A historiographic analysis of fuel-cell research in Asia – China racing ahead

Subbiah Arunachalam[1,]* and B. Viswanathan[2]

[1]M.S. Swaminathan Research Foundation, Chennai 600 113, India

[2]National Centre for Catalysis Research, Indian Institute of Technology Madras, Chennai 600 036, India

Fuel-cell research in China, India, Japan, Singapore, South Korea and Taiwan, over the years 1983–2007 is analysed and compared with that in USA for number of papers, document type, journals used and international collaboration. For India and China we have also identified the key researchers and institutions. Using HistCite, the visualization technique developed by Garfield and colleagues, we have constructed the historiographs for India and China based on both local citation scores (LCS) and global citation scores, and identified key papers. We find that the knowledge flow among different Asian countries is rather limited and that China has something to offer to India. The thrust in China is in developing noble metal nanoparticle catalysts supported on carbon nanotubes and the thrust in India is in the area of direct methanol fuel cells. In India, A. K. Shukla is the single most significant contributor to fuel cell research. He is the author of 14 of the 50 nodes in the India LCS historiograph.

Keywords: Fuel-cell research, historiographic analysis, local and global citation scores.

NOT many inventions have had to wait as long as fuel cells to be exploited. The invention in 1839, of a device to produce electricity from hydrogen and oxygen by William Robert Grove, a Welsh judge, remained virtually untapped and bereft of any development for more than a hundred years, until the beginning of the space race in the 1960s. It attracted wider attention following the oil crisis. Recent concerns of climate change and environmental degradation and the rise in price of all forms of energy have given fuel-cell research an impetus, and the hope is that fuel cells will eventually be used widely both as stationary and portable energy sources to power automobiles, homes, and electronic devices such as laptops, mobile phones, Walkman and MP3 players[1].

Till about the turn of the century, Japan was the only Asian country to have some significant presence in fuel-cell research, largely thanks to the interest shown by Japanese automobile and consumer electronics industries. In the past seven years fuel-cell research has picked up in other Asian countries as well, especially China and South Korea and to a lesser extent in Taiwan and India.

In this article we have attempted to quantify the contributions made by six Asian countries, viz. China, India, Japan, Singapore, South Korea and Taiwan, to the literature of fuel cell research, and tried to trace the evolution of the field through citation-based historiographs, using HistCite developed by Garfield and colleagues[2].

Most scientometric studies on fuel-cell research have looked at corporate research and patenting. For example, the white paper on the hydrogen revolution brought out by Thomson Scientific Ltd in October 2004 showed that patenting was rising rapidly in the field of fuel cells – from around 870 in 1999 to over 4000 in 2003 – and that Japan was a major player[1]. Alan Pilkington used patent data to identify main players, both inventors and firms, active in fuel-cell innovation[3–5]. Emmanuel Hassan looked at the evolution of the knowledge structure of fuel cells using both patent and publication data[6]. Jonathan Butler surveyed current developments in fuel cells in India[7].

Data and analysis

We used the *Science Citation Index Expanded* part of *Web of Science* as our source of data. We used the names of different countries in the address field and the following words in the topic field: 'fuel cell' OR 'fuel cells' OR PEMFC OR MCFC OR PAFC OR SOFC OR DMFC. We had to omit AFC (for alkaline fuel cells) from our search strategy, as it picked up a large number of papers in areas ranging from enology to electrical engineering and geology, where AFC stands for acceleration feedback control, adaptive feedforward cancellation, adaptive fuzzy controller, affinity chromatograph, antral follicle count, alternative forced choice, and so on. We did not restrict the years or document types. We made standard bibliometric analysis using the data downloaded from *Web of Science* and then did a HistCite analysis on the data for India and China.

Growth of fuel-cell research in Asia

The number of papers published from different countries during 1983–2007 is shown in Figure 1. The US is the

*For correspondence. (e-mail: subbiah.arunachalam@gmail.com)

Table 1. Distribution of publications on fuel cells from selected countries and the world by year [data from *Web of Science*]

Year	World	India	China	South Korea	Japan	Taiwan	Singapore	USA
1993	215	8	1	2	51	1	–	61
1994	302	6	1	5	73	4	–	61
1995	302	5	2	6	73	1	–	67
1996	459	9	6	17	115	4	–	99
1997	400	11	5	10	79	-	1	79
1998	556	13	16	21	92	3	1	113
1999	599	23	29	21	101	3	1	113
2000	775	13	27	32	126	7	2	142
2001	859	23	46	44	112	3	6	190
2002	1164	28	90	67	176	11	14	303
2003	1437	26	130	81	208	21	24	392
2004	2126	52	221	149	293	36	34	601
2005	2469	55	318	129	316	66	42	705
2006	3502	85	561	275	372	144	58	820
2007*	3270*	97*	591*	211*	324*	134*	52*	772*
1983–2007	19,468	477	2048	1072	2777	438	236	4899

*Data for 2007 not complete.

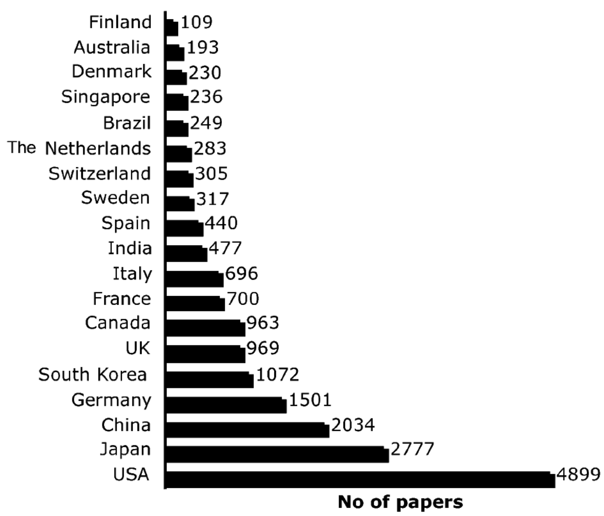


Figure 1. Number of fuel-cell papers from different countries, 1983–2007 [data from *Web of Science* 1983–2007].

undoubted leader, followed by Japan, China, South Korea and Germany.

The growth of fuel-cell research in several Asian countries, USA and the world as a whole is shown in Table 1, as a time series of number of papers published annually over a period of 15 years. There has been a dramatic rise in fuel-cell research only in the new millennium in all the countries considered. Although in the early years – up to 2000 – there was not much of a difference in the annual publication outputs of Japan and USA, in 2006, USA accounted for 24% of the world's publications as against Japan's less than 11%. Indeed, the People's Republic of China (PRC) had overtaken Japan in 2006. [But Japanese companies, especially the three leading automobile companies (Toyota, Honda and Nissan), are obtaining a large number of fuel cell-related patents every year]. India was ahead of China and South Korea till 1997, but in later years both China and South Korea raced ahead of India. In the 15 years considered here, India's share is less than 10% of the share of USA and less than 24% of the share of PRC. South Korea has published more than twice the number of papers from India and the relatively small Taiwan has recorded a larger annual publication output than India since 2005. Even the tiny city state of Singapore has a publication output comparable to that of India.

Arunachalam[8] had shown six years ago that China was racing ahead of India in all of science as seen from papers indexed in *Science Citation Index*, *Chemical Abstracts*, and *MathSciNet*. What is significant is that China is far ahead of India in niche areas such as fuel cells and nanotechnology also[9].

Document types and journals used

Table 2 provides data on the distribution of publications by document type. More than a third of the reviews have come from the US. With 16 reviews out of a total of 477 papers, India has accounted for almost the same per cent of reviews as USA – much higher than that of other Asian countries. The US also accounts for a large majority of meeting abstracts. This could be partly because *Web of Science* indexes the abstracts of papers presented at meetings of the American Chemical Society and other American societies, but not at many conferences held outside the US.

The journals used most often by fuel-cell researchers in Asia as well as USA are listed in Table 3 along with their 2006 impact factors (IFs). Virtually researchers from all the countries considered publish most of their work in the same set of international journals such as *Journal of Power Sources*, *Solid State Ionics* and *Electrochimica Acta*, with

Table 2. Distribution of publications on fuel cells by document type [data from *Web of Science* 1983–2007]

Article type	World	India	China	South Korea	Japan	Taiwan	Singapore	USA
Article	17,295	448	1987	1036	2647	434	229	4142
Review	501	16	32	15	34	–	4	170
Meeting abstract	561	7	10	11	30	2	1	451
Note	99	4	2	0	40	–	–	16
Letter	153	2	11	5	14	2	1	53
Total	19,468*	477	2048*	1072*	2777*	438	236*	4899*

*Includes editorial, correction and other types of documents.

Table 3. Distribution of publications on fuel cells by journal

Journal	IF* 2006	India	China	South Korea	Japan	Taiwan	Singapore	USA	World
J. Power Sources	3.521	81	346	288	257	157	49	789	3073
Solid State Ionics	2.190	14	62	37	306	3	16	189	1116
Electrochimi. Acta	2.955	13	100	67	90	10	9	141	741
Int. J. Hydrogen Energy	2.612	12	39	22	46	15	6	133	549
J. Appl. Electrochem.	1.409	12	18	9	32	3	5	38	306
J. Electroanal. Chem.	2.339	8	20	10	43	2	2	44	261
J. Mater. Sci.	0.999	8	13	10	14	3	3	18	134
J. Electrochem. Soc.	2.387	8	42	45	306	15	19	704	1472
Abstr. Papers of the Am. Chem. Soc.	–	7	12	10	13	2	1	348	420
J. Membr. Sci.	3.442	7	56	36	23	13	4	52	280
Mater. Chem. Phys.	1.657	7	15	15	–	8	–	–	63
Appl. Cataly. A	2.630	7	14	7	41	3	3	42	194
Ceramics Inter.	1.128	6	12	–	–	1	–	–	
J. Phys. Chem. B	4.115	6	30	15	24	7	8	116	268
J. Am. Ceramic Soc.	1.396	6	–	–	28	3	–	53	138
Catal. Lett.	1.772	5	8	10	11	3	–	20	71
Mater. Lett.	1.353	5	22	–	–	–	2	7	57
Electrochem. Solid State Lett.	2.009	4	33	–	63	3	10	135	299
J. Alloys Compounds	1.250	4	42	7	35	4	2	19	131
Electrochem. Commun.	3.484	3	82	18	35	5	12	33	271
J. Phys. Chem. C	–	3	20	–	–	4	–	–	92
Kor. J. Chem. Eng.	0.808			24					
Macromol. Res.	1.166			19					
J. Ind. & Eng. Chem.	0.957			17					
Bull. Korean Chem. Soc.	0.950			14					
J. Microbiol. Biotechnol.	2.037			14					
Catal. Today	2.148			13		3	1	38	
J. Electroceramics	1.157			12					
J. New Mater. for Electrochem. Syst.	1.095			11					
J. Eur. Ceram. Soc.	1.576			11			5		
Chem. J. Chinese Univ.	0.724		60						
Acta Physico–Chimica Sinica	–		53						
Chinese J. Catal.	0.659		51						
Rare Metal Mater. Eng.	0.251		51						
Acta Chim. Sin.	0.783		37						
Chinese J. Inorg. Chem.	0.583		33						
J. Inorg. Mater.	0.377		33						
Prog. Chem.	0.520		28						
J. Rare Earths	0.368		26						
Carbon	3.884		21				2	6	
Rare Metals	0.378		21						
Denki Kagaku	–			3	192				
Electrochemistry	0.574				157				
J. Ceram. Soc. Jpn.	0.997				44				
Nippon Kagaku Kaishi	–				37				
J. Chem. Eng. Japan	0.594				35				
Kagaku Kogaku Ronbunshu	0.294				35				
Chem. Lett.	1.734				32				
Chem. Commun.	4.520				21	3	2		
Bull. Electrochem.	0.259	19							
Indian J. Chem., Sec. A	0.631	9							
Bull. Mater. Sci.	0.522	7							
J. Solid State Chem.	2.107	7							
Ionics	0.305	6							

Table 4. Extent of international collaboration in the field of fuel cells

	India	China	South Korea	Japan	Taiwan	Singapore	USA
India	**477**	3	23	15	4	1	23
Peoples Republic of China	3	**2048**	22	53	10	47	81
South Korea	23	22	**1072**	29	1	–	96
USA	23	81	96	70	21	8	**4912**
Germany	19	47	8	13	2	–	57
Japan	15	53	29	**2777**	3	–	70
Italy	14	5	11	8	–	1	54
England	13	16	9?	12	1	13	36
Switzerland	13	–	–	9	–	–	23
Portugal	5	6	–	–	–	–	4
Australia	4	12	3	24	2	6	13
Taiwan	4	10	1	3	**438**	–	21
Canada	3	49	5	13	7	1	68
France	3	14	–	9	–	–	47
Mexico	3	–	1	1	1	–	7
Denmark	2	8	–	5	–	–	15
Israel	2	–	–	–	–	–	4
Belgium	1	3	–	1	–	–	3
Russia	1	2	1	2	1	–	14
Singapore	1	47	–	–	–	**236**	8
Slovakia	1	–	–	–	–	–	–
Spain	1	4	–	1	–	–	20
Sweden	1	23	–	4	2	2	4
New Zealand				14	–	–	10

Table 5. Distribution of papers from India and China by institution

Institution (India)	No. of papers	Institution (China)	No. of papers
Indian Institute of Sciences	63	Chinese Academy Sciences	565
Central Electrochemistry Research Institute	56	Tsing Hua University	149
Indian Institute Technology Madras	40	Harbin Institute Technology	139
Indian Institute of Technology Delhi	27	University of Science and Technology China	133
National Chemical Laboratory	21	Jilin University	116
SPIC Science Foundation	19	Shanghai Jiao Tong University	101
Bhabha Atomic Research Centre	17	Hong Kong University of Science and Technology	78
Indian Institute of Chemical Technology	14	Tianjin University	70
Central Glass Ceramic Research Institute	13	Xiamen University	69
Indian Institute Technology Bombay	13	Sun Yat Sen University	60
Central Salt Marine Chemical Research Institute	11	Dalian University of Technology	52

some minor variations in the extent of use. Electrochemistry journals dominate the list, followed by energy and materials science journals. Certain national journals are used predominantly by researchers from the concerned country. Of course there are some exceptions: Japanese researchers have published 21 papers in *Chemical Communications* [UK, 2006 IF 4.520] and Chinese researchers have published 21 papers in *Carbon* [Elsevier, 2006 IF 3.884]. As fuel cell is a hot field of research, papers in the field tend to appear in high IF journals: 1349 papers have appeared in journals with IFs higher than 3.000, and 458 papers have appeared in journals with an IF in the range 2.500–3.000.

Collaboration

The extent of international collaboration as seen from co-authored papers is presented in Table 4. USA has collaborated often with South Korea, China, Japan, Canada, Germany and Italy. Japanese researchers have co-authored papers with mainly researchers from USA, China, South Korea and Australia. China has collaborated often with USA, Japan, Canada, Singapore and Germany. South Korea's research partners include USA, Japan, India and China. Indian researchers have collaborated often with researchers based in USA, South Korea, Germany and Japan. Overall, the share of papers resulting from international collaboration is much less for India than all other countries considered here.

Distribution by institution

Table 5 provides data on the contribution made by Indian and Chinese institutions. Indian Institute of Science (IISc), Bangalore, tops the list (for India) with 63 papers which were cited 1314 times. Two CSIR laboratories, viz. Central

Electrochemical Research Institute (CECRI; 56 papers) and National Chemical Laboratory (21 papers) and two Indian Institutes of Technology, viz. IIT Madras (40 papers) and IIT Delhi (27 papers), have also published moderately in this field. No other Indian laboratory has published more than 20 papers during 1983–2007. In all, higher educational institutions, including universities and colleges have published 264 papers and laboratories of the Council of Scientific and Industrial Research have published 134 papers. SPIC Science Foundation, a non-profit organization has published 19 papers. The Government-owned Bharat Heavy Electrical Ltd (three papers) and the Defence contracting company High Energy Batteries India Ltd (two papers) are the only Indian companies to have any research presence in the area of fuel cells. This is in stark contrast to what is happening in Japan, where both automobile companies and other major industrial houses are active in fuel-cell research and innovation. India's Department of Atomic Energy has published 35 papers: Tata Institute of Fundamental Research (five papers), Bhabha Atomic Research Centre (17 papers) and Indira Gandhi Centre for Atomic Research (13 papers).

The Chinese Academy of Sciences leads the field in China with 564 papers during 1983–2007, followed by Tsing Hua University (153 papers), Harbin Institute of Technology (140 papers), University of Science and Technology, China (113 papers), Jilin University (116 papers) and Shanghai Jiao Tong University (101 papers). In about 90% of papers published from China, there is at least one Chinese author from a higher educational institution. In contrast, university researchers in India are authors in only about 55% of Indian papers.

Prominent Indian and Chinese researchers

A. K. Shukla (IISc and CECRI) is the most prolific Indian researcher in this field. He has published 51 papers from India during 1983–2007 and these were cited 1171 times for an average of 23 citations per paper. Shukla has also published four papers from the University of Newcastle upon Tyne, which have been cited 172 times. But these are not attributed to India in this study, as they do not have an Indian address in the byline. If these are included, Shukla's figures will be 55 papers, 1343 citations and average of 24.4 citations per paper. B. Viswanathan (IIT Madras; 24 papers and 192 citations), R. Pattabhiraman (CECRI; 22 papers and 62 citations), I. A. Raj (CECRI; 22 papers and 48 citations) and K. S. Dathathreyan (SPIC Science Foundation; 21 papers and 135 citations) are the other Indian researchers who have published more than 20 papers. The first Indian paper in this field came from CECRI [R. Pattabhiraman, V. K. Venkatesan and H. V. K. Udupa, 1981] Girijesh Govil (TIFR) was the next to write a paper in this field. He wrote two papers on biochemical fuel cells, one in 1982 (*Journal of the Indian Chemical Society*) and the other in 1983 (*International Journal Quantum Chemistry*). K. S. V. Santhanam *et al.* (TIFR), have published a paper in *Advanced Materials* in 1999 and it has been cited 169 times so far. In this paper and in another that Santhanam wrote after he started working in USA, P. M. Ajayan, the well-known nanotechnology researcher, is a co-author. A paper by Ravikumar and Shukla in the *Journal of the Electrochemical Society* (1996), has been cited 169 times so far. Five of Shukla's papers, not counting those he authored from Newcastle upon Tyne, have won 50 or more citations and 16 papers have won 30 or more citations.

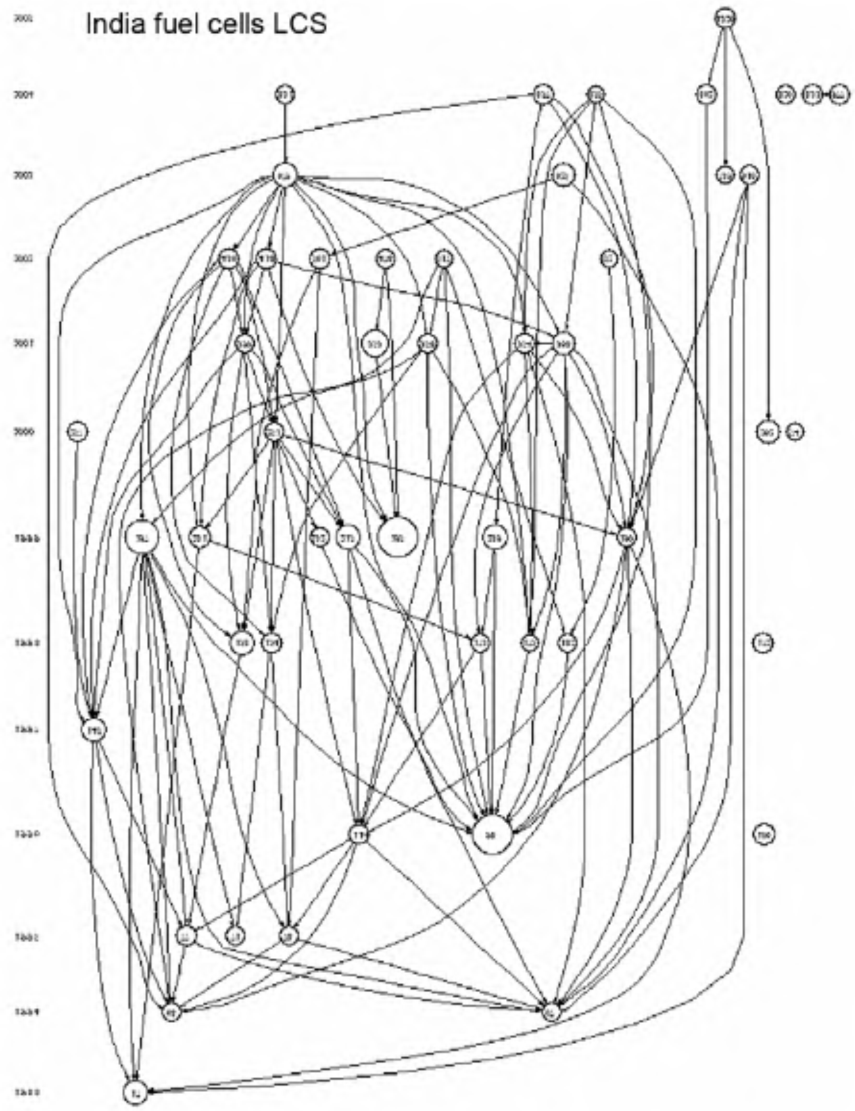
Since the first Indian paper in fuel-cell research appeared in 1981 from CECRI, there has been at least one paper from India every year. The first Chinese paper appeared in 1986 in the *International Journal of Hydrogen Energy*. The second paper from China had not appeared till 1991. And yet today, despite their late start, the Chinese are way ahead of India. There are at least 13 institutions in China which have published 50 or more papers in the period we have studied. In contrast, only two Indian institutions have published more than 50 papers. Fifty institutions in China have published ten or more papers, whereas only 13 Indian institutions have done so. More than 180 Chinese authors have published ten or more papers as against 13 from India. Only one Indian author has published more than 50 papers and five more than 20, as against 11 Chinese authors with 50 or more papers and 66 with 20 or more papers. B. L. Yi (98 papers and 718 citations), G. Y. Meng (91 papers and 431 citations), Q. Xin (87 papers and 1208 citations), G. Q. Sun (82 papers and 1134 citations), and W. Z. Li (33 papers and 948 citations) are among the most prolific authors of papers on fuel cells in China. Some Chinese authors have high citations/paper score. For example, W. J. Zhou, a co-author of W. Z. Li, has authored 25 papers and received 888 citations. Z. H. Zhou has 31 papers which have won 773 citations. I. M. Hsing has 31 papers and 476 citations.

Papers from USA have been cited relatively more often than papers from India and China. The 4899 fuel-cell research papers from USA have received 73,631 citations for an average of 15 and a *h*-index of 110. Eleven papers are cited 300 times or more, 53 are cited more than 150 times, 127 are cited 100 times or more, 195 are cited 75 times or more. And 367 are cited 50 or more times.

Historiographs for fuel-cell research in India

We have attempted to trace the evolution of fuel-cell research in India and China by constructing historiographs using HistCite software (developed by Garfield and colleagues) in conjunction with *Web of Science*.

We consider all of India's 477 fuel-cell papers. We include all the references quoted in these 477 papers. We add



			LCS	GCS
1.	17	PARSONS R, 1988, J ELECTROANAL CHEM, V257, P9	72	637
2.	67	SHUKLA AK, 1994, J ELECTROCHEM SOC, V141, P1517	38	38
3.	68	ARICO AS, 1994, J POWER SOURCES, V50, P295	39	39
4.	71	KUMAR GS, 1995, ELECTROCHIM ACTA, V40, P285	38	38
5.	77	SHUKLA AK, 1995, J APPL ELECTROCHEM, V25, P528	50	50
6.	78	ARICO AS, 1995, J POWER SOURCES, V55, P159	43	76
7.	98	Ravikumar MK, 1996, J ELECTROCHEM SOC, V143, P2601	169	169
8.	106	Quadakkers WJ, 1996, SOLID STATE IONICS, V91, P55	51	51
9.	114	Arico AS, 1996, J ELECTROCHEM SOC, V143, P3950	44	102
10.	145	Hamnett A, 1997, CATAL TODAY, V38, P445	66	192
11.	153	Gotz M, 1998, ELECTROCHIM ACTA, V43, P3637	66	183
12.	154	Liu L, 1998, ELECTROCHIM ACTA, V43, P3657	49	88
13.	172	Aruna ST, 1998, SOLID STATE IONICS, V111, P45	47	47
14.	173	Kuver A, 1998, J POWER SOURCES, V74, P211	41	73
15.	175	Reeve RW, 1998, J ELECTROCHEM SOC, V145, P3463	37	68
16.	182	Shukla AK, 1998, J POWER SOURCES, V76, P54	43	43
17.	190	Shukla AK, 1999, APPL SURF SCI, V137, P20	41	41
18.	195	Britto PJ, 1999, ADV MATER, V11, P154	169	169
19.	197	Wasmus S, 1999, J ELECTROANAL CHEM, V461, P14	129	359

(*Contd*)

20.	215	Arico AS, 1999, J APPL ELECTROCHEM, V29, P671	68	68
21.	231	McNicol BD, 1999, J POWER SOURCES, V83, P15	55	133
22.	232	Scott K, 1999, J POWER SOURCES, V83, P204	43	107
23.	239	Heinzel A, 1999, J POWER SOURCES, V84, P70	73	205
24.	251	Arico AS, 2000, ELECTROCHIM ACTA, V45, P4319	40	61
25.	257	Ren XM, 2000, J ELECTROCHEM SOC, V147, P466	49	162
26.	262	Jordan LR, 2000, J POWER SOURCES, V86, P250	65	65
27.	274	Jordan LR, 2000, J APPL ELECTROCHEM, V30, P641	36	36
28.	353	Luo HX, 2001, ANAL CHEM, V73, P915	75	301
29.	354	Arico AS, 2001, APPL SURF SCI, V172, P33	49	51
30.	358	Neergat M, 2001, J APPL ELECTROCHEM, V31, P373	43	44
31.	368	Shukla AK, 2001, J ELECTROANAL CHEM, V504, P111	65	66
32.	390	Steigerwalt ES, 2001, J PHYS CHEM B, V105, P8097	43	114
33.	418	Li WZ, 2002, CARBON, V40, P791	48	109
34.	436	Steigerwalt ES, 2002, J PHYS CHEM B, V106, P760	44	113
35.	478	Wang JX, 2002, ANAL CHEM, V74, P1993	41	287
36.	517	Shukla AK, 2002, ELECTROCHIM ACTA, V47, P3401	36	36
37.	552	Gurau B, 2002, J POWER SOURCES, V112, P339	37	86
38.	561	Rajesh B, 2002, FUEL, V81, P2177	46	46
39.	616	Antolini E, 2003, MATER CHEM PHYS, V78, P563	43	111
40.	625	Rajesh B, 2003, J PHYS CHEM B, V107, P2701	58	58
41.	679	Li WZ, 2003, J PHYS CHEM B, V107, P6292	68	177
42.	739	Smitha B, 2003, J MEMBR SCI, V225, P63	36	36
43.	820	Ratnasamy P, 2004, J CATAL, V221, P455	41	41
44.	831	Wang C, 2004, NANO LETT, V4, P345	43	110
45.	833	Einsla BR, 2004, J POLYM SCI A–POLYM CHEM, V42, P862	45	45
46.	855	Shukla AK, 2004, J ELECTROANAL CHEM, V563, P181	37	37
47.	857	Dillon R, 2004, J POWER SOURCES, V127, P112	45	113
48.	862	Smitha B, 2004, MACROMOLECULES, V37, P2233	47	47
49.	977	Hickner MA, 2004, CHEM REV, V104, P4587	44	229
50.	1326	Smitha B, 2005, J MEMBRANE SCI, V259, P10	44	44

Figure 2. Historiograph of fuel-cell research in India based on local citation scores. Nodes: 50, Links: 120, LCS, top 50; Min: 36, Max: 169 (LCS scaled).

all the papers that have cited these 477 papers as well as all the references quoted in those citing papers. The resulting aggregate is called the fuel-cell India collection. The collection is exported to HistCite to obtain a large list of 2851 papers and 60,615 cited references along with their local and global citation scores (LCS and GCS). The LCS for a paper denotes the number of times the paper is cited within the fuel-cell India collection, and the GLC denotes all citations to the paper (found in *Web of Science*). Thus LCS will always be a subset of GCS. HistCite enables one to draw a citation network among highly cited papers from which one gets a feel for the evolution of the subject (or research front) over the years.

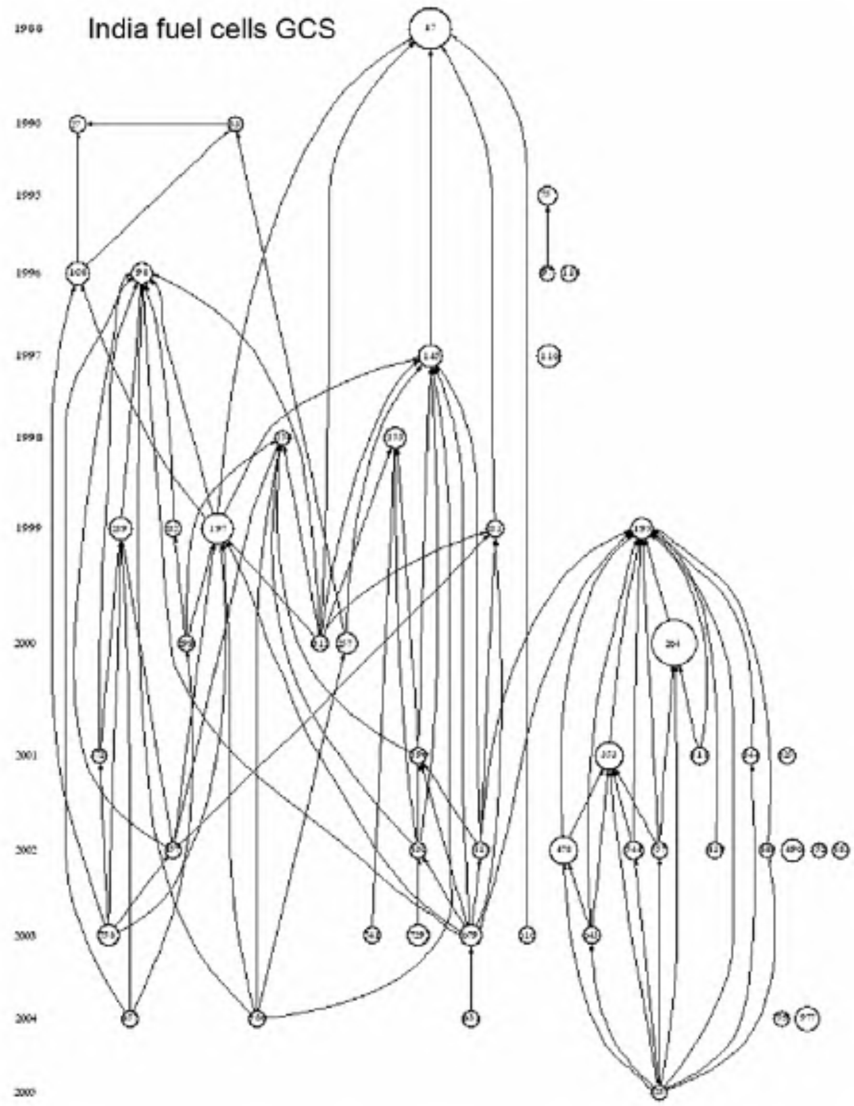
What HistCite does is to reduce the clutter: In the huge population of papers and citations that constitute the fuel-cell India collection, one would not get anywhere if one tried to view all the citation links. By clever use of algorithms and networking tools, HistCite prunes many of the not so important links and leaves one with a manageable and compact scientograph.

Figure 2 is the historiograph of fuel cell research in India based on the 50 most highly cited papers in the fuel cells India collection based on their LCS. Figure 3 is a similar historiograph but based on the LCS. Both cover the period 1988–2005, although we collected data on fuel-cell research from 1983. The papers published up to 1987 have not found a place in these historiographs, indicating that they have not proved to be significant.

In both these historiographs, the story begins with a paper by Roger Parsons and T. VanderNoot in *Journal of Electroanalytical Chemistry* published in 1988. Five of the 49 other highly cited papers in the fuel cells India collection have quoted this paper, which has reviewed the electrochemical literature during 1981–1987 on the oxidation of small organic molecules as potential fuels for fuel cells. The paper also discussed the nature of the poisoning species and intermediates, and suggested areas of future research. In the GCS historiograph, the 1988 Parson paper was cited by papers 145 (Hamnett), 197 (Wasmus), 231 (McNicol), 315 (Carrette) and 616 (Antolini). In the LCS historiograph, the paper was cited by 145 (Hamnett), 190 (Shukla), 197 (Wasmus), 251 (Arico) and 616 (Antolini).

The prominent nodes in the GCS historiograph are 98 (Ravikumar, ten citation links), 145 (Hamnett, eight links), 153 (Gotz, four links), 154 (Liu, six links), 195 (Britto, 13 links), 197 (Wasmus, seven links), 239 (Heinzel, four links) and 353 (Luo, five links).

The prominent nodes in the GCS historiograph are 67 (Shukla, ten links), 68 (Arico, seven links), 98 (Ravikumar,



			LCS	GCS
1.	17	PARSONS R, 1988, J ELECTROANAL CHEM, V257, P9	72	637
2.	27	VERBRUGGE MW, 1990, J ELECTROCHEM SOC, V137, P886	19	104
3.	33	VERBRUGGE MW, 1990, J ELECTROCHEM SOC, V137, P3770	9	82
4.	75	IWAHARA H, 1995, SOLID STATE IONICS, V77, P289	13	154
5.	97	Iwahara H, 1996, SOLID STATE IONICS, V86-8, P9	0	94
6.	98	Ravikumar MK, 1996, J ELECTROCHEM SOC, V143, P2601	169	169
7.	108	HeitnerWirguin C, 1996, J MEMBR SCI, V120, P1	19	199
8.	114	Arico AS, 1996, J ELECTROCHEM SOC, V143, P3950	44	102
9.	116	Radovic LR, 1997, CHEM PHYS CARBON, V25, P243	0	205
10.	145	Hamnett A, 1997, CATAL TODAY, V38, P445	66	192
11.	153	Gotz M, 1998, ELECTROCHIM ACTA, V43, P3637	66	183
12.	154	Liu L, 1998, ELECTROCHIM ACTA, V43, P3657	49	88
13.	195	Britto PJ, 1999, ADVAN MATER, V11, P154	169	169
14.	197	Wasmus S, 1999, J ELECTROANAL CHEM, V461, P14	129	359
15.	231	McNicol BD, 1999, J POWER SOURCES, V83, P15	55	133
16.	232	Scott K, 1999, J POWER SOURCES, V83, P204	43	107
17.	239	Heinzel A, 1999, J POWER SOURCES, V84, P70	73	205
18.	257	Ren XM, 2000, J ELECTROCHEM SOC, V147, P466	49	162
19.	264	Collins PG, 2000, SCIENCE, V287, P1801	21	725

(*Contd*)

20.	299	Kelley SC, 2000, ELECTROCHEM SOLID STATE LETT, V3, P407	19	101
21.	315	Carrette L, 2000, CHEMPHYSCHEM, V1, P162	25	109
22.	318	Ajayan PM, 2001, TOP APPL PHYS, V80, P391	5	125
23.	325	Rolison DR, 2001, J MATER CHEM, V11, P963	0	97
24.	344	Nugent JM, 2001, NANO LETT, V1, P87	23	110
25.	353	Luo HX, 2001, ANAL CHEM, V73, P915	75	301
26.	372	Choi WC, 2001, J POWER SOURCES, V96, P411	28	94
27.	390	Steigerwalt ES, 2001, J PHYS CHEM B, V105, P8097	43	114
28.	418	Li WZ, 2002, CARBON, V40, P791	48	109
29.	419	Frackowiak E, 2002, CARBON, V40, P1775	8	104
30.	436	Steigerwalt ES, 2002, J PHYS CHEM B, V106, P760	44	113
31.	449	Wang JX, 2002, ELECTROANALYSIS, V14, P225	20	93
32.	457	Jorissen L, 2002, J POWER SOURCES, V105, P267	32	102
33.	478	Wang JX, 2002, ANAL CHEM, V74, P1993	41	287
34.	483	Chaubey A, 2002, BIOSENS BIOELECTRON, V17, P441	2	103
35.	496	Jin W, 2002, ANAL CHIM ACTA, V461, P1	5	199
36.	544	Azamian BR, 2002, J AM CHEM SOC, V124, P12664	15	139
37.	552	Gurau B, 2002, J POWER SOURCES, V112, P339	37	86
38.	557	Zhao Q, 2002, ELECTROANALYSIS, V14, P1609	16	113
39.	616	Antolini E, 2003, MATER CHEM PHYS, V78, P563	43	111
40.	643	Yu X, 2003, ELECTROCHEM COMMUN, V5, P408	16	117
41.	679	Li WZ, 2003, J PHYS CHEM B, V107, P6292	68	177
42.	729	Serp P, 2003, APPL CATAL A-GENERAL, V253, P337	29	187
43.	741	Zhou WJ, 2003, APPL CATAL B–ENVIRONMENTAL, V46, P273	29	101
44.	758	Li QF, 2003, CHEM MATER, V15, P4896	28	182
45.	759	Liang HP, 2004, ANGEW CHEM INT ED ENGL, V43, P1540	9	87
46.	831	Wang C, 2004, NANO LETT, V4, P345	43	110
47.	857	Dillon R, 2004, J POWER SOURCES, V127, P112	45	113
48.	977	Hickner MA, 2004, CHEM REV, V104, P4587	44	229
49.	980	Wang CY, 2004, CHEM REV, V104, P4727	19	112
50.	1237	Gooding JJ, 2005, ELECTROCHIM ACTA, V50, P3049	11	91

Figure 3. Historiograph of fuel-cell research in India based on global citation scores. Nodes: 50, Links: 93 GCS, top 50; Min: 82, Max: 725 (GCS scaled).

14 links), 114 (Arico, six links), 190 (Shukla, six links) and 195 (Britto, four links).

In paper no. 68 (1994), Shukla and colleagues from IISc and Italy studied the electrooxidation of methanol in sulphuric acid electrolyte on a platinized carbon electrode with several functional group characteristics and found that small amounts of functional groups exhibit higher catalytic activity than large concentrations of acid/base functional groups. This paper has received 38 citations so far. Again in 1994, the Indo-Italian team of researchers continued with their investigation of methanol oxidation, but this time on carbon-supported platinum–tin electrodes in sulphuric acid [paper no. 79, *Journal of Power Sources*, 39 citations].

Paper no. 98 by M. K. Ravikumar and A. K. Shukla, published in the *Journal of the Electrochemical Society* (1990), is a key paper in this field and is quoted by ten other highly cited papers. In this paper, the authors reported on the performance of a liquid-feed direct methanol fuel cell employing a proton-exchange membrane electrolyte and showed that methanol crossover across the polymer electrolyte at concentrations over 2M methanol affected the performance of the cell. This paper has been cited 169 times so far.

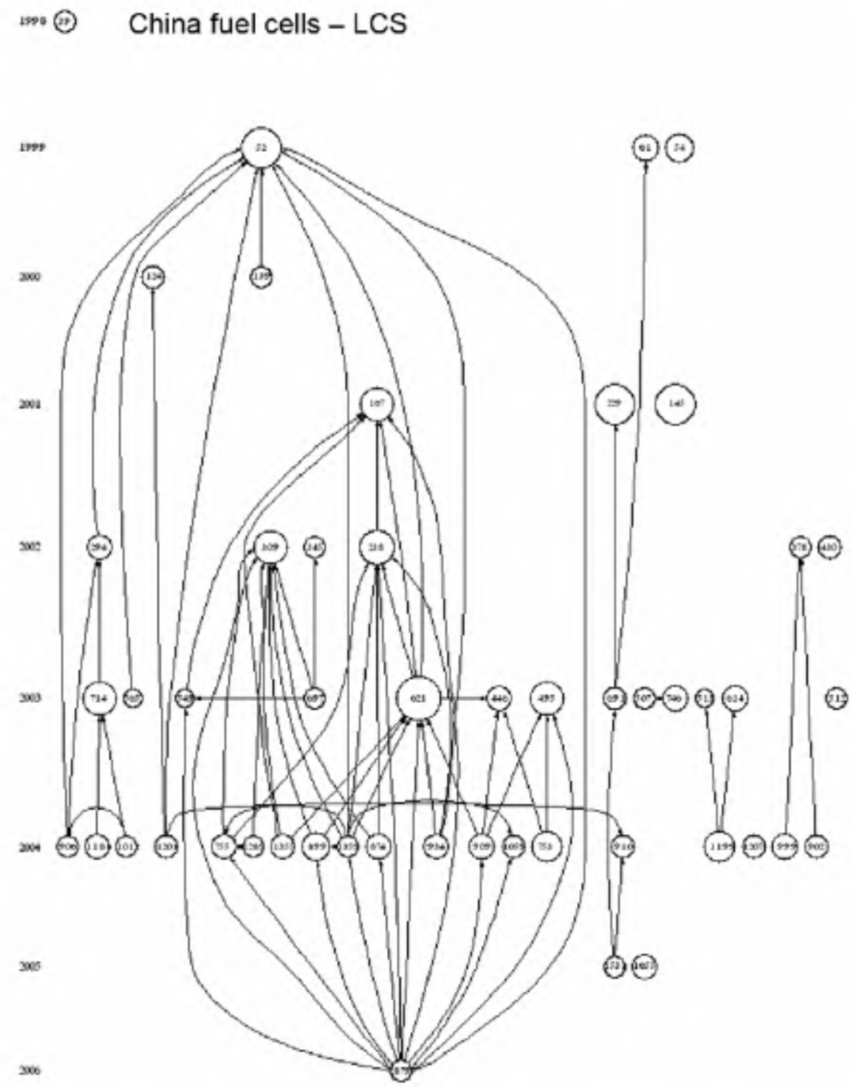
Paper no. 115 by Arico *et al.* (*Journal of the Electrochemical Society*, 1996) is about a vapour-feed direct methanol fuel cell based on a solid polymer electrolyte and employing 'platinum–ruthenium on carbon' catalyst for methanol oxidation and 'platinum on carbon' catalyst for oxygen reduction. This paper has been cited 102 times.

In 1997, A. Hamnett wrote a paper on the mechanism of electrocatalysis of methanol oxidation on platinum and platinum-containing alloys (in *Catalysis Today*) and showed that critical performance parameters for commercial exploitation were achievable with appropriate catalytic formulations and cell designs. This paper has received 196 citations so far.

Liu *et al.* from the Illinois Institute of Technology compared the performance of supported and unsupported catalysts in direct methanol fuel cells. Their paper in *Electrochimica Acta* (paper no. 154) has been cited 89 times.

Paper no. 198 is the most cited paper in this collection. This review of methanol oxidation and direct methanol fuel cells by Wasmus and Kuver in the *Journal of Electroanalytical Chemistry* has received more than 370 citations so far. This status report focuses on fundamental and applied electrochemistry aspects of DMFC and emphasizes strategies and approaches rather than individual results.

Paper no. 353 by Luo *et al.* from Beijing, is basically on electrochemical and electrocatalytic behaviour of the



			LCS	GCS
1.	39	Wang SZ, 1998, J ELECTROCHEM SOC, V145, P1932	40	40
2.	52	Wasmus S, 1999, J ELECTROANAL CHEM, V461, P14	143	359
3.	54	Tu HY, 1999, SOLID STATE IONICS, V117, P277	74	73
4.	61	Cheng XL, 1999, J POWER SOURCES, V79, P75	68	68
5.	124	Hsing IM, 2000, CHEM ENG SCI, V55, P4209	47	47
6.	139	Carrette L, 2000, CHEMPHYSCHEM, V1, P162	43	109
7.	145	Cheng HM, 2001, CARBON, V39, P1447	140	140
8.	167	Bessel CA, 2001, J PHYS CHEM B, V105, P1115	98	154
9.	229	Steele BCH, 2001, NATURE, V414, P345	141	484
10.	238	Li WZ, 2002, CARBON, V40, P791	109	109
11.	294	Wei ZB, 2002, J POWER SOURCES, V106, P364	56	57
12.	309	Liu ZL, 2002, LANGMUIR, V18, P4054	104	145
13.	345	Wang X, 2002, ELECTROCHIM ACTA, V47, P2981	44	44
14.	378	Dimitrova P, 2002, J ELECTROANAL CHEM, V532, P75	44	75
15.	430	Shao ZG, 2002, J MEMBRANE SCI, V210, P147	52	52
16.	446	Zhou ZH, 2003, CHEM COMMUN, P394	55	56
17.	495	Zhang X, 2003, CHEM MATER, V15, P451	99	100
18.	507	Li L, 2003, MATER LETT, V57, P1406	41	41
19.	512	Liu FQ, 2003, J MEMBR SCI, V212, P213	40	40
20.	513	Gao Y, 2003, J POLYM SCI A–POLYM CHEM, V41, P497	38	36

(*Contd*)

21.	549	Rajesh B, 2003, J PHYS CHEM B, V107, P2701	39	58
22.	565	Ma ZQ, 2003, J MEMBR SCI, V215, P327	38	38
23.	614	Yin Y, 2003, POLYMER, V44, P4509	61	61
24.	621	Li WZ, 2003, J PHYS CHEM B, V107, P6292	177	177
25.	691	Yu JR, 2003, J POWER SOURCES, V124, P40	49	49
26.	697	Prabhuram J, 2003, J PHYS CHEM B, V107, P11057	40	39
27.	714	Zhou WJ, 2003, APPL CATAL B–ENVIRONMENTAL, V46, P273	101	101
28.	746	Li L, 2003, J MEMBRANE SCI, V226, P159	61	61
29.	753	Liang HP, 2004, ANGEW CHEM INT ED ENGL, V43, P1540	87	87
30.	755	Tang H, 2004, CARBON, V42, P191	59	60
31.	874	Liu ZL, 2004, LANGMUIR, V20, P181	66	75
32.	899	Wang C, 2004, NANO LETT, V4, P345	70	110
33.	902	Shao ZG, 2004, J MEMBR SCI, V229, P43	50	50
34.	906	Zhou WJ, 2004, J POWER SOURCES, V126, P16	44	44
35.	909	Chan KY, 2004, J MATER CHEM, V14, P505	65	66
36.	910	Lu GQ, 2004, ELECTROCHIM ACTA, V49, P821	47	70
37.	934	Li WZ, 2004, ELECTROCHIM ACTA, V49, P1045	59	60
38.	999	Gil M, 2004, J MEMBR SCI, V234, P75	61	61
39.	1012	Zhou WJ, 2004, J POWER SOURCES, V131, P217	40	40
40.	1059	He ZB, 2004, MATER CHEM PHYS, V85, P396	49	49
41.	1188	Lamy C, 2004, ELECTROCHIM ACTA, V49, P3901	54	65
42.	1199	Hickner MA, 2004, CHEM REV, V104, P4587	94	229
43.	1201	Wang CY, 2004, CHEM REV, V104, P4727	49	112
44.	1207	He ZB, 2004, DIAMOND RELATED MATER, V13, P1764	48	48
45.	1289	Guo DJ, 2004, J ELECTROANAL CHEM, V573, P197	40	40
46.	1355	Xing YC, 2004, J PHYS CHEM B, V108, P19255	59	73
47.	1359	Girishkumar G, 2004, J PHYS CHEM B, V108, P19960	43	61
48.	1531	Yang H, 2005, J POWER SOURCES, V139, P79	43	43
49.	1655	Gasteiger HA, 2005, APPL CATAL B–ENVIRONMENTAL, V56, P9	54	130
50.	2879	Liu HS, 2006, J POWER SOURCES, V155, P95	45	52

Figure 4. Historiograph of fuel-cell research in China based on local citation scores. Nodes: 50, Links: 69 LCS, top 50; Min: 38, Max: 177 (LCS scaled).

single-wall carbon nanotube film on a glassy carbon electrode. This paper has been cited over 300 times.

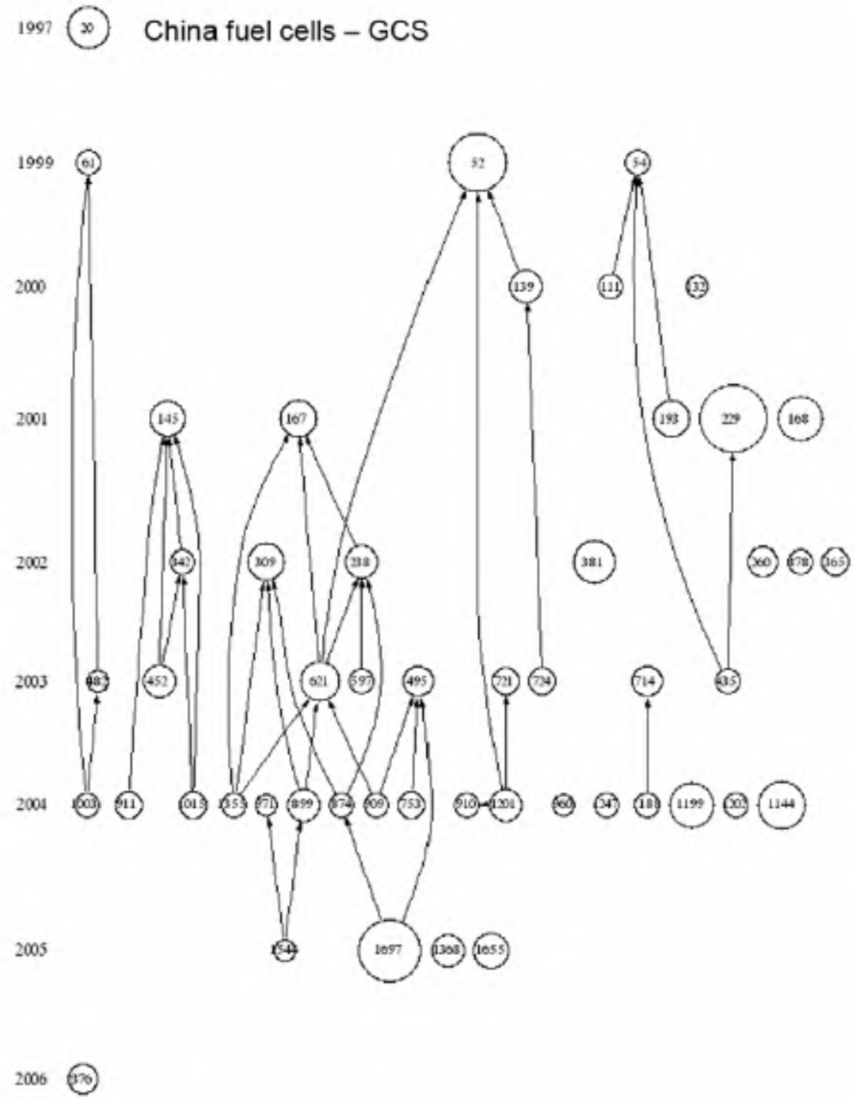
Shukla's work in fuel cells

In the LCS historiograph of India, 24 of the 50 papers are from India and in 14 of them A. K. Shukla is an author. In view of the prominent role played by Shukla in fuel cell research in India, we constructed historiographs (not shown here) based on his 55 papers which were cited 1343 times. The HistCite data consisted of 943 records and 17,322 cited references. Shukla's main interest is direct methanol oxidation and measurement of performance of single cells. The prominent nodes in the GCS historiograph are papers by Roger Parsons (1988), Ravikumar and Shukla (1996), Hamnett (1997), Wasmus and Kuver (1999) and Gotz (1998). The prominent nodes in the LCS historiograph are Parsons (1988), Shukla (1994), Arico (1994), Shukla (1995), Shukla (1995), Ravikumar (1996) Arico (1996) and Shukla (1999). In the LCS historiograph constructed from the Shukla fuel cell collection, 16 of the thirty papers were authored by Shukla. In contrast, in the GCS-based historiograph, only one paper was authored by Shukla. Also, in all these papers by Shukla we find that LCS and GCS were the same, indicating that virtually the entire influence of Shukla's work remains within the domain of fuel-cell research. We notice a similar trend in the nanoscience work of C. N. R. Rao (unpublished results). In both cases we found that there is a considerable difference between the LCS and GCS of papers by other prominent researchers which appear in the Indian collection of both fuel cell research and nano research.

Shukla has collaborated with 68 co-authors from 17 institutions spread over six countries. Five of his co-authors have collaborated with Shukla in seven or more papers, and eight scientists have co-authored at least in five papers with Shukla. Shukla has published his fuel-cell papers mostly in the mainstream journals: *Journal of Power Sources* (18), *Applied Electrochemistry* (9), and *Journal Electroanalytical Chemistry* and *Journal of the Electrochemistry Society* (four each). Seven of the 55 papers of Shukla have been cited 50 times or more often; 11 of them 40 times or more 17 of them 30 times or more, and 25 of them 20 times or more. Shukla's *h*-index for fuel-cell research is 23.

Historiographs for fuel-cell research in China

Figures 4 and 5 are the historiographs constructed from the fuel cells China collection consisting of 6216 records and 110,479 cited references. Figure 4 is based on LCS and Figure 5 is based on GCS. In both these, the first key



			LCS	GCS
1.	20	Radovic LR, 1997, CHEM PHYS CARBON, V25, P243	9	205
2.	52	Wasmus S, 1999, J ELECTROANAL CHEM, V461, P14	143	359
3.	54	Tu HY, 1999, SOLID STATE IONICS, V117, P277	74	73
4.	61	Cheng XL, 1999, J POWER SOURCES, V79, P75	68	68
5.	111	Matsuzaki Y, 2000, SOLID STATE IONICS, V132, P261	14	69
6.	132	Schoonman J, 2000, SOLID STATE IONICS, V135, P5	4	61
7.	139	Carrette L, 2000, CHEMPHYSCHEM, V1, P162	43	109
8.	145	Cheng HM, 2001, CARBON, V39, P1447	140	140
9.	167	Bessel CA, 2001, J PHYS CHEM B, V105, P1115	98	154
10.	168	Feng SH, 2001, ACCOUNT CHEM RES, V34, P239	1	214
11.	193	Pena MA, 2001, CHEM REV, V101, P1981	11	158
12.	229	Steele BCH, 2001, NATURE, V414, P345	141	484
13.	238	Li WZ, 2002, CARBON, V40, P791	109	109
14.	260	Hirscher M, 2002, J ALLOYS COMPOUNDS, V330, P654	18	100
15.	309	Liu ZL, 2002, LANGMUIR, V18, P4054	104	145
16.	342	Ma RZ, 2002, J AM CHEM SOC, V124, P7672	8	75
17.	365	Jusys Z, 2002, ELECTROCHIM ACTA, V47, P3693	31	79
18.	378	Dimitrova P, 2002, J ELECTROANAL CHEM, V532, P75	44	75
19.	381	Tian ZQ, 2002, J PHYS CHEM B, V106, P9463	20	205

(*Contd*)

20.	435	Brandon NP, 2003, ANNU REV MATER RES, V33, P183	31	72
21.	452	Rao CNR, 2003, DALTON TRANS, P1	0	119
22.	482	Qi ZG, 2003, J POWER SOURCES, V113, P37	33	62
23.	495	Zhang X, 2003, CHEM MATER, V15, P451	99	100
24.	597	Sherigara BS, 2003, ELECTROANALYSIS, V15, P753	6	65
25.	621	Li WZ, 2003, J PHYS CHEM B, V107, P6292	177	177
26.	714	Zhou WJ, 2003, APPL CATAL B–ENVIRONMENTAL, V46, P273	101	101
27.	721	Tuber K, 2003, J POWER SOURCES, V124, P403	34	78
28.	724	Haile SM, 2003, ACTA MATER, V51, P5981	27	78
29.	753	Liang HP, 2004, ANGEW CHEM INT ED ENGL, V43, P1540	87	87
30.	874	Liu ZL, 2004, LANGMUIR, V20, P181	66	75
31.	899	Wang C, 2004, NANO LETT, V4, P345	70	110
32.	909	Chan KY, 2004, J MATER CHEM, V14, P505	65	66
33.	910	Lu GQ, 2004, ELECTROCHIM ACTA, V49, P821	47	70
34.	911	Ichikawa T, 2004, J ALLOYS COMPOUNDS, V365, P271	3	87
35.	960	Gedanken A, 2004, ULTRASOUND SONOCHEM, V11, P47	1	62
36.	971	Xu Y, 2004, J AM CHEM SOC, V126, P4717	11	62
37.	1003	Litster S, 2004, J POWER SOURCES, V130, P61	33	73
38.	1015	Seayad AM, 2004, ADV MATER, V16, P765	10	80
39.	1144	Cushing BL, 2004, CHEM REV, V104, P3893	10	255
40.	1188	Lamy C, 2004, ELECTROCHIM ACTA, V49, P3901	54	65
41.	1199	Hickner MA, 2004, CHEM REV, V104, P4587	94	229
42.	1201	Wang CY, 2004, CHEM REV, V104, P4727	49	112
43.	1202	Adler SB, 2004, CHEM REV, V104, P4791	22	68
44.	1247	Kharton VV, 2004, SOLID STATE IONICS, V174, P135	14	72
45.	1355	Xing YC, 2004, J PHYS CHEM B, V108, P19255	59	73
46.	1368	Astruc D, 2005, ANGEW CHEM INT ED ENGL, V44, P7852	4	121
47.	1544	Fernandez JL, 2005, J AM CHEM SOC, V127, P357	22	62
48.	1655	Gasteiger HA, 2005, APPL CATAL B–ENVIRONMENTAL, V56, P9	54	130
49.	1697	Burda C, 2005, CHEM REV, V105, P1025	27	434
50.	2376	Hashmi ASK, 2006, ANGEW CHEM INT ED ENGL, V45, P7896	3	105

Figure 5. Historiograph of fuel cells research in China based on global citation scores. Nodes: 50, Links: 38 GCS, top 50; Min: 61, Max: 484 (GCS scaled).

paper is the 1999 review on DMFC by Wasmus (paper no. 52). In both these figures, the following nodes are found to be prominent: 52, 167, 238, 309 and 621. In addition, node numbers 54, 145 and 495 also seem to be important from the GCS historiograph.

In paper no. 167, Bessel (2001) demonstrated the superiority of carbon nanofibres over Vulcan-72 carbon as support for platinum-loaded electrodes for direct methanol oxidation, as they led to proper crystallographic orientation of the active platinum crystallites.

In paper no. 238, Li *et al*. report that a highly dispersed platinum nanoparticle catalyst supported on carbon nanotubes, employed as the cathode for a DMFC, led to higher activity of the oxygen reduction reaction and better performance of the DMFC, compared to the catalysts supported on commercial carbons.

In paper no. 309, Liu *et al*. (2002) demonstrated the better performance of platinum deposited on multiwall carbon nanotube by electroless method in direct methanol oxidation.

Paper no. 495 is again on methanol oxidation, this time by a bimetallic catalyst. Zhang (2003) showed that Pt–Ru nanoparticles supported on a carbon electrode possessed high dispersion and high catalytic activity for methanol oxidation at room temperature.

In paper no. 621, Li (2003) showed that platinum crystallites formed by reduction with ethylene glycol and formaldehyde on multiwall carbon nanotubes were more active than the system based on Vulcan XC-72. This difference in catalytic performance was attributed to a greater dispersion of the supported platinum particles on multi-wall nanotube support.

Tu *et al*. (paper no. 54, 1999) showed that perovskite oxides based on lanthanum, strontium, cobalt and iron showed the best catalytic activity for oxygen reduction.

In paper no. 145, Cheng (2001) made an overview of the potential of carbon nanotubes for hydrogen storage from both experimental and theoretical points of view.

Knowledge flow in the region

While much of the thrust in India is on direct methanol fuel cells, the thrust in China is mainly on the development of metallic nanoparticle catalysts supported on carbon nanotube electrodes. As the catalysts used in fuel cells involve expensive noble metals like platinum and ruthenium, it is important to reduce the amount of the metal used and yet increase the catalytic efficiency in order to make fuel cells cost-effective and competitive to petroleum and other sources of energy. Indeed, the goal is to reduce the loading of noble metals by an order of magnitude and to enhance preferential orientation of crystallites.

An analysis of the country of origin of the highly cited papers that find a place in the historiographs of different countries can give an idea of cross-national knowledge flows. The LCS historiograph of India has 24 papers (out of 50) from India, five from South Korea, four from China, one from Japan, seven from USA, seven from England and six from Germany. Remember that some of these nodes may also have authors from other countries, as there is much international collaboration in this field. The GCS historiograph of India has eight nodes from China, three from India, two each from South Korea and Japan, 18 from USA, and five each from England and Germany. Clearly, the work carried out in the West continues to be of great relevance to fuel-cell research in India as seen from the number of nodes from the West in the GCS historiograph. It is also seen that the work carried out in China is of great relevance to Indian researchers, as evidenced by the eight nodes from China as against three from India in the GCS historiograph.

In the LCS historiograph of fuel-cell research in China, 32 of the 50 highly cited papers are from China, 11 from USA, four from Germany, two from Japan and one from India. In the GCS historiograph for China, 12 of the 50 nodes are from China, 15 from USA, eight from Germany, three from Japan, two from England and one from India. Clearly, work done in India has limited influence on work carried out in China. Work done in the West continues to be of great relevance to Chinese research in this area.

With the data presented here we are unable to evaluate the flow of knowledge from Japan. For one thing, we have not constructed the LCS and GCS historiographs for Japanese fuel-cell research. For another, in this field Japan is more into patenting than into publishing in research journals. We have not so far examined the patent literature and its use in such studies.

1. The hydrogen revolution: An evaluation of patent trends in the fuel cell industry. A White Paper, Thomson Scientific Ltd, Philadelphia, October 2004.
2. Garfield, G., Soren, W. P. and Stock, W. G., HistCite: A software tool for informetric analysis of citation linkage. *Information*, 2006, **57**, 391–400. Also see www.histcite.com
3. Pilkington, A., Technology portfolio alignment as an indicator of commercialization: An investigation of fuel cell patenting. *Technovation*, 2004, **24**, 761–771.
4. Pilkington, A. and Liston-Heyes, C., Inventive concentration: An analysis of fuel cell patents. *Sci. Public Policy*, 2004, **31**, 15–25.
5. Pilkington, A., Key inventors and key firms in fuel cell development: A patent analysis. Research Paper Series, School of Management, Royal Holloway, University of London, #SoM-0605, 2006, p. 17.
6. Hassan, E., The evolution of knowledge structure of fuel cells. *Scientometrics*, 2005, **62**, 223–238.
7. Butler, J., Patent Review Q3, *Fuel Cell Today*, 2007; http://www.fuelcelltoday.com/online/survey?survey=2007-11%2F2007-Q3-Patent-Review-Free
8. Arunachalam, S., Is science in India on the decline? *Curr. Sci.*, 2002, **83**, 107–108.
9. Arunachalam, S., *Curr. Sci.* 2008 (submitted).

ACKNOWLEDGEMENTS. We are grateful to Dr Eugene Garfield for providing the HistCite software and to Soren Paris, who helped one of us to learn how to use it. We are indebted to Prof. A. K. Shukla for valuable discussion and Thulasi Krishna Rao and Subbiah Gunasekaran for help in data collection. Part of the work was carried out when S.A. was visiting the National Institute of Advanced Studies, Bangalore, as part of a project funded by the US Office of Naval Research. S.A. is grateful to Prof. N. V. Joshi, IISc for inviting him to be a visiting professor at the National Centre for Science Information, IISc, Bangalore.

Received 2 March 2008; accepted 12 May 2008