Typical Power Budget and Possible Energy Source for Autonomous Oceanographic Network (AOSN) Labrador Sea Experiment (LSE)

by

Henrich Henriksen

June 1996

Technical Report

Funding was provided by the Office of Naval Research through Grant No. N00014-95-1-1316

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George V. Frisk, Chair
Department of Applied Ocean Physics and Engineering
Typical Power Budget and Possible Energy Source For Autonomous Oceanographic Network (AOSN) Labrador Sea Experiment (LSE)

By Henrich Henriksen

The AOSN LSE (Ref. 1) will be held in the Labrador Sea at a seawater depth of 3000 - 3500 meters. The total system will consist of a number of AUVs which will operate from a set of moorings within a defined area. The AUVs will navigate within the defined area by using acoustic transponders on the moorings. Each mooring will be placed on the seafloor (ca 3000 meters). The docking stations will be placed in the water column at 1000 - 2000 meters water depth. Each AUV will have at least one possible docking station to charge batteries and to transfer data.

This memo will show two different load pattern examples (Case A and B) for the AOSN LSE, and the implications upon the power budget of the mooring. There are many uncertainties in the input numbers, but most of the power budget appears to be reasonable. The total duration of the experiment in both Cases (A and B) is set to 8 months. The experiment will be split into a number of events in which high AUV activity is required. The events are defined in duration, but they will not be as regular as modeled in this report. During each event the AUVs leave the moorings and go on missions. The time between the missions is the charging time. Some of the variables will be defined in order to work out the power usage. Some of the power users are known and measured, others will be qualified guesses. All of the choices are made so that the total system appears as easy and redundant as possible. This might reduce the performance of the system.

In the second part, the possible use of a seawater battery and its implications upon the system will be discussed. A preliminary design of the sizes and weights of a seawater battery for this application is also included. All the essential data is presented in tables and graphs as well as all the calculations which are in Appendix 1 and 2 as MathCad documents.

The power usage discussed later in this report will focus on the mooring, and not on the AUVs.

AUVs and moorings power usage

The total number of AUVs is put to 6 and they are dispersed to 3 moorings with two docking stations on each mooring. This means that there are no spare charging or data transfer stations. Each mooring might also accommodate one AUV extra on passive docking. This would make it possible to run six AUVs (at a certain duty cycle) from two moorings in the event that one mooring fails.

Power users on the Odyssey

The power usage on the Odyssey consists of three major components. The largest is the power required to drive the vehicle through the water. This is mainly a function of the vehicle speed (power/cubed). The drag power is set to ca 80 watts at a cruising speed of 1.4 m/sec and a Cd=0.08 (mechanical efficiency of 40%).

The second component is the acoustic modem. The power usage will be in the order of 20 watts and the modem is set to be on at all time during one event. The Odyssey is also using some energy during data transfer while docked, dominated by the acoustic modem. The duration of this data transfer is put to 50% of the event time and must occur during the time between two events.

The third user is the hotel load which consists of units like sensors and data storage. This is assumed to be in the order of 60 watts. In this report, the total power usage of one Odyssey during a mission is in the order of 160 watts.
Power users on the mooring

The main power usage on the mooring is for acoustic communication, computing and data storage. The acoustic modem (20 watts) on the mooring will be used during each event plus 50% of the duration of one event. The rest of the power users at the mooring are put to 10 watts on average, without large peaks. The energy required to do the satellite transfer is small and it will not be more than 3 kWhr over the entire experiment.

Duration and duty cycles

The following examples will be separated into A and B. In both cases, the total experiment duration will be put to 8 months.

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of AUVs</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Number of moorings</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total experiment duration</td>
<td>8 months</td>
<td>8 months</td>
</tr>
<tr>
<td>Maximum duration of event</td>
<td>72 hours</td>
<td>80 hours</td>
</tr>
<tr>
<td>Time between events</td>
<td>20 days</td>
<td>20 days</td>
</tr>
<tr>
<td>Minimum charging time</td>
<td>16 hours</td>
<td>24 hours</td>
</tr>
<tr>
<td>Maximum mission time</td>
<td>8 hours</td>
<td>16 hours</td>
</tr>
<tr>
<td>AUV cruising speed</td>
<td>1.4 m/sec</td>
<td>1.4 m/sec</td>
</tr>
<tr>
<td>Number of events</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Number of missions/event</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

In the graphs that follow (Fig. 1 and 2), the power usage of the Mooring is plotted against time. This means that the lower level is symbolizing the power usage at the mooring when the AUVs are sleeping. The graph for Case B (Fig. 1) is labeled with AUV 1 and AUV 2 when they are on mission (away from the mooring). The event starts and AUV 1 goes on mission (event starts at time equal zero on both plots), AUV 1 returns, it starts to charge it's batteries and AUV 2 goes on mission. This means that it is at maximum, one AUV from each mooring on mission during one event. The peaks occur when both AUVs are charging their batteries at the same time. The high level of power usage after each event is the mooring modem under data transfer. The first graphs shows the full 8 months (in hours) of the experiment duration and the peaks are the events which are distributed evenly. The second graphs of each case show an expanded view of one event.

Fig 1. This gives a duty cycle for Case B:
Values for each mooring:

(2 AUVs)

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average power at mooring</td>
<td>47 watts</td>
<td>56 watts</td>
</tr>
<tr>
<td>Total energy needed for mooring</td>
<td>256 kWh</td>
<td>304 kWh</td>
</tr>
<tr>
<td>Maximum peak power</td>
<td>296 watts</td>
<td>385 watts</td>
</tr>
<tr>
<td>Energy needed during one event</td>
<td>14.9 kWh</td>
<td>19.2 kWh</td>
</tr>
</tbody>
</table>

Values for the total experiment:

(6 AUVs and 3 moorings)

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum number of AUVs in the water during one event</td>
<td>2</td>
<td>2.4</td>
</tr>
<tr>
<td>Size of AUV batteries</td>
<td>1.3 kWh</td>
<td>2.6 kWh</td>
</tr>
<tr>
<td>AUV hours during one event</td>
<td>48 hrs</td>
<td>64 hrs</td>
</tr>
<tr>
<td>AUV distance traveled during event</td>
<td>242 km</td>
<td>322 km</td>
</tr>
<tr>
<td>Total AUV hours (experiment)</td>
<td>528 hrs</td>
<td>704 hrs</td>
</tr>
<tr>
<td>AUV distance traveled during experiment</td>
<td>2661 km</td>
<td>3542 km</td>
</tr>
</tbody>
</table>
Efficiencies

In the calculations above, the following efficiencies have been used: All charger efficiencies are put to 80%, energy transfers from mooring to AUV are put to 75%. The propulsion efficiency of the Odyssey is put to 40%, and it is used a \( \text{Cd} = 0.08 \) (based on frontal area). Later in this report the DC/DC converter of the seawater battery is put to 80%.

Fig 3. CASE A
Energy users and efficiencies

NDRE (Norwegian Defence Research Establishment) Seawater Battery

The Seawater cell developed at NDRE is a power source intended for powering stationary equipment in deep waters. The cell uses anodes made from commercial magnesium alloys, seawater as the electrolyte, and oxygen dissolved in the seawater as oxidant. The cathode is made of carbon fibers. Typical figures of merit from prototype cells are 4 watts over 6 months with a specific energy density of 800-1000 wh/kg based on dry weight, and a volumetric energy density of 125 Wh/liter (Ref. 2, Fig. 4). The seawater battery delivers a cell voltage of 1.2 - 1.6 volts, because of the nature of the battery, it is impossible to connect the batteries in series (short circuit). It is, therefore, necessary to use a DC/DC converter. In all the calculations below there have been used a DC/DC efficiency of 80%.
Environmental conditions

To ensure the transport of oxygen to the surface of the cathode there are many considerations. The surface area of the exposed cathode surface must be as large as possible. This means that a large cross section of the cell facing towards the seawater current is desirable. The average and minimum sea current at the location is important. The seawater battery requires above 5 cm/sec as average (this is a "High power cell"). Also, the oxygen content of the seawater is important. A content of 0.3 mole/m³ is more than enough (the relevant environmental data is in Appendix 3). The environmental conditions in the Labrador Sea varies but the basic feature of the area seems to be good mixing between the layers; a typical site (Appendix 4) has a close to constant oxygen content through the water column.

When a seawater battery is deployed it must not be shielded by any structure. It is also important to place it at a distance (2-5 meters) from the seafloor to ensure seawater flow through the battery.

It is worth noting that when using a seawater cell, it is important to remember the nature of the cell. A contact between any metallic part (except titanium) and the cathode of the cell will result in rapid galvanic corrosion. This means that the user must make sure that the cell is insulated from any metallic part of the mooring structure.

Size and weight of a Seawater Battery for use with AOSN

All the numbers presented here are crude estimates. The cell structure used is based upon prototypes which NDRE has developed over the past four years.

The seawater battery can be dimensioned by two different criteria: power requirements or long-term energy requirements. The difference with regards to an application like AOSN is typically the use of a secondary battery, and also the total volume of the battery. A battery dimensioned only to maintain the average power requirements must have a fairly large secondary cell to deliver power during events. The weight of a seawater battery is mainly a function of the energy content (the mass of magnesium), and will be nearly constant in an application like AOSN. The total volume of the seawater battery is mainly a function of the power requirements.
The seawater batteries in the tables below are built up by cylindrical cells of 0.6 meters in diameter and 1 meter height (double length of the cell in Fig. 4). The cells can be suited with one DC/DC converter each (placed in the middle) and the DC/DC converter output can then be connected in parallel. This will ensure a redundant system in the case of a failure in one of the DC/DC converters. It is also desirable (because of the low cell voltage and high currents) not to have a long distance between the DC/DC converter and the cells.

Fig 5. Cross section of a seawater cell as described above

For each of the Cases (A and B) it has been calculated a size of battery using the same configurations (Fig. 5), but two different anode diameters (22 mm and 32 mm). This shows different possibilities with regards to dimensioning. The anode diameters are commercially available sizes. Each of the cells can deliver a maximum of 8 watts and the energy content of one cell is either 24 kWh (22 mm anode) or 51 kWh (32 mm anode). These values are taken after the DC/DC converter but before the loss to a secondary battery. If the power users are assumed to be larger or smaller than the examples in case A or B the seawater battery can be scaled using these cell units.

<table>
<thead>
<tr>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 mm</td>
<td>32 mm</td>
</tr>
<tr>
<td>Energy content (before secondary)</td>
<td>288 kWh</td>
</tr>
<tr>
<td>Maximum power</td>
<td>77 watts</td>
</tr>
<tr>
<td>Number of cells</td>
<td>12</td>
</tr>
<tr>
<td>Weight in Air (including DC/DC)</td>
<td>369 kg</td>
</tr>
<tr>
<td>Weight in water (approx)</td>
<td>185 kg</td>
</tr>
<tr>
<td>Total volume</td>
<td>3393 l</td>
</tr>
<tr>
<td>Specific energy (in air)</td>
<td>780 Whr/kg</td>
</tr>
<tr>
<td>Energy density</td>
<td>85 Whr/l</td>
</tr>
<tr>
<td>Secondary battery</td>
<td>9.5 kWh</td>
</tr>
</tbody>
</table>

The variance of the secondary battery size with regards to number of missions at each event, for each of these cases, is plotted at the end of the MathCad documents in the Appendix.

The table below shows how fast it is possible to use the battery and how many events the cell can accommodate in such an application when the rest of the system is as defined above.

<table>
<thead>
<tr>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 mm</td>
<td>32 mm</td>
</tr>
<tr>
<td>Min. experiment duration</td>
<td>125 days</td>
</tr>
<tr>
<td>Max. number of events</td>
<td>16</td>
</tr>
<tr>
<td>Time between events</td>
<td>5 days</td>
</tr>
</tbody>
</table>

This means that the design of a battery which can deliver an excess of power makes the system more flexible and a
shorter duration between each event is possible.

The secondary battery and the DC/DC converters

The AOSN LSE seawater battery will almost certainly require a secondary battery. The size of a typical cell is in the order of 10 - 15 kWh. This is a cell which is 4-10 times larger than a typical Odyssey battery. It may be beneficial to use the same battery technology on both the mooring and the Odyssey.

The graph above (Fig. 6) shows how the size of a secondary battery will go down with each additional seawater battery cell. (This example is Case A with 22 mm anodes; four cells has an approximate volume of 1000 liter)

Recharging of seawater batteries

The seawater batteries, like the ones described above, can be reused a number of times (>5) by replacing the anodes and possibly the cathodes. This process is not expensive or difficult. The most expensive parts are the cathodes (which must be delivered by Simrad), and the labor. The magnesium costs in the order of $10/kg (typically 300 kg for Case A) plus the cost of machining each anode (simple process).

Advantages and disadvantages with using seawater battery

The main advantage of using a seawater battery is that there are no requirements of a large pressure vessel to accommodate the energy source. The secondary battery can be either a pressure compensated unit or it might require a pressure housing. The DC/DC converters and the charger will need a small pressure housing. The use of several DC/DC converters connected in parallel makes the system redundant. The seawater battery consists of no moving parts and does not contain any dangerous components either for the environment or people.

The battery has a low weight and high energy density both on land (800 Whr/kg) and in the water. This simplifies the handling and reduces the need for buoyancy. Although the battery is large in volume it can be dispersed out on the mooring wire (Fig. 7) in such a way that it should be possible to handle without difficulty. The battery is fairly robust.

Fig 6. Size of secondary battery as a function of additional seawater battery cells.
The main disadvantages are a large volume and a low power rate.

**Conclusion**

The energy usage on the mooring will be in the order of 250 - 500 KWhr, depending on number of sensors, number of AUVs on each mooring and the energy required to do data handling.

There are several types of power sources that can deliver 250 - 500 KWhr, but since the most attractive ones are those with a high energy density, the most obvious alternatives are a large lithium pack or a fuel cell. The disadvantages of such systems for underwater applications are several. This would almost certainly involve a pressure housing with an internal volume of 1500 - 2500 liters. The safety aspects of such a large lithium pack are serious and also the handling of a large fuel cell can be hazardous.

A large fuel cell has several moving parts in pumps, valves and combined with a highly corrosive environment inside the cell, there are questions about the reliability of the system.

The cost of a large fuel cell or a large lithium pack are traditionally high.

Energy delivery to an experiment like the AOSN LSE with the use of a seawater battery is feasible both technically and within the time span of the AOSN project. Due to of the large water depths involved and the simplicity of the system the seawater battery seems like a good candidate. The numbers chosen for case A and B are not ideal for a seawater battery. An ideally designed system would use the energy as constantly as possible. This would be a system where the missions were distributed evenly over the total experiment, then a system without the use of secondary batteries could then be designed.

The environment of the Labrador Sea is well documented and seems suitable to accommodate a seawater battery.

The cost of energy is assumed to be lower than $300/ kWhr, with a recharge cost lower than $50/kWhr. (estimate).
Simrad Norway is the producer of the NDRE seawater battery. The design and development is done by Norwegian Defence Research Establishment (NDRE). A first order price of a unit such as Case A (22 mm) will be obtained from Simrad as soon as possible.
Appendix

Appendix 1  Calculations on Case A, duty cycle and alternative seawater batteries
Appendix 2  Calculations on Case B, duty cycle and alternative seawater batteries
Appendix 3  Typical environmental data from the Labrador sea

References

1) Curtin, Bellingham, Catipovic and Webb, Autonomous Oceanographic Sampling Networks' Oceanography Vol. 6, No. 3 1993
2) Hasvold, Henriksen and Syversen (NDRE) 'Improvements in the rate capability of the magnesium-dissolved oxygen seawater cell' (1995) Power Sources 15
Calculations on Case A, duty cycle and alternative seawater batteries.

**Power budget of the Autonomous Oceanographic Sampling Network Moorings**

**SYSTEM CONFIGURATION**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of AUV's</td>
<td>AUV := 6</td>
</tr>
<tr>
<td>AUV speed</td>
<td>$v_{AUV} := 1.4 \frac{m}{sec}$</td>
</tr>
<tr>
<td>Number of MOORINGS</td>
<td>MOR := 3</td>
</tr>
<tr>
<td>Number of AUV's per mooring</td>
<td>$N_{AUV_{moo}} := \frac{AUV}{MOR}$</td>
</tr>
<tr>
<td>Charging efficiency</td>
<td>$C_{eff} := 80%$</td>
</tr>
<tr>
<td>Transfer efficiency (from mooring to AUV)</td>
<td>$T_{eff} := 75%$</td>
</tr>
<tr>
<td>Total time of experiment</td>
<td>$T_{time} := 5846\text{hr}$</td>
</tr>
<tr>
<td>Maximum mission duration</td>
<td>$T_{miss} := 8\text{hr}$</td>
</tr>
<tr>
<td>Minimum docking time</td>
<td>$T_{dock} := 16\text{hr}$</td>
</tr>
<tr>
<td>Minimum time between events</td>
<td>$T_{rest} := 20\text{day}$</td>
</tr>
<tr>
<td>Duration of events</td>
<td>$T_{happ} := 72\text{hr}$</td>
</tr>
</tbody>
</table>

**HOTEL LOAD ON EACH MOORING**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy hotel</td>
<td>$P_{hot} := 10\text{watt}$</td>
</tr>
<tr>
<td>Total energy hotel</td>
<td>$E_{hot} := P_{hot} \cdot T_{time}$</td>
</tr>
<tr>
<td></td>
<td>$E_{hot} = 58.46\text{kW} \cdot \text{hr}$</td>
</tr>
</tbody>
</table>

**ACOUSTIC MODEM**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duty cycle modem</td>
<td>$A_{mod} := 20\text{watt}$</td>
</tr>
<tr>
<td>Continuous power modem</td>
<td>$P_{mod} := A_{mod} \cdot A_{mod_{duty}}$</td>
</tr>
<tr>
<td></td>
<td>$P_{mod} = 10\text{watt}$</td>
</tr>
<tr>
<td>Total energy modem</td>
<td>$E_{mod} := (P_{mod}) \cdot T_{time}$</td>
</tr>
<tr>
<td></td>
<td>$E_{mod} = 58.46\text{kW} \cdot \text{hr}$</td>
</tr>
</tbody>
</table>

**Definitions:**

- $\text{nm} := 1852\text{m}$
- $\text{km} := 1000\text{m}$
- $\rho := 1028\frac{\text{kg}}{\text{m}^3}$
- $\text{mon} := \frac{1}{12}\text{yr}$
# Duty cycle of AUV

**Total number of events**

\[ N_{\text{happ}} := \text{ceil}\left( \frac{\text{Time}}{T_{\text{rest}} + T_{\text{happ}}} \right) \]

\[ N_{\text{happ}} = 11 \]

**Total number of missions on each happening pr AUV**

\[ N_{\text{miss, happ}} := \text{ceil}\left( \frac{T_{\text{happ}}}{(T_{\text{miss}} + T_{\text{dock}})} \right) \]

\[ N_{\text{miss, happ}} = 3 \]

**Total number of missions pr AUV**

\[ N_{\text{missions}} := N_{\text{happ}} \cdot N_{\text{miss, happ}} \]

\[ N_{\text{missions}} = 33 \]

**Total energy used pr AUV**

\[ E_{\text{ener, AUV}} := N_{\text{missions}} \cdot T_{\text{miss}} \cdot P_{\text{AUV}} \]

\[ E_{\text{ener, AUV}} = 70.293 \text{ kW-hr} \]

**Travel time pr AUV**

\[ T_{\text{auv}} := N_{\text{missions}} \cdot T_{\text{miss}} \]

\[ T_{\text{auv}} = 11 \text{ day} \]

\[ T_{\text{auv}} = 264 \text{ hr} \]

95 kWhr of the energy goes through the secondary battery the charger efficiency for. The secondary battery is in the order of 80%. This gives a total efficiency of \( \text{SBeff} = 94\% \)

\[ \text{SBeff} := 94\% \]
TOTAL energy and average power used pr mooring

**Power**

\[ \text{Power} = \frac{\text{Power}_\text{mooring}}{\text{SBeff}} \]

\[ \text{Power}_\text{mooring} = 46.86 \text{ watt} \]

\[ \text{Power}_\text{overhead} = \text{Power}_\text{mod} + \text{Power}_\text{hot} \]

\[ \text{Power}_\text{overhead} = 20 \text{ watt} \]

\[ \text{Energy}_\text{mooring} = \text{Power}_\text{mooring} \cdot \text{Time} \]

\[ \text{Energy}_\text{mooring} = 273.943 \text{ kW·hr} \]

**Energy**

\[ \text{Time}_\text{AUV} = \text{AUV·N\text{-}missions·T\text{-}miss} \]

\[ \text{Time}_\text{AUV} = 66 \text{ day} \]

\[ \text{Dist}_\text{AUV} = \text{Time}_\text{AUV} \cdot V\text{AUV} \]

\[ \text{Dist}_\text{AUV} = 7.983 \times 10^3 \text{ km} \]

**Energy needed under one event**

\[ \text{Ener}_\text{happ} = N\text{-}miss\text{-}happ \cdot T\text{-}miss \cdot N\_\text{AUV\_moo} \cdot (\text{Pow\_AUV}) + (\text{Pow\_hot} + A\text{co}\_\text{mod}) \cdot T\_\text{happ} \]

\[ \text{Ener}_\text{happ} = 14.9 \text{ kW·hr} \]

**Power needed during event**

\[ \text{Power}_\text{happ} = \frac{\text{Ener}_\text{happ}}{T\_\text{happ}} \]

\[ \text{Power}_\text{happ} = 207.508 \text{ watt} \]
SEAWATER BATTERY to use with AOSN case A1

All the numbers are conservative estimates.

Energy needed

Energy := 280-kW-hr

Power needed

Avg_pow := 48-watt

Density of magnesium

r_Mg := 1.81-kg/liter

Using SSS batteries DIMENSIONS of one CELL

height := 1-m

diameter := 0.6-m

volume := height\cdot\frac{1}{2}\cdot\frac{diameter}{2}\cdot\pi

volume = 282.743˙liter

anod_dia := 22-mm

Anod_nr := 36

Cathode_nr := 12

Magnesium

Mg_w := \left(\frac{anod_dia}{2}\right)^2\cdot\pi\cdot\text{height}\cdot r_Mg\cdot \text{Anod_nr}

Mg_w = 24.769-kg

Pot_w := 2-kg

Total weight of one unit

Cell_weight := Pot_w + Mg_w + 4-kg

DC/DC converter weights ca 5 kg/cell.

Cell_weight = 30.8-kg

Maximum power of one unit is assumed to be 2 times power of CFH cell (paper)

Power_cell := 8\cdot(80\%-\text{watt})

Energy_pr_cell

Energy_cell := (40\cdot\text{kW-hr})\cdot(75\%\cdot80\%)

Number of cells

Cell_nr := \left\lceil\frac{\text{Energy}}{(\text{Energy_cell})}\right\rceil

Cell_nr = 12

This gives:

Cathodes total number

K_n := Cell_nr\cdot\text{Cathode_nr}

K_n = 144
Total number of anodes \( A_n := \text{Cell}_{nr}\cdot\text{Anod}_{nr} \)

\[ A_n = 432 \]

Total weight of system \( \text{Total}_w := \text{Cell}_{weight}\cdot\text{Cell}_{nr} \)

\[ \text{Total}_w = 369\cdot\text{kg} \quad \text{Weight in the water will be less than half} \]

From DC/DC \( \text{Total}_\text{energy} := \text{Energy}_{cell}\cdot\text{Cell}_{nr} \)

\[ \text{Total}_\text{energy} = 288\cdot\text{kW}\cdot\text{hr} \]

Energy density \( \text{Energy}_{density} = \frac{\text{Total}_\text{energy}}{\text{Total}_\text{w}} \)

\[ \text{Energy}_{density} = 0.78 \cdot \frac{\text{kW}\cdot\text{hr}}{\text{kg}} \quad \text{in air energy to the user} \]

Total volume of battery \( \text{Total}_\text{volume} := \text{volume}\cdot\text{Cell}_{nr} \)

\[ \text{Total}_\text{volume} = 3393\cdot\text{liter} \]

Volume density \( \text{Volume}_{density} := \frac{\text{Total}_\text{energy}}{\text{Total}_\text{volume}} \)

\[ \text{Volume}_{density} = 84.883 \cdot \frac{\text{watt}\cdot\text{hr}}{\text{liter}} \]
Size of secondary battery is dependent upon the maximum power from the seawater battery and the number of missions during one event.

Maximum power available:

\[
\text{Power} := \text{Power} \cdot \text{Cell} \cdot \text{nr} \quad k := 0 .. 10
\]

\[
\text{Power} = 76.8 \cdot \text{watt}
\]

Overheads

\[
P_{\text{modem}} := 20 \cdot \text{watt}
\]

\[
P_{\text{hotel}} := 10 \cdot \text{watt}
\]

AUV

\[
P_{\text{auv}} := 160 \cdot \text{watt}
\]

Mission duration

\[
T_{\text{miss}} := 8 \cdot \text{hr}
\]

\[
A_k := T_{\text{miss}} \cdot k
\]

Event duration

\[
\text{Event} := 72 \cdot \text{hr}
\]

\[
\text{Secondary}_k := ((P_{\text{modem}} + P_{\text{hotel}}) - \text{Power}) \cdot \text{Event} + \frac{P_{\text{auv}} \cdot A_k}{75\% - 80\%}
\]

Secondary battery size for case A

\[
\text{Secondary}_6 = 9.43 \cdot \text{kW} \cdot \text{hr}
\]

Number of AUV*hr pr Kwhr secondary batt

![Graph showing the relationship between secondary battery size in kWh/hr and the number of AUV missions](image)
**SEAWATER BATTERY to use with AOSN Case A2**

All the numbers are conservative estimates.

**Energy needed**

Energy := 280\,\text{kW} \cdot \text{hr}

**Power needed**

Avg_pow := 48\,\text{watt}

**Density of magnesium**

\( \rho_{\text{Mg}} := 1.81 \cdot \frac{\text{kg}}{\text{liter}} \)

Using SSS batteries DIMENSIONS of one CELL

- height := 1 \cdot \text{m}
- diameter := 0.6 \cdot \text{m}
- volume := height \cdot \left( \frac{\text{diameter}}{2} \right)^2 \cdot \pi
- volume = 282.743 \cdot \text{liter}
- anod_dia := 32 \cdot \text{mm}
- Anod_nr := 36
- Cathode_nr := 12

**Magnesium**

\( \text{Mg}_w := \left( \frac{\text{anod_dia}}{2} \right)^2 \cdot \pi \cdot \text{height} \cdot \rho_{\text{Mg}} \cdot \text{Anod_nr} \)

\( \text{Mg}_w = 52.405 \cdot \text{kg} \)

Pot_w := 2 \cdot \text{kg}

**Total weight of one unit**

Cell_weight := Pot_w + Mg_w + 4 \cdot \text{kg}

DC/DC converter weights ca 5 kg/cell.

Cell_weight = 58.4 \cdot \text{kg}

Maximum power of one unit is assumed to be 2 times power of CFH cell (paper)

Power_cell := 8 \cdot (80\% \cdot \text{watt})

this is from the DC/DC converter

Energy_cell := (80\,\text{kW} \cdot \text{hr}) \cdot (80\% \cdot 80\%)

**Energy pr cell**

**Number of cells**

\( \text{Cell_nr} := \left[ \frac{\text{Energy}}{\text{Time}} \right] \)

Cell_nr := 6

This gives:

- Cathodes total number \( K_n := \text{Cell_nr} \cdot \text{Cathode_nr} \)
- \( K_n = 72 \)
Total number of anodes: $A_n := \text{Cell}_\text{nr} \cdot \text{Anod}_\text{nr}$

$A_n = 216$

Total weight of system: $Total_w := \text{Cell}_\text{weight} \cdot \text{Cell}_\text{nr}$

$Total_w = 350 \text{ kg}$  
Weight in the water will be less than half

From DC/DC: $Total_{energy} := \text{Energy}_\text{cell} \cdot \text{Cell}_\text{nr}$

$Total_{energy} = 307.2 \text{ kW} \cdot \text{hr}$

Energy density: $Energy_{density} := \frac{Total_{energy}}{Total_w}$

$Energy_{density} = 0.877 \frac{\text{kW} \cdot \text{hr}}{\text{kg}}$  
in air energy to the user

Total volume of battery: $Total_{volume} := \text{volume} \cdot \text{Cell}_\text{nr}$

$Total_{volume} = 1696 \text{ liter}$

Volume density: $Volume_{density} := \frac{Total_{energy}}{Total_{volume}}$

$Volume_{density} = 181.083 \frac{\text{watt} \cdot \text{hr}}{\text{liter}}$
Size of secondary battery is dependent upon the maximum power from the seawater battery and the number of missions during one event.

Maximum power available:

\[
\text{Power := Power\_cell\cdot Cell\_nr} \quad k := 0..10
\]
\[
\text{Power} = 38.4\cdot\text{watt}
\]

Overheads

\[
\text{P\_modem := 20\cdot\text{watt}}
\]
\[
\text{P\_hotel := 10\cdot\text{watt}}
\]

AUV

\[
\text{P\_auv := 160\cdot\text{watt}}
\]

Mission duration

\[
\text{T\_miss := 8\cdot\text{hr}}
\]
\[
A_k := T\_miss\cdot k
\]

Event duration

\[
\text{Event := 72\cdot\text{hr}}
\]

\[
\text{Secondary}_k := ((P\_modem + P\_hotel) - \text{Power})\cdot \text{Event} + \frac{\text{P\_auv}\cdot A_k}{75\%-80\%}
\]

Secondary battery size for case A2
\[
\text{Secondary}_k = 12.195\cdot\text{kW\cdot hr}
\]

Number of AUV\text{hr} per Kwhr secondary batt
Calculations on Case B, duty cycle and alternative seawater batteries

Power budget of the Autonomous Oceanographic Sampling Network

Moorings

SYSTEM CONFIGURATION

Number of AUV's
AUV := 6

AUV speed
V_{auv} := 1.4 \frac{m}{sec}

Number of MOORINGS
MOR := 3

Number of AUV's pr mooring
N_{AUV,moo} := \frac{AUV}{MOR} \quad N_{AUV,moo} = 2

Charging efficiency
\text{Cheff} := 80\%\quad

Transfer efficiency (from mooring to AUV)
\text{Treff} := 75\%

Total time of experiment
Time := 5846\,\text{hr} \quad \text{Time} = 8\,\text{mon}

Maximum mission duration
T_{miss} := 16\,\text{hr}

Minimum docking time
T_{dock} := 24\,\text{hr}

Minimum time between events
T_{rest} := 20\,\text{day} \quad T_{rest} = 0.657\,\text{mon}

Duration of events
T_{happ} := 80\,\text{hr} \quad T_{happ} = 3.333\,\text{day}

HOTEL LOAD ON EACH MOORING

Total energy hotel
Pow_{hot} := 10\,\text{watt}

Ener_{hot} := Pow_{hot} \cdot Time
Ener_{hot} = 5.846\,\text{kW} \cdot \text{hr}

ACOUSTIC MODEM

Aco_{mod} := 20\,\text{watt}

Duty cycle modem
Aco_{mod_duty} := 50\%

Continuous power modem
Pow_{mod} := Aco_{mod} \cdot Aco_{mod_duty}
Pow_{mod} = 10\,\text{watt}

Total energy modem
Ener_{mod} := (Pow_{mod}) \cdot Time
Ener_{mod} = 5.846\,\text{kW} \cdot \text{hr}

APPENDIX 2

\text{Defenitions:}

\text{nm} := 1852\, \text{m}

\text{km} := 1000\, \text{m}

\rho := 1028\, \frac{\text{kg}}{\text{m}^3}

\text{mon} := \frac{1}{12}\,\text{yr}
**Duty cycle of AUV**

Total number of events

\[
N_{\text{happ}} := \text{ceil} \left( \frac{\text{Time}}{T_{\text{rest}} + T_{\text{happ}}} \right)
\]

\[N_{\text{happ}} = 11\]

Total number of missions on each happening pr AUV

\[
N_{\text{miss,happ}} := \text{ceil} \left[ \frac{T_{\text{happ}}}{(T_{\text{miss}} + T_{\text{dock}})} \right]
\]

\[N_{\text{miss,happ}} = 2\]

Total number of missions pr AUV

\[N_{\text{missions}} := N_{\text{happ}} \cdot N_{\text{miss,happ}}\]

\[N_{\text{missions}} = 22\]

Total energy used pr AUV

\[E_{\text{ener,AUV}} := N_{\text{missions}} \cdot T_{\text{miss}} \cdot P_{\text{AUV}}\]

\[E_{\text{ener,AUV}} = 93.724 \text{kW}-\text{hr}\]

Travel time pr AUV

\[T_{\text{tau}} := N_{\text{missions}} \cdot T_{\text{miss}}\]

\[T_{\text{tau}} = 14.667 \text{ day} \quad T_{\text{tau}} = 352 \text{ hr}\]

95 kWhr of the energy goes through the secondary battery. The charger efficiency for the secondary battery is in the order of 80%. This gives a total efficiency of \( SB_{\text{eff}} = 94\%\)
TOTAL energy and average power used per mooring

Power

\[ Power\_mooring := \frac{\text{Power}_\text{mooring}}{\text{Time}} \]

\[ \text{Power}_\text{mooring} = 55.388 \text{watt} \]

\[ \text{Power}_\text{overhead} := \text{Power}_\text{mod} + \text{Power}_\text{hot} \]

\[ \text{Power}_\text{overhead} = 20 \text{watt} \]

\[ \text{Energy}_\text{mooring} := \text{Power}_\text{mooring} \cdot \text{Time} \]

\[ \text{Energy}_\text{mooring} = 323.796 \text{kw hr} \]

Energy

\[ \text{Time}_\text{AUV} := \text{AUV-N\_missions} \cdot \text{T\_miss} \]

\[ \text{Time}_\text{AUV} = 88 \text{day} \]

Total AUV traveled distance

\[ \text{Dist}_\text{AUV} := \text{Time}_\text{AUV} \cdot \text{Vauv} \]

\[ \text{Dist}_\text{AUV} = 1.064 \cdot 10^4 \text{km} \]

Energy needed under one event

\[ \text{Ener\_happ} := N\_\text{miss\_happ} \cdot \text{T\_miss} \cdot \text{N\_AUV\_moo} \cdot (\text{Pow\_AUV}) + (\text{Pow\_hot} + \text{Aco\_mod}) \cdot \text{T\_happ} \]

\[ \text{Ener\_happ} = 19.4 \text{kw hr} \]

Power needed during event

\[ \text{Power\_happ} := \frac{\text{Ener\_happ}}{\text{T\_happ}} \]

\[ \text{Power\_happ} = 243.01 \text{watt} \]
All the numbers are conservative estimates.

Energy needed

Energy := 330.0 kW·hr

Power needed

Avg_pow := 58 watt

Density of magnesium

ρ_Mg := 1.81 kg/liter

Using SSS batteries DIMENSIONS of one CELL

height := 1 m

diameter := 0.6 m

volume := height × \( \frac{\text{diameter}^2}{2} \) × π

volume = 282.743 liter

anod_dia := 22 mm

Anod_nr := 36

Cathode_nr := 12

Magnesium

Mg_w := \( \left( \frac{\text{anod_dia}}{2} \right)^2 \) × π × height × ρ_Mg × Anod_nr

Mg_w = 24,769 kg

Pot_w := 2 kg

Total weight of one unit

Cell_weight := Pot_w + Mg_w + 4 kg

DC/DC converter weights ca 5 kg/cell

Cell_weight = 30.8 kg

Maximum power of one unit is assumed to be 2 times power of CFH cell (paper)

Power_cell := 8 · (80 %) · watt

this is from the DC/DC converter

Energy_cell := (40 kW·hr) · (75 %) · 80 %

Energy := \( \frac{\text{Energy}}{\text{Time}} \) = 56.469 watt

volume · Cell_nr = 3.958 m³

Number of cells

\[ \text{Cell_nr} := \left\lceil \frac{\text{Energy}}{(\text{Energy_cell})} \right\rceil \]

Cell_nr = 14

This gives:

Cathodes total number

\[ K_n := \text{Cell_nr} \cdot \text{Cathode_nr} \]

K_n = 168

23
Total number of anodes: $A_n := \text{Cell}_\text{nr} \cdot \text{Anod}_\text{nr}$

$A_n = 504$

Total weight of system: $\text{Total}_w := \text{Cell}_\text{weight} \cdot \text{Cell}_\text{nr}$

$\text{Total}_w = 431 \text{ kg}$  
Weight in the water will be less than half

From DC/DC: $\text{Total}_\text{energy} := \text{Energy}_\text{cell} \cdot \text{Cell}_\text{nr}$

Total energy of battery: $\text{Total}_\text{energy} = 336 \text{ kW} \cdot \text{hr}$

Energy density: $\text{Energy}_\text{density} := \frac{\text{Total}_\text{energy}}{\text{Total}_w}$

$\text{Energy}_\text{density} = 0.78 \text{ kW} \cdot \text{hr} \text{ kg}^{-1}$

Energy to the user in air: $\text{Energy}_\text{density} = 0.78 \text{ kW} \cdot \text{hr} \text{ kg}^{-1}$

Total volume of battery: $\text{Total}_\text{volume} := \text{volume} \cdot \text{Cell}_\text{nr}$

$\text{Total}_\text{volume} = 3958 \text{ liter}$

Volume density: $\text{Volume}_\text{density} := \frac{\text{Total}_\text{energy}}{\text{Total}_\text{volume}}$

$\text{Volume}_\text{density} = 84.883 \text{ watt} \cdot \text{hr} \text{ liter}^{-1}$
Size of secondary battery is dependent upon the maximum power from the seawater battery and the number of missions during one event.

Maximum power available:

\[
\text{Power} = \text{Power}_\text{cell} \cdot \text{Cell}_\text{nr} \\
\text{Power} = 89.6 \text{watt}
\]

Overheads
\[
\text{P}_\text{modem} := 20 \text{watt} \\
\text{P}_\text{hotel} := 10 \text{watt} \\
\text{P}_\text{auv} := 160 \text{watt}
\]

mission duration
\[
\text{T}_\text{miss} := 16 \text{hr}
\]

\[
\text{A}_k := \text{T}_\text{miss} \cdot k
\]

event duration
\[
\text{Event} := 72 \text{hr}
\]

\[
\text{Secondary}_k := \left( (\text{P}_\text{modem} + \text{P}_\text{hotel}) - \text{Power} \cdot \text{Event} + \frac{\text{P}_\text{auv} \cdot \text{A}_k}{75\% - 80\%} \right)
\]

Secondary battery size for case B1 \( \text{Secondary}_4 = 12.775 \text{kW} \cdot \text{hr} \)

Number of AUV hr pr Kwhr secondary batt

<table>
<thead>
<tr>
<th>Secondary Battery (kW-hr)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>27</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>2</td>
</tr>
<tr>
<td>21</td>
<td>3</td>
</tr>
<tr>
<td>18</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
</tr>
</tbody>
</table>

![Graph showing size of secondary battery vs. number of AUV missions](image)

Number of AUV (8 hr) missions
Energy needed

Energy := 330 kW·hr

Power needed

Avg_pow := 58 watt

Density of magnesium

ρ_Mg := 1.81 kg/liter

Using SSS batteries DIMENSIONS of one CELL

height := 1 m

diameter := 0.6 m

volume := height \left( \frac{\text{diameter}}{2} \right)^2 \cdot \pi

volume = 282.743 liter

anod_dia := 32 mm

Anod_nr := 36

Cathode_nr := 12

Magnesium

Mg_w := \left( \frac{\text{anod_dia}}{2} \right)^2 \cdot \pi \cdot \text{height} \cdot \rho_Mg \cdot \text{Anod_nr}

Mg_w = 52,405 kg

Pot_w := 2 kg

Total weight of one unit

Cell_weight := Pot_w + Mg_w + 4 kg

DC/DC converter weights ca 5 kg/cell

Cell_weight = 58.4 kg

Maximum power of one unit is assumed to be 2 times power of CFH cell (paper)

Power_cell := 8.80%·watt

Energy_cell := 80 kW·hr·(75%·)·80%

Energy pr cell

Energy := cell \left[ \frac{\text{Energy}}{\text{Energy_cell}} \right] \cdot \text{Time}

Cell_nr := 7

This gives:

Cathodes total number

K_n := Cell_nr·Cathode_nr

K_n = 84
Total number of anodes \( A_n := \text{Cell}_n \cdot \text{Anod}_n \)

\[ A_n = 252 \]

Total weight of system \( \text{Total}_w := \text{Cell}_\text{weight} \cdot \text{Cell}_n \)

\[ \text{Total}_w = 409 \text{ kg} \quad \text{Weight in the water will be less than half} \]

From DC/DC \( \text{Total}_\text{energy} := \text{Energy}_\text{cell} \cdot \text{Cell}_n \)

\[ \text{Total}_\text{energy} = 336 \text{ kW} \cdot \text{hr} \]

Energy density \( \text{Energy}_\text{density} := \frac{\text{Total}_\text{energy}}{\text{Total}_w} \)

\[ \text{Energy}_\text{density} = 0.822 \frac{\text{kW} \cdot \text{hr}}{\text{kg}} \quad \text{in air energy to the user} \]

Total volume of battery \( \text{Total}_\text{volume} := \text{volume} \cdot \text{Cell}_n \)

\[ \text{Total}_\text{volume} = 1979 \text{ liter} \]

Volume density \( \text{Volume}_\text{density} := \frac{\text{Total}_\text{energy}}{\text{Total}_\text{volume}} \)

\[ \text{Volume}_\text{density} = 169.765 \frac{\text{watt} \cdot \text{hr}}{\text{liter}} \]
Size of secondary battery is dependent upon the maximum power from the seawater battery and the number of missions during one event.

Maximum power available:

\[
\text{Power} := \text{Power\_cell\_Cell\_nr} \\
\text{Power} = 44.8 \text{ watt} \\
\text{P\_modem} := 20 \text{ watt} \\
\text{P\_hotel} := 10 \text{ watt} \\
\text{P\_auv} := 160 \text{ watt} \\
\text{T\_miss} := 16 \text{ hr} \\
A_k := T\_miss \cdot k \\
\text{Event} := 72 \text{ hr} \\
\]

\[
\text{Secondary}_k := \left((\text{P\_modem} + \text{P\_hotel}) - \text{Power}\right) \cdot \text{Event} + \frac{\text{P\_auv} \cdot A_k}{75\% - 80\%}
\]

Secondary battery size for case B2: \(\text{Secondary}_4 = 16.001 \text{ kW\_hr}\)

Number of AUV\^hr pr Kwhr secondary batt

<table>
<thead>
<tr>
<th>Number of AUV (8 hr) missions</th>
<th>Size of secondary battery (kWhr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
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<td>12</td>
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<td>5</td>
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<td>6</td>
<td>18</td>
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<td>7</td>
<td>21</td>
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<td>8</td>
<td>24</td>
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<tr>
<td>9</td>
<td>27</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
</tr>
</tbody>
</table>

28
**Typical environmental data from the Labrador sea**

**OXYGEN CONTENT in water column**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Press</th>
<th>Depth</th>
<th>Temp</th>
<th>Pot Temp</th>
<th>Salinity</th>
<th>Sigma</th>
<th>Sigma</th>
<th>Sigma</th>
<th>Sigma</th>
<th>Oxy/2</th>
<th>SS</th>
<th>SO4</th>
<th>PO4</th>
<th>NO3</th>
<th>Depth</th>
</tr>
</thead>
</table>

**APPENDIX 3**

**STATION 4: LEG 1**

**POSITION: 55° 5' N 42° 57' W**

**DATE: 30 JUL 72**

**SAMPLE**

**PRESS**

**DEPTH**

**M**

**TEMP**

**DEG C**

**POT TEMP**

**DEG C**

**SALINITY**

**SS**

**OXY/2**

**SO4**

**PO4**

**NO3**

**DEPTH**

**M**
Labrador Current

The Labrador Current flows close to the Continental Shelf along the coast of Labrador at speeds from 0.2 to 0.5 knot; it is augmented by the current flowing out of Hudson Strait. Part of the Labrador Current flows southwest along the U.S. coast to about 36°N during the winter months; it usually extends farther south nearer to Cape Hatteras during the summer.
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La Jolla, CA 92093-0175

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University Park
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Dept. of Oceanography
College Station, TX 77843

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Seattle, WA 98195

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University of Miami
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Maury Oceanographic Library
Naval Oceanographic Office
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1002 Balch Blvd.
Stennis Space Center, MS, 39522-5001

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Birkenhead
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Service Documentation - Publications
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FRANCE
Typical Power Budget and Possible Energy Source for Autonomous Oceanographic Network (AOSN) Labrador Sea Experiment (LSE)

This report should be cited as: Woods Hole Oceanog. Inst. Tech. Rept., WHOI-96-05.

The Autonomous Oceanographic Network (AOSN) Labrador Sea Experiment (LSE) will be held in the Labrador Sea at a seawater depth of 300 - 3500 meters. The total system will consist of a number of AUVs which will operate from a set of moorings within a defined area. Each mooring will be placed on the seafloor. The docking stations will be placed in the water column at 100 - 200 meters water depth. Each AUV will have at least one possible docking station to charge batteries and to transfer data. This report will show two different load pattern examples for the AOSN LSE, and the implications upon the power budget of the mooring.

The possible use of a seawater battery and its implications upon the system will be discussed. A preliminary design of the sizes and weights of a seawater battery for this application is also included. Energy delivery to an experiment like the AOSN LSE with the use of a seawater battery is feasible both technically and within the time span of the AOSN project. The environment of the Labrador Sea is well documented and seems suitable to accommodate a seawater battery. Due to the large water depths involved and the simplicity of the system, and the lack of any large pressure housings the seawater battery seems like a good candidate both in respect to costs and feasibility.

17. Document Analysis
   a. Descriptors
      recharging of AUVs
      seawater battery
      typical power budget for AOSN

   b. Identifiers/Open-Ended Terms

   c. COSATI Field/Group

18. Availability Statement
    Approved for public release; distribution unlimited.