

A regenerative zinc–air fuel cell

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Abstract

The zinc regenerative fuel cell (ZRFC) developed by the former Metallic Power Inc. over the period from 1998 to 2004 is described. The component technologies and engineering solutions for various technical issues are discussed in relation to their functionality in the system. The system was designed to serve as a source of backup emergency power for remote or difficult to access cell phone towers during periods when the main power was interrupted. It contained a 12 cell stack providing 1.8 kW, a separate fuel tank containing zinc pellet fuel and electrolyte, and a zinc electrolyzer to regenerate the zinc pellets during standby periods. Offsite commissioning and testing of the system was successfully performed. The intellectual property of the ZRFC technology is now owned by Teck Cominco Metals Ltd.

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1. Introduction

Metal/air fuel cells are one of the more promising alternatives to conventional power sources. These fuel cells have tremendous potential because they are efficient, environmentally safe, and completely renewable. Metal/air fuel cells can be used for both stationary and mobile applications.

Zinc as an anode fuel has an advantage over other metals due to its unique set of attributes which include a low equilibrium potential with respect to hydrogen, electrochemical reversibility, stability in aqueous electrolytes, high specific energy, high volumetric energy density, abundance, low cost, environmental compatibility, and ease of storage and handling [1,2]. In particular, its low equilibrium potential and high over-potential for hydrogen reaction make zinc the element with the lowest standard potential among all the elements that can be efficiently reduced from aqueous electrolytes. This makes zinc uniquely suitable for high energy density and high power regenerative fuel cells.

The benefits of zinc regenerative fuel cell technology over rechargeable batteries, such as lead–acid batteries, are many. These benefits include very high specific energies, high energy

densities, and the de-coupling of energy and power densities. Further, these systems provide rapid on-site refueling that requires only a standard electrical supply.

Hydrogen fuel cell (HFC) technology has been well advanced, and functional systems are now commercially available. However, hydrogen fuel cell technology is currently very expensive, and how to efficiently and safely supply and store hydrogen for mobile applications remains a great challenge. Zinc regenerative fuel cell technology potentially has several benefits over hydrogen fuelled proton exchange membrane (PEM) fuel cells.

- i. The energy density of zinc is about 2500 times that of hydrogen at STP.
- ii. Zinc fuel requires no compression for storage and transport.
- iii. Zinc fuel has no explosive potential.
- iv. A zinc fuel cell utilizes a low cost electrolyte and electrode separators; the cell frames are fabricated by low cost injection molding.
- v. Precious metal catalysts are not required for the cathode. Oxygen reduction in basic systems can be catalyzed with a number of other low cost catalysts such as manganese oxide.
- vi. Zinc has a much lower standard potential with respect to hydrogen which allows the zinc–air cell to operate at a significantly higher working voltage of the hydrogen–air cell.

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Thus, it requires only about three quarters of the number of cells to obtain the same output voltage as a cell stack system.

- vii. Zinc anodes are very facile electrochemically which gives rise to low over-potentials at high current densities.
- viii. Due to its robust chemistry, the zinc fuel cell is not affected by impurities. Since the system utilizes a flowing electrolyte, it serves as a sink for pollutants and other materials that may find entry into the fuel cell.

2. Previous work

Several “zinc fuel cell” systems of different designs have been reported in the past [3]. Early designs used dendritic zinc as the form of fuel because dendrites can easily be electro-deposited from an alkaline electrolyte [4–6]. One disadvantage with dendritic zinc is the relatively large amount of hydrogen gassing associated with the large surface area. Another disadvantage is the difficulty in efficient and uniform distribution of dendritic powders in the cells.

An early and primitive zinc fuel cell, which uses zinc pellets as the fuel, was developed by Metallic Power Inc. (US Patent 6,162,555) [7] and is comprised of 15 cells electrically coupled in a serial fashion. Before discharge, each cell receives a mixture of zinc particles and electrolyte. The zinc particles in each cell form an anode bed. Each cell includes an electroactive zone where zinc undergoes electrolytic dissolution. In this zinc fuel cell or “refuelable battery”, the bottom portion of a full anode bed is in the electroactive zone, immediately adjacent to a cathode. The zinc in the remaining upper portion is in an inactive zone, the hopper, and does not undergo electro-dissolution. In the electroactive zone, the zinc dissolves, the particles reduce in diameter, and the particle bed collapses, allowing particles to fall from the hopper into the electroactive zone. When the cell is refueled, which typically occurs at the end of the discharge period, zinc pellets are fluidized in a stream of electrolyte and pumped into a feed tube which runs the length of the cell stack. The feed tube discharges directly into each cell until each hopper is full of zinc. The discharge and refueling phases occur sequentially. Similar approaches were taken by several other groups (US Patents 5,434,020; 5,441,820; 5,196,275) [8–10].

There are several problems with this approach to cell filling:

- i. High electrolytic shunt currents flow between the cells via the feed tube during refueling causing energy loss and zinc dendritic formation in the fueling path.
- ii. The filling procedure requires careful balancing of flow rates and zinc volume fractions to maximize zinc transfer rates while avoiding channel blockage.
- iii. The relatively long filling times (10–20 min for a typical application) that result even from the best zinc transfer rates.
- iv. The loss of hopper volumes within the cell stack as active, power-producing volume.
- v. The need to measure the zinc level in every hopper.
- vi. The difficulty of mechanically sealing the feed tube against the cell walls sufficiently to prevent zinc dendritic growth between filling procedures.

This paper describes the zinc regenerative fuel cell (ZRFC) developed by the former Metallic Power Inc. over the period from 1998 to 2004. As the first such disclosure since the development of the technology, the component technologies and engineering solutions for various technical issues are described. Also described is a system with the embodiment of these technologies and solutions designed to serve as a source of backup emergency power for remote or difficult to access cell phone towers during the periods when main power is interrupted.

Metallic Power ceased operation in September 2004 for financial reasons. However, the zinc regenerative fuel cell technology had been greatly advanced as will be described below. The intellectual property of the technology is now owned by Teck Cominco Metals Ltd.

3. The novel regenerative zinc fuel cell

3.1. Approach

From the outset of the technology development, Metallic Power was determined to develop a regenerative zinc–air technology that embodied the functions and facility of conventional fuel cells, i.e., the cell stack and fuel reservoir are physically separate. This “modular” approach allows the separate scaling of the energy and power. This had never previously been achieved with any other zinc–air electrochemical system and required several technology innovations. In a hydrogen or gas fuelled cell stack, the gas is fed from the gas reservoir to the cell stack where it is split into equal or nearly equal flows of gas and then fed into each cell anode chamber; each chamber remains completely filled with hydrogen gas during this process. Fuelling is relatively easy to achieve with a gas but much more difficult with dense metal particles.

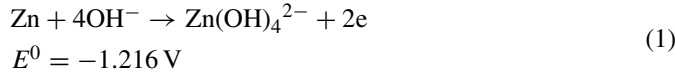
Thus, Metallic Power had several challenges:

- i. At the electrochemical cell level, to discover a method of feeding zinc particles to an anode chamber and to maintain that anode chamber in an essentially full state.
- ii. At the cell stack level, to discover a method of splitting the flow of particles delivered from the fuel reservoir into multiple equal streams so as to feed each cell in the stack.
- iii. To withdraw from the reservoir a stream of zinc particles sufficient to feed the cell stack without having to fluidize the massive bed of particles contained in the reservoir tank.
- iv. To find a method of preventing the growth of zinc dendrites which form as a result of shunt currents that flow between cells in any common electrolyte electrochemical system. Zinc dendrites can have a terminal effect on the cell stack function by blocking the zinc pellet and electrolyte flow channels.
- v. To develop a cathode that would operate at high current densities, above 250 mA cm^{-2} , in a liquid electrolyte system for up to 1000 h. Metallic Power tested virtually every “commercially” available cathode and found that they all lost activity by electrolyte flooding after 100–200 h.

- vi. To develop a zinc electrolyzer capable of making dense zinc pellets of uniform size.

3.2. Fundamentals

In a zinc–air fuel cell, the reaction is as follows:



Oxygen from the air reacts with the KOH electrolyte as follows:



The zinc reaction product, potassium zincate, remains in solution to the supersaturation limit described further below.

The zinc regeneration cycle can begin with zinc oxide or with potassium zincate:

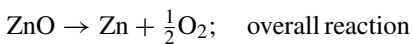
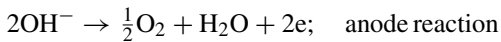
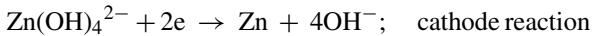


Fig. 1 shows the configuration of the regenerative fuel cell system. Zinc fuel, in the form of small particles, and KOH electrolyte are contained within the separate storage tank; a stream of zinc fuel is withdrawn from the tank and fed into the separate fuel cell where it is divided into multiple equal streams and fed into the cell stack. As the discharge continues, the zinc fuel reacts to form potassium zincate which remains in solution and continues to be circulated with the electrolyte. The end of the discharge phase occurs when all the zinc fuel is consumed.

Regeneration of the zinc particles is performed in the zinc electrolyzer or regenerator, which is shown as a separate entity but actually resides in the fuel tank. The potassium zincate solution is pumped through the electrolyzer and converted into zinc particles; these are stored in the fuel tank. The zinc electrolyzer, which generates the 0.5 mm particles, is of novel design and is described in Section 2.10 in *Zinc Particle Regeneration*.

The configuration described above allows the same flexibility for partitioning of power and energy as in a traditional hydrogen

fuel cell and, in contrast to traditional metal/air batteries, the fuel tank or energy reservoir can be scaled independently of the power. This is possible because of the development of a method to feed a continuous stream of zinc fuel pellets into the fuel cell while undergoing discharge. This is described in Section 2.4 in *Particle Feeding*.

In conjunction with the method of operating the fuel cell on a continuous stream of pellets is the need to split a single stream of zinc pellets and electrolyte into multiple equal streams for delivery into each cell. This was achieved with the development of a novel flow splitter also described below.

3.3. Single cell development

Principal issues with the electrochemical cell were the development of a low cost bipolar frame and a method of feeding the zinc particles. Fig. 2 shows the anode side of the plastic cell frame; the cathode was fixed to the backside of the cell frame and electrical contact was made by passing metal pins through the plastic cell frame (US [11] 6,706,433). These pins contacted the zinc anode particles on the anode side, passed through the plate, and contacted the current feeder nickel mesh pressed into the backside of the cathode. The pins were sealed to the plate to prevent leakage of electrolyte and air between the anode and cathode chambers. The bipolar design allows current to flow from the anode through the bipolar plate to the adjacent cathode with minimal electrical resistance.

3.4. Particle feeding

Zinc fuel pellets and electrolyte are provided in a continuous flow during discharge or on standby if required; oxygen or air is also supplied during discharge or on standby if required. Zinc particles and electrolyte are introduced to the top of the bed. The particles react according to Eq. (1), where zinc and hydroxide ions are consumed and potassium zincate is produced. Note that the concentration of the potassium zincate in the feed electrolyte increases with time of discharge. Conversely, the concentration of hydroxide decreases. Accordingly, the KOH flow rate must be sufficient to provide hydroxide ions at such a rate as to match the reaction stoichiometry at the surface of the zinc particles and remove the reaction product, typically at a rate three to four times that needed for stoichiometry. Clearly, if the electrolyte

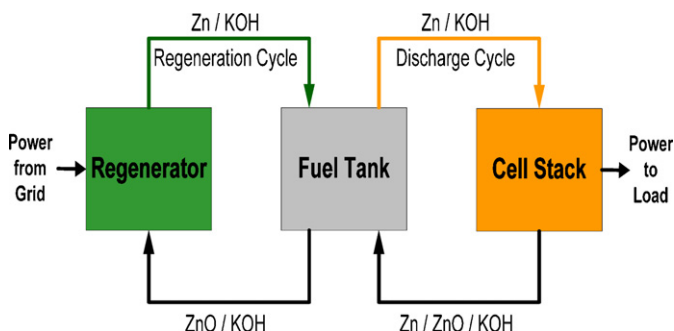


Fig. 1. Zinc regenerative fuel cell (ZRFC) configuration.

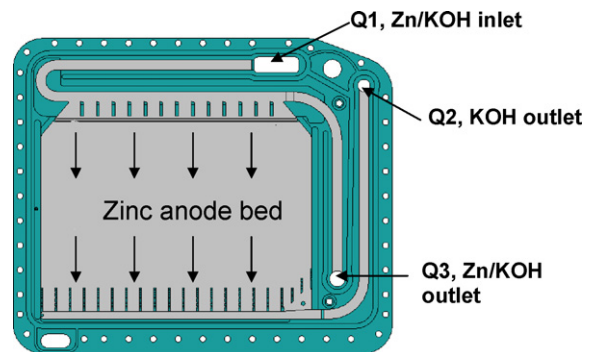


Fig. 2. Zinc fuel cell frame.

flow rate does not meet the conditions above, then zinc oxide will be formed in preference to potassium zincate.

As seen in Fig. 2, pellets and fuel particles enter the cell via flow channel Q1 and the flow passes over the vortex promoters whereby zinc particles are encouraged to drop out of the flow stream and into the zinc particle bed. The zinc particles are trapped within the bed but electrolyte continues to flow downwards through the bed and emerges at the bottom into flow channel Q2.

Electrolyte and zinc pellets, in excess of that required to maintain the zinc bed height, flow through channel Q3 and return to the fuel tank.

Cell frames of this design are bolted together to form a stack such that the current passes in series through each cell. Typically, a stack consists of 12 cells in a bipolar series configuration. In order to achieve the zinc particle and electrolyte distribution in each bundle of six cells, a distribution manifold or flow splitter is placed in an elongated hole at the entrance to Q1.

Channels Q1, Q2 and Q3 for each cell are quite long, about 15–20 cm and, thereby, substantially reduce the shunt currents that flow between cells when configured in a bipolar array. The circular hole at the top left of Fig. 2 is for air ingress; air passes between the bipolar plate and the cathode. The diagonally opposite elongated hole is for air egress. Air was pumped through at three times stoichiometric related to the maximum current of 180 A.

The anode in the Metallic Power zinc fuel cell consists of a substantially static bed of zinc particles immersed in a flow of potassium hydroxide electrolyte. Particles are introduced to the top of the bed and, as the particles dissolve, they become smaller and migrate to the bottom of the bed; thus a gradient in mean particle size exists downward in the bed, larger particles exist at the top, and smaller particles exist at the bottom. At the bottom of the bed is a mesh or gap that allows small particles to fall out of the bed and into the electrolyte flow which removes them from the flow channel and flushes the small particles into the zinc pellet and electrolyte reservoir tank.

In order to retain proper function at high current densities, the electrolyte flow must remain above about $50 \text{ cm}^3 \text{ min}^{-1}$ through a bed with an area of 500 cm^2 and a thickness of 2 mm. In order to achieve this flow, the bed must retain sufficient porosity such that the flow rates can be achieved with reasonable pressure difference of 4–6 psi between the top and bottom of the bed. The previously described concept of the “Recirculating Anode” provides a means for the small particles to escape from the bottom of the bed and, thereby, prevent plugging and severely reduced electrolyte flow. This is achieved by placing a mesh at the bottom of the bed or gap of controlled size between the walls of the anode bed. When particles have reduced sufficiently in size, they fall through the mesh or gap and are swept away in the electrolyte flow.

3.5. Zinc dendrite elimination

A potential gradient is created from a serial array of active cell plates in a cell stack in the shared electrolyte. The magnitude of the shunt currents can be reduced by the common practice of

introducing long electrical pathways to the electrolyte pathway as described above. These shunt currents consume zinc on the positive end of the array and deposit dendritic zinc at the negative end of the array at the point where the electrolyte first contacts the zinc bed. The growth of zinc dendrites is slow but will eventually block the zinc particle and electrolyte flow channels, resulting in cell failure due to insufficient zinc fuel and electrolyte. Metallic Power developed a unique method for mitigating the deleterious effects of these shunt currents by diverting the shunt current into the cathode to produce hydrogen. The approach is described in detail in US Patent 6,153,328 [12].

3.6. Cathode development

The cathode was developed and manufactured by Metallic Power. The cathode was constructed of three layers, an active layer, a backing layer, and a current collector layer. The active layer was prepared by mixing 20% by volume of platinized Vulcan XC-72 carbon (Johnson Matthey) and PTFE powder to provide a platinum loading of 0.2 mg cm^{-2} . This mixture was then milled and calendared into a 0.2 mm layer. The backing layer was prepared by mixing 50% by volume of Vulcan XC-72 carbon and PTFE powder which was then milled and calendared into a 0.2 mm layer. These two layers were then pressed and sintered together. Finally, a thin 0.1 mm expanded nickel sheet was pressed into the backing layer. Cathodes prepared in this manner were able to sustain current densities of 360 mA cm^{-2} for 1000 h. The platinum contributed about 10% to the total stack cost. The dimension of the finished cathode is $23 \text{ cm} \times 28.3 \text{ cm}$.

3.7. Single cell performance

Constant power discharge data for a single cell, with approximately 500 cm^2 of cathode/anode interface area, at 150 W, are shown in Fig. 3. The cell was connected to a separate reservoir for zinc and electrolyte and was maintained at 70°C . At the beginning of the discharge, the electrolyte was at 45 wt.% KOH at zero molar potassium zincate. As the discharge proceeded, zinc particles were continually fed into the anode bed which remained full at all times. However, as zinc was consumed, the zincate concentration increased as a function of the product of current and time, resulting in a decrease in electrolyte conductivity and an increase in cell resistance. The latter effect was responsible for the linear decrease in cell voltage and corresponding increase in current at constant power. At about 560 Ah, there was a dramatic decrease in voltage and the run was terminated at 0.7 V. At 580 Ah, the electrolyte contained 4.1 M potassium zincate. When the electrolyte was replaced with fresh 45 wt.% KOH, the cell performed in an identical manner to that shown in Fig. 1. Single cells of this type were successfully operated for many cycles up to about 1000 h.

It should be noted that because the anode remained fully charged with zinc, cell start up was virtually instantaneous requiring only that oxygen be supplied to the cathode, a process that takes about 3 s. It was planned to maintain the system

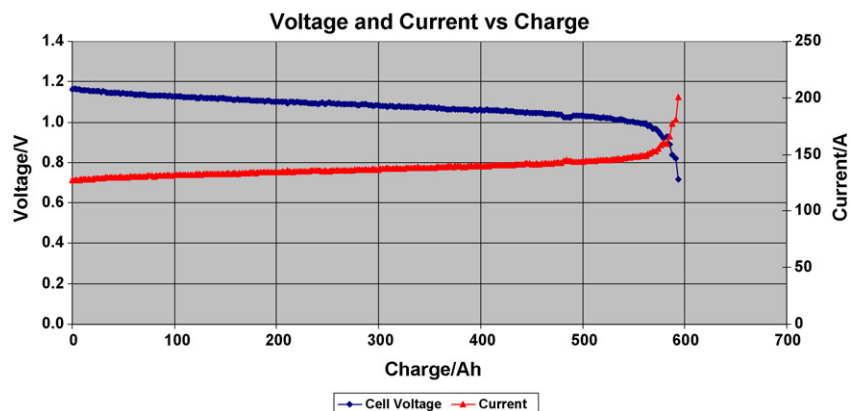


Fig. 3. Single zinc fuel discharge data at constant power of 150 W.

on standby at 50 °C and at low levels of potassium zincate. Under these conditions, the system could deliver the designed power rating of 150 W per cell in 3 s from start up.

3.8. Cell stack development

Twelve cells, stacked in a serial bipolar array, were bolted together to form a 1.8 kW fuel cell. Electrolyte and zinc particles were fed from each side into six cells as shown in Fig. 4. Each six cell group was in a parallel array as far as electrolyte flow was concerned, and separate from each other within the confines of the stack. This approach minimized the task of splitting a single electrolyte and particle flow into 6 equal streams rather than 12 streams; this also reduced the shunt current which would result from the serial connection of 12 cells.

Metallic Power developed a unique six cell distribution manifold (US Patent 6,945,266) [13] shown in Fig. 5. A flow of zinc particles entrained in electrolyte is injected into the entry port situated at the bottom right end of the diagram. The flow impinges normal to the back plate of the manifold and is then distributed into the flow channels which guide the flows into each cell in the six cell array.

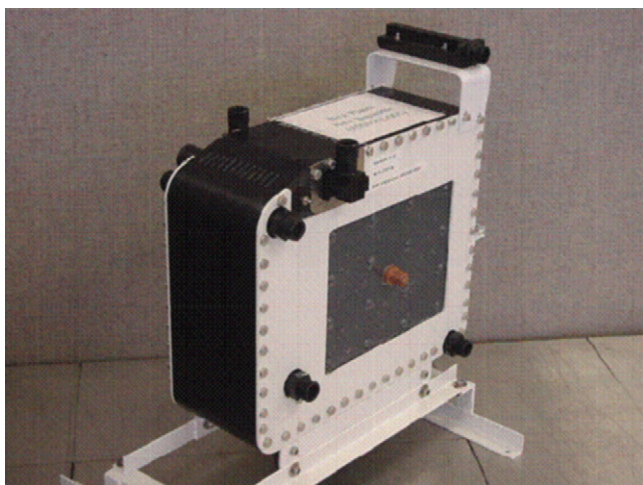


Fig. 4. Zinc fuel cell stack showing fuel inlet manifolds in top left corners and other electrolyte and air inlets and outlets as shown in Fig. 2.

3.9. Fuel tank particle feeding

Zinc fuel and 45 wt.% KOH electrolyte were stored in a 250 l plastic tank. Zinc particles were withdrawn from the tank in a constant stream and fed into the fuel cell. Several methods were developed to create this stream as described in US Patent application 10/661,087 [14]. The most successful method was to create a small fluidized zone of particles at the bottom of an inverted pyramidal tank; these particles then passed downwards through a U tube and then back into the tank and sprayed onto the stationary particle bed. The tube to the main fuel cell feed pump was placed in this stream of sprayed particles. Electrolyte and particles were sucked into the stream and fed into the fuel cells. The ratio of fuel to electrolyte could be easily adjusted by changing the position of the inlet tube.

3.10. Zinc particle regeneration

Regeneration of zinc fuel after the discharge cycle is a necessary part of a regenerative fuel cell system which differentiates it from other systems that do not use on-site regeneration. In earlier stages of development, Metallic Power attempted to develop

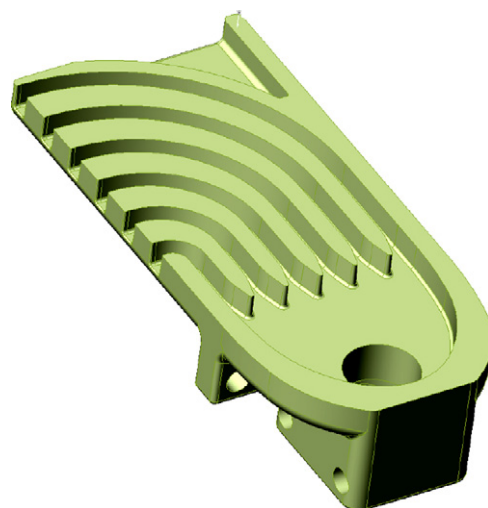


Fig. 5. Pellet distributor manifold.

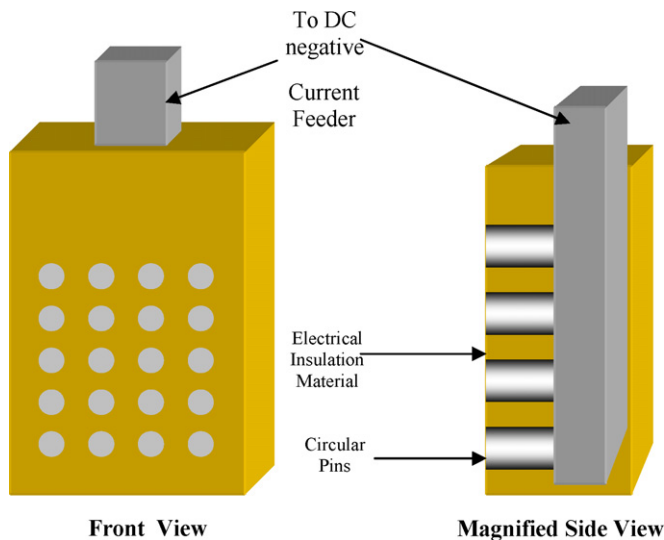


Fig. 6. Structure of the Discrete Particle Electrolyzer (DPE) cathode.

the regenerator using a spouted bed electro-plating method. This method involves a range of technical issues related to the requirement of seeds for particle growth.

The use of discrete particle plating on metal pins embedded in a substrate of non-conductive material was later developed as the technology for the regenerator.

Zinc particles were regenerated from the spent electrolyte by an electrolytic technique which electro-deposited zinc in the form of small 0.5–0.6 mm dense particles (US Patent application 10/424,539) [15]. The particles were grown at high current density, $\sim 20,000 \text{ A m}^{-2}$, on small pins on a cathode electrode surface with a structure as shown in Fig. 6.

Discrete particles were grown on each of the pins until they reached a desirable size, $\sim 0.5 \text{ mm}$; this size was found to have a good balance between fluid dynamic properties and effective surface area for anode activity. An SEM image of particles manufactured via this process is shown in Fig. 7.

Under suitable conditions of current density and electrolyte flow rate and composition, discrete particles grow on the surfaces

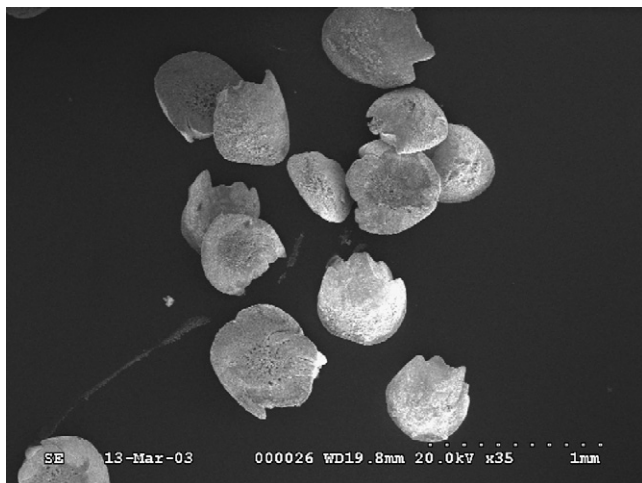


Fig. 7. SEM image of the pellets manufactured using the DPE process.

of the pins, hence the name Discrete Particle Electrolyzer (DPE). In a typical configuration, the cathode is planar and circular and placed opposite a planar and circular nickel metal anode. A mechanically driven scraper is placed between the anode and cathode and rotated about a central axis.

For packaging and shipment, it is most convenient for the fuel tank to be shipped empty and then be filled with the fuel at the user site. It is also more convenient to use ready fuel for the initial fuelling rather than to use the regenerator to generate fuel. For the initial fuel, Teck Cominco has developed a method of producing zinc metal particles of appropriate size, size distribution and composition. These particles were tested and found to meet the requirement for discharge and recharge.

4. Regenerative zinc fuel cell system test

During the summer of 2004, Metallic Power built a 1.8 kW demonstration regenerative fuel cell system. The system contained a 1.8 kW 12 cell stack, an electrolyte fuel tank capable of holding 250 l of 45 wt.% KOH and 50 kg of zinc particles, and a zinc DPE. This system provided approximately 24 h of run time and required 48 h to regenerate the fuel (Fig. 8).

Auxiliary components not described above included a temperature controlled radiator that directly cooled the flowing electrolyte and a lithium hydroxide-based carbon dioxide scrubber. The system was transported from San Diego, CA to a potential customer at a Midwest site, commissioned and cycled three times. Power from the fuel cell was dumped directly into an electrical load.

The commissioning process consisted of the following steps:

- i. Initial physical inspection for damage during transportation.
- ii. Filling tank with water and forming KOH solution.
- iii. Adding zinc pellets to the tank.
- iv. Initial filling of cell stack with zinc particles.
- v. Cathode break-in period.
- vi. Full discharge at full power.

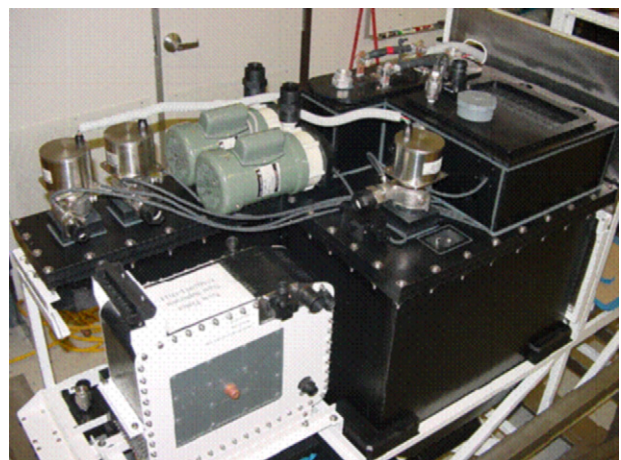


Fig. 8. ZRFC showing cell stack and fuel and electrolyte tank.

Step (ii) was performed by adding water to a mix of solid KOH and KOH·2H₂O. The enthalpy of solution of KOH is negative while that of the dihydrate is positive. When the compounds are mixed in the correct proportions, the addition of water can result in a final solution temperature of 70 °C, the optimum fuel cell operating temperature. The KOH and KOH·2H₂O solids were transported in the electrolyte tank so only water needed to be added to the tank for the commissioning process. The dissolution process required about 30 min.

Step (v) was required because the cathodes are quite hydrophobic and must be fully wetted before full power can be obtained. The process required incremental increases in power under alternate conditions of full air (oxygen) supply and depleted air (oxygen) supply. This step required about 30 min. At the completion of step (v), the stack underwent a full discharge with a stack output of 1.8 kW for 12 h. At this point, the system was placed in zinc regeneration mode for 24 h and the reservoir of zinc particles was replenished. This cycle was repeated two more times before the system was decommissioned and returned to San Diego.

5. Scale-up to a 5 kW (net) system

The advantage of the modular design of the Metallic Power system is that it allows scaling up of the power and energy independently, that is, one can add more cell stacks to increase the power output or one can add more fuel tanks to increase the capacity.

Metallic Power scaled-up the ZRFC to a 5 kW (net) system. This was achieved by essentially placing two 12 cell stacks together to form 24 cells in an electrical series. However, electrolyte and pellets were fed from each side into the 12 cells in a parallel electrolyte flow arrangement. This required the development and placement of a 12 cell particle distributor manifold in the Q1 inlet slot. Data from the discharge of a 24 cell stack are shown in Fig. 9.

The ripples in voltage and current are caused by a prototype boost converter control system used to provide constant 50 V output voltage. Note the rising current as the voltage decreases due to increasing zincate concentration.

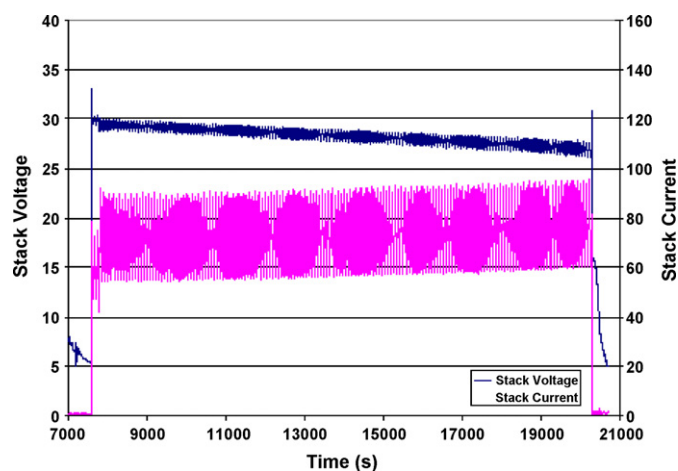


Fig. 9. Discharge data from a 24 cell stack used in the 5 kW (net) ZRFC.

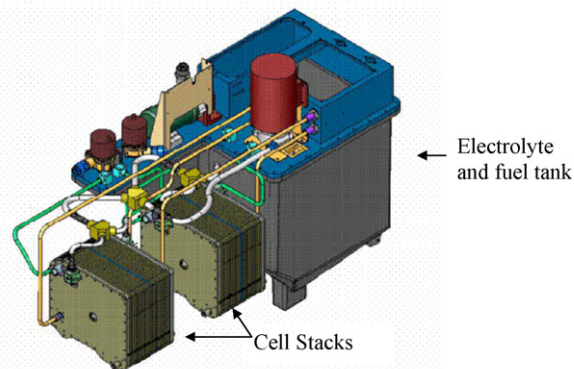


Fig. 10. A 5 kW (net) system showing two 24 cell stacks.

Fig. 10 shows an illustration of the 5 kW (net) system in which two 24 cell stacks were attached to the electrolyte and zinc particle reservoir. The Q1 inlet lines are depicted in white, the Q2 return line in yellow, and the Q3 electrolyte return line in green.

6. Conclusion

During the period from 1998 to 2004, Metallic Power developed the world's first Zinc Regenerative Fuel Cell system. Technology solutions were developed for many technical problems associated with various aspects of the system and the manufacturing processes. The system was designed to serve as a source of backup emergency power for remote or difficult to access cell phone towers during periods when the main power was interrupted. It could provide a net output power of 1.1 kW for 24 h. Specifically, the device contained a 12 cell stack providing 1.8 kW, a separate fuel tank containing zinc pellet fuel and electrolyte, and a zinc electrolyzer to regenerate the zinc pellets from main electricity during standby periods. Offsite commissioning and testing of the system were successfully performed. A 24 fuel cell prototype unit, which allowed scale-up to a 5 kW (net) system, was also developed. Further developments are still needed to determine and resolve potential issues related to product life, robustness and cost of production which have not yet been dealt with by Metallic Power.

There are several main benefits of the Metallic Power system:

1. It is a modular design in that the fuel tank and cell stack are separate and can be scaled-up to cover a very wide range of customer needs for energy or power.
2. It is regenerative; fuel does not need to be transported to the system, a major benefit for remote or difficult to access applications.
3. It uses zinc metal stored at atmospheric pressure; therefore, a simple low cost plastic tank can be used for fuel storage.
4. The zinc fuel is inherently safe and will not explode, providing a higher level of security than hydrogen-based systems.
5. Because of the above attributes, it is potentially lower in cost and simpler to manufacture than PEM-based fuel cells.

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