The Influence of Propulsion and Lightweight Materials Patents Funded by the U.S. Department of Energy's Vehicle Technologies Office and other DOE Offices

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Executive Summary

This report describes the results of an analysis tracing the technological influence of propulsion and lightweight materials research funded by the Vehicle Technologies Office (VTO) in the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) and its precursor programs – as well as propulsion and lightweight materials research funded by other offices in DOE. In this report, propulsion materials and lightweight materials are considered to be separate technologies. Each is analyzed individually, and the report contains separate results sections for the two technologies.

The influence tracing in this report is carried out both backwards and forwards in time, and focuses on patents filed in three systems: the U.S. Patent & Trademark Office (U.S. patents); the European Patent Office (EPO patents); and the World Intellectual Property Organization (WIPO patents). The primary period covered in this analysis is 1976 to 2018.

The main purpose of the backward tracing is to determine the extent to which VTO-funded propulsion/lightweight materials research has formed a foundation for innovations patented by leading propulsion/lightweight materials companies, particularly innovations related to vehicle applications. Meanwhile, the primary purpose of the forward tracing is to examine the broader influence of VTO-funded propulsion/lightweight materials research upon subsequent technological developments, both within and outside propulsion/lightweight materials technology. In addition to these VTO-based analyses, we also extend many elements of the analysis to other DOE-funded propulsion/lightweight materials patents, in order to gain insights into their influence.

Propulsion Materials

The main finding from the propulsion materials element of this report is:

- DOE-funded patenting in propulsion materials technology has increased over time, with VTO-funded patents representing a growing percentage of the total. While the portfolios of VTO-funded and Other DOE-funded propulsion materials patents are much smaller than those of the leading companies in this technology, their influence can be seen on innovations associated with these companies, notably in exhaust treatment. The influence of VTO-funded and Other DOE-funded propulsion materials patents also extends beyond the immediate technology to other areas such as earth drilling and advanced materials (with such materials not necessarily being restricted to propulsion applications).

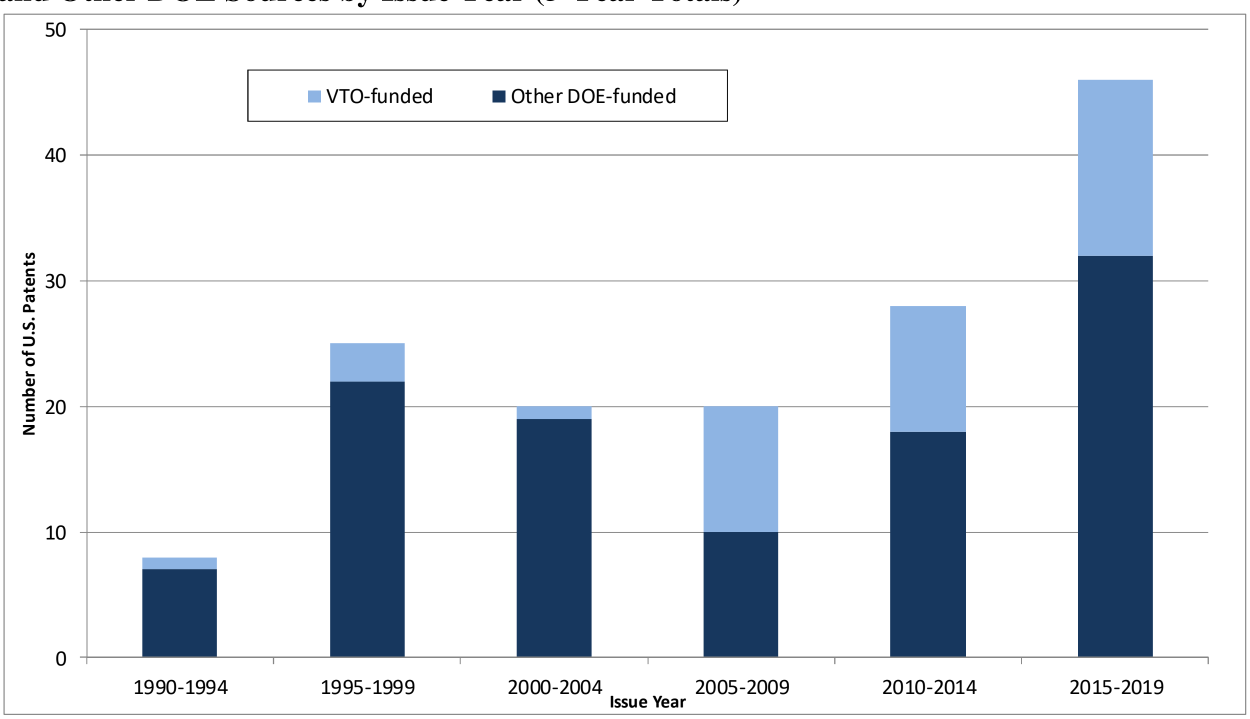
More detailed findings from the propulsion materials element of this report include:

- In propulsion materials technology, in the period 1976-2018, we identified a total of 31,053 patents (12,433 U.S. patents, 9,937 EPO patents and 8,683 WIPO patents) directed to vehicle applications. We grouped these patents into 19,791 patent families, where each family contains all patents resulting from the same initial application (named the priority application).

- 56 propulsion materials patents are confirmed to be associated with VTO funding (39 U.S. patents, 8 EPO patents, and 9 WIPO patents). We grouped these VTO-funded propulsion materials patents into 28 patent families.

- In addition, we identified a further 138 propulsion materials patents (108 U.S. patents, 12 EPO patents and 18 WIPO patents) that are associated with DOE funding. These "Other DOE-funded" patents are grouped into 86 patent families.
- Out of these 86 Other DOE-funded patent families, 57 are definitely not VTO-funded. These patent families were either funded by a different DOE office, or were marked as being not VTO-funded by inventors or VTO technology managers, but without specifying funding from another DOE source.
- The remaining 29 Other DOE-funded propulsion materials patent families could not be linked definitively to a specific DOE funding source, and may in fact have been funded by VTO. Hence, up to 33.7% (29 out of 86) of the Other DOE-funded propulsion materials patent families in this analysis may be VTO-funded. As such, the results in this report may understate the influence of VTO-funded propulsion materials research, relative to the influence of propulsion materials research funded by DOE in general.
- The total number of DOE-funded propulsion materials patents (VTO-funded plus Other DOE-funded) is 194, corresponding to 114 patent families. This represents 0.6% of the total number of propulsion materials patent families in the period 1976-2018.
- Figure PRL-E1 shows the number of DOE-funded propulsion materials granted U.S. patents.

Figure PRL-E1 - Number of Propulsion Materials Granted U.S. Patents Funded by VTO and Other DOE Sources by Issue Year (5-Year Totals)



Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

- Figure PRL-E1 reveals that the first such patents were issued in in the early 1990s, with a total of seven issued in 1990-1994 (one of which was funded by VTO). The number of DOE-funded propulsion materials patents then increased to 25 in 1995-1999 (three of which were funded by VTO), before falling to 20 in both 2000-2004 and 2005-2009. Half of the patents in the latter time period were funded by VTO. There was then an increase in DOE-funded propulsion materials patents, to 28 in 2010-2014 (10 funded by VTO) and 46 in 2015-2019 (14 funded by VTO).

- The ten companies with the largest number of propulsion materials patent families directed to vehicle applications are: Toyota (2,466 families); Ford (788); BASF (629); General Motors (560); Porsche (544); Bosch (495); Johnson Matthey (461); Honda (412); Continental (403); and Nissan (388). Five of these companies are based in Europe, three in Asia and two in the United States. The portfolio of 114 DOE-funded propulsion materials patent families is much smaller than those of these leading companies.

- VTO-funded propulsion materials patents have a particular focus on exhaust treatment technologies, with a somewhat lesser concentration on alloys and non-metallic elements. The leading companies share the focus on exhaust treatment, but have less emphasis on the other areas where VTO-funded patents are concentrated

- On average, each DOE-funded propulsion materials patent family is linked via citations to 3.5 patent families assigned to the leading companies. This puts DOE among a cluster of leading companies with similar averages – from Johnson Matthey in second place (4.1) down to Porsche in eighth (3.3) – all behind Nissan (6.3). As such, taking into account its relatively small size, the portfolio of DOE-funded propulsion materials patents has had a notable influence on propulsion materials research carried out by the leading companies.

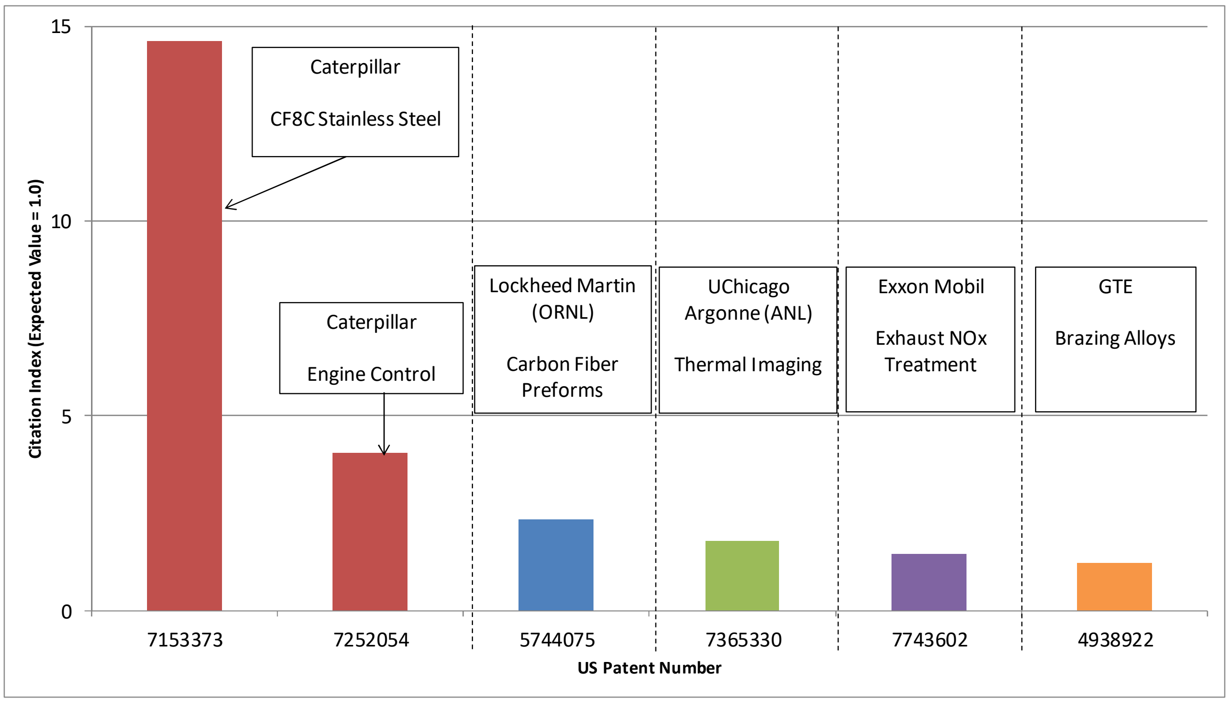
- Among the leading companies, patents assigned to BASF, Ford and General Motors are linked most extensively via citations to earlier VTO-funded and Other DOE-funded patent families. The influence of DOE-funded propulsion materials patents on the leading companies is particularly strong in exhaust treatment technologies.

- VTO-funded propulsion materials patents have an average Citation Index of 1.37 (the Citation Index is a normalized citation metric with an expected value of 1.0; a value of 1.37 shows that, based on their age and technology, VTO-funded propulsion materials patents have been cited as prior art 37% more frequently than expected by subsequent patents). This places VTO-funded patents in third place among the leading companies, behind only BASF and Johnson Matthey. The Citation Index for Other DOE-funded propulsion materials patents is lower at 0.87, showing that these patents have been cited 13% less frequently than expected.

- The forward tracing element of the analysis reveals that the influence of VTO-funded and Other DOE-funded propulsion materials research can be seen across a range of technologies, including earth drilling, brazing and advanced materials (with such materials not necessarily being restricted to propulsion applications).

- There are a number of individual high-impact VTO-funded propulsion materials patents, examples of which are shown in Figure PRL-E2. They include a Caterpillar patent (US #7,153,373) issued in 2006 that describes a stainless steel alloy (named CF8C). This patent has been cited as prior art by 141 subsequent patents, almost fifteen as many citations as expected. Many of these citations are from patents describing earth drilling applications. This figure also includes a second Caterpillar patent (US #7,252,054) describing a method for controlling a combustion engine. It also includes a number of other patents outlining various technologies, including carbon fibers, thermal imaging, exhaust treatment and brazing alloys.

Figure PRL-E2 – Examples of Highly-Cited VTO-funded Propulsion Materials Patents



Lightweight Materials

The main finding from the lightweight materials element of this report is:

- DOE-funded patenting in lightweight materials increased throughout the period examined, with VTO-funded patents representing a growing percentage of the total. There appears to be little overlap between VTO-funded and Other DOE-funded lightweight materials patents and the patents assigned to the leading companies. The former focus on advanced materials, while the latter concentrate on specific vehicle applications. This is borne out by evaluating the backward and forward tracing elements of the analysis in tandem. These analyses suggest that VTO-funded and Other DOE-funded lightweight materials research have had a significant influence on the advancement of materials technology, with these materials not necessarily restricted to vehicle applications. Their influence has been less extensive on patents related to the application of lightweight materials specifically in vehicles (although automotive companies may have used materials developed with DOE funding in production, without necessarily patenting their use in this application).

More detailed findings from the lightweight materials element of this report include:

- In lightweight materials technology, in the period 1976-2018, we identified a total of 31,613 patents (13,712 U.S. patents, 9,797 EPO patents and 8,104 WIPO patents) directed to vehicle applications. We grouped these patents into 22,694 patent families, with each family containing all patents related to the same underlying invention.

- 86 lightweight materials patents are confirmed to be associated with VTO funding (65 U.S. patents, 7 EPO patents, and 14 WIPO patents). We grouped these VTO-funded lightweight materials patents into 49 patent families.

- In addition, we identified a further 64 lightweight materials patents (43 U.S. patents, 9 EPO patents and 12 WIPO patents) that are associated with DOE funding. These "Other DOE-funded" patents are grouped into 37 patent families.

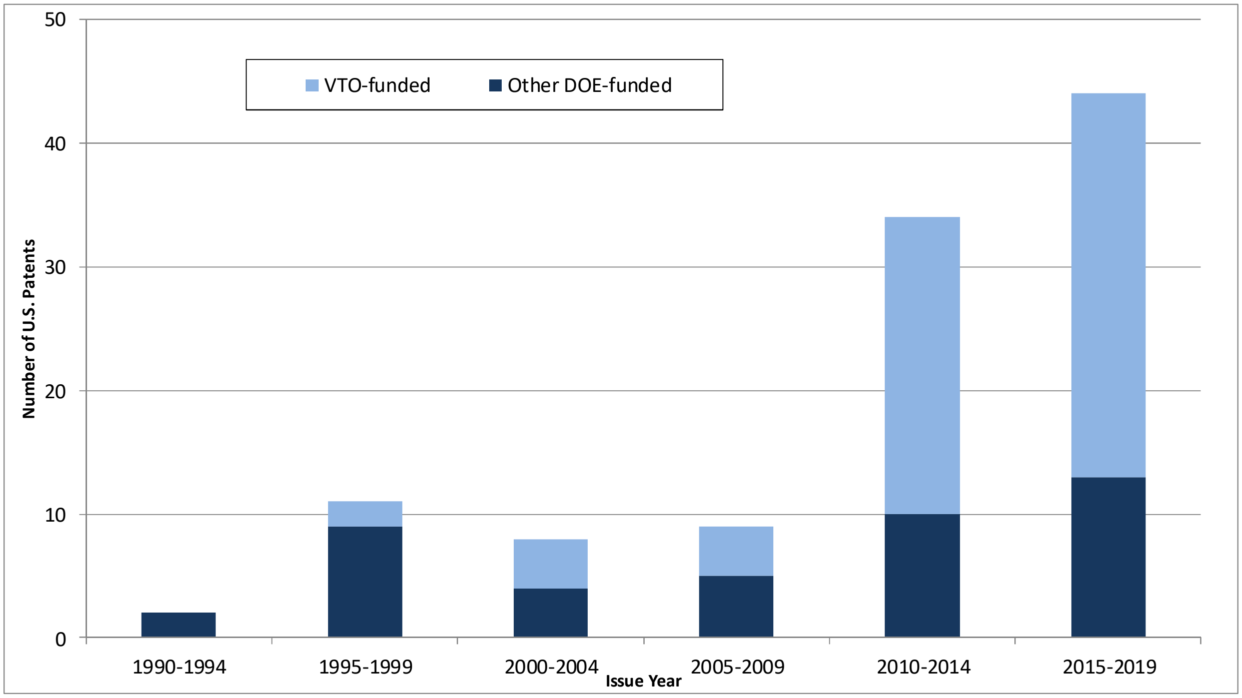
- Out of the 37 Other DOE-funded patent families, 29 are definitely not VTO-funded. These patent families were either funded by a different DOE office, or were marked as being not VTO-funded by inventors or VTO technology managers, but without specifying funding from another DOE source.

- The remaining eight Other DOE-funded lightweight materials patent families could not be linked definitively to a specific DOE funding source, and may in fact have been funded by VTO. Hence, up to 21.6% (8 out of 37) of the Other DOE-funded lightweight materials patent families in this analysis may be VTO-funded. As such, the results presented may understate the influence of VTO-funded lightweight materials research, relative to the influence of lightweight materials research funded by DOE in general.

- The total number of DOE-funded lightweight materials patents (VTO-funded plus Other DOE-funded) is 150, corresponding to 86 patent families. This represents 0.4% of the total number of lightweight materials patents families in the period 1976-2018.

- Figure LWM-E1 shows the number of lightweight materials granted U.S. patents funded by DOE. There is relatively little patent activity in the earlier time periods, with many of the patents defined as Other DOE-funded. Patenting has increased over time, particularly from 2010 onwards, with VTO-funded patents representing an increasing percentage of the overall number. In 2010-2014, there were 34 DOE-funded lightweight materials U.S. patents granted, 24 of which were VTO-funded. The number increased again in 2015-2019 to 44 DOE-funded U.S. patents, 31 of which were VTO-funded, even though data from this period are incomplete (see note below figure).

Figure LWM-E1 - Number of Lightweight Materials Granted U.S. Patents Funded by VTO and Other DOE Sources by Issue Year (5-Year Totals)



Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

- The ten companies with the largest number of lightweight materials patent families directed to vehicle applications are: Honda (1,187 families); Toyota (1,041); Ford (932); Porsche (918); General Motors (763); Daimler (607); Groupe PSA (606); Nissan (526); Mazda (442) and Renault (441). Four of these of these companies are based in Asia, four in Europe and two in the United States. The portfolio of 86 DOE-funded lightweight materials patent families is much smaller than those of these leading companies.

- UT-Battelle, through its management of Oak Ridge National Laboratory (ORNL), is by far the most prolific VTO-funded assignee in lightweight materials, with 25 patent families. This suggests that ORNL is an important center for VTO-funded research in this technology.

- The technological focus of VTO-funded and Other DOE-funded lightweight materials patents is very different to the focus of the patents assigned to the leading companies. Specifically, while the DOE-funded portfolios concentrate on advanced materials (e.g. carbon fibers and plastics), plus handling of these materials (e.g. soldering and welding), the patents of the leading companies focus more on practical applications of such materials in vehicle parts and structural elements.

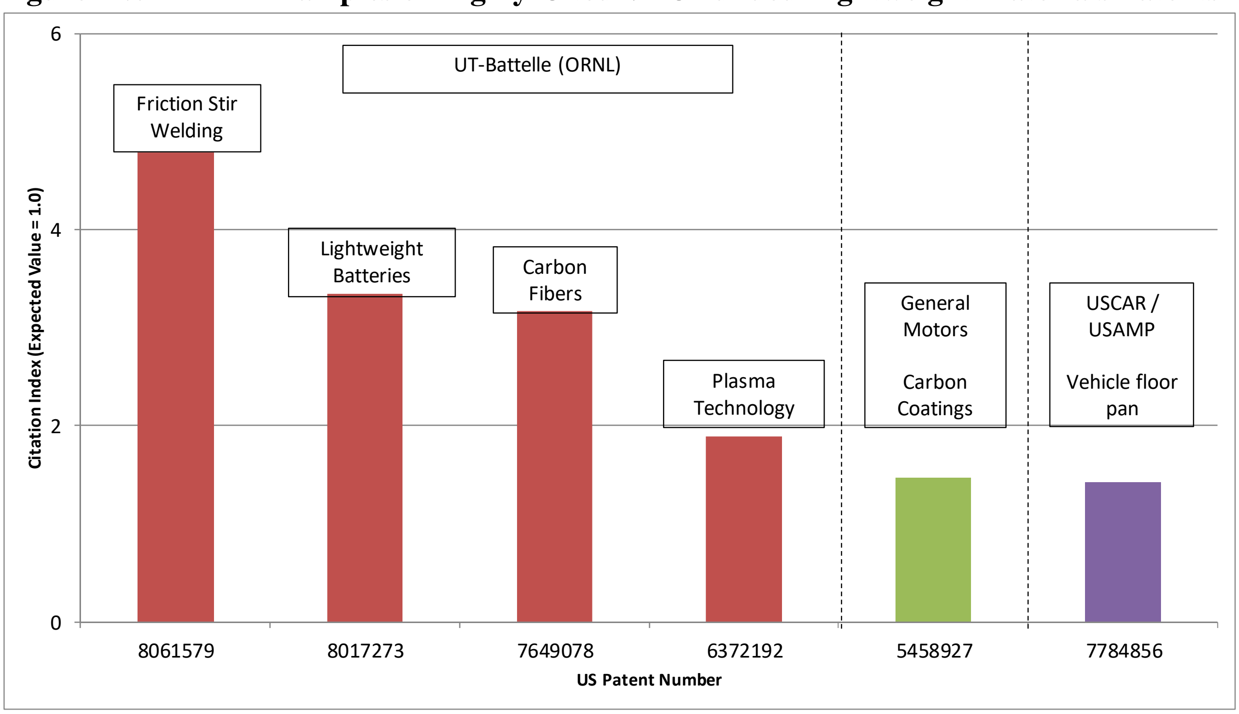
- This difference in focus is reflected in the fact that only ten lightweight materials patent families assigned to the leading companies are linked via citations to earlier DOE-funded lightweight materials patents (nine to VTO, one to Other DOE).

- VTO-funded lightweight materials patents have an average Citation Index of 1.06 (the Citation Index is a normalized citation metric with an expected value of 1.0; a value of 1.06 shows that, based on their age and technology, VTO-funded lightweight materials patents have been cited as prior art 6% more frequently than expected by subsequent patents). The Citation Index for Other DOE-funded lightweight materials patents is slightly higher at 1.11 (i.e. 11% more citations than expected). This puts both DOE-funded portfolios among the middle group of leading companies in terms of Citation Index values.

- Referring to the backward tracing results, the VTO-funded and Other DOE-funded had very few citation links to subsequent patents assigned to the leading companies. Yet their Citation Index values (which are based on citations from all patents) are above average, albeit marginally. The forward tracing element of the analysis reveals that the influence of VTO-funded and Other DOE-funded lightweight materials research can be seen across a range of technologies, notably semiconductors and advanced materials (with such materials not necessarily being restricted to automotive applications).

- There are a number of individual high-impact VTO-funded lightweight materials patents, examples of which are shown in Figure LWM-E2. They include a series of UT-Battelle (ORNL) patents covering various technologies such as friction stir welding (US #8,061,579), lightweight lead-acid batteries (US #8,017,273) and carbon fibers (US #7,649,078). They also include a General Motors patent (US #5,458,927) for carbon coatings, and a USCAR/USAMP patent (US #7,784,856) for vehicle floor pans.

Figure LWM-E2 – Examples of Highly-Cited VTO-funded Lightweight Materials Patents



1. Introduction

This report focuses on propulsion materials and lightweight materials.[1] Its objective is to trace the technological influence of propulsion/lightweight materials research funded by the Vehicle Technologies Office (VTO) in the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) and its precursor programs – as well as propulsion/lightweight materials research funded by other offices in DOE. The purpose of the report is to:

(i) Locate patents awarded for key VTO-funded (and Other DOE-funded) innovations in propulsion/lightweight materials technologies; and
(ii) Determine the extent to which VTO-funded (and Other DOE-funded) propulsion/lightweight materials research has influenced subsequent technological developments both within and beyond propulsion/lightweight materials.

The primary focus of the report is on the influence of VTO-funded propulsion/lightweight materials patents. That said, we also extend many elements of the analysis to DOE-funded propulsion/lightweight materials patents that could not be definitively linked to VTO funding. There are both evaluative and practical reasons for extending the analysis in this way. From an evaluation perspective, it is interesting to examine the influence of VTO itself upon the development of propulsion/lightweight materials technologies, while also tracing the influence of DOE more generally. Meanwhile, in practical terms, determining which patents were funded by VTO, versus other offices within DOE, is often very difficult.

In the U.S. patent system, applicants are required to acknowledge any government funding they have received related to the invention described in their patent application. Typically, this government support is listed at the level of the agency (e.g. Department of Energy, Department of Defense, etc.). Hence, the only way to determine which office within DOE funded a given patent is via other data resources (e.g. iEdison), or through direct input from offices, program managers and individual inventors. For older patents, such information is often unavailable, because records may be less comprehensive, and there is less access to the inventors and program managers involved.

Rather than discard patents confirmed as DOE-funded, but that could not be definitively categorized as VTO-funded, we instead included these patents in the analysis under a separate "Other DOE-funded" category. Some of these Other DOE-funded patents are confirmed as being linked to funding from other DOE offices, while for others the source of funding within DOE is unknown. Many of these "unknown" patents may in fact have been funded by VTO, although a definitive link could not be established. Hence, the results reported here may underestimate the influence of VTO-funded propulsion/lightweight materials research, relative to the influence of propulsion/lightweight materials research funded by the rest of DOE.

[1] In this report, propulsion materials and lightweight materials are considered to be separate technologies. Each is analyzed individually, and the report contains separate results sections for the two technologies. That said, we use the shorthand "propulsion/lightweight materials" in the Introduction, Project Design and Methodology sections of the report, rather than referring repeatedly to the more cumbersome "propulsion materials and lightweight materials".

This report contains three main sections. The first of these sections describes the project design. This section includes a brief overview of patent citation analysis, and outlines its use in the multi-generation tracing employed in this project. The second section outlines the methodology, and includes a description of the various data sets used in the analysis, and the processes through which these data sets were constructed and linked.

The third section presents the results of our analysis. This section is divided into two sub-sections, the first containing the findings related to propulsion materials, and the second containing findings related to lightweight materials. Within each sub-section, results are presented at the organizational level for both VTO-funded and Other DOE-funded patents. These results show the distribution of VTO-funded (and Other DOE-funded) patents across propulsion/lightweight materials technologies (as defined by Cooperative Patent Classifications). They also evaluate the extent of VTO's influence (and DOE's influence in general) on subsequent developments in propulsion/lightweight materials and other technologies. Patent level results are then presented to highlight individual VTO-funded propulsion/lightweight materials patents that have been particularly influential, as well as to reveal key patents from other organizations that build extensively on VTO-funded propulsion/lightweight materials research.[2]

2. Project Design

This section of the report outlines the project design. It begins with a brief overview of patent citation analysis, which forms the basis for much of the evaluation presented in this report. This overview is followed by a description of the techniques used to link the various patent sets in the analysis, along with a listing and description of the metrics employed in the study.

The analysis described in this report is based largely upon tracing citation links between successive generations of patents. This tracing is carried out both backwards and forwards in time. The primary purpose of the backward tracing is to determine the extent to which technologies developed by leading companies in the propulsion/lightweight materials industries used VTO-funded research as a foundation. Meanwhile, the primary purpose of the forward tracing is to examine how VTO-funded propulsion/lightweight materials patents influenced subsequent technological developments more broadly, both within and outside propulsion/lightweight materials technologies. Many elements of both the backward and forward tracing are also extended to the Other DOE-funded patents, in order to trace their influence, both overall and upon the leading propulsion/lightweight materials companies.[3]

[2] This is one of a series of similar reports examining research portfolios across a range of DOE offices. Note that the results are not designed to be compared across portfolios, for example in terms of numbers of patents granted, number of citations received etc. The portfolios have very different profiles with respect to research risks, funding levels and time periods covered, plus there are wide variations in the propensity to patent across technologies. Hence, the results reported in the various reports should not be used for comparative analyses across portfolios.

[3] The analyses described in this report were carried out separately for VTO-funded propulsion/lightweight materials patents and Other DOE-funded propulsion/lightweight materials patents. However, referring repeatedly to "VTO-funded/Other DOE-funded patents" or "VTO-funded/Other DOE-funded research" in describing the analyses is lengthy, so we instead use the collective terms "DOE-funded patents" and "DOE-funded research" in the Project Design and Methodology sections of the report.

Our analysis covers patents filed in three systems: the U.S. Patent & Trademark Office (U.S. patents); the European Patent Office (EPO patents); and the World Intellectual Property Organization (WIPO patents). By covering multiple generations of citations across patent systems, our analysis allows for a wide variety of possible linkages between DOE-funded propulsion/lightweight materials research and subsequent technological developments. Examining all of these linkage types at the level of entire technologies involves a significant data processing effort, and requires access to specialist citation databases, such as those maintained at 1790 Analytics. As a result, this project is more ambitious than many previous attempts to trace through multiple generations of research, which have often been based on studying very specific technologies or individual products.

Patent Citation Analysis

In many patent systems, patent documents contain a list of references to prior art. The purpose of these prior art references is to detail the state of the art at the time of the patent application, and to demonstrate how the new invention is original over and above this prior art. Prior art references may include many different types of public documents. A large number of the references are to earlier patents, and these references form the basis for this study. Other references (not covered in this study) may be to scientific publications and other types of documents, such as technical reports, magazines and newspapers.

The responsibility for adding prior art references differs across patent systems. In the U.S. patent system, it is the duty of patent applicants to reference (or "cite") all prior art of which they are aware that may affect the patentability of their invention. Patent examiners may then reference additional prior art that limits the claims of the patent for which an application is being filed. In contrast to this, in patents filed at the European Patent Office (EPO) and World Intellectual Property Organization (WIPO), prior art references are added solely by the examiner, rather than by both the applicant and examiner. The number of prior art references on EPO and WIPO patents thus tends to be much lower than the number on U.S. patents.[4]

Patent citation analysis focuses on the links between generations of patents that are made by these prior art references. In simple terms, this type of analysis is based upon the idea that the prior art referenced by patents has had some influence, however slight, upon the development of these patents. The prior art is thus regarded as part of the foundation for the later inventions.

In assessing the influence of individual patents, citation analysis centers on the idea that highly cited patents (i.e. those cited by many later patents) tend to contain technological information of particular interest or importance. As such, they form the basis for many new innovations and research efforts, and so are cited frequently by later patents. While it is not true to say that every highly cited patent is important, or that every infrequently cited patent is necessarily trivial, many research studies have shown a correlation between patent citations and measures of

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[4] Note that this analysis does not cover patents from other systems, notably patents from the Chinese, Japanese and Korean patent offices. This is because patents from these systems do not typically list any prior art. Hence, it is not possible to use citation links to trace the influence of DOE research on patents from these systems. Having said this, Chinese, Japanese and Korean organizations are among the most prolific applicants in the WIPO system. Our analysis thus picks up the role of organizations from these countries via their WIPO filings.

technological and economic importance. For background on the use of patent citation analysis, including a summary of validation studies supporting its use, see: Breitzman A. & Mogee M. "The many applications of patent analysis", *Journal of Information Science*, 28(3), 2002, 187-205; and Jaffe A. & de Rassenfosse G. "Patent Citation Data in Social Science Research: Overview and Best Practices", NBER Working Paper No. 21868, January 2016.

Patent citation analysis has also been used extensively to trace technological developments over time. For example, in the analysis presented in this report, we use citations from patents to earlier patents to trace the influence of DOE-funded propulsion/lightweight materials research. Specifically, we identify cases where patents cite DOE-funded propulsion/lightweight materials patents as prior art. These represent first-generation links between DOE-funded patents and subsequent technological developments. We also identify cases where patents cite patents that in turn cite DOE-funded propulsion/lightweight materials patents. These represent second-generation links between technological developments and DOE-funded research.

The idea behind this analysis is that the later patents have built in some way on the earlier DOE-funded propulsion/lightweight materials research. By determining how frequently DOE-funded propulsion/lightweight materials patents have been cited by subsequent patents, it is thus possible to evaluate the extent to which DOE-funded research forms a foundation for various technologies both within and beyond propulsion/lightweight materials.

Backward and Forward Tracing

As noted above, the purpose of this analysis is to trace the influence of DOE-funded propulsion/lightweight materials research upon subsequent developments both within and beyond propulsion/lightweight materials technologies. There are two approaches to such a tracing study – backward tracing and forward tracing – each of which has a slightly different objective.

Backward tracing, as the name suggests, looks backwards over time. The idea of backward tracing is to take a particular technology, product, or industry, and to trace back to identify the earlier technologies upon which it has built. In the context of this project, we first identify the leading propulsion/lightweight materials organizations in terms of patent portfolio size. We then trace backwards from the patents owned by these organizations. This makes it possible to determine the extent to which innovations associated with these leading propulsion/lightweight materials organizations build on earlier VTO-funded and Other DOE-funded research.

The idea of forward tracing is to take a given body of research, and to trace the influence of this research upon subsequent technological developments. In the context of the current analysis, forward tracing involves identifying all propulsion/lightweight materials patents resulting from research funded by DOE (i.e. VTO plus Other DOE). The influence of these patents on later generations of technology is then evaluated. This tracing is not restricted to subsequent propulsion/lightweight materials patents, since the influence of a body of research may extend beyond its immediate technology. Hence, the purpose of the forward tracing element of this project is to determine the influence of DOE-funded propulsion/lightweight materials patents upon developments both inside and outside these technologies.

Tracing Multiple Generations of Citation Links

The simplest form of tracing study is one based on a single generation of citation links between patents. Such a study identifies patents that cite, or are cited by, a given set of patents as prior art. The analysis described in this report extends the tracing by adding a second generation of citation links.[5]

The backward tracing starts with patents assigned to the leading patenting organizations in propulsion/lightweight materials technologies. The first generation contains the patents that are cited as prior art by these starting patents. The second generation contains patents that are in turn cited as prior art by these first generation patents. In other words, the backward tracing starts with propulsion/lightweight materials patents owned by leading organizations in these technologies, and traces back through two generations of earlier patents to identify the technologies upon which they were built, including those funded by DOE.

The forward tracing starts with DOE-funded patents in propulsion/lightweight materials technologies. The first generation contains the patents that cite these DOE-funded patents as prior art. The second generation contains the patents that in turn cite these first-generation patents. In other words, the analysis starts with DOE-funded propulsion/lightweight materials patents and traces forward for two generations of subsequent patents.

This means that we trace forward through two generations of citations starting from DOE-funded propulsion/lightweight materials patents; and backward through two generations starting from the patents owned by leading propulsion/lightweight materials organizations. Hence there are two types of links between DOE-funded patents and subsequent generations of patents:

1. **Direct Links**: where a patent cites a DOE-funded propulsion/lightweight materials patent as prior art.

2. **Indirect Links**: where a patent cites an earlier patent, which in turn cites a DOE-funded propulsion/lightweight materials patent. The DOE patent is thus linked indirectly to the subsequent patent.

The idea behind adding the second generation of citations is that agencies such as DOE often support basic scientific research. It may take time, and numerous generations of research, for this basic research to be used in an applied technology, for example that described in a patent owned by a leading company. Introducing a second generation of citations provides greater access to these indirect links between basic research and applied technology.

One potential problem with adding generations of citations must be acknowledged. Specifically, if one uses enough generations of links, eventually almost every node in the network will be linked. This is a problem common to many networks, whether these networks consist of people,

[5] As noted above, the forward and backward tracing were carried out separately for VTO-funded and Other DOE-funded propulsion/lightweight materials patents. The references in this section to "DOE patents" are shorthand, and do not mean that the tracing was carried out for all DOE-funded propulsion/lightweight materials patents as a single portfolio.

institutions, or scientific documents, as in this case. 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, almost all patents will be linked to this starting set. Hence, while including a second generation of citations provides insights into indirect links between basic research and applied technologies, adding further generations may bring in too many patents with little connection to the starting patent set.

Constructing Patent Families

The coverage of a patent is limited to the jurisdiction of its issuing authority. For example, a patent granted by the U.S. Patent & Trademark Office (a 'U.S. patent') provides protection only within the United States. If an organization wishes to protect an invention in multiple countries, it must file patents in each of those countries' systems. For example, a company may file to protect a given invention in the U.S., China, Germany, Japan and many other countries. This would result in multiple patent documents for the same invention.[6] In addition, in some systems – notably the U.S. – inventors may apply for a series of patents based on the same underlying invention.

In the case of this study, one or more U.S., EPO and WIPO patents may result from a single invention. To avoid counting the same inventions multiple times, it is necessary to construct "patent families". A patent family contains all of the patents and patent applications that result from the same original patent application (named the "priority application"). A family may include patents from multiple countries, and also multiple patents from the same country. In this project, we constructed patent families for DOE-funded propulsion/lightweight materials patents, and also for the patents owned by leading propulsion/lightweight materials organizations. We also assembled families for all patents linked via citations to DOE-funded propulsion/lightweight materials patents.

To construct these patent families, we matched the priority documents of the U.S., EPO and WIPO patents, in order to group them into the appropriate families. 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, which are grouped in the same patent family because they share the same Japanese priority document.

Metrics Used in the Analysis

Table 2-1 contains a list of the metrics used in the analysis. These metrics are divided into three main groups – technology landscape metrics (trends, assignees, and technology distributions), backward tracing metrics, and forward tracing metrics. Findings for each of these three groups of metrics can be found in the Results section of the report.

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[6] It also means that patents from a given country's system are not synonymous with inventions made in that country. Indeed, roughly half of all U.S. patent applications are from overseas inventors.

Table 2-1 – List of Metrics Used in the Analysis

Metric
Trends
• Number of VTO/Other DOE-funded propulsion/lightweight materials patent families by year of priority application
• Number of VTO/Other DOE-funded granted U.S. propulsion/lightweight materials patents by issue year
• Overall number of propulsion/lightweight materials patent families by priority year
• Percentage of propulsion/lightweight materials patents families funded by VTO/Other DOE by priority year
Assignee Metrics
• Number of propulsion/lightweight materials patent families for leading patenting organizations
• Assignees with largest number of propulsion/lightweight materials patent families funded by VTO/Other DOE
Technology Metrics
• Patent classification (CPC) distribution for VTO-funded propulsion/lightweight materials patent families (vs Other DOE-funded, leading propulsion/lightweight materials companies, all propulsion/lightweight materials)
Backward Tracing Metrics
• Total/Average number of leading company propulsion/lightweight materials patent families linked via citations to earlier patent families from VTO/Other DOE and other leading companies
• Number of propulsion/lightweight materials patent families for each leading company linked via citations to earlier VTO/Other DOE-funded patent families
• Total citation links from each leading company to VTO/Other DOE-funded patent families
• Percentage of leading company propulsion/lightweight materials patent families linked via citations to earlier VTO/Other DOE-funded patent families
• VTO/Other DOE-funded propulsion/lightweight materials patent families linked via citations to largest number of leading company propulsion/lightweight materials patent families
• Leading company propulsion/lightweight materials patent families linked via citations to largest number of VTO-funded propulsion/lightweight materials patent families
• Highly cited leading company propulsion/lightweight materials patent families linked via citations to earlier VTO-funded propulsion/lightweight materials patent families
Forward Tracing Metrics
• Citation Index for propulsion/lightweight materials patent portfolios owned by leading companies, plus portfolios of VTO/Other DOE-funded propulsion/lightweight materials patents
• Number of patent families linked via citations to VTO/Other DOE-funded propulsion/lightweight materials patents by patent classification
• Organizations (beyond leading propulsion/lightweight materials companies) linked via citations to largest number of VTO/Other DOE funded propulsion/lightweight materials patent families
• Highly cited VTO-funded propulsion/lightweight materials U.S. patents
• VTO/Other DOE-funded propulsion/lightweight materials patent families linked via citations to largest number of subsequent propulsion/lightweight materials/non-propulsion/lightweight materials patent families
• Highly cited patents (not owned by leading companies) linked via citations to earlier VTO-funded propulsion/lightweight materials patents families

3. Methodology

The previous section of the report outlines the objective of our analysis – that is, to determine the influence of VTO-funded (and Other DOE-funded) propulsion/lightweight materials research on subsequent developments both within and outside propulsion/lightweight materials technologies. This section of the report describes the methodology used to implement the analysis. Particular emphasis is placed on the processes employed to construct the various data sets required for the analysis. Specifically, the backward tracing starts from the set of all propulsion/lightweight materials patents owned by leading patenting organizations in these technologies. Meanwhile, the forward tracing starts from the sets of propulsion/lightweight materials patents funded by VTO and Other DOE. We therefore had to define these various data sets – VTO-funded propulsion/lightweight materials patents; Other DOE-funded propulsion/lightweight materials patents; and propulsion/lightweight materials patents assigned to the leading organizations in these technologies.

Identifying VTO-funded and Other DOE-funded Propulsion/Lightweight Materials Patents

The objective of this analysis is to trace the influence of propulsion/lightweight materials research funded by VTO (plus propulsion/lightweight materials research funded by the remainder of DOE) upon subsequent developments both within and outside propulsion/lightweight materials technologies. Outlined below are the three steps used to identify VTO-funded and Other DOE-funded propulsion/lightweight materials patents. These three steps are:

(i) Defining the universe of DOE funded patents;

(ii) Determining which of these DOE funded patents are relevant to propulsion/lightweight materials; and

(iii) Categorizing these DOE-funded propulsion/lightweight materials patents according to whether or not they can be linked definitively to VTO funding.

Defining the Universe of DOE-Funded Patents

Identifying patents funded by government agencies is often more difficult than locating 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.

Constructing a patent list for a government agency is more complicated, because the agency may fund research carried out at many different organizations. For example, DOE operates seventeen national laboratories. Patents emerging from these laboratories may be assigned to DOE. However, they may also be assigned to the organization that manages a given laboratory. For example, many patents from Sandia National Laboratory are assigned to Lockheed Martin

(Sandia's former lab manager), while many Lawrence Livermore National Laboratory patents are assigned to the University of California. Lockheed Martin and the University of California are large organizations with many interests beyond managing DOE labs, so one cannot simply take all of their patents and define them as DOE-funded.

A further complication is that DOE does not only fund research in its own labs and research centers, it also funds extramural research carried out by other organizations. If this research results in patented inventions, these patents are likely to be assigned to the organizations carrying out the research, rather than to DOE.

We therefore constructed a database containing all DOE-funded patents. These include patents assigned to DOE itself, and also patents assigned to individual labs, lab managers, and other organizations and companies funded by DOE. This "All DOE" patent database was constructed using a number of sources:

1. ***DOEPatents Database*** – The first source is a database of DOE-funded patents put together by DOE's Office of Scientific & Technical Information (OSTI), and available on the web at www.osti.gov/doepatents/. This database contains information on research grants provided by DOE. It also links these grants to the organizations or DOE labs that carried out the research, the sponsor organization within DOE, and the patents that resulted from these DOE grants.

2. ***iEdison Database*** – EERE staff provided us with an output from the iEdison database, which is used by government grantees and contractors to report government-funded subject inventions, patents, and utilization data to the government agency that issued the funding award.

3. ***Visual Patent Finder Database*** – EERE also provided us with an output from its Visual Patent Finder tool. This tool takes DOE-funded patents and clusters them based on word occurrence patterns. In our case, the output was a flat file containing DOE-funded patents.

4. ***Patents assigned to DOE*** – in the USPTO database, we identified a small number of U.S. patents assigned to DOE itself that were not in the any of the sources above. These patents were added to the list of DOE patents.

5. ***Patents with DOE Government Interest*** – A U.S. patent has on its front page a section entitled 'Government Interest', which details the rights that the government has in a 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. We identified all patents that refer to 'Department of Energy' or 'DOE' in their Government Interest field, including different variants of these strings. We also identified patents that refer to government contracts beginning with 'DE-' or containing the string '-ENG-'. The former string typically denotes DOE contracts and financial assistance projects, while the latter is a legacy code listed on a number of older DOE-funded patents. We manually checked all of the patents containing these strings that were not

already in any of the sources above, to make sure that they are indeed DOE-funded (e.g. '-ENG-' is also used in a small number of NSF contracts). We then included any additional DOE funded patents in the database.

The "All DOE" patent database constructed from these five sources contains more than 31,000 U.S. patents issued between January 1976 and December 2018 (the end-point of the primary data collection for this analysis).

Identifying DOE-Funded Propulsion/Lightweight Materials Patents

Having defined the universe of DOE-funded patents, the next step was to determine which of these patents are relevant to propulsion/lightweight materials technologies. VTO technology managers supplied a list of patents that they believed VTO had funded in each technology. In addition, they also provided an overview of VTO-funded research areas in both propulsion and lightweight materials. From this overview, and following discussions with VTO technology managers, we designed custom patent filters to identify additional propulsion/lightweight materials patents that may be funded by either VTO or a different office within DOE. These filters consist of a combination of Cooperative Patent Classifications (CPCs) and keywords. Details of the patent filters are shown in Table 3-1.

There are four different filters in Table 3-1, each directed to a different technology area – engine components containing selected materials or alloys; exhaust treatment; vehicle structural elements; and joining dissimilar materials. The first two of these filters are directed primarily to propulsion materials, while the latter two are largely related to lightweight materials. That said, there is some potential overlap between the two groups, for example in certain materials or alloys, or in techniques for handling such materials.

As an initial step, we thus selected all DOE-funded patents that qualified under any of the four filters (i.e. the form of the filter is Filter A OR Filter B OR Filter C or Filter D). This represented the initial combined set of DOE-funded propulsion and lightweight materials patents. We then manually checked each patent in this list against the overview provided by VTO technology managers, and allocated patents to either propulsion materials or lightweight materials based on this review. We also added patents from the original lists supplied by VTO. Note that this manual approach was possible due to the manageable number of patents involved.

Having constructed the draft patent lists, we then sent them to VTO for review. After incorporating feedback from VTO, we constructed the initial lists of propulsion and lightweight materials granted U.S. patents funded by DOE. The propulsion materials list contained 135 patents, while the lightweight materials list contained 98 patents.

Table 3-1 – Filters used to Identify Propulsion/Lightweight Materials Patents

Filter A (Engine Components containing Specific Materials/Alloys)
Cooperative Patent Classification
F02B – Internal combustion engines
F02D – Combustion engine control
F02F – Combustion engine cylinders and pistons
F02M – Combustion engine fuel supply
F02N – Combustion engine starters
F02P – Combustion engine ignition
AND
Cooperative Patent Classification
C22C – Alloys
C22F – Alloy treatment
OR
Title/Abstract
alloy* or nickel* or aluminum* or titanium* or iron* or magnesium* or carbon* or steel*
Filter B (Exhaust Treatment)
Cooperative Patent Classification
B01D 53/92-965 – Engine exhaust gas treatment
F01N 3/08-38 – Engine exhaust gas treatment
F02M 26 – Exhaust gas recirculation
Y02T 10/20-26 – Engine exhaust gas treatment
OR
Cooperative Patent Classification = B60K 13/04 (Engine exhausts) **AND** Title/Abstract = SCR or NOx or cataly*
Filter C (Vehicle Structural Elements)
Cooperative Patent Classification
B60J 5 – Vehicle doors
B62D 21 – Vehicle chassis
B62D 23 – Vehicle frames
B62D 24 – Vehicle frame connections
B62D 25 – Vehicle superstructures
B62D 27 – Vehicle superstructure connections
B62D 29 – Vehicle superstructure materials
B62D 31 – Vehicle superstructures
B62D 39 – Miscellaneous vehicle bodies
OR
Title/Abstract
((vehicle* or automobile*) **AND** (body or bodies or chassis or frame* or structure* or door* or panel*) **AND** (aluminum* or magnesium* or carbon* or steel* or light(-)weight* or ((lower* or reduc* or less*) +-3words weigh*))) **NOT** (CPC=B61 (Railways) or B63 (Boats) or B64 (Aircraft) or Title/Abstract=rail* or train* or boat* or ship* or air(-)plane* or air(-)craft*)
Filter D (Joining Dissimilar Materials)
Title/Abstract = stir(-)weld*or spot(-)rivet* or bit(-)join* or foil(-)weld*

Defining VTO-funded vs. Other DOE-funded Propulsion/Lightweight Materials Patents

As noted above, linking DOE-funded patents to individual offices is often a difficult task. For this analysis, EERE staff undertook an exhaustive process to determine which of the 135 DOE-funded propulsion materials patents and 98 lightweight materials patents in the initial lists could be linked definitively to VTO funding. This process involved a number of steps, which are listed below:

(i) Linking contract numbers listed in patents to EERE project contract numbers, for financial assistance projects,
(ii) Linking contract numbers listed in patents to EERE SBIR project agreement numbers,
(iii) Asking VTO technology managers to verify individual patents,
(iv) Asking VTO technology managers to send lab patents to lab POCs to get direct verification of these patents,
(v) Contacting individual inventors listed on patents to ask them to confirm whether individual patents were funded by VTO, and
(vi) Locating references to patents in available office annual project progress reports or patent disclosure documents with accomplishments reported by PIs.

Final List of VTO-funded and Other DOE-funded Propulsion/Lightweight Materials Patents

Based on the process described above, we divided the initial lists of DOE-funded propulsion/lightweight materials U.S. patents into two categories – VTO-funded and Other DOE-funded. We then searched for equivalents of each of these patents in the EPO and WIPO systems. An equivalent is a patent filed in a different patent system covering essentially the same invention. We also searched for U.S. patents that are continuations, continuations-in-part, or divisional applications of each of the patents in the final set. We then grouped the patents into families by matching priority documents (see earlier discussion of patent families). Table 3-2 contains a summary of the number of VTO-funded and Other DOE-funded propulsion materials and lightweight materials patents and patent families. Note that, while this analysis covers the period 1976-2018, the earliest DOE-funded patents were not issued until the early 1990s.

Table 3-2 – Number of VTO-funded and Other DOE-funded Propulsion/Lightweight Materials Patents and Patent Families

	# Patent Families	# U.S. Patents	# EPO Patents	# WIPO Patents
Propulsion Materials				
VTO-funded	28	39	8	9
Other DOE-funded	86	108	12	18
Total DOE-funded	114	147	20	27
Lightweight Materials				
VTO-funded	49	65	7	14
Other DOE-funded	37	43	9	12
Total DOE-funded	86	108	16	26

Table 3-2 shows that we identified a total of 28 VTO-funded propulsion materials patent families, containing 39 U.S. patents, eight EPO patents, and nine WIPO patents (see Appendix PRL-A for patent list). We also identified 86 Other DOE-funded propulsion materials patent families, containing 108 U.S. patents, 12 EPO patents, and 18 WIPO patents (see Appendix PRL-B for patent list).

Table 3-2 also shows that we identified a total of 49 VTO-funded lightweight materials patent families, containing 65 U.S. patents, seven EPO patents, and 14 WIPO patents (see Appendix LWM-A for patent list). We also identified 37 Other DOE-funded lightweight materials patent families, containing 43 U.S. patents, nine EPO patents, and 12 WIPO patents (see Appendix LWM-B for patent list).

As noted throughout this report, the approach used to define patents as VTO-funded was very stringent. Hence, a number of the Other DOE-funded propulsion and lightweight materials patent families may in fact have been funded by VTO, but are not categorized as such because a definite link could not be established. To get a better sense of how many of these Other DOE-funded patents (and patent families) may in fact be VTO-funded, we divided them into two groups.

The first group contains DOE-funded patent families that were definitely not funded by VTO. These include families linked specifically to funding from an office other than VTO, or that the inventor or VTO technology manager said were not funded by VTO (but without specifying funding from a different office). The second group contains DOE-funded patent families where the funding source within DOE could not be established, and inventors and VTO technology managers could not state categorically whether or not they were funded by VTO.

In propulsion materials, 57 of the 86 Other-DOE patent families are marked as definitely not VTO-funded, with the remaining 29 patent families marked as unknown. Meanwhile, in lightweight materials, 29 of the 37 Other-DOE patent families are marked as definitely not VTO-funded, with the remaining eight patent families marked as unknown. Hence, up to 33.7% (29 out of 86) of the Other DOE-funded propulsion materials patent families, and 21.6% (8 out of 37) of the Other DOE-funded lightweight materials patent families, may in fact be VTO-funded. As a result, the findings reported may understate the influence of VTO-funded propulsion and lightweight materials patents, relative to the influence of the remainder of DOE patents.

Identifying Propulsion/Lightweight Materials Patents Assigned to Leading Organizations

The purpose of the backward tracing element of our analysis is to evaluate the influence of VTO-funded (and Other DOE-funded) research upon propulsion/lightweight materials innovations produced by leading organizations in these technologies. To identify such organizations, we first defined the universes of propulsion and lightweight materials patents in the period 1976-2018 using the patent filters detailed earlier in Table 3-1. Note that, unlike in the case of DOE-funded patents, this involved many thousands of patents. It was thus impractical to use the same semi-manual approach to separate propulsion and lightweight materials patents. Instead, propulsion materials patents were identified using the top two filters (i.e. Filter A OR Filter B), while lightweight materials were identified using the bottom two filters (i.e. Filter C OR Filter D).

It should be noted that the filters are designed to restrict the patent sets to vehicle-related materials, rather than including materials in general. For example, Filter A is limited to patents in

CPCs related to internal combustion engines. Meanwhile, Filter C is restricted to patents that are either in CPCs related to vehicle structures, or refer specifically to vehicles or automobiles. Without these restrictions, the patent sets would include many materials patents without any vehicle applications, and the leading companies (i.e. those with the largest numbers of patents) could be outside the automotive industry. That said, it should be recognized that the number of leading company propulsion/lightweight materials patent families is likely to be conservative.

Based on the filters, we identified a total of 12,433 propulsion materials U.S. patents, 8,683 propulsion materials WIPO patents, and 9,937 propulsion materials EPO patents. We grouped these patents into 19,791 patent families by matching priority documents. We then located the most prolific patenting organizations in this overall propulsion materials patent universe, based on number of patent families. The ten organizations with the largest number of propulsion materials patent families directed to vehicle applications are shown in Table 3-3.

Table 3-3 – Top 10 Patenting Propulsion Materials Companies

Company	# Propulsion Materials Patent Families
Toyota	2466
Ford	788
BASF	629
GM	560
Porsche	544
Bosch	495
Johnson Matthey	461
Honda	412
Continental	403
Nissan	388

Also based on the filters, we identified a total of 13,712 lightweight materials U.S. patents, 8,104 lightweight materials WIPO patents, and 9,797 lightweight materials EPO patents. We grouped these patents into 22,694 patent families by matching priority documents. We then located the most prolific patenting organizations in this overall lightweight materials patent universe, based on number of patent families. The ten organizations with the largest number of lightweight materials patent families directed to vehicle applications are shown in Table 3-4.

Table 3-4 – Top 10 Patenting Lightweight Materials Companies

Company	# Lightweight Materials Patent Families
Honda	1187
Toyota	1041
Ford	932
Porsche	918
GM	763
Daimler	607
Groupe PSA	606
Nissan	526
Mazda	442
Renault	441

The number of patent families listed in Tables 3-3 and 3-4 includes all variant names under which each organization has patents, taking into account including all subsidiaries and acquisitions.[7] The propulsion/lightweight materials patent families of these companies form the starting point for the backward tracing element of the analysis. As such, this analysis evaluates the influence of VTO-funded and Other DOE-funded propulsion/lightweight materials research on technologies developed by leading companies in the propulsion/lightweight materials industries.

Constructing Citation Links

Through the processes described above, we constructed starting patent sets for both the backward and forward tracing elements of the analysis. The patent set for the backward tracing consisted of patent families assigned to the leading patenting organizations in propulsion/lightweight materials technologies. The patent sets for the forward tracing consisted of VTO-funded (and, separately, Other DOE-funded) propulsion/lightweight materials patent families.

Having defined these patent sets, we then traced backward through two generations of citations from the leading organizations' propulsion/lightweight materials patents, and forward through two generations of citations from the VTO/Other DOE-funded propulsion/lightweight materials patents. These included citations listed on U.S., EPO and WIPO patents, and required extensive data cleaning to account for differences in referencing formats across these systems. The citation linkages identified, along with characteristics of the starting patent sets, form the basis for the results described in the next section of this report. Results are reported first for propulsion materials and then for lightweight materials.

4. Results – Propulsion Materials

This section of the report outlines the results of our analysis tracing the influence of VTO-funded and Other DOE-funded propulsion materials research on subsequent developments both within and beyond propulsion materials technology. The results are divided into three main sections. In the first section, we examine trends in patenting over time in propulsion materials technology, and assess the distribution of VTO-funded and Other DOE-funded patents across propulsion materials technologies. The second section then reports the results of an analysis tracing backwards from propulsion materials patents owned by the leading companies in this technology. The purpose of this analysis is to determine the extent to which propulsion materials innovations developed by leading companies build upon earlier propulsion materials research funded by VTO (plus propulsion materials research funded by the remainder of DOE). In the third section, we report the results of an analysis tracing forwards from VTO-funded (and Other DOE-funded) propulsion materials patents. The purpose of this analysis is to assess the broader influence of DOE-funded research upon subsequent developments within and beyond propulsion materials technology.

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[7] All ten of the organizations in both Table 3-3 and Table 3-4 are companies. For clarity, they are referred to in the results section of the report as the leading propulsion/lightweight materials companies, rather than organizations. Also, note that they are selected based on patent portfolio size, which does not necessarily reflect number of units sold or revenues, profits etc. A fuller description would be the leading patenting propulsion/lightweight materials companies, but this is a cumbersome description to use throughout the results section of the report.

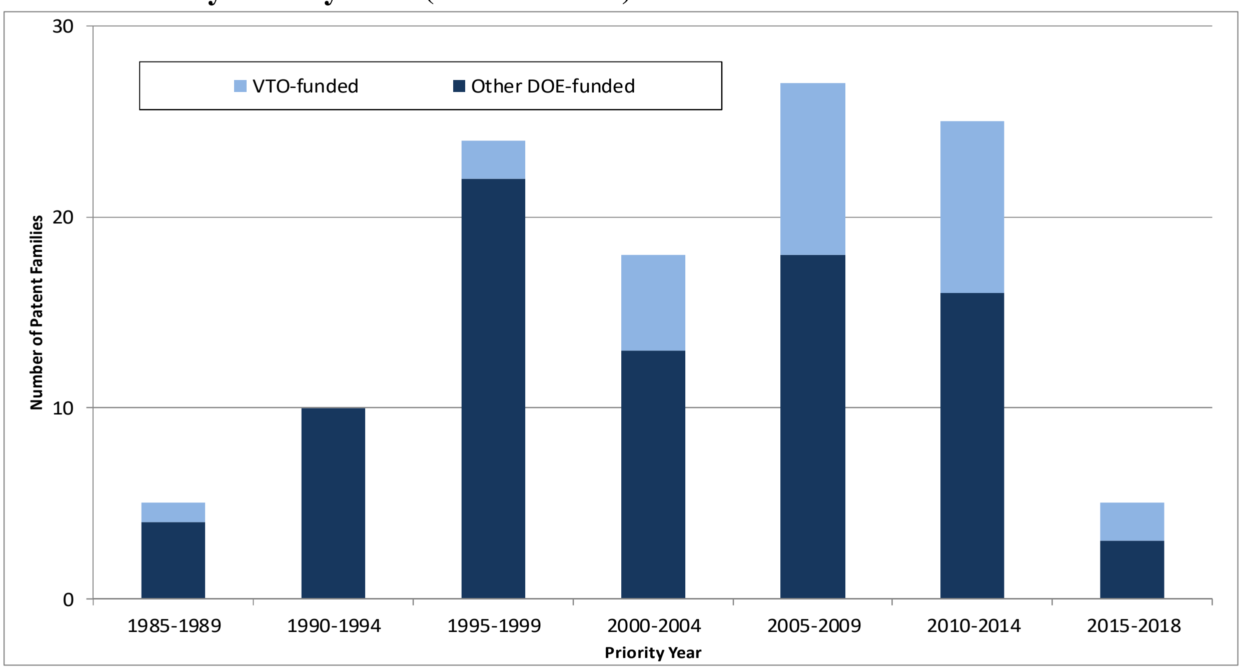
Overall Trends in Propulsion Materials Patenting

Trends in Propulsion Materials Patenting over Time

Figure 4-1 shows the number of DOE-funded propulsion materials patent families by priority year – i.e. the year of the first application in each patent family. This figure separates VTO-funded and Other DOE-funded patent families, and reveals an interesting pattern in terms of DOE-funded patent activity in propulsion materials technology.

While the data collection for this analysis covers patents back to 1975, the first DOE-funded propulsion materials patent families were not filed until 1989. Figure 4-1 reveals that there was then a steady increase in the number of DOE-funded patent families throughout the 1990s, reaching a total of 24 patent families filed in 1995-1999. Note that, out of the 39 DOE-funded patent families filed through 1999, only three were connected to VTO funding. After 1999, there was then a slight decrease in DOE-funded propulsion materials patenting, with a total of 18 patent families filed in 2000-2004, five of which were funded by VTO. The number of DOE-funded families then increased again to 27 in 2005-2009 and 25 in 2010-2014, with nine families in each of these time periods funded by VTO. The final time period in Figure 4-1 is 2015-2018, which contains only partial data due to time lags associated with the patenting process.

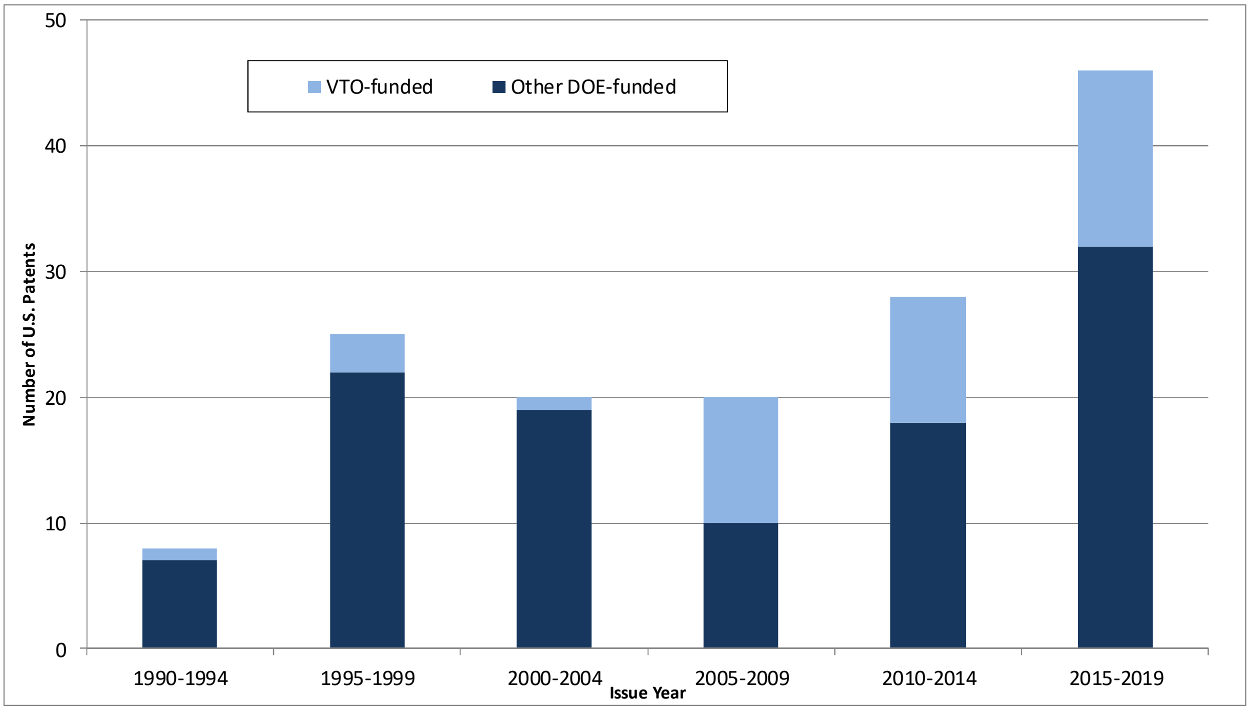
Figure 4-1 - Number of Propulsion Materials Patent Families funded by VTO and Other DOE Sources by Priority Year (5-Year Totals)



Note: The final time period in this figure is 2015-2018, and is shown for completeness, although data for this time period are incomplete. Our primary data collection covered only patents issued through 2018. Due to time lags associated with the patenting process, only a fraction of the patent families from 2015-2018 will be included.

Figure 4-2 shows the number of propulsion materials granted U.S. patents funded by DOE. This figure reveals that the first such patents were issued in in the early 1990s, with a total of seven issued in 1990-1994 (one of which was funded by VTO). The number of DOE-funded propulsion materials patents then increased to 25 in 1995-1999 (three of which were funded by VTO), before falling to 20 in both 2000-2004 and 2005-2009. Half of the patents in the latter time period were funded by VTO. There was then an increase in DOE-funded propulsion materials families, to 28 in 2010-2014 (10 VTO-funded) and 46 in 2015-2019 (14 VTO-funded).

Figure 4-2 - Number of DOE-Funded Propulsion Materials Granted U.S. Patents by Issue Year (5-Year Totals)



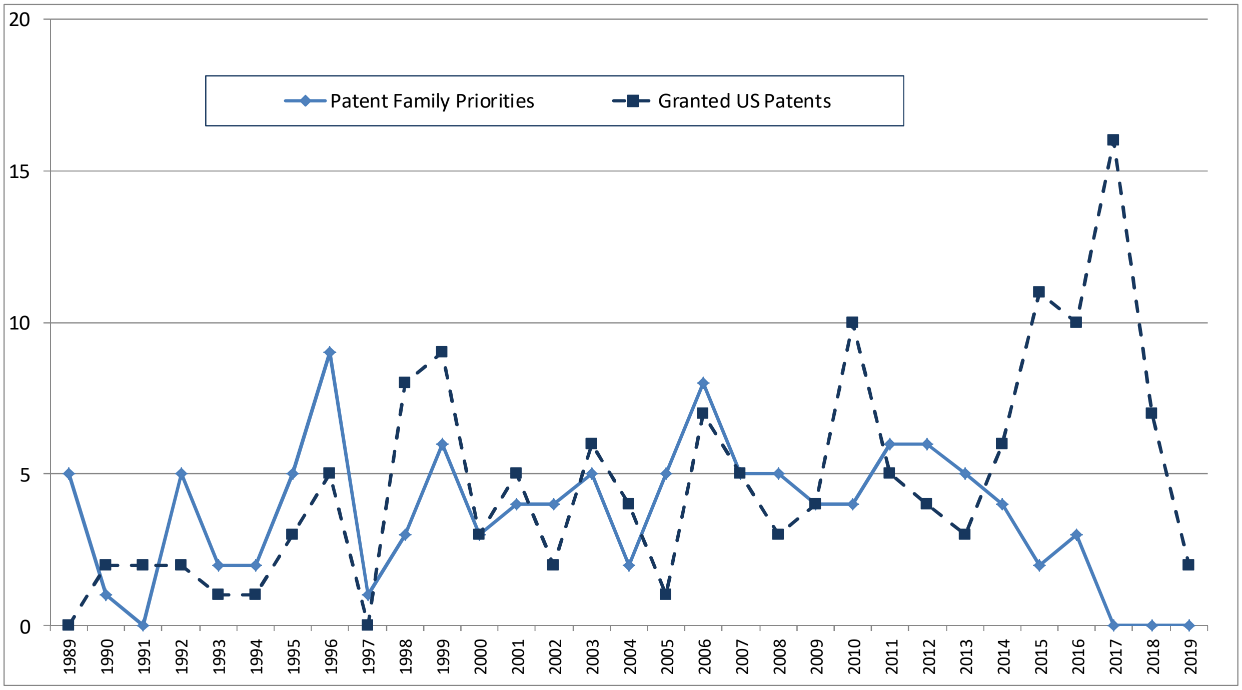
Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

Comparing Figures 4-1 and 4-2 shows the effect of time lags in the patenting process, with many of the patent families with priority dates in 2005-09 and 2010-14 (Figure 4-1) resulting in granted U.S. patents in 2010-14 and 2015-19 (Figure 4-2). These time lags can also be seen in Figure 4-3, which shows propulsion materials patent family priority years alongside issue years for granted U.S. propulsion materials patents (VTO and Other DOE are combined in this figure, in order to simplify the presentation).

In Figure 4-3, there are spikes in patent family priorities in 1996 and 2006, with corresponding peaks in granted U.S. patents occurring in 1999 and 2010. There is also a spike in granted U.S. patents in 2015-2017, but without an earlier corresponding uptick in patent families. This is due to a small number of patent families each containing several U.S. patents. Note that, due to the primary data collection for this analysis ending in 2018, the number granted U.S. patents declines sharply in 2019, and the number of patent families is zero.

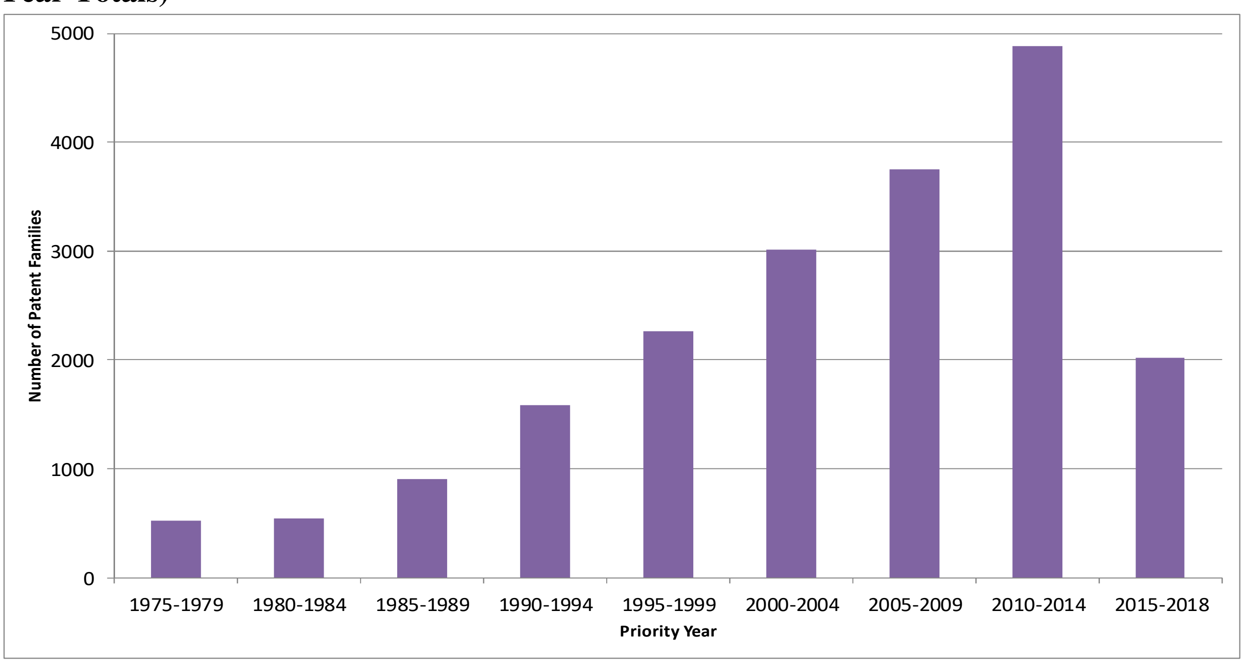
Figures 4-1 – 4-3 focus on DOE-funded propulsion materials patent families. Figure 4-4 broadens the scope, and shows the overall number of propulsion materials patent families by priority year (based on USPTO, EPO, and WIPO filings). This chart follows a distinct pattern, with the number of patent families increasing steadily throughout the period from 1975 onwards (the number of families declined in 2015-18, although data for this period are incomplete). In the early time periods (1975-1979 and 1980-1984), there were approximately 100 propulsion materials patent families per year. By the most recent complete time period (2010-2014), this number had increased to almost 1,000 patent families per year.

Figure 4-3 - Number DOE-funded Propulsion Materials Patent Families (by Priority Year) and Granted U.S. Patents (by Issue Year)



Note: The data collection period for this analysis ended with 2018. The 2019 patents have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

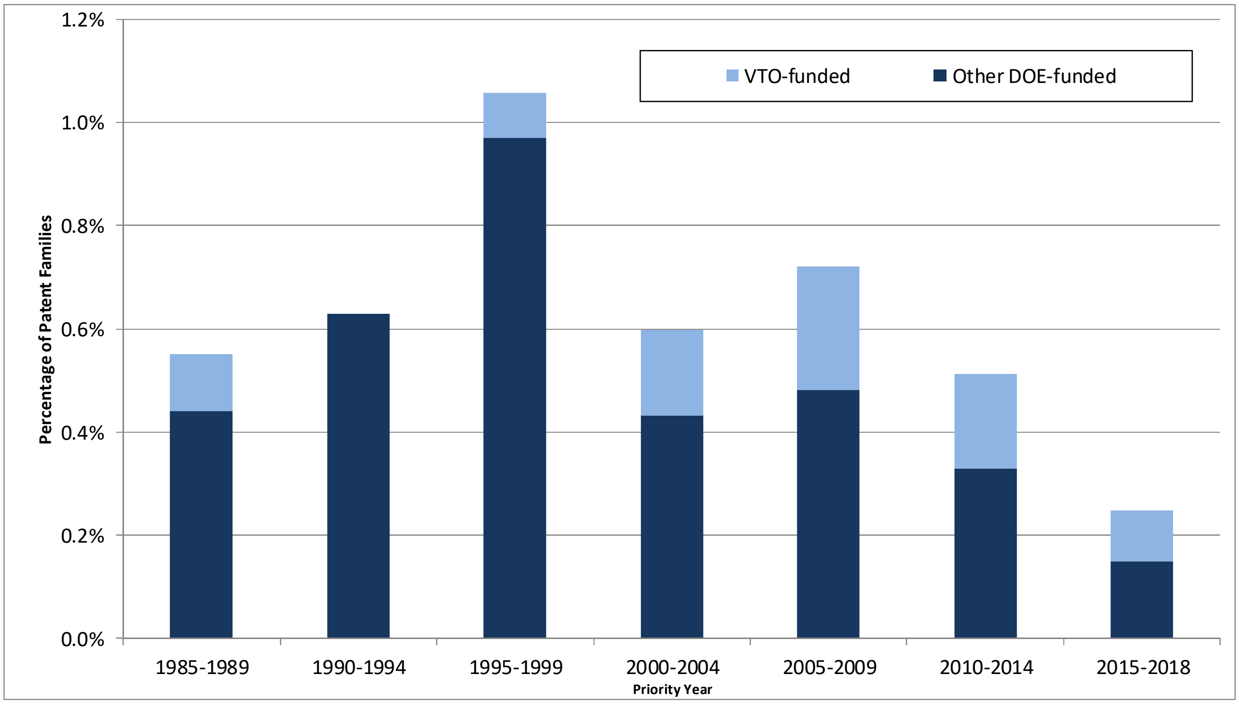
Figure 4-4 - Total Number of Propulsion Materials Patent Families by Priority Year (5-Year Totals)



Note: The final time period in this figure is 2015-2018. Data for this time period are incomplete. Due to time lags associated with the patenting process, only a fraction of the patent families from this time period will be included.

Figure 4-5 shows the percentage of propulsion materials patent families in each time period that were funded by DOE (VTO plus Other DOE). This figure reveals that less than 1% of patent families were funded by DOE in all time periods, with the exception of 1995-1999 (where the figure was just over 1%). This finding is not surprising, since propulsion materials is an active area of patenting for many leading automotive companies that have very large patent portfolios, as discussed below. Overall, 0.6% of propulsion materials patent families in 1976-2018 were funded by DOE.

Figure 4-5 - Percentage of Propulsion Materials Patent Families Funded by DOE by Priority Year

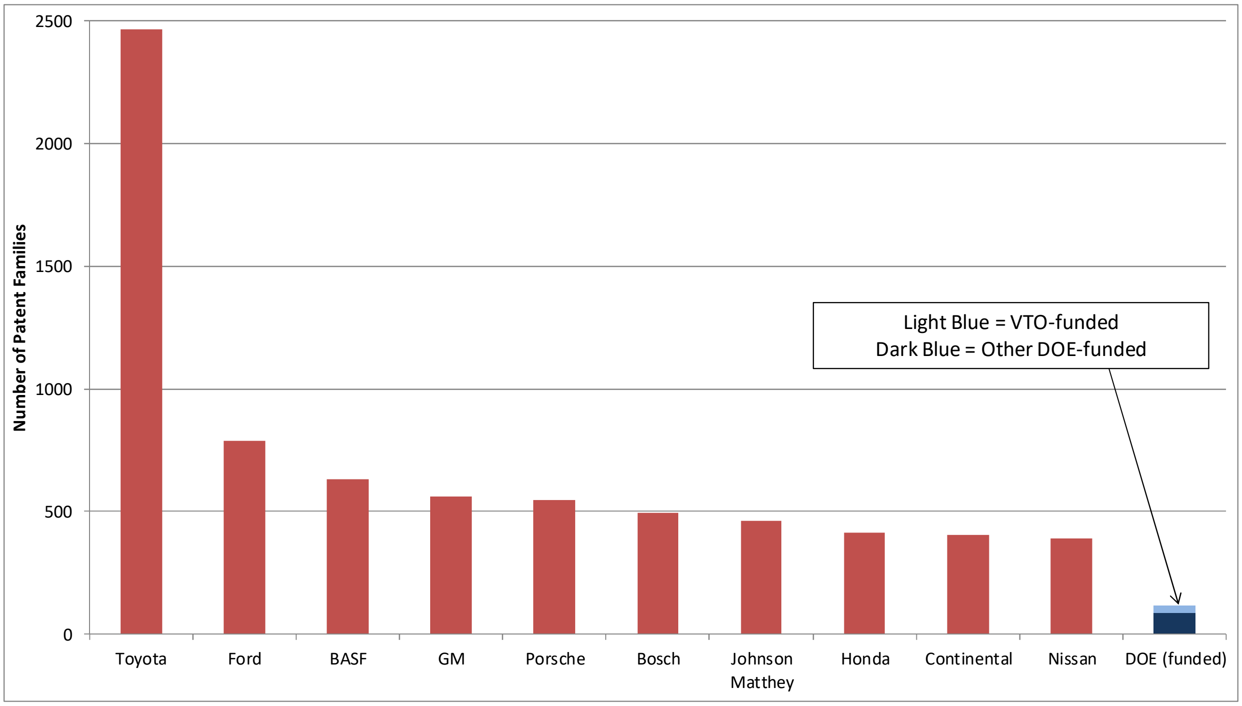


Note: The final time period in this figure is 2015-2018. Data for this time period are incomplete. Due to time lags associated with the patenting process, only a fraction of the patent families from this time period will be included.

Leading Propulsion Materials Assignees

The ten leading patenting companies in propulsion materials technology are listed above in Table 3-3, along with their number of propulsion materials patent families. These top ten companies are the basis for the backward tracing element of the analysis, as outlined below. Figure 4-6 shows the same information in graphical form, while also including DOE-funded patent families. This figure reveals that the Toyota has by far the largest propulsion materials patent portfolio, containing 2,466 patent families. This portfolio is more than three times larger than the second placed company – Ford with 788 patent families. The remaining companies in Figure 4-6 have relatively similar-sized propulsion materials patent portfolios, ranging from BASF (629 patent families) to Nissan (388). One notable feature of Figure 4-6 is the wide geographical distribution of the leading companies, with five from Europe, three from Asia and two from the U.S. This reinforces the earlier point that, while the analysis does not include patents from Asian systems, this does not mean that patents associated with Asian companies are excluded.

Figure 4-6 – Leading Propulsion Materials Companies (based on number of patent families)



The DOE-funded propulsion materials patent portfolio is shown at the right-hand end of Figure 4-6. This portfolio is much smaller than those of the leading companies, containing 28 VTO-funded patent families and 86 Other DOE-funded patent families. As such, the overall DOE-funded patent portfolio is less than one-third the size of all the other portfolios in Figure 4-6. Indeed, it is less than one-twentieth the size of Toyota's portfolio. In assessing the impact of VTO-funded and Other DOE-funded propulsion materials patents, versus the impact of the patent portfolios associated with the leading companies, we therefore take into account this difference in portfolio size.

It should be noted that there is a small amount of double-counting of patent families in Figure 4-6. Specifically, there are four BASF patent families and two Ford patent families that were funded by VTO. These six patent families are counted in both the VTO-funded segment of Figure 4-6 and in the respective company columns. This double-counting is appropriate, since these patent families are both funded by VTO and assigned to a leading company.

Assignees of VTO/Other DOE Propulsion Materials Patents

The DOE-funded propulsion materials patent portfolios are constructed somewhat differently from the portfolios of the top ten companies listed in Figure 4-6. Specifically, DOE's 114 patent families are those funded by DOE, but they are not necessarily assigned to the agency. For example, VTO (or another DOE office) may have partially or fully funded research projects at DOE labs or companies. In such cases, the assignees of any resulting patents may be the respective companies or DOE lab managers (as in the example of the BASF and Ford patent families discussed above).

Figure 4-7 shows the leading assignees on VTO-funded propulsion materials patent families. This chart is headed by UT-Battelle with eight patent families, through its management of Oak Ridge National Laboratory (ORNL). The remainder of this figure features numerous large companies – including Caterpillar, Cummins, BASF and Ford – plus UChicago Argonne, through its management of Argonne National Laboratory (ANL). The numbers of patent families in this figure are relatively low, which is not surprising given that there are only 28 VTO-funded propulsion materials patent families in total.

Figure 4-7 - Assignees with Largest Number of VTO-Funded Propulsion Materials Patent Families

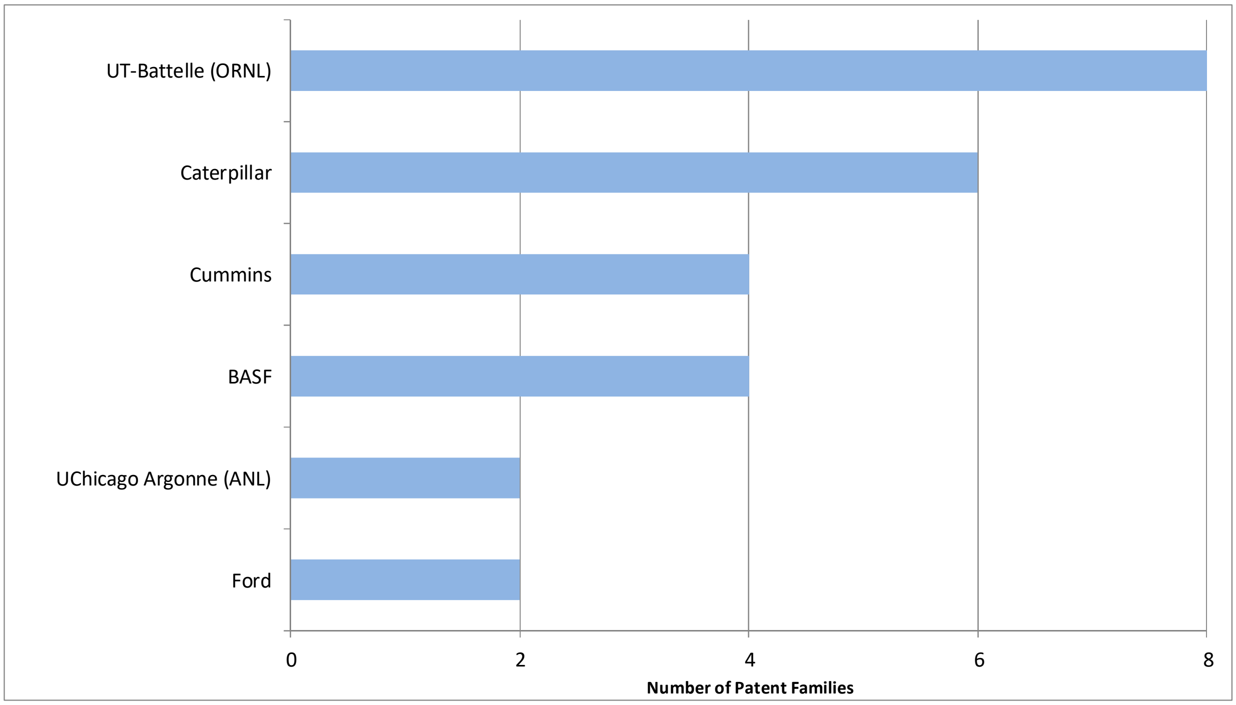
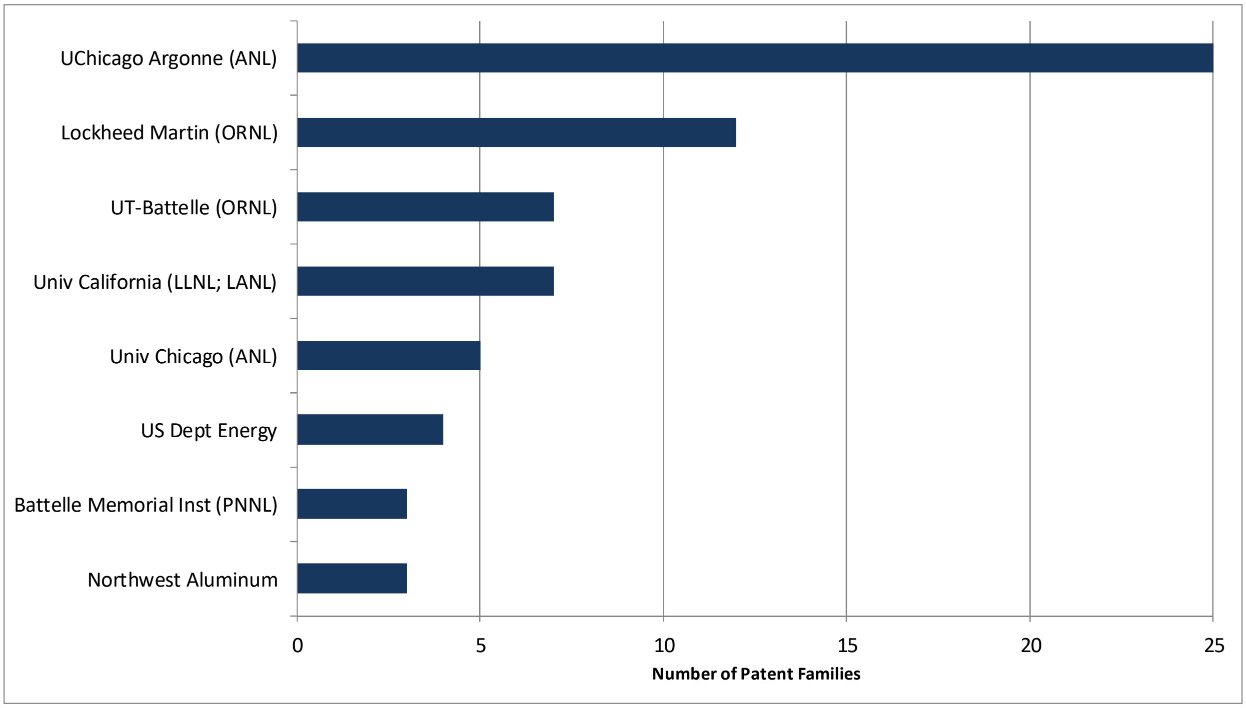


Figure 4-8 shows the leading assignees on Other DOE-funded propulsion materials patent families. This figure is dominated by DOE laboratory managers. The most prolific assignee is the UChicago Argonne, with 25 patent families through its management of ANL. Also, note that there are an additional five ANL patent families assigned to the University of Chicago. The second and third placed organizations in Figure 4-8 (Lockheed Martin and UT-Battelle) are both associated with ORNL, with a total of 19 patent families from this laboratory.

Other assignees featured in Figure 4-8 include the University of California (through its management of Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL)) and Battelle Memorial Institute, the manager of Pacific Northwest National Laboratory (PNNL). In addition, there are number of patent families assigned to DOE itself. This may occur for various reasons, including where the inventors are federal employees; where the funding recipient elects not to pursue patent protection for, or take title to, the invention; or where the funding recipient does not have the right to take title to the invention.

Figure 4-8 - Assignees with Largest Number of Other DOE-funded Propulsion Materials Patent Families



Distribution of Propulsion Materials Patents across Patent Classifications

We analyzed the distribution of VTO-funded propulsion materials U.S. patents across Cooperative Patent Classifications (CPCs).[8] We then compared this distribution to those associated with Other DOE-funded propulsion materials patents; propulsion materials patents assigned to the ten leading companies; and the universe of all propulsion materials patents. This analysis provides insights into the technological focus of VTO funding in propulsion materials, versus the focus of the remainder of DOE, leading propulsion materials companies, and propulsion materials technology in general.

The results from this CPC analysis are shown in two separate charts, each from a different perspective. The first chart (Figure 4-9) is based on the seven CPCs that are most prevalent among VTO-funded propulsion materials patents. The purpose of this figure is thus to show the main focus areas of VTO-funded propulsion materials research, and the extent to which these areas translate to other portfolios (Other DOE-funded; leading propulsion materials companies; all propulsion materials). This figure shows that VTO-funded research includes relatively balanced coverage across the seven CPCs (which is not particularly surprising, since the VTO-funded patent portfolio forms the basis for the CPCs included in the chart). The three most common CPCs among VTO-funded propulsion materials patents are B01D (Material Separation), B01J (Chemical Processes e.g. catalysis) and Y02T (Climate Change: Transport). The VTO-funded patents in these three CPCs are largely concerned with exhaust treatment.

[8] The CPC is a patent classification system. Patent offices attach numerous CPC classifications to a patent, covering the different aspects of the subject matter in the claimed invention. In generating these charts, all CPCs associated with each patent are included.

There are also CPCs in Figure 4-9 concerned with materials, notably C22C (Alloys) and C01B (Non-metallic Elements), with the latter focusing on zeolite-based catalysts.

The patent portfolios associated with the leading propulsion materials companies, and all propulsion materials patents combined, follow a different distribution to VTO-funded patents across CPCs. There is a much greater concentration on exhaust treatment, with CPC F01N (Exhaust Apparatus) particularly prominent. At the same time, there is less focus on materials such as alloys and non-metallic elements. Meanwhile, Other DOE-funded patents focus on exhaust treatment and alloys, but not non-metallic elements.

Figure 4-9 - Percentage of Propulsion Materials U.S. Patents in Most Common Cooperative Patent Classifications (Among VTO-Funded Patents)

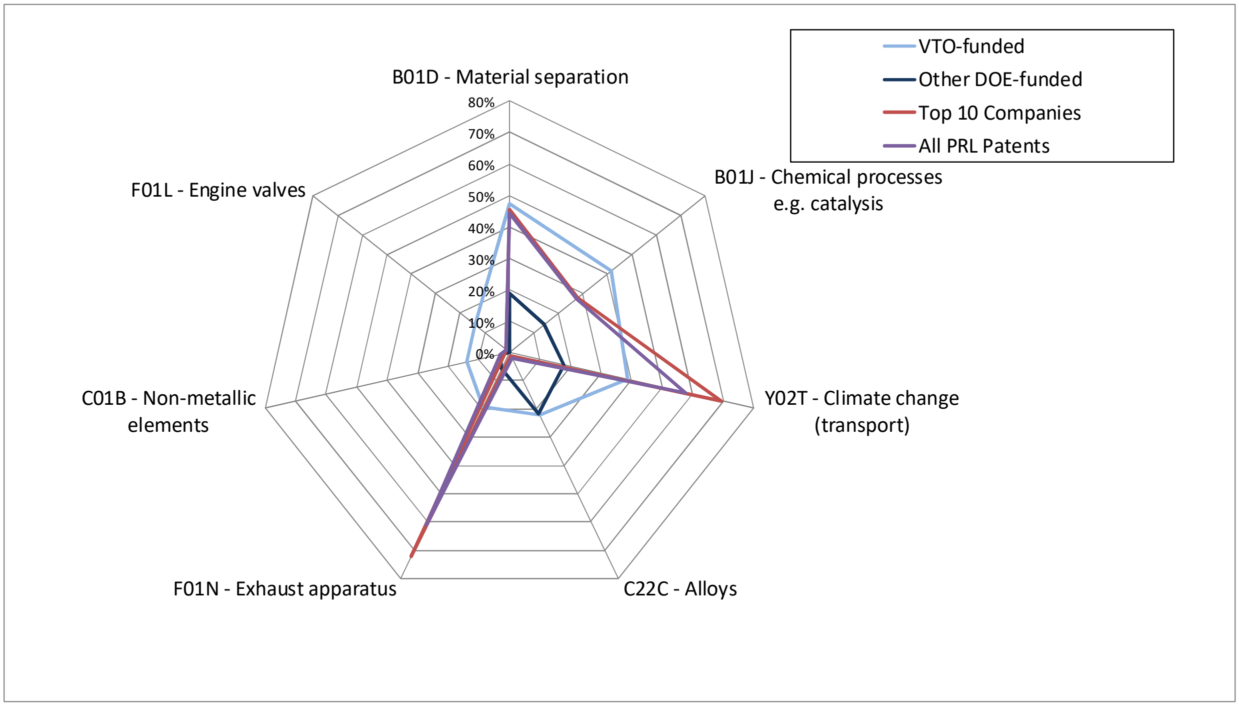


Figure 4-10 is similar to Figure 4-9, except that it is from the perspective of the most common CPCs among all propulsion materials patents. Hence, the purpose of this chart is to show the main research areas within propulsion materials as a whole, and how these areas are represented in selected propulsion materials portfolios (VTO-funded; Other DOE-funded; leading propulsion materials companies). Four out of the seven CPCs in Figure 4-9 also appear in Figure 4-10. The three new CPCs are F02B (Internal Combustion Engines), F02D (Engine Control) and Y02A (Climate Change: emission control). The leading companies have a large number of patents in these CPCs, while VTO-funded and Other DOE-funded patents have less presence in them.

Figure 4-11 compares the CPC distribution of VTO-funded propulsion materials U.S. patents across two time periods – patents issued through 2010, and those issued from 2011 onwards. This figure reveals that exhaust treatment was a common focus across both time periods. Meanwhile, after 2010 there was an increase in the number of patents in CPCs related to non-metallic elements (C01B) and engine valves (F01L), suggesting that these were areas of increasing focus for recipients of VTO propulsion materials funding.

Figure 4-10 - Percentage of Propulsion Materials U.S. Patents in Most Common Cooperative Patent Classifications (Among All Propulsion Materials Patents)

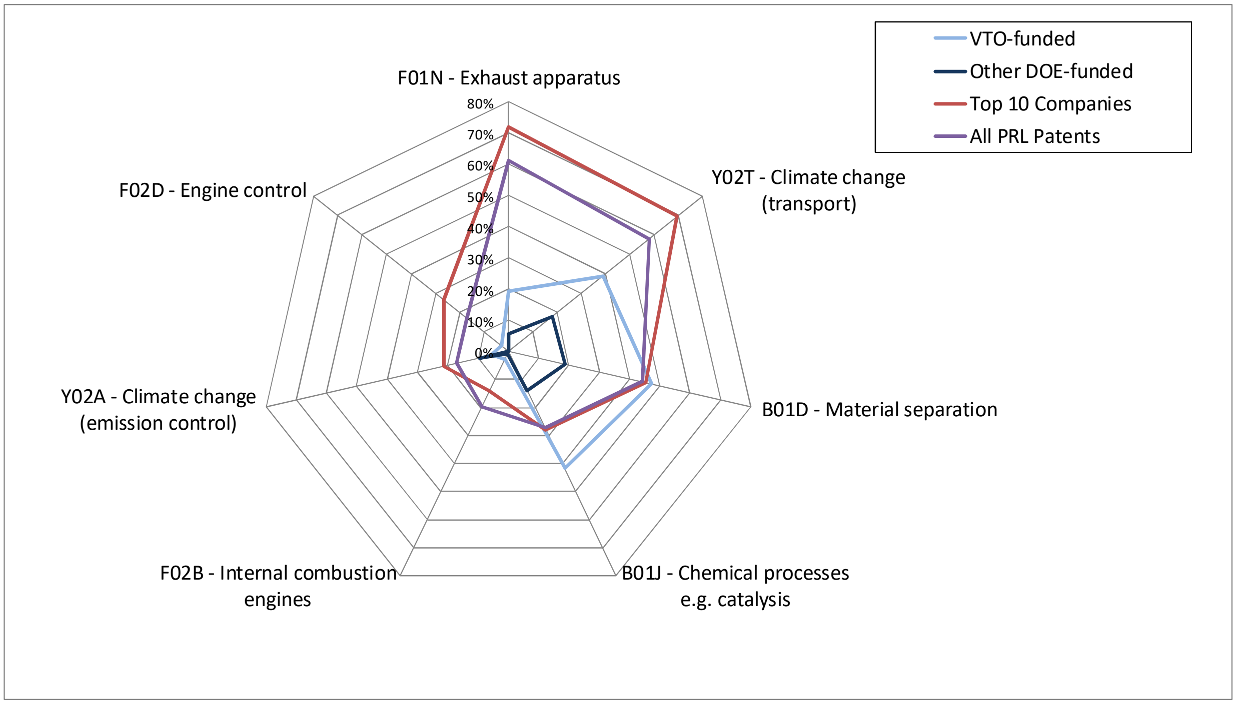
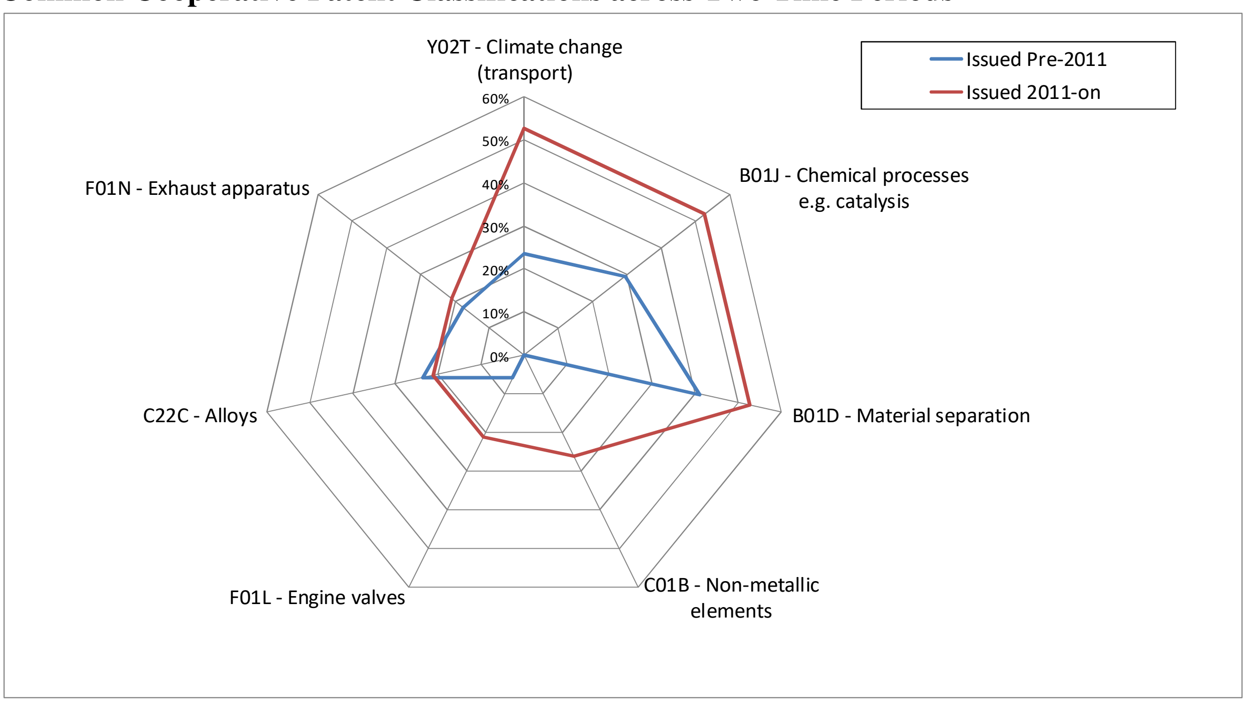


Figure 4-11 - Percentage of VTO-funded Propulsion Materials U.S. Patents in Most Common Cooperative Patent Classifications across Two Time Periods



Tracing Backwards from Propulsion Materials Patents Owned by Leading Companies

This section reports the results of an analysis tracing backwards from propulsion materials patents owned by leading companies in this technology to earlier research, including that funded by VTO (and by DOE in general). The results in this section are examined at two levels. First, we report results at the organizational level. These results reveal the extent to which VTO-funded (and Other DOE-funded) research forms a foundation for subsequent innovations associated with leading propulsion materials companies. Second, we drill down to the level of individual patents, with a particular focus on VTO-funded propulsion materials patents. These patent-level results highlight specific VTO-funded patents that have had a particularly strong influence on subsequent patents owned by leading companies. They also highlight which propulsion materials patents owned by these leading companies are linked particularly extensively to earlier VTO-funded research.

Organizational Level Results

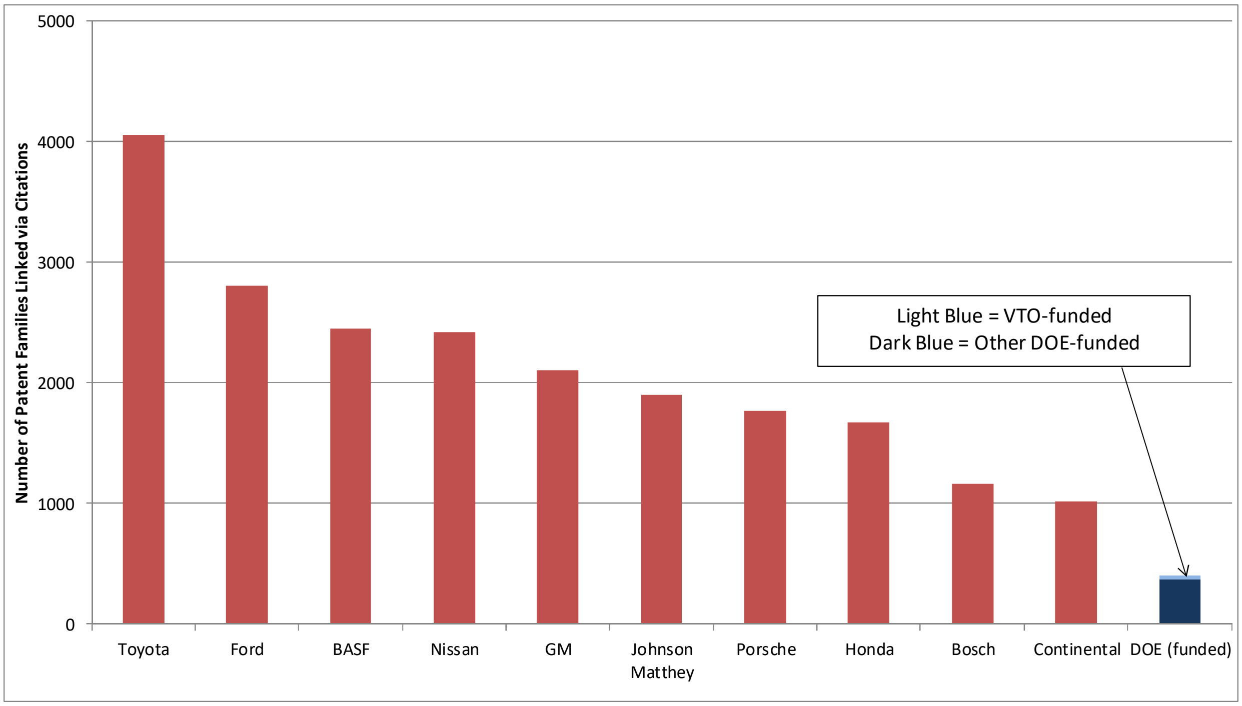
In the organizational level results, we first compare the influence of VTO-funded and Other DOE-funded propulsion materials research against the influence of leading companies in this technology. We then look at which of these leading companies build particularly extensively on DOE-funded propulsion materials research.

Figure 4-12 compares the influence of VTO-funded and Other DOE-funded propulsion materials research to the influence of research carried out by the top ten propulsion materials companies. Specifically, this figure shows the number of propulsion materials patent families owned by the leading companies that are linked via citations to earlier propulsion materials patent families assigned to each of these leading companies (plus patent families funded by DOE). In other words, this figure shows the companies whose patents have had the strongest influence upon subsequent developments made by leading companies in propulsion materials technology.[9]

In total, 401 leading company propulsion materials patent families (i.e. 5.6% of their 7,141 families) are linked via citations to earlier DOE-funded propulsion materials patents. Out of these 401 families, 25 are linked to VTO-funded propulsion materials patents (although this may underestimate the influence of VTO-funded patents relative to Other DOE-funded patents, since some of the Other DOE-funded propulsion materials patent families may in fact have been funded by VTO, as discussed earlier). This finding puts DOE-funded patents at the bottom of Figure 4-12. In comparison, over 4,000 leading company patent families are linked via citations to earlier Toyota patent families.

[9] This figure compares the influence of patents *funded* by VTO/Other DOE against patents *owned* by (i.e. assigned to) organizations. Such a comparison is reasonable, since patents funded by organizations through their R&D budgets will be assigned to those organizations. Also, organizations cannot choose to reference the patents of a non-competitor (such as DOE) rather than the patents of a competitor in order to reduce the "credit" given to that competitor. Such an omission could lead to the invalidation of their patents. Note that, as in Figure 4-6, there is a small amount of double-counting in Figure 4-12, as some patent families assigned to BASF and Ford were funded by DOE. Also, in Figures 4-12 – 4-15, leading company patent families linked to both VTO-funded and Other DOE-funded patents are allocated to the VTO-funded segment of the DOE column, in order to avoid double-counting these families.

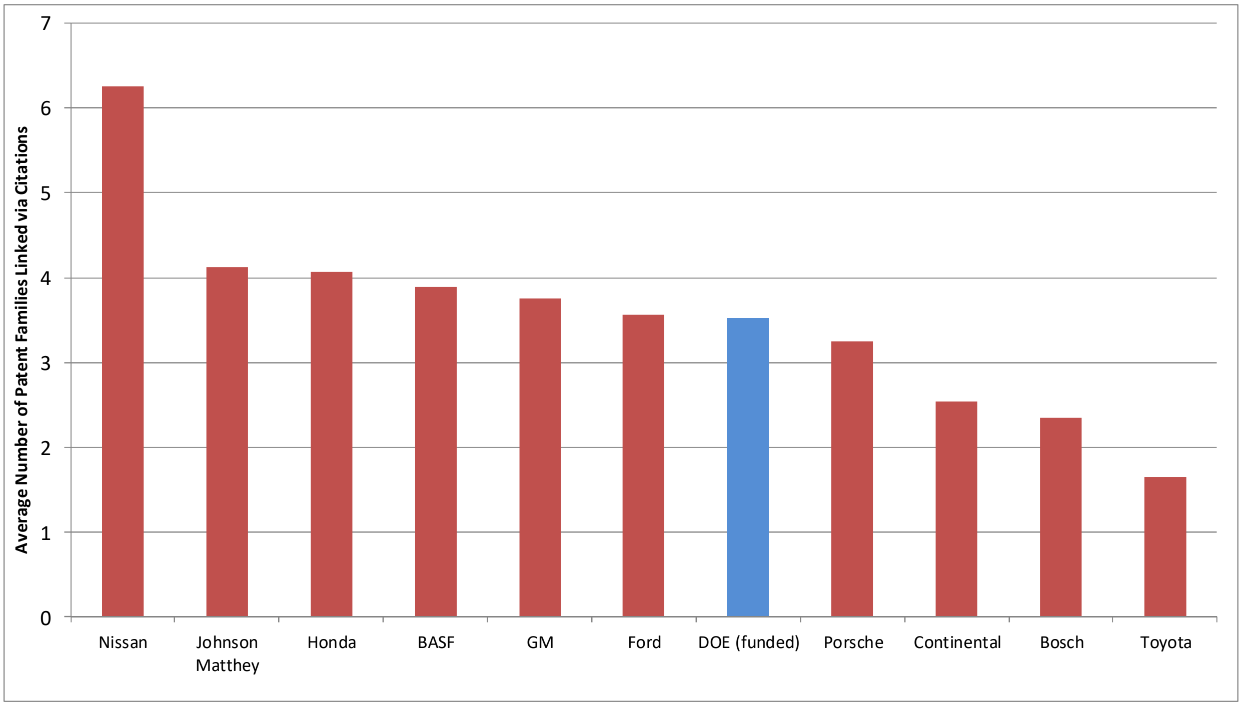
Figure 4-12 - Number of Leading Company Propulsion Materials Patent Families Linked via Citations to Earlier Propulsion Materials Patents from each Leading Company
e.g. 401 leading company families are linked to earlier VTO/Other DOE-funded families



At first glance, the finding in Figure 4-12 does not appear promising in terms of DOE's influence on propulsion materials technology. However, this figure does not take into account the different sizes of the patent portfolios associated with the various companies. For example, it is not surprising that many more patent families are linked via citations to Toyota than to DOE, since Toyota has twenty times as many patent families available to be cited as prior art.

Figure 4-13 takes into account the differences in patent portfolio size. It shows the average (mean) number of leading company patent families linked to patent families associated with each of the companies (plus DOE) in Figure 4-12. Nissan is at the head of this figure by some distance, with each of its patent families linked to an average of over six families assigned to the leading companies. Toyota, meanwhile, falls to the bottom in Figure 4-13, with each of its patent families linked to an average of less than two families assigned to the leading companies. On average, DOE-funded propulsion materials patent families are each linked to 3.5 patent families assigned to the leading companies. This puts DOE seventh in Figure 4-13, among a cluster of companies with similar averages, from Johnson Matthey in second place (4.1) down to Porsche in eighth (3.3). As such, taking into account its relatively small size, the portfolio of DOE-funded propulsion materials patents has had a notable influence on propulsion materials innovations associated with the leading companies.

Figure 4-13 – Mean Number of Leading Company Propulsion Materials Patent Families Linked via Citations to Propulsion Materials Families from Each Leading Company
e.g. on average, each DOE-funded patent family is linked to 3.5 subsequent patent families assigned to leading companies



Figures 4-14 through 4-16 examine which of the leading companies build particularly extensively on earlier VTO-funded and Other DOE-funded propulsion materials patents. Figure 4-14 shows how many propulsion materials patent families owned by each of the leading companies are linked via citations to at least one earlier DOE-funded propulsion materials patent. Out of the ten leading propulsion materials companies, five are linked particularly strongly to earlier DOE-funded patents. As such, they build most extensively on earlier DOE-funded propulsion materials research. General Motors heads this list, with 76 patent families linked via citations to DOE-funded patents, five of which are linked to VTO. Ford is second in Figure 4-14, with 75 patent families linked to DOE-funded patents (eight linked to VTO-funded patents), followed by BASF (66 linked to DOE; one to VTO), Toyota (59 linked to DOE; three to VTO) and Johnson Matthey (42 linked to DOE; eight to VTO).

Figure 4-15 counts the total number of citation links from leading companies to earlier DOE-funded patents. This differs slightly from the count of linked families in Figure 4-14, since a single patent family may be linked to multiple earlier DOE-funded patents. The same five companies are again at the head of Figure 4-15, reinforcing their link to earlier DOE-funded propulsion materials research. The biggest difference between Figures 4-14 and 4-15 is that Ford replaces General Motors at the head of the latter figure, with a total of 139 citation links to earlier DOE-funded patents (eight of which are links to VTO-funded patents).

Figure 4-14 - Number of Patent Families Assigned to Leading Propulsion Materials Companies Linked via Citations to Earlier VTO/Other DOE-funded Propulsion Materials Patents

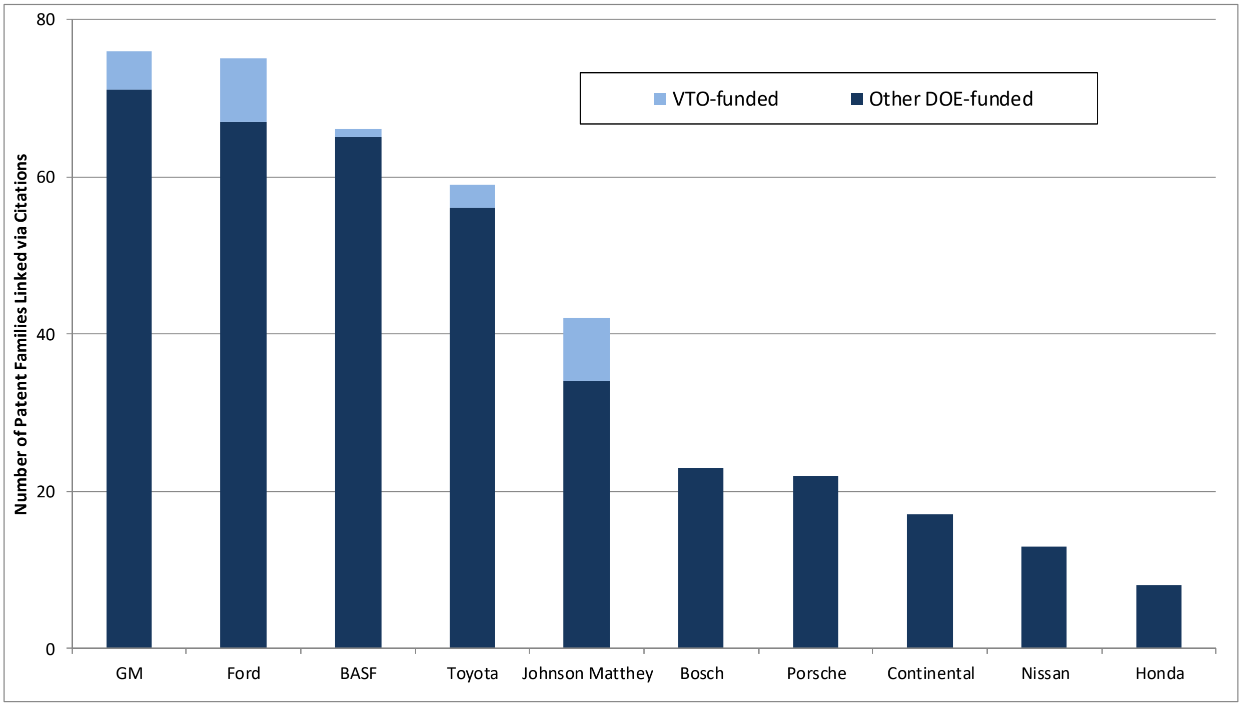
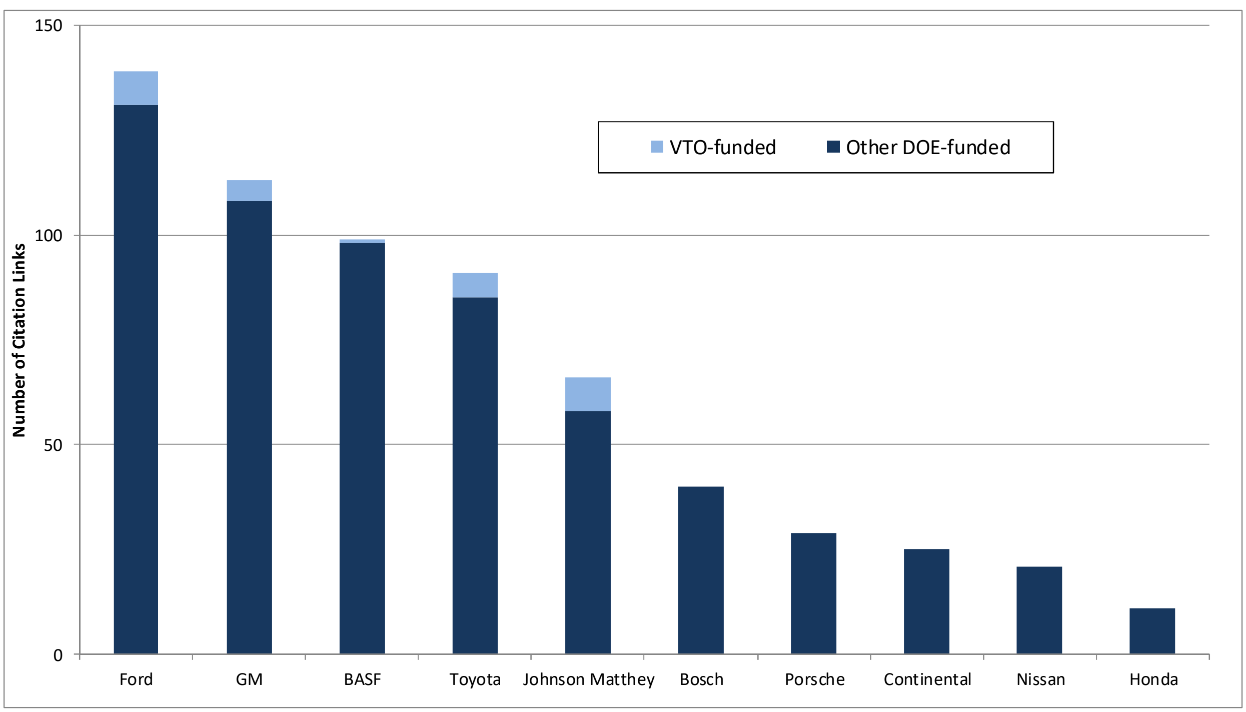


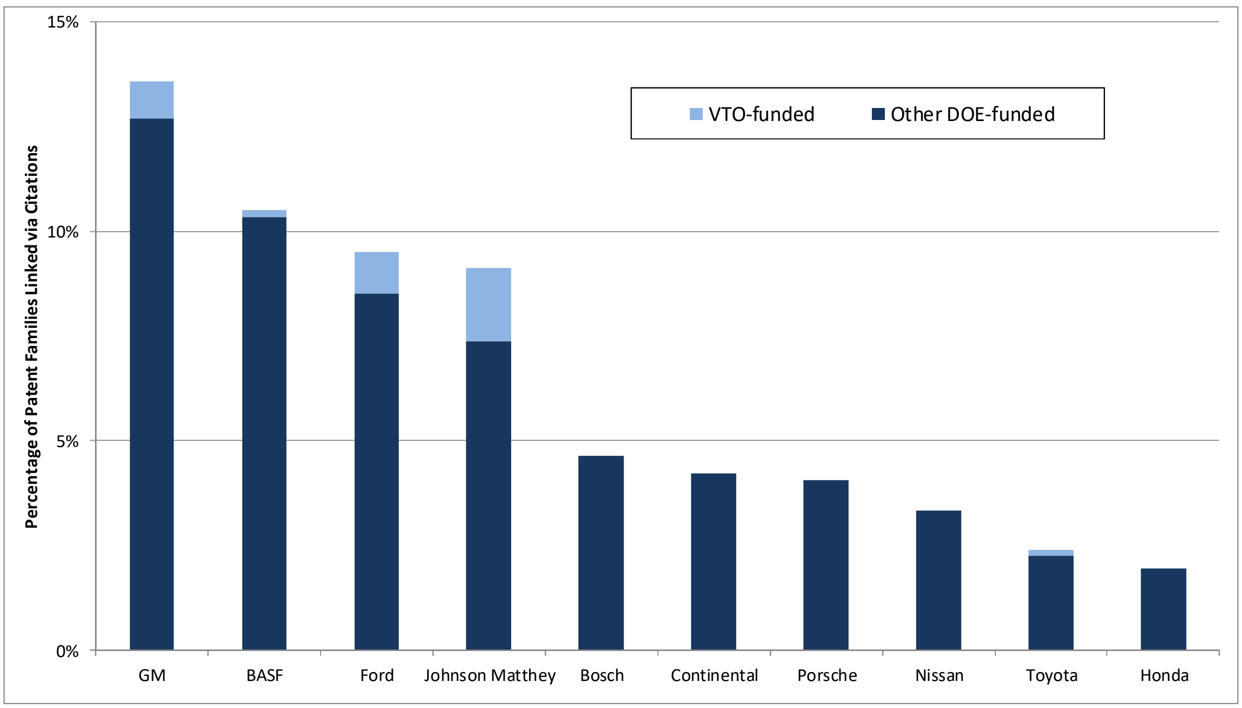
Figure 4-15 - Total Number of Citation Links from Leading Propulsion Materials Company Patent Families to Earlier VTO/Other DOE-funded Propulsion Materials Patents



There is an element of portfolio size bias in the patent family counts in Figures 4-14 and 4-15. Companies with larger propulsion materials patent portfolios are likely to have more patent families linked to DOE, simply because they have more families overall. Figure 4-16 accounts for this portfolio size bias by calculating the percentage of each leading company's propulsion materials patent families that are linked via citations to earlier DOE-funded propulsion materials patents, rather than their absolute number. This is a measure of how extensively each company builds on DOE-funded research, relative to their overall patent output.

Figure 4-16 reveals that two leading companies have more than 10% of their propulsion materials patent families linked via citations to earlier DOE-funded propulsion materials patents – General Motors (13.6%) and BASF (10.5%). Toyota is much less prominent in Figure 4-16, with only 2.4% of its patent families linked via citations to DOE-funded patents. Hence, its higher position in Figures 4-14 and 4-15 is largely due to its large number of patent families.

Figure 4-16 - Percentage of Leading Propulsion Materials Company Patent Families Linked via Citations to Earlier VTO/Other DOE-funded Propulsion Materials Patents



Patent Level Results

The previous section of the report examined results at the level of entire patent portfolios. The purpose of this section is to drill down to identify individual DOE-funded propulsion materials patent families (in particular VTO-funded families) that have had a particularly strong influence on subsequent propulsion materials patents owned by leading companies in this technology. Looking in the opposite direction, it also identifies individual propulsion materials patents owned by leading companies that have extensive links to earlier VTO-funded research.

Table 4-1 shows the VTO-funded propulsion materials patent families linked via citations to the largest number of subsequent patent families owned by leading companies in this technology. The patent family at the head of this table (whose representative patent[10] is US #7,743,602) has a priority year of 2005 and is co-assigned to ExxonMobil and Caterpillar. It describes a method for removing pollutants, particularly nitrogen oxides (NOx), from exhaust gas streams. Eight patent families assigned to the leading companies are linked via citations to this VTO-funded patent family, including exhaust purification families assigned to Ford, General Motors and Toyota.

The second-place patent family in Table 4-1 (representative patent #8,987,162) is also concerned with NOx reduction, especially for diesel and lean gasoline engines. This patent family is assigned to UT-Battelle through its management of Oak Ridge National Laboratory (ORNL), and is linked to six subsequent families owned by the leading companies, notably Johnson Matthey and Toyota. The primary focus of all the patent families in Table 4-1 is exhaust treatment, suggesting that this is an area where VTO-funded research has influenced technologies developed by leading companies.

Table 4-1 - VTO Funded Propulsion Materials Patent Families Linked via Citations to Most Subsequent Leading Company Propulsion Materials Patent Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
38710555	7743602	2005	8	ExxonMobil / Caterpillar	Reformer assisted lean NOx catalyst aftertreatment system and method
49003096	8987162	2012	6	UT-Battelle	Hydrothermally stable, low-temperature NOx reduction NH3-SCR catalyst
45888636	9120077	2010	4	BASF	Surface-coated zeolite materials for diesel oxidation applications
39125250	7943548	2006	3	BASF	Catalysts to reduce NOx in an exhaust gas stream and methods of preparation
49580145	8997461	2012	3	Cummins	Aftertreatment system having two SCR catalysts
35506714	7153810	2004	2	Caterpillar	Silver doped catalysts for treatment of exhaust

Table 4-1 lists VTO-funded patents linked to the largest number of subsequent propulsion materials patent families owned by leading companies. Table 4-2 looks in the opposite direction, and lists propulsion materials patent families owned by leading companies that are linked via citations to multiple VTO families. There are only two such leading company patent families. The first (representative patent US #8,955,313) is assigned to Toyota, and describes an exhaust treatment system containing a silver-alumina based catalyst. It is linked via citations to three earlier VTO-funded propulsion materials patent families, notably Caterpillar families describing silver-doped catalysts. The second patent family in Table 4-2 (representative patent US #9,849,433) is also owned by Toyota, through its shareholding in Cataler Corporation. This patent family is linked via citations to two VTO-funded patent families, including one of the Caterpillar patent families referred to above (representative patent US #7,153,810).

[10] The representative patent is a single patent from a family, but it is not necessarily the priority filing.

Table 4-2 - Leading Company Propulsion Materials Patent Families Linked via Citations to Largest Number of VTO Funded Propulsion Materials Patent Families

Patent Family #	Representative Patent #	Priority Year	# VTO Fams	Assignee	Title
46672130	8955313	2011	3	Toyota	Exhaust purification system of internal combustion engine
53371175	9849443	2013	2	Toyota	Exhaust gas purification catalyst

We also identified high-impact propulsion materials patents owned by leading companies that have citation links back to VTO-funded patents.[11] The idea is to highlight important technologies owned by leading companies that are linked to earlier propulsion materials research funded by VTO. There is only one patent that stands out from this perspective. This patent (US #8,409,515) was issued in 2013 to General Motors and describes exhaust treatment for lean burn engines. It has been cited as prior art by 17 subsequent patents, which is more than six times as many citations as expected given its age and technology. In turn, this General Motors patent is linked via citations to the ExxonMobil/Caterpillar patent family listed at the head of Table 4-1.

While the patent-level results focus on VTO-funded propulsion materials patent families, we also identified Other DOE-funded propulsion materials families linked to the largest number of subsequent patent families owned by leading companies in this technology. These Other DOE-funded families are listed in Table 4-3. The three patent families at the head of Table 4-3 are all assigned to the University of California, through its management of Lawrence Livermore National Laboratory (LLNL). All three patent families were filed in the late 1990s and share a number of common inventors, suggesting that they were associated with the same LLNL research group. Note that all three of these patent families are marked as "unknown" in terms of their connection to VTO funding, rather than being marked definitely as not being VTO-funded. As such, it is possible that they were actually funded by VTO.

The patent family at the head of Table 4-3 (representative patent US #5,711,147) describes NOx reduction based on plasma gas treatment combined with selective catalytic reduction. This patent family is linked via citations to 294 families assigned to the leading companies, with all ten of these companies represented among the 294 families. The second LLNL patent family in Table 4-3 (representative patent US #5,891,409) describes a two-stage catalyst involving oxidative and reductive stages. It is linked via citations to 168 patent families assigned to the leading

[11] High-impact patents are identified using 1790's Citation Index metric. This metric is derived by first counting the number of times a patent is cited as prior art by subsequent patents. This number is then divided by the mean number of citations received by peer patents from the same issue year and technology (as defined by their first listed Cooperative Patent Classification). For example, the number of citations received by a 2010 patent in CPC F01N (Exhaust Apparatus) is divided by the mean number of citations received by all patents in that CPC issued in 2010. 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. By extension, the expected Citation Index for a portfolio of patents is also one, with values above one showing that a portfolio has been cited more than expected, and values below one showing that a portfolio has not been cited as frequently as expected. Note that the Citation Index is calculated for U.S. patents only, due to the differences in citation practices across different countries' patent systems.

companies, with all ten companies once again represented in this list. The third patent family (representative patent US #5,891,409) also describes NOx reduction, this time by adding a small amount of fuel to the exhaust. It is linked via citations to 62 leading company patent families, with all of the companies except Johnson Matthey having families in this list.

Table 4-3 - Other DOE-Funded Propulsion Materials Patent Families Linked via Citations to Most Subsequent Leading Company Propulsion Materials Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
24809071	5711147	1996	294	Univ California (LLNL)	Plasma-assisted catalytic reduction system
27106405	5891409	1996	168	Univ California (LLNL)	Pre-converted nitric oxide gas in catalytic reduction system
23135832	6119451	1999	62	Univ California (LLNL)	Nitrogen oxide removal using diesel fuel and a catalyst
24708921	5830421	1996	30	Low Emissions Tech R&D	Material and system for catalytic reduction of nitrogen oxide in an exhaust stream of a combustion process
22585594	6514470	1999	16	Univ California (LANL)	Catalysts for lean burn engine exhaust abatement
24542927	6033641	1996	16	Univ Pittsburgh	Catalyst for purifying the exhaust gas from the combustion in an engine or gas turbines and method of making and using the same
24731029	5914015	1996	8	Battelle Mem Inst (PNNL)	Method and apparatus for processing exhaust gas with corona discharge
24847464	7081231	2000	4	Caterpillar; Battelle Mem Inst (PNNL)	Method and system for the combination of non-thermal plasma and metal/metal oxide doped .gamma.-alumina catalysts for diesel engine exhaust aftertreatment system
24880451	5778664	1996	4	Battelle Mem Inst (PNNL)	Apparatus for photocatalytic destruction of internal combustion engine emissions during cold start

Overall, the backward tracing element of the propulsion materials analysis suggests that exhaust treatment is the area where VTO-funded and Other DOE-funded patents have had the strongest influence on subsequent innovations associated with the leading propulsion materials companies. This influence can be seen both over time, and across these leading companies, with a number of DOE-funded patent families linked via citations to subsequent exhaust treatment patents assigned to many of the leading companies.

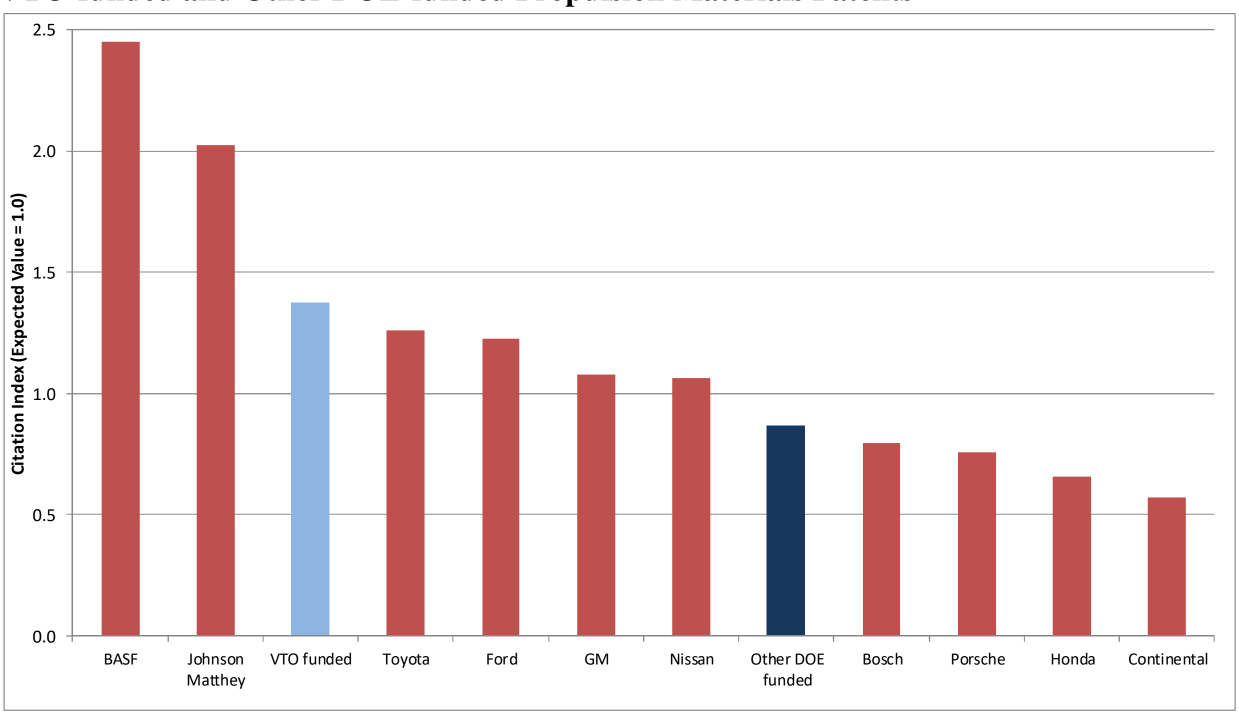
Tracing Forwards from DOE-funded Propulsion Materials Patents

The previous section of the report examines the influence of DOE-funded propulsion materials research upon technological developments associated with leading propulsion materials companies. That analysis was based on tracing backwards from the patents of leading companies to previous generations of research. This section reports the results of an analysis tracing in the opposite direction – starting with VTO-funded (and Other DOE-funded) propulsion materials patents, and tracing forwards in time through two generations of citations. Hence, while the previous section of the report focuses on DOE's influence upon a specific patent set (i.e. patents owned by leading propulsion materials companies), this section of the report focuses on the broader influence of VTO-funded (and Other DOE-funded) propulsion materials research, both within and beyond the propulsion materials industry. Also, in order to avoid repeating earlier results, the forward tracing concentrates primarily on patents that are linked to DOE-funded propulsion materials research, but are not owned by leading propulsion materials companies.

Organizational Level Results

We first generated Citation Index values for the portfolios of VTO-funded and Other DOE-funded propulsion materials patents. We then compared these Citation Indexes against those of the ten leading propulsion materials companies. The results are shown in Figure 4-17. This figure reveals that VTO-funded propulsion materials patents have an average Citation Index of 1.37, showing they have been cited 37% more frequently than expected by subsequent patents. This places VTO-funded patents in third place in Figure 4-17, behind only BASF and Johnson Matthey. The Citation Index for Other DOE-funded propulsion materials patents is lower at 0.87, showing that these patents have been cited 13% less frequently than expected. Referring to the backward tracing results, Other DOE-funded patents had more extensive citation links to the leading companies than VTO-funded patents. Given that the latter patents have a higher Citation Index, this suggests that much of their influence has been on technologies beyond those developed by the leading companies, a suggestion that is borne out in the forward tracing results below.

Figure 4-17 - Citation Index for Leading Companies' Propulsion Materials Patents, plus VTO-funded and Other DOE-funded Propulsion Materials Patents



The Citation Index metric measures the overall influence of the DOE-funded propulsion materials patent portfolios, but does not necessarily address the breadth of this influence across technologies. We therefore identified the Cooperative Patent Classifications (CPCs) of the patent families linked via citations to earlier VTO-funded (and Other DOE-funded) propulsion materials patent families.[12] These CPCs reflect the influence of DOE-funded research across technologies.

Figure 4-18 shows the CPCs with the largest number of patent families linked to VTO-funded propulsion materials patents. The CPCs in this figure are shown in two different colors – i.e. dark green for CPCs related to propulsion materials technology and light green for CPCs beyond propulsion materials. All but two of the CPCs in Figure 4-18 are in technologies related to propulsion materials. That said, one of the two other CPCs is at the head of Figure 4-18. This CPC (E21B) is related to Earth Drilling, and there are over 200 patent families in this CPC that are linked via citations to VTO-funded propulsion materials patents. These links are largely between a VTO-funded Caterpillar patent family (representative patent #7,153,373) describing a stainless steel alloy (named CF8C) and subsequent patents outlining the use of such alloys in drilling applications.

Figure 4-18 - Number of Patent Families Linked via Citations to Earlier VTO-Funded Propulsion Materials Patents by CPC (Dark Green = Propulsion-related; Light Green = Other)

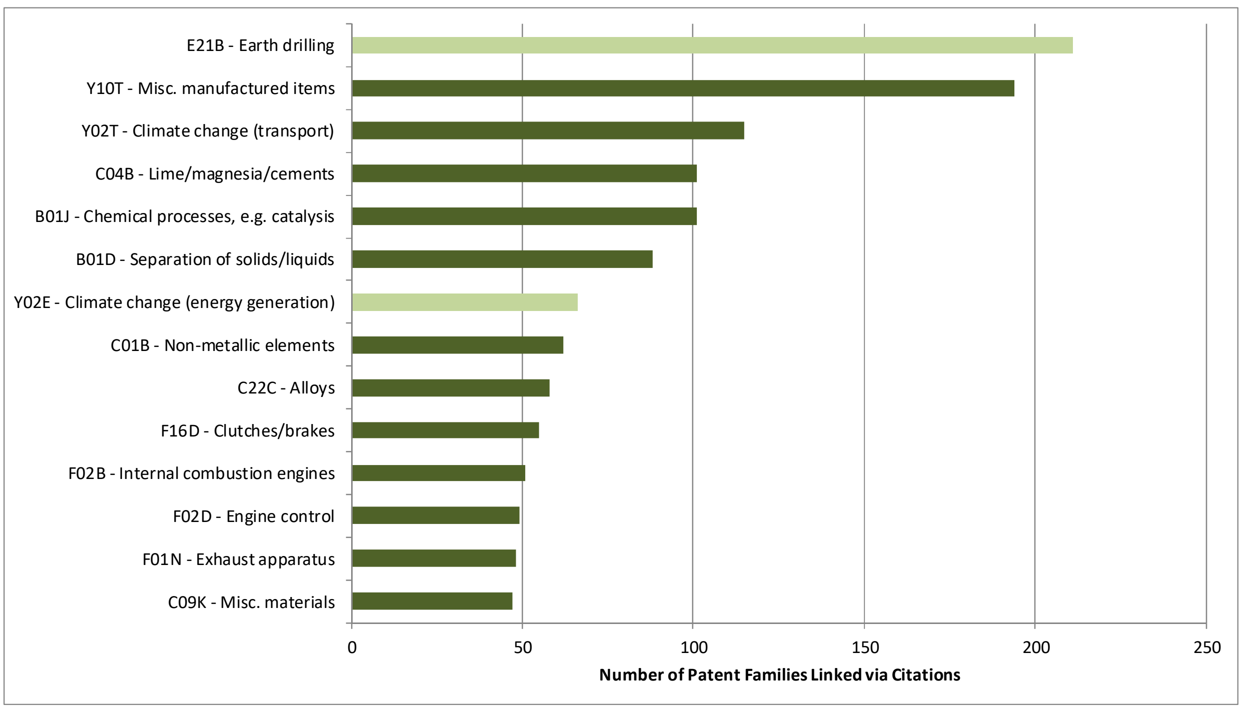
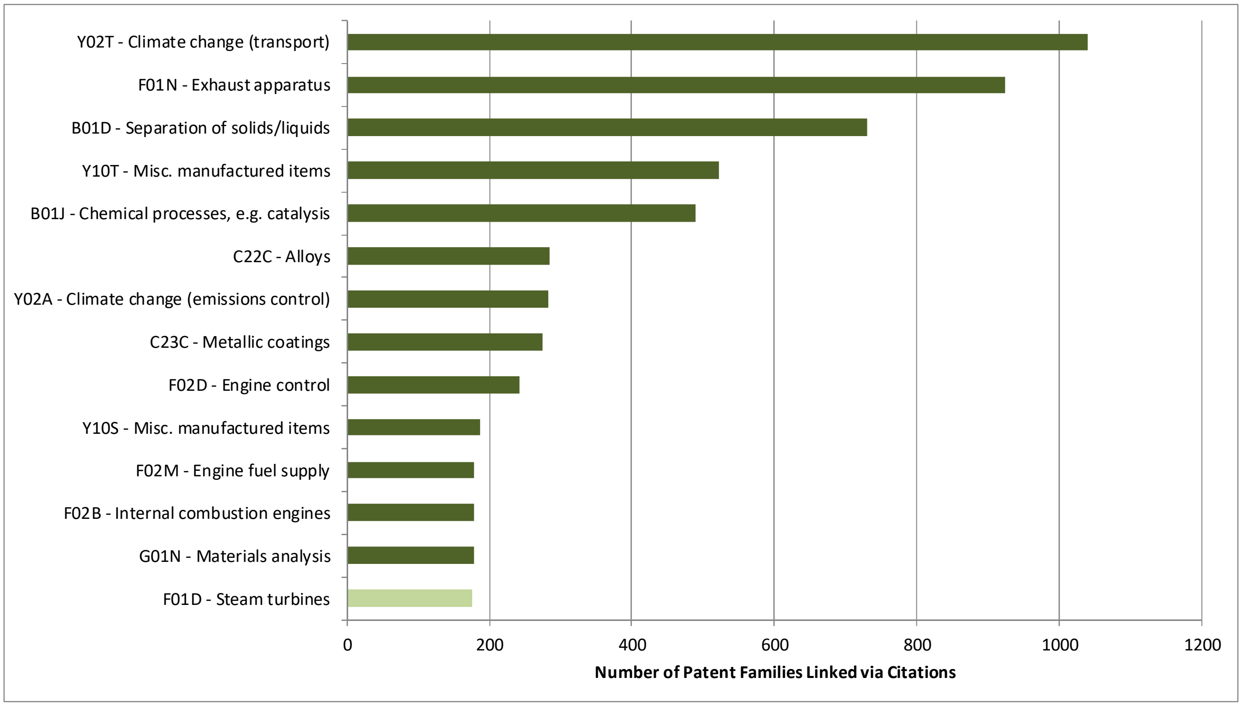


Figure 4-19 is similar to Figure 4-18, but is based on patent families linked to Other DOE-funded propulsion materials patents, rather than VTO-funded propulsion materials patents. The CPCs in this figure are even more concentrated on technologies related to propulsion materials. Only one CPC is not, and this CPC (F01D – Steam Turbines) is at the bottom of the figure.

[12] Patents typically have numerous CPCs attached to them, reflecting different aspects of the invention they describe. In this analysis, we include all CPCs attached to the patents linked to earlier DOE-funded propulsion materials patent families.

Figure 4-19 - Number of Patent Families Linked via Citations to Earlier Other DOE-Funded Propulsion Materials Patents by CPC (Dark Green = Propulsion-related; Light Green = Other)



The organizations with the largest number of patent families linked via citations to earlier VTO-funded propulsion materials patents are shown in Figure 4-20. To avoid repeating the results from earlier, this figure excludes the ten leading propulsion materials companies used in the backward tracing element of the analysis. Also, note that Figure 4-20 includes all patent families assigned to these organizations, not just their families describing propulsion materials.

Figure 4-20 contains various very large companies with interests in many technologies, including General Electric and Honeywell. It also features a number of energy companies, such as ExxonMobil, Shell and Saudi Aramco. General Electric is at the head of this figure, with 91 patent families linked via citations to earlier VTO-funded propulsion materials patents, more than twice as many as any other company. These General Electric patent families describe a range of technologies, including alloys, composite materials and catalysts. Meanwhile, the companies in second and third place, ExxonMobil and Shell, both have numerous patent families linked via citations to VTO-funded patents that describe drilling applications, with the former also having linked families related to catalysts.

Figure 4-21 shows the organizations with the largest number of patent families linked via citations to earlier Other DOE-funded propulsion materials patents. This figure contains a number of the companies featured in Figure 4-20, which focused on patent families linked to earlier VTO-funded propulsion materials patents. These include General Electric, United Technologies, ExxonMobil and Honeywell. Indeed, General Electric has 282 patent families linked via citations to Other DOE-funded patents, almost three times as many families as any other company in Figure 4-21. These General Electric patent families again describe various high-performance materials, plus applications for these materials in engine and turbine applications. Figure 4-21 also includes other engine companies such as Cummins and Delphi. The former has the second-most patent families in this figure, with a particular focus on exhaust treatment technologies.

Figure 4-20 - Organizations with Largest Number of Patent Families Linked via Citations to VTO-funded Propulsion Materials Patents (excluding leading propulsion materials companies)

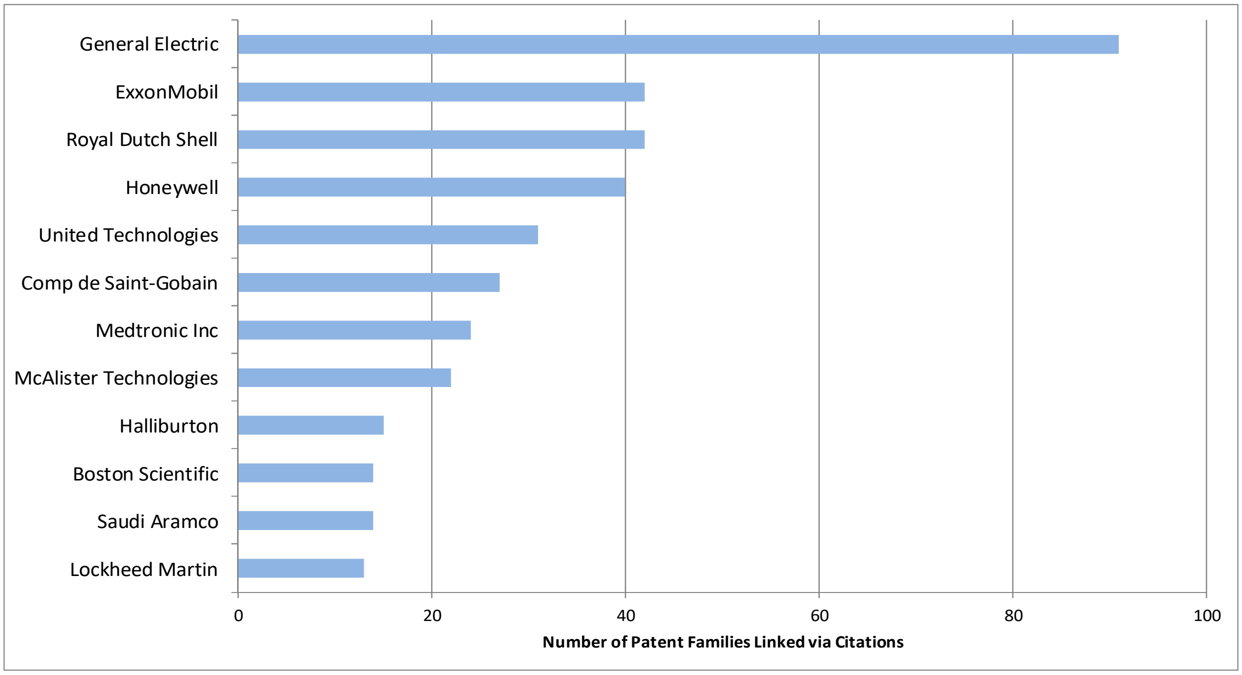
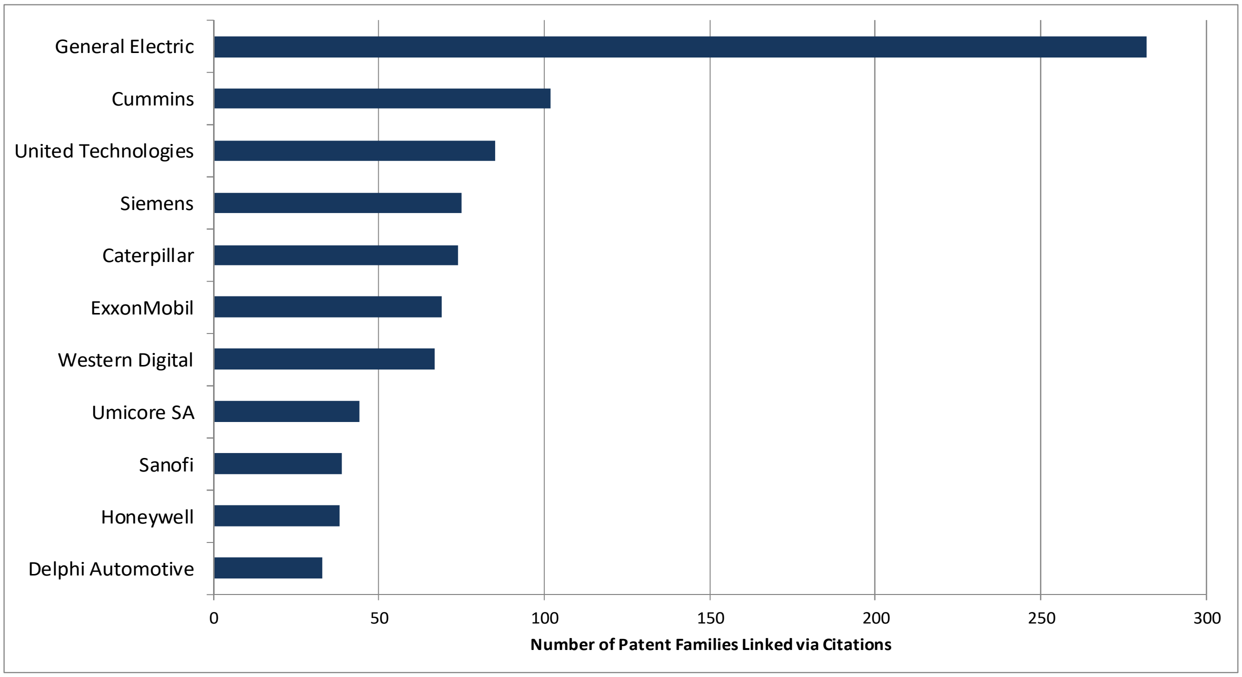


Figure 4-21 - Organizations with Largest Number of Patent Families Linked via Citations to Other DOE-funded Propulsion Materials Patents (excluding leading propulsion materials companies)



Patent Level Results

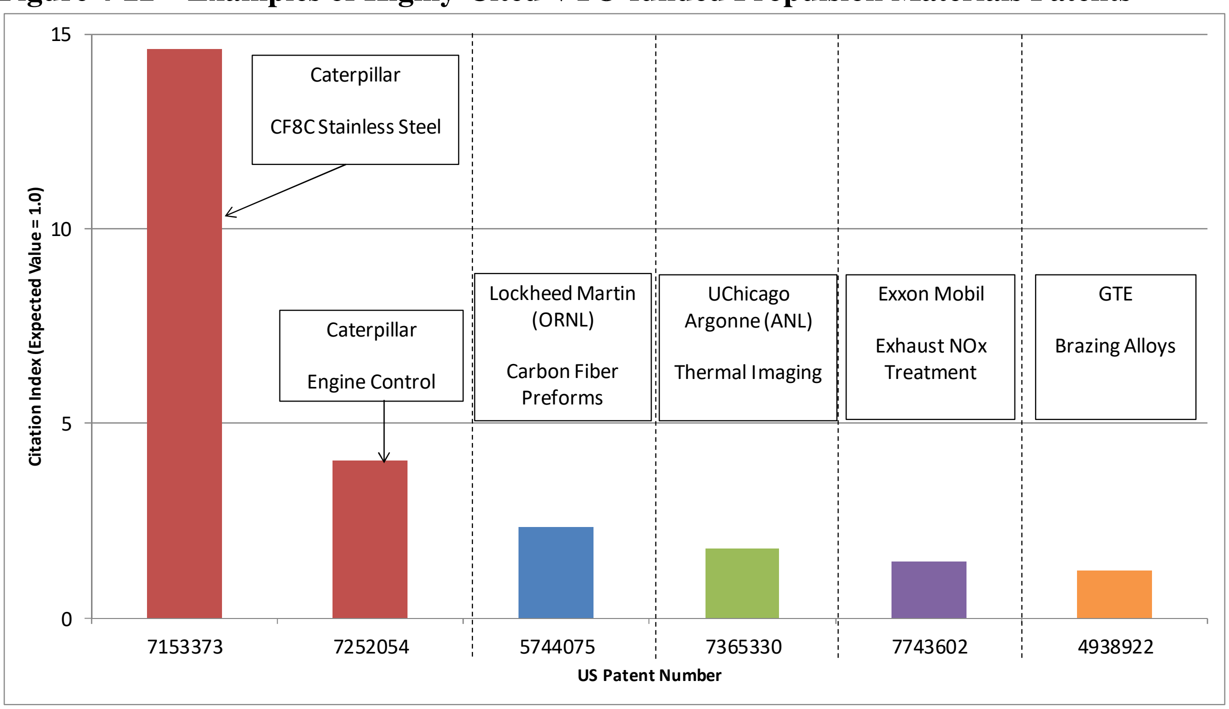
This section of the report drills down to identify individual DOE-funded (and particularly VTO-funded) propulsion materials patents whose influence on subsequent technological developments has been particularly strong. It also highlights patents that have extensive citation links to earlier VTO-funded propulsion materials research.

The simplest way of identifying high-impact VTO-funded propulsion materials patents is via overall Citation Indexes. The VTO-funded patents with the highest Citation Index values are shown in Table 4-4, and also presented in Figure 4-22.

Table 4-4 – List of Highly Cited VTO-Funded Propulsion Materials Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
7153373	2006	141	14.63	Caterpillar	Heat and corrosion resistant cast CF8C stainless steel with improved high temperature strength and ductility
7252054	2007	16	4.04	Caterpillar	Combustion engine including cam phase-shifting
5744075	1998	37	2.34	Lockheed Martin (ORNL)	Method for rapid fabrication of fiber preforms and structural composite materials
7365330	2008	17	1.78	UChicago Argonne (ANL)	Method for thermal tomography of thermal effusivity from pulsed thermal imaging
7743602	2010	11	1.44	ExxonMobil	Reformer assisted lean NOx catalyst aftertreatment system and method
4938922	1990	11	1.22	GTE Corp	Gold-nickel-titanium brazing alloy

Figure 4-22 – Examples of Highly-Cited VTO-funded Propulsion Materials Patents



The patent at the head of Table 4-4 (US #7,153,373) was issued in 2006, and is assigned to Caterpillar. This patent (which was highlighted earlier in the discussion of Figure 4-18) describes a stainless steel alloy (named CF8C), and has been cited as prior art by 141 subsequent patents, almost fifteen as many citations as expected. Many of these citations are from patents assigned to Shell, and describe earth drilling applications. The second-place patent in Table 4-4 is also assigned to Caterpillar. This patent (US #7,252,054) describes a method for controlling a combustion engine, and has been cited by 16 subsequent patents, four times as many as expected. Meanwhile the third patent (US #5,744,075) is from Oak Ridge National Laboratory (and assigned to Lockheed Martin) and describes high-density carbon fiber preforms. This patent has been cited by 37 subsequent patents, over twice as many citations as expected given its age and technology.

The Citation Indexes in Table 4-4 are based on a single generation of citations to VTO-funded propulsion materials patents. Table 4-5 extends this by examining a second generation of citations – i.e. it shows the VTO-funded propulsion materials patents linked directly or indirectly to the largest number of subsequent patent families. These subsequent families are divided into two groups, according to whether they are within or beyond propulsion materials technology (i.e. whether they are in the propulsion materials patent universe constructed in the initial step of this project). This provides insights into which VTO-funded patent families have been particularly influential within propulsion materials technology, and which have had a broader impact beyond propulsion materials.

Table 4-5 - VTO-funded Propulsion Materials Patent Families Linked via Citations to Largest Number of Subsequent Propulsion Materials/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Propulsion Fams	Assignee	Title
24961116	2000	7153373	422	5	Caterpillar	Heat and corrosion resistant cast CF8C stainless steel with improved high temperature strength and ductility
23767187	1995	5744075	220	0	Lockheed Martin (ORNL)	Method for rapid fabrication of fiber preforms and structural composite materials
23459892	1989	4938922	120	0	GTE Corp	Gold-nickel-titanium brazing alloy
46303351	2002	7252054	73	0	Caterpillar	Combustion engine including cam phase-shifting
38710555	2005	7743602	40	37	ExxonMobil	Reformer assisted lean NOx catalyst aftertreatment system and method
39321648	2006	7365330	30	0	UChicago Argonne (ANL)	Method for thermal tomography of thermal effusivity from pulsed thermal imaging
35506714	2004	7153810	17	15	Caterpillar	Silver doped catalysts for treatment of exhaust
49003096	2012	8987162	10	8	UT-Battelle (ORNL)	Hydrothermally stable, low-temperature NOx reduction NH3-SCR catalyst

The three patent families containing the patents with the highest Citation Indexes in Table 4-4 again feature prominently in Table 4-5. The Caterpillar stainless steel patent family is at the head of Table 4-5. It is linked via citations to 422 subsequent patent families, only five of which are within propulsion materials technology. The pattern is similar for the Oak Ridge National Laboratory composite preform and Caterpillar engine control patent families, with all of the subsequent patent families linked to them coming from outside propulsion materials. The same is also true for the GTE brazing alloy patent family (representative patent US #4,938,922) in third place in Table 4-5, which is linked via citations to 120 subsequent patent families, all from outside propulsion materials technology. There are patent families in Table 4-5 with more extensive links within propulsion materials, notably an ExxonMobil family (representative patent US #7,743,602) describing catalysts for exhaust treatment.

The tables above identify VTO-funded patent families linked particularly strongly to subsequent technological developments. Table 4-6 looks in the opposite direction, and identifies highly-cited patents linked to earlier VTO-funded propulsion materials patents. As such, these are examples where VTO-funded propulsion materials research has formed part of the foundation for subsequent high-impact technologies. This table focuses on patent families not owned by the leading propulsion materials companies, since those families were examined in the backward tracing element of the analysis.

Table 4-6 - Highly Cited Patents (not from leading Propulsion Materials Companies) Linked via Citations to Earlier VTO-funded Propulsion Materials Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
8425651	2013	55	29.71	Baker Hughes	Nanomatrix metal composite
9103193	2015	44	26.75	Evolution Well Services	Mobile, modular, electrically powered system for use in fracturing underground formations
6889890	2005	107	13.41	Hohoemi Brands	Brazing-filler material and method for brazing diamond
8720138	2014	50	10.55	Snap-On Inc.	Fire barrier
7771838	2010	51	9.04	Boston Scientific Corp.	Hermetically bonding ceramic and titanium with a Ti-Pd braze interface
7753036	2010	41	7.98	United Technologies Corp	Compound cycle rotary engine
7238415	2007	61	6.59	Catalytic Materials LLC	Multi-component conductive polymer structures and a method for producing same
5738698	1998	105	3.73	Compagnie de Saint-Gobain	Brazing of diamond film to tungsten carbide
6607843	2003	51	3.64	Enersys	Brazed ceramic seal for batteries with titanium-titanium-6A1-4V cases

The patents in Table 4-6 are assigned to a variety of organizations, and describe many different technologies. There are a number of patents describing brazing materials, assigned to Hohoemi Brands, Boston Scientific, Compagnie de Saint-Gobain and Enersys. In addition, there are patents related to earth drilling assigned to Baker Hughes and Evolution Well Services, plus fire barriers and polymer materials assigned to Snap-On and Catalytic Materials respectively. These are examples of VTO-funded propulsion materials patents influencing developments in other technologies.

As with the backward tracing element of the analysis, the patent-level results from the forward tracing focus on VTO-funded propulsion materials patents. However, within the forward tracing, we did also identify Other DOE-funded propulsion materials patent families linked to the largest number of subsequent patent families within and beyond propulsion materials technology. These Other DOE-funded propulsion materials families are shown in Table 4-7.

Table 4-7 - Other DOE-funded Propulsion Materials Patent Families Linked via Citations to Largest Number of Subsequent Propulsion Materials/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Propulsion Fams	Assignee	Title
24809071	1996	5711147	1145	644	Univ California (LLNL)	Plasma-assisted catalytic reduction system
27106405	1996	5891409	767	416	Univ California (LLNL)	Pre-converted nitric oxide gas in catalytic reduction system
23243580	1989	4961903	269	7	Lockheed Martin (ORNL)	Iron aluminide alloys with improved properties for high temperature applications
23135832	1999	6119451	260	147	Univ California (LLNL)	Nitrogen oxide removal using diesel fuel and a catalyst
24188989	1990	5084109	248	6	Lockheed Martin (ORNL)	Ordered iron aluminide alloys having an improved room-temperature ductility
23673998	1995	5571346	217	1	Northwest Aluminu m	Casting, thermal transforming and semi-solid forming aluminum alloys
22956715	1994	5495979	212	1	Surmet Corp	Metal-bonded, carbon fiber-reinforced composites
25384836	1992	5320802	171	6	Lockheed Martin (ORNL)	Corrosion resistant iron aluminides exhibiting improved mechanical properties and corrosion resistance
24708921	1996	5830421	163	89	Low Emissions Tech R&D	Material and system for catalytic reduction of nitrogen oxide in an exhaust stream of a combustion process
24731029	1996	5914015	153	39	Battelle Mem Inst (PNNL)	Method and apparatus for processing exhaust gas with corona discharge

There are two patent families that stand out in Table 4-7 in terms of the number of subsequent patent families to which they are linked via citations. Both of these patent families are assigned to the University of California, through its management of Lawrence Livermore National Laboratory (LLNL). These two families were also highlighted above in the backward tracing element of the analysis. The first of them (representative patent US #5,711,147) describes a plasma-assisted exhaust treatment system. It is linked via citations to 1,145 subsequent patent families, over half of which are from within propulsion materials technology. The second LLNL patent family (representative patent US #5,891,409) outlines a two-stage catalyst system for exhaust treatment. This family is linked via citations to 767 subsequent patent families, 416 of which are related to propulsion materials. Beyond these LLNL patent families, there are also two Oak Ridge National Laboratory patent families that are prominent in Table 4-7, both of which are assigned to Lockheed Martin. These two families (representative patents US #4,961,903 and US #5,084,109) describe iron aluminide alloys, and are each linked via citations to over 200 subsequent patent families, almost all of which are from outside propulsion materials technology.

The forward tracing element of the analysis shows that VTO-funded and Other DOE-funded propulsion materials patents are linked via citations to subsequent patents assigned to a number of very large companies. The influence of VTO-funded and Other DOE-funded propulsion materials research can also be seen across a range of technologies, including earth drilling, brazing and advanced materials in general (i.e. not restricted to propulsion applications).

Overall, the results from propulsion materials analysis suggest that DOE-funded patenting in this technology has increased over time, with VTO-funded patents representing a growing percentage of the total. While the portfolios of VTO-funded and Other DOE-funded propulsion materials patents are much smaller than those of the leading companies in this technology, their influence can be seen on innovations associated with these companies, notably in exhaust treatment. The influence of VTO-funded and Other DOE-funded propulsion materials patents also extends beyond the immediate technology to other areas such as earth drilling and advanced materials (where these materials are not necessarily restricted to propulsion applications).

5. Results – Lightweight Materials

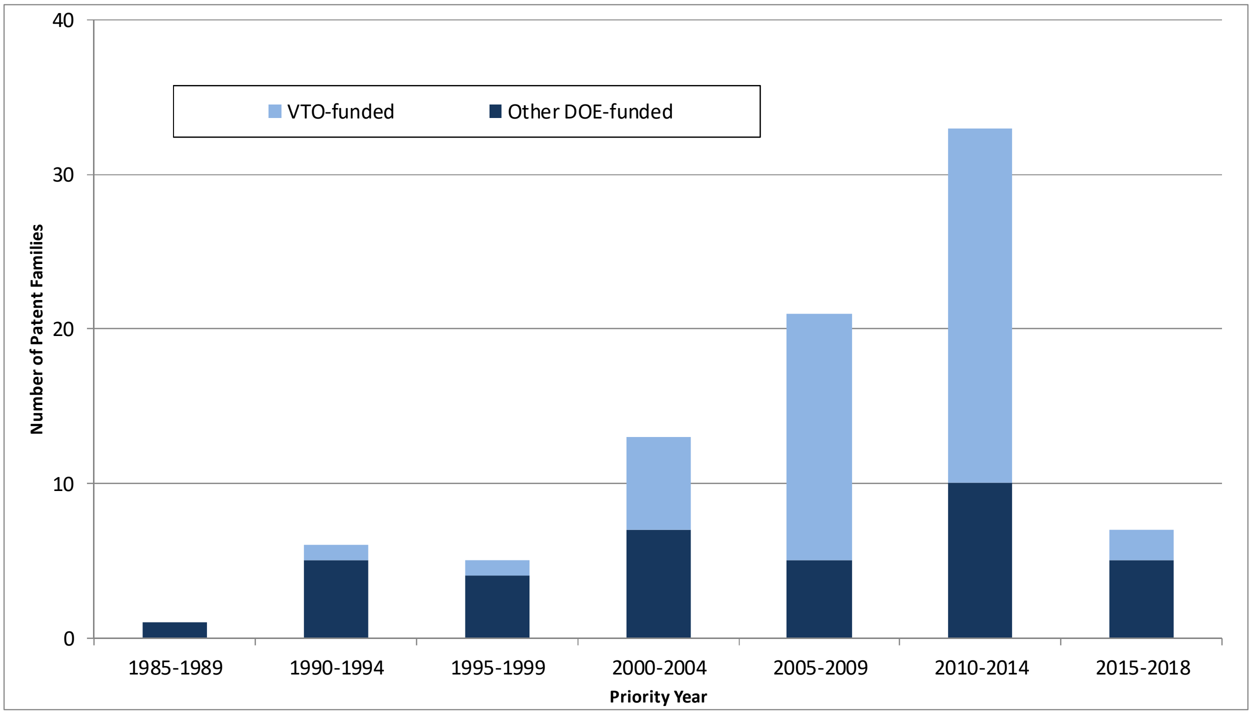
This section of the report outlines the results of our analysis tracing the influence of VTO-funded and Other DOE-funded lightweight materials research on subsequent developments both within and beyond lightweight materials technology. The results are divided into three main sections. In the first section, we examine trends in patenting over time in lightweight materials technology, and assess the distribution of VTO-funded and Other DOE-funded patents across lightweight materials technologies. The second section then reports the results of an analysis tracing backwards from lightweight materials patents owned by the leading companies in this technology. The purpose of this analysis is to determine the extent to which lightweight materials innovations developed by leading companies build upon earlier lightweight materials research funded by VTO (plus lightweight materials research funded by the remainder of DOE). In the third section, we report the results of an analysis tracing forwards from VTO-funded (and Other DOE-funded) lightweight materials patents. The purpose of this analysis is to assess the broader influence of DOE-funded research upon subsequent developments within and beyond lightweight materials technology.

Overall Trends in Lightweight Materials Patenting

Trends in Lightweight Materials Patenting over Time

Figure 5-1 shows the number of VTO-funded and Other DOE-funded lightweight materials patent families by priority year – i.e. the year of the first application in each patent family.

Figure 5-1 - Number of Lightweight Materials Patent Families funded by VTO and Other DOE Sources by Priority Year (5-Year Totals)



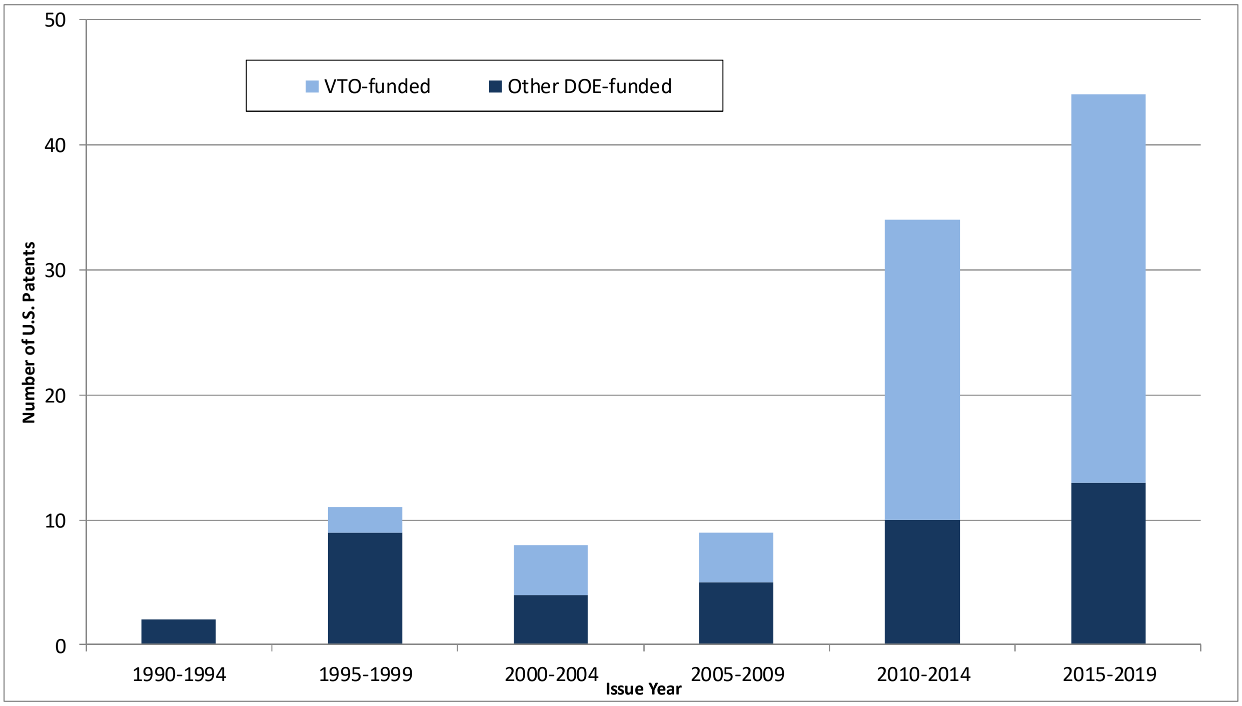
Note: The final time period in this figure is 2015-2018, and is shown for completeness, although data for this time period are incomplete. Our primary data collection covered only patents issued through 2018. Due to time lags associated with the patenting process, only a fraction of the patent families from 2015-2018 will be included.

While the data collection for this analysis covered the period from 1975 onwards, the first DOE-funded lightweight materials patent family was not filed until 1989. Throughout the 1990s, DOE-funded patenting in this technology remained sporadic, averaging around one patent family per year over this decade. Out of the twelve DOE-funded patent families filed through 1999, only two were funded by VTO.

DOE-funded lightweight materials patenting started to increase in 2000-2004, with thirteen patent families filed in this time period. This increase continued in the subsequent time periods, with 21 patent families filed in 2005-2009, and 33 families filed in 2010-2014. The final time period in Figure 5-1 is 2015-2018, which contains only partial data due to time lags associated with the patenting process. It is also notable that, from 2000 onwards, the percentage of DOE-funded patent families that are connected to VTO funding also increased, with 47 of the 74 (63.5%) of these families being VTO-funded.

Figure 5-2 shows the number of VTO-funded and Other DOE-funded lightweight materials granted U.S. patents. This figure follows a similar pattern to Figure 5-1. There is relatively little patent activity in the earlier time periods, with many of the patents defined as Other DOE-funded. Patenting then started to increase, particularly from 2010 onwards, with VTO-funded patents representing an increasing percentage of the overall number. In 2010-2014, there were 34 DOE-funded lightweight materials U.S. patents granted, 24 of which were VTO-funded. The number increased again in 2015-2019 to 44 DOE-funded U.S. patents, 31 of which were VTO-funded, even though data from this period are incomplete (see note attached to Figure 5-2).

Figure 5-2 - Number of DOE-Funded Lightweight Materials Granted U.S. Patents by Issue Year (5-Year Totals)

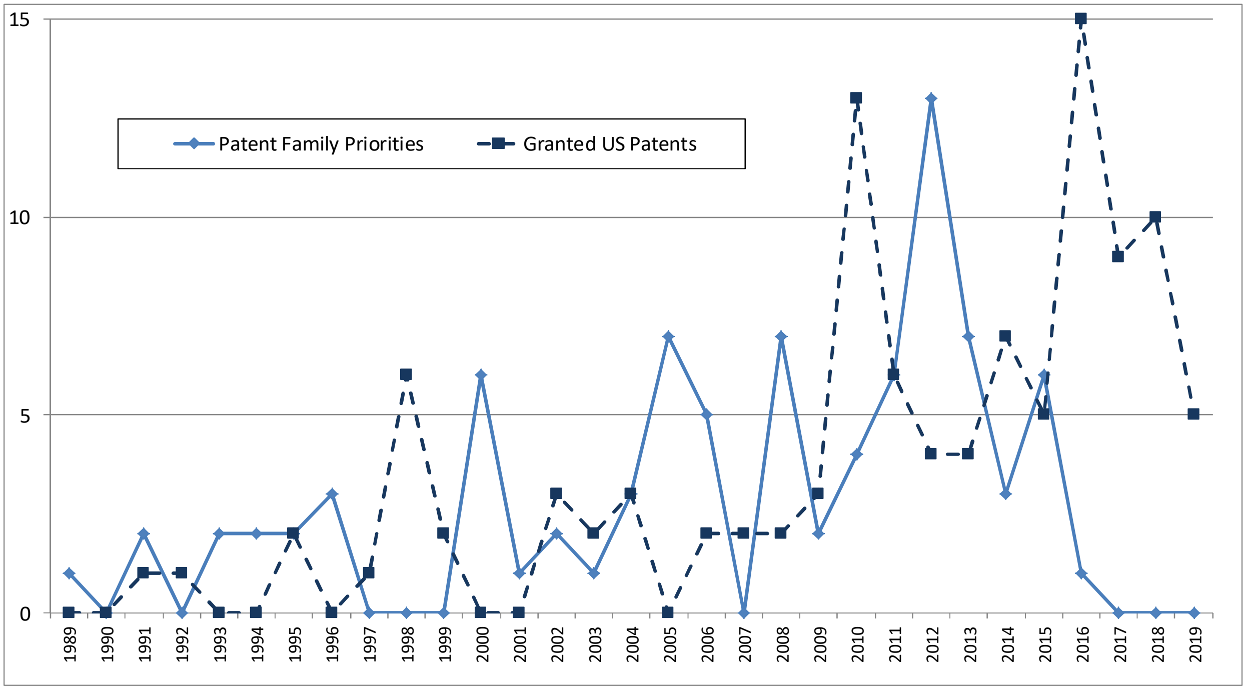


Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

Comparing Figures 5-1 and 5-2 shows the effect of time lags in the patenting process, with many of the patent families with priority dates in 2005-09 and 2010-14 (Figure 5-1) resulting in granted U.S. patents in 2010-14 and 2015-19 (Figure 5-2). These time lags can also be seen in Figure 5-3, which shows lightweight materials patent family priority years alongside issue years for granted U.S. lightweight materials patents (in this figure, VTO and Other DOE are combined, in order to simplify the presentation). Figure 5-3 reveals that the peak in patent family priorities was in 2012, with the peak in granted U.S. patents occurring in 2016 and remaining high through 2018 (note that, due to the primary data collection for this analysis ending in 2018, the number granted U.S. patents declines in 2019, and the number of patent families is zero). There was also an earlier spike in granted U.S. patents in 2010, which corresponds to earlier peaks in patent families filed in 2005 and 2008.

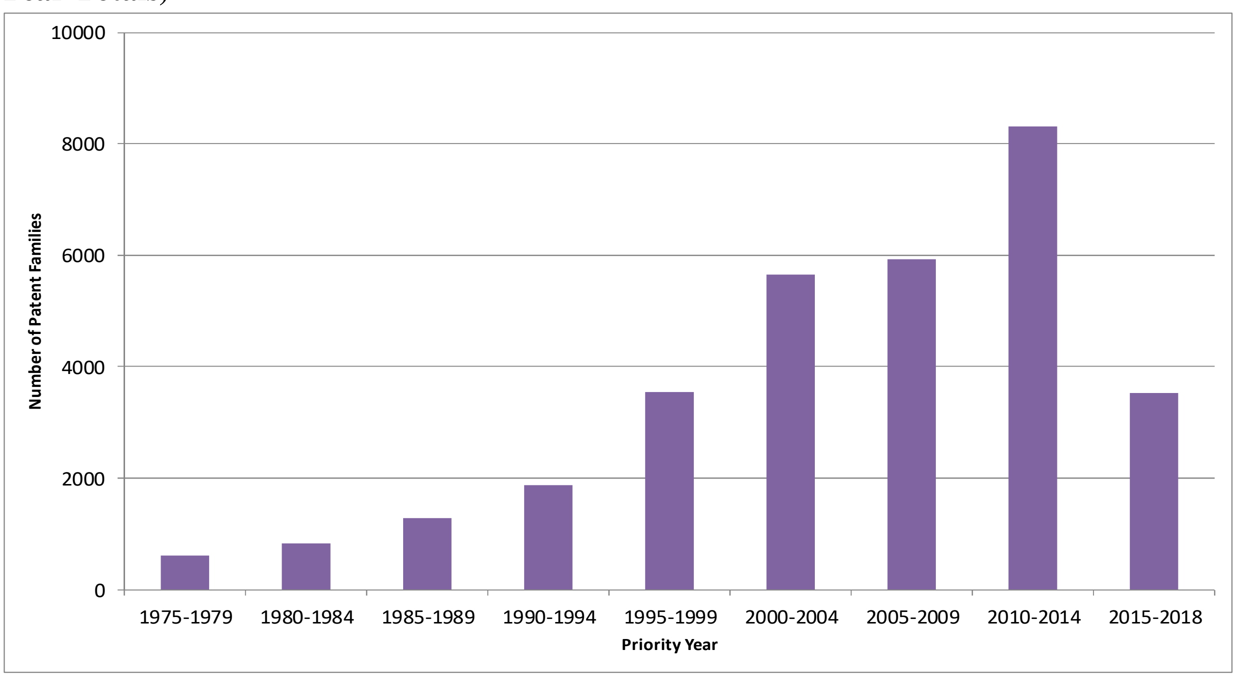
Figures 5-1 – 5-3 focus on DOE-funded lightweight materials patent families. Figure 5-4 broadens the scope, and shows the overall number of lightweight materials patent families by priority year (based on USPTO, EPO, and WIPO filings). This chart shows that patenting in lightweight materials pre-dates DOE's funding of this technology, with patent families dating back to the start of this analysis in 1975. From 1990 onwards, Figure 5-4 follows a relatively similar pattern to Figure 5-1, which focused solely on DOE-funded lightweight materials patent families. Overall lightweight materials patenting started to increase in the 1990s, and continued to grow throughout the next two decades, peaking at 8,318 patent families in 2010-14. The overall number of patent families declined in 2015-18, although data for this period are incomplete. Hence, it appears that the trend in DOE-funded lightweight materials patenting is in line with the broader trend in this technology in general.

Figure 5-3 - Number DOE-funded Lightweight Materials Patent Families (by Priority Year) and Granted U.S. Patents (by Issue Year)



Note: The data collection period for this analysis ended with 2018. The 2019 patents are included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

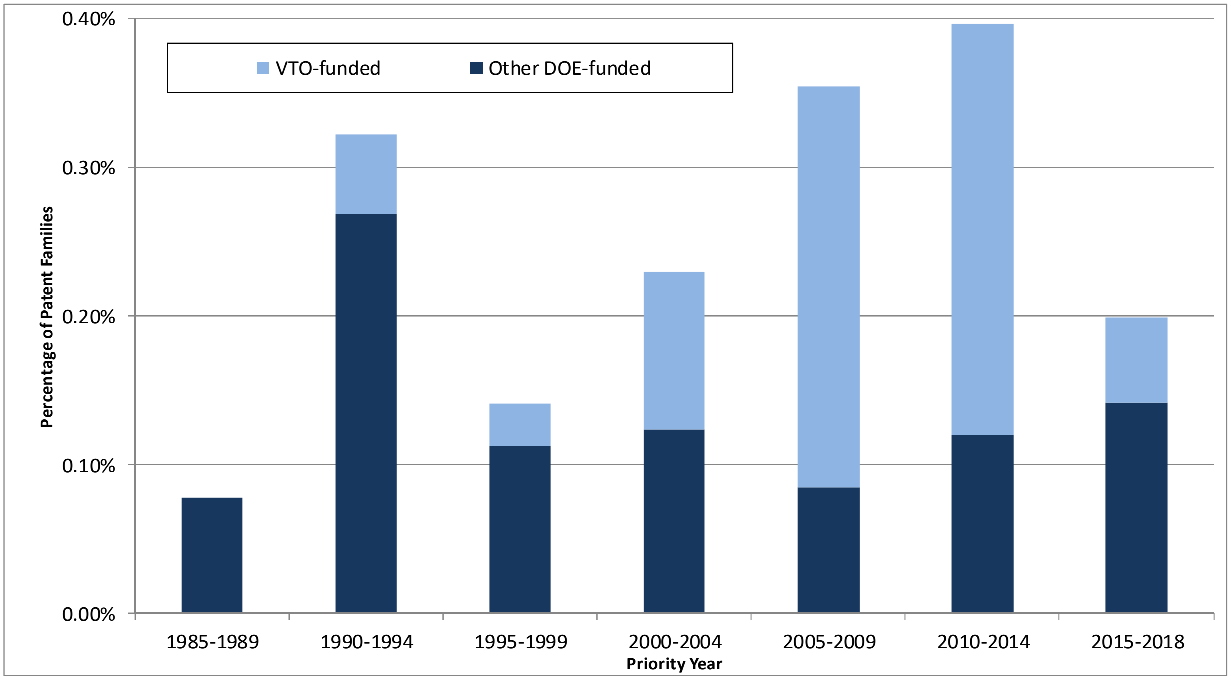
Figure 5-4 - Total Number of Lightweight Materials Patent Families by Priority Year (5-Year Totals)



Note: The final time period in this figure is 2015-2018. Data for this time period are incomplete. Due to time lags associated with the patenting process, only a fraction of the patent families from this time period will be included.

Figure 5-5 shows the percentage of lightweight materials patent families in each time period that were funded by DOE (VTO plus Other DOE). This figure reveals that less than 0.5% of patent families were funded by DOE in all time periods, with the peak of just under 0.4% coming in 2010-2014. This finding is not surprising, since lightweight materials is an active area of patenting for many leading automotive companies that have very large patent portfolios, as discussed below. Overall, 0.4% of lightweight materials patent families in 1976-2018 were funded by DOE.

Figure 5-5 - Percentage of Lightweight Materials Patent Families Funded by DOE by Priority Year



Note: The final time period in this figure is 2015-2018. Data for this time period are incomplete. Due to time lags associated with the patenting process, only a fraction of the patent families from this time period will be included.

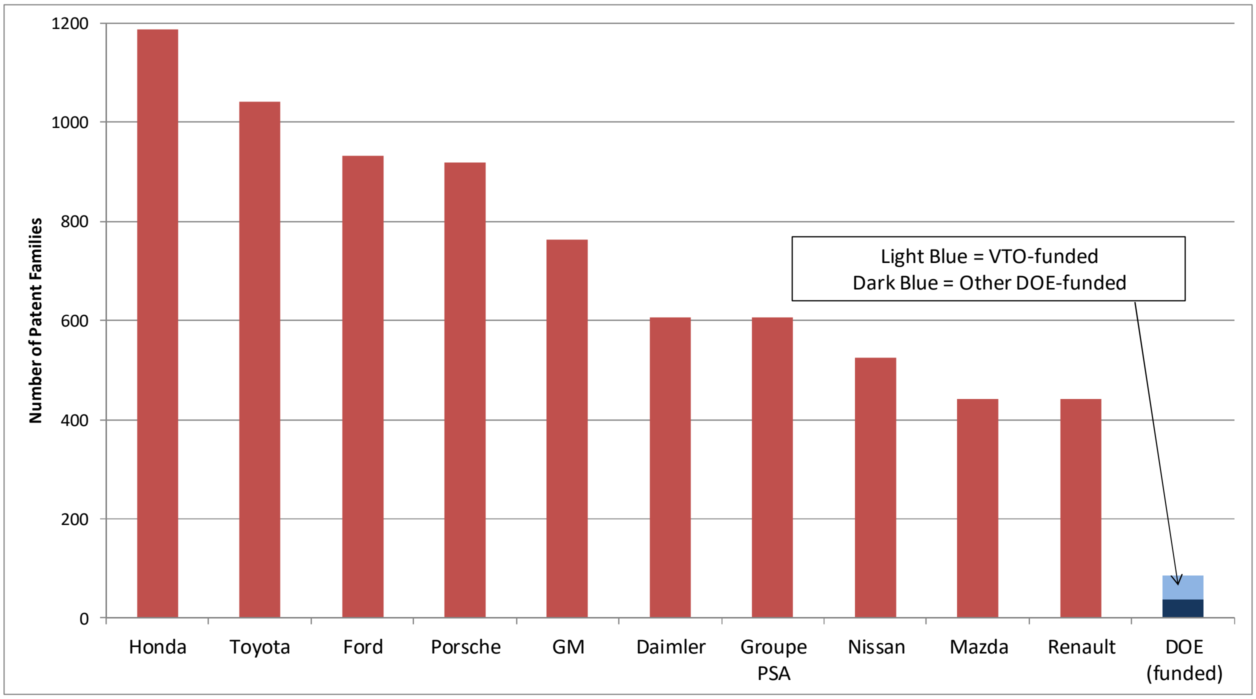
Leading Lightweight Materials Assignees

The ten leading patenting companies in lightweight materials technology are listed above in Table 3-4, along with their number of lightweight materials patent families. Figure 5-6 shows the same information in graphical form, while also including DOE-funded patent families. This figure reveals that Honda has the largest lightweight materials patent portfolio, containing 1,187 patent families, followed by Toyota (1,041 families), Ford (932) and Porsche (918). One notable feature of Figure 5-6 is the wide geographical distribution of the leading companies, with four from Europe, four from Asia and two from the U.S. This reinforces the earlier point that, while the analysis does not include patents from Asian systems, this does not mean that patents associated with Asian companies are excluded.

The DOE-funded lightweight materials patent portfolio is shown at the right-hand end of Figure 5-6. This portfolio is much smaller than those of the leading companies, containing 49 VTO-funded patent families and 37 Other DOE-funded patent families. As such, the overall DOE-funded patent portfolio is less than one-fifth the size of all the other portfolios in Figure 5-6.

Indeed, it is less than one-tenth the size of the four largest patent portfolios in this figure. In assessing the impact of VTO-funded and Other DOE-funded propulsion materials patents, versus the impact of the patent portfolios associated with the leading companies, we therefore take into account this difference in portfolio size.

Figure 5-6 – Leading Lightweight Materials Companies (based on no. of patent families)



It should be noted that there is a small amount of double-counting of patent families in Figure 5-6. Specifically, there are three Ford patent families and one General Motors patent family that were funded by VTO. These six patent families are counted in both the VTO-funded segment of Figure 5-6 and in the respective company columns. This double-counting is appropriate, since these families are both funded by VTO and assigned to a leading company.

Assignees of VTO/Other DOE Lightweight Materials Patents

The DOE-funded lightweight materials patent portfolios are constructed somewhat differently from the portfolios of the top ten companies listed in Figure 5-6. Specifically, DOE's 86 patent families are those funded by DOE, but they are not necessarily assigned to the agency. For example, VTO (or another DOE office) may have partially or fully funded research projects at DOE labs or companies. In such cases, the assignees of any resulting patents may be the respective companies or DOE lab managers (as in the example of the Ford and General Motors patent families discussed above).

Figure 5-7 shows the leading assignees on VTO-funded lightweight materials patent families. This chart is dominated by UT-Battelle, through its management of Oak Ridge National Laboratory (ORNL). There are a total of 25 VTO-funded lightweight materials patent families assigned UT-Battelle, and it is the only assignee with more than three such families. This suggests that ORNL has been a major center for VTO-funded lightweight materials research.

There are three organizations in Figure 5-7 that are each assigned three VTO-funded lightweight materials patent families – Ford, Dow and UChicago-Argonne, the latter through its management of Argonne National Laboratory (ANL).

Figure 5-7 - Assignees with Largest Number of VTO-Funded Lightweight Materials Patent Families

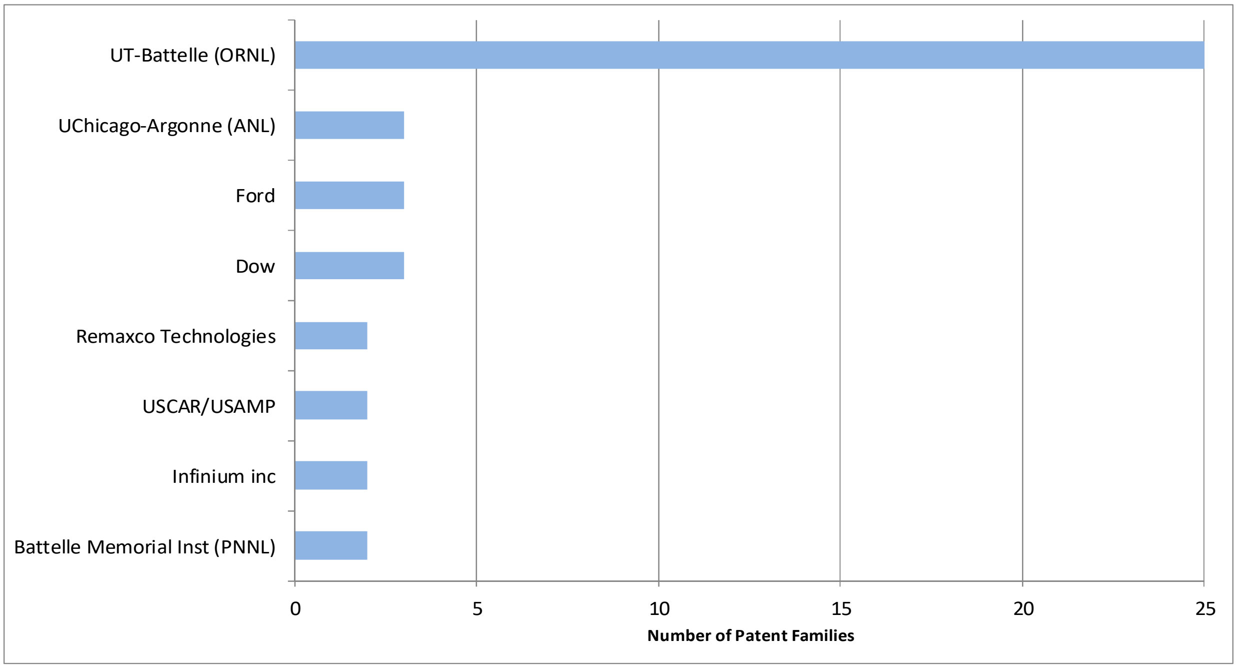


Figure 5-8 - Assignees with Largest Number of Other DOE-funded Lightweight Materials Patent Families

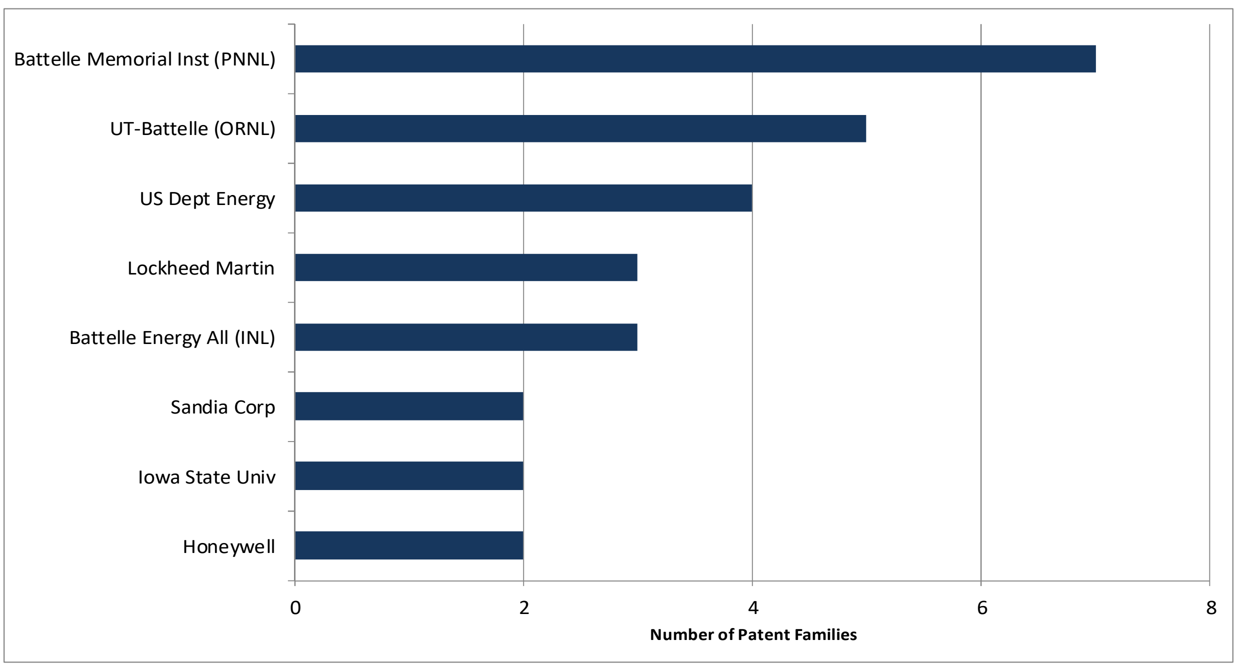


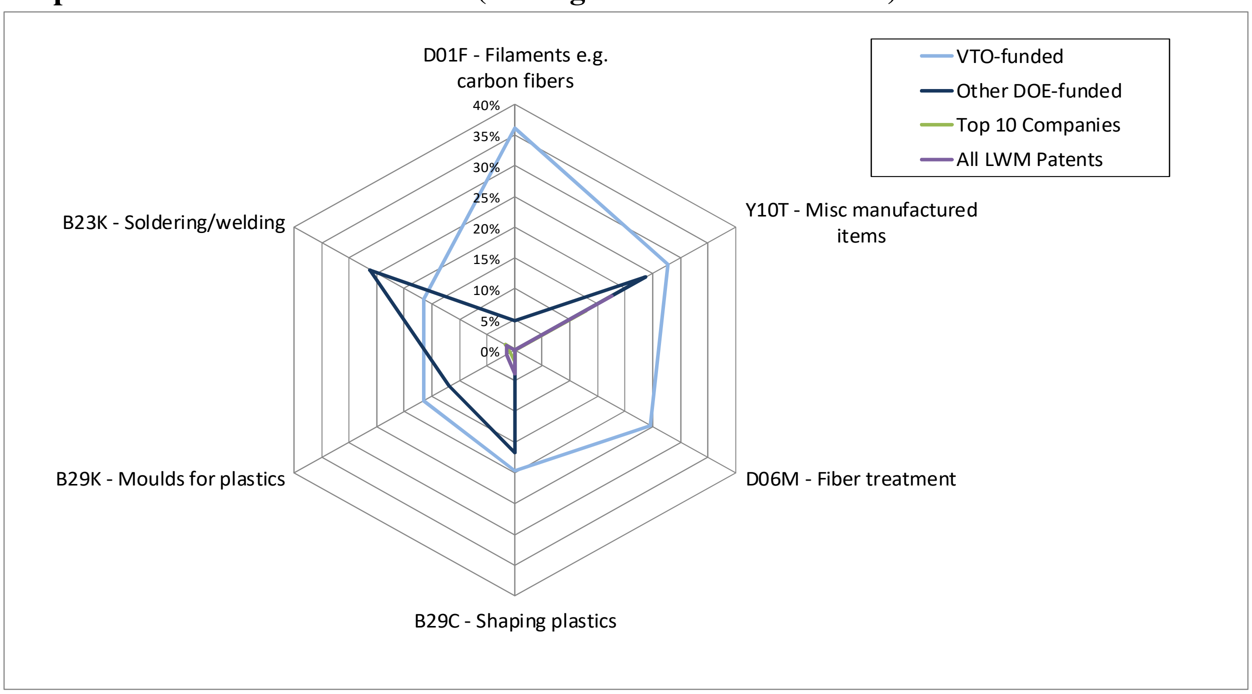
Figure 5-8 shows the leading assignees on Other DOE-funded lightweight materials patent families. This figure is headed by two DOE laboratory managers – Battelle Memorial Institute

(Pacific Northwest National Laboratory) and UT-Battelle (ORNL) – with seven and five Other DOE-funded patent families respectively. There are also patent families in Figure 5-8 assigned to Battelle Energy Alliance, through its management of Idaho National Laboratory (INL) and Sandia Corporation (Sandia National Laboratory). In addition, there are four patent families assigned to DOE itself. This may occur for various reasons, including where the inventors are federal employees; where the funding recipient elects not to pursue patent protection for, or take title to, the invention; or where the recipient does not have the right to take title to the invention.

Distribution of Lightweight Materials Patents across Patent Classifications

We analyzed the distribution of VTO-funded lightweight materials U.S. patents across Cooperative Patent Classifications (CPCs).[13] We then compared this distribution to those associated with Other DOE-funded lightweight materials patents; lightweight materials patents assigned to the ten leading companies; and the universe of all lightweight materials patents. This analysis provides insights into the technological focus of VTO funding in lightweight materials, versus the focus of the remainder of DOE, leading lightweight materials companies, and lightweight materials technology in general. The results from this CPC analysis are shown in two separate charts, each from a different perspective. The first chart (Figure 5-9) is based on the six CPCs that are most prevalent among VTO-funded lightweight materials patents. The purpose of this chart is thus to show the main focus areas of VTO-funded lightweight materials research, and the extent to which these areas translate to other portfolios (Other DOE-funded; leading lightweight materials companies; all lightweight materials).

Figure 5-9 - Percentage of Lightweight Materials U.S. Patents in Most Common Cooperative Patent Classifications (Among VTO-Funded Patents)

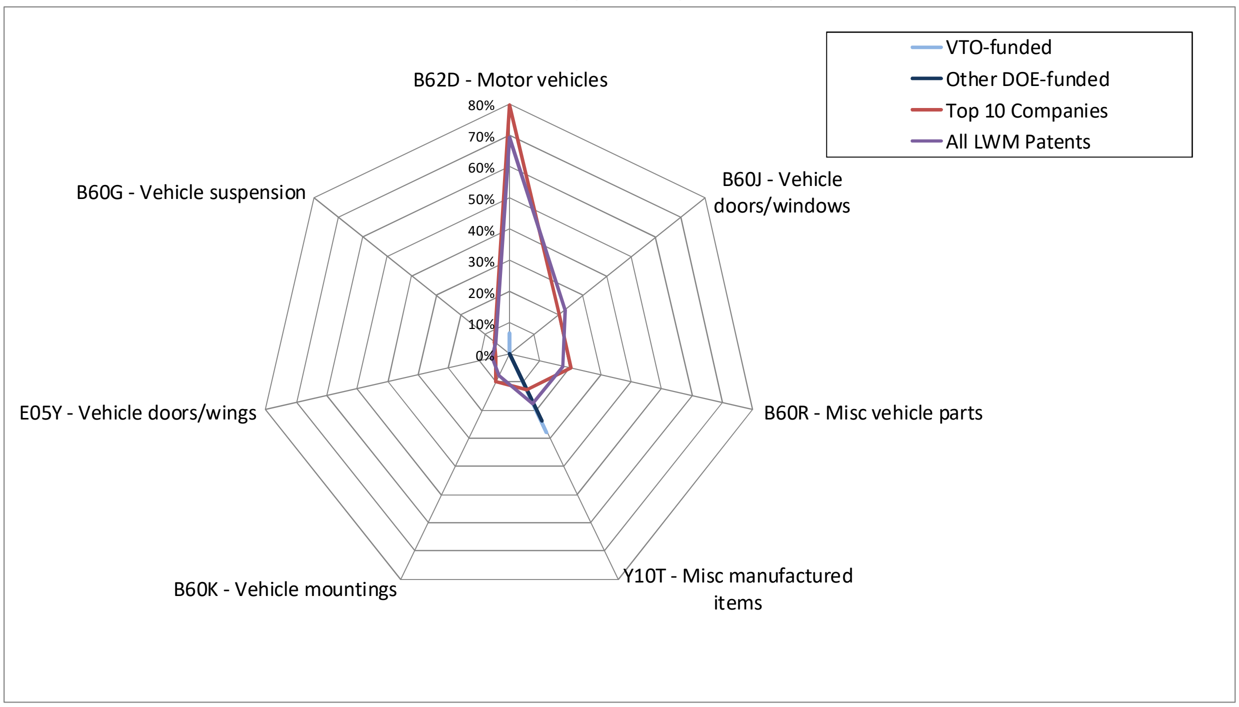


[13] The CPC is a patent classification system. Patent offices attach numerous CPC classifications to a patent, covering the different aspects of the subject matter in the claimed invention. In generating these charts, all CPCs associated with each patent are included.

This figure shows that VTO-funded research includes relatively balanced coverage across the six CPCs (which is not particularly surprising, since the VTO-funded patent portfolio forms the basis for the CPCs included in the chart). There are three main concentrations of the VTO-funded patents, namely carbon fibers (CPCs D01F and D06M), plastics (CPCs B29C and B29K) and soldering/welding (CPC B23K). The Other DOE-funded patents share the concentration on plastics and soldering/welding, but have much less focus on carbon fibers. Meanwhile, it is notable that the leading companies, and lightweight materials patents overall, have very little presence in the CPCs in Figure 5-9.

Figure 5-10 is similar to Figure 5-9, except that it is from the perspective of the most common CPCs among all lightweight materials patents. Hence, the purpose of this chart is to show the main research areas within lightweight materials as a whole, and how these areas are represented in selected lightweight materials portfolios (VTO-funded; Other DOE-funded; leading lightweight materials companies). The only CPC in Figure 5-9 that also appears in Figure 5-10 is Y10T, which relates to a wide variety of manufactured items. Beyond this CPC, Figure 5-10 focuses on CPCs related to different vehicle components and structural elements, such as suspensions, mountings and doors. Neither VTO-funded nor Other DOE-funded patents have a notable presence in these CPCs.

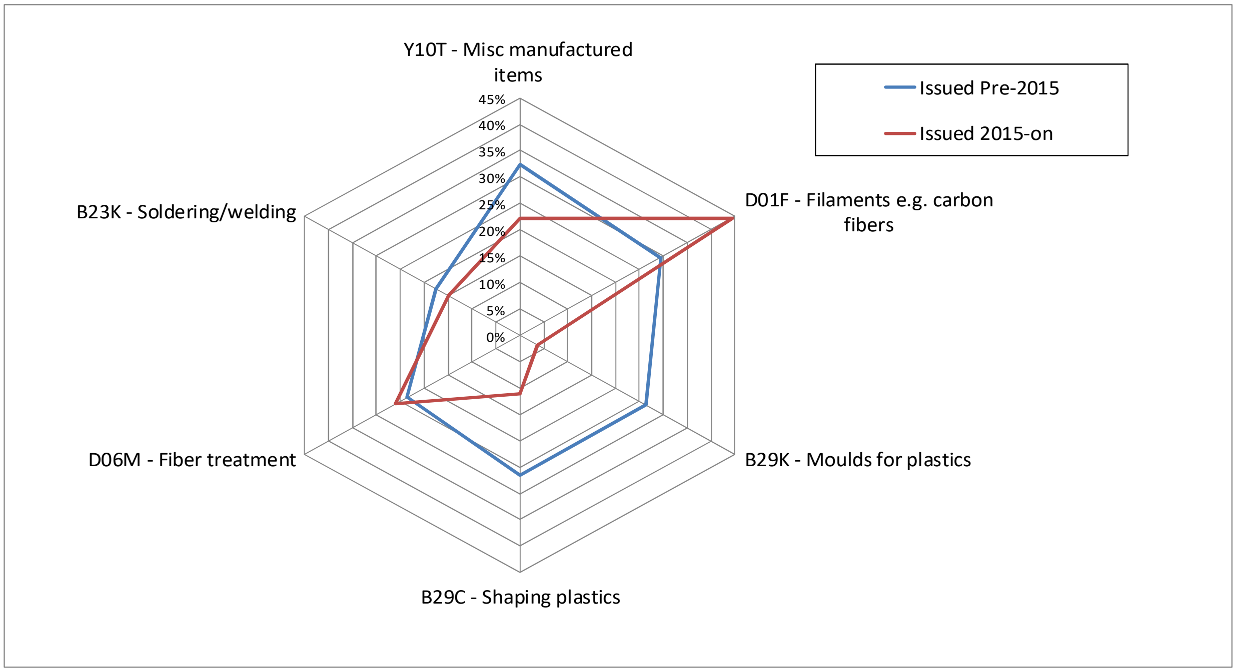
Figure 5-10 - Percentage of Lightweight Materials U.S. Patents in Most Common Cooperative Patent Classifications (Among All Lightweight Materials Patents)



When looked at in tandem, Figures 5-9 and 5-10 suggest that the technological focus of VTO-funded and Other DOE-funded lightweight materials patents is very different to that of the leading companies. Specifically, while the DOE-funded portfolios focus on advanced materials, plus handling of these materials, the patents of the leading companies concentrate more on practical applications of such materials in vehicle parts and structural elements.

Figure 5-11 compares the CPC distribution of VTO-funded lightweight materials U.S. patents across two time periods – patents issued through 2014, and those issued from 2015 onwards. This figure reveals that CPCs related to carbon fibers (i.e. D01F and D06M) are more prominent in the post-2015 period, while CPCs concerned with plastics (i.e. B29C and B29K) are associated more with earlier patents. This suggests that carbon fibers are an area of increasing focus for recent recipients of VTO lightweight materials funding.

Figure 5-11 - Percentage of VTO-funded Lightweight Materials U.S. Patents in Most Common Cooperative Patent Classifications across Two Time Periods



Tracing Backwards from Lightweight Materials Patents Owned by Leading Companies

This section reports the results of an analysis tracing backwards from lightweight materials patents owned by leading companies in this technology to earlier research, including that funded by VTO (and by DOE in general). The results in this section are examined at two levels. First, we report results at the organizational level. These results reveal the extent to which VTO-funded (and Other DOE-funded) research forms a foundation for subsequent innovations associated with leading lightweight materials companies. Second, we drill down to the level of individual patents, with a particular focus on VTO-funded lightweight materials patents. These patent-level results highlight specific VTO-funded patents that are linked to subsequent patents owned by leading companies. They also highlight which lightweight materials patents owned by these leading companies are linked to earlier VTO-funded research.

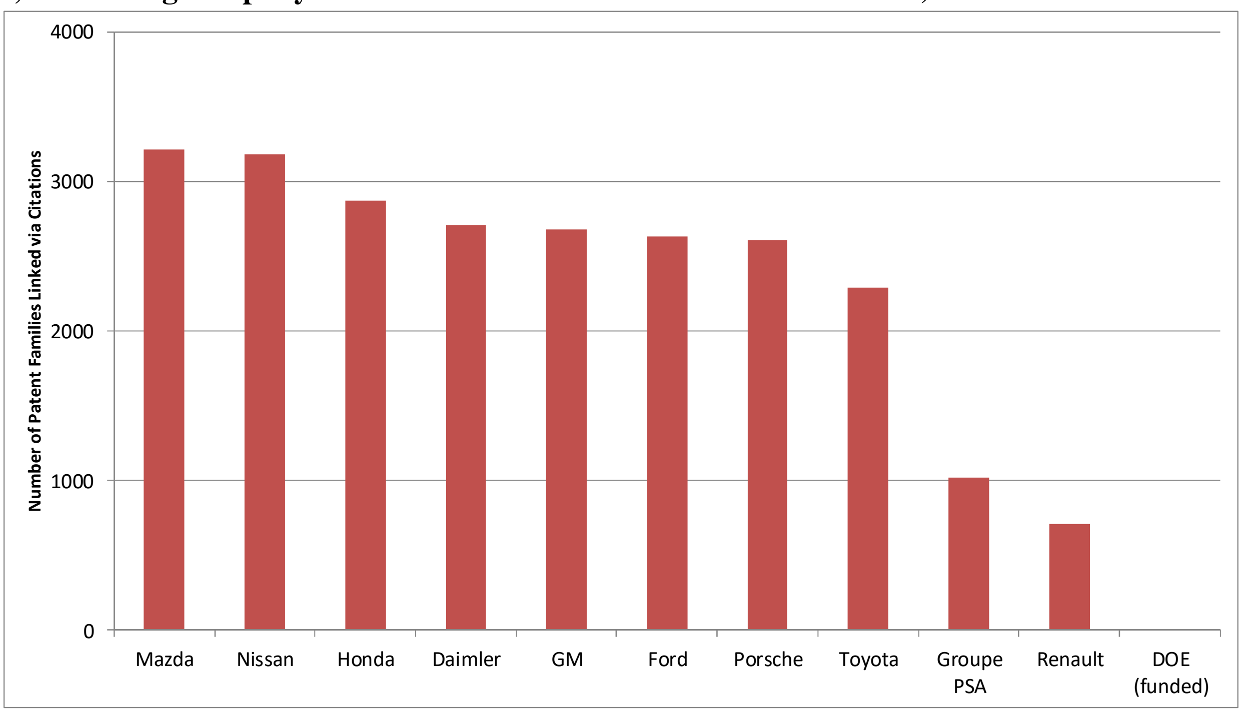
Organizational Level Results

In the organizational level results, we first compare the influence of VTO-funded and Other DOE-funded lightweight materials research against the influence of leading companies in this technology. We then identify which of these leading companies build on DOE-funded lightweight materials research.

Figure 5-12 compares the influence of VTO-funded and Other DOE-funded lightweight materials research to the influence of research carried out by the top ten lightweight materials companies. Specifically, this figure shows the number of lightweight materials patent families owned by the leading companies that are linked via citations to earlier lightweight materials patent families assigned to each of these leading companies (plus patent families funded by DOE). In other words, this figure shows the companies whose patents have had the strongest influence upon subsequent developments made by leading companies in lightweight materials.[14]

In total, only ten leading company propulsion materials patent families are linked via citations to earlier DOE-funded propulsion materials patents (nine to VTO-funded patents; one to Other DOE-funded patents). This finding puts DOE-funded patents at the bottom of Figure 5-12 by a wide margin. In comparison, over 3,000 leading company patent families are linked via citations to earlier Mazda and Nissan patent families.

Figure 5-12 - Number of Leading Company Lightweight Materials Patent Families Linked via Citations to Earlier Lightweight Materials Patents from each Leading Company (e.g. 3,210 leading company families are linked to earlier Mazda families)



[14] This figure compares the influence of patents *funded* by VTO/Other DOE against patents *owned* by (i.e. assigned to) organizations. Such a comparison is reasonable, since patents funded by organizations through their R&D budgets will be assigned to those organizations. Also, organizations cannot choose to reference the patents of a non-competitor (such as DOE) rather than the patents of a competitor in order to reduce the "credit" given to that competitor. Such an omission could lead to the invalidation of their patents. Note that, as in Figure 5-6, there is a small amount of double-counting in Figure 5-12, as some patent families assigned to Ford and GM were funded by DOE. Also, in Figures 5-12 – 5-15, leading company patent families linked to both VTO-funded and Other DOE-funded patents are allocated to the VTO-funded segment of the DOE column, in order to avoid double-counting these families.

Figure 5-12 does not take into account the different sizes of the patent portfolios associated with the various companies. For example, it is not surprising that many more patent families are linked via citations to Mazda than to DOE, since Mazda has many more lightweight materials patent families available to be cited as prior art.

Figure 5-13 takes into account the differences in patent portfolio size. It shows the average (mean) number of leading company patent families linked to patent families associated with each of the companies (plus DOE) in Figure 5-12. Mazda is again at the head of this figure, with each of its patent families linked to an average of over seven families assigned to the leading companies. On average, DOE-funded lightweight materials patent families are each linked to 0.12 patent families assigned to the leading companies. DOE thus remains at the bottom of Figure 5-13, even after accounting for patent portfolio size. This suggests that the VTO-funded and Other DOE-funded lightweight materials patent portfolios have had little influence on the vehicle-related lightweight materials patents of the leading companies. Hence, to the extent it extents, their influence must be found elsewhere.[15]

Figure 5-13 – Mean Number of Leading Company Lightweight Materials Patent Families Linked via Citations to Lightweight Materials Families from Each Leading Company (e.g. on average, each Mazda patent family is linked to 7.3 subsequent patent families assigned to leading companies)

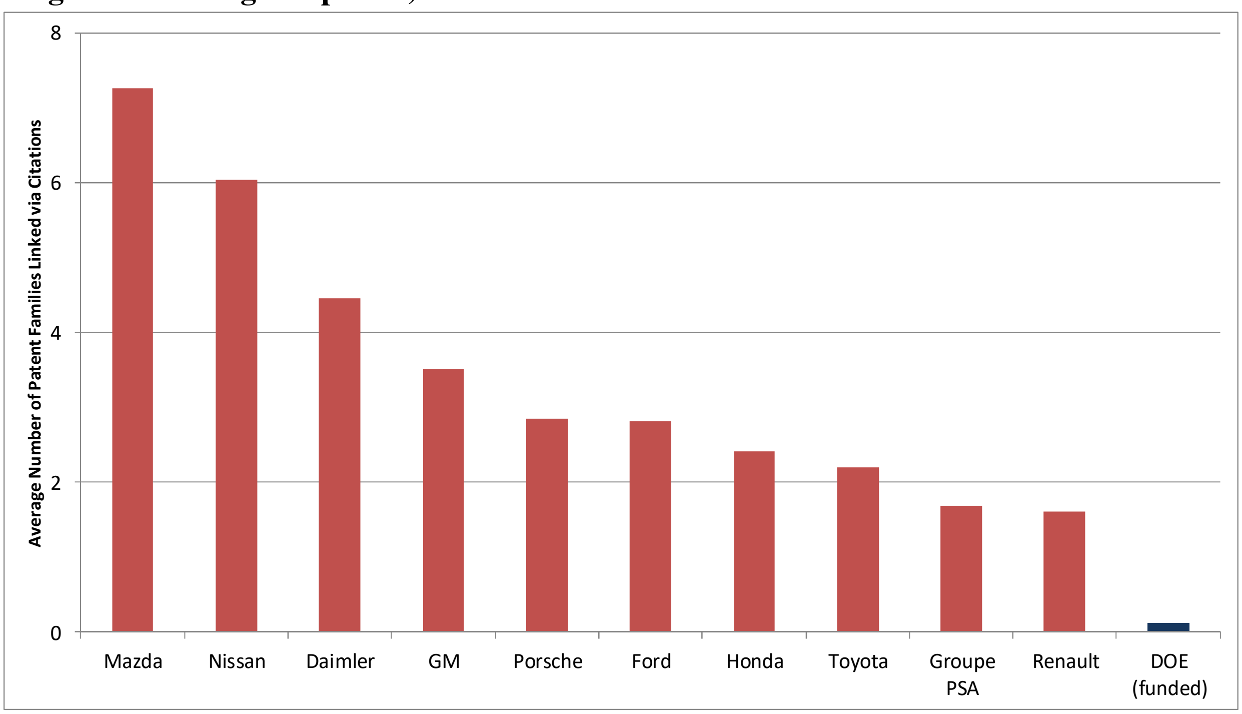
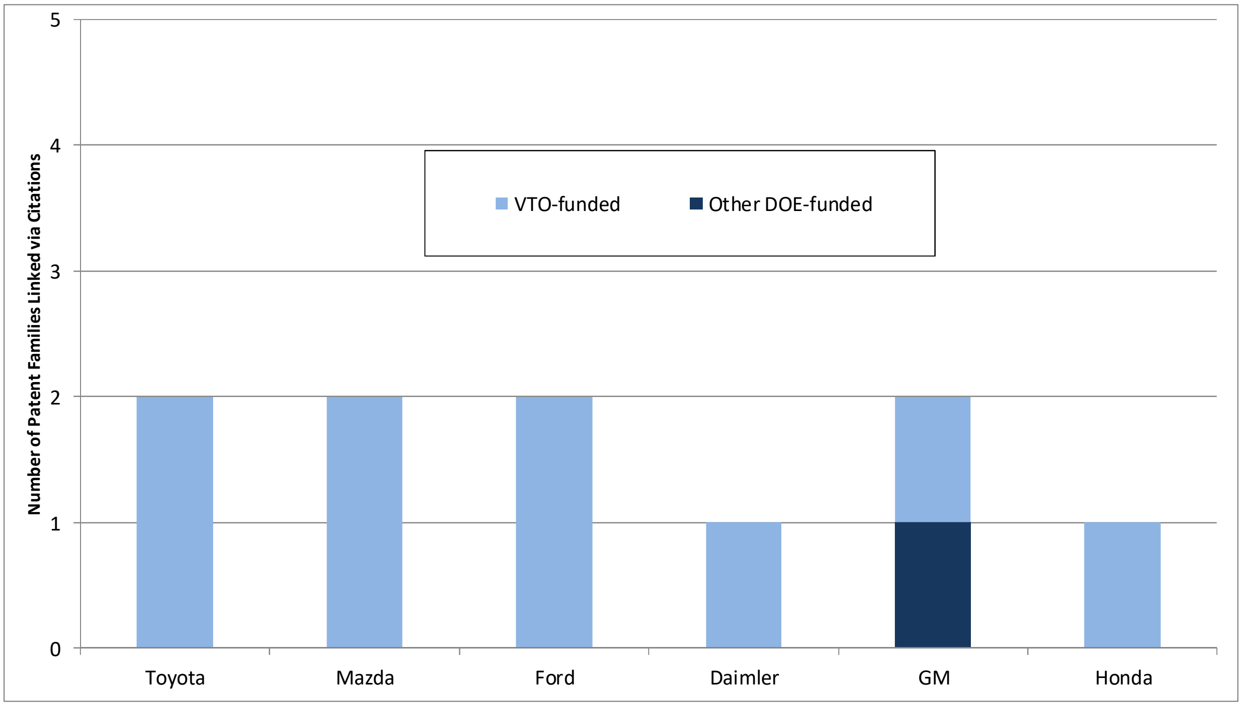


Figure 5-14 shows which leading companies have lightweight materials patent families linked via citations to earlier VTO-funded and Other DOE-funded patents. Six of the ten companies

[15] Note that, although there are few citation links between the lightweight materials patents of leading companies and earlier VTO-funded and Other DOE-funded patents, this does not rule out the possibility that these leading companies may have used materials developed with DOE funding in production (but without necessarily patenting the use of these materials in this application).

have at least one patent family linked to VTO-funded patents (Toyota, Mazda, Ford, Daimler, General Motors and Honda), but none of them have more than two such families. This reinforces the finding that VTO-funded lightweight materials patents are not connected extensively via citations to subsequent patents assigned to the leading companies.[16]

Figure 5-14 - Number of Patent Families Assigned to Leading Lightweight Materials Companies Linked via Citations to Earlier VTO/Other DOE-funded Lightweight Materials Patents



Patent Level Results

The previous section of the report examined results at the level of entire patent portfolios. The purpose of this section is to drill down to identify individual DOE-funded lightweight materials patent families (in particular VTO-funded families) are linked via citations to subsequent lightweight materials patents owned by leading companies in this technology. Looking in the opposite direction, it also identifies individual lightweight materials patents owned by leading companies that have citation links to earlier VTO-funded research.

Figure 5-12 (above) revealed that there is a total of nine leading company patent families linked citations to earlier VTO-funded families. Table 5-1 reveals that all nine of these citation links are to two VTO-funded patent families. Both of these VTO-funded families are co-assigned to the U.S. Council for Automotive Research (USCAR) and the U.S. Automotive Materials Partnership (USAMP), and were filed in 2008. The first of these patent families (whose representative patent[17] is US #7,819,452) describes composite panels for vehicles. It is linked via citations to

[16] Due to the small number of leading company patent families linked via citations to DOE in lightweight materials, we did not include figures equivalent to Figure 4-15 and 4-16 from the propulsion materials analysis.
[17] The representative patent is a single patent from a family, but it is not necessarily the priority filing.

five subsequent patent families assigned to the leading companies. These include Honda, Mazda and Toyota families related to vehicle body panels and methods for manufacturing them. The second VTO-funded patent (representative patent number US #7,784,856) describes a vehicle floor pan. It is linked via citations to four subsequent patent families assigned to the leading companies, including Daimler, Ford and GM families related to vehicle body stiffening and impact resistance.

Table 5-1 - VTO Funded Lightweight Materials Patent Families Linked via Citations to Most Subsequent Leading Company Lightweight Materials Patent Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
41266259	7819452	2008	5	USCAR/USAMP	Automotive structural joint and method of making same
40850005	7784856	2008	4	USCAR/USAMP	Dynamic load bearing composite floor pan for an automotive vehicle

Table 5-2 looks in the opposite direction to Table 5-1, and lists the nine lightweight materials patent families owned by leading companies that are linked via citations to earlier patents funded by VTO. The first five of these families are linked to the first VTO-funded patent family in Table 5-1, while the bottom four families are linked to the second VTO-funded family in that table.

Table 5-2 - Leading Company Lightweight Materials Patent Families Linked via Citations to Largest Number of VTO Funded Lightweight Materials Patent Families

Patent Family #	Representative Patent #	Priority Year	# VTO Fams	Assignee	Title
49881902	9676421	2012	1	Honda	Welded structure for vehicle body panel
47710841	8702160	2011	1	Mazda	Vehicle-body structure of vehicle and manufacturing method of the same
47665274	8708390	2011	1	Mazda	Vehicle-body structure of vehicle and manufacturing method of the same
46757489	9169860	2011	1	Toyota	Adhesion flange structure
54840017	9428225	2014	1	Toyota	Vehicle panel joint structure
52117857	9914489	2013	1	Daimler	Underbody stiffening and covering module
54010397	9327666	2014	1	Ford	Passive structural design that improves impact signal during side impact
59382472	9718498	2016	1	Ford	Vehicular body structure
52017519	9440682	2014	1	General Motors	Outward splayed mixed material longitudinal rail system

Beyond listing the nine leading company lightweight materials patent families linked via citations to earlier VTO-funded patents, we also examined the forward citation records associated with the patents in these nine families. The idea is to determine the extent to which leading company innovations linked to earlier VTO-funded patents have themselves started to influence subsequent technological developments.[18]

[18] The influence of patents is evaluated using 1790's Citation Index metric. This metric is derived by first counting the number of times a patent is cited as prior art by subsequent patents. This number is then divided by the mean number of citations received by peer patents from the same issue year and technology (as defined by their first listed Cooperative Patent Classification). For example, the number of citations received by a 2010 patent in CPC B60G (Vehicle Suspensions) is divided by the mean number of citations received by all patents in that CPC issued in 2010. The expected Citation Index for an individual patent is one. The extent to which a patent's Citation Index is greater

Table 5-3 lists the lightweight materials patents owned by leading companies that have Citation Index values above one (i.e. they have been cited more frequently than expected), and are linked via citations to earlier VTO-funded lightweight materials patents. The patents in this table are relatively new, so have not had much time to be cited by subsequent patents, hence the low citation counts. That said, these patents – assigned to Ford, Mazda and Toyota and describing structural elements for vehicles – have started to attract more citations than expected. In turn, they are linked to earlier VTO-funded research on vehicle structures.

Table 5-3 - Highly Cited Leading Company Lightweight Materials Patents Linked via Citations to Earlier VTO-funded Lightweight Materials Patents

Patent	Issue Year	# Cites Received	Citation Index	Assignee	Title
9327666	2016	3	1.77	Ford	Passive structural design that improves impact signal during side impact
8702160	2014	6	1.73	Mazda	Vehicle-body structure of vehicle and manufacturing method of the same
8708390	2014	6	1.69	Mazda	Vehicle-body structure of vehicle and manufacturing method of the same
9428225	2016	3	1.60	Toyota	Vehicle panel joint structure

Beyond the nine leading company lightweight materials patent families linked via citations to earlier VTO-funded patents, there is also one citation link to an Other DOE-funded patent family. This Other DOE-funded patent family (representative patent #5,799,238), which was filed in 1995, is shown in Table 5-4. It is assigned to the Department of Energy, and describes a titanium ceramic composite material with high strength and stiffness. It is linked via citations to a subsequent General Motors patent family (representative patent US #7,637,559) describing a shape memory alloy used for impact mitigation.

Table 5-4 - Other DOE-Funded Lightweight Materials Patent Families Linked via Citations to Subsequent Leading Company Lightweight Materials Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
23947309	5799238	1995	1	US Dept Energy	Method of making multilayered titanium ceramic composites

Overall, the backward tracing element of the lightweight materials analysis suggests that VTO-funded and Other DOE-funded patents have relatively few citation links to subsequent vehicle-related lightweight materials patents assigned to the leading companies. To the extent it exists, the influence of these DOE-funded patents must therefore be found elsewhere, a subject that is addressed in the analysis described in the following section.

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. By extension, the expected Citation Index for a portfolio of patents is also one. Values above one show a portfolio that has been cited more than expected, and values below one show a portfolio that has not been cited as frequently as expected. Note that the Citation Index is calculated for U.S. patents only, due to the differences in citation practices across different countries' patent systems.

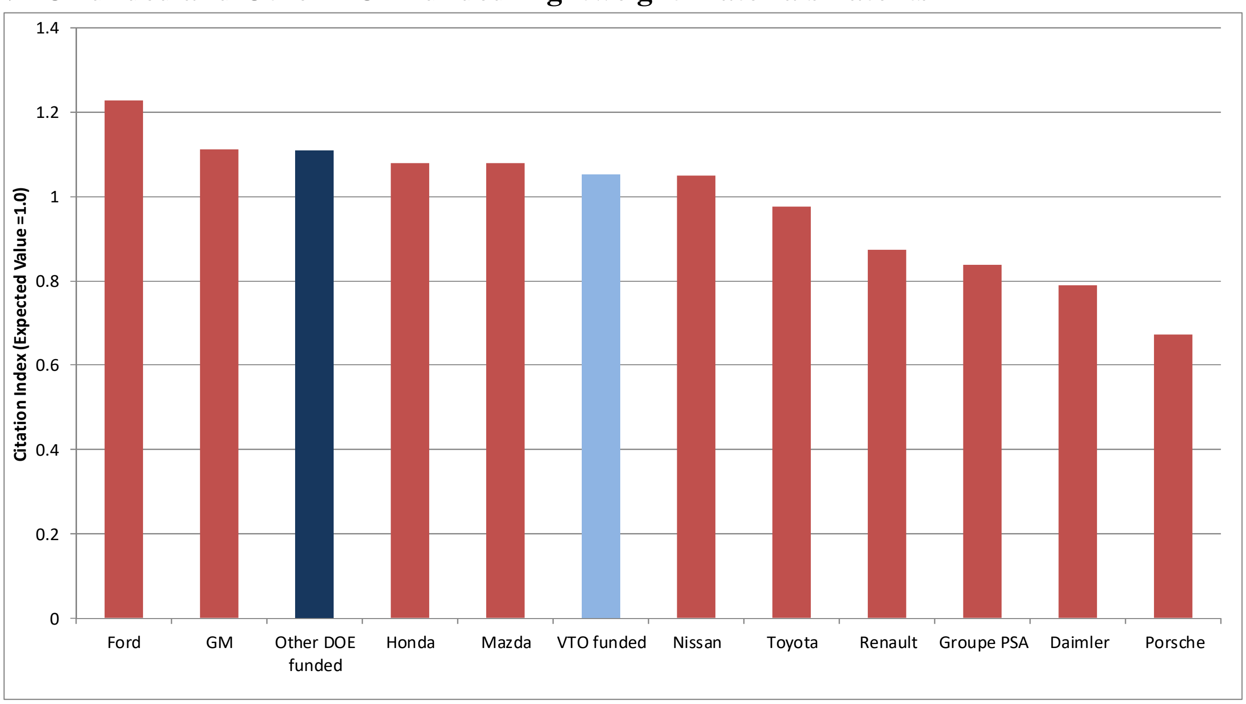
Tracing Forwards from DOE-funded Lightweight Materials Patents

The previous section of the report examines the influence of DOE-funded lightweight materials research upon technological developments associated with leading lightweight materials companies. That analysis was based on tracing backwards from the patents of leading companies to previous generations of research. This section reports the results of an analysis tracing in the opposite direction – starting with VTO-funded (and Other DOE-funded) lightweight materials patents, and tracing forwards in time through two generations of citations. Hence, while the previous section of the report focuses on DOE's influence upon a specific patent set (i.e. patents owned by leading lightweight materials companies), this section of the report focuses on the broader influence of VTO-funded (and Other DOE-funded) lightweight materials research, both within and beyond the lightweight materials industry. Also, in order to avoid repeating earlier results, the forward tracing concentrates primarily on patents that are linked to DOE-funded lightweight materials research, but are not owned by leading lightweight materials companies.

Organizational Level Results

We first generated Citation Index values for the portfolios of VTO-funded and Other DOE-funded lightweight materials patents. We then compared these Citation Indexes against those of the ten leading lightweight materials companies. The results are shown in Figure 5-15.

Figure 5-15 - Citation Index for Leading Companies' Lightweight Materials Patents, plus VTO-funded and Other DOE-funded Lightweight Materials Patents



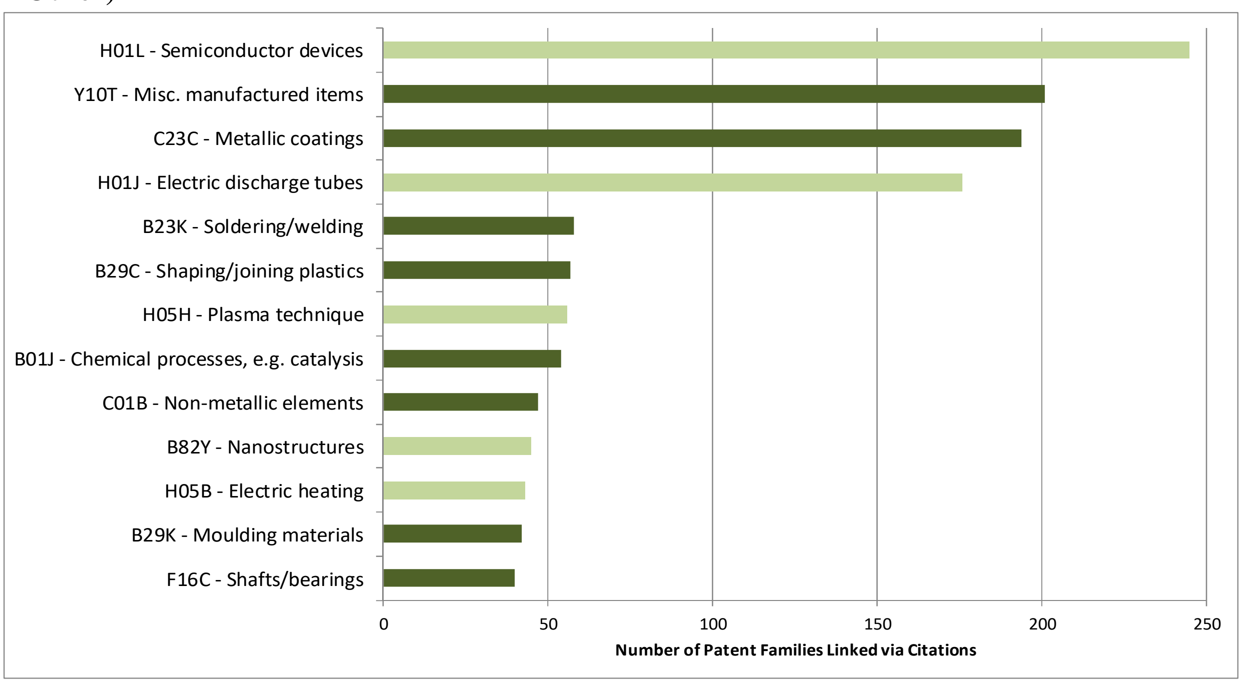
This figure reveals that the overall Citation Index values for all the companies, plus the portfolios of VTO-funded and Other-DOE funded lightweight materials patents, are relatively narrowly distributed. Ford has the highest Citation Index of 1.23 (i.e. its patents have been cited 23% more frequently than expected by subsequent patents), while Porsche has the lowest Citation Index of 0.67 (i.e. its patents have been cited 33% less frequently than expected). VTO-funded lightweight materials patents have an average Citation Index of 1.06, showing they have been cited slightly more frequently than expected (specifically 6% more frequently). The Citation Index for Other DOE-funded lightweight materials patents is slightly higher at 1.11 (i.e. 11% more citations than expected). This puts both DOE-funded portfolios among the middle group of companies in terms of Citation Index values.

Referring to the backward tracing results, the VTO-funded and Other DOE-funded patents had very few citation links to subsequent vehicle-related lightweight materials patents assigned to the leading companies. Yet their Citation Index values are above average, albeit marginally. This suggests that much of the influence of these DOE-funded lightweight materials patents has been on patents beyond vehicle-related lightweight materials patents assigned to the leading companies, a suggestion that is borne out in the forward tracing results below.

The Citation Index metric measures the overall influence of DOE-funded lightweight materials patents, but does not necessarily address the breadth of this influence across technologies. We therefore identified the Cooperative Patent Classifications (CPCs) of the patent families linked via citations to earlier VTO-funded (and Other DOE-funded) lightweight materials patent families.[19] These CPCs reflect the influence of DOE-funded research across technologies.

Figure 5-16 shows the CPCs with the largest number of patent families linked to VTO-funded lightweight materials patents.

Figure 5-16 - Number of Patent Families Linked via Citations to Earlier VTO-Funded Lightweight Materials Patents by CPC (Dark Green =Lightweight Materials; Light Green = Other)

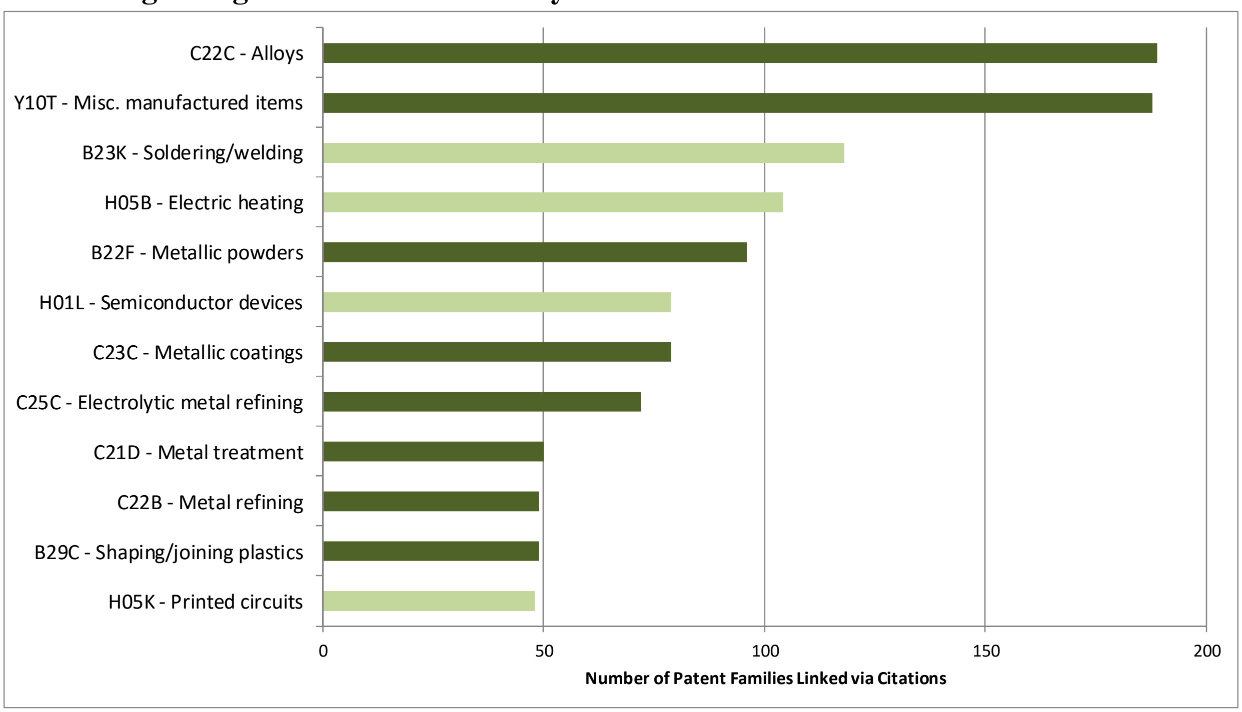


[19] Patents typically have numerous CPCs attached to them, reflecting different aspects of the invention they describe. In this analysis, we include all CPCs attached to the patents linked to earlier DOE-funded lightweight materials patent families.

The CPCs in this figure are shown in two different colors – i.e. dark green for CPCs related to lightweight materials technology and light green for CPCs beyond lightweight materials technology. The former group includes CPCs related to metallic coatings (C23C), soldering and welding (B23K), plastics handling (B29C), plus miscellaneous manufactured items (Y10T) with a particular focus on carbon fiber layers (Y10T 428/30). That said, there are no CPCs in Figure 5-16 directed specifically to vehicle applications of lightweight materials. Meanwhile, the most prominent CPCs in the latter group relate to semiconductors (H01L) and electric discharge tubes (H01J). Patents in these CPCs focus primarily on coatings and deposition techniques, and are linked via citations to earlier VTO-funded lightweight materials patents describing carbon fibers, and the manufacture of such fibers using plasma technology. These are examples of the influence of VTO-funded lightweight materials research extending into other technologies.

Figure 5-17 is similar to Figure 5-16, but is based on patent families linked via citations to Other DOE-funded lightweight materials patents. Again, CPCs related to lightweight materials are shown in dark green, while CPCs related to other technologies are in light green. Compared to Figure 5-16, there is more of a focus on CPCs related to lightweight materials (although there are again no CPCs for vehicle applications). These CPCs have a particular concentration on metals and metal processing technology. They include alloys (C22C), metallic powders (B22F) and metallic coatings (C23C), plus miscellaneous manufactured items (Y10T) with a focus on metallic composites (Y10T 428/31678).

Figure 5-17 - Number of Patent Families Linked via Citations to Earlier Other DOE-Funded Lightweight Materials Patents by CPC



The organizations with the largest number of patent families linked via citations to earlier VTO-funded lightweight materials patents are shown in Figure 5-18. To avoid repeating the results from earlier, this figure excludes the ten leading lightweight materials companies used in the backward tracing element of the analysis. Also, note that Figure 5-18 includes all patent families assigned to these organizations, not just their patent families describing lightweight materials technology. This figure is dominated by two semiconductor companies, Applied Materials and ASM International. The former has 133 patent families linked via citations to earlier VTO-funded lightweight materials patents, while the latter has 74 such patent families. Many of these families are in the semiconductor CPCs highlighted above in Figure 5-16.

Figure 5-18 - Organizations with Largest Number of Patent Families Linked via Citations to VTO-funded Lightweight Materials Patents (excluding leading lightweight materials companies)

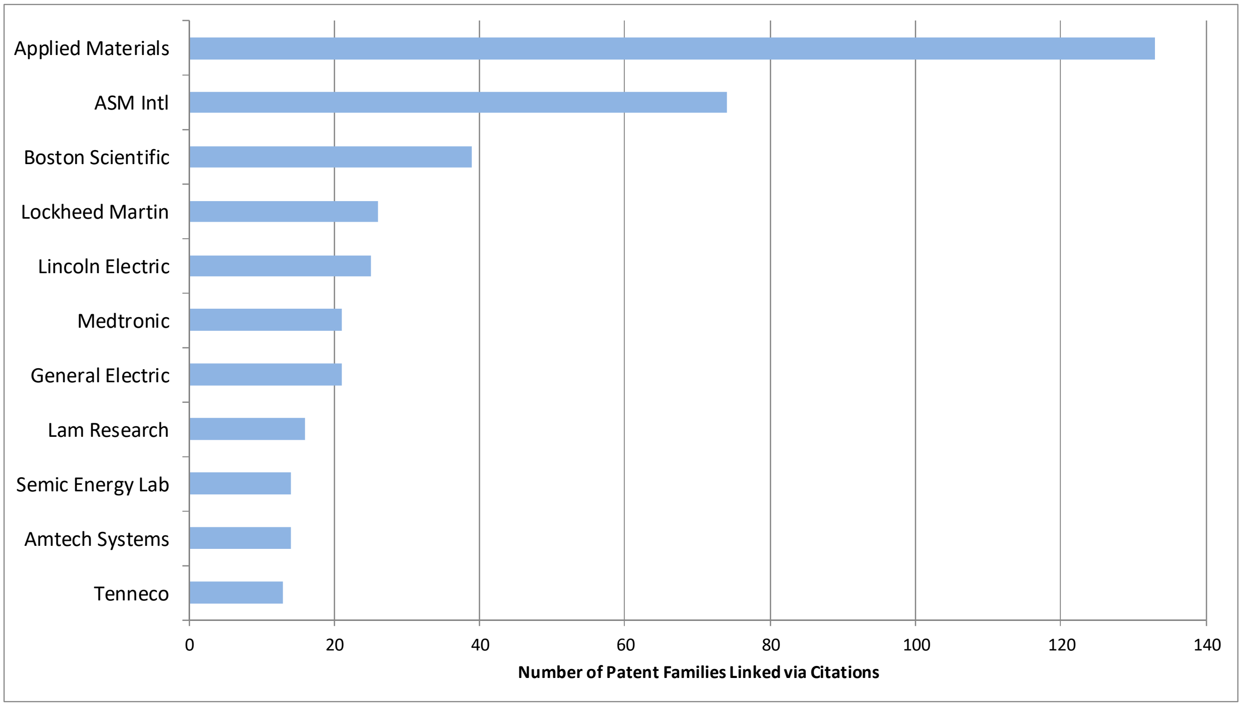
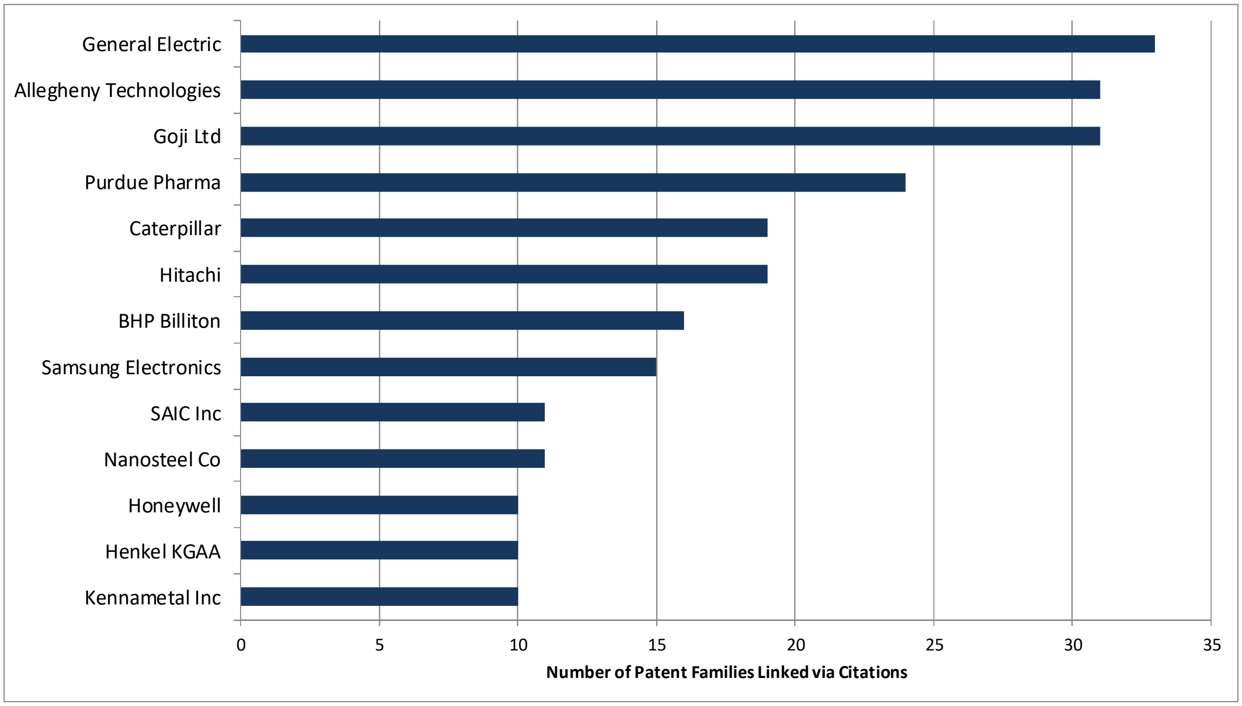


Figure 5-19 shows the organizations with the largest number of patent families linked via citations to earlier Other DOE-funded lightweight materials patents. General Electric is at the head of this figure, with 33 patent families linked via citations to earlier Other DOE-funded patents. These General Electric patent families focus on alloys, in particular alloys containing titanium. Allegheny Technologies is in second place in Figure 5-19, with 31 patent families linked via citations to earlier Other DOE-funded lightweight materials patents. A number of these Allegheny patent families also focus on titanium alloys, while others describe stainless steel compositions. Goji Limited also 31 patent families in Figure 5-19. These families describe RF heating, especially for cooking, and are linked via citations to earlier Other DOE-funded patent families related to adhesive bonding using microwave energy.

Figure 5-19 - Organizations with Largest Number of Patent Families Linked via Citations to Other DOE-funded Lightweight Materials Patents (excluding leading lightweight materials companies)



Patent Level Results

This section of the report drills down to identify individual DOE-funded (and particularly VTO-funded) lightweight materials patents whose influence on subsequent technological developments has been particularly strong. It also highlights patents that have extensive citation links to earlier VTO-funded lightweight materials research.

The simplest way of identifying high-impact VTO-funded lightweight materials patents is via overall Citation Indexes. The VTO-funded patents with the highest Citation Index values are shown in Table 5-5, with selected patents also presented in Figure 5-20. The patents in this table include older patents that have received large numbers of citations from subsequent generations of patents, and more recent patents that have attracted more citations than expected. One advantage of using Citation Indexes is that these two groups of patents can be compared directly, since each is benchmarked against peer patents of the same age and technology.

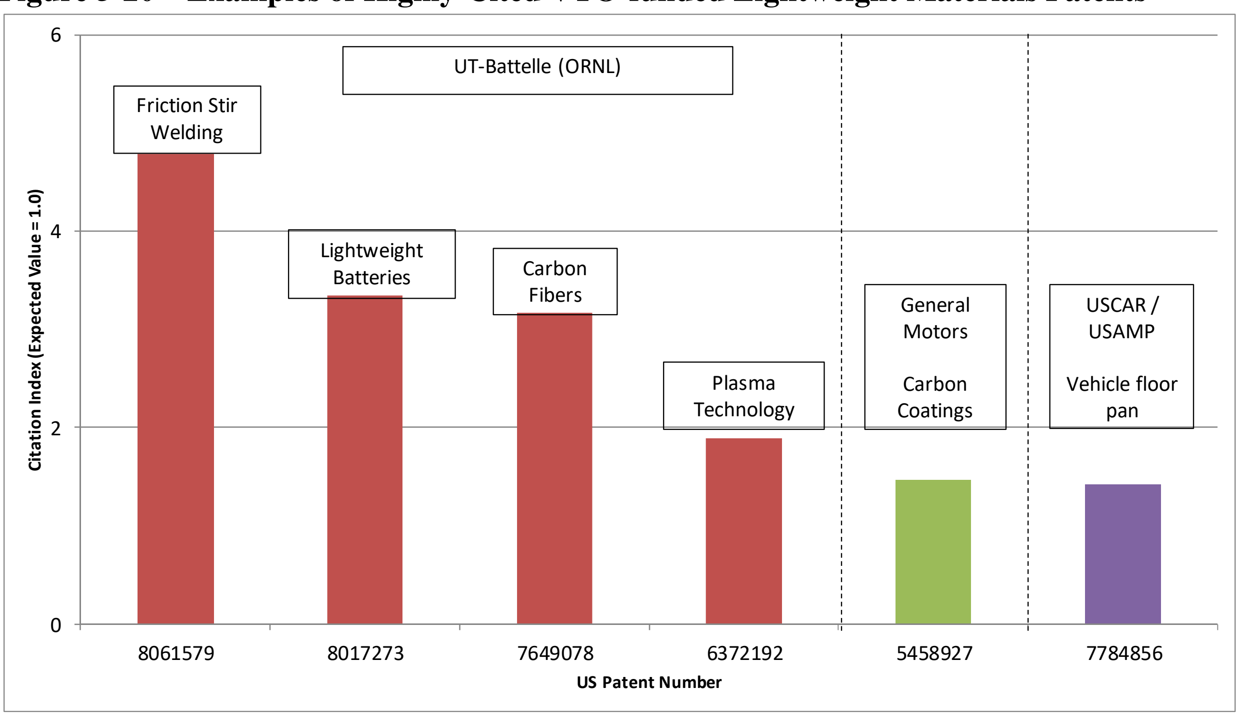
Out of the nine patents in Table 5-5, six are assigned to the UT-Battelle, through its management of Oak Ridge National Laboratory (ORNL). They include the five patents with the highest Citation Index values. The patent at the head of the table (US #8,061,579) describes fabricating structures using friction stir welding. This patent has been cited as prior art by thirteen subsequent patents, more than four times as many citations as expected for a patent of its age and technology. The second patent in Table 5-5 (US #8,017,273) describes a lightweight lead-acid battery. Since it was issued in 2010, this patent has been cited as prior art by ten subsequent patents, more than three times as many citations as expected.

Table 5-5 also includes two older patents. The first patent (US #6,372,192) was issued in 2002 and is assigned to UT-Battelle (ORNL). It describes the manufacture of carbon fibers using plasma technology, and has been cited by 34 subsequent patents, almost twice as many citations as expected. The second patent (US #5,458,927) was issued in 1995, and is assigned to General Motors. It outlines scuff resistant carbon coatings, and has been cited by 31 subsequent patents, almost 50% more citations than expected.

Table 5-5 – List of Highly Cited VTO-Funded Lightweight Materials Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
8061579	2011	13	4.78	UT-Battelle (ORNL)	Friction stir method for forming structures and materials
8017273	2011	10	3.34	UT-Battelle (ORNL)	Lightweight, durable lead-acid batteries
7649078	2010	11	3.17	UT-Battelle (ORNL)	Apparatus and method for stabilization or oxidation of polymeric materials
7534854	2009	10	2.72	UT-Battelle (ORNL)	Apparatus and method for oxidation and stabilization of polymeric materials
6372192	2002	34	1.89	UT-Battelle (ORNL)	Carbon fiber manufacturing via plasma technology
5458927	1995	31	1.47	General Motors	Process for the formation of wear and scuff resistant carbon coatings
7784856	2010	10	1.42	USCAR/USAMP	Dynamic load bearing composite floor pan for an automotive vehicle
7682556	2010	13	1.39	UT-Battelle (ORNL)	Degassing of molten alloys with the assistance of ultrasonic vibration
7255233	2007	12	1.24	UChicago Argonne (ANL)	Method and apparatus for separating mixed plastics using flotation techniques

Figure 5-20 – Examples of Highly-Cited VTO-funded Lightweight Materials Patents



The Citation Indexes in Table 5-5 are based on a single generation of citations to VTO-funded lightweight materials patents. Table 5-6 extends this by examining a second generation of citations – i.e. it shows the VTO-funded lightweight materials patents linked directly or indirectly to the largest number of subsequent patent families. These subsequent families are divided into two groups, according to whether they are within or beyond lightweight materials technology (i.e. whether they are in the vehicle-related lightweight materials patent universe constructed in the initial step of this project). This provides insights into which VTO-funded patent families have been particularly influential within vehicle-related lightweight materials technology, and which have had a broader impact beyond such materials.

Table 5-6 - VTO-funded Lightweight Materials Patent Families Linked via Citations to Largest Number of Subsequent Lightweight Materials/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Lightweight Fams	Assignee	Title
23586345	1995	5458927	536	0	General Motors	Process for the formation of wear and scuff resistant carbon coatings
23960353	2000	6372192	194	0	UT-Battelle (ORNL)	Carbon fiber manufacturing via plasma technology
23155333	1994	5603795	142	1	Lockheed Martin (ORNL)	Joining of thermoplastic substrates by microwaves
26889352	2000	6647802	52	0	Auto Composites Consortium	Creep testing fixture and method
24681568	2000	6514449	45	0	UT-Battelle (ORNL)	Microwave and plasma-assisted modification of composite fiber surface topography
35459379	2004	7255233	30	0	UChicago Argonne (ANL)	Method and apparatus for separating mixed plastics using flotation techniques
23956392	2000	6375875	21	0	UT-Battelle (ORNL)	Diagnostic monitor for carbon fiber processing
41266259	2008	7819452	20	8	USCAR / USAMP	Automotive structural joint and method of making same
40732084	2008	7762447	19	0	UT-Battelle (ORNL)	Multiple pass and multiple layer friction stir welding and material enhancement processes
40850005	2008	7784856	15	12	USCAR / USAMP	Dynamic load bearing composite floor pan for an automotive vehicle

The patent family at the head of Table 5-6 contains the General Motors carbon coatings patent (US #5,458,927) that was highlighted in Table 5-5. It is linked via citations to 536 subsequent patent families, all of which are from beyond vehicle-related lightweight materials. The patent family in second place in Table 5-6 is assigned to UT-Battelle, and contains the plasma technology patent (US #6,372,192) also highlighted in Table 5-5. This patent family is linked to

194 subsequent families, again all from beyond vehicle-related lightweight materials. Indeed, there are only two VTO-funded patent families in Table 5-6 that are linked to more than one subsequent lightweight materials family. These are the USCAR/USAMP vehicle structure patents (US #7,819,452 and US #7,784,856) highlighted in the backward tracing element of the analysis. This table thus reinforces the idea that much of the influence of VTO-funded lightweight materials patents can be seen across advanced materials in general, where such materials are not necessarily restricted to vehicle applications.

The tables above identify VTO-funded patent families linked particularly strongly to subsequent technological developments. Table 5-7 looks in the opposite direction, and identifies highly-cited patents linked to earlier VTO-funded lightweight materials patents. As such, these are examples where VTO-funded lightweight materials research has formed part of the foundation for subsequent high-impact technologies. This table focuses on patent families not owned by the leading lightweight materials companies, since those families were examined in the backward tracing element of the analysis.

The patent at the head of Table 5-7 (US #6,551,929) is assigned to Applied Materials, and describes a method for depositing metallic layers on semiconductor substrates. This patent has been cited as prior art by 246 subsequent patents, which is more than twelve times as many citations as expected for a patent of its age and technology. It is one of a number of patents in Table 5-7 related to semiconductor manufacturing, assigned to Semiconductor Energy Laboratory, ASM International and Applied Materials. There are also patents in this table describing metal bonding, RF power apparatus and induction heating. These are examples of VTO-funded lightweight materials patents influencing high-impact developments in other technologies.

Table 5-7 - Highly Cited Patents (not from leading lightweight materials companies) Linked via Citations to Earlier VTO-funded Lightweight Materials Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
6551929	2003	246	12.38	Applied Materials	Bifurcated deposition process for depositing refractory metal layers employing atomic layer deposition
6909114	2005	203	9.73	Semic Energy Lab	Semiconductor device having LDD regions
6878206	2005	208	9.50	Applied Materials	Lid assembly for a processing system to facilitate sequential deposition techniques
6902763	2005	93	7.24	ASM International	Method for depositing nanolaminate thin films on sensitive surfaces
7871387	2011	67	5.97	Medtronic	Compression sleeve convertible in length
7452800	2008	53	4.84	Univ California	Bonding a non-metal body to a metal surface using inductive heating
6030667	2000	102	4.58	Panasonic	Apparatus and method for applying RF power apparatus and method for generating plasma
5947710	1999	123	4.53	United Technologies	Rotary compressor with reduced lubrication sensitivity
6056844	2000	75	3.68	Triton Systems	Temperature-controlled induction heating of polymeric materials
7608798	2009	39	3.59	Amtech Systems	Plasma catalyst

As with the backward tracing element of the analysis, the patent-level results from the forward tracing focus on VTO-funded lightweight materials patents. However, within the forward tracing, we also identified Other DOE-funded lightweight materials patent families linked to the largest number of subsequent patent families within and beyond vehicle-related lightweight materials technology. These Other DOE-funded lightweight materials families are shown in Table 5-8.

Table 5-8 - Other DOE-funded Lightweight Materials Patent Families Linked via Citations to Largest Number of Subsequent Lightweight Materials/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Lightweight Fams	Assignee	Title
24509408	1994	5798395	226	0	Lambda Tech /Lockheed Martin (ORNL)	Adhesive bonding using variable frequency microwave energy
24558565	1996	5908486	196	0	Lockheed Martin (INL)	Strengthening of metallic alloys with nanometer-size oxide dispersions
23516410	1989	4995948	174	0	US Dept Energy	Apparatus and process for the electrolytic reduction of uranium and plutonium oxides
26915573	1991	5721286	140	0	Lockheed Martin (ORNL)	Method for curing polymers using variable-frequency microwave heating
24396892	1996	5849373	110	0	Sandia Corp	Process for the synthesis of nanophase dispersion-strengthened aluminum alloy
29732939	2000	6689234	93	0	Bechtel BWXT (INL)	Method of producing metallic materials
24734641	1991	5147471	85	0	US Dept Energy	Solder for oxide layer-building metals and alloys
23947309	1995	5799238	55	1	US Dept Energy	Method of making multilayered titanium ceramic composites
26825486	1993	5851317	42	0	Iowa State Univ	Composite material reinforced with atomized quasicrystalline particles and method of making same
21876367	1993	5445685	32	1	Univ California (LLNL)	Transformation process for production of ultrahigh carbon steels and new alloys
32230753	2001	6733737	25	0	Wright Materials	Rapid oxidation/stabilization technique for carbon foams, carbon fibers and C/C composites

The patent family at the head of Table 5-8 (representative patent #5,798,395) is co-assigned to Lambda Technologies and Lockheed Martin, the latter through its former management of ORNL.

It describes bonding of materials using microwave energy, and is linked via citations to 226 subsequent patent families, all of which are from outside vehicle-related lightweight materials technology (including the Goji RF heating patents highlighted earlier in Figure 5-19). The second-place patent family in Table 5-8 (representative patent #5,908,486) describes strengthening of nickel and stainless steel alloys. It is linked via citations to 196 subsequent patent families, covering technologies such as alloy powders and steel compositions. Many of these linked families are related to advanced materials, but do not necessarily specify an automotive application (even though they could potentially be used in vehicles). This is also the case for many of the Other DOE-funded patent families in Table 5-8, hence the string of zeros in the fifth column of the table. As such, this supports the idea that the influence of these Other DOE-funded patent families can be found across advanced materials, where these materials are not necessarily restricted to vehicle applications.

The forward tracing element of the lightweight materials analysis thus shows that VTO-funded and Other DOE-funded research has had a strong influence on subsequent technologies. This influence can be seen largely beyond the use of lightweight materials specifically in vehicle applications, and is particularly notable in semiconductors and advanced materials in general.

Overall, the results from the lightweight materials analysis show that DOE-funded patenting has increased throughout the period examined, with VTO-funded patents representing a growing percentage of the total. There appears to be little overlap between VTO-funded and Other DOE-funded lightweight materials patents and those assigned to the leading companies, with the former focusing on materials themselves and the latter concentrating on specific vehicle applications (although automotive companies may have used materials developed with DOE funding in production, without necessarily patenting their use in this application). This is borne out by evaluating the backward and forward tracing elements of the analysis in tandem. These analyses suggest that VTO-funded and Other DOE-funded lightweight materials research has had an important role in the advancement of materials technology, where these materials are not necessarily restricted to vehicle applications.

6. Conclusions

This report describes the results of an analysis tracing links between propulsion materials and lightweight materials research funded by DOE (VTO plus Other DOE) and subsequent developments both within and beyond these technologies. This tracing is carried out both backwards and forwards in time. The purpose of the backward tracing is to determine the extent to which VTO-funded (and Other DOE-funded) research forms a foundation for the technologies developed by leading propulsion and lightweight materials companies. The purpose of the forward tracing is to examine the influence of VTO-funded (and Other DOE-funded) propulsion and lightweight materials research upon subsequent developments, both within and outside these technologies.

The results from propulsion materials analysis suggest that DOE-funded patenting in this technology has increased over time, with VTO-funded patents representing a growing percentage of the total. While the portfolios of VTO-funded and Other DOE-funded propulsion materials patents are much smaller than those of the leading companies in this technology, their influence can be seen on innovations associated with these companies, notably in exhaust treatment. The influence of VTO-funded and Other DOE-funded propulsion materials patents also extends beyond the immediate technology to other areas such as earth drilling and advanced materials, where such materials are not necessarily restricted to vehicle applications.

The results from the lightweight materials analysis show that DOE-funded patenting has also increased throughout the period examined, with VTO-funded patents representing a growing percentage of the total. There appears to be little overlap between VTO-funded and Other DOE-funded lightweight materials patents and those assigned to the leading companies, with the former focusing on materials themselves and the latter concentrating on specific vehicle applications. This is borne out by evaluating the backward and forward tracing elements of the analysis in tandem. These analyses suggest that VTO-funded and Other DOE-funded lightweight materials research has had an important role in the advancement of materials technology in general, where such materials are not necessarily restricted to vehicle applications.

Appendix PRL-A. VTO-funded Propulsion Materials Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
4938922	1989	1990	GTE PRODUCTS CORP	GOLD-NICKEL-TITANIUM BRAZING ALLOY
RE034819	1992	1995	MORGAN CRUCIBLE COMPANY PLC	GOLD-NICKEL-TITANIUM BRAZING ALLOY
WO1996036473	1995	1996	LOCKHEED MARTIN CORP	METHOD FOR RAPID FABRICATION OF FIBER PREFORMS AND STRUCTURAL COMPOSITE MATERIALS
5744075	1995	1998	LOCKHEED MARTIN CORP	METHOD FOR RAPID FABRICATION OF FIBER PREFORMS AND STRUCTURAL COMPOSITE MATERIALS
EP0827445	1995	1998	LOCKHEED MARTIN CORP	METHOD FOR RAPID FABRICATION OF FIBER PREFORMS AND STRUCTURAL COMPOSITE MATERIALS
5871838	1996	1999	LOCKHEED MARTIN CORP	METHOD FOR RAPID FABRICATION OF FIBER PREFORMS AND STRUCTURAL COMPOSITE MATERIALS
6214289	1999	2001	UT-BATTELLE LLC	IRON-CHROMIUM-SILICON ALLOYS FOR HIGH-TEMPERATURE OXIDATION RESISTANCE
EP1219720	2001	2002	CATERPILLAR INC	HEAT AND CORROSION RESISTANT CAST STAINLESS STEELS WITH IMPROVED HIGH TEMPERATURE STRENGTH AND DUCTILITY
7094722	2002	2006	CATERPILLAR INC	NOX CATALYST AND METHOD OF SUPPRESSING SULFATE FORMATION IN AN EXHAUST PURIFICATION SYSTEM
7153373	2002	2006	CATERPILLAR INC	HEAT AND CORROSION RESISTANT CAST CF8C STAINLESS STEEL WITH IMPROVED HIGH TEMPERATURE STRENGTH AND DUCTILITY
7153810	2004	2006	CATERPILLAR INC	SILVER DOPED CATALYSTS FOR TREATMENT OF EXHAUST
7235221	2006	2007	CATERPILLAR INC	NOX CATALYST AND METHOD OF SUPPRESSING SULFATE FORMATION IN AN EXHAUST PURIFICATION SYSTEM
7252054	2004	2007	CATERPILLAR INC	COMBUSTION ENGINE INCLUDING CAM PHASE-SHIFTING
7255755	2002	2007	CATERPILLAR INC	HEAT AND CORROSION RESISTANT CAST CN-12 TYPE STAINLESS STEEL WITH

				IMPROVED HIGH TEMPERATURE STRENGTH AND DUCTILITY
7365330	2006	2008	UCHICAGO ARGONNE LLC	METHOD FOR THERMAL TOMOGRAPHY OF THERMAL EFFUSIVITY FROM PULSED THERMAL IMAGING
WO2008030293	2007	2008	EXXONMOBIL CO, CATERPILLAR INC	REFORMER ASSISTED LEAN NOX CATALYST AFTERTREATMENT APPARATUS AND METHOD
WO2008036797	2007	2008	BASF CORP	CATALYST, METHOD FOR ITS PREPARATION AND SYSTEM TO REDUCE NOX IN AN EXHAUST GAS STREAM
WO2008036803	2007	2008	BASF CORP; GEN MOTORS CORP	CATALYSTS TO REDUCE NOX IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
WO2008036813	2007	2008	BASF CORP	CATALYSTS TO REDUCE NOX IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
WO2008115664	2008	2008	CUMMINS INC	APPARATUS, SYSTEM, AND METHOD FOR DETECTING CRACKING WITHIN AN AFTERTREATMENT DEVICE
7538938	2006	2009	UCHICAGO ARGONNE LLC	OPTICAL FILTER FOR FLASH LAMPS IN PULSED THERMAL IMAGING
7541010	2003	2009	CATERPILLAR INC	SILVER DOPED CATALYSTS FOR TREATMENT OF EXHAUST
7572054	2007	2009	CUMMINS INC	APPARATUS, SYSTEM, AND METHOD FOR DETERMINING A TIME-TEMPERATURE HISTORY OF AN AFTERTREATMENT DEVICE
EP2069051	2007	2009	BASF CORP	CATALYST, METHOD FOR ITS PREPARATION AND SYSTEM TO REDUCE NOX IN AN EXHAUST GAS STREAM
EP2069052	2007	2009	BASF CORP; GEN MOTORS CORP	CATALYSTS TO REDUCE NOX IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
EP2069053	2007	2009	BASF CORP	CATALYSTS TO REDUCE NOX IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
EP2113581	2001	2009	CATERPILLAR INC	HEAT AND CORROSION RESISTANT CAST STAINLESS STEELS WITH IMPROVED HIGH TEMPERATURE STRENGTH AND DUCTILITY
7701231	2007	2010	CUMMINS INC	APPARATUS, SYSTEM, AND METHOD FOR DETECTING CRACKING WITHIN AN AFTERTREATMENT DEVICE
7743602	2006	2010	EXXONMOBIL CO, CATERPILLAR	REFORMER ASSISTED LEAN NOX CATALYST AFTERTREATMENT SYSTEM

			INC	AND METHOD
7759280	2006	2010	BASF CORP	CATALYSTS, SYSTEMS AND METHODS TO REDUCE NOX IN AN EXHAUST GAS STREAM
RE041100	2008	2010	CATERPILLAR INC	HEAT AND CORROSION RESISTANT CAST CN-12 TYPE STAINLESS STEEL WITH IMPROVED HIGH TEMPERATURE STRENGTH AND DUCTILITY
RE041504	2008	2010	CATERPILLAR INC	HEAT AND CORROSION RESISTANT CAST CF8C STAINLESS STEEL WITH IMPROVED HIGH TEMPERATURE STRENGTH AND DUCTILITY
7943548	2006	2011	BASF CORP	CATALYSTS TO REDUCE NOX IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
8173574	2007	2012	BASF CORP	CATALYSTS TO REDUCE NOX IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
WO2012044617	2011	2012	BASF CORP	SURFACE-COATED ZEOLITE MATERIALS FOR DIESEL OXIDATION APPLICATIONS
8431072	2011	2013	UT-BATTELLE LLC	CAST ALUMINA FORMING AUSTENITIC STAINLESS STEELS
EP2635779	2011	2013	BASF CORP	SURFACE-COATED ZEOLITE MATERIALS FOR DIESEL OXIDATION APPLICATIONS
WO2013126619	2013	2013	UT-BATTELLE LLC	HYDROTHERMALLY STABLE, LOW-TEMPERATURE NOX REDUCTION NH3-SCR CATALYST
WO2013177119	2013	2013	CUMMINS INC	AFTERTREATMENT SYSTEM HAVING TWO SCR CATALYSTS
8771439	2009	2014	UT-BATTELLE LLC	TITANIUM ALUMINIDE INTERMETALLIC ALLOYS WITH IMPROVED WEAR RESISTANCE
8822036	2013	2014	UT-BATTELLE LLC	SINTERED SILVER JOINTS VIA CONTROLLED TOPOGRAPHY OF ELECTRONIC PACKAGING SUBCOMPONENTS
8987161	2010	2015	UT-BATTELLE LLC	ZEOLITE-BASED SCR CATALYSTS AND THEIR USE IN DIESEL ENGINE EMISSION TREATMENT
8987162	2012	2015	UT-BATTELLE LLC	HYDROTHERMALLY STABLE, LOW-TEMPERATURE NOX REDUCTION NH3-SCR CATALYST
8997461	2012	2015	CUMMINS INC	AFTERTREATMENT SYSTEM HAVING TWO SCR CATALYSTS
9120077	2011	2015	BASF CORP	SURFACE-COATED ZEOLITE MATERIALS FOR DIESEL OXIDATION APPLICATIONS
EP2827984	2013	2015	UT-BATTELLE LLC	HYDROTHERMALLY STABLE, LOW-TEMPERATURE NOX

				REDUCTION NH3-SCR CATALYST
9272268	2014	2016	UT-BATTELLE LLC	CATALYSTS FOR LOW TEMPERATURE OXIDATION
9403156	2015	2016	UT-BATTELLE LLC	ZEOLITE-BASED SCR CATALYSTS AND THEIR USE IN DIESEL ENGINE EMISSION TREATMENT
9441520	2015	2016	CUMMINS INC	AFTERTREATMENT SYSTEM HAVING TWO SCR CATALYSTS
9475039	2015	2016	UT-BATTELLE LLC	HYDROTHERMALLY STABLE, LOW-TEMPERATURE NOX REDUCTION NH3-SCR CATALYST
9593642	2014	2017	FORD GLOBAL TECHNOLOGIES LLC	COMPOSITE CAM CARRIER
9605565	2014	2017	UT-BATTELLE LLC	LOW-COST FE-NI-CR ALLOYS FOR HIGH TEMPERATURE VALVE APPLICATIONS
9694352	2016	2017	UT-BATTELLE LLC	METHOD FOR TREATING ENGINE EXHAUST BY USE OF HYDROTHERMALLY STABLE, LOW-TEMPERATURE NOX REDUCTION NH3-SCR CATALYSTS
9752468	2014	2017	UNASSIGNED	LOW-COST, HIGH-STRENGTH FE-NI-CR ALLOYS FOR HIGH TEMPERATURE EXHAUST VALVE APPLICATIONS
9822671	2016	2017	FORD GLOBAL TECHNOLOGIES LLC	COMPOSITE HYBRID CAM CARRIER
10022667	2017	2018	CUMMINS INC	SYSTEMS AND METHODS FOR INCREASING NITROGEN DIOXIDE FRACTION IN EXHAUST GAS AT LOW TEMPERATURE

Appendix PRL-B. Other DOE-Funded Propulsion Materials Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
4961903	1989	1990	LOCKHEED MARTIN CORP	IRON ALUMINIDE ALLOYS WITH IMPROVED PROPERTIES FOR HIGH TEMPERATURE APPLICATIONS
WO1990010722	1990	1990	LOCKHEED MARTIN CORP	IRON ALUMINIDE ALLOYS WITH IMPROVED PROPERTIES FOR HIGH TEMPERATURE APPLICATIONS
WO1990015164	1990	1990	LOCKHEED MARTIN CORP	IMPROVED NICKEL ALUMINIDE ALLOY FOR HIGH TEMPERATURE STRUCTURAL USE
5006308	1989	1991	LOCKHEED MARTIN CORP	NICKEL ALUMINIDE ALLOY FOR HIGH TEMPERATURE STRUCTURAL USE
5016810	1989	1991	US DEPT ENERGY	METHOD FOR IMPROVING WELDABILITY OF NICKEL ALUMINIDE ALLOYS
EP0455752	1990	1991	LOCKHEED MARTIN CORP	IRON ALUMINIDE ALLOYS WITH IMPROVED PROPERTIES FOR HIGH TEMPERATURE APPLICATIONS.
5084109	1990	1992	LOCKHEED MARTIN CORP	ORDERED IRON ALUMINIDE ALLOYS HAVING AN IMPROVED ROOM-TEMPERATURE DUCTILITY AND METHOD THEREOF
5108700	1989	1992	LOCKHEED MARTIN CORP	CASTABLE NICKEL ALUMINIDE ALLOYS FOR STRUCTURAL APPLICATIONS
EP0476043	1990	1992	LOCKHEED MARTIN CORP	IMPROVED NICKEL ALUMINIDE ALLOY FOR HIGH TEMPERATURE STRUCTURAL USE.
5238645	1992	1993	LOCKHEED MARTIN CORP	IRON-ALUMINUM ALLOYS HAVING HIGH ROOM-TEMPERATURE AND METHOD FOR MAKING SAME
WO1993023581	1993	1993	LOCKHEED MARTIN CORP	CORROSION RESISTANT IRON ALUMINIDES EXHIBITING IMPROVED MECHANICAL PROPERTIES AND CORROSION RESISTANCE
5320802	1992	1994	LOCKHEED MARTIN CORP	CORROSION RESISTANT IRON ALUMINIDES EXHIBITING IMPROVED MECHANICAL PROPERTIES AND CORROSION RESISTANCE
5413876	1992	1995	LOCKHEED MARTIN CORP	NICKEL ALUMINIDE ALLOYS WITH IMPROVED WELDABILITY

5421914	1993	1995	UNIVERSITY OF CHICAGO	SURFACE MODIFICATION OF HIGH TEMPERATURE IRON ALLOYS
EP0642597	1993	1995	LOCKHEED MARTIN CORP	CORROSION RESISTANT IRON ALUMINIDES EXHIBITING IMPROVED MECHANICAL PROPERTIES AND CORROSION RESISTANCE.
5495979	1994	1996	SURMET CORP	METAL-BONDED, CARBON FIBER-REINFORCED COMPOSITES
5525779	1993	1996	LOCKHEED MARTIN CORP	INTERMETALLIC ALLOY WELDING WIRES AND METHOD FOR FABRICATING THE SAME
5545373	1994	1996	LOCKHEED MARTIN CORP	HIGH-TEMPERATURE CORROSION-RESISTANT IRON-ALUMINIDE (FEAL) ALLOYS EXHIBITING IMPROVED WELDABILITY
5571346	1995	1996	NORTHWEST ALUMINUM CO	CASTING, THERMAL TRANSFORMING AND SEMI?SOLID FORMING ALUMINUM ALLOYS
5580397	1995	1996	US DEPT ENERGY	CARBIDE AND CARBONITRIDE SURFACE TREATMENT METHOD FOR REFRACTORY METALS
WO1996032519	1996	1996	NORTHWEST ALUMINUM CO	THERMAL TRANSFORMING AND SEMI-SOLID FORMING ALUMINUM ALLOYS
5711147	1996	1998	UNIVERSITY OF CALIFORNIA	PLASMA-ASSISTED CATALYTIC REDUCTION SYSTEM
5725691	1996	1998	LOCKHEED MARTIN CORP	NICKEL ALUMINIDE ALLOY SUITABLE FOR STRUCTURAL APPLICATIONS
5725693	1996	1998	LOCKHEED MARTIN CORP	FILLER METAL ALLOY FOR WELDING CAST NICKEL ALUMINIDE ALLOYS
5778664	1996	1998	BATTELLE MEMORIAL INSTITUTE	APPARATUS FOR PHOTOCATALYTIC DESTRUCTION OF INTERNAL COMBUSTION ENGINE EMISSIONS DURING COLD START
5830421	1996	1998	LOW EMISSIONS TECHNOLOGIES R&D PARTNERSHIP	MATERIAL AND SYSTEM FOR CATALYTIC REDUCTION OF NITROGEN OXIDE IN AN EXHAUST STREAM OF A COMBUSTION PROCESS
5831187	1996	1998	LOCKHEED MARTIN CORP	ADVANCED NICKEL BASE ALLOYS FOR HIGH STRENGTH, CORROSION APPLICATIONS
5846350	1996	1998	NORTHWEST ALUMINUM CO	CASTING THERMAL TRANSFORMING AND SEMI-SOLID FORMING ALUMINUM ALLOYS

EP0822994	1996	1998	NORTHWEST ALUMINUM CO	THERMAL TRANSFORMING AND SEMI-SOLID FORMING ALUMINUM ALLOYS
WO1998000222	1997	1998	LOW EMISSIONS TECHNOLOGIES R&D PARTNERSHIP	MATERIAL AND SYSTEM FOR CATALYTIC REDUCTION OF NITROGEN OXIDE IN AN EXHAUST STREAM OF A COMBUSTION PROCESS
WO1998002233	1997	1998	BATTELLE MEMORIAL INSTITUTE	METHOD AND APPARATUS FOR PROCESSING EXHAUST GAS WITH CORONA DISCHARGE
WO1998009699	1997	1998	UNIVERSITY OF CALIFORNIA	PLASMA-ASSISTED CATALYTIC REDUCTION SYSTEM
5858144	1996	1999	IOWA STATE UNIVERSITY	LOW TEMPERATURE JOINING OF CERAMIC COMPOSITES
5891409	1997	1999	UNIVERSITY OF CALIFORNIA	PRE-CONVERTED NITRIC OXIDE GAS IN CATALYTIC REDUCTION SYSTEM
5893267	1997	1999	UNIVERSITY OF CALIFORNIA	CATALYTIC REDUCTION SYSTEM FOR OXYGEN-RICH EXHAUST
5911843	1998	1999	NORTHWEST ALUMINUM CO	CASTING, THERMAL TRANSFORMING AND SEMI-SOLID FORMING ALUMINUM ALLOYS
5914015	1996	1999	BATTELLE MEMORIAL INSTITUTE	METHOD AND APPARATUS FOR PROCESSING EXHAUST GAS WITH CORONA DISCHARGE
5922628	1998	1999	IOWA STATE UNIVERSITY	LOW TEMPERATURE JOINING OF CERAMIC COMPOSITES
5968292	1997	1999	NORTHWEST ALUMINUM CO	CASTING THERMAL TRANSFORMING AND SEMI-SOLID FORMING ALUMINUM ALLOYS
5972289	1998	1999	LOCKHEED MARTIN CORP	HIGH STRENGTH, THERMALLY STABLE, OXIDATION RESISTANT, NICKEL-BASED ALLOY
EP0946256	1997	1999	UNIVERSITY OF CALIFORNIA	PLASMA-ASSISTED CATALYTIC REDUCTION SYSTEM
6033641	1996	2000	UNIVERSITY OF PITTSBURGH	CATALYST FOR PURIFYING THE EXHAUST GAS FROM THE COMBUSTION IN AN ENGINE OR GAS TURBINES AND METHOD OF MAKING AND USING THE SAME
6119451	1999	2000	UNIVERSITY OF CALIFORNIA	NITROGEN OXIDE REMOVAL USING DIESEL FUEL AND A CATALYST
6165934	1998	2000	LOW EMISSIONS TECHNOLOGIES R&D PARTNERSHIP	MATERIAL AND SYSTEM FOR CATALYTIC REDUCTION OF NITROGEN OXIDE IN AN EXHAUST STREAM OF A COMBUSTION PROCESS
WO2000035669	1999	2000	HITCO CARBON COMPOSITES	ULTRA LOW FRICTION CARBON/CARBON COMPOSITES

			INC, UNIVERSITY OF CHICAGO	FOR EXTREME TEMPERATURE APPLICATIONS
6203924	1998	2001	UNIVERSITY OF CALIFORNIA	LIGHTWEIGHT FLYWHEEL CONTAINMENT
6214472	1999	2001	IOWA STATE UNIVERSITY	LOW TEMPERATURE JOINING OF CERAMIC COMPOSITES
6231636	1999	2001	IDAHO RESEARCH FOUNDATION INC	MECHANOCHEMICAL PROCESSING FOR METALS AND METAL ALLOYS
6255234	1998	2001	HITCO CARBON COMPOSITES INC, UNIVERSITY OF CHICAGO	ULTRA LOW FRICTION CARBON/CARBON COMPOSITES FOR EXTREME TEMPERATURE APPLICATIONS
EP1150835	1999	2001	HITCO CARBON COMPOSITES INC, UNIVERSITY OF CHICAGO	ULTRA LOW FRICTION CARBON/CARBON COMPOSITES FOR EXTREME TEMPERATURE APPLICATIONS
WO2001030696	2000	2001	UNIVERSITY OF CALIFORNIA	CATALYSTS FOR LEAN BURN ENGINE EXHAUST ABATEMENT
6436339	1999	2002	UNASSIGNED	CAST B2-PHASE IRON-ALUMINUM ALLOYS WITH IMPROVED FLUIDITY
6482355	1999	2002	UT-BATTELLE LLC	WEDLABLE NICKEL ALUMINIDE ALLOY
EP1205235	2001	2002	CATERPILLAR INC, BATTELLE MEMORIAL INSTITUTE	METHOD AND SYSTEM FOR DIESEL ENGINE EXHAUST TREATMENT USING A COMBINATION OF NON-THERMAL PLASMA AND METAL DOPED GAMMA-ALUMINA CATALYSTS
6514470	2000	2003	UNIVERSITY OF CALIFORNIA	CATALYSTS FOR LEAN BURN ENGINE EXHAUST ABATEMENT
6517236	2001	2003	UNIVERSITY OF CHICAGO	METHOD AND APPARATUS FOR AUTOMATED THERMAL IMAGING OF COMBUSTOR LINERS AND OTHER PRODUCTS
6517238	2001	2003	US DEPT ENERGY	THERMAL IMAGING MEASUREMENT OF LATERAL DIFFUSIVITY AND NON-INVASIVE MATERIAL DEFECT DETECTION
6542849	2001	2003	UNIVERSITY OF CHICAGO	METHOD FOR DETERMINING DEFECT DEPTH USING THERMAL IMAGING
6544668	1999	2003	UT-BATTELLE LLC	DUCTILE FILLER METAL ALLOYS FOR WELDING NICKEL ALUMINIDE ALLOYS
6668763	2002	2003	UNIVERSITY OF CHICAGO	PROCESS FOR IN-SITU PRODUCTION OF HYDROGEN (H2) BY ALCOHOL DECOMPOSITION FOR

				EMISSION REDUCTION FROM INTERNAL COMBUSTION ENGINES
6685897	2000	2004	UNIVERSITY OF CALIFORNIA	HIGHLY-BASIC LARGE-PORE ZEOLITE CATALYSTS FOR NOX REDUCTION AT LOW TEMPERATURES
6716783	2002	2004	UNIVERSITY OF CALIFORNIA	CATALYSTS FOR LEAN BURN ENGINE EXHAUST ABATEMENT
6730912	2002	2004	UNIVERSITY OF CHICAGO	METHOD AND APPARATUS FOR DETECTING NORMAL CRACKS USING INFRARED THERMAL IMAGING
6756091	2000	2004	UNIVERSITY OF CALIFORNIA	LIGHTWEIGHT FLYWHEEL CONTAINMENT
WO2004095619	2004	2004	UNIVERSITY OF CALIFORNIA	IMPROVED DIRECT METHANOL FUEL CELL STACK
6864004	2004	2005	UNIVERSITY OF CALIFORNIA	DIRECT METHANOL FUEL CELL STACK
WO2005017223	2004	2005	UT-BATTELLE LLC	BULK AMORPHOUS STEELS BASED ON FE ALLOYS
WO2005115949	2005	2005	UCHICAGO ARGONNE LLC	HYDROGEN TRANSPORT MEMBRANES FOR DEHYDROGENATION REACTIONS
7052561	2003	2006	UT-BATTELLE LLC	BULK AMORPHOUS STEELS BASED ON FE ALLOYS
7081231	2000	2006	CATERPILLAR INC, BATTELLE MEMORIAL INSTITUTE	METHOD AND SYSTEM FOR THE COMBINATION OF NON-THERMAL PLASMA AND METAL/METAL OXIDE DOPED .GAMMA.-ALUMINA CATALYSTS FOR DIESEL ENGINE EXHAUST AFTERTREATMENT SYSTEM
7083765	2004	2006	UNIVERSITY OF CALIFORNIA	CATALYSTS FOR LEAN BURN ENGINE EXHAUST ABATEMENT
7099141	2005	2006	US DEPT ENERGY	CERAMIC CAPACITOR EXHIBITING GRACEFUL FAILURE BY SELF-CLEARING, METHOD FOR FABRICATING SELF-CLEARING CAPACITOR
WO2006104923	2006	2006	UNIVERSITY OF CHICAGO	HIGH-TEMPERATURE POTENTIOMETRIC OXYGEN SENSOR WITH INTERNAL REFERENCE
7211323	2003	2007	UCHICAGO ARGONNE LLC	HARD AND LOW FRICTION NITRIDE COATINGS AND METHODS FOR FORMING THE SAME
7214442	2004	2007	LOS ALAMOS NATIONAL SECURITY LLC	HIGH SPECIFIC POWER, DIRECT METHANOL FUEL CELL STACK
7329791	2004	2008	UCHICAGO ARGONNE LLC	HYDROGEN TRANSPORT MEMBRANES FOR DEHYDROGENATION

				REACTIONS
7445658	2002	2008	UCHICAGO ARGONNE LLC	TITANIUM AND TITANIUM ALLOYS
WO2008034042	2007	2008	IAP RESEARCH INC	MICRON SIZE POWDERS HAVING NANO SIZE REINFORCEMENT
WO2008150507	2008	2008	SIEMENS ENERGY INC	SYSTEM AND METHOD FOR SELECTIVE CATALYTIC REDUCTION OF NITROGEN OXIDES IN COMBUSTION EXHAUST GASES
7488462	2006	2009	OHIO STATE UNIVERSITY	MULTI-STAGE CATALYST SYSTEMS AND USES THEREOF
7699946	2006	2010	LOS ALAMOS NATIONAL SECURITY LLC	PREPARATION OF NANOSTRUCTURED MATERIALS HAVING IMPROVED DUCTILITY
7722731	2006	2010	UCHICAGO ARGONNE LLC	JOINING OF ADVANCED MATERIALS BY PLASTIC DEFORMATION
7769201	2006	2010	UCHICAGO ARGONNE LLC	METHOD FOR ANALYZING MULTI-LAYER MATERIALS FROM ONE-SIDED PULSED THERMAL IMAGING
7796388	2009	2010	UT-BATTELLE LLC	DIRECT COOLED POWER ELECTRONICS SUBSTRATE
7846556	2007	2010	UCHICAGO ARGONNE LLC	MODULATED COMPOSITE SURFACES
EP2148736	2008	2010	SIEMENS ENERGY INC	SYSTEM AND METHOD FOR SELECTIVE CATALYTIC REDUCTION OF NITROGEN OXIDES IN COMBUSTION EXHAUST GASES
7968484	2007	2011	UT-BATTELLE LLC	USE OF ADDITIVES TO IMPROVE MICROSTRUCTURES AND FRACTURE RESISTANCE OF SILICON NITRIDE CERAMICS
8012323	2009	2011	UCHICAGO ARGONNE LLC	COMPACT ELECTROCHEMICAL BIFUNCTIONAL NOX/O2 SENSORS WITH INTERNAL REFERENCE FOR HIGH TEMPERATURE APPLICATIONS
8057652	2005	2011	UCHICAGO ARGONNE LLC	HIGH-TEMPERATURE POTENTIOMETRIC OXYGEN SENSOR WITH INTERNAL REFERENCE
8071504	2008	2011	CATERPILLAR INC	EXHAUST SYSTEM HAVING A GOLD-PLATINUM GROUP METAL CATALYST
8152980	2007	2012	UCHICAGO ARGONNE LLC	ELECTRONICALLY CONDUCTING CERAMIC ELECTRON CONDUCTOR MATERIAL AND THE PROCESS FOR PRODUCING AN AIR-TIGHT SEAL IN AN OXYGEN SENSOR WITH AN INTERNAL

				REFERENCE
8157931	2009	2012	NORTHWESTERN UNIVERSITY	CASE HARDENABLE NICKEL-COBALT STEEL
8236261	2011	2012	CATERPILLAR INC	EXHAUST SYSTEM HAVING A GOLD-PLATINUM GROUP METAL CATALYST
8465200	2010	2013	UCHICAGO ARGONNE LLC	METHOD FOR IMPLEMENTING DEPTH DECONVOLUTION ALGORITHM FOR ENHANCED THERMAL TOMOGRAPHY 3D IMAGING
8585807	2011	2013	UCHICAGO ARGONNE LLC	LOW-COST METHOD FOR FABRICATING PALLADIUM AND PALLADIUM-ALLOY THIN FILMS ON POROUS SUPPORTS
WO2013122924	2013	2013	SIEMENS ENERGY INC	SELECTIVE CATALYTIC REDUCTION SYSTEM AND PROCESS FOR CONTROL OF NOX EMISSIONS IN A SULFUR-CONTAINING GAS STREAM
8647737	2011	2014	UCHICAGO ARGONNE LLC	METHOD FOR FABRICATION OF CRACK-FREE CERAMIC DIELECTRIC FILMS
8691170	2008	2014	SIEMENS ENERGY INC	SYSTEM AND METHOD FOR SELECTIVE CATALYTIC REDUCTION OF NITROGEN OXIDES IN COMBUSTION EXHAUST GASES
8889065	2006	2014	IAP RESEARCH INC	MICRON SIZE POWDERS HAVING NANO SIZE REINFORCEMENT
8900523	2008	2014	UCHICAGO ARGONNE LLC	HYDROGEN TRANSPORT MEMBRANES FOR DEHYDROGENATION REACTIONS
EP2814595	2013	2014	SIEMENS ENERGY INC	SELECTIVE CATALYTIC REDUCTION SYSTEM AND PROCESS FOR CONTROL OF NOX EMISSIONS IN A SULFUR-CONTAINING GAS STREAM
WO2014183028	2014	2014	UCHICAGO ARGONNE LLC	RECHARGEABLE NANOELECTROFUEL ELECTRODES AND DEVICES FOR HIGH ENERGY DENSITY FLOW BATTERIES
8938993	2010	2015	UT-BATTELLE LLC	GLASS STRENGTHENING AND PATTERNING METHODS
8974856	2010	2015	UCHICAGO ARGONNE LLC	METHOD FOR FABRICATION OF CERAMIC DIELECTRIC FILMS ON COPPER FOILS
9079249	2011	2015	UCHICAGO ARGONNE LLC	INTERMETALLIC NANOPARTICLES
9080089	2012	2015	UCHICAGO ARGONNE LLC	NANOPARTICLES FOR HEAT TRANSFER AND THERMAL ENERGY STORAGE
9101877	2012	2015	SIEMENS	SELECTIVE CATALYTIC

			ENERGY INC	REDUCTION SYSTEM AND PROCESS FOR CONTROL OF NOX EMISSIONS IN A SULFUR-CONTAINING GAS STREAM
9108276	2012	2015	CONSOLIDATED NUCLEAR SECURITY LLC	HARDFACE COATING SYSTEMS AND METHODS FOR METAL ALLOYS AND OTHER MATERIALS FOR WEAR AND CORROSION RESISTANT APPLICATIONS
9187806	2015	2015	UCHICAGO ARGONNE LLC	INTERMETALLIC NANOPARTICLES
EP2869321	2014	2015	DELPHI TECHNOLOGIES INC, UCHICAGO ARGONNE LLC	LEAD LANTHANUM ZIRCONIUM TITANATE (PLZT) CAPACITOR ON INORGANIC FLEXIBLE GLASS SUBSTRATE
WO2015057566	2014	2015	EMISENSE TECHNOLOGIES LLC, LAWRENCE LIVERMORE NATIONAL SECURITY LLC	ELECTROCHEMICAL SENSING USING VOLTAGE-CURRENT TIME DIFFERENTIAL
9230739	2013	2016	DELPHI TECHNOLOGIES INC, UCHICAGO ARGONNE LLC	PLZT CAPACITOR ON GLASS SUBSTRATE
9255238	2011	2016	UCHICAGO ARGONNE LLC	METHOD TO PRODUCE CATALYTICALLY ACTIVE NANOCOMPOSITE COATINGS
9299496	2015	2016	DELPHI TECHNOLOGIES INC, UCHICAGO ARGONNE LLC	PLZT CAPACITOR ON GLASS SUBSTRATE
9340720	2010	2016	UCHICAGO ARGONNE LLC	HEAT TRANSFER FLUIDS CONTAINING NANOPARTICLES
9355761	2014	2016	UCHICAGO ARGONNE LLC	METHOD FOR FABRICATION OF CRACK-FREE CERAMIC DIELECTRIC FILMS
9359223	2011	2016	UCHICAGO ARGONNE LLC	METHOD FOR PRODUCING THIN FILM ELECTRODES
EP3005458	2014	2016	UCHICAGO ARGONNE LLC	RECHARGEABLE NANOELECTROFUEL ELECTRODES AND DEVICES FOR HIGH ENERGY DENSITY FLOW BATTERIES
EP3058355	2014	2016	EMISENSE TECHNOLOGIES LLC, LAWRENCE LIVERMORE NATIONAL SECURITY LLC	ELECTROCHEMICAL SENSING USING VOLTAGE-CURRENT TIME DIFFERENTIAL
9533352	2015	2017	UCHICAGO ARGONNE LLC	INTERMETALLIC NANOPARTICLES
9552911	2013	2017	UT-BATTELLE	HF-CO-B ALLOYS AS

			LLC	PERMANENT MAGNET MATERIALS
9581564	2013	2017	EMISENSE TECHNOLOGIES LLC, LAWRENCE LIVERMORE NATIONAL SECURITY LLC	ELECTROCHEMICAL SENSING USING VOLTAGE-CURRENT TIME DIFFERENTIAL
9646766	2012	2017	UCHICAGO ARGONNE LLC	METHOD OF MAKING DIELECTRIC CAPACITORS WITH INCREASED DIELECTRIC BREAKDOWN STRENGTH
9679705	2015	2017	UCHICAGO ARGONNE LLC	METHOD FOR FABRICATION OF CERAMIC DIELECTRIC FILMS ON COPPER FOILS
9692075	2016	2017	UCHICAGO ARGONNE LLC	MULTI-LAYERED PROTON-CONDUCTING ELECTROLYTE
9816952	2015	2017	UCHICAGO ARGONNE LLC	METHOD AND APPARATUS FOR IMPLEMENTING MATERIAL THERMAL PROPERTY MEASUREMENT BY FLASH THERMAL IMAGING
9826666	2015	2017	UCHICAGO ARGONNE LLC	SYSTEM FOR COOLING HYBRID VEHICLE ELECTRONICS, METHOD FOR COOLING HYBRID VEHICLE ELECTRONICS
9833837	2014	2017	IOWA STATE UNIVERSITY	PASSIVATION AND ALLOYING ELEMENT RETENTION IN GAS ATOMIZED POWDERS
9834843	2016	2017	UCHICAGO ARGONNE LLC	METHOD FOR FABRICATION OF CRACK-FREE CERAMIC DIELECTRIC FILMS
9845441	2016	2017	UCHICAGO ARGONNE LLC	METHOD TO PRODUCE CATALYTICALLY ACTIVE NANOCOMPOSITE COATINGS
9857239	2017	2018	EMISENSE TECHNOLOGIES LLC, LAWRENCE LIVERMORE NATIONAL SECURITY LLC	TEMPERATURE ANALYSIS WITH VOLTAGE-CURRENT TIME DIFFERENTIAL OPERATION OF ELECTROCHEMICAL SENSORS
9857325	2017	2018	EMISENSE TECHNOLOGIES LLC, LAWRENCE LIVERMORE NATIONAL SECURITY LLC	ELECTROCHEMICAL SENSING USING COMPARISON OF VOLTAGE-CURRENT TIME DIFFERENTIAL VALUES DURING WAVEFORM GENERATION AND DETECTION
9857326	2017	2018	EMISENSE TECHNOLOGIES LLC, LAWRENCE LIVERMORE	GAS STREAM ANALYSIS USING VOLTAGE-CURRENT TIME DIFFERENTIAL OPERATION OF ELECTROCHEMICAL SENSORS

			NATIONAL SECURITY LLC	
9908817	2012	2018	UCHICAGO ARGONNE LLC	MULTILAYER CAPACITORS, METHOD FOR MAKING MULTILAYER CAPACITORS
10128046	2015	2018	UCHICAGO ARGONNE LLC	WOUND/STACKED CERAMIC FILM CAPACITORS, METHOD FOR MAKING CERAMIC FILM CAPACITORS
10153511	2014	2018	UCHICAGO ARGONNE LLC, ILLINOIS INSTITUTE OF TECHNOLOGY	RECHARGEABLE NANOELECTROFUEL ELECTRODES AND DEVICES FOR HIGH ENERGY DENSITY FLOW BATTERIES
10287526	2017	2019	UCHICAGO ARGONNE LLC	METHOD TO PRODUCE CATALYTICALLY ACTIVE NANOCOMPOSITE COATINGS
10349563	2017	2019	UCHICAGO ARGONNE LLC	SYSTEM FOR COOLING HYBRID VEHICLE ELECTRONICS, METHOD FOR COOLING HYBRID VEHICLE ELECTRONICS

Appendix LWM-A. VTO-funded Lightweight Materials Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
5458927	1995	1995	GENERAL MOTORS CORP	PROCESS FOR THE FORMATION OF WEAR AND SCUFF-RESISTANT CARBON COATINGS
EP0731190	1996	1996	GENERAL MOTORS CORP	PROCESS FOR THE FORMATION OF CARBON COATINGS
5603795	1994	1997	LOCKHEED MARTIN CORP	JOINING OF THERMOPLASTIC SUBSTRATES BY MICROWAVES
WO2001055487	2001	2001	UT-BATTELLE LLC	CARBON FIBER MANUFACTURING VIA PLASMA TECHNOLOGY
6372192	2000	2002	UT-BATTELLE LLC	CARBON FIBER MANUFACTURING VIA PLASMA TECHNOLOGY
6375875	2000	2002	UT-BATTELLE LLC	DIAGNOSTIC MONITOR FOR CARBON FIBER PROCESSING
WO2002025003	2001	2002	UT-BATTELLE LLC	MICROWAVE AND PLASMA-ASSISTED MODIFICATION OF COMPOSITE FIBER SURFACE TOPOGRAPHY
6514449	2000	2003	UT-BATTELLE LLC	MICROWAVE AND PLASMA-ASSISTED MODIFICATION OF COMPOSITE FIBER SURFACE TOPOGRAPHY
6647802	2001	2003	AUTOMOTIVE COMPOSITES CONSORTIUM	CREEP TESTING FIXTURE AND METHOD
7255233	2004	2007	UCHICAGO ARGONNE LLC	METHOD AND APPARATUS FOR SEPARATING MIXED PLASTICS USING FLOTATION TECHNIQUES
7284528	2006	2007	FORD GLOBAL TECHNOLOGIES	CRANK SHAFT SUPPORT ASSEMBLY
7525010	2006	2009	UCHICAGO ARGONNE LLC	PROCESS TO WASH POLYMERS CONTAMINATED WITH POLYCHLORINATED BIPHENYLS (PCBS)
7534854	2006	2009	UT-BATTELLE LLC	APPARATUS AND METHOD FOR OXIDATION AND STABILIZATION OF POLYMERIC MATERIALS
WO2009117246	2009	2009	UT-BATTELLE LLC	MULTIPLE PASS AND MULTIPLE LAYER FRICTION STIR WELDING AND MATERIAL ENHANCEMENT PROCESSES
7649078	2006	2010	UT-BATTELLE LLC	APPARATUS AND METHOD FOR STABILIZATION OR OXIDATION OF POLYMERIC

				MATERIALS
7682556	2005	2010	UT-BATTELLE LLC	DEGASSING OF MOLTEN ALLOYS WITH THE ASSISTANCE OF ULTRASONIC VIBRATION
7699958	2006	2010	UT-BATTELLE LLC	METHOD FOR IMPROVING SEPARATION OF CARBOHYDRATES FROM WOOD PULPING AND WOOD OR BIOMASS HYDROLYSIS LIQUORS
7727932	2005	2010	UT-BATTELLE LLC	ACTIVATED CARBON FIBERS AND ENGINEERED FORMS FROM RENEWABLE RESOURCES
7762447	2008	2010	UT-BATTELLE LLC	MULTIPLE PASS AND MULTIPLE LAYER FRICTION STIR WELDING AND MATERIAL ENHANCEMENT PROCESSES
7766172	2009	2010	UCHICAGO ARGONNE LLC	FRICTION BASED MATERIAL SORTER
7784856	2009	2010	USCAR / USAMP	DYNAMIC LOAD BEARING COMPOSITE FLOOR PAN FOR AN AUTOMOTIVE VEHICLE
7786253	2009	2010	UT-BATTELLE LLC, SENTECH INC	APPARATUS AND METHOD FOR OXIDATION AND STABILIZATION OF POLYMERIC MATERIALS
7819452	2008	2010	USCAR / USAMP	AUTOMOTIVE STRUCTURAL JOINT AND METHOD OF MAKING SAME
7824495	2005	2010	UT-BATTELLE LLC	SYSTEM TO CONTINUOUSLY PRODUCE CARBON FIBER VIA MICROWAVE ASSISTED PLASMA PROCESSING
8017273	2008	2011	UT-BATTELLE LLC	LIGHTWEIGHT, DURABLE LEAD-ACID BATTERIES
8047593	2010	2011	USCAR / USAMP	AUTOMOTIVE STRUCTURAL JOINT AND METHOD OF MAKING SAME
8052783	2006	2011	UT-BATTELLE LLC	ROTARY ADSORBERS FOR CONTINUOUS BULK SEPARATIONS
8052951	2009	2011	UT-BATTELLE LLC	CARBON NANOTUBES GROWN ON BULK MATERIALS AND METHODS FOR FABRICATION
8061579	2010	2011	UT-BATTELLE LLC	FRICTION STIR METHOD FOR FORMING STRUCTURES AND MATERIALS
8227051	2005	2012	UT-BATTELLE LLC	APPARATUS AND METHOD FOR CARBON FIBER SURFACE TREATMENT
WO2012003070	2011	2012	WEYERHAEUSER NR CO	LIGNIN/POLYACRYLONITRILE-CONTAINING DOPES, FIBERS, AND METHODS OF MAKING

				SAME
8377843	2010	2013	UT-BATTELLE LLC	ACTIVATED CARBON FIBERS AND ENGINEERED FORMS FROM RENEWABLE RESOURCES
8434661	2012	2013	BATTELLE MEMORIAL INSTITUTE	FRICTION STIR WELDING TOOL AND PROCESS FOR WELDING DISSIMILAR MATERIALS
8445138	2011	2013	UT-BATTELLE LLC	LIGHTWEIGHT, DURABLE LEAD-ACID BATTERIES
WO2013033536	2012	2013	INFINIUM INC, BOSTON UNIVERSITY	CONDUCTOR OF HIGH ELECTRICAL CURRENT AT HIGH TEMPERATURE IN OXYGEN AND LIQUID METAL ENVIRONMENT
WO2013152153	2013	2013	OHIO STATE UNIVERSITY	ELECTRICALLY DRIVEN RAPIDLY VAPORIZING FOILS, WIRES AND STRIPS USED FOR COLLISION WELDING AND SHEET METAL FORMING
8679592	2010	2014	UT-BATTELLE LLC	SYSTEM TO CONTINUOUSLY PRODUCE CARBON FIBER VIA MICROWAVE ASSISTED PLASMA PROCESSING
8741395	2012	2014	UT-BATTELLE LLC, REMAXCO TECHNOLOGIES	APPARATUS AND METHOD FOR CARBON FIBER SURFACE TREATMENT
8753463	2011	2014	USCAR / USAMP	AUTOMOTIVE STRUCTURAL JOINT AND METHOD OF MAKING SAME
8771832	2010	2014	WEYERHAEUSER NR CO	LIGNIN/POLYACRYLONITRILE-CONTAINING DOPES, FIBERS, AND METHODS OF MAKING SAME
8815146	2012	2014	UT-BATTELLE LLC	ALUMINA FORMING IRON BASE SUPERALLOY
EP2761060	2012	2014	INFINIUM INC, BOSTON UNIVERSITY	CONDUCTOR OF HIGH ELECTRICAL CURRENT AT HIGH TEMPERATURE IN OXYGEN AND LIQUID METAL ENVIRONMENT
WO2014011457	2013	2014	DOW GLOBAL TECHNOLOGIES LLC	PROCESSES FOR PREPARING CARBON FIBERS USING GASEOUS SULFUR TRIOXIDE
WO2014011460	2013	2014	DOW GLOBAL TECHNOLOGIES LLC	TWO-STEP SULFONATION PROCESS FOR THE CONVERSION OF POLYMER FIBERS TO CARBON FIBERS
WO2014011462	2013	2014	DOW GLOBAL TECHNOLOGIES LLC	PROCESSES FOR PREPARING CARBON FIBERS USING SULFUR TRIOXIDE IN A HALOGENATED SOLVENT
WO2014078821	2013	2014	UT-BATTELLE LLC, REMAXCO TECHNOLOGIES	ATMOSPHERIC PRESSURE PLASMA PROCESSING OF POLYMERIC MATERIALS

				UTILIZING CLOSE PROXIMITY INDIRECT EXPOSURE
WO2014201274	2014	2014	INFINIUM INC	IMPROVED LIQUID METAL ELECTRODES FOR GAS SEPARATION
9021845	2013	2015	UNASSIGNED	ELECTRICALLY DRIVEN RAPIDLY VAPORIZING FOILS, WIRES AND STRIPS USED FOR COLLISION WELDING AND SHEET METAL FORMING
9096955	2012	2015	UT-BATTELLE LLC	METHOD FOR THE PREPARATION OF CARBON FIBER FROM POLYOLEFIN FIBER PRECURSOR, AND CARBON FIBERS MADE THEREBY
9133568	2014	2015	WEYERHAEUSER NR CO	LIGNIN/POLYACRYLONITRILE-CONTAINING DOPES, FIBERS, AND METHODS OF MAKING SAME
9216445	2011	2015	UT-BATTELLE LLC	METHOD OF FORMING MAGNESIUM ALLOY SHEETS
9222201	2013	2015	DOW GLOBAL TECHNOLOGIES LLC	PROCESSES FOR PREPARING CARBON FIBERS USING SULFUR TRIOXIDE IN A HALOGENATED SOLVENT
EP2834393	2013	2015	OHIO STATE UNIVERSITY	METHOD FOR FORMING A SHEET METAL BY IMPULSE FORMING
EP2850231	2013	2015	DOW GLOBAL TECHNOLOGIES LLC	PROCESSES FOR PREPARING CARBONIZED POLYMERS
EP2850232	2013	2015	DOW GLOBAL TECHNOLOGIES LLC	PROCESSES FOR PREPARING CARBON FIBERS USING SULFUR TRIOXIDE IN A HALOGENATED SOLVENT
EP2872681	2013	2015	DOW GLOBAL TECHNOLOGIES LLC	PROCESS FOR PREPARING CARBONIZED POLYMERS
EP2920808	2013	2015	UT-BATTELLE LLC, REMAXCO TECHNOLOGIES	ATMOSPHERIC PRESSURE PLASMA PROCESSING OF POLYMERIC MATERIALS UTILIZING CLOSE PROXIMITY INDIRECT EXPOSURE
WO2015200127	2015	2015	UNIVERSITY OF MICHIGAN	HYBRID FRICTION STIR WELDING FOR DISSIMILAR MATERIALS THROUGH ELECTRO-PLASTIC EFFECT
9228263	2012	2016	NEI CORP	CHEMICAL CONVERSION COATING FOR PROTECTING MAGNESIUM ALLOYS FROM CORROSION
9228276	2013	2016	DOW GLOBAL TECHNOLOGIES LLC	PROCESSES FOR PREPARING CARBON FIBERS USING GASEOUS SULFUR TRIOXIDE
9234288	2012	2016	INFINIUM INC,	CONDUCTOR OF HIGH

			BOSTON UNIVERSITY	ELECTRICAL CURRENT AT HIGH TEMPERATURE IN OXYGEN AND LIQUID METAL ENVIRONMENT
9239277	2012	2016	UT-BATTELLE LLC, OAK RIDGE ASSOCIATED UNIVERSITIES	MATERIAL MECHANICAL CHARACTERIZATION METHOD FOR MULTIPLE STRAINS AND STRAIN RATES
9266190	2014	2016	FORD GLOBAL TECHNOLOGIES	SOLID CARTRIDGE FOR A PULSE WELD FORMING ELECTRODE AND METHOD OF JOINING TUBULAR MEMBERS
9340677	2014	2016	UT-BATTELLE LLC	APPARATUS AND PROCESS FOR THE SURFACE TREATMENT OF CARBON FIBERS
9365685	2012	2016	UT-BATTELLE LLC	METHOD OF IMPROVING ADHESION OF CARBON FIBERS WITH A POLYMERIC MATRIX
9418779	2013	2016	BATTELLE MEMORIAL INSTITUTE	PROCESS FOR PREPARING SCALABLE QUANTITIES OF HIGH PURITY MANGANESE BISMUTH MAGNETIC MATERIALS FOR FABRICATION OF PERMANENT MAGNETS
9427720	2014	2016	UT-BATTELLE LLC	SYSTEM TO CONTINUOUSLY PRODUCE CARBON FIBER VIA MICROWAVE ASSISTED PLASMA PROCESSING
9435039	2012	2016	UNIVERSITY OF MISSOURI	PROTECTIVE CONVERSION COATING ON MIXED-METAL SUBSTRATES AND METHODS THEREOF
9447205	2012	2016	UT-BATTELLE LLC, REMAXCO TECHNOLOGIES	ATMOSPHERIC PRESSURE PLASMA PROCESSING OF POLYMERIC MATERIALS UTILIZING CLOSE PROXIMITY INDIRECT EXPOSURE
9528197	2013	2016	UT-BATTELLE LLC	CONTROLLED CHEMICAL STABILIZATION OF POLYVINYL PRECURSOR FIBER, AND HIGH STRENGTH CARBON FIBER PRODUCED THEREFROM
WO2016003564	2015	2016	FORD GLOBAL TECHNOLOGIES	SOLID CARTRIDGE FOR A PULSE WELD FORMING ELECTRODE AND METHOD OF JOINING TUBULAR MEMBERS
WO2016023021	2015	2016	FORD GLOBAL TECHNOLOGIES LLC	ELECTRODE CARTRIDGE FOR PULSE WELDING
9617398	2013	2017	UT-BATTELLE LLC	MULTIFUNCTIONAL CURING AGENTS AND THEIR USE IN IMPROVING STRENGTH OF

				COMPOSITES CONTAINING CARBON FIBERS EMBEDDED IN A POLYMERIC MATRIX
9676054	2014	2017	FORD GLOBAL TECHNOLOGIES	ELECTRODE CARTRIDGE FOR PULSE WELDING
9725829	2013	2017	UT-BATTELLE LLC	MAGNETO-CARBONIZATION METHOD FOR PRODUCTION OF CARBON FIBER, AND HIGH PERFORMANCE CARBON FIBERS MADE THEREBY
9732445	2015	2017	UT-BATTELLE LLC	LOW TEMPERATURE STABILIZATION PROCESS FOR PRODUCTION OF CARBON FIBER HAVING STRUCTURAL ORDER
9816207	2013	2017	DOW GLOBAL TECHNOLOGIES LLC	TWO-STEP SULFONATION PROCESS FOR THE CONVERSION OF POLYMER FIBERS TO CARBON FIBERS
9828700	2015	2017	UT-BATTELLE LLC	METHOD FOR THE PREPARATION OF CARBON FIBER FROM POLYOLEFIN FIBER PRECURSOR
9981338	2015	2018	UNIVERSITY OF MICHIGAN	HYBRID FRICTION STIR WELDING FOR DISSIMILAR MATERIALS THROUGH ELECTRO-PLASTIC EFFECT
10087539	2014	2018	INFINIUM INC	LIQUID METAL ELECTRODES FOR GAS SEPARATION
10099458	2016	2018	MICHIGAN STATE UNIVERSITY	REVERSIBLE ADHESIVE COMPOSITIONS AND RELATED METHODS
10138305	2016	2018	UT-BATTELLE LLC, REMAXCO TECHNOLOGIES	ATMOSPHERIC PRESSURE PLASMA PROCESSING OF POLYMERIC MATERIALS UTILIZING CLOSE PROXIMITY INDIRECT EXPOSURE
10240011	2017	2019	UT-BATTELLE LLC	MULTIFUNCTIONAL CURING AGENTS AND THEIR USE IN IMPROVING STRENGTH OF COMPOSITES CONTAINING CARBON FIBERS EMBEDDED IN POLYMERIC MATRIX
10351683	2016	2019	UT-BATTELLE LLC	METHOD OF IMPROVING ADHESION OF CARBON FIBERS WITH A POLYMERIC MATRIX
10457785	2016	2019	UT-BATTELLE LLC	METHOD OF IMPROVING ADHESION OF CARBON FIBERS WITH A POLYMERIC MATRIX
10501590	2016	2019	UT-BATTELLE LLC	SOLID COMPOSITES CONTAINING POLYMERIC MATRIX WITH CARBON FIBERS EMBEDDED THEREIN

Appendix LWM-B. Other DOE-funded Lightweight Materials Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
4995948	1989	1991	US DEPT ENERGY	APPARATUS AND PROCESS FOR THE ELECTROLYTIC REDUCTION OF URANIUM AND PLUTONIUM OXIDES
5147471	1991	1992	US DEPT ENERGY	SOLDER FOR OXIDE LAYER-BUILDING METALS AND ALLOYS
WO1992017617	1992	1992	US DEPT ENERGY	SOLDER FOR OXIDE LAYER-BUILDING METALS AND ALLOYS
EP0538446	1992	1993	US DEPT ENERGY	SOLDER FOR OXIDE LAYER-BUILDING METALS AND ALLOYS
5445685	1993	1995	UNIVERSITY OF CALIFORNIA	TRANSFORMATION PROCESS FOR PRODUCTION OF ULTRAHIGH CARBON STEELS AND NEW ALLOYS
WO1997036728	1997	1997	LAMBDA TECHNOLOGIES INC, LOCKHEED MARTIN CORP	ADHESIVE BONDING USING VARIABLE FREQUENCY MICROWAVE ENERGY
5721286	1995	1998	LOCKHEED MARTIN CORP	METHOD FOR CURING POLYMERS USING VARIABLE-FREQUENCY MICROWAVE HEATING
5798395	1996	1998	LAMBDA TECHNOLOGIES INC, LOCKHEED MARTIN CORP	ADHESIVE BONDING USING VARIABLE FREQUENCY MICROWAVE ENERGY
5799238	1995	1998	US DEPT ENERGY	METHOD OF MAKING MULTILAYERED TITANIUM CERAMIC COMPOSITES
5804801	1997	1998	LAMBDA TECHNOLOGIES INC, LOCKHEED MARTIN CORP	ADHESIVE BONDING USING VARIABLE FREQUENCY MICROWAVE ENERGY
5849373	1997	1998	SANDIA CORP	PROCESS FOR THE SYNTHESIS OF NANOPHASE DISPERSION-STRENGTHENED ALUMINUM ALLOY
5851317	1997	1998	IOWA STATE UNIVERSITY	COMPOSITE MATERIAL REINFORCED WITH ATOMIZED QUASICRYSTALLINE PARTICLES AND METHOD OF MAKING SAME
5895518	1996	1999	SANDIA CORP	SYNTHESIS OF ALLOYS WITH CONTROLLED PHASE STRUCTURE
5908486	1996	1999	LOCKHEED MARTIN CORP	STRENGTHENING OF METALLIC ALLOYS WITH NANOMETER-SIZE OXIDE

				DISPERSIONS
EP0889775	1997	1999	LAMBDA TECHNOLOGIES INC, LOCKHEED MARTIN CORP	ADHESIVE BONDING USING VARIABLE FREQUENCY MICROWAVE ENERGY
EP1155798	1997	2001	LAMBDA TECHNOLOGIES INC, LOCKHEED MARTIN CORP	ADHESIVE BONDING USING VARIABLE FREQUENCY MICROWAVE ENERGY
6475310	2000	2002	US DEPT ENERGY	OXIDATION RESISTANT ALLOYS, METHOD FOR PRODUCING OXIDATION RESISTANT ALLOYS
WO2003106718	2003	2003	BECHTEL BWXT IDAHO LLC	HARD METALLIC MATERIALS, HARD METALLIC COATINGS, METHODS OF PROCESSING METALLIC MATERIALS AND METHODS OF PRODUCING METALLIC COATINGS
6689234	2002	2004	BECHTEL BWXT IDAHO LLC	METHOD OF PRODUCING METALLIC MATERIALS
6719859	2002	2004	NORTHWEST ALUMINUM CO	HIGH STRENGTH ALUMINUM BASE ALLOY
6733737	2001	2004	WRIGHT MATERIALS RESEARCH CORP	RAPID OXIDATION/STABILIZATION TECHNIQUE FOR CARBON FOAMS, CARBON FIBERS AND C/C COMPOSITES
WO2004061145	2003	2004	UT-BATTELLE LLC	CR-W-V BAINITIC/FERRITIC STEEL COMPOSITIONS
EP1552027	2003	2005	BECHTEL BWXT IDAHO LLC	HARD METALLIC MATERIALS,HARD METALLIC COATINGS, METHODS OF PROCESSING METALLIC MATERIALS AND METHODS OF PRODUCING METALLIC COATINGS
WO2005014869	2004	2005	QUEEN CITY FORGING CO	PROCESS OF PREPARING METAL PARTS TO BE HEATED BY MEANS OF INFRARED RADIANCE
7067022	2004	2006	BATTELLE ENERGY ALLIANCE LLC	METHOD FOR PROTECTING A SURFACE
7074286	2002	2006	UT-BATTELLE LLC	WROUGHT CR-W-V BAINITIC/FERRITIC STEEL COMPOSITIONS
WO2006076023	2005	2006	BATTELLE MEMORIAL INSTITUTE	METHOD OF GENERATING HYDROCARBON REAGENTS FROM DIESEL, NATURAL GAS AND OTHER LOGISTICAL FUELS
EP1753843	2005	2007	BATTELLE MEMORIAL INSTITUTE	METHOD OF GENERATING HYDROCARBON REAGENTS FROM DIESEL, NATURAL GAS AND OTHER LOGISTICAL

				FUELS
7357292	2005	2008	BATTELLE ENERGY ALLIANCE LLC	FRICTION STIR WELDING TOOL
7435760	2005	2008	BATTELLE MEMORIAL INSTITUTE	METHOD OF GENERATING HYDROCARBON REAGENTS FROM DIESEL, NATURAL GAS AND OTHER LOGISTICAL FUELS
7544256	2004	2009	QUEEN CITY FORGING CO, US DEPT ENERGY	PROCESS OF PREPARING METAL PARTS TO BE HEATED BY MEANS OF INFRARED RADIANCE
WO2009155414	2009	2009	UNIVERSITY OF ARKANSAS	MICROWAVE-ASSISTED SYNTHESIS OF CARBON AND CARBON-METAL COMPOSITES FROM LIGNIN, TANNIN AND ASPHALT DERIVATIVES
WO2009155417	2009	2009	UNIVERSITY OF ARKANSAS	MICROWAVE-ASSISTED SYNTHESIS OF CARBON AND CARBON-METAL COMPOSITES FROM LIGNIN, TANNIN AND ASPHALT DERIVATIVES AND APPLICATIONS OF SAME
7744751	2008	2010	BATTELLE MEMORIAL INSTITUTE	METHOD OF GENERATING HYDROCARBON REAGENTS FROM DIESEL, NATURAL GAS AND OTHER LOGISTICAL FUELS
7785428	2004	2010	BATTELLE ENERGY ALLIANCE LLC	METHOD OF FORMING A HARDENED SURFACE ON A SUBSTRATE
7850057	2010	2010	VANDERBILT UNIVERSITY	LATERAL POSITION DETECTION AND CONTROL FOR FRICTION STIR SYSTEMS
EP2208800	2003	2010	BATTELLE ENERGY ALLIANCE LLC	METHOD OF FORMING A WIRE FROM A POWDER AND A METAL STRIP
EP2226398	2003	2010	BATTELLE MEMORIAL INSTITUTE	METHOD OF FORMING A HARDENED SURFACE ON A SUBSTRATE
7943073	2006	2011	BATTELLE MEMORIAL INSTITUTE	COMPOSITE MATERIALS AND METHOD OF MAKING
EP2297030	2009	2011	UNIVERSITY OF ARKANSAS	MICROWAVE-ASSISTED SYNTHESIS OF CARBON AND CARBON-METAL COMPOSITES FROM LIGNIN, TANNIN AND ASPHALT DERIVATIVES AND APPLICATIONS OF SAME
EP2297383	2009	2011	UNIVERSITY OF ARKANSAS	MICROWAVE-ASSISTED SYNTHESIS OF CARBON AND CARBON-METAL COMPOSITES FROM LIGNIN, TANNIN AND ASPHALT DERIVATIVES
8097095	2004	2012	BATTELLE	HARDFACING MATERIAL

			ENERGY ALLIANCE LLC	
8167973	2009	2012	UNIVERSITY OF ARKANSAS	MICROWAVE-ASSISTED SYNTHESIS OF CARBON AND CARBON-METAL COMPOSITES FROM LIGNIN, TANNIN AND ASPHALT DERIVATIVES
8191753	2011	2012	VANDERBILT UNIVERSITY	LATERAL POSITION DETECTION AND CONTROL FOR FRICTION STIR SYSTEMS
WO2012096976	2012	2012	BATTELLE MEMORIAL INSTITUTE	COMBINED ON-BOARD HYDRIDE SLURRY STORAGE AND REACTOR SYSTEM AND PROCESS FOR HYDROGEN POWERED VEHICLES AND DEVICES
8544714	2012	2013	FLUOR TECHNOLOGIES CORP	CERTIFICATION OF A WELD PRODUCED BY FRICTION STIR WELDING
8881964	2010	2014	UT-BATTELLE LLC	FRICTION STIR WELDING AND PROCESSING OF OXIDE DISPERSION STRENGTHENED (ODS) ALLOYS
8889097	2012	2014	BATTELLE MEMORIAL INSTITUTE	COMBINED ON-BOARD HYDRIDE SLURRY STORAGE AND REACTOR SYSTEM AND PROCESS FOR HYDROGEN-POWERED VEHICLES AND DEVICES
WO2014043701	2013	2014	TEXAS A&M UNIVERSITY	METHOD FOR PRODUCING HIGH STACKING FAULT ENERGY (SFE) METAL FILMS, FOILS, AND COATINGS WITH HIGH-DENSITY NANOSCALE TWIN BOUNDARIES
9283637	2013	2016	BATTELLE MEMORIAL INSTITUTE	FRICTION STIR WELD TOOLS HAVING FINE GRAIN STRUCTURE
9499880	2015	2016	BATTELLE MEMORIAL INSTITUTE	SYSTEM AND PROCESS FOR PRODUCTION OF MAGNESIUM METAL AND MAGNESIUM HYDRIDE FROM MAGNESIUM-CONTAINING SALTS AND BRINES
9527746	2012	2016	HONEYWELL INC	CARBONIZED ASPHALTENE-BASED CARBON-CARBON FIBER COMPOSITES
WO2016144396	2015	2016	BATTELLE MEMORIAL INSTITUTE	SYSTEM AND PROCESS FOR PRODUCTION OF MAGNESIUM METAL AND MAGNESIUM HYDRIDE FROM MAGNESIUM-CONTAINING SALTS AND BRINES
9580839	2012	2017	HONEYWELL INC	METHODS OF MAKING CARBON FIBER FROM ASPHALTENES

9650309	2013	2017	IOWA STATE UNIVERSITY	STABILITY OF GAS ATOMIZED REACTIVE POWDERS THROUGH MULTIPLE STEP IN-SITU PASSIVATION
9815224	2015	2017	UT-BATTELLE LLC	CARBON FIBER REINFORCEMENTS FOR SHEET MOLDING COMPOSITES
WO2017007908	2016	2017	UT-BATTELLE LLC	CASTABLE HIGH-TEMPERATURE CE-MODIFIED AL ALLOYS
9862140	2015	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	ADDITIVE MANUFACTURING OF SHORT AND MIXED FIBRE-REINFORCED POLYMER
9869000	2014	2018	BATTELLE ENERGY ALLIANCE LLC	METHODS OF MAKING BAINITIC STEEL MATERIALS
9963770	2016	2018	UT-BATTELLE LLC	CASTABLE HIGH-TEMPERATURE CE-MODIFIED AL ALLOYS
10023977	2013	2018	TEXAS A&M UNIVERSITY	METHOD FOR PRODUCING HIGH STACKING FAULT ENERGY (SFE) METAL FILMS, FOILS, AND COATINGS WITH HIGH-DENSITY NANOSCALE TWIN BOUNDARIES
10053760	2017	2018	UT-BATTELLE LLC	METHOD OF THERMOMAGNETICALLY PROCESSING AN ALUMINUM ALLOY
10109418	2014	2018	BATTELLE MEMORIAL INSTITUTE	SYSTEM AND PROCESS FOR FRICTION CONSOLIDATION FABRICATION OF PERMANENT MAGNETS AND OTHER EXTRUSION AND NON-EXTRUSION STRUCTURES
10207427	2017	2019	UT-BATTELLE LLC	CARBON FIBER REINFORCEMENTS FOR SHEET MOLDING COMPOSITES

An Analysis of the Influence of VTO-funded Propulsion/Lightweight Materials Patents

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