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

Subbiah Arunachalam1,* and B. Viswanathan2

1M.S. Swaminathan Research Foundation, Chennai 600 113, India
2National 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 benefited 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.

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.

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. Alan Pilkington used patent data to identify main players, both inventors and firms, active in fuel-cell innovation. Emmanuel Hassan looked at the evolution of the knowledge structure of fuel cells using both patent and publication data. Jonathan Butler surveyed current developments in fuel cells in India.

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

<table>
<thead>
<tr>
<th>Year</th>
<th>World</th>
<th>India</th>
<th>China</th>
<th>South Korea</th>
<th>Japan</th>
<th>Taiwan</th>
<th>Singapore</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>215</td>
<td>8</td>
<td>1</td>
<td>2</td>
<td>51</td>
<td>1</td>
<td></td>
<td>61</td>
</tr>
<tr>
<td>1994</td>
<td>302</td>
<td>6</td>
<td>1</td>
<td>5</td>
<td>73</td>
<td>4</td>
<td></td>
<td>61</td>
</tr>
<tr>
<td>1995</td>
<td>302</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td>73</td>
<td>1</td>
<td></td>
<td>67</td>
</tr>
<tr>
<td>1996</td>
<td>459</td>
<td>9</td>
<td>6</td>
<td>17</td>
<td>115</td>
<td>4</td>
<td></td>
<td>99</td>
</tr>
<tr>
<td>1997</td>
<td>400</td>
<td>11</td>
<td>5</td>
<td>10</td>
<td>79</td>
<td>7</td>
<td></td>
<td>79</td>
</tr>
<tr>
<td>1998</td>
<td>556</td>
<td>13</td>
<td>16</td>
<td>21</td>
<td>92</td>
<td>3</td>
<td>1</td>
<td>113</td>
</tr>
<tr>
<td>1999</td>
<td>599</td>
<td>23</td>
<td>29</td>
<td>21</td>
<td>101</td>
<td>3</td>
<td>1</td>
<td>113</td>
</tr>
<tr>
<td>2000</td>
<td>775</td>
<td>13</td>
<td>27</td>
<td>32</td>
<td>126</td>
<td>7</td>
<td>2</td>
<td>142</td>
</tr>
<tr>
<td>2001</td>
<td>859</td>
<td>23</td>
<td>46</td>
<td>44</td>
<td>112</td>
<td>3</td>
<td>6</td>
<td>190</td>
</tr>
<tr>
<td>2002</td>
<td>1164</td>
<td>28</td>
<td>90</td>
<td>67</td>
<td>176</td>
<td>11</td>
<td>14</td>
<td>303</td>
</tr>
<tr>
<td>2003</td>
<td>1437</td>
<td>26</td>
<td>130</td>
<td>81</td>
<td>208</td>
<td>21</td>
<td>24</td>
<td>392</td>
</tr>
<tr>
<td>2004</td>
<td>2126</td>
<td>52</td>
<td>221</td>
<td>149</td>
<td>293</td>
<td>36</td>
<td>34</td>
<td>601</td>
</tr>
<tr>
<td>2005</td>
<td>2469</td>
<td>55</td>
<td>318</td>
<td>129</td>
<td>316</td>
<td>66</td>
<td>42</td>
<td>705</td>
</tr>
<tr>
<td>2006</td>
<td>3502</td>
<td>85</td>
<td>561</td>
<td>275</td>
<td>372</td>
<td>144</td>
<td>58</td>
<td>820</td>
</tr>
<tr>
<td>2007*</td>
<td>3270*</td>
<td>97*</td>
<td>591*</td>
<td>211*</td>
<td>324*</td>
<td>124*</td>
<td>52*</td>
<td>772*</td>
</tr>
<tr>
<td>1983–2007</td>
<td>19,468</td>
<td>477</td>
<td>2048</td>
<td>1072</td>
<td>2777</td>
<td>458</td>
<td>236</td>
<td>4899</td>
</tr>
</tbody>
</table>

*Data for 2007 not complete.

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

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 country of Singapore has a publication output comparable to that of India.

Arunachalam 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.

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 (IF’s). 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
RESEARCH ARTICLES

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

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

*Includes editorial, correction and other types of documents.

Table 3. Distribution of publications on fuel cells by journal

<table>
<thead>
<tr>
<th>Journal</th>
<th>IF* 2006</th>
<th>India</th>
<th>China</th>
<th>South Korea</th>
<th>Japan</th>
<th>Taiwan</th>
<th>Singapore</th>
<th>USA</th>
<th>World</th>
</tr>
</thead>
<tbody>
<tr>
<td>J. Power Sources</td>
<td>3.521</td>
<td>81</td>
<td>346</td>
<td>288</td>
<td>257</td>
<td>157</td>
<td>49</td>
<td>789</td>
<td>3073</td>
</tr>
<tr>
<td>Solid State Ionics</td>
<td>2.190</td>
<td>14</td>
<td>62</td>
<td>37</td>
<td>306</td>
<td>3</td>
<td>16</td>
<td>189</td>
<td>1116</td>
</tr>
<tr>
<td>Electrochim. Acta</td>
<td>2.955</td>
<td>13</td>
<td>100</td>
<td>67</td>
<td>90</td>
<td>10</td>
<td>9</td>
<td>141</td>
<td>741</td>
</tr>
<tr>
<td>Int. J. Hydrogen Energy</td>
<td>2.612</td>
<td>12</td>
<td>39</td>
<td>22</td>
<td>46</td>
<td>15</td>
<td>6</td>
<td>153</td>
<td>549</td>
</tr>
<tr>
<td>J. Appl. Electrochem.</td>
<td>1.409</td>
<td>12</td>
<td>18</td>
<td>9</td>
<td>32</td>
<td>3</td>
<td>5</td>
<td>38</td>
<td>306</td>
</tr>
<tr>
<td>J. Eletronal. Chem.</td>
<td>2.339</td>
<td>8</td>
<td>20</td>
<td>10</td>
<td>43</td>
<td>2</td>
<td>2</td>
<td>44</td>
<td>261</td>
</tr>
<tr>
<td>J. Mater. Sci.</td>
<td>0.999</td>
<td>8</td>
<td>13</td>
<td>10</td>
<td>14</td>
<td>3</td>
<td>3</td>
<td>18</td>
<td>134</td>
</tr>
<tr>
<td>J. Electrochem. Soc.</td>
<td>2.387</td>
<td>8</td>
<td>42</td>
<td>45</td>
<td>306</td>
<td>15</td>
<td>19</td>
<td>704</td>
<td>1472</td>
</tr>
<tr>
<td>Abstr. Papers of the Am. Chem. Soc.</td>
<td>–</td>
<td>7</td>
<td>12</td>
<td>10</td>
<td>13</td>
<td>2</td>
<td>1</td>
<td>348</td>
<td>420</td>
</tr>
<tr>
<td>J. Membr. Sci.</td>
<td>3.442</td>
<td>7</td>
<td>56</td>
<td>36</td>
<td>23</td>
<td>13</td>
<td>4</td>
<td>52</td>
<td>280</td>
</tr>
<tr>
<td>Mater. Chem. Phys.</td>
<td>1.657</td>
<td>7</td>
<td>15</td>
<td>15</td>
<td>–</td>
<td>8</td>
<td>–</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Appl. Catal. A</td>
<td>2.630</td>
<td>7</td>
<td>14</td>
<td>7</td>
<td>41</td>
<td>3</td>
<td>3</td>
<td>42</td>
<td>194</td>
</tr>
<tr>
<td>Ceramics Inter.</td>
<td>1.128</td>
<td>6</td>
<td>12</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>J. Am. Ceramic Soc.</td>
<td>1.396</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>11</td>
<td>3</td>
<td>–</td>
<td>20</td>
<td>71</td>
</tr>
<tr>
<td>Catal. Lett.</td>
<td>1.772</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td>11</td>
<td>3</td>
<td>–</td>
<td>53</td>
<td>138</td>
</tr>
<tr>
<td>Mater. Lett.</td>
<td>1.353</td>
<td>5</td>
<td>22</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2</td>
<td>7</td>
<td>57</td>
</tr>
<tr>
<td>Electrochem. Solid State Lett.</td>
<td>2.009</td>
<td>4</td>
<td>33</td>
<td>–</td>
<td>63</td>
<td>3</td>
<td>10</td>
<td>135</td>
<td>299</td>
</tr>
<tr>
<td>J. Alloys Compounds</td>
<td>1.250</td>
<td>4</td>
<td>42</td>
<td>7</td>
<td>35</td>
<td>4</td>
<td>2</td>
<td>19</td>
<td>131</td>
</tr>
<tr>
<td>Electrochem. Commun.</td>
<td>3.484</td>
<td>3</td>
<td>82</td>
<td>18</td>
<td>35</td>
<td>5</td>
<td>12</td>
<td>33</td>
<td>271</td>
</tr>
<tr>
<td>Kor. J. Chem. Eng.</td>
<td>0.808</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Macromol. Res.</td>
<td>1.166</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>J. Ind. &amp; Eng. Chem.</td>
<td>0.957</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Bull. Korean Chem. Soc.</td>
<td>0.950</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>J. Microbiol. Biotechnol.</td>
<td>2.037</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Catal. Today</td>
<td>2.148</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>1</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>J. Electroceramics</td>
<td>1.157</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J. New Mater. for Electrochem. Syst.</td>
<td>1.095</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chem. J. Chinese Univ.</td>
<td>0.724</td>
<td></td>
<td></td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acta Physico-Chimica Sinica</td>
<td>–</td>
<td></td>
<td>53</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chinese J. Catal.</td>
<td>0.659</td>
<td></td>
<td>51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rare Metal Mater. Eng.</td>
<td>0.251</td>
<td></td>
<td>51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acta Chim. Sin.</td>
<td>0.783</td>
<td></td>
<td>37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chinese J. Inorg. Chem.</td>
<td>0.583</td>
<td></td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J. Inorg. Mater.</td>
<td>0.377</td>
<td></td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prog. Chem.</td>
<td>0.520</td>
<td></td>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J. Rare Earths</td>
<td>0.368</td>
<td></td>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>3.884</td>
<td>21</td>
<td></td>
<td>2</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rare Metals</td>
<td>0.378</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Denki Kagaku</td>
<td>–</td>
<td></td>
<td>3</td>
<td>192</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrochemistry</td>
<td>0.574</td>
<td></td>
<td>157</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J. Ceram. Soc. Jpn.</td>
<td>0.997</td>
<td></td>
<td>44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nippon Kagaku Kaishi</td>
<td>–</td>
<td></td>
<td>37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J. Chem. Eng. Japan</td>
<td>0.594</td>
<td></td>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kagaku Kagaku Bombunshu</td>
<td>0.294</td>
<td></td>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chem. Lett.</td>
<td>1.734</td>
<td></td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chem. Commun.</td>
<td>4.520</td>
<td>21</td>
<td>3</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bull. Electrochem.</td>
<td>0.259</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indian J. Chem., Soc. A</td>
<td>0.631</td>
<td></td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bull. Mater. Sci.</td>
<td>0.522</td>
<td></td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J. Solid State Chem.</td>
<td>2.107</td>
<td></td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ionics</td>
<td>0.305</td>
<td></td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 predominately 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
RESEARCH ARTICLES

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 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. Dathathreya (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
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th>LCS</th>
<th>GCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>17</td>
<td>PARSONS R, 1988, J ELECTROANAL CHEM, V257, P9</td>
<td>72</td>
<td>637</td>
</tr>
<tr>
<td>2.</td>
<td>67</td>
<td>SHUKLA AK, 1994, J ELECTROCHEM SOC, V141, P1517</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>4.</td>
<td>71</td>
<td>KUMAR GS, 1995, ELECTROCHIM ACTA, V40, P285</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>5.</td>
<td>77</td>
<td>SHUKLA AK, 1995, J APPL ELECTROCHEM, V25, P528</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>6.</td>
<td>78</td>
<td>ARICO AS, 1995, J POWER SOURCES, V55, P159</td>
<td>43</td>
<td>76</td>
</tr>
<tr>
<td>7.</td>
<td>98</td>
<td>Ravikumar MK, 1996, J ELECTROCHEM SOC, V143, P2601</td>
<td>169</td>
<td>169</td>
</tr>
<tr>
<td>8.</td>
<td>106</td>
<td>Quadakkers WJ, 1996, SOLID STATE IONICS, V91, P55</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>9.</td>
<td>114</td>
<td>Arico AS, 1996, J ELECTROCHEM SOC, V143, P2950</td>
<td>44</td>
<td>102</td>
</tr>
<tr>
<td>15.</td>
<td>175</td>
<td>Reeve RW, 1998, J ELECTROCHEM SOC, V145, P3463</td>
<td>37</td>
<td>68</td>
</tr>
<tr>
<td>16.</td>
<td>182</td>
<td>Shukla AK, 1998, J POWER SOURCES, V76, P54</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>17.</td>
<td>190</td>
<td>Shukla AK, 1999, APPL SURF SCI, V137, P20</td>
<td>41</td>
<td>41</td>
</tr>
</tbody>
</table>

(Contd)
RESEARCH ARTICLES

25. Ren XM, 2000, J ELECTROCHEM SOC, V147, P466
27. Jordan LR, 2000, J APPL ELECTROCHEM, V30, P641
28. Luo HX, 2001, ANAL CHEM, V73, P915
31. Shukla AK, 2001, J ELECTROANAL CHEM, V504, P111
32. Steigerwald ES, 2001, J PHYS CHEM B, V105, P8097
33. Li WZ, 2002, CARBON, V40, P791
34. Steigerwald ES, 2002, J PHYS CHEM B, V106, P760
36. Shukla AK, 2002, ELECTROCHEM ACTA, V47, P3001
38. Rajesh B, 2002, FUEL, V81, P2177
39. Antolini E, 2003, MATER CHEM PHYS, V78, P563
40. Rajesh B, 2003, J PHYS CHEM B, V107, P2701
41. Li WZ, 2003, J PHYS CHEM B, V107, P6292
42. Smitha B, 2003, J MEMBR SCI, V225, P63
43. Ratnasamy P, 2004, J CATAL, V221, P455
46. Shukla AK, 2004, J ELECTROANAL CHEM, V563, P181
48. Smitha B, 2004, MACROMOLECULES, V37, P2233
49. Hickner MA, 2004, CHEM REV, V104, P4587
50. Smitha B, 2005, J MEMBRANE SCI, V259, P10

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 cited 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 Parsons paper was cited by papers 145 (Hammett), 197 (Wasmus), 231 (McNicol), 315 (Carrette) and 616 (Antolini). In the LCS historiograph, the paper was cited by 145 (Hammett), 190 (Shukla), 197 (Wasmus), 251 (Arico) and 616 (Antolini).

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

The prominent nodes in the LCS historiograph are 67 (Shukla, ten links), 68 (Arico, seven links), 98 (Ravikumar,
methyl alcohol 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. Hammett 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
2. Wasmus S, 1999, J ELECTROANAL CHEM, V461, P14
3. Tu HY, 1999, SOLID STATE IONICS, V117, P277
5. Hsing IM, 2000, CHEM ENG SCI, V55, P4209
6. Carrette L, 2000, CHEM PHYS CHEM, V1, P162
10. Li WZ, 2002, CARBON, V40, P791
12. Lu ZL, 2002, LANGMUIR, V18, P4054
15. Shao ZG, 2002, J MEMBRANE SCI, V210, P147
18. Li L, 2003, MATER LETT, V57, P1406

(Contd)
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 (1996), Rajkumar (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
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 petro-
leum 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 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 three 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.


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 Thulasii 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