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Recycling and life cycle assessment of fuel cell materials

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12.1 Introduction

Fuel cell technologies are expected to substantially reduce consumption of oil and emissions of pollutants such as greenhouse gases as compared with conventional combustion-based power generation technologies. Fuel cell technologies have the additional advantages of high efficiency, at times including the ability to take advantage of cogeneration or hybrid applications. While much has been done to develop fuel cell technology and emphasis has been placed on the environmental benefits of its use, less emphasis has been placed on material sources and hardware materials recovery.

As fuel cells move from laboratory and/or pilot plant settings to wide-scale deployment, an opportunity exists to consider the environmental aspects of the hardware life cycle. Here, the 'life cycle' extends from material sources (acquisition from the earth) through recovery with Section 12.2 introducing the environmental aspects of fuel cell materials. Section 12.3 continues by defining hardware recovery to include collection, separation, and subsequently system or component reuse and remanufacturing, materials recycling, or energy recovery and describing issues for hardware disassembly and recycling process availability. Section 12.4 considers the role of materials selection and recovery in the life cycle fuel cell system improvements. Finally, future trends for fuel cells centered on voluntary and mandated recovery and the movement of life cycle considerations from computational research laboratories to design complete the discussion.

12.2 Environmental aspects of fuel cells

Fuel cells promise 'clean' energy generation. Here and by in large, 'clean' refers to negligible or substantially lower operating emissions when compared with combustion-based power generation technologies. However, lower operating emissions are only part of the story for fuel cells.

First, extending the definition of 'clean' to include **hardware recovery** means component reuse, remanufacturing, materials recycling and energy recovery are considered for fuel cell maintenance and retirement processes. For example, Plug Power[1], a manufacturer of distributed proton exchange membrane fuel cell (PEMFC) systems, employs a 'zero-to-landfill' (ZTL) principle during hardware design. The ZTL principle was developed at Xerox as a part of the Lakes program [Hotchkiss *et al.*, 2000] with the goal that every product, every component, and every material should be reused, remanufactured, or recycled after it reaches the end of its service life. Essentially, Plug Power designers seek the maximum use of reusable, remanufacturable, and recyclable components and ensure that these components can be separated from the system during maintenance activities or when equipment is retired.

Plug Power designers have applied the principles of ZTL in the development of PEMFC systems that are more than 85% recyclable or reusable by weight[2]. Further, the company has found that the application of zero-to-landfill principles fosters additional benefits in system assembly and during service activities. In fact, as a result of their zero-to-landfill initiatives, Plug Power has netted over US$ 1.4 million in cost savings by the end of 2006 [Elter and Cooper, 2007]. Also, Plug reserves the right to buy their system back at the end of its life, to ensure that the minimum materials reach a landfill.

However, for Plug Power and many others involved in the development and deployment of fuel cell systems, 'clean' has more recently come to include not only the consideration of operating emissions and hardware materials recycling, but also the consideration of fuel and hardware production, system maintenance, and in fact the full fuel cell life cycle. As in Fig. 12.1, the fuel cell 'life cycle' includes the acquisition of materials and fuels (e.g. mining and agricultural activities); the processing of materials and fuels; and fuel cell manufacturing, use, maintenance, remanufacturing, and retirement including the ultimate management of materials (e.g., recycling, landfilling, and incineration). Life cycle 'environmental aspects' include for example resource use (e.g. the use of energy, natural resources, and land) and contributions to impacts such as climate change, smog formation, and damage to human health.

The assessment of life cycle environmental aspects, including hardware recycling, is described by the International Organization for Standardization's (ISO) Life Cycle Assessment (LCA) series standards in the ISO14040 series. In the ISO LCA process, material and energy use and waste are estimated for each life cycle process and for the system as a whole (e.g. how much energy

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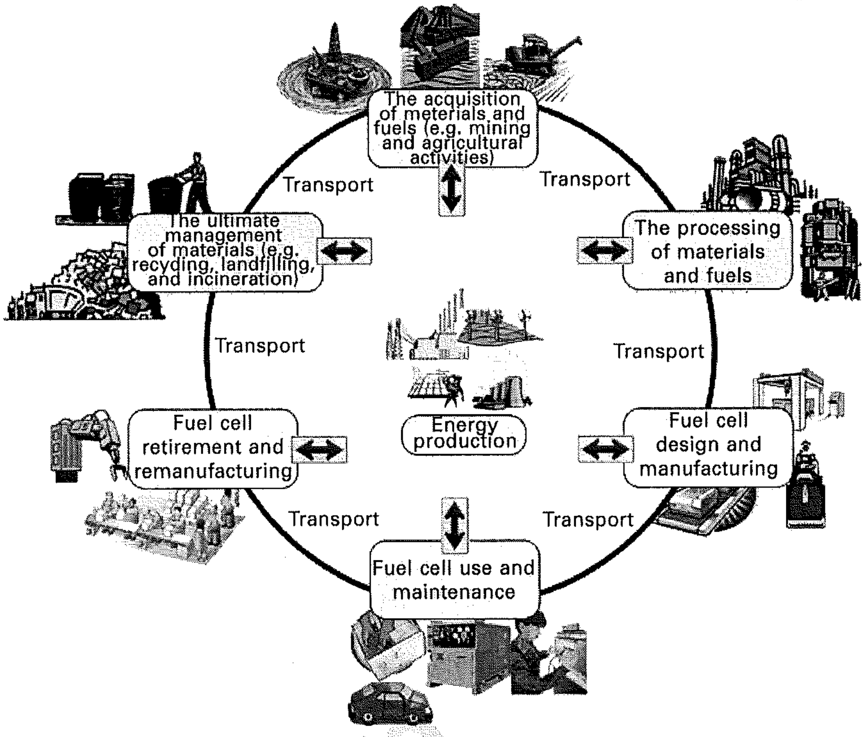
[1] See http://www.plugpower.com

[2] See http://www.plugpower.com/news/pdf/ACFJ6h2PH.pdf



12.1 Activities combine to form the fuel cell life cycle.

is consumed and carbon dioxide is emitted by processes throughout the life cycle). From this energy and materials inventory, the contribution of the life cycle to a variety of environmental aspects is estimated (e.g. how much material is recycled or how much life cycle air emissions contribute to global climate change). As fuel cells move from the laboratory to wide-scale use, knowing the potential life cycle contribution to environmental aspects provides valuable insights into the evaluation of design variants, in the comparison to other energy generation technologies, and in meeting corporate, community, and national goals.

12.3 Fuel cell hardware recycling

Fuel cell hardware recycling promises to be an important environmental aspect of mass-produced systems. In recovery, materials are collected and separated before being reused, remanufactured, recycled, or used for energy recovery, as follows:

- *Collection* moves hardware from the point-of-use to separation sites by truck, rail, barge, ocean freighter, and/or air transport. As in the case of

Plug Power, hardware manufacturers can coordinate fuel cell hardware collection from operating sites. When technologies are prevalent throughout a region, municipal collection systems can be developed, for example as pursuant to waste electronic directives.

- *Separation systems* first purge all fluids from hardware (from fuel tanks and processors) followed by hardware separation and sometimes chemical recovery. In hardware separation, subassemblies, components, or materials are divided into groups that are compatible for subsequent processes (e.g. metals that can be recycled together). Hardware separation systems, such as those operated by a municipality or a company, can be automated or manual. In automated systems, materials can undergo shredding followed by magnetic, shape, density, or visual-based separation systems. Bras [2005] for example notes that aluminum alloys, steel, and magnesium alloys are readily separated and recycled from shredder output. When volumes offer economies of scale, automated systems can also be based on robotic disassembly for hardware separation. Manual hardware separation is essentially disassembly and can use powered hand tools and often move materials between work stations using conveyors. Although manual systems can be more suited to hardware reuse and remanufacturing systems and can be more easily accept wide variations in hardware design, they require a relatively high level of skill to achieve reasonable disassembly rates. In addition, chemical recovery, including thermal, chemical, or electrochemical separation, can be used to access for example precious metals [Society of Automotive Engineers, 2003]. Following separation, materials are most often transported to recycling sites that manage specific types or classes of materials.
- *Reuse of components* tends to be preferred among hardware recycling options. Reuse refers to the directly use of components and subassemblies back into fuel cells without additional processing. The Society of Automotive Engineers [2003] notes that reuse depends on separability, the demand for reusable components in repair or replacement, component durability, the cost of new components, and the collection and distribution infrastructure. However, reuse is also hampered by design changes, as new features are incorporated into fuel cell systems old components become obsolete [Handley *et al.*, 2002; Cooper, 2003].
- *Remanufacturing* is the process of restoring components, e.g. by replacing worn or damaged parts, again for use back into fuel cells. Remanufacturing issues are similar to those faced in component reuse.
- *Recycling processes* subjects materials to a variety of transformations (e.g., heat treatments to remove contaminants or combine small parts) prior to re-entering the commodity market. The level of refinement is dependent upon the requirements of the receiving products. For some materials, recycling processes seek to prepare materials with physical

and chemical properties similar to their primary/unrecycled material counterparts (e.g. in metals recycling). For other materials, recycling targets lesser quality products (known as downcycling) and are used in new products often with less stringent material requirements (e.g. in plastics recycling, lower grade plastics are often produced from higher-grade plastics).

- *Energy recovery:* Often considered the least preferable recycling option, some components and materials are used for energy generation, such as in the incineration of plastics.

Given this process flow, fuel cell hardware 'recyclability' is dependent upon two things: (1) whether or not the recyclable components and materials can be separated from incompatible materials during maintenance operations and when the fuel cell system is retired and (2) whether or not recycling processes are readily available. Whereas separability is dependent upon fuel cell stack and balance-of-plant design, availability is a function of the state of the recycling infrastructure throughout the globe.

12.3.1 Recycling process availability

'Availability' for recovery in general refers to the prevalence of facilities that reuse, remanufacture, recycling, or convert to energy components and materials of interest. Infrastructures for fuel cell reuse and remanufacture are currently managed by individual companies like Plug Power. The success of recycling depends on the cost of retrieving and processing materials from products throughout an economy and, for each type of component and material, the relation to the price of a component or material made from primary (or unrecycled) materials. By far, metals currently offer the greatest availability and other fuel cell materials (single polymers, composites, insulation, reforming media, etc.) offer the greatest opportunity for improvement.

Starting with metals, Wernick and Themelis [1998] note that metals can be recycled nearly indefinitely. Unlike polymer plastics and composites, the properties of metals can theoretically (however, often not economically) be restored fully regardless of their chemical or physical form in a given component. Thus, metals used in fuel cell stacks and the balance-of-plant are recyclable at much higher rates than other materials. In fact, according to data from both the United States Geological Survey and the British Metals Recycling Association, recycling rates in their respective study regions are quite similar with lead recycling leading at ~75% (dominated by lead acid battery recycling), followed by iron and steel, aluminum, copper, and zinc recycling [Papp, 2005; Kumar *et al.*, 2007]. By mass, these metals can dominate fuel cell systems when considering both stacks and balance-of-plant and therefore offer substantial opportunity for fuel cell hardware recycling.

Of particular interest within the context of fuel cell metals recycling are steels, catalyst metals, and metals used in batteries (for energy storage in the balance-of-plant). First, steel recycling offers perhaps the easiest path to achieving a high percentage of the mass of any fuel cell system is recycled. This would apply, for example, to the housings of most stationary fuel cell systems (e.g. the standing enclosures around low-pressure systems and pressure vessels for high-pressure systems) as well as to interconnects, flow field plates, tie rods, piping, and heat exchangers in select designs.

Also dominant on a mass basis, metals in fuel cell system batteries may or may not offer an easy recycling option. If based on lead acid batteries (either conventional or valve regulated), wide-scale recycling can almost be guaranteed. In fact, the lead acid battery industry recycled >99% of the available lead scrap from spent lead acid batteries from 1999 to 2003, according to a report issued by the Battery Council International (BCI) in June 2005, ranking the lead recycling rate higher than that of any other recyclable material [Gabby, 2006]. However, emerging technologies such as lithium ion batteries, nickel metal hydride batteries, and ultra-capacitors offer improved energy storage performance and, should they be widely used in fuel cells systems, promise to either reduce recycling opportunities or spur the development of a new recycling infrastructure.

Unlike steel and the metals in batteries, catalyst family metals can be expected to be recycled on the basis of their value, as opposed to the dominance of their mass in fuel cell systems. For example, platinum family catalyst metals are currently quite successfully recycled from today's vehicles (including both platinum and rhodium). Bhakta [1994] notes that in today's catalytic converters, the catalyst is housed in a stainless steel canister. Therefore, to recycle the catalyst, special machines have been developed to slit the canisters and remove the catalyst. Given an estimated increase in the amount of platinum group metals in fuel cells of 15 to over 200 times that of the catalytic converter for mobile fuel cell applications, it can be expected that similar technological development would follow wide-scale deployment of fuel cells based on platinum group metals [Cooper, 2003, 2004a].

In contrast, recycling rates for nonmetallic fuel cell materials are much lower than metals throughout the world, even when considering all aspects of recycling (reuse, remanufacturing, recycling, and energy recovery). For the balance-of-plant, although fuel storage hydrides, reforming media, and insulation materials have been recycled in laboratory and/or pilot plant settings, substantial construction would be needed to support recycling for wide-scale fuel cell deployment. For the stack, flow field materials such as graphite, carbon composites, and ceramics can be expected to be chemically and physically altered during stack operation in ways that will prohibit reuse and remanufacturing. There may however be opportunities to use flow field materials in steel manufacturing or as insulation for fuel cell or other electronic products. For the electrodes, recycling process availability for both membranes and ceramic structures is also quite low. However, again there may be an opportunity to move processes from the laboratory to wider use.

12.3.2 Material compatibility and hardware separation

Materials are incompatible for recycling when they cannot be refined together. For example, because steel and copper are incompatible in recycling processes, solid oxide fuel cells, (SOFC) interconnects must be separated from any copper components in preparation for recycling. During fuel cell design, recycling compatibility charts can be useful in guiding materials selection and the assignment of hardware configurations. Compatibility charts are typically presented for classes of materials (i.e. plastics, metals, glasses and ceramics as presented by Bras [2005]) with an excerpt for fuel cell metals presented in Table 12.1.

Unless recycling is to be dominated by reuse or remanufacturing, due to compatibility issues fuel cell hardware designers should preferably eliminate incompatible materials or, when this is not possible, they should ensure incompatible materials are easily separated. The reason elimination is preferred is that it facilitates the largest number of separation options (from heat treatment, to shredding, to manual disassembly). For example, PEMFC membrane material substitution offers one example of the benefits of incompatible materials elimination. Specifically, Handley *et al.* [2002] identify fluorine-based membranes as a contaminant in bipolar plate recycling, platinum recycling, and any instances of incineration or energy recycling. This concern

Table 12.1 Compatibility of fuel cell metals[1]

Metal	Recycling is reduced if the metal is contaminated with
All	Plating materials
Iron or steel	Copper, tin, zinc, lead, or aluminum, also steel and cast irons, should be separate from stainless
Aluminum	Iron, steel, chromium, zinc, lead, copper, magnesium, silicon, platinum group metals, also wrought and cast aluminum should be separate
Zinc	Iron, steel, lead, tin, or cadmium
Platinum group metals	Copper
Copper	Platinum group metals, mercury, beryllium, antimony, nickel, bismuth, aluminum

[1] Based in part on Bras (2005); Brezet and Van Hemel [1997]; van Schaik *et al.* [2003]

is related to the possible formation of hydrogen fluoride at elevated temperatures. Handley *et al.* suggest municipal incineration is not a favorable option for related PEMFC components in that costly hydrogen fluoride recycling plants would be needed. As an alternative, as presented by Mehta and Cooper [2003], non-fluorinated membrane materials are being investigated. However, further analysis is needed to determine if any issues can be related to the disposition of these materials.

When incompatible materials cannot be removed from fuel cell systems, designers can ensure incompatible materials are easily separable. Coulter *et al.* [1998] provide guidelines on designing for separability. For example, designers should ensure recyclable components are accessible within an assembly and avoid instances where materials are welded or attached by different or numerous fasteners). Also, Kroll *et al.* [1996] present a procedure for evaluating the ease of disassembly or separability of products for recycling which can be applied to fuel cells and facilitates all recycling aspects (reuse through energy recovery). Specifically, a rating scheme allows the translation of design properties into quantitative scores based on the number of subassemblies being disassembled, an ideal (or the minimum) number of subassemblies, and the type, direction, tools used and difficulty rating (related to availability, position, force, and time) for each disassembly task. As an example, Cooper [2004a,b] applies Kroll *et al.*'s methods to the evaluation of various PEMFC flow field plate designs for stacks used in mobile applications. She finds that disassembly efficiencies are driven by the number of subassemblies (related to the number of cells in the stack and the use of plates with integrated cooling) and the removal of manifolding and cooling fluid fixtures. Disassembly issues identified using the Kroll *et al.* method included the following:

- All fluids must be removed prior to hardware disassembly.
- The removal of all stack subassemblies up tie rods (in a single direction) required the stack be fixed (e.g. to the floor by one of the end-plates). This process was improved using a platform to raise the stack as disassembly proceeded.
- The possibility that components fuse or become brittle during stack operation may be a concern, not only for PEMFC disassembly for the purposes of recycling, but also during maintenance operations.

However, for fuel cells more than other systems designed for disassembly, separability will be trumped by the need for intimate connections between materials are not needed for electric or heat transfer or sealing). As such, energy recovery will most likely be limited to balance of plant components (mostly polymers).