[Note: While the following is dated, it was written back in Summer 2000 and so has been overtaken by more recent news, this may be of background interest].

Five Types of Fuel Cells

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It's first worth one's while to explore how five current types of fuel cell vary from one another, in key ways. But before highlighting differences, ponder a similarity among all: they're all cleaner, than the inelegant oil-fired, internal combustion engine (ICE). The gasoline engine/ICE requires hundreds of dirty explosions a minute to turn its friction-laden machinery, and anyway, it loses much energy potential in the burning.

As an electrochemical device, the fuel cell is instead far different from the ICE— it can run silently like a battery, yet provides desired power directly so long as the fuel is supplied to it like an engine. To illustrate the basic reaction common to fuel cell types, picture a simple acid fuel cell developed by lawyer/inventor William Grove in 1839. He put electrolyte liquid acid into a container with two electrodes — a negative anode, and a positive cathode. Grove supplied hydrogen to the anode (hydrogen is surely the best fuel, but others work too), and just left the cathode in contact with the air.

Simplistically, the electrolyte there causes hydrogen on the anode side to be 'ionized' — separating electrons from protons. Ionization thus produces both free electrons (recall that electrons are what make-up electric power), along with hydrogen ions (protons). That electrolyte also prevents those freed electrons from passing directly through it to reach the attractant oxygen at the cathode: the electrons must thus take an external circuit of wire. That wire carries the desired electrical power.

The electrolyte importantly conducts the ions, which are able to migrate directly through it to the cathode. These ions coming across the electrolyte react at the cathode with electrons arriving across the circuit, and with oxygen in the air, to form pure water. Hence the only products from this reaction are desired electricity — along with formed water and waste heat, so long as hydrogen is used as the fuel.

Technically speaking, the fuel cell reaction is $2H_2 + O_2 \;--\; 2H_2O$ (I'll keep equations to a minimum — but this balance shows the profound simplicity of forces at work). In the reaction, two parts hydrogen at anode balance out one part oxygen at the cathode.

If that reaction could only give off electrons in powerful enough fashion, there might be no need for further complications, or even a variety of FC types. Unfortunately the reaction rates in a simple acid FC described above, produces electrons at a much slower rate than what's typically needed. The net result is that only very low currents and hence smallish amounts of power flow from an acid fuel cell — but, not surprisingly, FC designs have improved considerably since Mr. Grove's work. Three options that can speed up those lugubrious reaction rates, and so get more power are:

*   increase electrode area
*   use catalysts at the electrodes
*   raise FC temperatures

All three methods are now commonplace in many FCs. For instance, recent advances in electrode design have led to complex porous structures, and so have improved FC outputs greatly. Unlike early acid cells that just used exposed plates as electrodes, there's now a high degree of three-dimensional surface area. Miniature sponge-like microstructures help accelerate release of energy from fuel cells, moving them forward. As will be shown, catalysts and high temperatures are used too.

A Typical Fuel Cell Stack

Physics has so far dictated that voltage from each anode/electrolyte/cathode cell usually tops at about 0.7 volts DC. But a number of cells easily can be, and often are, stacked together to increase total wattage output greatly. This is known as the 'stack' and is heart of a FC system. It also displays an inherent scalability of cells according to the power demand. Since cells are often combined, much work has gone into making each cell very thin, so many placed together won't grow unwieldy. That in turn creates problems, however, such as how to ensure the H2 and O2 (or air) reach each cell. So stacks create more power, but add a great deal of complexity and cost.

One approach to building fairly compact multi-celled stacks with good gas flow, has been the 'bipolar plate.' These plates have channeled (raised) surfaces allowing a cathode of each cell, to connect with anode of the following cell. The electrical contact is on raised parts of the plates, between complex channels machined in repeat patterns. In essence bipolar plates sandwich each anode/electrolyte/cathode cell. Hydrogen (or another gas) is thus pumped through insides of one channel to all anodes in the stack. Conversely, oxygen or air is pumped through another set of channels to reach cathodes throughout the stack. (However, adding pumps moves the device away from portability, or the tiny size that's desired in many applications).

Bipolar plates may facilitate electron flow from one cell to the next, improve gas flow, and help physically support the entire stack. But trade-offs come in their design. Making large contact areas for greater electron flows, reduces channel size for gas flows, and visa-versa. To make graphite plates thinner helps cut total stack size, but that also hurts gas flow. Note too that product water forms at cathodes — as the hydrogen ions, electrons and oxygen meet, so there must be sufficient room to evaporate and remove water from gas channels. That complexity is vexing as well.

In the end, then, informed judgments must be made balancing competing needs for electron flows, gas flows, water management, and sometimes for cooling liquid as well. And gas channels in the plate may create a need for air pumps, further complicating matters. Nonetheless, bipolar plates boost efficiencies. Yet given their complexity, expense, and lack of breakthroughs, they're an area where significant improvements should be expected. In years ahead, FCs may look far different and much simpler.

Playing to Strengths

At the time of this writing, in 2000, there are five main basic fuel cell types, each with unique strengths providing advantages in certain applications. These five types are mainly known according to electrolyte material. Before enumerating, it's helpful to stress again that 'modern' fuel cell technology is at the time of this writing, and despite the FC being invented back in 1829 — in its earliest infancy. There's bound to be a plethora of FCs ahead, that paraphrasing President Franklin Roosevelt (speaking on another topic) "will be limited only by the inventive genius of mankind."

As a practical matter, costs will be a driving force determining whether FCs begin to be seen in everyday applications, since the huge costs burdening FCs today prevent their use in all but the most specialized applications. If they do begin to penetrate markets such as powering portable electronics, then millions of dollars spent now pursuing incremental improvements from gasoline-powered ICEs, may look instead for greater returns in researching new FC types. In the future, we may potentially see a 'leap-frog' ahead to wholly new FCs based on novel chemistries. But as of now, the chart below shows five current fuel cells today, distinguished by electrolyte:

Fuel Cell Type	Operating Range
Proton Exchange Membrane (PEM)	50 to 100 C°, 'lower temps'
Alkaline Fuel Cell (AFC)	50 to 200 C°, 'lower temps'
Phosphoric Acid (PAFC)	around 220 C°, 'middle-temps'
Molten Carbonate (MCFC)	around 650 C°, 'higher temps'
Solid Oxide (SOFC)	around 500 - 1000 C°, 'higher temps'

Best known of common FC types today, is the PEM, or the 'Proton Exchange Membrane' FC. This lower-temperature PEMFC has a few advantages due to its electrolyte being a polymer (with the feel of cloth) that allows the protons — but not electrons — to migrate across it. This PEM material however is very costly to make.

PEMFC also faces many unique and delicate problems at present, including the fact it's easily poisoned by impurities in fuel such as sulphur, or by carbon monoxide in even tiny amounts. This can make a PEMFC most appropriate in situations where pure H2 is supplied to the cell. Happily this is not a problem if electrolysis of deionized water generates the H2, or if H2 comes from appropriate chemical reaction, or is made pure elsewhere and carried in pressurized in tanks, etc. (Or, potentially, if it is linked such as to a solid oxide fuel cell for hybridized FC use more on that later).

Supply pure hydrogen and PEMFCs work without fuel reforming, at relatively 'low' temperatures of 50-100 degrees Celsius; for comparison room temperature is about 20 degrees Celsius, so these low-temperature FCs still get very warm, a real problem in many cases. Their temperatures may suit them for small & mid-sized applications or combined heat and power (CHP) requiring heat in undemanding ways. But 'low' temperatures carry the penalty of slow stack reaction rates, so getting more current may demand pressure from blowers, adding considerable system complexity and cost.

This persistent need to increase either temperature or pressure to get more power, raises as noted a major issue common in all save small or simple FC systems now using current technology: there's likely to be substantial Balance of Plant (BOP). The BOP

comprises items like pumps, compressors, control valves, heat exchanger, etc. Many FC systems nonetheless will take advantage of greater output that the extensive BOP can bring. Indeed one finds when a test fuel cell 'black box' today is opened up, most of the inside is made up of the BOP. The stack itself is but a small part.

Overshadowing and surrounding the FC stack, may be an attendant heat exchanger, hoses, blowers, control systems, power conditioner, fuel reformer, inverter and so forth that occupy most interior space. They can account for most of a system's expense. In many types of FC, for instance, the core stack may be a third or less of the cost of the 'black box' — the rest of expense going to BOP. It seems clear that eliminating BOP could be a major arena for reducing costs of FCs in future. For instance a portable FC based on liquid H2-rich/borohydride fuel, and based on a single cell that eliminates all BOP, might produce current for trickle charge if it is stepped up via a DC/DC converter. A point here is to simplify as much as possible.

Notably, proprietary trade secrets have indeed led to a splintering of designs among FC types. Thus it may be useful to compare relative power output (like varying engine horsepower in cars) of various designs. One widely-used way to compare FC output, is by 'Power Density', which is expressed as a function of Power over Volume (P / V).

This is spoken of as kW/liter, or, alternatively as kilowatts per cubic meter. It's possible perhaps that these figures might one day become bandied about, should FCs ever find real-world applications, like car lovers boast of horsepower today. Of course comparing *cost* per unit output, is highly important too, and is expressed often as (U.S.) dollars per kilowatt. Hence for FC prototypes in vehicle propulsion, one of the toughest places for FCs to compete with ICEs today, one might take note of both the power densities, and cost per kilowatt. For rough comparison, a modern gas engine alone (no transmission) can be manufactured for about $10/kW. It should last about 4,000 hours — translating to about 10 years at 1 hour's use per day.

Early FC propulsion in vehicles wouldn't need to beat figures achieved after a hundred years of refining the ICE. For instance a FC car won't need a transmission, since electric motors can be made to turn at precisely the right speeds. Notably too a FC power plant may eventually be longer-lived than the ICE. While output from FC will see a gradual drop over time due to aging electrodes and electrolyte (expressed as mV/1000 hours or 'percentage deterioration per hour') they'll have far fewer moving parts than the ICE and may in time require less servicing. That said, propulsion is one of the toughest applications for FCs. given very low cost of competition ICEs, their durability and ubiquitous gasoline infrastructure. Hence the vast attention paid in the press to FCs in cars may be a bit misleading, since initial FC applications may well come from a number of much different settings. Those early devices may be much smaller than a PEMFC, and be portable, or be much larger units of varying types.

In stationary power situations where longevity & durability are of great importance, and where heat exchanging demands may need to be met for hot water, or warming homes and the like, one goal is to bring down FCs towards a cost target of $1,000 per kW. 'Helpfully' that target price has migrated northwards recently, as power crises in California and elsewhere have led to consumers paying significantly more for power and heat from coal, natural gas, oil, etc. Additionally, increasing black-outs have fed

demand for firm power (spoken of as perhaps 'four nines'--meaning on line 99.99% of the time) that FCs could deliver. A stationary FC should run at least 40,000+ hours.

It might be striking, that fuel cell makers may have a difficult cost target as low as say $60 per kilowatt for FC stack + BOP in cars — and yet there's a much higher target of say, $1,200 per kilowatt for stack + BOP for the FCs in stationary power. But take note that expected longevity and tasks are so very different in these settings. Costs must thus be compared for the FC vs. ICE competition within their particular sector, rather than to costs of power across unrelated contexts.

Clearly, a hurdle now for FC adoption (in addition to fuel infrastructure) is their dear cost is prohibitive. Fix that, and other issues like fuel could get fixed as well. So to move away from exotic to easily mass-produced materials is one way to lower costs. But materials still face persistent problems. For instance an electrolyte may be chosen for the ability to conduct ions — while blocking electrons — but some electrons still migrate as 'internal current' to the cathode directly, robbing the cell of power. In addition there's a problem of 'fuel crossover' where small amounts of hydrogen diffuse to the cathode both unreacted by the catalyst, and unstopped by electrolyte. In the case of lower temperature cells like PEMFCs, fuel crossover is a real concern. Then there's efficiency limits per laws of physics. For example wind generators may face a Betz Coefficient ceiling on maximum efficiencies, or in heat engines like gas turbines, there's a Carnot limit. While the fuel cell ceiling is still uncertain, FCs will enjoy higher limits than for ICEs and so that at least is scope for improvement.

The Proton Exchange Membrane Fuel Cell

Sometimes also called the 'solid polymer fuel cell', this PEMFC saw early commercial use in the U.S. space program where it made onboard electrical power for space vehicles. In the 1990s, the proton exchange membrane FC enjoyed a wider renaissance, with goodly amounts of money, technical work, and media attention on improvements. Great reductions in platinum needed as catalyst at electrodes have been especially striking. (Recall the use of catalyst as one way for FCs to increase their reaction rates). This has shrunk dramatically from some 28 mg of platinum per cm2 in earlier development, to far less now, and at better performance than previous amounts.

As noted, in a PEMFC the ion conducting polymer (electrolyte) is sandwiched between two catalyzed porous electrodes. This has made a goal of manufacturing thin anode/ electrolyte/ cathode cells normal practice. These "membrane electrode assemblies" (MEAs) are part of the nomenclature like the bipolar plates that mate them in series in a stack. Note that in a PEMFC, bipolar plates may take up most of the volume inside the stack, and about 80% of the mass. A result too is high costs of a PEMFC stack can be dominated by costs of the bipolar plates (and as noted, there's BOP outside).

In principle the PEMFC works like a simple acid fuel cell, but with no corrosive liquids. It may operate in any orientation (upside-down etc). The PEMFC starts quickly, and responds fairly well to varying load demands. As authors James Larminie and Andrew Dicks state in their (excellent and recommended) book 'Fuel Cell Systems Explained', "[I]t could be argued that PEMFCs exceed all other electrical energy generating technologies in the breadth of scope of their possible applications. They are a possible

power source at a few watts for powering mobile phones and other equipment such as computers, right through to a few kW for boats and domestic systems, to tens of kW for cars, to hundreds of kW for buses and industrial CHP systems." (62).

Although there's variation (and there will be far greater ahead), it's common for PEM electrolyte to use sulphonated fluoropolymers such as fluoroethylene. Best known now is Nafion, a trademark of Dupont and early leader in PEMs. This modified polymer-like polytetrafluoroethylene (PTFE for short) is also widely known and sold as Teflon. Interestingly, this material is partly hydrophobic (it repels water) and sulphonic acid is added to PTFE when making the PEM. Because sulphonic acid is hydrophilic, and so it attracts water, the final PEM electrolyte will have both 'water-loving' regions, and be water-repelling. This complexity is also an area ripe for improvement.

The resulting Nafion™-like PEM ionomers claim notable characteristics, as they are:

*   good proton conductors, when well hydrated
*   able to absorb large quantities of water
*   chemically resistant
*   mechanically strong, and can be made quite thin

PEMFCs have come a way in a few years. Yet many criticisms persist, such as they still require costly platinum as catalyst (though less is required now in a PEMFC) and also the electrolyte is costly, as is BOP, all rightly concerning their very high marginal cost overall. Note too the modern approach is to construct electrodes directly onto the PEMFC MEA — however specifics are generally proprietary as of the late 1990s.

Compared to say, a typical automobile engine that may be about 18-20% efficient, a PEMFC could in theory be about 45% efficient (though efficiency #'s are notoriously hard to pin down or compare). What is clear is PEMFC is better than an ICE, but it's still far from mature. One consequence is for each watt of potential energy supplied a PEMFC as fuel — some will be the desired power — but much is released as waste heat.

Getting excess heat away from the FC stack is even more important than cooling an ICE. There's two basic ways a PEMFC can deal with waste heat. Below 100 watts in size, a PEMFC might rely on convection alone to evaporate product water, and carry it away. This avoids bulk and complexity from blowers, motors, etc. Similarly under 200 watts, a small fan can be used on a PEMFC with little parasitic power loss.

But a second common approach involves purposive use of larger amounts of air, or water pumped through the stack, for cooling. Air cooling is simpler of the two, but requires separating reactant air going to the cathodes — from the cooling air — both of which are pumped though bipolar plates. While this raises the need for two sets of fans, the air could cool small PEMFCs from 250 watts through 2.5 kilowatts. From 2.5 on up to 10 kW, the situation may dictate whether air or water-cooling is best.

At 10 kilowatts, and above, water is still the best choice for cooling PEMFCs. Water is especially useful for CHP (combined heat and power) situations where latent heat in water may be re-directed to domestic situations such as heating a house, or a home's hot water. Or it could heat a swimming pool if desired. Here the tandem benefits of clean power, and heat derived from a fuel cell for distributed generation is clear.

For smaller systems one approach to the PEMFC has been to making it cylindrical. An advantage is the simple integration of PEM with reactant gas supply; in this case a cylinder of hydrogen basically contains MEA wrapped around it in a fully incorporated design. The cylinder's outside is exposed to air circulation and so has the cathode.

Problems with such simple design include high electrical resistance, and maintaining the proper balance of heat and humidity across each cell (more easily done in bipolar plates in a stack). If one cell heats up more than others, that can increase drying and so resistance, meaning output from a unit wired in series falls. In response, small systems operate well below optimum levels. Clearly that's not ideal, but for some low-demand situations, advantages of FC power might outweigh limits of low output.

Another variation is a small 12-watt unit based on a 'purer' FC approach. Here the H2 may flow up a tube with electrodes designed as rings inside. Above each MEA is a space allowing air to diffuse in, while product water migrates towards an outer edge where it evaporates to air. This set-up is largely self-regulating. Drawing more power, produces more heat and water, which in turn is evaporated away by less dense air near the cylinder. Nor does MEA dry out at low power demands. If efficiency is about 48% (a possible figure with each cell producing 0.6 volts), a lack of parasitic and other power demand for blowers etc means a supply of some 25 watts worth of H2 may yield 12 watts of electrical power, with another 13 watts of energy lost as heat.

Interestingly there are variations. If hydrogen comes from a pressure vessel, then a PEMFC might piggyback on incoming pressure; no pumps are needed to supply the anode. Or in theory, an electrolyzer might supply pressurized hydrogen as well as oxygen too, by splitting water into H2 and O2. Having pure oxygen at the cathode is more efficient than getting it from air: data have suggested PEM output can grow by 30% due to pure O2, in the cases where the ambient air supply is poor. Otherwise the compressors for air may cost about 20% of power from a 100 kW FC system.

If something other than O2, or other than pure hydrogen is used for fuel, such as a special low-sulphur gasoline, methanol, etc., then the PEMFC suffers for having to first reform fuel to a high degree to remove contaminants. That adds cost, bulk, and complexity to a PEMFC, which is already en expensive proposition among FC types. For these and many other reasons, other FC types may often make greater sense. Especially if a proprietary liquid fuel is potentially available, it could designed for a specific FC type in mind, and allow ease of use if it is non-toxic and inexpensive.

One approach for small units has been to use methanol blend as fuel. (This is apart from reforming methanol separately for a PEM). A "direct methanol fuel cell" (DMFC) has advantages of using available liquid fuel, without complex fuel reforming. However reaction rates are slow even when using a catalyst at the electrodes. Also absorption of methanol by the electrolyte makes fuel crossover a vexing technical problem. Note methanol is toxic to the skin, and flammable; dilution is one approach to that.

The DMFC has very low efficiencies, compared to most other FC types. On the other hand, if the competition is a battery, efficiency may not have to be high for a DMFC to come out in front. For instance, it's suggested a DMFC only need be >5% efficient to

compete with an advanced lithium battery. If power is needed remotely, or if continuous output of a FC is advantageous, it could, potentially, make some sense.

Another approach with even greater advantages of simplicity could be a FC that uses proprietary liquid fuel, together with a liquid electrolyte. Such an inexpensive FC using one cell only wouldn't require any BOP. If costly platinum can be eliminated as catalyst, and the solid membrane is avoided as well, it might potentially be used such as in cell phones and portable electronics. Having only one cell (not stacked), they'd produce only a trickle of current and so maybe require a DC-DC step up converter. But that may be enough to use and/or trickle-charge, as in low-demand cell phones.

Finally, nanotechnology may produce future outcomes that can only be guessed-at, today. Because theoretical upper limits for FC efficiency, are much more attractive than for the ICE, this may become an area for substantial R&D in the future. It may also open paths for hydrogen storage, making H2 fuel issues less thorny. Since one can only speculate here on outcomes, it's not further addressed here in this paper.

The Alkaline Fuel Cell

In special cases when a fuel cell is "air independent", meaning it operates apart from the atmosphere such as in submarines or in spacecraft — or more to the point, when both H2 and the O2 are supplied pure — then an alkaline fuel cell (AFC) may make some unique sense. Potential advantages of the AFC include that its inexpensive electrolyte can work better in some ways than other FCs and no exotic materials may be needed. As with the above idea of single cell FC using proprietary fuel, cutting costs is crucial.

The electrolyte commonly has been a potassium hydroxide solution, although there are different AFCs. All are 'lower temperature' operating near or above the operating temperatures for PEMFCs. Comparatively less effort has gone into developing these FCs so far, and a thing to note is small amounts of carbon dioxide extant in air can swiftly erode electrolyte performance. Simplistic demonstration AFCs with a KOH solution have reaction-depleting electrolyte — while an arcane technical issue, it perhaps may be questionable if those are true "fuel cells" (in some technical sense). But the latter's really a non-issue, if the "FC" performs as desired for tasks at hand.

AFC use may conceivably return to what was once supposed by Bacon some fifty years ago. They were envisioned long ago as part of a true regenerative fuel cell system. Here, desired power is mainly made from renewable (but non-firm) sources, like solar, wind, hydro, etc. However, when there's little demand, the excess power instead electrolyzes water into hydrogen and oxygen. Later, when the sun isn't shining, or wind blowing, the AFC converts those two gases back to electricity. This gets around AFC's special need for H2 and O2. And it uses AFC advantages including low cost, broad range of temperatures and pressures, and independence from exotic materials. As emphasized, an ability to make fuel cells cost as little as possible is a key here.

Higher Temperature FCs: Phosphoric Acid, Molten Carbonate, and Solid Oxide

Three remaining types are the phosphoric acid (PAFC), molten carbonate (MCFC), and the solid oxide (SOFC) fuel cell. All may confer benefits due of their rather higher

efficiencies and ability to provide CHP. The least attention will be paid here to PAFC, which like PEMFC is easily poisoned by carbon monoxide and requires reformers for anything other than hydrogen fuel. Common to all three is they should be considered in context of fuel available, and the setting that demands power — rather than any one approach being a universal fuel cell system (at least at present, in 2000).

The exit gases for all three, may possess value that can be recaptured in a 'bottoming cycle.' For instance, using heat to turn an adjoining turbine, or power a heat engine can better efficiencies overall. With process integration, stack exhausts might help pre-heat the fuel and oxidant by utilizing for instance 'pinch technology' or other tools. Overall given their hot operating characteristics, and except for some noted mobile SOFC applications such as auxiliary power in transportation (like powering the cab in parked tractor-trailers), they're more limited to stationary uses.

The PAFC so far has lowest efficiencies among the three. To use fuels other than hydrogen here (like natural gas), means that fuel reforming will be required, and that process generally must achieve temperatures >500 degrees Celsius. Yet exhaust heat from a PAFC is about 200 degrees, requiring additional fuel to raise heat. That can reduce overall PAFC efficiencies noticeably, which as a result may be around 40-45%.

Briefly, PAFC works something like PEMFC with an electrolyte that conducts protons, and platinum catalyst at the electrodes. The electrolyte however is phosphoric acid (H_3PO_4) that can notably operate with some CO_2 in fuel and oxidant. PAFC is the FC type that's undergone perhaps the most commercial use so far, but arguably it may be inferior in some instances to future commercial MCFC or SOFC units. Its operating characteristics are rather well understood, and a PAFC unit producing some 200 kW costs about $900,000 (in 2000). It may run 40,000 hours, with some electrode decay.

One developer aimed in early 1990s to achieve stack costs alone of less than $400 per kW with a power density of 0.188 W.cm-2, and they achieved densities of 0.323 W.cm-2 in single cells at 645 mA.cm-2, and 0.66 volts per cell. Published data by one Japanese PAFC developer showed degradation rates of 2 mV/1000 hours for a test run of 10,000 hours, at 200 to 250 mA.cm-2, in a short stack. An existing PAFC commercial unit costs some $4,500 per kW, and they may face competition from MCFCs & SOFCs. A price target here in PAFC and MCFC development has been ~$1,200 per kW.

There's been increasing attention given to MCFCs and SOFCs. Compared to the PAFC, both MCFC and SOFC may offer higher efficiencies and simpler overall designs. They can tolerate more sulphur or carbon monoxide than the PEMFC or PAFC. And because they operate at around 600 degrees C and above, they actually can steam reform various fuels (other than hydrogen) within the stack itself. Uniquely their product water forms at anode (rather than cathode), so the reforming steam is present.

Three ways their heat might further be used include 1) making steam in a boiler for a steam turbine, 2) pressurizing the system for gas turbine, or 3) combining steam and gas turbines, for a triple cycle system. This latter idea is still in the future, but such an elegant system is interesting. Whichever path, it may be possible for heat engines to capture 'waste' heat from MCFCs or SOFCs so each balances strengths and weaknesses of the other. At around say, 800 degrees where fuel cells can be nearer

maximum theoretical efficiency, an added heat engine can be made from non-exotic materials. A.J. Appleby notes (in Larmine and Dicks, 2000, at 132) that:

> "Thus, a high temperature fuel cell combined with, for example, a steam cycle condensing close to room temperature is a 'perfect' thermodynamic engine. The two components of this perfect engine also have the advantage of practically attainable technologies.... Thus the fuel cell and the thermal engine are complimentary devices, and such a combination would be a practical 'ideal black box' (or because of its low environmental impact, a 'green box') energy system." (Blomen et al., 1993, p. 168).

Potentially attainable figures indicate that to combine a SOFC, with a steam turbine in a combined cycle power plant using natural gas as fuel, could yield high overall system efficiencies. Put in a gas turbine as well, and the efficiencies may potentially climb higher. Little wonder then FCs are attracting some interest, especially if run better in renewable fashion from clean hydrogen, derived from solar or wind.

The electrolyte in a MCFC so far, may be a molten mix of alkali metal carbonates, like lithium and potassium, or lithium and sodium carbonates in a matrix made of ceramic. It is kept at 600-700 degrees C to allow ionic conduction. Remarkably, this FC may require CO_2 at cathode, along with O_2, and product water forms at the anode. In operation it's quite unlike a lower temperature PEMFC or AFC; this shows how each type is best suited to applications supporting its own advantages or handicaps.

Unlike a PEMFC with cloth-like polymer electrolyte, MCFC faces daunting challenges in managing liquid in a porous matrix. If not done properly, and evenly distributed to all cells, then various problems can ensue such as consumption by corrosive reactions, salt creep and vaporization, and a potential driven migration in capillaries.

Nonetheless, the MCFC is seeing interest and development, although it remains far too costly still. Efficiencies over 50% appear achievable — looking ahead, combined efficiencies of 60%, or even 70% may perhaps be do-able in the long term. Many fuels could in theory be used in MCFC from clean hydrogen made renewably, to a fossil fuel like natural gas, down to some of the 'worst', most carbon-laden fossil fuels. But clean fuels in a MCFC should produce very few pollutants. Noise is less than 65 dbA.

In addition to MCFCs, another key opportunity among FCs may be the solid oxide fuel cell (SOFC). Like the MCFC, the SOFC so far has key advantages that come with high temperatures, such as better efficiencies, high quality waste heat for additional CHP, and the ability to use a wide variety of fuels without reformers (though once again 'clean hydrogen' is clearly the best fuel, when viewed from many perspectives).

Unlike the MCFC which must hold corrosive liquid in a matrix and so faces electrolyte management issues, the SOFC is fully solid state. Hence its core stack design need cope with only two phases (gases and solids), since no liquids exist there. The high SOFC temperatures hasten electrochemical reaction rates too, which rids the need for precious metal catalysts. Anything mitigating high costs of platinum, helps.

Interestingly the product water in a SOFC forms at the anode, due to a migration 'back' from the cathode through the electrolyte of (oxygen) ions. Basics of SOFC were first described back in 1899, so the concept has existed for some time. The SOFC is the hottest of present fuel cell types, and not long ago, most designs used a solid electrolyte based on zirconia with small amounts of yttria as stabilizer. Such stack makes use of the fact that above 800 degrees C, zirconia conducts oxygen ions.

More recent work aims to bring down SOFC costs, in part through use of less exotic materials. At the anode, use of zirconia cermet--a combination of ceramic and a metal (here, nickel) has helped. And nickel also allows internal fuel reforming to take place directly on the anode. Reducing costs for cathode has moved researchers away from noble metals, and towards conductive oxides, or ion conducting ceramics.

While theoretically speaking, a SOFC operating at a hot 1,000 degrees may be somewhat less efficient than a well designed MCFC working at around 650 degrees, this penalty may be practically offset by SOFCs lower internal resistance and different electrolyte. Reducing operating temperatures may help lower the costs of SOFCs. For a SOFC operating at 800-1,000 degrees for instance, interconnections between the cells may be made from expensive materials like 'inconel' stainless steels. By reducing somewhat temperatures of the SOFC to a relatively less hot design, it is possible to substitute 'austentic' steels which are less dear in cost. As always, cost is the key.

Ceramics might be used in 'lower-temperature' cylindrical SOFCs, where conductivity can be bolstered, by adding magnesium or alkaline Earth elements. All this doping and complex materials however raises issues of varying thermal coefficients — and thorny engineering concerns, since some parts of the SOFC could expand more rapidly at high temperature, than others. There is research being done to optimize materials for SOFCs, but not surprisingly the data that are being produced are closely-held.

One approach to the SOFC stack is a tubular design, in which long thin tubes are in direct contact: fuel is supplied to the outside of these tubes, and so the anode is on the outside. A mid layer on each tube has deposited electrolyte, and an inner layer is the cathode. This eliminates the need for any gas-tight, high-temperature seals.

Another option for SOFC stack is planar design, more akin to the PEMFC stack. An advantage is higher potential power densities, and better overall performance. Moreover, it's possible to make use of less-costly fabrication methods such as tape casting and screen-printing. But unlike a tubular SOFC, it's necessary to employ gas-tight, high-temperature seals around edges of these components. Additionally the brittleness of planar zirconia SOFCs has been an issue, given limits of allowable tension. A range of new SOFC designs may be considered in years ahead.

As with all fuel cell types, there's also the possibility of enhancing SOFC performance by increasing gas pressures. But just as with greater temperatures, such pressures can bring extra burden in terms of cost and complexity of the system. That said, one interesting prospect with lingering use of fossil fuel infrastructure, might be to marry a SOFC with a PEMFC. This hybrid might allow each FC to derive benefit from the other's presence. First the fossil fuel enters a SOFC where it is reformed at the stack, at low utilization settings. This produces power but yields sizable unused fuel. At the anode, shift reaction makes it possible to remove carbon monoxide. The fuel is now

mostly hydrogen, and carbon dioxide, along with steam. Once this gas has cooled, it can become input for a joined PEM fuel cell. Overall results might be better than a PEM or SOFC alone could achieve — environmentally, and economically.

In sum, if severe problems of FC expense are ever solved, it's possible that hydrogen *might* make too much sense, to be perpetually relegated to a "fuel of the future." But that's still years away, and much will depend upon technological improvements in fuel cells that can make them simpler, easy to use, and reduce their exotic materials.

Dr. Robert Wilder
Summer, 2000

Reference:
James Larminie and Andrew Dicks, "Fuel Cell Systems Explained'. John Wiley & Sons (2000). As noted, I recommend this book. It's usefully technical, and yet readable — an essential read for fuel cell enthusiasts. *[It has also been updated, since 2000].*