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# Flow Battery System Design for Manufacturability

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## ABSTRACT

Flow battery energy storage systems can support renewable energy generation and increase energy efficiency. But, presently, the costs of flow battery energy storage systems can be a significant barrier for large-scale market penetration. For cost-effective systems to be produced, it is critical to optimize the selection of materials and components simultaneously with the adherence to requirements and manufacturing processes to allow these batteries and their manufacturers to succeed in the market by reducing costs to consumers.

This report analyzes performance, safety, and testing requirements derived from applicable regulations as well as commercial and military standards that would apply to a flow battery energy storage system. System components of a zinc-bromine flow battery energy storage system, including the batteries, inverters, and control and monitoring system, are discussed relative to manufacturing. The issues addressed include costs and component availability and lead times. A service and support model including setup, maintenance and transportation is outlined, along with a description of the safety-related features of the example flow battery energy storage system to promote regulatory and environmental, safety, and health compliance in anticipation of scale manufacturing.

# ACKNOWLEDGMENTS

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## NOMENCLATURE

| | |
|---|---|
| CFR | Code of Federal Regulations |
| COTS | Commercial Off the Shelf |
| DoD | United States Department of Defense |
| DOE | United States Department of Energy |
| DOT | United States Department of Transportation |
| DETL | Distributed Energy Technology Laboratory |
| ESS | Energy Storage System |
| FCC | Federal Communications Commission |
| GR | Generic Requirement |
| HDPE | High Density Polyethylene |
| IEEE | Institute of Electrical and Electronics Engineers |
| MIL STD | United States Military Standard |
| MRL | Manufacturing Readiness Level |
| MSDS | Material Safety Data Sheet |
| NEBS | Network Equipment-Building System |
| NEMA | National Electrical Manufacturers Association |
| OEM | Original Equipment Manufacturer |
| OSHA | Occupational Safety & Health Administration |
| PPE | Personal Protective Equipment |
| PVC | Polyvinyl Chloride |
| R&D | Research and Development |
| SCADA | Supervisory Control and Data Acquisition |
| TRL | Technology Readiness Level |
| UL | Underwriters Laboratory |
| ZBM | Zinc Bromine Module |

# 1 INTRODUCTION

Flow battery technologies may be applied to provide modular, configurable, and scalable energy storage. Flow battery energy storage systems (ESSs) can support renewable energy generation and increase energy efficiency. Applications may include providing power to remote, off-grid locations (e.g., military sites or remote communities). From a financial and environmental vantage point, flow matteries can help in minimizing expense of and emissions from diesel fuel generators. When used in conjunction with renewable resources such as photovoltaic solar generation or wind turbines, flow batteries can play a part in maximizing energy storage efficiencies as well as reducing use of grid power at peak power rates. Lastly, flow batteries can assist in resolving power shortages after natural disasters, and provide battery backup capabilities.

Currently, the costs of flow battery ESSs are a barrier for large-scale market penetration. These costs are largely dependent on materials and components for flow battery manufacturing, as well as the manufacturing process—including, at least initially, costs related to testing and certification for quality and reliability in accordance with regulatory, industry, and military standards. An economically viable system will be one made from low-cost materials and components, manufactured efficiently into a product that meets the requirements of various potential users.

This report provides an engineering analysis of a flow battery ESS and an outline of the associated manufacturing engineering process used to develop a system toward cost-effective large-scale manufacture. This report includes lessons learned in developing a prototype flow battery energy storage system for military and telecommunications applications and outlines an engineering process that can guide manufacturers to scale up production and reduce costs of the technology.

The prototype ESS referenced in this report is the Raytheon Ktech RK30, a 30kW/120kWh system consisting of 12 zinc-bromine flow batteries arranged in two banks of six batteries. [See the Appendix A for a full description of zinc-bromine flow batteries.]The RK30 has recently undergone testing at Sandia National Laboratories' Distributed Energy Technology Laboratory (DETL), documented in SAND2013-8639 at http://www.sandia.gov/ess/publications/SAND2013-8639.pdf, and is being prepared for testing in an operational environment. The analysis and engineering examples are focused on the RK30 system, but experience from the development of smaller systems is also reflected in the discussion of lessons learned.

## 1.1 Scope and Content

This report addresses manufacturability of flow battery ESSs by outlining design and manufacturing requirements; components of the ESS and the manufacturing issues and potential improvements that pertain to them; issues regarding quality, reliability, and origin of manufacture; a service and support model; and topics related to environmental, safety, and health and regulatory compliance.

Section 2 summarizes the applicable regulatory requirements and industry standards for performance, materials, transportation, and testing to identify design and manufacturing requirements that would apply to a zinc-bromine flow battery ESS accepted for use by primary commercial markets and the military. It also outlines the use of the Technology Readiness Level (TRL) measurement approach of the Department of Defense as a guide to advancing flow battery and ESS technologies from basic research and design concepts to technology deployment. The requirements, standards, and guidance summarized in Section 2 include:

- Environmental, safety, and health standards that apply to manufacturing, transportation, and use of flow battery ESSs
- Federal Communications Commission (FCC) rules under 47 CFR Part 15 for electromagnetic interference or "unintentional emissions"
- Industry standards and certifications such as Underwriters Laboratories (UL) standards and certifications that may apply to a range of applications of flow battery energy storage technology as well as industry-specific constraints such as the telecommunications industry's Network Equipment-Building System (NEBS) that are effectively required for implementation of flow battery ESSs in telecommunications applications

Section 3 provides a description of a flow battery ESS, summarizing the important issues of form, fit, and function of its key system components, including (1) power electronics (inverters, contactors, breakers, etc.); (2) the supervisory control and data acquisition (SCADA) control and monitoring system; (3) the battery units, including the frames, connectors, and electrolyte management; and (4) the mechanical features, including the enclosure or container, thermal load and ventilation, connectors, and penetrations. Improvements to the example RK30 prototype's components especially those with impacts on manufacturability are also discussed.

Section 4 reviews key materials and their capability to meet or exceed required quality, reliability, and origin of manufacture requirements and their readiness for a scale manufacturing process. In addition, this section includes a non-proprietary bill of materials, identifying the potential availability of materials for manufacturing, including lead times and estimated component costs.

Section 5 outlines a service and support model for an ESS emphasizing ease of service and shipping, based on a typical expeditionary force concept of operations.

Section 6 discusses environmental, safety, and health and regulatory compliance issues applicable to development and manufacture of a zinc-bromine flow battery ESS like the RK30.

# 2 DESIGN AND MANUFACTURING REQUIREMENTS

Primary commercial markets and military engineers maintain specific design and manufacturing requirements for zinc-bromine flow battery energy storage systems. This section will summarize the associated performance, materials, transportation and industry testing standards

It also outlines the use of the Technology Readiness Level measurement approach of the Department of Defense as a guide to advancing flow battery and ESS technologies from basic research and design concepts to technology deployment.

## 2.1 Regulatory Requirements and Industry Standards

The requirements that guide development of flow battery ESSs, all of which have important impacts on manufacturability, include (1) regulations for safety during manufacture, transportation, installation, use, and maintenance of ESSs; (2) FCC rules that address electromagnetic interference; and (3) industry standards that are invoked for ESSs generally and also dependent on application. These requirements are summarized in Table 1.

For an ESS with zinc-bromine flow batteries, the safety requirements are invoked because of the bromine content of the electrolyte. Bromine is listed by the Occupational Safety & Health Administration (OSHA) as a hazardous substance in 29 CFR 1910.1000, Table Z-1, which sets enforceable permissible exposure limits to protect workers against the potential health effects of exposure. Likewise, the Department of Transportation (DOT) regulates bromine as a hazardous material in its transportation regulation 47 CFR Part 172. The environmental, safety, and health implications for manufacturability related to the ESS are discussed in Section 6 of this report. Other electrolytes utilized in a flow battery ESS will be subject to other safety limitations and requirements, of course, but workplace and product safety is a primary consideration in assessing manufacturability of any system.

The FCC Part 15 rules apply to any product that may generate electromagnetic energy, intentionally or unintentionally. Such products must be reviewed to comply with Part 15 before being marketed or sold in the United States. For the RK30, these requirements are applicable due to its electronics and communications components.

Traditionally, utility electric power grids were not designed to accommodate active generation and storage at the distribution level. The technologies and operational concepts to properly integrate distributed resources into the existing power grid continue to be further developed to fully realize benefits and to avoid negative impacts on system reliability and safety. Standards specifically developed for application to new technologies in energy storage are only recently being developed: UL 1973, *Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications*, was first published in 2010, and the first product certified under that standard was certified in 2013.

## Table 1. Compliance Matrix for RK30 Zinc-Bromine Battery Energy Storage System

| Standard, Requirement, or Specification | Application (Requirement, Limitation, or Guidance) for Flow Battery Energy Storage System |
|---|---|
| 29 CFR Part 1910, Occupational Safety and Health Standards | OSHA Permissible Exposure Limit (Bromine, 29 CFR 1910.1000, Table Z-1).<br>The OSHA permissible exposure limit for bromine exposure to workers is an airborne concentration of 0.1 ppm, 0.7 $mg/m^3$ (8-hour time-weighted average). This applies during manufacture, and it must also be anticipated for installation and customer use and maintenance.<br>Limits on other flow battery electrolytes may vary. |
| 49 CFR Part 172, Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, Training Requirements, and Security Plans | Department of Transportation classifications in the §172.101 Hazardous Materials Table and associated requirements for transportation of hazardous materials. Bromine is categorized in the Hazardous Materials Table as follows:<br>• Identification number: UN1744, Bromine or Bromine solutions<br>• Hazard Class 8 (Corrosive)<br>• Packing Group I<br>• §172.102 Special Provisions 1, B9, B64, B85, N34, N43, T22, TP2, TP10, TP12, and TP13<br>• Bromine may transported only in cargo aircraft and railcars, not in passenger-carrying aircraft or railcars<br>Requirements and limits on other flow battery electrolytes may vary. |
| 47 CFR Part 15, Radio Frequency Devices | Electromagnetic Interference. FCC Part 15 regulations apply to unintentional emissions of electromagnetic energy to ensure electromagnetic interference is minimized. A flow battery system for commercial, industrial, or business (non-residential) applications would be considered a Class A device, and subject to less restrictive limitations than Class B devices, which are those marketed to the general public for use in residential environments. |
| UL 1741, *Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources* | UL 1741 is applicable to the inverter of the ESS. It includes requirements for construction, safety, output power characteristics, rating, marking, manufacturing and production tests, and performance standards including maximum voltage, temperature, dialectic voltage withstand tests, output power characteristics, abnormal tests, grounding impedance, overcurrent protection calibration, strain relief, overvoltage, stability, static load, compression, and rain and sprinkler tests, among others. For utility-interactive equipment, these requirements are intended to supplement and be used in conjunction with IEEE 1547, *Standard for Interconnecting Distributed Resources With Electric Power Systems*, and in associated test procedures in IEEE 1547.1, *Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems.* |
| UL 1973, *Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications* | The UL 1973 standard covers energy storage for use as energy storage for stationary applications such as for photovoltaic, wind turbine storage, or for uninterrupted power supply applications (as well as similar systems for use in light electric rail power supplies). Its test requirements include electrical tests (e.g., for overcharge, short circuit, overdischarge protection, temperature and operating limits, imbalanced charging, dielectric voltage withstand, continuity, failure of cooling and thermal stability, working voltage, and tests of electrical components), mechanical tests (e.g., static force, impact, drop impact, mold stress, pressure release, and start-to-discharge tests) and environmental tests (thermal cycling, resistance to moisture, salt fog, and fire exposure tests). In addition, it contains appendices addressing specific requirements for particular battery technologies, including an appendix providing requirements specific to flowing electrolyte batteries. |

| Standard, Requirement, or Specification | Application (Requirement, Limitation, or Guidance) for Flow Battery Energy Storage System |
|---|---|
| IEEE 1547, *Standard for Interconnecting Distributed Resources with Electric Power Systems* | IEEE 1547 is applicable to the inverter of the ESS. The standard includes eight sections that provide guidance for safe connection to utility grids, namely the islanding aspect for inverter applications. UL 1741 is intended to be harmonized with IEEE 1547. |
| SR-3580, *NEBS™ Criteria Levels* | Telecommunications industry requirement. SR-3580 groups requirements of NEBS GR-63 and GR-1089 into three functional levels (I, II, or III). Grouping the criteria into levels helps clarify the impact of nonconformance and allows the broad range of NEBS requirements to be judiciously applied to equipment, based on the equipment's application and impact on the operation of the network. "NEBS Level 3" means the equipment meets all of the requirements of GR-63 for physical protection and GR-1089 for electromagnetic compatibility and electrical safety. NEBS Level 3 has strict specifications for fire suppression, thermal margin testing, vibration resistance (earthquakes), airflow patterns, acoustic limits, failover and partial operational requirements, failure severity levels, radio-frequency emissions and tolerances, and testing/certification requirements. |
| NEBS GR-63-CORE, *NEBS™ Requirements: Physical Protection* | Telecommunications industry requirement. NEBS GR-63 identifies the minimum spatial and environmental criteria used for new telecommunications equipment for new telecommunications equipment to be used in a carrier central office (as such, most requirements may not be directly applicable to an offsite ESS; however, these requirements are considered on a graded basis by NEBS SR-3580, as described above). The environmental criteria include temperature, humidity, altitude, fire resistance, equipment handling earthquake, office vibration, transportation vibration, airborne contaminants, and acoustic noise. |
| NEBS GR-1089-CORE, *Electromagnetic Compatibility (EMC) and Electrical Safety* | Telecommunications industry requirement. The electromagnetic compatibility and electrical safety requirements of GR-1089 address system-level electrostatic discharge and electrical fast transient; electromagnetic interference; lightning and power fault; steady-state power induction; electrical and optical safety criteria; corrosion; bonding and grounding; and criteria for DC power port of telecommunications load equipment. |
| NEBS GR-3108, *Generic Requirements for Network Equipment in the Outside Plant (OSP)* | Telecommunications industry requirement. GR-3108 defines environmental, mechanical and electrical testing criteria and provides design and performance requirements to help ensure that electronic equipment located in outside plant facilities will operate reliably over its expected lifetime. GR-3108 addresses environmental criteria such as operating temperatures, humidity, particulate contamination, pollution exposure, and heat dissipation; mechanical criteria such as structural requirements, packaging, and susceptibility to vibration, earthquake, and handling; electrical protection and safety including protection from threats of lightning surges, AC power induction and faults, electromagnetic interference, and DC power influences; and closure considerations. |
| NEBS GR-513, *Power Requirements in Telecommunications Plant* | Telecommunications industry requirement. GR-513 addresses power system requirements including ESSs; monitoring, control, and alarms; outside plant sites; reporting and listing requirements; reliability, quality and documentation requirements; and functional requirements. |
| MIL-STD-810G, *Environmental Engineering Considerations and Laboratory Tests* | Environmental analysis, design analysis, and laboratory testing. Testing may be required for military procurement. Testing protocols described are: temperature shock; contamination by fluids; solar radiation (sunshine); rain; humidity; fungus; salt fog; sand and dust; explosive atmosphere; immersion; acceleration; vibration; acoustic noise; shock; pyroshock; acidic atmosphere; gunfire shock; temperature, humidity, vibration, and altitude; icing/freezing rain; ballistic shock; vibro-acoustic/temperature; freeze-thaw; time waveform replication; rail impact; multi-exciter testing; and mechanical vibrations of shipboard materiel. |

The two main UL standards of importance for a flow battery ESS are UL 1741, *Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources*, which is applicable to the inverter, and UL 1973, which applies to stationary ESSs for distributed energy generation such as photovoltaic and wind turbines. As discussed in Section 3.1, the anti-islanding requirements of UL 1741 and IEEE 1547, which create requirements for utility grid-connected energy storage, can conflict with requirements for customers with off-grid applications, including military applications.

The NEBS standards in GR-63-CORE, *NEBS™ Requirements: Physical Protection* and GR-1089-CORE, *Electromagnetic Compatibility (EMC) and Electrical Safety*, are telecommunications industry standards intended to provide uniform criteria for equipment design to reduce the cost of deployment and maintain reliability of the network. SR-3580, *NEBS Criteria Levels*, groups these NEBS criteria into three functional levels (I, II, or III). Grouping the criteria into levels helps clarify the impact of nonconformance and allows the broad range of NEBS requirements to be judiciously applied to equipment, based on the equipment's application and impact on the operation of the network. For "outside plant" locations, such as cell towers, where an ESS would be deployed, the most demanding criteria, Level III, would be applicable. GR-3108, *Generic Requirements for Network Equipment in the Outside Plant*, provide additional requirements that must be addressed for energy storage applications. It should be noted that AT&T and Verizon use their own standards, similar to the NEBS standards, and may independently approve testing facilities for certification. Testing and certification to NEBS standards, or to a carrier's independent standards, should be considered a requirement to enter the telecommunications market.

For energy storage in military applications, MIL-STD-810G, *Environmental Engineering Considerations and Laboratory Test*, provides guidance for program planning and engineering direction for considering environmental stresses on military hardware. It does not impose design or test requirements. Instead the standard describes an environmental "tailoring process" that matches an item's environmental design and test limits to the conditions that it would be subject to, establishing laboratory test methods that replicate likely environmental effects on the system, rather than trying to reproduce the (various) environments themselves.

## 2.2 Use of Technology Readiness Level Development Approach as a Development Guideline

Many U.S. government agencies, including the Department of Defense (DoD 2011), Department of Energy (DOE 2011), and National Aeronautics and Space Agency (Mankins 1995) have adopted a standardized approach to Technology Readiness Assessment. Each agency tailors the approach slightly to best represent the kinds of technologies and the special requirements needed in their respective areas. Table 2 provides an outline of the technology readiness level (TRL) definitions for the Department of Defense, which Raytheon Ktech used as guidance in developing the RK30 prototype toward military applications.

## Table 2. U.S. Department of Defense Technology Readiness Levels

| TRL & Definition | Description | Supporting Information |
|---|---|---|
| TRL 1<br>Basic principles observed and reported. | Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties. | Published research that identifies the principles that underlie this technology. References to who, where, when. |
| TRL 2<br>Technology concept and/or application formulated. | Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies. | Publications or other references that outline the application being considered and that provide analysis to support the concept. |
| TRL 3<br>Analytical and experimental critical function and/or characteristic proof of concept. | Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. | Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed. |
| TRL 4<br>Component and/or breadboard validation in a laboratory environment. | Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory. | System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals. |
| TRL 5<br>Component and/or breadboard validation in a relevant environment. | Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components. | Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals? |
| TRL 6<br>System/subsystem model or prototype demonstration in a relevant environment. | Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment. | Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level? |

| TRL & Definition | Description | Supporting Information |
|---|---|---|
| TRL 7<br>System prototype demonstration in an operational environment. | Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space). | Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level? |
| TRL 8<br>Actual system completed and qualified through test and demonstration. | Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications. | Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design? |
| TRL 9<br>Actual system proven through successful mission operations. | Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions. | Operational test and evaluation reports. |

Although TRLs can be useful as a measure of technology maturity, they cannot be used as the sole tool in supporting technology and manufacturing decisions. The TRL measurements can provide a snapshot of where a technology is on the readiness scale at a particular time, but they do not assess the difficulty of improving to a higher maturity level. While TRLs have proven to be useful in evaluating a technology's performance and in providing guidance as to the manufacturability based on collected product data, as demonstrated in the laboratory or in a test environment, TRLs do not measure whether the technology product can actually be produced on-time and in an affordable manner.

The addition of manufacturing readiness levels (MRLs) incorporates producibility concerns into a technology readiness assessment. MRLs are a metric used to assess the system engineering/design process and the maturity of a technology's associated manufacturing processes to accomplish rapid and affordable transition to production. In a TRL calculator such as the one developed by the U.S. Air Force, MRL definitions and manufacturing topics can be embedded with the associated TRL; and both TRL and MRL can be applied at the individual component, subsystem, or system level.

Raytheon Ktech conducted an internal, formal TRL Assessment in October 2012 that found the RK30 system to be at TRL 3, with about 67% of TRL 4 completed. However, the assessment also noted that the system was well-positioned to quickly advance from TRL 3 to TRL 6. Subsequent testing of the RK30 system in Raytheon Ktech's laboratory to investigate the operational environment provided the necessary evidence to score the system internally at TRL 6. More recently, the RK30 has recently undergone testing at Sandia National Laboratories' Distributed Energy Technology Laboratory (DETL), which serves to confirm the accomplishment of TRL 6. Currently planned testing in an operational environment should support advancement of the RK30 to TRL 7 and, in parallel, increase focus on manufacturability issues.

# 3 MANUFACTURING ISSUES AND POTENTIAL IMPROVEMENTS

Alternative energy systems have expanded their scope based on innovative renewable technology and various energy storage types. Although most applications deal solely with one renewable energy resource or one type of storage, the market is now looking at energy storage as a combined unit of both renewables and storage, consequently constructing an ESS. In addition, enabling an ESS that incorporates multiple means of storage adds a layer that has not been well-defined by organizational standards. To meet manufacturability of a product, namely commercially, the product needs to meet criteria that maximizes mean time to failure and provides a well-defined set of components that have been thoroughly tested and have data that characterizes the system directives. Because the market is new in this area, long term characteristic data determining lifetime, efficiencies, and limits are few.

As a manufacturer of an ESS product, the RK30, Raytheon Ktech has had a number of challenges defining the precise objectives that will meet both the customer's parameters as well as the utility market's target certifications. Both of these factors play a key role in transitioning from a prototype to a manufacturable product. Some important points that need to be defined when making this transition include design characteristics, component consideration, marketability, system efficiency as a function of price, and quantities to be produced. [See Appendix B for the comparison of energy storage systems according to characteristics and costs.]

At the completion of the first prototype, not only did we have to look at how we could improve the system from the perspectives of energy efficiency and ease of use, but we also had to determine how to build consecutive systems, reducing time and cost. Because we were limited to a single system as a reference, we took a deeper look at how we could use the system's component data to meet these objectives. The bill of materials was reviewed to determine those components that had limited life expectancies, limited temperature ranges, long lead times and substantial costs. From this analysis it was determined that there were a few key components that would determine the manufacturability of the RK30. These components included namely the inverters, the flow batteries, and the supervisory control and data acquisition (SCADA) control system. In addition, there were some environmental and mechanical factors that played a substantial role in product integrity and life. These items include penetrations into the enclosure, flow battery management, thermal loading, system corrosion and transportation.

## 3.1 Inverters

The primary goal of most ESSs is to provide AC power to a grid. Renewable generation and energy storage devices provide DC power. Consequently, inverters become a necessary component for interfacing the DC source to the AC output in an energy storage system.

Although there are a large number of inverters available in the current market, there are very few that have been used with battery technology in a bi-directional manner. One dilemma that the energy storage community faces is determining what certifications are representative for specified applications. The two certifications that are most widely used are UL 1741 and IEEE 1547. The inverter market caters to the photovoltaic and wind turbine renewable energies, these applications are deterministic. Energy is sent to the grid, thus the inverter works uni-directionally. Although inverters can inherently provide bi-directional power, the UL certifications are only recognized for uni-directional operation.

Bi-directionality is necessary for energy storage systems which incorporate battery technology to allow a means for charging and discharging. The type of battery used adds yet another layer of complexity. Flow batteries maintain certain characteristics that define what type of inverters are needed. Flow batteries, unlike the conventional lead acid predecessor, can discharge to 0 VDC. Inverters have a voltage threshold limitation; for flow batteries the lower the voltage threshold the better to allow longer discharge capability. Another factor that plays into the selection of an inverter for flow batteries is the input voltage range. Dependent on the stack characteristics and the parallel or series arrangement of batteries, the inverter choice must encompass the flow battery voltage range.

For some applications, it is not necessarily the UL certifications, but rather the project objectives that drive the inverter characteristics. For example, in remote site applications, the energy storage unit will be islanded. This condition is not compliant with IEEE 1547, which assumes grid connections. The ESS will also, most likely, interface with generators on a common grid and therefore not meet UL 1741 guidelines. The energy storage system may serve as the master frequency generator or the slave. In either case, the fluctuation on the local grid frequency range will most likely exceed the nominal bounds of 59.3 and 60.5 Hz per UL 1741. For other straightforward applications that simply charge and discharge to a utility grid, the inverter's UL 1741 certifications are viable.

## 3.2 Flow Batteries

The flow batteries are key design components for the ESS in terms of cost, manufacturability and functionality. The following features must be considered in any design that incorporates a zinc bromine flow battery:

- Leak detection
- Temperature control and management
- Strip operation
- Pump management
- Float modes
- Enclosure design issues, including
  - Bromine fumes
  - Hydrogen explosive atmospheres
  - Ventilation

The flow battery used in the RK30 is the Zinc Bromine Module (ZBM) developed by RedFlow Technologies. This section discusses the design considerations listed above as they pertain to the RedFlow ZBM and improvements for manufacturability.

### *3.2.1 Leak Detection*

A failure of electrolyte containment must be first recognized and then resolved. The ZBM battery controller has two novel “capacitance cancelling” leak detector inputs. This leak detector design allows recognition of both open circuit and short circuit failure modes. The ZBM surface is contoured so that any leaks will flow to the positions where the leak detector sensors are located. The leak detector sensor elements are arranged so that input 1 is physically lower than input 2. This positioning means that triggering of Leak Detector #1 can be associated with a small volume leak and Leak Detector #2 with a larger volume leak. This differentiation in leak sensing allows for a graduated control response.

There are multiple aspects to be considered when designing a systematic response for a leak scenario:

1. The leak may be aggravated by pump pressure
2. There may be sufficient time to reduce stack energy
3. The leak may contain bromine complex and cause fumes

4. The operator must be alerted
5. The ZBM must be prevented from further operation

For a Leak 1 event, the recommended responses are to:

1. If possible, change to discharge mode (could consider dump to shorting contactor?)
2. Halt bromine pump
3. “Stack dump” into load until discharged
4. Halt zinc pump
5. Flag "leak" and "do not charge"

For a leak 2 event, the recommended responses are to:

1. Halt both pumps
2. Flag “leak” and “do not charge”

### *3.2.2 Temperature Control and Management*

The ZBM can operate over a wide temperature range (−10°C to +50°C), however excessively elevated temperate may signify a fault condition. Temperature sensors are positioned within the stack core and within the ambient inlet air stream. Some of the zinc electrolyte flows through a set of heat exchanger coils positioned between the stack and the tank. The battery controller can activate a fan to draw air over the heat exchanger and exhaust over the pump motors. The battery controller includes a hysteresis thermostat function where the cooling fan is activated based on the difference between the sensed stack temperature and an operator selected set-point.

The recommended action when the stack temperature is greater than the set point is to activate the cooling fan. The recommended action when the stack temperature is greater than the alarm level (a.k.a. “high high”) is to (1) halt charging and discharging and (2) flag “temperature trip.”

### *3.2.3 Strip Operation*

Flow batteries suffer a unique loss mechanism known as “shunt currents.” Shunt currents occur because the manifolds feeding the conductive electrolyte provide a form of short circuit discharge path for the ZBM. Shunt currents are non-linear; they remove more zinc plate from the center cells than the outer cells. This leads to an imbalance in the zinc loading that must eventually be relieved by “stripping.” Stripping is the process whereby a ZBM is completely discharged with sufficient time to dissolve residual zinc metal. Depending on operations, this action should be performed approximately weekly (or conveniently when the ZBM is routinely discharged).

Stripping strategy depends on the circumstances, as follows:

- Strip every cycle: In many cases the ZBM may operate on a regular cycle with sufficient time to strip on every occasion. This is a certain way to avoid accumulated zinc maldistribution.
- Discharge into load: Some load types allow the ZBM to be fully discharged so that it is effectively stripped. Other types of load require a minimum voltage for discharge thus preventing the ZBM from being fully discharged and so an explicit strip will be required.

- Self-discharge strip: This is a slow process. The pumps are run continuously until all zinc is fully dissolved.
- Active strip: This is a fast process. The ZBM is discharged into a load device that is capable of full discharging. The strip load can be a DC/DC converter or a shorting contactor. In the latter case the designer must manage the potential for high initial currents.
- Rerating Factor: Some applications cannot afford the time required for stripping every cycle. The Rerating Factor provides a mechanism for the battery controller to reduce the maximum state of charge in line with the accumulated shunt current effect. This option allows the user a choice to extend operation with reduced capacity.

### *3.2.4 Pump Management*

The electrolyte circulation pumps are critical to the ZBM operation. These pumps generate a flow of electrolyte over the electrode surface. The zinc flow is also used in the cooling of the ZBM through the heat exchanger. The pump power represents a burden on the overall system efficiency, and this burden should be minimized.

In any hydraulic circuit, flow is directly related to pressure. The pressure acting on the two sides of the separator within a cell determines the position of the separator, especially its proximity to the zinc electrode. The two pumps are different: the electrolytes in the two circuits are different, and the electrolytes in the two circuits evolve differently as the state of charge progresses. The system is designed so that during charging the separator position is biased away from the zinc electrode.

Pump behaviors include:

- Bubble purge: Air bubbles can be entrained in the flow especially when the pumps are started. Bubbles that remain lodged in the zinc channels have been observed to prevent zinc plating. The purge process is intended to rid the cell of bubbles prior to the initiation of charging. In the simplest case both pumps run for a set period prior to charging. A more complex mode briefly interrupts the zinc pump in an attempt to “flutter” the separator without entraining more air.
- Complex flush: In some ZBM designs the presence of complex in the bromine electrolyte is controlled. The flush process is intended to remove excess complex from the stack. A similar effect can be achieved by running only the zinc pump. Then the (relatively slow) through-separator flow from the zinc circuit can flush the complex.
- Float mode: A full description of the several techniques developed for this capability is provided in Section 3.2.5. Pump management is required during floating.

### *3.2.5 Float Modes*

Float is a term borrowed from conventional batteries that implies a method of charging that maintains a high state of charge for an extended duration. Self-discharge has been described as a strip method; it reduces the ZBM state of charge. The dominant causative factor is diffusion of dissolved bromine through the porous separator that then goes on to effectively dissolve the zinc plate. Self-discharge is occurring at all times in the ZBM. Of particular concern is the self-discharge that occurs during a hiatus after charge completion and before discharging commences.

Some ZBM applications require that the system be capable and ready to deliver full power without notice. Other applications may place more emphasis on maximizing total efficiency or delivered energy. These considerations constrain float mode selection.

**Both pumps continuous**—Provides full power readiness, maximum auxiliary power cost, and maximum self-discharge rate.

**Duty cycle synchronized pumps**—Depending on the duty cycle, provides near full power readiness, reduced auxiliary power cost, and near maximum self-discharge rate.

**Duty cycle zinc pump**—Provides reduced power readiness, reduced auxiliary power cost, and reduced self-discharge rate.

**Staccato charge**—Bromine pump off, zinc pump duty cycled and synchronized with brief charging pulse; provides full power readiness, reduced auxiliary power cost, and maintains near maximum state of charge.

**Through separator flush**—At charge completion halt bromine pump and continued running of zinc pump; after the flush time (1 to 2 hour) duty cycle zinc pump; provides poor power readiness, moderate auxiliary power cost, and minimum self-discharge rate.

**Constant voltage charge**—At charge completion both pumps continue while a constant voltage is presented to the ZBM. This voltage is chosen to be approximately equal to the open circuit voltage. Provides full power readiness, maximum auxiliary power cost, and maintains near maximum state of charge.

**Self-discharge compensation**—At charge completion both pumps continue while a constant current is presented to the ZBM. This current is chosen to be approximately equal to the self-discharge current. Provides full power readiness, maximum auxiliary power cost, and maintains near maximum state of charge.

**Storage battery**—At charge completion both pumps halt while a constant voltage is presented to the stack. Provides full power readiness, moderate auxiliary power cost, and maintains near maximum state of charge.

### *3.2.6 Enclosure Design*
System integrators must inevitably confront the enclosure that must contain the ZBM(s) and balance of system. Use of the ZBM raises three main considerations for enclosure design: (1) bromine fumes, (2) hydrogen explosive atmospheres, and (3) ventilation.

*3.2.6.1 Bromine fumes*—There are two concerns about bromine in the air: (1) its potential to corrode materials at low concentrations (e.g. fasteners and structural supports), and (2) the risk to humans exposed to high concentrations in exhaust ventilation.

*3.2.6.2 Hydrogen explosive atmospheres*—Lead-acid batteries have established standards for managing the potential for hydrogen evolution generating explosive atmospheres. ZBMs have a very different electrochemistry. Under some circumstances, they too can evolve hydrogen. For this reason, the ZBM designer must account for this contingency.

In most cases the ventilation required for cooling will more than suffice for avoiding explosive conditions. Any gas released from the ZBM is constrained to flow via the pressure release valve and connected tubing. The pressure release tubing can then be ducted to exhaust the enclosure in a controlled manner. Exhaust fans drawing a potentially hydrogen-laden mixture should be specified as intrinsically safe.

*3.2.6.3 Ventilation*—The in-built ZBM cooling fan is rated at 0.1 $m^3/s$ (200 cfm), therefore an enclosure fan will require at least this capacity for each ZBM in the ventilated space.

### *3.2.7 Improving Flow Battery Manufacturability*

Flow battery technology is relatively new to the manufacturing arena. The continued research and development related to efficient stack design and superior material choice by flow battery manufacturers will increase battery longevity and thus decrease the cost per megawatt-hour. In addition, as the flow battery market increases, volume manufacturing is then applicable and the ability to have a contracted third party manufacturer produce flow batteries will decrease the overall commercial manufacturing cost. With both of these factors (longevity and contracted battery manufacturing), the overall battery cost for ESSs will decrease substantially.

Specifically in the case of the RK30, the RedFlow ZBM has made and continues to make substantial improvements in longevity. RedFlow has been developing and manufacturing its ZBM since 2001. More than 600 units have been produced. Much effort has been devoted to improving the ZBM manufacturability, so that contract mass production is imminent. Performance testing has been conducted at Sandia National Laboratories, as described by Rose and Ferreira (2012, 2013). In a recent review that identified a number of improvements with the potential to increase manufacturability of the battery, Corey (2013) observed:

> 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.

## 3.3 Control and Monitoring System (SCADA)

An ESS SCADA system should meet the design parameters described in this section.

**Control and Data Acquisition**—The system should provide for a rapid and flexible development environment with a proven design and deployment platform. Component costs related to the development process should be managed to be low as reasonably possible while meeting quality and safety requirements.

COTS and OEM parts should be used when possible to facilitate ready availability.

The interface should utilize an industrial PC for development and configuration that allows control of the system and features an external display that permits viewing operations and fault status externally.

Real-time controller and data acquisition should include an autonomous/headless operation mode that allows the system to run without activating the operator interface and monitors faults and safes the system if needed.

Remote monitoring and event notification should be included so the system can notify staff in the event of a fault, thus facilitating  check operating status remotely.

The system should include on-board data logging for up to one year.

Power requirements for the SCADA system are industrial standard 24VDC with minimal current draw for better system efficiency.

Reliability design parameters must include environmental factors appropriate for the intended application.  The operational ranges should include temperatures of −40°C to +70°C and altitudes of 0 to 4,000 m (158° F  and 2.485 miles respectively).

**Desired Modes of Operation**—Modes of operation should address one or more of the following considerations:

- schedule and arbitrage;
- generator replacement;
- load support/supplement;
- frequency response; and
- voltage response.
-

**I/O Point Requirements**—Analog and digital signals are utilized for internal power supply voltage and current; battery bank voltage and current; sensors; E-Stop; interlocks; surge protector fault detection; smoke/heat detector; and inverter fault detection; contactors and fans.

The battery controller interface includes (1) operation modes for “run,” “stop,” “float,” and “strip”; (2) battery calibration; (3) monitoring for state of charge, battery health, and analog and digital I/O points; and (4) data logging.

The inverter interface monitors AC voltage and current DC voltage and current and includes charge/discharge control, fault detection, and data logging.

**Environment, Safety, and Health**—The SCADA system monitors and controls hazards related to (1) electrical safety, such as AC and DC voltages above 50 V; (2) industrial hygiene, such as bromine gas levels; and (3) door interlocks, set to disable systems to prevent inadvertent exposure to hazards.

## 3.4 Environmental and Mechanical Systems

In addition to the general concerns based on external connections from the ESS to the grid, restrictions are also placed on the enclosure. ESSs may be located in harsh environments that would mandate enclosure specifications for rain, dust, heat, etc. that are compliant with NEMA Standards Publication 250-2003. In addition, there may also be restrictions on penetrations to the enclosure based on the mode of transportation.

For the smaller 10kW systems, a NEMA 4 or 4X enclosure would be most efficient. Inevitably when transitioning to a manufacturable product based on the “actual” space requirements with the required components, a custom enclosure would be preferred. The drawback in creating a custom enclosure is the initial design and certification cost, however for high volume production, these initial costs would eventually be compensated. For the RK30 system, the enclosure chosen was a Tricon. This allows for easy mobility, specifically for transportation.

A Tricon can be easily loaded/unloaded and stacked onto a trailer or ship. The main concern for these enclosures is maintaining structural soundness with the necessary penetrations for venting and power feedthrough connectors and still meeting thermal requirements. Tricons are ISO tested (ISO 1496) and CSC approved based on legislation (ADR, RID, IMDG, USDoT, etc.) for structural integrity and transportation methods by a third party vendor.

Two other enclosure design considerations with flow batteries include the need to vent any corrosive or hazardous fumes efficiently and separation. Flow batteries should be housed in enclosures that separate them from the electronics to avoid corrosive fumes that may come in contact with the electronics.

# 4 QUALITY, RELIABILITY, AND ORIGIN OF MANUFACTURE

For any manufacturable product, quality and reliability are critical to continued marketability. To mitigate manufacturing issues (mean-time-to-failure, maintenance, lead times) a number of factors need to be examined including component history and lifetime, reputable manufacturers, and origin of manufacture. A summary bill of materials for a flow battery ESS is shown in Table 3.

The price point is highly dependent upon the batteries and inverters. For large scale production, substantial advantages exist for increased quantity buys, leading to a lower cost point and thus a more commercially marketable product. When looking at the technology and the needs of specific customers, reduction in price is definitely advantageous. However, while price in large measure drives the size of the market for an ESS, price alone does not determine its viability. Reliable energy storage systems are needed around the globe thus allowing manufacturing of an ESS product with a mission in mind—to extend battery life and increase system efficiencies.

Lead time of components and component selection are other important topics that need to be addressed when pursuing product manufacturing. In the case of RK30 system, all parts can be ordered and in-house within 4 to 6 weeks for smaller quantities (less than 25 ESS units). For energy storage system production quantities greater than 25, some of the critical items (i.e. batteries and inverters) may have a longer lead time due to their standard off-the-shelf quantities manufacturing processes and their origin of manufacture.

**Table 3. Flow Battery Energy Storage System Bill of Materials**

| | Description | Lead Time | Estimated Cost Summary |
|---|---|---|---|
| Battery | ZBM battery (including battery controller) | 4–6 weeks | $8000 |
| Battery Venting | Hydrogen venting | 2 weeks | $1000 |
| Battery Safety | Secondary containment of flow battery | 2 weeks | $175 |
| Electrical Hardware | Connectors, distribution blocks, fuses, lugs, wire, bus bars | 3–4 weeks | $7500 |
| Electrical Components | Power supplies, inverters, contactors, breakers | 4–6 weeks | $28500 |
| Mechanical Enclosure | Tricon | 3–4 weeks | $5800 |
| Mechanical Hardware | Nuts, bolts, backplates, cable trays | 2 weeks | $500 |
| Mechanical Structure | Internal frame, mechanical structure | 4–6 weeks | $3500 |
| Safety | Gas sensors, interlocks, smoke detector | 4–6 weeks | $1000 |
| SCADA/communication | Controller, data converters, Ethernet switch, modem, antenna, display | 3–4 weeks | $3400 |

# 5 SERVICE AND SUPPORT MODEL

There are unique considerations when developing service and support capabilities for a flow battery energy storage system. The system would have the ability to be deployed to a location that would allow it to be tied to a local grid or to a remote location where there is no established grid. Both scenarios need to be addressed from the support aspect.

The key to having a successful product is to design with serviceability in mind. The new product introduction process should mandate serviceability as part of any product rollout. If serviceability is not planned into system support, then it is likely that the product may prove to be too difficult to maintain and repair.

Training and support materials are also key to creating a successful product. Training materials need to be developed so that, for example, site telecommunication contractors or technicians stationed at forward operating bases have complete guidance needed to initially setup a unit for operation as well as to dis-assemble the unit for transportation to another site. Equipment training should include operator as well as unit-level maintenance training. The areas that need to be covered as part of an overall training plan are:

- Theory of operations
- Initial unit setup
- General maintenance

- Troubleshooting
- Preparation for transportation
- Preparation for long term storage

Operating support guides need to be available through multiple delivery mechanisms such as downloadable via an online site, hardcopy manuals delivered with the unit and directly available through the control system as a PDF file.

Another aspect of support is providing a mechanism for gathering updates from the field. This can be done by capturing metrics directly from the control system and having that data sent or uploaded to a site where the data can be analyzed by engineers for trend analysis and evaluation of how well the measurements are staying within design parameters.

Support can also be establishing a means to remotely access the unit for troubleshooting purposes. Capitalizing on the abilities of an engineer or technologist can assist field support staff. The technical expert can make suggestions for adjusting system parameters, check the status of critical components or determine if the unit is functioning properly within specifications..

General considerations for the three main areas of initial setup, general maintenance and transportation are covered in the sections below.

## 5.1 Initial Setup

Depending on specifics of the ESS, initial setup should follow manufacturer's instructions. Batteries would be fully discharged upon initial setup. Setup would likely include:

- Verify that the battery is fully discharged (essentially 0V at battery terminals)
- Verify that all connections have been made for battery control and safety are intact
- Turn on the control system and verify that all battery diagnostics are present
- Run an initial battery cycle to verify standard charge and discharge characteristics (If a battery needs to be calibrated, follow manufacturer's instructions. For the ZBM, the process does not involve setting the batteries to specific predefined levels, but rather provides readings for battery efficiencies (74% to 80%), ensures communications are functioning as expected, and identifies any problems with the batteries.)

## 5.2 General Maintenance

While the RK30 system is designed to operate for long unattended periods with minimum maintenance requirements, a systematic approach to preventative maintenance is recommended for any ESS to ensure a long and fault-free power system life. Typical maintenance requirements are straightforward and are listed below. It is recommended that maintenance inspections occur at installation and at 6-month intervals. Maintenance procedures are separated into those that require the system to be shut down (de-energized) and those that require the system to be powered (energized).

## 5.3 General Safety Guidelines

- Electrolyte must be stored in an appropriate container; HDPE (high density polyethylene) is recommended.
- Necessary Equipment
  - Full Respirator (Charged Electrolyte)
  - Partial Respirator (Discharged Electrolyte)
  - Safety Goggles
  - Safety Gloves (PVC)
  - Eye Wash Station

### *5.3.1 General Care and Maintenance*

- Only operate and store the electrolyte containers upright and in a stationary condition.
- Do not place any heavy loads on top of the electrolyte containers.
- In the use of ZBM batteries used in the RK30 unit, ensure that the ZBM is stripped regularly (ideally each cycle) to ensure optimal zinc plating in the stack.
- Operate the batteries within the designed performance envelope (charge and discharge rates).
- Operate the batteries within the ambient temperature specifications and ensure sufficient ventilation for effective operation of the installed cooling fan.
- Always ensure that the batteries are FULLY discharged if they are to be stored for extended periods.

### *5.3.2 Maintenance Checklist—System De-energized*

At installation and at 6-month intervals:

- Check the system for corrosion or damage.
- Check inside the container for animal ingress, repair if necessary and remove any non-standard material(s).
- Remove any dust or debris from inside the container.
- Check that the Switchboard door locks are working and lubricated.
- Check the Switchboard door seals for damage.
- Check the Switchboard door hinges for damage.
- Check that the rear container door locks are working and lubricated.
- Check the rear container door hinges for damage.
- Check that the mechanical barriers for cabling between the system and the external switchboard are intact.
- Check each ZBM for leaks.
  - Visual inspection
  - Smell—if there is a leak, a chlorine-like smell will be present.
- Check that all hose clamps and battery connections are securely fitted.
- Check that all cabling connections behind the Switchboard are secure.
- Test that the smoke alarm is working.
- Check that all labels are intact and fitted correctly.
- Check that the fire extinguisher is installed and its tag date is current.
- Check that the spill station is present.
- Check that all documentation is onsite.

### *5.3.3 Maintenance Checklist—System Energized*

At installation and at 6-month intervals:

- Check for electrolyte leaks using the software interface.
- Check that the electrolyte pump runs properly.
- Check that the impeller and cooling fans are operating properly.
- Check that the temperature readings are accurate.
  - Battery temperature
  - Air temperature
- Check that the Battery Controller is running in Auto Mode with no faults.

#### *5.3.4 ZBM Stripping*

Charging a ZBM electroplates metallic zinc onto the zinc electrode. The energy delivered when the metal dissolves back into the electrolyte allows the ZBM to do electrical work under discharge. The presence of zinc metal on the electrodes drives the voltage measured on the battery terminals. It does not matter how thick that metal layer is, although the cell voltage will fall if the zinc does not fully cover the electrode surface. This is the process observed at the end of discharge when there is a rapid fall off in terminal voltage.

Stripping is the process whereby poorly distributed zinc is removed from a ZBM. Zinc distribution becomes uneven for several reasons: (1) variations in electrolyte flow within and between cells, (2) variations in cell geometry and material properties, (3) incomplete discharge, and (4) shunt currents.

In many ZBM applications thorough stripping can be implemented after every charge/discharge cycle. This conservative approach is preferred. However, with careful planning, multiple contiguous cycles can be scheduled. If each discharge is halted at 50 VDC followed immediately by another charge, where it is possible that one may get as many as five cycles without stripping. The amount of accumulated zinc increases with each cycle. Deferring the strip this way will require a longer cycle in the end.

## 5.4 Transportation

Prior to moving the ESS, there are general steps that ensure safe shut down. These include:

1. Fully discharge and strip all the batteries.
2. Using a DVM set to VDC, check the voltage level. There should be 0 V present on each battery.
3. At the control pad, select the option to shut down the system.
4. Turn off the system via its control interface, if necessary.
5. Ensure system breakers are OFF.
6. Disconnect the external power connections to the ESS.
7. Remove any obstructions and review area around system.

Per transportation requirements for the given customer and location, batteries may need to be drained and/or removed from the ESS. The electrolyte may have differing transportation requirements than the balance of system and must be taken into account for transporting the ESS to another location.

# 6 ENVIRONMENTAL, SAFETY, AND HEALTH AND REGULATORY COMPLIANCE

The use of bromine in the flow batteries makes the occupational safety and transportation regulations of 29 CFR Part 1910 and 49 CFR Part 172, respectively, applicable in the manufacture and operation of the RK30 ESS. Compliance with those requirements should be accounted for in a manufacturer's and user's safety planning. This section gives a description of the safety-related features of the RK30 that can help ensure safe and compliant system operation.

## 6.1 General Safety

An LCD touch panel display is affixed to the outside of the Tricon. This display allows personnel to observe operating conditions, alarms, faults, and other parameters without system entry so that the environment inside the Tricon is known before attempted entry. The display is password protected to disable some functions unless authorized.

## 6.2 Fire Safety

As described in Section 3.2.6 of this document, flow batteries have the potential for hydrogen generation under some conditions. Two methods are used to prevent the buildup of hydrogen in the Tricon. An exhaust fan is used to cycle air through the Tricon to prevent excessive heat buildup. This air circulation also exhausts any hydrogen or bromine gas that might otherwise accumulate in the Tricon. Additionally, the gas handling units of the flow batteries are plumbed into a manifold, which then vents to the outside of the Tricon. This prevents hydrogen buildup as well.

An installed fire detection system should be designec and programmed such that the system will disable itself in the event of heat, smoke, or fire.

## 6.3 Electrical Safety

The system doors are interlocked to prevent entry by personnel while the system is operating. The interlocks are tied to the DC bus contactors to remove power in the event of a door opening. Additionally, an emergency off (EMO) switch is incorporated into the design. The emergency off switch allows safing the system in an emergency situation by pressing the switch, located on the outside of the system, which will open the DC contactors. Lexan shields are used to prevent contact with the DC bus during system maintenance. Polarity maintaining DC connectors are used in the flow batteries to ensure proper connections.

## 6.4 Chemical Safety

The flow batteries in the system contain a zinc-bromine complex that, depending on state of charge, presents varying chemical safety concerns. Under normal operating conditions, the liquid is contained within the flow battery tank. In the event of a spill or breach, the supplied Material Safety Data Sheet (MSDS) and the information in the flow battery handling procedure should be followed. Personal protective equipment (PPE) is provided in the system.

## 6.5 Other

Periodic inspections should be performed to check for any electrolyte leaks from the flow batteries. The system should be inspected for any damage after shipment to a new location.

# 7 SUMMARY

Flow batteries represent an enabling technology that can provide modular, configurable, and scalable electrical energy storage solutions for special use cases. The costs associated with the manufacture of flow batteries tend to be a significant barrier to market penetration. Raytheon Ktech has designed and built several iterations of the zinc-bromine model according to commercial and military standards. The RK-30 electrical energy system (ESS), which serves as the Zinc-Bromide Model (ZBM) in this discussion was tested, analyzed, and evaluated at Sandia National Laboratories' Distributed Energy Test Laboratory for grid-scale certification. Improvements in components, service and support regimes for the ZBM can reasonably be translated to improvements in quality, reliability, environmental and safety compliance, manufacturability and product costs

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## Appendix A

### A brief description of Flow Batteries

A flow battery is a type of rechargeable battery where rechargeability is provided by two chemical components dissolved in liquids contained within the system and separated by a membrane. Ion exchange (providing flow of electrical current) occurs through the membrane while both liquids circulate in their own respective space.

The Zinc-bromine battery is another type of flow battery in which the zinc is solid when charged and dissolved when discharged. The bromine is always dissolved in the aqueous electrolyte.

Each cell is composed of two electrode surfaces and two electrolyte flow streams separated by a micro-porous film. The positive electrolyte is called a catholyte; the negative is the anolyte. Both electrolytes are aqueous solutions of zinc bromine (ZnBr2). During charge, elemental zinc is plated onto the negative electrode. Elemental bromine is formed at the positive electrode. Ideally, this elemental bromine remains only in the positive electrolyte. The micro-porous separator allows zinc ions and bromine ions to migrate to the opposite electrolyte flow stream for charge equalization (see Figure 56 below). At the same time, it inhibits elemental bromine from crossing over from the positive to the negative electrolyte, reducing self-discharge because of direct reaction of bromine with zinc.

The cell electrodes are composed of carbon plastic and are designed to be bipolar. This means that a given electrode serves both as the cathode for one cell and the anode for the next cell in series. Carbon plastic must be used because of the highly corrosive nature of bromine. The positive electrode surface is coated with a high-surface-area carbon to increase surface area. The two electrolytes differ only in the concentration of elemental bromine; both should have the same zinc and bromine ion concentrations at any given time during the charge/discharge cycle. This can best be accomplished through the use of an ion-selective membrane as the separator. This membrane would allow the passage of zinc and bromine ions without allowing the passage of elemental bromine or polybromine. In practice, such membranes have proven more costly and less durable than nonselective membranes. For these reasons, nonselective micro-porous membranes are usually used for the separator. The electrolyte is circulated for a number of reasons. Circulation serves to remove bromine (in the form of polybromine) from the positive electrode quickly, freeing up the surface area for further reaction. It also allows the polybromine to be stored in a separate tank to minimize self-discharge.

**Characteristics**

Redox flow batteries, and to a lesser extent hybrid flow batteries, have the advantages of flexible layout (due to separation of the power and energy components), long cycle life (because there are no solid-solid phase transitions), quick response times, no need for "equalisation" charging (the overcharging of a battery to ensure all cells have an equal charge) and no harmful emissions. Some types also offer easy state-of-charge determination (through voltage dependence on charge), low maintenance and tolerance to overcharge/ over-discharge.

**Advantages/Disadvantages**

| **Advantages** | **Disadvantages** |
|---|---|
| Circulating electrolyte allows for ease of thermal management and uniformity of reactant supply to each cell. | Auxiliary systems are required for circulation<br>and temperature control |
| Good specific energy | System design must ensure safety as for all<br>Batteries |
| Good energy efficiency | |
| Made of low-cost and readily available materials | Initially high self-discharge rate when shut down while being charged |
| Low-environmental-impact recyclable/reusable components made using conventional manufacturing processes | Improvements to moderate power capability may be needed |
| Flexibility in total system design | |
| Ambient-temperature operation | |
| Adequate power density for most applications | |
| Capable of rapid charge | |
| 100% depth of discharge does not damage battery<br>but improves it | |

## Enabling Capabilities

Low cost materials and mass production efficiencies offer potential for inexpensive bulk energy storage systems. The modular design of the RedFlow ZBM allows for systems to be readily scaled from residential, to commercial-industrial, and utility sized systems. The relatively immature state of current development implies potential for significant early gains in operational efficiency and longevity.

## Battery Stack

The ZBM stack is a critical determinant of battery performance and longevity. Materials selection and design for manufacture are important in achieving these goals. Much effort has been devoted to full-scale long-term testing of improved electrode formulations, but it must be recognised that this kind of testing requires years to completion. Evidence collected to date (from ZBMs built over one year ago) supports a claim for a minimum of 500 full capacity cycles. Earlier indications of electrode performance can be gained through the employment of proprietary accelerated aging test methods, and these guide the selection of superior electrode formulations.

## Appendix B

## Energy Storage Characteristics by Application (Megawatt-scale)

The following tables from EPRI (Ref 9) compares competitor energy storage systems:

### Energy Storage Characteristics by Application (Megawatt-scale)

| Technology Option | Maturity | Capacity (MWh) | Power (MW) | Duration (hrs) | % Efficiency (total cycles) | Total Cost ($/kW) | Cost ($/kW-h) |
|---|---|---|---|---|---|---|---|
| **Bulk Energy Storage to Support System and Renewables Integration** | | | | | | | |
| **Pumped Hydro** | Mature | 1680-5300 | 280-530 | 6-10 | 80-82 (>13,000) | 2500-4300 | 420-430 |
| | | 5400-14,000 | 900-1400 | 6-10 | | 1500-2700 | 250-270 |
| **CT-CAES (underground)** | Demo | 1440-3600 | 180 | 8 | See note 1 (>13,000) | 960 | 120 |
| | | | | 20 | | 1150 | 60 |
| **CAES (underground)** | Commercial | 1080 | 135 | 8 | See note 1 (>13000) | 1000 | 125 |
| | | 2700 | | 20 | | 1250 | 60 |
| **Sodium-Sulfur** | Commercial | 300 | 50 | 6 | 75 (4500) | 3100-3300 | 520-550 |
| **Advanced Lead-Acid** | Commercial | 200 | 50 | 4 | 85-90 (2200) | 1700-1900 | 425-475 |
| | Commercial | 250 | 20-50 | 5 | 85-90 (4500) | 4600-4900 | 920-980 |
| | Demo | 400 | 100 | 4 | 85-90 (4500) | 2700 | 675 |
| **Vanadium Redox** | Demo | 250 | 50 | 5 | 65-75 (>10000) | 3100-3700 | 620-740 |
| **Zn/Br Redox** | Demo | 250 | 50 | 5 | 60 (>10000) | 1450-1750 | 290-350 |
| **Fe/Cr Redox** | R&D | 250 | 50 | 5 | 75 (>10000) | 1800-1900 | 360-380 |
| **Zn/air Redox** | R&D | 250 | 50 | 5 | 75 (>10000) | 1440-1700 | 290-340 |
| **Energy Storage for ISO Fast Frequency Regulation and Renewables Integration** | | | | | | | |
| **Flywheel** | Demo | 5 | 20 | 0.25 | 85-87 (>100,000) | 1950-2200 | 7800-8800 |
| **Li-ion** | Demo | 0.25-25 | 1-100 | 0.25-1 | 87-92 (>100,000) | 1085-1550 | 4340-6200 |
| **Advanced Lead-Acid** | Demo | 0.25-50 | 1-100 | 0.25-1 | 75-90 (>100,000) | 950-1590 | 2770-3800 |
| **Energy Storage for Utility T&D Grid Support Applications** | | | | | | | |
| **CAES (aboveground)** | Demo | 250 | 50 | 5 | See note 1 (>10,000) | 1950-2150 | 390-430 |
| **Advanced Lead-Acid** | Demo | 3.2-48 | 1-12 | 3.2-4 | 75-90 (4500) | 2000-4600 | 625-1150 |

| Technology Option | Maturity | Capacity (MWh) | Power (MW) | Duration (hrs) | % Efficiency (total cycles) | Total Cost ($/kW) | Cost ($/kW-h) |
|---|---|---|---|---|---|---|---|
| Sodium-Sulfur | Commercial | 7.2 | 1 | 7.2 | 75 (4500) | 3200-4000 | 445-555 |
| Zn/Br Flow | Demo | 5-50 | 1-10 | 5 | 60-65 (>10,000) | 1670-2015 | 340-1350 |
| Vanadium Redox | Demo | 4-40 | 1-10 | 4 | 65-70 (>10,000) | 3000-3310 | 750-830 |
| Fe/Cr Flow | R&D | 4 | 1 | 4 | 75 (>10000) | 1200-1600 | 300-400 |
| Zn/air | R&D | 5.4 | 1 | 5.4 | 75 (4500) | 1750-1900 | 325-350 |
| Li-ion | Demo | 4-24 | 1-10 | 2-4 | 90-94 (4500) | 1800-4100 | 900-1700 |
| **Energy Storage for Commercial and Industrial Applications** | | | | | | | |
| Advanced Lead-Acid | Demo-Commercial | 0.1-10 | 0.2-1 | 4-10 | 75-90 (4500) | 2800-4600 | 700-460 |
| Sodium-Sulfur | Commercial | 7.2 | 1 | 7.2 | 75 (4500) | 3200-4000 | 445-555 |
| Zn/Br Flow | Demo | 0.625 | 0.125 | 5 | 60-63 (>10000) | 2420 | 485-440 |
| | | 2.5 | 0.5 | 5 | | 2200 | |
| Vanadium Flow | Demo | 0.6-4 | 0.2-1.2 | 3.5-3.3 | 65-70 (>10000) | 4380-3020 | 1250-910 |
| Li-ion | Demo | 0.1-0.8 | 0.05-0.2 | 2-4 | 80-93 (4500) | 3000-4400 | 950-1900 |

## Energy Storage Characteristics by Application *(Kilowatt-scale)*

| Technology Option | Maturity | Capacity (kWh) | Power (kW) | Duration (hrs) | % Efficiency (total cycles) | Total Cost ($/kW) | Cost ($/kW-h) |
|---|---|---|---|---|---|---|---|
| **Energy Storage for Distributed (DESS) Applications** | | | | | | | |
| Advanced Lead-Acid | Demo-Commercial | 100-250 | 25-50 | 2-5 | 85-90 (4500) | 1600- 3725 | 400- 950 |
| Zn/Br Flow | Demo | 100 | 50 | 2 | 60 (>10000) | 1450-3900 | 725-1950 |
| Li-ion | Demo | 25-50 | 25-50 | 1-4 | 80-93 (5000) | 2800-5600 | 950-3600 |
| **Energy Storage for Residential Energy Management Applications*** | | | | | | | |
| Lead-Acid | Demo-Commercial | 10 | 5 | 2 | 85-90 (1500-5000) | 4520-5600 | 2260 |
| | | 20 | | 4 | | | 1400 |
| Zn/Br Flow | Demo | 9-30 | 3-15 | 2-4 | 60-64 (>5000) | 2000-6300 | 785- 1575 |
| Li-ion | Demo | 7-40 | 1-10 | 1-7 | 75-92 (5000) | 1250-11,000 | 800-2250 |

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