Recommendations for Reports About Argo Float Batteries

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Executive Summary

Argo floats return engineering data related to the float operation. Information gleaned from this data can shed light on what is going on inside the instruments. This information may help the Argo community find ways to extend the life of its floats, including floats now in the water. It may also help the community identify designs that could be improved to extend float life.

This report describes how lithium batteries work inside Argo floats as a foundation for analyzing and understanding the data. Key elements of lithium batteries include battery efficiency (Appendix A), passivation (Appendix B), battery resistance, and the EOL transition. The EOL transition reliably indicates that the batteries are nearly depleted. The battery resistance is a measure that is useful in mid mission for evaluating whether the batteries are running normally.

Most of the main report is used to present voltage and battery resistance data, mostly from normal Navis, Apex, and SOLO II floats that have completed their missions. These results provide a basis for comparison with floats early in their missions and floats that appear to be having trouble. The end of the main report includes three case studies where battery data provide insight into what happened in floats that died young.

The report makes the following recommendations:

1) Routine data plots should include the battery resistance, plotted with bounds that are normal for like floats (page 12, Figures 2 and 6).

2) Color contour plots like Figures B3, B5, and B7 in Appendix B might provide even better insight.

3) Floats with Tadiran batteries should have a different presentation (Figure 9, page 10).

4) Battery efficiency (Appendix A) is the best way to judge battery performance and to identify how much potential there is for improvement.

5) The community could do a better job documenting dive energy (page 11).

6) The EOL transition can be used to decide when to recover old floats for postmortem evaluation (page 12).

7) When floats are recovered for examination, remove the batteries and measure the remaining capacities by monitoring voltage while depleting them with resistors (page 13)

8) Operationally, Apex and Navis floats are much more alike than they are to SOLO II floats. The large difference in battery efficiency between Apex and Navis warrants examination, which might lead to changes that could extend Navis float life (Page A5).

9) Floats with faulty sensors have value as test platforms to see if it is possible to depassivate batteries such that improved battery efficiency more than pays for the cost of depassivation. If so, missions could be extended (Page A5)

Introduction

This report reviews Argo float battery data from Navis, Apex, and SOLO II floats. Its purpose is to provide a basis for evaluating behavior of Argo float batteries and for monitoring battery performance while floats perform their missions. The two most useful parameters to monitor are the voltage *Vocv* under the lowest load, and the internal resistance *Rb* under the highest load. It is also valuable to compute battery efficiency once missions are complete.

This information may assist efforts to increase mission durations. When missions terminate prematurely, the information can identify problematic batteries, or exclude batteries so that attention can be focused elsewhere. The information can help identify floats that would be valuable to recover and dissect. The information can provide a basis for evaluating how much room there is to improve battery efficiency in order to extend mission durations.

My detailed recommendations are at the end of the report.

Lithium batteries

Electrochem builds battery packs for Argo floats using CSC93DD cells, which are high current 3.9 V cells. They are constructed in sheets, rolled up, and inserted into the cylinder. The large surface area of the sheets is the reason the cells produce high current.

Tadiran battery packs combine TL6930 low current D cells with HLC1550A rechargeable AA lithium ion cells. The HLCs provide the power floats need for their dives, and the primary cells slowly recharge the HLCs.

Battery efficiency is a useful measure of Argo float performance. Batteries arrive with stored energy, and battery efficiency is the fraction of this stored energy that goes to float operation. Battery efficiency is a property of the whole system, including batteries, the instrument, and how the instrument is operated. Appendix A reviews battery efficiency in depth.

The EOL transition is a sudden fall in the battery voltage near the end of life. It occurs in both Electrochem and Tadiran batteries, and it is a reliable indicator that the batteries are nearly depleted. With some uncertainty, it can be used to forecast how many dives floats will ultimately get. The EOL transition is discussed in more detail later in this report.

The Argo community is well acquainted with Electrochem's battery passivation. Passivation builds up during long intervals of inactivity, and produces transient voltage drops that dissipate in time. Batteries also have internal resistances that are more or less steady while under load. Both this transient passivation resistance and this "steady" resistance vary over the life of the battery. Appendix B shows that these battery resistances are actually pretty complicated and variable.

Battery resistance affects floats in several ways. Voltage drops dissipate energy in the form of heat inside the cells. This dissipation is not generally a large fraction of the battery energy, but it costs some dives. Voltage drops have little effect on the operation of Apex and Navis floats because they draw little current, but the high power required by SOLO II floats produces problematic voltage drops. Lastly, passivation appears to reduce the efficiency of batteries on floats with standard 10 day dive intervals.

Battery resistance *Rb* produces voltage drops when batteries are under load. We can calculate this resistance using:

$$Rb = (Vocv - V)/(I - Iocv) \quad (1)$$

where *V* and *I* are the voltage and current under load. *Vocv* should be measured with no load, but in Argo floats, measuring *Vocv* always entails some current, hence (1) includes the current *Iocv* when the float measured *Vocv*. In some floats, the best voltage to use for *Vocv* is accompanied by 100 ma currents, which is substantial. Nevertheless, the voltage at that current turns out to be a reasonable value to use for *Vocv*.

Navis floats

Navis floats hold 12 Electrochem CSC93DD cells. Core Argo Navis floats dissipate around 13 kJ/dive. They use little energy to open a valve at 1000 m, fall to 2000 m, then start the ascent by pumping at around 10 w. The pump runs for 30 s on and off for 10 s, repeating the pattern five or so times. The pump starts up again after the float ascends several hundred m. As the float rises, the pump uses less power.

Each time the pump turns on, the float records time, voltage, and current. The float also reports voltages at other times during dives. These data are reported in log files sent home.

Figures in this section use data from seven PMEL Navis floats and four CSIRO floats. All had standard Electrochem battery packs. All were core Argo floats, except that the CSIRO floats cycled every 3 days instead of the standard 10.

Figure 1 shows data from PMEL Navis Float 124. Figure 2 combines data from seven PMEL floats, plotting voltages and *Rb*. *Vocv* in Figure 1 is almost constant before the EOL transition, so *Vocv* tells us nothing about the state of discharge before the EOL transition. Both *Vpump1* and *Rb* vary with reasonably consistent patterns, so they provide an indication of the battery's discharge state in the middle of a mission. *Rb* is a better value to use than *Vpump1* because it also accounts for the current.

Rb in Figure 2 clusters within ±20% bounds. This means we may be able to see when individual battery packs drop out. If *Rb(cell)* is the resistance of one cell, then the resistance *Rb(packs)* of four packs is *3/4 Rb(cell)*, accounting for three cells in series, four in parallel. The loss of one pack increases *Rb(packs)* by 33%. This increase would be readily apparent relative to the 20% bounds. However, Appendix A, Figure A2, shows that increasing the current reduces *Rb(cell)*, which reduces the increase in *Rb(packs)* making the change harder to see. The data in Appendix A suggest that we might see only half of a 33% rise in *Rb(packs).* However, a 16% increase should still be sufficient for us to see when a pack drops out.

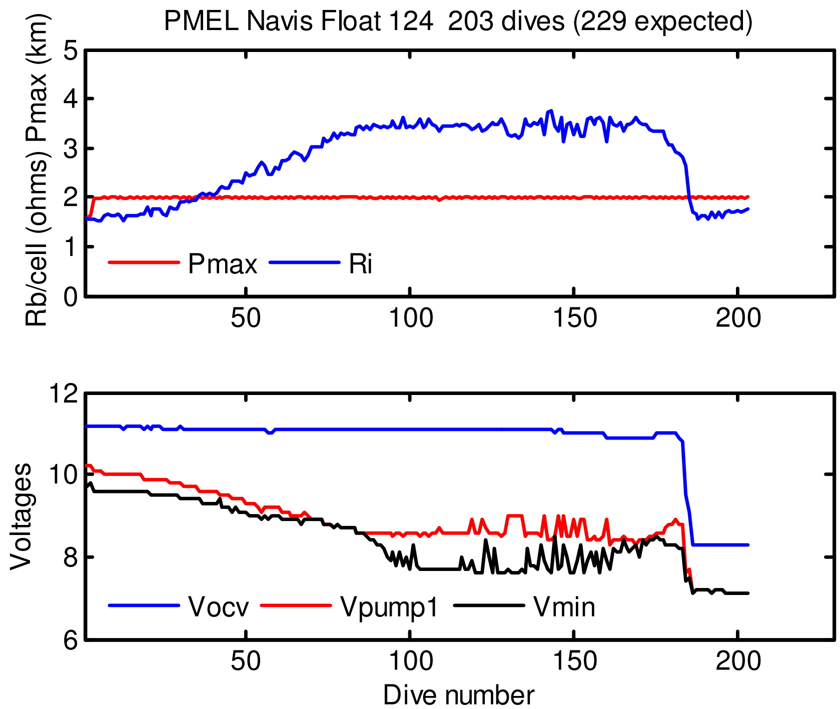

Figure 1. Dive depth Pmax, battery resistance Rb and several voltages. Vpump1 is the voltage when the pump first starts at the beginning of the ascent from 2000 m. Vmin is the lowest voltage at any time during the dive. It often occurs at park depth when the float adjusts its depth.

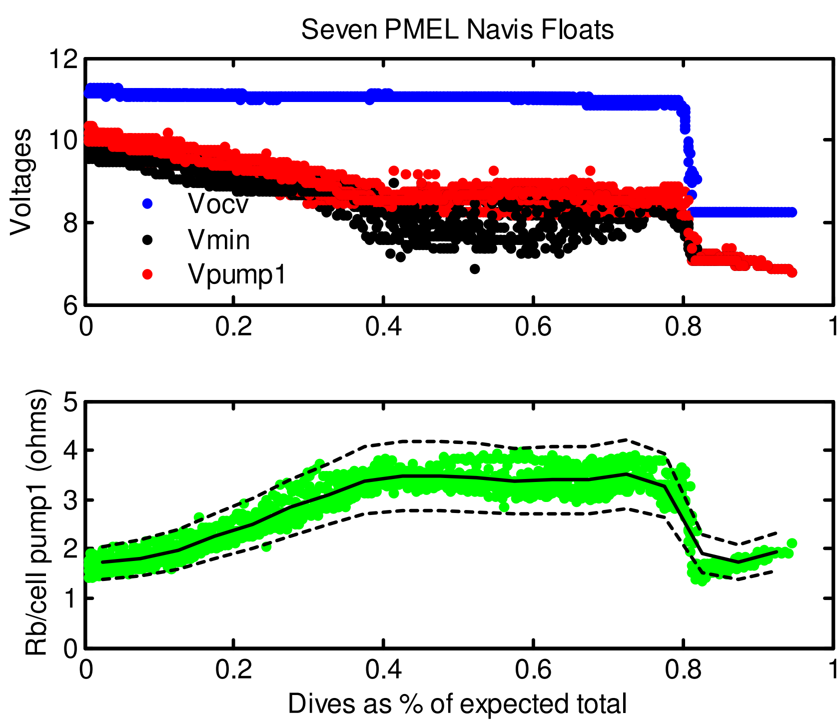

Figure 2. Voltages and Rb combined from all seven PMEL floats. The black line in the lower plot is the mean Rb, and dashed lines are ±20% bounds. Time is normalized by setting the EOL transition to 0.8.

Data from four CSIRO Navis floats are plotted in Figure 3. These CSIRO floats are the same as the seven PMEL Navis floats except that they used a 3 day dive interval instead of 10 days. Figures 2 and 3 are similar in many ways. The 3-day CSIRO floats had lower *Rb*, and the pattern of variation is a bit different, but, as in Figure 2, *Rb* stays mostly inside ±20% bounds. The lower *Rb* of the CSIRO floats show that longer dive intervals increase *Rb*. This behavior is consistent with passivation.

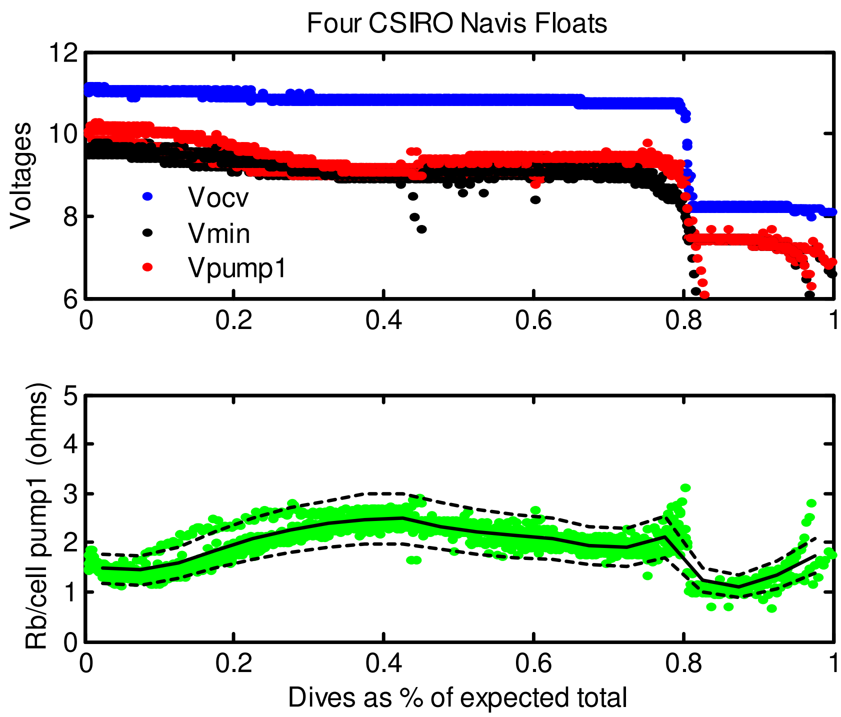

Figure 3. Data from four CSIRO floats.

The CSIRO 3-day floats produced an average of 296 dives (2.5 years), and the PMEL 10-day floats appear to be on track for somewhere around 225 dives (6.2 years). Appendix A estimates battery efficiencies to be 52% in the PMEL Navis floats and 71% in the CSIRO Navis floats.

CSIRO has some 10-day core Argo Navis floats in the water that have thus far collected around 50 dives to 2000 m. Figure 4 shows float 632, which is one of these floats. The dashed lines in the top panel of Figure 4 are the limits for *Rb* from Figure 2 based on the PMEL 10 day floats. The time scaling for the dashed limit lines assumes a mission life of 225 dives, the same as the PMEL floats.

Float 632's *Rb* fits neatly inside the PMEL limits, which suggests the CSIRO floats are behaving about the same as the PMEL floats. In contrast, float 632's *Rb* clearly differs from the 3 day CSIRO floats (Figure 3). Float 637's curves (not shown here) are nearly identical to Figure 4. These results are encouraging that *Rb* is a consistent parameter that can provide insight into how Navis missions are going.

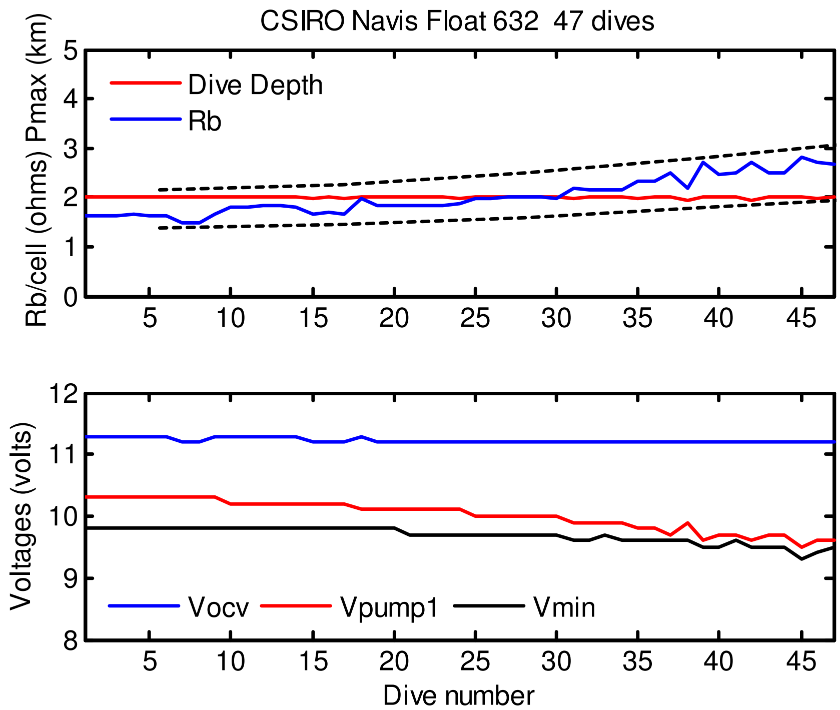

Figure 4. Voltages, Rb, and dive depths for CSIRO Navis float 632. The dashed lines are the same as the dashed lines for the PMEL float in Figure 2.

PMEL Apex Floats

Figures 5-7 are from PMEL Apex floats, each holding 12 CSCDD93 cells. Figure 5 is an example PMEL core Argo float that has completed its mission. Figure 6 combines data from the same float along with five others, all deployed in 2009-2010, and all of which have completed their missions.

As above, time in Figure 6 is normalized by setting the EOL transition to 0.8. Several of the floats transitioned at about 80%, and then completed 20% of their dives after the transition. The average transition was at 82%.

Figure 7 shows voltages and resistances from three 5000 series PMEL Apex floats. The resistances in the 4000 and 5000 series floats are also similar while differing in small details. Resistances at normalized time 0.2 look to be reliably different. The small detail differences are not important by themselves, but they do suggest that 'normal' curves ought to be computed from like floats. The 4000 and 5000 series PMEL Apex floats use different firmware, and there could be differences in how they were set up for their missions.

The battery internal resistances in the bottom panel of Figure 6 were roughly the same as the resistances in the PMEL Navis floats (Figure 2), differing in small details.

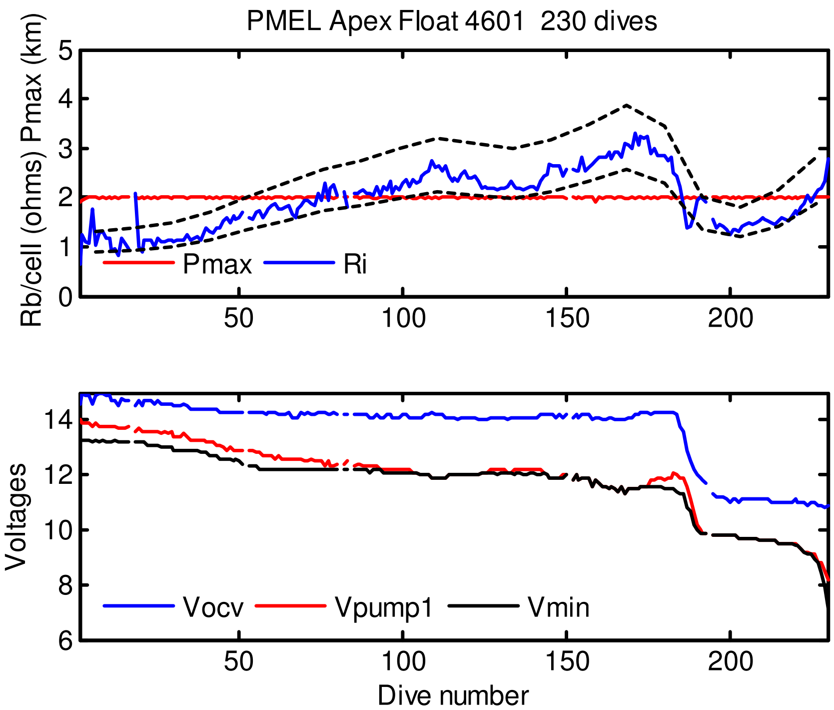

Figure 5. Voltages, dive depth, and internal resistance for one PMEL Apex float.

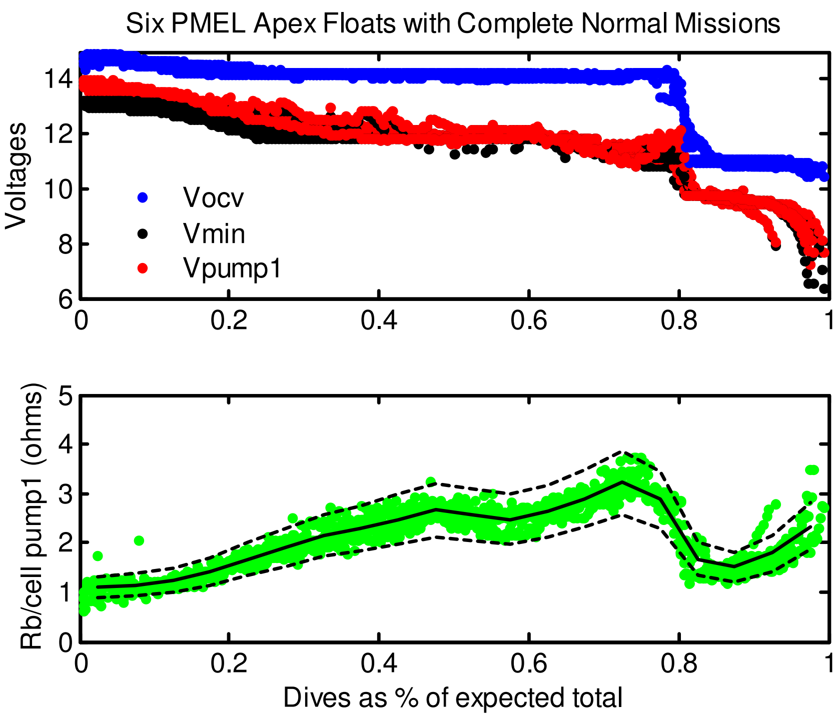

Figure 6. Voltages and internal resistances for six PMEL Apex floats, all 4000 series.

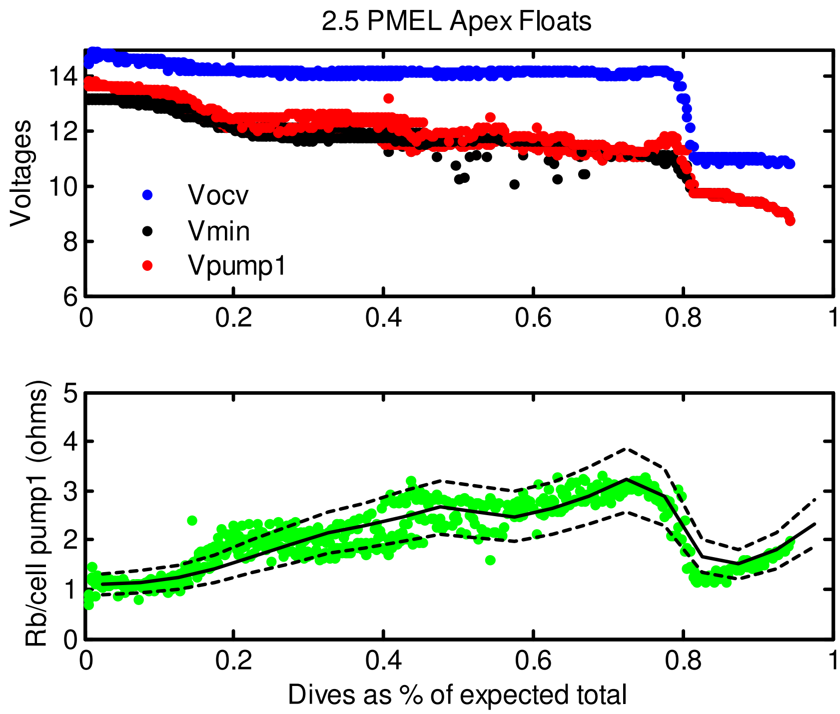

Figure 7. Voltages, and internal resistance from two almost complete 5000 series PMEL Apex floats plus one that disappeared after completing around half its expected dives. The black lines in the bottom panel are from the six 4000 series floats. Resistances are similar, but a slight increase in resistance around 0.2 appears to be a consistent difference between the 4000 series and 5000 series floats.

SOLO II Floats with Electrochem Batteries

SOLO II floats originally held 8 Electrochem CSC93DD cells, and later 12 cells. Scripps and Woods Hole recently switched to Tadiran packs, which combine 24 TL6930 D cells with 12 HLC1550A lithium ion cells. SOLO II floats require 9.5 kJ per dive, for pump and sensors. At 2000 m, their pumps require 40 W, about 4 times the power required for Navis and Apex floats.

Because of the higher power, passivation in Electrochem batteries causes serious problems for the SOLO II floats. Figure 8 shows what passivation did to float 8054. Voltages stayed sufficiently high for normal operation until 2014, but then they fell too low while pumping for proper sensor operation. Starting in 2015, Scripps introduced ‘strategic sampling’ in an effort to prolong float life. In the meantime, SOLO II *Vocv* looked about the same as in the Navis floats, and the EOL transition at the end tells us that the batteries had depleted their energy.

Figure B6 in Appendix B shows *Rb* for five 10-day SOLO II floats and eight 5-day floats, all of which dove to 2000 m. *Rb* was considerably greater in the 10-day floats. Some floats produced per-cell resistances as high as 8 ohms, and others were less than half that. This means that *Rb* varies too much to provide insight as to whether a battery pack has dropped out. It is not clear at this point whether anything about early *Rb* behavior provides insight into the ultimate lifetime of the float. There have been too few completed 10 day missions, but perhaps in time, patterns will emerge.

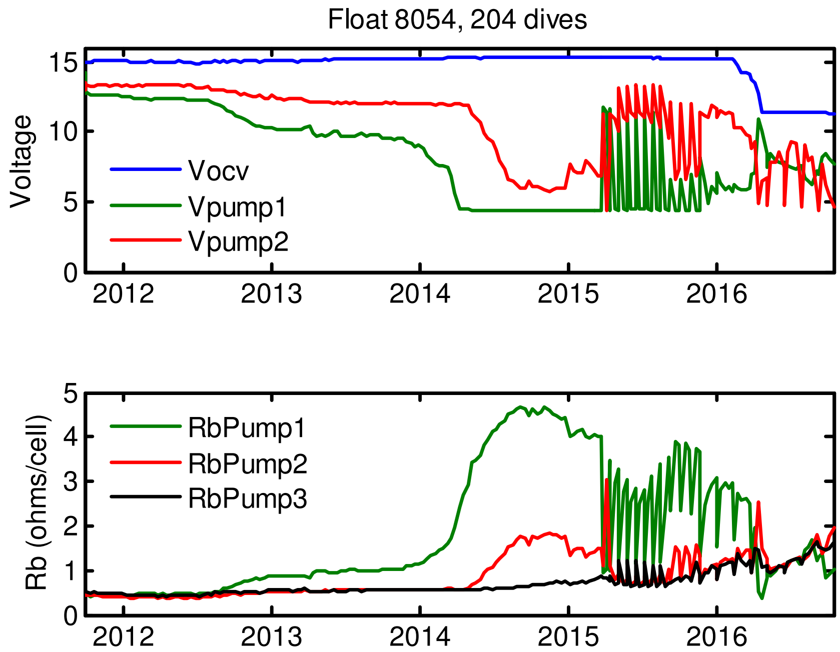

Figure 8. SOLO II float voltages and battery resistances. Resistance grew suddenly in mid mission. The first pump cycle dissipated passivation and generally diminished resistance in the second cycle, but in 2014, high resistance persisted into the second pump cycle. Fluctuations starting in 2015 are the result of 'strategic sampling', an effort to prolong the float's life.

SOLO II Floats with Tadiran Batteries

Float 8381 was deployed for testing the Tadiran batteries. It holds two batteries and ran for a period using short dive intervals in order to get the batteries into mid life. It then ran using a variety of dive intervals. Six dives started after 10 day intervals and 42 dives started after 7 day intervals. These longer intervals were used to look for passivation, but there has been nothing like the passivation seen in SOLO II Electrochem floats. The float's batteries reached the EOL transition in mid October, 2017, and the float is running out time with 2 weeks of 1 day dives followed by 2 weeks of 7 day dives, all to 2000 m. Data shown below was downloaded on October 20, 2017. As of the date of this report, float 8381 has completed 291 dives and is likely to continue to around 300 dives.

The reason the Tadiran batteries don't passivate is because dive power is provided primarily by the rechargeable HLC1550A lithium ion cells. The internal resistance of an HLC is about 0.1 ohm. The voltage drop when the pump turns on is caused by this resistance, resistance in the wiring, and by discharge of the HLC. The HLC behaves like a 1000 F capacitor, so the voltage falls as it discharges. The HLC largely recharges before the next pump cycle.

Figure 9 shows float 8381's voltages and *Rb* from the first four pump cycles. *Rb* is bounded above by a straight line:

$$RbFit = 0.0002 \text{ ohm/dive} * DiveNumber + .14 \text{ ohm} \qquad (2)$$

where *DiveNumber* is the number of the dive (1 to 275 for 8381). Most of the *Rb* values cluster close to this line, and values that fall well below the line are the result of round off error, and they are not real battery resistances.

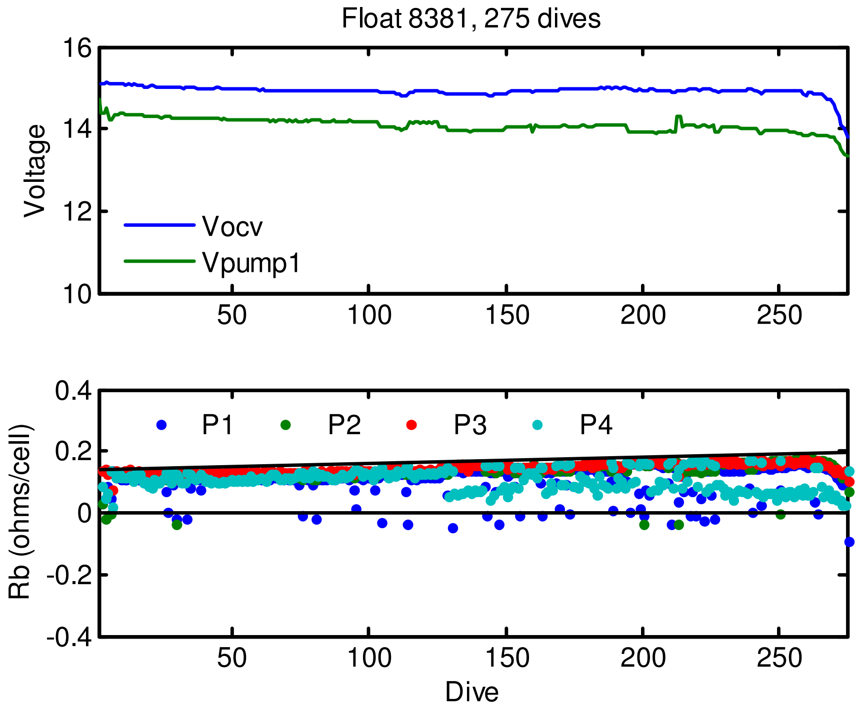

Figure 9. Voltages and Rb from SIO SOLO II float 8381. Rb is from the first four pump intervals. A straight black line bounds the maximum Rb. The line rises from 0.15 ohm at the start to 0.2 ohms near the end.

Scripps has some Tadiran floats that have completed 30-39 dives by now, plus another that has completed 99 dives. Using *Rb* from the first four pump intervals, 33 of these floats produced 5300 independent *Rb* measurements. The blue distribution in Figure 8 is the distribution of these 5300 *Rb* measurements, after subtracting *RbFit*, computed using (2). Subtracting *RbFit* from the measured *Rb* produces a tighter distribution than *Rb* by itself. I excluding (*Rb - RbFit)* values that were too low (below -0.06 ohm) because they are probably not real. The result shows that (*Rb - RbFit)* clusters with a standard deviation of 24 milliohms around a mean of -2 milliohms.

The Tadiran batteries are more consistent than the Electrochem batteries, but Figure 2 also demonstrates the consistency of the SOLO II floats. The wide variations seen in the SOLO II Electrochem data are caused by the batteries, not the instrument. The other Argo floats are probably equally consistent.

All of the Tadiran SOLO II floats have three batteries except for 8381, which had two. Scaling the data from 8381 as if it had three packs produced the red distribution in Figure 10. This is what it would look like if a three pack float lost one pack, and the difference in the two distributions should make a missing pack obvious.

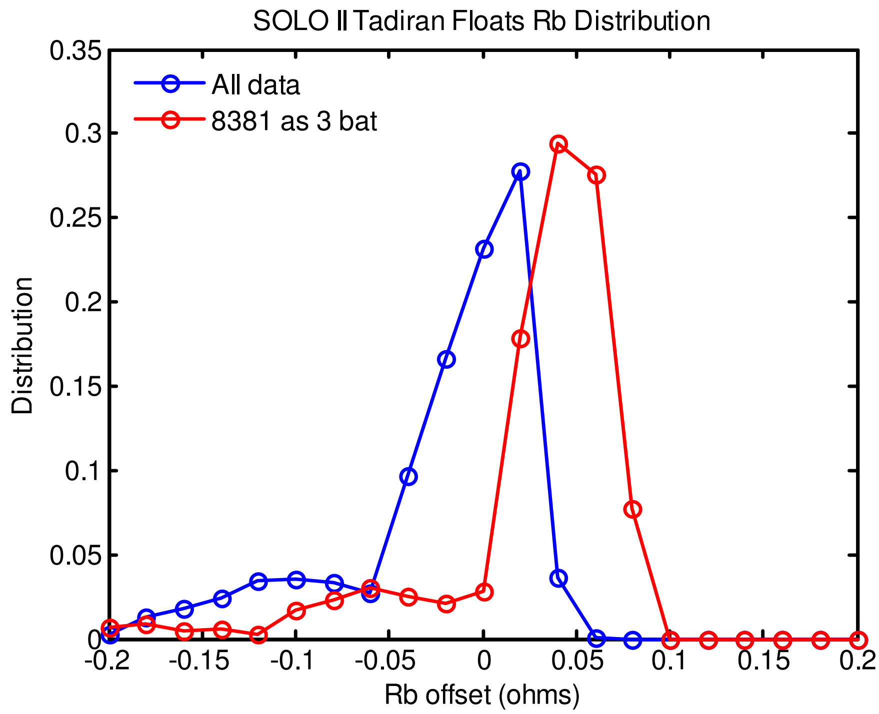

Figure 10. Distributions of (Rb - RbFit). Data are from 33 floats, most of which have 30-39 dives. The red distribution is for float 8381 scaled as if it has 3 batteries instead of 2. The difference between the distributions is readily apparent.

Dive energy

Evaluating the efficiency of float batteries requires an understanding of the energy consumed for each dive. Dive energy goes mostly to the pump, the sensors, and data communication. Appendix C contains an example energy budget prepared by Dana Swift. Dana pointed out that dive energy varies considerably, depending on how floats are operated, even with identically equipped floats.

Dana's energy model is detailed and thorough, but a simpler model and energy budget is probably sufficient for estimating battery efficiency. Manufacturers should provide energy models to users, perhaps in the form of a spreadsheet. In the meantime, I understand that manufacturer's already assist users by providing energy budgets based on how users plan to use the floats. Users should document the energy budget for each float and include it with the rest of a float’s documentation.

Dana's energy budget in Appendix C includes self discharge in the dive energy, and it lists derated battery capacity. Dana’s derating is based on dive simulation tests he performs in his lab. For estimating battery efficiency, dive energy should include only energy used to operate the float, sensors, communications, etc. Energy used for pre-mission testing, self discharge, and solely to dissipate passivation all reduce battery efficiency. Battery capacity should include all of the energy stored in new battery packs, i.e. assuming packs are optimally depleted. Battery efficiency is addressed in more detail in Appendix A.

Recommendations for Data Collection and Reporting

SOLO II, Navis, and Apex floats report all the information necessary to monitor battery health. Navis and Apex floats could measure *Vocv* under a smaller load, but what they do now appears to be good enough. Everyone seems to display *Vocv* and *V* from the first pump interval on their websites. These displays are useful, and I see no reason to change them. I recommend adding plots of *Rb* from the first pump interval. Color contour plots of *Rb*, like those in Appendix B, could also be useful. I am not sure now how they will be used, but eyes are sensitive to patterns and anomalies, so in time they could provide insight to help diagnose battery performance.

Navis and Apex floats should display *Rb* in a plot like Figure 3 which includes bounds based on like floats. Problematic floats can be identified when *Rb* falls outside the bounds.

SOLO II floats with Electrochem batteries are so variable that I am not sure how we will use reported data to diagnose battery problems. I recommend displays similar to Figure 6, as well as color contour plots as in Appendix B. The contour plots could end up being the most useful.

Floats with Tadiran batteries should plot *Rb* from the first few pump intervals with a bounding line similar to Figure 7's *RbFit*. Plots like this will unequivocally tell us when a battery pack drops out. As core Argo Tadiran SOLO II floats age, equation (2) could be updated.

EOL Transition as a forecaster of the last dive

The sudden voltage drop at the EOL transition provides a reliable indicator that the battery is nearly depleted.

Figure A1 in Appendix A shows voltage curves for cells depleted with a small continuous load. The Electrochem CSC93DD cell's voltage fell suddenly when it had supplied 83% of its energy (assuming the battery is effectively dead when its voltage fell to 2.65 V). The Tadiran cell did the same at 85% depleted.

The batteries in floats do the same, but the details are different. Table 1 shows that there is some variation in the location of the EOL transition.

We have no floats yet with Tadiran batteries that have reached the end of life. Several lab tests suggest that EOL transitions in floats with Tadiran batteries will take place at around 90% depletion.

It is interesting to have an idea how much longer floats might last, but the EOL transition is valuable as a means to determine whether a float had depleted its batteries when it disappears. It is also valuable if you decide to recover an old float because it gives you an idea of how much time you have to get it.

Table 1. Minimum, average, and maximum EOL transitions as a fraction of the mission life. These data were taken from 5-6 floats of each type, and all had reached end of life. All floats in the table used Electrochem batteries.

	min	**mean**	**max**
PMEL Apex	80%	85%	89%
CSIRO Navis	80%	83%	85%
SOLO II	85%	89%	94%

Float recovery

These displays could be used to identify floats for recovery and dissection. When floats appear to lose battery packs, it will be nice to know whether the problem is in a battery pack, the connectors, or an electronic or mechanical fault. My bet is that connectors are more trouble than the rest. When batteries prematurely reach EOL voltages, it will be nice to know if the system is dissipating more energy than it should. If not, then attention should focus on the batteries. Navis and Apex floats, depending on how they are set up, appear to produce consistent patterns in *Rb* as batteries age. Floats with *Rb* that deviate from these patterns warrant scrutiny, and could be candidates for recovery and evaluation.

Since you cannot ship depleted batteries, you should test the batteries when you recover a float. If one battery's remaining capacity is greater than the others, that would suggest a bad connection. You can check this by depleting the batteries with a resistor while monitoring voltage and counting joules. A 50 ohm 5W resistor depletes a new CSC93DD battery pack in around 5 days, so batteries from floats recovered late in their missions will take less time. Batteries depleted this way should produce reasonably consistent voltages, so abnormally low voltages would indicate a faulty battery pack.

If you identify a float you want to recover, consider increasing its dive interval to allow more time for recovery. Longer dive intervals could lead to greater battery passivation, but data in Appendix B suggest that passivation largely disappears after the EOL transition.

Postmortem examination

Figures 11-13 present short lived PMEL Apex floats with discussion of what the battery data tell us.

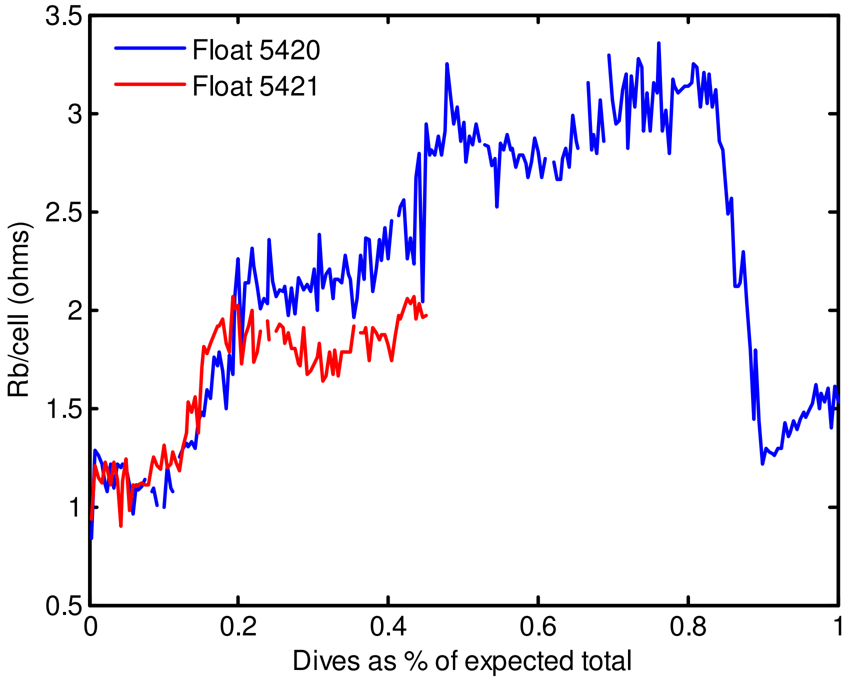

Figure 11.

Figure 11 compares internal resistances from two 5000 series floats. Float 5420 has almost completed a normal mission, while float 5421 disappeared almost halfway into its mission. *Rb* from the two floats tracked each other well at first, but at time 0.2, float 5421's *Rb* fell noticeably below float 5420's *Rb*. I don't see how battery defects could reduce *Rb*, so it seems more likely that the reduction was related to some other change inside the float. At the time float 5421 disappeared, the battery was far from depleted.

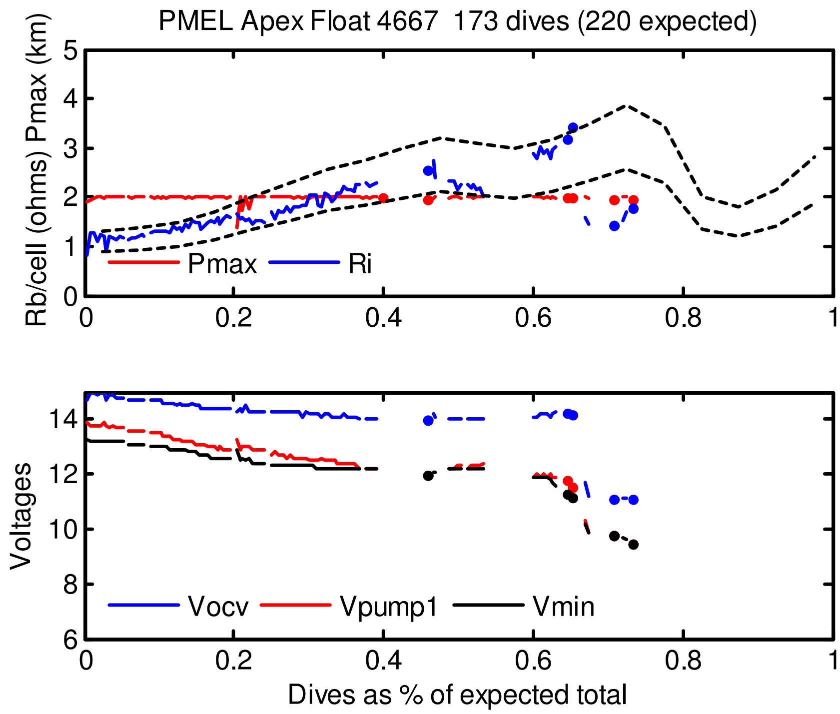

Figure 12.

Float 4667 in Figure 12 appears to have performed normally up to time 0.4, but then it became erratic. *Vocv* fell sharply at time 0.65. This drop was almost certainly the EOL transition. Following the EOL transition, the float made a reasonable number of dives, then disappeared. The end of life behavior indicate that the batteries were depleted when the float disappeared. Assuming energy consumption was normal up to time 0.4, energy consumption would have had to roughly double from then to the end. Whatever happened inside float 4667, it must have substantially increased its energy consumption.

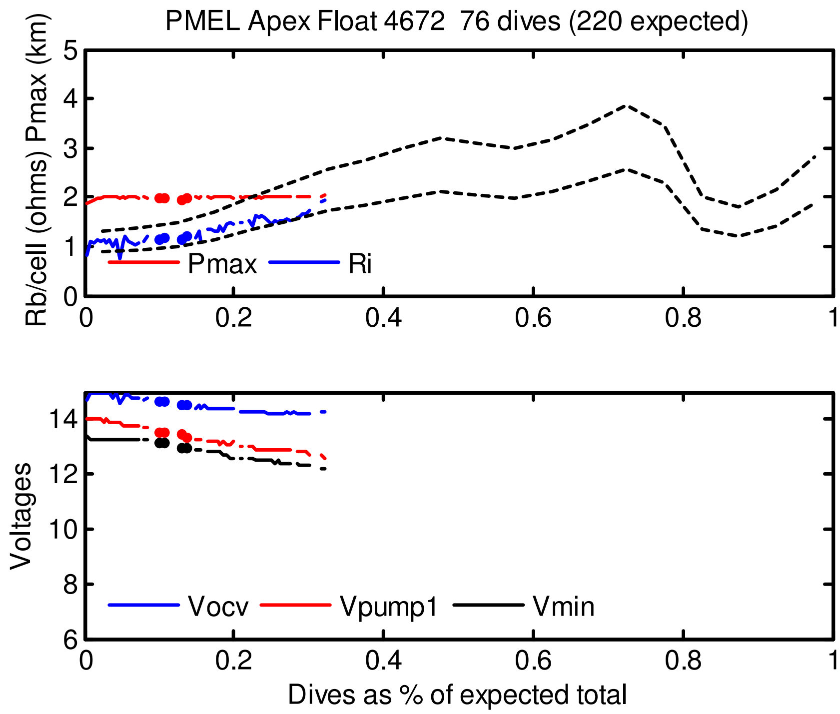

Figure 13.

Float 4667's *Rb* (Figure 13) was normal up to time 0.3, when the float disappeared. This suggests that both batteries and float energy consumption were normal up to the time the float disappeared. Therefore, the float's disappearance likely had nothing to do with the batteries.

Appendix A

Battery Efficiency

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November 21, 2017

When batteries arrive from the manufacturer, they hold more energy than what gets into an instrument. Energy is wasted by self discharge, dissipation by voltage drops across cells under load, and energy remaining inside the cells after the end of a mission. Battery energy dissipates when floats are tested before deployment. Scripps dissipated energy at the beginning of dives to depassivate the batteries, but without performing useful work. Any energy dissipated for other than dive operation is wasted. The battery efficiency is ratio of the total dive energy to the energy originally stored in the battery. Battery efficiency is a function of the whole system, including the batteries, the float, and the way the float was operated.

An accurate battery efficiency provides a measure of the room available to improve a float's longevity. The first part of this appendix estimates the energy capacity of new batteries. The second part of this appendix estimates the energy consumed for dives by Apex, Navis, and SOLO floats and uses that energy to estimate battery efficiencies.

Estimating Battery Capacity By Discharging a Cell
You can measure most of the energy stored in a battery by discharging it with a steady load. I placed a resistor across the battery, recorded the voltage as it discharged. and computed the Coulombs and Joules dissipated by the resistor. This test missed energy that dissipated as heat inside the cell, and it missed energy lost to self discharge before to the test. These additional dissipations are estimated below. Figure A1 shows voltage curves from this test.

The test used a four year old Electrochem CSC93DD cell and a seven year old Tadiran TL6930 cell. Both had been stored at room temperature. The cells were depleted in around 12 days, the CSC93DD with a current of 100 ma to start, and the TL6930 with a current of 60 ma. Table A1 presents the measured capacities based on this test. Capacities are computed up to when the voltages fell to 2.65 V and also to when the cells fell to zero. Dissipation between 2.65 V and 0V represents around 5% of the stored energy, which we will ignore.

Table A1. Measured cell capacities.

	CSC93DD	**TL6930**
Vocv	3.9 V	3.9 V
Specified capacity	30 ah	16 ah
Current discharged to 2.65 V	30.4 ah	16.2 ah
Energy dissipated to 2.65 V	376 kJ	206 kJ
Current discharged to 0 V	32.3 ah	18.0 ah

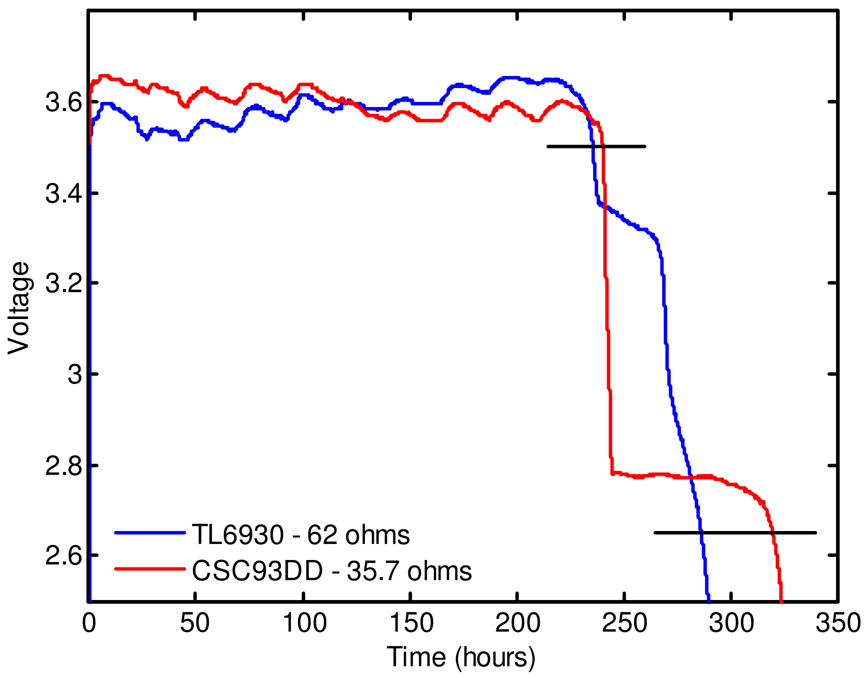

Figure A1. Voltage on a Tadiran TL6930 D cell and an Electrochem CSC93DD cell, each with the resistance shown in the figure legend, placed across the terminals. The test was at room temperature, and the small voltage fluctuations in the first several hundred hours were caused by day/night temperature variations. The black lines are for voltage transitions at 3.5V and 2.65V.

Energy Dissipated to Battery Resistance

Current I through the cell causes the cell's output voltage to fall, and the difference between $Vocv$ and the output voltage V represents energy that is dissipated against the battery resistance of the cell. This dissipation heats the cell, and its power Pd is:

$$Pd = I\ (Vocv - V)$$

Figure A2 shows how the output voltage depends on the current in one midlife Electrochem CSC93DD cell. Rb depends on current such that, as the current increases, Rb decreases. The voltage drop across Rb wastes energy by dissipating it to heat. Tadiran TL6930 cells have similar behavior.

Based on Figure A2, the average voltage drop against battery resistance in the Electrochem cell was about 0.2 V. The corresponding energy dissipation was 0.2 V times the capacity in ah. A similar calculation for the TL6930 used numbers from the Tadiran spec sheet. This calculation does not have to be terrifically accurate since it is a small part of the total energy.

Self Discharge Energy

In spite of the age of the cells, the measured amp-hour capacities to 2.65 V are about equal to the manufacturer's specifications. However, self discharge is well understood, and these cells lost energy while in storage. Electrochem's specs sheet states a capacity of 30 ah, but a graph on the page shows capacity at 250 ma continuous discharge to be 32 ah. Electrochem also specifies self discharge to be 3%/year. Four years of self discharge would dissipate 12% of the capacity, which increases the measured 30.4 ah capacity to 33.6 ah. This is reasonably close to the 32 ah specification. Similarly, Tadiran's 0.7%/year self discharge adds about 5% to the measured capacity, increasing it from 16.2 to 17 ah. Both capacities are higher than manufacturer specifications, which are probably conservative.

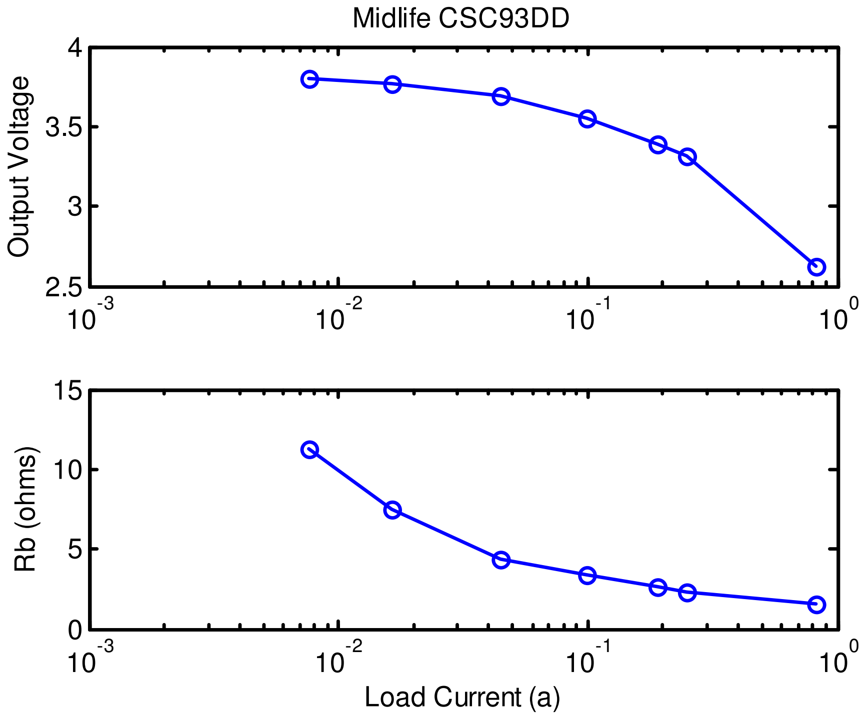

Figure A2. Top panel: Output voltage vs. load current on one CSC93DD cell. Bottom panel: battery resistance Rb vs. load current.

Total Energy Stored in New Cells

Table A2 adds up the total energy stored in new cells. The 2.65V voltage cutoff used to produce Table A2 is approximately where Argo floats fail. This cutoff is a bit arbitrary, but the voltage falls so quickly at that point that varying the cutoff will not have much effect on the result. The 3.5 V voltage is where both batteries initiated their EOL transition in this test. This transition is obvious for both Electrochem and Tadiran batteries in Argo floats. The CSC93DD cell supplied 20% of its capacity between 3.5V and 2.65V and the TL6930 supplied 17%.

Table A2. Accounting the total energy of new cells.

	CSC93DD	**TL6930**
Measured energy to 2.65 V	376 kJ	206 kJ
Self discharge energy	45 kJ	10 kJ
Voltage drop energy	22 kJ	12 kJ
Total stored energy of a new cell	443 kJ	228 kJ

Battery Efficiency in Argo missions

The floats summarized in Table A3 all use Electrochem CSC93DD cells. The SOLO float in Table A4 has Tadiran TL6930 cells. These tables summarize battery efficiencies from these floats.

Table A3. Comparison of mission battery efficiencies from floats using Electrochem batteries. The PMEL Navis floats are operational but near the ends of their missions. Their ultimate mission durations assume the EOL transition occurred at 83% of the final dive count (this number comes from the CSIRO Navis floats). SOLO II float 8054 used 47 shallow dives to depassivate its batteries; it collected 157 dives to 2 km.

	SIO SOLO II 8054	SIO SOLO II 8027	PMEL Apex 6 floats	PMEL Navis 7 floats	CSIRO Navis 4 floats	
Dive energy	11	11.5	16	13	13	kJ
Dive interval	10	5	10	10	3	days
Dive count	157	214	222	216	307	dives
Battery packs	2	2	3	3	3	packs
Battery energy	3540	3540	5310	5310	5310	kJ
Energy, good dives	1727	2461	3555	2810	4001	kJ
Energy, depassivation dives	290	-	-	-	-	kJ
Self discharge @1%	272	206	289	335	164	kJ
Energy, voltage drops	232	155	94	25	137	kJ
Missing energy	1019	718	1372	2140	1008	kJ
Battery efficiency	49%	68%	66%	52%	74%	

Table A4. Mission battery efficiency for one SOLO II float using Tadiran batteries. This float is still operational, but near its end. The dive count assumes the EOL transition occurred at 90% of the final dive count.

	SIO SOLO II 8381	
Dive energy	9.5	kJ
Dive interval	2.5	days
Dive count	300	dives
Battery packs	2	packs
Battery energy	3800	kJ
Energy, good dives	2850	kJ
Self discharge @0.7%	53	kJ
Energy, voltage drops	51	kJ
Missing energy	846	kJ
Battery efficiency	75%	

Table A3 shows that the efficiency of Electrochem batteries depends on both the power draw and the dive interval. The 10 day SOLO II float 8054 had the lowest efficiency of the floats I looked at. Reducing the interval to 5 days in SOLO II float 8027 increased efficiency by 20%. The peak power of SOLO II floats is 40 W, compared with 10 W in the Apex and Navis floats. Both produce higher efficiency than the SOLO II floats. I have some doubt about the 52% efficiency of the PMEL Navis floats. This value seems too low, particularly in comparison with the 66% efficiency of the PMEL Apex floats. The relatively high 74% efficiency of the CSIRO 3 day Navis floats appears to rule out any intrinsic inefficiency in the Navis hardware as an explanation.

The Navis and Apex floats are similar enough that it is reasonable (in my opinion) that they should achieve similar efficiencies. If the Navis float battery efficiency really is 52%, it may be worthwhile to perform a detailed evaluation of the floats to see if there is anything the Apex does that improves efficiency, and which could be incorporated into Navis floats.

Table A4 shows the efficiency of the SOLO II float 8381, which holds Tadiran battery packs. It has completed 291 as of the date of this report, and I expect it to get to around 300. Float 8381 with its Tadiran packs produced the best efficiency of the floats I have considered.

Where does "missing" energy go?

The Tables A3 and A4 show that we cannot account for sizable amounts of missing energy. Batteries go into Argo floats with a relatively well known initial energy, and energy does not just disappear. The estimates of the consumed energy in these tables above could easily warrant reexamination, but if they are reasonably close, then there are only two places the energy could have gone. One possibility is that the energy is still inside the cell, but inaccessible. Another is that it has dissipated in the cell, which would suggest that self discharge is greater than manufacturer's specifications. Herzel Yamin, Tadiran's top scientist, has studied this, and is convinced the missing energy is the result of elevated self discharge associated with passivation-depassivation cycles.

Herzel's explanation is consistent with what we see here. Longer dive intervals, which increase passivation, also produce more missing energy. The high currents in SOLO II floats produce larger and more problematic *Rb* than the other floats, and the SOLO II floats with Electrochem batteries have the lowest battery efficiency of all.

Passivation appears to be the primary cause of low battery efficiency. If so, it could be worthwhile to try various strategies to depassivate the batteries before the high power of deep dives. The key question is whether improvements in battery efficiency sufficient to return the costs of depassivation. There are some floats in the water today with faulty sensors that reduce the value of collected data. These floats could be used productively for depassivation experiments. The ultimate measure is the number of good dives they end up getting. While this takes years, *Rb* may provide a useful measure in the short term.

Appendix B

Lithium Battery Passivation

Lee Gordon
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November 21, 2017

Passivation layers in lithium metal batteries are essential because they limit self discharge. The passivation layer is a chemical insulator on top of the metallic lithium. Passivation grows during inactivity and current loads dissipate passivation.

Passivation produces transient voltage drops when battery power is drawn in pulses. The battery's voltage initially falls under the pulse load, then it recovers. This is often called voltage lag. The voltage drop and the current can be used to compute a passivation resistance, which is a transient resistance that disappears with the voltage lag. Figure 1 shows the voltage lag from a midlife CSC93DD cell.

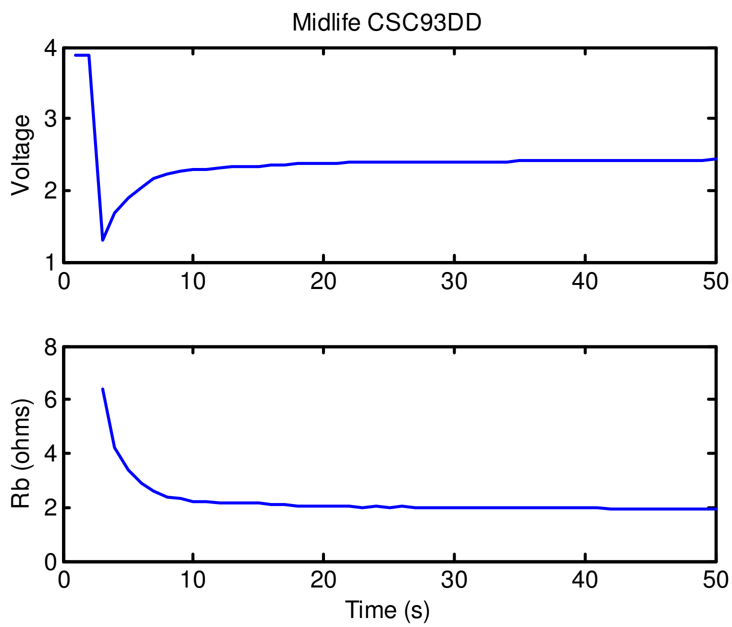

Figure B1. Measured passivation voltage lag and battery resistance in a CSC93DD cell under a load of around 0.8 a. The load began at time 2 s when a 3.2 ohm resistor was placed parallel to the cell. The voltage lag was largely over in about 10 s, after depleting about 25 J from the cell.

Lithium metal cells also have internal resistance that differs from passivation resistance in that it does not go away after power is drawn. Battery resistance *Rb*, whether passivation or internal, is computed as follows:

$$Rb = (Vocv - V)/C$$

where *Vocv* is the voltage under no load, and *V* and *C* are the voltage and current under load. The internal resistance in Figure B1, after passivation dissipated, was around 2.3 ohms.

Figure B2 displays the rest of the Figure B1 test, showing that the voltage continued to rise slowly after the voltage lag. The voltage settled down at around 2.6V, about 1.2V below *Vocv*.

This voltage drop was caused by *Rb* around 1.6 ohms. When the load resistor was removed, the battery voltage returned to near the original *Vocv*.

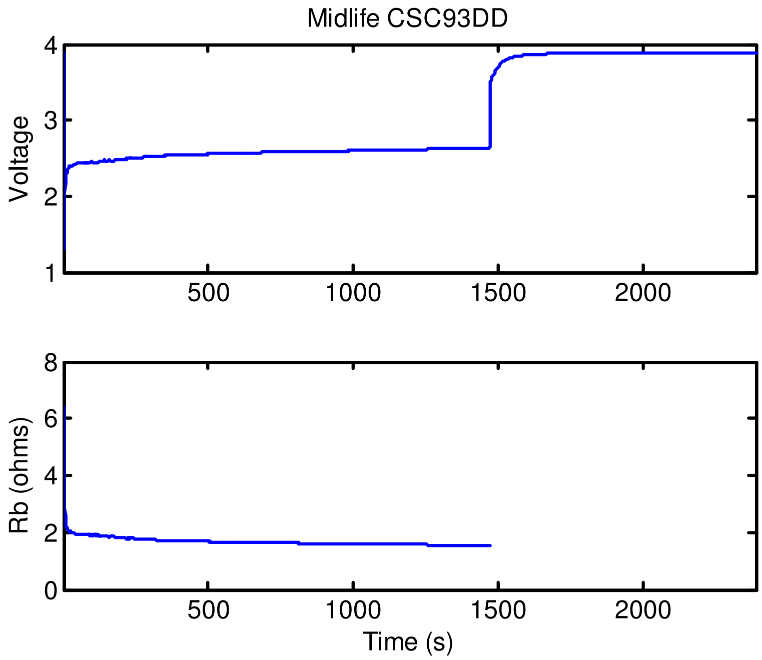

Figure B2, continuation of the test in Figure B1. The load resistor was removed around time 1500 s.

Prior to looking at data from a selection of Argo floats, I thought that internal resistance was roughly constant and that passivation resistance was dissipated by current loads. Data below shows that Argo float battery resistance is more complicated. This data shows the following about Electrochem cells:

1) Battery resistance is generally largest in the middle of a mission. It often, but not always, falls toward the end of the mission, before *Vocv* reaches the EOL transition.

2) Battery resistance is lowest when the cell is new, starting around 0.5 ohms/cell. The maximum resistance in this data, whether passivation or other, was around 8 ohms/cell.

3) Long dive intervals produce more battery resistance than shorter intervals. This is true for all resistances, whether passivation or otherwise.

5) Navis floats exhibited reasonably consistent resistance patterns from one mission to the next. Resistance patterns did not fit well with either passivation or constant internal resistance.

6) SOLO II floats, which dissipate four times the power of Navis floats, exhibited much more variability than Navis floats. Resistances were not especially higher than in the Navis floats, but high power produced large voltage drops which was problematic. Some SOLO II floats exhibit what looks like classic passivation, while others produced large resistances that did not go away. Resistance magnitudes in otherwise identical floats varied by a factor of 3. Some SOLO II floats with no sign of passivation experienced sudden large internal resistances that then remained relatively constant.

All of the floats in this appendix used Electrochem CSC93DD cells.

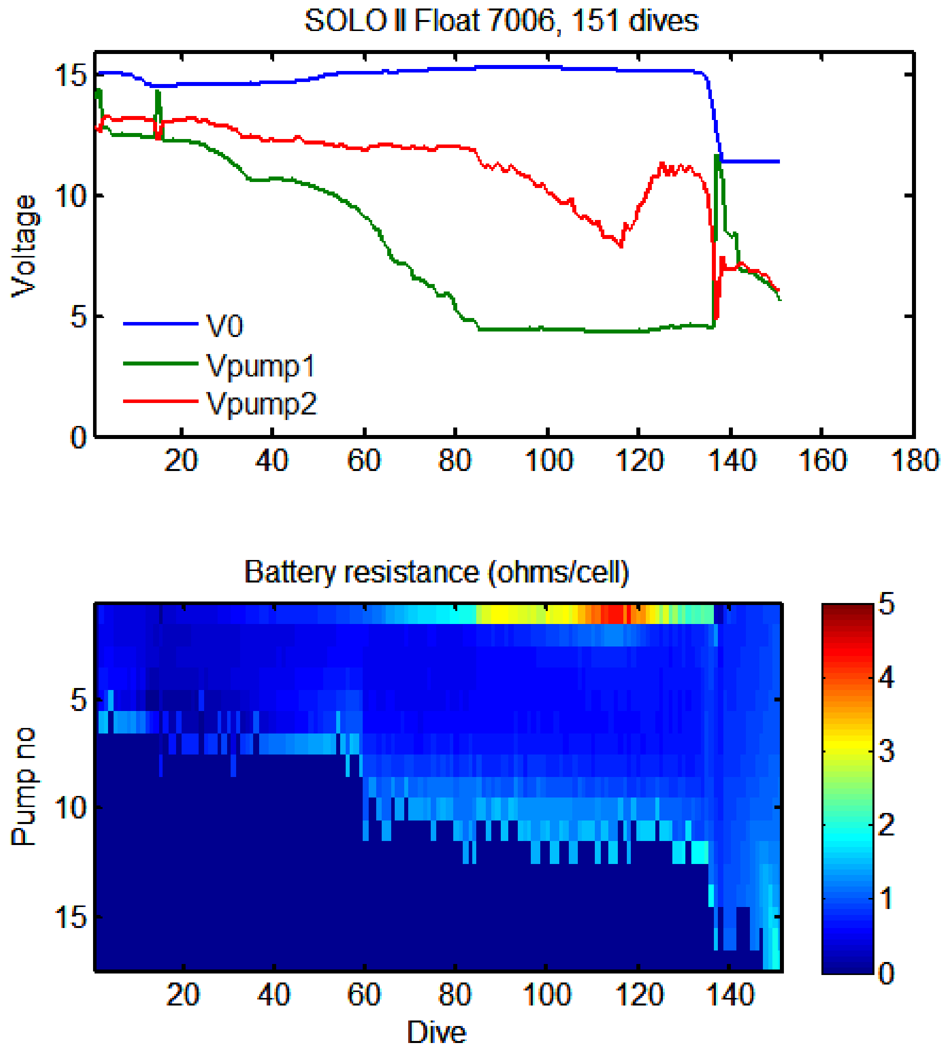

Figure B3. SOLO II float 7006 had two Electrochem packs (8 DD cells), and it ran for 4.1 years on a 10 day interval. Vpump1 and Vpump2 were voltages from the first and second pump pulses. Peak currents were around 1.5 a/cell. Passivation resistance appears in the first pump pulse from dive 80 to dive 140.

I do not know how to unify all of this behavior, so the following figures are intended primarily to illustrate the range of variability.

Float 7006 in Figure B3 had a battery resistance of 0.6 ohm/cell most of the time, but starting around dives 60-80, passivation appeared in the first pump pulse. Passivation resistance grew to 5 ohms/cell and stayed that way until nearly the end of the mission. Dissipating the passivation took 100-250 joules/cell.

Note the increase in resistance in Figure B3 toward the end of dives when pumps approached the surface (for example, pump no. 10 for dives 60-140). This is where pressure was low and pump current light. The increase of resistance at lower power is consistent with Appendix A, Figure A2.

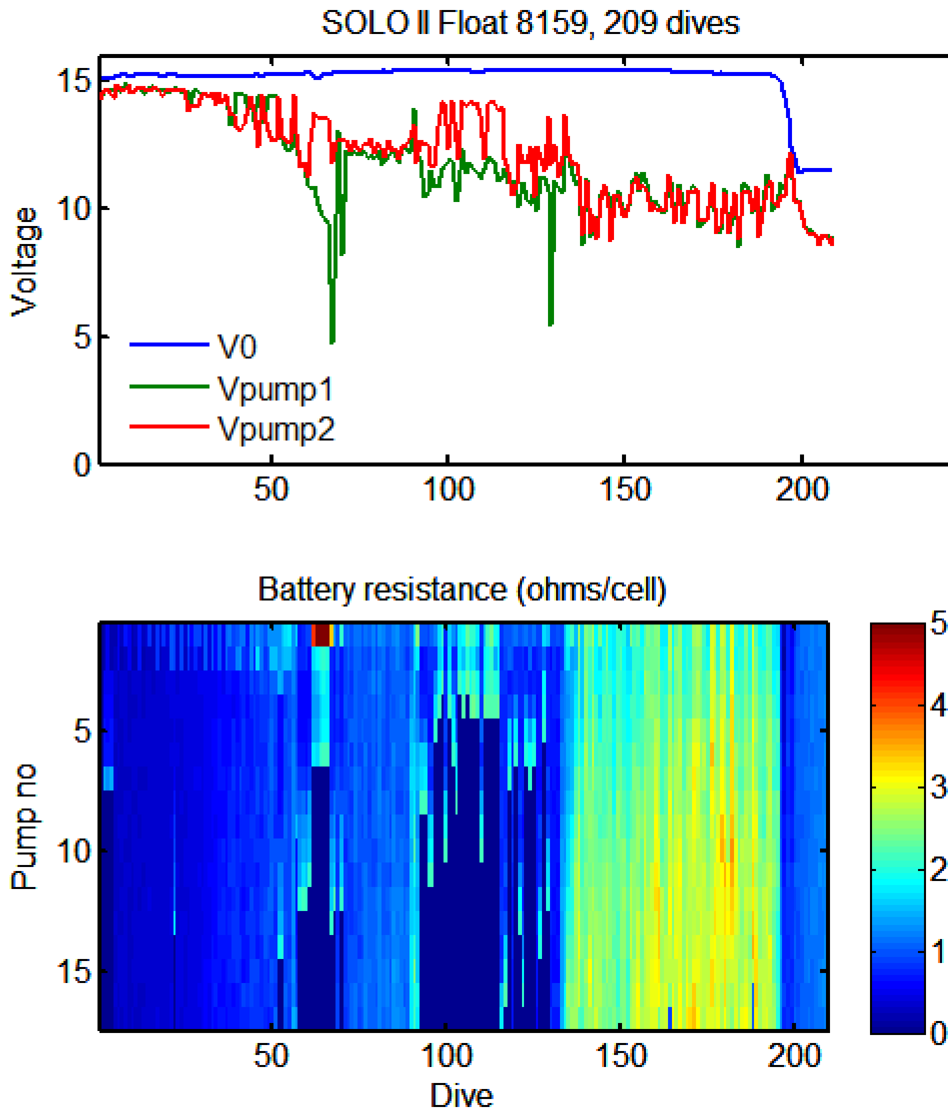

Figure B5. SOLO II float 8159 had three Electrochem packs (12 DD cells), and it ran for 4 years on a 7 day interval. Peak currents were 0.6-1 a/cell.

Float 8159 had an internal resistance of 0.5 V/cell to start. At the beginning, there was little suggestion of voltage lags associated with passivation. However, starting around dive 135, internal resistance took a jump, with an average value of around 2.5 ohm/cell. The internal resistance was roughly constant through the ascent.

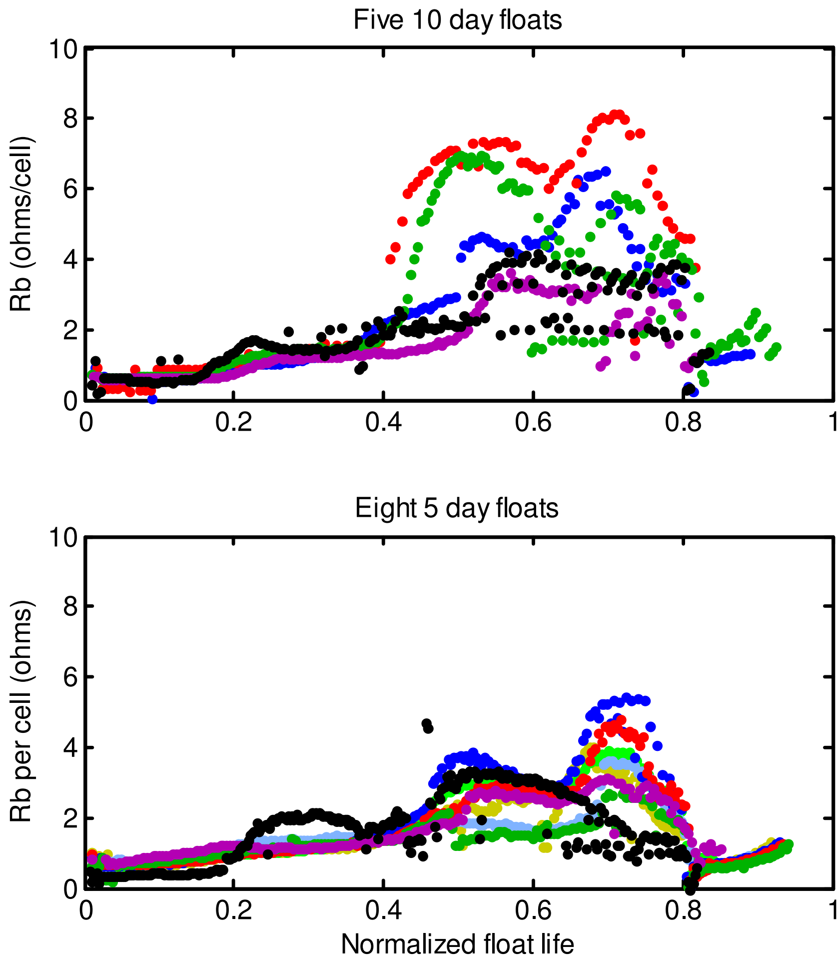

Figure B6. Per cell passivation resistance Rp for 5- and 10-day SOLO-II floats. Each float is plotted with a different color.

Figure B6 shows *Rb* from 5-day and 10-day SOLO II floats, all of which reached the end of life. These *Rb* are from the first pump pulse beginning the ascent. Passivation in 10-day floats is roughly double the 5-day floats, but the variability is roughly a factor of 3 for floats that are essentially identical.

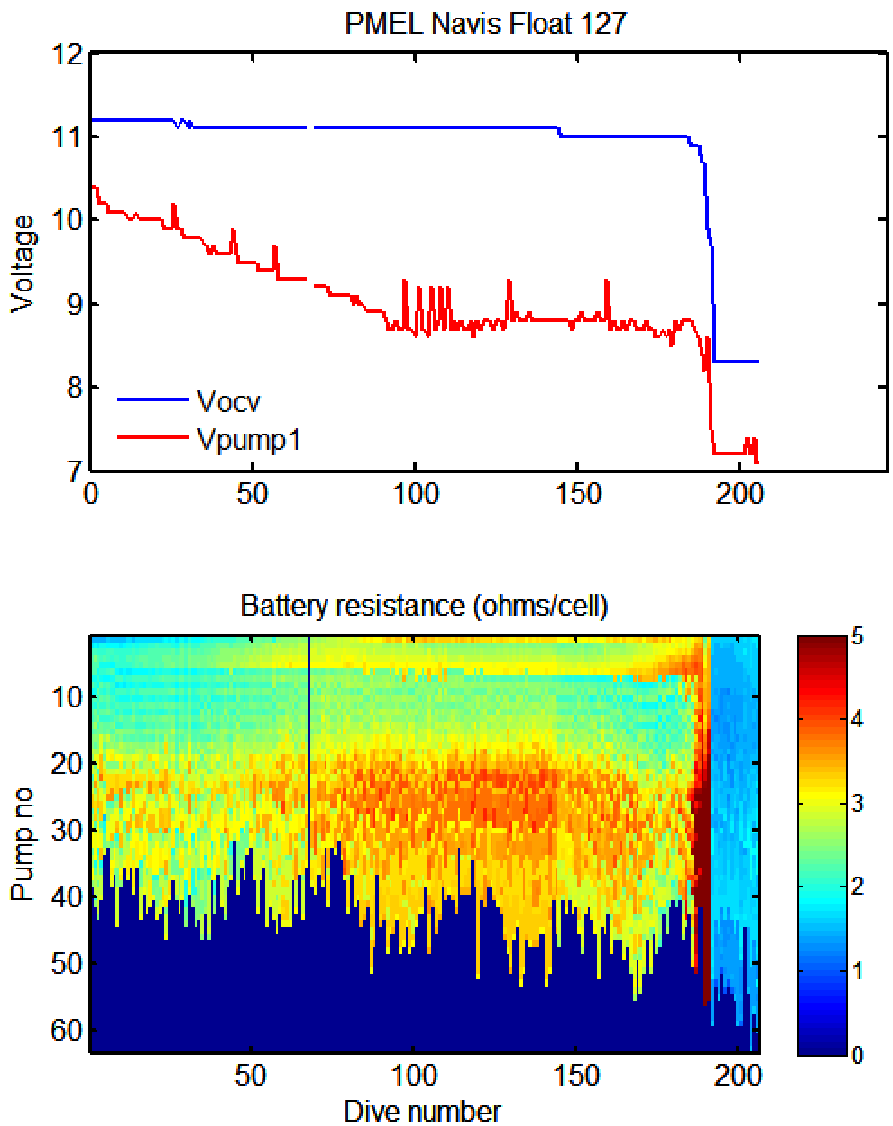

Figure B7, Core Argo Navis float with 10 day dive intervals. Peak currents are around 250 ma/cell.

The pattern of battery resistance in PMEL Navis float 127 (Figure B7) does not fit well with either passivation or steady internal resistance. Passivation seems to appear in the middle of the mission with 3 ohm/cell during the first pump pulse. It diminishes a little for the second pump pulse, which looks a little like passivation, but the resistance then goes back up again. Drawing a load does not dissipate this resistance. The pattern looks considerably different from SOLO II floats.

The float 127 pattern of battery resistance is typical of the seven PMEL Navis floats that are near the end of their missions. The same pattern is visible in CSIRO floats (below), but with lower resistance.

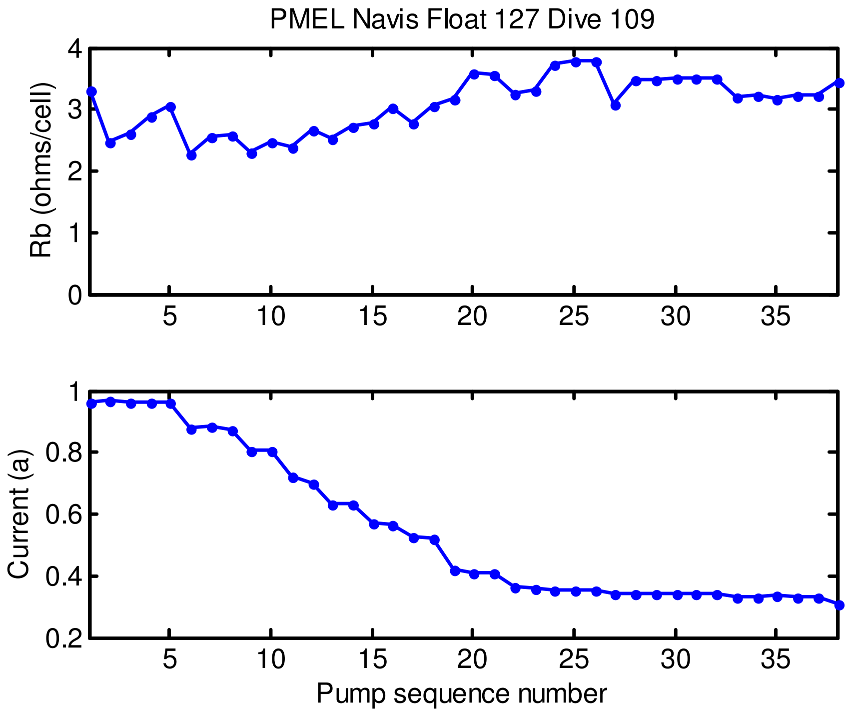

Figure B8. Battery resistance and pump current for a mid-mission dive from PMEL Navis float 127.

Figure B8 shows how *Rb* varies with pump cycles. The pump current in the bottom panel is a surrogate for pressure. The first sequence of five 30 s pump pulses was at 2000 m, where the pump current is the highest. These pulses were each separated by 10 s of no power. The internal resistance fell a little after the first pulse, but rebounded after that. This behavior is inconsistent with either passivation or steady internal resistance.

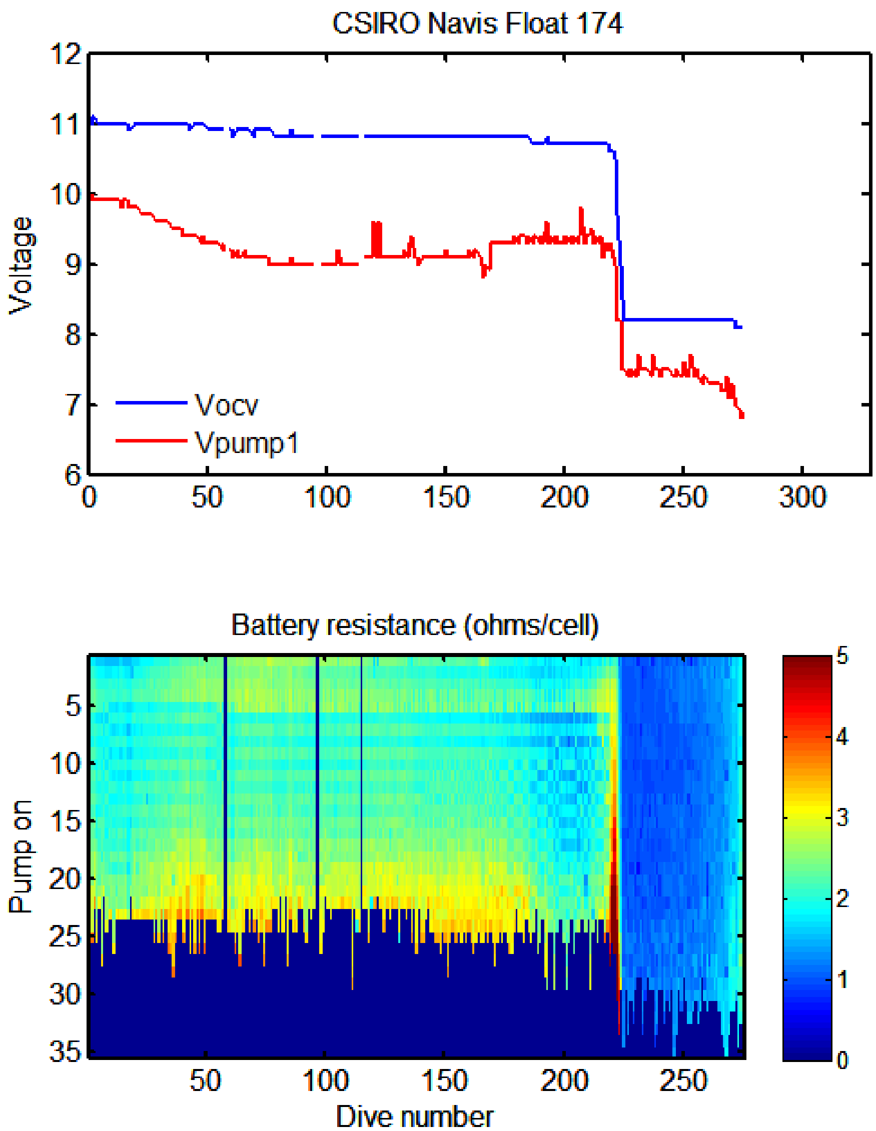

Figure B9. CSIRO Navis float 174 operated like a core Argo float, except that it dove every three days instead of ten.

The pattern of resistance for CSIRO float 174 (Figure B9) is similar to the PMEL Navis floats, except that *Rb* is lower. Lower resistance is likely caused by the float's shorter dive intervals. Resistance starts small then grows with time, diminishing toward the end of the mission.

Appendix C
Dana Swift's Float 7553 Energy Budget

```
$ Cmd Line: Apex260Sbe41cpApf9iOptodeIsus down=120 Eo=5200 m=4
of=/app/swift/EnergyBudget.7553
$
$ Hydrography:    Hawaii-Pacific (21.85N, 155.03W) Sep-09-1973
$      pres    temp     sal    density
$      dbar       C     PSU       g/ml
$       0.0  25.527  35.133   1.023282
$      10.0  25.527  35.135   1.023327
$      20.0  25.531  35.146   1.023377
$      30.0  25.536  35.148   1.023420
$      50.1  25.495  35.285   1.023623
$      76.1  22.779  35.226   1.024500
$     101.2  21.420  35.233   1.024997
$     126.3  20.299  35.195   1.025383
$     151.4  19.643  35.192   1.025664
$     176.5  18.128  34.946   1.025974
$     201.6  16.691  34.771   1.026300
$     226.7  14.940  34.510   1.026613
$     251.9  13.488  34.361   1.026922
$     303.1  11.342  34.209   1.027459
$     353.4   9.662  34.169   1.027958
$     404.8   8.655  34.159   1.028351
$     454.1   7.914  34.195   1.028721
$     504.5   7.151  34.205   1.029075
$     554.8   6.478  34.253   1.029440
$     605.2   6.230  34.313   1.029752
$     655.6   5.793  34.330   1.030056
$     706.1   5.643  34.368   1.030337
$     757.5   5.351  34.400   1.030636
$     806.9   5.105  34.423   1.030913
$     858.4   4.866  34.445   1.031197
$     908.9   4.589  34.453   1.031470
$     959.4   4.481  34.472   1.031730
$    1009.9   4.295  34.489   1.031997
$    1111.0   4.016  34.505   1.032507
$    1212.1   3.737  34.527   1.033020
$    1313.3   3.444  34.543   1.033531
$    1415.5   3.243  34.555   1.034031
$    1515.7   3.035  34.564   1.034519
$    1617.1   2.834  34.576   1.035014
$    1719.4   2.664  34.585   1.035507
$    1819.8   2.518  34.595   1.035988
$    1922.3   2.371  34.604   1.036477
```

```
$    2023.8   2.219  34.613   1.036962
$    2227.0   2.028  34.626   1.037911
$    2434.5   1.895  34.639   1.038870
$    2636.0   1.737  34.648   1.039799
$    2837.7   1.650  34.657   1.040716
$    3041.7   1.583  34.662   1.041634
$
$ Battery model:             Lithium
$    Maximum current:         1 Amp
$    Initial energy reserves: 5200 kJoules
$    Number of battery packs: 4
$    Self-discharge rate:     2%/year
$
$ Float Model:                          Apex260Sbe41cpIridium
$    Down time:                         120 hours
$    Ballast piston position:              16
$    Initial piston extension:             25
$    Piston full extension:               227
$    Target pressure:                    1050 dbar
$    Park pressure:                     1050 dbar
$    CP activation pressure:                950 dbar
$    Park-n-Profile cycle length:             254
$    Vertical rate of ascent:              0.1 dbar/sec
$    Pressure sample-rate during autoballast:    1 hr
$    Pressure sample-rate during low-res ascent: 10 sec
$    Pressure sample interval in vertical:       2 dbar
$    Table of sampled pressures (dbar):
$         6   15   20   25   30   35   40   45   50   55   60   65   70   75   80
$        85   90   95  100  110  120  130  140  150  160  170  180  190  200  210
$       220  230  240  250  260  270  280  290  300  310  320  330  340  350  360
$       380  400  450  500  550  600  650  700  750  800  850  900  950 1000 1050
$      1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800
$      1850 1900 1950 2000
$
$ Bouyancy engine model:                     Apex(260ml)
$    Mass:                              25775 g
$    Compressibility:                      2.53e-06 per dbar
$    Thermal expansion coefficient:           6.9e-05 per C
$    Winding resistance of pump motor:         3.776 Ohms
$    Back-EMF generation factor of pump motor: 64.6 volts/(ml/sec)
$    Volume pumped per A/D count:              1.157 ml/count
$    Pump current as a function of pressure (dbar, Amps):
$       (   0, 0.120)  (  41, 0.122)  (  62, 0.125)  (  97, 0.135)  ( 155, 0.150)
$       ( 234, 0.160)  ( 334, 0.190)  ( 445, 0.230)  ( 569, 0.255)  ( 700, 0.295)
$       ( 834, 0.330)  ( 972, 0.370)  (1107, 0.410)  (1248, 0.450)  (1386, 0.490)
$       (1517, 0.550)  (1620, 0.590)  (1689, 0.620)  (2500, 0.828)
```

$
$ Sensor Model: Sbe41cp
$ Power consumption during continuous STP measurement: 0.28 Watts
$ Energy consumed for STP sample (Volts, Joules):
$ (4.0, 5.10) (8.0, 5.10) (10.0, 5.20) (11.0, 5.20) (12.0, 5.30)
$ (13.0, 5.30) (14.0, 5.30) (15.0, 5.60) (16.0, 5.60)
$ Energy consumed for PT sample (Volts, Joules):
$ (4.0, 0.450) (8.0, 0.450) (10.0, 0.450) (11.0, 0.450) (12.0, 0.450)
$ (13.0, 0.450) (14.0, 0.450) (15.0, 0.450) (16.0, 0.450)
$ Energy consumed for P-only sample (Volts, Joules):
$ (4.0, 0.090) (8.0, 0.090) (10.0, 0.090) (11.0, 0.090) (12.0, 0.090)
$ (13.0, 0.090) (14.0, 0.090) (15.0, 0.090) (16.0, 0.090)
$
$ Oxygen Sensor Model: Optode
$ Energy per sample: 1.4 Joules
$ Telemetry bytes per sample: 48
$
$ Nitrate Sensor Model: ISUS
$ Energy per sample: 45 Joules
$ Metabolic current drain: 1.06 milliamps
$ Telemetry bytes per sample: 400
$
$ Controller Model: Apf9i
$ Metabolic current drain: 80 microamps
$ Wake-state current drain: 8 milliamps
$ Boot-up: 0.16 Joules/boot-up
$ P-only sample: 0.4 Joules/sample
$ PT sample: 1.15 Joules/sample
$ PTS sample: 5.6 Joules/sample
$
$ Telemetry model: Iridium (Daytona 9522A)
$ Power consumption during connect: 4.2 Watts
$ Effective data transmission rate: 160 bytes per second
$ Time required to establish and break login: 60 sec
$ Power consumption by GPS module: 0.221 Watts
$ Typical time required to acquire GPS fix: 120 sec
$
$ Telemetry payload:
$ Number of profiles: 374
$ Total: 23125.2 kbytes
$ Mean: 61.8 kbytes/profile
$ Standard Deviation: 2.0 kbytes/profile
$ Minimum: 58.4 kbytes/profile
$ Maximum: 65.3 kbytes/profile
$

Subsystem:	percent	mean	stdDev	min	max
(374 profiles)	%	kJ	kJ	kJ	kJ
Apex(260ml):	28.9	4.01	0.000	4.01	4.01
Apf9i:	10.0	1.39	0.000	1.39	1.39
Iridium/GPS:	13.9	1.94	0.054	1.85	2.03
Isus:	21.3	2.97	0.000	2.97	2.97
Optode:	0.6	0.09	0.000	0.09	0.09
Sbe41cp:	20.2	2.80	0.000	2.80	2.80
Self-Discharge:	5.0	0.70	0.412	0.00	1.42
Total:	100.0	13.90	0.416	13.11	14.69