NORTH-HOLLAND

Innovation Forecasting

ROBERT J. WATTS and ALAN L. PORTER

ABSTRACT

Technological forecasting is premised on a certain orderliness of the innovation process. Myriad studies of technological substitution, diffusion, and transfer processes have yielded conceptual models of what matters for successful innovation, but most technological forecasts key on limited empirical measures quite divorced from those innovation process models. We glean a number of concepts from various innovation models, then present an array of bibliometric measures that offer the promise of operationalizing these concepts. Judicious combination of such bibliometrics with other forms of evidence offers an enriched form of technological forecasting we call "innovation forecasting." This provides a good means to combine technological trends, mapping of technological interdependencies, and competitive intelligence to produce a viable forecast. We illustrate by assessing prospects for ceramic engine technologies. © 1997 Elsevier Science Inc.

Introduction

Technological forecasting purports to provide timely insight into the prospects for significant technological change. Such information should help management make better decisions with regard to strategic corporate planning, R&D management, product development, investment in new process technology, production and marketing, purchasing of new technology, and so forth. Technological forecasting encompasses varied objectives, time horizons, and approaches (c.f. [1–3]). Table 1 offers one listing of forecasting techniques as categorized by Vanston [4].

The conceptual foundation upon which technological forecasting rests is a degree of orderliness in the innovation process. Emergence of new or improved technologies depends on successful completion of the innovation process—"any system of organized activities that transforms a technology from an idea to commercialization" [5].

We draw upon various innovation and technological change models to generate a set of concepts pertinent to gauging the prospects of particular technologies becoming successes. Various technological forecasting approaches provide context for our "innovation forecasting." This draws particularly upon bibliometrics, which we briefly overview. We propose candidate bibliometric measures to operationalize a number of innovation

---

ROBERT WATTS is on the senior staff of the U.S. Army Tank-automotive and Command Armaments (TACOM), Warren, MI.

ALAN PORTER directs the Technology Policy and Assessment Center and is Professor of Industrial and Systems Engineering, and Public Policy, at Georgia Tech.

Address reprint requests to Robert Watts, 22430 St. Clair Drive, St. Clair Shores, MI 48081. E-mail: wattsb@cc.tacom.army.mil

For information about Technology Opportunities Analysis, contact Alan Porter. E-mail: alan.porter@isye.gatech.edu

Technological Forecasting and Social Change 56, 25–47 (1997)

655 Avenue of the Americas, New York, NY 10010
0040-1625/97/$17.00
PII S0040-1625(97)00050-4

TABLE 1
Forecasting Techniques

Extrapolator	Goal analyst	Intuitor
Technical trend analysis[a]	Implication analysis	Delphi surveys[b]
Substitution analysis[a]	Content analysis[b]	Nominal group conference[b]
Growth limit analysis[a]	Stakeholder analysis	Structured/unstructured interviews[b]
Learning curves[a]	Patent analysis[b]	Comprehensive opportunity analysis[b]
Pattern analyst	Counterpuncher	
Analogies[b]	Scanning	
Precursor trends[a]	Monitoring[b]	
Morphological analysis	Alternate scenario planning[b]	
Feedback models[a]	Monte Carlo models[a]	

Source: Vanston, John H., Technology Futures Inc., Austin, Texas [4]. [See also Note Added in Proof appearing before the reference list.]

[a] Highly quantitative.

[b] Semi-quantitative.

concepts. The second part of this article illustrates innovation forecasting by showing how selected measures can be combined with other information to assess the prospects for ceramic engine innovation.

Toward Innovation Forecasting

Attempted technological innovation may or may not be successful. Successful innovation relies on many variables, including the technology's characteristics, the fit between the innovating firm and the technology, familiarity of the firm with the market and associated infrastructure, market forces, the economic climate and resource commitments, other socioeconomic factors, and institutional actions or interactions (c.f. [3, 5, 6]). Underlying each of these variables there exist organizational elements that view a new technology from different perspectives and act to influence its development toward their own interests [7]. For example, in assessing national strategic value, a country might well appraise a new technology's trade balance implications, the technology's indispensability (i.e., viability of substitutes and associated economic impacts, if displaced), the development capacity and pervasiveness (e.g., diffusion capacity to other industries), the available work-force skills and know-how, the versatility and flexibility of the resulting industry, the exploitation of resources, and the attendant environmental impacts [6, 8].

Much research on technological innovation documents the factors that either promote or inhibit successful product development. Many researchers have performed postmortem assessments of technology transfer activities, technology diffusion, and technology substitution processes to characterize significant factors and recommend managerial practices that promote success in new product technology innovation (c.f. [9, 10]. We have scavenged "innovation success" concepts from various sources. In particular:

- Michael Porter's four-factors framework highlighting the importance of various competitive forces [6]
- William Souder's identification of statistically significant organizational factors relating to either the technical or commercial success of an innovation project [5]
- Steven Dunphy et al.'s juxtaposition of the factors of an "innovation funnel" [11]
- Clayton Smith's specification of levels and forms of substitution [12]
- Ted Modis' observations on compatibility with infrastructure and complementary products [13]

- Anderson and Tushman's evidence on the interplay of industry participants [14]
- Isreal Dror's use of patent information to infer design standards [15]
- Metcalfe's technology diffusion considerations [16, 17]
- Cetron, Cohen, and Rogers each identifying sets of factors contributing to technology transfer [18–20]
- Souder et al. on roles of sponsor and adopter [21]

We will return to the innovation success concepts in the next section.

The technological literature is immense. To capture some of the information inherent in the content and patterning of the literature, a field called "bibliometrics" has emerged. Bibliometrics uses counts of publications, patents, or citations to measure and interpret technological advances. Such analyses assume that counts of papers or patents provide useful indications of R&D activity and of innovation, depending on the sources examined. Another key tenet is that one can ascertain important links by analyzing which topics occur together, which organizations produce what papers and patents, and who cites what [22]. Bibliometric applications range from the strategic (e.g., classifying British science [23]) through the tactical (e.g., providing competitive intelligence on who is doing what on a particular technology). Various forms of bibliometric analysis have emerged. Citation analysis (c.f., [24]) examines referencing patterns among papers and/or patents to detect seminal contributions and interaction patterns, and even to forecast emerging research areas. Patent analysis relates patenting activity to profile company interests and trends. Publication analyses take articles and such as telling indicators of R&D activities.

Linkage is a particular interest in bibliometrics, leading to the development of several analytical approaches based on entities appearing together—co-occurrences [25]. Co-citation analysis identifies pairings of articles jointly cited by later articles. From these, cognitive structure may be inferred (c.f. [26, 27]). Co-word analysis, dating mainly from the 1980s in Europe, looks for words appearing together [28]. Some focus on keywords (index terms); Kostoff has extended these analyses to whole texts (c.f. [29]). Mapping is particularly useful in facilitating interpretation of bibliometric findings [30, 31].

Bibliometric limitations need to be noted. Counts do not distinguish quality, and much technological development work is not reflected in publications or patents, at least not in a timely manner. Publishing and patenting practices vary considerably across fields and by institutions (e.g., one company may publish heavily; another, not at all). Nonetheless there is a wealth of information to be mined using these approaches. Such information should be combined with other measures and expert opinion to develop a balanced assessment [32].

Forecasting—including technology or technological ("tech") forecasting—depends on theory, data, and methods [2]. The *theory* behind tech forecasting consists of the conceptualizations of the innovation process in its various guises. The linkage between that theory and tech forecasting practice is weak. Innovation forecasting seeks to tighten this linkage to take better advantage of lessons learned in efforts to model innovation processes. *Data* for tech forecasting are usually weak. Emerging technologies offer only short time series potential to begin, but this is typically weakened because a government has not emphasized collection of tech indicators[1] and industry often seeks to protect

---

[1] Of course there are many notable sources of data technology; for instance, the U.S. National Science Foundation's biennial *Science and Engineering Indicators*, UN Statistical Office data on exports by SITC categories, Elsevier's *Electronics*.

proprietary information. Expert opinion becomes a vital complement to statistical measures. The bibliometric measures advocated herein provide an interesting alternative data source of both quantitative counts of evidence of R&D activity and interesting text materials to be exploited. Tech forecasting *methods* (Table 1) do the best job possible with limited theory and data. The cornerstone for innovation forecasting is *monitoring*.

Monitoring is vital in its own right to comprehend "who is doing what now?" with respect to a technology under scrutiny. It underlies forecasting in two critical ways—forthcoming tech change is foreshadowed by current developments and will be influenced by changes in related technologies and socioeconomic influences. Monitoring of the target technology, related technologies, and the relevant contextual influences is the most essential ingredient in effective tech forecasting [2].

Innovation forecasting extends traditional monitoring (e.g., literature review) by tapping the newfound electronic information resources. Information on a given technology often abounds on the Internet and in electronic databases. We emphasize the latter because the data have been screened and structured. The worldwide web, however, is a rich "icing on the cake" in providing access to a wealth of more current and more varied sources. As intelligent search and retrieval tools improve, the web will become an increasingly valuable source for tech monitoring.

Since 1990, the Technology Policy and Assessment Center (TPAC) at Georgia Tech has been developing a bibliometrically based approach to technology monitoring, forecasting, and assessment. Since 1993 this has centered upon development of proprietary software to facilitate exploitation of bibliographic (text) sources—the Technology Opportunities Analysis™ Knowbot (TOAK). TOAK has enabled us to collect a range of measures from electronic search results [33]. Those searches take place in large, publicly accessible databases such as *The Engineering Index* (*ENGI*), *INSPEC*, and *U.S. Patents*. TOAK capabilities have advanced in an iterative, empirical fashion—the software enables a tabulation; that leads TOA analysis to request a refinement; the programmers provide that capability; the analysts working with particular users then come up with additional desires; and so forth. The result has been a nice growth in empirical capabilities to identify technology opportunities.

We now turn to using the empirical capabilities of TOA (bibliometrics) to operationalize the innovation concepts compiled from the technological innovation, diffusion, and transfer literatures. The premises are that those concepts provide important clues to the potential success of nascent innovations and that those concepts can be measured. Bibliometrics provide a nicely accessible and cost-effective means to obtain critical innovation measures in a timely fashion for midterm forecasting (i.e., 3- to 10-year horizon). The resulting sets of conceptually linked measures, when combined with other information such as expert opinion, can provide a better basis to forecast the prospects for successful technological innovation.

Innovation Forecasting

WHAT

Innovation forecasting seeks to garner information on:

1. Technology life cycle status
2. Innovation context receptivity
3. Product value chain and market prospects

Technology life cycle information keys on determining how far along the development

TABLE 2
Technology Life Cycle Indicators

Factor	Indicator
R&D profile	
Fundamental research	Number of items in databases such as *Science Citation Index*
Applied research	Number of items in databases such as *Engineering Index*
Development	Number of items in databases such as *U.S. Patents*
Application	Number of items in databases such as *Newspaper Abstracts Daily*
Societal impacts	Issues raised in the Business and Popular Press abstracts
Growth rate	Trends over time in number of items
Technological issues	Technological needs noted
Maturation	Types of topics receiving attention
Offshoots	Spin-off technologies linked

pathway the technology has advanced, its growth rate, and the status of technologies upon which it is dependent. Contextual factors include economic and other influences on development of the target technology. Product value chain issues concern the potential payoffs and requirements to enable them to be fulfilled. These influences interlink in complex ways so that our separation is somewhat arbitrary.

Tables 2, 3, and 4 offer our distillation of technological innovation process concepts for which we believe bibliometric measures can be obtained. Table 5, discussed in the next subsection, indicates steps to be taken to gather and interpret such measures. To set the context, our approach calls for downloading a set of bibliographic abstracts (e.g., perhaps 100 to 10,000) gathered on the topical technology (or function or product) of interest. One then tabulates and analyzes that information in various ways to get at the innovation success indicators.

The *technology life cycle* indicators begin by locating the focal technology on a putative life cycle curve. The simplest metric is to count the number of hits from searching on the technology in various databases that emphasize different stages along an *R&D profile* (Table 2). The precise databases to be explored depend on availability[2] and the nature of the target technology. For instance, were one probing the status of a new chemical, *Chem Abstracts* would be preferable to the general science and technology databases indicated.

Growth rate can be ascertained by partitioning the item counts, either for the general technology or for specific contributing technologies, over time. This can combine nicely with the R&D profile by plotting hits/year in each database studied. In the "clean" case, one would expect to see the topic first rise, then decline, in fundamental research; with a similar but lagged pattern in a more applied research database; followed in turn by evidence of development, application, and possibly impact.

Trend models can be fit to bibliometric time series data. Examination of raw frequencies can be informative. Moreover, fitting of logistic growth curves (c.f., [2]) to cumulative frequencies can help one perceive the life cycle with respect to the underlying aspect being tracked. Evidence of a fast life cycle has significant implications for other innovation factors too, implying heightened sensitivity to complementary technologies and the innovator's market experience.

---

[2] The TOA approach relies on accessing sets of abstracts in electronic form. To keep costs reasonable, this implies that one must license access to the databases of prime interest rather than paying for each abstract downloaded. This is supported by database providers offering CD-ROM and unlimited access dial-in subscriptions to their databases.

TABLE 3
Innovation Context Indicators

Factor	Indicator
Supporting technologies	
Identification	Technologies mentioned in articles on target technology
Status	Technology decomposition
Players	Individuals, institutional affiliations
Technology accessibility	Patent concentration profiles
Requirements for success	Status of standards, government backing, private backing
Constraints (regulations, etc.)	Regulations
Competition	
Alternative technologies	Functional equivalency identification
Institutional interests	Profiling competitor interests
Issues	Tabulation of issues posed (i.e., in business press)

Several databases provide technology class codes—for instance, *INSPEC, Derwent's Worldwide Patents.* Occurrence of secondary codes in conjunction with a target technology provides an indicator of technology diffusion.

Software such as the Georgia Tech TOAK can facilitate quick tabulation of keywords, title words, abstract words, and abstract phrases. Jumping ahead a bit to our ceramic engine example, Table 9 notes certain materials, including "superalloys." By pulling up the abstracts in which the term is prominent, one can see what needs and issues are being addressed (e.g., Table 9 shows that one abstract linked "superalloys" with "production"). Depending on one's initial familiarity with the focal technology, selectivity examining search results in this manner can be an effective way to delimit many of the vital issues. (We emphasize that it is highly desirable to validate such observations by experts in the technology.)

Maturation can be gauged by recognition of the sorts of issues linked to the technology and the degree of detail (this will be illustrated in depth in the following ceramic engine example).

Offshoots suggest additional variants of the technology that may have potential in their own right. These could include incorporation of the technology, or one or more of its major components, with other technologies to form functional systems. Working backwards in the ceramics case, we found that most of the R&D was being done with semiconductor interests. From the standpoint of those developing that technology, ceramic bonding of engine parts would likely be an offshoot technology, as well as a different application domain.

Table 2 emphasizes indicators deriving from publication and patent abstracts databases. One could extend the list to other bibliometrics. For instance, examination of the most-cited authors is a strong indicator of leaders in the field. Profiling of citation

TABLE 4
Product Value Chain Indicators

Factor	Indicator
Gap analysis	Self-profile over component technologies
Know-how availability	Extent and identification of sources of trained personnel
Applications	Range of possible applications noted
Economic dispersion	Sectoral activity concentration
Geographical dispersion	Location of activity

TABLE 5

Steps of an Innovation Forecasting Process

1. Search on the basic topical term(s) in multiple databases.
2. Download electronic abstracts from a prime, available database; examine cumulated keywords, etc., to refine topic understanding to generate a good search algorithm.
3. Redo search in most advantageous database(s); download abstracts.
4. Examine keywords, title words, and abstract words and phrases; read abstracts to gain fluency with related activities, applications, key players, dispersion.
5. Plot trends in overall activity, topic-specific activity, institution-specific activity, etc.
6. Consider activity patterns by type (academic, government, industry) or other delimiters of interest.
7. Model the technology life cycle.
8. Cluster technological or other activity associated with the target.
9. Map key supporting technologies, institutional interests, etc.
10. Depict maps at different time slices.
11. Map likely future technological or competitive profiles, if appropriate.
12. Develop a technology decomposition tree, including tagging players; breakout for key contributing technologies.
13. Perform analyses on special areas (e.g., gap analysis).

patterns across fields or sectors can point to likely progression (e.g., interest in the use of scanning tunneling microscopy rapidly spread across multiple fields enabling molecular level R&D never before possible).

Table 3 outlines *innovation context indicators*. The TOAK software facilitates tabulation of which other technologies, features, and issues are prominent in the search set results (e.g., in the 214 abstracts relating to ceramic turbines analyzed later). These can then be grouped (e.g., "production" issues, "automotive" applications, components relating to "injectors") to develop a map of the related technologies [33]. Another approach is to develop a "tree" showing a system branching into its component functions, with particular technologies contributing to attainment of each function shown as another branching layer.

Such analyses can identify alternative technologies to the target technology or alternative technologies for component technologies. In terms of innovation prospects for the target technology, alternative technologies competing with it for potential market are a threat; they may warrant separate examination of their own innovation prospects. Conversely, identification of alternative component technologies to fulfill a need of the parent target technology are a boon. If one were an automotive manufacturer considering commitment to some aspect of ceramic engines, having several alternative technologies competing for your favor would enhance your prospects of finding a successful and cost-effective component for that need.[3] In this situation, one would likely probe to ascertain the *status* of each of those technologies (analogously to how we describe determining the status of the original target technology). In addition, one could benefit by identifying the *players* to seek potential contacts. In the ceramic engine case, the Army Tank Automotive Research Development and Engineering Center (TARDEC) managers pursued technology decomposition to identify the tree of contributing technologies, then identified the status of development and who was pursuing those with the intent of leveraging that external R&D. Indeed, one result was the establishment of TARDEC programs to adapt ceramic technologies under development elsewhere to tank needs.

---

[3] Conversely, if one represented the developer of the technology, the absence of viable alternatives could make one's technology "Indispensable," enhancing Product Value Chain prospects.

Several socioeconomic factors extend beyond the technological context just noted. *Technology accessibility* may be constrained by other companies' or agencies' patenting. Patent concentration profiles can be developed by combining search on the technology term per se, pertinent patent subclasses, and closely linked technology terms or specific applications. Given the sometimes wily ways of patent attorneys, a combination of measures may be needed to comprehend the situation. It may be particularly helpful also to search on the key companies interested in the technology to determine if they, in fact, have patent concentrations spreading around the technology per se. Profiling competitor activities in terms of both patents and publications can provide valuable competitive intelligence.

We have found that a set of electronic abstracts can provide a gratifying sweep of information. While perhaps not decisive, a search on a target technology is likely to indicate if action is being directed to standards, regulations, or other legal obstacles, and other critical supporting or impeding factors. If one locates significant activity, time slices may help show whether the topic is heating up and how it is spreading. Finally, we note that topical activity in the popular press or the policy literature can show trends in public interest (e.g., any indications of opposition to particular applications of the target technology on environmental or other grounds?). This can be augmented by search and retrieval wherein certain key phrases, such as "pollution" or "ban" are linked to the target technology.

Product value chain indicators (Table 4) seek to evaluate the market potential for the technology, possibly from the perspective of a particular enterprise (e.g., its developer). *Gap analysis* begins by laying out the set of enabling technologies required to take the technology to market. The analyst then steps through each of those to ascertain whether the enterprise has the requisite capabilities in house. If not, TOA can help identify outside sources that might provide those capabilities (e.g., through partnering, recruiting persons with critical skills, licensing critical enabling technologies). *Know-how availability* can be suggested by noting what institutions and which individuals are active in those technologies. For instance (hint?), were these academics, this might indicate opportunities to obtain skilled consultants or hire students trained on those technologies.

Application profiles can be sketched by cumulating keywords or other terms appearing in publication or patent abstracts. This is a good way to initiate contact outside one's own domain (e.g., ceramic semiconductor vs. automotive interests). As for many of the other innovation success indicators, it can be worthwhile to cross-validate. Suppose we turned up some hints of ceramic prosthesis application potential in *Engineering Index*. We might now search in a biomedical database to assess the prominence of ceramics in this arena.

An extension of the application indicators is to ascertain *economic dispersion* of application activity by sector. Many databases provide classification codes (e.g., standard industry coes [SIC] codes) that can be cross-searched to determine the extent of involvement with the target technology. That is, one performs a new search on Code X to assess the relative preponderance of the target technology.

Geographic dispersion is easily gauged by tabulating extent of activity by country or state codes. For instance, in a 1994 TOA analysis for the Critical Technologies Institute, we were able to show declining interest in the U.S. and Germany in metal casting R&D but an increasing interest in China and Russia. In addition, the distribution of U.S. R&D by state was of interest to national policymakers. That study also benefited from breakout of the R&D activity by performer type—whereas U.S. industrial metal casting R&D showed a precipitous decline in the early 1990s, academic activity was increasing.

In sum, Tables 2–4 present a set of bibliometric measures to help the innovation forecaster assess the current status of a technology in terms of its life cycle prospects, significant contextual influences on the technology's development, and its product value chain potentials.

HOW

Table 5 lays out one way to gather electronic information, process it to generate indicators, and interpret these to generate an innovation forecast. This is offered as an example process, not *the* way. Our presentation of innovation forecasting aims to get others to consider bibliometric measures of various sorts and to employ them in various ways to enrich tech forecasting practices. This section offers a quick run through the steps, some of which are elaborated in the example TOA in the next section.

Step 1 (Table 5) initiates the search process (e.g., on ceramic engines). This requires facility with one's search engine to target well. In particular, Boolean adjacency operations contribute greatly. A search on ceramic "and" engine would generate horrible noise; a search on ceramic "adjacent to" engine might leave out a lot. We experiment with various searches, such as ceramic "within 3 words of" engine to get on target. Incorporation of additional terms such as "trend," "forecast," "delphi," "assessment," and so forth may call up other forecasts and assessments relating to the topic technology. Where one searches depends on the focal interests. For a technology broaching commercial introduction, one might concentrate on diffusion issues, thus tapping economic and market databases. For a technology still in the laboratory, one would likely concentrate on research databases.

Step 2 examines the preliminary search results of Step 1 to refine understanding of the technology and related factors and issues to depict the "technology space" of interest and refine the search algorithms for Step 3.

Step 4 repeats Step 2 but in depth on the actual search set of abstracts generated in Step 3. This is an excellent step in which to engage subject-matter experts to ensure the analysis is on target. Significant "indicators" information can be generated by reviewing lists (e.g., keywords, affiliations) to sort for leading issues and players in conjunction with the focii of Tables 2–4. TOAK generates abstract phrases that allow one to display the noun phrases containing a particular term—a useful way to gain perspective on its context.

Step 5 involves plotting trends. These can depict technology growth rate or other factors for which temporal patterns are of interest (e.g., emergence of an issue, extent of a competitor's interest in a related technology). Fitting trend models, logistic or otherwise, can be informative. However, one should perform sensitivity analyses quite thoroughly. Bibliographic time series are vulnerable to shifts in terminology over time, noisy data, and lagging data (e.g., it takes time for articles to get published and more time to get incorporated into databases that often show considerable delay in completing a year's data entries). Smoothing may be in order to reduce year-to-year variability [2]. For many purposes, it will be advantageous to group several years together to compare with earlier or later time periods to ascertain changes.

Step 6 entails grouping items by type. TOAK automatically groups[4] academic, governmental, and business affiliations. Other groups can be tailored to meet case-specific interests (e.g., "materials" seen in Table 9).

---

[4] TOAK generates cumulative lists across the records in the dataset being analyzed. Classification is based on a combination of thesaurus (look up), fuzzy rules, and syntactic and semantic algorithms. TOAK "learns" with repeated use as the thesaurus grows.

Step 7 combines results of Step 5 with broader understanding (exemplified later for ceramic engines).

Steps 8, 9, 10, and 11 cluster like items and depict these as "maps" of various forms [33].[5]

Step 12 addresses one major framework. TARDEC has demonstrated utility in "technology decomposition" wherein functions are linked to alternative technologies that can achieve them, and alternative technologies are linked to competent technologies. At any node of interest, one can break out key players, issues, and the like.[6]

Step 13 is an open-ended invitation to mine the abstracts for information to key on particular innovation success indicators of interest. We are still exploring.

Innovation Forecast for Ceramic Engines

This inquiry addressed a possible technological substitution for the U.S. Army—use of ceramics in place of steel in tank or automotive engine components [35]. The U.S. Army has considerable interest in advances made in ceramic engine technology. Budgetary constraints may require that the existing military fleet be maintained in inventory beyond the year 2010. Rapid global technology advancements and foreign military R&D investments heighten military needs and threaten U.S. superiority on the future battlefield. Army R&D investments, therefore, must strive to maximize functional performance improvements while retaining systems configurations compatibility (i.e., technology insertion through form and subsystem/component interface). One way to achieve this is through advanced materials engine technology insertion programs. Ceramic engine components enable lower wear rates and permit higher operational temperatures, along with the associated combustion benefits of reduced exhaust emissions and increased engine performance (i.e., greater on-demand horsepower or extended vehicle range, enabled further by complementary ceramic component weight reductions).

Ceramic engine technology has not gone unnoticed by the commercial automotive industry. Though unconcerned about long-term form and interface technology compatibility, the automotive engine manufacturers have recognized ceramic technology as industry capability enhancing, rather than destroying. Unlike the competing vehicle power-source technologies, ceramic engines would promote automotive manufacturer maximization of existing investments in manufacturing and assembly while meeting ever-more stringent exhaust emission standards. Ceramic engine technology utilization, therefore, offers a medium for the orderly transition between present and future engine technologies.

A preliminary search (Step 1, Table 5) located prior forecasts, in particular, a Delphi study [36]. The Delphi respondents had identified enabling technologies and application barriers that existed in the mid-1980s. These provided good leads for further bibliometric searches on both the enabling and primary technologies from *Engineering Index* and *U.S. Patents* (Step 3). The main search addressed 1985 to 1995 on "ceramic"

---

[5] TOAK applies a variety of matrix operations over terms by records to cluster similar terms or similar records. One can address normalized or raw data, rotated or unrotated factors, independent or linked rotations, and so forth to help identify clusters of interest. The key matrix manipulation applies singular valued decomposition to generate factors on which terms or records load. This shares somewhat with factor analysis and with latent semantic indexing [34].

[6] With Defense Advanced Research Projects Agency support, we are currently working to improve the TOAK software to facilitate analyst discovery processes. Our vision includes automatically marking links and applying relevance scores to generate "MASTs" (automated abstracting of abstracts) on chosen subtopics, capability to view abstracts most relevant to such a subtopic, or to call up related issues or players.

TABLE 6
Ceramic Engine Publications (ENGI)

	Universities		Labs		Firms		Labs		Firms	
Year	NT	C	NT	C	NT	C	T	T, C	T	T, C
1985	1	1	7	7	18	18	13	13	13	13
1986	5	6	3	10	20	38	4	17	15	28
1987	27	33	18	28	59	97	5	22	15	43
1988	5	38	3	31	7	104	2	24	6	49
1989	2	40	3	34	2	106	4	28	9	58
1990	4	44	1	35	7	113	4	32	6	64
1991	2	46	1	36	4	117	1	33	20	84
1992	7	53	0	36	6	123	2	35	1	85
1993	14	67	2	38	5	128	8	43	11	96
1994	1	68	1	39	0	128	3	46	7	103
1995	3	71	3	42	5	133	3	49	6	109
1996	1	72		42		133	1	50		109

Abbreviations: NT = nonturbine, C = cumulative, T = turbine.

within 6 words of "engine." The resulting search records were downloaded in electronic form and subdivided into two files—turbine and other. Turbines (file of 214 records) provide a possible lead technology indicator. For some purposes, the files were further pruned to include only records from the top 100 institutions—universities, government labs, and commercial films—publishing on ceramic engines.

Table 6 provides the chronology of the publications for the three source groupings for the two categories of ceramic engine publications. (Note only five plots are provided in the Table 6-assembled database shown in Figure 1—there were only three turbine abstracts from universities.) Table 7 shows the co-occurrence matrix for the government laboratory organizations that produced the most nonturbine publications and the number of matches of the most frequently used keywords. Similar tables were compiled for academia and industry. These tables identify those who are most active in publication

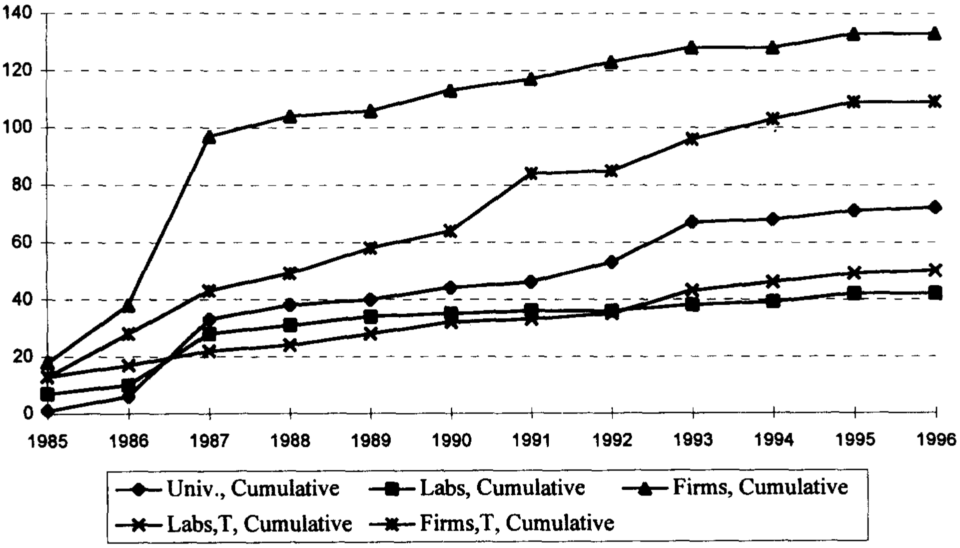

Fig. 1. Ceramic engine publication. Abbreviation: T = turbine.

TABLE 7
National Labs versus Ceramic Engine Keywords

	Ceramic materials	Diesel engines	Tribology	Mechanical properties	Heat engines	Thermomechanical ceramic	Physical properties	Ceramic products	Silicon nitride	Superchargers and supercharging	Wear of materials	Materials testing	Impact damage	Impact testing	Grinding (machining)	Microcrack	Durability	Cracks	Protective coatings	Scanning electron microscopy	Air engines	Surface properties	Degradation	Rocket engines	Total
Inst natl des hydrocarbures et de la chimie	6	3	2	2	2	2	2	2	2	0	2	2	0	0	2	1	0	0	0	0	1	0	0	0	31
Oak Ridge Natl Lab	6	6	1	1	2	0	0	1	1	0	1	0	1	1	1	1	1	1	0	1	0	1	1	0	28
NASA	4	2	0	2	2	1	1	2	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	1	18
Acad of Sciences	5	3	1	0	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	15
Battelle Memorial Inst	3	2	2	1	0	1	0	0	0	0	1	1	2	0	0	1	0	0	0	0	0	0	0	0	14
Government Industrial Research Inst at Nagoya	4	1	3	0	0	0	0	0	1	1	0	1	0	0	0	1	1	0	0	1	0	0	0	0	14
Chinese Acad of Sciences	3	0	1	2	0	1	1	0	0	1	0	0	1	1	0	0	1	1	1	0	0	0	0	0	14
Lawrence Berkeley Lab	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	12
Commission of the European Communities	1	1	2	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	1	1	0	9
Argonne Natl Lab	2	1	1	0	1	0	1	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
Southwest Research Inst	4	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	7
Admiralty Research Establishment	3	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
Acad of Sciences of the Ukrainian SSR	0	2	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
Battelle	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
Government Industrial Research Inst	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
Battelle Columbus Lab	1	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Federal Dep of Science & Technology	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Total	50	32	15	9	8	7	6	6	6	5	5	5	5	4	4	4	4	3	3	3	3	3	2	2	

TABLE 8
Ceramic Coating and Bonding Patents

Year	Patents	Cumulative
1980	13	13
1981	6	19
1982	6	25
1983	3	28
1984	4	32
1985	1	33
1986	16	49
1987	16	65
1988	11	76
1989	11	87
1990	20	107
1991	22	129
1992	29	158
1993	33	191
1994	27	218
1995	16	234

of ceramic engine R&D. The co-occurring keywords begin to define the areas of concentration. One can note the balance of development cycle participants, with industry taking a strong lead in applied research and development. For less mature technologies (i.e., electrorheology or artificial intelligence), a greater proportion of activity by basic research institutions and lower activity from influential sponsors might be observed. The abstracts also revealed a balance of R&D activity across the industry infrastructure (i.e., components, engine, and vehicle manufacturers).

Table 6 reveals a surge in publication activity in 1987 from all three source groupings for nonturbine topics. The Delphi study conducted during this period provided expert opinions on the benefits and barriers, and rate of progress in overcoming the barriers, for utilization of ceramic engine components [36]. Current literature points to the following enabling issues: lower cost of raw materials; more efficient and lower cost manufacturing processes; component materials consistency and end-product structural verification (i.e., nondestructive testing); and ceramic coating, bonding, and joining technologies. Production cost reduction is important to the use of ceramics; advantages to applying ceramics to wear-resistant parts have been confirmed [37]. This general theme of acknowledged potential rings through the referenced material with the exception of Razim and Kaniut, who elaborate on the hurdles confronting ceramic engine component adoption [38]. In addition to the material weaknesses at which research has been directed, these authors pointed out the salient issues of limited materials, design experience, materials properties verification, and (most important) different performance standards expected of the new material (i.e., higher operational temperatures and speeds and lower use of ancillary cooling and lubrication support systems).

The literature conveys that the advantages of ceramic components have begun to be proven; the technology is maturing. The three most-cited barriers include cost, material properties verification, and coating and bonding technologies—three candidates to explain the 1987 surge in publication activity. Using the terms "ceramic" adjacent to "coating" or "ceramic" adjacent to "bonding" yielded 234 related patents during the 1980 to 1995 period. Table 8 and Figure 2 depict the chronology of patents issued and the cumulative patent growth in the ceramic coating and bonding field. The significant rise in number of patents issued in 1986 and 1987 may provide an explanation for the industrial publication surge in 1987; with proprietary confirmation in hand, a technical capabilities announcement through these publications could follow. The anticipated precadence of applied research publications ahead of patents appears to be violated here. The drop in patent activity in 1994 might represent the passage of an inflection point on the technology growth curve. Knowledge growth and engineering productivity in a given technology have often been likened to a logistics function, as might be predicted by the Fisher–Pry equations. The cumulative ceramic coating and bonding patents were modeled (Step 7, Table 5) by three Fisher–Pry equations, each with a different technology growth limit (i.e., 350, 450, and 550 patents). Each of the three equations provided coefficients of determination greater than .99. The growth limits were selected because limits below 350 patents and above 600 patents provided lower coefficients of determination. These equations were then used to generate patent forecasts through the year 2005, as shown in Figure 3. The upper and lower growth limits provide a visual sensitivity analysis for the models and serve as surrogate confidence intervals for the future growth in this technology, assuming that 450 patents represent the actual anticipated growth. In assessing these growth curves in respect to technology maturity, we suggest that, although the capabilities have begun maturing and new entry into the field would be most difficult because of the pace being set by the current participants, there still will be significant technology growth in the next 9 years.

To extend the maturity analysis from enabling technologies (i.e., ceramic coating and bonding) to ceramic engine technology more generally, two bibliometric approaches were applied. The 100 most-used keywords from the 426 nonturbine ceramic engine abstracts were subdivided into two groups: material types and a combined group of material properties and applications. We then generated a co-occurrence matrix—materials versus properties and applications (Table 9). Two observations from this table, in regard to ceramic engine technology, include the apparent emergence of silicon nitride as the ceramic material of choice and the presence of competing materials (e.g., aluminum compounds, metal matrix composites, metals and alloys, superalloys). For silicon nitride (Row 1, Table 9), note the considerable level of use of application, process, and property verification terms—an indication of technological maturation.

To obtain a temporal perspective on the types and usage of keywords related to ceramic engine technology, the nonturbine ceramic engine abstract file was subcategorized into five 2-year periods of publication abstracts. Co-occurrence matrices of sources versus keywords were generated. Table 10 summarizes the co-occurrence matrices by defining the level of activity (e.g., the number of discrete publication sources and associated number of publications) and the level of focus of the documented research (e.g., the number of discretely different keywords). The evolution of a technology can be observed in Figure 4, which depicts Table 10 data, and considered in terms of the Utterback and Abernathy model on product and process innovations [39]. That model prescribes that early research is product focused and attracts many industry participants. Once a dominant design emerges, research shifts towards process technology, and the number of industry participants declines. In the 1987–1988 period, the level of interest in the technology peaked as indicated by the numbers of publications (207) and participating organizations (120). The areas of R&D, however, were quite focused, as indicated by the number of different keywords used (29). Contrast this profile with that for 1993–1995: far fewer participating organizations (42), a proportional reduction in number

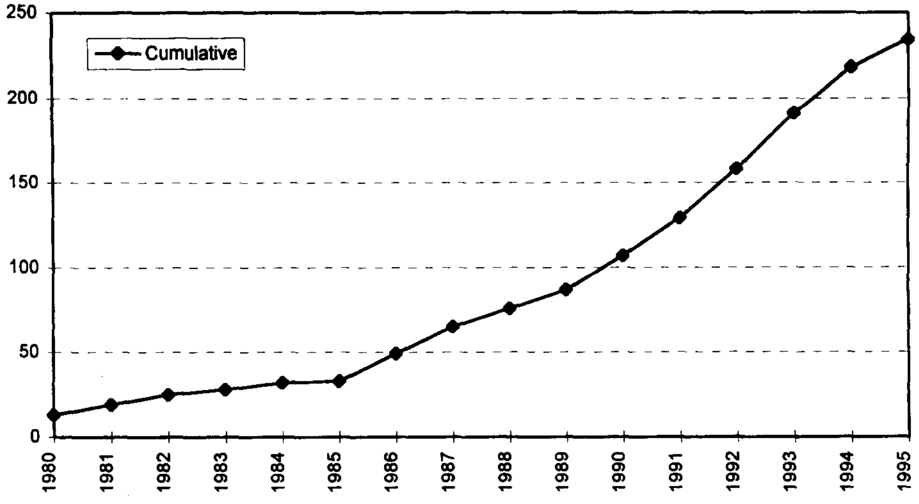

Fig. 2. Cumulative ceramic coating and bonding patents.

of publications, but tremendous expansion of the detail and issues addressed (201 different keywords used)!

To see the evolution of the types of technological activities addressed over the time periods, the common keywords across periods were eliminated. Table 11 presents the chronology of the use of the remaining words. Innovation sequences often start with an invention (e.g., technology application such as the invention of the internal combustion engine), followed by the emergence of related sciences (e.g., tribology, combustion, etc.). As observed in Table 11, the ceramic engine technology terms have

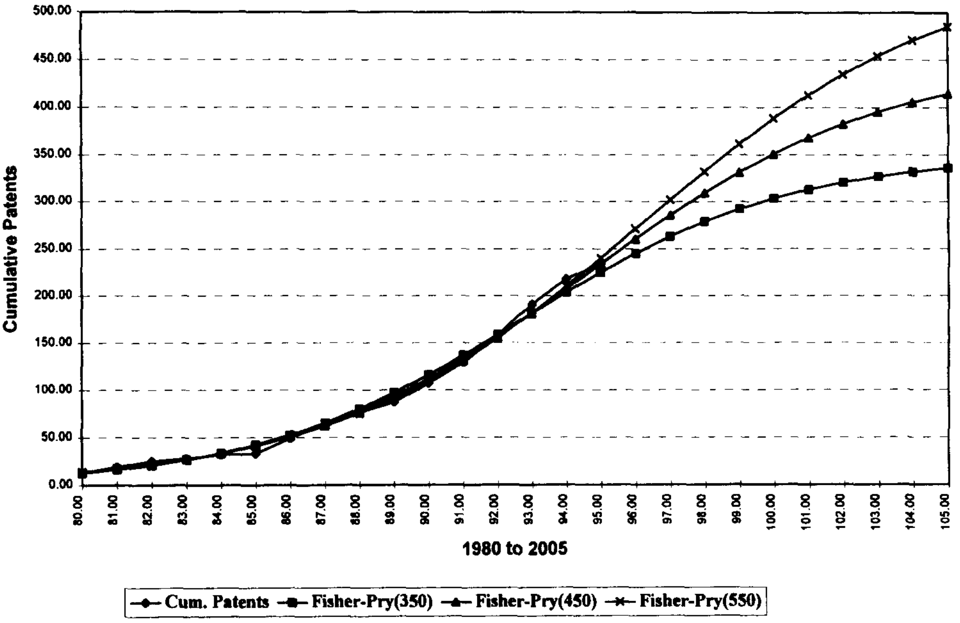

Fig. 3. Ceramic coating and bonding patent projection.

TABLE 9
Ceramic Engine Materials versus Material Properties/Applications

	Properties	Strength	Applications	Application	Performance	Process	Structural	Piston	Parts	Coatings	Processing	Production	Valve	Reliability	Coating	Characteristics	Problems	Automotive	Cost	Economy	Quality	Processes	Durability	Fatigue	Manufacturing	Liner	Pistons	Turbocharger	Valves
Silicon nitride	14	15	5	5	2	4	4	0	1	0	4	6	2	2	0	3	0	2	1	0	1	4	2	2	0	0	0	1	1
Composite materials	2	0	2	0	0	0	1	1	0	0	1	0	0	1	0	0	0	1	2	1	1	0	0	1	0	0	0	0	0
Aluminum compounds	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Metallic matrix composites	1	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	1	1	0	0	0	0	0
Metals and alloys	1	0	0	1	1	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0
Superalloys	1	0	2	0	0	0	1	0	0	1	0	1	0	0	1	0	1	0	1	0	0	0	1	1	0	0	0	0	0
Ceramic heat engines	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Aluminum titanate	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceramic fibers	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceramic matrix composites	0	1	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Low-cost ceramic composite	0	1	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Metallic silicon alloys	1	0	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Ceramic coatings	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Titanium alloys	1	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	1	1	1	0	0	0	1
Titanium oxides	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Yttrium	0	1	0	0	0	1	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zirconia	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 10
Co-occurrence Matrices Summary

Years	Discrete sources	Number of publications	Number of keywords
1985–1986	44	79	17
1987–1988	120	207	29
1989–1990	35	44	17
1991–1992	29	36	15
1993–1996	42	60	201

evolved toward analytic sciences in addition to expanding to processes, material properties verification, and application fields. This supports the notion of a maturing technology poised to assume niche positions in specialty material growth markets.

The other two application barrier issues (cost and manufactured material property verification) support the coming of age of ceramic engine technology in a different manner—through the absence of publicly available information. Component cost data were sought through both literature review and phone contacts with material journal publishers and ceramic engine component manufacturers. These efforts uncovered the fact that ceramic component cost data represent confidential information between component suppliers and end-item manufacturers (e.g., automotive and engine). The engine manufacturers have begun using ceramic components (Table 12) and must perceive that their actions provide a competitive advantage. One can assume that until an aftermarket emerges for replacement ceramic engine components, cost information will most probably be closely guarded. Takao et al. [37] noted that once a component probability of failure on the order of 10^{-6} has been achieved, the material weight used in automotive systems is inversely related to the square of the component cost-to-weight ratio (WP^{-2}).

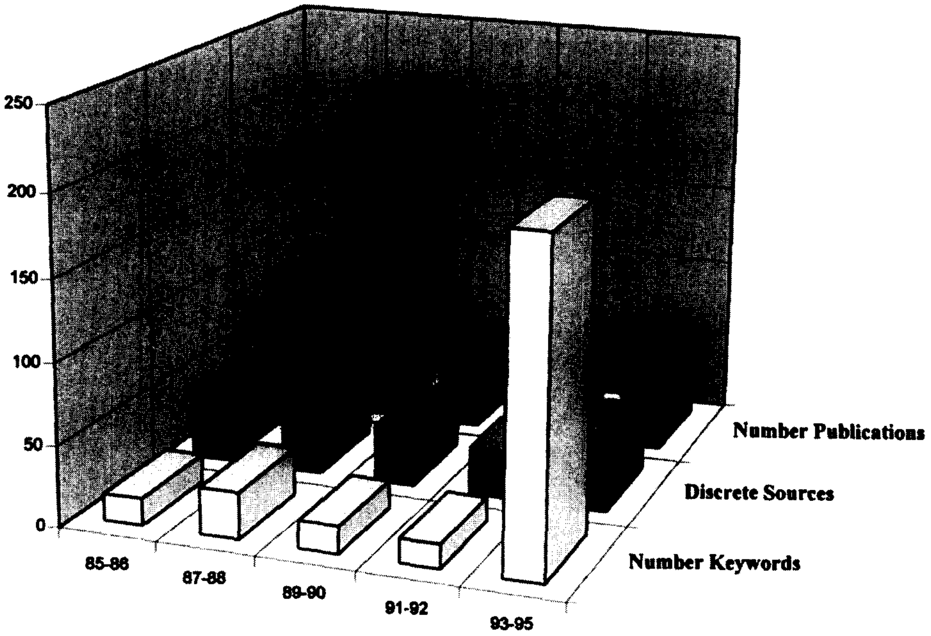

Fig. 4. Technology maturity and keyword diffusion.

TABLE 11
Technology Maturity versus Keyword Usage

Report period	Generic material	Generic application	Needs/function	Specific material	Specific application
1985–1986	Materials, metallic silicon alloys, refractory materials	Air engines, sensors, superchargers and supercharging	Lubricants		
1987–1988	Materials, metals and alloys, refractory materials, superalloys, composite materials	Machine components, superchargers and supercharging	Protective coatings, waste heat utilization	Silicon nitride, silicon carbide	Combustors, domes and shells
1989–1990	Composite materials	Gas engines	Friction materials, heat transfer	Silicon nitride	Domes and shells, valves and valve gear
1991–1992	Metals and alloys, nonmetallic materials			Zirconia	Pistons
1993–1995	Porous materials, aluminum compounds, amorphous materials, metallic matrix composites, composite materials		Thermal insulating materials, lubricants, thermomechanical ceramic	Silicon nitride, ceramic fibers, aluminum titanate	Seals, ceramic heat-insulated engine, braided ceramic fiber seals, adiabatic engines

	Generic approach	Specific approach/process	Material characteristic verification	Enabled technology	Analytical science
1985–1986					
1987–1988	Powders, automotive engineering, powder metallurgy				
1989–1990		Castings			
1991–1992			Microscopic examination	Hydrogen fuels, methanol, diesel fuels (alternative fuels)	
1993–1995		Sintering, braiding process	Microstructure, strength of materials, material testing, physical properties, volume fraction, high temperature properties, mechanical properties, fatigue testing, reliability, wear of materials, durability, axial/circumferential strength, creep, defects	Aromatic polyphenyl ether type oil	Mathematical models, tribology, finite element method, computer simulation, computational geometry

TABLE 12
Ceramics Automotive Applications

Ceramic components	Material	Supplier	User
Intake and exhaust valves	Silicon nitride	Ceramtec Div. of Hoechst A.G.	Daimler Benz
Exhaust portliner	Aluminum titanate	Ceramtec Div. of Hoechst A.G.	Porsche A.G.
Brake engine retarder master piston wear pad	Silicon nitride	ENCERATEC, Inc.	Cummins N14 Engine
Cam roller follower	Silicon nitride	Kyocera Corp.	Detroit Diesel (Series 50)
Ceramic tappet	Sintered silicon nitride	NKG Spark Plug Co.	Nissan Diesel Motor Co.
Ceramic coatings		Ceramics Corp. of America (Cercoa)	
Ceramic coatings	Zirconia coating with strain isolator	Technetic's Corp.	

This material cost-to-weight relationship remains true except when government requirements (i.e., exhaust emissions) mandate a materials usage, as in catalytic converters. Since ceramic component usage has begun, one might assume that the just-stated probability of failure level has been achieved and verification procedures developed. However, component material property verification both reflects and embodies one competence of the manufacturing process. Management of technology principles stress that distinctions must be made between technologies and technical competencies. Competencies represent the essence of competitive advantage and must be more closely protected than technologies, which can be imitated and designed around. Manufacturing competence involves a complex mixture of employee training and involvement, supplier integration, statistical process control and value engineering, as well as design for manufacture and end-product verification [40]. A search of *U.S. Patents* using the terms "ceramic material quality," "ceramic non-destructive test," and "ceramic property test," uncovered only four relevant patents. The fruitless component cost and patent searches, along with commercialization announcements, support one conclusion: the manufacturing costs and process verification techniques are being held secret to obtain and maintain competitive advantage.

Interpretation

This assessment concentrates on issues considered most relevant to Army policy decisions related to this technology. Institutional forces impact ceramic engine developments. As affirmed by the bibliometrics, ceramic engine R&D emanates from government laboratories and the automotive industry infrastructure, not from the ceramics industry (that emphasizes semiconductors in particular). This fact warrants that the ceramics industry R&D be monitored by the automotive sector for potential offshoots (desired ceramic functions) to speed recognition and diffusion of new technology discoveries to automotive applications.

The automotive industry "need" for specialized engine materials, including ceramic components, has resulted primarily from government mandates on exhaust emissions and fleet fuel economy standards. This imposed need creates a delicate balance between the degree of legislated stringency and the allocation of commercial R&D resources. Too tight or too loose legislative mandates would significantly reduce the commercial R&D available to leverage. This suggests ongoing monitoring of regulatory developments.

Zero-based exhaust emission requirements could force premature adoption of electric vehicle technology and pull scarce R&D resources away from ceramic engine development. Less stringent requirements could reduce the demand for more efficient, hotter burning, and lighter engines and could drain commercial ceramic engine R&D. Gradual and ever-tightening requirements are likely to promote specialized component development and extend the evolution of the internal combustion engine (ICE). This scenario advances automotive manufacturing capital investments stability and a supporting infrastructure that remains familiar to a large proportion of the participants, both businesses and consumers alike, thereby promoting the probability of technology acceptance.

Another oil embargo or an extended Middle East war could drive oil and fuel prices higher and make alternative, perhaps methanol, fuels more competitive in respect to cost. However, current ICE incompatibilities preclude the use of fuels such as methanol without experiencing high engine wear rates and increased oil consumption [41]. An accelerated development pace for specialized materials—particularly to modify engine combustion chambers with high-temperature, corrosion-, and wear-resistant materials—would better prepare the country for such a crisis. Implementation, obviously, would still be subject to a mortality substitution rate, one which under normal attrition would require 10 to 20 years to transition. Again, these contextual influences on ceramic engine innovation merit continued monitoring.

The most significant impact of ceramic engine technology adoption and commercial diffusion will be on automotive component suppliers. Ceramic engine technology represents the early stage of a materials revolution, one where material properties will be designed and developed for specific applications. Suppliers lacking material design capabilities, as well as the emerging specialized material manufacturing and component properties certification competencies, will be supplanted by larger more affluent companies that can and will develop the needed skills. Ceramic Division of Hoechst A.G., Kyocera Corporation, NGK Spark Plug Company, and Enceratec Incorporated (Table 12) represent a sample of the firms that have been strategically positioning themselves to be the next generation automotive component suppliers. One can speculate that the automobile industry involvement in the ceramic engine and specialized material R&D activities strives to develop suppliers' certification capabilities and, more important, to have proprietary interest in the new technology to create licensing revenues and avoid limited source situations. This automotive industry supplier issue could force costs higher due to inadequate competition. These higher costs would impact the Army fleet due to increases in both initial acquisition and operational and support component expenses.

Conclusions

Bibliometrics are limited by the secrecy of some R&D and variations in publication practices among organizations. This was demonstrated by conspicuous absences of firms such as General Motors and Chrysler from the publications and patents on ceramic engine technology. It would be naive to believe these companies' R&D programs do not include ceramic engine technology. Such variations in publication practices create caveats against simplistic literature source analyses. More important, they justify the more sophisticated bibliometric process analyses and measures proposed in this article. Time lags between R&D performance and subsequent documentation also limit bibliometrics. To confirm conclusions from our innovation forecasting, expert opinions were obtained from TARDEC propulsion personnel and the Ceramic Information and Analysis Center at Purdue University. Such expert opinion usage should be standard practice.

As demonstrated with the ceramic engine case assessment, bibliometric limitations can be minimized by searching for general trends rather than specific events. Innovation forecasting processes and models (see Tables 2–4) can also provide corroborating analyses for traditional forecasting techniques (Table 1).

This case analysis demonstrates that innovation success factors can be gauged by using bibliometric measures. These, in turn, serve to assess prospects for next-generation technologies. Many innovation concepts were applied during the sample ceramic engine forecast. In particular, we point to the effort to operationalize a number of the innovation success indicators offered in Tables 2–4. A key to the conclusions drawn, resulting in initiation of two major TARDEC ceramic engine programs, was the evidence that this family of technologies is really maturing.[7] The evolution of keyword usage and the empirical evidence of movement toward process technology development proved especially compelling.

Our development of innovation forecasting continues. Monitoring programs promote technology awareness and diffusion to operational programs. This goal is being pursued through a joint Defense Advanced Research Projects Agency (DARPA) and Tank-automotive and Armaments Command (TACOM) Small Business Technology Transfer (STTR) program. Under this combined program, the TPAC TOAK will be modified to expand its analysis capabilities and to implement a menu-driven operator interface. The enhanced TOAK will facilitate the development of a database containing military vehicle technologies hierarchy breakout ("technology decomposition"). Related "technology space" information (i.e., the who, what, when, where, and how) can be updated as needed. One of the efficiencies of the innovation forecasting approach is its use of established databases. Sources such as *Engineering Index* and *U.S. Patents* are orders of magnitude richer than one's own database could ever be. Through tools like TOAK, we are able to tap such resources quickly and effectively.

We invite others to consider the use of bibliometric indicators as a major asset in forecasting technology. The framework proposed in Tables 2–4 is a start toward truly more effective innovation forecasting.

Note Added in Proof: Additional sources regarding forecasting techniques (such as those in this article's Table 1) have been suggested by John H. Vanston which include the article "Technology Forecasting: A Practical Tool for Rationalizing the R&D Process" published in the *New Telecom Quarterly*, Vol. 4, Issue 1 (First Quarter), 1996, and Technology Futures, Inc. website under "Who We Are" and "Tools and Techniques" (http://www.tti.com).

References

1. Martino, J. P.: *Technological Forecasting for Decision Making.* McGraw-Hill, New York, 1993.
2. Porter, A. L., Roper, A. T., Mason, T. W., Rossini, F. A., and Banks, J.: *Forecasting and Management of Technology.* Wiley, New York, 1991.
3. Twiss, B. C.: *Forecasting for Technologists and Engineers: A Practical Guide for Better Decisions.* Peter Peringrinus, London, 1992.
4. Vanston, J. H.: *Technology Forecasting: An Aid to Effective Technology Management.* Technology Futures, Inc., Austin, TX, 1995.
5. Souder, W. E.: *Managing New Product Innovations.* Lexington Books, New York, 1987.

---

[7] This was a true challenge because the Army had been "burned" before (investing in ceramic technologies into the 1980s without notable payoff), so considerable initial skepticism had to be overcome. The innovation success indicators accomplished this.

6. Porter, M. E.: *Competitive Advantage: Creating and Sustaining Superior Performance.* Free Press, New York, 1985.
7. Linstone, H. A.: *Multiple Perspectives for Decision Making: Bridging the Gap Between Analysis and Action.* Prentice Hall, Englewood Cliffs, NJ, 1984.
8. Barbiroli, G.: Towards a Definition and a Dynamic Measure of Strategic Technology, *Technovation* 12 (5), 285–296 (1992).
9. Millson, M. R., Raj, S. P., and Wilemon, D.: A Survey of Major Approaches for Accelerating New Product Development, *Journal of Product Innovation Management* 9, 53–69 (1992).
10. Mahajan, V., and Muller, E.: Timing, Diffusion, and Substitution of Successive Generations of Technological Innovations: The IBM Mainframe Case, *Technological Forecasting & Social Change* 51, 109–132 (1996).
11. Dunphy, S. M., Herbig, P. R., and Howes, M. E.: The Innovation Funnel, *Technological Forecasting & Social Change* 53, 279–292 (1996).
12. Smith, C. G.: Understanding Technology Substitution: Generic Types, Substitution Dynamics and Influence Strategies, *Journal of Engineering/Technology Management* 9, 279–302 (1992).
13. Modis, T.: Technology Substitutions in the Computer Industry, *Technological Forecasting & Social Change* 43, 157–167 (1993).
14. Anderson, P., and Tushman, M. L.: Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change, *Administrative Science Quarterly* 35, 604–633 (1990).
15. Dror, I.: Technology Innovation Indicators, *R&D Management* 19, 243–249 (1989).
16. Metcalfe, J. S.: The Diffusion of Innovations: An Interpretive Survey, in *Technical Change and Economic Theory.* G. Dorsi, C. Freeman, R. Nelson, G. Silverberg, and L. Soete, eds., Printer, London, 1988, pp. 560–589.
17. Metcalfe, J. S.: Impulse and Diffusion in the Study of Technological Change, *Futures* 13, 347–357 (1981).
18. Cetron, M. J.: Technology Transfer: Where We Stand Today, *21st Joint Engineering Congress,* 11–28 (1973).
19. Rogers, E. M.: *Diffusion of Innovation.* 3rd ed. Free Press, New York, 1983.
20. Cohen, H. S., Keller, S., and Streeter, D.: The Transfer of Technology from Research to Development, *Research Management* 22(3), 11–17 (1979).
21. Souder, W. E., Nashar, A. S., and Padmanabhan, V.: A Guide to the Best Technology Transfer Practices, *Technology Transfer* 5–16 (Winter–Spring, 1990).
22. Narin, F., Olivastro, D., and Stevens, K. A.: Bibliometrics—Theory, Practice and Problems, *Evaluation Review* 18(1), 65–76 (1994).
23. Cunningham, S. W. *The Content Evaluation of British Scientific Research.* Ph.D. thesis. Science Policy Research Unit, University of Sussex, Brighton, UK, 1997.
24. Garfield, E., Malin, M. V., and Small, H.: Citation Data as Science Indicators, in *The Metric of Science: The Advent of Science Indicators.* Y. Elkana et al., eds. Wiley, New York, 1978.
25. Kostoff, R. N.: Research Impact Assessment: Problems, Progress, Promise, in *Fourth International Conference on Management of Technology.* Miami, FL, 1994, pp. 423–433.
26. Small, H., and Griffith, B.: The Structure of Scientific Literatures, *Science Studies* 4, 17–40 (1974).
27. Franklin, J. J., and Johnston, R.: Co-citation Bibliometric Modeling as a Tool for S&T Policy and R&D Management: Issues, Applications, and Developments, in *Handbook of Quantitative Studies of Science and Technology.* A. F. J. van Raan, ed. North-Holland, New York, 1988.
28. Kostoff, R. N.: Co-word Analysis, in *Evaluating R&D Impacts: Methods and Practice.* B. Bozeman and J. Melkers, eds. Kluwer, Boston, 1993, pp. 63–78.
29. Kostoff, R. N.: Database Tomography: Origins and Applications, *Competitive Intelligence Review* 5(1), 48–55 (1994).
30. Tijssen, R. J. W., and van Raan, A. F. J.: Mapping Changes in Science and Technology, *Evaluation Review* 18(1), 98–113 (1994).
31. Rip, A.: Mapping of Science: Possibilities and Limitations, in *Handbook of Quantitative Studies of Science and Technology.* A. F. J. van Raan, ed., North-Holland, New York, 1988.
32. Kostoff, R. N.: Research Impact Quantification, *R&D Management* 24(3), 207–218 (1994).
33. Porter, A. L., and Detampel, M. J.: Technology Opportunities Analysis, *Technological Forecasting and Social Change* 49, 237–255 (1995).
34. Deerwester, S., Dumals, S. T., Furnas, G. W., Landauer, T. K., and Harshman, R.: Indexing by Latent Semantic Analysis, *Journal of the American Society for Information Science* 41(6), 391–407 (1990).
35. Watts, R. J.: *Defining Next Generation Technologies,* Management of Technology Thesis. National Technological University, Fort Collins, CO, 1996.
36. Larsen, R. P., and Vyas, A. D.: *The Outlook for Ceramics in Heat Engines, 1990–2010: Results of a Worldwide Delphi Survey,* Society of Automotive Engineers, International Congress and Exposition, pp. 4–6, 9, 1988.

37. Takao, H., Okada, A., Akimune, Y., and Hirosaki, N.: Ceramics for Reciprocating Engines: An Application Review, *Proceedings of the International Symposium on Ceramic Materials and Components for Engines*. 4th. Goeteborg, Elsevier, London, 1991, p. 130.
38. Razim, C., and Kaniut, C.: Ceramics in the Automotive Industry, Mercedes-Benz AG. 1991, pp. 277–278.
39. Burgelman, R., Maidique, M., and Wheelwright, S., *Strategic Management of Technology and Innovation*. 2nd ed. Irwin, Homewood, IL, 1996, p. 159.
40. Hamel, G., Doz, Y., Prahalad, C.: Collaborate with Your Competitors and Win, in *Strategic Management of Technology and Innovation*. 2nd ed., R. Burgelman, M. Maidique, and S. Wheelwright, eds., Irwin, Homewood, IL, 1995, p. 596.
41. Funatani, K., Kurosawa, K., Fabiyi, P. A., and Puz, M. F.: Engine Performance Improvements, *Automotive Engineering* 15–16 (January, 1995).

Received 14 October 1996; accepted 11 April 1997