1. Fuel Cells- An Appealing Energy Conversion Technology for Space Power, Power Generation/Cogeneration, Transportation and Portable Power Applications

Since the birth of the NASA and Russian Space Programs in the late 1950s, the topic of fuel cells has been an appealing energy conversion technology, mainly because of its attractive characteristics of (i) direct conversion of chemical energy to electrical energy with theoretical efficiencies as high as 80% and (ii) ultra-low or zero level emissions of air pollutants. A multitude of applications have been proposed from the time the solid polymer electrolyte (SPEFC, currently more commonly referred to as PEMFCs) and alkaline fuel cells (AFC) found their applications, as auxiliary power sources in space vehicles. The proposed terrestrial applications include (i) power generation/ cogeneration (ii) transportation (iii) portable power sources and (iv) defense power. The thought-provoking question is "why has it taken more than 40 years for fuel cells to find these applications?" .The technologies arising from Electronics Era since the 1960s and the Information Technology Era since the 1990s had taken considerably lesser times to find applications. The present paper addresses the above question and deals with the topics presented briefly in the following sections.

2. Status of Fuel Cell Technologies and Demonstrated/ Potential Applications

Though all types of fuel cells were invented in the 19^{th} century and early part of the 20^{th} century, there have been quantum jumps in the technology development of the different types of fuel cells since the space program in the 1950s, the Energy Crisis in 1973 and the Environmental Legislations in California and other states since 1985. Among the different types of fuel cells, PEMFCs and AFCs were rapidly developed and found their applications in space vehicles. Every space flight has had fuel cell power sources-PEMFC in the Gemini flights and AFC in all Apollo and Space Shuttle flights. Because of the high levels of performance, achieved in PEMFCs, there has been great enthusiasm for developing PEMFCs, primarily for the transportation application and secondarily for cogeneration, residential power (electricity and heat) and portable power (campers, auxiliary power, video cameras, laptop computers, cell phones etc.). Power plants/ power sources, delivering power levels ranging from a few watts to about 250 kW, have been demonstrated. The direct methanol fuel cell (DMFC) has been found to be attractive for the portable power applications due to the high energy density of methanol and using the PEMFC technology, demonstration units for some of the above-mentioned applications have been developed. Of all fuel cell technologies, the phosphoric acid fuel cell technology was the first to be commercialized (UTC Fuel Cells) for terrestrial applications-200 kW power plants for on-site integrated energy systems. Efficiencies of over 80% for conversion of chemical energy of the fuel (natural gas) to electrical and heat energy have been achieved. During the last three to five years the molten carbonate fuel cell (MCFC) power plants have been scaled up to levels in the range of 250 kW-1 MW by Fuel Cell Energy in the USA, Ansaldo in Italy and/or IHI in Japan; these power plants integrated with combined cycle gas turbines in hybrid can have efficiencies of over 60%. The solid oxide fuel cell (SOFC), a 2-phase system and not a 3-phase system as in the case of all other types of fuel cells, has several advantages. Siemens-Westinghouse has greatly advanced in this technology and power plants with a designed power output of 100 kW have been demonstrated. Just as in the case of MCFCs, these can also be incorporated in a hybrid system with gas turbines, to yield efficiencies for energy conversion over 65%.

3. Assessment of Fuel Cells vs. Competing Technologies

Fuel cells have tough competition from gas turbines for power generation/cogeneration applications; for the transportation application, the competition is from IC or diesel engines and more so from hybrid systems consisting of these power sources and batteries. For the portable power applications, the competition is from advanced rechargeable nickel/metal hydride and lithium ion batteries. The advantages of fuel cells are the lower or zero emissions and fewer moving parts.

4.Techno-Economic Challenges Faced by Fuel Cell in Entering the Commercial Sector

Bringing down the cost of fuel cell power plants by factors ranging from about 5 to 100 is the major challenge for fuel cells to compete with the advanced thermal power plants for the power generation/cogeneration and transportation applications. A second challenge is that compared to the conventional systems, the fuel cell power plants have a considerably shorter lifetime; this is because of the potentially high corrosive environment, particularly near the cathode. Thirdly, is the problem of the selection of the fuel and the required fuel processing. While natural gas is the ideal fuel and the products of steam reforming can be readily fed into the MCFCs and SOFCs, further fuel processing (two stage water gas shift reaction) is necessary for PAFCs; a third sub-system (preferential oxidizer) is necessary for a PEMFC because of its ultra-low tolerance level of 10 ppm (<10 ppm at 80^0 C) and an even more complex for AFCs because the CO_2 has to be removed and pristine hydrogen is necessary. DMFCs still face the challenges of low electrocatalytic activity for electrooxidation of methanol and crossover of methanol from anode to cathode, which reduces the columbic efficiency of the DMFC and slows down the oxygen reduction kinetics. Apart from these, there are also problems of thermal and water management in the low temperature fuel cells (PEMFCs, DMFCs and AFCs).