From:	Dana Swift
To:	Webb Research, Pete Furze
Date:	October 31, 2017
Subject:	**Hypothesis: Hull corrosion as an AWOL failure mechanism for APEX.**

During the Float User Group Meeting in September, I showed the images at the right. I wondered aloud if this exceedingly unlikely and serendipitous recovery revealed a hitherto unknown AWOL mechanism.

This is PMEL's Apex (WrcId) 3020 that was deployed in the South Pacific in February, 2007. The float functioned for only 58 profiles before it drifted into shallow water and became stuck to the bottom (∼850m) of the ocean in October, 2008. In July, 2015, the float was recovered from the seafloor by a fishing trawler and transported to port in New Zealand.

The region inside the red ellipse in the top image reveals corrosive erosion so severe that the o-ring has been exposed. The loss of containment resulted in the flooding of the float. The contact in New Zealand reported that no trace of the anode remained.

A major topic of the meeting related to achieving longer-lived floats. Statistics and data analysis demonstrate that the most effective way to increase the average lifespan is via reliability improvements.

We have a couple of undergraduate students (Ian & Chanelle) working with our group and so after the meeting was over, Rick asked them to review available engineering data from deployed floats to look for evidence of various failure mechanisms so that we could work on fixing them. They started by reviewing all 48 UW floats that were deployed on the 2010 voyage of the Kaharoa. This ensemble of floats were homogeneous except that some were equipped with compressees; all used ARGOS telemetry.

Figure 1: PMEL Apex 3020 was recovered from the ocean bottom by a fish trawler. *Upper:* The region inside the red ellipse reveals corrosive erosion so severe that the o-ring has been exposed. The loss of containment resulted in flooding of the float. *Lower:* The painted hull appears to be unaffected by corrosion. The redish discoloration suggests rust that leaked out from inside the float.

Analysis: The syndrome and the hallmark symptom.

Ian's analysis revealed a widespread systematic set of symptoms that are the topic of this report. A canonical example is shown in Figure 2. The symptoms are a gradual gain of buoyancy relatively early in the float's life followed by long period of steady buoyancy and then frequently a sudden severe loss of buoyancy prior to premature failure of the float. The crucial hallmark of this syndrome is the sudden severe loss of buoyancy just prior to float failure.

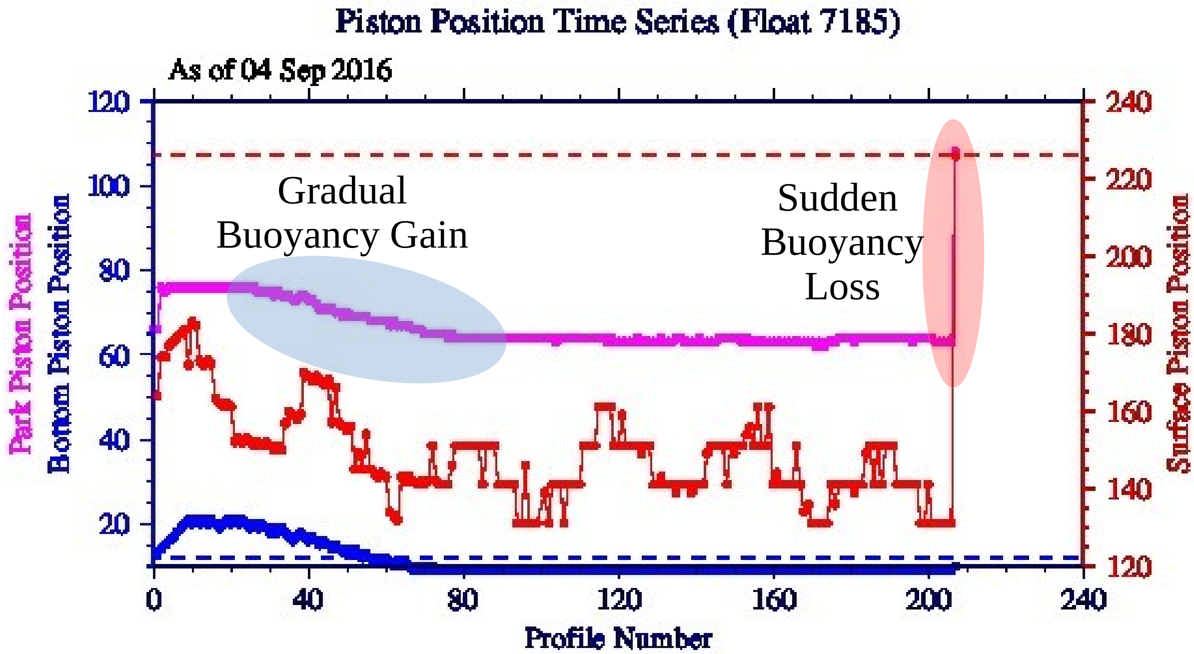

Figure 2: The magenta curve measures the float's buoyancy during the park-phase of each profile cycle. The blue shaded region corresponds to a gradual gain of buoyancy that is compensated by piston retraction. The red shaded region represents a sudden loss of buoyancy just prior to float failure.

The magenta curve represents a profile-series of the park piston position. Of course, during the park phase, the float actively ballasts itself to maintain the user-specified park pressure (ie., 1000dbars). Hence, the park piston position represents an accurate measure of the float's buoyancy. The shaded blue region in Figure 2 suggests that the float is reducing its buoyancy in order to compensate for a gradual increase in overall buoyancy of the float. Thereafter, the buoyancy remains steady until profile 207 when the float apparently suffers a sudden loss of buoyancy before failing entirely.

Hypothesis: Flooding due to corrosion-induced loss of containment.

I have cast the description above in a way that is consistent with and suggestive of the same mechanism that caused PMEL's float 3020 to fail. My hypothesis is that the gradual gain of buoyancy is caused by the corrosive loss of anode mass and eventual loss of aluminum mass that starts out distributed over the unpainted anodized surfaces of the upper and lower end-caps. Over time, the corrosion bores through the protective anodizing and thereafter the corrosion becomes more focused on a relatively smaller area of exposed raw aluminum. Eventually, a leak-path develops that causes the sudden loss of buoyancy. After a leak develops, most floats flood and sink without ever reaching the surface again. However, some floats manage to profile once or twice after a leak first develops. These floats exhibit the crucial hallmark symptom that so strongly supports the hypothesis.

Other explanations for the symptoms shown in Figure 2 can be conjured that do not involve the gain or loss of buoyancy. However, Figure 3 demonstrates that this same cluster of symptoms are widespread and systematic. Forty-five out of the total forty-eight floats in the ensemble that Ian analyzed exhibit these symptoms. The systematic character of these symptoms renders any alternate hypotheses that I can think of to be not viable.

Of these forty-five floats, twenty-six floats failed prematurely leaving nineteen that still remain functional after more than seven years of operation. Ten of these floats that failed exhibited the sudden buoyancy loss just prior to failure. It is these ten floats that lend credibility to the supposition that all twenty-six floats failed due to corrosion-induced flooding.

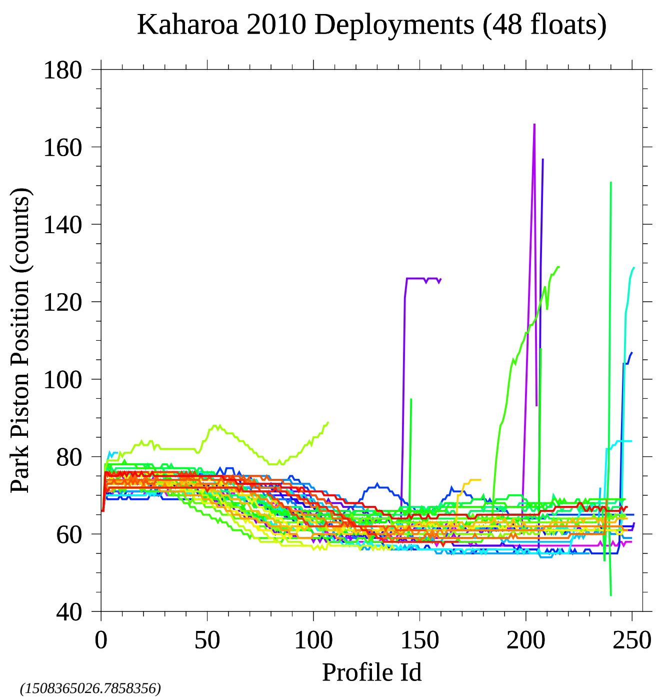

Figure 3: The profile-series of the park piston position for the ensemble of 48 floats reveals a coherent pattern of gradual buoyancy gain in the span between profiles 35 and 135. The buoyancy gain of 10–15g is surprisingly uniform for all floats except one. This strongly suggests a systematic causal mechanism.

Change of anode material.

If the hypothesis is correct then this represents a large-scale systematic premature failure mechanism that did not exist previously. We have quite a number of floats that are still functioning 9-12 years after deployment that do not suffer this syndrome.

I think we have identified an important clue that potentially represents the root cause of these failures. I think that at some time prior to 2010, the anode material was changed from aluminum to zinc.

Here is my evidence: UW still has old CTDs and float mannequins that were assembled in the early days of ARGO and are used for demonstration purposes. These have anodes on them that were manufactured circa a decade or more ago. We measured the wet and dry weight to be W=3.9g and M=7.0g, respectively. Hence, the material for these old anodes has a specific gravity of $\frac{\rho}{\rho_w} = \frac{M}{M-W} = 2.3$ which is consistent with an aluminum alloy. We also measured the wet and dry weight of recent anodes to be W=17.6g and M=20.5g, respectively. Hence, the recent anodes have a specific gravity of 7.1 which is consistent with zinc.

Hence, these measurements leave no doubt that the anode material has changed; my guess is that the recent anodes are zinc. We've been aware since the earliest days of ARGO that zinc anodes do not offer effective protection with anodized aluminum hulls. I strongly urge you to consult Doug Webb regarding this topic. I recall two separate episodes where Dan Webb had difficulty with finding a vendor of suitable aluminum anode material. My recollection is that the aluminum alloy contained mercury which became a problem for US manufacturers. I think that he ended up finding a Chinese manufacturer.

As mentioned, I strongly urge you to consult Doug Webb regarding the use of zinc anodes with aluminum hulls. I think there are three potential problems:

- The protection capacity of zinc is less than that of aluminum. For a given mass, aluminum will protect longer than zinc. The New Zealander that was possession of PMEL's float 3020 reported that no trace remained of the anode.
- Some zinc alloys have higher galvanic potential than 6061 aluminum from which the hull and end-caps are made. Obviously, such a zinc alloy won't work because the aluminum is more anodic than the zinc.
- Zinc can self-protect by forming a nonconductive scaly crust. Figure 4 shows an anode that has started to form this crust after only brief exposure to saltwater.

Figure 4: A white scaly crust has started to form on this anode after only brief submersion in saltwater.

Circumstantial confirmation of zinc anode as cause for buoyancy gain.

A few days ago, I entrained Elizabeth Steffen to ask about details of WrcId 3020 that is shown in Figure 1. Later, she identified this same syndrome in some of her Apex floats from around 2009. In particular, she provided me with nearly ideal circumstantial evidence that the change in anode material might indeed be the root cause of the gradual gain in buoyancy that is characteristic of this syndrome.

PMEL Apex (WrcId) 2332 was deployed near Chile in January, 2006, and then eventually recovered by Chilean fishermen in June, 2009, after it drifted into shallow water. The float was refurbished at WRC which included replacement of no wet parts except for the anode. The float was re-deployed near Hawaii in August, 2010, and executed 245 profiles before failing for unknown reasons (ie., an AWOL failure).

The left plot of Figure 5 shows the profile-series for the first deployment. Note that the park piston position remains steady throughout the mission until profile 104 when the float drifted into shallow water. The symptoms of the syndrome are completely absent during this deployment.

The right plot of Figure 5 shows the profile-series for the second deployment. The park piston position remains steady at 77 counts for the first 28 profiles after which it gradually decreases to 65 counts at profile 130. This 12-count change is very consistent with the gradual increase in buoyancy of UW floats as shown in Figure 3.

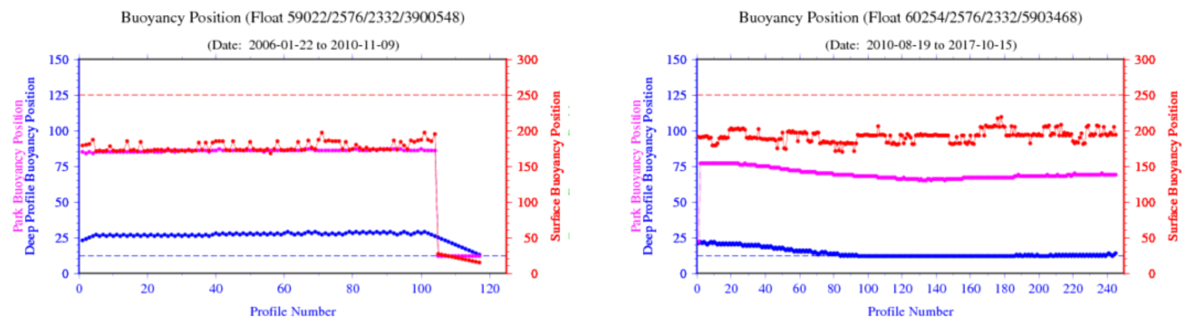

Figure 5: PMEL Apex (WrcId) 2332 was deployed, recovered, refurbished, and redeployed. No wet parts were replaced during the refurbishment except for the anode. Symptoms of the syndrome are absent in the first deployment but present in the second.

For these two missions executed by the same float, the parts in direct contact with seawater differed only due to replacement of the anode. This constitutes pretty convincing circumstantial evidence that the anode was the root cause of the gradual increase in buoyancy that is characteristic of this syndrome. It strongly suggests that the change in anode material happened sometime between 2006 and 2010.

Confirmation of hypothesis.

In order to confirm the hypothesis, we are looking into the possibility of recovering a float that has exhibited the syndrome described herein. Of particular interest is an iridium Apex float that exhibits the canonical symptoms, has executed ~ 200 profiles, and happens to be suitably located to facilitate recovery. We are considering only Iridium APEXs because they have a recovery mode, are subject to remote control, and they use GPS for geolocation.

None of the 48 floats mentioned in this report are good candidates for recovery because they all used ARGOS telemetry and they are in the open southern Pacific Ocean.

Another vein of potential recovery options relates to floats that have washed up on a beach somewhere or have been picked-up by fishing boats and transported to port. Historically, these have almost all been ARGOS floats because they remain transmitting at the surface for much longer and because they can still effectively communicate with satellites even if laying on a beach.

Until we (or someone else) can examine a float affected by this syndrome to look for corrosion, the corrosion hypothesis will remain unconfirmed. It is also conceivable that other hypotheses could fit the available symptoms and data. Can you think of any competing hypotheses that could reasonably explain all of the symptoms described herein?

To help facilitate your review of the data from the 45 affected floats referenced in this report, I have provided the ApfId and WrcId for each float in Table 1. To view a profile-series plot of the park piston position, point your browser to the URL: **http://runt.ocean.washington.edu/argo/engineering/????/index.shtml** where "????" represents the ApfId.

We have broadened our analysis to survey all of our floats (deployed 2000 to present) in order to learn the scope of this syndrome. The analysis indicates that this syndrome was completely absent for floats deployed

ApfId	WrcId	ApfId	WrcId	ApfId	WrcId	ApfId	WrcId	ApfId	WrcId	ApfId	WrcId
6536	4970	6537	4971	6630	4854	6542	4972	6746	4963	6747	4857
6748	4984	6749	4987	6750	4992	6751	4983	6745	4985	7138	4986
7140	4990	7141	4991	6752	4973	6753	4974	6754	4989	6756	4968
6757	4998	6711	5020	7166	5022	7167	5026	7181	5031	7182	5032
7183	5030	7184	5063	7185	5064	7186	5065	7187	5066	7189	5070
7190	5071	7191	5072	7153	5016	7154	5017	7155	5018	7158	5023
7151	5013	7152	5015	7156	5019	7159	5024	7160	5025	7161	5027
7164	5028	7165	5029	0066	4434						

Table 1: The ApfId and WrcId of 45 floats that are affected by the syndrome described in this report.

in 2008 or earlier. Floats deployed in 2009 or later are affected in manner that appears large-scale and systematic.

It takes at least a year after deployment before on-set of symptoms and at least two years before the gradual buoyancy-gain can be clearly identified. Deployment year 2014 is the most recent for which we can confirm significant numbers of affected floats. We're seeing hints of on-set in floats deployed in 2015. It's too early yet to find symptoms in 2016 deployments.

Based on analysis done so far, it seems pretty evident that whatever is causing this syndrome exists in floats right up to present.

Corrective measures.

If this hypothesis is eventually confirmed, then it's clear that we've suffered the introduction of a large-scale systematic failure mechanism that didn't exist a decade ago. We are still analyzing data to deduce the timing of this new failure mechanism. In connection with this, it would be useful to learn when the change from aluminum to zinc anodes happened. If these dates coincide then it will be further evidence that the change from aluminum to zinc anodes is the root cause.

If confirmed, then correcting the problem might be as straightforward as reverting to the use of a suitable aluminum anode. To further protect the vulnerable parts of the end-caps, we could also consider painting a band near the hull o-ring groove to seal it from contact with seawater.

As previously mentioned, one of the main objectives of the September meeting was to find a way to make floats last longer. Most people seem naturally to gravitate toward adding energy. I find this a little frustrating because we already pack a decade's worth of energy in floats, we don't need more.

More than half of floats fail before executing 250 profiles; well before energy limitations are of concern. The most effective way to make floats last longer is to improve reliability. Aside from shallow water, AWOL mechanisms are the biggest cause of float failures for us. AWOL mechanisms are more difficult to attack because they leave no obvious trace in engineering data; the universe of hypothetical AWOL mechanisms is large and no data exist to eliminate any particular hypothesis.

The trawling of PMEL float 3020 was terribly unlikely but also very fortunate. It unequivocally identified hull corrosion as a cause of AWOL failure; this much is no longer hypothetical. Now we've identified symptoms in engineering data that are consistent with large scale systematic float failures due to corrosion and hull failure.

In one respect we are fortunate because the corrosion hypothesis (if correct) might reasonably apply to 45 of the 48 floats referenced herein, twenty-six of which we have hitherto regarded as AWOL failures. Hence, if the hypothesis is correct then we can make a very significant reliability improvement by fixing only a single problem. We might not have to contend with fixing lots of lower-grade problems in order to make real progress toward improving reliability.

Revision Log.

The following revision log summarizes the history of this article.

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$Log: WrcApexCorrosion.tex,v $
Revision 1.4  2017/10/31 18:14:03  swift
Fleshed-out corrective measures by reporting that a significant improvement
to float reliability might be realized by fixing the corrosion mechanism.

Revision 1.3  2017/10/23 20:02:15  swift
Phil Sutton revealed that no trace of an anode remained on PMEL
Apex (WrcId) 3020.

Revision 1.2  2017/10/20 19:29:00  swift
Elizabeth Steffen provided nearly ideal circumstantial evidence
to support the hypothesis that the change in anode material is
the root cause of the syndrome.

Revision 1.1  2017/10/19 17:21:56 swift
Corrosion hypothesis for failure mechanism of AWOL floats.
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