

The Current State of Development of Fuel Cells
Utilizing Semipermeable Membranes

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1.0 Introduction

The upsurge of interest in the last several years in fuel cell research is abundantly documented in the literature found in scientific, engineering and business articles. It may be of value to draw our thoughts together in one area of this field and to assess its accomplishments, its present status, and take a look at future development in that area.

In this paper we shall concentrate on the applications of semipermeable membranes, in particular, ion-membrane fuel cells. Most representative of this group are the single membrane fuel cell (Reference 1) the dual membrane fuel cell (Reference 2) and a significant hybrid, the gas-liquid single membrane fuel cell (Reference 3).

It may be of value to review briefly the advantages and disadvantages of an ion-membrane fuel cell in comparison with fuel cells with porous electrode and liquid electrolytes. Some of the advantages are:

1. The construction of electrode-catalyst configurations is non-critical - the exact sizing of electrode pores, the criticality of catalyst deposition and the requirements for water proofing are all minimized.
2. No loss of gaseous reactants due to pore inexactitude. The gaseous reactants cannot be lost to the electrolyte but simply rebound back into the gas chamber if they do not react.
3. Compactness.
4. Light weight.

The disadvantages in the ion-membrane fuel cell are:

1. Only moderate current densities have been achievable although the compactness of configurations mitigates this problem to some extent.
2. Heat removal is more difficult than in systems where an electrolyte can be circulated; for example, approximately 40-50% the realizable power in a fuel cell ends up as heat. The Hydrogen-Bromine Fuel Cell (HBFC) and the Dual Membrane Fuel Cell (DMFC) described later represent compromises instituted to overcome this problem.
3. The most highly developed ion-membrane fuel cells are organic and therefore sensitive to heat even when they are in an aqueous environment.
4. Water removal from electrode-catalyst site represents a variable

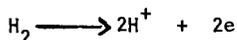
which is difficult to control quantitatively and directly influences voltage output.

The basic membrane used in the three generalized configurations described below are of two physical species - a homogeneous fabric supported polymer (Reference 4) and a grafted polymeric type (Reference 5). In both cases the polymers are sulfonated polystyrenes cross linked to a greater or lesser extent. The mechanism of operation of the membrane, however, differs appreciably in the three type of fuel cells to be discussed. Sketches of the three types of fuel cells are represented in Figure 1.

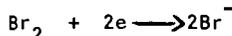
All of the fuel cells described in Figure 1 have been amply described in the literature (Reference 1, 2, 3, 6, 7, 8). Only brief descriptions will be given since the main purpose here is to delve more into the limiting factors inherent in the operation of such devices.

In Figure 1-A, the Single Membrane Fuel Cell which uses H_2 and O_2 as reactants is illustrated. H_2 is converted to H^+ at the anode, electromigrates through the membrane and unites with a reduced O_2 species at the cathode to form water which must be removed.

In Figure 1-B, the Hydrogen-Bromine Fuel Cell, the anode reaction is



and the cathode reaction



The net result of the reaction is the formation of HBr in the aqueous catholyte.

Finally in Figure 1-C, the Dual Membrane Fuel Cell, the anode and cathode reactions are identical to those in the Single Membrane Fuel Cell. The difference in these cells is that in the former a layer of H_2SO_4 is found between two membranes which serves to improve water balance problems and also functions as a heat transfer fluid.

1.1 Single Membrane Fuel Cell

The Single Membrane Fuel Cell (SMFC) is the system which has been most intensively investigated in the last few years. The membrane used in this case is a completely water leached ion-membrane where all of the electrical transport is due to the migration of H^+ ion formed at the anode from one sulfonic acid group to another until water is formed at the cathode.

If the ion exchange membrane is considered a polymer network of a linear or branched variety crosslinked at various sites and swollen with solvent, an adequate physical network can be envisioned for the transport of solute. It is apparent in envisioning this network as a "solid gel" that the velocity of H^+ ion in this network will be sterically hindered and if, as seems likely, the velocities of ions in "gel" structures is a function of the increased viscosity of the internal solvent phase (Reference 9) then it follows that the Stokes frictional resistance to flow

$$F = 6\pi\eta r \quad (1)$$

where

η = viscosity

r = radius of migrating particle

should be increased producing slower ionic migration whether the forces are purely

those of diffusion or electromigration. In the case of electromigration, this retardation will be manifested by lower ionic mobilities. For example, the ionic mobility of H^+ ion in an aqueous electrolyte is about 362×10^{-5} cm/sec. in contrast to a velocity of H^+ ion in sulfonated phenolformaldehyde resin of about 19×10^{-5} cm/sec. (Reference 9).

If one accepts as an operating basis that the SMFC is now utilizing the optimum catalysts obtainable for the $H_2 - O_2$ system and that operating voltages much greater than 0.93 V are not likely to be obtained (Reference 10), (a fact that the writer concurs in as a result of his experience in development of $H_2 - O_2$ fuel cells), then theoretically the net power that can be obtained will be a function of the ionic mobility of the H^+ ion over a given transit thickness.

Approximate calculations may be of some value in guiding us with respect to the limiting current densities that can be achieved in a leached H^+ transport system. Using the approach of Kortum and Bockris (Reference 11) and Spiegler and Coryell (Reference 12), the limiting current density of a leached membrane system may be defined as

$$\mathcal{J} = \frac{R}{Z_i F} \frac{\lambda TC}{i_L} \quad (2)$$

where

- \mathcal{J} = thickness of diffusion layer
- R = constant
- Z_i = valence
- F = Faraday
- λ = ionic mobility
- C = g. ions/mole
- i_L = limiting current

Substituting appropriate values

$$\begin{aligned} \mathcal{J} &= \text{thickness of diffusion layer} = \text{thickness of membrane} = 0.0165 \text{ cm.} \\ \lambda_{H^+ \text{ membrane}} &= 0.1 \lambda_{H^+ \text{ solution}} = 35 \text{ ohms}^{-1} \text{ cm}^2 \\ C &= 0.6 \text{ g. ion/liter} \end{aligned}$$

we find $i_L = c. 330 \text{ ma/cm}^2$

The writer recognizes that equation (2) holds strictly for cases at infinite dilution and that endosmotic transfer of water has not been considered, but, for our purposes the approximation is sufficient.

Another means of corroborating the order of magnitude of i_L is to use experimental data of resistances of membranes in the H^+ form in calculating achievable current density limits. The data presented by Grubb (Reference 13) on the specific resistance of ion exchange membranes yields on Ohms Law calculation for a membrane thickness of 0.0165 cm. current densities in the range of 400 ma/cm². Finally, it is of value to note that Maget (Reference 6), in his extrapolations of limiting current density for SMFC, projects values of the order of 500 ma/cm².

It can be assumed, based on the preceding approximations, that high current densities are achievable by the SMFC and indeed laboratory evidence (Reference 14) indicates that such is the case in single cell test units. It may then be valid to initiate thinking of thin ion membranes (<.02 cm) as diffusion barriers through which in theory, large amounts of current can flow in a fashion analogous to the thin diffusion barriers resulting from stirred electrolytes.

Candidly, while the preceding analysis is of interest in small, single cell test configurations, engineering factors have played a critical role in limiting the achievement of higher power densities in multiple fuel cell configurations. Firstly, the necessity of uniform rapid water removal at high current densities, which must be performed by gas circulation or a combination of condensation and capillary wick action is unsatisfactory. (Reference 8). Inability to remove water uniformly and rapidly enough can cause voltage fluctuations in individual cells and can in fact "drown" electrodes causing failure. Another important engineering problem is the removal of heat generated in the membrane. The removal of heat can be performed in a number of ways, but in all cases involves transit through a gaseous phase. In any case, it is our conviction that if the heat generated could be conducted into a fluid medium, the heat transfer considerations related to the rapidity of heat removal and energy expended for such transfer would be more favorable from overall systems considerations. It is interesting to note that in larger power sources, that heat transfer fluids will most likely be introduced to carry away large quantities of waste heat.

1.2 Hydrogen-Bromine Fuel Cell

The Hydrogen-Bromine Fuel Cell (HBFC), a secondary fuel cell device, (Reference 2) represents an attempt at overcoming the engineering difficulties inherent in one aspect of the SMFC, particularly heat transfer problems. A comparison of the heat transfer coefficients of O_2 , H_2 and H_2O in handbooks indicates the advantages of using an aqueous system such as the bromine - hydrobromic acid solution in water that serves as a catholyte for the HBFC.

In addition the Br_2/Br^- electrode is a highly reversible couple compared to the oxygen electrode in the SMFC. Oster (Reference 14) indicates that a certain activation loss of 0.35 V - 0.40 V occurs at the oxygen electrode in the SMFC. Calculations and experimental data (Reference 2, 15, 16) show that losses due to activation overvoltage for the HBFC on discharge should follow the equation

$$\eta = \frac{0.059}{0.6} \log i + \frac{0.059}{0.6} \log (3.10^{-3}) \quad (3)$$

where

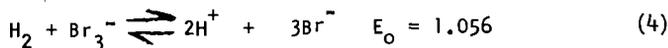
$$\begin{aligned} \eta &= \text{activation over voltage} \\ i &= \text{current density in amps/cm}^2 \end{aligned}$$

Therefore, at 100 amps/cm^2 on a plain electrode surface, the activation overvoltage for reduction of Br_2 to Bromide ion is equal to -.05 V.

It should be recognized however, that a disadvantage of the Br_2/Br^- couple is that the equivalent weight of Br_2 is considerably greater than O_2 , an important consideration in a practical engineering sense. This is mitigated to some extent by other considerations. For instance, when electrical regeneration of secondary fuel cells is called for, the higher voltage efficiency of the HBFC requires less weight of solar cells for recharging than a comparable secondary SMFC.

Once again our analysis of the maximum current density limitation will be based on the membrane as the limiting feature of the fuel cell and assuming that the anode and cathode are not limiting with respect to current densities.

A closer look at the ionic species involved in the performance of this cell is warranted before proceeding further inasmuch as this is an important factor in determining practical cell performance. The overall reaction of the cell is



The voltage of the cell is determined by the Nernst relationship

$$E = E^{\circ} - \frac{RT}{nF} \ln \frac{[H^+]^2 [Br^-]^3}{[H_2] [Br_3^-]} \quad (5)$$

Equation (5) implies that the major portion of the Br_2 exists in solution as Br_3^- . Since the equilibrium constant for $Br_2 + Br^- \rightleftharpoons Br_3^-$ is 17 and the equilibrium constant for $Br_3^- + Br_2 \rightleftharpoons Br_5^-$ is 0.055, it appears that at concentrations in the applicable catholyte range $H^+ = 6$, $Br^- = 6$, $Br_2 = 1 - 2$, the assumption is justified by a few simple calculations e.g., at $Br_2 = 1$, $Br_3^- = 0.99$ and $Br_5^- = 6 \cdot 10^{-4}$.

Proceeding onward to explore the nature of the discharge process at the anode, it can be seen that the ideal situation is where only H^+ and Br^- are in the membrane and Br_3^- is excluded. If this is the case $t_+ + t_- = 1$ and hydrogen ion formed at the anode is neutralized by Br^- . Clearly, if Br_3^- can diffuse into the membrane and migrate toward the anode, loss of electrical energy can result from the reaction of hydrogen and bromine complex at the noble metal catalyst electrode. It is exactly this problem that Berger and co-workers (Reference 2) found to be a limiting factor in cell life. A reformulation of the membrane in order to decrease the mean intramolecular diameter of the membrane was successful in limiting the diffusion of Br_3^- into the membrane and led to long cycling lines of greater than 9000 charge-discharge cycles.

One marked difference between the SMFC and the HBFC is that the major transport in the latter is a function of imbibed HBr rather than the H^+ ion in equilibrium with the fixed ionic sites in the ion exchange membrane. Let us assume that 6N HBr and 2N Br_3^- catholyte solution are in equilibrium with a cation membrane and if we assume that the migration of Br_2 into the membrane is strongly hindered, then an imbibition of 2-3 milliequivalents of HBr per milliliter of membrane volume can be assumed (Reference 17).

If we assume as previously discussed above that the limiting factor in i_d is the membrane itself then we can setup a series of limiting conditions. For the bromine electrode

$$i_d = \frac{DnF(C)}{(l - t_-)d} \quad (6)$$

or

$$i_d \approx 1.8 (10^{-1}) C \text{ amp/cm}^2, \text{ (Reference 16)} \quad (7)$$

where

$$\begin{aligned} D &= 4 \cdot 10^{-5} \text{ cm}^2/\text{sec} \\ n &= 2 \text{ electrons} \\ F &= 96,500 \text{ coulombs per equivalent} \\ t_- &\approx 0.15 \text{ (max)} \\ d &= 0.05 \text{ cm. (max)} \end{aligned}$$

At solution normality of 6N we have an activity of about 2-3 (Reference 18) and therefore could expect a limiting current density of about 360-540 ma/cm^2 even without considering surface roughness factors. The surface factor assumption is reasonable since smooth platinum was utilized for the cathode. We now turn to an analysis of the limiting current at the membrane-anode interface.

Presuming that the hydrogen electrode has its diffusion layer in the form of a membrane within which catalyst is imbedded, the diffusion barrier will be a membrane into which H^+ ion is discharged and which must be neutralized with electromigrating Br^- . The calculation of the limiting current for the hydrogen electrode may be expressed as

$$i_d = \frac{DnF(C)}{(1 - t_+) \delta} \quad (8)$$

or

$$i_d \approx \frac{4 \times 10^{-6} \times (1) 96,500 \times C}{(1 - .85) (.0165) 1000} = .156 C \quad (9)$$

where

$$\begin{aligned} D &= 4 \times 10^{-6} \text{ cm}^2/\text{sec} \text{ (Reference 16)} \\ n &= 1 \\ F &= \text{Faraday} \\ t_+ &= .85 \\ \delta &= .0165 \text{ cm.} \end{aligned}$$

Making the assumption that the concentration of HBr in the membrane has a limiting value of about 2.5 m.e. of HBr per ml of resin. The activity coefficient of 2.5 N HBr is about 1.2 and therefore an effective activity of 2.04. Substituting this value into (11) $i_d = 325 \text{ ma/cm}^2$.

Both of the limiting currents derived for the bromine electrode and the hydrogen electrode are deemed to be within conservative limits, e.g., the roughness factors have been assumed to be one.

1.3 Dual Membrane Fuel Cell

The ultimate extension of the combination of the membrane and electrolyte solution is found in the DMFC where the hydrogen and the oxygen electrodes are both placed against cation membranes and a 6N H_2SO_4 acid solution interposed between the membranes. It is clear that if we once again make the assumptions that ionic diffusion in the membrane is limiting, that limiting current calculations may be performed for both membranes.

$$i_d \approx \frac{4 \times 10^{-6} \times 1 \times 96,500 \times C}{0.15 \times 0.0165 \times 10^3} \quad (10)$$

or

$$i_d \leq .156 C$$

$$i_d \leq 94 \text{ ma/cm}^2$$

The assumptions made in this case are similar to those in the HBFC. It is assumed that the diffusion coefficient will be equivalent to or less than HBr, that the transference number of H^+ is slightly greater than for the HBFC, and we have also made the assumption that similar quantities of H_2SO_4 are imbibed but that the activity of 2-3N H_2SO_4 is much lower (Reference 20). There is one factor here however, which is not present in HBFC. A film of water forms at the oxygen cathode, the tendency of which is to migrate into the 6N liquid electrolyte between the membranes. In practice, interestingly enough this is borne out by the fact that all of the water formed is found ultimately in the central compartment. The film of water which forms can not be removed as rapidly as in the case of the SMFC because of the counter osmotic forces in the membrane tending to draw the water toward the central

electrolyte compartment. The presence of this water film causes significant IR losses and is a limiting factor in the operation of the DMFC.

2.0 Engineering Consideration

The approximations presented above with reference to current density limitations are no more than target areas which could be achieved if certain practical considerations are overcome. What then is the present stage of achievement of these three different fuel cells. A graph of attainable operating characteristics, based on available publications for these single fuel cells is shown in Figure 2. (References 14, 21, 22, 2, 23).

2.1 Single Membrane Fuel Cell

The SMFC shows the most advanced operational capability, one of the obvious reasons for this being that a great deal more research and development has been committed to this concept. Although current densities as high as 150 ma/cm² have been achieved, a number of practical limitations appear to limit gains for the SMFC in multiple fuel cell configurations.

1. Water removal from the area of the oxygen electrode must be carefully controlled so that enough water is removed from each cell of a multiple cell unit to keep the electrode from drowning or more practically to keep all single cell voltages in a multiple series configuration from widely diverging and tending to instability of cell output (Reference 24).

The removal of water from the electrode surface in the present apparatus is accomplished by the condensation on a bipolar cell separator of the moisture from the electrode surface. Mechanically, the potential for water removal is supplied by a difference in temperature (C. 5-10°F) between the electrode surface and the cell separator. It can be seen that the rate of product removal from the reaction site will vary with the temperature differential, the gas temperature and content of gas chamber and factors related to the heat removal system. In light of these complicated engineering problems, the writer projects that current densities of about 50-75 ma/cm² at 0.78-0.72 V appear to be achievable in multiple units within the next 18-24 months but it is not likely that operating current densities of greater than 100 ma/cm² will be achieved within the next 36 months unless important break-throughs in engineering know-how occurs. This does not appear to be an important limitation, since it is likely that operational current densities in the range of 25-35 ma/cm² will suffice for space missions such as orbital manned flights.

2. 40-50% of the total energy generated in the SMFC results in heat which must be dissipated. This can be effected by heat transfer through metal cell separators with radiative heat loss to space or the recirculation of fuel gas (H₂) to pickup heat and moisture with subsequent cooling and condensation and finally the use of a separate liquid circulation system to remove heat from the separator plate area. If the last approach is used for units in the 1-5 Kw range (Reference 25) then it appears that the weight and volume of the circulation system would at least equal the electrolyte inventory required in the HBFC or the DMFC. In addition, in contrast to the DMFC, the water recovery system for the SMFC requires a separate subsystem for transport and recovery of water, an important factor in decreasing overall reliability and in adding weight to the system.

3. Reproducibility and the quality control appears to be an important engineering area where more research must be performed. The leached membrane used in the SMFC must have an absolute homogeneity of physical and chemical characteristics in order to avoid areas of intense heating and uneven water formation and removal. This is avoided to a great extent by HBFC and DMFC since the electrolyte imbibed by the membranes in this system serves as a leveling factor for physical properties and water balance problems.

2.2 Hydrogen-Bromine Fuel Cell

The HBFC limiting diffusion current is high as indicated in 300 ma/cm^2 and when used, as is commonly the case, as a secondary battery charge, acceptance efficiency is high compared to the $\text{H}_2 - \text{O}_2$ system. This is due to the considerable irreversibilities encountered on charging a leached $\text{H}_2 - \text{O}_2$ SMFC system compared to the HBFC where overvoltage is a minor consideration.² In practicality this calls for 20-30% greater power requirement for recharging at a given current density (Reference 2). The major factor which has held back the rapid development of this concept has been the lack of solid advances in membrane technology. Recently, however, (Reference 2) advances have been made which auger well for the development of this cell. It will continue to suffer, however, from one basic limitation. In order to prevent the migration of Br_2 , or Br_3^- more accurately, the network of the ion membrane fuel cell must be made less porous, i.e., diffusivity must be decreased. This will lead to lower limiting current densities as a result of decreased ionic mobility and cause higher IR drops. It therefore seems unlikely that effective operation of greater than $50\text{-}60 \text{ ma/cm}^2$ at $0.62 \text{ V} - 0.57 \text{ V}$ will be achieved in multiple configurations of HBFC in the next 36 months. The maximums could probably be improved by 30-50% if substantially more effort is devoted to this type of device than is presently contemplated. It is likely in fact that fuel cell optimization studies will indicate that values of about 30 ma/cm^2 and 0.72 V are more appropriate for design considerations at the present time. Since, however, this output is good for a secondary battery, solid practical achievements (orbital unmanned missions) may be anticipated.

2.3 Dual Membrane Fuel Cell

A number of factors indicate the advantages possessed by the DMFC. The membranes are continually in equilibrium with $6\text{N } \text{H}_2\text{SO}_4$, thereby eliminating problems related to water balance and drying of membranes (Reference 21). Moreover, the removal of generated heat can be efficiently performed by circulation of the electrolyte. Finally, since water formed at the cathode migrates into the central electrolyte reservoir, (Reference 3) we essentially eliminate the water transfer system required in the SMFC, eliminate complexity and increase reliability.

Factors detrimental to the achievement of higher operating current densities in the device are the good probability of the low activity of equilibrated H_2SO_4 in the membrane thereby lowering the conductivity substantially as compared to HBr of the same concentration in the membrane and also, most importantly, the formation of a water film on the oxygen electrode-membrane interface, suggests a limiting factor, the diffusion rate of the water from the interface into the membrane and the central reservoir. The water film appears to have a definitive means of leaving the area of the oxygen electrode by ordinary mass diffusional processes. If one assumes a diffusion constant of an order equivalent to that used in calculating limiting currents in membranes and taking into account the ambiguities in working with activities at membrane interfaces, then a rate of migration of water or more properly H_2SO_4 up to the O_2 electrode of about $8\text{-}16 \text{ ma/cm}^2$ for a membrane .050 cm thick can be calculated, or values of about $24\text{-}48 \text{ ma/cm}^2$ for membranes .0165 cm thick. It is interesting to note that the former value agrees rather well with the results obtained during the course of a research program related to the DMFC (Reference 3). It appears likely that using thinner membranes and with sufficient development, current densities of $40\text{-}50 \text{ ma/cm}^2$ at $.67 - .63 \text{ V}$

can be achieved in multiple configuration within the next few years. Possible improvements in this area might result from operating at higher temperatures or the removal of water via gas circulation. Of note here, however, is that because of the simplicity and ruggedness of this fuel cell, that fuel cell units have been offered to industry and government since 1962, (Reference 21).

3.0 Summation

The writer has taken operating parameters that he feels may be achieved within the next 18 months for multiple fuel cells of the three general classes of devices discussed in this paper bearing in mind that one of them, HBFC, is fundamentally used as a secondary battery. Of particular interest are projections of approximate weight volumes and power density based on projections of reasonable voltage and current densities. These are found in Table 1.

Type	Voltage	Amp/ft	Thickness (inches)	Pounds/ft ²	Volume(ft ³)	watts/ft ²	Kw./ft ³	Watts/lb
SMFC	.72	75	.205	1.37	.0171	55.0	3.2	40.2
DMFC	.72	30	.194	1.97	.0162	21.6	1.33	10.97
HBFC	.72	30	.165	1.67	.0138	21.6	1.56	12.92

Table 1. Volume and Weight Factors

It is important to reiterate the basis on which the calculations were made.

1. The weights and dimensions refer to a unit cell with no instrumentation, electrolyte holdup, water removal or any other system factors considered. For instance, it is clear that in long missions requiring primary cells, the increased weight of fuel needed will tend to improve markedly the watt hours/lb obtained from the system. It is because of this variability of missions in space, on land, or in the sea that no attempt has been made to go beyond the unit cell structure in analysis. Table 2 however, should be of value as a general starting point for systems analysis and is presented in the non-metrical units for engineering convenience.
2. The SMFC and DMFC are primary cells and therefore not strictly comparable with HBFC.
3. The SMFC has been the subject of a far greater investment of time and effort than either the DMFC or the HBFC. It is almost certain that the values of watts/lb and Kwatts/ft³ for the latter, two would increase by a factor of 2-4 times with an intensive development effort. Projections made in this paper assume that the development of neither the DMFC nor HBFC will be at as high a level in the next three years as has been the case with the SMFC.

Little has been said about quasi-membrane systems, such as gelled electrolytes and electrolytes absorbed in materials such as asbestos. In general, it is our feeling that with regard to gas permeability, retention of electrolytes under accelerative or vibrational forces, removal of waste water and heat that such systems are as yet unproven compared to ion membrane fuel cells. This in no sense indicates however, that systems such as H₂ - O₂ regenerable fuel cell with asbestos electrolytes (Reference 26)

or other primary systems (Reference 27) may not come to fruition in the future.

It may be of value, hazardous though it always appears to be, to suggest possible research and development areas that appear promising over the next few years:

1. Firstly, it is of some value due to advances in producing thinner membranes (Reference 5) to regard the membrane as less of a structural electrolyte and more as a diffusion barrier up against an electrode. In this conceptual framework we find that the membrane for instance, can be regarded as a means for producing low cost porous electrodes since thin membrane barriers will lessen the need for the elegant procedures used at present for preparation of metal and carbon electrodes. Moreover, such combined electrode membrane systems could be used in various electrolytes. Finally, if very thin membranes are used (<0.01)cm., there should be little difficulty in eventually sustaining current densities in excess of 200 ma/cm² at reasonable voltage levels.
2. Inorganic membrane systems have strong potential as intermediate temperature range (100 - 200°C) solid electrolytes both as cationic and anionic systems. Recent results (References 28, 29) indicate that novel inorganic systems have achieved resistances of 2-3 ohm cm.² at 115°C.
3. Research relevant to attaining a high level of quality control for membranes and membrane electrode assemblies would appear to be of much value in promoting the commercial manufacture of multiple unit cells.
4. The exploration of the advantages in using liquid ion exchangers would appear to be of value.
5. Although considerable effort has been expended in recent years in basic membrane research (References 5, 9, 10, 12, 13, 17, 30) intensified and well planned efforts may yet bring important breakthroughs in this field.

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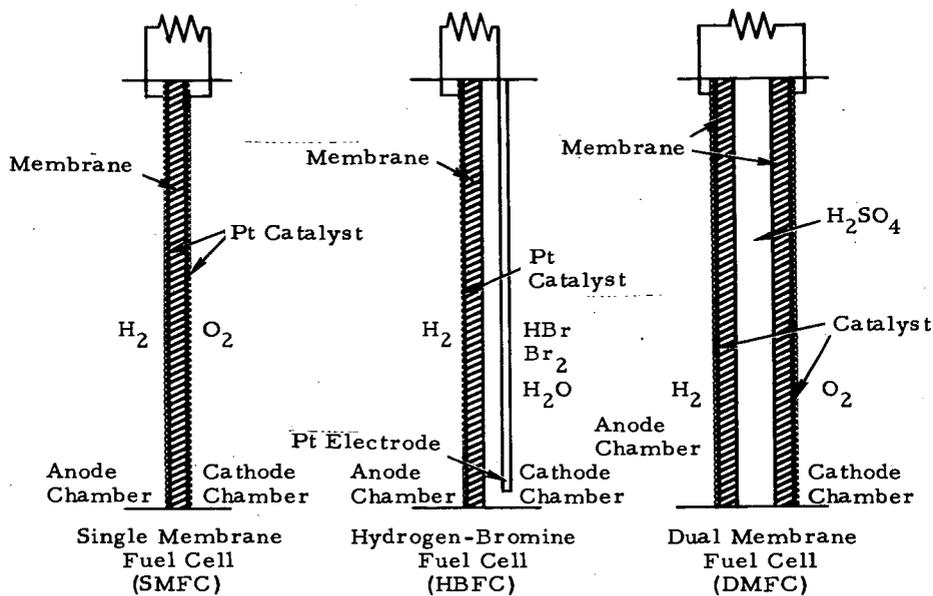


Figure 1. Three Representative Ion-Membrane Fuel Cells

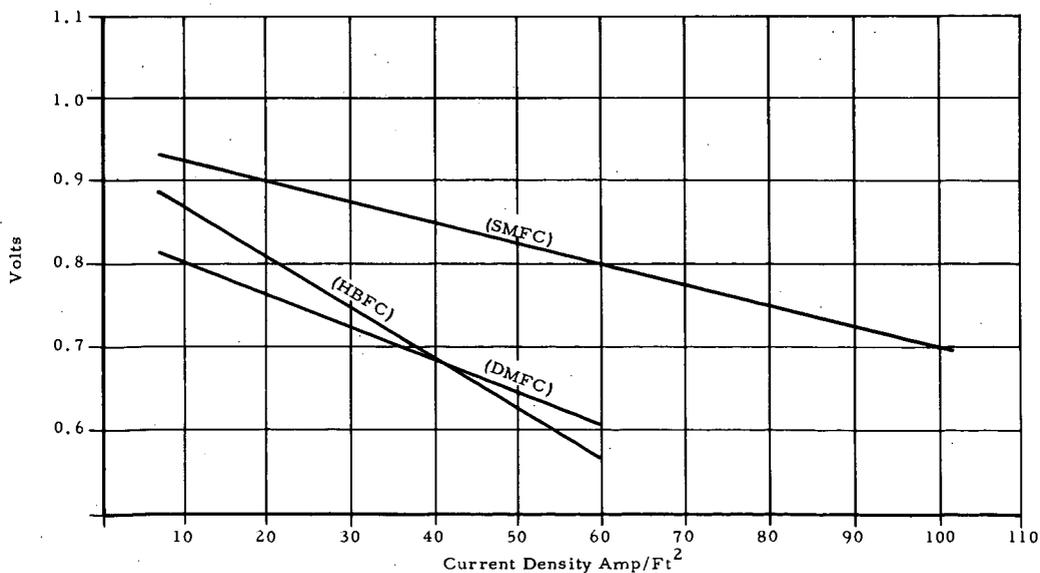


Figure 2. Comparison of Discharge Curves for SMFC, HBFC and DMFC