U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Linkages from DOE's Geothermal R&D to Commercial Power Generation

February 2011

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Acknowledgments

This report traces the connections from U.S. Department of Energy (DOE) geothermal research and development (R&D) to downstream commercial power generation. Prepared for the U.S. Department of Energy under Purchase Order No. 718187, this report also includes contributions from Sandia National Laboratories in Albuquerque, New Mexico, U.S.A. Sandia is operated by Sandia Corporation, a subsidiary of Lockheed Martin Corporation.

Project initiation was directed by Jeff Dowd of DOE's Office of Energy Efficiency and Renewable Energy (EERE)'s Office of Planning, Budget and Analysis (OPBA). Oversight of the project was provided by Gretchen Jordan, a principal member of the technical staff at Sandia National Laboratories.

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

The authors extend appreciation to the following DOE staff who made valuable contributions to the study: Lauren Boyd and Nicole Reed of EERE's Geothermal Technologies Program (GTP), who provided liaison with the Program; Doug Blankenship of Sandia National Laboratories and Gregory Mines of Idaho National Laboratory, who provided expert review of the candidate patent list attributed to DOE-funded geothermal research; and Karsten Pruess of Lawrence Berkeley National Laboratory, who discussed the development and use of reservoir models.

In addition, we thank the following individuals who served as EERE Reviewers and as External Expert Panel Reviewers for their constructive comments:

EERE Reviewers:

Lauren Boyd, EERE Geothermal Technologies Program
Jeff Dowd, EERE Office of Planning, Budget, and Analysis

External Panel Reviewers:

Connie Chang, Independent Consultant
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Caroline Wagner, CEO, Science-Metrix Corporation

Any errors contained in this report remain solely the authors' responsibility.

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Executive Summary

Study Purpose

This study provides an evaluation of the Geothermal Technologies Program (GTP) of the U.S. Department of Energy (DOE). Specifically, for the period 1976 to 2008, it investigates the linkages between GTP's outputs and their downstream use by others to produce power from geothermal energy. The results are relevant for assessing DOE's past and future roles in the development and advancement of the nation's geothermal resources. In addition, the study investigates other applications of the GTP's outputs beyond power generation.

Study Methods

The study uses a historical tracing framework and bibliometric and supporting methods to determine if there are identifiable and measurable linkages between GTP’s outputs and technological and commercial advances in power production by geothermal energy. The study is designed to address a series of questions to identify if and to what extent there are linkages, what those linkages are, and who and what technologies are involved. As background to formulating the evaluative questions, the study reviewed GTP's mission, goals, strategies, activities, and outputs to ascertain its program logic.

The study primarily uses bibliometric methods —namely patent and publication analyses—to trace the creation and dissemination of GTP's outputs. As for many federal civilian applied research programs, knowledge embodied in patents and publications are important explicit outputs of the GTP. Bibliometric methods offer the advantage of enabling an objective, quantitative analysis of the GTP's explicit knowledge outputs of patents and publications.

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, with its objectively derived quantitative results, has been used extensively in the study of technological change.

Backward patent tracing is used to assess the extent of linkage of innovations by companies in the geothermal industry to earlier GTP-funded research. Forward patent tracing is used to assess the broader influence of GTP-funded research on subsequent developments both within and outside the field of geothermal energy. Both backward and forward patent tracing are performed at two levels: (1) organizational level, and (2) individual patent level. This approach provides both a comparative assessment of GTP's influence on other organizations, and the identification of particularly noteworthy inventions.

Publications are also of keen interest as knowledge outputs of DOE-funded geothermal research and as a mechanism linking the research to downstream developments in geothermal energy and other areas of technology. An analysis of a selection of DOE geothermal publications cited by patents is presented as a bridge between a pure patent analysis and a pure publication analysis.

In addition, the study analyzes authorship/co-authorship and citations of publications from two DOE laboratories active in geothermal research.

Other important GTP outputs, beyond patents and publications, include models and computer code; test data; research tools; research prototypes; demonstrations; number of trained geothermal technologists; and stimulation of interest, innovation, and understanding by others in the field of geothermal energy. To some extent, these outputs are reflected in the outputs of patents and publications (such as by user manuals accompanying models and computer code, publications on test data, and contractor reports accompanying prototype development). However, some are tacit knowledge outputs that are more difficult to capture. These other outputs are explored using document/database review and, to a limited extent, interviews with DOE staff.

Findings

The study found multiple lines of compelling evidence linking patents, publications, and other outputs resulting from GTP-funded research to downstream applications. Linkages were found from GTP outputs to companies, universities, and other organizations in the geothermal industry, as well as to organizations in the oil and gas industry.

Overall, the results of the backward tracing analysis showed that DOE-funded geothermal research has influenced subsequent innovation by leading geothermal energy companies, most notably Chevron (through its merger with Unocal) and Ormat. DOE-funded geothermal research, together with that of Chevron, with its own strong patent ties back to DOE, has shown the largest influence on innovation among organizations performing research in the geothermal field. When the search was widened to include connections from the total geothermal patent set back to all patents in all industries, the large influence of leading oil and gas companies, such as Exxon Mobil, on innovations in geothermal was also apparent, as well as the influence of DOE-funded geothermal research on subsequent innovations in the oil and gas industry. Specific findings include the following:

- A total of 90 U.S. geothermal energy patents, and a total of 90 patent families are attributed to DOE-funded research. (A patent family contain all of the patents, patent applications, continuations, and divisionals that result from an original patent application.) Through an extended search of the U.S. Patent and Trademark Office (USPTO), European Patent Office (EPO), and World Intellectual Property Organization (WIPO), a total of 115 U.S. patents (i.e., the original 90 patents plus their continuations, continuations-in-part, or divisionals), 16 EPO patents, and 17 WIPO patents were found—all arising from the inventions represented by the original 90 patents attributed to DOE-funded geothermal research, and, thus contained in 90 patent families.
- Although the 90 GTP-attributed geothermal patent families comprise a relatively small share of total geothermal patenting, they appear to have had a dramatic impact on developments in the industry.
- Of a population of more than 1,000 geothermal patent families identified by the study, 21% are linked to earlier GTP-attributed geothermal patents and publications, second

only to the percentage linked to the geothermal patent portfolio of Chevron (25%), which is reportedly the world's largest producer of geothermal energy.

- Chevron (which obtained many of its geothermal patents by a takeover of Unocal) and Ormat (another leading company in the geothermal industry) are the two organizations with the largest number and percentage of their own geothermal patents linked back to earlier GTP-attributed geothermal patents, each in different geothermal technology areas.
    - Chevron's geothermal patent families build on earlier DOE-attributed geothermal patents focused mainly on methods for treating geothermal fluid.
    - Ormat's patent families build mainly on earlier DOE-attributed patents pertaining to geothermal power plants and the use of geothermal energy to produce an uninterruptible power supply.
- GTP-funded geothermal research, together with research by Chevron (Unocal) and Exxon Mobil, was found to have formed an important part of the foundation for highly cited innovations by other organizations within the geothermal and oil and gas industries.
- There is a close relationship between geothermal technology and oil and gas technology. This is reflected in the large number of linkages of patent families of the major oil company Exxon Mobil to later geothermal patent families. Of the more than 1,000 geothermal patent families identified by the study, 32% are linked to earlier Exxon Mobil patent families describing a variety of technologies, such as drilling and down-hole electronics.
- GTP-attributed geothermal patents that have been highly cited include those describing:
    - Fluid-assisted drilling
    - The Organic Rankine and Kalina thermodynamic cycle technology used in heat exchangers in geothermal power plants
    - Cements for use under adverse conditions found in geothermal wells
    - Electronics for down-hole data transmission
    - Silica control in geothermal plants
    - Methods for generating geothermal energy from unpromising sites, such as hot dry rocks
- Tracing GTP-attributed geothermal patents downstream to see where they lead outside the geothermal industry shows influence particularly in the oilfield service industries.
    - Oilfield service companies, including the three largest—Halliburton, Schlumberger, and Baker Hughes—had the most patents linked to earlier GTP-attributed geothermal energy patents.
    - Patents of the oilfield service companies are linked strongly back to GTP-invented advanced cements for use in wells under harsh conditions, drilling techniques, and down-hole data transmission.
- A few GTP research papers were heavily cited by downstream industry patent families—mainly research papers reporting DOE national laboratory research on lightweight

cements for use in wells under harsh conditions, polycrystalline diamond compact (PDC) drill bit performance, data communication through drill strings, and condensers for use in geothermal power plants. This form of patent citing is of particular interest because it is regarded as an indicator of leading edge patenting activity.

- Analyses of sampled geothermal publications from Idaho National Laboratory (INL) and the National Renewable Energy Laboratory (NREL) found:
  - Diverse authorship of INL geothermal publications. Publications included researchers affiliated with universities from across the nation, companies under contract to INL, state and regional organizations typically involved in planning and permitting geothermal projects, and associations representing the geothermal and related industries.
  - Heavy citing of both INL and NREL publications by university publications, from a mix of domestic and foreign universities.
  - Citing of these publications by international and non-profit institutes; U.S. and foreign national government agencies; state and regional governmental bodies; and domestic and foreign companies.
- Influential outputs of the GTP not fully captured by the patent and publication analyses of this study include the following:
  - Geothermal models, particularly the TOUGH series of reservoir models, used to study fluid processes in reservoirs
  - Geothermal maps that show the location, nature, and potential of geothermal resources
  - Test data, such as that for drill bits
  - The effects of GTP partnerships with companies that not only develop geothermal technologies, but are relied upon by GTP to take the technologies into commercialization
  - Prototypes of technologies whose development was funded by GTP
  - Demonstrations that influence interest in and understanding of geothermal systems
  - Trained geothermal technologists
  - A network of geothermal researchers and research organizations

1. Introduction

The Geothermal Technologies Program (GTP) of the U.S. Department of Energy (DOE) was established in 1976.[1] Cumulative spending by DOE on geothermal energy in undiscounted 2008 dollars was $2.6 billion from 1976 through 2008. In present value dollars, the expenditure was $1.66 billion discounted at 7%, and $2.08 billion discounted at 3%, in both cases computed for a base year of 1976—the first year of DOE GTP expenses.[2]

This study focuses on the analysis of GTP patent and publication outputs and their downstream uses from 1976 through 2008.[3] The results are relevant for assessing DOE's past and future roles in the development and advancement of the nation's geothermal resources. The study is an evaluation of GTP, and, as such, is responsive to both congressional and administrative directives for greater emphasis on program evaluation in federal agencies.

1.1 About the Evaluation Study

This study uses bibliometric and supporting methods to determine if there are identifiable and measurable linkages between outputs of the GTP and observed technological and commercial advances in power production by geothermal energy. The focus of the study is a quantitative analysis of GTP's explicit knowledge outputs of patents and publications. In addition, the study identifies other explicit, as well as tacit, knowledge outputs, and discusses these in qualitative terms. Sufficient time has passed to allow many of the patents and publications resulting from GTP's funding to be taken up by others, such that bibliometric tracking can be feasibly applied.

To plan the study, GTP's program logic was assessed by examining background information on the Program's mission, goals, strategies, activities, outputs, and intended outcomes and impacts. With this background, the study formulated a series of questions to identify if and to what extent there are linkages between GTP's outputs—particularly patents and publications—and downstream outcomes. The study determined what linkages exist, with whom, and what technologies are involved. The questions and methods are described further in Section 3.

The use of GTP's patent outputs by companies in the geothermal industry is compared with their use of patents of other organizations to show the relative importance of DOE's role in advancing this form of renewable energy through its patented R&D. Also, the study examines linkages from GTP's outputs to downstream applications in all fields to reveal if the research has influenced

[1] To capture the history of the Program, its strategies, activities, and its achievements, a series of reports were prepared by DOE that give a detailed account of the Program's investment within each of its major research topical areas: Exploration, Drilling, Reservoir Engineering, and Energy Conversion. See GTP (2010, 2008a-d). It should be noted that DOE's geothermal research program has had multiple names over the years, but the current one is used throughout for convenience of exposition.
[2] These figures are from Gallaher, et al. (2010), Table 4-6.
[3] The study's principal period of coverage extends from 1976 through 2008. However, in a few cases the period of coverage is extended to 2009, where later market data were available, or the periods were ended variously in 2007, 2008, or 2009, in order to maintain consistently sized time intervals for trend data.

fields other than geothermal energy. In addition, the results of the current study have lent support to a benefit-cost study[4] by providing an account of knowledge benefits, and by providing additional evidence of attribution of benefits to DOE.

1.2 Report Organization

The report is presented in six chapters and three appendices.

Chapter 2, "Background," provides contextual background for the study's analysis. It presents a brief primer on geothermal energy, a market overview, and an overview of GTP.

Chapter 3, "Evaluation Methodology," presents the study's historical tracing framework, the set of questions to be addressed by the study, and the bibliometric evaluation methodology featured in conducting the study. It explains why patent analysis is particularly suitable for tracing outputs from a federal civilian applied research program to its downstream applications. It also describes supporting approaches used in the study, and study limitations.

Chapter 4, "Linkages Found by Patent Analysis," presents the results of patent analysis. Trends in geothermal patenting are examined, and leading organizations in geothermal patenting are identified. Analysis results are provided at the organizational level and the individual patent level for both backward and forward patent tracing.

Chapter 5, "Linkages Found by Publication Analysis," presents the results of publication analysis. Random samples of reports issued by the Idaho National Research Laboratory and the National Renewable Energy Laboratory (NREL) are analyzed, both for co-authorship and for citations by other publications. In addition, a sample of GTP publications is analyzed for citations by patents.

Chapter 6, "Other Modes of Linkages," discusses linkages from other GTP outputs to downstream applications. Featured topics include modeling tools, resource maps, test data, demonstrations, training of geothermal technologists, and fostering of a social research network in geothermal energy.

Appendices A, B, and C supplement Chapter 4 with details on construction of key patent data needed for the analysis, and lists of the individual patents and publications traced in the study.

A list of references concludes the report.

[4] Gallaher, et al. (2010), Section 9.

2. Background

To provide context for tracing GTP outputs to downstream uses and users, three overviews are provided in this chapter. The first is an overview of geothermal technologies. The second is an overview of geothermal markets, including the growth of U.S. geothermal installed capacity for electricity production, and the ranking of the United States in worldwide installed capacity for electricity production. The third is a brief overview of GTP; its history, goals, strategies, activities, outputs, and intended outcomes and impacts.

2.1 Overview of Geothermal Technologies

Geothermal energy relies on the fact that heat from the earth's core continuously flows outward, heating rainwater that flows down into cavities below the surface, or heating rocks which in turn can heat fluid added from other sources. Exploitable geothermal resources occur near the surface and at depths extending to a mile and more.[5]

The generation of electricity from geothermal energy is of particular interest because it offers a viable clean, renewable alternative for base-load power generation by traditional fossil fuels, such as coal. Geothermal heat can be used to generate electricity through any of the following approaches: 1) Moderate-to-high-temperature reservoirs in combination with dry steam or flash steam conversion plants to produce steam that drives turbine generators. 2) Low-temperature fluids from a reservoir in a binary cycle generator to heat another fluid that vaporizes at a lower temperature or higher pressure than water, the resulting vapor from which drives turbine generators. 3) Enhanced Geothermal Systems (EGS), an emerging technology, used to generate heat where existing resources are inadequate and must be engineered to make them suitable for production—generally by introducing an external source of fluid into the earth that is then heated by hot rocks and used to drive turbine generators.[6] 4) Geothermal energy co-produced with oil and gas resources when heated water is a by-product of that production or when mechanical pressure from highly pressurized natural gas is present.

Distinct technologies support each of five major types of activities in the process of generating electric power from geothermal energy. These activities, listed in Figure 2-1, are exploration; drilling; reservoir modeling, engineering, and preparation; plant and energy conversion process design, engineering and construction; and on-going operation and maintenance of the well, reservoir, and plant. R&D enables and advances the capabilities required for each activity, and is listed first in the figure. Permitting and financing are also shown in the figure because they are essential to achieving facility development and are positively influenced by technology advancements, other factors being the same.

[5] Basics of geothermal energy are presented at GTP's website. See http://www1.eere.energy.gov/geothermal/geothermal_basics.html.
[6] A 2006 MIT-led panel study (MIT, 2006) assessed the feasibility, potential environmental impacts, and economic viability of using EGS technology to expand the provision of electricity from wider-scale deployment of geothermal energy.

Figure 2-1. Activities in Developing Geothermal Energy Power Generation, and Supporting Functions

Aside from generating electricity, geothermal energy has long been used for numerous direct applications, particularly those requiring low-temperature energy. Among these direct applications are district space heating, aquaculture, greenhouses, agricultural and industrial processes, snow-melting on sidewalks, and spas and pools. Among the early direct geothermal commercial spa applications in the United States were the Homestead Spa in Hot Springs, Virginia, established in 1766; Saratoga Springs in New York State, established in the late 1700s; and mineral baths in Hot Springs, Arkansas, established in 1830. More than 100 hot springs offered commercial services at the peak of the hot-spring resort era in the United States in the 1910s, and many are still in operation.[7]

Geothermal energy is also used for space heating and cooling of buildings, and to provide domestic hot water through the use of geothermal heat pumps. Geothermal heat pump

[7] For more on the history of geothermal energy in the United States, see EERE/GTP website: http://www1.eere.energy.gov/geothermal/history.html; and the Center for Renewable Energy and Sustainable Technology (CREST)/Renewable Energy Policy Project (REPP) website: http://www.repp.org/geothermal/geothermal_brief_history.html.

technology relies on the relatively constant temperature of shallow sub-surface earth and the fact that the earth's temperature tends to be warmer than ambient temperature during the winter, and cooler during the summer.

These areas of application vary in terms of the remaining challenges that inhibit their widespread use. The technologies for heat pumps and for direct use of low-temperature geothermal energy are generally considered relatively mature, although the resource is considered under-utilized in these applications. In contrast, EGS is an emerging technology, with critical technical barriers impeding its exploitation. As a result, a commercial scale EGS operation has not yet been implemented in the United States. Hydrothermal systems continue to entail research issues in exploration, geochemistry, drilling, reservoir and equipment operation and maintenance, and other areas that affect system cost effectiveness. The ability to more effectively use low-temperature resources for power generation also entails continuing research challenges.

2.2 Overview of Commercial Power Production from Geothermal

As of 2008, the cumulative total for electricity production from geothermal energy in the United States was 3,040 MW.[8] By 2010, the cumulative total had risen to 3,086 MW produced by 77 power plants, with most recent additions to capacity coming from binary plants.[9] Currently, the U.S. geothermal industry is increasing its development activity, and 188 geothermal projects were reportedly underway in 15 different states in 2010.[10]

A depiction of recent yearly installed capacity from 2005 to 2009, and of aggregate installed capacity over the same period is shown in Figure 2-2, with the annual scale on the left and the aggregate scale on the right. The jump in capacity installed in 2009 is notable—the result of seven geothermal projects coming on line in that year.

As shown in Figure 2-3, California is the clear leader to date in the United States in installed capacity, with Nevada, Utah, Hawaii, and Idaho following, in that order. The identified greatest potential for electric generation in the United States, with today's geothermal technology, is concentrated in 13 western states, including those listed above, plus Alaska, Oregon, Wyoming, New Mexico, Washington, Montana, Colorado, and Arizona. But potential also exists in other states, particularly from low-temperature applications, EGS, and co-production of heated water with oil and gas extraction.

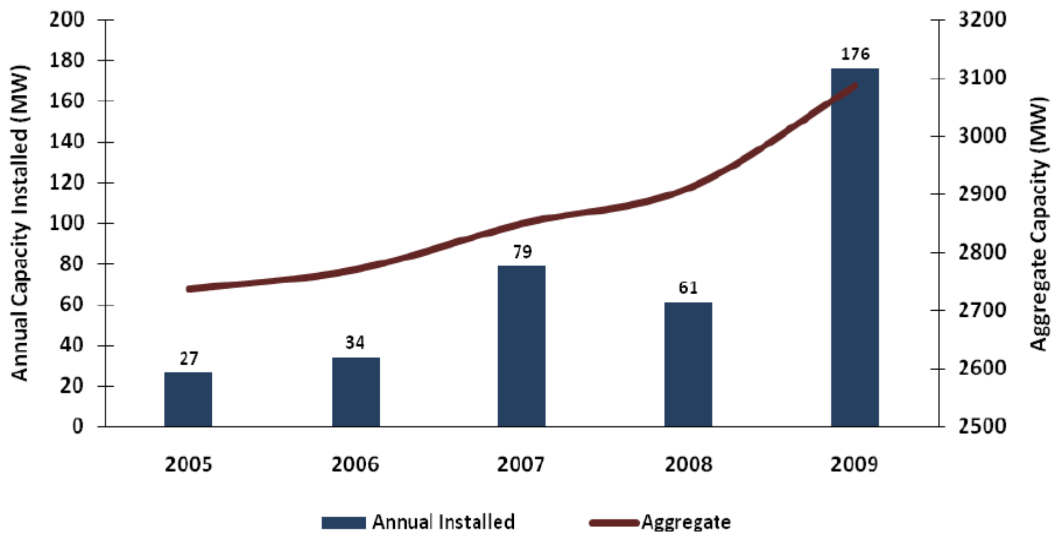
Figure 2-4 helps to put into perspective the contribution of geothermal to overall U.S. energy consumption. In 2009, renewable energy accounted for 8% of total primary U.S. energy consumption, and geothermal accounted for 5% of the renewable share.

Despite the relatively small share of U.S. energy consumption comprised by geothermal, the United States, with its 2010 installed capacity of 3,086 MW, is the world's top producer of electricity by geothermal power. Following the United States in installed capacity are the

[8] NREL (July 2009), p. 11.
[9] Geothermal Energy Association (GEA) (April 2010), p. 3.
[10] Ibid, p. 4.

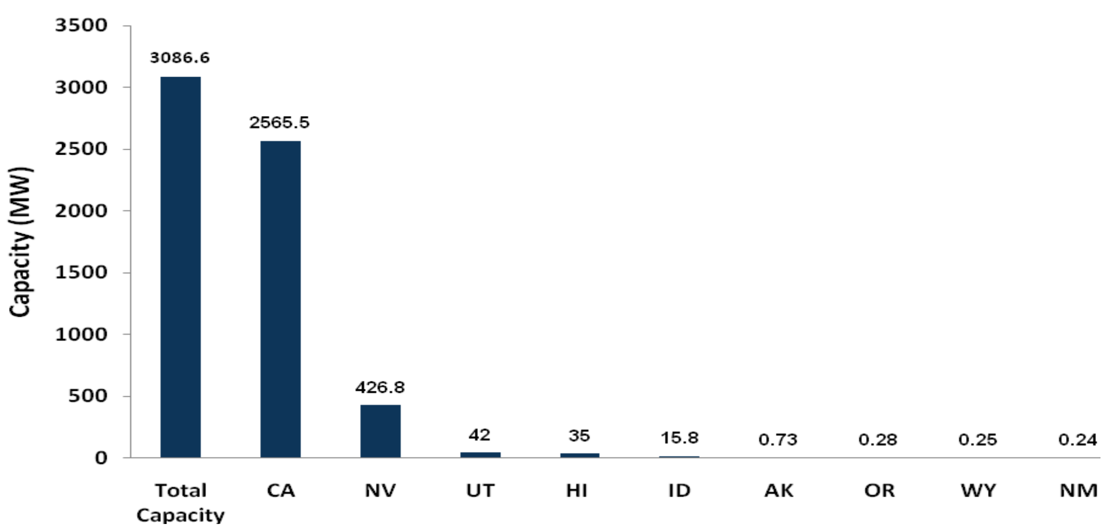
Philippines (1,904 MW), Indonesia (1,197 MW), Mexico (958 MW), Italy (843 MW), New Zealand (628 MW), Iceland (575 MW), and Japan (536 MW). Sixteen additional countries have installed capacity, ranging on the higher end of the scale from El Salvador's 204 MW, to Russia's 82 MW, to France's 16 MW, down to Australia's 1.1 MW and Thailand's 0.3 MW.[11]

Figure 2-2. U.S. Installed Capacity, March 2006-March 2009



Source: Geothermal Energy Association (GEA) (April 2010), Figure 2.

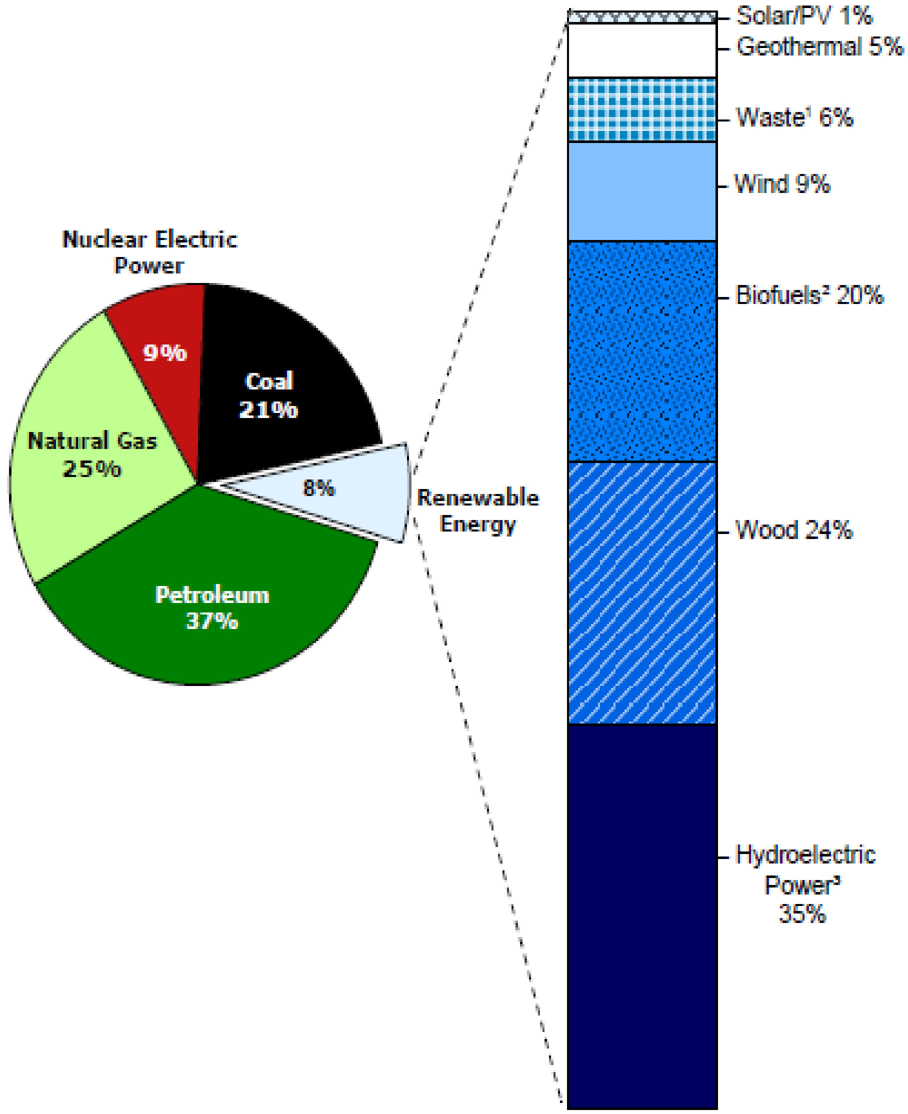
Figure 2-3. U.S. Geothermal Power Capacity On-Line (MW), Total and by State, April 2010



Source: GEA (April 2010), Figure 1.

[11] GEA (May 2010), p. 7.

Figure 2-4. Renewable Energy as Share of Total U.S. Primary Energy Consumption, 2009



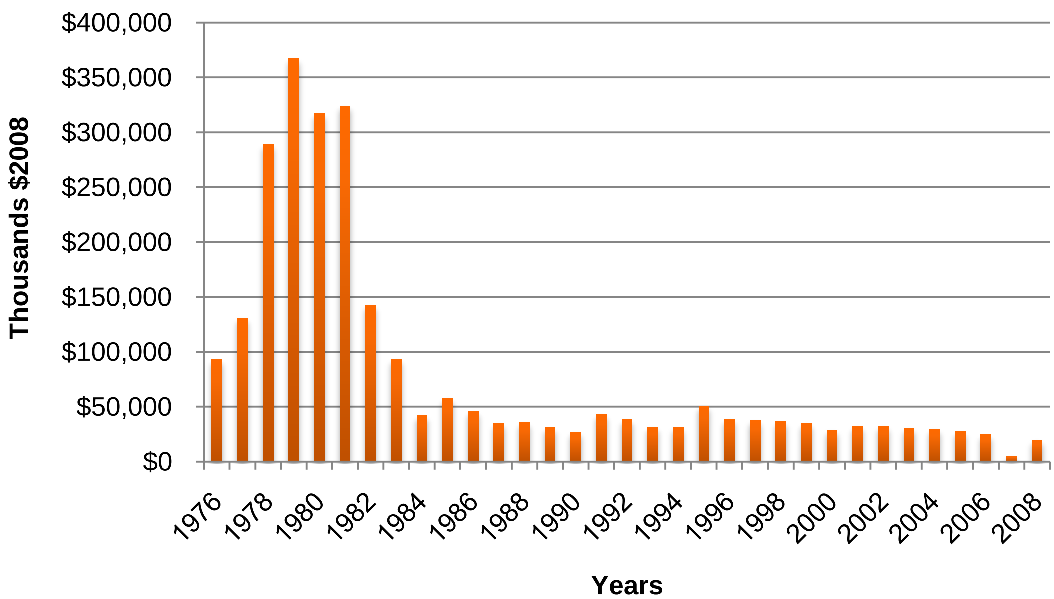
Source: U.S. Energy Information Administration (EIA), (August 2010), p. 282.

2.3 Overview of DOE's Geothermal Technologies Program (GTP)

DOE's role in federal geothermal technology research was mandated by the Geothermal Research, Development, and Demonstration Act of 1976. Prior to the transfer of federal responsibilities for geothermal research to DOE in 1977, DOE's predecessor, the Energy Research and Development Administration (ERDA) conducted geothermal research. ERDA's geothermal research program had resulted from consolidation of geothermal research programs in a number of agencies, such as the Atomic Energy Commission, National Science Foundation (NSF), the Bureau of Mines, and the Bureau of Reclamation.

Historically, DOE-funded geothermal research has been applied to developing technologies for each of the five stages depicted previously in Figure 2-1: exploration; drilling; reservoir modeling; plant and process design; and on-going operation and maintenance of the well, reservoir, and plant. DOE expenditures (stated in 2008 dollars) on geothermal research, development, and demonstration from 1976 through 2008 are shown in Figure 2-5. As is the case for most of the DOE alternative energy programs, funding peaked from the late 1970s to the early 1980s as the government responded to the energy crises of the 1970s. Plunging budgets followed in the 1980s. Funding for geothermal research again declined over most of the decade of the 2000s, with the lowest level reached in 2007.

Figure 2-5. GTP Expenses, 1976-2008 (in Thousands of 2008 Dollars)



Source: Chart prepared from GTP expenses data provided by DOE and reported by Gallaher, et al. (2010), in tabular form in table 4-5.

During its first 30 years, DOE's geothermal research effort was aimed at developing core technologies to assist the geothermal industry in finding, operating, and managing geothermal fields, to expand the geothermal resource base through innovative technologies for heat extraction, and to make geothermal electricity more cost-competitive. When the DOE energy conversion R&D program first began, power production from geothermal resources was limited to The Geysers, a dry-steam field located in northern California. Because vapor-dominated resources (like those found at The Geysers) are rare, DOE focused on the technologies needed for the cost-effective use of more common liquid-dominated resources in order to enable geothermal to become a larger contributor to the nation's power portfolio. Also, DOE began to emphasize development of binary cycle technologies in order to improve the economic viability of using lower temperature resources to generate power.

From its outset, DOE conducted research in partnership with the geothermal industry, but in the early days of the GTP no commercial facility in the United States used liquid-dominated resources for power production. To support its research activities, therefore, DOE developed test facilities in California at the Salton Sea, East Mesa, and Heber; in Idaho at Raft River; and later in Texas at Pleasant Bayou. Power plants were constructed at selected DOE facilities to incorporate the "first use" of specific technologies, including multiple boiling binary cycles, supercritical binary cycles using working fluid mixtures, and hybrid cycles for geopressured-geothermal resources. In addition to funding research at the national laboratories and universities, DOE contracted with the geothermal industry to conduct research at the test facilities.

From the late 1970s to mid-1980s, DOE's geothermal R&D program supported exploration and resource definition for lower-temperature systems suitable for direct use. Exploration research included DOE support of limited exploration of the eastern United States to determine geology, measure thermal gradients with depth, and calculate heat flow in the Atlantic Coastal Plain from New Jersey to southern Georgia.

In the mid-1980s, DOE's research and development emphasis shifted toward improvements in drilling technology and advances in the process efficiency of binary power plants. Both areas, as well as reservoir analysis, were considered critical to reducing the cost of geothermal energy and making it economically available.

As the geothermal industry began to build commercial plants using liquid-dominated resources, field validation of technologies shifted from DOE facilities to commercial geothermal power plants. By the early 1990s, all DOE-supported test facilities had been closed. National laboratory investigators worked closely with industry at commercial plants on field validation of technologies to improve the economic feasibility of geothermal power production. Needed technology improvements for the operation and maintenance (O&M) of geothermal power plants were identified jointly, and addressed through cost-shared research with industry, as well as DOE-funded research by national laboratories and universities.[12]

The American Recovery and Reinvestment Act (ARRA) of 2009 provided new funding for implementation by GTP of a wide range of research, development, demonstration, and deployment activities. Funding was provided for the following areas:[13]

- Innovative Exploration and Drilling Projects
- Co-produced and Geo-pressured Projects
- Low Temperature Projects
- Enhanced Geothermal System Demonstrations and Component R&D
- Geothermal Data Development, Collection, and Maintenance

[12] Details on the history of the DOE Geothermal Technologies Program can be found in a multi-volume series produced by the Program. (USDOE/EERE/GTP, 2010, 2008a, 2008b, 2008c, 2008d).
[13] Descriptions of recent DOE and industry funding of geothermal projects by state are provided by GEA (April 2010), Section 2.1.

- Ground Source Heat Pump Demonstrations.

GTP's outputs include: dissemination of geothermal knowledge through publications, patents, various modes of formal and informal communication, and embodied in people; prototypes; technology demonstrations; models and computer codes; and maps of geothermal resources.

3. Evaluation Methodology

This chapter describes the framework and methods used in the study to identify and trace linkages from R&D funded by GTP to power generation from geothermal energy. Because evaluation methods have limitations both in theory and practice, the chapter closes with a discussion of limitations.

3.1 Historical Tracing Framework: Overview[14]

Knowledge outputs from research typically take lengthy and complex paths to downstream applications. Over time, institutional memory of a program's contributions fades. The many twists and turns of a technology's development often obscure a clear understanding of a program's contributions. The adoption of the program's knowledge in other fields and applications is usually unanticipated and tends to remain unknown in an evaluative sense. In this case, research funded by GTP has a history of more than 30 years. The geothermal field and the industries and organizations involved in it have even longer histories. A historical tracing framework is appropriate for examining the creation and diffusion of GTP's knowledge outputs.

To conduct a historical tracing study of GTP, evaluation tools that can quantitatively and objectively assess relevant developments over time are valuable. Bibliometric evaluation methods are well suited for this purpose, because they permit detailed analyses of the Program's patents and publications, which are among its principal knowledge outputs. Patent and publication citation analyses provide objectively derived, quantitative measures of linkages without reliance on institutional memory. This form of analysis shows that knowledge and, in the case of patents, intellectual property have been created, who created it, where it resides initially, the extent to which it is being disseminated and used (or at least referenced), and by whom.

Specific bibliometric methods used by this study include patent and publication counts; patent-to-patent, patent-to-publication, and publication-to-publication citation analyses. Methods used also include comparisons of organizations with respect to the frequency with which their patents are cited, and comparisons among patents in terms of their citation intensity.

Supporting evaluation methods are also used to extend the analysis beyond patents and publications. Document and database review and interviews with experts help to identify other linkages from research outputs to downstream applications both within and outside the field of geothermal energy. The use of additional methods allows the study to provide a more comprehensive treatment of a program's knowledge outputs and the dissemination of knowledge in various forms.

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[14] Historical tracing is one of multiple evaluation methods that are used to evaluate R&D programs. A directory of evaluation methods is provided by Ruegg and Jordan (2006). The Directory is available online athttps://apps3.eere.energy.gov/ba/pba/analysis_database/docs/pdf/2007/evaluation_methods_r_and_d.pdf.

3.2 Questions Addressed by the Study

Table 3-1 lists questions formulated by assessing GTP's implicit program logic[15] and addressed by the study. The table pairs each question with the study's method of answering it. These questions drive the evaluation's identification and documentation of linkages between GTP's outputs and downstream applications of those outputs.

Table 3-1. Study Questions and Evaluation Methods Used to Address Them

Study Question	Method Used
Did the outputs of GTP's research in geothermal energy reach a downstream audience well positioned to apply them to commercial development of electricity?	Bibliometrics: Backward patent tracing at the organizational level, starting with potential users and linking back to GTP-funded research
How does the influence of GTP's body of geothermal patents compare with that of the leading companies in the field?	Bibliometrics: Comparing organizations based on the extent of citing of their bodies of geothermal patents by others
Which GTP-attributed geothermal patents have had notable influence on subsequent geothermal patenting by companies?	Bibliometrics: Backward patent tracing at the individual patent level
Which company patents appear most influenced by GTP-funded research?	Bibliometrics: Backward patent tracing at the individual patent level
What are the highest-impact company patents with links back to GTP-attributed patents?	Bibliometrics: High-impact patent analysis and backward patent tracing at the individual patent level
Are there indications of interest in GTP outputs beyond the geothermal industry?	Bibliometrics: Forward patent tracing at the organizational level, to assess the broader influence of GTP's research; classification by International Patent Code of all patents families linked to earlier GTP-attributed patent families
What have been the principal innovations in all fields and by all organizations linked to earlier GTP-funded research?	Bibliometrics: Forward patent tracing at the individual patent level
To what extent have co-authoring and citing of geothermal publications provided paths of knowledge dissemination?	Bibliometrics: Analysis of publication authoring and of publication-to-publication and patent-to-publication citations
What are other modes by which the outputs of GTP-funded research have been disseminated to others?	Document and database review and interview

[15]The fundamentals of constructing and using logic models are described by W.K Kellogg (2004, Updated), and their use in R&D programs is discussed by McLaughlin and Jordan (2010). A logic model was informally developed to provide guidance for structuring the study, and the elements are discussed in the text; however, it is not shown here because it is not part of GTP's official program description.

3.3 Patent Analysis Methodology

When looking for connections from knowledge creation in a research program to commercialized technologies, patents are of particular interest because they are considered close to application. The use of patents as indicators of technology creation and patent citation analysis as indicative of technology diffusion reflects the central role that patents play in the innovation system. Patent citation analysis has been used extensively in the study of technological change.[16] 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 art in patent law refers to all information that has previously been made publicly available and might be relevant to a patent’s claim of originality and, hence, its validity. Prior art may be in the form of previous patents, scientific papers, technical disclosures, trade magazines, or other forms of relevant information publicly known before the invention.

Patent citation analysis centers upon the links between generations of patents and the links between patents and scientific papers, that are made by these prior art references. The analysis is based on the idea that the prior art[17] referenced by a patent has had some influence on the development of the later patent. The prior art is thus regarded as part of the foundation for the later invention. In the patent analysis presented in this report, the idea is that the downstream technologies represented by patents that cite earlier patents attributed to DOE's geothermal research funding have built in some way on the knowledge base that research has generated.

An additional concept employed in 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.[18]

Patent analysis has been employed in other studies of DOE/EERE programs, as it is here, to assess linkages from the programs to downstream technological developments. These include studies of energy storage for vehicles, wind energy, vehicle combustion research, and solar photovoltaic energy.[19]

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[16] 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).

[17] The front page of a patent document contains a list of references to prior art. As indicated earlier, “prior art” in a patent law system refers to all information that previously has been made available publicly such that it might affect 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, and trade magazines.

[18] For background on the use of patent citation analysis to identify important technological information, including a review of studies discussing the relationship between high citations and technological importance, see Breitzman and Mogee (1999), p. 196 and pp. 203-205; and Thomas (1999), Chapter 3.

[19] See Ruegg and Thomas (2008, 2009, 2010A, and 2010B) for other historical tracing studies of energy efficiency and renewable energy systems.

3.4 Forward and Backward Patent Tracing

Two approaches are used in the study to trace linkages between DOE's geothermal research and downstream developments. One approach—forward patent tracing—takes a broad look at downstream linkages. The other approach—backward patent tracing—focuses specifically on linkages from downstream geothermal power generation back to patents attributable to DOE's funding of geothermal research.

3.4.1 Forward Patent Tracing

The idea of forward patent tracing is to take a given body of patents, and to trace their influence upon subsequent technological developments reflected by patents. In the context of this geothermal analysis, forward tracing entails identifying all geothermal patents resulting from the DOE research program, and assessing the influence of these patents on downstream innovations as revealed by two generations of patent citations. This tracing is not restricted to later geothermal patents. Rather it is recognized that the influence of a body of research may extend beyond its immediate targeted technology area. Hence, the purpose of the forward tracing element is to determine the influence DOE- attributed geothermal patents have had on the development of downstream geothermal technologies and other technologies beyond geothermal energy.

3.4.2 Backward Patent Tracing

The idea of backward patent tracing is to start with the intended (targeted) area of DOE's research program (downstream of the program), and determine if this target area did, in fact, build on a set of earlier DOE-attributed patents in the same technology area. In this study, the backward patent tracing starts by identifying a total set of geothermal patents, and traces backward to the geothermal patent portfolios attributable to DOE and to other organizations. This analysis helps to determine if the results of DOE's geothermal research were taken up by companies well positioned to take the results into application for commercial power generation. Comparing the extent of linkages of the total geothermal set to those attributed to DOE and to other organizations indicates the relative importance of DOE in forming a foundation for technologies used in the geothermal energy industry.

3.5 Extensions of the Patent Citation Analysis

The simplest form of a patent tracing study is one 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) Extension to Patents Citing Scientific Papers and Other Publications

It extends the analysis to include patent citations of DOE-sponsored papers and publications. Adding prior art references to DOE-funded scientific papers and publications thus takes into account the influence of these outputs on innovations reflected in patents.

(2) Extension to Multiple Generations of Citation Links

It extends the analysis by the addition of a second generation of citation links. This means that the study traces forward through two generations of citations starting from DOE-supported geothermal energy patents, and backward through two generations starting from the total set of geothermal patents.

The idea behind adding the second generation of citations is that DOE applied R&D programs often support elements of fundamental scientific research that may take time, and multiple generations of research for this research to be used in an applied technology, such as that described in a patent. The impact of the research may not therefore be reflected in a study based on referencing a single generation of prior art. Adding a second generation of citations allows for a more detailed analysis of the impact of DOE's geothermal energy research.

A potential problem with adding a second generation of citations must be acknowledged. This is a problem common to many networks, whether these networks consist of people, institutions, or scientific documents, as in this case. The 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 and publications 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 additional generations may bring in too many patents with little connection to the starting patent and publication sets.

(3) Extension Beyond the U.S. Patent System

The report looked beyond the U.S. patent system to include 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 geothermal research and subsequent technological developments.

Additionally, examining multiple types of linkages at the level of an entire technology area, such as geothermal, involves a significant data processing effort, requiring access to specialist databases. As a result, most previous attempts to trace through multiple generations of prior art have been limited to studying the development of very specific technologies or individual products.

3.6 Constructing Data Sets Used in the Geothermal Patent Analysis

To determine the impact of DOE-funded geothermal research both within and outside the geothermal energy industry, as revealed by patents, multiple data sets had to be constructed. This section describes the construction of these data sets.

3.6.1 Identifying the Set of Total Geothermal Energy Patents

In order to identify the set of geothermal patents for the backward tracing analysis, a patent filter was designed. To identify U.S. patents, the filter used a combination of keywords and Patent Office Classifications (POCs). The filter to identify EPO and WIPO patents used a combination of keywords and International Patent Classifications (IPCs).

To identify patents concerned with geothermal power plants, geothermal reservoirs, drilling such reservoirs, geothermal process technology, and other relevant patents, the patent filter was applied in four separate searches. The first search was designed to identify all patents for the POC "Power plants using geothermal heat" and the IPC "Producing mechanical power from geothermal energy." The second search was designed to identify U.S. patents classified as being concerned with natural heat sources, with the added keyword requirement that they refer to terms such as geothermal and underground. The third search was designed to identify patents for the POC "Boring or penetrating the earth" and the IPC "Earth and rock drilling," with keyword restrictions that the patents would refer specifically to terms related to geothermal energy. The fourth search was designed to identify all patents referring to the "Organic Rankine Cycle" or "ORC" or "Kalina Cycle," as well as to any other that used the term "geothermal," irrespective of their POC or IPC classification. Additional specifications of the patent filter approach are provided in Appendix A.

Patents identified by any of the four searches were considered for inclusion in the final set of geothermal patents. The titles of all these candidate patents were read individually, and irrelevant patents removed from the set. This process resulted in a final geothermal patent set consisting of 871 U.S. patents, 180 EPO patents, and 234 WIPO patents.

The design of the patent filter has important implications for the backward tracing element of the analysis presented in this report. It is this filter that determines which patents are included in the geothermal patent set used as the starting point for the backward tracing. More specifically, the keyword restrictions used in Searches 2-4 have a particular impact. These restrictions require that a patent must refer specifically to a geothermal, hot rock, or hot spring application in its title or abstract in order to be considered as a geothermal patent. The keyword restriction is included because of the nature of geothermal technology. Some technologies are relatively self-contained, and their patents use unique terminologies. This is not the case with geothermal technology, in particular because it shares many similarities with oilfield technology. For example, technologies such as drill bits, down-hole sensors, data transmission techniques, and well cements and casings may have applications for both the oilfield and geothermal industries. Including all such patents would swamp the geothermal patents with the much larger set of oilfield patents (for example, there are over 11,000 U.S. patents in POC 175 "Boring or penetrating the earth" alone). The keyword restriction in Searches 2-4 is designed to prevent this swamping effect from happening.

The drawback of the keyword restriction in Searches 2-4 is that it may understate the number of patents that should be included because patent applicants may not specify an application for their invention to avoid narrowing the scope of their patent. For example, a patent for a drill bit may not specify the industry in which it would be particularly advantageous. Such a patent will not be defined as geothermal in this analysis, even if the geothermal industry were actually its main focus.

There may also be patents that use the term geothermal in their specification (which provides more detailed background and description of the invention), but not in their title or abstract. Past experience has shown that including patents that use a particular term in their specification, but not in their title or abstract, introduces a great deal of noise to an analysis, since the added patents may make only passing reference to the technology of interest. The only way to overcome this is to read the specifications of all potential added patents – something that is impractical at the level of defining patents of an entire technology area. For this reason, defining geothermal patents for the backward tracing follows the conservative approach of requiring patents to make a reference to geothermal applications in their title or abstract.

The effects of this conservative approach can be seen in the results of the patent citation analysis, presented in Chapter 4. Specifically, the backward tracing element of the analysis focuses more on geothermal power plants and geothermal fluid treatments because there are large numbers of patents related to these technologies, and these patents do tend to make specific reference to their geothermal focus. Meanwhile, the forward tracing element of the analysis, which starts with the identified set of DOE-attributed geothermal patents and is not limited in its tracing of subsequent linkages, identifies more technologies such as drilling, well cements, and down-hole electronics. There are large numbers of patents in these technologies that are linked to DOE's geothermal research, but are not themselves defined as geothermal. This highlights the benefit of carrying out the analysis in two directions, since the forward tracing element helps to demonstrate DOE’s impact on all subsequent patents whether they are explicitly related to geothermal or not. Furthermore, a step was taken (in Chapter 4) to broaden the results of the backward tracing in view of the restrictive boundaries on the definition of geothermal used to construct the total set of geothermal patents. This step (in implementing the backward tracing) was to extend the analysis by examining the backward linkages of the starting set of geothermal patents to all earlier DOE-attributed patent families, in addition to those defined as geothermal patent families.

3.6.2 Identifying DOE-Attributed Geothermal Energy Patents

Identifying patents funded by government agencies is often 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. In order 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 government agency such as DOE may fund research in a variety of organizations. For example, DOE operates a number of laboratories and research centers, such as Ames, Argonne, Brookhaven, Livermore, Los Alamos, Oak Ridge and Sandia. Patents emerging from these laboratories and research centers may be assigned to DOE. However, the patents may alternatively be assigned to the organization that manages the laboratory or research center. For example, patents from Sandia may be assigned to Lockheed Martin, while Livermore patents may be assigned to the University of California.

A further complication is that DOE not only funds research in its own labs and research centers. It also funds research carried out by private companies in partnership with DOE. If this research results in patented inventions, these patents are likely to be assigned to the company carrying out the research, rather than to DOE. Sometimes these patents acknowledge a government interest in the patent, but not always.

To identify geothermal patents that resulted from research funded by DOE (referred to in this report as "DOE-attributed"), the first approach was to match patents from the total geothermal set, identified as described in Section 3.6.1, to the following three sources:

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 second source used was a set of U.S. patents identified by the study as assigned to DOE but not found in the OSTI database, usually because they had been issued since the latest updated version of that database. Patents in the total set of geothermal patents that matched the DOE-assigned patents—that were not in the OSTI database—were added to the list of DOE-attributed patents.

3. ***Patents with DOE Government Interest***—the third source used was a set of U.S. patents identified by the study that have in the section of each patent entitled 'Government Interest' an acknowledgement of the rights that DOE has in the particular invention. For example, if a government agency funds research at a private company, the government may have certain rights to patents granted based on this research. 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 the total set of geothermal patents that matched patents acknowledging DOE in the Government Interest section—that were neither in the OSTI database nor assigned to DOE—were added to the list of DOE-attributed patents.

In addition, a second approach was to search DOE reports for patents attributed to DOE-funded geothermal research, and add those found to the list identified by the first approach of matching patents from the total geothermal set to the above three sources.

In some cases, the DOE reports identified organizations whose geothermal energy research had been funded by DOE, indicated the period of funding, and described to some extent the subject technologies. By matching the organizations, time periods (with appropriate lags), and technologies from these reports, with patents assigned to the organizations, it was possible to identify additional candidate patents that were likely based on research funded (at least in part) by DOE.

To ensure that patents on the list of candidates identified through the two approaches described above were in scope, and that they were rightly attributed to DOE, the candidate list was provided to geothermal experts in DOE/EERE for verification. The DOE program experts provided feedback as to which of the candidate patents should be included in the final set of DOE-funded patents, which should be omitted, and identified any additional patents they thought should be added. Based on this process, a total of 90 U.S. geothermal energy patents attributed to DOE-funded research resulted.

The next step was to search for equivalents of each of these 90 patents in the EPO and WIPO systems. An equivalent is a patent filed in a different patent system covering essentially the same invention. The search was also extended to U.S. patents that are continuations, continuations-in-part, or divisionals of each of the 90 U.S. patents. In total, 115 U.S. patents (i.e., the 90 plus their continuations, continuations-in-part, or divisionals), 16 EPO patents, and 17 WIPO patents attributed to DOE-funded geothermal research were identified. (See further explanation below in Section 3.6.3.) A list of these patents can be found in Appendix B.

3.6.3 Constructing Patent Families

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, 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.

In this project, it was necessary to construct patent families for the set of total geothermal patents, for the set of DOE-attributed patents, and also for all of the patents/applications linked through citations to DOE. Constructing these patent families required matching the priority documents of the U.S., EPO, and WIPO patents/applications, in order to group them in the appropriate families. Fuzzy matching algorithms were used to achieve this, along with a small amount of manual matching, because priority documents have different number formats in the different patent systems. It should be noted that 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.

As a result of this process, the U.S., EPO, and WIPO geothermal energy patents/applications attributed to DOE (containing 115 U.S. patents, 16 EPO patents, and 17 WIPO patents) were grouped into 90 patent families. Meanwhile, the set of all U.S., EPO, and WIPO geothermal energy patents/applications (containing 871 U.S. patents, 180 EPO patents, and 234 WIPO patents) were grouped into 1,016 patent families.

3.6.4 Identifying DOE-Attributed Geothermal Scientific Papers/Publications

The search for scientific papers/publications cited by patents as priority documents is difficult and resource intensive. It was not feasible to conduct a patent-citation search of the more than three thousand DOE-sponsored publications in the geothermal field identified by a search of the OSTI database. Furthermore, this approach would have missed cited DOE-sponsored scientific papers that were not included in the OSTI database.

Thus, to provide a feasible list that would feature papers/publications regarded as being of strong emerging scientific interest in the field, a review was conducted of DOE reports that described PGTP and in that context listed important papers and publications from then current research. To the list of papers compiled from the reports of current geothermal research, papers by the same authors also pertaining to geothermal research were added, resulting in a total set of 45 scientific papers/publications. This list is provided in Appendix C.

3.7 Constructing Citation Links

Having constructed the patent and publication sets, it was necessary to link them via citations. Four types of citation linkage are considered in the patent analysis (patent-patent; patent-publication; patent-patent-patent; and patent-patent-publication). These four linkage types are constructed using two different components: citation links between patents and patents, and citation links between patents and publications. The patent-patent citation links are relatively straightforward to identify, since patents can be identified and linked via their patent numbers.

The patent-paper/publication links (i.e., cases where a patent cites a publication as prior art) are more difficult to generate than patent-patent links. One difficulty in generating patent-paper/publication linkages is that prior art references to publications appear on patents as free text, and as such do not follow a prescribed format. For example, journal names may be abbreviated in different ways, the number of authors listed may vary, or elements of the reference may simply be missing. These factors make the analysis resource intensive. To assist the process, fuzzy matching algorithms were used to generate links between non-patent references in patents and the list of DOE-funded geothermal scientific papers/publications (see Section 3.6.4 and Appendix C for more about the list). Various combinations of journal name, report number, page number, author, title words and publication year were matched in order to produce a candidate list of potential citations from patents to these papers/publications. This candidate list was then checked to determine which of the matches were correct.

Two types of two-generation links other than those listed above are not included in this patent analysis. The first is patent-publication-publication (i.e., cases where a patent cites a DOE-supported geothermal publication, which in turn cites another DOE-supported geothermal publication). This type of citation link is not included due to time and resource considerations.

The other type of link not included in the analysis is patent-publication-patent (i.e., cases where a patent cites a DOE-supported geothermal publication, which in turn cites a DOE-attributed geothermal patent). This type of link was not included because scientific publications reference patents relatively infrequently. As a result, the number of links that would be identified through the patent-publication-patent route is likely to be very small, particularly relative to the amount of data processing required to include these additional links.

The various data sets described in Section 3.6, and the linkages among them, formed the basis for the analysis described in the patent results section (Chapter 4) of this report.

3.8 Publication Co-authoring and Citation Analyses

Bibliometric theory holds that citations of scientific papers/publications by other papers/publications generally acknowledge scientific, intellectual debts, rather than technology debts. [20] Thus, publication-to-publication citation analysis is generally considered a less effective approach to tracing linkages from R&D to downstream commercial activity than patent-to-patent and patent-to-publication analysis. However, the study found that analyses of publication co-authorship and publication citations by other publications offer additional insights into the linkages from DOE's geothermal research to other institutions and researchers, including companies engaged in commercializing geothermal technologies, universities, and other domestic and foreign government institutions.

Co-authoring by DOE geothermal researchers and researchers from other organizations may indicate collaboration and potential linkages between DOE researchers and those involved in downstream technology development and commercialization. Citations of publications resulting from DOE research by other publications may show additional paths of linkages to downstream applications.

The publication citation search is facilitated by the use of a publication citation database and search engine. For a long period, the U.S.-based firm Thomson Scientific (formerly the Institute for Scientific Information [ISI]) was the principal tool facilitating publication citation analysis. However, today there are a growing number of publication citation databases and search tools, such as Scopus, CiteSeer, and Google Scholar, which provide more comprehensive coverage beyond the major journals, to include, for example, conference proceedings, book chapters, dissertations, and research reports.[21] 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.[22] A comparison of alternative publication search tools rated Google Scholar among the best.[23]

[20] Martin (2005), Chapter 4
[21] Meho (2007), p. 32.
[22] Harzing & Wal (2008) also makes the point that Google Scholar provides a more complete listing of publications beyond journals.
[23] Meho (2007), pp. 31-36, and Meho & Yang (2007), pp. 2105-2125.

3.9 Database and Document Review and Interview

The database and document reviews and interviews with experts helped define the parameters for the patent analysis and a set of patents for study. The reviews and interviews also helped identify multiple paths for investigation, and provide a more comprehensive treatment of knowledge outputs from DOE's geothermal energy research. A review of databases and documents and online program sites were principal resources in identifying companies and universities that have been funded for geothermal research by DOE. Interviews with experts identified several DOE-funded models important to geothermal resource development and of particular importance for inclusion.

3.10 Study Limitations

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 does, however, provide evidence of relationships and connections, and is a step toward establishing cause and effect.

Historical tracing can be expected to miss connections worthy of inclusion. Many factors go into producing a commercially successful innovation. There are important linkages that tend not to be captured by publication and patent analyses. Examples are flows of information along informal lines, information transferred by reverse engineering, information that is placed in the public domain with access by all, and information flows by means that are held confidential.

Interview also 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, misunderstood, especially if a long period of time has elapsed. The number of interviews for the study is limited by resources and time such that the results are 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, information on licensing of patents by DOE is generally considered confidential. Still others 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 is very resource intensive, in addition to typically being considered proprietary and confidential. Hence, the study did not trace licensing activity by individual companies, 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 of significance is embodied in patents and publications. Frequently, innovations funded by DOE laboratories are made freely available to any who wish to use them. In addition, some of the DOE strategies for advancing technology and fostering markets are by their nature not reflected in patent or publication data. Another limitation is 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. Not all patents and publications reveal their source(s) of support. Lack of comprehensive databases in support of evaluation likely means that the number of patents and publications included is an understatement of the actual number receiving DOE-support. The publication citation analysis may suffer from citing errors due to imperfect citation search tools. [24] Other limitations include 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.[25]

[24] Harzing (2008), pp. 61-73.
[25] Meho (2007), pp. 33-35.

4. Linkages Found by Patent Analysis

This chapter describes the results of a patent analysis, which traces connections between GTP's geothermal energy research and subsequent developments both within and outside the geothermal power industry. See Section 3.6 and Appendix A for a description of initial patent data sets used in this analysis.

First, trends in geothermal patenting are examined and the leading organizations in geothermal patenting are identified. Then the results of the backward patent tracing at the organizational level are presented, followed by the results of the forward patent tracing at the organizational level. Finally, results of tracing backward and forward at the individual patent level are presented.

Among the findings is that the 90 geothermal patent families attributed to DOE put DOE at the top of the list of organizations in terms of number of geothermal patent families. Nevertheless, the number attributed to DOE constitutes a small share of the more than 1,000 geothermal patent families identified by the study. The patent analysis shows that DOE-funded geothermal research has influenced subsequent innovation by leading geothermal energy companies. Organizations with the highest percentage of their geothermal patent families linked to earlier DOE-attributed geothermal patent families include Alstom, Ormat, Chevron (Unocal), Dow Chemical, and Occidental Petroleum. Widening the patent analysis to include linkages from the total geothermal set back to all earlier patents reveals the large influence of leading oil and gas companies, such as Exxon Mobil, on geothermal innovation. Tracing forward from the 90 DOE-attributed geothermal patent families to subsequent linked patent families in all industry areas reveals the close linkage of the DOE-attributed set to patents of the largest oilfield services companies. The patent analysis also identifies the individual DOE-funded inventions that have had a particularly strong impact on downstream innovation, such as patents describing methods for generating geothermal energy from unpromising sites; the Organic Rankine and Kalina thermodynamic cycle technology used in heat exchangers in geothermal power plants; drilling using high pressure fluids; cements for use under adverse conditions found in geothermal wells; electronics for down-hole data transmission; and silica control in geothermal plants.

4.1 Trends in Geothermal Energy Patenting

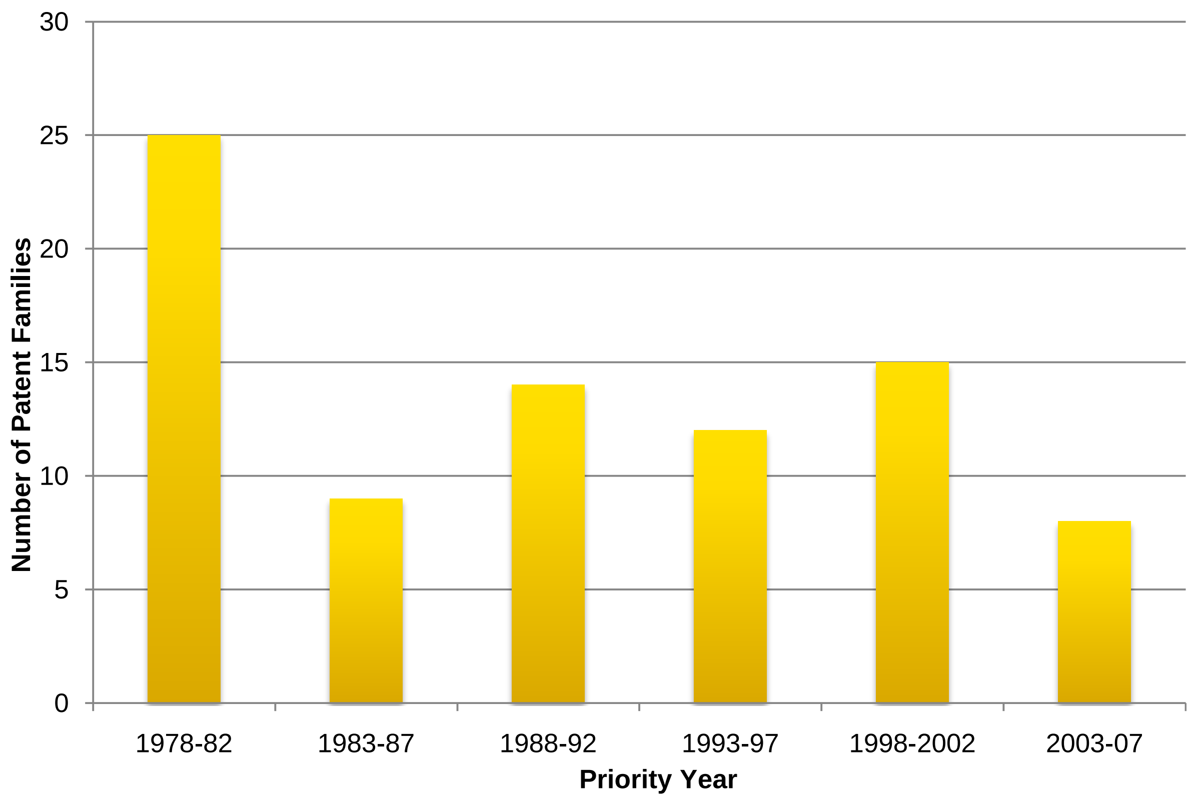
DOE has funded research in geothermal energy for more than 30 years. Figure 4-1 shows that DOE-attributed geothermal patent families peaked between 1978 and 1982, a period in which 25 such patent families were filed. The number of DOE-attributed geothermal patent families has not exceeded fifteen in any five year time period since then, and fell to a low of eight patent families filed between 2003 and 2007. This pattern is based on the filing date of the patent family's priority patent, rather than on individual patent issue dates. That is, the data as shown in

Figure 4-1 eliminate the effect of multiple patents resulting from a single invention and reflect the date of the initial invention within each family of related patents.[26]

The larger trend in geothermal patenting is shown in Figure 4-2, with the total number of geothermal patents divided into those attributed to DOE and those attributed to other entities. This figure reveals that, until recent years, patenting due to DOE funding of geothermal research followed the overall trend described in this section relatively closely. Overall geothermal patenting peaked at 185 patent families in the earliest time period shown, between 1978 and 1982. It then declined for the following three time periods, with approximately 125 patent families filed in each five-year period between 1983 and 1997. Overall patenting then started increasing between 1998 and 2002, and increased again to 175 in the most recent time period covered, between 2003 and 2007.

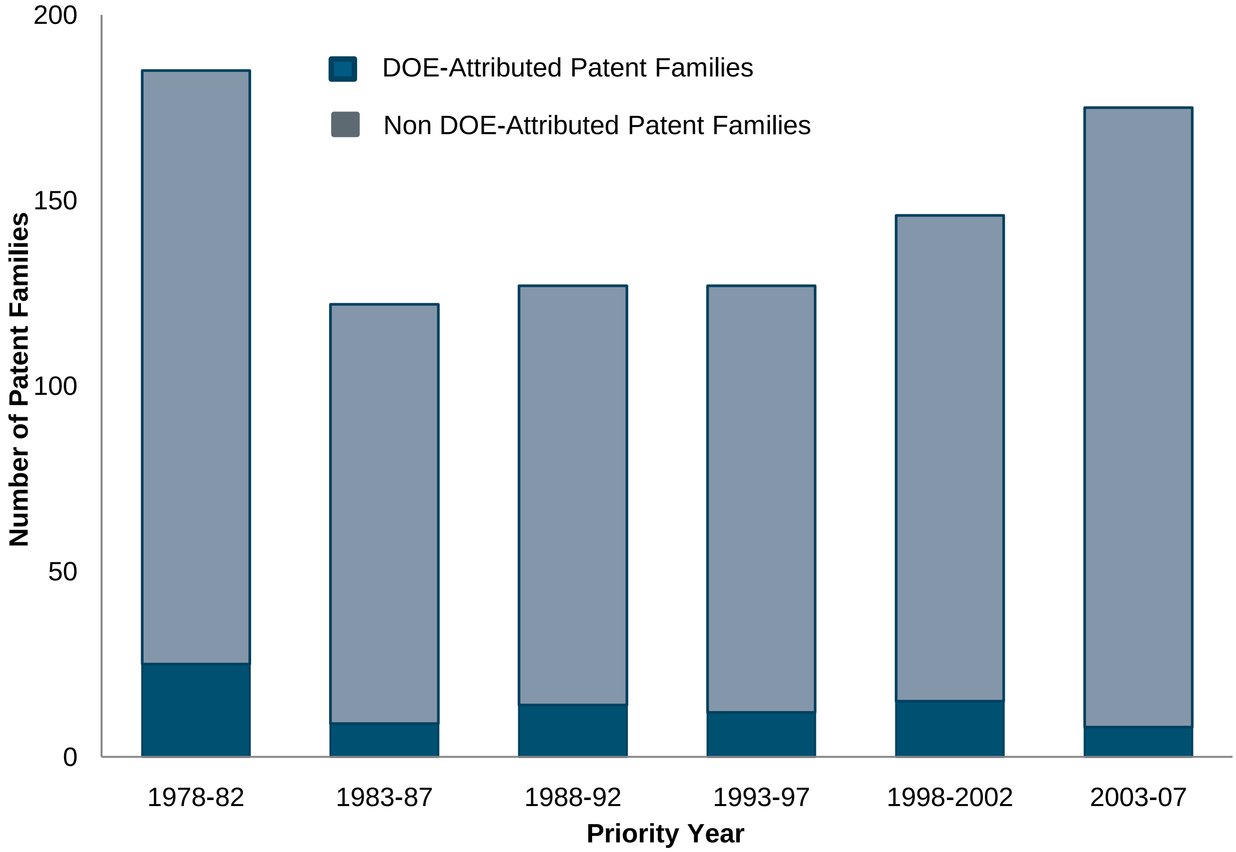
It is noticeable that DOE-attributed geothermal patent families comprised a relatively small share of this recent increase. Hence, while DOE-attributed geothermal patent families made up 13.5% of families filed between 1978 and 1982, they represented only 4.5% of families filed between 2003 and 2007.

Figure 4-1. Number of DOE-Attributed Geothermal Patent Families by Priority Year



[26] If individual patents attributed to DOE are counted, instead of families, a single invention filed in 2002, which spawned issuance of a large number of related patents within the same family in 2006 and 2007, would cause it to appear that there has been a recent increase in DOE-attributed patenting in geothermal energy. Although all are legitimate patents, it may present a misleading impression since they all result from a single invention filed in 2002. Therefore, the number of patent families by priority date is used to depict trend. The priority date, sometimes called the "effective filing date", is the date used to establish the novelty of a particular invention relative to other art.

Figure 4-2. Total Number of Geothermal Patent Families by Priority Year, with a Breakout of DOE-Attributed and Non DOE-Attributed Patent Families

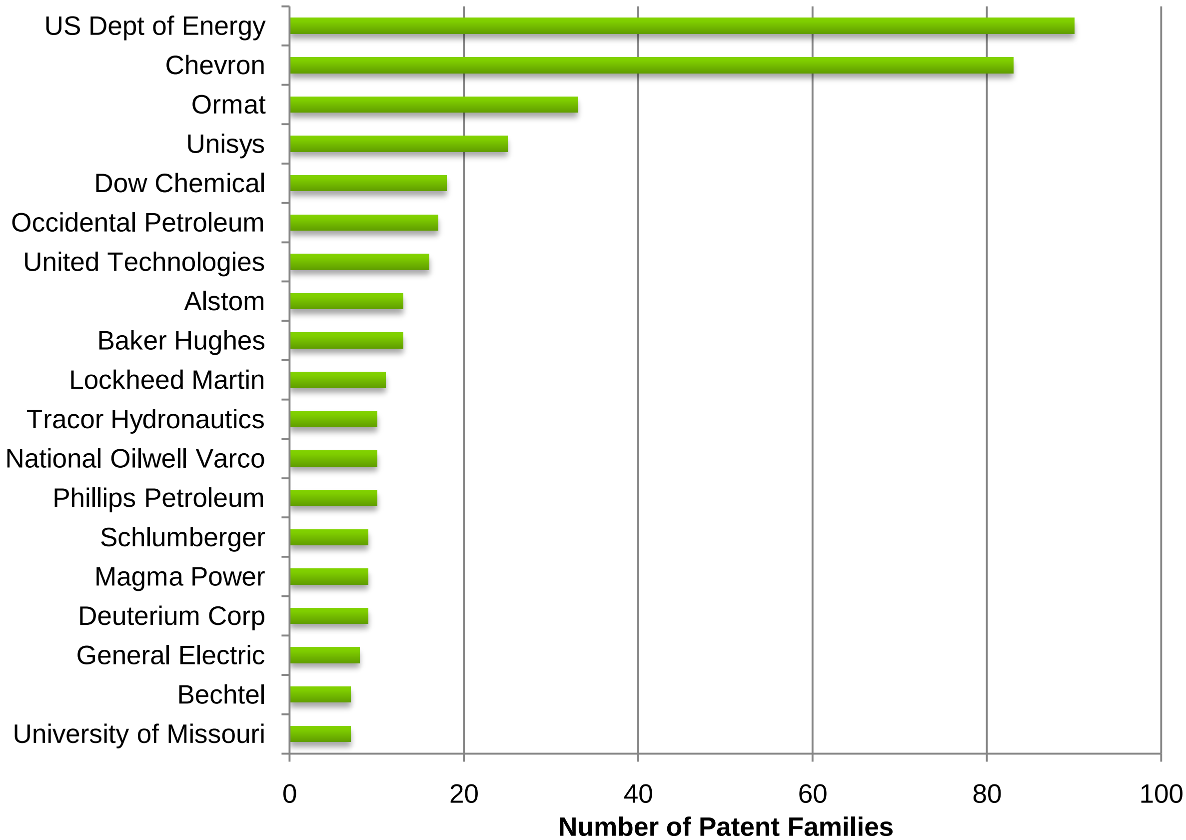


4.2 Organizations with the Largest Number of Patent Families in Geothermal Energy

Although DOE's share of total geothermal patent families is relatively small, as was shown in Figure 4-2, DOE is nevertheless the dominant organization in terms of geothermal patents attributed to it. As shown in Figure 4-3, only one company, Chevron, which currently claims to be the world's largest producer of geothermal energy, approaches DOE's number, with 83 geothermal patents assigned to it. Much of Chevron's technological expertise related to geothermal energy appears to result from the 2005 merger of Union Oil Company of California (Unocal) with Chevron. Of the 83 Chevron geothermal energy patent families, 80 were originally assigned to Unocal. These Unocal patent families describe a wide variety of technologies related to geothermal energy, including drilling techniques, well casings, and methods for processing geothermal brine and steam.

Next among the leading organizations in geothermal energy patenting is Ormat Technologies, with less than half the number of geothermal patents as Chevron. Ormat is one of the few companies in Figure 4-3 that has geothermal power as its primary focus. Ormat's patent families describe various aspects of geothermal energy, with a particular focus on processing geothermal fluids, and on using geothermal technology to produce a reliable source of energy.

Figure 4-3. Organizations with the Largest Number of Geothermal Energy Patent Families



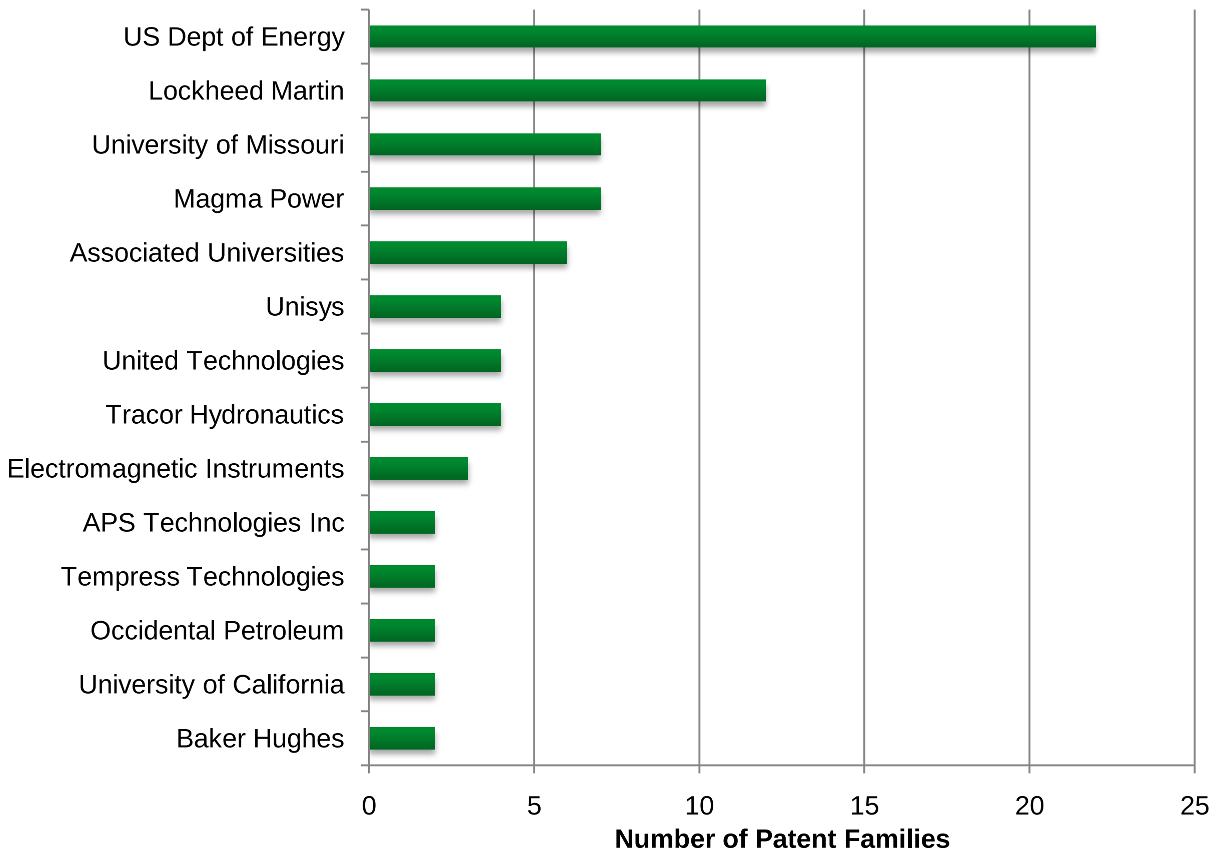
Fourth listed Unisys is not a company typically associated with geothermal energy, but it is the only other company in Figure 4-3 with more than 20 patent families. The company has a series of patent families describing control systems for geothermal wells. However, the last patent in these families was issued in 1984, so the company appears to no longer be active in geothermal technology.

Other organizations on the list of those with the largest number of geothermal energy patent families include Dow Chemical, Occidental Petroleum, United Technologies, Alstom, Baker Hughes, Lockheed Martin, Tracor Hydronautics, National Oilwell Varco, Phillips Petroleum, Schlumberger, Magma Power, Deuterium Corporation, General Electric, Bechtel, and the University of Missouri. However, all of these organizations have fewer than 20 geothermal patent families, and the last few on the list have fewer than 10.

It should be noted that the number of geothermal patent families attributed to DOE is derived somewhat differently than the patent family counts for the other organizations in Figure 4-3. Specifically, DOE's 90 patent families are those attributed to research funded by DOE, not all of which are assigned to DOE. In contrast, the companies' geothermal patent families are only those assigned to each company. Therefore, the comparison of DOE with the companies in terms of their numbers of geothermal patent families bears closer inspection.

Figure 4-4 shows the top assignees of the 90 geothermal energy patent families attributed to DOE funding. This figure indicates the breadth of organizations whose geothermal energy research has been funded by DOE, although the number of patent families produced by each organization has generally been relatively small. DOE itself is the most prolific assignee, with 22 patent families assigned to it by name, followed by Lockheed Martin (manager of the Sandia National Laboratories (SNL)) with 12 families, University of Missouri (7 families), and Magma Power (7 families).

Figure 4-4. Top Assignees of DOE-Attributed Geothermal Energy Patent Families in Declining Order of Number of Families



DOE has funded a wide range of organizations in geothermal technology, and these organizations have used the funding to develop a variety of technologies. For example, Baker Hughes, Honeywell, and Intelliserv (now part of National Oilwell Varco) used DOE funding to help develop electronics and data transmission capabilities for geothermal wells. Unisys used DOE funding to help develop patents related to control systems for geothermal energy generation. DOE-funded research led to patents related to sensors and drilling components at SNL (managed by Lockheed Martin and assigned to it); and DOE-funded research led to patents in lightweight well cements at Brookhaven National Laboratory (then managed by Associated Universities and assigned accordingly). In addition, DOE-funded geothermal research at

Hydronautics and the University of Missouri led to the development of fluid jet nozzles (and related patents) for more effective drilling of wells. DOE-funded research also led to the development of Organic Rankine Cycles (ORC) and to a series of related patents held by United Technologies.

Notice that the list of assignees of the most patents funded by DOE geothermal research does not match the list of organizations with the largest number of geothermal patents. However, there are a number of assignees in Figure 4-4 that also appear in Figure 4-3, such as Lockheed Martin, Unisys, Occidental Petroleum, University of Missouri, and Magma Power. As a result, there is some degree of overlap in the patent counts in Figure 4-3 between those attributed to DOE and those assigned to other organizations, most notably the 12 patent families resulting from research performed at SNL and assigned to Lockheed Martin. These acknowledge DOE support and, thus, are included in the patent set attributed to DOE funding. On the other hand, none of the Chevron geothermal patent families—the largest set after DOE—are funded by DOE geothermal research and included in the DOE set.

4.3 Results of Tracing Backward: Organizational Level

This section reports the results of the backward tracing analysis to determine the extent to which subsequent patents in geothermal energy trace back to the DOE-funded geothermal research as compared with that of other organizations. This is an important part of the analysis because it starts with the end goal—to advance geothermal technology for commercial power generation—and provides an answer to a major question addressed by this study: Did the outputs of GTP's research in geothermal energy reach a downstream audience well positioned to apply them to commercial development of electricity?

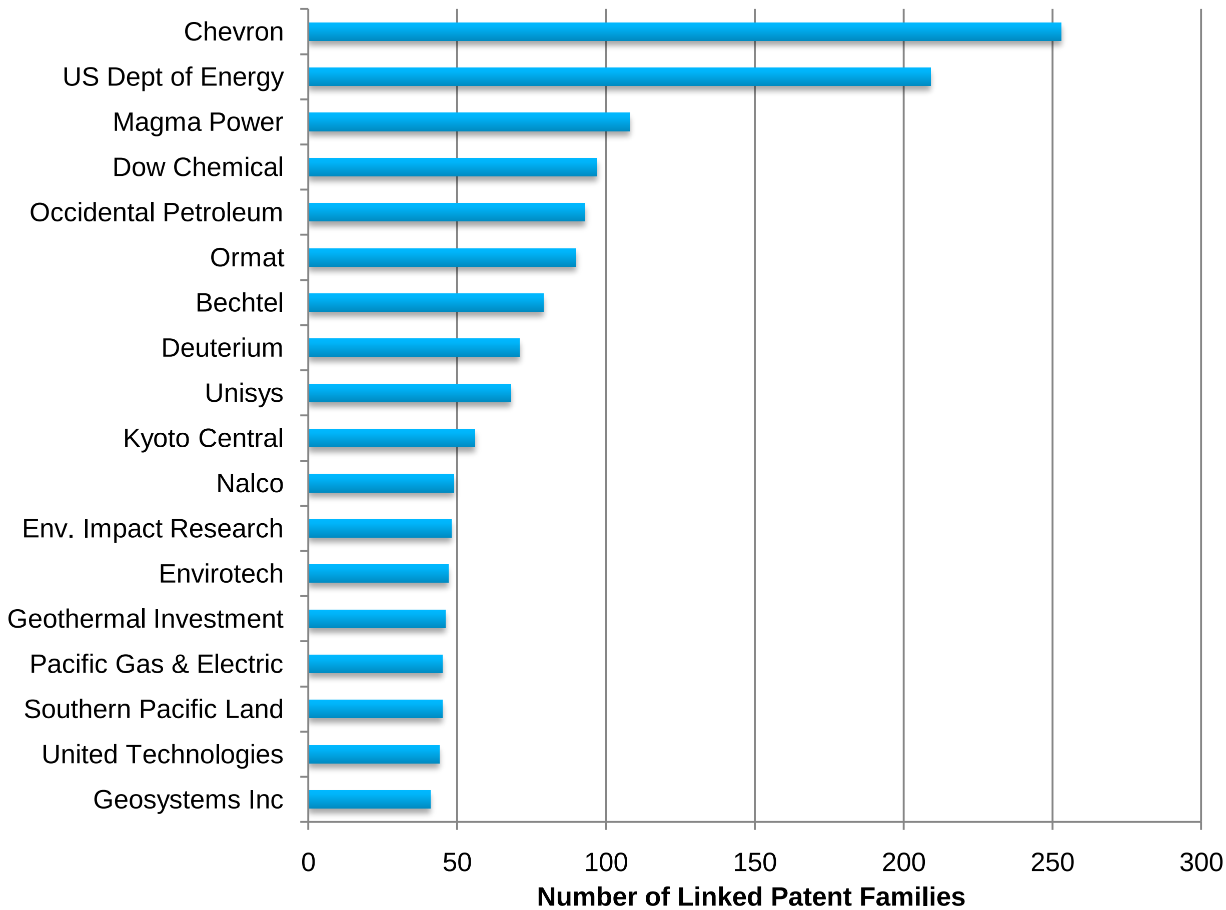
There are various ways to assess DOE's influence on geothermal energy innovation at the organizational level. These various analyses are presented in the following two subsections, 4.3.1 and 4.3.2.

4.3.1 Comparison of the Influence of DOE-Funded Research with that of Other Organizations on Subsequent Developments in Geothermal Energy

Figure 4-5 is one of the most revealing figures in this analysis. It shows the organizations whose geothermal patents have had the strongest impact upon downstream developments in geothermal energy. It compares the influence of DOE-funded geothermal research with the influence of that of other organizations active in geothermal energy research.

Chevron and DOE are at the head of Figure 4-5, again, Chevron by virtue of its merger with Unocal. Of the 1,016 total geothermal patent families identified through the process described in Section 3.6.1, 253 (24.9%) are linked to earlier geothermal patents of Chevron. Meanwhile, 209 geothermal patent families (20.6%) are linked to earlier DOE-attributed geothermal patent families.

Figure 4-5. Organizations Whose Geothermal Patent Families Are Linked to the Most Subsequent Geothermal Patent Families

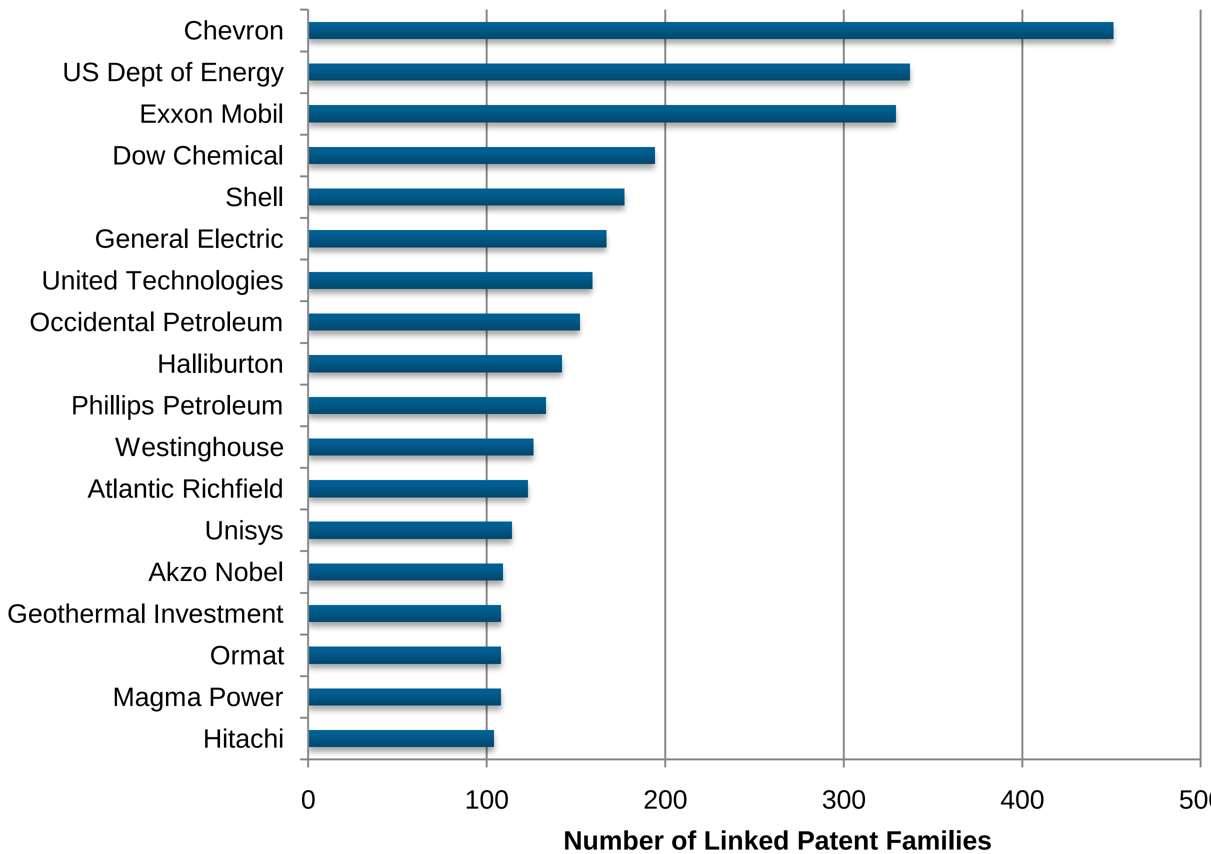


The presence of these two organizations at the head of Figure 4-5 may not be surprising, given that they have the largest geothermal patent portfolios, and, therefore, have the most patents available to be linked to subsequent patents. Having said this, Figure 4-5 does reinforce the importance of both Chevron (primarily through Unocal) and DOE in the development of the field of geothermal technology. Moreover, it may be seen by comparing the list of organizations in Figure 4-3 with that of Figure 4-5, that some of the companies with fewer geothermal patent families place high on the list of organizations having influential patent sets. For example, Magma Power is relatively low in terms of its number of geothermal patent families, but relatively high in terms of the influence of those patent families. Similarly, some organizations among those with the most geothermal patent families score relatively low in terms of their influence.

As was noted in Section 3.6.1, defining the boundaries of geothermal technology for purposes of identifying the total list of patent families for geothermal energy was not straightforward. Some patents may have applications both within and outside geothermal energy, and some geothermal patents may build on previous patents that are not defined specifically as geothermal in this analysis. Figure 4-6 helps to address this shortcoming by examining the number of geothermal patent families linked to earlier patent families by organization, irrespective of whether these earlier families are defined as geothermal.

Chevron and DOE are once again prominent in Figure 4-6. Of the 1,016 geothermal patent families in the starting set, 451 (44.4%) are linked back to all earlier Chevron (Unocal) patents, including those not identified as geothermal. Meanwhile, 337 (33.2%) are linked back to earlier DOE-attributed patents. Both of these numbers are significantly higher than those reported in Figure 4-5. This suggests that geothermal technologies not only built on other earlier geothermal patents, but also on patents describing other technologies (such as mining, and oil and gas exploration) not identified in their patent descriptions as having geothermal applications.

Figure 4-6. Organizations Whose Patent Families (Including All, Not Just Geothermal) Are Linked to the Most Subsequent Geothermal Patent Families



The close relationship between geothermal technology and oil and gas technology is reflected by the now prominent position of Exxon Mobil in the listing of influential organizations. Of the 1,016 geothermal patent families, 329 (32.4%) are linked to earlier Exxon Mobil patent families. These Exxon Mobil patent families describe a variety of technologies, such as drilling components and down-hole electronics, which have potential applications in both the oil and gas and the geothermal energy industries, but are not characterized as relating to geothermal. Taken together, Figures 4-5 and 4-6 suggest that DOE, together with Chevron (Unocal) and Exxon Mobil, have formed an important part of the foundation for geothermal technologies.

Other organizations that now appear in the listing of those whose patent families have strongly influenced later geothermal technologies include Dow Chemical, Shell Oil and other large petroleum companies. Large diverse companies, such as General Electric, United Technologies, and Westinghouse also appear. The focused geothermal companies, Geothermal, Ormat, and Magma Power, are still on the list, but farther down.

4.3.2 Comparison of Companies in Terms of How Extensively Their Geothermal Patent Families are Linked to Earlier DOE-Attributed Geothermal Patent Families

This section addresses the question of which organizations have geothermal patents that build particularly extensively on earlier DOE-attributed geothermal patents. The question is addressed in different ways using different statistics in Figures 4-7 through 4-10.

Figure 4-7 shows the organizations with the largest number of their geothermal patent families linked to earlier DOE-attributed geothermal patent families. This figure reveals that Chevron and Ormat are the two organizations with the largest number of patent families linked back to the DOE set. This is an interesting finding, given the prominent role of these two companies within the geothermal energy industry. However, the finding is not particularly surprising, because Figure 4-7 is based on absolute numbers of patent families linked to DOE, and therefore has a natural bias toward companies with extensive geothermal energy patent portfolios.

Figure 4-8 overcomes the bias by looking at the share of each organization's geothermal energy patent families that are linked to DOE, rather than their absolute number. This analysis confirms the influence of DOE-funded research on geothermal technology developed by Chevron and Ormat. Over half of Ormat's geothermal patent families, and over 40% of Chevron's, are linked to earlier DOE-attributed geothermal patent families. However, the company at the head of Figure 4-8 is Alstom, with over 80% of its geothermal patent families linked to earlier DOE-attributed geothermal patent families. These Alstom patents describe Kalina cycles for power generation, and are linked to a key patent for an invention by Alexander Kalina, whose research was funded by DOE. Yet another way of examining the impact of DOE-funded geothermal energy research on different companies in the industry is provided by Figure 4-9. This figure shows the organizations with the highest average (mean) number of links per geothermal patent family to earlier DOE-attributed geothermal patent families.

Chevron is again prominent in this figure, with almost two links to DOE per geothermal patent family. Ormat is less prominent, with an average of only one link to DOE per family. Occidental Petroleum Corporation, an international oil and gas exploration and production company, is again prominent, with an average of two links to DOE per patent family.

There are two organizations in Figure 4-9 with more than two links to DOE per patent family: ENRO Geothermie GmbH, a German company, and Earth to Air Systems, LLC, a U.S. company focusing on direct exchange geothermal heating and cooling technologies. Each company holds fewer patents than Chevron, Ormat, and Occidental, but those held have multiple links to the DOE geothermal set.

Figure 4-7. Organizations with the Largest Number of Their Geothermal Energy Patent Families Linked to Earlier DOE-Attributed Geothermal Energy Patent Families

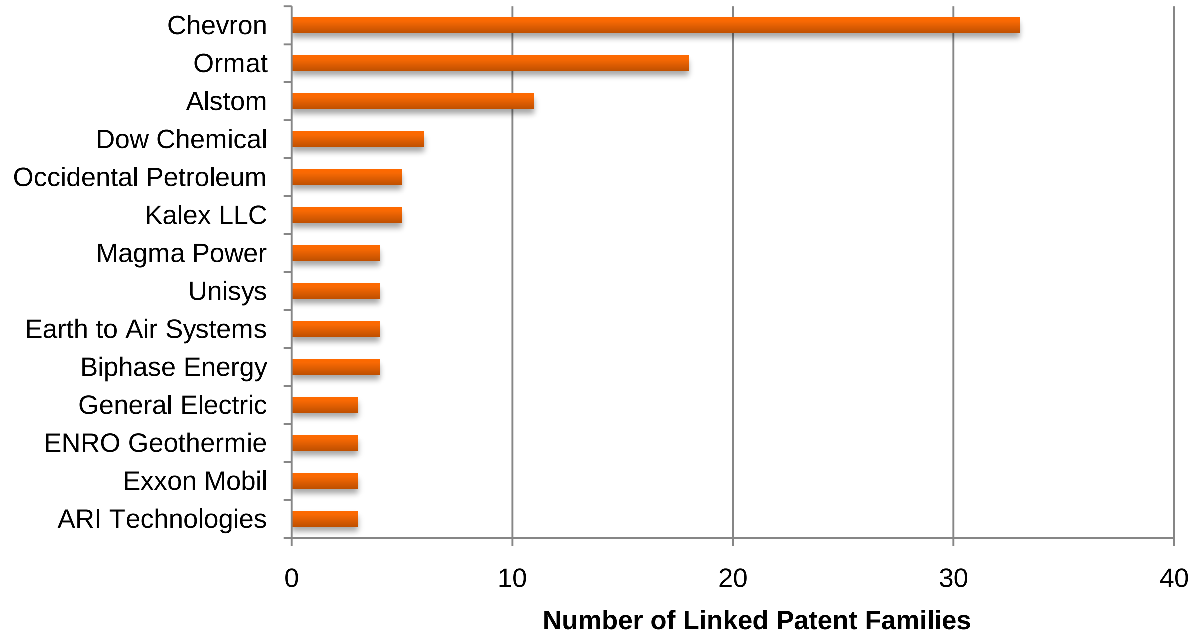


Figure 4-8. Organizations with the Highest Share of Their Geothermal Energy Patent Families Linked to Earlier DOE-Attributed Geothermal Energy Patent Families

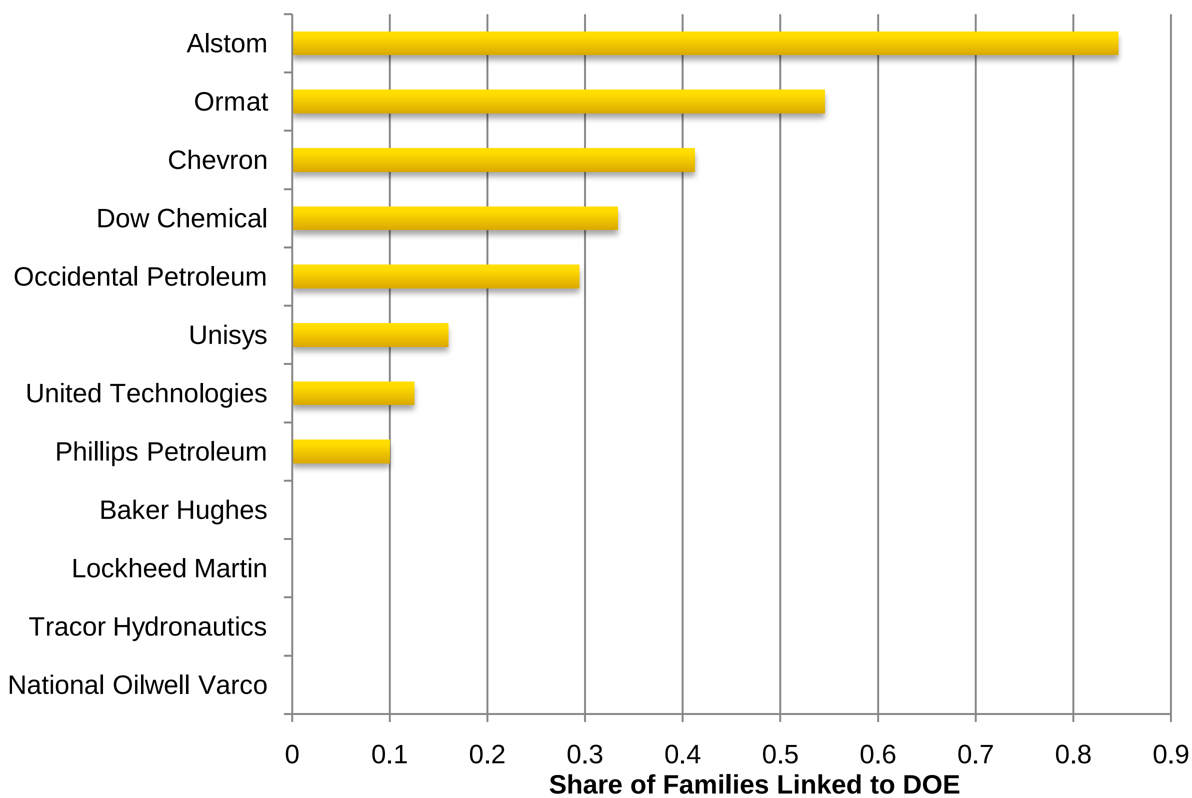
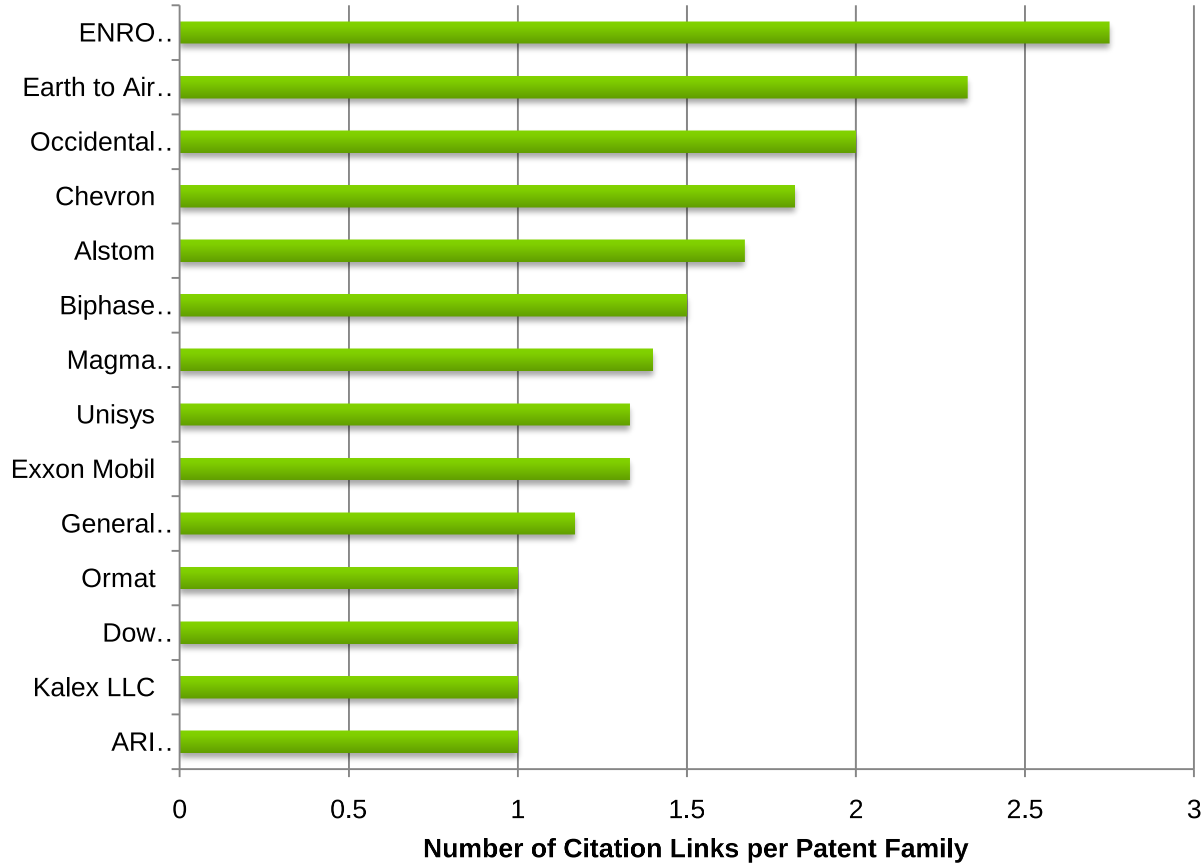


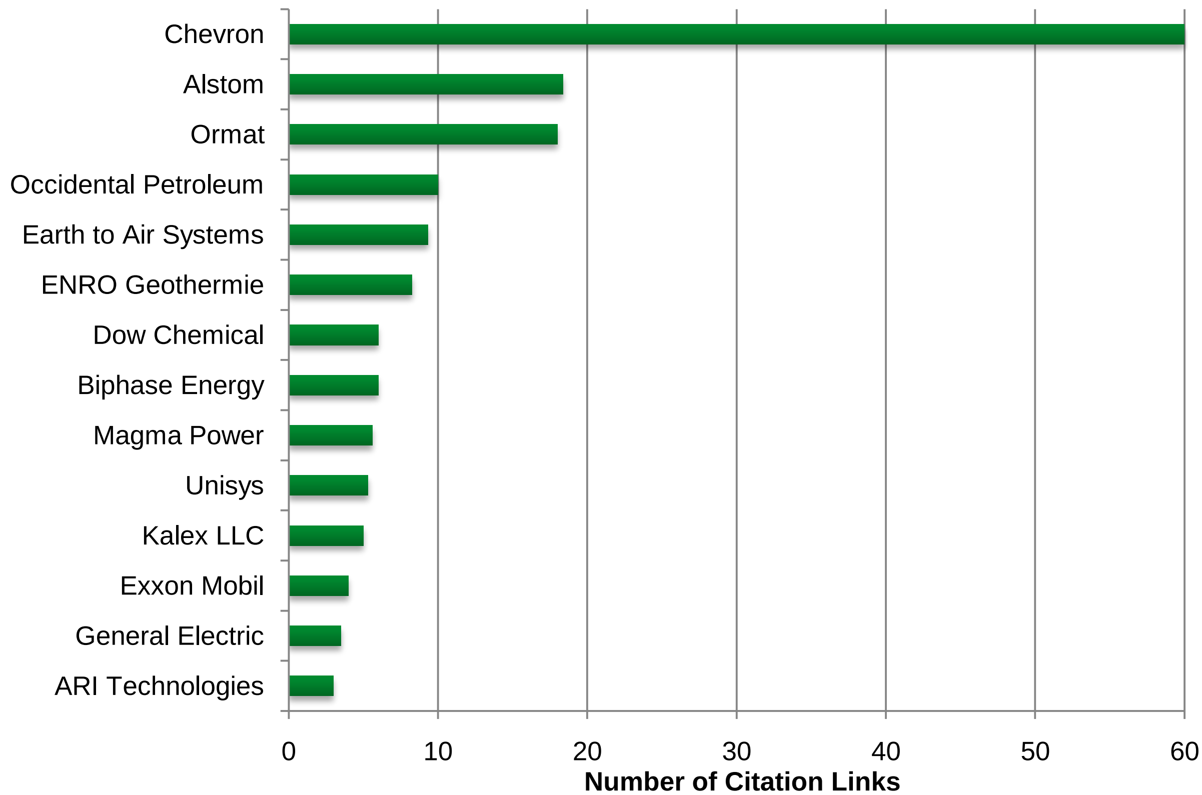
Figure 4-9. Organizations with the Highest Average Number of Citation Links per Geothermal Patent Family to Earlier DOE-Attributed Geothermal Patent Families



As an overview, a measure of the breadth of DOE's influence upon these organizations' geothermal technology is provided by Figure 4-8, which shows the percentage of each organization's geothermal patent portfolio that is linked to DOE-funded research. Figure 4-9, which shows the number of links per patent family, may be regarded as a measure of the depth of DOE's influence on individual patents. Companies that appear prominently in both Figures 4-8 and 4-9 have geothermal energy portfolios that appear to build particularly extensively on earlier DOE-funded geothermal research. Chevron is the clearest example of this.

Figure 4-10 highlights those companies, including Chevron, whose geothermal energy patent portfolios have built extensively on earlier DOE-funded geothermal research. It lists organizations that have the largest number of total citation links from their sets of geothermal patent families back to DOE-funded geothermal research. The number is computed as the number of company geothermal patent families linked to earlier DOE-attributed geothermal patent families multiplied by the average number of links per patent. Chevron is at the head of Figure 4-10 by a wide margin followed by Alstom and Ormat.

Figure 4-10. Organizations with the Largest Number of Total Citation Links to Earlier DOE-Attributed Geothermal Patent Families



4.3.3 Highlights of Findings from Backward Patent Analysis at the Organizational Level

Overall, the results of this backward tracing analysis have shown that DOE-funded geothermal research has influenced subsequent innovation by leading geothermal energy companies, most notably Chevron (through its merger with Unocal) and Ormat. DOE-funded geothermal research, together with that of Chevron (Unocal), with its own strong patent ties back to DOE, have exhibited the largest influence among organizations on subsequent technological developments in the geothermal industry. When the search for linkages is widened to include connections from the total geothermal set back to all patent families (not just geothermal), the large influence of leading oil and gas companies, such as Exxon Mobil, on geothermal innovations also becomes apparent.

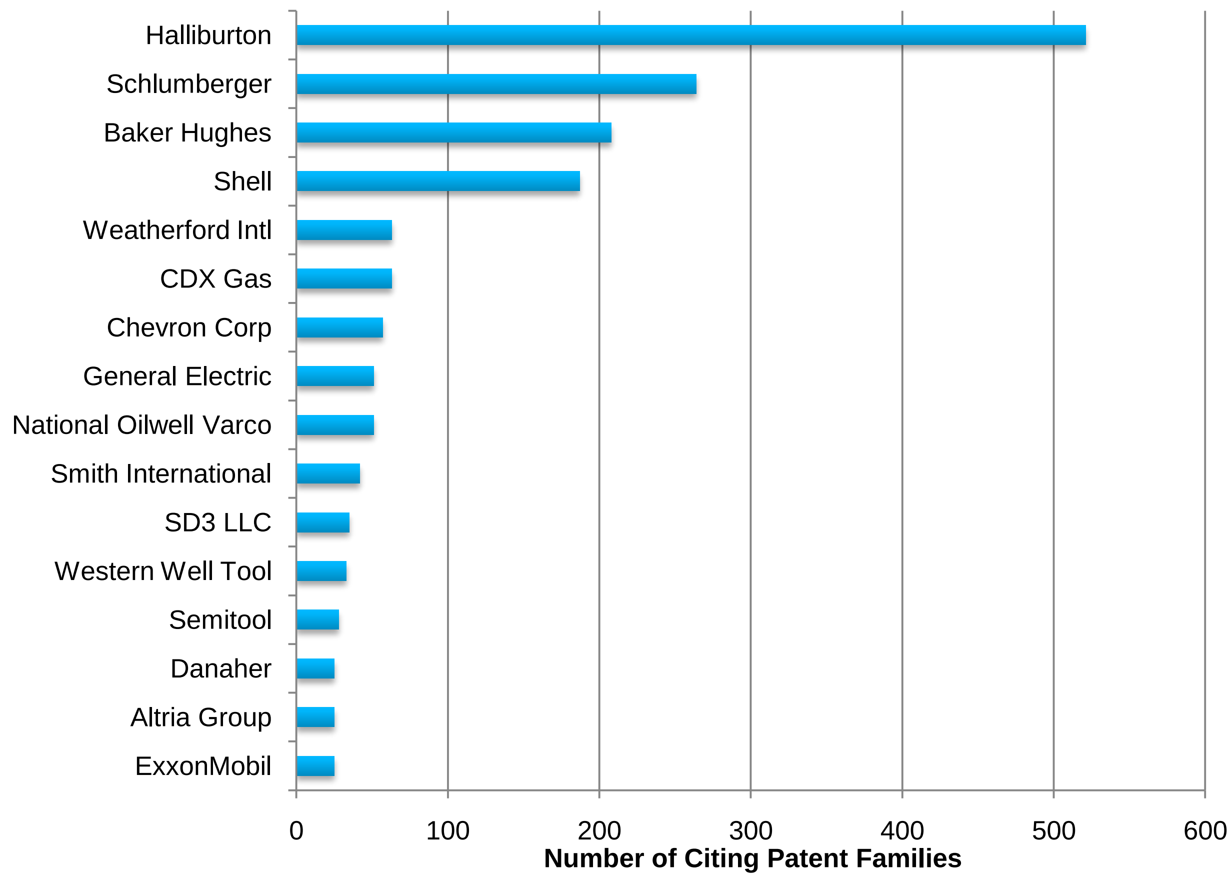
4.4 Results of Tracing Forward: Organizational Level

This chapter continues the previous chapter's focus at the organizational level, but the results here start with the set of 90 DOE-attributed patent families and trace forward. This analysis is designed to help address the following question: has DOE's geothermal research influenced organizations and technology areas outside of the geothermal industry, and, if so, which ones and to what extent?

4.4.1 Organizations with the Most Patent Families in All Technology Areas Linked to Earlier DOE-Funded Geothermal Research

Organizations with the largest number of all patent families linked to earlier DOE-attributed geothermal energy patent families are listed in Figure 4-11. It should be emphasized that this figure includes all patent families, not just those describing geothermal technology. For example, Figure 4-11 reveals that Chevron has a total of 57 patent families that are linked to one or more earlier DOE-attributed geothermal patent families. This is much higher than the number of Chevron geothermal patent families linked to earlier DOE-attributed geothermal patent families (33), as shown earlier in Figure 4-7.

Figure 4-11. Organizations with the Largest Number of Their Patent Families in All Areas Linked to Earlier DOE-Attributed Geothermal Patent Families



The main point to note in Figure 4-11 is the dominance of oilfield services corporations. The three companies at the head of Figure 4-11—Halliburton, Schlumberger, and Baker Hughes—are the three largest oilfield services companies in the world. These oilfield services companies were much less prominent in the backward tracing element of the analysis, largely because most of their patents were not identified as geothermal by the patent filter used in this project. They were not identified as geothermal because they do not specify a geothermal application in their titles or abstracts. The links between individual patent families assigned to these leading oilfield services companies and earlier geothermal patent families attributed to DOE are examined in more detail in Section 4.5 of this Chapter.

4.4.2 Broad Areas of Influence of DOE-Funded Geothermal Research as Revealed by International Patent Classifications (IPCs)[27]

Another approach to identifying broader areas of influence of the DOE-funded geothermal research is to determine how the DOE-attributed geothermal patent families are linked to all downstream patent families categorized by their International Patent Classifications, or IPCs. It is helpful to take this analysis sequentially through two generations of citations in order to see if the areas of influence as shown by IPCs shift over time.

The first-generation results are revealed in Figure 4-12, which shows the four-digit IPCs with the largest number of patent families that cite the DOE-attributed geothermal patents directly as prior art. The IPC at the head of this figure is E21B, which is entitled Earth & Rock Drilling.

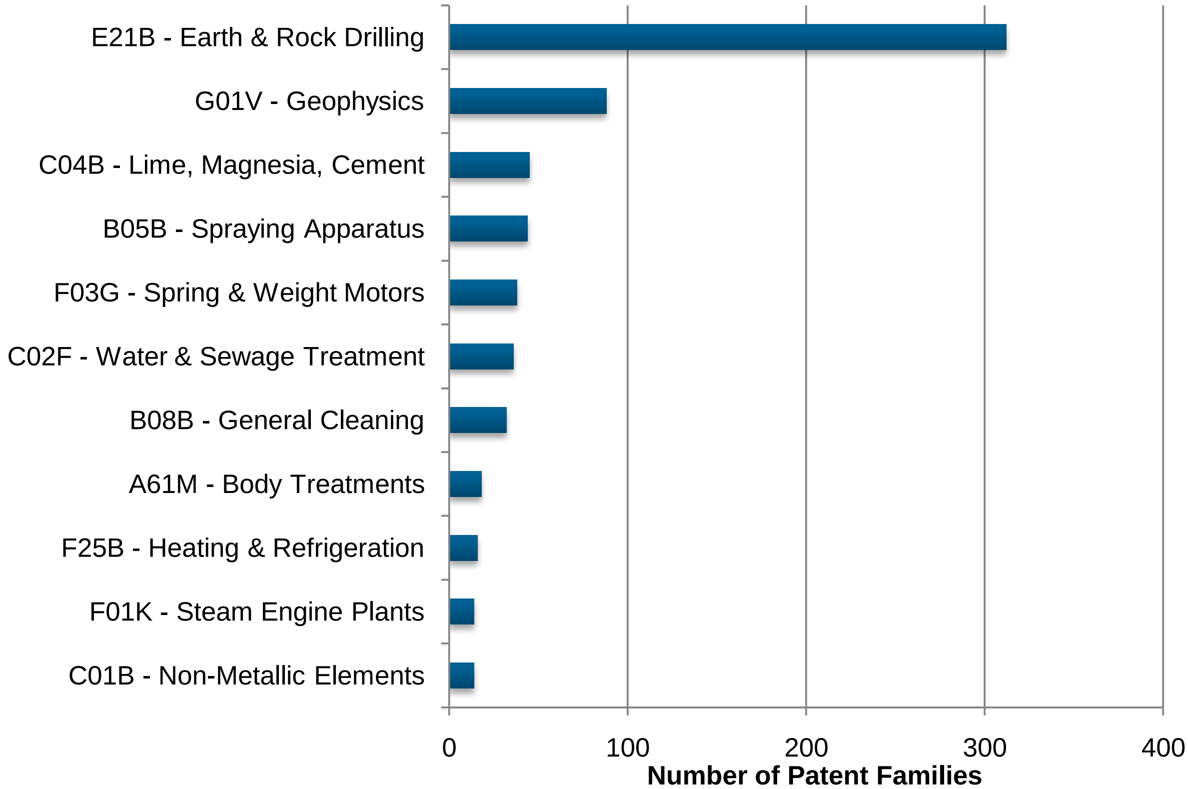
Over 300 patent families with this primary IPC cite DOE's geothermal energy patent families as prior art. This is more than three times as many patent families as the IPC in second place in the same figure. Figure 4-12 thus suggests that DOE's geothermal research has been particularly influential in the development of drilling techniques and components.

The IPC in second position in Figure 4-12 is G01V. This IPC is concerned with Geophysics, including seismic testing and prospecting, and reflects the influence of DOE's geothermal research upon techniques for identifying promising geothermal sites for exploration.

The next two areas of influence of DOE-funded geothermal research, as revealed by Figure 4-12, include developments in cements (as reflected in IPC C04B), and sprayers and nozzles (IPC B05B). These are of equal importance, and represent a substantial drop from the first two areas.

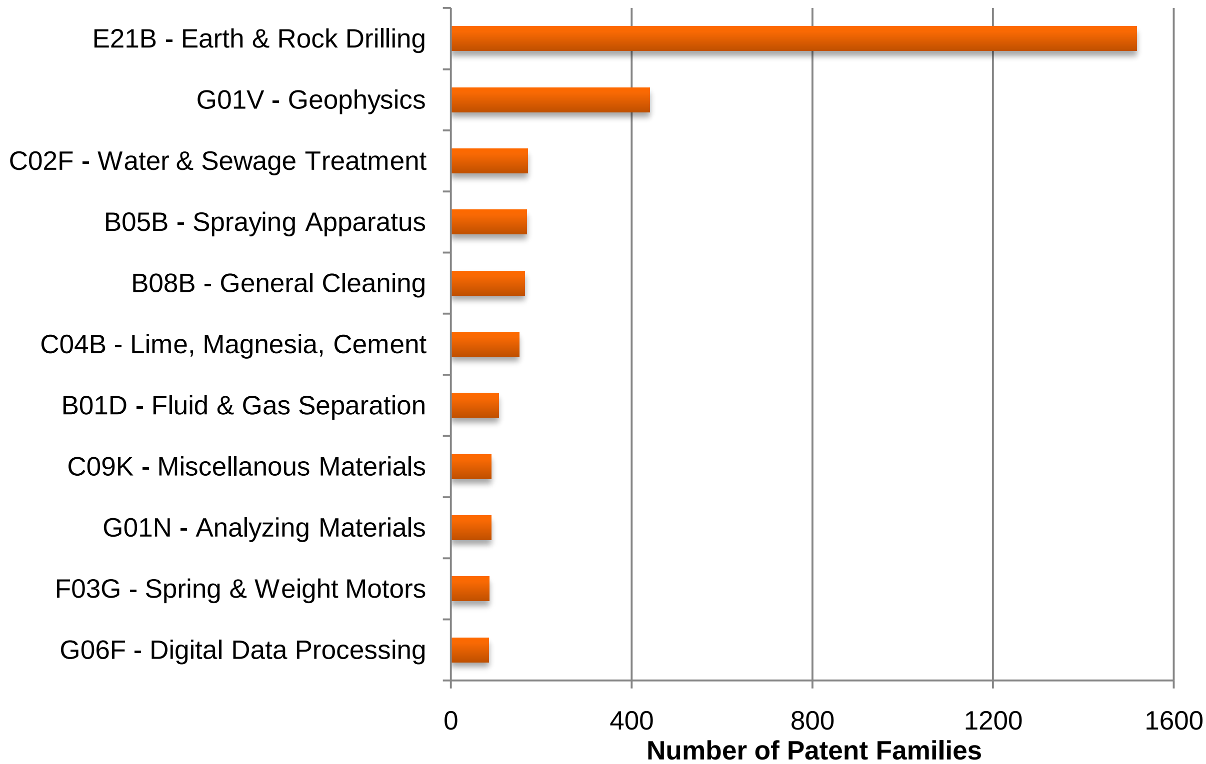
[27] The International Patent Classification (IPC) provides a hierarchical system for the classification of patents according to the different areas of technology to which they pertain. It was developed to establish an effective search tool for the retrieval of patent documents. The IPC is available on the WIPO IPC website www.wipo.int/classifications/ipc/.

Figure 4-12. Linkages from DOE-Attributed Geothermal Patent Families to Downstream Patent Families Categorized by IPC Codes (First-Generation Citations Only)



Similar to Figure 4-12, Figure 4-13 shows the 4-digit IPCs for patents linked to DOE geothermal research through two generations of forward citations, rather than a single generation. Again, the point of showing both figures is to see if there was a shift in areas of influence over time. There is little difference between the two figures in terms of showing that the influence of DOE's geothermal research has occurred mainly in the development of drilling techniques and components (IPC E21B) and in geophysics and identifying promising sites for exploration (IPC G01V). However, the inclusion of a second generation of citations does reveal shifts in relative importance among the other IPCs. The category IPC C02F, Water & Sewage Treatment, moves up in importance, reflecting the linkage of remediation technologies to the geothermal set, while the category IPC C04B, Lime, Magnesia, and Cement, moves down slightly in importance. At the same time, the number of citations in all of these categories expands considerably with the addition of another generation of citations. Taken together, Figures 4-12 and 4-13 show that DOE-funded geothermal research has had a growing impact across a range of technologies, but its influence on developments in drilling technology has been particularly strong.

Figure 4-13. Linkages from DOE-Attributed Geothermal Patent Families to Downstream Patent Families Categorized by IPC Codes (Two Generations of Citations Included)



4.4.3 Highlights of Findings from Forward Tracing at the Organizational Level

Overall, forward tracing revealed strong links between the set of 90 geothermal patent families attributed to DOE and patent families assigned to the leading oilfield services companies. Forward tracing also assessed the linkages of the DOE-attributed geothermal patent families to all downstream patent families categorized by their IPCs. The first-generation analysis showed that DOE's geothermal research has been particularly influential in the IPC category concerned with development of drilling techniques and components. Adding a second generation of patent citations showed a large expansion in the number of citations, and indicated that the DOE-funded geothermal research has had a growing impact in other areas, such as water and sewage treatment, though it continued to be dominant in drilling technology.

4.5 Individual Patent-Level Results of Backward and Forward Tracing

While the preceding Sections 4.3 and 4.4 showed the results of backward and forward tracing at the organizational level, this section shows results at the individual patent level. To identify the more influential patents from multiple perspectives, the analysis addresses the following questions: (1) Which DOE-attributed geothermal patents are linked to the largest number of subsequent geothermal energy patent families? (2) Which DOE-attributed geothermal patent families are linked to the most patent families owned by the largest oilfield services companies? (3) Which DOE-attributed "other" patent families (i.e., those not included in the geothermal set of 90) are linked to the largest number of subsequent geothermal patent families? (4) Which among the total set of geothermal patent families have built particularly extensively on earlier DOE-funded geothermal research? (5) Which highly cited geothermal patent families are linked to earlier DOE-attributed geothermal patent families? (6) Which highly cited patents in all industry areas are linked to earlier DOE-attributed geothermal patent families? (7) What are the most highly cited of the DOE-attributed geothermal patents?

4.5.1 DOE-Attributed Geothermal Patent Families Linked to the Largest Number of Subsequent Geothermal Patent Families

Table 4-1 identifies the DOE-attributed geothermal patent families—each represented by an anchor patent,[28] which is generally the first granted U.S. patent in the family—that are linked to the largest number of subsequent geothermal patent families. These DOE-attributed patent families are considered to have had a particularly extensive influence upon subsequent research in geothermal energy. Most of the patents in this table are relatively old, and have long since expired. For example, the two patents at the head of the table—US #3,640,336 and US #3,786,858—both date from the first half of the 1970s. These patents describe methods for generating geothermal energy from unpromising sites, the former via underground nuclear detonations, and the latter through injection of fluid into dry reservoirs. These patents are linked to many later patents describing methods for generating geothermal energy from unpromising locations.

Another patent that describes methods for generating geothermal energy from hot dry rocks that is also listed in Table 4-1 is US #5,685,362. This patent was issued in 1997, and assigned to the University of California. The reference to hot dry rocks is to geological strata that exist at high temperatures, but do not act like geysers or hot springs because no ground water percolates into them. Geothermal energy is extracted from hot dry rocks by pumping liquid into a well drilled into them, where the liquid is then heated by the rocks. The ‘362 patent describes such a system, and is linked to numerous subsequent geothermal patent families, including families assigned to Ormat and to the Netherlands Organization for Applied Scientific Research (TNO).

The patent family in Table 4-1 represented by anchor patent US #4,489,563 is also of interest. This 1984 patent, assigned to Exergy Inc., describes the basic elements of the Kalina thermodynamic cycle, which is named after Alexander Kalina, the inventor of this patent. The Kalina cycle is often used in heat exchangers in geothermal power plants. The ‘563 patent is linked to 32 subsequent geothermal patent families. These later geothermal patent families

[28] The "anchor patent" is used to designate a patent family; the priority patent is not used for this purpose because only patents in the US, EPO, and WIPO systems are included in the study and the priority document (i.e., the initial filing) could be from another system. The anchor patent is designated according to the following priority: the first granted U.S. patent in the patent family is given first priority; if there are no U.S. patents, then the first EPO application is designated; if there are no EPO applications, then the first WIPO filing is designated. The anchor patent is simply a study designator for a patent family, and lacks legal standing.

describe the use of Kalina cycles for low temperature geothermal systems. In addition, the '563 patent is linked to 81 other patent families (not shown in the table).

4.5.2 DOE-Attributed Geothermal Patent Families Heavily Cited by the Largest Oilfield Services Companies

Table 4-2 focuses on the DOE-attributed geothermal patent families linked to the most patent families owned by the three largest oilfield services companies. Two of the three DOE-attributed patent families at the head of this table describe lightweight cements for use in wells, including geothermal wells. These patent families describe inventions by a DOE research team headed by Toshifumi Sugama at Brookhaven National Laboratory. They are linked extensively to subsequent Halliburton patent families describing elements of its ThermaLock™ cements. These cements are designed for use in wells operating in harsh environmental conditions, notably geothermal wells and sub-sea oil and gas wells. The extensive links from Halliburton's patent families to earlier DOE-attributed patent families reflect the importance of DOE-funded research to the development of these cements.

Also in Table 4-2 are a number of patent families related to drilling techniques, and down-hole data transmission. All three leading oilfield services companies have extensive patent portfolios related to these technologies, and these portfolios have a large number of links to earlier geothermal patent families attributed to DOE. This extensive citing reflects the importance of DOE-funded research in the development of key drilling technologies.

Table 4-1. DOE-Attributed Geothermal Patent Families Linked to the Largest Number of Subsequent Geothermal Patent Families

Anchor Patent[a]	Issue Date	# Linked Subsequent Patent Families	Assignee	Title
3640336	1972	58	U.S. Dept. of Energy	Recovery of geothermal energy by means of underground nuclear detonations
3786858	1974	42	U.S. Dept. of Energy	Method of extracting heat from dry geothermal reservoirs
4489563	1984	32	Exergy Inc.	Generation of energy
4196183	1980	24	U.S. Dept. of Energy	Process for purifying geothermal steam
4328106	1982	21	U.S. Dept. of Energy	Method for inhibiting silica precipitation and scaling in geothermal flow systems
4342197	1982	12	Unisys Corp.	Geothermal pump down-hole energy regeneration system
3938334	1976	10	Unisys Corp.	Geothermal energy control system and method
5685362	1997	10	University of California	Storage capacity in hot dry rock reservoirs
4380903	1983	8	Unisys Corp.	Enthalpy restoration in geothermal energy processing system
4358930	1982	8	U.S. Dept. of Energy	Method of optimizing performance of rankine cycle power plants
4167099	1979	6	Occidental Petroleum	Countercurrent direct contact heat exchange process and system
4556109	1985	5	Dow Chemical Co.	Process for cementing geothermal wells
6251179	2001	5	U.S. Dept. of Energy	Thermally conductive cementitious grout for geothermal heat pump systems
4078904	1978	5	U.S. Dept. of Energy	Process for forming hydrogen and other fuels utilizing magma

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

Table 4-2. DOE-Attributed Geothermal Patent Families Linked to the Largest Number of Subsequent Patent Families Owned by the Top Three Oilfield Services Companies (Halliburton, Schlumberger, and Baker Hughes)

Anchor Patent	Issue Year	# Linked Subsequent Patent Families	Assignee	Title
4871395	1989	199	Associated Universities	High temperature lightweight foamed cements
5128901	1992	175	Baker Hughes	Acoustic data transmission through a drill string
4927462	1990	161	Associated Universities	Oxidation of carbon fiber surfaces for use as reinforcement in high temperature cementitious material systems
5508616	1996	144	Sekiyushigen Kaihatsu/Tohoku University	Apparatus and method for determining parameters of formations surrounding a borehole in a preselected direction
5363095	1994	87	Lockheed Martin	Down-hole telemetry system
5056067	1991	74	Baker Hughes	Analog circuit for controlling acoustic transducer arrays
4556109	1985	58	Dow Chemical	Process for cementing geothermal wells
4262757	1981	54	Hydronautics Inc	Cavitating liquid jet assisted drill bit and method for deep-hole drilling
4875015	1989	42	University of Utah	Multi array borehole resistivity and induced polarization method with mathematical inversion of redundant data
5477505	1995	34	Lockheed Martin	Down-hole pipe selection for acoustic telemetry
4317492	1982	25	University of Missouri	Method and apparatus for drilling horizontal holes in geological structures from a vertical bore

4.5.3 DOE-Attributed "Other" Patent Families Linked to the Largest Number of Subsequent Geothermal Patent Families

Earlier, Figure 4-6 and supporting text highlighted the fact that geothermal patents have built not only on previous DOE-attributed geothermal research, but also on other DOE research not classified as geothermal. That analysis, which focused on organizations, is extended here by a focus on patent families. Table 4-3 lists the DOE-attributed "other" (i.e., those not included in the 90 geothermal set) patent families that are linked to the largest number of subsequent geothermal patent families. These DOE-attributed patent families describe a variety of technologies, including heat exchangers, solar collectors, and separation of coal gasification products. This shows how a technology is often built on or informed by elements from different technologies, such that earlier patent families describing these elements are cited as prior art. Thus, both Tables 4-1, 4-2, and 4-3 list DOE-attributed patent families that are linked to large numbers of subsequent geothermal and oilfield-related patent families.

4.5.4 Geothermal Patent Families that Have Built Extensively on Earlier DOE-Attributed Geothermal Patent Families

Table 4-4 lists geothermal patent families from the total set of geothermal patent families that have built particularly extensively on earlier DOE-attributed geothermal patent families. The two patents at the head of this table are assigned to the TNO, and describe the use of geothermal energy in contaminated locations. These two patents are both linked to six earlier DOE-attributed geothermal patent families, mostly describing methods for extracting heat from geothermal reservoirs.

Chevron and Ormat both have a series of patent families that have built on multiple DOE-attributed geothermal patent families. The Chevron patent families are focused mainly on methods for treating geothermal brine in order to modify its pH, and to control salt precipitation and scale deposition. Meanwhile, Ormat's patent families that have built on multiple earlier patent families in the DOE geothermal set describe geothermal power plants and the use of geothermal energy to produce an uninterruptible power supply. The different technologies of TNO, Chevron, and Ormat, all substantially linked to earlier DOE-funded research, as well as technologies of other organizations, suggest that the influence of DOE research within geothermal technology has been relatively broad.

Table 4-3. DOE-Attributed "Other" Patent Families Linked to the Largest Number of Subsequent Geothermal Patent Families

Anchor Patent[a]	Issue Date	# Linked Subsequent Patent Families	Assignee	Title
4217765	1980	20	Atlantic Richfield Co.	Heat exchanger accumulator
4002729	1977	17	U.S. Dept. of Energy	Method for thermochemical decomposition of water
4361135	1982	16	U.S. Dept. of Energy	Cooperative heat transfer and ground coupled storage system
4696680	1987	12	U.S. Dept. of Energy	Method and apparatus for the selective separation of gaseous coal gasification products by pressure swing adsorption
4737166	1988	12	Bend Research Inc.	Acid gas scrubbing by composite solvent swollen membranes
3994279	1976	9	U.S. Dept. of Energy	Solar collector with improved thermal concentration
4874575	1989	6	Rockwell Automation	Multiple discharge cylindrical pump collector
3711598	1973	6	U.S. Dept. of Energy	Increased recovery in dual temperature isotope exchange process
5554453	1996	6	FuelCell Energy Inc.	Carbonate fuel cell system with thermally integrated gasification
4674285	1987	6	McDermott International	Start up control system and vessel for LMFBR

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

Table 4-4. Geothermal Patent Families with the Most Citation Links to Earlier DOE-Attributed Geothermal Patent Families

Anchor Patent[a]	Issue Year	Total Links to DOE Geothermal Set	Assignee	Title
EP1607627	2005	6	Netherlands Org Appl Sci Res (TNO)	Contaminant abatement method and system for geothermal plant
EP1766232	2007	6	Netherlands Org Appl Sci Res (TNO)	Method and system for heating and/or cooling buildings with geothermal energy, at a contaminated location
6301894	2001	5	Unassigned	Geothermal power generator
6537796	2003	4	Brookhaven Science Associates	Conversion of geothermal waste to commercial products including silica
EP1586831	2005	4	ENRO Geothermie	Method for use of geothermal energy
4905473	1990	4	Magma Power	Geothermal power plant steam entrainments removal system and method
6494042	2002	4	Ormat Industries	Method and apparatus for producing uninterruptible power
7320221	2008	4	Ormat Industries	Method and apparatus for using geothermal energy for the production of power
EP1966488	2008	4	Rexorce Thermionics	Thermodynamic power conversion cycle and methods of use
7448214	2008	4	Unassigned	Geothermal hydrogen production facility and method
5268108	1993	4	Chevron Corp.	Control of scale deposition in geothermal operations
5664420	1997	3	Biphase Energy	Multistage two-phase turbine
7146823	2006	3	Earth to Air Systems	Horizontal and vertical direct exchange heating/cooling system sub-surface tubing installation means
7124584	2006	3	General Electric Company	System and method for heat recovery from geothermal source of heat
7373785	2008	3	Kelix Heat Transfer Systems	Geo-thermal heat exchanging system facilitating the transfer of heat energy using coaxial-flow heat exchanging structures installed in the earth for introducing turbulence into the flow of the aqueous-based heat transfer fluid flowing along the outer flow
6708494	2004	3	Klett-Ingenieur	Device for utilizing geothermal heat and method for operating the same
5867988	1999	3	Ormat Industries	Geothermal power plant and method for using the same

Table 4-4 (continued). Geothermal Patent Families with the Most Citation Links to Earlier DOE-Attributed Geothermal Patent Families

Anchor Patent[a]	Issue Year	Total Links to DOE Geothermal Set	Assignee	Title
5685362	1997	3	University of California	Storage capacity in hot dry rock reservoirs
6668554	2003	3	University of California	Geothermal energy production with supercritical fluids
4537684	1985	3	Chevron Corp.	Control of metal containing scale deposition from high temperature brine
5256301	1993	3	Chevron Corp.	Control of salt precipitation from geothermal brine
5656172	1997	3	Chevron Corp.	pH modification of geothermal brine with sulfur-containing acid

[a] The "anchor patent," generally the first granted U.S. patent in a family, is used to designated each patent family. In this table, the first EPO application is used to designate several patent families in lieu of the first U.S. patent granted, following priorities explained in the text.

4.5.5 Highly Cited Geothermal Patents of Various Organizations with Links to Earlier DOE-Attributed Geothermal Patent Families

DOE's influence can also be seen on specific highly cited patents owned by geothermal energy organizations, as shown in Table 4-5. This table contains patents that are linked to earlier DOE-funded geothermal research, and that have in turn been cited frequently by subsequent patents. The table lists both the number of citations received by each of the patents, together with their Citation Index.[29]

All of the patents in Table 4-5 have Citation Index values above 1.5, ranging up to 4.13. This means that each of them has been cited at least one and a half times more frequently than expected given their age and technology, and at least one has been cited in excess of four times more frequently than expected. As such, these patents represent relatively high-impact geothermal technologies that are linked to one or more previous DOE-attributed geothermal patent families.

The patents in Table 4-5 are assigned to a variety of organizations, and describe different elements of geothermal technology. However, the particular focus of many of the patents in the table is the treatment of geothermal brine, and the reduction of contaminants. These include a series of patents assigned to Chevron (Unocal). This reinforces the earlier view that DOE-funded geothermal research has had a particularly strong influence on developments in the treatment of geothermal fluids.

4.5.6 All Highly Cited Patents Linked to Earlier DOE-Attributed Geothermal Patents

Table 4-6 shows all highly cited patents of various organizations in all industry areas that are linked to earlier DOE-attributed geothermal patents. It shows how DOE-funded geothermal research has helped to form part of the foundation for subsequent high-impact technologies more broadly. All of the patents in Table 4-6 have Citation Indexes over ten, indicating that they have been cited at least ten times more frequently than expected given their age and technology. This suggests that DOE-funded research has helped form part of the foundation for a range of very high impact technologies.

[29] The Citation Index is a normalized measure of the impact of a particular patent. It is 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 defined by Patent Office Classifications). The expected Citation Index for an individual patent is one. The extent to which a patent's Citation Index is greater or less than one reveals whether it has been cited more or less frequently than expected, and by how much. For example, a Citation Index of 1.5 shows that a patent has been cited 50% more frequently than expected. Meanwhile a Citation Index of 0.7 reveals that a patent has been cited 30% less frequently than expected.

Table 4-5. Highly Cited Geothermal Patents Linked to Earlier DOE-Attributed Geothermal Patent Families

Patent[a]	Issue Date	Total Links to DOE Geothermal Set	# Citations Received	Citation Index	Assignee	Title
6615601	2003	1	12	4.13	Earth to Air Systems	Sealed well direct expansion heating and cooling system
6539718	2003	3	12	3.06	Ormat Industries	Method of and apparatus for producing power and desalinated water
5613242	1997	9	36	3.02	Unassigned	Method and system for disposing of radioactive solid waste
4451442	1984	1	19	2.67	Dow Chemical	Removal of hydrogen sulfide from fluid streams with minimum production of solids
5723781	1998	2	24	2.48	Halliburton Energy	Borehole tracer injection and detection method
4830766	1989	2	30	2.43	Chevron Corp.	Use of reducing agents to control scale deposition from high temperature brine
4537684	1985	2	32	2.43	Chevron Corp.	Control of metal containing scale deposition from high temperature brine
4756888	1988	2	17	2.16	Chevron Corp.	Recovery of silver containing scales from aqueous media
4912941	1990	1	23	2.13	Unassigned	Method and apparatus for extracting and utilizing geothermal energy
4201060	1980	3	16	2.10	Chevron Corp.	Geothermal power plant
4967559	1990	5	19	1.96	SAI Engineers	Contaminant abatement process for geothermal power plant effluents
4629608	1986	1	16	1.81	Dow Chemical	Process for the removal of H2S from geothermal steam and the conversion to sulfur
5937934	1999	1	12	1.68	Geohil AG	Soil heat exchanger
4765913	1988	1	21	1.67	Chevron Corp.	Process for removing silica from silica rich geothermal brine
5277823	1994	2	16	1.52	Rohm & Haas	Silica scale inhibition

[a] Note that this column does not reference anchor patents, rather just "patents." The reason is that this figure contains citation counts and indexes for the specific patents listed, and not for patent families as a whole. The citations counted are from all U.S. patents, and not from the closed system of just geothermal patents, enabling the use of Citation Indexes, which are calculated at the individual patent level, not at the patent family level.

Table 4-6. All Highly Cited Company Patents of Various Organizations Linked to Earlier DOE-Attributed Geothermal Patents

Patent[a]	Issue Year	# Cites Received	Citation Index	Assignee	Title
6488763	2002	137	22.54	Halliburton Co.	Lightweight high temperature well cement compositions and methods
6670880	2003	87	19.65	Novatek Engineering	Down-hole data transmission system
6689208	2004	62	19.54	Halliburton Co.	Lightweight cement compositions and methods of cementing in subterranean formations
6717501	2004	54	18.88	Novatek Engineering	Down-hole data transmission system
6063738	2000	150	16.26	Halliburton Co.	Foamed well cement slurries, additives and methods
6258757	2001	109	13.93	Halliburton Co.	Water based compositions for sealing subterranean zones and methods
6929493	2005	43	13.11	National Oilwell Varco	Electrical contact for down-hole drilling networks
6945802	2005	44	12.90	National Oilwell Varco	Seal for coaxial cable in down-hole tools
6888473	2005	40	12.09	National Oilwell Varco	Repeatable reference for positioning sensors and transducers in drill pipe
6508305	2003	162	11.04	BJ Services Co.	Compositions and methods for cementing using elastic particles
6908508	2005	22	11.00	Halliburton Co.	Settable fluids and methods for use in subterranean formations
6793730	2004	31	10.83	Halliburton Co.	Methods of cementing
6857486	2005	44	10.64	Smart Drilling & Completion	High power umbilicals for subterranean electric drilling machines and remotely operated vehicles
6494951	2002	56	10.64	Halliburton Co.	Cementing compositions using dry cementitious materials having improved flow properties
6192748	2001	85	10.42	Computalog Ltd	Dynamic orienting reference system for directional drilling
6143069	2000	77	10.27	Halliburton Co.	Light weight high temperature well cement compositions and methods
6050346	2000	94	10.19	Baker Hughes Inc.	High torque, low speed mud motor for use in drilling oil and gas wells
6830467	2004	46	10.18	National Oilwell Varco	Electrical transmission line diametrical retainer

[a] Note that this column does not reference anchor patents, rather just "patents." The reason is that this figure contains citation counts and indexes for the specific patents listed and not for patent families as a whole. The citations counted are from all U.S. patents, and not from the closed system of just geothermal patents, enabling the use of Citation Indexes, which are calculated at the individual patent level, not at the patent family level.
Note: The numbers of cites received and the Citation Index values are based on a single generation of citations, because computation of the Citation Index requires that a single generation be used.

Halliburton is responsible for almost half of the highly cited patents in Table 4-6. These Halliburton patents describe lightweight well cements, and cite both DOE-attributed geothermal patents and papers as prior art. In turn, Halliburton patents have been cited frequently by subsequent patents, showing their strong impact on developments in well technology. For example, the Halliburton patent at the head of Table 4-6 (US #6,488,763) has been cited by 137 subsequent U.S. patents, more than 22 times as many citations as expected for a patent of its age and technology. There are two other companies' patents that are prominent in Table 4-6—Novatek Engineering and National Oilwell Varco.[30] The high-impact patents of these two companies that are linked to earlier DOE-funded geothermal research are concerned with power and data transmission in down-hole applications.

4.5.7 Highly Cited DOE-Attributed Geothermal Patents Overall

A straightforward way of identifying high-impact DOE-attributed geothermal energy patents is through overall citation counts and Citation Indexes. The results of this approach can be seen in Table 4-7. This table lists the most highly cited DOE-attributed geothermal patents, sorted in descending order based on their Citation Indexes. The results are based on a single generation of citations—due to requirements in computing the Citation Indexes—but take into account citations in all industry areas.

There are three patents in this figure that have Citation Indexes over five (i.e., they have been cited more than five times more frequently than expected given their age and technology). Two of these three patents (US #4,389,071, assigned to Hydronautics, and US #4,317,492, assigned to University of Missouri) describe drilling using high pressure fluids. There are also a number of other similar patents in Table 4-7, suggesting that DOE-funded research in this area of drilling technology has been particularly influential. The third patent with a Citation Index over five (US #4,489,563) is the fundamental Kalina cycle patent discussed earlier, again emphasizing the strong impact of this patent on subsequent technological developments. The Citation Index on the next patent—assigned to Magma Power and describing silica control in geothermal fluid—drops to 2.79. There are a number of other highly cited patents in Table 4-7 describing different technologies, including cements, data transmission, electronics for down-hole applications, and extraction of heat from dry geothermal reservoirs.

Table 4-8 extends the analysis of Table 4-7 to include two generations of citations, and lists the DOE-attributed geothermal patent families (designated by an anchor patent) with the largest number of citation links from subsequent patent families. This table again shows the large number of patent families that link back to the earlier DOE-attributed Hydronautics and University of Missouri patent families describing fluid assisted drilling. There are also DOE-attributed patent families describing other technologies that are linked to large numbers of subsequent patent families. These include DOE-attributed patent families describing down-hole electronics and data transmission assigned to Baker Hughes (US #5,222,049 and US #5,056,067) and Sandia (US #5,363,095); lightweight cements assigned to Associated Universities/Brookhaven (US #4,871,395 and US #4,927,462); and mud hammers assigned to Novatek (US #5,396,965).

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[30] National Oilwell Varco's patents were originally assigned to Intelliserv, which was bought by Grant Prideco in 2005; Grant Prideco was in turn acquired by National Oilwell Varco in 2008.

Table 4-7. Highly Cited DOE-Attributed Geothermal Patents, Based on One Generation of Citations, as Measured by a Citation Index

Patent[a]	Issue Year	# Cites Received	Citation Index	Assignee	Title
4389071	1983	54	6.08	Hydronautics Inc.	Enhancing liquid jet erosion
4489563	1984	45	5.14	Exergy Inc.	Generation of energy
4317492	1982	74	5.09	University of Missouri	Method and apparatus for drilling horizontal holes in geological structures from a vertical bore
4429535	1984	22	2.79	Magma Power	Geothermal plant silica control system
4262757	1981	33	2.78	Hydronautics Inc.	Cavitating liquid jet assisted drill bit and method for deep hole drilling
6251179	2001	15	2.78	U.S. Dept. of Energy	Thermally conductive cementitious grout for geothermal heat pump systems
5508616	1996	39	2.63	Sekiyushigen Kaihatsu/Tohoku Univ.	Apparatus and method for determining parameters of formations surrounding a borehole in a preselected direction
4106577	1978	37	2.61	University of Missouri	Hydromechanical drilling device
5165243	1992	25	2.47	U.S. Dept. of Energy	Compact acoustic refrigerator
5274606	1993	21	2.12	Baker Hughes Inc.	Circuit for echo and noise suppression of acoustic signals transmitted through a drill string
4119160	1978	29	2.02	University of Missouri	Method and apparatus for water jet drilling of rock
4508577	1985	27	1.90	Hydronautics Inc.	Fluid jet apparatus and method for cleaning tubular components
3786858	1974	14	1.83	U.S. Dept. of Energy	Method of extracting heat from dry geothermal reservoirs
4871395	1989	25	1.80	Associated Universities	High temperature lightweight foamed cements
6186248	2001	17	1.71	Boart Longyear	Closed loop control system for diamond core drilling
6347675	2002	14	1.67	Tempress Technologies	Coiled tubing drilling with supercritical carbon dioxide

[a] Note that this column does not reference anchor patents, rather just "patents." The reason is that this figure contains citation counts and indexes for the specific patents listed, and not for patent families as a whole. The citations counted are from all U.S. patents, and not from the closed system of just geothermal patents, enabling the use of Citation Indexes, which are calculated at the individual patent level, not at the patent family level.
Note: The numbers of cites received and the Citation Index values are based on a single generation of citations, because computation of the Citation Index requires that a single generation be used.

Table 4-8. DOE-Attributed Geothermal Patent Families Cited by the Largest Number of All Later Patent Families

Anchor Patent[a]	Issue Year	Total Linked Patent Families	# Linked Geothermal Patent Families	# Linked Non-Geothermal Patent Families	Assignee	Title
4389071	1983	540	0	540	Hydronautics Inc.	Enhancing liquid jet erosion
5222049	1993	467	5	462	Baker Hughes Inc.	Electromechanical transducer for acoustic telemetry system
4262757	1981	459	0	459	Hydronautics Inc.	Cavitating liquid jet assisted drill bit and method for deep hole drilling
4317492	1982	324	0	324	University of Missouri	Method and apparatus for drilling horizontal holes in geological structures from a vertical bore
5508616	1996	260	0	260	Sekiyushigen Kaihatsu/Tohoku Univ.	Apparatus and method for determining parameters of formations surrounding a borehole in a preselected direction
4871395	1989	256	0	256	Associated Universities	High temperature lightweight foamed cements
4119160	1978	215	0	215	University of Missouri	Method and apparatus for water jet drilling of rock
4508577	1985	213	0	213	Hydronautics Inc.	Fluid jet apparatus and method for cleaning tubular components
4369850	1983	208	0	208	University of Missouri	High pressure fluid jet cutting and drilling apparatus
5363095	1994	202	3	199	Sandia Corp.	Down-hole telemetry system
5396965	1995	200	0	200	Novatek Engineering	Down-hole mud actuated hammer
4328106	1982	191	28	163	U.S. Dept. of Energy	Method for inhibiting silica precipitation and scaling in geothermal flow systems
4927462	1990	186	1	185	Associated Universities	Oxidation of carbon fiber surfaces for use as reinforcement in high temperature cementious material systems

Table 4-8 (continued). DOE-Attributed Geothermal Patent Families Cited by the Largest Number of All Later Patent Families

Anchor Patent[a]	Issue Year	Total Linked Patent Families	# Linked Geothermal Patent Families	# Linked Non-Geothermal Patent Families	Assignee	Title
5056067	1991	171	2	169	Baker Hughes Inc.	Analog circuit for controlling acoustic transducer arrays
4106577	1978	146	0	146	University of Missouri	Hydromechanical drilling device
3786858	1974	143	42	101	U.S. Dept. of Energy	Method of extracting heat from dry geothermal reservoirs
4376462	1983	141	3	138	U.S. Dept. of Energy	Substantially self powered method and apparatus for recovering hydrocarbons from hydrocarbon containing solid hydrates
4429535	1984	140	51	89	Magma Power	Geothermal plant silica control system
5165243	1992	140	0	140	U.S. Dept. of Energy	Compact acoustic refrigerator
4875015	1989	127	0	127	University of Utah	Multi array borehole resistivity and induced polarization method with mathematical inversion of redundant data

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

4.5.8 Highlights of Findings from the Individual Patent-Level Analysis

The analysis at the individual patent level has revealed answers to the questions posed at the beginning of Section 4.5, and, thereby, has helped identify particularly influential patents based either directly on DOE-funded research or linked to it. Answers to the questions are summarized as follows:

(1) DOE-attributed geothermal patent families that are linked to the largest number of subsequent geothermal patent families include those that describe methods for generating geothermal energy from unpromising sites, and those that describe the Kalina cycle, which is often used in heat exchangers in geothermal power plants. (See Section 4.5.1.)

(2) DOE-attributed geothermal patent families linked to the largest number of subsequent patent families owned by the top oilfield services companies (i.e., Halliburton, Schlumberger, and Baker Hughes) include those describing lightweight cements for use in wells operating in harsh environmental conditions, drilling techniques, and down-hole data transmission. (See Section 4.5.2.)

(3) DOE-attributed "other" patent families (i.e., those not included in the geothermal set of 90) that are linked to the largest number of subsequent geothermal patent families include those describing a variety of technologies, including heat exchangers, solar collectors, and separation of coal gasification products, illustrating that geothermal technology has been built on, or informed by, elements from different technologies. (See Section 4.5.3.)

(4) Of the total set of geothermal patent families, those that have built particularly extensively on earlier DOE-funded geothermal research include patents assigned to the TNO describing the use of geothermal energy in contaminated locations; patents assigned to Chevron describing methods for managing geothermal brine; and patents assigned to Ormat describing geothermal power plants and the production of an uninterruptible power supply. (See Section 4.5.4.)

(5) Highly cited patents owned by a variety of geothermal organizations—and linked to earlier DOE-funded geothermal research—include a series of patents assigned to Chevron (Unocal) describing the treatment of geothermal brine and the reduction of contaminants, reinforcing the earlier view that DOE-funded geothermal research has had a particularly strong influence on developments in the treatment of geothermal fluids. (See Section 4.5.5.)

(6) Taking into account highly cited patents in all industry areas that are linked to earlier DOE-funded geothermal research, Halliburton patents describing cements are dominant, as are Novatek Engineering and National Oilwell Varco patents describing power and data transmission in down-hole applications. (See Section 4.5.6.)

(7) The most highly cited DOE-attributed geothermal patents include patents assigned to Hydronautics, the University of Missouri, and others describing fluid-assisted drilling; a patent assigned to Exergy Inc., describing the Kalina cycle; patents assigned to Baker Hughes and Sandia describing down-hole electronics and data transmission; patents assigned to Associated Universities/Brookhaven describing high-temperature lightweight cements; a patent assigned to

Magma Power describing silica control in geothermal fluid; and a patent assigned to DOE describing extraction of heat from dry geothermal reservoirs, among others. (See Section 4.5.7.)

4.6 Summary of Chapter 4 Findings

Overall, the results of patent tracing showed that DOE-funded geothermal research has influenced subsequent innovation by geothermal energy companies, notably Chevron (through its merger with Unocal) and Ormat. DOE's funded geothermal research, together with that of Chevron (Unocal), with its own strong patent ties back to DOE, have shown the largest influence among organizations on subsequent technological developments in the geothermal industry. When the search for linkages was widened to include connections from the geothermal set back to all patents, the large influence of leading oil and gas companies, such as Exxon Mobil, also became apparent. Thus, DOE, together with Chevron (Unocal) and Exxon Mobil, were found to have formed an important part of the foundation for geothermal technology.

Research funded by DOE was found to have had a strong influence on a number of subsequent innovations as reflected by individual patents. Particularly influential patents attributed to DOE-funded geothermal research include those describing methods for generating geothermal energy from unpromising sites; the Kalina cycle used in heat exchangers in geothermal power plants; fluid-assisted drilling; high-temperature lightweight cements for use in wells operating in harsh conditions; electronics for down-hole data transmissions; and the treatment of geothermal fluids and silica control in geothermal plants. A number of highly cited patent families of other organizations were also found to be linked to earlier DOE-attributed geothermal patent families, such as those describing the treatment of geothermal fluids, cements, and power and data transmission in down-hole applications.

5. Linkages Found by Publication Analysis

This chapter continues the bibliometric analysis of the previous chapter, with a shift in focus from patents to publications. Publications serve as another mechanism linking the research to downstream developments. That said, it may be recalled from the methodology chapter that according to bibliometric theory, citations of scientific papers by other papers in a field generally acknowledge scientific and intellectual debts. This is in contrast to citations of publications by patents, which are considered to acknowledge the intellectual debt of a technology to the science base on which it draws. It is even more in contrast to citations of patents by other patents (treated in the previous chapter), which are taken to acknowledge technological debt.[31]

First, this chapter reveals trends in the quantity of geothermal publications issued by DOE and others to provide context, along with a characterization of DOE geothermal publications by type of publication. Then, an analysis of citing by patents of a selection of DOE geothermal publications is presented as a bridge between a pure patent analysis and a pure publication analysis. Patents citing research papers are of particular interest because they are regarded as indicators of leading edge patenting activity.[32] These results are followed by analyses of authorship/co-authorship and citations of samples of DOE geothermal publications from two DOE laboratories: Idaho National Laboratory (INL) and the National Renewable Energy Laboratory (NREL).

The chapter shows that a few DOE papers and publications were heavily cited by downstream industry patent families—mainly those reporting DOE national laboratory research on lightweight cements and PDC drill bit performance. It further shows diverse authorship of a sample of INL geothermal publications, including researchers affiliated with universities across the nation, companies under contract to INL, state and regional organizations that are typically involved in planning and permitting geothermal projects, and associations representing the geothermal and related industries. The chapter also shows heavy citing of both INL and NREL publications by university publications, from a mix of domestic and foreign universities.

5.1 Trends in DOE and All Geothermal Publications

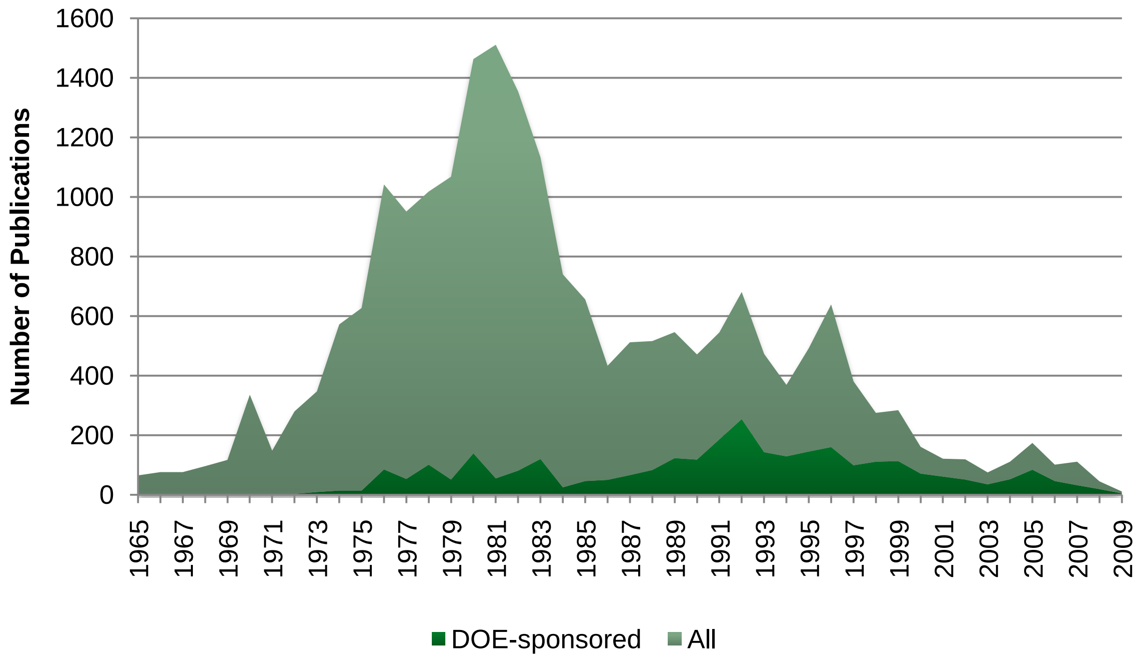
Figure 5-1 shows an estimated total output of DOE geothermal publications by year, in comparison with an estimated total of "all" geothermal publications, including DOE publications and others. The number of publications from all sources (totaling more than 18,000, of which

[31] Martin (2005), Chapter 4.
[32] Breitzman and Mogee (2002), p. 196.

more than 7,000 are archived in a DOE legacy collection) substantially exceeds the number identified as sponsored by DOE (totaling approximately 3,000).[33]

The annual output of geothermal publications from all sources peaked in the early 1980s, while the annual number of DOE-sponsored geothermal publications peaked in the early 1990s. Another point of comparison is that the share of the annual output of total publications comprised by DOE increased over time. In 1981, DOE's share comprised less than 4% of the year's total output; in 2005, DOE's share comprised 93% of the year's total.

Figure 5-1. Annual Number of DOE Geothermal Publications Compared with the Annual Number of All Geothermal Publications, 1965-2009



Source: OSTI geothermal publication database.

[33] The total counts of geothermal publications were obtained by searching year-by-year in the DOE Office of Science and Technical Information (OSTI) database—specifically the OSTI geothermal technologies collection for both legacy and non-legacy documents. The "legacy" reports are said to be among the most valuable sources of geothermal information; they include reports from various sources including DOE and its national laboratories, as well as industry and organizations around the world. The counts for DOE geothermal publications were obtained by searching the same database collection while specifying "USDOE OR US_DOE OR DOE OR U.S. Department of Energy" as the Sponsoring Organization. The year-by-year searches for this analysis were made in the fall of 2009, and subsequent database revisions may affect the counts. Relevant documents may be omitted from the OSTI geothermal collection, and not all DOE-sponsored documents may be found by specifying DOE (in its various forms) as the sponsoring organization.

5.2 Characteristics of DOE Geothermal Publications

Multiple DOE national laboratories contributed to the body of DOE geothermal publications, prominent among them Idaho National Laboratory (INL), Sandia National Laboratories (SNL), Brookhaven National Laboratory (BNL), the National Renewable Energy Laboratory (NREL), Los Alamos National Laboratory (LANL), Pacific Northwest National Laboratory (PNNL), Lawrence Livermore National Laboratory (LLNL), and Lawrence Berkeley National Laboratory (LBNL). Also, DOE-sponsored university geothermal programs, such as Stanford University's Geothermal Program (SGP), are responsible for a large number of geothermal publications.[34]

Of the set of all DOE-sponsored geothermal publications, 50% were technical reports, 44% were conference reports, 4% were journal articles, and the remaining small fraction (2%) were books, thesis/dissertations, and miscellaneous.[35] This distribution of DOE-sponsored publications differs from that of the non-DOE-sponsored geothermal publications. The proportions of journal articles and books were much larger for the non-DOE-sponsored set (37% and 6%, respectively), and the proportions of technical reports and conference papers were smaller (32% and 22%, respectively).[36]

5.3 DOE Geothermal Scientific Papers/Publications Cited by Patents

The fact that certain DOE geothermal scientific papers and publications have been cited by patents suggests that they have provided a scientific base on which subsequent technological developments have drawn. An extended feature of the study's bibliometric analysis is to take into account DOE-sponsored geothermal papers/publications cited by patents as prior art.[37]

One finding is that the counts of patent citations of DOE geothermal papers/publications are much fewer than the counts of patent citations of DOE-attributed geothermal patents. Yet, this does not mean that adding papers/publications to the patent citation analysis is without value. In particular, there are patents linked to DOE geothermal papers/publications that are not linked to

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[34] A breakdown of counts of geothermal publications by organization was originally developed by the study using the OSTI database, but the breakdown appears unreliable and is not presented here. For example, a large variation was found among the number of DOE-sponsored SGP publications depending on the source used. Searching the OSTI geothermal collection for publications whose identifier number contains SGP produced nearly 700 publications. In contrast, searching using SGP or Stanford University as the research organization produced a few less than 100. Meanwhile, the SGP's own website lists 191 publications. The large number of geothermal publications with the SGP identifier appears to reflect the inclusion of older conference papers authored by others and archived by SGP in the OSTI database.

[35] When DOE geothermal publications in the OSTI database were broken out by type, the total (3,221) exceeded the total obtained when tallied year-by-year across types (3,038); the cause of the discrepancy was not found. The percentages are based on the total of 3,221.

[36] The percentage of DOE-sponsored conference papers may be biased upward by the inclusion of SGP-identified papers authored by others and presented at SGP-hosted conferences.

[37] As explained in Sections 3.5.4 and 3.6, due to the resource intensiveness of an analysis of DOE-sponsored geothermal papers/publications cited by patents, this analysis is based on a selected list of papers/publications compiled from DOE reports of geothermal research of particular interest, to which was added additional related papers by the same authors. Appendix C lists the DOE-sponsored geothermal papers/publications that were used in this analysis.

DOE-attributed geothermal patents. These links back to DOE-funded research would be missed without the additional analysis of patents citing DOE geothermal papers/publications. Moreover, as noted earlier, patents citing research papers are regarded as indicators of leading edge patenting activity.[38]

DOE geothermal papers/publications that were identified as having been cited as prior art by the largest number of subsequent patent families are listed in Table 5-1. These results are for first-generation citations (i.e., a patent citing an earlier DOE paper/publication as prior art).

Table 5-1. DOE Geothermal Papers/Publications Identified as Cited Directly by the Largest Number of Patent Families

# Citations Received	DOE Papers/Publications
17	"Interfaces and Mechanical Behaviors of Fiber-Reinforced Calcium Phosphate Cement Compositions," by T. Sugama, et al., prepared for the Geothermal Division U.S. Department of Energy; Department of Applied Science (June 1992)
14	"Hot Alkali Carbonation of Sodium Metaphosphate Fly Ash/Calcium Aluminate Blend Hydrothermal Cements," by T. Sugama, *Cement and Concrete Research Journal*, vol. 26, No. 11, pp. 1661-1672 (1996)
14	"Carbonation of Hydrothermally Treated Phosphate-Bonded Calcium Aluminate Cements," by T. Sugama, et al., U.S. Department of Energy, Washington, D.C. under contract No. DE-AC02-76CH00016 (Undated)
14	"Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part 1--Development of a PDC Cutting Force Model," by Glowka, D.A., *JPT*, pp. 797-799, 844-849 (August 1989)
13	"Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part II--Development and Use of PDCWEAR Computer Code," by Glowka, D.A., *JPT*, pp. 850-859 (August 1989)
11	"Microsphere-Filled Lightweight Calcium Phosphate Cements," by Sugama, T., et al., U.S. Department of Energy, Washington, D.C. under contract No. DE-AC02-76CH00016 (December 1992)
11	"Acoustical Properties of Drill Strings," by Drumheller, D., *The Journal of the Acoustical Society of America*, No. 3, New York, pp. 1048-1064 (March 1989)
10	"Mullite Microsphere-Filled Light-weight Calcium Phosphate Cement Slurries For Geothermal Wells: Setting and Properties", by Sugama, T. et al., *Cement and Concrete Research Journal*, vol. 25, No. 6, pp. 1305-1310 (1995)
7	"Calcium Phosphate Cements Prepared by Acid-Base Reaction," by Sugama, T. et al., J*ournal of the American Ceramic Society*, vol. 75, No. 8, p. 2076-2087 (August 1992)
6	"The Propagation of Sound Waves in Drill Strings," by Drumheller, D., et al., *The Journal of the Acoustical Society of America*, No. 4, pp. 2116-2125 (April 1995)
4	*Sourcebook on the Production of Electricity from Geothermal Energy*, Kestin, J., editor, Publication No. DOE/RA/4051, Chap. 4, p. 536 (1980)

[38] Breitzman and Mogee, p. 196.

Table 5-1 (continued). DOE Geothermal Papers/Publications Identified as Cited Directly by the Largest Number of Patent Families

# Citations Received	DOE Papers/Publications
4	"Direct-Contact Condenser Applications," by Bharathan, National Renewable Energy Laboratory, Geothermal Program Review XII, San Francisco, Calif., pp. 127-130 (April 25-28, 1994)
4	"Direct-Contact Condensers for Geothermal Applications," by Bharathan, National Renewable Energy Laboratory, NREL/PG&E CRADA Progress Review, Golden, Colorado (November 30-Dec. 2, 1994)
4	"Geysers Advanced Direct Contact Condenser Research" by Henderson, et al., *Proceedings Geothermal Program Review XV*, San Francisco DOE/EE-0139, pp. 3-3 to 3-9 (March 24-26, 1997)
4	"Acoustical Properties of Drill Strings," by Drumheller D, Sandia National Laboratories, SAND88 0502 (August 1988)

The analysis is extended in Table 5-2 by examining two generations of citations (i.e., a patent cites an earlier patent, which in turn cites an earlier paper/publication). The table lists the DOE geothermal papers/publications linked through two generations of citations to the largest number of subsequent patent families. The much larger numbers of patents linked to the set of DOE papers/publications through two generations of citations is striking.

Table 5-2. DOE Geothermal Papers/Publications Linked to the Largest Number of Patent Families through Two Generations of Citations

# Linked Patents	DOE Papers/Publications
203	"Interfaces and Mechanical Behaviors of Fiber-Reinforced Calcium Phosphate Cement Compositions," by T. Sugama, et al., prepared for the Geothermal Division U.S. Department of Energy; Department of Applied Science (June 1992)
197	"Microsphere-Filled Lightweight Calcium Phosphate Cements," by Sugama, T., et al., U.S. Department of Energy, Washington, D.C. under contract No. DE-AC02-76CH00016 (December 1992)
197	"Hot Alkali Carbonation of Sodium Metaphosphate Fly Ash/Calcium Aluminate Blend Hydrothermal Cements," by T. Sugama, *Cement and Concrete Research Journal*, vol. 26, No. 11, pp. 1661-1672 (1996)
192	"Calcium Phosphate Cements Prepared by Acid-Base Reaction," by Sugama, T. et al., *Journal of the American Ceramic Society*, vol. 75, No. 8, p. 2076-2087 (August 1992)
185	"Mullite Microsphere-Filled Light-weight Calcium Phosphate Cement Slurries For Geothermal Wells: Setting and Properties", by Sugama, T. et al., *Cement and Concrete Research Journal*, vol. 25, No. 6, pp. 1305-1310 (1995)

Table 5-2 (continued). DOE Geothermal Papers/Publications Linked to the Largest Number of Patent Families through Two Generations of Citations

# Linked Patents	DOE Papers/Publications
185	"Carbonation of Hydrothermally Treated Phosphate-Bonded Calcium Aluminate Cements," by T. Sugama, et al., U.S. Department of Energy, Washington, D.C. under contract No. DE-AC02-76CH00016 (Undated)
108	"Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part 1--Development of a PDC Cutting Force Model," by Glowka, D.A., *JPT*, pp. 797-799, 844-849 (August 1989)
105	"Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part II--Development and Use of PDCWEAR Computer Code," by Glowka, D.A., *JPT*, pp. 850-859 (August 1989)
101	"Acoustical Properties of Drill Strings," by Drumheller, D., *The Journal of the Acoustical Society of America*, No. 3, New York, pp. 1048-1064 (March 1989)
56	"The Propagation of Sound Waves in Drill Strings," by Drumheller, D., et al., *The Journal of the Acoustical Society of America*, No. 4, pp. 2116-2125 (April 1995)
37	"Acoustical Properties of Drill Strings," by Drumheller D, Sandia National Laboratories, SAND88 0502 (August 1988)
32	*Sourcebook on the Production of Electricity from Geothermal Energy*, Kestin, J., editor, Publication No. DOE/RA/4051, Chap. 4, p. 536 (1980)

Of the 15 papers/publications in Table 5-1, six describe cements, including the most highly cited. These six papers/publications also are identified in Table 5-2 as having the largest number of links when two generations of citations are taken into account. The six were authored by the BNL group headed by Toshifumi Sugama. In the same way that patents produced by this group have been cited frequently by subsequent cement patents assigned to Halliburton, the scientific papers and publications from the group also have strong links to subsequent Halliburton cement patents.

DOE papers/publications describing data analyzing the performance of PDC drill bits are also linked extensively to subsequent patents. DOE researchers at Sandia carried out extensive field tests of the performance and potential application of PDC drill bits. This Sandia research resulted in publications. The presence of the two highly linked Sandia publications on PDC drill bits in Tables 5-1 and 5-2 shows the influence that the DOE field tests have had on subsequent developments in drilling technology. These two publications are linked to large numbers of drilling patents assigned to leading oilfield services companies, notably Halliburton, Schlumberger, Baker Hughes, and Smith International.

Three of the papers/publications in Table 5-1 describe data communications through drill strings. This further demonstrates the influence of DOE-funded geothermal research on developments related to techniques for monitoring down-hole conditions, an area of significant interest to both the geothermal and oilfield industries.

There are also three publications in Table 5-1 describing direct contact condensers for use in geothermal power plants. This reinforces DOE's influence on developments related to handling geothermal fluids, an area highlighted earlier in the backward tracing element of the patent analysis.

In summary, there are four main technologies described by multiple DOE papers/publications that have been heavily cited by subsequent patents. The most prominent is lightweight cements for harsh environments. The others are PDC drill bits, data communication through drill strings, and condensers for use in geothermal power plants. The citing by patents of these research papers signals leading edge patenting activity in these four technologies.

5.4 Publication-to-Publication Author/Co-Author and Citation Analysis

Sets of geothermal publications from two national laboratories—INL and NREL—are examined for co-authoring and citing by others. Both sets are drawn by searching the OSTI geothermal collection for publications with the INL and NREL organization identifiers. For the larger population of INL publications found by the search, the analysis is based on a random sample. For the smaller population of NREL publications, the analysis is based on the population of NREL geothermal publications found by the search.[39]

5.4.1 Idaho National Laboratory (INL) Publication Author/Co-Author Analysis

The sample of 162 INL publications drawn randomly from the population of 286 identified as INL geothermal publications comprises 81% technical reports and 15% conference papers, 4% journal articles, and 1% thesis/dissertations. As shown in Figure 5-2 the major topical areas of the sample publications are "reservoir or well" (34%), followed by "exploration" (26%), and "plant" and "drilling" (8% and 7%, respectively). Other papers in the sample pertain to "economic/efficiency/financial studies" (5%), and "information about geothermal " (4%). Sixteen percent were categorized as "other."

As shown in Figure 5-3, most of the papers—many of which are technical reports—are authored by university researchers (52%) and by companies (14%) under contract with INL. INL researchers, authoring alone (13%), or with other INL researchers (9%), or with university researchers (1%), accounted for 23% of the total. Non-INL federal, state, and regional government entities and other organizations together accounted for 11% of the papers.

[39] Of 286 publications identified as INL geothermal outputs, a random sample of 162 was drawn, sufficient for a confidence level of 95% and an interval of +/- 5%. Of 58 publications identified as NREL geothermal outputs, one duplicate was eliminated, and 57 were used in the analysis. (It should be noted that the count of NREL geothermal publications found in the OSTI database was below that found in NREL's publication database).

Figure 5-2. Distribution of the Sample of INL Publications by Topical Category

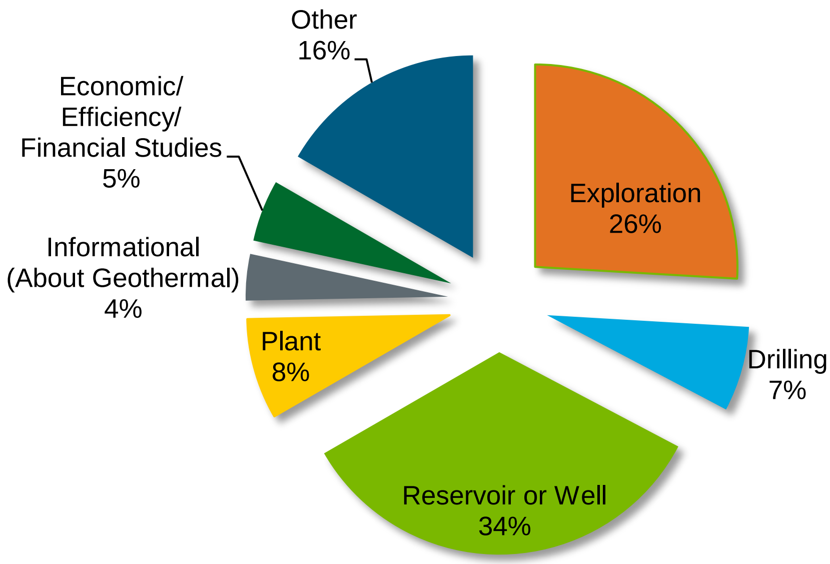
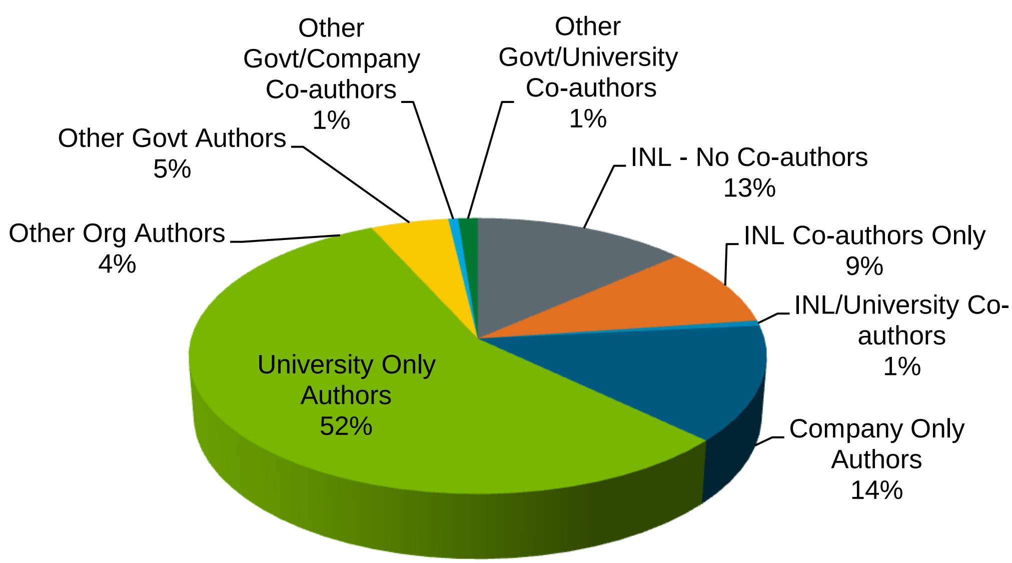


Figure 5-3. Distribution of Sample of INL Publications by Authorship



Among the many universities whose researchers authored reports under contract with INL are Stanford University, University of Texas at Austin, Oregon Institute of Technology, University of North Dakota, Kansas State University, Louisiana State University, Southern Methodist

University, the University of North Carolina at Chapel Hill, the University of Maryland at College Park, and the University of Hawaii. The participation of researchers from universities from all parts of the country suggests that INL funding of university geothermal research is building expertise in the field across the nation.

Among the companies whose researchers authored reports under contract with INL are the Pacific Gas and Electric Company, Maurer Engineering, Bechtel National, Earth Power Resources, GeoProducts Corporation, Trans-Pacific Geothermal Corporation, Dynaflow, and Oxbow Power Services. The relatively strong presence of company researchers authoring reports under contract to INL shows commercial interest in INL-sponsored research.

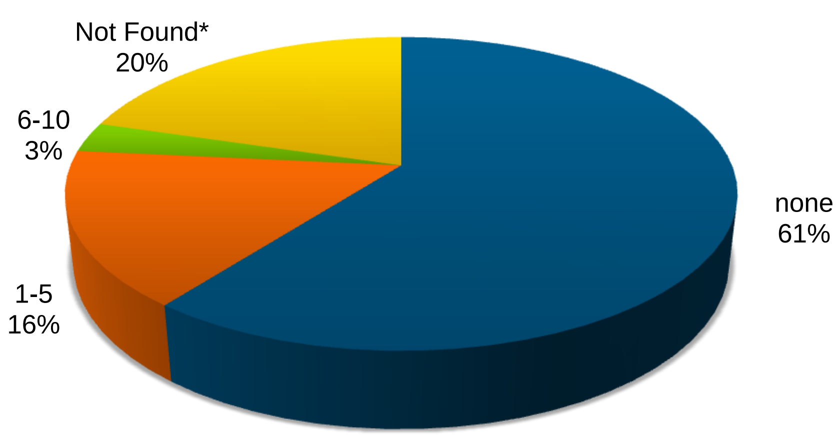
Among the state and regional bodies whose researchers authored reports for INL are the Idaho Department of Water Resources, Washington State Department of Natural Resources, Utah Geological and Mineral Survey, and the California Lake County Sanitation District. The participation of researchers from state and regional organizations shows the research involvement of another element typically present in large geothermal projects for power generation.

Other organizations whose affiliated researchers authored INL reports include the National Geothermal Association, the American Rock Mechanics Associations, and the Institute of Gas Technology. The participation of association researchers suggests that INL connects through some of its publications to wide audiences in the geothermal industry, as well as to specialized fields concerned with geothermal energy.

5.4.2 INL Publication-to-Publication Citation Analysis

Although, as shown in Figure 5-4, many of the INL geothermal publications had not been cited or could not be found by the citation search tool, 16% had received between one and five citations, and another 3% had between six and 10 citations. Furthermore, researchers in a variety of organizations had cited INL publications.

Figure 5-4. Distribution of the Sample of INL Publications by Number of Citations Received



*Not Found category refers to INL publications in the random sample that were not found by application of the citation search tool.

Affiliations of those citing the sample of INL geothermal publications include a number of domestic and foreign universities, companies, and state and regional government bodies, as listed in Table 5-3. As shown in the first column of the table, self-citations and citations by other INL researchers are relatively few, and other DOE researchers citing the INL publications include Lawrence Livermore National Laboratory, Sandia National Laboratories, and Oak Ridge National Laboratory. The second column lists company publications citing the INL publications. Most of these were authored without DOE co-authors. The third column lists the large number of domestic and foreign university publications that cite the INL publications—again most without DOE co-authors.

Among the papers in the INL sample with the most citations is a 2002 conference paper (INEEL/CON-02-01206) by Smith, et al., "A High-Resolution Aeromagnetic Survey to Identify Buried Faults at Dixie Valley, Nevada" (a 62 MW geothermal power plant was built in Dixie Valley in1988). Organizational affiliations of those citing the paper include the U.S. Geological Survey, LLNL, and multiple companies and universities.

Two older reports from 1995 and 1996 are also among the INL sample with the most citations. One is a technical report by Witcher (DOE/ID/13223-T8, 1995), "A Geothermal Resource Data Base: New Mexico;" and the other is a conference report by Shook (INEL-96/00233; CONF-960913, 1996), "Matrix-Fracture Interactions in Dual Porosity Simulations."

Table 5-3. List of Organizational Affiliations of those Citing Publications in the INL Random Sample

DOE Affiliated	Company Affiliated	University Affiliated	Other Organization Affiliated
INL Self Citations (6)	HyVista Corporation	University of California, Santa Clara	U.S. Geological Survey
INL Other (2)	Maurer Engineering, Inc.	University of Idaho	US Army Waterways Experiment Station, U.S. Army Engineer Research and Development Center
Lawrence Livermore National Laboratory	GEDCO	Colorado School of Mines	U.S. Geological Survey
Sandia National Laboratory	Wintermoon Geotechnologies, Inc.	Istanbul Teknik Üniversitesi	Utah Geological Survey
Oak Ridge National Laboratory	Geowatt AG, Switzerland	Southern Methodist University	
	EGI	Oregon State University	NASA Ames Research Center
	Bruce S. Sibbett, consultant	Indiana University	
	School of Thought	East Tennessee State University	Naval Air Weapons Station, China Lake
	Heatway	DePaul University	China Academy of Geological Sciences Mineral Resources Research Institute
	KenGen - Kenya Electricity Generating Company Ltd.	University of Utah	China Geological Survey
	Maurer Engineering, Inc.	University of Texas	Qingdao Institute of Marine Geology, China Geological Survey
	Geomechanics International	Texas A&M University	Edwards Aquifer Authority
	Coso Operating Co.	Tsinghua University, Beijing	National Geophysical Research Institute, Hyderabad, India
	Woodward-Clyde Federal Services, Inc.	China University of Geology, Beijing	
		Oregon Institute of Technology	
		Izmir Institute of Technology, Turkey	
		Dokuz Eylul University, Izmir, Turkey	
		University of Glasgow, UK	
		San Jose University	

Table 5-3 (continued). List of Organizational Affiliations of those Citing Publications in the INL Random Sample

DOE Affiliated	Company Affiliated	University Affiliated	Other Organization Affiliated
		University of California	
		Kansas State University	
		University of Texas, El Paso	
		New Mexico Institute of Mining and Technology	
		New Mexico State University	
		Rice University	
		Georgia Institute of Technology	
		Nanjing University, China	
		Massachusetts Institute of Technology	
		Vanung University, Taiwan	
		National Chiao Tung University, Taiwan	
		Technical University of Catalonia, Spain	
		Swiss Federal Institute of Technology, Zurich	

5.4.3 National Renewable Research Laboratory (NREL) Publication Author/Co-Author Analysis

Brochures and booklets comprised the largest share (42%) of NREL publications found in the OSTI database, followed by technical reports (33%), and conference reports (25%).[40] Reflective of its various roles in DOE's geothermal research, the predominant topic of NREL's geothermal publications was informational (61%), followed by economic, efficiency, and financial studies (18%). At the same time, there were publications in the major technical categories: plant (7%), reservoir/well (7%), drilling (2%), and exploration (2%).

[40] Based on the population of NREL geothermal publications found by searching the OSTI geothermal collection for DOE-sponsored publications, with identifier numbers containing NREL.

Almost all (91%) of the NREL geothermal publications in the set examined are authored by one or more NREL authors. Nine percent are co-authored by NREL with others: a few with company researchers, one with university researchers, and one with researchers from Brookhaven National Laboratory. None of those found are authored without NREL co-authorship. These results suggest that NREL, unlike INL, did not contract extensively with companies and universities for independent geothermal research (alternatively, these reports may have been under-reported to OSTI).

5.4.4 NREL Publication-to-Publication Citation Analysis

The distribution of citation counts for the NREL publications was quite similar to that for INL, despite differences in the make-up of their publications by topic. The majority (61%) had not been cited as of mid-2009, and 21% were not found by the citation search tool. Twelve percent were cited 1-5 times; 4%, 6-10 times; and 2%, 11-15 times.

As for INL publications, self-citations and citations by other NREL researchers are quite small. Citations by those in other DOE laboratories are greater, with researchers at BNL, Oak Ridge National Laboratory (ORNL), INL, and the DOE-sponsored Rocky Mountain Oilfield Testing Center citing the NREL publications. Prominent among those citing the NREL publications are researchers in domestic and foreign universities, followed by those in other organizations, such as the World Resources Institute; RAND Corporation; the Energy Research Centre of the Netherlands; the California Energy Commission; and Western Resource Advocates, a non-profit environmental law and policy organization. In addition, researchers in a few companies cited the publications.

6. Other Modes of Linkages

There are important types of outputs of DOE-funded geothermal research that are not well captured by the patent and publication analyses featured in this study. Among these are models and computer codes distributed through software licensing agreements; maps of geothermal resources, which can be downloaded electronically; and test data, which may be accessed primarily electronically without necessarily generating patents or papers and citation trails. Also highly important is the tacit knowledge embodied as human capital. Trained students and experienced researchers entail a major knowledge benefit not captured by the previous analysis. Increased general awareness of geothermal energy as a potential supplier of power needs is not reflected in the explicit output measures. This section provides a brief treatment of these additional modes of outputs from DOE-funded geothermal research, primarily as a reminder that they are also important knowledge outputs of research, development, and demonstration.

6.1 Computer Models/Codes, Maps of Geothermal Resources, and Test Data

The DOE EERE website provides links to DOE-supported software programs for modeling geothermal systems and economics, as well as to geothermal resource maps, and test data. Most of these resources can be freely downloaded.[41] In some cases the software must be licensed, but the fees are modest.

The TOUGH series of reservoir models is a leader in the category of DOE-developed geothermal models. These models are used to study fluid processes in geothermal reservoirs, to project reservoir capacity, and in the planning and management of reservoirs as part of larger systems. Related workshops and symposia held by LBNL have helped to disseminate the models. In addition, publications have helped to explain and disseminate the models and code—captured to some extent in the publication samples analyzed previously. The software, which is available from LBNL (with a modest licensing fee), has been used in geothermal projects worldwide and in the United States, as well as for nuclear storage and CO_2 sequestration. The TOUGH series of reservoir models is treated in detail in a recent benefit-cost study of GTP.[42]

INL and others have produced geothermal maps that show subterranean temperatures to provide information about the location, nature, and potential of geothermal resources. Again, these maps are freely available to the general public, and are an enabling output of DOE-funded geothermal research.[43]

[41] www1.eere.energy.gov/geothermal/software_data.html.
[42] Gallaher, et al. (2010), Section 4.1.3.
[43] Geothermal research maps for 13 states and for the Western United States are available for download at INL's website http://inlportal.inl.gov/portal/server.pt/community/geothermal/422/maps. Information about the maps is available at http://geothermal.inel.gov/maps/state_map_explanation.pdf.

6.2 Relationships Formed with Industry, Universities, and Others

Another important output of DOE-funded geothermal research not captured by analysis of its more explicit outputs is the building of a knowledge network among diverse organizations. This network fosters both knowledge creation and dissemination. Figure 6-1 depicts elements of the network.

Partnerships with industry formed by GTP over its history are an important element of the network. These partnerships link DOE's R&D program directly to companies that help to develop new technologies and are positioned to apply the resulting innovations commercially to generate power from geothermal energy. Among the partnering companies are those known mainly as geothermal companies, others known mainly as oil and gas companies, electric power companies, engineering and consulting companies, as well as at least one user of geothermal energy. Partnering companies include, but are not limited to, Calpine Corporation, Ormat International Inc., U.S. Geothermal Inc., Earth Power Resources Inc., Western Geothermal Partners, Chevron Resources Co., Getty Oil Company, Phillips Petroleum Company, Union Oil Company, Caithness Energy LLC, Vulcan Power Company, Utah Municipal Power Agency, Arizona Public Service, California Energy, and Chena Hot Springs Resort LLC.

Universities also participate in the DOE Geothermal R&D Program. In addition to research results, trained geothermal technologists are a Program output.

Some of these universities have been funded to carry out individual geothermal research projects, including New Mexico Technical University, Northern Arizona University, Duke University, Pennsylvania State University, University of North Carolina, and the University of California.

Beyond this, a few university earth science groups are, or have been, funded more extensively by GTP—some on an on-going basis to develop and operate geothermal centers. These DOE-supported[44] and university-based geothermal centers include the Energy and Geoscience Institute at the University of Utah; Stanford University's Geothermal Program; the Great Basin Center for Geothermal Energy at the University of Nevada, Reno; the Geothermal Laboratory of the Department of Earth Sciences at Southern Methodist University; and the Geo-Heat Center at the Oregon Institute of Technology. These university geothermal programs tend to have an international involvement in geothermal energy research, involvement with both the national laboratories and the industry, and active conference participation.[45]

Examples of contributions by several of these university geothermal research centers follow: The University of Utah Earth and Geoscience Institute has played a large role in DOE's geothermal exploration research and development.[46] Stanford's Geothermal Program has made substantial contributions in reservoir engineering; it "serves the industry by (i) graduating reservoir engineers and (ii) carrying out research in flow in fractured and low permeability

[44] DOE is generally one of multiple sources of funding for these university geothermal programs, which also receive funding from others such as other government agencies and industry sponsors.
[45] As an example, see map of current projects of the Energy and Geosciences Institute at the University of Utah, http://www.egi.utah.edu/HomeCurrentProjects.aspx.
[46] http://www.egi.utah.edu/GeothermalCapabilitiesStudies.aspx.

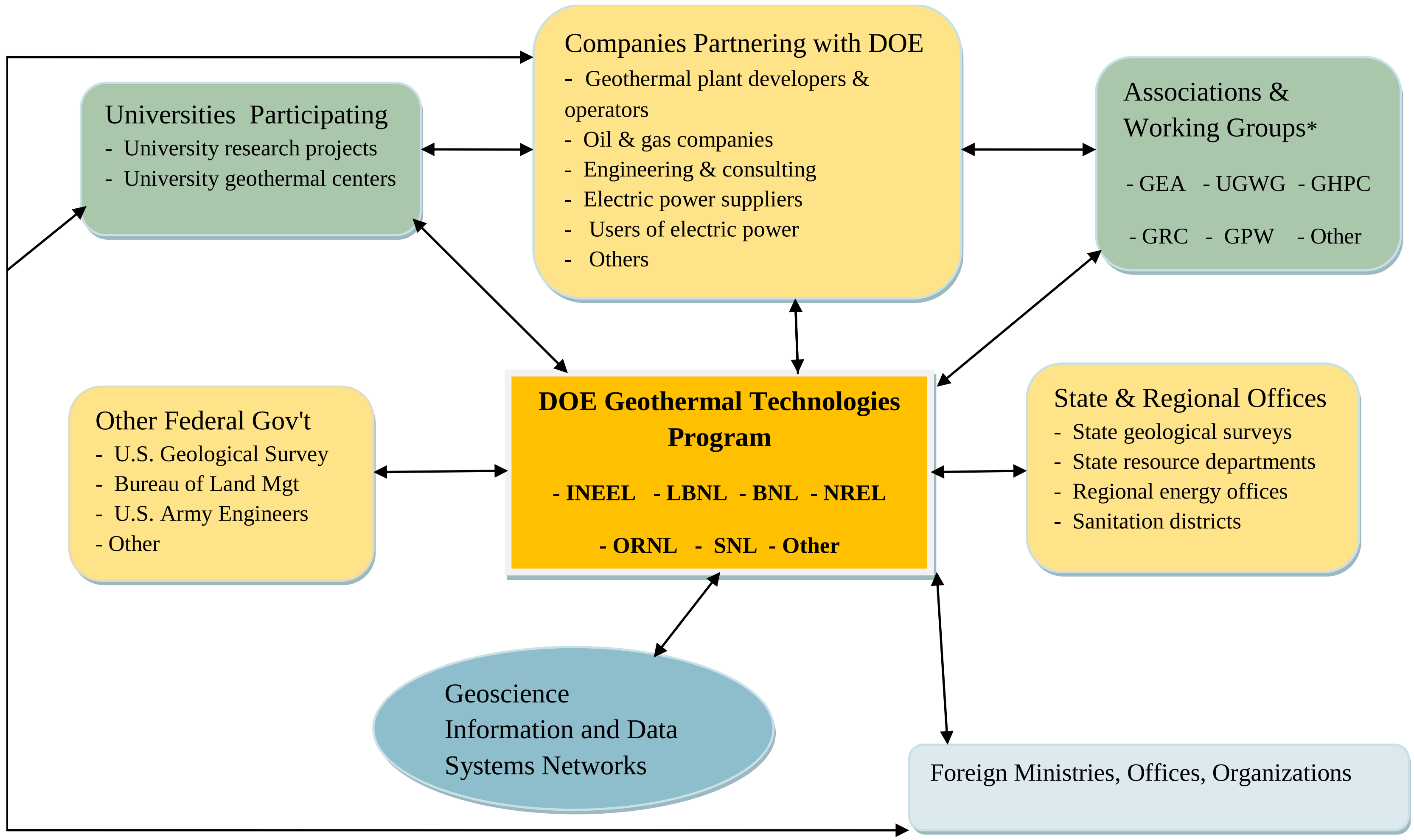
rocks..." [47] Southern Methodist University's Laboratory of the Department of Earth Sciences has, among other things, contributed to the construction of geothermal resource maps.[48]

Recently, DOE funded Boise State University to lead a consortium of academic institutions, including the university geothermal centers listed above, and government agencies to establish a National Geothermal Data System (NGDS). The NGDS is a distributed network of databases and data sites that collectively form a system for the acquisition, management, and maintenance of geothermal and related data.[49]

DOE laboratories have played key roles throughout DOE's history of geothermal research. Since the 1980s, BNL, INL, LLNL, NREL, and other DOE laboratories have been active in a variety of geothermal research areas.

The Program also has funded state agencies to foster development of expertise in geothermal energy. State agencies receiving DOE geothermal funding have been centered in the West. Among those funded are California, Nevada, New Mexico, Utah, Washington, Wyoming, Alaska, Idaho, and Oregon.

[47] See the Stanford Geothermal Program description at http://pangea.stanford.edu/ERE/research/geoth/affiliates/index.html.
[48] http://smu.edu/geothermal/georesou/georesourcesmap.htm.
[49] Further information on the NGDS website is available at http://www.geothermaldata.org.



* Abbreviations are used for associations and working groups as follows: GEA denotes Geothermal Energy Association; UGWG denotes Utility Geothermal Working Group; GHPC denotes U.S. Geothermal Heat Pump Consortium; GRC denotes Geothermal Resource Council; and GPW denotes U.S. Geothermal Heat Pump Consortium.

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Ruegg, R. & Thomas, P. (2008). *Linkages of DOE's Energy Storage R&D to Batteries and Ultracapacitors for Hybrid, Plug-In Hybrid, and Electric Vehicles*. Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

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Ruegg, R. & Thomas, P. (2010a). *Linkages from DOE's Advanced Combustion R&D to Improved Vehicle Engine Performance.* Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

Ruegg, R. & Thomas, P. (2010b). *Linkages from DOE's Solar Photovoltaic R&D to Commercial Renewable Power Generation: A Bibliometric Study.* Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

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Appendix A

Design of the Patent Filter for Identifying Candidate Patents

To identify the set of all geothermal patents for the use in the backward tracing analysis, the study designed a patent filter. To identify U.S. patents, the filter was based on a combination of keywords and Patent Office Classifications (POCs). To identify EPO and WIPO patents, the filter was based on a combination of keywords and International Patent Classifications (IPCs).

The four separate searches performed using the filter are outlined below. In each search, the same set of keywords was employed, combined with POCs for U.S. patents, and IPCs for EPO and WIPO patents. In these searches, * is a wildcard denoting unlimited characters, while ? is a wildcard denoting a single character, including a space. Hence, the search geo?therm* includes geothermal, geothermic, geo-thermal, geo thermal, etc.

Search 1:
POC = 60/641.2-5 Power plants using geothermal heat
IPC = F03G 4 Producing mechanical power from geothermal energy

- this search identifies all patents in these patent classifications, with no further keyword restrictions, since the classifications are directed specifically to geothermal energy.

Search 2:
POC =
60/641.1 Power plants using natural heat
60/398 Power plants using natural energy or having a geographic feature
and
Title/Abstract =
Geo?therm*
Earth*
Well*
Underground
Down-hole
(Ground?source) and (heat?pump*)

- this search is designed to identify U.S. patents classified as being concerned with natural heat sources, with the added keyword requirement that they refer to terms such as geothermal, underground etc.

Search 3:
POC = 175 Boring or Penetrating the Earth
IPC = G01V Earth and rock drilling
and
Title/Abstract =
Geo?therm*
Molten?rock*

Hot?rock*
Hot?dry?rock*
Hot spring*

- the classifications used in this search are concerned with drilling, and the keywords restrict the search to patents that refer specifically to terms related to geothermal energy.

Search 4:
Title/Abstract =
Organic Rankine Cycle
ORC
Kalina Cycle*
Geo?therm*

- this search identifies all patents that use specific terms, including any patent that uses the term 'geothermal', irrespective of their patent classification.

Appendix B

List of DOE-Attributed Patents

Table B-1. Chronological Listing of U.S., EPO, and WIPO Patents Attributed to DOE-Funded Research

Issue/Publication Year	Patent	Assignee	Title
1974	3786858	U.S. Dept. of Energy	Method of Extracting Heat from Dry Geothermal Reservoirs
1975	3905196	Unisys Corp.	Geothermal Energy Pump Thrust Balance Apparatus
1975	3910050	Unisys Corp.	Geothermal Energy System and Control Apparatus
1975	3908380	Unisys Corp.	Geothermal Energy Turbine and Well System
1976	3938334	Unisys Corp.	Geothermal Energy Control System and Method
1977	4025240	Unisys Corp.	Geothermal Energy Control System and Method
1977	4005289	U.S. Dept. of Energy	Method for Identifying Anomalous Terrestrial Heat Flows
1978	4078904	U.S. Dept. of Energy	Process for Forming Hydrogen and Other Fuels Utilizing Magma
1978	4106577	University of Missouri	Hydromechanical Drilling Device
1978	4119160	University of Missouri	Method and Apparatus for Water Jet Drilling of Rock
1979	WO1979000565	Occidental Petroleum Corporation	Countercurrent Direct Contact Heat Exchange Process and System
1979	4167099	Occidental Petroleum Corporation	Countercurrent Direct Contact Heat Exchange Process and System
1979	4134077	Unisys Corp.	Amplifier Circuit Operable Over a Wide Temperature Range
1980	4196183	U.S. Dept. of Energy	Process for Purifying Geothermal Steam
1980	4221271	University of Missouri	Water Jet Cutting Nozzle Transition Section
1981	4262757	Hydronautics Inc.	Cavitating Liquid Jet Assisted Drill Bit and Method for Deep-Hole Drilling
1981	4276748	Occidental Petroleum Corporation	Recovery of Energy from Geothermal Brine and Other Hot Water Sources

Issue/Publication Year	Patent	Assignee	Title
1981	4306879	U.S. Dept. of Energy	Chemical Logging of Geothermal Wells
1981	4265487	University of Missouri	High Pressure Water Jet Mining Machine
1982	EP0062111	Hydronautics inc	Enhancing liquid jet erosion
1982	4342197	Unisys Corp.	Geothermal Pump Down-Hole Energy Regeneration System
1982	4326581	U.S. Dept. of Energy	Direct Contact Binary Fluid Geothermal Boiler
1982	4313342	U.S. Dept. of Energy	Method and Apparatus for Determining Vertical Heat Flux of Geothermal Field
1982	4328106	U.S. Dept. of Energy	Method for Inhibiting Silica Precipitation and Scaling in Geothermal Flow Systems
1982	EP0042752	U.S. Dept. of Energy	Method of optimizing performance of Rankine cycle power plants
1982	4358930	U.S. Dept. of Energy	Method of Optimizing Performance of Rankine Cycle Power Plants
1982	4346560	U.S. Dept. of Energy	Multi-stage Flash Degaser
1982	4332520	U.S. Dept. of Energy	Velocity pump reaction turbine
1982	4337899	University of Missouri	High pressure liquid jet nozzle system for enhanced mining and drilling
1982	4317492	University of Missouri	Method and apparatus for drilling horizontal holes in geological structures from a vertical bore
1983	4391339	Hydronautics Inc.	Cavitating liquid jet assisted drill bit and method for deep-Hole drilling
1983	4389071	Hydronautics Inc.	Enhancing liquid jet erosion
1983	4380903	Unisys Corp.	Enthalpy restoration in geothermal energy processing system
1983	4376462	U.S. Dept. of Energy	Substantially self-Powered method and apparatus for recovering hydrocarbons from hydrocarbon-Containing solid hydrates
1983	4369850	University of Missouri	High pressure fluid jet cutting and drilling apparatus
1984	4489563	Exergy Inc.	Generation of energy

Issue/Publication Year	Patent	Assignee	Title
1984	4474251	Hydronautics Inc.	Enhancing liquid jet erosion
1984	4428200	Magma Power Co.	Geothermal plant fluid reinjection system
1984	4429535	Magma Power Co.	Geothermal plant silica control system
1984	4424858	U.S. Dept. of Energy	Apparatus for recovering gaseous hydrocarbons from hydrocarbon-containing solid hydrates
1984	4430042	U.S. Dept. of Energy	Velocity pump reaction turbine
1985	4556109	Dow Chemical Co.	Process for cementing geothermal wells
1985	4508577	Hydronautics Inc.	Fluid jet apparatus and method for cleaning tubular components
1985	4492083	Magma Power Co.	Geothermal salinity control system
1985	4513352	U.S. Dept. of Energy	Thermal protection apparatus
1985	4559818	U.S. Dept. of Energy	Thermal well-test method
1986	EP0124107	Hydronautics Inc.	Fluid jet apparatus and method for cleaning tubular components
1986	EP0204187	Hydronautics Inc.	Improved erosive-jet diver tool
1987	4681264	Hydronautics Inc.	Enhancing liquid jet erosion
1987	4665705	Magma Power Co.	Geothermal plant silica control apparatus and method
1988	4716849	Hydronautics Inc.	Erosive-jet diver tool
1988	4741398	U.S. Dept. of Energy	Hydraulic accumulator-compressor for geopressured enhanced oil recovery
1989	4822422	Associated Universities Inc.	Ca(oh).sub.2 -treated ceramic microsphere
1989	4871395	Associated Universities Inc.	High temperature lightweight foamed cements
1989	WO1989010572	Baker Hughes Inc.	Acoustic data transmission through a drill string
1989	4824447	U.S. Dept. of Energy	Enhanced oil recovery system
1989	4875015	University of Utah	Multi-array borehole resistivity and induced polarization method with mathematical inversion of redundant data

Issue/Publication Year	Patent	Assignee	Title
1989	WO1989000705	University of Utah	Multi-array borehole resistivity and induced polarization system
1990	4936384	Associated Universities Inc.	Ca(oh).sub.2 -Treated ceramic microsphere
1990	4927462	Associated Universities Inc.	Oxidation of carbon fiber surfaces for use as reinforcement in high-temperature cementitious material systems
1990	4930316	Magma Power Co	Geothermal plant noncondensable gas removal and heat recovery system and method
1990	4905473	Magma Power Co.	Geothermal power plant steam entrainments removal system and method
1990	WO1990008004	Novatek Inc.	Down-hole mud actuated hammer
1991	EP0408667	Baker Hughes Inc.	Acoustic data transmission through a drill string
1991	5056067	Baker Hughes Inc.	Analog circuit for controlling acoustic transducer arrays
1991	EP0406411	Novatek Inc.	Down-hole mud actuated hammer
1992	5128901	Baker Hughes Inc.	Acoustic data transmission through a drill string
1992	5130655	Electromagnetic Instruments Inc.	Multiple-coil magnetic field sensor with series-connected main coils and parallel-connected feedback coils
1992	5165243	U.S. Dept. of Energy	Compact acoustic refrigerator
1992	5121993	U.S. Dept. of Energy	Triaxial thermopile array geo-Heat-Flow sensor
1993	5246496	Associated Universities Inc.	Phosphate-bonded calcium aluminate cements
1993	EP0565141	Baker Hughes Inc.	Acoustic data transmission through a drill string
1993	5274606	Baker Hughes Inc.	Circuit for echo and noise suppression of accoustic signals transmitted through a drill string
1993	5222049	Baker Hughes Inc.	Electromechanical transducer for acoustic telemetry system
1994	5366891	Associated Universities Inc.	Biochemical solubilization of toxic salts from residual geothermal brines and waste waters

Issue/Publication Year	Patent	Assignee	Title
1994	5363095	Lockheed Martin Corp.	Down-hole telemetry system
1994	5305607	Magma Power Co.	Geothermal power plant scale separation method and apparatus
1994	5343968	U.S. Dept. of Energy	Down-hole material injector for lost circulation control
1994	5311766	U.S. Dept. of Energy	Method and apparatus for determining two-Phase flow in rock fracture
1995	5477505	Lockheed Martin Corp.	Down-hole pipe selection for acoustic telemetry
1995	5396965	Novatek Inc.	Down-hole mud actuated hammer
1996	5567932	Lockheed Martin Corp.	Geomembrane barriers using integral fiber optics to monitor barrier integrity
1996	5508616	Sekiyushigen Kaihatsu Kk/Tohoku Univ	Apparatus and method for determining parameters of formations surrounding a borehole in a preselected direction
1997	5604040	Associated Universities Inc	Zinc phosphate conversion coatings
1997	WO1997021902	Boart Longyear Company	Drilling rig
1997	5703836	Lockheed Martin Corp.	Acoustic transducer
1997	WO1997039219	Lockheed Martin Corp.	Apparatus and method for downhole drilling communications
1997	5685362	University Of California	Storage capacity in hot dry rock reservoirs
1998	5794723	Boart Longyear Company	Drilling rig
1998	5722488	Lockheed Martin Corp.	Apparatus for down-hole drilling communications and method for making and using the same
1998	5823261	Lockheed Martin Corp.	Well-pump alignment system
1998	WO1998042434	Midwest Research Institute	Method and apparatus for high-efficiency direct contact condensation
1999	WO1999039078	Boart Longyear Company	Closed loop control system for diamond core drilling
1999	EP0900317	Lockheed Martin Corp.	Apparatus and method for downhole drilling communications
1999	5925291	Midwest Research Institute	Method and apparatus for high-efficiency direct contact condensation

Issue/Publication Year	Patent	Assignee	Title
2000	6147932	Lockheed Martin Corp.	Acoustic transducer
2000	EP1011849	Midwest Research Institute	Method and apparatus for high-efficiency direct contact condensation
2001	6186248	Boart Longyear Company	Closed loop control system for diamond core drilling
2001	WO2001020367	Electromagnetic Instruments Inc.	An electromagnetic induction method and apparatus for the measurement of the electrical resistivity of geologic formations surrounding boreholes cased with a conductive liner
2001	WO2001041319	Electromagnetic Instruments Inc.	Component field antenna for induction borehole logging
2001	6294917	Electromagnetic Instruments Inc.	Electromagnetic induction method and apparatus for the measurement of the electrical resistivity of geologic formations surrounding boreholes cased with a conductive liner
2001	6182755	Lockheed Martin Corp.	Bellow seal and anchor
2001	6188647	Lockheed Martin Corp.	Extension method of drill string component assembly
2001	6282497	Midwest Research Institute	Method for analyzing the chemical composition of liquid effluent from a direct contact condenser
2001	6251179	U.S. Dept. of Energy	Thermally conductive cementitious grout for geothermal heat pump systems
2002	EP1195011	Electromagnetic Instruments Inc.	Component field antenna for induction borehole logging
2002	6347675	Tempress Technologies Inc.	Coiled tubing drilling with supercritical carbon dioxide
2002	6427791	U.S. Dept. of Energy	Drill bit assembly for releasably retaining a drill bit cutter
2003	6537796	Brookhaven Science Associates LLC.	Conversion of geothermal waste to commercial products including silica
2003	6577284	Electromagnetic Instruments Inc.	Component field antenna for induction borehole logging

Issue/Publication Year	Patent	Assignee	Title
2003	6668554	University of California	Geothermal energy production with supercritical fluids
2004	6791470	Lockheed Martin Corp.	Reducing injection loss in drill strings
2004	WO2004043606	United Technologies Corp.	Organic rankine cycle waste heat applications
2005	6853798	Lockheed Martin Corp.	Down-hole geothermal well sensors comprising a hydrogen-resistant optical fiber
2005	WO2005079224	Tempress Technologies Inc.	Hydraulic impulse generator and frequency sweep mechanism for borehole applications
2005	6962056	United Technologies Corp.	Combined rankine and vapor compression cycles
2005	6892522	United Technologies Corp.	Combined rankine and vapor compression cycles
2005	6880344	United Technologies Corp.	Combined rankine and vapor compression cycles
2005	EP1576256	United Technologies Corp.	Combined rankine and vapor compression cycles
2005	WO2005078046	United Technologies Corp.	Organic rankine cycle fluid
2005	EP1567750	United Technologies Corp.	Organic rankine cycle waste heat applications
2006	7139218	National Oilwell Varco	Distributed down-hole drilling network
2006	EP1718995	National Oilwell Varco	Distributed downhole drilling network
2006	EP1664475	National Oilwell Varco	Load-resistant coaxial transmission line
2006	6982384	National Oilwell Varco	Load-resistant coaxial transmission line
2006	7142129	National Oilwell Varco	Method and system for down-hole clock synchronization
2006	7123160	National Oilwell Varco	Method for triggering an action
2006	7098802	National Oilwell Varco	Signal connection for a down-hole tool string

Issue/Publication Year	Patent	Assignee	Title
2006	7036612	Lockheed Martin Corp.	Controllable magneto-rheological fluid-based dampers for drilling
2006	7139219	Tempress Technologies Inc.	Hydraulic impulse generator and frequency sweep mechanism for borehole applications
2006	WO2004044386	United Technologies Corp.	Combined rankine and vapor compression cycles
2006	WO2006012406	United Technologies Corp.	Combined rankine and vapor compression cycles
2006	7100380	United Technologies Corp.	Organic rankine cycle fluid
2006	EP1713877	United Technologies Corp.	Organic rankine cycle fluid
2006	6986251	United Technologies Corp.	Organic rankine cycle system for use with a reciprocating engine
2007	7201239	Aps Technologies Inc.	Power-generating device for use in drilling operations
2007	7219752	Aps Technologies Inc.	System and method for damping vibration in a drill string
2007	7200070	National Oilwell Varco	Down-hole drilling network using burst modulation techniques
2007	7193526	National Oilwell Varco	Down-hole tool
2007	7224288	National Oilwell Varco	Link module for a down-hole drilling network
2007	7207396	National Oilwell Varco	Method and apparatus of assessing down-hole drilling conditions
2007	7193527	National Oilwell Varco	Swivel assembly
2007	WO2007102863	Honeywell Inc.	Ping-pong auto-zero amplifier with glitch reduction
2007	7174716	United Technologies Corp.	Organic rankine cycle waste heat applications
2007	WO2007001344	University of Chicago	Chemically bonded phosphate ceramic sealant formulations for oil field applications
2008	7321260	Honeywell Inc.	Ping-pong auto-zero amplifier with glitch reduction
2008	7438755	University of Chicago	Chemically bonded phosphate ceramic sealant formulations for oil field applications

Issue/Publication Year	Patent	Assignee	Title
2009	EP1992067	Honeywell Inc.	Ping-pong auto-zero amplifier with glitch reduction

Appendix C

List of Selected DOE-Sponsored Papers/Publications

Table C-1. Selected DOE-Sponsored Geothermal Scientific Papers/Publications Used in the Patent-to-Publication Citation Analysis

A. Ortega and D.A. Glowka, “Frictional Heating and Convective Cooling of Polycrystalline Diamond Drag Tools During Rock Cutting,” *Society of Petroleum Engineers Journal*, pp. 121-128 (April 1984).
D.A. Glowka and C.M. Stone, “Effects of Thermal and Mechanical Loading on PDC Bit Life,” *Society of Petroleum Engineers Drilling Engineering*, pp. 201-214 (June 1986).
D.A. Glowka and C.M. Stone, “Thermal Response of Polycrystalline Diamond Compact Cutters under Simulated Down-hole Conditions,” *Society of Petroleum Engineers Journal*, pp. 143-156 (April 1985).
D.A. Glowka, "The Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part I--Development of a PDC Cutting Force Model", *Journal of Petroleum Technology*, pp. 797-849 (August 1989).
D.A. Glowka, "The Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part II--Development of PDC WEAR Computer Code", *Journal of Petroleum Technology*, pp. 850-859 (August 1989).
D.A. Glowka, “Optimization of Bit Hydraulic Configurations,” *Society of Petroleum Engineers Journal*, pp. 21-32 (February 1983).
D.H. Zeuch, D.V. Swenson, and J.T. Finger, “Subsurface Damage Development in Rock During Drag-bit Cutting: Observations and Model Predictions,” Rock Mechanics: Theory-Experiment-Practice." *Proceedings of the 24th U.S. Symposium on Rock Mechanics*, Texas A&M University, College Station Texas (1983).
D.V. Swenson, *Modeling and Analysis of Drag Bit Cutting*, Sandia Report SAND83-0278, Sandia National Laboratories (1983).
D.V. Swenson, D. L. Wesenberg, and A.K. Jones, “Analytical and Experimental Investigations of Rock Cutting Using a Polycrystalline Diamond Compact Drag Cutter,” presented at the 56th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, San Antonio Texas (1981).
J.A. St. Clair, F. A. Duimstra, and S.G. Varnado, “Continuous Chain Bit Development,” *Geothermal Resources Council TRANSACTIONS*, v. 3 (1979).
J.T. Finger and D.A. Glowka, “PDC Bit Research at Sandia National Laboratories,” Sandia Report SAND89-0079, (1989).
Normann R.A., "Geothermal High Temperature Instrumentation Applications", Sandia National Laboratories (1998).
Radian Corp., *Material Selection Guidelines for Geothermal Energy Utilization Systems* (1981).
EPRI , *Next Generation Geothermal Power Plants* (1995).
Geothermal Energy as a Source of Electricity, Brown University (1980).
J.R. Kelsey, editor, *Geothermal Technology Development Program, Annual Progress Report, October 1980—September 1981*, Sandia Report SAND81-2124 (1982).

J.R. Kelsey, editor, *Geothermal Technology Development Program, Annual Progress Report, October 1982—September 1983*, Sandia Report SAND84-1028 (1984).

J. Kestin, editor, *Sourcebook on the Production of Electricity from Geothermal Energy*., Publication No. DOE/RA/4051, Chap. 4, p. 536 (1980).

M.L. Allan and S.P. Kavanaugh, "Thermal Conductivity of Cementitious Grouts and Impact on Heat Exchanger Length Design for Ground Source Heat Pumps", presented at ASHRAE Winter Meeting (2000).

D.S. Drumheller, "Acoustical Properties of Drill Strings," *J. Acoustical Soc of Amer*., vol. 85, No. 3, pp. 1048-1064 (March 1989).

D.S. Drumheller, "Attenuation of Sound Waves in Drill Strings," J. Acoustical Soc of Amer., vol. 94, No. 4, pp. 2387-2396 (October 1993).

D.S. Drumheller, "Extensional Stress Waves in One-Dimensional Elastic Waveguides," *Acoustical Soc of Amer*., vol. 92, No. 6, pp. 3389-3401 (December 1992).

D.S. Drumheller, "Propagation of Sound Waves in Drill Strings," *Acoustical Soc of Amer*., vol. 97, No. 65, pp. 2116-2125 (April 1995).

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J. Henderson et al., "Geysers Advanced Direct Contact Condenser Research," *Proceedings Geothermal Program Review XV*, San Francisco, DOE/EE-0139, pp. 3-3 to 3-9 (March 24-26, 1997).

E.T. Premuzic, S.L. Mow, and H. Lian, "Biochemical Processing of Geothermal Brines and Sludges," Biosystems and Process Sciences Division, Dept. of Applied Science, (March 1995).

E.T. Premuzic, M.S. Lin, and J.Z. Jin, "Recent Developments in Geothermal Waste Treatment Biotechnology," *Heavy Metals in the Environment*, 1:356-363 (September 1993).

E.T. Premuzic, M.S. Lin, and H. Lian, "Biochemical Technology For The Detoxification of Geothermal Brines and The Recovery of Trace Metals," Biosystems and Process Sciences Division, Brookhaven National Laboratory, 321-324 (September 1995).

E.T. Premuzic, M.S. Lin, and L.H. Lian, "Recent Advances in Biochemical Technology for the Processing of Geothermal Byproducts," Biosystems and Process Sciences Division, Department of Applied Sciences, Brookhaven National Laboratory (April 1996).

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T. Sugama, "Microsphere-Filled Lightweight Calcium Phosphare Cements" U.S. Department of Energy, Washington, D.C. under Contract No. DE-AC02-76CH00016 (Undated).
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T. Sugama, et al., "Mullite Microsphere-Filled Lightweight Calcium Phosphate Cement Slurries for Geothermal Wells: Setting and Properties", *Cement and Concrete Research Journal*, vol. 25, No. 6. pp. 1305-1310 (1995).

Note: As explained in Section 3.6, the search of patents citing papers/publications as priority documents is difficult and resource intensive. It was not feasible to conduct a search of patents citing the more than 3,000 publications sponsored by DOE in this field. Furthermore, this approach would have missed scientific papers that were not included in the OSTI database. Thus, this list of scientific papers/publications was compiled from a review of DOE reports that described the DOE Geothermal Technologies Program and in that context listed important papers and publications. In some cases, incomplete references were provided. In the case of the reference to the 1992 paper by Sugama, listed above, an incomplete reference was provided and the paper was not located in the OSTI database, but it was found to be heavily cited by subsequent patents.

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