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Comparison of China/USA science and technology performance☆

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ABSTRACT

The relative performance of science and technology (S&T) in the USA and PRC was compared in terms of quantity and quality, as reflected in their technical literatures. Three databases (Science Citation Index (SCI), INSPEC, Ei Compendex) were selected for the quantity comparison, and citation analysis in the SCI was used for the quality comparison. Thirty technology and research areas were compared for quantity production, and are presented in this paper. These 30 areas were selected based on our previous assessment of PRC S&T output, and represented areas of emphasis by the PRC in physical, environmental, engineering, and life sciences.

In almost all technical areas, the USA had the quantity (number of papers) lead (for the period 2002–2007) based on the *SCI* results, although the PRC has made dramatic strides to overtake the USA. In most of the technical areas, by 2007 PRC had attained parity with, or exceeded, the S&T literature production of the USA in the *INSPEC* database. The major exceptions were the biomedical field and some aspects of environmental science, where the USA still had a large lead. For most technical areas, by 2007 the PRC had even higher relative S&T literature production, based on the *Ei Compendex*, compared to the INSPEC results. Moreover, the USA production appears to have peaked (in the Ei Compendex) in the 2005 time frame, despite increasing amounts of funding for S&T research. The PRC challenge in non-biomedical research and technology sectors becomes apparent in those databases that do not contain substantial biomedical research papers, and therefore remove a substantial intrinsic USA advantage.

For quality computations, the publication and citation results were normalized to discrete slices of time, and are presented for nanotechnology only (for the period 1998–2003). While the USA held a commanding lead in quality over the PRC (and the other major nanotechnology producer nations as well) during the past decade, the PRC has increased the quality of its publications monotonically, and now appears to be competitive with France, Italy, Japan, and Australia, using the quality metric in this paper.

1. Background

Since World War II, the USA has been the global leader in science and technology (S&T), as evidenced by the quality and quantity of its S&T publications. This leadership was due not only to government and private investment in S&T in the USA in the last half of the 20th century, but also to the physical destruction of S&T, associated infrastructure resources, and

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the intellectual S&T human capital in many countries during World War II, the post-WWII Cold War conflict, and post-war political upheavals (e.g., Cardona & Marx, 2005).

Over the past few decades, many countries have recovered from WWII and subsequent political upheavals. Some have had the resources, stability, and national motivation to concentrate on improving their global S&T posture. These countries have begun to challenge USA S&T leadership. Prominent among these has been the Peoples Republic of China (PRC). Our previous studies of the PRC's S&T literature have shown exponential growth in the numbers of technical publications over the past few decades (Kostoff, Briggs, Rushenberg, Bowles, Icenhour, et al., 2007; Kostoff, Briggs, Rushenberg, Bowles, Bhattacharya, et al., 2007). The quality of this literature, as evidenced by paper citation results, is less clear (e.g., King, 2004).

In fact, scientometric studies of the global S&T literature have become a cottage industry in recent years (Bissey & Viossat, 2003; Garfield & Melino, 1997; Guan & Ma, 2007; Sombatsompop et al., 2007; Sigogneau, 2000; Stefaniak, 2001; van Leeuwen, Moed, Tijssen, Visser, & van Raan, 2001), with increased emphasis on the growth of PRC S&T publications (Liang, 2003; Moed, 2002), as well as the dramatic increase in the S&T publications of other Asian countries (South Korea, Taiwan, India) (Arunachalam & Doss, 2000). These comparative scientometric studies are based almost exclusively on the Science Citation Index (SCI) database (SCI, 2007). Since the SCI has a large biomedical research component, countries that are strong in biomedical basic research have an inherent advantage in any cross-country comparison when the SCI is used.

Nanotechnology studies published in the 2005–2008 time period (Calero, Buter, Valdes, & Noyons, 2006; Guan & Ma, 2007; Kostoff, Stump, et al., 2005, 2006; Kostoff, Murday, Lau, & Tolles, 2005, 2006; Miyazaki & Islam, 2007; Mogoutov & Kahane, 2007; Porter, Youtie, Shapira, & Schoeneck, 2008; Schummer, 2007), as well as other studies published during that time frame (Basu & Lewison 2005; He, Zhang, & Teng, 2005; Kademani, Kumar, Sagar, Kumar, 2006; Zhou & Leydesdorff, 2006), also used the SCI for comparison purposes. All these studies concluded the USA was still leading the PRC in numbers of nanotechnology publications, and in quality of these publications, but the PRC was rapidly closing this gap.

2. Analysis

2.1. Output quantity

Almost all the published scientometrics studies comparing countries (as well as most other research units) have used the basic-research oriented SCI. How do these comparative results change if other premier S&T databases are used? To compare performance between any research units, two key factors are the metrics used for the comparison, and the databases used to compute the metrics. In the present paper, the metrics used for total country publication output are straight-forward (numbers of papers). More metrics are available for publication quality, and one metric is selected to evaluate quality of nanotechnology papers only.

2.1.1. Nanotechnology

We updated our SCI nanotechnology results (from a study conducted in 2006 (Kostoff, Koytcheff, & Lau, 2007a, 2007b)) in third quarter 2007. The metric selected was the time trend of the ratio of China (PRC) to USA nanoscience/nanotechnology publications in three S&T databases, including SCI (see Appendix 1 for a description of these three databases).

Fig. 1 is a time plot of the ratio of the number of China's nanotechnology publications to those of the USA, using SCI, INSPEC, and Compendex data. The SCI data were retrieved in Fall 2007, and the Inspec and Compendex data were retrieved in early 2008. The SCI ratio rose from less than 10% in 1991 to about 90% in first half 2007, and the trend is linear or accelerating. The Inspec ratio has gone from about 0.5 to over 1.5, a relatively dramatic threefold increase over this short period, and again the trend may be accelerating. The Compendex ratio has gone from about 0.5 to 2.0, an even more dramatic fourfold increase, and again the trend may be accelerating.

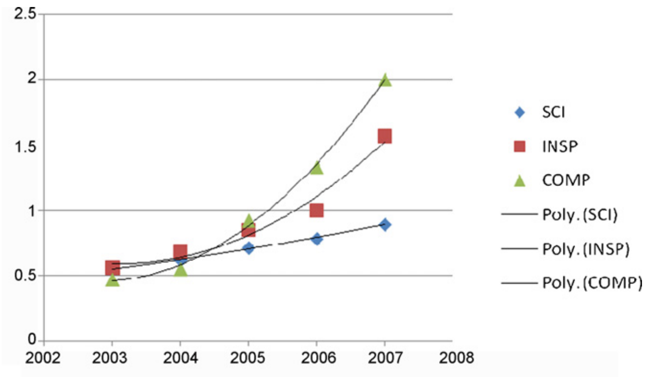

Fig. 1. Ratio of China/USA nanotechnology publications—SCI; INSPEC; Compendex.

What are the reasons for these differences in the China/USA quantity of nanotechnology publications? The SCI database has significant numbers of biomedical research publications. The USA has overwhelming dominance in biomedical research, especially compared to China. The INSPEC database, by comparison, is basically a physical sciences research database, without the major biomedical research component of the SCI. Removing these biomedical research publications shows more clearly China's increasing strength in the physical sciences. The Ei Compendex is a very applied database, and also does not contain the numbers of basic biomedical research publications of the SCI database. Removing these basic biomedical research publications shows more clearly China's increasing strength in the applied sciences and technology regarding nanotechnology.

These differences are important because most published bibliometric analyses use the SCI/SSCI for comparing countries' publication and citation outputs (e.g., King, 2004). The strong biomedical basic research component of the SCI/SSCI over-represents those countries with substantial outputs of biomedical research (such as the USA), and tends to show such countries as performing well overall in S&T publication production comparisons. However, S&T production in non-biomedical areas, such as the physical, material, and engineering sciences and technology, is very important for military and commercial applications. In some sense, examining aggregated bibliometric results from the SCI/SSCI databases can mask performance in the non-biomedical areas, for those countries with strong biomedical research performance.

2.1.2. Other research areas

As a result of the nanotechnology findings, we explored China/USA trends in numbers of publications from other technical disciplines, to ascertain whether the nanotechnology trends extend to other S&T discipline areas. Data from these other disciplines were generated in January 2008.

In our previous assessment of China's S&T output (Kostoff, Briggs, Rushenberg, Bowles, Icenhour, et al., 2007; Kostoff, Briggs, Rushenberg, Bowles, Bhattacharya, et al., 2007), we had identified a number of S&T areas of relative output emphasis. We sampled thirty of these S&T areas, divided among the four major S&T categories: physical/information, engineering, environmental, and life sciences. However, physical and engineering sciences were emphasized much more strongly in China's S&T output literature than the environmental and life sciences. Because of limited space, we summarize these research publication trends (in disciplines other than nanotechnology) in Table 1.

The first column in Table 1 shows the technical discipline analyzed, divided under the four major groupings of physical/information sciences, engineering sciences, life sciences, and environmental sciences. Due to time constraints, the queries were simple and very specific, in most cases being the word or phrase shown. Columns 2 and 3 are the China/USA ratios from the SCI only (using Abstracts/Titles/Keywords) for the years 2002–2007. Columns 4 and 5 use INSPEC Abstracts and Titles, while Columns 6 and 7 use the INSPEC Controlled Vocabulary, essentially indexer-supplied Keywords. Columns 8–11 are analogous to Columns 4–7, except they apply to Compendex.

For the SCI, the physical sciences 2002 China/USA ratios are the highest of the disciplines, followed by the engineering and information sciences ratios, then by the environmental sciences ratios, and finally by the life sciences ratios. On average, the ratios grow by factors of 2–3 over the 6-year period, but China–USA parity in numbers of publications is achieved in only a few physical sciences disciplines. However, the ratio growth is remarkable, coming over such a short time period (2002–2007). For most of the disciplines, the growth curves were monotonic, although not in all cases as smooth as the nanotechnology curves displayed.

For the INSPEC Abstracts, the China/USA ratios are higher than their SCI counterparts, usually by 25–50%, but in some rare cases by factors of 2–3. Publication parity is now the norm for most of the physical sciences examples, but still less in the other disciplines. Growth ratios over the six-year period are still in the 2–3 range, with low end increases in areas of intense USA interest such as robotics, and high end increases in soil/geology.

For the INSPEC Controlled Vocabulary, the ratio increases are in the same range as that of the INSPEC Abstracts over the 6-year period. Typically, the magnitudes of the ratios are somewhat higher than those of the INSPEC Abstracts, but there is much volatility. The absolute values of the Controlled Vocabulary retrievals are typically much lower than that of the Abstracts. The indexing procedure that assigns the Controlled Vocabulary appears to apply much harsher criteria than appearance of the phrase or phrases in the text fields, and the scope of the retrieved articles we have compared tends to be more constrained for the Controlled Vocabulary than the Abstracts. The combination of lower retrievals and less robustness for the Controlled Vocabulary results in higher volatility. Compared to the 2007 SCI Abstracts ratios, the 2007 INSPEC Controlled Vocabulary ratios are about 1.5–3 times larger, with some high end exceptions in areas like missiles, radar, aerodynamics, biophysics and geology/soils.

For the Compendex Abstracts, the life sciences and to some extent the environmental sciences ratios for 2007 are moderately larger (on average) than their INSPEC counterparts, the information and engineering sciences ratios are on the order of about twice as large as their INSPEC counterparts (with noticeable high end exceptions like missiles), and the physical sciences ratios are on the order of about 50% larger than their INSPEC counterparts.

For the Compendex Controlled Vocabulary retrievals, there is too much volatility in most category ratios to make definitive statements relative to their 2007 INSPEC counterparts (except for the information sciences ratios, which are about 50–100% larger for 2007 than their INSPEC counterparts). However, when the 2007 Compendex ratios are compared to their 2007 SCI counterparts, the nominal trend is about 50–100% larger. There are some notable high end exceptions, such as biophysics (~8), missiles (~13), robotics (~7), radar (~8), aerodynamics (~9), finite elements (~5), imaging (~6), signal processing (~6), and computer simulation (~6).

Table 1
China/USA Publication Ratios for selected technical disciplines (italicized numbers reflect ratios greater than unity)

Technology	SCI (China/USA ratio)		INSPEC (China/USA ratio)				Compendex (China/USA ratio)			
	ABS		ABS		CV		ABS		CV	
	2002	2007	2002	2007	2002	2007	2002	2007	2002	2007
Physical/info sciences										
Physical sciences										
Composites	0.589	*1.18*	0.79	*2.1*	*1.08*	*2.58*	0.548	*2.74*	0.634	*3.38*
Silicon	0.333	0.548	0.32	0.712	0.528	*1.24*	0.229	*1.1*	0.255	*1.22*
Semiconductor*	0.25	0.591	0.263	0.65	0.366	*1.04*	0.211	0.996	0.22	*1.09*
Polymer*	0.258	0.649	0.323	0.895	0.471	*1.33*	0.304	*1.38*	0.365	*1.99*
Nanostructure*	0.452	0.996	0.318	*1.15*	0.841	*1.69*	0.262	*1.42*	0.563	*1.83*
X-ray diffraction	0.937	*2.14*	*1.27*	*4.03*	*1.57*	*5.4*	*1.15*	*5.43*	*1.18*	*4.85*
Photoluminescence	0.842	*2.34*	0.976	*3.29*	0.956	*3.79*	0.762	*4.53*	0.617	*4.39*
Laser*	0.275	0.587	0.507	*1.11*	0.578	*1.38*	0.396	*1.7*	0.366	*1.51*
Catalysis*	0.525	*1.12*	0.682	*1.88*	0.763	*2.26*	0.621	*2.68*	*3.74*	*1.68*
Thin film*	0.426	0.82	0.451	0.97	0.512	*1.38*	0.37	*1.3*	0.374	*1.6*
Chemical react*	0.278	0.584	0.381	0.895	0.469	0.905	0.307	0.903	0.377	*1.64*
Information sciences										
Remote sensing	0.099	0.323	0.31	0.62	0.142	0.483	0.27	*1.26*	0.21	0.916
Computer simulation	0.294	0.475	*1.69*	*2.15*	0.664	0.692	0.952	*3.08*	0.32	*1.56*
Signal process*	0.162	0.304	0.434	0.791	0.617	*1.17*	0.265	*1.79*	0.339	*1.9*
Imaging	0.045	0.103	0.143	0.276	0.279	0.543	0.099	0.564	0.125	0.632
Network*	0.206	0.415	0.591	*1.11*	0.471	*1.03*	0.406	*1.77*	0.401	*1.52*
Engineering sciences										
Finite element*	0.283	0.467	0.477	1.06	0.568	*1.27*	0.372	*2.2*	0.408	*2.2*
Aerodynamic*	0.145	0.261	0.467	0.811	0.517	0.985	0.318	*2.3*	0.238	*2.09*
Bandwidth	0.17	0.531	0.273	0.739	0.443	0.802	0.236	*1.01*	0.157	*1.14*
Radar	0.1	0.249	0.342	0.945	0.381	*1.05*	0.217	*1.7*	0.216	*1.9*
Missile*	0.083	0.125	*1.1*	*2.25*	*1.12*	*3.22*	0.636	*6.13*	0.851	*16.4*
Robot*	0.146	0.215	0.616	0.643	0.564	0.572	0.362	*1.49*	0.322	*1.14*
Life sciences										
Protein*	0.062	0.184	0.131	0.287	0.138	0.345	0.063	0.336	0.062	0.296
Enzyme*	0.079	0.238	0.2	0.711	0.125	0.575	0.09	0.542	0.082	0.37
Biophys*	0.024	0.078	0.065	0.119	0.14	0.365	0.034	0.125	0.142	0.666
Genetics	0.061	0.167	0.185	0.345	0.133	0.325	0.076	0.359	0.102	0.403
Environmental sciences										
Ocean*	0.08	0.183	0.065	0.152	0.076	0.154	0.05	0.278	0.055	0.239
Climate*	0.125	0.198	0.112	0.232	0.12	0.226	0.089	0.368	0.082	0.254
Geolog*	0.237	0.397	0.203	0.95	0.352	*5.36*	0.514	*1.1*	0.339	*1.15*
Soil	0.135	0.36	0.325	*1.35*	0.449	*1.36*	0.186	*1.36*	0.235	*1.58*

Overall, by 2007 the Chinese have not achieved publication parity with the USA in all but a few of the (physical science) SCI disciplines examined. However, by 2007 the Chinese appear to have achieved publication parity, or even more than parity in the physical and engineering sciences when the INSPEC or Compendex is examined, and possibly some smaller part of the environmental sciences. To reduce the volatility of the numbers, more comprehensive queries on the order of the 300+ term nanotechnology query would be required. Development of such queries was beyond the scope of this study, but because of the unmistakable message conveyed by the above first-order results (and the more definitive nanotechnology results), we strongly recommend that such comprehensive queries be developed for future studies. What these numbers above do show straight-forwardly is that China becomes a real contender (in terms of the number of publications) with the USA in 2007 when premier databases with less emphasis on biomedical research are accessed.

2.1.3. Overall Ei Compendex trends

Due to space limitations, we examine only the Compendex results from a broader perspective to gain a better understanding of the underlying dynamics. All the technical areas examined in the Compendex had similar generic characteristics, but the actual numbers presented showed some volatility. The ratios of China/USA publications increased with time, and the magnitude of the increase over the short 2002–2007 time frame was substantial. In some areas, PRC had a sizeable lead in absolute numbers of publications in 2007, and the smoothness of the trend curves that we examined indicates the 2007 results will be real when the final 2007 publication numbers are known.

While the Chinese absolute numbers of publications continued to increase over time (in some cases with the exception of 2007, since the databases had not fully populated with 2007 data when the data were taken in early 2008), *the USA absolute publications numbers in some cases appeared to have peaked in the 2004-2005 time frame, or flattened out*. Given that USA funding for S&T has not declined in recent years, the reason for this peaking/flattening is unclear.

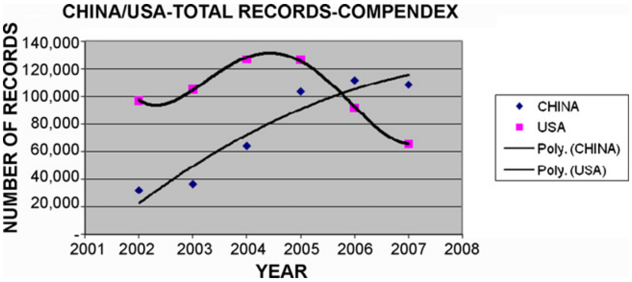

Fig. 2. Total records—compendex.

Several speculative explanations of these trends are suggested. Research in the USA may have become more expensive, leading to lower productivity and fewer publications The leveling off of publications may reflect 'bracket creep,' that is, journal editors and reviewers may perceive applied research as being "too applied" for journal publication. For national security reasons, there may be a reluctance to publish applied research since the 9/11 terrorist attack. Also for national security reasons, the increasingly restrictive immigration since 9/11 may be limiting the numbers of foreign scientists coming to the USA and thereby impacting S&T publication productivity. USA researchers may be attending fewer international meetings since 9/11, and thus contributing and publishing fewer conference papers. To obtain further insight into the causes of these disturbing trends, we performed additional analyses.

We examined the total number of records published by China and the USA in the Ei Compendex, and then examined the major document type components. Fig. 2 shows the total number of USA and China publications in the Ei Compendex from 2002–2007. Fig. 3 contains the China/USA ratio of total publications, journal publications, and conference publications.

As Fig. 2 shows, in 2002 the USA had approximately three times the number of total records in the Ei Compendex as PRC. From 2002 to near 2004, the trend lines were similar in shape, with PRC exhibiting a somewhat faster increase in growth. However, by 2004–2005, the USA appeared to have *peaked*, while PRC still exhibited rapid growth. Following this peak, the USA exhibited a rather rapid decline, while PRC increased until near 2007 (when the Ei Compendex is not fully populated with 2007 data). By 2007, the PRC had approximately 65% more total publications than the USA. Fig. 3 displays the ratio of total publications in a remarkably smooth second-order polynomial fit, suggesting the recent trend is not an anomaly. The characteristics of Fig. 3 (increase by a factor of four over 6-year period, smoothness of curve) are reflective of the nanotechnology Compendex results of Fig. 1. In order to get a better understanding of the mechanisms behind these overall Ei Compendex trends, the total Ei Compendex records were decomposed into two major components: journal publications and conference publications/proceedings.

Fig. 4 shows the numbers of journal publications of China and USA. Comparison of this figure with Fig. 2 shows the Chinese curves are similar, and the USA curves on both figures peak between 2004 and 2005, but the USA curve on Fig. 4 exhibits a less radical downturn after 2005 than the analogous curve on Fig. 2. The total publications ratio curve in Fig. 3 has a moderately different shape from the journal publications ratio curve in Fig. 3. The total publications ratio curve in Fig. 3 is well represented by a second order polynomial, and continues its sharp climb until the present, while the journal publications ratio curve in Fig. 3 is well represented by a third-order polynomial, and moderates its climb in recent years. The range of ratio values increases by about four over the time frame for the journal publications ratio curve, while the similar ratio range increases by more than a factor of four for the total publications ratio curve.

Fig. 5 shows the numbers of conference papers and proceedings for the USA and China, and Fig. 3 shows the ratio of China/USA conference papers and proceedings. While the PRC curve in Fig. 5 resembles its curves in Figs. 2 and 4, the USA curve contains much steeper declines than on the two previous figures, especially the downturn in recent years, when 2006

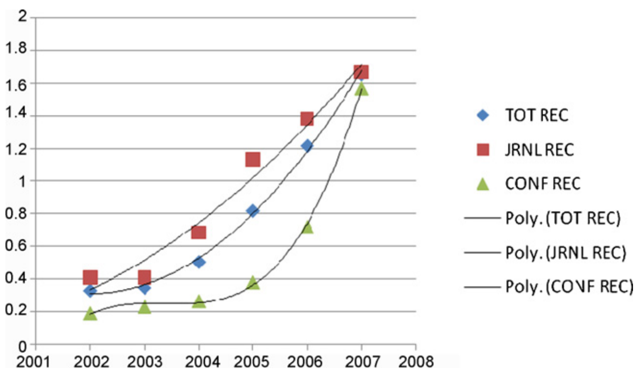

Fig. 3. China/USA records ratio—compendex.

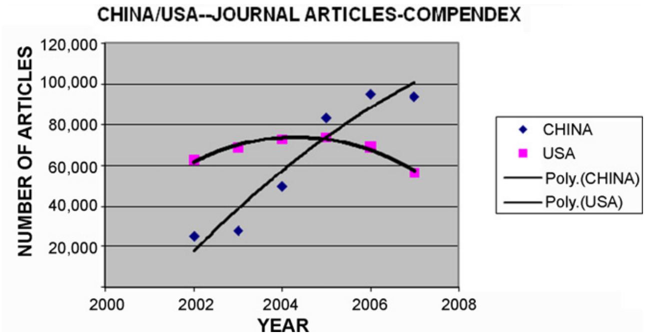

Fig. 4. Journal publications—compendex.

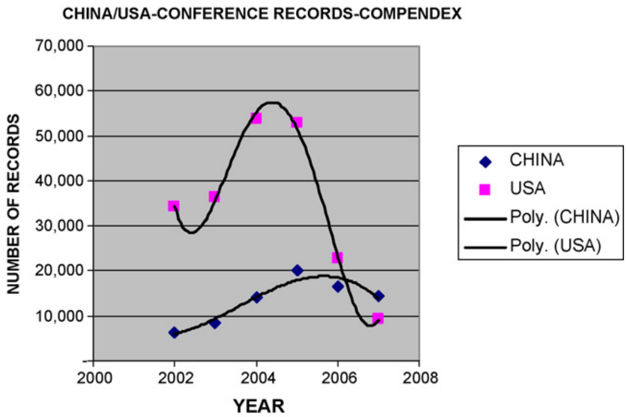

Fig. 5. Conference papers and proceedings—compendex.

and 2007 conference proceedings publications reach their lowest levels in this time period. The conference papers and proceedings ratio curve in Fig. 3 starts out more slowly than the two other ratio curves in Fig. 3, but accelerates much faster in recent years due largely to the dramatic US decline in 2006–2007.

Thus, the peaking occurs on all the graphs, but is much more pronounced for conference publications than for journal publications. USA researchers have drastically reduced their attendance at, or at least their written contributions to, technology conferences in recent years.

2.1.4. Language/publication type

A short analysis of language/publication type issues reveals some interesting perspectives that may influence type of publication output. Consider the main languages in which Chinese authors publish. In Fig. 6, all the articles have at least one author with a Chinese address. In the INSPEC and Compendex results, all the first authors have a Chinese address.

In the SCI, the number of Chinese authors who publish in Chinese is perhaps 10% of those who publish in English (search limited to Articles and Reviews), and the fraction has dropped by a few percent over the past decade. In the Compendex (compared to the SCI), the number of authors who publish in Chinese is much higher relative to those who publish in English.

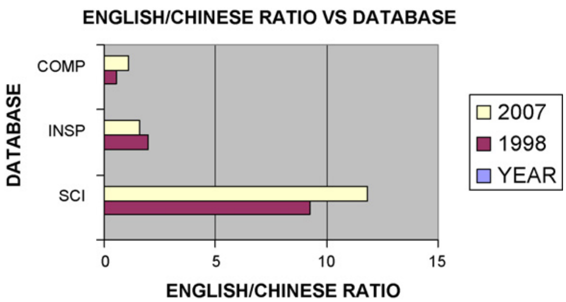

Fig. 6. Ratio of English/Chinese articles vs. database.

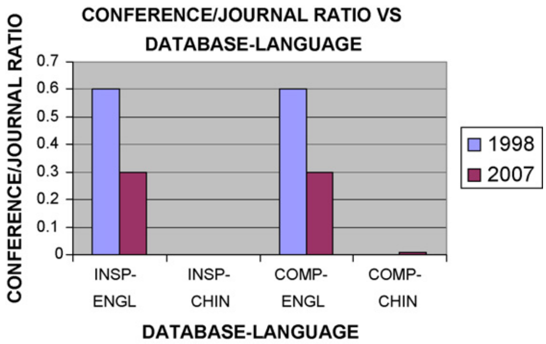

Fig. 7. Conference/journal ratio vs. database-language.

The Chinese/English ratio has dropped from almost two in 1998 Compendex to slightly less than one in 2007. In INSPEC, the numbers of Chinese articles are about 55–65% of the number of English articles, and the Chinese/English ratio has actually increased in the last decade.

However, probably the most interesting results come from the breakdown by type of publication (See Fig. 7). For INSPEC, in 1998, all the Chinese language articles were published in journals, whereas the ratio of conference/journal articles published in English was about 60%. In 2007, all the Chinese language articles were published in journals, whereas the ratio of conference/journal articles published in English was about 30%. For Compendex, in 1998, all the Chinese language articles were published in journals, whereas the ratio of conference/journal articles published in English was about 60%. In 2007, the ratio of conference/journal articles published in Chinese was about 1%, whereas the ratio of conference/journal articles published in English was about 30%.

One interpretation is that the quality of research in China improved, and Chinese were able to publish more papers in the higher quality English-language journals. Since journal publications, on average, tend to be more prestigious than conference publications, the Chinese have preferentially tended to publish a higher fraction of their papers in the English-language journals compared to the English-language conferences. These results supplement the findings in our earlier China S&T assessment (Kostoff, Briggs, Rushenberg, Bowles, Icenhour, et al., 2007; Kostoff, Briggs, Rushenberg, Bowles, Bhattacharya, et al., 2007), where we found that the Chinese authors were increasing their publications in (English language) high Impact Factor journals faster than their average increase in all journals.

3. Output quality

3.1. Nanotechnology

Only the nanotechnology results for quality are presented here. How did the quality of the PRC's nanotechnology publications change under such high publication growth conditions, and how does the quality compare with that of other countries?

The quality metric employed for this analysis is the efficiency of highly cited nanotechnology document production; i.e., the ratio of highly cited nanotechnology documents produced to the overall production of nanotechnology documents. We define a citation threshold for highly cited nanotechnology documents as the top 1% of total nanotechnology publications (for the global analysis). For each country, we calculate the number of highly cited papers that were produced in selected time frames of interest. Then, we take the ratio of this number to total number of publications the entity has produced over the selected time frame, and use this as our Figure of Merit.

Citations (and publications) for nanotechnology documents published by major producing nations in four uneven time frames were examined. All nanotechnology documents in the Science Citation Index for 1998, 1999–2000, 2001–2002, 2003 were retrieved using a 300+ term query (Kostoff, Koytcheff, and Lau, 2007c) and analyzed in March–June 2007.

The distributions of numbers of publications among countries were computed, the most highly cited publications were extracted, and the country distributions for the highly cited documents were generated. The country publication distributions were then compared to the citation distributions. This allowed a comparison of countries with high numbers of citations relative to the number of their publications. Such countries were thus producing highly cited papers more efficiently than their overall publication statistics would predict.

4. Results

Because of space considerations, only one table for 2003 will be shown, a summary temporal trend figure will be presented, and results for 1998–2003 will be discussed. Table 2 contains the country distributions for 2003. A country publication means that it was listed in the address field of the publication; other countries may have been listed as well. The left side is the

Table 2
Country distributions – overall records/ top 1% cited records – 2003

Total records 47945					Most cited: 1% = 480 records (73 cites min)				
Country/territory	Record count	CIT%	PUB%	CIT/PUB	Country/territory	Record count	CIT%	PUB%	CIT/PUB
2003									
USA	11408	62.50%	23.79%	2.63	USA	300	62.50%	23.79%	2.63
Japan	7196	6.67%	15.01%	0.44	Germany	48	10.00%	10.24%	0.98
Peoples Republic of China	6717	6.25%	14.01%	0.45	Japan	32	6.67%	15.01%	0.44
Germany	4911	10.00%	10.24%	0.98	UK	32	6.67%	5.85%	1.14
France	3338	3.75%	6.96%	0.54	Peoples Republic of China	30	6.25%	14.01%	0.45
UK	2805	6.67%	5.85%	1.14	France	18	3.75%	6.96%	0.54
South Korea	2640	3.13%	5.51%	0.57	Netherlands	17	3.54%	1.74%	2.04
Russia	2015	0.42%	4.20%	0.10	Switzerland	16	3.33%	1.68%	1.99
Italy	1803	2.29%	3.76%	0.61	South Korea	15	3.13%	5.51%	0.57
India	1498	0.63%	3.12%	0.20	Spain	14	2.92%	2.69%	1.09
Spain	1288	2.92%	2.69%	1.09	Italy	11	2.29%	3.76%	0.61
Taiwan	1234	0.42%	2.57%	0.16	Israel	9	1.88%	1.06%	1.77
Canada	1193	0.83%	2.49%	0.33	Sweden	9	1.88%	1.67%	1.12
Poland	857	0.21%	1.79%	0.12	Denmark	7	1.46%	0.62%	2.35
Netherlands	834	3.54%	1.74%	2.04	Austria	6	1.25%	0.95%	1.32
Switzerland	804	3.33%	1.68%	1.99	Australia	5	1.04%	1.60%	0.65
Sweden	803	1.88%	1.67%	1.12	Belgium	4	0.83%	1.20%	0.69
Australia	768	1.04%	1.60%	0.65	Brazil	4	0.83%	1.57%	0.53
Brazil	755	0.83%	1.57%	0.53	Canada	4	0.83%	2.49%	0.33
Singapore	662	0.83%	1.38%	0.60	Singapore	4	0.83%	1.38%	0.60

total publications ranked by country, and the right side is the number of highly cited publications (top 1%) again ranked by country. On either side, the first column is the country, the second column (Rec Count) is number of SCI/ SSCI records, the third column (CIT%) is the country's highly cited papers as a percentage of the total highly cited papers, the fourth column (PUB%) is the country's published papers as a percentage of total published papers in that year, and the last column (CIT/PUB) is the ratio of highly cited papers fraction to total papers fraction.

As an example, in 2003 there were 480 most cited papers. The USA at 300 record count produced 62.5% (300/480) of the most cited nanotechnology papers, and the USA produced 11,408 papers out of the total 47,945 papers, or 23.79% (11,408/47,945) of total nanotechnology papers. Thus, the USA is both the most prolific nanotechnology publishing country and most represented country on highly cited nanotechnology papers for 2003. Its ratio of percent representation on most highly cited nanotechnology papers to percent of total nanotechnology publications (ratio = 62.5/23.79) is 2.63. A ratio greater than one means that a country has higher representation on most cited papers than would be expected from its publications alone, and a ratio less than one means that a country has lower representation. In other words, a ratio higher than one means that a country's papers are cited more often relative to the number of papers it publishes. A ratio of 2.63 for the USA means that the USA representation on most highly cited records is 2.63 times what would be expected based on proportionality to the number of nanotechnology publications alone.

None of the other large producers have ratios approaching that of the USA (for 2003 publications), and only some of the smaller hi-tech countries have ratios of two or greater (Denmark, Netherlands, Switzerland). Countries that have exhibited rapid growth in SCI/ SSCI nanotechnology paper production in recent years (e.g., PRC, South Korea) had ratios an order of magnitude less than that of the USA for 1998, but by 2003 had increased to about 20% that of the USA. The lowest tier for 1998 consisted of Belgium, Poland, Taiwan, and India, and by 2003 the lowest tier included Russia, Poland, Taiwan, and India.

For 1999–2000, the USA was dominant in nanotechnology publications and representation on most highly cited nanotechnology papers ratio as well. Switzerland and the Netherlands remained on par with the US, but Israel dropped in ratio while Canada moved up. For 2001–2002, the US at 2.50 remains dominant in the ratio of CIT/PUB, without any other country coming even close.

Over the total time frame from 1998 to 2003, the USA's performance was remarkably consistent, with about 25% of total nanotechnology publications and about 60% of total highly cited papers. Its ratio hovered around 2.5. Switzerland and Netherlands maintained reasonably high ratios, and except for one time period, so did Israel and Denmark.

Of the other large producers of publications, Japan hovered around a ratio of about 0.5, indicating that its papers are less cited, on average, than one would expect from proportionality to the large number of papers, although there may be individuals who are cited highly. Germany climbed slightly to a ratio near unity, the UK hovered around a ratio of unity, and thus the citations are as one would expect: proportional to the number of papers published. France oscillated around a ratio of about 0.65. Russia had a remarkably consistent ratio of about 0.37, but dropped recently to 0.10. Poland and Taiwan have remained consistently very low.

PRC and South Korea have climbed in the publications rankings from 6th and 9th in 1998, respectively, to 3rd and 7th in 2003, respectively (and to 2nd and 6th in 2005, respectively (Kostoff, Koytcheff, and Lau, 2007c)). PRC's ratio monotonically increased from .16 to .45 over the 1998–2003 period, and South Korea's ratio increased from .11 to about .6 over that same period, indicating their papers are getting more and more citations proportionately. Thus, under rapid growth conditions,

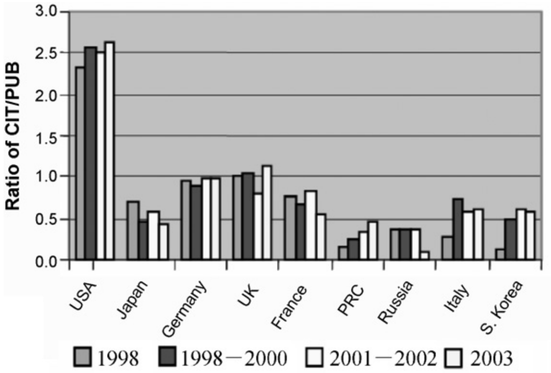

Fig. 8. Citation/publication ratio—nanotechnology.

PRC and South Korea have been able to increase their share of participation in highly cited papers. As of 2003, PRC and South Korea have ratios comparable to nations like Japan, France, Italy, and Australia, but not yet approaching those of the highly cited countries. This can be seen more graphically in Fig. 8, where ratio is plotted vs time for selected countries.

The numbers for PRC and South Korea have to be viewed in a larger context. For technology and engineering development, it is very important to have a trained cadre of researchers available to address the research issues that inevitably arise in the course of development. It is not necessary for these researchers to all be highly cited authors in order for them to have substantial value for supporting and accelerating technology and engineering development. If researchers are of the caliber to publish in the high quality journals typically accessed by the SCI/SSCI, they can offer expert assessment of what is being produced globally, and can exploit this cutting edge research in the development process.

Thus, if PRC and South Korea are increasing the numbers of nanotechnology researchers rapidly, and if their participation in highly cited papers is increasing at the same time, this rapid and increasing quality growth translates into a powerful foundation for accelerated growth in the industrial capability of their national development in the future. These countries are building a strong foundation not only for enhanced research quantity and quality capability, but for the more commercially and militarily important industrial capability as well.

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Appendix A. Database description

Three databases were used for the present study: the Science Citation Index; INSPEC; Ei Compendex. The SCI is developed by Thomson Reuters, and the latter two databases are developed by Engineering Village, Inc.

1. Science Citation Index (expanded):
   This database accesses over 5800 of the world's leading basic and applied technical research journals in many areas of science and technology, including the biomedical research literature. A key feature is the inclusion of reference and citation information, which identifies the citing and cited documents for any document of interest.
2. INSPEC:
   The INSPEC database contains nearly 10 million bibliographic abstracts and indexing to journal articles, conference proceedings, technical reports and other literature in the fields of science and technology.
   Inspec provides comprehensive coverage of traditional and cutting-edge publications in the specific fields of physics, electrical and electronic engineering, communications, computer science, control engineering, information technology, manufacturing and mechanical engineering.
   In addition there is significant coverage of areas such as operations research, material science, oceanography, engineering mathematics, nuclear engineering, environmental science, geophysics, nanotechnology, biomedical technology and biophysics.
   A key feature is the inclusion of indexer-supplied keywords, such as Controlled Vocabulary, which allows documents to be retrieved that do not contain query terms in their text fields (Abstracts, Titles).
3. Ei Compendex
   The Ei Compendex® database provides abstracted information from the world's significant engineering and technological literature. Ei Compendex provides worldwide coverage of more than 4500 journals and selected government reports

and books. Subjects include: civil, energy, environmental, geological, and biological engineering; electrical, electronics, and control engineering; chemical, mining, metals, and fuel engineering; mechanical, automotive, nuclear, and aerospace engineering; computers, robotics, and industrial robots. In addition to journal literature, there are more than 480,000 records of significant published proceedings of engineering and technical conferences formerly indexed in Ei Engineering Meetings®. A key feature is the inclusion of indexer-supplied keywords, such as Controlled Vocabulary, which allows documents to be retrieved that do not contain query terms in their text fields (Abstracts, Titles).

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