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Design analysis of PEMFC bipolar plates considering stack manufacturing and environment impact

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Abstract

Stack and vehicle performance, design for manufacturing, and design for environment principles are used to develop bipolar plate design requirements and analyze design concepts for PEM fuel cells. Specifically, a list of 18 requirements identified in the literature is extended to 51 requirements and design rules. Given these design requirements, engineering characteristics or metrics used to indicate how well different bipolar plate designs meet each requirement and related targets and benchmarks are identified. Next, a subset of the engineering characteristics are used to evaluate six example bipolar plate designs made from graphite, stainless steel, and carbon composite in solid and integrated cooling configurations for a specific hybrid vehicle. For the case study of bipolar plates, correlations are interpreted for the considering relationships to compressive strength, the mass of the bipolar and cooling plates, the size of the stack required to move the 'generic vehicle', stack volume, disassembly efficiency, and select manufacturability metrics. Also, advantages and disadvantages specific to materials and design configurations are presented and discussed. Finally, power density and specific volume without consideration for vehicle performance was found not to be enough to assess the case study plates and, because of their common use in assessing fuel cell system design, is an important conclusion of this research.

Keywords: PEM fuel cells; Bipolar plates; Design requirements; Design for manufacturing; Design for environment

1. Introduction

In a fuel cell stack, bipolar (a.k.a. flow field or separator) plates typically have four functions: (1) to distribute the fuel and oxidant within the cell, (2) to facilitate water management within the cell, (3) to separate the individual cells in the stack, and (4) to carry current away from the cell. In the absence of dedicated cooling plates, the bipolar plates also facilitate heat management. Mehta and Cooper [1] note that plate topologies and materials facilitate these functions. Topologies can include straight, serpentine, or inter-digitated flow fields, rigid or flexible plates, internal or external manifolding, internal or external humidification, and integrated cooling. Also, plate materials can include graphite, a variety of coated or uncoated metals, and a number of composite structures. In fact, Mehta and Cooper reviewed over 100 topology-material combinations and related fabrication options for PEMFC bipolar plates.

For the many design options, bipolar plate design requirements have been proposed by many researchers and are summarized in Table 1. Here, requirements have been grouped into four categories: stack performance related design criteria, system performance (for the vehicle, building, or other product or process needing power) related design criteria, manufacturing related design criteria, and environmental impact related design criteria. Although most researchers who discuss bipolar plate design discuss the former two categories, fewer investigate manufacturing and environmental design requirements.

Given these bipolar plate design requirements, some studies specify engineering characteristics or metrics used to indicate how well different plate designs meet each requirement. Within this context, targets are the values for each engineering characteristic established by a baseline design, product developers, or others interested in the development or transfer of PEMFC technology. Specifically, previous studies have presented engineering characteristics both with and without specific targets. For example, Büchi and Ruge [7] suggest plate materials have an electric conductivity ≥ 10 S/cm, heat conductivity ≥ 20 W/m K, and gas tightness/permeation $< 10^{-7}$ mbar l/s cm^2. The targets for electric and heat conductivities are required to keep the voltage loss in the bipolar plate below 3% at full load and ensure

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Table 1
Summary of PEMFC bipolar plate design requirements (summarized from [1–8])

Category	Requirements
Stack performance related design criteria	Electrical resistance is minimized/conductivity is maximized Thermal resistance is minimized/conductivity is maximized Allows distribution of the fuel, oxidant, residual gases, and water without leaks Withstand mechanical loads during operation Resistant to corrosion/passivation in contact with an acidic electrolyte, oxygen, heat, and humidity. Minimizes differences in the coefficient of thermal expansion between metal plates and any coatings
System performance related design criteria	Mass/kW is minimized (plates should be lightweight) Volume/kW is minimized (plates should be slim) Stacks must operate in freeze and cold conditions. The design life is maximized
Manufacturing related design criteria	The stack is inexpensive to manufacture (materials, fabrication including machine tools, assembly, etc.) Plate designs should call for manufacturing processes with high yields relative to mass production Length/width should be system defined (flexible cross section) The plate surface finish requirements are minimized to increase manufacturing options Plate tolerances should be maximized to increase manufacturing options
Environmental impact related design criteria	Plate materials are recyclable at vehicle service, following a vehicle accident, or when the vehicle is retired Plates are made of recycled materials

low temperature gradients, respectively. The gas tightness target is required to prevent dangerous leaks to the exterior as well as cross leaks between the fluids in the stack. Also, Büchi and Ruge suggest a number characteristics without specific targets: the plates be corrosion resistance in contact with an acidic electrolyte, oxygen, heat, and humidity; that plates should be slim, light, and made using processes with a short production cycle, for minimal cost; and that design features should include the distribution of gases on and removal of product water from active area, heat removal, and the inclusion of manifolds for fluids.

Similarly, researchers at the Institute of Gas Technology [4] suggest targets based in part on their stack design (for molded composite graphite plates) and in part on targets suggested by the USDOE. Their targets are for conductivity (>100 S/cm measured by ASTM C-661), for corrosion ($<16\,\mu A/cm^2$) and for hydrogen permeability ($<16E\text{-}6\,cm^3/cm^2\,s$) for dry, non-porous plates. They also cite the performance of their plates including conductivity (250–350 S/cm), corrosion ($<5\,\mu A/cm^2$), and hydrogen permeability rates ($<2E-6\,cm^3/cm^2\,s$ for dry, non-porous plates and a bubble pressure (15 psig) for wet, porous plates), for crush strength (>3000 psi), flexibility (3–6% deflection at midspan or a flexural strength 6420 psi), total creep (∼1% at 200 psi and 100 °C), a cell life of 5000 h and a water-cooled stack life of 2300 h, with a material cost ∼US$ 4/kW, and a manufactured cost <US$ 10/kW.

Given these requirements, engineering characteristics, and example targets and because PEMFCs are not yet in wide scale production, an opportunity exists to explore additional design requirements and engineering characteristics. For example, design literature is available for design for manufacturing (DFM), design for the environment (DFE) and life cycle design (LCD), design for maintenance, etc. Specifically, Redford and Chal [9] define DFM as the integration of product design and process planning into one common activity with the goals of cost reduction and quality improvements. When broadly defined, DFM can include consideration of fabrication, assembly, product reliability, safety, serviceability, and many other design goals. DFE is a technique to add consideration of environmental impacts within the design process. Again when broadly defined, LCD is a form of DFE that includes consideration of the product life cycle (from materials acquisition through manufacturing, product use and maintenance, and product retirement).

This research presents an analysis of bipolar plate design focusing on requirements for stack and automotive performance, DFM, and LCD. Specifically, the set of design requirements presented in Table 1 has been extended to better reflect current literature in each focus area and suggestions for engineering characteristics are made. As a case study, six bipolar plate designs for automotive applications are analyzed using the suggested engineering characteristics. The first design is made from solid non-porous graphite with flow fields either machined or molded on one side (for use next to cooling plates and current collectors) and on two sides for use elsewhere within the stack. The second design again uses non-porous graphite but incorporates integrated cooling. The third and fourth designs are made from stainless steel with the latter again incorporating integrated cooling. The fifth and sixth designs are made from carbon–graphite composites, again with and without integrated cooling.

2. Identification of design requirements

For this case study, design requirements for bipolar plates were identified using the method described by Rounds and

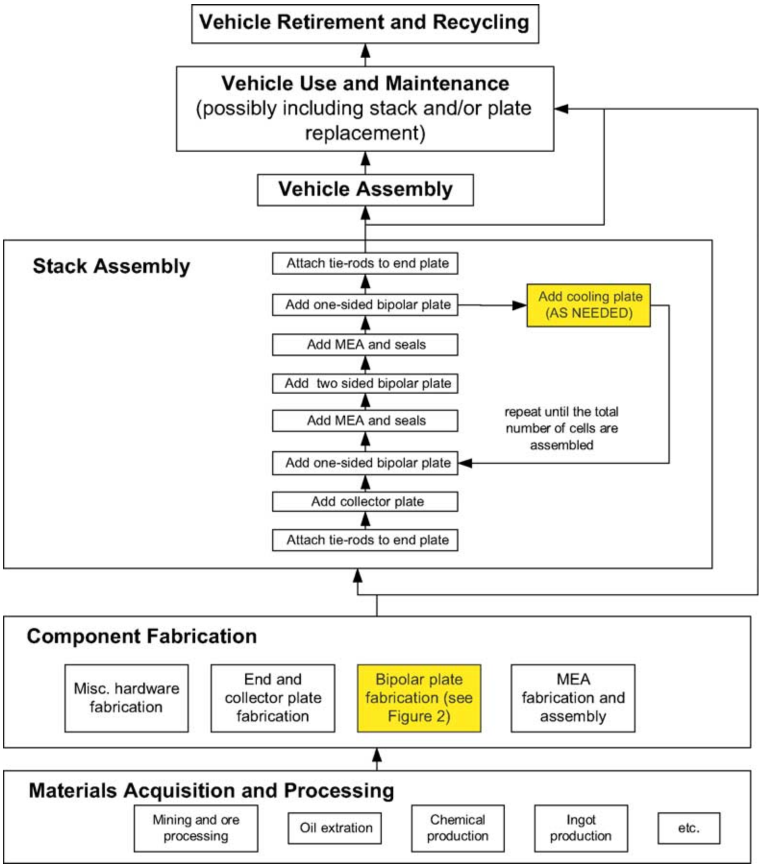

Fig. 1. Life cycle process flow diagram.

Cooper [10]. Specifically, they suggest three approaches to the development of design requirements including consideration of assembly and life cycle environmental issues. Rounds and Cooper's second approach (applied here) creates a taxonomy of environmental concerns for specific manufacturing processes. Here, the manufacturing processes of interest are plate fabrication and stack assembly and the goals of the design requirements are to reduce assembly time, to reduce fabrication scrap, improve ergonomics of assembly operations, and to improve energy efficiency for the life cycle of fuel cells used in vehicle power trains.

To create taxonomies for bipolar plate design, a process flow diagram was developed for the fuel cell vehicle life cycle for the six bipolar plate design concepts (see Figs. 1 and 2) and then a literature review was used to identify design features and requirements for each process that applied to the bipolar plates. For example, search terms included each process name (such as machining, molding, composite fabrication, assembly, etc.) and terms such as DFM, DFA, DFE, ergonomics, safety, materials, scrap, waste, electricity, fuel, and energy. To assist in this process, requirements were categorized as in Table 1 and with respect to stakeholders throughout the life cycle. The resulting 51 requirements are presented in Table 2 based on the fuel cell research cited above and a variety of DFM and DFE references [11–23]

Among the design requirements listed in Table 2, many additions and some changes were made to those presented in Table 1. Specifically, in the stack performance category, the requirement 'withstand mechanical loads during operation' was extended to include stack assembly, operation, or maintenance to better reflect the life cycle of the stack. Also, the requirement 'maximize power density' was added to reflect differences in stack performance for different plate designs.

For system performance, the requirements 'mass/kW is minimized (plates should be lightweight)' and 'volume/kW is minimized (plates should be slim)' were modified to consider vehicle performance as opposed to stack performance. This change was made to ensure the requirements account for differences in stack performance and mass for different plate designs. Specifically, for an equitable comparison of bipolar plates, "mass compounding" or changes in the mass of the power train that equate to changes in mass of the vehicle that equate to changes in the power requirements to move an equivalent vehicle must be considered. In this context, an equivalent vehicle moves the same payload with the same acceleration (e.g. 0–100 km/h in 12 s), hill climbing (maintaining a certain speed on a certain grade), cruise and top speeds, and range. Also, the requirement 'minimize fuel use during stack use' has been added to again reflect differences in stack performance and mass for equivalent vehicles.

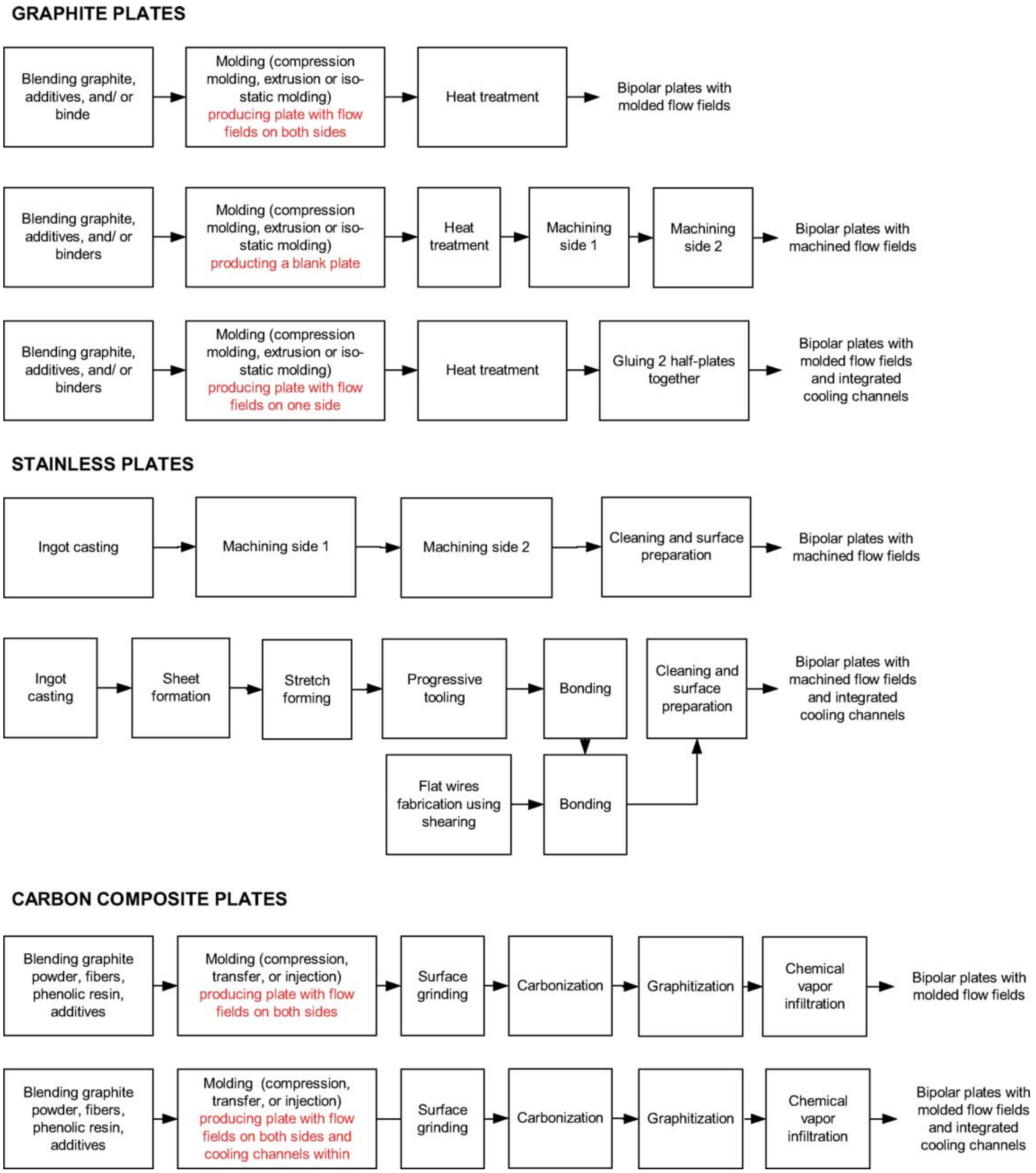

Fig. 2. Bipolar plate fabrication for six design concepts.

For the requirements related to manufacturing, the very broad requirement ‘the stack is inexpensive to manufacture (materials, fabrication including machine tools, assembly, etc.)’ has been replaced by many DFM requirements intended to reduce fabrication and assembly costs. For example, requirements such as ‘allow generous clearance,’ ‘design self-aligning and locating parts that cannot be installed incorrectly,’ and ‘maximize symmetry or make plates obviously asymmetrical’ make assembly easier and ultimately improve the efficiency of assembly operations and reduce defects. Also, most of these cost-reducing requirements also facilitate stack maintenance.

For the requirements related to the environment, the requirements focusing on the use of recycled and recyclable materials have been extended to include consideration of materials acquisition and processing, plate reuse, and the separatability of recyclable materials. Specifically, requirements have been added for energy intensity, abundance, and distribution. Also, recyclability now includes not only whether the material can be recycled but also whether the material can be separated for recycling at vehicle service, following a vehicle accident, or when the vehicle is retired.

3. Identification of engineering characteristics

For each requirement presented in Table 2, knowledge of the bipolar plate materials and topologies, materials selec-

Table 2
Extended list of bipolar plate design requirements

	Design requirements	Material acquisition and processing (requirements for material processors and suppliers)	Product design and manufacturing (requirements for plate designers and fabricators, stack designers, stack assemblers and testers)	Product use, maintenance, and reuse (requirements for stack purchasers and vehicle engineers, product users, product maintainers, secondary market users)	Vehicle retirement and material recovery (requirements for product disassemblers and material recyclers)
Stack performance related design criteria	Allows distribution of the fuel, oxidant, and residual gases and liquids without permeation or leaks		×		
	Electrical resistance is minimized/conductivity is maximized		×		
	Resistant to corrosion/passivation in contact with an acidic electrolyte, oxygen, heat, and humidity		×		
	The plate should be mechanically sound during stack assembly, operation, or maintenance		×		
	Thermal resistance is minimized/conductivity is maximized		×		
	Maximize power density		×		
	Minimize differences in the coefficient of thermal expansion between metal plates and any coatings		×		
Vehicle performance related design criteria	Maximize design life			×	
	Minimize fuel use during stack use			×	
	Minimize stack mass		×	×	
	Minimize stack volume		×	×	
	Stacks must operate in freeze and cold conditions.		×	×	
	Length/width should be system defined (flexible cross section)		×	×	
Manufacturing related design criteria	Accessible and visible within the stack and system		×	×	
	Allow generous clearance		×	×	
	Avoid creating the need for a new or expanded facilities		×	×	
	Avoid heavy parts		×	×	
	Avoid sharp, delicate, slippery, or sticky surfaces		×	×	
	Avoid tasks that require repetitive motion		×	×	
	Avoid the use of equipment that produces loud noise or vibrates		×	×	
	Avoid the use of materials (lubricants, etc.) that contribute to climate change in parts or as assembly aids		×	×	
	Avoid very large or very small parts		×	×	
	Design for disassembly (ease part separation from product, assists in rework, maintenance, and recycling)		×	×	
	Design self-aligning and locating parts that cannot be installed incorrectly		×	×	
	Design so parts can be easily accessed and assembled from a single station		×	×	
	Ease separation of parts from bulk (same part separation from bins)		×		
	Eliminate adjustments and reorientation		×	×	
	Ensure easy operation of tools and equipment		×	×	
	Ensure selected fabrication and assembly processes can be performed by local, readily available equipment		×	×	
	Low fabrication and assembly times		×	×	
	Maximize symmetry or make plates obviously asymmetrical		×	×	
	Minimize depth and force of insertion		×	×	
	Minimize number of operations and the quantity and variety of tooling required		×	×	
	Minimize number of parts		×	×	
	Minimize variety of parts		×	×	
	Modularize subassemblies		×	×	
	Plate and processing materials are inexpensive		×	×	
	Plate designs should call for manufacturing processes with high yields relative to mass production		×	×	
	Plate tolerances should be maximized		×	×	
	Provide smooth bearing surfaces for insertion		×	×	
	The plate surface finish requirements are minimized		×	×	
	Use standard parts and processes		×	×	
	Utilize fixturing as needed to ensure alignment		×	×	
Environmental impact related design criteria	Plates are made of recycled material	×			×
	Select local material suppliers	×			
	Use abundant materials	×			
	Avoid the use of energy intensive materials for plates, assembly tools, and fixtures	×			
	Label parts to instruct reuse or recycling				×
	Plates are made of recyclable material				×
	Plates are reusable				×
	Recyclable materials are easily separated from the stack at vehicle service, following a vehicle accident, or when the vehicle is retired				×

tion metrics, and processing and assembly methods were used to develop related engineering characteristics. Specifically, metrics were based on those identified in fuel cell design research [1,4,7] and those suggested by Rounds and Cooper [10] as related to assembly processes and environmental requirements [24–26]. The results are presented in Table 3.

Among the engineering characteristics listed, many are presented on the basis of an equivalent vehicle. Again this relates to the need to compare bipolar plate designs for vehicles with the same performance.

Information needed to generate values for the 69 unique engineering characteristics presented in Table 3 are the location of material suppliers and manufacturing facilities, manufacturing process flows, manufacturing process time, material and manufacturing costs, plate configuration, plate insertion tests, plate materials, stack configuration (the type of bipolar plates, the pitch of any cooling plates, etc.) and stack performance tests. In other words, this information is needed to use all the engineering characteristics to analyze a set of possible stack designs.

For the analysis of the six plate designs in the case study, a subset of the 69 engineering characteristics presented in Table 3 was used. Specifically, the 69 metrics were categorized as *used in the case study* (see the analysis to follow); *assumed to be the same for all designs* (including finish, clearance dimension, hydrogen permeability, the number of large parts, assembly stations, tools for assembly and disassembly, accessibility within the stack, difficulty in separating parts from bins, plate symmetry, and sharp, delicate, or sticky surfaces); *not applicable to the six designs* (the thermal expansion differences[1]); and *those left for future research*. Also, the requirements for labeling the plates for recycling and using fixtures for part alignment were reclassified as a design feature or design rule.

4. Design concept analysis

For the case study, the first design is made from solid non-porous graphite with flow fields either machined or molded on one side (for use next to cooling plates and current collectors) and on two sides for use elsewhere within the stack. This design is considered typical in today's PEM fuel cells. The second design again uses non-porous graphite but incorporates integrated cooling based on the plates described by Büchi and Ruge [7] at 330 W/kg. Specifically, to provide a void for cooling fluid in the middle of the graphite plate, the plate is composed from two half-plates united by a gluing process. A complete two-sided bipolar plate has a thickness of 3.1 mm and a weight of approximately 130 g for 200 cm^2 of active area.

The third and fourth designs are made from stainless steel. Specifically, the third design is a solid machined stainless steel plate based on those described by Davies et al. [27]. These researchers describe analyses of both coated and uncoated stainless steel that can be shaped into thin sheets that result in lower cost, high strength, easy to fabricate bipolar plates. Even though polarization was impacted by oxide film at the plate surface, one the film was formed performance was maintained for over 3000 h. The fourth design incorporates integrated cooling based on the plates described by Allen [28]. He developed a modular metallic bipolar plate that provides for parallel flow of coolants within each sub-section. Also, flat wire current collectors are bonded to the diffusion electrode or to the flow channels of the bipolar plate.

The fifth and sixth designs are made from carbon–graphite composites. The fifth design is based on the plates described by Besmann et al. [29]. The plate is made from phenolic resin with graphite particulate filler. The sixth design incorporates integrated cooling based on the plates described by Onischak et al. [4]. They describe a composite plate with flow fields on one side and water flow channels on the other with performance about 3% lower performance of ∼15 mV at 400 mA/cm^2 mainly due to the slightly higher surface resistance.

Thirty of the 69 engineering characteristics presented in Table 3 were used in the analysis of the six bipolar plate designs. The results are presented in Table 4 given the plate design characteristics described above, an analytical model used to size fuel cells for an equivalent vehicle, and assembly time and disassembly efficiency analysis methods as described in Table 5 and as follows.

5. Sizing stacks for an equivalent vehicle

For an equitable comparison of bipolar plate designs, several of the engineering characteristics are presented on the basis of the fuel cell power required for a specific vehicle including consideration of: (1) parasitic losses for supporting systems (for air compression, cooling, fuel storage, fuel delivery, humidification, intake, inverter, water circulation systems, and vehicle accessories) (2) integration losses, and (3) mass compounding. For the case study, a model developed by Crawford [30] combines the fuel cell and vehicle design models developed at Directed Technologies, MIT, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and by Bosch [31,37–45] to create a single model that uses vehicle design parameters and expected fuel cell performance to estimate fuel cell and battery power requirements. Based on the power requirements, Crawford's model can be used to estimate the several of the engineering characteristics.

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[1] The six case study plates are impermeable and the metallic plates are not coated. Within this context, Davies suggests coatings are not needed for stainless steel plates because the nickel and chromium alloying elements provide sufficient corrosion protection to reduce resistance to a tolerable level [27].

Table 3
Bipolar plate engineering characteristics

Design requirements	Engineering characteristics[a]
Allows distribution of the fuel, oxidant, and residual gases and liquids without permeation or leaks	Hydrogen permeability ($\mathrm{cm^3/s\,cm^2}$) (dry, non-porous plates) Bubble pressure (psig) (wet, porous plates) Mean time between failure (hours)
Electrical resistance is minimized/conductivity is maximized	Resistivity of a material (Ω m) or conductivity (S/cm)
Resistant to corrosion/passivation in contact with an acidic electrolyte, oxygen, heat, and humidity	Corrosion or passivation related reduction in performance ($\mu\mathrm{A/cm^2}$)
The plate should be mechanically sound during stack assembly, operation, or maintenance	Compressive strength (Pa) (relates to the goal for "crush strength") Total creep (%) Plate thickness for the desired stiffness (cm with stiffness as the deflection for a given load)
Thermal resistance is minimized/conductivity is maximized	Thermal resistance ($\mathrm{m^2\,{}^\circ C\,s/Btu}$) or thermal conductivity (W/m K)
Maximize power density	Power density ($\mathrm{W/cm^2}$) Stack power per equivalent vehicle (kW/vehicle)
Minimize differences in the coefficient of thermal expansion between metal plates and any coatings	ΔCTE ($\mathrm{K^{-1}}$)
Maximize design life	Life of stack (hours of operation based on different start-up scenarios)
Minimize fuel use during stack use	Fuel use (kg/195,000 km) Plate mass (kg) Mass of bipolar and cooling plates per equivalent vehicle (kg/vehicle)
Minimize stack mass	Stack specific mass (kg/kW) Mass of stack per equivalent vehicle (kg/vehicle)
Minimize stack volume	Plate thickness (cm) Specific volume ($\mathrm{m^3/kW}$) Stack volume per equivalent vehicle ($\mathrm{m^3}$/vehicle)
Stacks must operate in freeze and cold conditions	Freeze and cold performance reductions (%)
Length/width should be system defined (flexible cross section)	Plate cross section can be specified by vehicle designers (yes or no)
Accessible and visible within the stack and system	Plates are accessible and visible within the stack (yes or no)
Allow generous clearance	Clearance dimension (mm)
Avoid creating the need for a new or expanded facilities	Area of new facility required ($\mathrm{m^2}$)
Avoid heavy parts	Plate mass (kg) Mass of bipolar and cooling plates per equivalent vehicle (kg/vehicle)
Avoid sharp, delicate, slippery, or sticky surfaces	Sharp, delicate, or sticky surfaces per equivalent vehicle (number of/vehicle)
Avoid tasks that require repetitive motion	Number of parts per equivalent vehicle (number of/vehicle)
Avoid the use of equipment that produces loud noise or vibrates	Time with loud or vibrating equipment per equivalent vehicle (min/vehicle)
Avoid the use of materials (lubricants, etc.) that contribute to environmental impact in parts or as assembly aids	Manufacturing environmental impact potentials per equivalent vehicle (equivalents/vehicle, see discussion)
Avoid very large or very small parts	Large parts per equivalent vehicle (number of/vehicle) Small parts per equivalent vehicle (number of/vehicle)
Design for disassembly (ease part separation from product, assists in rework, maintenance, and recycling)	Disassembly efficiency (unit less, see below)
Design self-aligning and locating parts that cannot be installed incorrectly	Non-self-aligning and locating parts per equivalent vehicle (number of/vehicle)
Design so parts can be easily accessed and assembled from a single station	Number of assembly operations per equivalent vehicle (number of/vehicle)
Ease separation of parts from bulk (same part separation from bins)	Plates are difficult to separate from each other (yes or no)
Eliminate adjustments and reorientation	Number of adjustments and reorientations per equivalent vehicle (number of/vehicle)
Ensure easy operation of tools and equipment	Time with difficult equipment (min/plate fabrication and stack assembly)
Ensure selected fabrication and assembly processes can be performed by local, readily available equipment	Distance from plate fabrication to assembly (km) Number of non-standard processes per equivalent vehicle (number of/vehicle)
Low fabrication and assembly times	Fabrication time (min)

Table 3 (*Continued*)

Design requirements	Engineering characteristics[a]
	Stack assembly time (min)
Maximize symmetry or make plates obviously asymmetrical	Plates are symmetrical or obviously asymmetrical (yes or no)
Minimize depth and force of insertion	Length of stack (for depth of insertion) (m) Insertion force (N)
Minimize number of operations and the quantity and variety of tooling required	Number of fabrication operations per plate (number of/plate) Number of assembly operations per equivalent vehicle (number of/vehicle) Number of tools for stack assembly (number of/vehicle) Number of different tools for stack assembly (number of/vehicle)
Minimize number of parts	Number of parts per equivalent vehicle (number of/vehicle)
Minimize variety of parts	Number of different parts per equivalent vehicle (number of/vehicle)
Modularize subassemblies	Number of different parts per equivalent vehicle (number of/vehicle)
Plate and processing materials are inexpensive	Material cost ($) Fabrication cost ($) Assembled cost ($)
Plate designs should call for manufacturing processes with high yields relative to mass production	Fabrication process economic batch size (units) Number of parts per equivalent vehicle (number of/vehicle)
Plate tolerances should be maximized	Tolerance (mm)
Provide smooth bearing surfaces for insertion	Finish (μm)
The plate surface finish requirements are minimized	Finish (μm)
Use standard parts and processes	Number of non-standard parts per equivalent vehicle (number of/vehicle) Number of non-standard processes per equivalent vehicle (number of/vehicle)
Utilize fixturing as needed to ensure alignment	Number of fixtures needed (number of)
Plates are made of recycled material	Recycle fraction (%)
Select local material suppliers	Distance from material supplier to plate fabrication (km)
Use abundant materials	Amount of catalyst per equivalent vehicle (g/vehicle) Abundance category (infinite, ample, adequate, potentially limited, or potentially highly limited supply, see [25])
Avoid the use of energy intensive materials for plates, assembly tools, and fixtures	Material energy content per equivalent vehicle (MJ/vehicle) Energy content of assembly tools and fixtures per equivalent vehicle (MJ/vehicle)
Label parts to instruct reuse or recycling	Number of labeled parts/number of unlabeled parts per equivalent vehicle (/vehicle)
Plates are made of recyclable material	Recyclability = recycle fraction × mass recyclable per equivalent vehicle (kg/vehicle) % recyclable = recyclable mass/stack mass (/equivalent vehicle)
Plates are reusable	Plates are reusable (yes or no)
Recyclable materials are easily separated from the stack at vehicle service, following a vehicle accident, or when the vehicle is retired	Disassembly efficiency (unit less, see below) Number of different tools required for disassembly per equivalent vehicle (number of/vehicle) Number of tools required for disassembly per equivalent vehicle (number of/vehicle)

[a] Engineering characteristics marked with an asterik (∗) are included in the case study presented below.

Specifically, Crawford [30] and Cooper [33] provide detail on the mathematical development of the power requirements model and the assumptions and parameter values that can be evaluated. The model uses a high power fuel cell (at 0.6 V) with a short-term power requirement based on the acceleration of the vehicle, an acceleration speed goal, a rotational inertia coefficient, the loaded vehicle mass after mass compounding, the vehicle power loss during acceleration and hill climbing, accessory loads, and integration and parasitic losses to estimate the power needed of all energy production systems. Thus, based on a set of vehicle design information (the mass of the vehicle, the frontal area, the drag coefficient, and the coefficient of rolling resistance), vehicle performance information (acceleration, hill climbing (maintaining a certain speed on a certain grade), cruise and top speeds, and range), and fuel cell design information (cell voltage, current density, active area, and various material loadings) the model developed by Crawford allows

Table 4
Analysis of bipolar plate designs

Engineering characteristics	Solid graphite	Solid stainless plate	Solid carbon composite plate	Graphite with integrated cooling	Stainless with integrated cooling	Carbon composite with integrated cooling	Published targets or benchmarks for comparison
Plate thickness for equivalent stiffness (m)	0.0024	0.0013	0.0019	0.0031	0.0017	0.0025	0.002–0.003 m [30]
Compressive strength (MPa)	27–58	170–1000	50–60	unknown	unknown	unknown	Not found
Power density (kW/m^3)	902 kW/m^3	953 kW/m^3	773 kW/m^3	972 kW/m^3	1230 kW/m^3	905 kW/m^3	PNGV goals for fuel cell systems range from 300 kW/m^3 for 1997 to a goal of 500 kW/m^3 for 2004 [31]. Also, GM's latest stack cites a power density of 1750 kW/m^3 [6]
Stack power per equivalent vehicle (kW/vehicle)	70	90	86	69	88	84	[32] lists power for prototype sedans (the 'generic vehicle' class) ranging from 50–100 kW. Also, GM's latest stack has a design power of 102 kW with a peak power of 129 kW [6]
Stack specific mass (kg/kW)	2.63	3.85	1.83	1.44	3.30	1.26	DOE Technical Target of 2.9 kg/kW by 2000 and 2.0 kg/kW by 2004. Also, GM's latest stack cites a specific mass of 0.8 kg/kW [6]
Mass of stack per equivalent vehicle (kg/vehicle)	185	345	158	99	290	106	Not found
Mass of each bipolar plate (kg)	0.50	0.63	0.19	0.29	0.63	0.19	0.3–0.6 kg (adjusted for the plate area in the case study) [30]
Mass of bipolar and cooling plates per equivalent vehicle (kg/vehicle)	165	319	131	77	262	77	Not found
Specific volume (l/kW)	1.11	1.05	1.29	1.03	0.81	1.11	DOE Technical Target of 2.9 L/kW by 2000 and 2.0 L/kW by 2004. Also, GM's latest stack cites a specific volume of 0.57 L/kW [6]
Stack volume per equivalent vehicle (l/vehicle)	78	94	112	71	71	93	GM's design is 74 L/vehicle based on peak power [6]
Fuel use (kg/195,000 km)	2,745	3,498	3,365	2,690	3,416	3,286	Not found
Number of parts per equivalent vehicle (number of/vehicle)	1346	2135	2152	1226	1879	1894	Not found
Small parts per equivalent vehicle (number of/vehicle)	0	0	0	136	209	211	Not found
Number of assembly operations per equivalent vehicle (number of/vehicle)	135	214	216	136	209	211	Not found
Stack assembly time (min)	48	92	110	53	82	108	Not found
Length of stack (for depth of insertion) (m)	1.25	1.51	1.79	1.14	1.14	1.49	Not found
Number of fabrication operations per plate (number of/plate)	∼3–5	∼4	∼6	∼4	∼8	∼6	Not found

Table 4 (*Continued*)

Engineering characteristics	Solid graphite	Solid stainless plate	Solid carbon composite plate	Graphite with integrated cooling	Stainless with integrated cooling	Carbon composite with integrated cooling	Published targets or benchmarks for comparison
Number of different parts per equivalent vehicle (number of/vehicle)	8	8	8	8	8	8	Not found
Tolerance (mm)	0.001–1	0.001–1	0.025–1	0.001–1	0.04–1	0.025–1	Not found
Disassembly efficiency (unit less)	51%	32%	32%	98%	64%	63%	Not found
Plate recycle fraction (%)	0.15–0.20	0.65–0.90	0.65–0.70	0.15–0.20	0.65–0.90	0.65–0.70	Not found (ideal is 1.0)
Amount of catalyst per equivalent vehicle (g/vehicle)	117	187	188	119	183	184	10–400 g/vehicle for sedans at loadings ranging from 0.4 to 4 g/kW [33]
Material energy content per equivalent vehicle (MJ/vehicle)	25,521	42,806	22,821	10,001	27,864	8,007	Not found
Recyclability = recycle fraction × mass recyclable per equivalent vehicle (kg/vehicle)	47–57	216–248	94–104	14–18	173–200	53–57	Not found
Plates are reusable (yes or no)	no	possibly	no	no	possibly	no	Handley et al. [34] suggest stainless may be durable enough to be reused but note that rapid design changes will impact reusability
% recyclable = recyclable mass/stack mass (/equivalent vehicle)	90%	93%	84%	82%	92%	76%	Not found

for analysis of a wide range of vehicle and fuel cell designs (combinations of different fuel cell stacks in different types of vehicles for select power management schemes).

Table 6 presents the example application of Crawford's fuel cell sizing model to hybrid fuel cell vehicles using the six fuel cells described above. All three power trains are intended to power the "generic vehicle" described by Sullivan et al. [46]. The generic vehicle power train is assumed to have a mass of 418 kg or 27% of the total vehicle mass of 1532 kg. For the fuel cell vehicles, the base glider mass of 1113 kg is assumed to linearly increase with increases in the power train mass. Assuming for each fuel cell vehicle the acceleration (a) is 2.24 m/s^2, the acceleration speed goal (v) is 28.8 m/s, the rotational inertia coefficient (km) is 1.00, and the drive train, fuel cell integration, and battery integration efficiencies (η_{dt}, η_{ifc}, η_{ib}) are 0.95, 0.91, and 0.93 respectively, the results in Table 6, show fuel cell power ranges from 69 to 90 kW for the one vehicle.

For comparison, Cooper [33] summarizes fuel cell power requirements for prototype and demonstration vehicles described in Fuel Cells 2000 [32] with omissions for four reasons: because the use the fuel cell is used only as an auxiliary power unit (APU), the fuel cell power or maximum speed was not specified, the maximum speed was less than 97 km/h (60 mph), or the vehicles were built prior to 1995. For the remaining vehicles, the fuel cell power for the fuel cell only configurations ranges from 50 to 94 kW and from 20 to 100 kW for the hybrid vehicles with the power for sedans (the 'generic vehicle' class) ranging from 50 to 100 kW. Also, power density is high and specific mass and volume are low in relation to the PNGV goals but within the range anticipated when GM's design is considered. In fact, within the context of stack design, the current GM design [6] reports 1.75 kW/l and 1.25 kW/kg for their 2001 fuel cell stack. In his evaluation, the elimination of the need for external humidification reduced part count by 62% and the cost of catalyst by 50% as well as made the stack capable of freeze start at −40 °F.

These variations, in the application of the Crawford model and in the summary presented by the *Fuel Cells 2000* summary, are the result of so many design options related to fuel cell and supporting system performance and how power is managed within the vehicle. For example, design options such as high efficiency or high power fuel cell operation, regenerative breaking, variations in the type of and power of batteries, Honda's ultra capacitor system, and GM's no-humidification design will have substantial impact on the size of the fuel cells in production vehicles and ultimately the related material intensities of the power trains. Given these variations in how power might be managed in production vehicles and variations based on how fuel cells might be designed (as represented by the three designs described above), understanding the exact power requirements is quite difficult. For the case study, how stack and vehicle design parameters might impact a single power management scenario (that suggested by the Crawford model) is analyzed as an example recognizing that evaluation of other design scenarios is an area for further study.

Table 5
Methodologies and data sources used for the estimation of engineering characteristics

Engineering characteristics	Methodologies and data sources
Plate thickness for equivalent stiffness	Estimated using the model described by Cooper [33]. Also, it has been assumed that the thickness of integrated cooling plates is 1.3 times the thickness of the solid plates
Compressive strength	Strength data from [35]. Also, because integrated cooling will change mechanical properties, values are listed as unknown
Power density	Estimated using the model described by Crawford [30] in the section describing fuel cell sizing as described below
Stack power per equivalent vehicle	
Stack specific mass	
Mass of stack per equivalent vehicle	
Plate mass	
Mass of bipolar and cooling plates per equivalent vehicle	
Specific volume	
Stack volume per equivalent vehicle	
Fuel use	Estimated using the model described by Thomas et al. [31] as described in the energy analysis presented below
Number of parts per equivalent vehicle	Estimated as part of the assembly time and disassembly efficiency analysis as described below
Small parts per equivalent vehicle	
Number of assembly operations per equivalent vehicle	
Stack assembly time	
Length of stack	Estimated using the model described by Crawford [30] in the section describing fuel cell sizing as described below
Number of fabrication operations per plate	Estimated based on Fig. 2. Note that because no method was defined to determine the level of abstraction for each process in the flow diagram, these values should only be used as a guide. Further research is needed to develop such a methodology
Number of different parts per equivalent vehicle	Estimated as part of the assembly time and disassembly efficiency analysis as described below
Tolerance	Based on range of processes in Fig. 2 for each part and the tolerance suggested by [35]
Disassembly efficiency	Estimated as part of the assembly time and disassembly efficiency analysis as described below
Plate recycle fraction	Data from [35]
Amount of catalyst per equivalent vehicle	Estimated using the model described by Crawford [30] in the section describing fuel cell sizing as described below
Energy content per equivalent vehicle	Data from [35]. Includes bipolar plates, cooling plates, hardware, and catalyst. Estimated as described in the energy analysis presented below
Recyclability	Recyclability has been defined as the recycle fraction times the mass recyclable per equivalent vehicle. Recycle fraction data from [35] and the mass recyclable has been estimated using the model described by Crawford [30] in the section describing fuel cell sizing as described below. Includes bipolar plates, cooling and current collector plates, hardware, and catalyst
Plates are reusable	Handley et al. [34] suggest that because the design of plates will rapidly change, plates will not be reusable. Alternatively, Cooper [36] suggests there will be limited reuse opportunities for metallic plates which should be the most durable among those evaluated in the case study
% recyclable	Percent recyclable has been defined as the recyclable mass/stack mass. Estimated using the model described by Crawford [30] in the section describing fuel cell sizing as described below

Given the power requirements for equivalent vehicles, Crawford [30] combines the fuel cell design information presented by Gottesfeld and Zawodski [47], Woodman et al. [48], Kimble et al. [49], and others in the development of a method to estimate material masses and component volumes for PEM fuel cells dependent upon the cell current density (A/cm^2), the cell voltage (V), and the active area per cell (cm^2) and component design information including the density and thickness of the all plates, the gas diffusion layer, and membrane, the pitch of the cooling plates, the catalyst loading, and the ratio of the active area to the total area for all components. Then, for many stack designs, cells can be combined to obtain the desired power for the system.

For the case study, Crawford's model has been applied here to the six stacks. Power densities have been estimated relative to the baseline-graphite design which was assumed to operate at 0.6 V with a current density of 1 A/cm^2. Specifically, Davies et al. [27] noted an 80% reduction in performance between a cell with graphite and a stack with stainless steel plates at 0.6 V. Similarly, Busick and Wilson [50] noted a 76% reduction between a stack with graphite and a cell with composite plates at 0.6 V. These values have been applied to both the solid and cooled stainless and composite designs. The performance of the graphite plate with integrated cooling was based on a current density of 0.97 as suggested by Büchi and Ruge [7]. Also, it has also been assumed that this

Table 6
Example sizing of systems for a fuel cell vehicle

	Assumed FC performance at 0.6 V (A/cm^2)	Estimated power train mass (kg)	Adjusted loaded vehicle mass (kg)	Vehicle power loss during acceleration (kW)	Vehicle power loss during hill climbing (kW)	Parasitic losses and accessory loads (kW)	Power required for acceleration (kW)	Fuel cell power (kW)	Battery power (kW)
Solid graphite plates	1.00	533	1645	15.3	39.2	27.5	119	70	86
Solid stainless steel plates	0.80	762	1875	15.4	42.7	42.9	134	90	98
Solid composite plates	0.76	543	1656	15.3	39.3	43.2	120	86	87
Graphite plates with integrated cooling	0.97	436	1548	15.3	37.6	27.8	113	69	81
Stainless steel plates with integrated cooling	0.80	696	1808	15.4	41.7	42.0	132	88	97
Composite plates with integrated cooling	0.76	482	1594	15.3	38.4	42.3	116	84	83

performance scales up to stacks, which may not hold true.

To complete the power train, the consideration of supporting equipment, batteries, and the transmission is also important. Masses for the fuel cell's supporting equipment (including the motor-inverter, battery controller, cooling system, humidification system, cables/miscellaneous, fuel storage) suggested by Little [51] and Karakoussis [52] have been added to those estimated by Crawford's model for the stack materials. For the batteries, the battery power needed for either hybrid or fuel cell only configurations can be represented by a specific power range from 0.4 to 1.26 kW/kg [31,43]. For the transmission, based on the work of Thomas et al. [31], the transmission mass is approximately 27 kg for an 82 kW drive train. This assumes a single ratio transmission, or a gearbox. Also, the transmission is not assumed to be directly proportional to power. Instead, Crawford suggests the carbon steel transmission components will scale based on the motor power such that the mass of the transmission is estimated as $27 + 0.01$ (motor power-82).

Stack design information for the three stacks is presented in Table 7. Important among the parameters listed is the thickness of the bipolar plates. For the solid plates, it has been assumed that, using the graphite plates as a baseline, the stainless steel and composite plates must provide equivalent stiffness (deflection for a given load). The method used to estimate plate thickness is detailed in Cooper [53]. Also, it has been assumed that the thickness of integrated cooling plates is 1.3 times the thickness of the solid plates. From these values, the densities for the stainless steel and composite plates with integrated cooling are estimated assuming a mass the same as its solid plate counterpart considering the differences in thickness and the density of the graphite plate with integrated cooling is based on the value provided by Büchi and Ruge [7] adjusted for the difference in the plate area.

Given the power requirements presented in Table 6 and the fuel cell design parameters presented in Tables 6 and 7, the power density, stack power, volume and specific volume of the stack, the mass, and specific mass of stack, and the amount of catalyst used were estimated. Also, the recyclable mass was estimated as the mass of each plate material, the aluminum for cooling and current collector plates, the steel for hardware, and the platinum catalyst assuming the stack would be disassembled to create uncontaminated recyclates. The results are presented in Table 4.

6. Assembly and disassembly assessments

The assembly and disassembly assessments described by English [54] and Kroll et al. [24] were used not only to estimate assembly time and disassembly efficiency but also to approximate how the fuel cell components might flow of through each process. For both analyses, each stack was divided into subassemblies based on the need for cooling

Table 7
Fuel cell design parameters

Design parameter	Values	References from which parameter values were identified
Active area	440 cm^2	[51]
Bipolar plate thickness and density	Solid graphite: 0.24 cm and 2260 kg/m^3 Solid Stainless Steel: 0.13 cm and 7800 kg/m^3 Solid Composite: 0.19 cm and 1540 kg/m^3 Graphite with Integrated Cooling: 0.31 cm and 800 kg/m^3 Stainless Steel with Integrated Cooling: 0.17 cm and 4052 kg/m^3 Composite with Integrated Cooling: 0.25 cm and 999 kg/m^3	[53]
Cooling and current collector plate thickness and density (cooling plates for solid plate stacks)	0.24 cm and 2.71 g/cm^3	[30]
Cooling plate pitch (for solid plate stacks)	2	[30]
End plate thickness and density	1.78 cm and 2.71 g/cm^3	[30]
Gas diffusion layer thickness and density	0.03 cm and 400 kg/m^3	[47]
Catalyst loading	1 mg/cm^2 for both electrodes	[30]
Ratio of the active to total area	70%	[51]

plates. For the solid plate designs, each subassembly designs included two cells and contained a cooling plate next to a one-sided bipolar plate, a MEA with two seals, a two-sided bipolar plate, another MEA with two seals, and another one-sided bipolar plate. For the plates with integrated cooling, each subassembly included two cells and contained a two-sided bipolar plate, a MEA with two seals, a cooling fluid fitting, another two-sided bipolar plate, and another MEA with two seals. Additional half plates, current collection plates, end plates, and tie rods and related hardware were also included in each design as needed to complete each stack. Again, the results are presented in Table 4.

To estimate assembly time, the analysis begins with the development of an assembly flow chart to describe the sequence in which parts are assembled. Based on the process flow, English describes the ‘GE method’ which prescribes penalties for parts having multiple motions or actions during insertion or fastening and any action more difficult than a downward motion. For the case study, it was assumed the end plates with the tie rods installed would be fixtured to the floor to aid in assembly (given stack lengths varying from 1.25 to over 2 m for the six designs). A platform that lowers as assembly continues. Because of this operation, each subassembly is added to the stack in a downward motion which does not receive a penalty. Also, for the integrated cooling designs, addition of the cooling fluid fitting received a penalty of 20% for a horizontal motion and a penalty of 30% for a rotating motion. Also, the time to add each subassembly to the stack was estimated as 2 s times the length of the stack.

For the disassembly assessment, Kroll et al. [24] present a procedure for evaluating the ease of disassembly of products for recycling. 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 accessibility, position, force, and time) for each disassembly task. To estimate Kroll et al.’s disassembly efficiency, the ideal number of subassemblies was taken to be that of the graphite plate with integrated cooling design. This design has the fewest subassemblies (and the fewest parts) among the designs analyzed however did not receive a disassembly efficiency score of 100% due to a time penalty associated with removing cooling fluid fittings. Other designs were therefore penalized for additional subassemblies and the disassembly tasks that accompany them. Application of the method also assumed that all fluids were removed prior to hardware removal, that all subassemblies were removed up the tie rods (in a single direction), that the stack would be fixed to the floor by one of the endplates to aid in disassembly with a platform available to raise the stack as disassembly continues, that nothing fuses or becomes brittle during stack operation (parts are not difficult to remove), and that subsequent disassembly of each subassembly is the same for all designs.

7. Energy analysis

The energy analysis for the case study included an analysis of the energy content of materials in each stack and an analysis of fuel use during stack operations. Fig. 3 (and Table 4) present the results of the energy analyses based on the energy content analysis method provided by Granta Design [35] and the fuel use analysis presented by Thomas et al. [31]. Specifically, Granta Design provides a range of energy content values (MJ/kg) for use in materials selection. They define energy content as the energy needed to acquire and process materials for use in manufacturing (e.g., for machining, injection molding, etc.). For the case study, the energy content value for each material is multiplied by the amount of material used in each stack, which does not include the amount wasted in manufacturing (this is left for future research). The analysis included materials

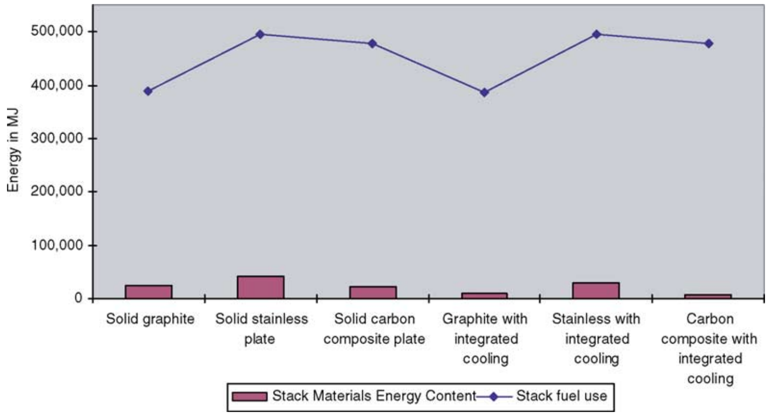

Fig. 3. Energy analysis.

used in bipolar plates, cooling plates, hardware, and catalyst with the remainder of the materials also left for future research.

Thomas et al. [31] performed fuel use calculations based on federal driving schedules over 611 km (380 miles). The specific driving schedule is 55% Federal Highway Driving Schedule (FHDS) and 45% Federal Urban Driving Schedule (FUDS). To update the aging driving schedule, the acceleration speeds where multiplied by 1.25. This modification is claimed to more closely meet current driving demands. Specifically, a ratio of 0.1234 kg/kW for the fuel cell power is used to estimate fuel use. If preferred, the USDOE's ADVISOR software can be used to estimate fuel use for a wide variety of driving schedules and fuel cell and vehicle design parameters.

8. Discussion

Tables 2 and 3 present design requirements and engineering characteristics considering stack and vehicle performance, DFM, and DFE. The case study uses a subset of the engineering characteristics to assess six bipolar plate designs. A correlation matrix is presented in Table 8 to identify trends among the engineering characteristics. The matrix searches for a correlation factor with an absolute value

Table 8
Correlation of engineering characteristics[a]

	Compressive strength(for solid plates)	Stack specific mass	Mass of stack/vehicle	Plate mass	Mass of bipolar and cooling plates/vehicle	Specific volume	Fuel use/vehicle	Number of parts/vehicle	Number of assembly operations/vehicle	Stack assembly time/vehicle	Length of stack/vehicle	Tolerance	Recycle fraction	Amount of catalyst/vehicle	Energy content/vehicle	Recyclability/vehicle	Plates are reusable	% recyclable/vehicle
Plate thickness	-																	
Compressive strength (for solid plates)		+	+		+										+	+	+	
Power density						-												
Stack power/ vehicle							+	+	+				(+)	+				
Stack specific mass			+	+	+										+			+
Mass of stack/ vehicle					+										+	+	+	
Plate mass																	(+)	
Mass of bipolar and cooling plates/ vehicle															+	+	+	+
Stack volume/ vehicle											+							
Fuel use/ vehicle								+	+				(+)	+				
Number of parts/ vehicle									+	+			(+)	+				
Number of assembly operations/ vehicle										+			(+)	+				
Stack assembly time/ vehicle														+				
Number of fabrication operations per plate												(+)						
Recycle fraction														(+)				
Energy content/ vehicle																		+
Recyclability/ vehicle																	+	

[a] When the reason for correlations were possibly coincidental or an infrastructure issue (for recycle fraction) the + or − have been plated in parentheses.

greater than 0.9 and includes whether the correlation is positive or negative. Although each metric provides insight into each focus area, correlations can be used to indicate trends.

For the case study bipolar plates, correlations can be interpreted by considering relationships to compressive strength, the mass of the bipolar and cooling plates, the size of the stack required to move the 'generic vehicle', stack volume, disassembly efficiency, and select manufacturability metrics:

- *Compressive strength:* For the solid plate designs, bipolar plate thickness was based on the compressive strength (the stronger the material, the thinner the plate). Reusability also correlates with compressive strength for all designs, but in this case it is a material issue for those in the case study: in addition to being the strongest material, stainless is also expected to be the most durable within the context of reusability [36]. Although no data was developed for the compressive strength of the integrated cooling designs, specific strength could be estimated for all types of plates and similarly used as an engineering characteristic that would also incorporate the lightweight requirement (see [55]).
- *Mass of the bipolar and cooling plates:* For all designs, the combined mass of the bipolar and cooling plates drives the mass-driven engineering characteristics (stack specific mass, mass of stack/vehicle, material energy content/vehicle, the recyclability/vehicle and the % recyclable). These engineering characteristics also correlate with compressive strength and plate thickness for the solid plate designs. It is interesting to note that the bipolar plate mass alone does not correlate with these metrics for the case study plates. Also, % recyclable/vehicle is a mass-based engineering characteristic that did not correlate and in fact was dominated by the weighting factor (the recycle fraction) applied.
- *Size of the stack/vehicle:* The size of the stack (capturing the number of cells) required to move the 'generic vehicle' dictates fuel use, the amount of catalyst and the number of parts. In turn, the number of parts influences the number of assembly operations and the assembly time. The recycle fraction is also found to correlate but it is assumed this is an infrastructure issue (at present, stainless has the highest recycle fraction and, because of mass compounding, requires the largest stacks).
- *Stack volume:* Stack volume for the 'generic vehicle' positively correlates with stack length. For the length of the stack, this relationship was dictated by the fact that it was estimated from the stack volume based on a constant plate area. Also, the length of the stack might be added to the system level design requirements should stack performance fall to a level that makes the stack too long for a given vehicle.
- *Disassembly efficiency:* Disassembly efficiency did not correlate with any of the engineering characteristics assessed. The disassembly efficiencies were driven by the number of subassemblies (related to the number of cells in the stack) and the need to remove the cooling fluid fixtures for the integrated cooling designs. Specifically, although fixtures for supplying fuel and oxidant and managing water were assumed to be the same per cell for all designs, removing the extra fixtures for the cooled plates was considered an additional disassembly step.
- *Other manufacturability metrics:* Engineering characteristics related to the number of fabrication operations per plate, tolerance, and the number of different and small parts/vehicle was identified as useful in rating design alternatives. Specifically, the number of different and small parts did not correlate with any other engineering characteristic. For the number of different parts, the values were the same per subassembly for both solid and cooled bipolar plates because whereas the solid plates required the addition of a separate cooling plate, the plates with integrated cooling required fixtures for cooling fluids. For the number of small parts, the cooled plates were penalized for the addition of fixtures for bringing fluids to the stack. Finally, the number of fabrication processes and tolerances did correlate with each other. In fact, the range of possible tolerances was determined by type of fabrication options (not the number of options) as defined by Granta Design [35].

Interestingly, power density and specific volume for the six bipolar plate designs did not correlate with any other engineering characteristic. It is important to note that the power density estimates were derived from different references and therefore are assumed to be for illustration only (testing conditions cannot be expected to be consistent). Therefore, presenting power density and specific volume without consideration of vehicle performance was found not to be enough to assess the case study plates and, because of their common use in assessing fuel cell system design, is an important conclusion of this research.

For the case study plates, the solid and integrated cooling options provide advantages and disadvantages. Specifically, solid plates are preferred for their plate thickness, the number of small parts (due to the additional cooling fluid fixtures), and the % recyclable. Plates with integrated cooling are preferred for the power density, the stack power, the stack specific and total mass and the mass of the bipolar and cooling plates, the specific and volumes and the length of the stack, the number of parts, the fuel use, the disassembly efficiency, and the energy content. Also, a major advantage of the cooled plates is being able to control stack operating temperatures which was not evaluated and is expected to play a major role in optimizing stack operation. This is clearly a shortcoming of the models applied in this analysis and is an important subject of future research, especially as related to fuel use.

Again for the case study plates, specific materials dominated several engineering characteristics. Specifically, graphite are preferred for thermal conductivity, corrosion resistance, the power and length and volume of the stack, fuel and catalyst use, number of parts, number of assembly operations, stack assembly time, and disassembly efficiency. Stainless plates are preferred for plate thickness and compressive strength, power density and specific volume, and for %recyclable and reusability. Finally, carbon composite plates are preferred for specific mass, plate mass, energy content, and recyclability.

Again for the case study plates, specific designs dominated several engineering characteristics. Specifically, the graphite plates are preferred for corrosion or passivation related reduction in performance, the number of assembly operations, and the amount of catalyst. The stainless plates are preferred for recycling and reusability. Also, the solid graphite plates are preferred for the number of fabrication operations per plate and the stack assembly time, the latter as a result of the number of parts and extra time associated with the cooling fluid fittings. Finally, the stainless plate with integrated cooling and the solid composite plate are preferred for tolerance (driven by the ability to use stamping processes as opposed to machining or molding) and plate mass respectively.

Certainly the correlations among engineering characteristics and dominance of specific design features are dependent upon the models chosen for the measurement of each engineering characteristic. Also, considering that only a subset of engineering characteristics were assessed and the variety of fuel cell designs and power management options, further analysis is needed to consider these six categories of metrics described above as indicative of stack and systems performance, DFM, and DFE design requirements. Specifically, for the stack and system performance-based engineering characteristics not included in the analysis, resistivity, corrosion or passivation related reduction in performance, and thermal conductivity are frequently cited in bipolar plate design literature are. These were not included in the correlation analysis because they were not used in the vehicle sizing model. Specifically, these engineering characteristics can be assumed to be captured in assumptions related to the power density used in the model. Other performance based metrics requiring further investigation are the life of stack and mean time between failure, total plate creep, and changes due to operation in freeze and cold conditions.

For the manufacturability requirements, area of new facility required, material and assembled cost, plate fabrication cost and time, fabrication process economic batch size, insertion force for all parts and subassemblies, the number of non-self-aligning and locating parts, the number of adjustments and reorientations, the number of non-standard parts and processes, and time with difficult, loud or vibrating equipment are left for future research. In fact, Dayton [3] describe a project to identify possible fabrication methods that have the potential to achieve manufacturing volume(s) and cost goals. Specifically, they reduced material scrap by eliminating or reducing machining operation, eliminated machining operation, and were able to use a high volume process.

For requirements related to environmental impact, distance from material supplier to plate fabrication and from plate fabrication to assembly, energy content of MEAs and assembly tools and fixtures, and environmental impact potentials are left for future research. Also, application of life cycle assessment [56,57] would either add requirements and engineering characteristics for specific environmental impacts (such as metrics which represent the contribution to global warming, ozone depletion, acidification, eutrophication, toxicity, land use, etc.) which is the topic of research at the University of Washington. Also, aggregated ‘eco-indicators’ that capture more than one environmental impact (recyclability, contribution to global warming, acidification, toxicity impacts, etc.) could also be used as an engineering characteristic. Such aggregated metrics however include some type of value system to determine how much each impact contributes to the overall score (for example, toxicity might be considered twice as important as recyclability). Also, when aggregated metrics are used, it is more difficult for the designer to determine what aspects of a particular design contribute most to the total or any individual impact.

The research presented here extends the design requirements for bipolar plates in the areas of stack and vehicle performance, DFM and DFE. Engineering characteristics and models for estimating their value are presented for many of the requirements. For those estimated and remaining, the lists of 51 requirements and 69 engineering characteristic can be used for quantitative analysis or as a qualitative guide. The intent of this work was to suggest additional considerations for designers and those publishing research related to bipolar plate design. Certainly, opportunity exists for analysis of addition design configurations as well as addition areas of requirements.

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