A follow-on Assessment of the Progress in Refining the Gen2 ZBM Product

for

RedFlow Technologies Ltd.

Brisbane, Queensland, Australia

by

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Purpose

The purpose of this document is to present my findings from the follow-on assessment that I have completed in my study of the scope and success of the improvements made to the initial RedFlow ZBM Gen2 design which has resulted in the development of the ZBM Gen3 product.

Introduction

In early September, 2010, I visited the RedFlow offices in Brisbane, Queensland, Australia, to perform an on-site assessment of the state of the development effort for an advanced Zinc Bromine technology flow battery. Over a 4-day period, I was provided with detailed information on the early development effort of the ZBM Gen2 device. I evaluated initial progress toward commercialism and future plans for full deployment of a truly innovative and quickly maturing version of a utility scale battery using Zinc Bromine flow technology.

My current study addresses and discusses the status of the following technical topics:

- Tank design, materials, fittings and manufacturing methods
- Stack design, materials, fittings and manufacturing methods
- Electrode design, materials, fittings and manufacturing methods
- Hydraulic system design and components
- Electrolyte formulations
- Battery Management System components and algorithms
- Systems operation (e.g. Charge/Discharge/Strip regimes)
- Thermal management

Material and design specifications were provided through documentation sent from the RedFlow Brisbane Offices and through several face-to-face interviews with Stephen Hickey located in the local RedFlow Albuquerque Offices. RedFlow was very cooperative in providing detail information on the design improvements of the Gen2 product that has resulted in a much improved ZBM Gen3 system.

The approach taken by RedFlow in the past three years has focused primarily on improving their initial design in preparation for delivery of a mass producible product that will provide the performance expected from reliable energy storage devices while reducing the cost from its original price point. They have been very successful in meeting the goals they initially set for improving their Gen2 product, migrating through the development of Gen2.5 and culminating in Gen3 which is in final planning for mass production. In my opinion, they have succeeded in developing a ZBM Gen3 Zinc Bromide flow battery that is ready to enter the market for a wide range of applications.

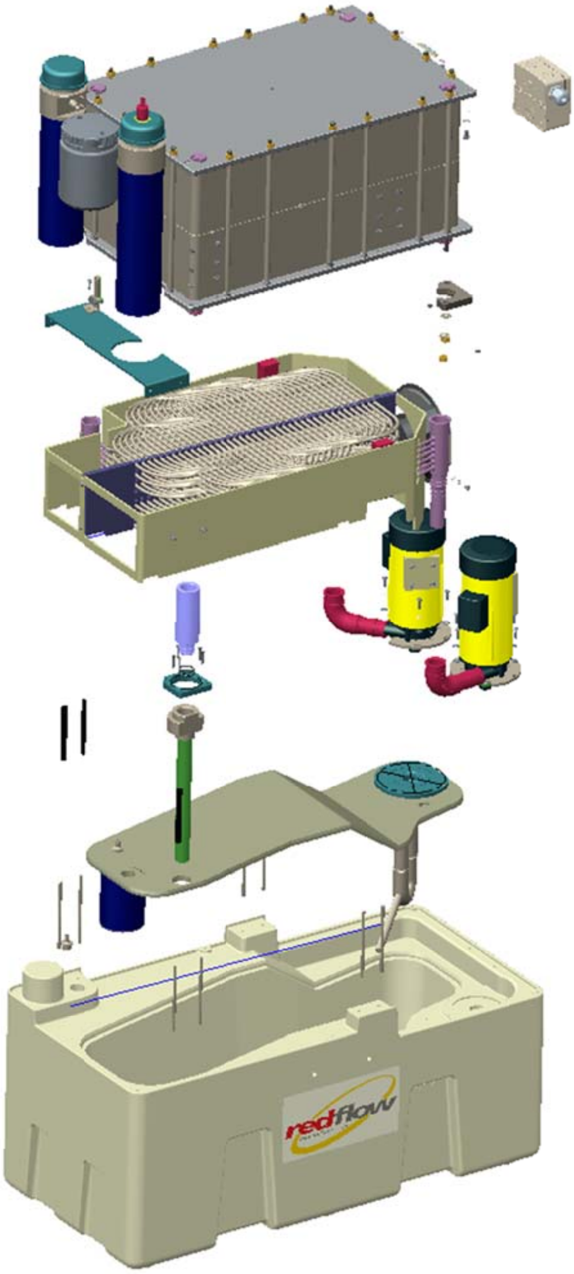
This report will conclude with an overall assessment of the progress that has been made since my initial design review study completed 3 years ago.

Design Improvements

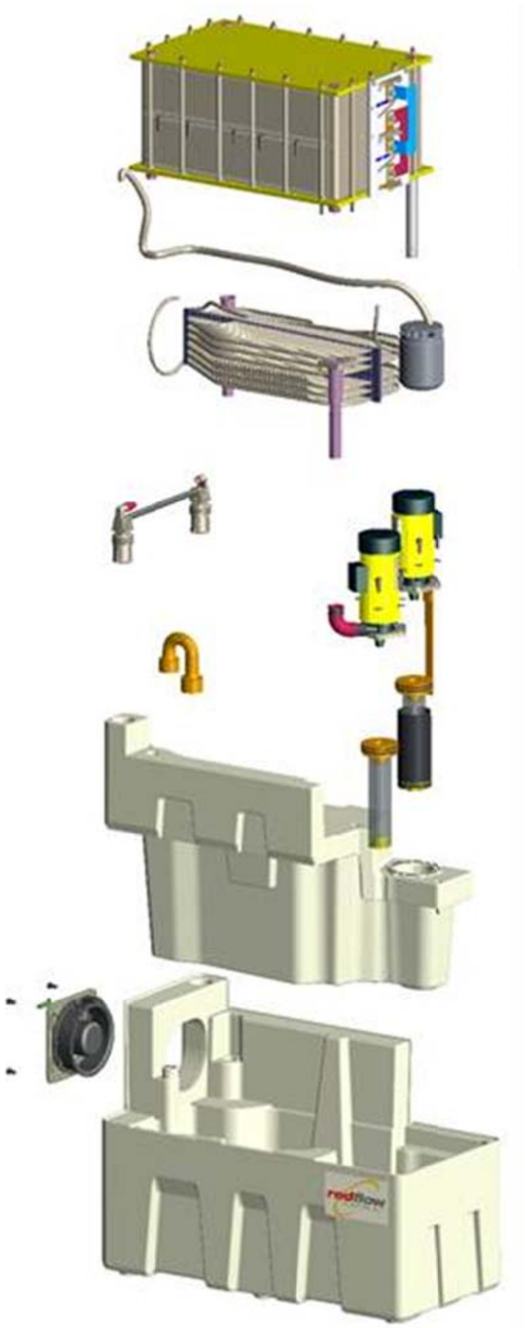
Tank design, materials, fittings and manufacturing methods

Tank design and manufacturing has undergone considerable improvement over the initial Gen2 design. The initial tank design required 23 welds, 11 being critical in order to avoid potential leakage. The follow-on design has eliminated all welds for both the Bromine and Zinc tanks. The Bromine and Zinc tanks were redesigned as individually separate tank systems resulting in the elimination of many welds. Volume of the Zinc tank was reduced from 54 to 52 liters while the volume of the Bromine tank was increased from 32.6 liters to 45 liters, primarily due to the weld eliminating design. This results in a tank volume ratio which is more in line with the requirements of the Zinc-Bromine electrochemistry. Tank redesign also included a major change in the superstructure for the cooler shroud which allows the stack to be bolted directly to the tank using plastic bolts thereby eliminating much of the shroud mounting hardware required in the initial design.

One of the major fittings, the gas handling unit (GHU), required 4 critical welds in the Gen2 design. The GHU was totally redesigned by moving its location from the stack to a location on the tank such that all welds were eliminated. Additionally, the relocated GHU fitting was more than doubled in volume from 2 liters to 8.5 liters which can now capture the total volume of electrolyte in the stacks thereby reducing the potential of overflow. The larger GHU also eliminates problems with priming the pumps because of the additional liquid volume available.



Gen2 tank exploded view

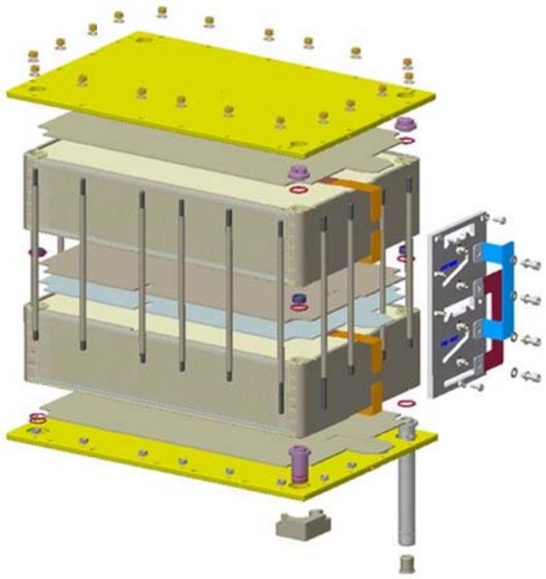


Gen3 (with gen2.5 stack) tank exploded view

Tank redesign eliminated a significant number of separate parts. Overall design modifications reduced the total parts count from 232 to 98 (a reduction of more than 50%) which dramatically improves the manufacturability of the Gen3 product.

Stack design, materials, fittings and manufacturing methods

Stack redesign has been significant in moving from the Gen2 design to the Gen3 design. Most changes were made in order to simplify the manufacture complexities in fabricating the electrodes and while providing for a better flow path while minimizing structural stresses at the interfaces between the electrodes. Collector assembly parts count was reduced to simplify the fabrication process. The two-stack design of Gen2 with 33 cells per stack has been replaced with a single stack of 48 cells helping to simplify the assembly of the stacks. Performance has not been compromised with this change as other modifications have been made to the electrodes and electrode materials that have measurably improved performance. These improvements are discussed in the next section of this report.



Gen2 stack pack assembly

Gen3 stack pack assembly

Electrode design, materials, fittings and manufacturing method

Electrode components are the most important part of the system design and, as such, have been exposed to substantial design revision to improve the life and performance of the Gen3 product. Much has been learned from evaluating the performance of the Gen2 and Gen2.5 products in field applications. Consequently, changes have been implemented to both improve operational performance and life. Electrode surface area has been increased from 750 cm^2 to 1530 cm^2 which will result in reduced current density at full power which is expected to extend the life of the battery. Total battery surface has been increased from 4.95 m^2 to 7.34 m^2 which will also contribute to longer life. Electrode fabrication moulds have been refined through field testing and experimentation to improve clamping leading to better quality control of electrode frame components.

Electrode blanks were originally fabricated using compression moulded pellets. The improved electrode blanks are now made from glass reinforced carbon plastic plates which increases strength, toughness, and conductivity at a lower cost. Before electrodes are assembled in a stack, they are vacuum tested to insure they meet all quality control standards, particularly microscopic fissure or leaks.

Materials have gone through a series of improvements using activated carbon cloth variations in the Bromine electrode that is expected reduce cost while extending battery life. The Zinc electrode has been improved with the addition of a thin, high carbon, high conductivity surface coating which is expected to significantly extend service life. The coating is expected to improve manufacturability leading to improved quality control.

Hydraulic system design and components

The hydraulic system has undergone extensive design improvements. The original pumps were AC magnet drive pumps (below left) which were a primary failure source in the mild Bromine environment. Gen3 pumps are variable speed DC pumps (below right) which have no motor bearings and are expected to operate with a 40% increase in operating efficiency. Furthermore, the pump speed can be varied to suit the operating mode of the battery or power levels.

AC Pumps

Variable speed DC pumps

The use of carbon felt in the Bromine electrodes requires filtering of the electrolyte. Originally, 500 micron mesh filters were used. However, to improve the filter reliability and effectiveness, partial flow filtering was introduced in the Bromine flow to eliminate build-up of fibres in the flow path. Twenty micron filtering was also introduced in the Zinc flow to eliminate particle build-up in the cells and tubes.

During discharge, it is necessary to introduce Bromine Complex into the electrolyte to react with the plated Zinc in the charged battery to result in an electrical current flow. The Complex is a very high density, oily like material that becomes concentrated in the bottom of the Bromine electrolyte tank during battery charging. Initially the inlet assembly that extracts this Complex was manufactured with 7 welds that have been eliminated by using components that snap together resulting in lower cost manufacturing. The Complex must be reintroduced to the electrolyte in a uniform ratio throughout the discharge cycle. This recombination is accomplished in a very innovative way using a venturi metering design eliminating the need for an active pump to combine the Complex with the electrolyte during the discharge cycle.

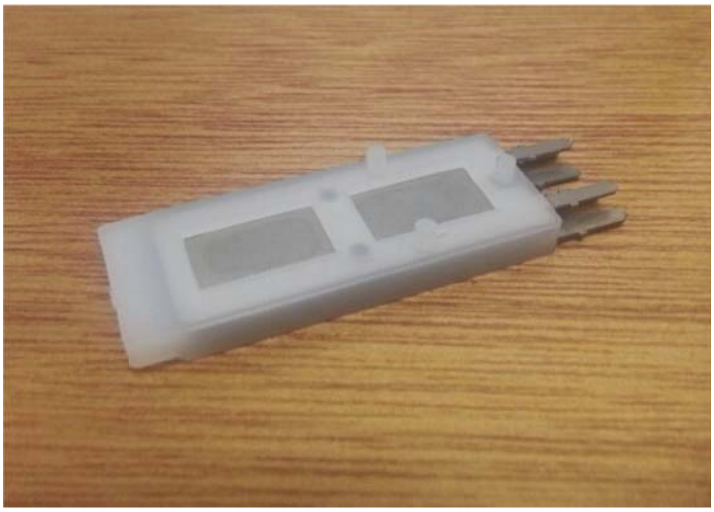
Electrolyte formulations

Electrolyte formulations are critical to system efficiency and life expectancy. Volume of electrolyte has been increased by 20 liters in the Gen3 design. This allows improved conductivity and extends the life of the Bromine electrode. Potential dendrite buildup is minimized with the introduction of a dendrite suppression additive.

Battery Management System (BMS) components and algorithms

The BMS is critical to the moment-to-moment management of battery operations. A primary responsibility of the BMS is to avoid events that could shorten life or potentially damage the battery. Consequently, it is extremely important to have reliable and accurate sensors to measure all transient activity ranging from voltage and current variations to electrolyte temperature changes. It is equally important to have accurate and bug-proof control software in the system controller. Wiring and connections of the monitored points must also have high integrity. In the Gen3 system design, the use of water proof connectors for the analog loom has eliminated failures due to connector corrosion. Redflow has displayed excellent results in their development of the BMS.

Leak detection is also extremely important but, because of the corrosive nature of the electrolyte, leak detection sensors have been prone to failures in the early Gen2 design. In the Gen3 design, a Titanium sensor has been introduced to improve robustness (pictured below). Additionally the introduction of this new leak detection sensor has resulted in lower cost.

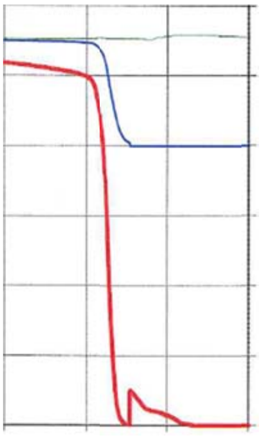


Titanium leak detector

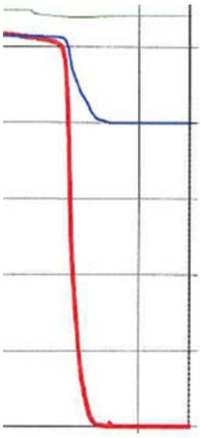
Systems operation (e.g. Charge/Discharge/Strip regimes)

Stripping, the extraction of all plated Zinc from the cell stack at the end of a discharge cycle, is critical to the health of all Zinc plating electrochemical processes. However, stripping, by its nature, is an efficiency reducing operation as the battery is not delivering useful power during the final stripping operation which can last for an extended period. Much work has been done to minimize the stripping period while avoiding damage to the battery. Procedural and material modifications have been introduced in the Gen3 design to minimize the duration of the stripping period and still result in a clean strip of the Zinc electrodes.

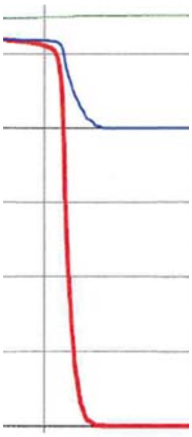
Overall cell geometry and electrode uniformity can be gauged by the amount of zinc still in the stack when the voltage has been electrically stripped to zero through a resistive load. The following figures show the improvement from Gen2 electrode plates through Gen2.5 to Gen3. The red curve depicts the voltage collapsing at the end of an 18 hour charge/discharge cycle. Once 0.1 volts is reached, the resistor is disconnected and any remaining zinc on the electrodes will become visible as a voltage kick. This voltage then decays as the battery continues to strip chemically. The figures below show the Gen2 electrode plates require approximately one hour to chemically strip to 0 Volts. Gen2.5 plates will strip in a matter of minutes while the Gen3 plates require no chemical stripping.



Gen2 Stripping performance



Gen2.5 Stripping performance



Gen3 Stripping performance

Thermal management

Thermal management is conducted using a very innovative cooling radiator that has been greatly improved in the Gen3 design. The larger stack design and modifications to the shroud mount have resulted in a 3.3 m^2 cooling area, up from 2.6 m^2 in the Gen2 design. Cooling surfaces were increased by 20 % due to the tank integrated cooling shroud. The shroud redesign also resulted in the elimination of 5 parts.

An AC fan was originally used when active cooling was necessary. A variable speed DC fan has been introduced in the Gen3 design which is more energy efficient and has a higher maximum air flow for improved cooling. In addition, a fast response temperature sensor and logic provides significant improvement in energy consumption with improved cooling performance.

Future Design Considerations

As the final preparations continue in the move from the Gen2.5 design to the final Gen3 design, activities are in progress to refine some of the current design improvements before the system is approved for mass production. The following is a recap of some of these activities taken from a spread sheet generated by Alex Winter of Redflow and provided to me as supporting documentation. I concur with Alex's observations of the expected improvements that will result from the implementation of these actions.

- Electrode surface area: Total electrode area to be increased from 6.6 m^2 to 8.2 m^2 which will lower current density and Zinc loading for a specific state of charge.
- Dissolved gas and pH: Dissolved gas recombinator and re-acidification device. This will maintain the pH at an artificially low value, protecting the bromine electrode from oxidation. The increased hydrogen formed on the zinc electrode due to the low pH will be recombined and not cause a pH shift. A lower pH increases the electrode potential of the oxygen reaction, increasing its electrochemical separation from the bromine reaction.
- Separator positioning ribs: Replacement of the conductive V ribs used to position the separator with non-conductive ribs reduces the dissolved oxygen in the electrolyte and hence the bromine electrode oxidation wear. Oxygen is produced on the tops of the v ribs due to its proximity to the zinc electrode.
- Bromine electrode surface: 3D activated carbon matrix has significantly higher surface area than ACC8 as well as competitor bromine electrodes. It also has the potential of ablating with battery use, therefore exposing fresh carbon for optimal battery operation. The higher surface area reduces the over-potential, increasing the electrochemical separation the bromine reaction from the oxygen reaction.
- Zinc electrode surface: Pure carbon electrode surface on Zinc electrode has shown two orders of magnitude increase in oxidation resistance particularly during high reverse current (seen during end of discharge/strip). Ablation permits long term operation without loss of performance. The strip performance has improved such that no stripping is needed after reaching 0.1V on discharge.
- Bromine concentration: Higher Bromide concentration in the electrolyte lowers the electrode potential of the Bromine reaction, increasing its electrochemical separation from the oxygen reaction.

Conclusions

In my opinion, RedFlow Pty. Ltd has been very successful in the final design of the ZBM Gen3 product, a very innovative and functional Zinc Bromine flow battery that is ready to move to the next phase of commercialization. Currently, RedFlow is nicely positioned to make a major impact on the emerging energy storage systems market based on several field operations currently in progress, which I have been following closely over the past several years. They are also very active in partnering with system integrators, a function that will be critical to bridging the gap between laboratory development and system deployment. They have avoided many of the errors I have noted in other startup companies involved in bringing new, advanced technologies to market. RedFlow has taken a success-proven path. They have not outpaced their engineering capabilities but have taken a deliberate, conservative stand in bringing a specific product to a specific market at the best price point possible. It has been my observations that only a few energy storage technologies have made a successful entry into the energy storage market; however, RedFlow has managed to avoid many of the pit-falls that have resulted in early failures of previous energy storage systems to successfully enter the energy storage market.

In my opinion, RedFlow is in an extremely strong position to successfully enter the expanding energy storage market.

Author Biography

Garth P. Corey, recently retired as a Principal Member of the Technical Staff, Sandia National Laboratories, had project management responsibilities with the Energy Infrastructure and Distributed Energy Resources Department. Most of his Sandia career was dedicated to communicating his system engineering and battery system management knowledge to engineers involved in the integration of various energy storage technologies with the balance of plant needed for a successful operational energy storage system.

During his more than 15 years at Sandia, he was involved in high technology energy storage R&D projects. He has managed projects that span the utility scale energy storage arena that includes flywheels and ultra capacitor systems, sodium sulfur, nickel cadmium, lead acid, (including advanced lead-acid technologies), and lithium ion batteries, and several flow battery technologies. Much of his time was dedicated to assisting Sandia Renewable Power engineers in the proper integration of batteries in off-grid and grid-tied Photovoltaic systems.

He is a member of the IEEE Power and Energy Society and active with the PES Stationary Battery Committee. In addition to continuing his association with Sandia as a consultant, with responsibilities related to electric energy storage system development, he is also very active in a consulting role to industry in the evaluation of emerging energy storage technologies for distributed energy and storage applications on the national grid.