A Saltwater Battery Inspired by the Membrane Potential Found in Biological Cells

Andrew Jester, Ross Lee, Pritpal Singh

Abstract—As the world transitions to a more sustainable energy economy, the deployment of energy storage technologies is expected to increase to develop a more resilient grid system. However, current technologies are associated with various environmental and safety issues throughout their entire lifecycle; therefore, a new battery technology is desirable for grid applications to curtail these risks. Biological cells, such as human neurons and electrocytes in the electric eel, can serve as a more sustainable design template for a new bioinspired (i.e., biomimetic) battery. Within biological cells, an electrochemical gradient across the cell membrane forms the membrane potential, which serves as the driving force for ion transport into/out of the cell akin to the charging/discharging of a battery cell. This work serves as the first step for developing such a biomimetic battery cell, starting with the fabrication and characterization of ionselective membranes to facilitate ion transport through the cell. Performance characteristics (e.g., cell voltage, power density, specific energy, roundtrip efficiency) for the cell under investigation are compared to incumbent battery technologies and biological cells to assess the readiness level for this emerging technology. Using a Na+-Form Nafion-117 membrane, the cell in this work successfully demonstrated behavior like human neurons; these findings will inform how cell components can be re-engineered to enhance device performance.

Keywords—Battery, biomimetic, electrocytes, human neurons, ion-selective membranes, membrane potential.

I. INTRODUCTION

THE transition to a sustainable energy economy will include energy storage as a key component in grid systems to provide more reliable electrical service; among these technologies, secondary (i.e., rechargeable) battery systems serve as the most deployed solution for grid applications, such as peak-shaving, renewables integration, and black-start. According to the Global Energy Storage Database, various utility-scale battery technologies have been deployed across the globe. However, three types are worth mentioning: lithium-ion battery (LIB) systems, flow battery systems, and lead-acid battery systems [1], [2].

LIB systems, due to their high specific energy and power density, can serve in a variety of grid applications, making them the most ubiquitous among those installed across the globe; however, LIB cells are energy-intensive to produce, their manufacturing contributes to severe environmental and health impacts (e.g., climate change, fossil fuel depletion, particulate matter formation, human toxicity, etc.), and there are complications with recycling these materials due to the complexity of the cathode materials [3]-[7]. Flow batteries can be custom-manufactured to meet certain design requirements within a certain area footprint, but exhibit low specific energy and power density, and their operation requires the use of pumps and other ancillary equipment that increases operation and maintenance (O&M) costs [8]-[12]. Lead-acid batteries are often deployed for renewables integration in developing countries due to their relatively low capital and O&M costs [10]; like flow batteries, lead-acid batteries also exhibit lower performance (i.e., specific energy, power density, and roundtrip efficiency) than other technologies, and pose environmental and human health risks due to materials used within the cell (i.e., lead-based materials used for the electrodes and concentrated sulfuric acid as the electrolyte) [8].

Despite the many applications that these battery technologies can serve for grid operations, it is clear that a new technology is desired, given the various holistic issues of these incumbent technologies for a more sustainable future for energy storage systems. For this reason, the development of a biomimetic (i.e., bio-inspired) battery cell is discussed, for which the drawbacks associated with incumbent battery technologies can be addressed from the beginning. This paper reports the results of investigating Na^+ -Form Nafion-117 for potential use as the separator membrane in the final design.

II. THE MEMBRANE POTENTIAL

In biological systems, proper cell function is dictated by concentration gradients of ions (e.g., sodium, potassium, calcium, magnesium, chloride, etc.) across the cell membrane. These concentration gradients develop a chemical potential, which is then counteracted by an electrical potential that arises due to charge density distributions across these ion-selective channels; this electrochemical potential is better known as the membrane potential in the field of biology [13].

The membrane potential can be simplified into two separate modes of operation: the resting potential and the action potential. The resting potential refers to the membrane potential when the cell is in a resting or "steady" state. When the cell is stimulated, the ion-selective channels open to allow the transport of ions into/out of the cell and generate the action potential for the cell [13]-[16]. Fig. 1 shows the voltage, conductance, and current profiles of neurons that are stimulated

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to produce the action potential [13].



Fig. 1 Generation of the Action Potential in Human Neurons [13]

One common example that is referenced for biomimetic inspiration for emerging energy systems is the electrocyte within the electric eel. Electrocytes can be found in various electric fish, such as the knifefish and the torpedo ray, to assist with navigation, hunting prey, and/or defending against predators [17]. Unlike neurons, electrocytes have an asymmetric structure comprised of an innervated membrane and a non-innervated membrane. In the electric eel, the release of acetylcholine triggers the innervated membrane to cause sodium channels to open and form the action potential (+65 mV); this occurs while the non-innervated membrane remains at the resting potential for the cell (-85 mV). With thousands of these electrocytes connected in a series-parallel arrangement, the associated voltage across a single electrocyte (i.e., +150 mV) allows the eel to perform electric organ discharge at 600 - 860 V depending on eel species [18], [19]. Fig. 2 shows electrocyte at rest and under stimulation to show the effect of stimulation on the overall cell voltage. Therefore, developing a biomimetic battery cell based on the electric eel involves the development of an ion-selective membrane to allow for membrane potentials like those found in electrocytes. This phenomenon of the membrane potential is common in all animal species, though there are some key differences to discuss. First, the membrane potential will vary by species; therefore, concentration gradients across the cell membrane will vary as a result [13]-[19]; this is shown in Table I for various species. Secondly, the membrane potential is governed by the overall function that the cell provides; therefore, there are different membrane potentials that can exist in a single species to serve different applications according to the species under investigation [13]-[19].



Fig. 2 Single Electrocyte (a) at Rest and (b) under Stimulation in the Electric Eel (*Electrophorus electricus*) (Adapted from [18])

III. ION-SELECTIVE MEMBRANES

A. General Theory

1. Ion-Selectivity

The electrochemical potential that acts as the driving force for ion transport is estimated using the Nernst Equation, as shown in (1); *E* represents the net cell voltage, E^0 represents the redox potential of electrodes used in the electrochemical cell, *R* represents the universal gas constant (8.314 *J/mol* · *K*), *T* represents the absolute temperature, *z* represents the valence number of the ionic species in transport, and *F* represents Faraday's Constant (96,485 *C/mol*), *c*_H represents the molarity of the ionic species in the high-concentration half-cell, and *c*_L represents the molarity of the ionic species in the lowconcentration half-cell [8].

$$E = E^0 - \frac{RT}{zF} \ln\left(\frac{c_H}{c_L}\right) \tag{1}$$

TABLE I

COMPARISON OF MEMBRANE POTENTIAL BY SPECIES [13], [14], [18]

Species	Membrane Potential [mV]
Giant Squid (Axon)	
Na ⁺ Channels	+55
K^+ Channels	-76
<i>Cl</i> ⁻ Channels	-66
Ca^{2+} Channels	+145
Human (Neurons)	
Na ⁺ Channels	+56
K^+ Channels	-102
Cl^- Channels	-76
Ca^{2+} Channels	+125
Electric Eels (Electrophorus electricus)	
Innervated Membrane (Resting)	-85
Innervated Membrane (Stimulated)	+65

In the case of ion-selective membranes, the Nernst Equation needs to be modified to account for the ion-selectivity of the membrane used within the electrochemical cell. When the redox potential is ignored, (2) can be used to represent the reversal voltage of the cell as a function of the concentration gradient across the membrane, where t_+ represents the cation transference number for the membrane [20]; other terms in (2) are previously defined for (1).

$$V_{rev} = (2t_+ - 1)\frac{RT}{zF}\ln\left(\frac{c_H}{c_L}\right)$$
(2)

2. Membrane Conductivity

Overall, the ion transport through the membrane is due to the presence of functional groups that form along the inner surface of pores within the membrane. For instance, these functional groups can include carboxyl (-COOH) and hydroxyl (-OH) groups for cation-selectivity, or amine $(-NH_2)$ groups for anion selectivity at neutral pH [20]-[30].

Experimentally, conductivity can be assessed based on analyzing current-voltage (IV) characteristics obtained when applying an external bias voltage across the membrane. Conductance for the cell with and without the membrane is

evaluated as the slope within the linear (i.e., ohmic) region of the *IV* characteristic curve using (3):

$$G = \frac{dI}{dV} \approx \frac{I_2 - I_1}{V_2 - V_1} \tag{3}$$

In the context of this research, measuring the conductance of the cell with (G_c) and without (G_s) the membrane under test for various *NaCl* concentrations will help quantify the membrane conductance (G_s) using (4); this equation assumes a set of series resistances that dictate the overall conductivity of the cell.

$$G_m = \frac{G_c G_s}{G_s - G_c} \tag{4}$$

Finally, the membrane conductivity (κ) can be calculated using (5), where *L* represents the distance between the electrodes which apply the external voltage across the membrane, and *d* represents the wetted diameter of the membrane.

$$\kappa = \frac{4G_m L}{\pi d^2} \tag{5}$$

B. Battery Performance Characteristics

1. Power Density

Power density within an energy storage system represents the maximum power per unit mass at which the system can deliver energy to the system load. Using Joule's Law and Ohm's Law, along with a current profile for the battery when discharging the cell, (6) allows for calculation of maximum power density $(p_{d,max})$ for the battery per cycle; *I* represents the measured current, R_L represents the load resistance, and m_{cell} represents the mass of the electrochemical cell used for testing.

$$p_{d,max} = \frac{max(l^2 R_L)}{m_{cell}} \quad (discharge) \tag{6}$$

2. Specific Capacity

Specific Capacity within an energy storage system can be quantified as either charge capacity or energy storage capacity. Charge capacity refers to the total charge that can be stored within the device and can be determined by integrating the discharge current profile of the cell. Energy storage capacity refers to the total energy that can be stored within the device and can be determined by integrating the discharge power profile of the cell. For the purposes of this study, specific energy storage capacity was used as one of the performance characteristics for the cell using Simpson's Rule for the numerical integration as shown in (7) [31]; N represents the number of nodes for the discharge power profile for each cycle with index i, and h represents the constant step size for the numerical integration as calculated by (8) (a and b represent the start and end times to define the duration of the discharge phase for each cycle, respectively).

$$e_d = \frac{h}{3} \sum_{i=1,3,5}^{N-2} \left(p_{d,i+2} + 4p_{d,i+1} + p_{d,i} \right)$$
(7)

$$h = \frac{b-a}{N} \tag{8}$$

3. Roundtrip Efficiency

Roundtrip efficiency refers to the ratio of how much energy can be discharged from the system with respect to how much energy is required to fully charge the system. Roundtrip efficiency (η) can be quantified by integrating the charge and discharge power profiles as shown in (9); e_c represents the specific energy required to charge the battery to full state-ofcharge, which can be calculated using (7) and (8) for the charging phase.

$$\eta = \frac{e_d}{e_c} \tag{9}$$

C. Ion-Selective Membrane Development

Generally, an ion-selective membrane can be developed from any material (or set of materials) that allows the transport of a desired ion from a high-concentration solution to a lowconcentration solution. These membranes have been developed from various materials, ranging from polymers (e.g., polyethylene terephthalate (PET), polyimide (PI), polycarbonate (PC), etc.) to more complex materials (e.g., metal organic frameworks, two-dimensional materials, selfassembling biomaterials, etc.) [20]-[30].

For simplicity, ion-selective membranes can be separated into two main types: track-etched polymer membranes and hybrid membranes. Track-etched membranes can be developed with a symmetric or asymmetric structure and can have their nanopores remain bare or functionalized with foreign functional groups to tune for desired ion selectivity. Hybrid membranes consist of two or more membrane layers that contribute to ion selectivity; in some cases, one of these membrane layers consists of a track-etched polymer membrane.

Despite the various materials that have been used to produce these types of membranes, there are various drawbacks to their production and performance. For example, the track-etching process calls for the use of concentrated strong bases such as NaOH [20]-[24], which can serve as a safety risk in the manufacturing of membranes that require this process. Additionally, track-etched membranes exhibit low power generation when subjected to a concentration gradient, usually in the *pW* scale [20]-[24], which renders them infeasible for commercialization. Most hybrid membranes provide slightly enhanced performance because of drastic increases in ionic rectification [26]-[28]; however, this effect may serve as a challenge for use in a battery, which requires a membrane structure to allow easy charging and discharging of the cell.

The main takeaways from literature in this field, including studies outlined in [20]-[30], suggest the following:

- functional groups found in the membrane structure strongly correlate to performance of the membrane in terms of ion-selectivity and ionic conductivity.
- ionic conductivity increases if the ionic species of interest (i.e., the ionic species that is desired for transport across the membrane) is bound to the membrane structure.
- symmetric membrane structures will yield symmetric

current-voltage (*IV*) characteristics, which are desirable for a battery cell that requires the membrane to operate bidirectionally.

For these reasons, this work starts with the investigation of a Nafion-117 membrane that is functionalized with Na^+ ions to allow the membrane to mimic sodium channels found in biological cells. The next section goes into further detail on the Nafion structure that makes it desirable for this research.

D.Nafion-117 Membrane

Nafion is typically used in electrochemical devices such as proton-exchange membrane (PEM) fuel cells and vanadium redox flow batteries (VRFBs) due to its great proton conductivity [32], [33]. However, the Nafion membrane can also undergo chemical and thermal treatments to modify the membrane for cation selectivity; thus, an as-received Nafion-117 membrane can be easily converted to its Na^+ -Form [33]-[38] for desired Na^+ transport. Due to its very low equilibrium constant for the sulfonate groups found within the overall structure (i.e., pKa = -6.0) [39], Nafion serves as a great candidate membrane for this work.

To explain the transport phenomena within Nafion membranes, various models have been proposed to conceptualize the surface morphology of the membrane and its effect on ionic conductivity. Gierke's network-cluster model shown in Fig. 3 is often referenced to conceptualize the ionic properties of the membrane based on its sulfonate group (SO_3^-) -dominated regions for enhanced ionic conductivity, with a polytetrafluoroethylene (PTFE)-dominated backbone [34]. In the cluster-network model, reverse micelles are lined with SO_3^- groups which act as nanochannels (about 4 *nm* in diameter) for ion transport within a lattice structure.



Fig. 3 Gierke's Network-Cluster Model for Nafion Membranes [34]

Despite the convenience of the cluster-network model, the surface morphology of Nafion is more accurately conceptualized using a parallel cylindrical model, which suggests that ion transport occurs because of the alignment of cylindrical nanochannels (2.4 nm in diameter) that changes based on temperature and hydration status for the membrane. In the dry state, nanochannels run parallel to the membrane surface and inhibit ion transport; as the water content increases, nanochannels re-align to form perpendicular nanochannels to promote ion transport as shown in Fig. 4 [38].



Fig. 4 Nanochannel Re-Alignment in Nafion Membranes in (a) Dry, (b) Hydrated, and (c) Semi-Hydrated States [38]



Fig. 5 Nafion in its H^+ -Form and Na^+ -Form (Adapted from [33])

IV. RESULTS & DISCUSSION

A. Sample Preparation

The Nafion-117 membrane was converted to its Na^+ -form via thermal treatment like the process mentioned in [33]. The following procedure was conducted: boil the membrane in 3% H_2O_2 solution for one hour to clean the membrane, boil the membrane in deionized water for one hour to allow H^+ to dissociate from sulfonate groups contained within the nanopores, boil in 1M NaCl for one hour to allow Na⁺ to bond with sulfonate groups, then boil in deionized water for one hour to remove any excess NaCl from the membrane. Fig. 5 shows the conversion in the chemical structure of the Nafion-117 membrane because of this process [34].

The converted Nafion membrane remained in 1*M* NaCl solution overnight to maintain adequate hydration for the membrane. Directly before use, the membrane was rinsed with deionized water to remove any excess NaCl from the membrane surface.

B. Materials Characterization

Scanning Electron Microscopy (SEM) and Energy-Dispersive X-Ray Spectroscopy (EDS) were conducted using a Hitachi S4800 scanning electron microscope to examine the surface morphology of each membrane under investigation. Nafion membranes contain a Teflon (PTFE) backbone, which contributes hydrophobic regions to the overall structure, along with hydrophilic nanochannels lined with sulfonate groups that contribute to Na^+ transport through the membrane [33].

Fig. 6 shows the SEM images, sodium mapping, and fluorine mapping for the Nafion membrane in the dry and lyophilized states. Figs. 6 (a) and (d) show the smooth regions which indicate the PTFE backbone of the overall structure, while the fibrillar regions represent the cylindrical nanochannels originally aligned parallel to the membrane surface in the dry state (Fig. 6 (a)), which then change orientation once the membrane becomes hydrated (Fig. 6 (d)); these results are confirmed for in the fluorine mappings indicated by Figs. 6 (c) and (f). The sodium mappings shown in Figs. 6 (b) and (e) confirm successful conversion to the Na^+ -form.



Fig. 6 (a) Raw SEM Image, (b) Sodium Mapping, (c) and Fluorine Mapping of Dry Na⁺-form Nafion; (d) Raw SEM Image, (e) Sodium Mapping, and (f) Fluorine Mapping of Lyophilized Na⁺-form Nafion

C. Current-Voltage (IV) Characteristics

A Keithley 617 electrometer was used to obtain currentvoltage (IV) characteristics for each membrane under investigation at various saltwater concentrations: 1 mM NaCl, 10 mM NaCl, 100 mM NaCl, and 1M NaCl. The electrometer applied an external voltage across the membrane ranging from -1V to +1V in 0.1V increments. This procedure employed a two-probe configuration using Ag/AgCl reference electrodes as shown in Fig. 7. A representative wiring diagram for this experimental setup is shown in Fig. 8 to account for resistances within the electrolyte, each of the reference electrodes, and the membrane under test.



Fig. 7 Two-Probe Configuration of the Cell for Conductivity Testing



Fig. 8 Representative Wiring Diagram for Conductivity Testing

Obtaining conductance values from each IV characteristic involved the use of a MATLAB® script to identify the linear (ohmic) region and estimate the associated membrane conductance for various saltwater concentrations.

Fig. 9 shows the *IV* characteristic curves for the cell using the converted (Na^+ -Form) Nafion membrane in various NaCl solutions. The conductance of the cell increases with increasing saltwater electrolyte concentration, as expected. Due to the symmetry of the membrane, each of the curves exhibits linear (ohmic) behavior in the presence of an externally applied voltage. This implies that the charge and discharge phases should exhibit similar peak currents for each cycle performed for the cell using each of these equilibrium NaCl concentrations. Additionally, the ionic conductance is simply calculated as the slope of each of the *IV* characteristic curves. The high conductivity of the membrane is due to its low pKa value.

Using the IV characteristics for the cell with and without the Nafion membrane, the membrane conductivity was calculated using (3) through (5). Fig. 10 shows the ionic conductivity of the Nafion membrane as a function of electrolyte concentration, indicating that as the electrolyte concentration increases, so does the membrane conductivity.

The logarithmic trend in membrane conductivity with increasing electrolyte concentration is consistent with what is reported in literature for conductivity measurements using a Guillou cell [30], though the calculated conductivity of the Nafion membrane at 1M NaCl is more consistent with reported values using an LMEI clip cell [41], [42]. This elevated membrane conductivity, with respect to results reported for the Guillou cell, is partially due to keeping the Nafion membrane in 1M NaCl prior to use; therefore, Na^+ ions bound within the membrane may act as a contributing factor to the enhanced performance. Additionally, deviations in the reported values for membrane conductivity occur due to various operating limitations of each method employed for obtaining measurements [40]-[42].

D. Cation-Transport Number

Open-circuit voltage (OCV) measurements were taken to investigate the cation transport of each membrane. Measurements were conducted using a three-probe configuration for the cell connected to a Solartron EChem Lab XM potentiostat. The concentration ratio applied across the membrane was varied 1-10, with the electrolyte concentration in the counter-electrode half-cell fixed at $100 \ \mu M \ NaCl$; this was to allow the Debye Length to be large enough to mitigate the effects of diffusion-driven self-discharge within the cell





Fig. 9 IV Characteristic Curves for Cell with Na⁺-Form Nafion



Fig. 7 Membrane Conductivity vs. NaCl Concentration

Fig. 12 shows the linear fit for the OCV measurements for the Nafion-117 membrane over the concentration ratio range of 1-10. The cation (i.e., sodium) transport number associated with this curve fit for the Nafion-117 membrane was calculated as $t_+ = 0.8983$, which is consistent with what is reported in literature for Nafion-117 over various electrolyte concentrations [42], [43]. The correlation coefficient for the curve fit was calculated as $R^2 = 0.9479$, which indicates strong adherence to modified Nernst Equation from (2).

E. Cycle Testing and Performance Characteristics

Cycle testing will investigate the effects of equilibrium concentration on the following parameters: cell voltage, power density, energy capacity, and roundtrip efficiency. Equilibrium concentrations used for this study included 0.1 *M* NaCl, 0.25 *M* NaCl, 0.5 *M* NaCl, 0.75 *M* NaCl, and 1.0 *M* NaCl treatment for the saltwater electrolyte. The charging phase of

each cycle will employ a constant voltage (i.e., float voltage) of $V_f = 0.25 V$. The Keithley 617 electrometer was used to

measure current, while an Agilent 34401a multimeter was used to measure voltage.



Fig. 8 Three-Probe Configuration of Cell for OCV Measurements



Fig. 9 OCV vs. Concentration Ratio

Unlike typical cycle testing, that switches between charge/ discharge phases based on cell voltage, this work adopted a time-based switching protocol for the cycle testing. The charge and discharge time varied for each equilibrium concentration; currently, charge and discharge phases will each last 5 minutes. Fig. 13 shows a wiring diagram of the circuit used for cycle testing. An Automatic Transfer Switch (ATS) facilitates the switching between the charge and discharge phases for each cycle for the cell. To set the position of the ATS, a relay module receives a digital input from an Arduino Mega microcontroller (not shown) for switching between the charge and discharge phases; for safety, the normally closed (NC) contact for the relay module closes the circuit on the discharge phase, while the normally open (NO) contact is associated with the charge phase. A preset float voltage (V_f) governs the charge phase for each cycle, and a load resistor $(R = 0.47\Omega)$ closes the circuit to allow the cell to perform the discharge phase. A three-probe arrangement is employed for the cell to allow the osmotic current (I_{osm}) to flow through a working (WE) and counter electrode (CE) pair, while measuring voltage between the CE and an Ag/AgCl reference electrode (RE). Prior to testing, the RE is allowed to equilibrate with the saltwater electrolyte to set the reference potential for the collected cycle data.

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Fig. 12 Specific Energy for Various Electrolyte Concentrations

Figs. 14 and 15 show the nominal cell voltage and capacity for the cell over 300 cycles (corresponding to 50 hours) using electrolyte concentrations of 0.1 *M* NaCl, 0.25 *M* NaCl, 0.5 *M* NaCl, 0.75 *M* NaCl, and 1.0 *M* NaCl. The cell voltage does not have a dependence on electrolyte concentration (i.e., changing conditions of the reference electrode can explain the variation in these values), while the specific energy for the cell increases with electrolyte concentration due to the higher presence of ions available for transport. Table II shows a comprehensive comparison of each performance characteristic; power density follows the same trend as specific energy, while no definitive trend between roundtrip efficiency and electrolyte concentration currently exists.

I ABLE II SUMMARY STATISTICS OF PERFORMANCE CHARACTERISTICS					
Electrolyte Concentration [<i>M NaCl</i>]	Cell Voltage [mV]	Power Density [W/ kg]	Specific Energy [Wh/kg]	Roundtrip Efficiency	
1.0	30.5	1.04E-14	2.95E-17	3.08E-08	
0.75	27.5	8.42E-15	2.35E-17	3.01E-08	
0.50	30.4	6.09E-15	1.77E-17	1.92E-08	
0.25	24.7	5.23E-15	1.60E-17	2.47E-08	
0.10	34.1	4.46E-15	1.43E-17	1.82E-08	

Table III shows a comparison of the membrane potential for the cell investigated in this work to ion channels in human neurons and electrocyte membranes in the electric eel. For all concentrations, the electrochemical cell operates in the same order of magnitude of biological cells and exhibits similar membrane potentials to human neurons. These results suggest successful demonstration for an energy storage device intended to mimic the performance of biological cells found in nature.

OVERALL MEMBRANE POTENTIAL COMPARISON				
Species	Membrane Potential [mV]			
Human (Neurons)				
Resting	-40			
Stimulated/Action	+20			
Electric Eels (Electrophorus electricus)				
Innervated Membrane (Resting)	-85			
Innervated Membrane (Stimulated/Action)	+65			
Saltwater Battery (Na ⁺ -Form Nafion-117)				
1.0M NaCl	+30.5			
0.75 <i>M NaCl</i>	+27.5			
0.5M NaCl	+30.4			
0.25 <i>M NaCl</i>	+24.7			
0.1M NaCl	+34.1			

Table IV compares the performance of the electrochemical cell using 1.0 M NaCl electrolyte to the incumbent battery technologies discussed earlier. Since the electrochemical cell

operates on the same scale as biological cells, comparing its performance to incumbent battery technologies suggests that further development is required. As a result, Electrochemical Impedance Spectroscopy (EIS) results provide additional insight for how these characteristics can be enhanced based on certain components of the cell that contribute to the overall performance of the cell.

TABLE IV	
COMPARISON OF SALTWATER BATTERY TO INCUMBENT TECHNOLOG	HES

Battery Technology	Cell Voltage [V]	Power Density [W/kg]	Specific Energy [Wh/kg]	Roundtrip Efficiency
Lithium-Ion	3.0-4.2	500-2,000	75-200	0.85-0.90
VRFB	1.40	-	10-30	0.85-0.90
Lead Acid	2.00	75-200	35	0.63-0.80
Saltwater Battery (1.0M NaCl)	0.03	1.04E-14	2.95E-17	3.08E-08

F. Electrochemical Impedance Spectroscopy (EIS)

A perturbation voltage of 5 mV was applied across the cell over a frequency range of 100 kHz-50 mHz using a Solartron EChem Lab XM potentiostat to obtain Nyquist plots for the cell. The electrolyte concentrations and cell configuration follow the conditions used for the cycle testing to further investigate the contribution of the membrane to overall cell performance. Nyquist plots were obtained for using the following electrode configurations, (shown in Fig. 16) with 10 trials for each treatment: CE-RE, WE-RE, and CE-RE (without the separator membrane). The summation of the CE-RE and WE-RE traces provide insights for the overall cell performance, while the difference between the CE-RE traces with and without the separator membrane provides insights around the contribution of the membrane to overall cell performance. The Solatron EChem Lab XM-Studio software (which operates the potentiostat) was used to perform Nyquist Plot curve fittings for the raw traces, while ZView was used to perform curve fitting for composite plots for the CE-RE and WE-RE traces.



Fig. 13 Cell Configuration for EIS Measurements



Nyquist Plots (1.0M NaCl)

Fig. 14 Nyquist Plots for using 1.0M NaCl Electrolyte

Fig. 17 shows the average Nyquist plot traces for each of the three configurations when using 1.0 M NaCl electrolyte and the Nafion-117 membrane. Due to the semi-circle shape of each trace, the Nyquist plots were fitted using a modified Randles circuit model as shown in Fig. 18; in this equivalent circuit model, the double-layer effect (for the interactions between the electrolyte and electrodes) is represented as a constant-phase element (CPE) within the circuit model. Due to noise obtained for the EIS traces below 200 mHz, the curve fitting range was adjusted to account for frequencies of 100 kHz-200 mHz.



Fig. 15 Modified Randles Circuit used for EIS Curve Fitting

A summary of these results is shown in Table V when using a $1.0 \ M \ NaCl$ electrolyte. Due to the insignificant impact that the membrane has on the double-layer effect for the cell, ohmic resistance for the membrane was determined for the membrane based on the difference in ohmic resistance between the CE-RE and CE-RE (no membrane) traces.

TABLE V				
AVERAGE FITTED VALUES FOR EIS CURVE FITTING (1.0M NACL)				
Configuration	$R_s[\Omega]$	$R_p \left[k \Omega \right]$	$C_0 \left[\mu S \cdot (rad/s)^{-n}\right]$	n
CE-RE	43.32	116.2	3.79	0.7944
WE-RE	22.86	4.02	154	0.8637
CE-RE (No Membrane)	41.61	84.33	4.34	0.7991
Membrane	1.71	-	-	-
Cell Average (CE-RE + WE-RE)	66.15	101.7	3.21	0.8479

The curve fitting results for the composite traces to assess full-cell performance (CE-RE + WE-RE) for each electrolyte concentration are shown in Table VI. As the electrolyte concentration increases, the ohmic and faradaic resistance terms decrease, like the individual traces mentioned earlier. Interestingly, as the electrolyte concentration increases, both CPE components also increase, whereas only the coefficient term increased in value for the individual traces; this indicates stronger capacitive behavior within the cell at higher concentrations and is in corroboration with the specific energy results shown previously.

TABLE VI					
FULL-CELL P	ERFORMA	ANCE BY EI	LECTROLYTE CONCENT	RATION	
Concentration	$R_s[\Omega]$	$R_p \left[k \Omega \right]$	$C_0 \left[\mu S \cdot (rad/s)^{-n}\right]$	n	
0.1M NaCl	502.0	1094.3	1.99	0.8194	
0.25M NaCl	210.0	454.0	2.25	0.8296	
0.5M NaCl	116.3	419.3	2.34	0.8293	
0.75 <i>M NaCl</i>	77.93	243.0	2.47	0.8353	
1.0M NaCl	66.15	101.7	3.21	0.8479	

Based on the trends found between the specific energy results from the cycle testing data and those found for the CPE coefficient values from the EIS measurements, Fig. 19 shows the correlation between the value of the CPE coefficient and the specific energy storage capacity for the cell. Remembering that the amount of charge stored through a capacitor is based on (10), where *C* represents the capacitance of the device and *V* represents the voltage applied across the device:

$$Q = CV \tag{10}$$

The strong linear trend exhibited in Fig. 19 indicates adherence to this fundamental principle of capacitors. This linear fit can therefore be considered as a possible prediction equation for the specific capacity of the cell based on CPE coefficients obtained through EIS measurements.



Linear (Specific Capacity)

Specific Capacity

Fig. 19 Specific Capacity as a Function of the CPE Coefficient

V. CONCLUSIONS

Based on the results obtained from OCV measurements, IV characterization, and cycle testing, a commercially available Nafion membrane (i.e., Nafion-117) can successfully be converted to its Na^+ -Form and be used as a suitable separator membrane for a saltwater battery cell inspired by biological cells such as human neurons. According to cycle data and EIS results, a higher electrolyte concentration provides better performance for the electrochemical cell. This methodology can be applied to exploring sustainable materials that may be used as the separator membrane for the device.

Based on Table IV, further development of the cell should focus on efforts to increase the operating voltage of the cell to become more competitive with incumbent battery technologies, including further membrane development for better cationselectivity and a multi-cellular design that mimics the structure of electrocytes found in the electric eel. Once this performance characteristic has been optimized, the cycle testing protocol can be reconsidered to optimize roundtrip efficiency for the cell.

Currently, the cell operates like a saltwater capacitor, with very low specific energy capacity; therefore, secondary focus should be placed on increasing specific energy capacity for the device. Based on Fig. 19, EIS measurements can be leveraged to estimate specific energy capacity for the cell based on fitted CPE values to accelerate the development of the device, including other components such as the electrodes (which can also increase the operating voltage if redox electrodes are used) and cell geometry.

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