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Reliability Case Notes No. 4

Autosub6000 and Autosub3 actuator potentiometer
failure analysis and testing report

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ABSTRACT

During the *James Cook* Cruise 27 Autosub6000 aborted mission 12 due to a failure in the position feedback potentiometer of the stern plane actuator. The same actuator is used on Autosub3 which is heading to the Pine Island glacier in Antarctica in January 2009. A similar failure of the Autosub3 actuator while under the ice would result in the loss of the AUV.

This report initially describes the investigation into the failure of the feedback potentiometer and shows that the potentiometer's conductive plastic track became detached from its ceramic substrate and broke up. The report then describes the testing performed to evaluate the reliability of the potentiometer. This involved an accelerated aging test to simulate the worst case conditions seen by the potentiometer in the actuator. This was achieved by oscillating the potentiometer at 4Hz to simulate the actuator movements whilst cycling the pressure of the Morlina 10 oil surrounding the potentiometers.

During the testing the 10kΩ potentiometers used in the actuator were not available, and so 5kΩ potentiometers from the same range were tested as a substitute. It was assumed that these 5kΩ potentiometers would produce similar results, however it was found during the testing that the formulation of the 5kΩ potentiometer track was different from the 10kΩ; whether this affects the reliability is not known.

Due to the large amount of time required to perform each test only 16 5kΩ potentiometers were tested. Although no failures occurred, the sample was too small to give a high statistical confidence that the potentiometers would survive the cruise. To further reduce the risk four 5kΩ potentiometers that were to be used on Autosub3 were tested for approximately 72 hours in a 'burnt in' process. As an early failure similar to that of Autosub6000 potentiometer would have been detected during this process, the chance of the potentiometers failing was significantly reduced. Thus the burnt in potentiometers were considered acceptable for use on Autosub 3 during the Pine Island campaign.

KEYWORDS

Autosub, Autosub6000, actuator, potentiometer failure, pressure testing

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Terms and Definitions

JC027	Cruise 27 of the RRS *James Cook* (Jul.-Sept. 2008). Principle Investigator Russell Wynn.
D323	Cruise 323 of the RRS *Discovery* (Sept. 2007). Principle Investigator Stephen McPhail.
Autosub3	NERC's 1600m rated AUV developed by the platforms team of USL and it's predecessors
Autosub6000	NERC's 6000m rated AUV developed by the platforms team of USL.

Abbreviations

NERC	Natural Environment Research Council.
NOCS	National Oceanography Centre, Southampton
USL	Underwater Systems Laboratory
AUV	Autonomous Underwater Vehicle
SEM	Scanning Electron Microscope

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1. Introduction

This report details the analysis of the stern plane actuator potentiometer failure that occurred during mission 12 of the Autosub6000 campaign on the JC027 cruise. The report attempts to determine the chance of a similar failure occurring during the Autosub3 Antarctic cruise to take place on the RV *Nathaniel B. Palmer* during the beginning of 2009. This is necessary as a failure in the actuator will cause the loss of the AUV if it occurs under the ice.

2. The Actuator Potentiometer

The Autosub3 and Autosub6000 actuators are oil filled and pressure balanced. They use a potentiometer, which fills with oil through the shaft bearing, to measure the stroke position of the actuator. The actuator stroke is then used to indicate the angle of the control plane. Without this angular feedback it is not possible to control the position of the plane and in effect the vehicle becomes uncontrolled.

The potentiometer used in the actuators is a 10 kΩ Vishay precision industrial potentiometer part number (157-21-10k) (Farnell number 1213248). It is free spinning and hence capable of complete 360° rotation. The part has a rotational life of 10 million shaft rotations, and uses a conductive plastic bonded to a ceramic substrate as the track. The output is connected to the track via a wiper which has three tiny fingers which rub along the track as the potentiometer rotates. The potentiometers are not specifically designed to run in oil, nor are they designed to run at high pressures, thus they are being used outside of their design specification.

2.1 Analysis of the Failed Autosub6000 Potentiometer

The actuator potentiometer failed approximately 6 hours after the start of Autosub6000 mission 12. The AUV was altitude following at just over 4700m and was just about to start the main lawnmower survey when the potentiometer failed. This failure caused the stern plane to move down resulting in the AUV going into a steep dive. Once the AUV had passed the abort depth, power was cut and the abort weight dropped. The AUV then floated to the surface and was recovered.

On investigation of the potentiometer, it was found that the total track resistance was 14.63kΩ, higher than 10kΩ +/- 20% of the spec sheet. The potentiometer also felt rough and wouldn't turn smoothly. Disassembling the potentiometer it was found that the track had started to come away from the substrate (illustrated in Figure 1.) The faint broken section around the edge of the potentiometer is common to all potentiometers examined, and is believed to be part of the laser trimming process for linearity.

Discussions with the ROV team revealed that they had also suffered similar track failures, with the track coming away from the substrate, in their oil filled pressure compensated linear potentiometers used as position feedback for the hydraulic manipulator arms. These potentiometers are designed to run in oil, but not to the pressures seen by the ROV.

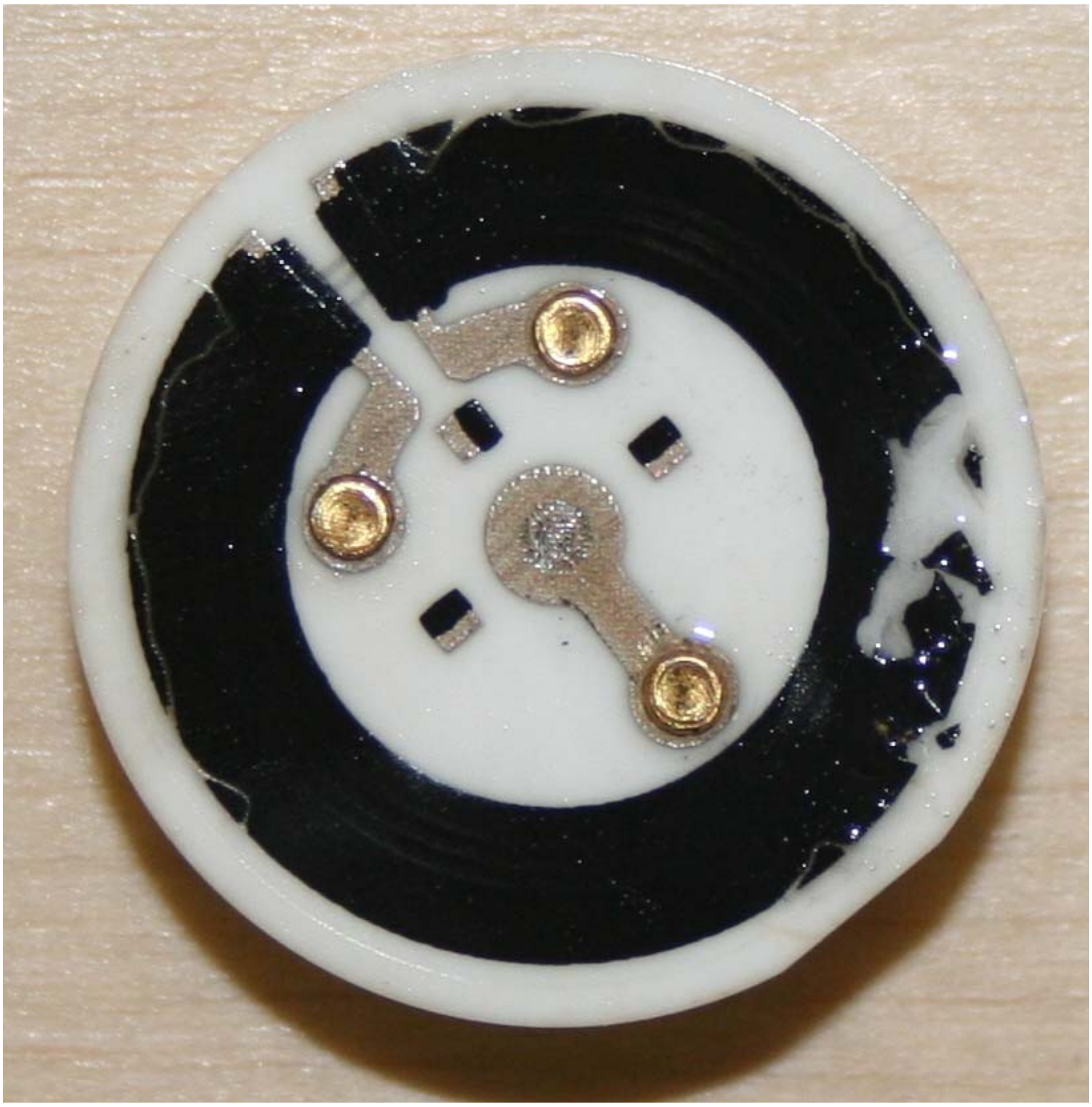

Figure 1: The potentiometer track coming away from the substrate

A more detail investigation of the track was performed using a scanning electron microscope (SEM). This revealed cracks in the track surface (Figures 2 and 3) near the detached region indicating this area was starting to fail as well. The hypothesis is that these cracks are the pre-cursor to the track failing and act as initiation points for large sections of the track to come away from the substrate.

The images suggest that the full failure mechanism started with the initiation cracks and these cracks were then ‘picked’ at when the fingers of the wiper move over them. These fingers would then start lifting out sections of the track as appears to have happened in one section of the failed potentiometer, illustrated in Figure 4. Here the track marks can clearly be seen intersecting the section that has come away from the substrate.

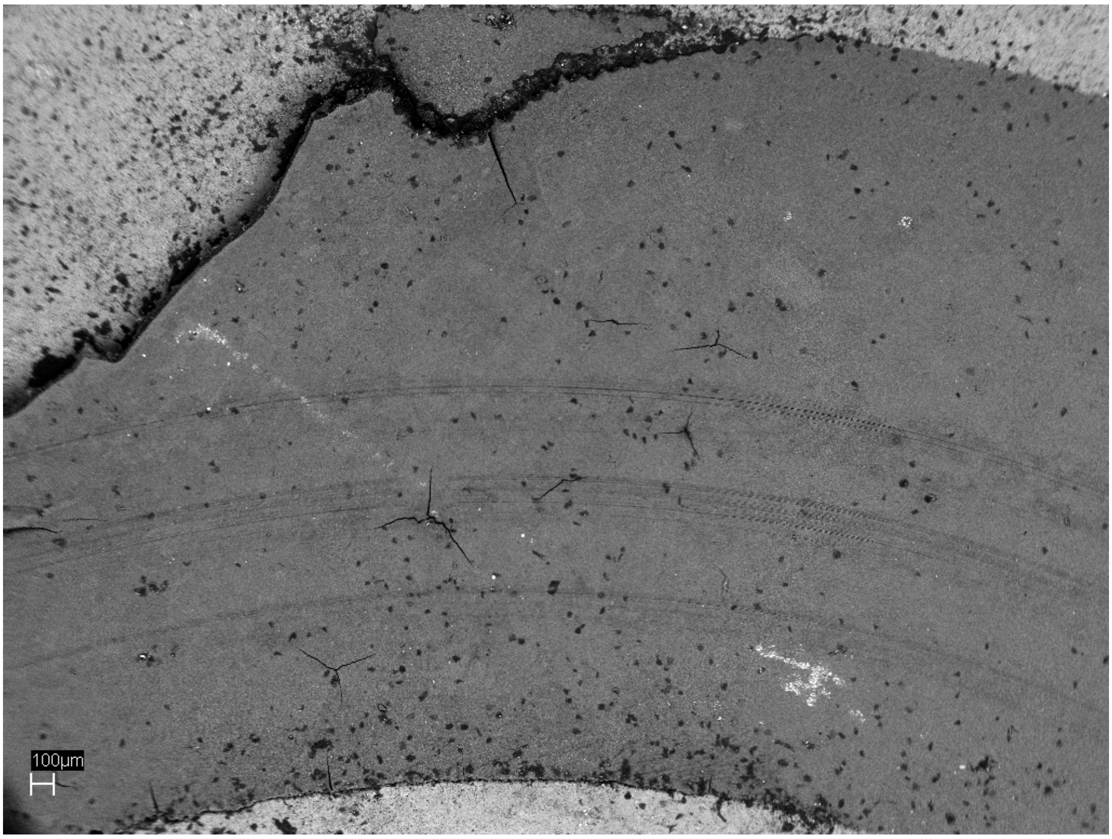

Figure 2 – Initiation cracks of the failed potentiometer

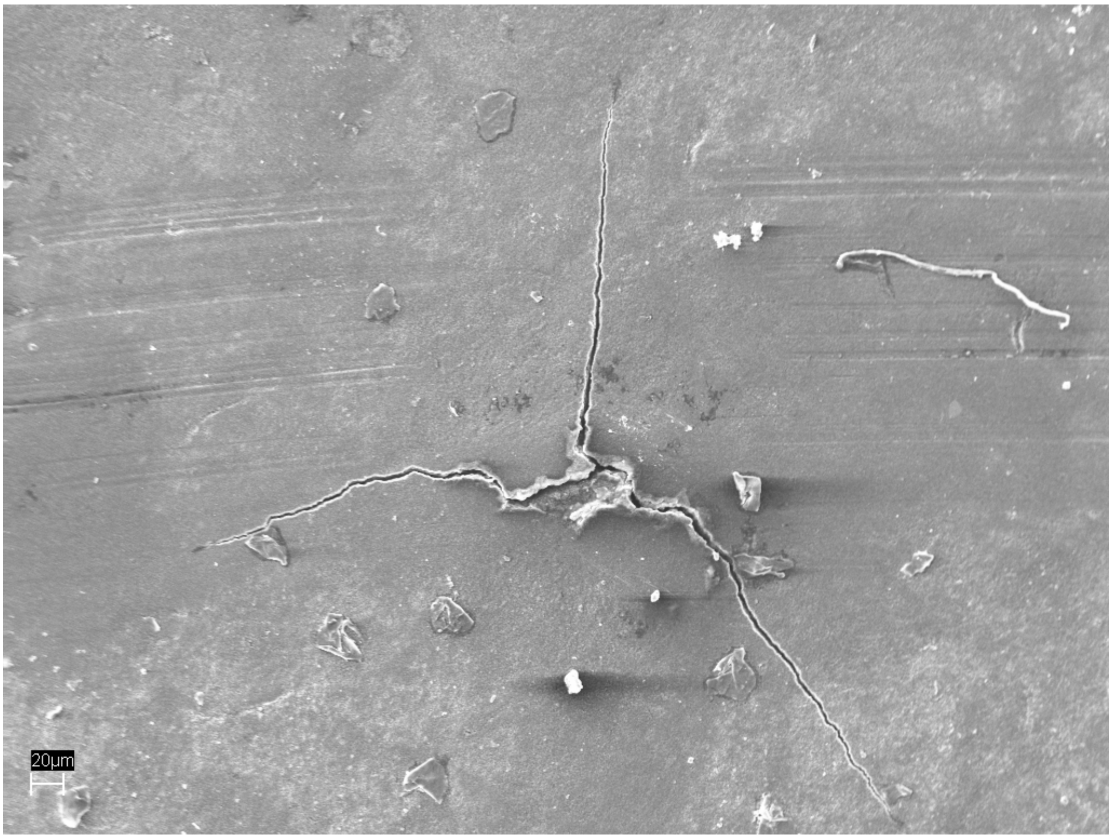

Figure 3 – Close up of one of the initiation cracks of the failed potentiometer

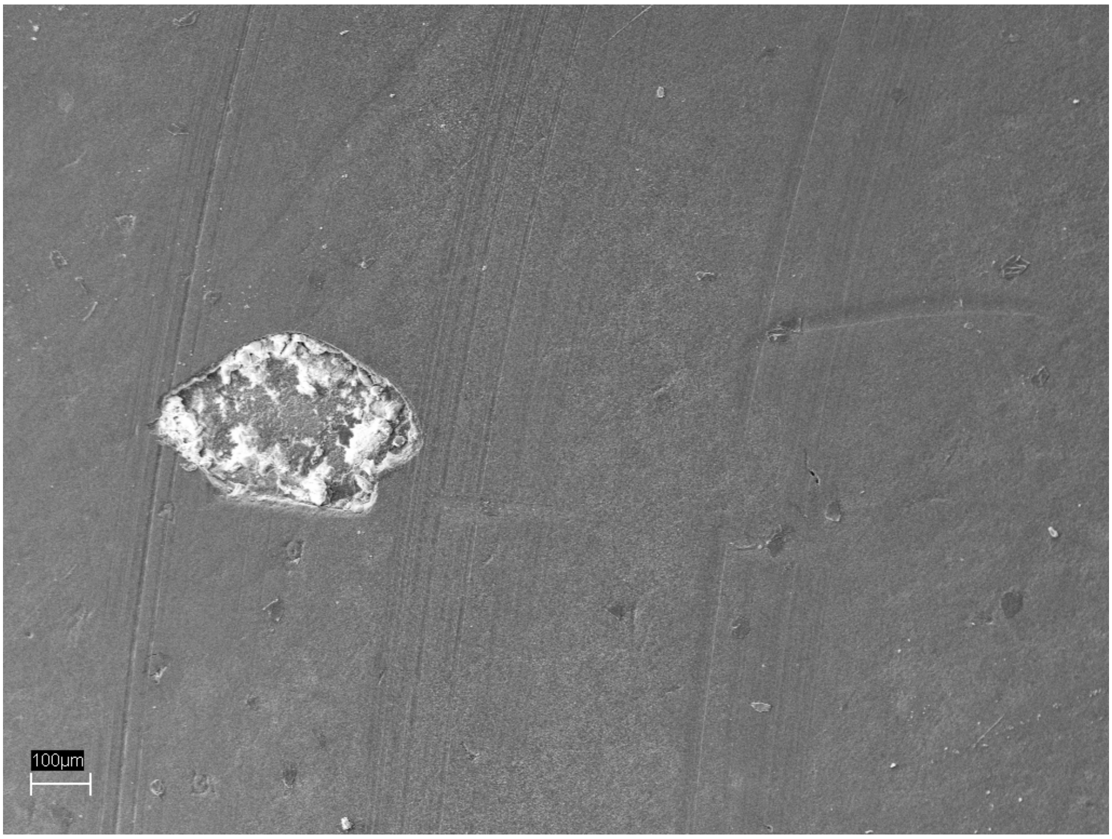

Figure 4 – Hole in track assumed to occur after an initiation crack has been picked away by the potentiometer wiper

2.2. Potentiometers Life History

The potentiometer had failed after a relatively short life and had seen significantly less rotations than the 10 million cycles design life. It has been subjected to the following pressures and cycles during lab testing and subsequent deployments at sea.

Lab Test	Duration	Cycles	Maximum Pressure
Bench 1	16 hours 32 minutes	11904	0
Bench 2	1hr 5minutes	780	0
Pressure 1	6 hours 58 minutes	5016	680bar
Pressure 2	21 hours 42minutes	15624	680bar
Total	***46 hour 17minutes***	***33324***	***680bar***

Table 1. Laboratory based testing of the failed actuator

Mission	Mission Duration	Estimated Cycles	Maximum Depth
Mission 10	26 hours 6 minutes	93960	4535.3m
Mission 11	24 hours 26 minutes	84360	4727.2m
Mission 12	5 hours 33minutes	19980	4733.2m
Total	***56 hour 5minutes***	***201900***	***4733.2***

Table 2. In-service use of the failed actuato.

On the AUV the stern plane angle is measured at approximately 1Hz, and for simplicity it is assumed that the plane ‘dithers’ at 1Hz for the estimated cycles calculation, although this is probably an overestimation (see the stern plane position traces in Appendix A)

2.3. Comparisons with the other actuators

Two other actuators containing the same type of potentiometer have been used on Autosub6000 without any problems. Both the rudder and the other stern plane actuator had been used for longer periods of time than the failed actuator. The data for their laboratory testing along with their in-service use on the trials cruise (D323) and the first science mission (JC027) are shown in Appendices B and C respectively. Table 3 compares the lives seen by the potentiometers used in the three actuators.

	Failed Actuator	**Stern Plane**	**Rudder**
Testing	46hr 17min 33324 cycles 680bar	52hrs 34min 37848 cycles 650bar	51hr 57min 37356 cycles 634bar (9200psig)
Service at sea	56hrs 5min 201900 cycles 4733.2m	84hrs 1min 302460 cycles 4537.3m	164hrs 30min 592200 cycles 4733.2m
Results	***Failed***	***No observable track damage***	***No observable track damage***

Table 3. The life history of the potentiometers used in the three actuators

Neither the stern plane nor the rudder potentiometers showed the same initiation cracks as seen in the failed potentiometer when examined under the SEM.

3. The Failure Mechanisms

From the analysis of the failed potentiometer it would appear that the failures arises from the breakdown of the bond between the plastic track and the ceramic substrate. It is hypothesised that once the bond deteriorates cracks are formed in the track and then sections are broken away by the scraping of the wipers.

The root cause of the bond failure is not clear. It is not known whether the failure was due to a manufacturing defect such as foreign matter on the ceramic substrate causing bond problems when the plastic track was applied, or to some underlying mechanism associated with the way the potentiometers are used in the actuators. Thus, it is not clear whether we were merely unlucky or whether there is a fundamental problem with the potentiometers. By testing the potentiometers it is hoped that we can answer this question.

As the potentiometers are used outside of their design specification, the following factors have been assessed to see how likely they were to cause the bond failure and subsequent cracking.

- Immersion in oil
- Excessive heat during soldering
- High pressures experienced by the potentiometers

The hypothesis that the oil caused a breakdown in the conductive plastic track was rejected as the potentiometers have been immersed in oil for many months before and after the cruise without any problems.

Another concern was that heating of the track during soldering would cause the track to degrade hence breaking the bond with the substrate and causing the cracking. However, a hot (400+°C) soldering iron was held onto one of the connection pin for a number of minutes until all the pins would flow solder indicating the substrate had got hot. This heating did not appear to affect the track in any way. Also as the ROV had seen similar track failures in their linear potentiometers which weren't subject to heating in the same way the heat hypothesis was rejected.

The final hypothesis was that the pressure would cause the breakdown in the track. This was tested by simulating running conditions of the potentiometer in an accelerated aging test in the pressure pots within NOCS. To speed up the testing a rig was built that could test four potentiometers together. The rig is shown in Figure 5 and Figure 6.

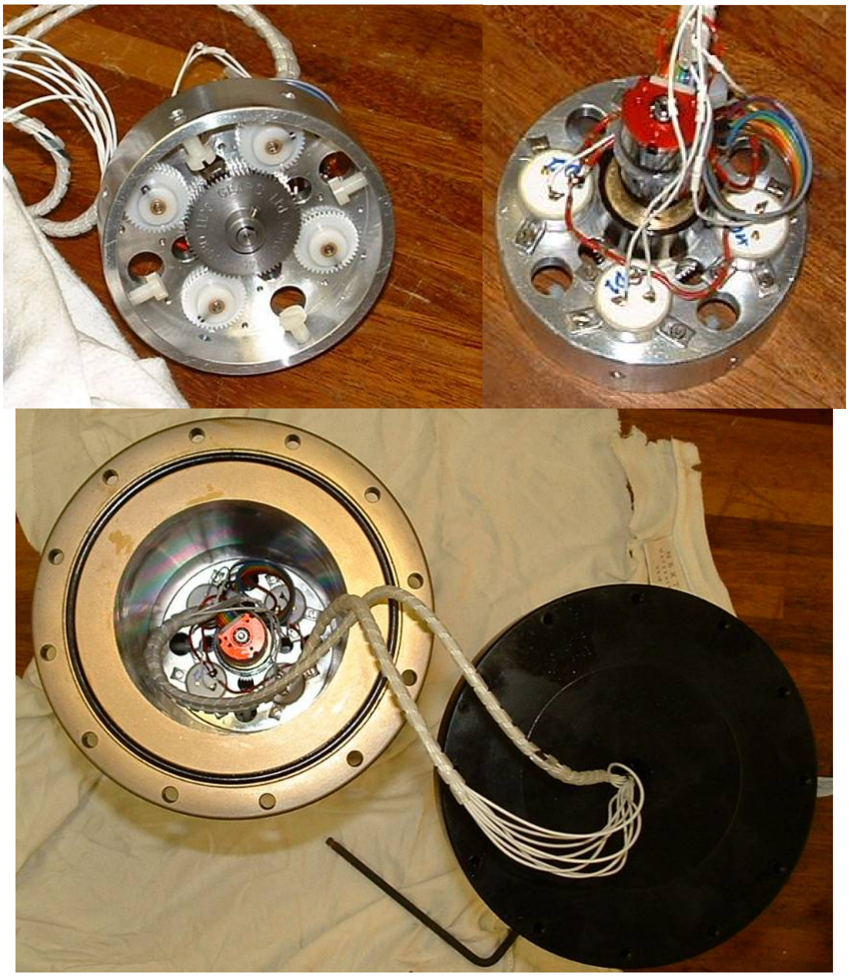

Figure 5 – Internal arrangement of the potentiometer tester

Figure 6 – The potentiometer tester in the large pressure pot

The potentiometers were driven using a Maxon brushless dc motor powered by the Autosub6000 actuator test rig. This in turn was controlled using Labview to control the potentiometer oscillations. One of the potentiometers was used for feedback to the rig. During testing the Labview software logged the resistance of the potentiometer tracks as well as the input voltage and orientation of the potentiometers.

When the testing was started it was not possible to purchase any 10kΩ potentiometers, thus 5kΩ potentiometers from the same product range were bought instead with the assumption that they would produce similar results to the 10kΩ potentiometers. However, it turns out that the potentiometers were not as similar as hoped.

4. Comparison between the 5kΩ and the 10kΩ pot

It was initially thought that the 5kΩ potentiometer would give the same results as the 10kΩ potentiometer as externally they are physically identical. However, during the testing it was found that the formulation of the 5kΩ track is different to that of the 10kΩ track, in both the 0.5% and 2% linearity versions. This difference is illustrated in the high resolution SEM images shown in Figures 7 and 8. The difference in track formulation resulted in the wiper producing substantially more wear in the 10kΩ track than the 5kΩ track as shown in Figures 9 and 10 respectively.

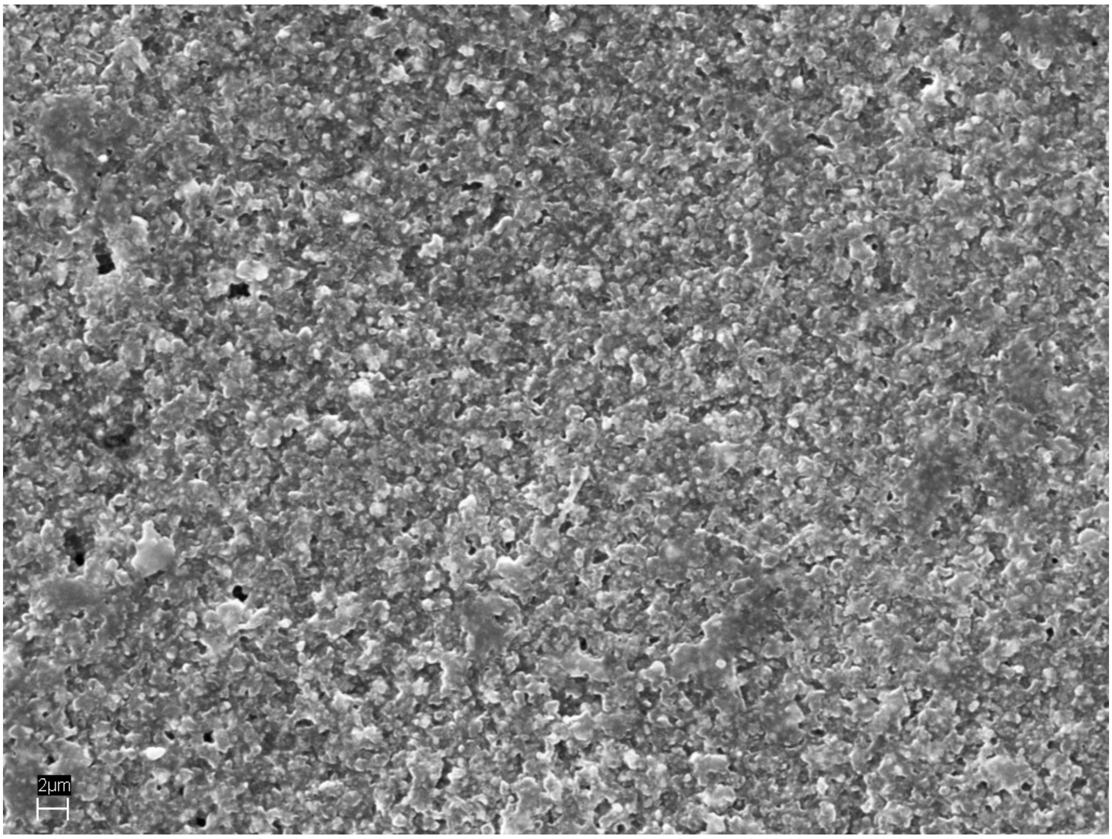

Figure 7 – High resolution SEM image of the 10kΩ potentiometer (AS6k_Stern) surface

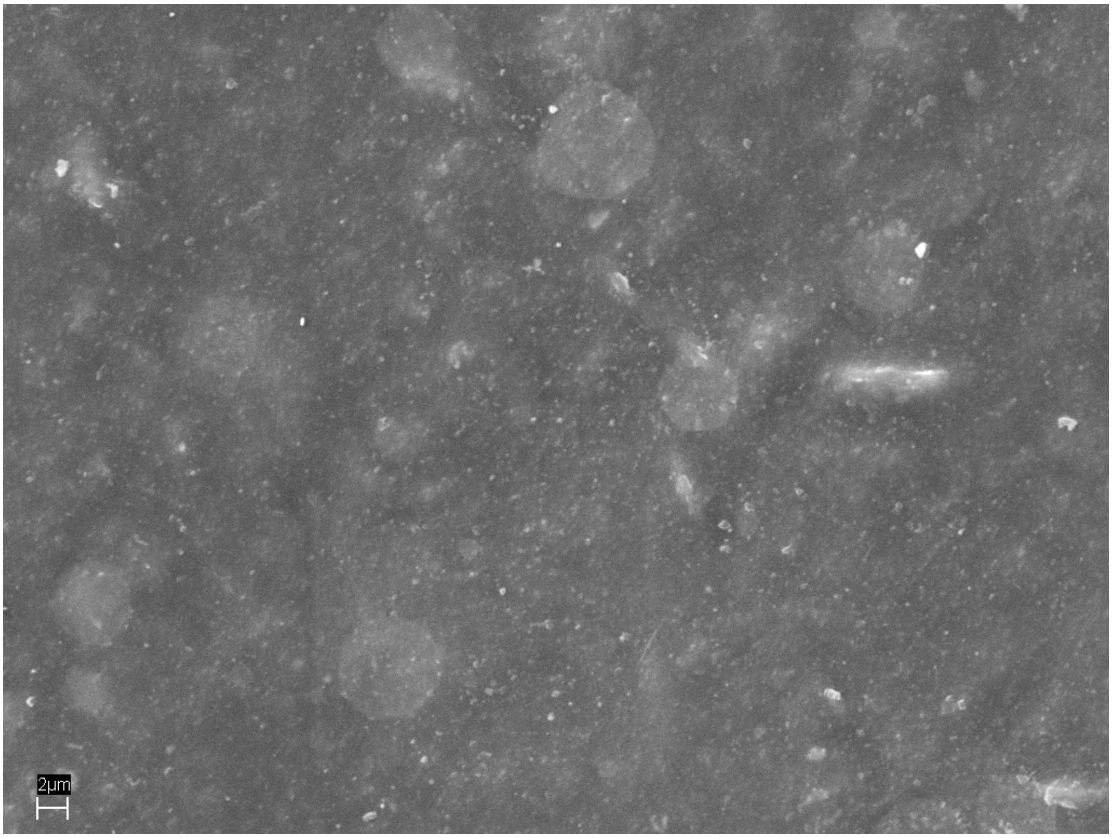

Figure 8 – High resolution SEM image of the 5kΩ potentiometer (A4) surface

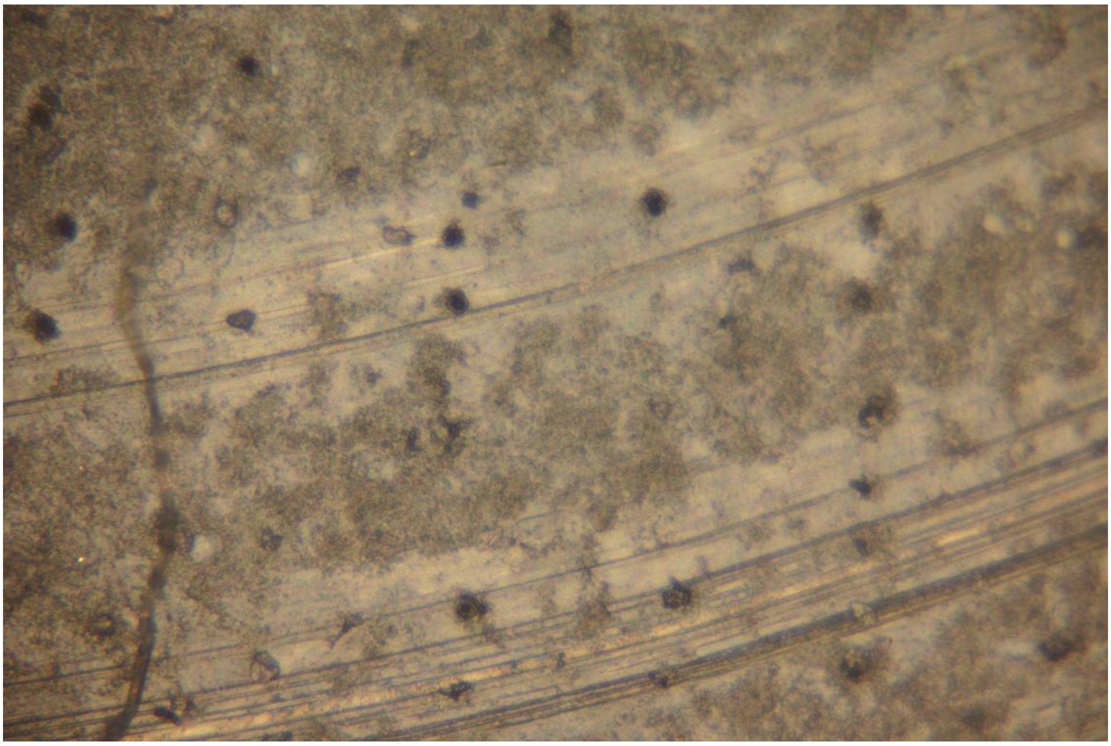

Figure 9 – Track surface scoring 10kΩ potentiometer surface

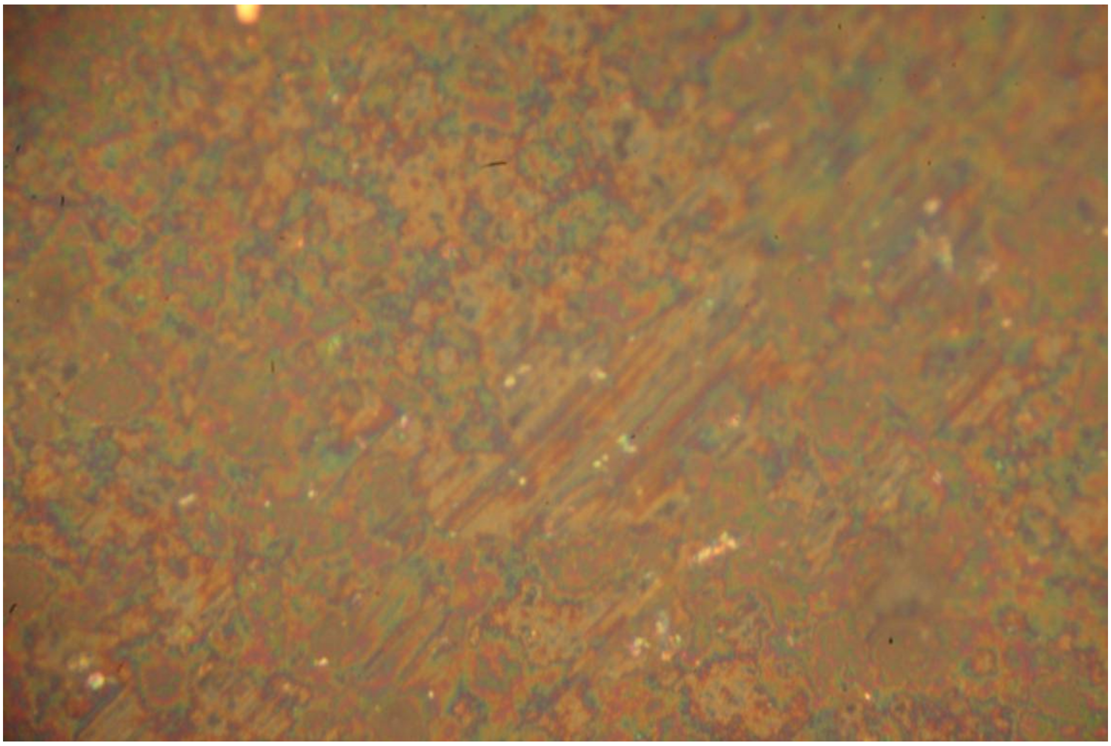

Figure 10 – Track surface scoring 5kΩ potentiometer surface

The difference in the track properties poses a problem as it is not clear whether the failure seen in the 10kΩ potentiometer is dependent upon the track formulation or not.

5. Testing

There were five batches of four randomly selected potentiometers tested using the test rig described previously. Four of these batches (A to D) involved the potentiometer being oscillated during the pressure testing, and the final batch (PT) only involved the potentiometer track. For test PT four potentiometers were dismantled and the exposed track was imaged before and after pressure cycling to see if there were any changes. To identify the potentiometers, each was labelled with the batch letter along with its number within the batch. Thus potentiometer B1 is potentiometer 1 from batch B.

Of the four potentiometer test batches A to D, batches A to C were tested to try and simulate an accelerated Pine Island campaign, with the potentiometers being disassembled and inspected post testing. Test batch D was a ‘burn in’ test for the potentiometers to be used on Autosub3.

The details of the pressure cycling performed during the testing are described in Appendix E.

The details of the testing experienced by each batch are shown in Table 4.

	Pot Type	Test	Max Pressure	Duration (hrs)	Pot cycles	Pressure Cycles
A1 -- A4	5K	Ambient pressure	0bar	24.0967	350077	0
		Pressure testA1	161bar nom (5500psig max)	70.2411	1027512	2
		Pressure testA2	161bar	113.0381	1657719	423
Total				***207.3759***	***3035308***	***425***
B1 -- B4	5K	Pressure testB1	620bar	145.994	2118240	156
Total				***145.994***	***2118240***	***156***
C1 -- C4	5K	Pressure testC1	161bar	94.1667	1260694	353
		Pressure testC2	161bar	67.2117	974232	224
Total				***161.3784***	***2234926***	***577***
D1 -- D4	5K	Pressure testD1	161bar	71.606	1035927	285
Total				***71.606***	***1035927***	***285***
PT1 -- PT4	5K	Pressure testA2	161nom	113.0381	0	423
Total				***113.0381***	***0***	

Table 4 – Details of the potentiometer pressure testing

On completion of the testing the potentiometers (excluding those in batch D) were disassembled and then inspected using a SEM to see if there were any initiation cracks in the surface of the track. None were found in any of the 16 potentiometers (batches A-C and PT).

The resistances of the potentiometer tracks were also measured using a Fluke bench top multi-meter before and after pressure testing, and the results showed very little variation (see Appendix D). This correlates well with the SEM findings.

Finally during the testing the resistance of each track was monitored by measuring the voltage across a 1kΩ resistor which formed the bottom section of potential divider circuit with the track. The voltage was logged using LabView, and the resistance ratio calculated. If the resistor is assumed to be exactly 1 kΩ then the resistance ratio is the track resistance in kΩ.

This continuous monitoring of track resistance revealed that the potentiometer's track resistance is affected by the pressure on the potentiometer. This is illustrated in Figure 11 which shows both the pressure on the potentiometer and the relative track resistance of potentiometer B1. The most likely cause for this change in resistance is the compressive strain in the track due to the hydrostatic pressure.

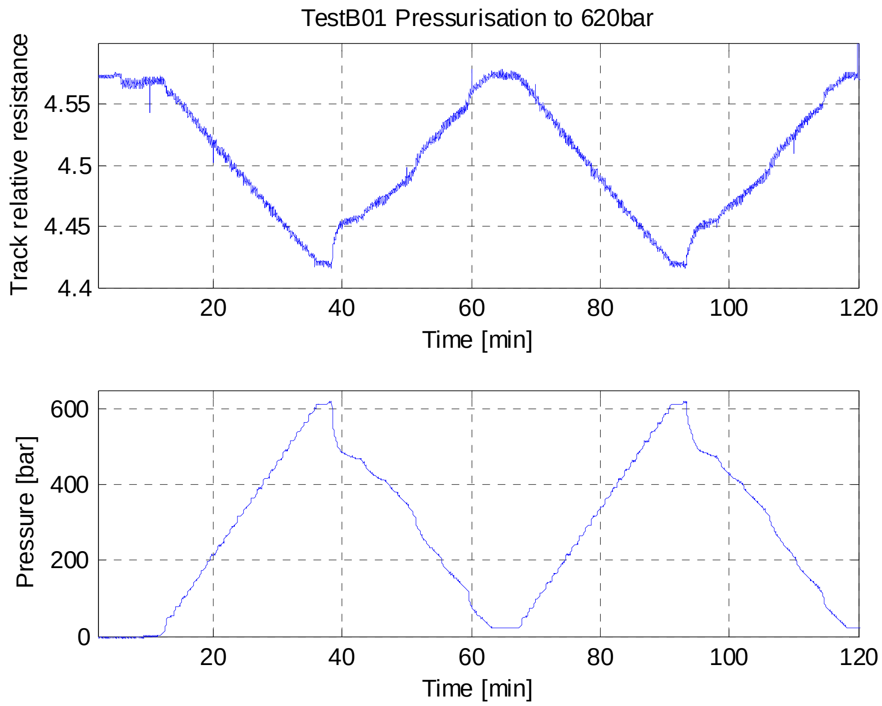

Figure 11 – Effect of pressure on track resistance

The continuous monitoring also showed that there is a small change in the track resistance over the cycling, but that it is minor compared to the pressure related effect. The resistance ratio for track potentiometer B1 for the entire test is shown in Figure12.

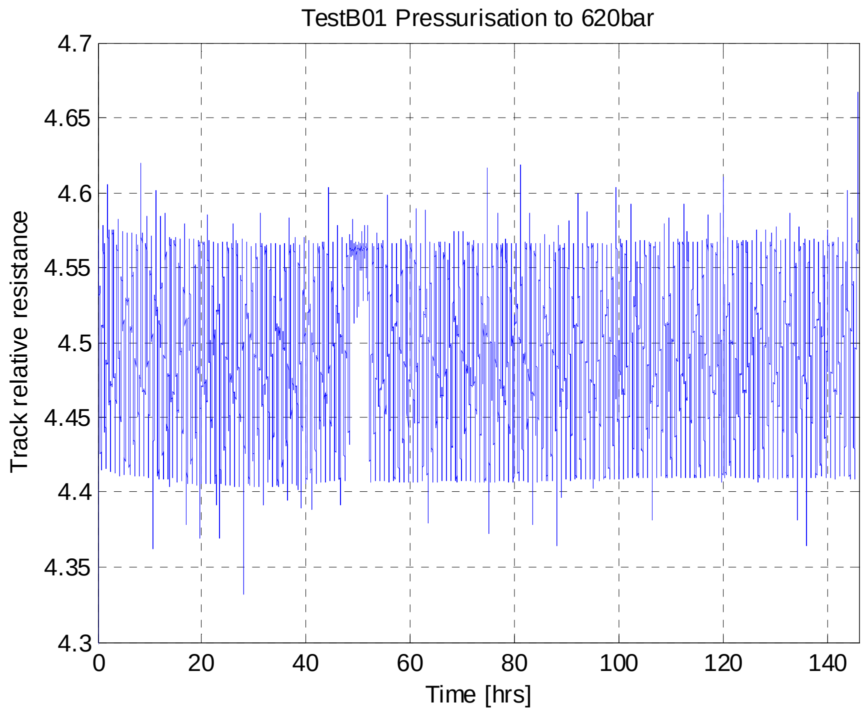

Figure 12 – track resistance variation for TestB01

However, if you look at the resistance during the constant pressure test (testA01) the minor changes in track resistance can be seen more clearly, as illustrated in Figure 13.

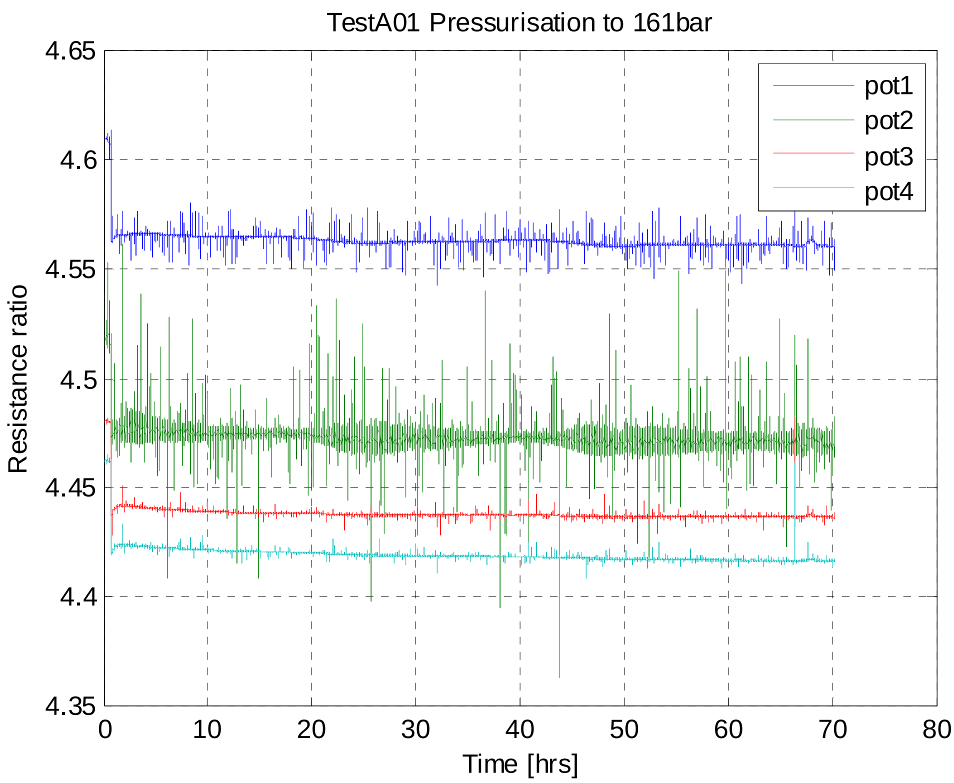

Figure 13 – Change in resistance ratio over time for the testing

6. Statistical Analysis of Results

Although no potentiometer failed during the testing, the sample was small and it is important to quantify the statistical significance of the experiments. As the 5 kΩ potentiometer tracks are different to those of the 10kΩ potentiometers, it is assumed that they are from a different population and only the testing results gathered here are used to calculate the statistics.

As described in Section 5 of this report, 20 potentiometers were tested at different operating pressure regimes (see Table 3). The aim was to infer whether or not the actuator potentiometers would failure during the Autosub3 Pine Island campaign. The following analysis considers that if the potentiometer survives the accelerated aging tests it is equivalent to the potentiometer surviving the Pine Island campaign. The formulation presented in equation 1, is based on statistical sampling theory (Saglietti, 2004). Given a number of n successful tests and the degree of confidence, β, it allows us to compute the probability of failure, p, for the potentiometer.

$$p \leq -\frac{\ln(1-\beta)}{n} \qquad (1)$$

It is usually said, that for a given number of tests n, there is β percent confidence that the probability of failure p is at least lower than the term on the right hand side of the equation.

Figure 14 shows the probability of component failure for different degrees of confidence. All batches were tested for different amount of time. The probability of potentiometer failure for a 200hrs campaign can only be computed using the data from batch A1-A4. On the other hand, if the aim is to estimate the probability of failure for an operation of at least 113 hours, then the data from batches A1-A4, B1-B4, C1-C4 and PT1-PT4 can be used with batch D being ignored as it was only tested for just less than 72 hours. Thus, considering these 16 successful tests, one can infer with 90% confidence that the probability of a potentiometer failure is less than or equal to 0.14. For the same number of tests one can infer with 99% confidence that the probability of a potentiometer failure is less than or equal to 0.29.

The 5 kΩ potentiometer is used in the stern plane as well as in the rudder actuator; the probability that both potentiometers will survive can be computed via joint probability. Assuming that these two events are independent then the joint probability is obtained via the product of individual probabilities. For 16 successful tests (i.e. a campaign of 113 hours), one can infer that the probability of both actuators surviving is at least 0.7396 with a confidence of 90% or at least 0.5041 with a confidence of 99%.

Figure 14 shows that if a lot of 50 potentiometers were tested and if all potentiometers had survived the test then it would be possible to claim a much lower probability of failure for the potentiometer.

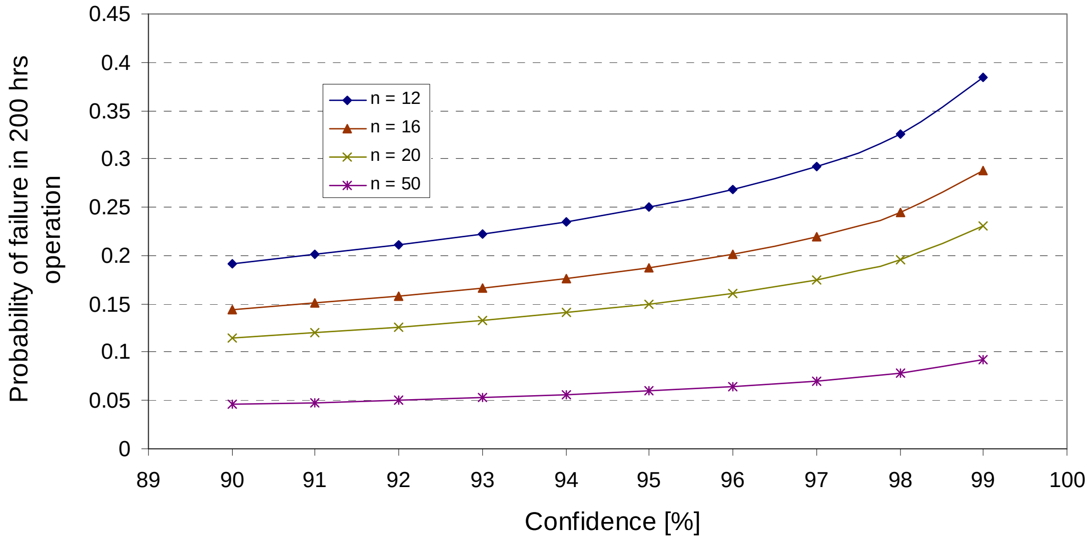

Figure 14 - Probability of potentiometer failure. Considering 12 successful tests (in blue - diamonds); 16 successful tests (red - triangle); 20 successful tests (green - crosses); and 50 successful tests (purple - square)

7. Conclusions & Recommendations

The samples tested to date do not show any similar failures to those seen during the Autosub6000 trial. Unfortunately, the sample size is small therefore, solely using this data, it is not possible to say any more than the chance of both actuators surviving the Pine Island campaign is higher than 74% with a 90% confidence level.

To further increase the survival chances of the potentiometer the batch D potentiometer, which will be used on Autosub3, have been 'burnt in'. This 'burn in' process involves performing the accelerated aging test on the potentiometers for approximately 72hours, using the 0-161bar pressure cycle. This testing would identify any early failures similar to that seen in Autosub6000. Also, as no significant wear was seen on the 12 tested potentiometers (batches A-C) it is reasonable to expect the tested potentiometers to last considerably longer if the testing had continued. Thus, it is assumed that the burn in process has not used up a significant portion of the potentiometer's life. As no problems were found during the testing of Batch D, the risks associated with an early failure of the potentiometer have been significantly reduced.

Therefore the risks of these 'burnt in' potentiometers failing in the same way as the Autosub6000 potentiometer is considered to be minimal, and as such they are considered to be safe to used during the Autosub3 campaign to Pine Island in 2009.

Acknowledgements

We would like to thank Peter Stevenson and Mark Squires for the development of the potentiometer test rig used in this work.

References

Saglietti, F., 2004. Licensing Reliable Embedded Software for Safety Critical Applications. Real-Time Systems, 28, pp.217-236.

Appendix A – Plots of the Stern Plane Actuator Position during Missions 10, 11 and 12

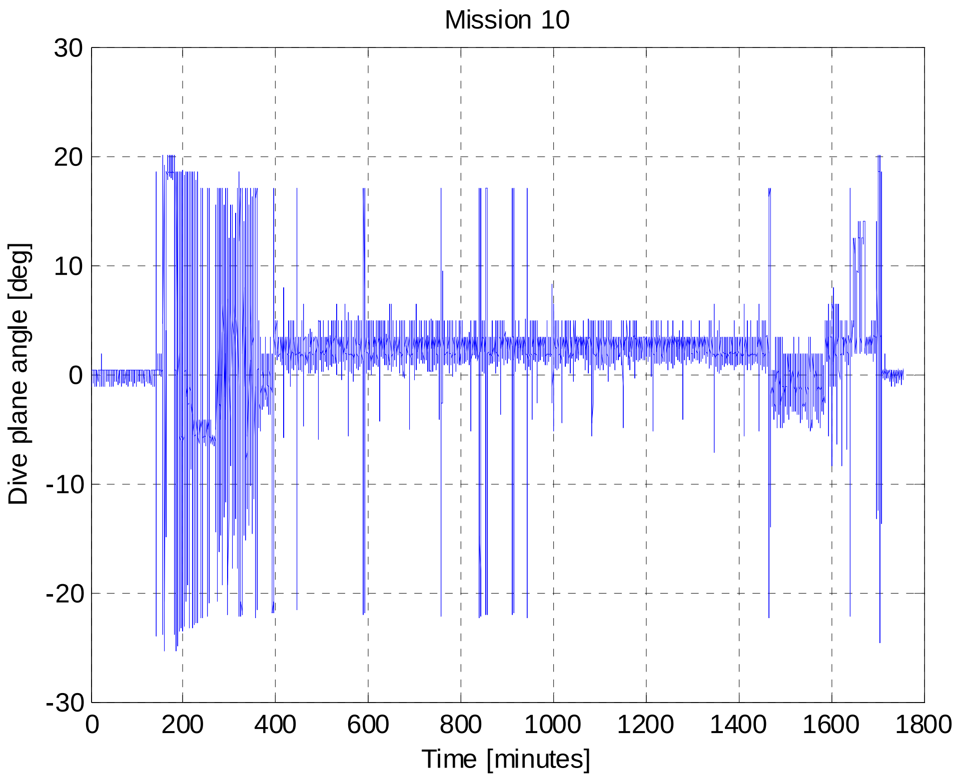

Figure 15 – Stern plane motion Autosub6000 Mission 10

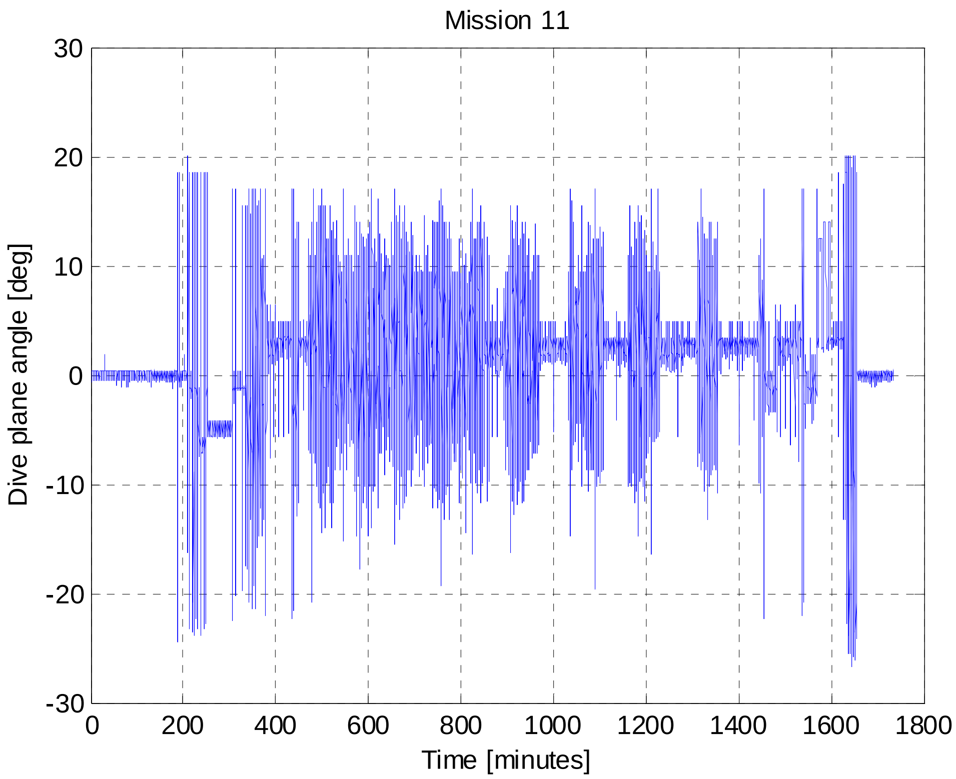

Figure 16 – Stern plane motion Autosub6000 Mission 10

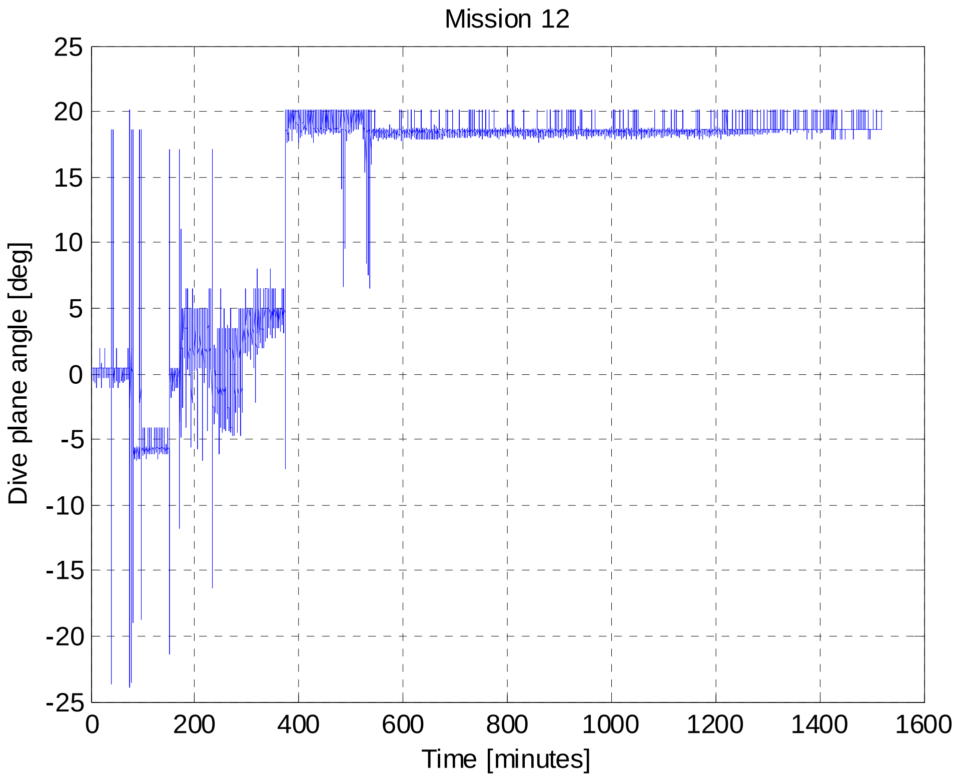

Figure 17 – Stern plane motion Autosub6000 Mission 12

Appendix B – Original Actuator Testing Summary

Actuator Testing Results							
Summary of the actuator testing performed before the Autosub6000 trials cruise of 2007							
The actuators tested were the blue anodised original style actuators							
Compiled by M. Furlong 10th Nov 2008							
Actuator 1 testing							
Test Name	**Date**	**Duration**	**Depth**	**Cycles**	**Offset**	**Amplitude**	**Period**
Act1B001	17-May-07	16min	Bench	192	2.5	1.5	5
Act1P001	22-May-07	4hrs 48min	650bar	3456	2.5	1.5	5
Act1P002	24-May-07	54min	650bar	648	2.5	1.5	5
Act1P003	13-Aug-07	26min	8900psig	312	2.5	1.5	5
Act1P004	01-Sep-07	46hrs	9200psig	33120	2.5	1.5	5
Act1B002	04-Sep-07	10min	bench	120	2.5	1.5	5
	Totals	***52hrs 34min***		***37848***			
Actuator 2 testing							
Test Name	**Date**	**Duration**	**Depth**	**Cycles**	**Offset**	**Amplitude**	**Period**
Act2P001	16-Aug-07	18min	8900psig	216	2.5	1.5	5
Act2B001	28-Aug-07	10min	bench	120	2	1.5	5
Act2P002	28-Aug-07	18hrs 45min	9200psig	13500	2.5	1.5	5
Act2P003a	30-Aug-07	13hrs 30min	9200psig	9720	2.5	1.5	5
Act2P003b	31-Aug-07	19hrs 0min	9200psig	13680	2.5	1.5	5
Act2B002	04-Sep-07	10min	bench	120	2.5	1.5	5
	Totals	***51hrs 57min***		***37356***			

Table5 – Details of the testing of the original actuators

Actuator 1 is the Stern Plane
Actuator 2 is the Rudder

Appendix C – Trials Cruise Mission Summary

Autosub6000 mission List					
Campaign	Mission	Date	Location	Depth	Duration
D323	1	19/09/2007 21:05	50.0931 lat, -4.9478 long.	15.7	1hr 6 min
	2	22/09/2007 06:45	47.2176 lat, -11.1747 long.	4537.3	6hrs 30min
	3	26/09/2007 00:30	47.7936 lat, -11.2900 long.	4280.5	13hr 47min
	4	27/09/2007 16:41	47.2176 lat, -11.1747 long.	4140.3	13hrs 49min
	5	28/09/2007 20:27	47.4759 lat, -10.3724 long.	4100.1	11hrs 29min
	6	30/09/2007 05:15	47.3810 lat, -10.1803 long.	3999.3	4hrs 52min
	7	30/09/2007 11:34	47.3781 lat, -10.1901 long.	501.4	2hrs 23min
	8	01/10/2007 09:34	48.2906 lat, -9.4711 long.	81.9	5hrs 55min
				total time	***59hrs 51min***
JC027	9	08/08/2008 14:27	32.4968 lat, -13.2696 long.	4174	24hrs 10min
	10	14/08/2008 16:36	35.7480 lat, -9.9908 long.	4535.3	26hrs 6min
	11	20/08/2008 08:36	38.0794 lat, -10.4985 long.	4727.2	24hrs 26min
	12	22/08/2008 10:06	38.3659 lat, -10.4041 long.	4733.2	5hrs 33min
	13	31/08/2008 05:34	46.8068 lat, -9.9791 long.	4517.9	24hrs 24min
				total time	***104hrs 39min***

Table 6 – Details of the Autosub6000 missions

Appendix D – Variation in Track Resistance Before and After Testing

Potentiometer	Initial Resistance (k ohms)	Post testing resistance (k Ohms)	Change
A1	4.470	4.483	0.013
A2	4.505	4.504	-0.001
A3	4.455	4.455	0.000
A4	4.438	4.438	0.000
B1	4.426	4.433	0.007
B2	4.417	4.419	0.002
B3	4.354	4.360	0.006
B4	4.324	4.308	-0.016
C1	4.457	4.449	-0.008
C2	4.435	4.429	-0.006
C3	4.446	4.437	-0.009
C4	4.358	4.352	-0.006
D1	4.425	4.434	0.010
D2	4.463	4.471	0.008
D3	4.433	4.440	0.007
D4	4.432	4.440	0.008

Table 7 –Track resistance variations before and after testing

Appendix E – The Test Pressure Record

During the pressure cycling in the large pressure pot, the target and actual pressures were recorded. The actual pressure does not track the target pressure that accurately particularly during the pressure release phase of the cycle (see Figures 18 and 19). This results in the pressure not reaching the target minimum pressure of zero bar. Although not ideal, it was not considered to be a serious issue for these tests.

Two different pressure cycles were used during the testing. The first was intended to vary between 0-161 bar to simulated diving to 1600m (Autosub3's depth rating). This cycled would be performed over a 16 minute period and is shown in Figure 18. The second test was intended to vary between 0-620 bar to simulate diving to 6000m. This was performed over a 55 minute period and the target trace is illustrated in Figure 19.

Although these two basic cycles were used during the testing, there was a programming error with TestC02. Here the 0-161bar test had an extra two minutes at zero bar at the end of the cycle. This did not significantly affect the results.

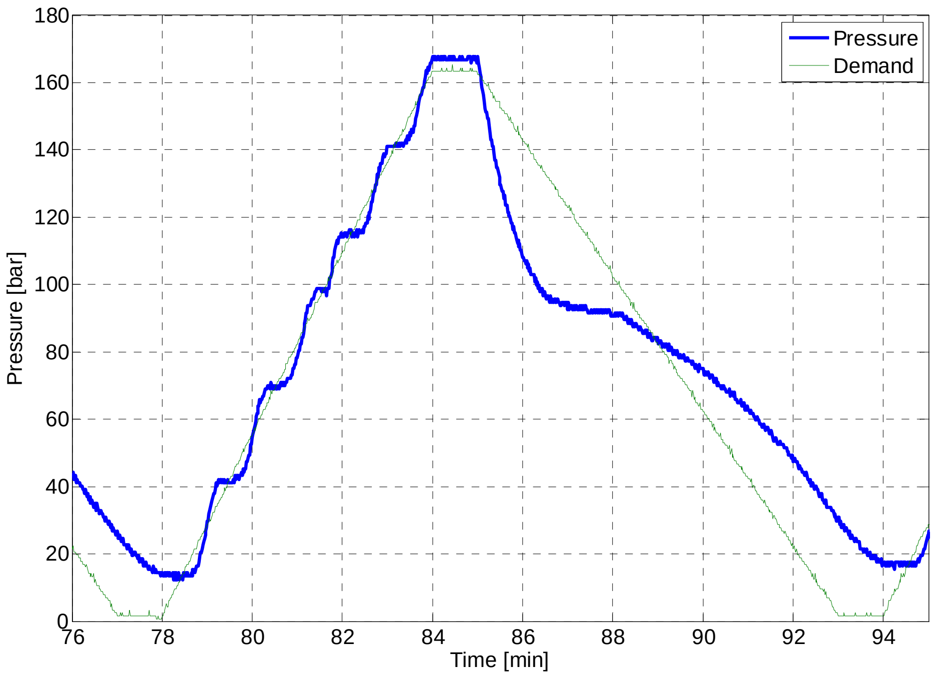

Figure 18 – Single pressure cycle for TestA02 – low pressure test

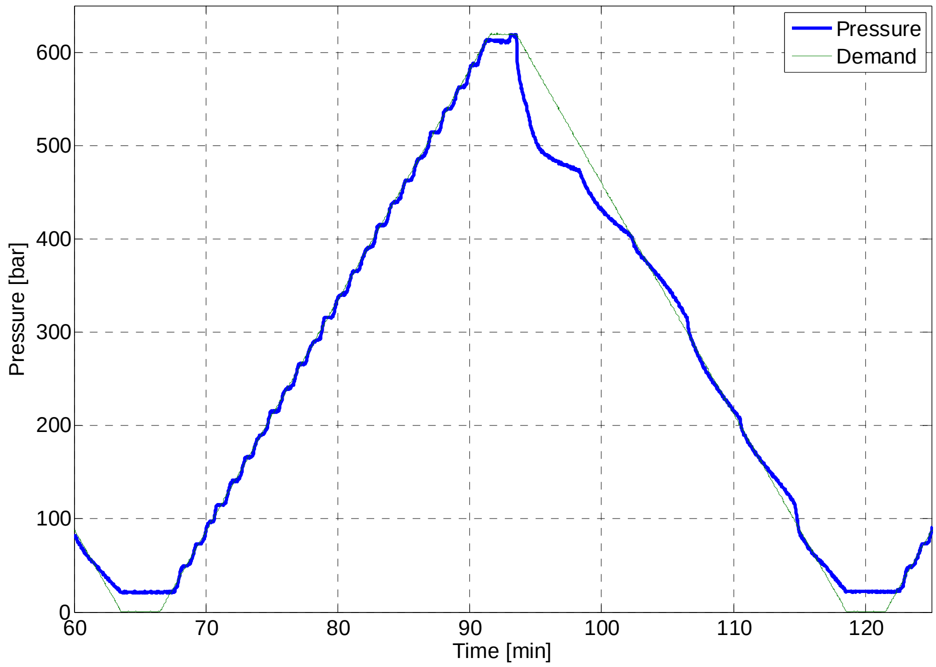

Figure 19 – Single pressure cycle for TestB01 – high pressure test

The minimum pressure achieved during each cycle also varies over time. This is illustrated in Figure 20 for TestD01.

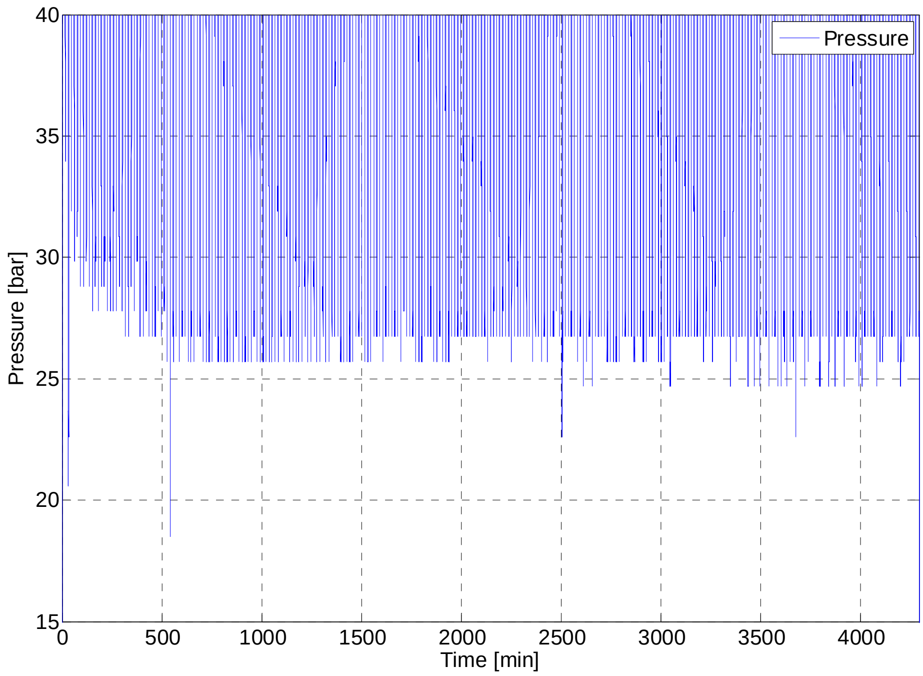

Figure 20 – Minimum pressures achieved duringTestD01

The average maximum and minimum pressures achieved during the tests are shown in the Table 8.

Test	Min Average Pressure	Max Average Pressure
TestA02	14.5 bar	166.5 bar
TestB01	21.5 bar	617.0 bar
TestC01	14.5 bar	167.0 bar
TestC02	6.2 bar	167.5 bar
TestD01	26.5 bar	167.5 bar
Test PT1	14.5 bar	166.5 bar

Table 8 – Minimum and maximum average pressures at the top and bottom of each pressure cycle

Note. TestC02 had an 18 minute pressure cycle not the 16 minute pressure cycled used in the other 161 bar pressure tests.