, emission solutions and electrical power generation systems.[22] Cummins has 54 patent families linked to earlier DOE-attributed combustion patent families. These Cummins patent families describe a variety of technologies related to combustion, notably EGR and HCCI engines.

The second company near the head of Figure 3-8 that is not among the companies included in the backward tracing analysis is the Bosch Group, a leading global supplier of automotive and industrial technology, consumer goods, and building technology. It has 49 patent families linked to the earlier DOE-attributed combustion patent families. These Bosch patent families are largely concerned with spark plugs and fuel injection techniques.

The forward tracing analysis also identified three organizations, listed in Figure 3-8, whose patents are linked to earlier DOE-funded advanced combustion research through a non-combustion technology—namely ion mobility spectrometry for use in detection of materials such as narcotics and explosives. These organizations are Thermo Electron Corporation, which features a product line of analytical instruments, laboratory equipment, and other products used in scientific analysis; Sionex Corporation, which is involved in defense threat detection from chemical and biological warfare agents, explosives and narcotics, monitoring of industrial and petrochemical compounds, and consumer products; and Charles Stark Draper Laboratory, from which Sionex has licensed patented technology, and which was the MIT Instrumentation Laboratory until it was spun out of the university in 1973 to become a U.S. Government contractor. The fact that these three organizations are among the organizations with the most patent families linked to the DOE advanced combustion patent family set indicates the importance of DOE developments in spectrometry as a research tool.

The spectrometry patents of these three organizations link back to Sandia patent US #5,789,745, a 1998 patent describing ion mobility spectrometry. Ion mobility spectrometry was developed as a research tool by DOE to "see" and better understand the combustion process within the cylinder. It appears, however, that the technology was further developed and taken into new application areas well beyond engine combustion research.

3.3.2 Broad Topic Areas of Influence Found by Forward Tracing

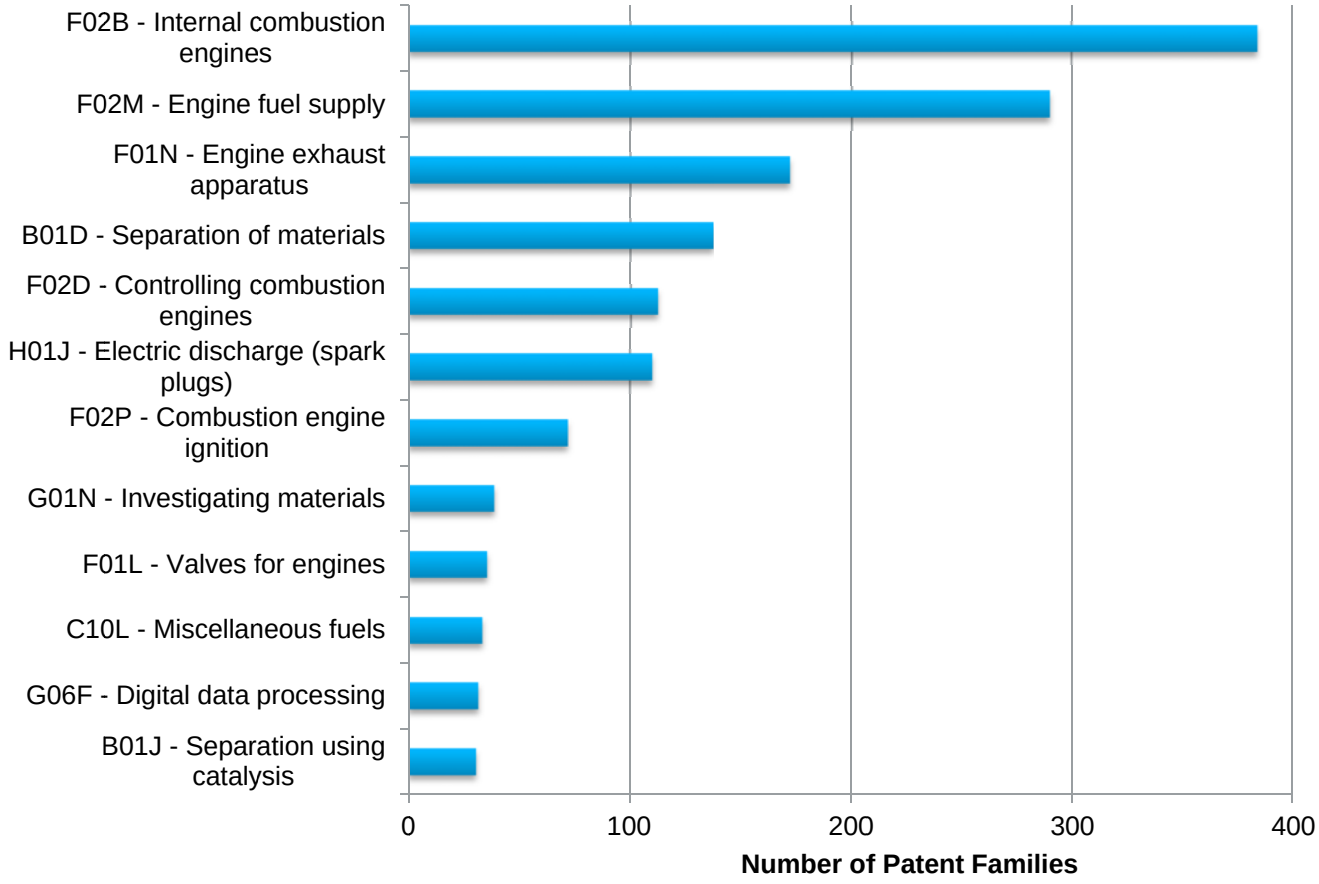
The forward tracing analysis identified the broad topic areas of all patent families linked to earlier DOE-attributed advanced combustion patent families. This was done by using the primary International Patent Classifications (IPCs) to show the four-digit IPCs for all patents linked to earlier DOE-funded advanced combustion research through two generations of forward citations, as shown by Figure 3-9.

[22] Though Cummins is a leader in the design and manufacture of engines, the company was not among the top 10 vehicle and engine manufacturers in terms of total patenting.

The most dominant IPC to which the DOE-attributed patent families are linked through forward citations is F02B, "internal combustion engines." Next is F02M, "engine fuel supply." These are followed by "engine exhaust apparatus," and "separation of materials." Note that G01N, "investigating materials," a category concerned with analyzing the properties of materials, also appears in Figure 3-9. The patents linked to DOE in this IPC are mainly concerned with ion mobility spectrometry—a research technology used to analyze and detect materials that have applicability beyond engines and combustion, as indicated in the previous section. Additional forward linkages are G06F, "digital data processing," and B01J, "separation using catalysts."

Overall, these results suggest that the influence of DOE's advanced combustion research is by far the strongest on subsequent developments in engine and combustion technology—as intended by the DOE Program. However, the influence also has spread to several other areas, particularly to those related to detection and analysis of materials.

Figure 3-9. All Patent Families Linked to DOE-Attributed Advanced Combustion Patents through Two Generations of Patent Citations Identified and Grouped by Their International Patent Classifications (IPCs)



3.3.3 Highlights of Findings from Forward Tracing at the Organization Level

The study's forward patent tracing started with the 109 DOE-attributed advanced combustion patent families and traced their linkages to subsequent developments both inside and outside vehicle engine combustion technology. The study found linkages from the DOE-attributed combustion patents to related combustion technologies developed not only by the 10 leading innovative vehicle and engine companies, but also by other leading companies in the engine technology, particularly Cummins, Bosch, and Hitachi.

Forward patent tracing also found influence of the DOE combustion research in several other areas, especially in the analysis and detection of materials. It revealed three organizations, Thermo Electron Corporation, Sionex Corporation, and Charles Stark Draper Laboratory, all with patents linked to the ACE R&D Subprogram through a non-combustion technology, namely ion mobility spectrometry. The Subprogram had funded ion mobility spectrometry research at SNL and LLNL to provide a tool for in-engine combustion research. This work was later extended and applied by the three companies for use in detection of materials, such as narcotics and explosives.

3.4 Individual Patent-Level Results of Backward and Forward Tracing

Here attention shifts to the level of the individual patent. To shed light on technological developments that have been particularly influenced by DOE-attributed advanced combustion patents, the section addresses the following specific questions:

- Which DOE-attributed advanced combustion patents are linked to the largest number of subsequent combustion energy patent families?
- Which DOE-attributed "other" patent families (i.e., those not included in the combustion set of 109) are linked to the largest number of subsequent combustion patent families?
- Which among the combustion patent families of the leading companies have built particularly extensively on earlier DOE-funded combustion research?
- Which highly cited combustion patent families of the leading companies are linked to earlier DOE-attributed combustion patent families?
- Which highly cited patents in all industry areas are linked to earlier DOE-attributed combustion patent families?
- What are the most highly cited of the DOE-attributed combustion patents?

3.4.1 DOE-Attributed Advanced Combustion Patents Linked to the Largest Number of Subsequent Combustion Patent Families of Leading Companies

Using "anchor patents," Table 3-1 shows which DOE-attributed advanced combustion patent families are linked to the largest number of subsequent combustion patent families of the 10 leading companies.[23] The patent family at the head of this table is represented by anchor patent US #4,924,828. This patent was issued in 1990. It was the result of research carried out by Lawrence Berkeley National Laboratory (LBNL) and was assigned to the University of California, the manager of LBNL. It is one of three similar patent families in the table originating at LBNL that describe improved fuel injection techniques, especially for diesel engines—the other two are represented by anchor patents US #4,974,571 and US #4,926,818.

The patent family represented by anchor patent US #4,924,828 is linked to 110 subsequent combustion patent families owned by the 10 leading vehicle and engine companies—almost twice as many links to these companies as any other DOE-attributed combustion patent family. There are also other older fuel injection patent families included in Table 3-1, including families assigned to Ford (anchor patent US #5,671,716), Geo-Centers (US #4,493,297) and DOE itself (US #5,271,365). This suggests a strong influence of DOE's fuel injection research on subsequent developments made by leading vehicle and engine companies.

Also it is notable that Table 3-1 includes a number of recently issued patents, such as those funded by DOE and assigned to Caterpillar, which are already linked to significant numbers of subsequent patent families. For example, the patent family in fourth place in Table 3-1 (anchor patent US #6,843,231, issued in 2005) is assigned to Caterpillar, and describes a method for cylinder-to-cylinder balancing in a combustion engine. This family is linked to 27 subsequent combustion patent families owned by the leading companies. This suggests that DOE-funded combustion research is quickly influencing downstream developments in combustion technology by commercial companies.

[23] Each patent family in the table is represented by a single anchor patent," i.e., a single patent from the family which is generally the first patent issued and the priority filing unless the priority filing was outside the U.S. Patent Office, the EPO, or the WPTO, such as a Japanese application.

Table 3-1. DOE-Attributed Combustion Patent Families Linked to the Largest Number of Subsequent Combustion Patents of the 10 Leading Vehicle and Engine Companies

DOE Anchor Patent	Issue Year	# of Top 10 Company Linked Families	Assignee	Title
4924828	1990	110	University of California	Method and system for controlled combustion engines
6035640	2000	66	Ford Motor Co.	Control method for turbocharged diesel engines having exhaust gas recirculation
6116026	2000	39	Daimler (Detroit Diesel)	Engine air intake manifold having built-in intercooler
6843231	2005	27	Caterpillar Inc.	Cylinder to cylinder balancing using intake valve actuation
6173567	2001	27	University of Chicago	Method to reduce diesel engine exhaust emissions
6923167	2005	25	University of California	Controlling and operating homogeneous charge compression ignition (HCCI) engines
6055808	2000	24	University of Chicago	Method and apparatus for reducing particulates and NO_x emissions from diesel engines utilizing oxygen enriched combustion air
4974571	1990	19	University of California	Pulsed jet combustion generator for non premixed charge engines
6769635	2004	18	Caterpillar Inc.	Mixed mode fuel injector with individually moveable needle valve members
5671716	1997	18	Ford Motor Co.	Fuel injection system and strategy
6119451	2000	12	University of California	Nitrogen oxide removal using diesel fuel and a catalyst
4493297	1985	12	Geo-Centers Inc.	Plasma jet ignition device
6516787	2003	11	Caterpillar Inc.	Use of exhaust gas as sweep flow to enhance air separation membrane performance
5271365	1993	10	U.S. Dept. of Energy	Jet plume injection and combustion system for internal combustion engines
4926818	1990	9	University of California	Pulsed jet combustion generator for premixed charge engines
6769392	2004	9	Caterpillar Inc.	Variable valve timing in a homogenous charge compression ignition engine

3.4.2 DOE-Attributed "Other Patents" Linked to the Largest Number of Subsequent Combustion Patent Families of Leading Companies

It is possible that DOE-attributed patent families other than the 109 patents recognized here as attributed to ACE R&D have influenced the development of combustion technologies of the leading companies. Thus, while the study used the 109 approved patent families in its main analysis, a search was also conducted to see what other DOE-attributed patent families might be linked to large numbers of subsequent combustion families owned by the 10 leading vehicle and engine companies. The results are shown in Table 3-2.

The "other" DOE patent family that is linked to the largest number of combustion patent families of the leading companies is anchored by patent US #4,031,864, issued in 1977, and assigned to DOE. It describes a method for allowing multiple fuels to be supplied to an engine. It is linked to 155 combustion patent families of the leading companies, describing both fuel systems and combustion control techniques.

The second patent in the "other" category represented in Table 3-2 is anchored by patent US #4,543,930, issued in 1985, and assigned to Southwest Research Institute. It describes staged direct fuel injection for diesel engines, allowing for the use of lower cetane number fuel,[24] and is linked to 138 combustion patent families of the leading companies, many describing techniques of fuel injection and of engine control.

It is also noteworthy that most of the patent families in Table 3-2 are relatively old. All but two were issued prior to 2000, and those two were issued in 2000.

These findings suggest that DOE's influence on combustion innovations by leading vehicle and engine companies comes from a broader base of patent families than the 109 patent families approved by DOE for the study, attributed to ACE R&D and pertaining to "in-cylinder" advanced combustion research. The findings also suggest that newer DOE combustion patents influencing commercial combustion developments have come from the list of 109 patent families attributed to ACE R&D. A further observation is that the "other patent families" of Table 3-2 come principally from DOE national laboratory research, while the 109 patent families of Table 3-1 exhibit a larger industry involvement through their assignees.

[24] Similar to the octane number rating that is applied to gasoline to rate its ignition stability, the cetane number is the rating assigned to diesel fuel to rate its combustion quality.

Table 3-2. DOE-Attributed "Other Patent Families" (Not in the List of 109) Linked to the Most Combustion Patent Families of Leading Companies

DOE Anchor Patent	Issue Year	# of Top 10 Company Linked Families	Assignee	Title
4031864	1977	155	U.S. Dept. of Energy	Multiple fuel supply system for an internal combustion engine
4543930	1985	138	Southwest Research Institute	Staged direct injection diesel engine
5012777	1991	66	Southwest Research Institute	Internal combustion engine
5271357	1993	64	General Electric Company	Method of combustion for dual fuel engine
5922142	1999	63	Midwest Research Institute	Photovoltaic devices comprising cadmium stannate transparent conducting films
5601058	1997	50	U.S. Dept. of Energy	Starting apparatus for internal combustion engines
5711147	1998	38	University of California	Plasma-assisted catalytic reduction system
5735245	1998	37	Southwest Research Institute	Method and apparatus for controlling fuel/air mixture in a lean burn engine
6038854	2000	34	University of California	Plasma regenerated particulate trap and NO_x reduction system
5891409	1999	30	University of California	Pre-converted nitric oxide gas in catalytic reduction system
3981321	1976	28	U.S. Dept. of Energy	Vehicle fuel system
5746984	1998	25	Low Emissions Technologies R&D Partnership	Exhaust system with emissions storage device and plasma reactor
6038853	2000	24	University of California	Plasma-assisted catalytic storage reduction system
5715677	1998	22	University of California	Diesel NO_x reduction by plasma-regenerated absorbend beds
4572738	1986	22	U.S. Dept. of Energy	Managing super alloys and heat treatment processes
4095580	1978	20	U.S. Dept. of Energy	Pulse-actuated fuel-injection spark plug
5248566	1993	20	U.S. Dept. of Energy	Fuel cell system for transportation applications

3.4.3 Combustion Patent Families of the Leading Companies that Have Built Extensively on Earlier DOE-Attributed Advanced Combustion Patent Families

Table 3-3 looks in the opposite direction of Tables 3-1 and 3-2, listing the combustion patent families owned by the leading companies that are linked particularly extensively to earlier DOE-attributed advanced combustion patent families. The patent family at the top of the list is anchored by US #7,484,494 assigned in 2009 to General Motors, describing fuel injection for spark-ignited direct injection engines. It is linked to eight earlier DOE-attributed combustion patent families, notably families related to improved fuel injection. A number of patents assigned to Caterpillar are also among those with the most citation links back to DOE. All of these are very recent and describe various advanced combustion engine techniques, and they build on multiple earlier DOE-attributed patent families. For example, the patent family anchored by US #7,398,743, assigned to Caterpillar in 2008, describes a compression ignition device. It is linked to seven earlier DOE-attributed patent families, including those describing compression ignition engines.

Table 3-3. Combustion Patent Families of Leading Companies Linked Back to to the Most DOE-Attributed Combustion Patent Families

Anchor Patent	Issue Year	# Linked DOE-Attributed Patent Families	Assignee	Title
7484494	2009	8	General Motors Corp.	Method and apparatus for a spark-ignited direct injection engine
7398743	2008	7	Caterpillar Inc.	Compression ignition initiation device and internal combustion engine using same
7422000	2008	6	Caterpillar Inc.	Method of transitioning between operating modes in an internal combustion engine
7493884	2009	5	Caterpillar Inc.	Method and system for reducing pollutant emissions of an engine
7171924	2007	5	Caterpillar Inc.	Combustion control system of a homogeneous charge
7273045	2007	5	Ford Motor Co.	System and method for reducing NO_x emissions during transient conditions in a diesel fueled vehicle with EGR
7465337	2008	4	Daimler AG	Internal combustion engine with an air separator and methods for realizing such an internal combustion engine

Table 3-3 (continued). Combustion Patent Families of Leading Companies Linked Back to the Most DOE-Attributed Combustion Patent Families

Anchor Patent	Issue Year	# Linked DOE-Attributed Patent Families	Assignee	Title
7496443	2009	4	Ford Motor Co.	Emissions control
7556017	2009	4	Caterpillar Inc.	Twin needle valve dual mode injector
7500475	2009	4	Caterpillar Inc.	Engine and method for operating an engine
6595181	2003	4	General Motors Corp.	Dual mode engine combustion process

3.4.4 Highly Cited Combustion Patents of the Leading Companies with Links to Earlier DOE-Attributed Advanced Combustion Patents

Also of interest are the leading companies' "high-impact patents" that have links back to earlier DOE-attributed advanced combustion patents. High-impact patents are defined here as those cited by large numbers of subsequent patents, as measured by Citation Index values.[25]

To conduct this part of the analysis, the highly cited patents were divided into two groups. The first group is defined as advanced combustion patents, in that they refer specifically in their titles or abstracts to Homogeneous Charge Compression Ignition (HCCI) engines; Exhaust Gas Recirculation (EGR); Compression Ignition Direct Injection (CIDI) engine; lean burn; direct injection; or low temperature combustion (including variations of these terms). The second group contains all other combustion patents. It should be noted that the division is far from perfect, since patents for advanced combustion techniques may not always make reference to specific terms or acronyms in their title or abstract.

Table 3-4 lists the highly cited advanced combustion patents owned by the 10 leading vehicle and engine companies that are linked to earlier DOE-attributed advanced combustion patents. All of the patents in this table have Citation Index values above two. This means that each of them has been cited at least twice as frequently as expected given their age and technology. The patent at the top of this list is a 2002 patent assigned to Ford that describes an engine control strategy, specifically a method for transitioning between HCCI and spark ignition operation. This Ford patent is linked to an earlier DOE combustion patent, and in turn is cited by 42 subsequent patents—more than six times as many citations as expected given its age and technology. This is

[25] The Citation Index is a normalized measure derived by dividing the number of citations received by a patent by the mean number of citations received by peer patents from the same issue year and technology as indicated by its Patent Office Classification (POC). For example, the number of citations received by a particular 2002 patent in POC 60/278 is divided by the mean number of citations received by all patents in that POC issued in 2002 to derive its Citation Index. The expected Citation Index for a patent is one. An index of 10 means that the patent has been cited 10 times more frequently than would be expected given its age and technology. An index of 0.7 means that a patent has been cited 30% less often than expected.

an example of a DOE-attributed patent forming part of the foundation for a later high-impact technology, namely HCCI.

A number of other highly cited patents in Table 3-4 are concerned with EGR. These include a U.S. patent assigned to Toyota, through its Hino Motors subsidiary (US #6,338,245); to Ford (US #6,095,127); to Detroit Diesel (US #6,305,167); and to Caterpillar (US #6,609,374). These patents are linked to a variety of earlier DOE-attributed patents describing air intake and engine control, and are themselves linked to large numbers of subsequent patents. This suggests that DOE-funded advanced combustion research has helped form part of the foundation for high-impact EGR technologies.

Table 3-5 lists "other" highly cited combustion patents owned by the 10 leading vehicle and engine companies that are linked to earlier DOE-attributed advanced combustion patents. (These are the highly cited combustion patents from the second group, i.e., those that do not refer specifically in their titles or abstracts to HCCI, EGR, CIDI, lean burn, direct injection, low temperature combustion, or to variations of these terms.) The two patents at the head of this table have both been cited by more than 11 times as frequently as would be expected given their relatively recent issue dates (both were issued in 2005). The first is a Toyota patent describing a fuel injection system enabling the use of lower octane fuel. It cites an earlier U.S. patent (US #6,550,430) describing a dual fuel engine, which in turn cites an earlier DOE-attributed patent (US #5,858,030) describing improved fuel compositions. Hence, the DOE-attributed patent is linked through second-generation citing to Toyota's high-impact fuel injection patent. The second patent at the head of Table 3-5 is a Nissan patent (US #6,912,995) describing variable valve control for combustion engines.

Table 3-4. Highly Cited Advanced Combustion Patent Families of 10 Leading Companies Linked to Earlier DOE-Attributed Advanced Combustion Patent Families

Patent	Issue Date	# Cites Received	Citation Index	Assignee	Title
6390054	2002	42	6.49	Ford Motor Co.	Engine control strategy for a hybrid HCCI engine
6338245	2002	41	5.42	Toyota (Hino Motors)	Internal combustion engine
5467757	1995	27	2.44	Toyota Motor Company	Compression-ignition type engine and combustion method of same
5979398	1999	24	2.73	Toyota Motor Company	Compression-ignition type engine
5259348	1993	24	2.13	Toyota Motor Company	Direct injection type engine
6095127	2000	24	3.24	Ford Motor Co.	Fuel limiting method in diesel engines having exhaust gas recirculation

Table 3-4 (continued). Highly Cited Advanced Combustion Patent Families of 10 Leading Companies Linked to Earlier DOE-Attributed Advanced Combustion Patent Families

Patent	Issue Date	# Cites Received	Citation Index	Assignee	Title
6662552	2003	19	3.42	Daimler AG	Exhaust-gas cleaning system and method with internal ammonia generation, for the reduction of nitrogen oxides
6305167	2001	16	2.34	Daimler (Detroit Diesel)	Method of controlling an engine with an EGR system
6457461	2002	15	2.55	Daimler (Detroit Diesel)	EGR and VGT system diagnostics and control
6722349	2004	15	4.92	Caterpillar Inc.	Efficient internal combustion engine valve actuator
6769635	2004	14	6.05	Caterpillar Inc.	Mixed mode fuel injector with individually moveable needle valve members
6182632	2001	12	2.02	Toyota Motor Company	Compression-ignition type engine
6786210	2004	11	3.61	Daimler (Detroit Diesel)	Working fluid circuit for a turbocharged engine having exhaust gas recirculation
6863058	2005	11	6.37	Ford Motor Co.	System and method for reducing NO_x emissions during transient conditions in a diesel fueled vehicle
6609374	2003	11	2.70	Caterpillar Inc.	Bypass venturi assembly for an exhaust gas recirculation system
6681171	2004	10	2.57	Daimler (Detroit Diesel)	Condensation control for internal combustion engines using EGR

Table 3-5. Highly Cited Other Combustion Patent Families of Leading Companies Linked to Earlier DOE-attributed Advanced Combustion Patent Families

Patent	Issue Date	# Cites Received	Citation Index	Assignee	Title
6959693	2005	23	11.21	Toyota Motor Company	Fuel injection system and method
6912995	2005	22	11.11	Nissan Motor Co. Ltd.	Control apparatus for internal combustion engine
6732685	2004	15	7.25	Caterpillar Inc.	Engine valve actuator

Table 3-5 (continued). Highly Cited Other Combustion Patent Families of Leading Companies Linked to Earlier DOE-Attributed Advanced Combustion Patent Families

Patent	Issue Date	# Cites Received	Citation Index	Assignee	Title
6845616	2005	12	6.14	General Motors Corp	Internal combustion engine which can be operated with a choice of different fuels, especially for a motor vehicle drive system
6672060	2004	15	4.23	Ford Motor Co.	Coordinated control of electronic throttle and variable geometry turbocharger in boosted stoichiometric spark ignition engines
6314940	2001	20	3.25	Daimler AG	Fuel feed system for a spark-ignition internal combustion engine and a method of operating such an internal combustion engine
6659068	2003	13	2.83	Nissan Motor Co. Ltd.	Feedback control for auto-ignition two-stage combustion of gasoline in engine cylinder
6490857	2002	15	2.73	Toyota Motor Company	Device for purifying the exhaust gas of an internal combustion engine
6112720	2000	20	2.47	Caterpillar Inc.	Method of tuning hydraulically-actuated fuel injection systems based on electronic trim
5839420	1998	23	2.47	Daimler (Detroit Diesel)	System and method of compensating for injector variability
5603303	1997	24	2.44	Denso Corp.	High pressure fuel supply pump
6079641	2000	14	2.14	Caterpillar Inc.	Fuel injector with rate shaping control through piezoelectric nozzle lift
6006720	1999	17	2.12	Toyota Motor Company	Internal combustion engine
6067973	2000	15	2.07	Caterpillar Inc.	Method and system for late cycle oxygen injection in an internal combustion engine

Note: This “other” group, unlike the group in Table 3-4, does not refer specifically in their titles or abstracts to HCCI, EGR, CIDI, lean burn, direct injection, or low temperature combustion, or to variations of these terms.

3.4.5 Highly Cited Patents of Other Organizations Linked to Earlier DOE-Attributed Advanced Combustion Patent Families

The analysis of highly cited patents linked to earlier DOE-attributed advanced combustion patents is extended here to those not owned by the 10 leading vehicle and engine companies. A Citation Index is used to determine highly cited patents. The results show how DOE-funded advanced combustion research has helped to form part of the foundation for subsequent high-impact technologies developed by organizations not among the list of 10 leading vehicle and engine companies. They also show how the DOE-funded advanced combustion research has helped to establish high-impact technologies outside the area of engine combustion.

Table 3-6. Highly Cited Patents of Other Organizations (Not the 10 Leading Companies) Linked to Earlier DOE-attributed Advanced Combustion Patents

Patent	Issue Date	# Cites Received	Citation Index	Assignee	Title
6739295	2004	25	12.08	Hitachi Ltd.	Compression ignition internal combustion engine
6504149	2003	69	11.80	National Research Council of Canada	Apparatus and method for desolvating and focusing ions for introduction into a mass spectrometer
6621077	2003	56	10.74	National Research Council of Canada	Apparatus and method for atmospheric pressure-3-dimensional ion trapping
6561157	2003	48	10.46	Cummins Inc.	Multiple operating mode engine and method of operation
6512224	2003	59	10.09	Charles Stark Draper Laboratory Inc	Longitudinal field driven field asymmetric ion mobility filter and detection system
6639212	2003	52	10.05	National Research Council of Canada	Method for separation of isomers & different conformations of ions in gaseous phase
6495823	2002	63	9.57	Charles Stark Draper Laboratory Inc	Micro-machined field asymmetric ion mobility filter and detection system
6770875	2004	46	9.21	National Research Council of Canada	Apparatus and method for desolvating and focusing ions for introduction into a mass spectrometer
6286482	2001	70	8.93	Cummins Inc.	Premixed charge compression ignition engine with optimal combustion control
6787765	2004	44	8.81	Thermo Electron Corp	FAIMS with non-destructive detection of selectively transmitted ions

Table 3-6 (continued). Highly Cited Patents of Other Organizations (Not the 10 Leading Companies) Linked to Earlier DOE-Attributed Advanced Combustion Patents

Patent	Issue Date	# Cites Received	Citation Index	Assignee	Title
6230683	2001	67	8.55	Cummins Inc.	Premixed charge compression ignition engine with optimal combustion control
6276334	2001	67	8.55	Cummins Inc.	Premixed charge compression ignition engine with optimal combustion control
6753522	2004	43	8.10	Thermo Electron Corp	FAIMS apparatus having plural ion inlets and method therefore
6570265	2003	35	7.42	Hitachi Ltd.	Hybrid vehicle driven by composite torque generated by an internal-combustion engine and an electric motor& method of operating
6774360	2004	37	7.41	National Research Council of Canada	FAIMS apparatus and method using carrier gas of mixed composition

All of the patents in Table 3-6 have Citation Indexes over seven, showing they have been cited at least seven times more than would be expected given their age and technology. Among them are highly cited engine and combustion patents owned by Hitachi (US #6,739,295 and US #6,570,265) and by Cummins (US #6,561,157 and US #6,286,482).

Also among the highly cited patents of Table 3-6 are spectrometry patents assigned to the National Research Council of Canada (US #6,504,149 and US #6,621,077), Draper Labs (US #6,512,224 and US #6,495,823), and Thermo Electron (US #6,787,765 and US #6,753,522). The presence of these highly cited spectrometry patents linked to earlier DOE-attributed patents suggests that DOE-funded research has established part of the foundation for high-impact spectrometry technologies further developed by a variety of organizations.

3.4.6 Highly Cited DOE-Attributed Advanced Combustion Patents

Citation Index values are used in the identification of highly cited (high-impact) DOE-attributed advanced combustion patents, based on a single generation of citations.[26] The results are shown in Table 3-7. The patents included in the table have Citation Index values ranging from 1.51 to 8.51. These values indicate that each of them has been cited at least 50% more frequently than would be expected based on its age and technology area, and, in most cases, much more frequently.

The patents in Table 3-7 describe a wide variety of engine and combustion technologies, and are assigned to a range of different organizations. At the top of Table 3-7 is US #6,923,167,

[26] Computations of Citation Index values require the use of a single generation of citations.

developed by LLNL and assigned to the University of California. It describes an HCCI engine including exhaust gas recirculation. Since being issued in 2005, this patent has been cited by 17 subsequent patents. The average number of citations for a 2005 patent in the same technology is approximately two, so this LLNL-developed patent has been cited more than eight times as often as expected, as indicated by its Citation Index of 8.51.

There are also two relatively recent Caterpillar patents near the head of Table 3-7. The first of these patents (US #6,769,635) describes a fuel injection technique, while the second (US #6,706,660) describes an exhaust catalyst specifically designed for use with lean burn engines. Both of these patents have already attracted many more citations than expected since they were issued in 2004, suggesting that they are having relatively immediate impact on subsequent technology developments.

Table 3-7 also includes a number of older patents that have been cited frequently by subsequent patents. These include the Sandia ion mobility spectrometry patent (US #5,789,745) discussed previously. They also include two patents developed by Argonne National Laboratory, and assigned to the University of Chicago (US #5,649,517 and US #5,636,619). These patents were issued in 1997 and describe a method for decreasing emissions by introducing oxygen or nitrogen into the engine intake. There are also highly cited Lockheed Martin patents in the table describing additives for diesel fuel designed to reduce emissions (US #5,746,783), and methods for removing particulates from fuel injectors (US #5,803,983).

These findings support the conclusion that DOE has funded the development of more than a dozen high-impact combustion technologies, rather than having only one or two successes. This is despite the relatively short period over which most of the DOE-attributed patents cluster (1999-early 2009) and the relatively small set of patents.

Table 3-7. Highly Cited DOE-Attributed Advanced Combustion Patents Identified Through One Generation of Forward Tracing and Use of a Citation Index

Patent	Issue Date	# Cites Received	Citation Index	Assignee	Title
6923167	2005	17	8.51	University of California	Controlling and operating homogeneous charge compression ignition (HCCI) engines
6769635	2004	14	6.05	Caterpillar Inc	Mixed mode fuel injector with individually moveable needle valve members
5789745	1998	72	5.41	Sandia Corp.	Ion mobility spectrometer using frequency-domain separation
6706660	2004	10	4.81	Caterpillar Inc	Metal/metal oxide doped oxide catalysts having high de NO_x selectivity for lean NO_x exhaust after-treatment systems

Table 3-7 (continued). Highly Cited DOE-Attributed Advanced Combustion Patents Identified Through One Generation of Forward Tracing and Use of a Citation Index

Patent	Issue Date	# Cites Received	Citation Index	Assignee	Title
6035640	2000	45	4.05	Ford Motor Co.	Control method for turbocharged diesel engines having exhaust gas recirculation
5649517	1997	39	3.89	University of Chicago	Variable oxygen/nitrogen enriched intake air system for internal combustion engine applications
5746783	1998	20	2.75	Lockheed Martin	Low emissions diesel fuel
4924828	1990	23	2.24	University of California	Method and system for controlled combustion engines
5636619	1997	22	2.20	University of Chicago	Method and apparatus for reducing cold-phase emissions by utilizing oxygen-enriched intake air
6199519	2001	13	2.10	Sandia Corp	Free-piston engine
5803983	1998	15	1.91	Lockheed Martin	Method for removing solid particulate material from within liquid fuel injector assemblies
6116026	2000	21	1.89	Daimler (Detroit Diesel)	Engine air intake manifold having built-in intercooler
6202407	2001	17	1.51	University of California	NO_x reduction system utilizing pulsed hydrocarbon injection

Table 3-8 extends the analysis shown in the previous table by examining two generation of citations of DOE-attributed advanced combustion patents. It also divides the citations of the DOE-attributed patent families into two groups: (1) citations by patents of the 10 leading vehicle and engine companies, and 2) citations by patents of all other organizations. Separating these citing patent families into two groups makes it possible to identify the DOE-attributed advanced combustion patents whose influence on subsequent combustion technologies of the leading vehicle and engine companies has been particularly strong, and those that have had notable influence beyond technologies developed by these companies. The table lists DOE-attributed anchor patent by those with the largest total number of citations over two generations of citations.

Almost one-third of the 339 patent families linked to the DOE patent at the head of Table 3-8—US #4,924,828, developed at LBNL and assigned to the University of California—are combustion patent families owned by the 10 leading vehicle and engine companies. The patent describes fuel injection for diesel engines. Two-thirds of the citations are by patents owned by other organizations.

Similarly, 40% of the 165 patent families linked to DOE-attributed patent US #6,035,640—a Ford patent describing intake for turbocharged engines—are combustion patent families owned by the 10 leading companies. Sixty percent are citations by patents owned by other organizations.

Another example of a highly cited patent linked strongly to combustion patent families of the 10 leading companies is US #6,843,231—a patent at the bottom of the table assigned to Caterpillar describing cylinder to cylinder balancing using intake valve actuation. A little more than half of its citations are by combustion patent families owned by the 10 leading companies.

Turning to examples of DOE-attributed advanced combustion patents whose influence extends strongly beyond combustion technologies developed by leading companies, the patent in second place in Table 3-8 is prominent. It is the Sandia ion mobility spectrometry patent (US #5,789,745) highlighted previously. Of the 200 patent families linked to this Sandia patent, none are combustion families owned by the 10 leading vehicle and engine companies.

Similarly, none of the 58 patent families linked to DOE-attributed patent US #5,451,781—a patent developed by LLNL and assigned to the University of California describing a mass spectrometer—are combustion patent families owned by the leading companies. Another example is US #5876195—also developed by LLNL and assigned to the University of California describing laser preheat enhanced ignition—whose 40 links all lie outside the combustion patent families of the 10 leading companies.

These findings reinforce the conclusion that DOE's spectrometry research—used to improve understanding of in-cylinder combustion processes—has had a broader impact beyond subsequent developments in combustion technology. Further investigation showed this impact to extend to technologies designed to detect materials such as narcotics and explosives. In addition, most of the other highly cited patents among the DOE-attributed advanced combustion patents are linked well beyond the combustion patent families of the 10 leading vehicle and engine companies.

Table 3-8. DOE-Attributed Advanced Combustion Patent Families Linked to the Largest Number of Subsequent Patent Families in Combustion and in Other Fields through Two Generations of Citations

DOE Anchor Patent[a]	Issue Year	Total Linked Patents	# Linked Combustion Patents of Leading Cos	# Other Linked Patents	Assignee	Title
4924828	1990	339	110	229	University of California	Method and system for controlled combustion engines
5789745	1998	200	0	200	Sandia Corp.	Ion mobility spectrometer using frequency-domain separation
6035640	2000	165	66	99	Ford Motor Co.	Control method for turbocharged diesel engines having exhaust gas recirculation

Table 3-8 (continued). DOE-Attributed Advanced Combustion Patent Families Linked to the Largest Number of Subsequent Patent Families in Combustion and in Other Fields through Two Generations of Citations

DOE Anchor Patent[a]	Issue Year	Total Linked Patents	# Linked Combustion Patents of Leading Cos	# Other Linked Patents	Assignee	Title
6116026	2000	135	39	96	Detroit Diesel	Engine air intake manifold having built-in intercooler
4974571	1990	122	19	103	University of California	Pulsed jet combustion generator for non premixed charge engines
4493297	1985	121	12	109	Geo-Centers Inc.	Plasma jet ignition device
6119451	2000	111	12	99	University of California	Nitrogen oxide removal using diesel fuel and a catalyst
6173567	2001	87	27	60	University of Chicago	Method to reduce diesel engine exhaust emissions
6055808	2000	84	24	60	University of Chicago	Method and apparatus for reducing particulates and NO_x emissions from diesel engines utilizing oxygen enriched combustion air
4926818	1990	68	9	59	University of California	Pulsed jet combustion generator for premixed charge engines
5746783	1998	65	2	63	Lockheed Martin	Low emissions diesel fuel
5451781	1995	58	0	58	University of California	Mini ion trap mass spectrometer
5671716	1997	43	18	25	Ford Motor Co.	Fuel injection system and strategy
5271365	1993	41	10	31	U.S. Dept. of Energy	Jet plume injection and combustion system for internal combustion engines
5876195	1999	40	0	40	University of California	Laser preheat enhanced ignition
6199519	2001	33	1	32	Sandia Corp.	Free-piston engine
5921221	1999	30	2	28	Lockheed Martin/Ford	Method of controlling cyclic variation in engine combustion
6843231	2005	29	27	2	Caterpillar Inc.	Cylinder to cylinder balancing using intake valve actuation

[a]The "anchor patent," generally the first granted U.S. patent in a family, is used to designate each patent family.

3.4.7 Highlights of Findings from the Individual Patent-Level Analysis

Both backward and forward patent tracing were used to identify particularly influential patents based either directly on DOE-funded research or linked to it. The analysis was organized according to the series of questions posed at the beginning of Section 3.5. A conclusion was that over a relatively short period DOE has funded the development of more than a dozen high-impact advanced combustion technologies. Among the results, assessed from multiple perspectives, are those reported below:

- DOE-attributed advanced combustion patent families that are linked to the largest number of subsequent combustion patent families of the 10 leading vehicle and engine companies describe improved fuel injection techniques, cylinder-to-cylinder balancing, HCCI, EGR, and other methods of engine control and exhaust emissions reduction.
- DOE-attributed "other" patent families (i.e., those not included in the combustion set of 109) that are linked to the largest number of subsequent combustion patent families of the 10 leading companies tend to be relatively older patents. Most notable of these are those that describe a method for allowing multiple fuels to be supplied to an engine, and staged direct fuel injection for diesel engines.
- The group of patent families of leading companies linked back to the most DOE-attributed combustion patents features a patent assigned to General Motors that describes fuel injection for spark-ignited direct injection engines; a number of very recent patents assigned to Caterpillar, which describe various advanced combustion engine techniques, such as a compression ignition device; and a patent assigned to Ford describing methods for reducing NO_x emissions.
- Highly cited combustion patent families of leading companies linked to earlier DOE-attributed combustion patent families include a patent assigned to Ford describing a method for transitioning between HCCI and spark ignition operation; patents assigned to Toyota, Ford, Chrysler, and Caterpillar describing EGR technologies; a Toyota patent describing a fuel injection system enabling the use of lower octane fuel; and a Nissan patent describing variable valve control for combustion engines.
- Highly cited patents of other organizations (not among the list of 10 leading vehicle and engine companies) that are linked to earlier DOE-attributed advanced combustion patent families include engine and combustion patents owned by Hitachi and by Cummins; and spectrometry patents assigned to the National Research Council of Canada, Draper Labs, and Thermo Electron.

- The most highly cited of the DOE-attributed advanced combustion patents describe a wide variety of engine and combustion technologies, assigned to a range of different organizations. Among these is a patent developed by LLNL and assigned to the University of California describing an HCCI engine; patents assigned to Caterpillar describing a fuel injection technique and exhaust catalyst specifically designed for use with lean burn engines; an ion mobility spectrometry patent assigned to SNL; two patents developed by Argonne National Laboratory and assigned to the University of Chicago describing a method for decreasing emissions by introducing oxygen or nitrogen into the engine intake; a patent assigned to Lockheed Martin describing additives for diesel fuel designed to reduce emissions, and methods for removing particulates from fuel injectors.

3.5 Summary of Chapter 3 Findings

The assessment of DOE-attributed patents in advanced energy combustion identified 109 patent families (i.e., groups of patents based on the same invention) containing a total of 166 individual patents. Most of these patents were filed since 1999, and are assigned to multiple organizations, including companies, universities, DOE laboratories, and organizations managing DOE laboratories.

To identify the research base on which combustion patents of leading vehicle and engine companies had built, the study identified 22,103 patent families related to combustion technology and assigned to the 10 most innovative vehicle and engine companies as indicated by their volume of patenting. The 22,103 patent families related to combustion were used as the starting point for the backward tracing analysis.

Compared with the body of combustion patent families produced by these 10 leading companies, the DOE-attributed advanced combustion patent set of 109 is quite small. The small number of DOE-attributed combustion patent families and the relatively recent average issue date are reflective of the fact that the DOE ACE R&D was aimed at overcoming specific persistent and challenging technical barriers within a mature industry.

In an international comparison of where the priority patents of combustion patent families have been filed, it was found that the 10 leading vehicle and engine companies filed most of their priority patents in the United States, followed by Japan. Moreover, it appears that most of the impact of DOE-attributed advanced combustion patents has been on subsequent technologies developed in the United States.

Findings from the study's backward patent tracing analysis found that combustion patenting of the 10 leading companies built substantially on the set of earlier DOE-attributed advanced combustion patent families. To compare the influence of DOE's ACE R&D with that of the 10 leading companies, an adjustment was made for the much larger and older combustion patent portfolios of the companies by examining the period since 1999 and using average citing per patent issued. Since 1999, the average number of citations of DOE-attributed advanced combustion patent families by the 10 leading companies' combustion patent families was second only to that of Nissan. An analysis of the leading companies' combustion patent portfolios

revealed Caterpillar, Ford, and Chrysler as those leading companies whose portfolios have built particularly extensively on the DOE-funded advanced combustion research.

The study's forward patent tracing analysis started with the 109 DOE-attributed advanced combustion patent families and traced their linkages to subsequent developments both inside and outside vehicle engine combustion technology. The study found linkages from the DOE-attributed combustion patent families to related combustion technologies developed not only by the 10 leading companies but also by other leading companies in the field of engine technology, including Cummins, Bosch, and Hitachi. Forward patent tracing also revealed three organizations—Thermo Electron Corporation, Sionex Corporation, and Charles Stark Draper Laboratory—that have patents linked to earlier DOE-funded advanced combustion research through a non-combustion technology, namely ion mobility spectrometry. The forward tracing analysis also identified broad topic areas of linkages as indicated by International Patent Classifications (IPCs). The results suggested that the influence of DOE's advanced combustion research was strongest on subsequent developments in engine and combustion technologies, as intended by the DOE Program, but also found linkages in the areas of "separation of materials," "digital data processing," and "separation using catalysts."

Both backward and forward patent tracing were used to identify particularly influential patents based either directly on DOE-funded research or linked to it. A conclusion was that over a relatively short period DOE has funded the development of more than a dozen high-impact combustion technologies. The most highly cited of the DOE-attributed advanced combustion patents describe a wide variety of engine and combustion technologies, assigned to a range of organizations. Among these is a patent developed by LLNL and assigned to the University of California describing an HCCI engine; patents assigned to Caterpillar describing a fuel injection technique and exhaust catalyst specifically designed for use with lean burn engines; a patent developed by SNL describing ion mobility spectrometry technology; patents developed by Argonne National Laboratory (ANL) and assigned to the University of Chicago describing a method for decreasing emissions by introducing oxygen or nitrogen into the engine intake; and patents assigned to Lockheed Martin describing additives for diesel fuel designed to reduce emissions and methods for removing particulates from fuel injectors.

In addition, there are highly cited (high-impact) combustion patent families of leading companies linked to earlier DOE-attributed combustion patent families, including a patent assigned to Ford describing a method for transitioning between HCCI and spark ignition operation; patents assigned to Toyota, Ford, Chrysler, and Caterpillar describing EGR technologies; a patent assigned to Toyota describing a fuel injection system enabling the use of lower octane fuel; and a patent assigned to Nissan describing variable valve control for combustion engines. There are also highly cited patents of other organizations that are linked to earlier DOE-attributed advanced combustion patent families, including engine and combustion patents assigned to Hitachi and by Cummins; and spectrometry patents assigned to the National Research Council of Canada, Draper Labs, and Thermo Electron.

4. Publication Analysis

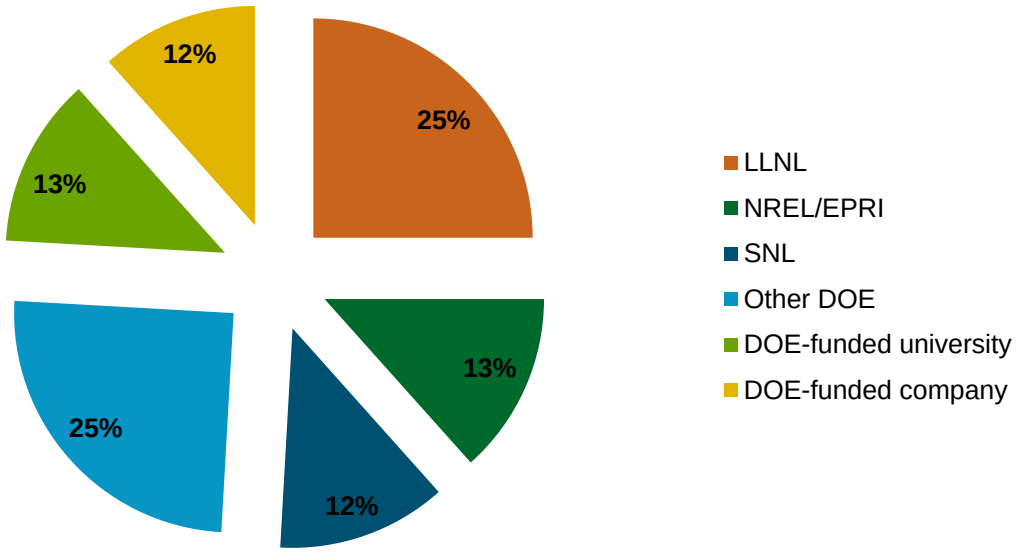
The analysis of publications includes both a co-author analysis and a citation analysis. It is based on two sets of DOE-funded publications: a set of DOE-published reports drawn from the DOE OSTI database using a keyword search, and a set of DOE-contributed papers in combustion-related publications of SAE.[27]

4.1 Analysis of the OSTI Publication Set

4.1.1 Publication Profile

Figure 4-1 shows the organizations credited with the DOE-attributed publications that were drawn from the OSTI database. The OSTI publication set is composed of 25% LLNL publications, 13% NREL publications, 12% SNL publications, 13% university publications,[28] 12% company publications, and 25% "other" DOE publications, including publications credited to Los Alamos National Laboratory (LANL), Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), DOE/NASA, and various other organizations.

Figure 4-1. Publications Based on DOE-Funded Research in Advanced Combustion Drawn from the OSTI Database, Shown by Performing Organization

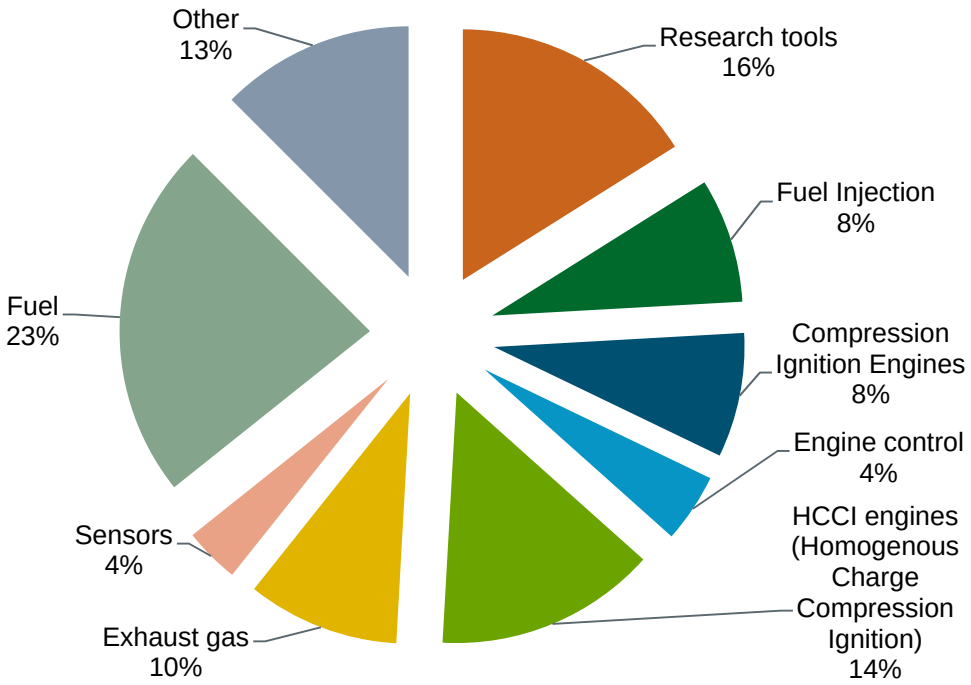


[27] For more details about these two publications sets used in the analysis, see Section 2.6.
[28] These were publications identified as sponsored by DOE, but without an additional DOE identifier. The assumption is that these are papers sponsored by University centers with partial DOE funding.

Slightly more than half (54%) of this set of publications are technical reports, and the rest are mostly conference papers (45%). The remainder (1%) includes theses and dissertations, and miscellaneous types of publications.

Figure 4-2 shows the topical distribution of the OSTI set of DOE combustion publications. Fuel-related topics comprised 23%; research tools accounted for 16% of the total set; HCCI engines accounted for another 14%; exhaust gas, 10%; fuel injection, 8%; engine control and sensors, 4% each; and other, 13%.

Figure 4-2. Distribution of the OSTI Set of DOE Advanced Combustion Publications by Topic

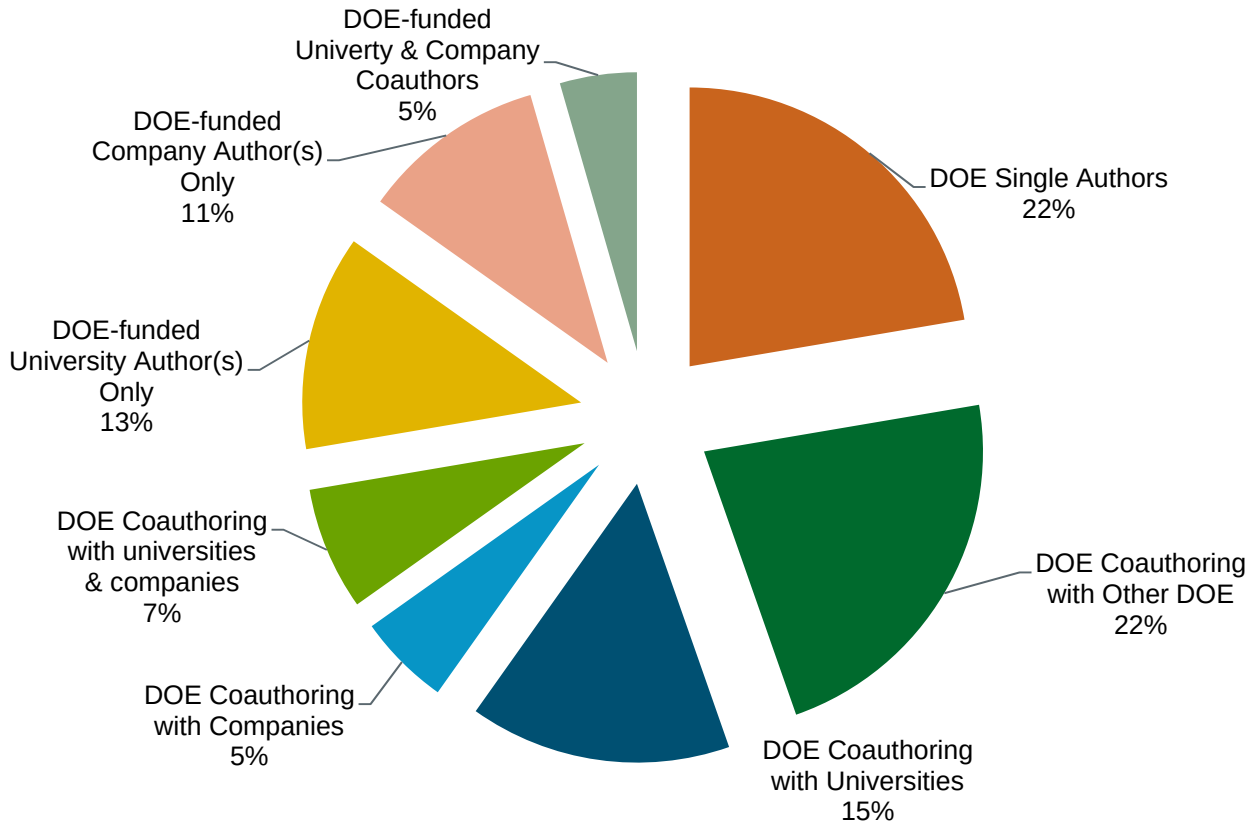


4.1.2 Author/Co-Author Analysis

Figure 4-3 shows the authors and co-authors of the OSTI set of publications by affiliation. Co-authoring collaborations are of interest because they provide another path by which DOE research results are transferred out of the lab. The figure shows that slightly more than a quarter of the publications were co-authored by DOE with outside researchers—5% with university researchers; another 5% with company researchers; and 7% jointly with universities and companies. University researchers alone authored 13% of the publications; company researchers alone authored 11%; and universities and companies in combination co-authored 5%. Co-authoring between university and company researchers is also of special interest in that it may accelerate the transfer of DOE-funded research out of the university and into commercialization.

The remaining 44% of the publications were evenly divided between authorship by DOE researchers alone and by multiple DOE researchers co-authoring with one another. Among the company researchers co-authoring with DOE were those from Ford Motor Company, ConocoPhillips, Air Products and Chemicals, Inc., Shell Global Solutions, and Cummins Engine Company. University researchers co-authoring with DOE included those from the University of California at Berkeley, University of Michigan, University of Wisconsin, University of Tennessee, and the University of West Virginia.

Figure 4-3. Distribution of the OSTI Set of DOE Advanced Combustion Publications by Author/Co-Author Organizational Affiliation



4.1.3 Publication Citation Analysis

As of late 2009, slightly more than 20% of these OSTI publications had been cited six or more times, and 6% had been cited more than 40 times each. As shown by Figure 4-4, no citations were found for 55% of this set of OSTI publications.

Among the publications in this set with the highest number of citations are two LANL technical reports pertaining to the KIVA Code (one of these publications, *Implementation of the Turn Function Method in KIVA-F90*, LA-13313-MS, by O'Rourke, Fairfield, et al, published in 1993,

has been cited 266 times; and the other, *KIVA-3V, Release 2: Improvements to KIVA-3V*, LA-13608-MS, by Amsden, published in 1999, has been cited 63 times). LANL was instrumental in developing KIVA, a multi-dimensional model and computer code for the analysis of chemically reacting flows with sprays. KIVA provides 3D simulation of the in-cylinder processes of an advanced diesel engine.

While the dissemination of computer models and code generally tend not to be well captured by patent and publication citation analysis, in this case the frequent citing of these two technical reports on KIVA serve to signal its significance. Another indicator of its significance would be data on the extent of its licensing from DOE.[29]

Figure 4-4. Distribution of the OSTI Set of DOE Advanced Combustion Publications by Number of Citations Received

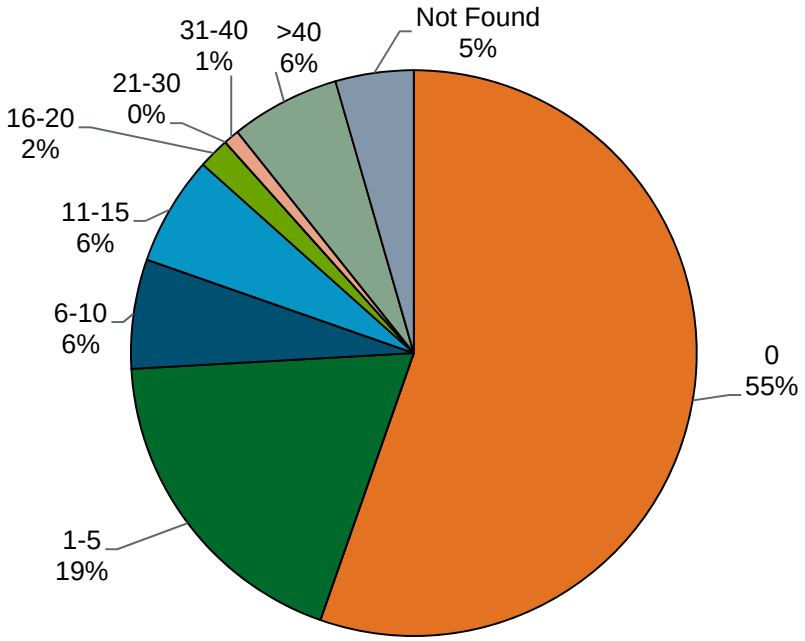


Table 4-1 shows the affiliations of some of those citing the two heavily cited KIVA technical reports. Citing by U.S. and foreign universities is apparent. Multiple citing was found by Ford General Motors, and Caterpillar—three companies active in engine design and manufacture.

The citation analysis also found evidence of multiple applications of KIVA. Not only were the KIVA publications cited, as expected, by publications on engine simulations and vaporization of gasoline in direct injection and HCCI engines, but also in scientific papers on fluid-particle interaction models defined more broadly, and even in a paper on modeling biospray for upper airways of humans. These findings suggest that the KIVA models and codes have found

[29] The code is available for a fee from DOE's Energy Science and Technology Software Center (ESTSC) 865-576-2606. www.lanl.gov/orgs/t/t3/codes/kiva.shtml. LANL also distributes the KIVA code to its R&D collaborators.

application not only in the automotive industry, but also as a more general research tool, and in other industries, including medicine.

Other highly cited publications include four conference reports by LLNL researchers, published by the University of California. The most cited of these was *A Sequential Fluid-mechanic Chemical-kinetic Model of Propane HCCI Combustion*, UCRL-JC-14527, 2000, by Aceves, Flowers , et al., with co-authors from Cummins Engine Company, the University of Wisconsin-Madison, and the University of California-Berkeley.

The three other highly cited conference reports by LLNL were *Compression Ratio Effect on Methane HCCI Combustion*, UCRL-JC-131908, 1998, by Aceves, Pitz, Smith, et al.; *Detailed Chemical Kinetic Modeling of Diesel Combustion with Exygenated Fuels*, UCRL-JC-135216, 2000, by Curran, Fisher, Glaude, et al.; and *HCCI in a CFR Engine; Experiments and Detailed Kinetic Modeling*, UCRL-JC-136454, by Flowers, Aceves, and Smith, together with co-authors from University of California-Berkeley, 1999.

Affiliations of those citing these four LLNL papers included Caterpillar, Markel Engineering, Hilltner Combustion Systems, Ford, General Motors, Volvo Powertrain, Shell Global Solutions, ExxonMobil Research and Engineering Company, Jaguar Cars Ltd, Renault SA, United Technologies Research Center, other DOE researchers, National Institute of Standards and Technology, Swedish Royal Institute of Technology, and a variety of domestic and foreign universities and other institutions.

Another highly cited paper among this DOE combustion set drawn from the OSTI database was another conference report, this one published by SAE entitled *Emissions from Trucks using Fischer-Tropsch Diesel Fuel*, SAE/TPS-982526, 1998, by Norton, Vertin, Bailey, et al. The authors were NREL researchers with other DOE co-authors, together with co-authors from West Virginia University. Affiliations of those citing this SAE paper include environmental and health offices in NY State, Canada, Sweden, Australia, and Taiwan. Affiliations of those citing also include ExxonMobil, Shell, various engineering and consulting companies, national institutes, research councils, and universities.

The analysis of affiliations of these several papers suggests that the results of DOE-funded combustion research disseminated through publications are reaching the appropriate and intended audiences. It suggests that DOE's combustion research results are being taken up by companies, thereby providing a direct path to commercialization; by universities, which suggests that it may be providing a base for further research; by other researchers in DOE laboratories, which suggests synergy among DOE researchers in building the knowledge base in advanced combustion; and by a variety of applied institutions concerned with environmental and health effects of emissions. The presence of those citing in diverse fields, such as medicine, suggests influence of the research beyond engines for transportation. A worldwide audience for DOE's combustion research results suggests that its impact is far-reaching.

Table 4-1. Examples of Affiliations of Authors/Co-Authors of Publications that Cite KIVA Code Publications Numbered LA-13313-MS or LA-13608-MS

Companies	Universities and Institutes	DOE & Other U.S. Government & Other Organizations
Caterpillar	University of Wisconsin	Other DOE
Ford Motor Company	University of Michigan	NASA John Glenn Research Center
ICEM CFD Engineering	University of Technology, Sweden	LLNL
General Motors R&D Center	University of Cassino Via G. Di Biasio, Italy	National Traffic Safety & Environment Lab, Japan
Ford Research Center, Aachen, Germany	Purdue University	
Delphi Corporation	University of Illinois	
	Pennsylvania State Uniersity	
	Michigan Technological University	
	Massachusetts Institute of Technology	
	University of Texas at Austin	
	Delft University of Technology, Netherlands	
	Doshisha University, Japan	
	Korean Institute of Machinery & Materials	
	University of Adelaide, Australia	
	Sungkyunkwan University, South Korea	
	University of Toronto	
	Beijing Polytechnic University	
	Swiss Federal Institute of Technology of Lausanne	
	University School of Engineering and Design, Uxbridge, UK	
	Universidad Automonoma de Barcelona	
	University e Sciences et Technologies de Lille	
	Institut fűr Technishche Mechanik, Gemany	

4.2 Analysis of the SAE Publication Set

The second set of publications analyzed are all papers based on DOE-funded combustion research and published in SAE publications—namely, two SAE special publication series[30] and an SAE journal all related to combustion. The two special publication series are 1) *Combustion and Flow Diagnostics*, with seven annual volumes published from 2003-2009; and 2) *Compression Ignition Processes*, with five annual volumes published from 2005-2009. The journal is the *SAE International Journal of Engines*, for which two issues in 2009 are included in the analysis. These publications are available to SAE members, among which companies from the vehicle and engine industries targeted by DOE's advanced combustion research figure prominently. Thus, these publications appear to provide a direct path of knowledge flow from DOE advanced combustion research to commercial vehicle and engine producers.

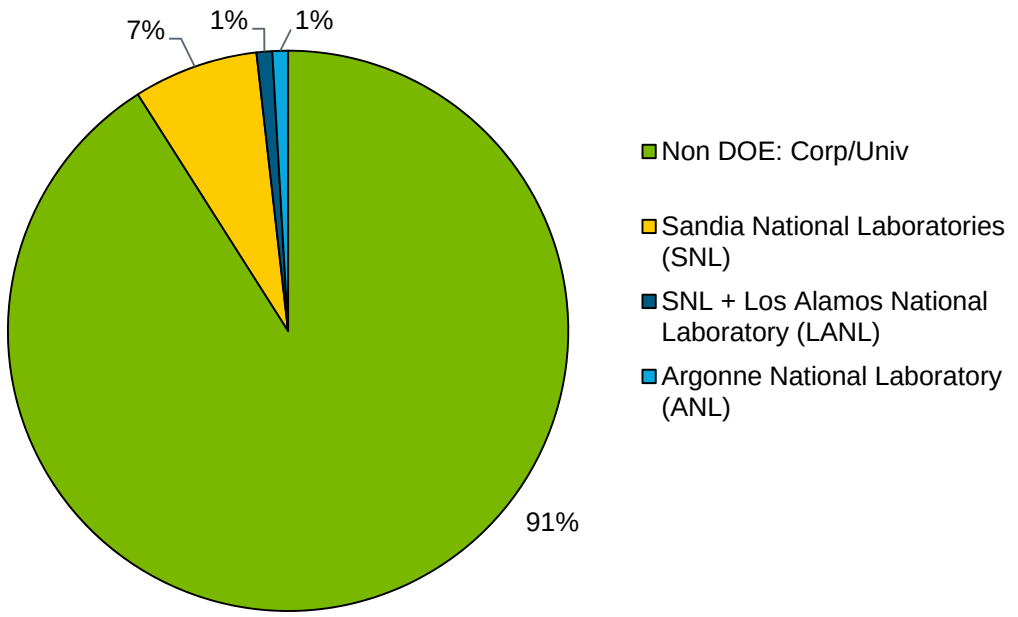
Each of these three SAE publication sources is analyzed separately below.

1) Analysis of DOE Contributions to SAE Special Publication Series, *Combustion and Flow Diagnostics*, Seven Annual Volumes 2003-2009:

Papers in the seven volumes of this SAE Special Publication Series totaled 111. As shown in Figure 4-5, 9% of the papers in the series included DOE laboratory contributors. Nearly all of these contributors were SNL researchers. In addition, researchers at ANL and LANL co-authored several of the papers. Most of the papers in the series were authored by company and university researchers.

[30] An SAE special publication is a print collection of technical papers from one or more sessions of an SAE conference. The topics reflect key challenges facing the industry (SAE International).

Figure 4-5. Distribution of SAE Papers in the Special Publication Series, *Combustion and Flow Diagnostics*, Seven Annual Volumes Issued 2003-2009, by Composition of Author Affiliation



As shown in Figure 4-6, the DOE contribution of papers to this SAE series grew over time. In the first three volumes, no contributions by DOE laboratory authors were found, but contributions were found in the last four volumes.

Despite their recent publication, the majority of these papers with DOE co-authoring have been cited at least once. Table 4-2 gives examples of the affiliations of those citing these reports. The largest group comprises domestic and foreign universities. Companies are also represented.

Among the DOE authors of these papers were a half-dozen with the SAE designation "prolific authorship." This designation was defined by SAE as meaning that each author had contributed more than 10 papers to SAE publications. These "prolific" DOE authors included Jin Wang of ANL, Charles Mueller of SNL, Lyle Pickett of SNL, Paul Miles of SNL's CRF, John Dec of SNL, and Richard Steeper of SNL.

Figure 4-6. Number of DOE Researchers' Contribution of Papers to SAE Series *Combustion and Flow Diagnostics, 2003-2009*

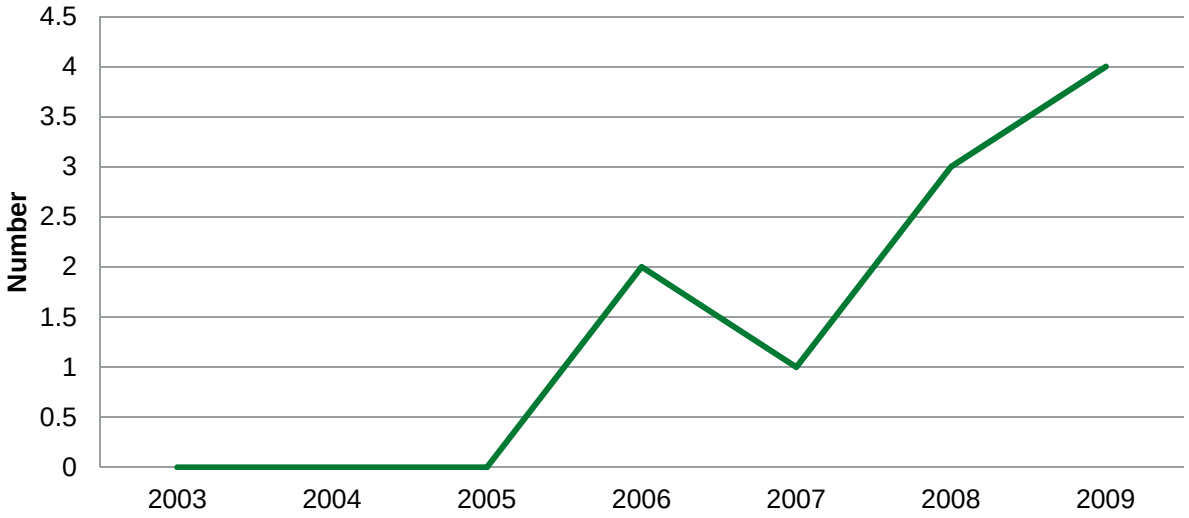
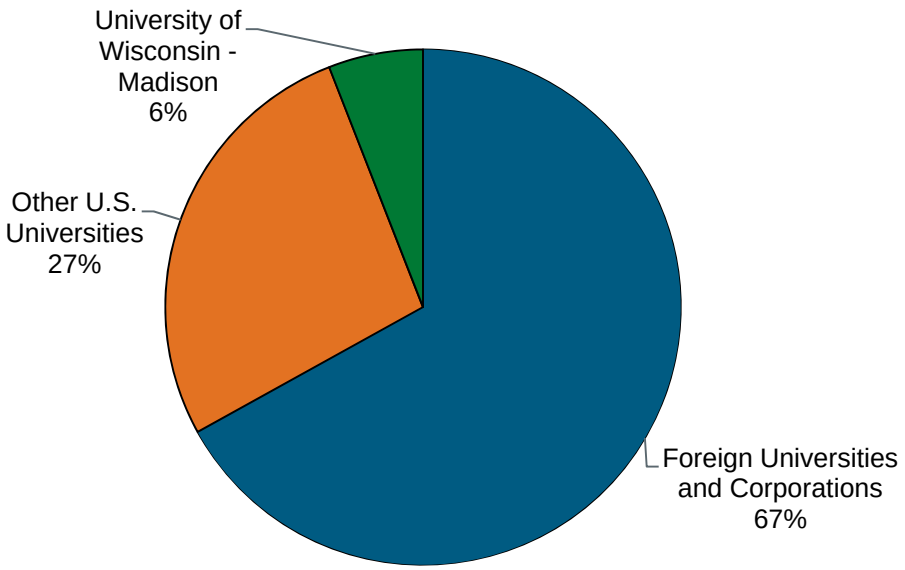


Table 4-2. Examples of Affiliations of Authors/Co-Authors of Publications that Cite Papers Co-Authored by DOE Researchers in the SAE Series *Combustion and Flow Diagnostics, 2003-2009*

DOE Affiliated	Company Affiliated	University Affiliated
SNL	Delphi Powertrain Systems	Cornell University
ORNL	Mitsubishi Electric Corp.	University of Wisconsin-Madison
	UMAK Consultants, Canada	Stanford University
	Robert Bosch GmbH	Wayne State University
		University of Hiroshima, Japan
		Okayama University
		University of Duisburg-Essen, Germany
		Imperial College, London

Contributions by researchers from the University of Wisconsin and other U.S. universities to papers in this SAE series are highlighted in Figure 4-7. This figure shows a breakdown of the 91% of papers in Figure 4-5 that did not include direct contributions by researchers at DOE laboratories. Domestic university contributions are of interest because often the combustion research laboratories of U.S. universities receive support from the DOE ACE R&D Subprogram. For example, DOE support for the Combustion Research Laboratory at the University of Wisconsin is acknowledged by the University on its website. U.S. university researchers, including University of Wisconsin researchers, contributed a third of the total papers in Figure 4-7, and the University of Wisconsin contributed 6%.

Figure 4-7. Contribution of University of Wisconsin-Madison Researchers to Papers in the SAE Special Publication Series, *Combustion and Flow Diagnostics*, Annual Volumes 2003-2009



2) Analysis of DOE Contributions to SAE Special Publication Series, *Compression Ignition Combustion Processes*, Five Annual Volumes 2005-2009:[31]

A similar analysis of the second SAE special publication series produced comparable results to the first. Again, SNL researcher contributions to the series increased over time. Again, the total share of papers with direct contributions by DOE laboratory researchers was near the 10% mark, though higher than for the former series.

Most of the papers with DOE researcher contributions had been cited once and a third of them more than 5 times. Table 4-3 gives examples of the affiliations of those citing these papers.

[31] The annual volume in the series for 2006 was not found and appears to have been omitted from the series.

Table 4-3. Examples of Affiliations of Authors/Co-Authors of Publications that Cite Papers Co-Authored by DOE Researchers in the SAE Special Publication Series, *Compression Ignition Combustion Processes,* Annual Volumes 2005-2009

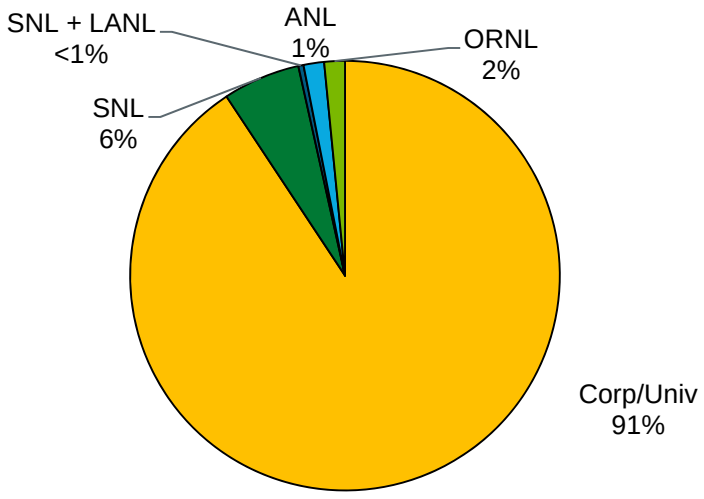
DOE & Other U.S. Gov't Affiliated	Company Affiliated	University Affiliated
SNL	General Motors R&D	Princeton University
US Army TARDEC	Caterpillar	Wayne State University
		University of Michigan
		University of Wisconsin-Madison
		Tokyo Institute of Technology
		Shanghai Jiaotong University
		Tianjin University, China

Researchers from U.S. universities contributed to about a fourth of the papers in the series, with University of Wisconsin researchers contributing to 15% of the papers of the second special publication series.

(3) Analysis of DOE Contributions to the *SAE International Journal of Engines, 2 volumes from 2009*

The first volume, issued in April 2009, contained 114 papers. The second volume, issued in October 2009, contained 144 papers, for a total of 258 papers. Figure 4-8 shows the share of these 258 papers having contributions by DOE laboratory researchers. Again, the breakdown is quite similar to the results for the SAE special publications, in that the DOE direct share is close to 10%, and that share is accounted for mainly by SNL contributions. Researchers from ORNL, ANL, and LANL also contributed.

Figure 4-8. Share of DOE-Contributed Papers in the *SAE International Journal of Engines,* 2009



Nearly half the papers with DOE contributions had been cited at least once, despite the 2009 publication date, and several already had as many as six citations. Table 4-4 gives examples of the affiliations of those citing the SAE journal papers with DOE co-authors. The companies and universities citing the journal papers appear more often to be based in the United States than those citing the special publication collection of conference papers. This is not surprising in that conferences often attract international audiences.

Table 4-4. Examples of Affiliations of Authors/Co-Authors of Publications that Cite Papers Co-Authored by DOE Researchers in 2009 Issues of the *SAE International Journal of Engines*

DOE Affiliated	Company Affiliated	University Affiliated
ANL	A123 Systems	University of Wisconsin-Madison
INL	The MathWorks	Virginia Tech
ORNL	Caterpillar	Stanford University
SNL	DTNA-Detroit Diesel Corporation	Marquette University
	Delphi Powertrain Systems	University of Illinois
		Wayne State University

Nearly a fifth (50) of the 258 papers in the two 2009 issues *SAE International Journal of Engine* have contributions by U.S. universities. Again, the University of Wisconsin-Madison, with its partially DOE-funded combustion research laboratory, featured prominently as a contributor of papers to the two issues of the Journal examined by the study, contributing 8% of the total.

The analysis of multiple SAE publications confirms that this industry membership organization is providing a path through which the results of ACE R&D are disseminated to companies, universities, and other organizations in the vehicle and engine industries. DOE national laboratory researchers were found to contribute 10% of papers in the two series of SAE special publications examined, and also in two issues of a relevant journal. Moreover, there are numerous other relevant SAE publications, beyond those examined in the study, that also carry papers by DOE researchers in advanced combustion, as well as a sizable contribution of papers by researchers from university combustion research programs that have received DOE funding.

5. Analysis of Tacit Knowledge

DOE's ACE R&D Subprogram has produced other important outputs beyond patents and publications that embody research knowledge and are associated with alternative modes of knowledge dissemination. These other outputs include models and computer codes; test data; laboratory prototypes of components resulting from partnerships and CRADAs with companies and funding of university research; value-added from use of special facilities; and tacit knowledge embodied as human capital through the training of students, the experience gained by researchers, and the network of researchers and research organizations fostered by DOE's funding of research in the field of advanced combustion research. The quality of the research is indicated by numerous awards to both the DOE laboratories and its partners for their research results.

An important output of DOE-funded geothermal research not fully captured by analysis of its more explicit outputs is the creation of tacit knowledge and the fostering of a network among researchers at diverse organizations. Figure 5-1 depicts elements of a network of research organizations funded for advanced combustion research by DOE. A comparison of Figures 5-2a and b, which are DOE's depictions of its funded research participants in 1999 and again in 2001, suggests the relatively rapid increase in the number of organizations involved in DOE-funded advanced combustion research that accompanied the boost in funding in 1999.

5.1 Role of National Laboratories and Special Facilities

DOE laboratories that have played active roles in carrying out advanced combustion research include SNL, LLNL, LANL, ORNL, ANL, Pacific Northwest Nation Laboratory (PNNL), and others. DOE special combustion research facilities that have played important roles in advancing knowledge about the in-cylinder engine combustion process include SNL's Combustion Research Facility (CRF), and ANL's simulated engine-combustion chamber with windows, plus use of X-rays from the Advanced Photon Source (APS)—a third-generation Synchrotron Light Source—to allow researchers to see details of the engine fuel injection process.

5. 2 Partnerships with Industrial Firms

DOE's combustion research program developed many research partnerships with industrial firms that build and use combustion devices and systems. These partners included Detroit Diesel Corporation, Makel Engineering, Inc., General Motors, Ford Motor Company, Chrysler, Cummins Engine Company, Caterpillar, Babcock and Wilcox, Combustion Engineering, Bechtel, General Electric, Westinghouse, Johnson Matthey, Engelhard Corporation, Exxon, Unocal, Chevron and other companies.[32] In still other cases, companies partnered with DOE in CRADAs.

[32] DOE/EERE Annual Reports on Advanced Combustion Engine Technologies identified companies involved in DOE-funded advanced combustion research.

Companies developed and demonstrated laboratory prototype engine hardware, developed and calibrated engine cycle simulation models, and developed new fabrication methods. To some extent these developments are reflected in the patents and publications analyses, but the full effect is unlikely to be captured. Not captured, for example, are impacts on a company's innovation capacity which may be carried over to its other endeavors.[33]

A collaborative research effort to develop relevant components and infrastructure was provided by the FreedomCAR and Fuel Partnership, a collaboration among DOE, energy companies—BP America, Chevron Corporation, ConocoPhillips, Exxon Mobil Corporation, and Shell Hydrogen (US) —and the U.S. Council for Automotive Research (USCAR) with partners Chrysler Corporation, Ford Motor Company, and General Motors Corporation. The collaborating partners jointly have produced technology roadmaps, determined technical requirements, suggested research and development (R&D) priorities, and monitored the R&D activities undertaken to achieve the goals of the Partnership. An additional collaborative effort has been provided by the 21st Century Truck Partnership, an agreement between the federal government and the heavy duty vehicle industry.

5.3 Participating Universities

Trained technologists have resulted from ACE R&D funding of university combustion research, particularly from its funding of special university centers for combustion research, such as that at the University of Wisconsin-Madison. Participating universities in DOE's advanced combustion research have included universities across the nation. Among them are the University of Michigan, the University of Houston, the University of Kentucky, Texas A&M University, the University of Texas, MIT, Stanford University, Princeton University, and others. In addition, as shown in the publication analysis of Chapter 4, both domestic and foreign universities have been users of the resulting publications.

[33] Laidlaw (1997) found evidence of benefits to companies participating in research projects funded by the Advanced Technology Program that were reportedly carried over to other company activities.

Figure 5-1. A Network of Organizations Facilitates Combustion Knowledge Creation and Flow

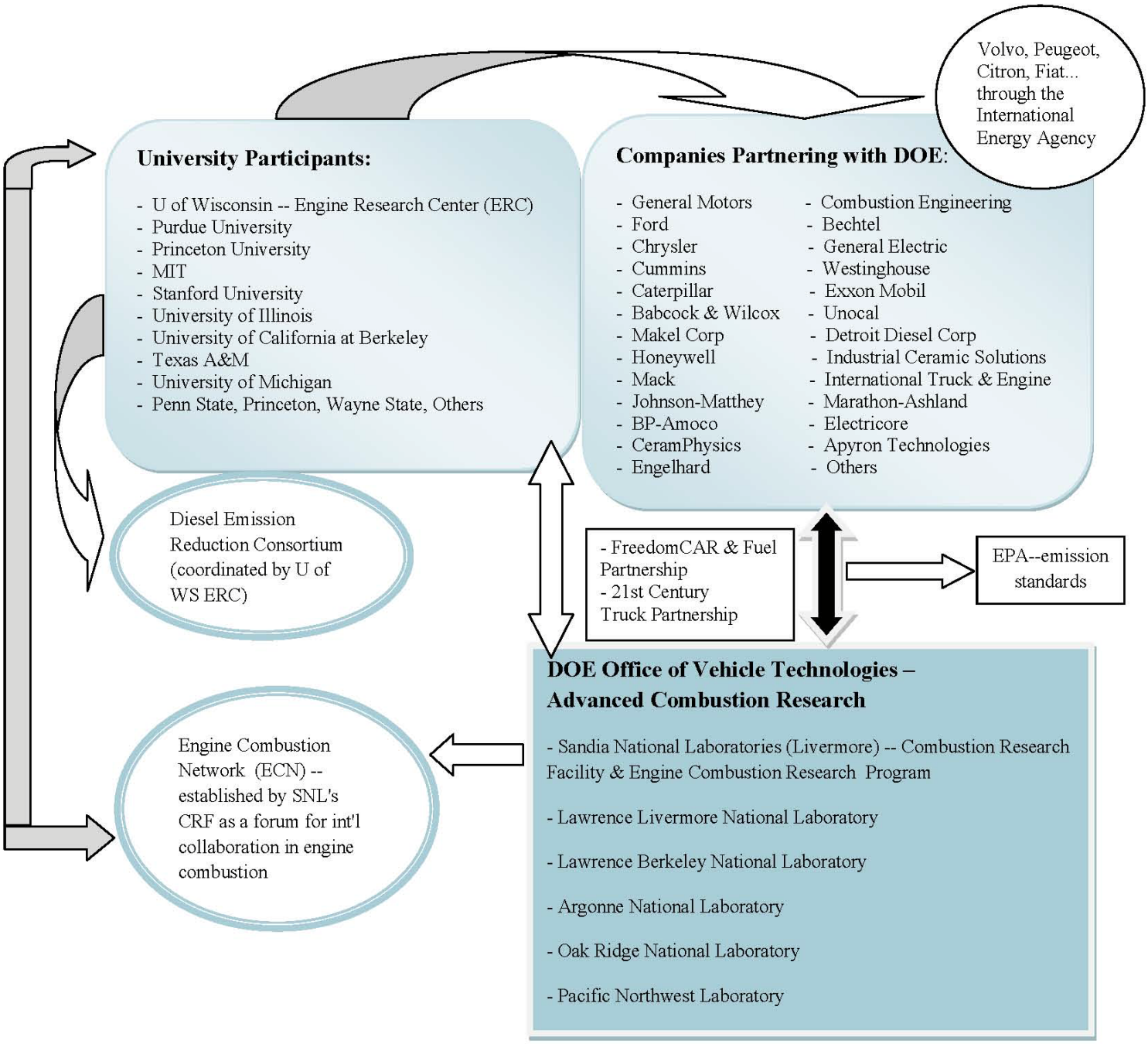
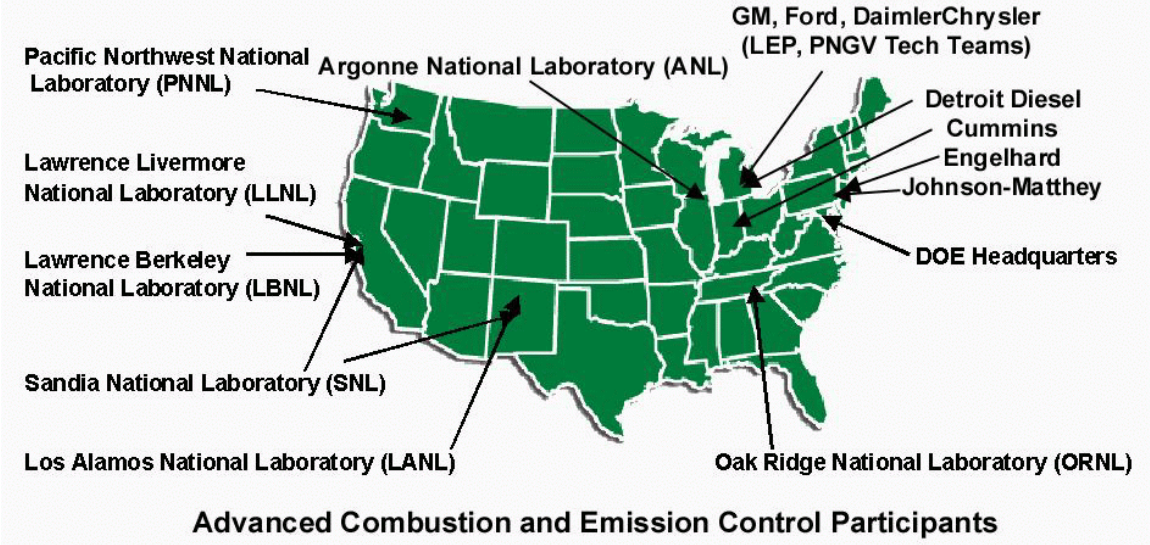
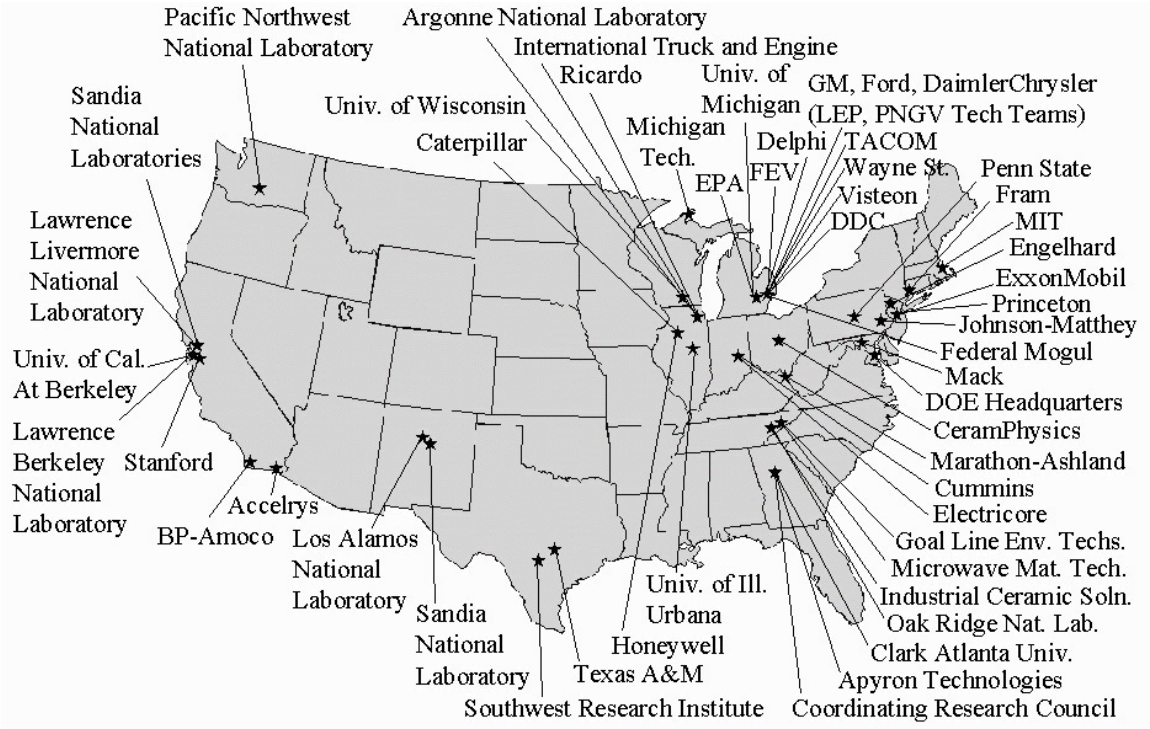


Figure 5-2a. Depiction of Participants in Advanced Combustion and Emission Control in DOE's FY 1999 Combustion and Emission Annual Progress Report



Source: DOE (1999).

Figure 5-2b. Depiction of Participants in Advanced Combustion and Emission Control in DOE's FY 2001 Combustion and Emission Annual Progress Report



Source: DOE (2001).

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Appendix A
Constructing Data Sets Needed for the Patent Analysis

I. Constructing a Data Set of DOE-Attributed Advanced Combustion Patents

The process for constructing a data set of DOE-attributed advanced combustion patents is described in Section 2.4 of the body of the report. It describes the use of a patent filter to identify a candidate list of combustion related patents from the larger population of DOE-attributed patents, but it defers details on construction of the patent filter to this Section I of Appendix A.

As a starting point for the filter, the study identified a set of U.S. Patent Office Classifications (POCs) and International Patent Classifications (IPCs) related to engine combustion. The search was restricted to patents in these IPCs and POCs. Restricting the search by patent classification reduces the chance of including irrelevant patents using the same terms, especially the same acronyms. Both broad IPCs and POCs that relate to combustion technology in general, and specific IPCs and POCs that relate to combustion technologies of particular interest were used in the patent filter. These IPCs and POCs are listed in Table A-1.

Table A-1. IPCs and POCs Used in Advanced Combustion Patent Filter

IPCs/POCs in Patent Filter
Broad IPCs
F02B Internal combustion engines
F02D Controlling combustion engines
F02F Cylinders, pistons or casings for combustion engines
F02M Fuel supply for combustion engines
F02N Starting combustion engines
F02P Ignition and ignition timing for combustion engines
G01N 27/407 Investigating properties of gases
Specific IPCs
F02M 25/06-07 Adding exhaust gases to fuel air mixture (i.e. exhaust gas recirculation)
F02M 39-71 Fuel injection apparatus
H01J 49 Particle spectrometers
Broad POCs
123 Internal combustion engines
60/272-324 Internal combustion engines with treatment of exhaust gas
204/424-429 Gas sample sensors
Specific POCs
60/278-279 Material from exhaust fed to engine intakes (i.e. exhaust gas recirculation)
239/533.1-12 Fuel injectors

DOE-attributed patents in the specific patent classifications were considered for inclusion in the analysis without any further keyword restriction. However, patents in the broad classifications had to use at least one of a set of keywords or phrases, including such keywords as HCCI and compression ignition, to avoid including irrelevant patents. That is, they had to use at least one of the keywords or phrases in Table A-2 to be considered for inclusion.

Thus, the search was (Specific POC/IPC OR (Broad POC/IPC plus keyword)). In the keywords and phrases in Table A-2, "*" is a wildcard denoting unlimited characters, while "?" is a wildcard denoting zero or one character, including a space. Hence, the search "fuel?inject*" includes the terms fuel injection, fuel injector, fuel-injection, etc.

Table A-2. Keywords Used in Advanced Combustion Patent Filter

Keyword	
Homogenous?charge?compression?ignition	Exhaust?gas?re?circulation
HCCI	EGR
Compression?ignition?direct?inject*	Fuel?inject*
CI?DI	Lean?burn
Homogenous?charge	Low?temperature?combustion
Compression?ignition	LTC
Direct?inject*	Spectromet*
NOT gas?turbine, coal, power?plant, power?station, fuel?cell	

Note: "*" is a wildcard denoting unlimited characters; "?" is a wildcard denoting zero or one character, including a space.

II. Identifying the Leading Innovative Vehicle and Engine Companies and their Combustion Patents for Backward Tracing

To serve the purpose of the backward tracing element of the analysis, the study constructed a list of leading innovative vehicle and engine companies defined as those with the largest number of U.S. patents (from all areas) granted since 1992. These companies are listed in Table A-3. The number of patents included those assigned to all company subsidiaries and acquisitions. The study used the combustion patents of the top 10 innovative vehicle and engine companies in the backward tracing analysis.

Table A-3. Vehicle and Engine Companies with the Most US Patents Granted Since 1992

Company	Number of US Patents
Honda	10210
Denso	8699
Toyota	8182
Ford	6854
General Motors	6333
Daimler	5774
Delphi	4670
Nissan	4766
Caterpillar	3768
Fiat	2615

The study then used a patent filter to identify all U.S., EPO, and WIPO combustion patents assigned to each of the 10 companies in Table A-3. This filter was a modified version of the filter used to identify DOE-attributed advanced combustion patents. The filter was modified to include all patents owned by the leading vehicle and engine companies that are classified in any of the broad or specific patent classifications in Table A-1, or that use any of the keywords in Table A-2. Hence, the filter for identifying all U.S., EPO, and WIPO combustion patents assigned to each of the ten companies is (Broad IPC/POC OR Specific IPC/POC OR Keyword).

The modification in the filter was made because the backward tracing element of the study is designed to determine DOE's impact on all combustion technologies owned by leading companies, not just on specific advanced combustion technologies. For example, if a DOE-attributed patent describing an HCCI engine is cited by a subsequent Honda patent describing engine control, this link should be identified in the backward tracing, even if the Honda patent does not make a specific reference to a term such as HCCI. However, patents were removed that use terms related to exhaust gas treatment (such as catalyst, particulate trap, and after-treatment) since, as noted above, patents describing these technologies were considered by DOE to be beyond the scope of the desired analysis.

As a result of this process, the study identified 18,091 U.S. patents, 4,358 EPO patents and 1,556 WIPO patents that are related to combustion technology and are owned by the 10 leading vehicle and engine companies. This set of all U.S., EPO, and WIPO combustion patents/applications owned by the 10 leading vehicle and engine companies was then grouped into 22,103 patent families.

Appendix B
DOE-Attributed Advanced Combustion Patents

Note: Patent list is shown prior to forming individual patents into patent families

Table B-1. List of DOE-Attributed Advanced Combustion Patents in Chronological Order of Issue

Issue Date	Patent	Assignee	Title
1979	4141324	US Dept of Energy	Low emission internal combustion engine
1985	4493297	Geo-Centers Inc	Plasma jet ignition device
1990	4924828	University of California	Method and system for controlled combustion engines
	WO1990010143	University of California	Method and system for controlled combustion engines
	WO1990010512	University of California	Process for producing mold
	4974571	University of California	Pulsed jet combustion generator for non-premixed charge engines
	WO1990010153	University of California	Pulsed jet combustion generator for non-premixed charge engines
	4926818	University of California	Pulsed jet combustion generator for non-Premixed charge engines
1991	5061513	General Electric	Process for depositing hard coating in a nozzle orifice
	WO1991015611	General Electric	Process for depositing hard coating in a nozzle orifice
	EP0460059	University of California	Method and system for controlled combustion engines
	EP0460061	University of California	Pulsed jet combustion generator for non-premixed charge engines
	EP0460077	University of California	Pulsed jet combustion generator for non-pemixed charge engines

Issue Date	Patent	Assignee	Title
1992	EP0474796	General Electric	Process for depositing hard coating in a nozzle Orifice
1993	5271365	US Dept of Energy	Jet plume injection and combustion system for internal combustion engines
1994	5373993	General Electric	Apparatus and process for depositing hard coating in a nozzle orifice
1995	5391233	General Electric	Apparatus for depositing hard coating in a nozzle orifice
	5477046	University of California	Electron source for a mini ion trap mass spectrometer
	5451781	University of California	Mini ion trap mass spectrometer
1996	5526641	University of Chicago	NO_x reduction method
1997	5671716	Ford Motor Co.	Fuel injection system and strategy
	WO1997045678	University of California	Laser Preheat Enhanced Ignition
	5636619	University of Chicago	Method and apparatus for reducing cold-phase emissions by utilizing oxygen-enriched intake air
	5640845	University of Chicago	Nitrogen spark denoxer
	5649517	University of Chicago	Variable oxygen/nitrogen enriched intake air system for internal combustion engine applications
1998	5789745	Lockheed Martin Corp.	Ion mobility spectrometer using frequency-domain separation
	5746783	Lockheed Martin Corp.	Low emissions diesel fuel
	5803983	Lockheed Martin Corp.	Method for removing solid particulate material from within liquid fuel injector assemblies

	Patent	Assignee	Title
	5769621	University of California	Laser ablation based fuel ignition
1999	5858030	Air Products and Chemicals Inc.	Diesel fuel composition comprising dialkoxy alkanes for increased cetane number
	EP0903395	Air Products and Chemicals Inc.	Diesel fuel composition comprising dialkoxy alkanes for increased cetane number
	5921221	Ford Motor Co.	Method of controlling cyclic variation in engine combustion
	5876195	University of California	Laser preheat enhanced ignition
	WO1999067508	University of Chicago	Method and apparatus for reducing particulates and NO_x emissions from diesel engines utilizing oxygen enriched combustion air
2000	6116026	Detroit Diesel Corporation	Engine air intake manifold having built-in intercooler
	EP1010889	Detroit Diesel Corporation	Engine air intake manifold having built-in intercooler
	6035640	Ford Motor Co.	Control method for turbocharged diesel engines having exhaust gas recirculation
	EP1024263	Ford Motor Co.	Control method for turbocharged diesel engines having exhaust gas recirculation
	6156162	Low Emissions Technologies R&D Partnership	Power supply for dielectric barrier discharge plasma
	6103080	University of California	Hydrocarbon sensors and materials therefore
	6119451	University of California	Nitrogen oxide removal using diesel fuel and a catalyst
	6055808	University of Chicago	Method and apparatus for reducing particulates and NO_x emissions from diesel engines utilizing oxygen enriched combustion air

	Patent	Assignee	Title
	WO2000015951	University of Chicago	Method to Reduce Diesel Engine Exhaust Emissions
2001	6330875	Caterpillar Inc.	Engine with hydraulic fuel injection and ABS circuit using a single high pressure pump
	6311668	Caterpillar Inc.	Monovalve with integrated fuel injector and port control valve, and engine using same
	WO2001057368	Cummins Inc.	Valve Train with a Single Camshaft
	6199519	Lockheed Martin Corp.	Free-piston engine
	6202407	University of California	NO_x reduction system utilizing pulsed hydrocarbon injection
	6173567	University of Chicago	Method to reduce diesel engine exhaust emissions
2002	6378497	Caterpillar Inc.	Actuation fluid adapter for hydraulically-actuated electronically-controlled fuel injector and engine using same
	6354270	Caterpillar Inc.	Hydraulically actuated fuel injector including a pilot operated spool valve assembly and hydraulic system using same
	6474295	Caterpillar Inc.	Monovalve with integrated fuel injector and port control valve, and engine using same
	6363913	Caterpillar Inc.	Solid state lift for micrometering in a fuel injector
	6390046	Cummins Inc.	Valve train with a single camshaft
	WO2002088535	University of Wisconsin	Diesel Engine Emissions Reduction by Multiple Injections having Increasing Pressure

Issue Date	Patent	Assignee	Title
2003	6668788	Caterpillar Inc.	Homogenous charge compression ignition engine having a cylinder including a high compression space
	6564772	Caterpillar Inc.	Injector tip for an internal combustion engine
	6523529	Caterpillar Inc.	Integration of air separation membrane and coalescing filter for use on an inlet air system of an engine
	6601549	Caterpillar Inc.	Two stroke homogenous charge compression ignition engine with pulsed air supplier
	6516787	Caterpillar Inc.	Use of exhaust gas as sweep flow to enhance air separation membrane performance
	6592731	Ceramphysics Inc	Amperometric oxygen sensor
	EP1350090	Ceramphysics Inc	Combined Oxygen and NO_x Sensor
	WO2003008957	Ceramphysics Inc	Combined Oxygen and NO_x Sensor
	6659056	Cummins Inc.	Valve train with a single camshaft
	6666201	Ford Motor Co.	System and method for diagnosing EGR performance using NO_x sensor
	WO2003044434	University of California	Multi-Stage Combustion Using Nitrogen-Enriched Air
	6668763	University of Chicago	Process for in-situ production of hydrogen (H2) by alcohol decomposition for emission reduction from internal combustion engines
	6526939	University of Wisconsin	Diesel engine emissions reduction by multiple injections having increasing pressure

	Patent	Assignee	Title
	6668789		Internal combustion engine using premixed combustion of stratified charges
2004	6758870	Air Products and Chemicals Inc.	Method of producing a diesel fuel blend having a pre-determined flash-point and pre-determined increase in cetane number
	WO2004109095	Caterpillar Inc.	Fuel Injector Nozzle for an Internal Combustion Engine
	6706660	Caterpillar Inc.	Metal/metal oxide doped oxide catalysts having high deNO_x selectivity for lean NO_x exhaust aftertreatment systems
	6703343	Caterpillar Inc.	Method of preparing doped oxide catalysts for lean NO_x exhaust
	6769635	Caterpillar Inc.	Mixed mode fuel injector with individually moveable needle valve members
	6752104	Caterpillar Inc.	Simultaneous dual mode combustion engine operating on spark ignition and homogenous charge compression ignition
	6708655	Caterpillar Inc.	Variable compression ratio device for internal combustion engine
	6769392	Caterpillar Inc.	Variable valve timing in a homogenous charge compression ignition engine
	6824661	Ceramphysics Inc	Combined oxygen and NO_x sensor
	6790030	University of California	Multi-stage combustion using nitrogen-enriched air
	6700662	University of Chicago	Portable LII based instrument and method for particulate characterization in combustion exhaust

	Patent	Assignee	Title
	EP1381767	University of Wisconsin	Diesel Engine Emissions Reduction by Multiple Injections Having Increasing Pressure
	6736106	University of Wisconsin	Engine valve actuation for combustion enhancement
2005	6918941	Battelle Memorial Institute	Cermet materials, self-cleaning cermet filters, apparatus and systems employing same
	6843231	Caterpillar Inc.	Cylinder to cylinder balancing using intake valve actuation
	6945475	Caterpillar Inc.	Dual mode fuel injection system and fuel injector for same
	6843434	Caterpillar Inc.	Dual mode fuel injector with one piece needle valve member
	6948482	Caterpillar Inc.	Engine cylinder temperature control
	6843239	Caterpillar Inc.	High speed exhaust gas recirculation valve
	6978760	Caterpillar Inc.	Mixed mode fuel injector and injection system
	6971258	Honeywell International Inc.	Particulate matter sensor
	WO2005066611	Honeywell International Inc.	Particulate matter sensor
	6923167	University of California	Controlling and operating homogeneous charge compression ignition (HCCI) engines
	6969851	University of Chicago	Ion-mobility spectrometry sensor for NO_x detection
	EP1588040	University of Wisconsin	Engine Valve Actuation for Combustion Enhancement
	WO2005068809	University of Wisconsin	Engine Valve Actuation for Combustion Enhancement
2006	7022647	Battelle Memorial Institute	Methods of fabricating cermet materials and methods of utilizing same

	Patent	Assignee	Title
	7055469	Caterpillar Inc.	Combustion engine variable compression ratio apparatus and method
	7007669	Caterpillar Inc.	Distributed ignition method and apparatus for a combustion engine
	7032566	Caterpillar Inc.	Fuel injector nozzle for an internal combustion engine
	6981370	Caterpillar Inc.	Method and apparatus for PM filter regeneration
	7018442	Caterpillar Inc.	Method and apparatus for regenerating NO_x adsorbers
	WO2006096220	Caterpillar Inc.	NO_x Adsorber and Method of Regenerating the Same
	7134615	Caterpillar Inc.	Nozzle insert for mixed mode fuel injector
	7153810	Caterpillar Inc.	Silver doped catalysts for treatment of exhaust
	WO2006052918	Cummins Inc.	Mass Spectrometry System and Method
	7080511	Detroit Diesel Corporation	Method for controlling engine air/fuel ratio
	6981375	Detroit Diesel Corporation	Turbocharged internal combustion engine with EGR flow
	EP1706722	Honeywell International Inc.	Particulate Matter Sensor
	7153401	University of California	Current-biased potentiometric NO_x sensor for vehicle emissions
	7051956	US Dept of Energy	Ejector device for direct injection fuel jet
	7128046	US Dept of Energy	Fuel mixture stratification as a method for improving homogeneous charge compression ignition engine operation
	7018524	US Dept of Energy	Reformulated diesel fuel
	7096123	US Dept of Energy	Reformulated diesel fuel and method
2007	7278412	Caterpillar Inc.	Combustion-gas recirculation system

Patent	Assignee	Title
7174714	Caterpillar Inc.	Electric turbocompound control system
7219649	Caterpillar Inc.	Engine system and method of operating same over multiple engine load ranges
WO2007021336	Caterpillar Inc.	Engine System and Method of Operating Same over Multiple Engine Load Ranges
7287522	Caterpillar Inc.	Engine system having carbon foam exhaust gas heat exchanger
WO2007075185	Caterpillar Inc.	Engine system having carbon foam exhaust gas heat exchanger
7287372	Caterpillar Inc.	Exhaust after-treatment system with in-cylinder addition of unburnt hydrocarbons
7290520	Caterpillar Inc.	Fuel injector nozzle for an internal combustion engine
7198024	Caterpillar Inc.	Low emissions compression ignited engine technology
7201137	Caterpillar Inc.	Mixed mode control method and engine using same
WO2007008282	Caterpillar Inc.	Mixed mode control method and engine using same
7168243	Caterpillar Inc.	NO_x adsorber and method of regenerating same
7287506	Caterpillar Inc.	Thermoelectric system
7211793	Cummins Inc.	Mass spectrometry system and method
EP1831913	Cummins Inc.	Mass Spectrometry System and Method
7182074	Detroit Diesel Corporation	Manifold assembly for an internal combustion engine
7185642	Detroit Diesel Corporation	Manifold body for an internal combustion engine
7281518	Detroit Diesel Corporation	Method and system of diesel engine setpoint compensation for transient operation of a heavy duty diesel engine

	Patent	Assignee	Title
	7212908	Detroit Diesel Corporation	System and method for reducing compression ignition engine emissions
	7275415	Honeywell International Inc.	Particulate-based flow sensor
	WO2007015995	Honeywell International Inc.	Particulate-based flow sensor
	7247383	US Dept of Energy	Integrated self-cleaning window assembly for optical transmission in combustion environments
	7277790	UT-Battelle LLC	Combustion diagnostic for active engine feedback control
2008	7468089	Battelle Memorial Institute	Cermet materials
	7470393	Battelle Memorial Institute	Methods of producing cermet materials and methods of utilizing same
	7464540	Caterpillar Inc.	Ammonia producing engine utilizing oxygen separation
	7380540	Caterpillar Inc.	Dynamic control of a homogeneous charge compression ignition engine
	WO2008094231	Caterpillar Inc.	Dynamic control of a homogeneous charge compression ignition engine
	7370613	Caterpillar Inc.	Eccentric crank variable compression ratio mechanism
	WO2008079180	Caterpillar Inc.	Electric Turbocompound Control System
	7467621	Caterpillar Inc.	Engine and method for operating an engine
	WO2008054568	Caterpillar Inc.	Engine and method for operating an engine
	EP1913248	Caterpillar Inc.	Engine System and Method of Operating Same over Multiple Engine Load Ranges
	7377270	Caterpillar Inc.	Exhaust gas recirculation in a homogeneous charge compression ignition engine

Patent	Assignee	Title
WO2008051315	Caterpillar Inc.	Exhaust gas recirculation in a homogeneous charge compression ignition engine
7371353	Caterpillar Inc.	Exhaust purification with on-board ammonia production
7377254	Caterpillar Inc.	Extending operating range of a homogeneous charge compression ignition engine via cylinder deactivation
7444980	Caterpillar Inc.	Fuel injector nozzle for an internal combustion engine
7469181	Caterpillar Inc.	High load operation in a homogeneous charge compression ignition engine
WO2008094230	Caterpillar Inc.	High load operation in a homogeneous charge compression ignition engine
7320219	Detroit Diesel Corporation	Method for controlling an internal combustion engine using model based VGT/EGR control
EP1907801	Honeywell International Inc.	Particulate-based Flow Sensor
7455046	University of Chicago	Nitrogen enriched combustion of a natural gas internal combustion engine to reduce NO_x emissions
7464690	University of Wisconsin	Adaptive engine injection for emissions reduction
7337763	University of Wisconsin	Engine valve actuation for combustion enhancement
7469693	UT-Battelle LLC	Advanced engine management of individual cylinders for control of exhaust species
7431011	UT-Battelle LLC	Method and device for diagnosing and controlling combustion instabilities in internal combustion engines operating in or transitioning to homogeneous charge combustion ignition mode

Issue Date	Patent	Assignee	Title
2009	7552583	Caterpillar Inc.	Exhaust purification with on-board ammonia production
	7523606	Caterpillar Inc.	Parasitic load control system for exhaust temperature control
	7541010	Caterpillar Inc.	Silver doped catalysts for treatment of exhaust
	7497138	Ford Motor Co.	System and method for improving performance of a fluid sensor for an internal combustion engine
	7549317	Honeywell International Inc.	Particle-based flow sensor
	7555945	Michigan State University	Mass air flow sensor having off axis converging and diverging nozzles

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