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Recommended Practice to Design for Recycling Proton Exchange Membrane (PEM) Fuel Cell Systems

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1. *Scope*

1.1 Mission Objective—In 1999, the Society of Automotive Engineers established a Committee for Fuel Cell Standards. The Committee is organized in subcommittees that address issues such as Safety, Performance, and Recycling. The mission of the Recycling Subcommittee is to develop a recommended practice document that incorporates existing recycling practices and identifies technical and environmental sustainability issues and applies them to proton exchange membrane (PEM) fuel cell (FC) systems.

Recyclability is best considered early in the product engineering design/development process. The design engineer should be concerned with the product after its useful life and adopt a mindset of designing for disassembly and recycling.

The purpose of this SAE Recommended Practice document is to provide a tool that helps the FC system designers and engineers incorporate recyclability into the PEM FC design process. This document was derived by considering existing recycling recommended practices then applying them to assess and evaluate the recyclability of the PEM FC system. This document should be used to continually assess the recyclability of component and assembly designs during the early design phase, in order to reach optimized recyclability, recycled content, and minimized environmental impact associated with those designs. This document defines a PEM FC rating system that assesses the ease of removal of the PEM FC system and/or components from a vehicle; then upon removal from the vehicle, the ease of recycling those components and materials. The derived rating is used as a PEM FC component design tool for continual improvement opportunities and not for purposes of calculating recyclability of the entire vehicle. While other trade-offs such as mass, piece-cost, volume, etc. must also be considered when designing these systems, they are not discussed in this document.

1.2 Scope of Recommended Practice—While there are various types of Fuel Cell architectures being developed, the focus of this document is on Proton Exchange Membrane (PEM) fuel cell stacks and ancillary components for automotive propulsion applications. Within the boundaries of this document are the: Fuel Supply and Storage, Fuel Processor, Fuel Cell Stack, and Balance of Plant, as shown in Figure 1.

1.3 Limitations of Recommended Practice—There are numerous issues that affect recyclability: economics, infrastructure, market demand, technical feasibility and legislation. These are all closely related to making recycling possible, but are beyond the influence of the design engineer. This document addresses only end-of-life technical recyclability design practices. It does not address material preparation, component fabrication, or in-use environmental impacts. While there are environmental issues associated with these stages of material use, they are outside the scope of this document and are expected to be considered in design for the environment and environmental life cycle studies.

Additionally this document does not provide the methodology for calculating the recyclability of a vehicle or its components per OEM calculation methods. In addition to the use of this recyclability design document for the development of a recyclability rating for FC system and components, calculation methods similar to those mentioned previously may be required by the OEMs for calculating the recyclability of entire vehicles. FC design engineers should reference specific automobile manufacturers' specifications and other industry standards (ISO 22628) for calculation methods and requirements.

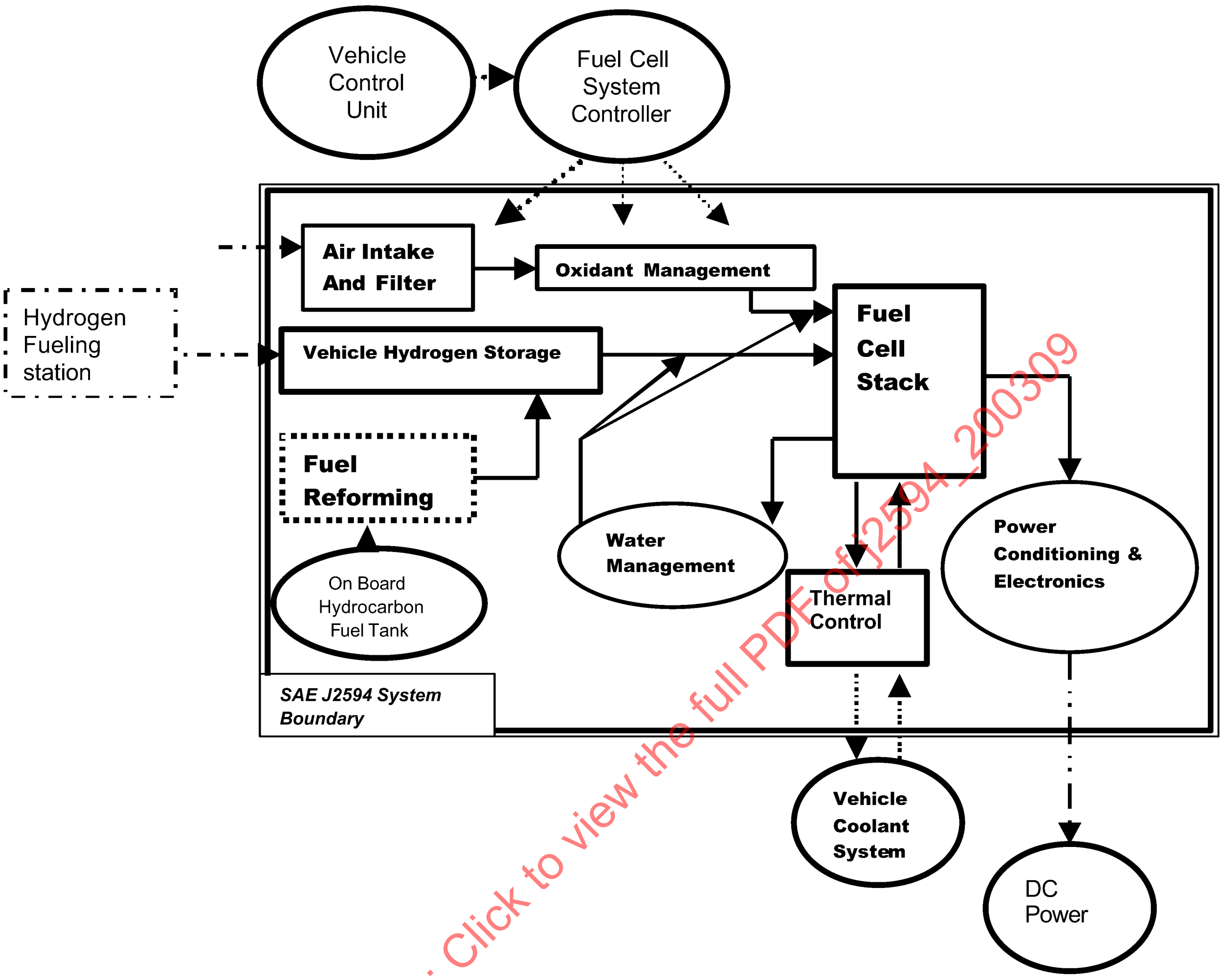

FIGURE 1—SCHEMATIC ILLUSTRATION OF THE PEM FUEL CELL SYSTEM BOUNDARY

1.4 Organization of the Recommended Practice—This document is organized to provide easy access for frequent as well as occasional reference. Chapter 3 provides a list of definitions. Chapter 4 provides guidance on handling fuel cell systems within the existing automotive recycling framework, a description and instructions on the use of Disassembly and Recyclability evaluation tables, and recommendations on design considerations for enhancing disassembly and recyclability. These tables allow the user to evaluate the recyclability of a new or existing fuel cell component/system design. A detailed chart describing materials of construction for fuel cell system components is presented and described in Chapter 5. An Appendix provides information on plastics compatibility.

1.5 How to Use the Document—This document can be used for new and existing designs. Uses of the document are described in Figure 2.

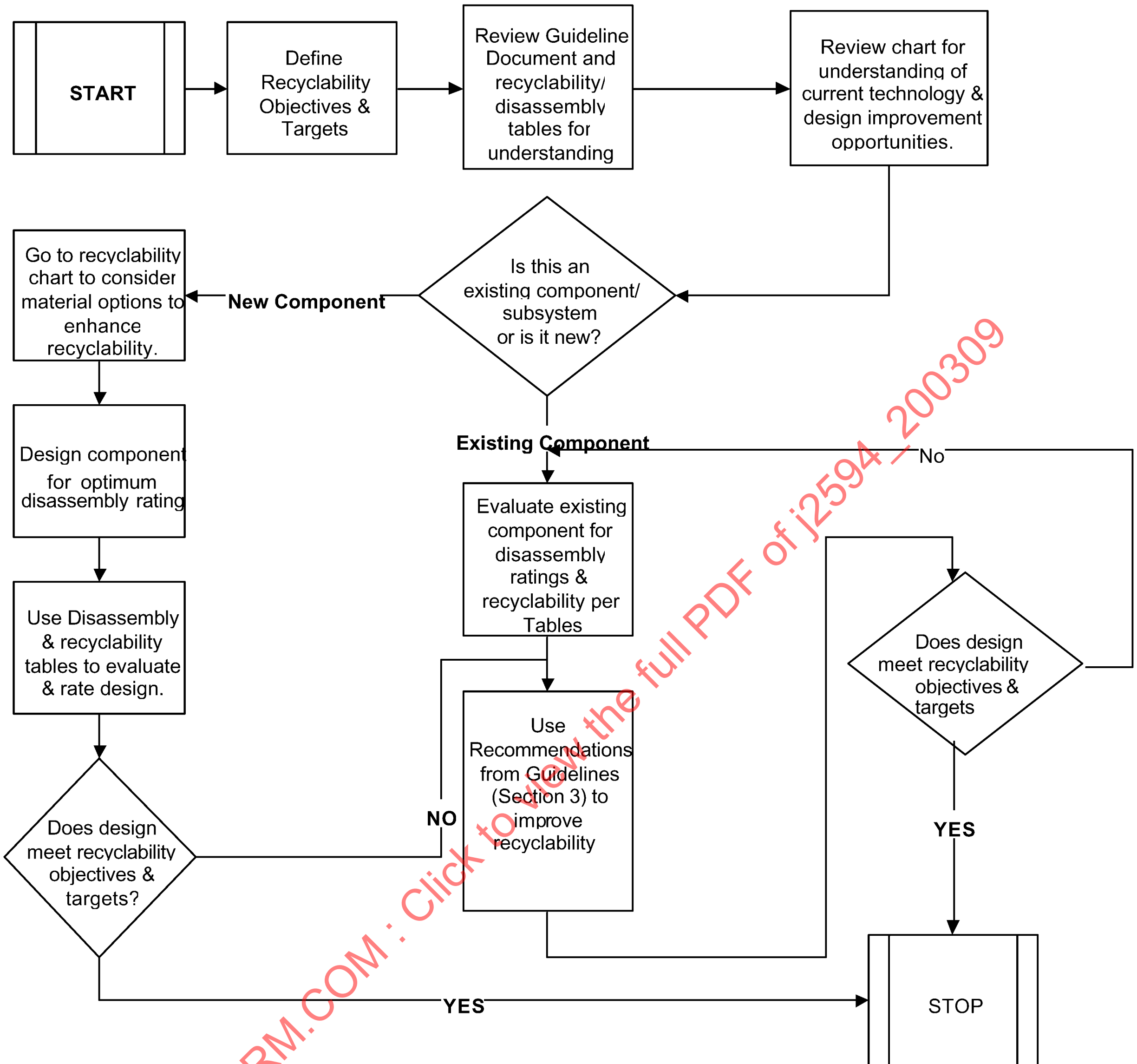

FIGURE 2—HOW TO USE THE FUEL CELL RECYCLABILITY RECOMMENDED PRACTICE: PROCESS FLOW CHART

2. *References*

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest version of SAE publications shall apply.

2.1.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J2578—Recommended Practice for General Fuel Cell Vehicle Safety
SAE J2574—Fuel Cell Vehicle Terminology
SAE J1344—Marking of Plastic Parts

2.1.2 EC Publication—Available from European Union in Brussels. website: http://europa.eu.int/abc/doc/off/rg/en/welcome.htm.

Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles, Official Journal of the European Communities, 21.10.2000.

2.1.3 ISO Publications—Available from ANSI, 25 West 43rd Street, New York, NY 10036-8002.

ISO 22628:2002—Road vehicles—Recyclability and recoverability—Calculation method
ISO 11469—Plastic—Generic identification and marking of plastic products
ISO 1043—Plastics—Symbols—Part 1: Basic polymers
ISO 1043-2—Plastics—Symbols—Part 2: Fillers and reinforcing materials
ISO 1629-1—Rubber—Nomenclature—Part 1: Dry rubber and lattices
ISO 1629-2—Rubber—Nomenclature—Part 2: Thermoplastic Elastomers Mark Rubber Parts

2.1.4 USCAR Publication—Available from USCAR, 1000 Town center, Suite 300, Southfield,MI 48075.

Design for Recycling Guidelines, Vehicle Recycling Partnership/USCAR, 1996, (http://www.uscar.org/consortia&teams/VRP/preferredpractices.pdf).

2.2 Related Publications—The following publications are provided for information purposes only and are not a required part of this specification.

2.2.1 SAE Publications—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

J.C. Alonso, et al. Proceedings of the 2002 Environmental Sustainability Conference and Exhibition, Society of Automotive Engineers, 2002.
Analysis and Assessment of Automobiles with Regard to the Requirements of Design for Recycling, J. Boes, et al., Proceedings of the 2002 Environmental Sustainability Conference and Exhibition, Society of Automotive Engineers, 2002.
Analysis and Assessment of Automobiles with Regard to the Requirements of Design for Recycling, J. Boes, et al., Proceedings of the 2002 Environmental Sustainability Conference and Exhibition, Society of Automotive Engineers, 2002.

2.2.2 Alliance of Automobile Manufacturers Publication—Available from Alliance of Automobile Manufacturers, 2000 Town Center, Suite 1140, Southfield,MI 48075.

Automotive Facts and Figures, Alliance of Automobile Manufacturers, 2001.

2.2.3 Other Publications

Impact of the European Union vehicle waste directive on end-of-life options for polymer electrolyte fuel cells, C. Handley, et al., Journal of Power Sources, 2002
Practical guide to environmental management, 8th Edition, May, 2000, Environmental Law Institute
Integrating LCA and DfE in the Design of Electrical and Electronic Products in the Automotive Sector

3. Definitions—The primary reference for fuel cell terminology is the SAE J2574. Several additional definitions required for the recycling of PEM Fuel Cell Systems are included here and listed as follows.

3.1 Automotive Shredder Residue (ASR)—The material in a vehicle that is not sold for reuse after dismantling, or separated for recycling after shredding and is typically land filled. This material contains about 34% plastic, 17% fluids, 12% rubber, 16% glass, 21% other contaminants (e.g., fibers, dirt, foam).

3.2 **Dismantling—**Process of removing component parts from the vehicle.

3.3 **End-of-Life Vehicle (ELV)—**A vehicle that has completed its useful life and is taken out of service for disposal.

3.4 **Post-Consumer Recycled Content—**The portion of a material's or product's mass that is composed of materials that have been recovered from or otherwise diverted from the solid waste stream after consumer use.

3.5 **Post-Industrial Recycled Content—**The portion of a material's or product's mass that is composed of materials that have been recovered from or otherwise diverted from the solid waste stream during the manufacturing process (pre-consumer).

3.6 **Recyclable Material—**Material which can be diverted from an end-of-life stream to be recycled.

3.7 **Recycled Content—**Proportion by mass in a product or material that is composed of materials that have been recovered from or otherwise diverted from the waste stream.

3.8 **Post-Consumer Recyclate—**Material generated by a business or consumer that has served their intended end-uses and has been recovered or otherwise diverted from the waste stream for the purpose of recycling.

3.9 **Post-Industrial Recyclate—**Material generated during any step in the production of a product or material, including intermediary steps in the process, that has been recovered or otherwise diverted from the waste stream for the purpose of recycling.

3.10 **Recovery—**Reprocessing waste materials for original use, for other purposes, or as a means of generating energy.

3.11 **Recyclability—**The potential to recover or otherwise divert products or materials from the waste stream for purposes of recycling.

3.12 **Recyclability Rate—**Percentage by mass of the vehicle that can potentially be recycled, reused, or both.

3.13 **Recyclability Rating—**The numeric value (as defined in this document) given to assess the potential to re-use, remanufacture, recycle, or recover the parts or materials from a vehicle.

3.14 **Recycling—**Reprocessing waste materials for the original purpose or for other purposes, excluding the processing as a means of generating energy.

3.15 **Recycling Engineering Issues—**A reference to issues of potential concern or attention to design engineers related to the ease of dismantling various components of PEM fuel cell systems.

3.16 **Recycling Environmental Issues—**A reference to issues of potential concern or attention to design engineers related to the potential impacts of recycling various components of PEM fuel cell systems.

3.17 **Residue Treatment—**Any process applied to ASR to further separate, recycle material(s) or recover energy contained therein, including landfilling the residue.

3.18 **Re-use—**Any operation by which component parts of end-of-life vehicles are used for the same purpose for which they were initially intended.

3.19 **Remanufacture—**The process of restoring used durable product to a “like new” condition.

4. Section I

4.1 Background—Automobile recycling has been practiced since the early 1900s, shortly after the first automobiles were built, specifically in the area of metals recovery. Generally, over 94% of all End of Life Vehicles (ELVs) are recycled with an average rate of recycling of 75% by weight per vehicle. The remaining 25%, made up primarily of foam, glass, plastic, and rubber, is known as Automotive Shredder Residue (ASR) and is usually disposed of in landfills. Worldwide, approximately 30 million end-of-life vehicles and 8 million tons of ASR are generated annually. This is an issue due to limited landfill space in some areas and has resulted in legislation in various regions around the world. In other areas, ASR is legally permitted as a landfill day cover.

The handling of an entire end-of-life vehicle is a four-step process: pre-treatment (depollution), dismantling (also known as disassembly), metal separation (shredding), and residue treatment. Within each step of the ELV process, a variety of vehicle components and/or materials are recovered for reuse, recycling, remanufacture, or energy recovery.

4.2 Vehicle Recyclability Calculations—An international industry work group was formed, under the International Standards Organization (ISO) to develop a calculation method for determining the recyclability/ recoverability rate of end-of-life vehicles, ISO 22628. This method is based upon the 4 main stages of ELV treatment and proven recycling technologies. This is the preferred industry standard used by the OEMs to calculate the recyclability of the entire vehicle.

4.3 Fuel Cell System Recyclability Overview—The term PEM FC recyclability as used in this document refers to the reuse, remanufacturing, recovery, and/or recycling of materials used in the components of the PEM FC system. Fuel cell system and subsystem recyclability depends on two main factors: the ease of disassembly (part removal) from a vehicle, and the inherent recyclability of the components/materials. For the entire fuel cell system, a variety of recycling methods may be applied to the various subsystems and components. These include manual separation (where a dismantler removes the sub-components by hand), chemical recovery (thermal, chemical or electro-chemical separation to recover materials such as precious metals), and mechanical treatment (where materials are separated and/or shredded together then separated by material properties e.g., magnetic, density, etc.). It may be possible to selectively remove sub-components containing a number of mixed materials so that the remainder of the fuel cell system can be recycled more easily. High value materials may be manually separated, with the balance of the system being recycled along with the bulk of the vehicle during the shredding process.

Reuse of parts is the highest form of recycling (parts may be used directly without any additional processing, e.g. fender, trim, tail light lenses) and depends on the ease of disassembly, market demand for use in repair or replacement, part durability, cost of a new part, and the existing infrastructure for collection, distribution and service for part replacement. Other parts may be remanufactured by restoring original quality and performance levels through the replacement of all worn or deteriorated components and re-tested to Original Equipment (OE) specifications. This reuse saves energy, natural resources, landfill space, and cost.

Factors influencing remanufacture are similar to reuse. Material recycling is based on technology available to process the material, the existence of a supporting infrastructure, cost of virgin material, the ability to separate the materials into pure streams, any hazardous materials content and the inherent economic value of the material. These points are discussed in more detail throughout this recommended practice.

4.4 Fuel Cell System Disassembly and Recyclability Ratings—Disassembly rating refers to the ease of removing the component/assembly from the vehicle. In general, the disassembly of the component/assembly from the vehicle is dependent on the part location/accessibility on the vehicle, its value, and the treatment method used. Recyclability ratings refer to the ability to re-use, remanufacture, recycle, or recover the materials in the component/assembly, after removal/disassembly from the vehicle.

The following FC Disassembly and Recyclability Tables (Tables 1 and 2) should be used as an example of one method of calculating disassembly and recyclability ratings since several methods exist within the industry and may not be consistent with OEM specific methods. FC system and component designers and engineers can use these examples along with other methods to evaluate their current design. The disassembly rating is best applied from the system perspective rather than evaluating each individual component. System "design for disassembly" efforts should concentrate on parts and materials that have significant value and/or mass. The recyclability rating is applicable to components within the system. These rating tools should be used together for comparison of alternative materials and designs and for the identification and evaluation of system and component recyclability opportunities. In each case a lower rating is preferred.

4.4.1 DISASSEMBLY RATING—The Disassembly Table (Table 1) is a tool for evaluating joining aspects and configurations of fuel cell parts and components as to their suitability for disassembly. Fuel cell designers can use the results of this tool along with other industry and OEM specific tools to estimate ease of disassembly of fuel cell components from end-of-life vehicles for reuse, remanufacturing or material recycling. Once the disassembly potential is evaluated, fuel cell designers may consider changes or improvements to increase disassembly potential.

The table addresses joining aspects, joining configurations and ratings for each selected parameter. Joining aspects include factors such as location, disconnectability, accessibility, number of joinings, joining tools and joining types. Joining configurations describe possible designs to facilitate disassembly and ratings are assigned for evaluating designs. Desirable designs are given low numerical ratings and a low total rating indicates better design for disassembly. Although a low total rating indicates better design for disassembly, the individual joining aspects should be evaluated as well for ways to improve the disassembly potential.

For example, fuel cell components which are located (aspect) in a visible (configuration) area (rating = 1) are more desirable than a covered (rating = 2) or hidden (rating = 3) location. Covered parts may be partially visible behind another component, while hidden parts cannot be seen and would require the removal of other components. Accessibility (aspect) may be direct axial (configuration) which allows direct-line access to the part (rating = 1) for dismantling, or indirect axial which allows access with greater effort (rating = 2), or radial access which is the most difficult (rating = 3). Number of joinings refers to the advantages of fewer attachments to secure the part, and joining tools describes the degree of standardization of disassembly tools needed for part removal. Standardization in this case means the tool is the same for all joinings on a part (rating = 1), the tools are the same type for all joinings on a part (rating = 2) or tools required are of multiple types for different joinings on a part (rating = 3). Types of joinings refer to the method of attachment. The best type (rating = 1) is no fastener (e.g., pressure or snap fit). Other methods include screws, bolts, clips (rating = 2), and the least desirable are bondings such as rivets, welding, soldering and adhesives (rating = 3). However, any joining method selected must consider safety and integrity of the system as a priority.

The disconnectability aspect is more subjective and addresses less well-defined criteria for nondestructive disassembly of the part (rating = 1), partial part destruction (rating = 2), or removal only by part destruction (rating = 3). This requires more speculative engineering assessments and decisions.

TABLE 1—FUEL CELL SYSTEM DISASSEMBLY RATING

Joining Aspects	Joining Configuration	Joining Score	Joining Score	Joining Score
	Visible	1		
1. Location	Covered		2	
	Hidden			3
	Disconnected nondestructively	1		
2. Disconnectability	Partial destruction		2	
	Disconnected only by part destruction			3
	Direct axial direction	1		
3. Accessibility	Indirect axial direction		2	
	Radial direction			3
	One or few joinings	1		
4. Number of Joinings	Low number of joinings		2	
	High number of joinings			3
	Joining elements standardized	1		
5. Joining Tools	Standardized within type of joining		2	
	Not (or almost not) standardized			3
	Pressure fit, snap fit, or no fastener	1		
6. Joining types	Clips, screws, bolts, etc.		2	
	Rivets, welding, soldering, adhesives			3
	Total Score (Lower score is better)	+	+	=

4.4.2 RECYCLABILITY RATING—The recyclability table (Table 2) is a tool for evaluating the ability to re-use, remanufacture, recycle, or recover the parts and/or materials in fuel cell components/assemblies subsequent to disassembly from the vehicle. Once the recyclability potential is evaluated, fuel cell designers may consider changes or improvements to increase the recycling potential.

There are six recyclability categories and ratings in the table, which may have different ratings and definitions from other categories within the industry or OEM specific categories. The most favorable recycling category is re-use, rating 1. For example, some parts (e.g., fender, trim, tail light lenses) from ELVs may be used directly without any additional processing. Other parts must be remanufactured (rating 2) by restoring to original quality and performance levels through the replacement of all worn or deteriorated components and re-tested to OE specifications. The potential for remanufacturing and re-use is dependent on the remaining safe and useful life of the component. This in turn is dependent upon such factors as model/platform match, time in service, use/abuse, exposure to various environments, service/warranty history, and other factors.

Parts with a rating of 3 include parts and materials that are currently recycled in an established infrastructure. This includes all metallic content, batteries, catalytic converters, and fluids. Materials with a rating of 4 can technically be recycled, however no infrastructure currently exists to economically recycle them. Materials in this category have the potential to be economically recycled once sufficient volume and an infrastructure is in place to support recycling. This category may include many plastic parts, especially those of substantial mass that are readily accessible for disassembly from the vehicle. Some examples may include bumper/ fascia, door panels, and body side moldings. Ratings of 5 and 6 are less desirable and attempts should be made to avoid these ratings through design improvement opportunities.

TABLE 2—FUEL CELL COMPONENT RECYCLABILITY RATING

Recyclability Rating	Category	Description/Examples
1	Re-Use	A radio or bumper/fascia can be removed from an ELV and be re-used as a replacement part in an appropriate make/model vehicle.
2	Remanufacture	Products such as brake cylinders, alternators, pumps, and motors can be removed from vehicle and reconditioned for use as after-market parts.
3	Recycled	Part removed for materials recycling or materials separated and recycled, e.g., metals, batteries, catalytic converters, fluids, etc.
4	Technically Feasible, but not recycled	Parts made out of pure materials, compatible materials, or materials that can be separated into recyclable streams using technologies that have no infrastructure and/or are not economic to recycle, e.g., polypropylene, glass, elastomers.
5	Energy Recovery	Part is made out of mixed or contaminated materials that cannot be readily recycled, but contains materials that can be incinerated for generation of energy, e.g., automotive shredder residue, tires.
6	None of the above	Part has no calorific value, e.g., ceramics, mineral fibers.

4.5 Design for Disassembly and Recyclability Recommendations—The following General Recommendations should be kept in mind while designing fuel cell systems and subsystems and used in conjunction with the previous tables to accomplish changes that will increase the disassembly and recycling potential of the fuel cell system and its components. These guidelines provided below are derived from the Vehicle Recycling Partnership (VRP) Preferred Practices, but provide more detail for the designer and engineer. The more abbreviated VRP Preferred Practices can be found on the USCAR website, (see 2.1.4).

a. Design components and assemblies so that they may be easily and cost effectively removed from the vehicle for re-use or recycling.
b. Develop Durable Designs—Design parts so that the life of the product can be extended to decrease the need for replacement parts and so that it can be easily disassembled and remanufactured for re-use.
c. Minimize Need for Fluids/Lubricants/Other Consumables—Parts not containing fluids or lubricants are easier to recycle and decrease the use of other materials and consumables. Design to minimize lubrication, spillage, leakage, service, etc. Parts containing fluids should be designed for easy fluid removal/drainage.
d. Non-Appearance Plastic Parts—Design and select recycled non-color matched plastic materials for non-critical, non-appearance, or covered parts.
e. Design Parts for De-Pollution/End-of-Life Treatment—Many parts are currently removed from the vehicle prior to shredding to recycle valuable materials or to remove parts/materials that may compromise safety or the environment. For example, batteries are currently dismantled from the vehicle for proper treatment of the acid and recycling of the lead, and catalytic converters are removed from the vehicle for recycling of the precious metals. Design for easy removal should be considered.
f. Eliminate/minimize use of Substances of Concern—Parts containing hazardous substances (for example, those containing lead, mercury, cadmium, or hexavalent chromium) should be designed for easy removal when elimination of the substance of concern is not technically or economically feasible. In response to government regulations, environmental goals (hazardous materials reduction, recycling), etc., vehicle manufacturers are prohibiting or restricting the use of certain substances in the products. Currently OEMs have separate and unique lists of restricted and reportable chemicals. Suppliers are required to report on the use of these substances if they are contained in the parts and materials used in vehicles. (See specific automobile manufacturers' specifications for details).
g. Use Recyclable Materials—Select materials for which recycling technologies are currently practiced.
   1. Metals are considered recyclable.
   2. Plastics, Textiles, Rubbers, and Glass are technically feasible for recycling if not laminated, coated, combined, or bonded with or to other materials.

3. Select materials and recycling technologies that preserve the greatest material value. (e.g., single materials have more value than mixed materials.)
4. Thermoplastic polymers are more recyclable than thermoset polymers. Thermoplastic materials can be remelted for reuse in the same or other application.

h. Use Recycled Materials—Select materials that contain Post-Consumer or Post-Industrial recyclate. Post-Consumer recyclate is preferred. Materials Engineers and material suppliers can provide guidance on materials containing recycled content.
i. Standardize Material Selection—Standardize the material type(s) used on selected parts such as pipes and hoses. Some OEMs have preferred material catalogs to facilitate this requirement.
j. Limit Material Types Used within Assemblies—Use one material type for all components within an assembly. Reducing material types minimizes separation and cost of recycling.
k. Reduce or Eliminate Coatings/Finishes—Uncoated materials are easier and less costly to recycle.
l. Use Compatible Materials—Select materials that do not require separation for recycling. Some materials are considered contaminants in current recycling processes. See Plastics Compatibility Chart, in the Appendix. Materials specialists and material suppliers are also good sources of compatibility information.

1. Assemblies—When the use of only one polymer or metal in an assembly is not possible, select materials that are compatible for recycling without complete disassembly.
2. Laminates/Composites—Select metals, plastics, textiles, and adhesives that do not require separation for recycling. (e.g., Acrylonitrile-Butadiene-Styrene (ABS) and polycarbonate used together in a plastic part are more compatible than a part made out of ABS and polyamide. ABS and polycarbonate may not require separation and may be recycled together.)
3. Incompatible Materials—If incompatible materials are used in an assembly or composite construction, attempt to select materials with greater than 0.03 density differences to facilitate separation. (Recycling technologies exist for the mechanical grinding and density separation of materials. Although the process may not result in a 100% pure stream of materials, the goal of the process is to generate clean streams of materials, free of contaminants, that may be used in new applications.)

m. Promote Renewable/Bio-Based Products—Consider the use of materials derived from trees, crops, and agricultural and forest waste to reduce dependency on non-renewable petroleum-based products. Natural materials such as cotton, wood, and flax are renewable, biodegradable, and rarely present a health risk. They can be low in mass and extremely strong. Some of the natural fibers can be used to reinforce thermoplastic materials as a replacement for glass fibers. Vegetable oils and derivatives are being developed for use in polymers and automotive fuels and fluids.
n. Facilitate Disassembly –

1. Select fastening systems that facilitate quick, easy, and economic removal from the vehicle by any method, including destruction of attachment, for re-use or recycling.
2. Utilize attachments that allow for easy separation of components within an assembly.
3. Minimize the additional use of adhesives with mechanical fasteners.

o. Reduce Fasteners—Reduce the number and types of fasteners used. Select fasteners that do not require disassembly for recycling.
p. Consider use of Snap Fits—Use molded-in snap fits where possible to reduce use of additional fastening or attachment systems. Snap fits can be used to accommodate quick disassembly by unsnapping or destruction.
q. Minimize the Joining of Dissimilar Materials—If dissimilar materials must be joined, do it such that they can easily be separated.

1. Do not weld dissimilar materials.
2. Avoid steel fasteners in aluminum parts.
3. Avoid copper brazing of ferrous parts.

r. Minimize the Use of Adhesives—If adhesive bonding is required, utilize adhesives and substrates that are compatible for recycling. If adhesive use is unavoidable, use small, localized areas to adhere, similar to spot welding, without compromising part integrity.

s. Mark Parts—Use the following part marking specifications to facilitate easy identification of materials for recycling, unless otherwise specified by customer.

1. Markings should be legible, easy to locate, and appear on a "non-show" surface without affecting fit, function, or appearance.
2. Mark plastic parts per ISO 11469 and ISO 1043 Part 1 and Part 2.
3. Mark Rubber Parts per ISO 1629 Part 1 and Part 2.
4. Where practical, identify alloy used in manufacture of aluminum and magnesium parts. It is often more favorable to separate metal alloys to maximize material value and avoid cross-contamination.

5. Section II—In this section we introduce and explain the PEM Fuel Cell System Recyclability Chart as shown in Figure 3. The following 5.1 through 5.9 describe the table headers.

5.1 PEM Fuel Cell System Recyclability Chart—Currently, the fuel cell system has three basic sub-systems: the fuel supply (on-board storage, on-board reformers), balance of plant, and the fuel cell stack. Figure is organized by subsystem and includes the principal components within an automotive PEM fuel cell system.

The following section details the PEM Fuel Cell System Recyclability chart that can be used as a tool to identify major recyclability and sustainability issues associated with PEM FC systems and sub-systems based on the present knowledge of the technology and the associated recyclability capability. The chart is comprised of the following columns:

a. System and system components
b. Material Types
c. Recyclability Issues (disassembly, reuse or alternative use, technical, infrastructure)
d. Sustainability – resource depletion, ELV environmental issues

Following is a brief description of each section of the Fuel Cell System Recyclability Chart.

5.2 System and System Components—This section describes the major PEM fuel cell components and system components, depending on the configuration chosen and as known at the time of publication of this document. These three systems are:

a. Fuel supply
b. Balance of Plant
c. Fuel Cell Stack

5.3 Material Types—Material types are the compositional materials that make up the system components. This section of the chart identifies potential component materials, depending on system configuration. This section is not intended to quantify the amounts or percentage of each material type in each system component. Detailed compositional information for each system component may vary between different system configurations.

5.4 Recyclability Issues—This section of the table summarizes the potential recyclability issues associated with the PEM fuel cell components from the following perspectives:

a. Disassembly
b. Reuse or Alternative Use
c. Technical
d. Infrastructure

It should be noted that while a component may be targeted for recycling due to its inherent economic value, at this early stage of development of fuel cell-powered vehicles a recycling infrastructure might not exist. It is assumed that if recycling is technically feasible, the economics will drive the creation of the infrastructure.

5.4.1 DISASSEMBLY ISSUES—This section highlights the issues that should be considered during component removal from the vehicle and/or from the FC system prior to re-use or recycling.

5.4.2 REUSE OR ALTERNATIVE USE—One way to reduce further environmental impact is to reuse the component. This column identifies components that can be reusable in the same application or as an application in other industry sectors.

5.4.3 TECHNICAL—The technical recyclability potential of PEM fuel cell components is highlighted in this section. A material or component that is technically recyclable means that a viable technology exists to recycle or recover the material or component in question.

5.4.4 INFRASTRUCTURE—This column describes the current state of the recycling infrastructure with respect to the material or component listed. In order for a viable infrastructure to exist to recycle a component or material, it is assumed that there are valid technical, economic and/ regulatory drivers in place to ensure the viability of the infrastructure.

5.5 Sustainability Issues—Although "Sustainability" incorporates a broad range of environmental, social and economic issues associated with the full life cycle of a product, process or corporate well being, this section of the chart focuses only on the environmental aspect of sustainability. From this perspective, the chart assesses both Resource Depletion and End-of-Life Environmental Issues.

5.5.1 RESOURCE DEPLETION—The objective of this column is to alert the design engineer to the actual prevalence of a base material from a "resource availability" standpoint. Renewable resources are preferred over non-renewable resources whenever possible in order to reduce the consumption rate of those materials that are known to be scarce in our ecosystem. The continued reliance on non-renewable resources may lead to long-term irreparable environmental impairment. This condition may also be considered "unsustainable" to ensure the continuation of certain aspects of our ecosystem. This condition may also have a strong negative impact on "economic sustainability" as a highly consumed, highly depleted resource leads to higher costs to use the resource. While the scope of this document is only to alert the engineer to the resource depletion potential of a resource or material, consideration should also be given to the environmental impacts associated with the extraction of the resource from primary sources.

5.5.2 END OF LIFE ENVIRONMENTAL ISSUES—The objective of this column is to identify the potential environmental issues associated with the fate of the component or material at the end of its useful life. The impacts or stressors described in this section are expressed in terms of:

a. Hazardous substances contained in the material or component,
b. Unique environmental issues associated with specific end-of-life treatment (e.g., incineration of PVC or fluorinated polymers),
c. Solid waste generation of materials that are not recycled, recovered, or reused.

It is important to clearly understand the philosophy used in assessing the end-of-life environmental issues of materials. For the purpose of this document, materials of concern have been considered with a view toward the following items:

a. Probability of escape/release to the environment (how the substance is bound or contained, physical state of substance -gas/liquid/solid),
b. Concentration (mass/volume),
c. Inherent toxicity,
d. Probability/opportunity of reuse/recycling using existing collection and recycling system,

e. Probability/opportunity of interaction with humans,
f. Generation of non-recyclable waste.

In cases where the element or material can be considered to be permanently bound within a substance and in this bound condition is not an environmental threat considering its expected end of life treatment; and, further at end-of-life has a high probability of reuse/recycling, then the element or material is not identified as and end-of-life environmental issue. For example, while stainless steel contains nickel and chromium, these elements are considered to be permanently bound within the steel and if reused or recycled will not escape into the environment and therefore the nickel and chromium within stainless steel are not identified as end-of-life issues. In this example both nickel and chromium are toxic substances when in direct contact with the ecosystem and humans. As another example, ethylene glycol is expected to be processed using existing processes, however as a liquid it has a higher chance of release into the environment leading to potential human exposure and therefore it is identified as an end-of-life environmental issue.

5.6 PEM Fuel Cell Subsystems, Materials, and Related Environmental Issues

5.6.1 GASEOUS HYDROGEN STORAGE—There are four types of compressed gaseous hydrogen storage cylinders. They are as follows:

Type 1: All Metal Construction
Type 2: Metal liner reinforced with hoop-wrapped continuous filaments in a resin matrix
Type 3: Metal liner reinforced with full-wrapped continuous filaments in a resin matrix
Type 4: Plastic liner reinforced with full-wrapped continuous filaments in a resin matrix

The type of cylinder used for fuel cell vehicles will be dependent on a number of factors including mass, size, cost, storage pressure, etc. All tanks need to be purged of any remaining fuel before removal from the vehicle. For compressed gas systems, this process includes depressurizing and purging the on-board fuel, as described in SAE J2578.

5.6.1.1 Type 1 Tank

5.6.1.1.1 System Components and Material Types—The material makeup for Type 1 tanks will either be all steel or all aluminum.

5.6.1.1.2 Recycling Engineering Issues—The tanks can be dismantled from the vehicle for further reuse, remanufacturing or disposal.

5.6.1.1.3 Recycling Environmental Issues—Because of its metal construction, Type 1 tanks are completely recyclable. If the tanks are recycled rather than reused or remanufactured, they are processed through customary metal recycling processes.

5.6.1.2 Type 2 Tank

5.6.1.2.1 System Components and Material Types—The material makeup for Type 2 tanks includes steel or aluminum liners and composite hoop wrap. The composites include resins (thermoplastic or thermoset polymers) and fibers (glass, aramid, or carbon).

5.6.1.2.2 Recycling Engineering Issues—The tanks can be dismantled from the vehicle for further reuse, remanufacturing or disposal. The composite material would be separated from the tank during the metal recycling process. If tanks are recycled rather than reused or remanufactured, metal part would be processed as in Type 1 tanks.

5.6.1.2.3 Recycling Environmental Issues—After separating the recyclable metal from the composites, composites may be considered for fillers, incinerated for energy recovery, or disposed.

System	System Components	Material Types	Recyclability Issues				Sustainability Issues	
			Disassembly	Reuse or Alternative Use	Technical	Infrastructure	Resource Depletion	End of Life Environmental
Fuel Supply	**On Board H_2 Storage**							
	Compressed H_2							
	- Type 1 Tank	Non-composite metallic	Tank must be purged prior to disassembly	Dependent on tank condition	No issue	No issue	Depends on metal	No issues
	- Type 2 Tank	Composite metallic hoop wrapped	Tank must be purged prior to disassembly	Dependent on tank condition	Material separation	Infrastructure for composite recycling	Fossil fuel depletion for composites	Composites waste generation
	- Type 3 Tank	Composite metallic full wrapped	Tank must be purged prior to disassembly	Dependent on tank condition	Material separation	Infrastructure for composite recycling	Fossil fuel depletion for composites	Composites waste generation
	- Type 4 Tank	Composite non-metallic full wrapped	Tank must be purged prior to disassembly	Dependent on tank condition	Material separation, plastic compatibility	Infrastructure for composite recycling	Fossil fuel depletion for composites	Composites waste generation
	Liquid H_2							
	- Hardened Aluminum	w/composite wrap	Tank must be purged prior to disassembly	Dependent on tank condition	Material separation	Infrastructure for composite recycling	Fossil fuel depletion for composites	Composites waste generation
	- Stainless Steel Tank	Stainless Steel, Insulation (mineral wool or fibreglass)	Tank must be purged prior to disassembly	Dependent on tank condition	Material separation Stainless steel is 100% recyclable	Infrastructure for insulation recycling	Ni	Solid wastes (insulation)
	Metal Hydrides	Titanium, Magnesium, Nickel Alloys doped w/ rare earths (e.g. Lanthanum - nickel, iron - titanium)	Potentially pyrophoric when exposed to air	Lifetime restrictions for recharging	No issue	Infrastructure needed	Ni and La alloys may have issues	Hydrides cannot be landfilled
	- Hydride Tank	Composites or Metals	Remove from vehicle prior to shredding; special procedures required to remove hydrides	Dependent on condition of tank. Lifetime restrictions for recharging.	No issue	Infrastructure for composite recycling	Depends on metal	Potential hydride contamination
	- Hydride Vessel	Composites or Metals	Purge fluids	None	No issue			
	- Burner	Metals	No issue	Potential for reuse	No issue	No issue	Depends on metal	No issue
	- Heat Exchanger	Metals	Purge fluids	Potential for reuse	No issue	No issue	Depends on metal	No issue
	Chemical Hydrides	Lithium Hydride and Mineral oil and polymeric dispersant	Tank must be purged prior to disassembly; chemical is caustic	Potential for reuse or recycling.	No issue	Spent hydride infrastructure needed	Lithium, fossil fuel depletion for dispersant	Neutralize prior to disposal; lithium hazardous
		Sodium Hydride and polyethylene or other inert plastic coating	Tank must be purged prior to disassembly; chemical is caustic	Potential for reuse or recycling.	No issue	Spent hydride infrastructure needed	Fossil fuel depletion for plastic	Neutralize prior to disposal; NaH hazardous
		Sodium Borohydride	Tank must be purged prior to disassembly	Potential for reuse or recycling.	No issue	Spent hydride infrastructure needed	No issue	Neutralize prior to disposal; NaBH4 hazardous

FIGURE 3A—PEM FUEL CELL SYSTEM RECYCLABILITY CHART

System	System Components	Material Types	Recyclability Issues				Sustainability Issues	
			Disassembly	Reuse or Alternative Use	Technical	Infrastructure	Resource Depletion	End of Life Environmental
Fuel Supply	**On Board H_2 Storage**							
	- Reactor Chamber	Stainless steel	Purge fluids	Potential for reuse	No issue	No issue	No issue	No issue
	- Piping	Stainless steel	Purge fluids	Potential for reuse	No issue	No issue	No issue	No issue
	- Pumps	Metals, teflon, rubbers, and plastics	Purge fluids	Potential for reuse	No issue	No issue	Depends on metal, fossil fuel depletion for plastics	No issue
	- Heat Exchanger	Metals, heat exchange fluids	Purge fluids	Potential for reuse	No issue	No issue	Depends on metal	Glycol coolant
	- Containment Vessel (for NaH only)	Plastic, stainless steel, and carbon composite	Purge fluids	Potential for reuse	Material separation	No issue	Fossil fuel depletion for plastic	No issue
	- Catalyst (for $NaBH_4$ only)	Precious & transition metals		Lifetime restrictions for catalyst activity	No issue	No issue	Precious metals	No issue
Fuel Supply	**On Board Fuel Processor**							
	Fuel Reformers							
	- Steam	**Stainless steel vessel, tubes, ceramic insulation** alumina, silica, and/or zirconia**, Catalyst: pellet substrate:** Mg, Al, Si, Zr, Corderite, Fe, C, Ni, Cr ; **active Ingredients** : Ni, Pt, Rh, Ru, **washcoat:** La, Al, Zr, Ce, Ba.	Purge fuel from vessel prior to disassembly	Lifetime restrictions for catalyst activity	No issue	No issue	Zr, Pt, Rh, Ru, Ni, La	Ceramic solid waste
	- Auto Thermal	**Stainless steel vessel, ceramic insulation** alumina, silica, and/or zirconia**, Catalyst: monolith substrate:** Mg, Al, Si, Zr, Corderite, Fe, C, Ni, Cr ; **active Ingredients** : Ni, Pt, Rh, Ru, **washcoat:** La, Al, Zr, Ce, Ba, Gd.	Purge fuel from vessel prior to disassembly	Lifetime restrictions for catalyst activity	No issue	No issue	Zr, Pt, Rh, Ru, Ni, La, Gd	Ceramic solid waste
	- Partial Oxidation	**Stainless steel vessel, ceramic insulation** alumina, silica, and/or zirconia**, Catalyst: monolith substrate:** Mg, Al, Si, Zr, Corderite, Fe, C, Ni, Cr ; **active Ingredients** : Ni, Pt, Rh, Ru, **washcoat:** La, Al, Zr, Ce, Ba, Gd.	Purge fuel from vessel prior to disassembly	Lifetime restrictions for catalyst activity	No issue	No issue	Zr, Pt, Rh, Ru, Ni, La, Gd	Ceramic solid waste
	Desulfurization	**Stainless steel vessel, Sorbent:** ZnO, activated carbon, zeolite, ZnS.	Purge fuel from vessel prior to disassembly	Lifetime restrictions for sorbent activity	No issue	Sorbent regeneration infrastructure needed	None	ZnS waste, SOx generation

FIGURE 3B—PEM FUEL CELL SYSTEM RECYCLABILITY CHART (CONTINUED)

System	System Components	Material Types	Recyclability Issues: Disassembly	Recyclability Issues: Reuse or Alternative Use	Recyclability Issues: Technical	Recyclability Issues: Infrastructure	Sustainability Issues: Resource Depletion	Sustainability Issues: End of Life Environmental
	Carbon Monoxide Clean-up	**Stainless steel vessel, ceramic insulation -** alumina, silica, and/or zirconia **, catalyst: substrate -** Mg, Al, Si, Zr, Corderite, Fe, C, Ni, Cr ; **active ingredients -** Fe, Cr, Cu, Zn, Pt, Rh, Ru, Ce; **washcoat -** La, Al, Zr, Ce, Ba.	Purge fuel from vessel prior to disassembly	Lifetime restrictions for catalyst activity	No issue	No issue	Zr, Pt, Rh, Ru, Ni, La	Ceramic solid waste
	Permeable Metal Membrane	**Stainless steel vessel , permeable membrane -** Pd, PdAg, PdCu, other Pd alloys, **ceramic insulation -** alumina, silica, and/or zirconia.	Purge fuel from vessel prior to disassembly	Potential for reuse	No issue	No issue	Pd, Ag, Zr	Ceramic solid waste
	Combustor	**Stainless steel vessel, ceramic insulation** alumina, silica, and/or zirconia **, Catalyst: monolith substrate:** Mg, Al, Si, Zr, Corderite, Fe, C, Ni, Cr ; **active Ingredients** : Ni, Pt, Rh, Ru, **washcoat:** La, Al, Zr, Ce, Ba.	Purge fuel from vessel prior to disassembly	Lifetime restrictions for catalyst activity	No issue	No issue	Zr, Pt, Rh, Ru, Ni, La	Ceramic solid waste
	Vaporizer	Stainless Steel	Purge fuel from vessel prior to disassembly	Potential for reuse	No issue	No issue	No issue	No issue
Balance of Plant								
	Oxidant Management System							
	- Compressor / Blower	Metals and plastics	None	Potential for reuse	No issue	No issue	Depends on metal	No issue
	- Filtration Devices	Paper, rubber, steel (maybe PVC, flexible tubing)	None	No opportunity for reuse	Material separation , plastic compatibility	No issue	Fossil fuel depletion for plastic and rubber	Solid waste, potential PVC incineration issue
	Water Management System							
	- Deionized Water System	Metals, plastics, and deionizing resins	Drain fluids and purge system	Yes	Material separation , plastic compatibility	None for metals, yes for plastics, resins	Depends on metal, Plastics: fossil fuel depletion	None
	- Humidification System	Polymeric membrane, metals, and plastics	Drain fluids and purge system	Yes	Material separation , plastic compatibility	Yes for membranes, plastics; no for metals	Depends on metal, Plastics: fossil fuel depletion	None

FIGURE 3C—PEM FUEL CELL SYSTEM RECYCLABILITY CHART (CONTINUED)

System	System Components	Material Types	Recyclability Issues: Disassembly	Recyclability Issues: Reuse or Alternative Use	Recyclability Issues: Technical	Recyclability Issues: Infrastructure	Sustainability Issues: Resource Depletion	Sustainability Issues: End of Life Environmental
	Piping System							
	- Manifold	Metals or plastics	Drain fluids	Yes	None	None	Depends on metal, Plastics: fossil fuel depletion	None
	- Piping	Metals, plastics, and rubbers	Drain fluids	Possible	None	None	Depends on metal, Plastics: fossil fuel depletion	None
	- Valves	Metals, plastics, nylon, and teflon	None	Possible	None	None	Nylon, Teflon: Fossil fuel depletion	Fluorinated material
	- Gaskets	Paper, rubber, and plastics	None	None	None	Volume and infrastructure	Paper: None, Plastics: fossil fuel depletion	None
	Power Electronics							
	- Power Conditioning	Plastics, metals, precious metals, potting compounds, and semi-conductor materials	None	None	Material separation	Volume and infrastructure	Depends on metal, Plastics: fossil fuel depletion	Pb solder
	- Printed Circuit Boards	Plastics, metals, precious metals, potting compounds, and semi-conductor materials	None	None	Material separation	Volume and infrastructure	Depends on metal, Plastics: fossil fuel depletion	Pb solder, brominated flame retardants
	Sensors & Controls	Plastics, metals, precious metals, glass and semi-conductor materials	None	None	Material Separation	Volume and infrastructure	Depends on metal, Plastics: fossil fuel depletion	Pb solder, brominated flame retardants
	Thermal Management							
	- Heat Exchangers	Metals	Drain fluids	Yes	None	None	Depends on metal	Glycol coolant
	- Water Condensor	Stainless Steel	Drain fluids	Yes	None	None	Look above	None
	Mechanical Svstems							
	- Pumps	Metals, teflon, rubbers, and plastics	Drain fluids	Yes	Material Separation	Volume and infrastructure	Depends on metal, Plastics: fossil fuel depletion	None
	- Injectors	Metals and plastics	Drain fluids	Possible	Material Separation	Volume and infrastructure	Depends on metal, Plastics: fossil fuel depletion	None
	- Regulators	Metals, plastics, natural and synthetic rubbers	Drain fluids	Yes	Material Separation	Volume and infrastructure	Depends on metal, Plastics: fossil fuel depletion	None

FIGURE 3D—PEM FUEL CELL SYSTEM RECYCLABILITY CHART (CONTINUED)

System	System Components	Material Types	Recyclability Issues: Disassembly	Recyclability Issues: Reuse or Alternative Use	Recyclability Issues: Technical	Recyclability Issues: Infrastructure	Sustainability Issues: Resource Depletion	Sustainability Issues: End of Life Environmental
	Insulation	Fiberglass, mineral wool, and foam rubber	None	None	No process defined	Volume and infrastructure	Concern	None
	Adhesives	Epoxies, acrylics, phenolics, and urethanes	Makes disassembly difficult/impossible	None	None	None	Concern	None
	Operating Fluids							
	- Lubricants	Oil, teflon, grease, graphite, and paste	Drain oil	Potential	None	None	fossil fuel depletion	Potentially hazardous
	- Cooling Fluids	Ethylene Glycol, Propylene Glycol, and water	Drain	Potential	None	None	Water: None, Glycol - fossil fuel dependent	Glycol
Fuel Cell Stack								
	Bipolar Plates	Graphite, Conductive molded thermoset material, graphite composites, metals	Stack hardware must be removed prior to removing plates from cell row assemblies.	For non-metallic plates, could be reused as a Raw material for steel manufacturing or insulation material for electronics industry.	Material separation issues if plates made from graphite and thermoset material.	If non-metallic plates are used, economic feasibility unlikely due to high separation costs & high availability of materials In the market-place.	Depends on metal, thermoset material: fossil fuel depletion	Possible air pollutants
	MEA	Gas Diffusion Layer (GDL): carbon fiber, polymer coating (e.g., Teflon). Anode and Cathode catalyst: platinum (Pt) or platinum/ruthenium (Pt/Ru) on carbon, or other related Group 8 metals. poly[perfluorosulfonic] acid membrane, or other polymeric membranes	Stack hardware must be removed prior to removing MEA from cell row assemblies.	Lifetime restriction for catalytic activity and membrane	Processes to separate the membrane from the catalysts that result in a metal material stream compatible with existing precious metal recycling processes are being developed. Membrane recycling is under development and is heavily influenced by membrane composition.	Infrastructures for separation of MEA and recycling of membrane do not exist. Membrane recycling will depend upon volume generated and value attributed to the material. There are no infrastructure issues for recycling precious metal.	Depends on metal, polymers: fossil fuel depletion	Possible air pollutants, I.e HF
	MEA Seals	separate or integral seals - elastomeric (rubbers) or plastics.		None		Seal recovery expensive due to separation costs, loss of material integrity and low volume use.	Plastics: fossil fuel depletion	

FIGURE 3E—PEM FUEL CELL SYSTEM RECYCLABILITY CHART (CONTINUED)

System	System Components	Material Types	Recyclability Issues				Sustainability Issues	
			Disassembly	Reuse or Alternative Use	Technical	Infrastructure	Resource Depletion	End of Life Environmental
	Stack Hardware	Insulating plates, end plates and bus plates: plastics, metal alloys (brass, steel, gold, etc.)	Remove enclosure; High-value items (e.g., electronics) can be easily removed; operating coolant fluids must be drained	Potential	None for metals; plastics compatibilty may be an issue; electronic components, cables, wiring harnesses, etc. may be difficult to recycle due to lack of infrastructure (economic and technical limitations)	None for metals; plastics compatibilty may be an issue; electronic components, cables, wiring harnesses, etc. may be difficult to recycle due to lack of infrastructure (economic and technical limitations)	Depends on metal, Plastics: fossil fuel depletion	Possible Air Pollutants
		Stack compression hardware: tie rods/bars, compression springs strapping, misc. fasteners, etc. (metals, plastics, potting compounds)		None				
		Electronic components & misc. control devices (cell voltage monitors, acutators, operating system modules, and supporting components (actuators, cables, wiring harnesses, printed circuit boards, etc.) - metals, plastics, potting compounds and semi-conductor materials		None				
		Fittings, clamps, flanged connectors, hoses, stack enclosure: metals, plastics, rubber		None				

FIGURE 3F—PEM FUEL CELL SYSTEM RECYCLABILITY CHART (CONTINUED)

5.6.1.3 Type 3 Tank

5.6.1.3.1 System Components and Material Types—As in Type 2 tanks, materials include steel or aluminum liner and composites. The primary difference between Type 2 and Type 3 tanks is the use of composites for full wrapping, instead of for hoop wrapping. As in Type 2 tanks, a Type 3 tank design includes multi-layer materials. Composites are mixed organic materials including resin matrices, fibers, and surface treatments for fibers.

5.6.1.3.2 Recycling Engineering Issues—The tanks can be dismantled from the vehicle for further reuse, remanufacturing or disposal. However, the multi-layer materials that makeup the tanks will not be easily separated.

5.6.1.3.3 Recycling Environmental Issues—Generally, the Type 3 tank is the same as Type 2, but contains less metal and more plastics and is therefore less recyclable than Types 1 or 2 tanks.

With respect to recycling environmental issues, because full wrapped tanks require additional amounts of carbon fiber, the environmental impact associated with carbon fiber waste treatment would be greater than with a tank 2 design.

5.6.1.4 Type 4 Tank

5.6.1.4.1 System Components and Material Types—Type 4 tanks are all- composite with continuous filaments in a resin matrix, including a metal boss for attaching the valve. The plastic materials used for the plastic liner are typically thermoplastics. As with Type 2 and 3 tanks, composite filaments can be made from glass, carbon, or aramid fibers.

5.6.1.4.2 Recycling Engineering Issues—The recycling engineering issues referenced for Type 2 and Type 3 also apply to Type 4 tanks.

5.6.1.4.3 Recycling Environmental Issues—In general, the composite tank materials are less recyclable than materials in Types 1, 2, and 3. The only metal component for potential separation is the metal boss.

5.6.2 LIQUID HYDROGEN STORAGE

5.6.2.1 System Components and Material Types—Vehicular liquid hydrogen tanks consist of an outer shell and inner vessel composed of steel, multi-layer insulation in the annular space, and, if deemed necessary, an additional radiation shield designed to distribute heat evenly around the tank. The tank may also require fiber glass supports for additional thermal protection, and a hydrogen gas "getter" to absorb errant gases. A "gas getter" is used to create or maintain a vacuum and a common material is a silica gel packet.

The inner and outer vessels are made from steel. The multilayer insulation is comprised of alternating thin layers of fiberglass, and either aluminized mylar or aluminum foil, and is used to prevent unwanted boil- off. The radiation shield is either all copper, or copper piping and aluminum.

5.6.2.2 Recycling Engineering Issues—Hydrogen tanks may be recycled. In order to prepare for tank recycling, all hydrogen must be purged (SAE J2578).

If insulation is used on the outside of the tank, it may or may not be bonded to the vessel. The aluminized mylar or aluminum foil and fiber glass layers can be unraveled and separated for disposal treatment (or potential reuse for the fiber glass and recycling of the aluminum foil), or the insulation can be reused intact prior to unraveling.

If fiberglass supports are needed, they could either be bonded with the steel or held together by the construction of the vessel. Incorporating them into the tank design without adhesives or other bonding agents would assist in maintaining a “pure” steel waste stream and the supports could be stripped off.

In terms of the metals, the inner and outer steel vessels, and the separate copper or copper and aluminum radiation shield if used, are 100% recyclable.

5.6.2.3 Recycling Environmental Issues—All metals are processed through customary recycling processes.

If the insulation is not reused, the technology, volume, and infrastructure do not exist to recycle the aluminized mylar (which has a very small amount of aluminum), or the fiberglass.

5.6.3 HYDRIDE HYDROGEN STORAGE SYSTEMS—Metal and chemical hydrides hydrogen storage systems are discussed in this section. Other hydrogen storage systems are under development, but the technologies are currently too early to address in this document.

5.6.3.1 Metal Hydrides

5.6.3.1.1 System Components and Material Types—Hydrogen can be stored on a fuel cell vehicle in the form of metal hydrides, which are materials based on the idea that gaseous hydrogen can be absorbed in certain metals, alloys, and intermetallic compounds to give high volumetric storage densities. Metal hydrides may include metals such as magnesium (Mg), aluminum (Al), nickel (Ni), iron (Fe), titanium (Ti), lanthanum (La), etc., and are typically in a granular or powder form. Some examples are lanthanum nickel hydride ($LaNi_5H_6.7$), magnesium nickel hydride ($Mg2NiH_4$) and titanium doped sodium aluminum hydride ($NaAlH_4$). To achieve uniform distribution, higher surface area, and improved physical integrity of the metal hydride powders, they are often supported on metallic substrates that are pellets or cylindrically wound sheets. The supported metal hydrides are stored within metal or composite vessels, which are then contained in a metallic or composite tank. To release hydrogen gas, it is necessary to heat the metal hydride to a certain temperature. Thus, an integrated metal hydride fuel system will also include heat exchangers, conduits for heating/cooling fluids (e.g. water or glycol), pumps, and valves for the control of hydrogen flow. The materials of construction of these supporting systems are generally metallic. Figure 4 provides an illustration of a generic metal hydride system.

5.6.3.1.2 Recycling Engineering Issues—Before dismantling, the metal hydride fuel system should be purged of heat exchange fluids and any remaining hydrogen.

Certain metal hydrides can be pyrophoric (flammable if exposed to air) and may cause problems especially if the hydrides are not fully depleted of hydrogen. Therefore the metal hydride should not be removed from the storage tank, and the hydride and tank should be considered as one unit for re-use and/or recycling. The metal hydride/tank unit must be designed for dismantling in the pre-treatment phase of vehicle recycling. The hydride supporting components, such as piping, heat exchangers, and pumps, can be handled by the existing metal recycling infrastructure.

5.6.3.1.3 Recycling Environmental Issues—Metal hydrides can be recharged by exposing the hydrides to compressed hydrogen and temperature conditioning. However, as a result of dimensional changes in the hydride materials during the charge/discharge and cooling/heating cycles, for some metal hydrides there are lifetime restrictions on the number of times the materials can be recharged. An infrastructure is needed for the recycling of used metal hydrides. Recycling is important for these materials since resource depletion is a potential issue for some metals used in metal hydrides.

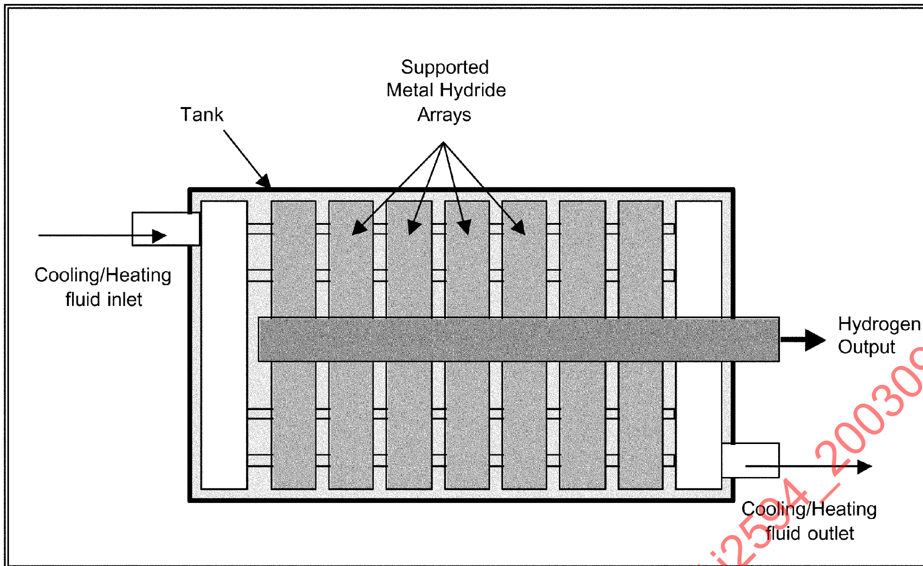

FIGURE 4—CROSS-SECTIONAL SCHEMATIC OF METAL HYDRIDE HYDROGEN STORAGE SYSTEM

5.6.3.2 Chemical Hydrides

5.6.3.2.1 System Components and Material Types—Chemical hydrides are chemical compounds such as lithium hydride (LiH), sodium hydride (NaH), sodium aluminum hydride ($NaAlH_4$), and sodium borohydride ($NaBH_4$) that evolve hydrogen when reacted with water. NaH and LiH react rigorously with water to liberate hydrogen, whereas $NaBH_4$ reacts with water in a more controllable fashion. Once depleted of their hydrogen, these chemical hydrides may be "recharged" via a chemical regeneration process. Each one of these chemical hydride systems uses different materials as briefly described as follows. This section presents only a small subset of alternative chemical hydride options that are based on current knowledge. Figure 5 provides a generic schematic of a chemical hydride hydrogen storage system.

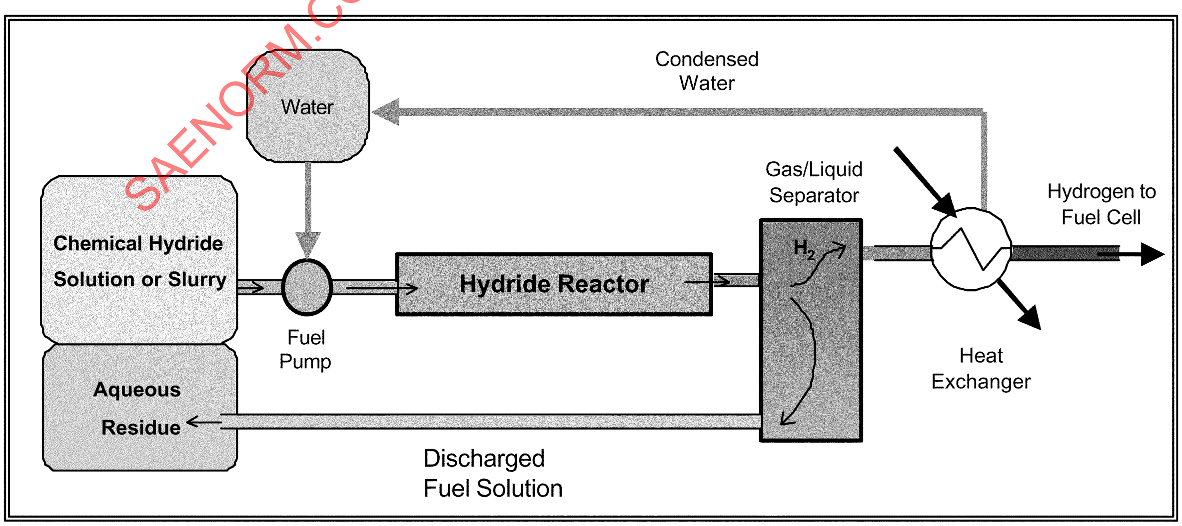

FIGURE 5—SIMPLIFIED FUEL CELL STACK DIAGRAM

a. Sodium Hydride - NaH
One system for storing hydrogen on-board a vehicle involves the use of polyethylene-encapsulated sodium hydride (NaH) pellets. Hydrogen is produced when the polymer housing is cut and the hydride pellets are exposed to water. The exposed NaH reacts with water, releasing hydrogen and forming sodium hydroxide (NaOH) as a by-product, which is collected in a containment vessel. The "hydride reactor" is constructed from stainless steel. The by-product, concentrated NaOH, is a highly caustic substance, thus the containment vessel is made from materials that can withstand caustic conditions, usually stainless steel or a selective number of plastic materials.

b. Lithium Hydride - LiH
Another method of storing hydrogen involves using chemical hydride slurry of mineral oil and LiH. The slurry serves two functions: (1) it protects the hydride from unanticipated contact with moisture in the air, and (2) it makes the hydride pumpable. The fuel tank that holds the slurry is constructed from caustic resistant plastic materials or stainless steel. The reaction byproduct is lithium hydroxide (LiOH), which is a caustic substance, collected in a containment vessel. LiH is considered pyrophoric as it spontaneously ignites in moist air, therefore proper precaution should be taken even though the slurry provides a protective barrier.

c. Sodium Borohydride - $NaBH_4$
In this chemical hydride system the hydrogen is stored in stabilized, aqueous sodium borohydride solutions. The fuel tank that holds the aqueous $NaBH_4$ solution is made from stainless steel or caustic-resistant plastic materials. By passing the liquid through a chamber containing a solid phase catalyst, the hydrogen is liberated. The catalyst contains nobel metals and transition metals that can be recycled or reused. The catalyst chamber and its associated piping and valves are constructed from stainless steel or selected plastics.
The reaction byproduct, sodium metaborate ($NaBO_2$), is used to regenerate sodium borohydride. Similar to the previous hydride cases, but to a lesser extent, the $NaBO_2$ solution is caustic, thus the vessel for holding the aqueous residue is constructed from plastic materials or stainless steel.

5.6.3.2.2 Recycling Engineering Issues—The hydride supporting components, such as piping, heat exchangers, and pumps, can be handled by the existing metal recycling infrastructure. Prior to vehicle dismantling and recycling, the chemicals, both the un-used hydride and the reaction by-product, need to be drained from the system (similar to what is done currently with various vehicular fluids). To facilitate draining of the chemical hydride, the system must be designed such that there is easy access to the storage tanks for removal of their contents. The chemicals thus collected are regenerated into hydrides, forming a closed fuel-recycling loop. The hazards associated with the removal of the various chemical hydrides range from slight caustic to highly caustic. The depleted chemical hydride should be collected and recycled.

5.6.3.2.3 Recycling Environmental Issues—Prior to dismantling the system for recycling, all fluids should be drained and flushed. In the sodium hydride and lithium hydride cases, care should be taken when flushing the system prior to recycling, so as to not allow water to mix with un-reacted hydrides, and not allow the spent liquid to come into contact with skin or eye as they are highly corrosive. In the case of sodium borohydride, any un-used fuel or spent fuel is drained prior to recycling, and the system can be flushed with water to clean out any residue.

The by-product of the hydrogen generation process can be recycled to regenerate the chemical hydride via multi-step chemical processes involving the addition of hydrogen. Recycling of the chemical hydride is recommended to prevent resource depletion. In certain situations, these by-products, after some cleanup treatment, may also be used in other industries. For example depleted sodium hydride, sodium hydroxide, is commonly used as a commodity chemical. If not recycled, these by-products, especially sodium and lithium hydrides, may pose an adverse environmental risk due to their caustic nature and should be neutralized prior to disposal. Lithium can present a human exposure risk and should be properly treated and disposed.

5.6.4 ON BOARD HYDROGEN REFORMING

5.6.4.1 Fuel Processing

5.6.4.1.1 System Components and Material Types—Fuel processing is required to allow a PEM fuel cell to work with common infrastructure fuels (liquid hydrocarbon fuels). Fuel processing is the implementation of a series of chemical reactions necessary to liberate hydrogen from the primary fuel and to remove associated fuel constituents that degrade the PEM fuel cell performance (See Figure 6). This series of chemical reactions includes reforming, desulfurization of the gas (when sulfur exists in the fuel), carbon monoxide removal (typically using the water-gas shift reaction together with preferential CO oxidation or methanation), and tail gas combustion.

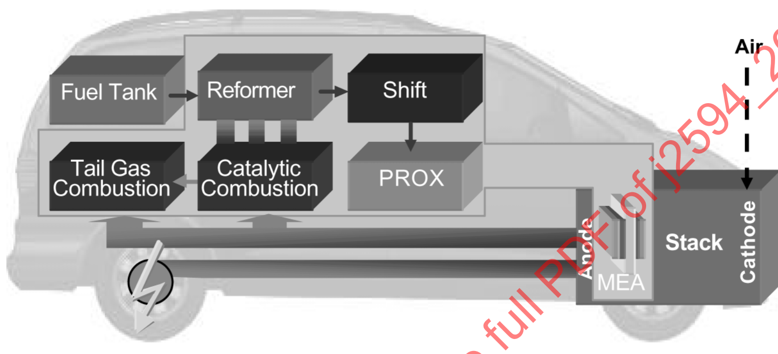

FIGURE 6—ON BOARD HYDROGEN REFORMING USING FUEL PROCESSING SYSTEM

The fuel processing will generally be carried out within a metallic vessel, commonly corrosion-resistant, high alloy nickel chromium steel. Contained within the vessel is a ceramic monolith, typically made from a-alumina, magnesia and/or zirconia, which is coated with a catalyst, commonly precious metal based. The catalyst composition will be determined by the specific processing operation. Catalytic materials may include precious metals such as platinum, rhodium, and palladium, or base metals such as nickel, copper, chromium, and iron. High temperature ceramic insulation made from a-alumina, silica, and/or zirconia is typically installed internal to the metallic vessel. When desulfurization is required, a zinc oxide sorbent is often used to remove sulfur from the fuel. The zinc oxide is converted to zinc sulfide and retained on-board until it can be properly disposed or regenerated. Activated carbon or zeolite based material may also be used to remove sulfur from the fuel stream. An alternative way to purify the hydrogen is through the use of hydrogen-selective permeable metal membranes. These membranes typically consist of palladium, palladium-silver and other palladium alloys, which are contained within a steel vessel. In such cases fuel pressurization is typically accomplished using a pump.

5.6.4.1.2 Recycling Engineering Issues—Drain and purge the fuel from the fuel tank and fuel processing system. The fuel tank needs to be designed for draining before disassembly in the pretreatment phase. Components utilizing pyrophoric catalysts should be designed to provide controlled oxidation of the catalyst during air purge prior to disassembly.

Recycling of on-board fuel processing hardware depends on issues such as materials selection, hardware accessibility, and ease of materials separation. Access to fuel processing hardware should be such that they can be easily removed for recycling or reuse. It is expected that the steel components will be recycled using existing recycling technology. Access to the catalysts contained within the vessels should be provided if catalyst recycling is planned. Currently, nickel catalysts with a metal content of more than 20% and precious metal catalysts can be economically recycled using existing processes similar to those used to recover precious metals from vehicle exhaust catalytic converters.

5.6.4.1.3 Recycling Environmental Issues—At the end of life, the on-board reforming system is expected to be handled within the existing recycling infrastructure for recovery of metals and precious metals. Associated solid wastes are not expected to create any adverse environmental impacts. The sorbent (ZnO, activated carbon or zeolites) in the desulfurizer may be regenerated, however no infrastructure is in place. As a result, the ZnS byproduct may create a solid waste or when combustion regeneration is used, sulfur oxide emissions are produced.

5.6.5 BALANCE OF PLANT

5.6.5.1 System Components and Material Types—The purpose of the balance of plant is to support the efficient operation of the fuel cell both upstream and downstream of the fuel cell stack. The balance of plant consists of the following principle subsystems:

a. Oxidant management
b. Water management
c. Thermal management
d. Piping
e. Power electronics/power conditioning

5.6.5.1.1 Oxidant Management—Upstream of the fuel cell stack, the oxidant management subsystem consists of an air compressor, fan, or blower to move or boost oxidant to the fuel cell stack. In some design configurations, temperature-controlling inter-coolers are used. From a material of construction standpoint, the predominant materials used include stainless steel, some aluminum alloys, specially coated aluminum, plastics and insulating polymers. Filtration is required to keep the air clean. Air filtration devices are typically made from a combination of paper material, rubber and steel.

5.6.5.1.2 Water Management—The water management subsystem is used to control water produced from the fuel cell's operation and to ensure the proper balance of fuel cell stack hydration. This is commonly achieved by using a humidification system. In a vehicle operating with a fuel processor, the reformate gas will have sufficient moisture content to preclude the need for a separate humidifier. A stored supply of water is maintained using water produced from the fuel cell stack. A de-ionized water system is also required to avoid ionic materials from impairing fuel cell stack performance. The principal materials include polymeric membranes, common metals, plastics, and de-ionizing resins. The de-ionizing resins consist of a mixed-bed of sulfonated copolymer of styrene and divinylbenzene materials in either hydroxide form or hydrogen form mixed with trimethylamine, functionalized. The ion exchange resins are not considered hazardous and are not expected to be recycled due to a lack of infrastructure.

5.6.5.1.3 Thermal Management—Various energy recovery devices are used for thermal management purposes such as stack temperature control, stream preheating, and waste heat control from the fuel processor. These devices include heat exchangers, economizers, water condensers or similar heat recovery units. Once again, due to the nature of the gases and materials exposed to the system, the typical materials of construction are stainless steel and related metal alloys.

5.6.5.1.4 Power Conditioning and Power Electronics—Electrical equipment is required to convert and condition the electricity produced at the fuel cell stack in order to supply DC rated equipment in the vehicle. Similar to that used in a battery-electric vehicle, the high-voltage, high-power output of the fuel-cell stack must be distributed to the rest of the car- to the drivetrain, and to a DC to DC voltage converter to power the auxiliary electronics systems. In general, fuel-cell vehicles also use the same kind of computer controls, current and voltage controls, sensors, multiplexers, and analog-to-digital converters as current IC-engine vehicles, although the control algorithms are different. The power train control is also close to that of a battery-powered vehicle. It is divided into torque-generating control for the drivetrain and a power-generating control for the fuel-cell system.

The components used in power conditioning/power electronics include plastics, metals, some precious metals, potting compounds, and semi-conductor materials. Printed circuit boards used also contain these same types of materials.

5.6.5.1.5 Piping Systems and Miscellaneous Mechanical, Systems—Piping systems are used to deliver fuel, water, and air into and out of the system. These subsystems are typically made of stainless steels, polymeric materials, or metal-alloy compounds. Various injectors, pumps, valves, and regulators are used to control the distribution of oxidant, fuel and exhaust gases throughout the system. These components are typically made from various conventional materials, including stainless steels, metal alloys, plastics, and synthetic rubbers. Fiber-glass reinforced insulation may also be used to minimize condensation and maintain temperature throughout the piping systems.

5.6.5.2 Recycling Engineering Issues—The metallic materials of the subsystems, can be handled by the existing recycling infrastructure. The location and accessibility of these subsystems for recycling, requires careful consideration. There will be a requirement to drain the operating fluids, such as coolant in the air compressors, water in humidifiers and reservoirs, coolant from the stack and the piping systems (glycol or equivalent coolant).

The principle electronic components, such as computer controls, current and voltage controls, sensors, multiplexers, and analog-to-digital converters and related electronic equipment can be removed and segregated for recovery. Any residual electrical charge must be discharged prior to disassembly, (SAE J2578). Alternatively these components may enter the electronics-recycling infrastructure, which at present is in its infancy.

5.6.5.3 Recycling Environmental Issues—Based on the material make-up of the balance of plant subsystems, it appears that there are no significant recycling environmental issues. A recycling infrastructure currently exists for metals and metal components, as well as for lubricants and coolants. If ethylene glycol or other coolant is present in the system, these substances should be recycled in accordance with local regulatory requirements.

5.6.6 FUEL CELL STACK

5.6.6.1 System Components and Materials Types—The power generated by a PEM FC system originates in the electrochemical reaction occurring within the fuel cell stack assembly. The stack is comprised of a multitude of repeated unit assemblies of dissimilar materials as shown in Figure 7. In a typical stack design each unit assembly is made in a layered method and consists of bipolar (active) plates and a membrane electrode assembly (MEA). In addition to these repeat units, at certain locations along the length of the stack there are typically cooling plates. The stack is usually enclosed with insulating plates and sturdy end plates with a series of tie bars, compression springs, metallic strapping, a cover/enclosure, isolation bags and/or other similar arrangements to hold the stack together. Finally, the stack is fitted with operating system hardware components, such as cell voltage monitoring devices, operating system module, and supporting components (actuators, cables, wiring harnesses, printed circuit boards etc.) Some designs will emerge where the system is completely sealed and no tie rods will be used, more like conventional batteries.

The bipolar and cooling plates are typically made from a conductive molded thermoset and thermoplastic resin material (usually highly filled with graphite) or a corrosion resistant metal.