Battery Theory of Operation

Rev	Description	Approval	Date
A	Initial Release	C. Bernat	6/1/24

Table of Contents

1 Document Overview

The *Battery Theory of Operation Manual* is intended to provide a high-level overview of battery system operation. A functional description of the main systems of the battery is provided, including:

- Fluids System
- Electrical System
- Stack Operation
- Battery Management System
- Hydrogen Mitigation
- Thermal Control

Please read this manual in its entirety prior to beginning operation or servicing of the battery system. In addition, before operating or servicing the battery system, make sure the *Customer Acceptance Test* has been signed, verifying the battery system has been properly installed and is functioning properly.

1.1 Who Should Use this Manual

This manual is intended for both battery Operators and Service Technicians. This manual is informational and does not contain specific procedures to which training or certification is required. In addition, the *Battery Theory of Operation Manual* is not intended to provide specific parts descriptions or ordering information.

- Both Operators and Service Technicians should add this manual as a component section to either the *Operator Manual Assembly* or the *Service Manual Assembly* so that it may be used as a reference for battery system functionality.
- A glossary of terms and abbreviations is contained at the end of both the Operator Manual and Service Manual and will also serve as a glossary for this manual.

1.2 Exclusions for Documentation

By using this manual, you agree to the terms stated below. If you do not agree, return this manual and the product described here.

UNLESS SPECIFICALLY AGREED TO IN WRITING, Acme,

- Makes no guaranty or warranty to the completeness of any information contained in this manual, as infrequent and unintentional inaccuracies may be present.
- In no event, will be liable for damages arising out of the use or misuse of, or the inability to use, the content described in this manual, even if advised of the possibility of such damages.
- Reminds site personnel that if this manual is in any language other than English, although steps have been taken to maintain the accuracy of translation, the accuracy cannot be guaranteed.

1.3 Conditions of Use

This document and all information contained within it are the property of Acme Energy Systems. Any distribution or dissemination of this document, in whole or in part, is strictly prohibited unless expressly permitted by Acme Energy Systems.

1.4 Overview of Theory of Operation

The flow battery system is built into high cube shipping containers. Each GS200 battery system consists of two containers on foundation with platforms:

- Power Module (PM) – top container which contains the battery stacks and electronics.
- Energy Module (EM) – bottom container which contains the Anolyte & Catholyte Electrolyte tanks, pumps, and heaters.
- Foundation and Platform – (customer supplied) foundation and container mounting materials along with a service platform that provides service access to the containers. These components are designed by the Engineering Procurement & Construction (EPC) or appropriate engineering firm, taking into account local code, seismic requirements, grounding, and personal safety elements.

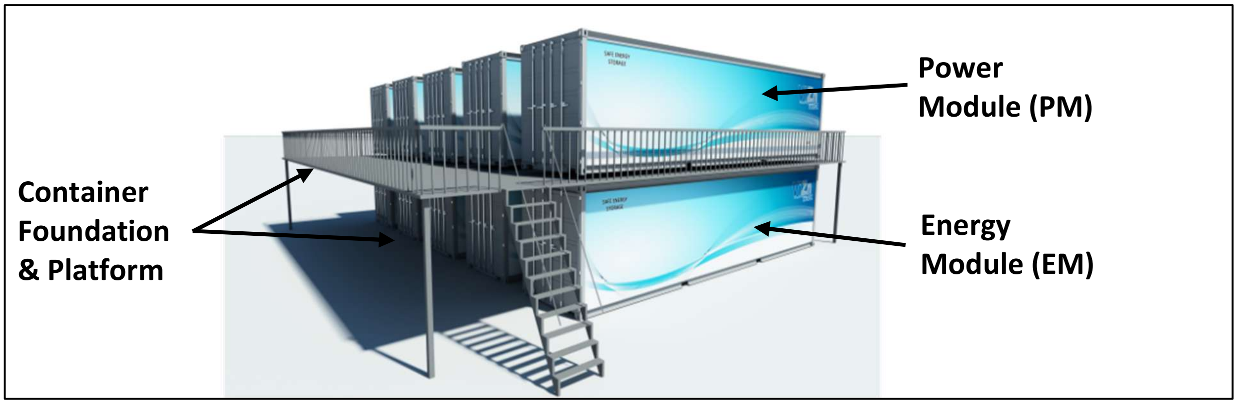

Figure 1: GS200 Battery Containers

1.5 Battery System and Service Locations

There are doors on both sides of the Power Module container to provide access to either the electronics' enclosures area or the battery stacks' area for maintenance and service work. (Refer to Figure 2). The Power Module doors are positioned to provide service access depending on the degree of Tier-level training and certification required to perform the service work.

- Tier-level 2 certification is required for electrical enclosure service work, and access is provided for this work at the AC Service Side Doors.
- Tier-level 3 certification is required for stack and/or chemistry-exposure service work, and access is provided for this work at the DC Service Side Doors.
- The plumbing access area, in the center of the PM, has viewable access to Tier 2 level technicians (via AC side doors) and direct service work access to Tier 3 level technicians (via DC side doors).

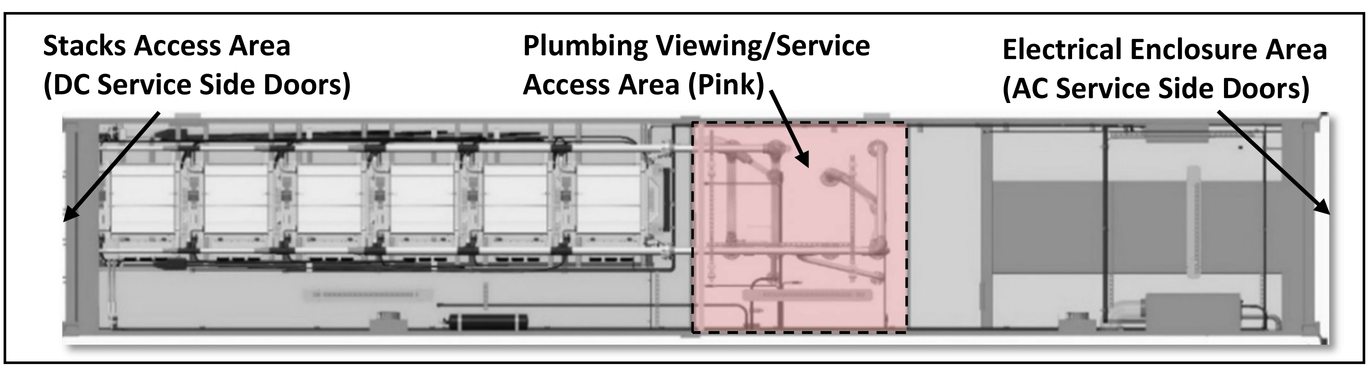

Figure 2: GS200 Power Module – Top-Down View

2 Fluids' System

This section describes the Electrolyte fluids delivery system implemented for the batteries. The fluids system supporting the flow battery has these functional characteristics:

- Pulls bulk Electrolyte from the tanks that store the Electrolytes.
- Provides Electrolytes to the stacks for reaction at the same rate for each stack.
- Provides a return flow to the storage tanks.
- Provides mixing within the storage tanks.
- Operates with low energy load to reduce impact on the energy efficiency of the system.
- Allows the Electrolyte to drain from the stacks into the tanks to limit Shunt Currents and to isolate reactants. Depending on operational state, this process is automatic or may be applied manually.
- Is designed to be compatible with Electrolytes and not fatigue or break over time, causing leaks.
- Is electrically isolated to avoid ground faults. This is because the Electrolytes may float up to 900+ VDC.
- Prevents the flow of Electrolyte from causing damage or loss of efficiency during startup/shutdown and while in operation.
- Provides for a positive PSI pressure to be applied to the Anolyte side of the stack over the Catholyte side. This pressure differential ensures that during operation, the Catholyte will flow though the Ni foam and not over it. It further prevents the membrane from being pushed into the plated zinc.
- Carries fluid by minimizing excessive pressures or differential pressures. This is required because, when the system is turned On, the Electrolytes will take some time to fill the stacks.

2.1 Fluid System Process

Table 1 describes the stages of Electrolyte fluid passage through the battery system.

Table 1: Stages of Electrolyte Fluid Passage

Fluid System Process	
1	**Pump Activation** – Starting up the battery into the **Ready, Remote Charge,** or **Rejuvenation** states begins the pump operation. A Variable Frequency Drive (VFD) motor controller located within the HVE directs (in Hz) the high-flow pump motors required for fluid delivery.
2	**Delivery of Fluid to Stacks** – After the startup of pump operation, there is a dwell period, which happens between initiating the **Ready** state and the available start-time for charge/discharge action. During this dwell-period time, the four pump pressures are normalized to allow for the Electrolyte to move at the same rate from the tanks to the stack trunk lines, and then evenly to the individual stacks (6 per ESU).
3	**Fluid Pressure Optimization** – When the Operator begins applying charge (or discharge) to the battery stacks, the battery system initiates a fluid-flow optimization process, which varies the pump speeds. The pump speeds are adjusted higher when the battery is at a high State of Charge (SOC) and/or at high current. The pump speeds are subsequently adjusted lower when the battery is at a low SOC and/or at low current. This optimization process compensates for the narrower fluid passage through the Anolyte side of the stacks due to the zinc plating and/or when high current increases the amount of particles required for reaction.
4	**Return of Fluid to Tanks** – Once the Electrolyte has passed through the stacks, the reacted Electrolyte is returned to the tanks at the opposite end from the pumps to promote Electrolyte mixing. It remains in the tanks until the Operator initiates a discharge to return it to the stacks.

2.2 Fluid System Components

The main functional components of the fluids' delivery system are explained below and shown in Figure 3.

- **Electrolyte Tanks (x4)** – holds the Anolyte and Catholyte Electrolyte chemistry.
- **High Flow Pumps (x4)** – circulates the Electrolyte fluid through the battery system.
- **Interconnect Plumbing** (x4) -- transports the Anolyte and Catholyte from the tanks to the stacks through the Supply Lines, and also transports the fluid from the stacks back to the tanks through the Return Lines.

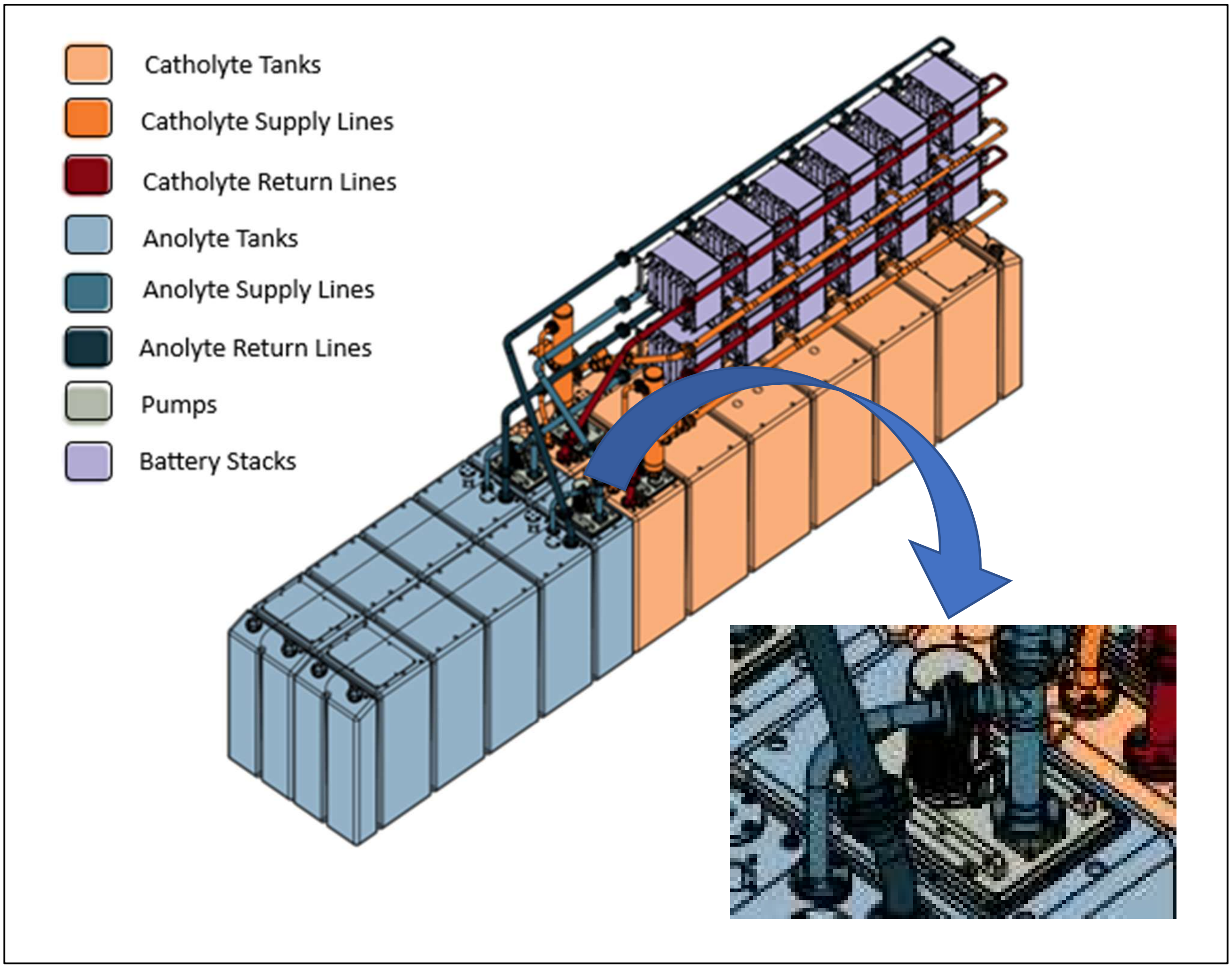

Figure 3: Fluid System Functional Components

2.3 Electrolyte Tanks

There are four Electrolyte Tanks in each GS200 Battery System, consisting of 2 Anolyte Tanks and 2 Catholyte Tanks (2 tanks for each ESU). (Refer to Figure 4).

2.3.1 Electrolyte Tanks Main Components

The main components of the Electrolyte tanks include:

- **Tanks** – holds the Anolyte & Catholyte Electrolyte Chemistry. Each GS200 has:
  - two 3,380 gal Anolyte Tanks
  - two 4,728 gal Catholyte Tanks

- **Heaters** – warms the Anolyte & Catholyte fluid within the tanks – 1 heater per tank.
- **Thermocouples (TC)** – measures the fluid temperature (bath) in tanks – 3 thermocouples (heat sensors) per tank. Tank temperature range is 45° C to 50° C. Tank temperatures may be viewed/modified within the BESS Web Client.
    - **Element TC** (near heater) – monitors the temperature of the heater element device.
    - **Bath TC** (near tank center) – monitors the temperature of the fluid in tank.
    - **Secondary TC** (near draw/sample ports) – not used, but may be used if the primary Bath TC fails.
- **Tank Level Sensors** – monitors the fluid level in tanks – 1 level sensor per tank. Tank volume levels may be viewed within the BESS Web Client. Levels include:
    - **Over Full** – indicates fluid levels in tanks are too high. Pumps will not operate when in Over Full.
    - **Max** – indicates fluid levels are approaching a level of Over Full.
    - **Min** – warns that fluid levels are approaching a level of Low-Low. Normal tank volume is between Min and Max.
    - **Low Low** – indicates that fluid levels in tanks are too low. Pumps and heaters will not operate in Low Low.

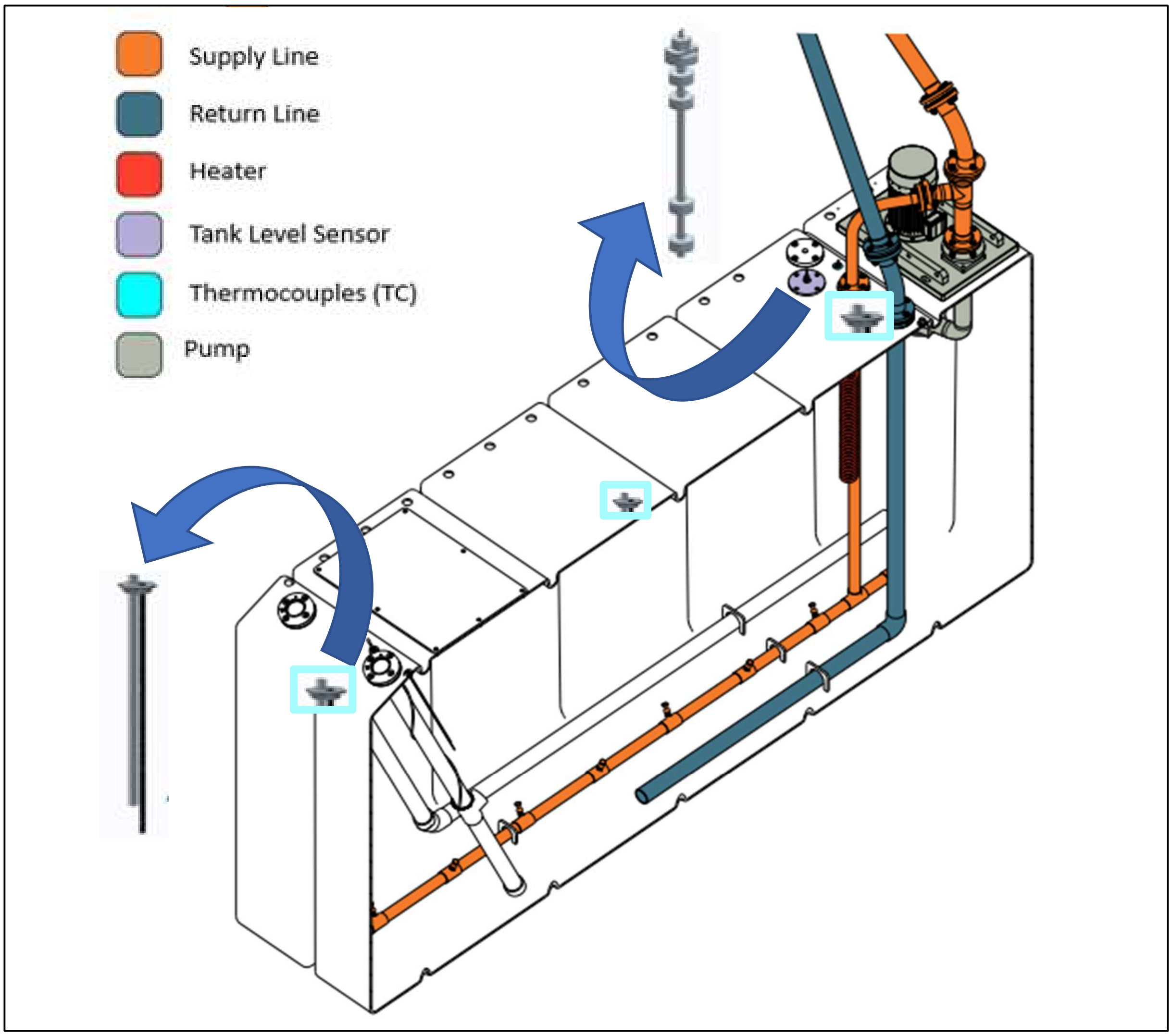

Figure 4: Electrolyte Tank Components – Anolyte Tank Shown

2.3.2 Tank Composition and Berm

The Energy Module contains a Secondary Spill Containment System (Berm) to prevent any spill from exiting the container. (Refer to Figure 5). The berm has a capacity that is greater than the total GS200 Electrolyte volume and thus will contain any spill. In addition, the berm is made of extremely resistant geo-membrane 8130 XR-5 or similar approved equivalent. XR-5 was developed to contain and protect against acids, oils, methane, and alkaline chemicals.

The Power Module is further protected by a berm under all stack and fluid manifolds. Each stack is equipped with an additional containment (Drip) tray to retain any leakage directly from the stacks. Leak Sensors will detect any Electrolyte leaks from stacks, fluid manifolds, or tanks. For redundancy reasons, each leak detector array is equipped with two detectors. This redundancy improves the reliability of measurement and enables a two-stage Warning and Alarm measurement system to be utilized.

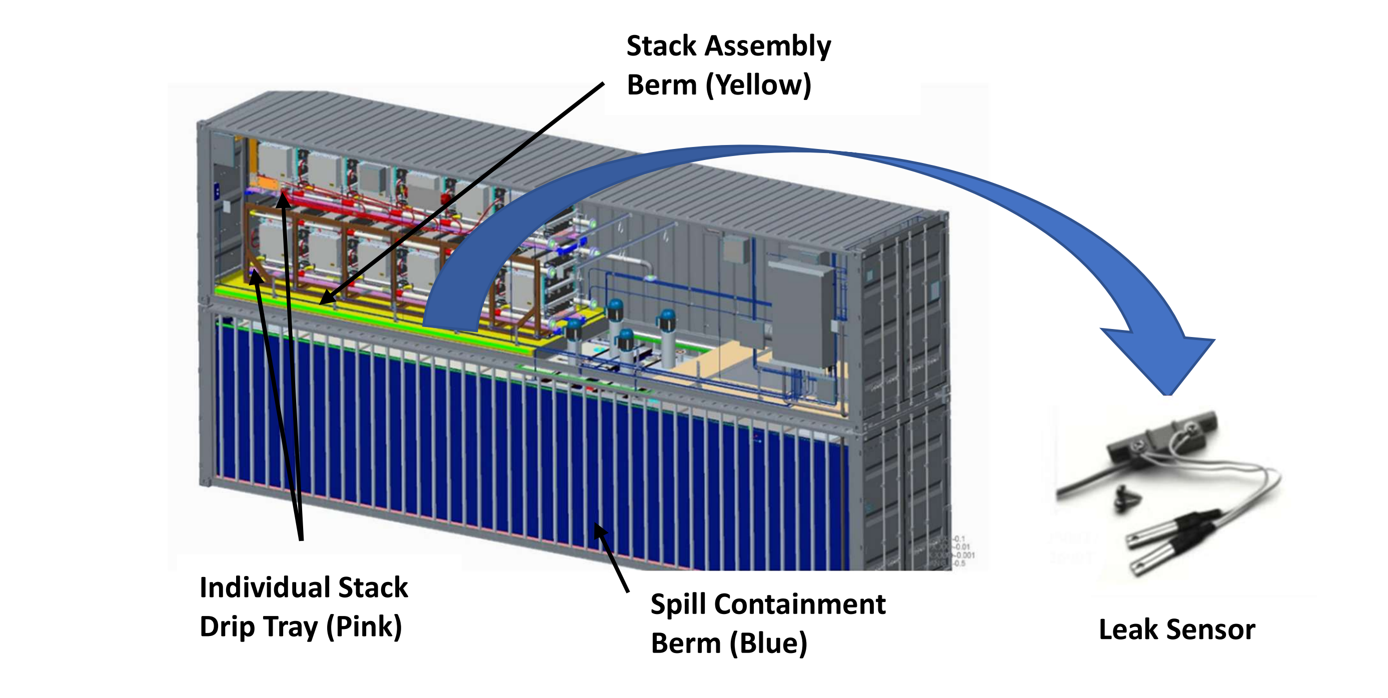

Figure 5: EM Containment Berm, Stack Berm, and Leak Sensors

2.3.3 Water Fill Ports on Tanks

To allow for water filling without entering the container, there are fill ports located on the outer ends of the Energy Module. (Refer to Figure 6). It is important to note that the fill ports on the GS200 tanks are not in the same location. The Anolyte Fill Port is on the right-hand side (RH) side, and the Catholyte Fill Port is on the left-hand (LH) side. (Catholyte Tanks are larger than Anolyte tanks. The other ports are for Electrolyte mixing).

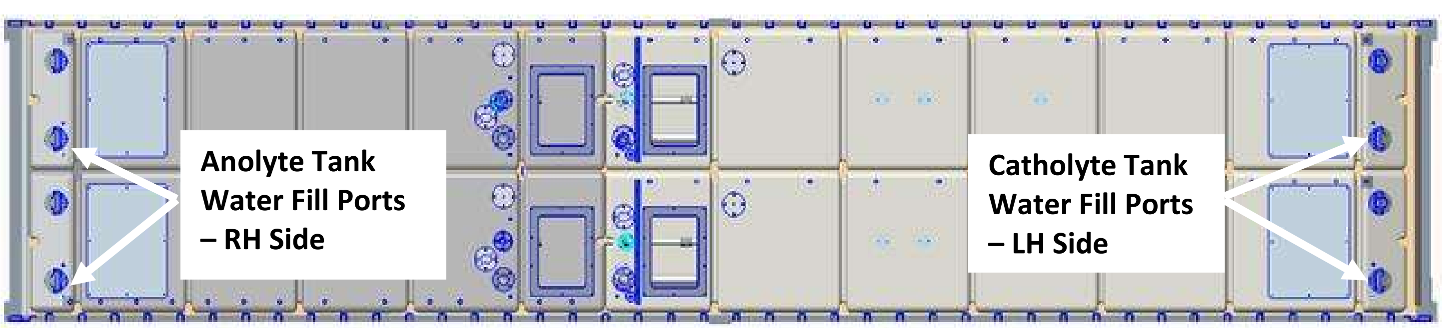

Figure 6: Water Fill Ports on Anolyte and Catholyte Tanks

2.3.4 Tank Assembly Design

Tank design is an integral part of the fluid delivery system. The Electrolytes are highly concentrated, and without sufficient stirring, active material would settle and not be available for the chemical reaction. As such, the tanks are modelled with return plumbing running the length of the tank bottom to the opposite end from the pumps which allows for stirring. In addition, there is Eductor Plumbing on the supply lines which rotates some of the fluid back into the tanks for stirring, without going through the stacks. (Refer to Figure 7). The stirring occurs whenever pumps are On.

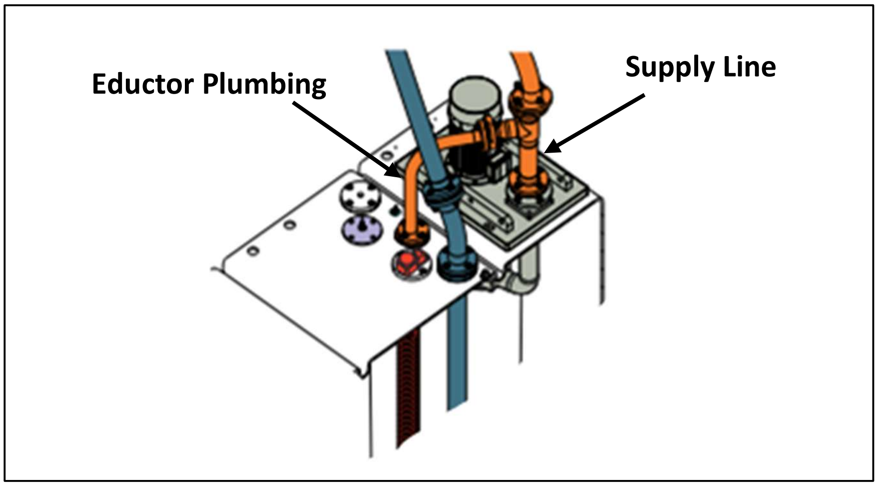

Figure 7: Eductor Plumbing

2.4 High Flow Pumps

There are four High Flow Pumps for each GS200 battery system, consisting of 2 Anolyte Pumps and 2 Catholyte Pumps (2 pumps for each ESU). (Refer to Figure 8).

2.4.1 Main Components

The main components of the pump assemblies include:

- **Variable Frequency Drive (VFD)** – The VFDs drive the pump motors by varying the frequency (Hz) of the power supplied to them. The VFDs are located within the High Voltage Enclosure (HVE), and the frequency settings may be viewed/modified on the display windows located on the front of the HVE. VFD (pump) frequencies may also be viewed/modified within the BESS Web Client.
- **Pumps**—The pumps, located within the tanks, provide the fluid pressure, via a motor shown in blue in Figure 8, to move the Electrolyte through the battery system. Pumps are active in **Remote Charge, Ready,** and **Rejuvenation** operational control states. Pumps do not run during **System Check, Shutdown**, or **Shutdown Idle** states. Pumps may also be manually applied within the BESS Web Client.

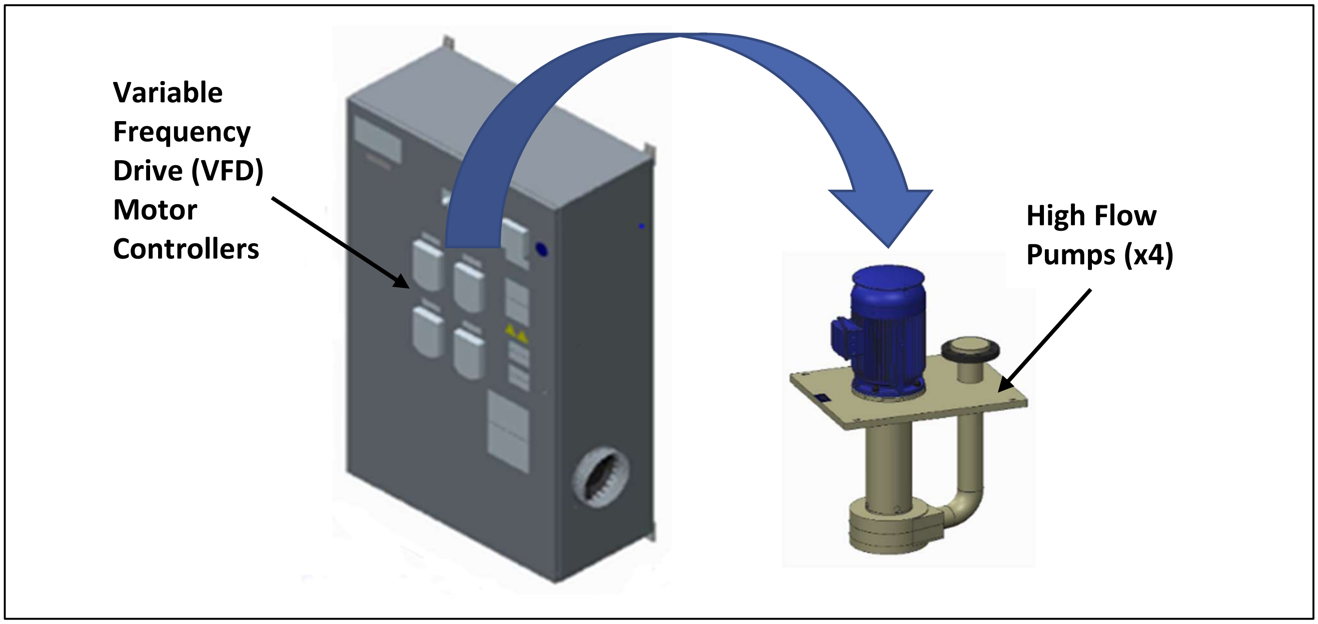

Figure 8: VFD Controls on Front of HVE

2.4.2 Start Up Configuration – Ready Delay

Upon start-up, there is a programmed delay to operation to ensure the fluid delivery system is stabilized. Otherwise, a Warning or Alarm condition may be triggered if out of range. For a period of time, the Anolyte Pressure is initially unstable. The battery software compensates for this instability by creating a delay (dwell period) after the **Ready** state is initiated but before charging/discharging can occur. Charging/Discharging will not be permitted during the dwell period.

2.4.3 VFD Settings for Set Point, Warnings & Alarms

The pumps' set point (nominal ramping rates) of the Variable Frequency Drives (VFD) must be precisely quantified at installation and after servicing. Due to environmental variables, required pump rates may vary between sites and must be precisely set to ensure that the correct PSI pressures are obtained. After installation, pump set point rates may be viewed/edited within the BESS Web Client. (Before installation, pump rates are set to a default value of 0 to ensure that pump rates will be ramped up correctly at installation). Table 2 and Table 3 provide the parameters for determining the VFD Warning and Alarm condition rates after the correct nominal set points (Anolyte-X, and Catholyte-Y) are determined at installation or after servicing. (Refer to the *Full System Start-up and Charge*, *GS200* document for complete details on determining nominal set point rates).

Table 2: Anolyte Pump Set Point, Alarm and Warning Settings

State	Set Point	Alarm High	Warning High	Alarm Low	Warning Low
System Check	0	0	0	0	0
Remote Charge	X	X + 5	X + 3	X - 5	X - 3
Ready	X	X + 5	X + 3	X - 5	X - 3
Shutdown Idle	0	0	0	0	0
Shutdown	0	60	60	0	0
Rejuvenation	X	X + 5	X + 3	X - 5	X - 3

- where X represents the Anolyte VFD frequency rate determined at installation or after servicing.

Table 3: Catholyte Pump Set Point, Alarm and Warning Settings

State	Set Point	Alarm High	Warning High	Alarm Low	Warning Low
System Check	0	0	0	0	0
Remote Charge	Y	Y + 5	Y + 3	Y - 5	Y - 3
Ready	Y	Y + 5	Y + 3	Y - 5	Y - 3
Shutdown Idle	0	0	0	0	0
Shutdown	0	60	60	0	0
Rejuvenation	Y	Y + 5	Y + 3	Y - 5	Y - 3

- where Y represents the Catholyte VFD frequency rate determined at installation or after servicing.

2.4.4 Pump Pressure Flow Optimization

There is pump fluid-flow optimization process implemented during battery operation. Without this optimization, the battery system would be less efficient at a high State of Charge (SOC) due to reduced fluid flow because of the zinc plating on the Anolyte side of the stacks. In addition, a high current rate would also cause less efficiency due to the availability of reactants to be converted. This means that at high SOC or at high current rates, the utilization of the battery would be reduced.

The remedy for this issue is to optimize the flow rates to low levels when the battery is at a lower current and/or low SOC, and then to increase the flow rate when the battery is at a higher current and/or high SOC. Figure 9 shows the operational control areas recognized by the battery system that include Bottom of Charge (BOC), Middle of Charge (MOC), and Top of Charge (TOP). A higher flow rate is automatically applied when the battery moves from the MOC area to the TOC area. Unfortunately, the Electrolyte fluid also requires mixing in the tanks to stir the reactants, so when there is reduced flow at lower current and SOC, this may reduce the efficiency and availability of reactants. Both of these efficiency reduction factors must be considered as part of the fluid delivery parameters.

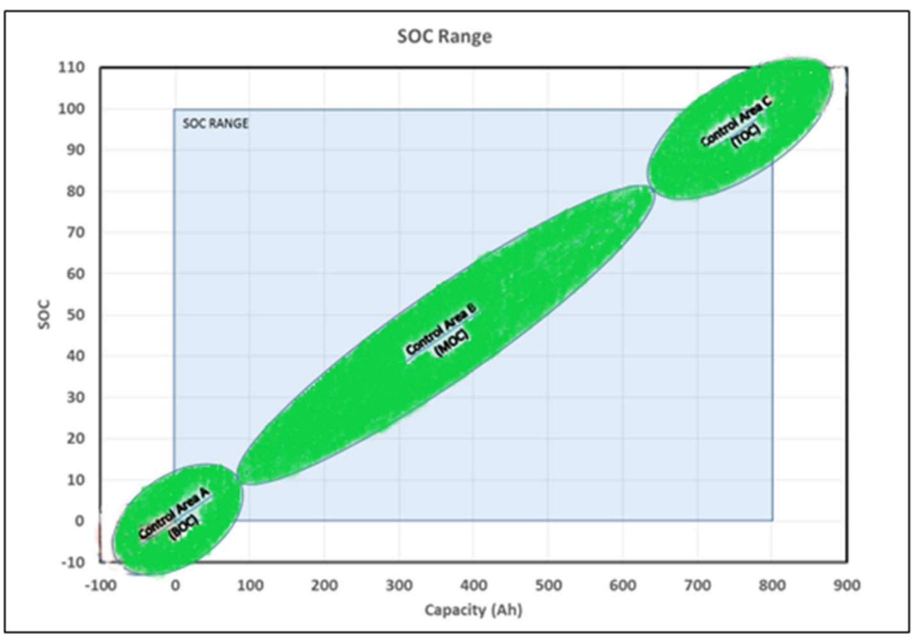

Figure 9: Battery Control Areas for SOC Range

The nominal pump speed setting (when battery is in **Ready** State) is called "Active Flow %", and the default is 100%. However, this value can be adjusted to improve efficiency depending on customer need. Consequently, as stated in the previous section, the system will automatically adjust into a higher flowrate when the system is running at high State of Charge (SOC) or at high current. This higher pump speed setting is called "High Flow %".

Table 4 explains the SOC control parameters, including the current and SOC thresholds to change from "Active Flow %" to "High Flow %" and the minimum hold time once activated. These parameters are per ESU, and both the Anolyte and Catholyte nominal VFD set points (along with warning & alarm conditions) will be adjusted by the same percentage value.

Table 4: Pump Control Parameters Depending on SOC

Parameter	Description	Value
Active Flow %	The percentage (at or above) the **Ready** (nominal) set point used while charging/discharging the battery.	Variable default = 100%
High Flow %	The percentage above the **Ready** (nominal) set point used while charging/discharging AND (must be above the Current Threshold OR above the SOC Threshold).	110%
Current Threshold	An ESU Current Threshold (in A) setting used to determine when to activate the High Flow %. When the current reaches this threshold, the higher flow rate is enabled.	Variable default = 900
SOC Threshold	A State of Charge (percentage) Threshold used to determine when to activate the High Flow %. When the State of Charge percentage of the system (as determined by the SOC counter) reaches this value, the higher flow rate is enabled.	Variable default = 85
Minimum Hold Time	The minimum time the system will run at the Active Flow % Rate or High Flow % Rate after enabled.	Variable default = 120

2.4.5 Pressure Considerations

The nominal set point for **Ready, Remote Charge,** and **Rejuvenation** is the VFD frequency settings needed for Anolyte and Catholyte flow through the stacks. However, there must always be an (at least) .5 PSI higher positive pressure differential to the Anolyte side than the Catholyte side of the stack cells. This is because a positive pressure to the Anolyte side than to the Catholyte side during operation will ensure that the Catholyte will flow though the Ni foam and not over it, and that the membrane will not get pushed into the zinc plating.

During initial battery installation and after servicing, the differential set points for the Anolyte and Catholyte must be verified to ensure there is at least a .5 higher PSI applied to the Anolyte fluid flow than to the Catholyte fluid flow. This differential must be further applied to all Warning and Alarm pressure conditions for both the Anolyte and Catholyte. (Refer to Section 2.4.3). In addition, with ESU1 positioned above ESU2, there is an increased pump speed required to overcome the extra height and gravity of ESU1 and allow the fluid flow through its stacks. Generally, an additional 5 PSI of fluid pressure is required to be applied for fluid flow to ESU1. This higher set point frequency value needed for ESU1 will need to be confirmed at installation and after servicing.

2.5 Interconnect Plumbing

There are four sets of Interconnect plumbing in each GS200 battery system. For each ESU, there is an Anolyte Supply & Return Line, and a Catholyte Supply & Return line. (Refer to Figure 10).

2.5.1 Main Components

The main components of the Interconnect plumbing include:

- **Anolyte & Catholyte Supply Lines (x2)** – moves the Electrolyte from the tanks to the stacks.
- **Anolyte & Catholyte Return Lines (x2)** – moves the Electrolyte from the stacks to the tanks.
- **Anolyte & Catholyte Eductor Mixing Lines (x2)** – moves the Electrolyte from the supply lines back to the tanks to provide fluid for tank mixing by the eductors.
- **Pressure Transducers (x4)** – located on supply lines near stacks, these pressure monitors measure the Electrolyte fluid pressure (PSI). Fluid PSI may be viewed within the BESS Web Client:
  - The required Anolyte fluid pressure is 5.5 PSI**.
  - The required Catholyte fluid pressure is 5.0 PSI**.
- **Relief Valves (x4)** – opens at specified times or manually to allow the stacks to drain Electrolyte back to the tanks. Relief valves open automatically at **Shutdown** and **Shutdown Idle** state and can be manually opened within the BESS Web Client.
- **ECC Valve (x2)** – prevents Catholyte from flowing out of the Stacks during the Electrical Chemical Clean (ECC) procedure. The ECC maintenance procedure is utilized to clean the Catholyte fluid of Iron Oxide Deposition (IOD) buildup. (Refer to Figure 11).

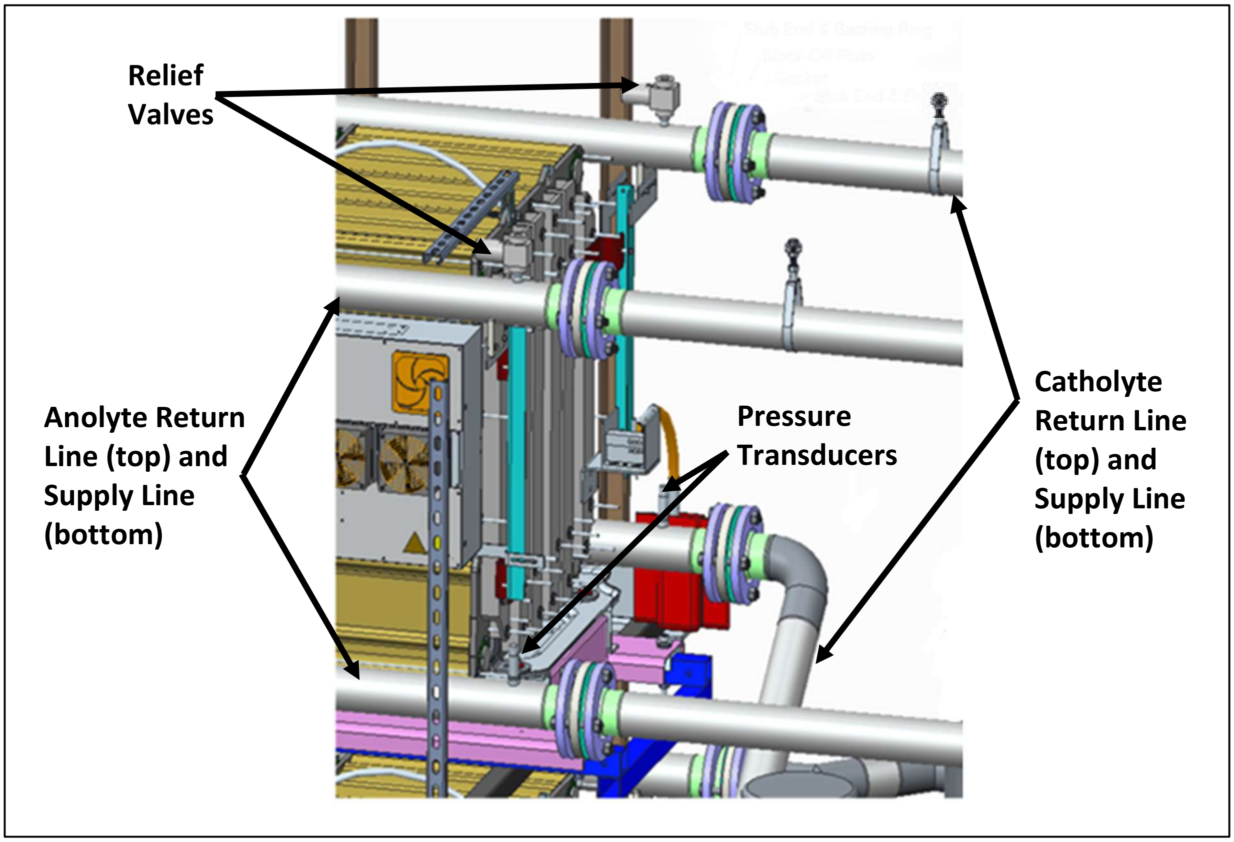

Figure 10: Interconnect Plumbing – ESU 1 (upper ESU, plumbing access area shown)

** Fluid pressures are subject to change. Contact Acme Engineering for additional information.

2.5.2 Anolyte & Catholyte Filters

Both the Anolyte and Catholyte Supply Lines have filters to remove contaminants before the fluid reaches the stacks. (Refer to Figure 11). The Anolyte "Cone" filter is located within the Anolyte Supply Line(s). It is shaped similar to a cone with large pores and is intended to capture large debris that may have been introduced into the Anolyte fluid. Generally, this filter will only need to be occasionally cleaned.

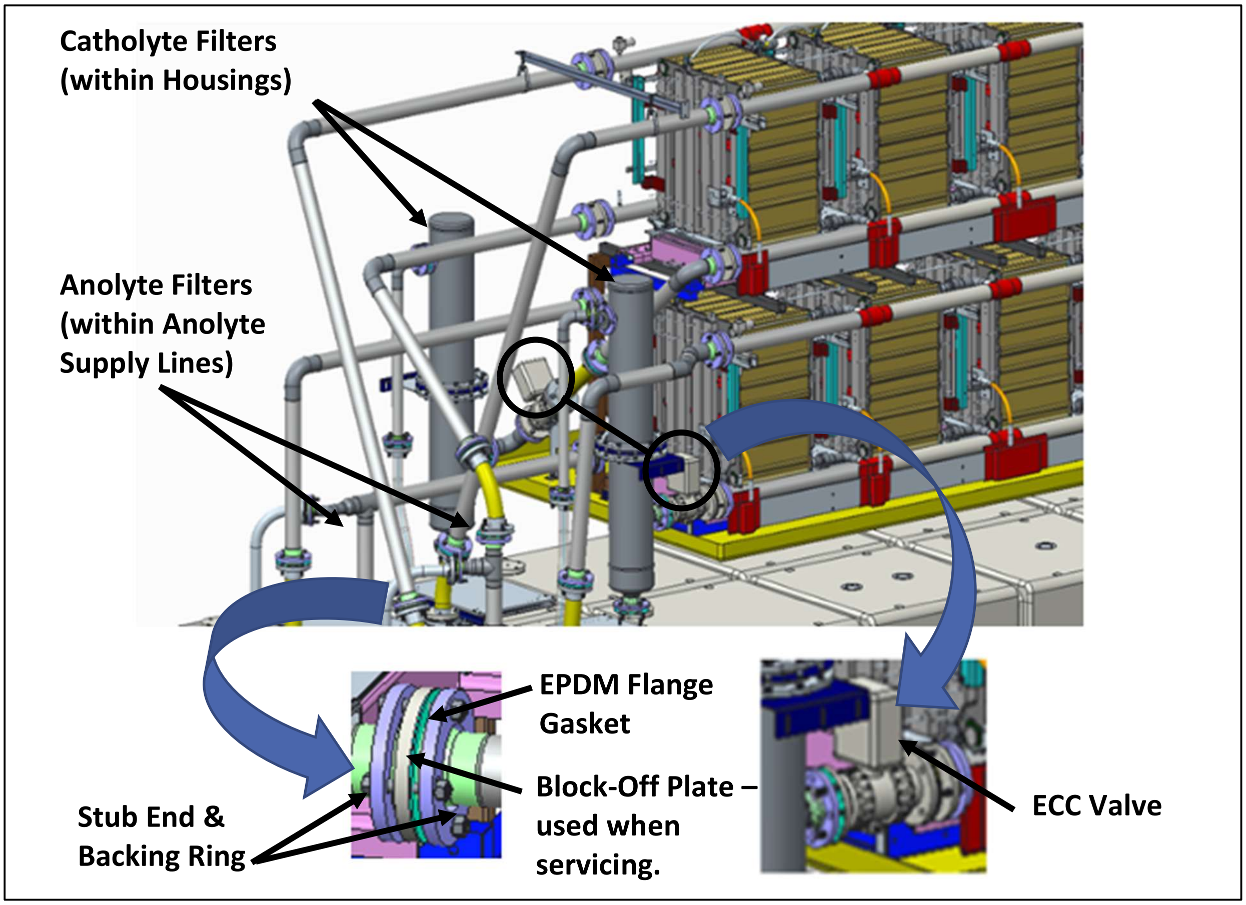

Figure 11: Anolyte & Catholyte Filters and Other Plumbing

The Catholyte Filter has a finer pore, 70-micron filter with an all-polypropylene construction and is located within the filter housing on the Catholyte Supply Line(s). The Catholyte filter usually becomes contaminated after the Electrical Chemical Clean (ECC) maintenance procedure has been performed. The ECC procedure is required to clean Iron Oxide Disposition (IOD) (Iron rust) from the Catholyte. IOD forms over time on the Nickle foam and also on the surface of the Catholyte tanks. After the ECC process is completed, the Iron Oxide will have been released into the Catholyte fluid and then will be collected by the filter, eventually clogging the filter.

When the filter becomes clogged, the Catholyte pressure will decrease, and the Catholyte pump frequency will need to be raised in order for the pressure to stay within the ~ .5 PSI negative differential to the Anolyte. As a general rule, if the Catholyte pump frequency requires being raised more than once in one week, then it is likely that the Catholyte Filter will need to be replaced. The EPDM Flange Gaskets will also require periodic replacement due to corrosion and should be checked when the Catholyte Filter is changed. When servicing plumbing components, there are block off plates (included with battery system) that can be installed to prevent Electrolyte from entering the stacks during servicing.