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COMMERCIAL PHOSPHORIC ACID FUEL CELL SYSTEM TECHNOLOGY DEVELOPMENT

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U.S. DEPARTMENT OF ENERGY
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Fourteenth Intersociety Energy Conversion Engineering Conference
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ABSTRACT

A review of the current commercial phosphoric acid fuel cell system technology development efforts is presented. In both the electric utility and on-site integrated energy system applications, reducing cost and increasing reliability are the technology drivers at this time. While joint technology is the attainment of some goals, which manifests itself in a number of ways, this has been materialized. The differences in approach among the three major participants (United Technologies Corporation (UTC), Westinghouse Electric Corporation/ Energy Research Corporation (ERC), and Engelhard Industries) and their unique technological features, including electrodes, matrices, intercell cooling, bipolar separator plates, electrolyte management, fuel selection and system design philosophy are discussed.

BACKGROUND

For a number of years the Phosphoric Acid Fuel Cell has been the leading candidate fuel cell power plant system for terrestrial applications. Initially, development funds came primarily from electric and gas utility sources, from fuel cell manufacturers, and from the U.S. Army. The emergence of the Nation's energy program provided new direction coupled with increased government support for the development of commercial fuel cell power plant systems. The commercial field, the phosphoric acid fuel cell was clearly identified as the near-term or first generation system aimed at both utility electric generation as well as on-site integrated energy systems. Currently, three major contractors or contractor teams are active in the terrestrial phosphoric acid fuel cell field: United Technologies Corporation (UTC), Westinghouse Electric Corporation (ERC), and Engelhard Industries. This paper is a report of the status of these major phosphoric acid fuel cell development efforts, with emphasis on the differences among the contractors and the unique technological features.

Similarities exist in the basic cell technology of the three major contractors in that all three employ carbon or carbon paper electrode structural elements, platinum-supported-on-carbon catalyst layers and silicon carbide/Teﬂon matrices. However, beyond this, the various technologies become very diverse.

At present, the UTC, the technology leader, is working toward commercializing fuel cell power plants for both electric utility and on-site, integrated energy (OS/IES) applications. The electric utility program is in the system demonstrations or operational feasibility phase with a 4.8 MW module test scheduled to be conducted on the Con Ed network in mid-1980. The OS/IES program is in the engineering and design phase of a prototype 40 MW system. This is to culminate in a prototype system demonstration test in mid-1980.

The 4.8 MW demo test represents an earlier phase of cell development than the 40 MW prototype. There, therefore, differences exist in the basic cell configurations of the two systems. However, it is expected that the general characteristics of the cell and stack technology to be developed for commercialization will be very similar for both applications. Both will employ similar catholyte layers, two-phase liquid cooling systems, fibrous carbon/graphite cell elements and reactant seal and supply systems. Though similar, some optimization of various aspects of the technology will be required to address the differences in design power level and operating conditions of the two applications. The present electric utility system (4.8 MW) operates at 375°F and 50 psia over a profile from 1/4 to full load; for the ultimate commercial power plant, current thinking by UTC is to utilize a large area cell operated at approximately 400°F and up to 120 psia. On the other hand, the OS/IES is to be operated at atmospheric pressure, 375°F, over a load profile from open circuit to full-rated loads.

Of the competitive suppliers, ERC has been in the OS/IES development effort the longest. In 1970, ERC contracted with the Army to develop a methanol fueled phosphoric acid power plant; a fully automatic 1.5 MW demonstration unit was delivered in 1978. DOE (then ERDA) contracted with ERC in 1977 to apply the experience gained under the Army program to the somewhat different requirements of OS/IES. In 1978, ERC teamed up with Westinghouse, a marriage that added system analysis, system design, and marketing capability to ERC's electrochemical technology/engineering background.

The Westinghouse/ERC program is at the point where most of the enabling electrochemical component technology has been developed. Presently, the electrochemical components are being optimized for cost and life, basic design and development is starting for other power plant components and an initial system design effort is starting. The Westinghouse/ERC power plant is the DIDS (Distributed Gas) cooling concept. In this cooling scheme, the air feed stream is split inside the manifold into a reactant stream and a coolant stream. The two streams flow independently into the fuel cell stack and are merged in the exit manifold.

Westinghouse's approach is to develop the OS/IES to be a fuel to electric conversion device, but a total energy system that will supply all the space conditioning, water heating, and electric power requirements for a residential or commercial application.

Engelhard, contracted with DOE in 1975 to study several fuel cell applications and to develop fuel cell stack technology. Their previous experience included research on chemistry and physics of the electrochemical fuel cell. They also have an Army funded fuel cell development contract. Presently, Engelhard is concentrating on stack component development and is beginning to define application fuel combinations in preparation of an OS/IES system conceptual design effort. The component development effort has resulted in several unique approaches to fuel cell design. One area of innovation is the bipolar plate, the device which separates and directs the flow of reactants as it provides electrical conduction between individual cells. The conventional bipolar plate is a single piece of conductive material with reactant flow channels either molded or machined on either side. Engelhard's approach is to split the bipolar plate into three sections, an impervious cen-
ter section (for reactant separation), with an open-cell foam section on either side (for reactant flow). All sections are made from organic precursors that are graphitized when densified. This process is very compatible with mass production and permits considerable cost savings over one-piece, bipolar plates which must be individually molded or machined. Engelhard has also developed a process that can be used for conventional materials and fabricated using conventional furnace brazing techniques. The coolant is a dielectric liquid. This cooler offers potential cost reduction over other liquid and ebullient liquid coolers.

Phosphoric acid fuel cell technology and development efforts for both the electric utility and OES/IES applications are directed toward reducing cost, increasing performance, increasing life, and improving reliability. These, in turn, can be reduced simply to cost and reliability goals. In the technology area, the most vexing problem, the long-standing barrier to the attainment of these goals has been materials. In the cell catalyst layer, the carbon support must resist oxidative corrosion while the catalyst must resist dissolution and sintering at the operating temperature, pressure, and potential. Both cell and fuel processor catalysts must possess sufficient tolerance to fuel contamination. The carbon/graphite cell and stack materials must possess just the right combination of structural integrity and electrical conductivity to be durable, and not contaminate. Metal parts throughout the system must possess the right structural and thermal properties, and also be durable. Finally, all materials must be well-tolerated and easy to manufacture. It has been very difficult to find and to develop materials that could meet, simultaneously, the cost and reliability goals. The approach to solving these problems has involved technology development efforts guided by system trade-off studies.

Beyond materials, a difficult problem has been the ability to provide the cell stack with sufficient electrolyte to contain the cell stack over the temperature range of operation (50 to 120 psia). From the overall power plant standpoint, the optimal pressure and temperature depend not only on stack technology and development, but also on the cost and performance implications upon balance of system (turbocompressors, heat exchangers, piping, etc.).

UNIVERSAL TECHNOLOGIES CORPORATION

CELL STRUCTURE - The advanced cell structure concept is illustrated in Figure 1. The ribbed substrate is UTC's approach to lowering cell stack cost and, simultaneously, increasing electrolyte capacity. In part, the cost reduction is brought about by the substitute for the conventional 2-week molding and curing process produces a complex bipolar separator plate. Aside from being complex, the molded process method places a limitation on the size of the plate that can be fabricated. Eliminating the size constraint on the cell structure thereby provides the possibility to go to a higher and more cost effective cell. The unique features of the integral ribbed substrate concept are: 1) replacing with a simple impermeable flat plate the complex bipolar/separating plate (which normally contains a ribbed reactant flow field on either side perpendicular to each other); 2) transferring the function of each solid ribbed flow field onto a ribbed porous element which, after deposition of catalyst on one side, behaves like an electrode and which is also the water/oxygen transport path. Figure 1 illustrates the differences between the molded cell and the ribbed substrate cell approach. The ribbed substrate is fabricated from a blend of carbon fibers and resin which are 1) made into a preform, 2) graphitized, and 3) filled flat and ribbed in a single pass out of a milling machine.

In addition to this method of forming the ribbed substrate, an advanced method with even lower cost potential, is being pursued under DOE contract. The key difference is that instead of forming the initial structure from a blend of fibers and resin, the process begins with a fabric-like material. Currently, a needle felt precursor has been developed and successfully tested.

HIGHER TEMPERATURE AND PRESSURE OPERATION - Quantitative data on the performance increases due to higher temperature (375°F to 425°F) and to higher pressure operation (50 to 120 psia) have been obtained. At initial time, an expression was obtained for the effect of reactant pressure change (15 to 150 psia) upon IR-free cell voltage for a cell operating at a constant 300 ASF.

\[ \Delta E_{cell} = b_2 \log P_2/P_1 \] (1)

where \( P_1 \) is reactant pressure and \( P_2 \) is the sum of the anode Nernst (thermodynamic) effect and cathode Tafel slope (kinetic) at the given temperature.

At 120 psia, 400°F, 25 psia, and 300 ASF, however, as expected, the higher temperatures and, to a lesser extent, pressures also cause an acceleration in the decay rates. In the UTC power plant system, increasing pressure without increasing temperature is not possible because of the interdependence of cell coolant and reformer conditions. Progress has been made in reducing the sharp cell performance decay rate occurring during high temperature and pressure operation. The rate of decay has been reduced from 60 psia per 1000 hr, to approximately 12 psia per 1000 hr, which is the 4.8 MHz decay rate at 50 psia. (See Figure 2)

From the overall power plant standpoint, the optimum pressure and temperature depend not only on stack technology and development, but also on the cost and performance implications upon balance of system (turbocompressors, heat exchangers, piping, etc.).

INTERCELL COOLING - Two-phase water cooling is the method used. Thin-walled, 2-pass copper tubes with a stainless steel header are the latest design. The coolant is a dielectric liquid. This cooler offers potential cost savings over one-piece, bipolar plates which must be individually molded or machined. The coolant is a dielectric liquid. This cooler offers potential cost reduction over other liquid and ebullient liquid coolers.

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much less importance than years ago when unsupported electrocatalysts were used. However, the recent sharp rise in fuel cell research with recent operation for the 40 kW system (2) versus the 4.8 MW system increases the importance of electrolyte cost particularly for the OIGAS system.

WESTINGHOUSE/ERC

Probably the most important innovation of the ERC technology program is the DIGAS (di-stributed gas) cooling method, which is illustrated in Figure 3. The DIGAS method distributes process air to both the cathodes (via bipolar plates) and to special cooling plates. The total amount of air, that required for reaction plus that required for cooling, is supplied to the air inlet manifold. The air then flows through the cell via either the cathode flow channels (from the bipolar plate or the channels of a special cooling plate. All of the air is collected in a common exit manifold and flows to an external heat exchanger where heat is removed. The oxygen depleted air is then mixed with fresh air, and the mixture is added to the cell in the same manner as a bipolar plate is stacked. No special manifolding, connections or seals are required.

Process gas cooling is the simplest of all. There are no special cooling plates or cooling systems needed. Several times the stoichiometric reaction requirement of cool air is supplied to the stack. All the cooling air enters the gas channels of the bipolar plate. Upon exiting the stack, the air can be bypassed or recycled as in the DIGAS method.

Liquid cooling is by far the most complex and expensive. It involves passing a liquid coolant through cooling plates or a collection of liquid cooling plates. Standard heat transfer materials such as copper or aluminum are corroded by phosphoric acid and must be protected. Inexpensive metal fuel cells are not particularly successful in composites present difficulties in sealing and making connections. Finally, the liquid itself and coolant lines provide a possible shorting path in the cell (short currents result in parasitic losses) which must be minimized.

ELECTROLYTE LOSS - Since the vapor pressure of phosphoric acid (hence electrolyte loss) is a weak function of temperature, the main consideration here is the amount of gas flowing past the electrodes to carry off electrolyte. In both DIGAS and liquid cooling methods, a small excess of reactants flow past the electrodes, and in a process gas stack all of the cooling air must pass the electrodes. Process gas cooling has the highest electrolyte loss which translates to the shortest life or the longest mean time between electrolyte replacement.

RELIABILITY - For both process gas and DIGAS, reliability is high since there is no special cooling fluid and no complex manifold or connections. A leak in the stack liquid cooling system would cause a shutdown while the leak was repaired or the defective cooling plate replaced. If an organic cooling fluid were used, a leak could conceivably poison the catalyst and make replacement of the entire stack necessary. Most air leaks could be ignored.

EXTERNAL HEAT EXCHANGE - Heat recovery is by far the best with a liquid or two-phase liquid cooling system. Heat recovery is possible, though more difficult, with either of the recirculating air cooling systems.

COST COMPARISON - This is an estimate based on materials used and construction complexity; it reflects the materials and construction problems of liquid cooling.

TOTAL DIFFERENTIAL TEMPERATURE - This concerns temperature gradients across a fuel cell stack. The total temperature differential, AT, between any two points in the stack contains two components; a AT in the stack due to the temperature gradient across the stack (perpendicular to both reactant flows) and a AT in the flow direction (parallel to one reactant flow). It is important to maintain the stack temperature within a fairly narrow band. If the temperature drops too low, CO poisoning of the catalyst becomes a problem, and if the temperature is too high, the operating limit of the stack material is exceeded. A commonly accepted operating range is between 350° and 480°F. Since very little difference in flow direction component of the total AT. Also, since the coolant directly contacts every cell, the inlet area is cooled more than in other methods; this accounts for the large AT in the flow direction. For both the DIGAS and liquid cooling methods, the same amount of coolant is used. This sets the stacking direction AT at 15°F for both systems. The difference in flow direction AT results from the differences in liquid and gas heat transfer characteristics.

TOTAL AUXILIARY POWER - These requirements are mainly a function of the amount of coolant circulated and the cross-sectional area of the coolant passages. As expected, the power requirement for pumping a liquid coolant is quite small. The air flows through the cathodic channels of the bipolar plate, the power requirement is quite large for the process gas method. Power for DIGAS lies between the two. The same amount of air must be circulated through the stack as in the process gas method, but a large fraction passes through the large area cooling plate passable heat drop.

PRESSURE DROP ACROSS CELL - This is a function of the air flow through the cathodic channels of the bipolar plate. The same amount of air is required for both DIGAS and liquid cooling, hence the same pressure drop. The high pressure drop for process gas cooling reflects the high air flow rate required through the cathodic channels.

Based on the above considerations, ERC has concluded that the DIGAS concept offers the best compromise between reliability, life-cycle cost, and heat recovery.

Westinghouse has recently made a more detailed study of DIGAS cooling. Under DOE contract(3) they developed a lumped parameter fuel cell stack simulation code that calculates reactant gas composition, current-voltage characteristics, and cooling characteristics for an air cooled fuel cell stack.
In the model, the cell area is broken down to a grid of finite elements so that temperature and reactant composition, as each varies from point to point in a cell.

As discussed previously, one of the major drawbacks of DIGAS cooling is a higher total differential stack temperature than that of liquid cooling. Westinghouse is presently redesigning the DIGAS cooling plates in an effort to reduce the differential temperature. Results of the simulation show that a 28°F differential temperature can be achieved with proper design. This matches what can be achieved with liquid cooling.

Wesnghouse is expanding their computer model to include simulation of the other subsystems in the fuel cell power plant and total energy system. The model includes performance and economic calculations so that trade-offs can be made that will optimize the total energy system as a whole rather than optimizing just the fuel cell power plant itself.

ENGELHARD INDUSTRIES

The unique features of the Engelhard OS/IES effort currently are in the following areas: 1) development of a fuel conditioner that will operate on methanol (methyl fuel); 2) novel bipolar plate approaches; 3) liquid intercell cooling; and 4) matrix and electrolyte transport reservoir technology. In the current two-year contract with DOE the electrocatalysis task is solely funded by Engelhard. Therefore, the details of any unique developments are proprietary.

FUEL PROCESSING - Methanol will be initially used in the Engelhard OS/IES natural gas, the choice in both the UTC and Westinghouse/ERC programs, will receive emphasis in later phases of the work. Methanol selection was based upon its projected availability from coal in the 1990 time frame. A subscale fuel processor is being readied for parametric investigations.

BIPOLAR PLATES - In the stack area, two novel bipolar approaches appear promising. Under subcontract, Pfizer is developing chemically resistance carbon (vitreous, carbon and graphite) structures starting with reticulated vitreous carbons or cloths. One of these structures, the so-called B element, is impermeable to gas transport and will serve as the bipolar plate connecting two adjacent cells. See Figure 4. (In the UTC ribbed substrate integral cell concept, this is UTC's separator plate.) The other structure, the so-called A element, is porous to permit fuel or oxidizer transport to the electrochemically active electrode areas which could be on the A elements. Graphite structures using Pfizer's chemical vapor deposition technology are being utilized to help produce the required properties in both A and B elements. The resulting bipolar plate consists of a B element sandwiched between two A elements. Electrolyte storage can be accommodated in the A element.

In the second approach, thin graphite plates are separated by a gas-impermeable layer of a chemically resistant material (such as graphite or plastic) that permits satisfactory electrical and thermal conductivity. Grooves in each plate will permit reaction transport. If the graphite plates are porous and connected suitably to the matrix, they can provide an electrolyte reservoir for matrix replenishment or for overflow volumes resulting from changing conditions (volume tolerance). Several promising material combinations are under test. The Engelhard/Pfizer bipolar plate approach has some aspects in common with the UTC ribbed substrate integral cell approaches previously discussed.

INTERCELL COOLING - A brief discussion of the liquid intercell cooling approach employing a dielectric fluid, the Engelhard method, was discussed previously in connection with the Westinghouse/ERC cooling approach. The Engelhard design makes use of baffles to provide good heat transfer control yet designed for ease of fabrication. Not yet determined is the suitability of the dielectric fluid selected (Monsanto Therminol 44) or the ability of the aluminum cooler to hold up for the five year stack life goal under the corrosive acid environment of the fuel cell stack.

MATRIX - The matrix effort emphasizes materials capable of operating at temperatures up to 400°F and construction that results in good electric and thermal conductivity, good transport (flow) properties, and satisfactory reactant crossover resistance. A thin SiC-fluorocarbon matrix is laminated to each electrode. Improved electrolyte transport, needed when operating conditions change, is provided by sandwiching an electrolyte transport member between the two laminates. This electrolyte transport member also facilitates electrolyte replenishment to the matrix from a storage area.

CONCLUDING REMARKS

As part of the Nation's energy program three major contractor or contractor teams (UTC, Westinghouse/ERC, and Engelhard), active in the terrestrial phosphoric acid fuel cell field, are receiving government...
support to develop commercial fuel cell power plant systems. At present, only UTC, the technology leader, is working toward commercializing fuel cell power plants for both electric utility and OS/IES applications. The other contractors are a few years behind in their OS/IES development efforts.

While similar in many respects, significant technological and system differences exist among the three contractors. These include intercell cooling, bipolar/separator plate, electrolyte management, materials, fuel selection, and system design philosophy.

Phosphoric acid fuel cell technology/development efforts for both the electric utility and OS/IES applications are directed toward reducing cost and increasing reliability. The longstanding barrier to the attainment of these goals, which manifests itself in a number of ways, has been materials.

In addition, for the electric utility application, UTC is pursuing higher temperature and pressure operation (400°F and up to 120 psia). The initial performance gains due to higher temperature and pressure must be balanced against possible shorter life as well as the cost and performance implications upon the balance of the system.

REFERENCES


A review of the current commercial phosphoric acid fuel cell system technology development efforts is presented. In both the electric utility and on-site integrated energy system applications, reducing cost and increasing reliability are the technology drivers at this time. The longstanding barrier to the attainment of these goals, which manifests itself in a number of ways, has been materials. The differences in approach among the three major participants (United Technologies Corporation (UTC), Westinghouse Electric Corporation/Energy Research Corporation (ERC), and Engelhard Industries) and their unique technological features, including electrodes, matrices, intercell cooling, bipolar/separator plates, electrolyte management, fuel selection and system design philosophy are discussed.