VARIABLE ORIFICE GAS INJECTOR

DESIGN VERIFICATION REPORT

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DEPARTMENT:	**Engineering**
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APPROVALS	
Hardware Architect	Date
Project Manager	Date
Quality Officer	Date

Controlled Document ☐ Classified Document ☐
Unclassified if clear.

Revision History

Revision	Date	Description
A	10th Nov 2006	Initial report
A1	25th Dec 2006	Updated with additional test results (Russian office, working day)
B	21st Feb 2007	Updated with Rev B design for reducing hysteresis to 3um
B2	2nd March 2010	Determination of causes for valve leakage and O2 compatibility review

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1. Executive Summary

Open Safety's eCCR and eSCR rebreather models use a variable orifice to add oxygen to the breathing loop. A batch of variable gas injectors was fabricated and tested in accord with a test plan.

The flow tests used a smaller orifice size than normal, 200um instead of 300um, to highlight any tolerance issues: the injector can be fitted with 200um, 300um or 400um orifices but the smaller orifice creates the most strain on the valve as there is a greater differential pressure on the actuator and tolerances are much reduced compared to the larger orifice sizes.

The test plan was reviewed by a competitor as well as open peer review. The test plan was intended to be rigorous, covering all operational and fault conditions. The test plan was checked against a rebreather accident review list to include abnormal operating conditions.

The results from the tests were compared against those predicted using formal verification.

The conclusions from the verification work are as follows:

1. Overall the injector meets the requirements, after three changes: adding a further bearing, changing the orifice seat from a hard seat to soft seat, separating the sensor and motor ground wiring and increasing the orifice size to 330um.
2. The use of the Hall sensor to detecting orifice position is linear and sufficiently accurate. Simple moving average filtering is sufficient to reduce the noise to below the resolution of the sensor.
3. The orifice drive has 20 step backlash instead of 3 steps. This was corrected by adding a further bearing to the injector.
4. There is 0.3l/m of leakage around the orifices. This was corrected using micro O rings around two of the orifices.
5. The flow rate tests using the deliberately undersized injector confirms that total tolerances and misalignment is sub 130um, therefore the orifice should be oversized by 100um to ensure the full orifice range is available at all times.
6. The effect of an 80C temperature rise is equivalent to a change in position of 80um, and is accommodated by the feedback system. The cylinder valve should open gradually as a needle valve, rather than a conventional valve, to prevent O2 surge.
7. Tests were carried out with the balancing pressure on the orifices removed to simulate the effect of this component being frozen or jammed. The orifice operates for 30 minutes in this state before moving out of tolerance.
8. The injector is O2 compatible.
9. The reaction bearing was upgraded to handle the effect of chamber lockout, where the intermediate pressure can rise to over 70 bar in commercial diving applications, from the normal 9 to 14 bar.
10. Dual redundancy accommodates all extremes of O2 metabolism combined with all extremes of intermediate pressure. However, the large orifice availability means that this is probably over-kill and single injector systems could meet SIL 4 if there was suitable independent automatical bail out and gas shut off.

The design can proceed to a pre-production batch for retest and evaluation at an operational level.

2. PURPOSE AND SCOPE

This document reports the verification of the variable orifice gas injector, for application in rebreathers.

The scope of this document is a design verification report, according to Quality Procedure QP-20. This procedure is designed to meet the requirements of EN61508 for systems operating to SIL 4 (1 billion hour between critical failure). This report covers a component in such a system that must be fail safe in its operation, with a minimum of dual redundancy to achieve the operation up time requirement.

3. ABBREVIATIONS

OSEL: Open Safety Equipment Ltd

4. REQUIREMENT

1. The maximum flow rate is determined by the worst of 3 cases:
    a. **EN14143:2003** requires a minimum of 6l/min of pure O2 flow. Through an orifice, the worst case flow is at the surface. The lowest surface pressure that will be dived is 0.7 atm – on a mountain.
    b. **Uncontrolled ascent eCCR**. The fastest ascent with a full BCD is 350ft/min, or 107m/min. The metabolic rate is considered to be 2l/min, due to the extreme stress and hyperventilation the diver is doing to prevent a barotrauma. The deepest ascent at this rate that can survived without explosive DCS is believed to be 100m, other than submarine escapes in which case a higher initial PPO2 is used. The worst case PPO2 at the start of the ascent that shall be considered is 0.7. This requires up to 12l/min of O2 injection. This requires 12l/min with worst case dead volume in the rebreather (16l).
    c. **Commercial diving at 600m** using SCR mode where the makeup gas has a PPO2 of 1.3 for O.C. bailout purposes, so has a FO2 of 2.13% but could be as low as 1.5%. Taking the FOC of 2.13%, this requires 83.5l/m of heliox at that extreme depth. This is the same as for an orifice providing 8l/m of air at 1 atm with an intermediate pressure of 14 bar.

    What this means is that the Gas injector should provide oxygen at rates from off, then 0.1 to 12 litres per minute of oxygen, at all ambient pressures from 0.7 bar absolute to 61 bar absolute and with the oxygen content of the supply gas from 2.13% to 100%, the remainder being helium.
2. The injector should operate with all known SCUBA first stages: this requires the input pressure to vary from 4 bar to 14 bar relative to ambient.
3. The injector must be able to be operated open loop, that is driven by electronics with failure of the position sensing circuitry, but shall provide full sensing of the injector position as an analogue scale for either safety verification of the injector operation.
4. The sensor should not combust when particulate is in the oxygen stream: particulate over 15 microns in diameter should be screened by a sintered filter. Aluminum powder of 10 micron mesh size, entrained in the O2 supply, at the maximum flow rate, should not cause combustion of the injector body or catastrophic failure of the orifice.

5. The intermediate pressure may rise from 0 to maximum in 0.1 seconds.
6. The maximum ascent rate of 350ft/min (107metres/min) shall be supported, including the increase in intermediate pressure this causes, with hoses of 1 metre length, and worst case dead volume in the rebreather of 16 litres.
7. If the orifice is blocked, the injector shall not present a safety hazard if the intermediate pressure is 71 bar. This is to enable a unit with a blocked injector at the maximum depth ever dived, 701m, to be evacuated to the surface without release of intermediate pressure.
8. The injector should operate over a temperature range from -4C to 100C.
9. The injector should withstand being dropped 3m onto a hard surface when in a rigid mount.
10. The response time from 0 to full scale shall be less than 1 second.
11. The injector should fail with the injection rate being the same as the operating mean injection rate.
12. The injector should be capable of being driven into a completely off state, but the injector must never fail in this state, unless the unit is off.
13. The injector must never fail in the completely open state.

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5. Design Review

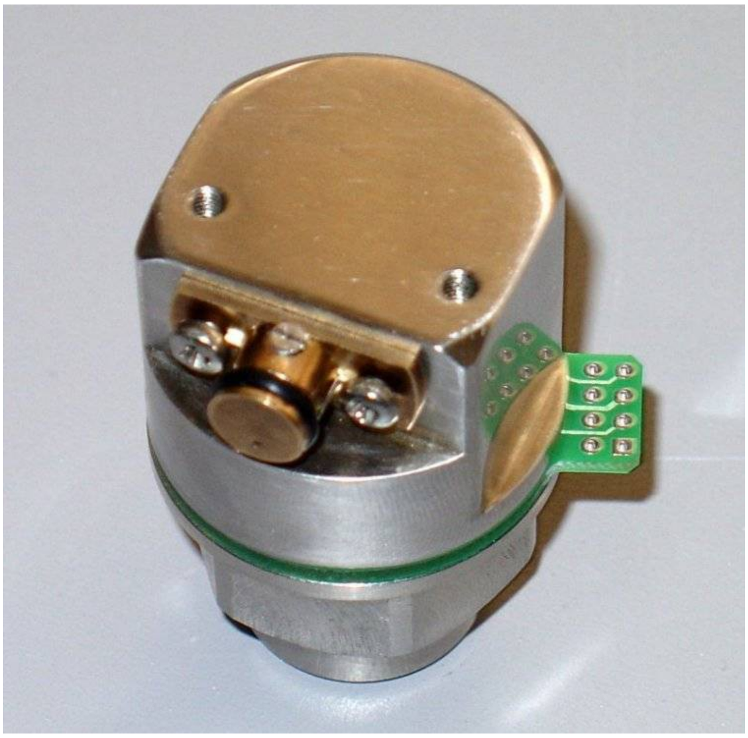
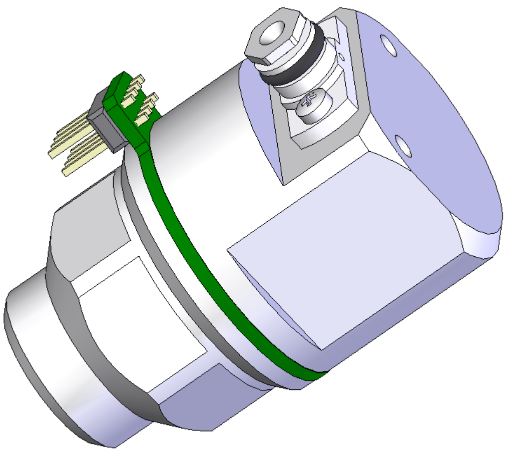
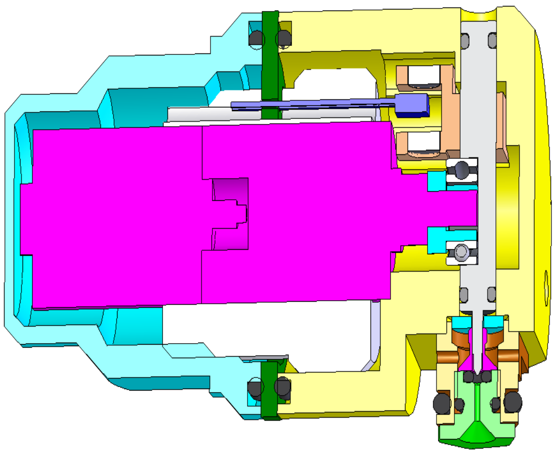


Fig 5-1: The realisation of the variable orifice injector in close up. Two injectors are fitted per scrubber.



Variable-orifice Gas Injector, external view



Sectional view of variable-orifice Gas Injector. .

Fig 5-2: Variable Orifice Gas Injector, 3D CAD views

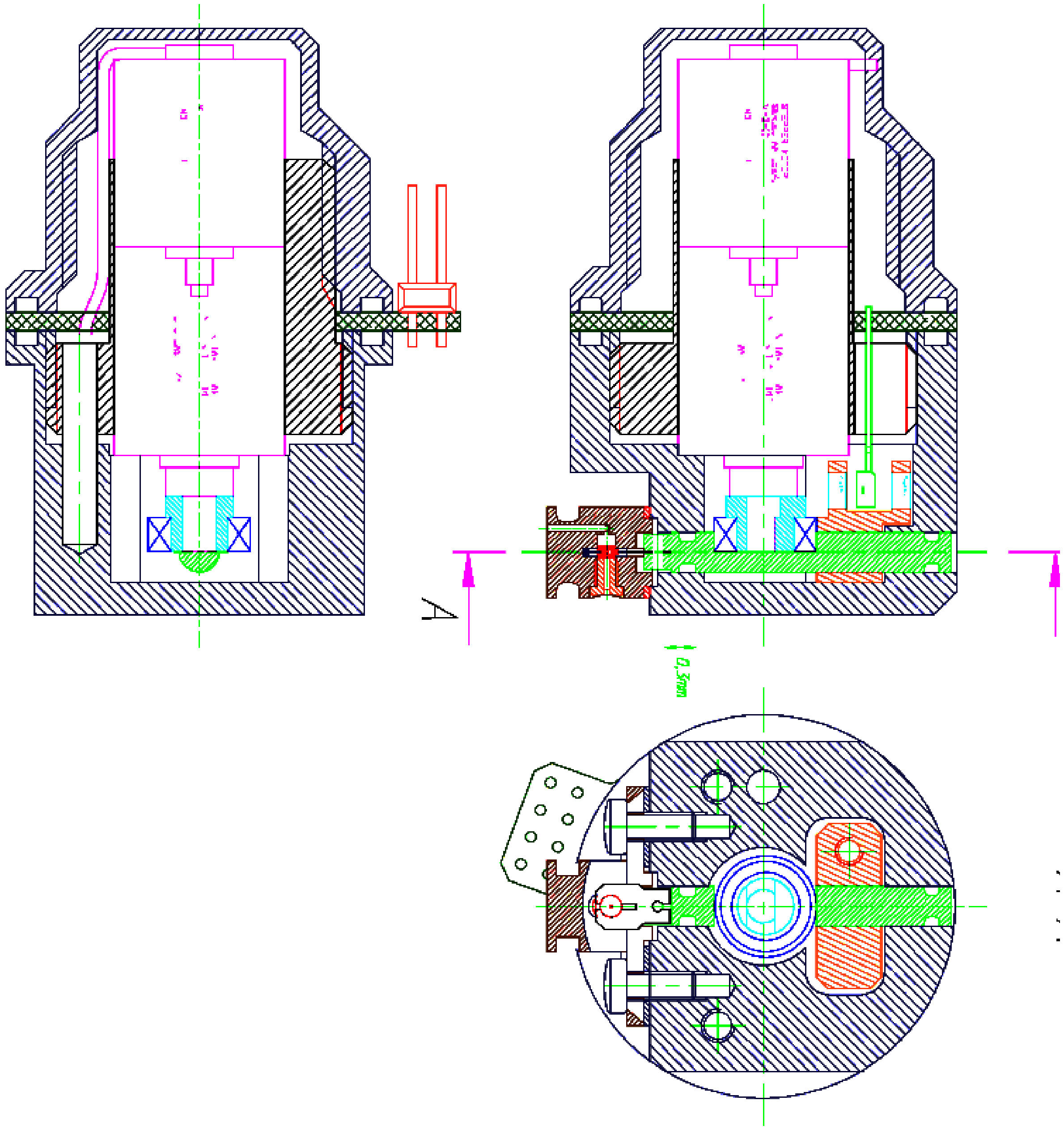


Fig 5-3: Further sections through the injector. Taking the Section A-A in the Top Right image, gas enters the injector through a nickel-bronze pathway, shown in green, then turns 90 degrees into the injector orifice area, pass through three orifices where the centre orifice is moveale, before exiting the injector into the rebreather. The Intermediate Pressure gas is supplied by a T piece containing a 15um sintered bronze filter. The motor and gearbox is maintained at 1 ATM, being sealed. Leakage of gas into the gearbox area from the rebreather is designed such that it does not pose a safety risk from over-pressurisation. There are no wiping seals: all O rings are immobile, except for the 300um stress on the O ring on the piston. All fixtures in the gas pathway are either nickel, nickel bronze or sapphire.

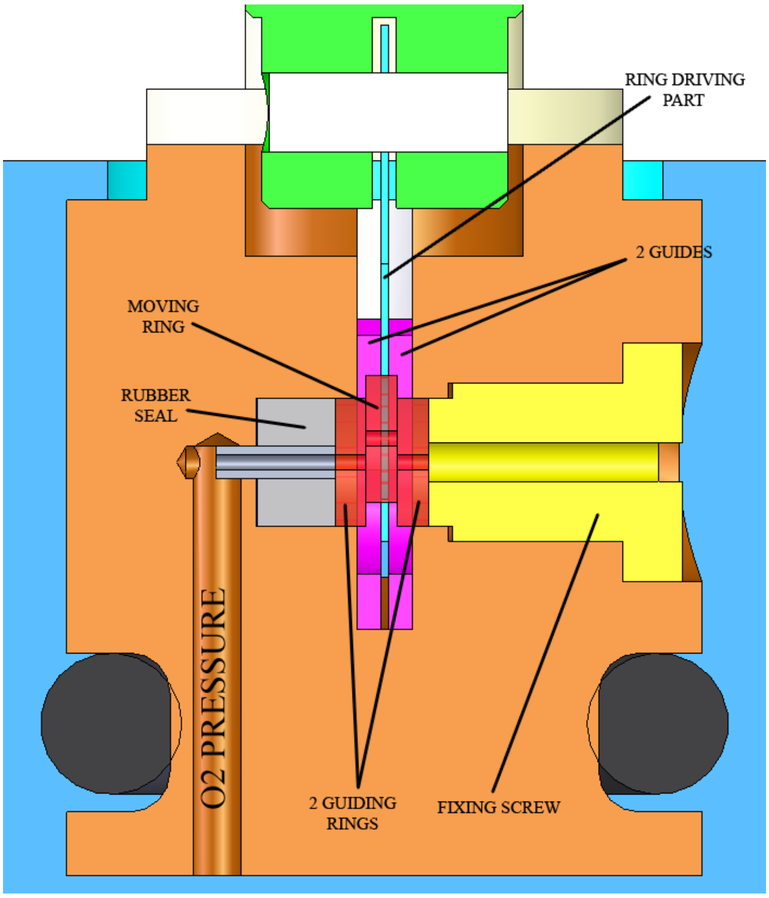


Fig 5-4: Close up cross section showing the orifice and gas path.

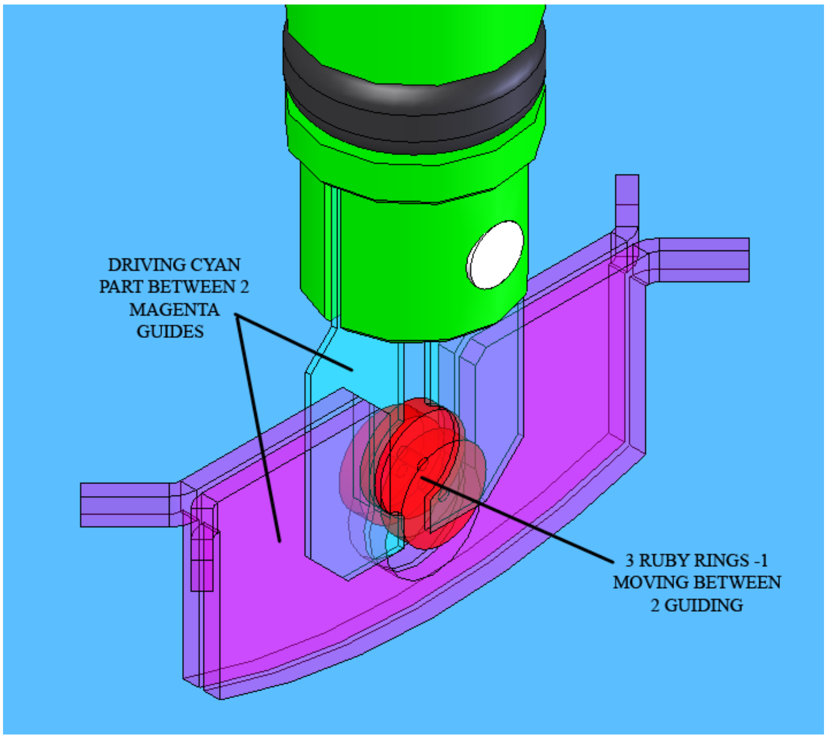


Fig 5-5: Close up of the orifice holder, showing flexible bronze drive plate for good alignment. Ruby rings replaced by Sapphire in example tested.

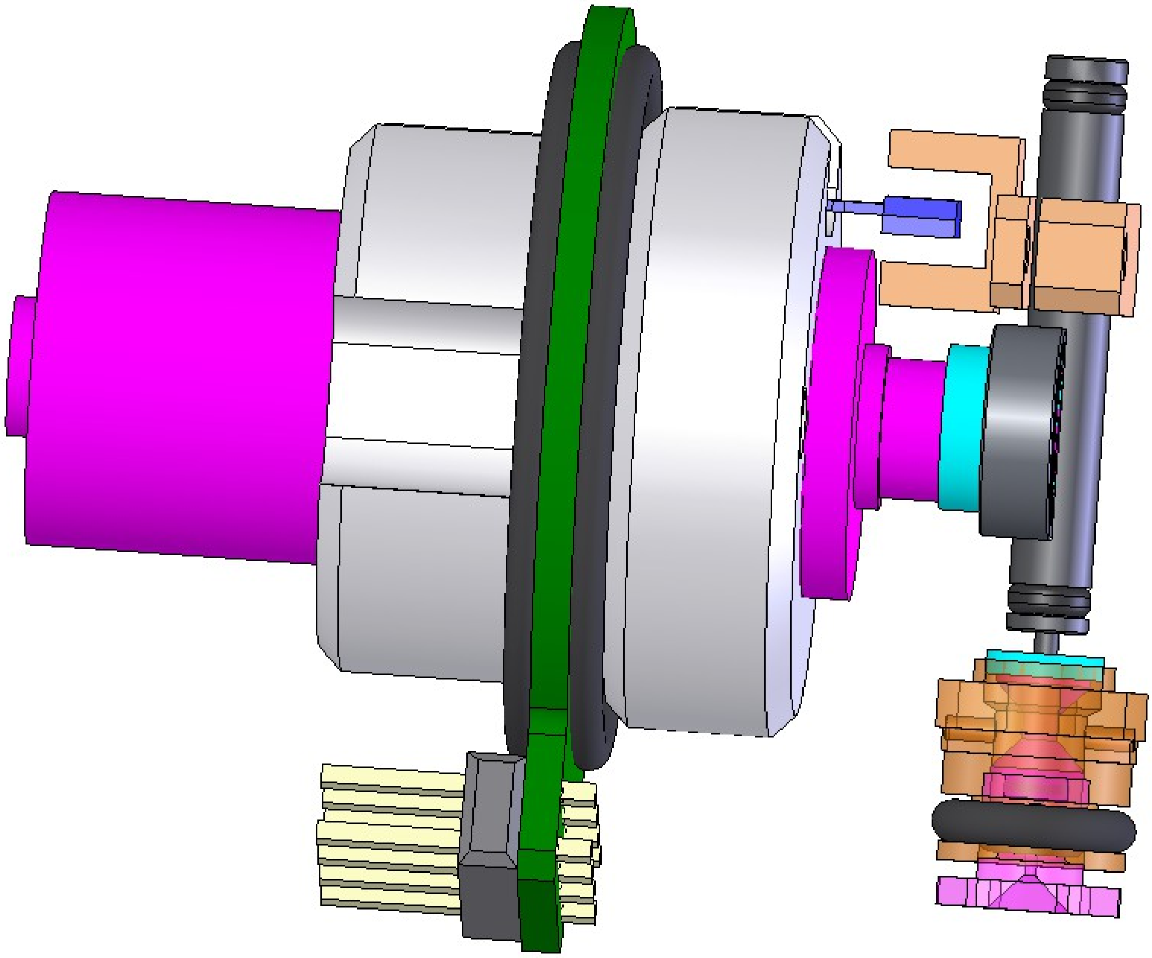


Fig 5-6: Injector with case removed, showing Hall sensor position (top), drive piston and circuit board holding the sensor and connecting to motor. Circuit board acts as a feed-through, to prevent off-gas components reaching the breathing loop.

The injector comprises a DC motor with 12 steps per revolution driving a 14:1 gear box, which drives a piston via a cam. The piston has the orifice at one end of the piston. The position of the piston is sensed using a linear Hall Effect sensor.

In the event of the complete destruction of the electronics, the injector will continue to inject gas at the metabolic rate and ascent/descent rate of the point at which the failure occurred.

During ascent more gas is injected, due the ambient pressure falling and intermediate pressure falling only as gas is injected. The increase in gas injection tends to keep PPO2 constant in the case of complete failure. The actual rates are tabulated in the design documentation.

The orifice uses three sapphires, the centre one sliding between the other two, to provide a variable orifice. Sapphires are used for each orifice for O2 compatibility and to provide a long bearing life.

The injectors are designed to be used in duplicate over each scrubber connected directly to a T piece containing a 15 micron sintered bronze filter. This keeps intermediate pressure gas out of the breathing loop: failure of an intermediate pressure line is a critical failure otherwise. The T piece pierces the wall of the End Cap for direct connection to the intermediate pressure gas hose from the umbilical termination block, and from one of the bail-out cylinders (per pair of injectors).

The variable orifice injector provides completely closed-loop control of the injector: that is, it does not rely on a motor performing an action; instead a Hall effect sensor confirms actuator movement. The variable orifice injector provides multiple redundancy in the event of orifices being blocked.

The injector operates with any intermediate pressure in common use: 4 bar over ambient to 14 bar, and is designed to operate in either SCR or CCRs at depths up to 600m.

The injector is designed to be insensitive to intermediate pressure changes, which causes solenoid-type injectors to fail.

The main housing is produced entirely by three axis CNC lathe operations.

The effect of wear on the drive was considered. At the MTBF of a single injector assembly of 100,000 hours, the wear could result in tolerance errors of an additional 100um. The test regime should be carried out with this degree of error introduced artificially be reducing the orifice size – therefore requiring greater precision to achieve the same result.

The primary fault mode is of orifice blocking. It is essential the orifice is preceded by a 15 micron sintered filter, and the injector is used in duplicate. The injector controller should seek to remove a blockage by opening the orifice to its maximum before passing control to second injector. The second injector should be set to the minimum flow rate when the unit is on, not rest in the full off position.

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6. Formal Verification

In line with the design procedures specified in QP-20, a formal model was created of the gas injector, its specification and its environment, and predictions of the performance derived from that model.

An overview of the model is shown in Fig 6-7Fig 6-9 to below, and the results from using the model are shown alongside the appropriate points of the test schedule, later.

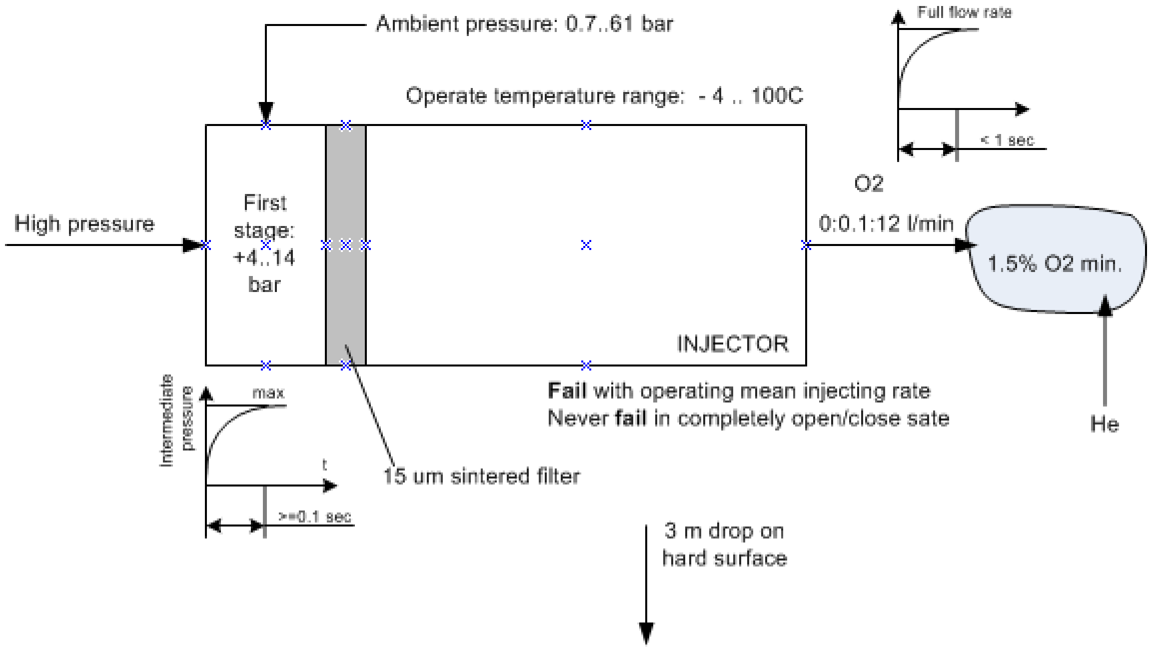


Fig 6-7:. Requirement model showing one of the three requirement cases.

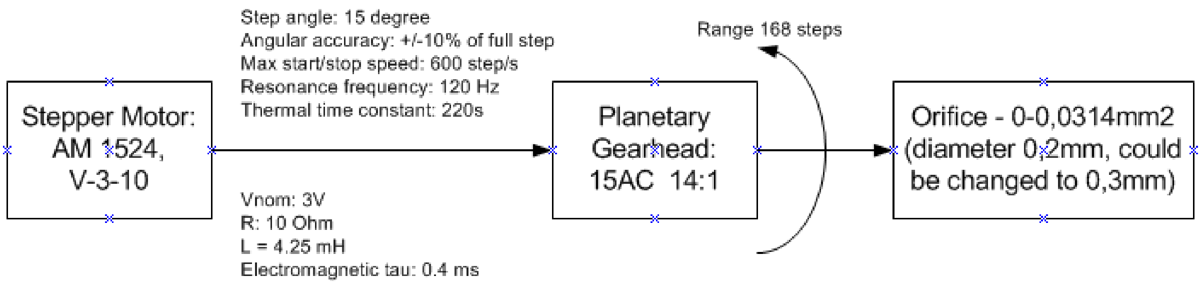


Fig 6-8:. Injector driver showing the test case (with orifice reduced from 300um to 200um to create the effect of 100um tolerance error in orifice drive alignment). The motor is available in either DC motor or stepper motor form. Both of the samples used for these tests were fitted with the stepper motor option.

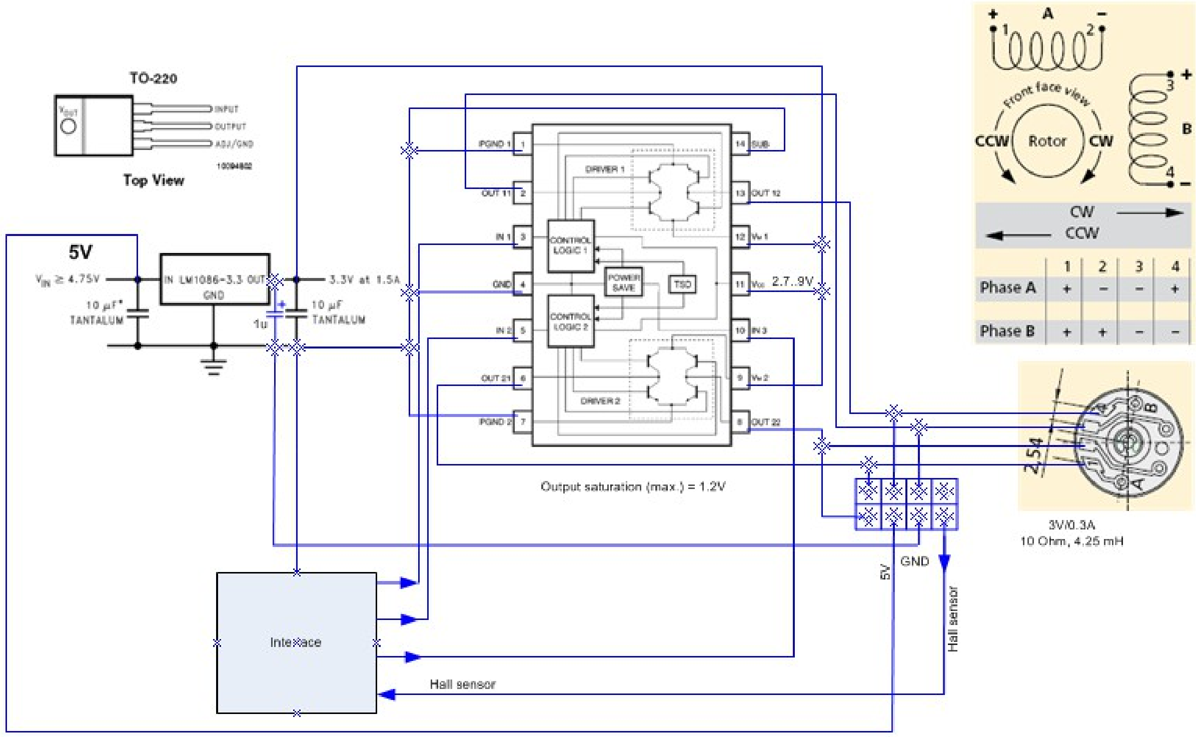


Fig 6-9: Injector drive system.

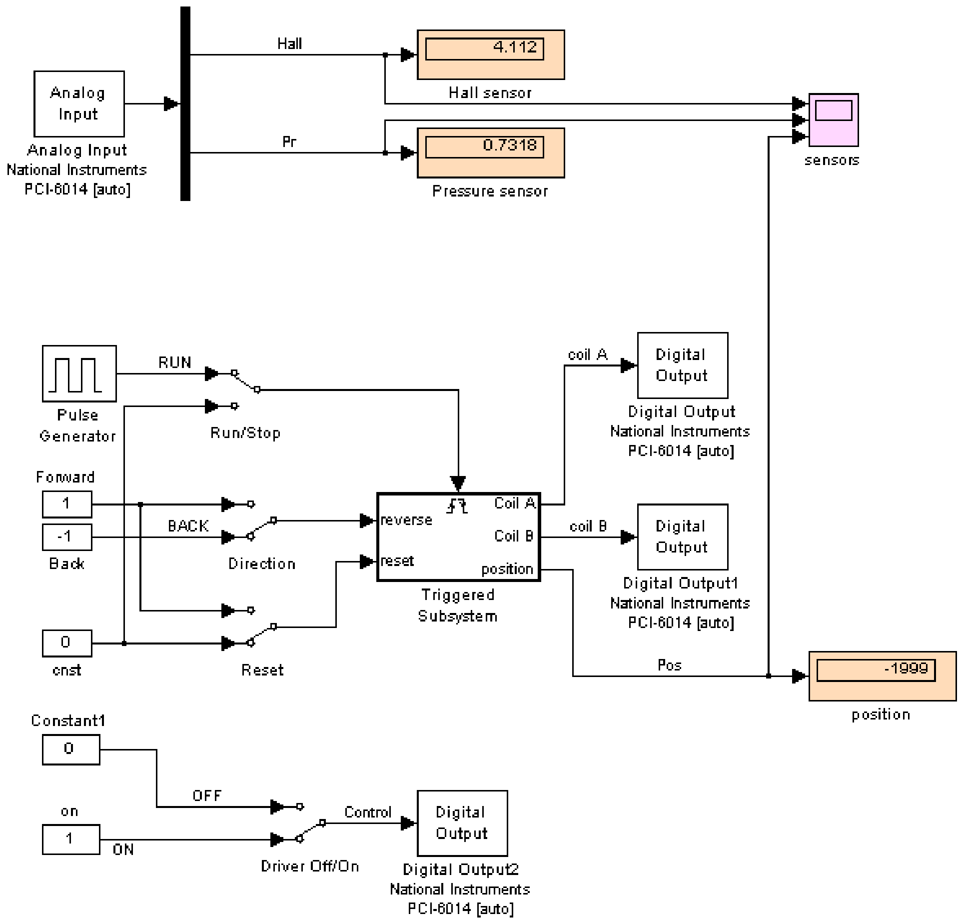


Fig 6-10: Example of one of the real-time test structures in MatLAB, using with the math model for the formal verification results, against which actual test results are then compared.

7. Test Plan

During prototype tests, a 200um orifice should be fitted instead of 300um, to accentuate the effect of tolerance errors. All flow rates in the tests should be adjusted to reflect the reduction in the maximum orifice size.

Prior to starting formal tests, the injector should be characterised to confirm that it is representative and meets the "data sheet", other than the orifice size being reduced deliberately. The characterization should establish the amount of noise in the measurement system and confirm the efficacy of any filtering.

The initial characterisation should determine the noise level in the sensing and measurement system and determine the overall sensitivity of the test fixturing to external parameters.

Table 1. List of tests.

Test	Purpose	Method	Nonconformance Action
1. Examination of computer flow simulation	To verify the flow rate is optimised to meet the specification.	Computer flow simulation. Matlab using a formal model of the injector, gas mechanics, rebreather environment.	Design change
2. Examination of materials for O2 compatibility.	To avoid O2 fire hazards taking into account the flow rate over any surface.	Material compatibility. Physical examination of materials. Comparison with BOM. Use latest NASA O2 Materials Compatibility Guide.	Remanufacture.
3. Linearity in air at 1ATM	Characterisation of injector.	For each motor increment from off to full on, measure position sensor reading and flow rate. Compare with calculated.	Review.
4. Intermediate pressure range	Test range of intermediate pressures over which the injector operates.	Increase intermediate pressure from 0 to 20 bar while cycling injector from full off to full on. Log intermediate pressure range over which unit operates.	Must operate over range 4 bar to 14 bar relative to ambient.
5. 3m Hard Drop test.	Test robustness. The size of the drop is chosen to reflect the shock loading from a RIB in worst case weather that still permits safe diver recovery.	Photograph the injector to be tested. Drop 3m onto a wooden board laid on concrete 10 times and measure flow rates at 1ATM. Photograph the external surfaces again and determine if there has been	Design change

		any internal changes by measuring linearity in air again .	
6. Linearity in helium at 1ATM	Characterisation of injector.	For each motor increment from off to full on, measure position sensor reading and flow rate. Compare with calculated.	Review.
7. Temperature range.	To verify flow over full temperature range.	Set to maximum flow at 1 atm, using air, and immerse in salt water at -4C. Heat the water at 1C per minute. Confirm flow rate by measuring gas consumption (pressure from supply cylinder).	
8. Linearity in helium at depths to 60 ATM	Characterisation of injector over range of designed operating depth.	For each motor increment from off to full on, measure position sensor reading and flow rate. Compare with calculated.	Review.
9. Intermediate pressure tolerance	Test safe range of intermediate pressure	Increase intermediate pressure from 0 to 141 bar while cycling injector from full off to full on. Log intermediate pressure range over which unit operates.	Ensure no catastrophic failure. Note operating range.
10. Torpedo test	Test effect of sudden ambient pressure increase	In a chamber rated to 600 bar, increase pressure from 1 ATM to 300 bar in under 1 second, and test flow while cycling injector from full off to full on. Intermediate pressure 140 bar of helium, fixed.	Review
11. MTBF check	To check reliability of sensor	Drive injector at maximum rate from full off to full on, measuring flow rate. Log flow rate with time.	Review
12. O2 BOMB test.	To verify O2 safety	Use fixture defined in EN14143:2003, but with following extensions to test conditions. Apply 14 bar intermediate pressure at 140 bar ambient, with entrained 10 micron mesh aluminium powder. Injector must be in	Review

		600 bar O2 BOMB test chamber, within a further 600 bar test chamber. Cycle injector from full off to full on at maximum rate. All lines must be Iconel. Operate for 1 minute. Disassemble injector following test and examine under metallurgical microscope for damage to all components.	
13. EMI and EMS	Electomagnetic immunity and susceptibility for FCC and EC approval	Normal FCC test with injector cycling from full off to full on.	Review
14. Corrosion test	To test resistance to corrosion	In artificial sea water, with air percolated through the water, test the injector body for corrosion for 3 months.	Review materials

8. MEASUREMENT EQUIPMENT

The test schedule used the following equipment. Serial numbers are recorded in log books.

8.1 General Equipment

The following general test and measurement equipment was used for the tests:

1. EMI and EMS tests are carried out at a DTI certified laboratory: York EMC as part of the overall equipment certification and recorded in the EMI report.
2. Deep Life 3U motor driver card
3. TTi 1906 8½ digit Computing Bench Precision Multimeter, used to read the Hall sensor position.
4. Laboratory DC power supply unit, Goodwill Instruments GPR-1850, driving the sensor power.
5. 600 bar rated O2 BOMB test chamber.
6. 600 bar rated 300mm diameter test chamber.
7. Digital pressure gauge, calibration traceable to national standards

Air, He and O2 supply to 141 bar.

In addition to the above equipment, a sensory and data acquisition system was used, detailed below.

8.2 Temperature sensor

Technical data:

- Type: LM35DZ
- Nominal temperature range: -55..+150 °C
- Accuracy: ±1.5°C
- Non-linearity: ±0.5°C
- Sensor gain: +9.8..10.2 mV/ °C
- Self-heating: 0.08 °C in still air
- Supply voltage: 4..30 V
- Impedance output: 0.1¬ΓΙ for 1 mA load

8.3 Pressure sensor

- Technical data:
- Type: ME 705
- Nominal pressure range: 0..100/0..400 bar
- Overpressure: 150/600 bar
- Supply voltage: 5 V
- Output signal: 0.5..4.5V
- Accuracy of offset: ±1%FS(max.), ± 0.5%FS(typ.)
- Permissible load: > 10 k¬ΓΙ
- Max. current: < 4 mA
- Linearity: ±0.2...1.5%FS(typ.)
- Hysteresis, repeatability ±0.3%FS(typ.)
- Operating temperature range: -25 .. +125 °C
- Thermal sensitivity shift: ±0.04%FS/K

8.4 Hall position sensor

Type: A1321EUA

Features and Benefits
Analogue Hall effect position sensor with 1mm range
Temperature-stable quiescent output voltage
Precise recoverability after temperature cycling
Output voltage proportional to magnetic flux density
Ratiometric rail-to-rail output
High sensitivity
4.5 to 5.5 V operation
Immunity to mechanical stress
Solid-state reliability
Robust EMC protection

8.5 Micrometer

Type: KI, serial number: 7218511

Technical data:

- Range: 10 mm
- Resolution: 10 um

8.6 National Instruments Computer Data Acquisition System.

Type: PCI-6014
Analogue Input

- Number of channels: 16 single-ended or 8 differential
- Max sampling rate: 200 kS/s guaranteed
- Input signal gain: 0.5; 1; 10 ;100
- Nominal range: ± 10; 5; 0.5; 0.05 V
- Absolute Accuracy at Full Scale: 10 mV
- Relative accuracy: ±1.5 LSB typ, ±3.0 LSB max
- Offset error: ±2.0 μV max
- Gain error: ±74 ppm of FSD
- Input impedance: Normal powered on 100 GΩ in parallel
- with 100 pF
- CMRR (DC to 60 Hz), Gain 0.5, 1.0: 85 dB
- Bandwidth (-3 dB): 425 kHz
- Settling time for full-scale step: ±2 LSB: 5 μs max
- Stability:
  - Recommended warm-up time: 15 min
  - Offset temperature coefficient: ±20 μV/°C
  - Gain temperature coefficient: ±32 ppm/°C

Analogue Output

- Number of channels: 2
- Range: 10V

- Resolution: 16 bits, 1 in 65,536
- Relative accuracy (INL): ±3 LSB, typ
- DNL: ±2 LSB, typ
- Monotonicity: 15 bits
- Offset error: ±250 mV max
- Gain error: ±22,700 ppm
- Output impedance: 0.1 Ω max
- Current drive: ±5 mA max
- Protection: Short-circuit to ground
- Settling time for full-scale step: 8 µs to ±1 LSB accuracy
- Slew rate: 4 V/µs
- Noise: 360 μV_{rms}, DC to 400 kHz
- Offset temperature coefficient: ±128 µV/°C
- Gain temperature coefficient: ±26.8 ppm/°C

Digital I/O

- Number of channels: 8 input/output
- Compatibility: TTL/CMOS

Timing I/O

- Number of channels: 2
- Resolution: 24 bits
- Compatibility: 5 V TTL/CMOS

I/O connector

68-pin male SCSI-II type

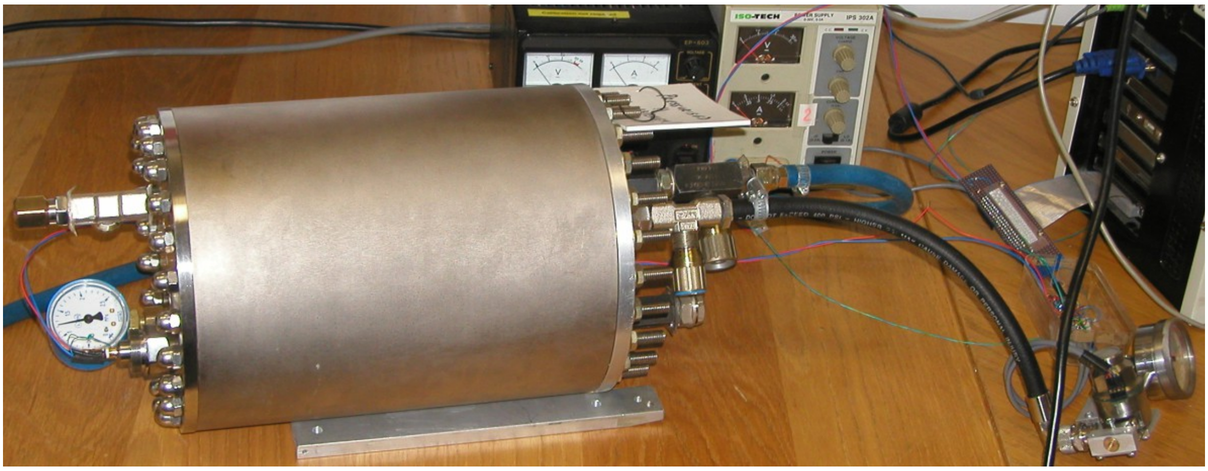


Fig 8-11:. Photograph of example test arrangements including the injector, micrometer and the chamber for intermediate pressure. The dial gauges are for safety purposes only: all measurements were taken using digital sensors.

9. INITIAL CHARACTERISATION

Where plots are small, use Zoom to show the scale.

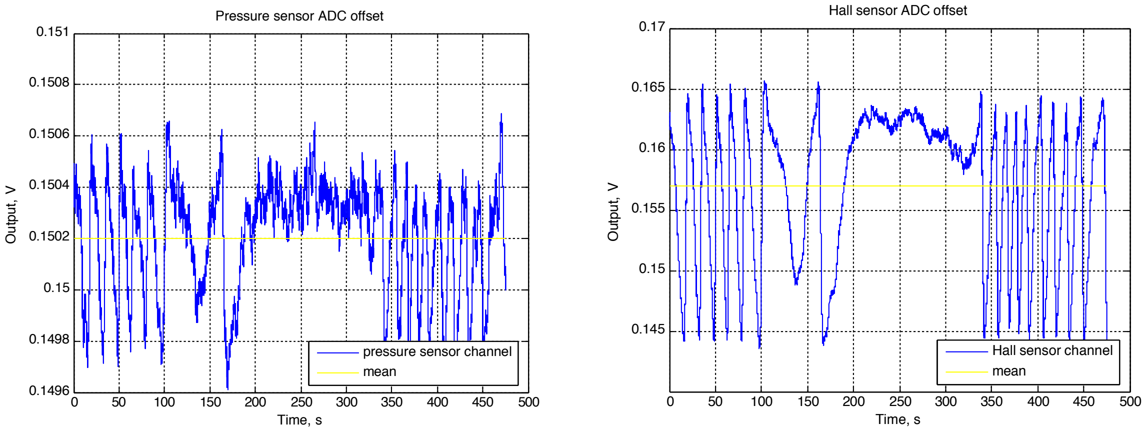


Fig 9-12: Offset of the ADC Pressure and Hall sensor channels recorded at the same time. The ADC offset is 0.1502 V and 0.1570 V correspondingly. Both sensors are connected to the ADC. Sensor supply power is off.

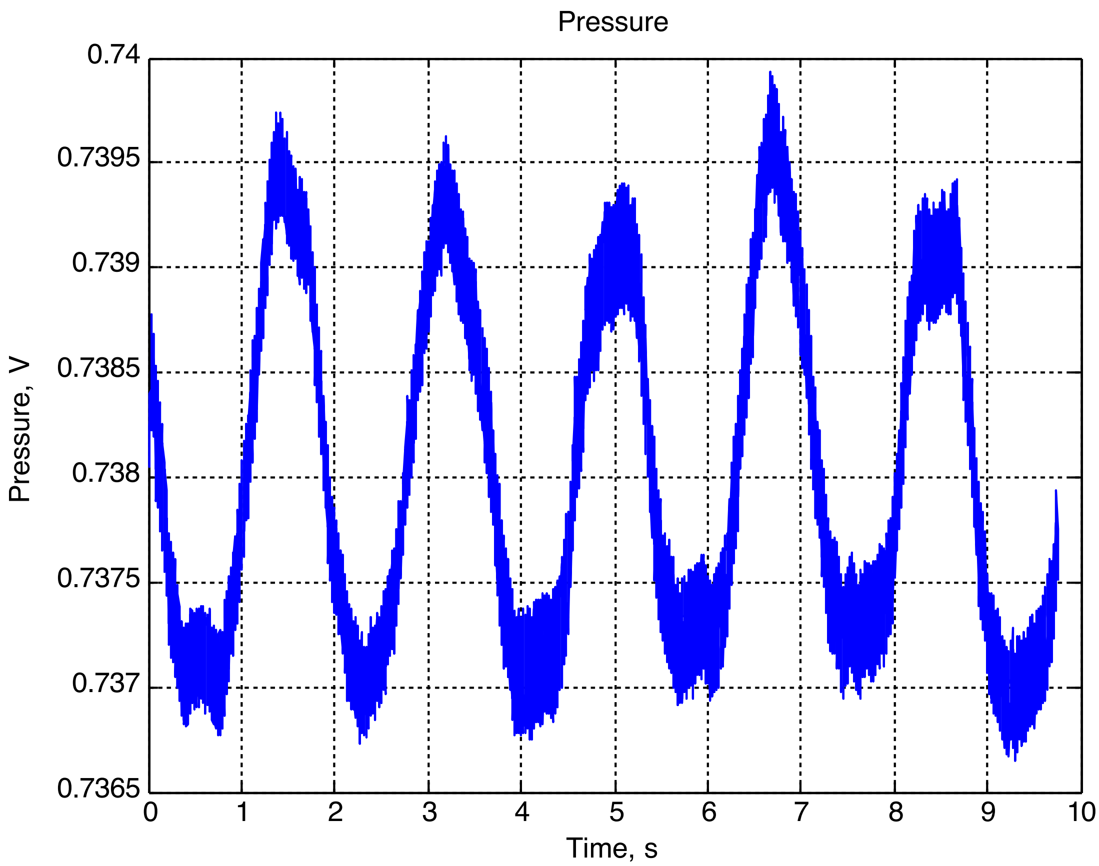


Fig 9-13: Interference on the Hall sensor measuring channel. 200Hz step motion. Filter is 50 point moving average. Amplitude is 2.5 mV or 2.5 bar. Filtered noise amplitude is 0.5 mV pk-pk or 0.5 bar.

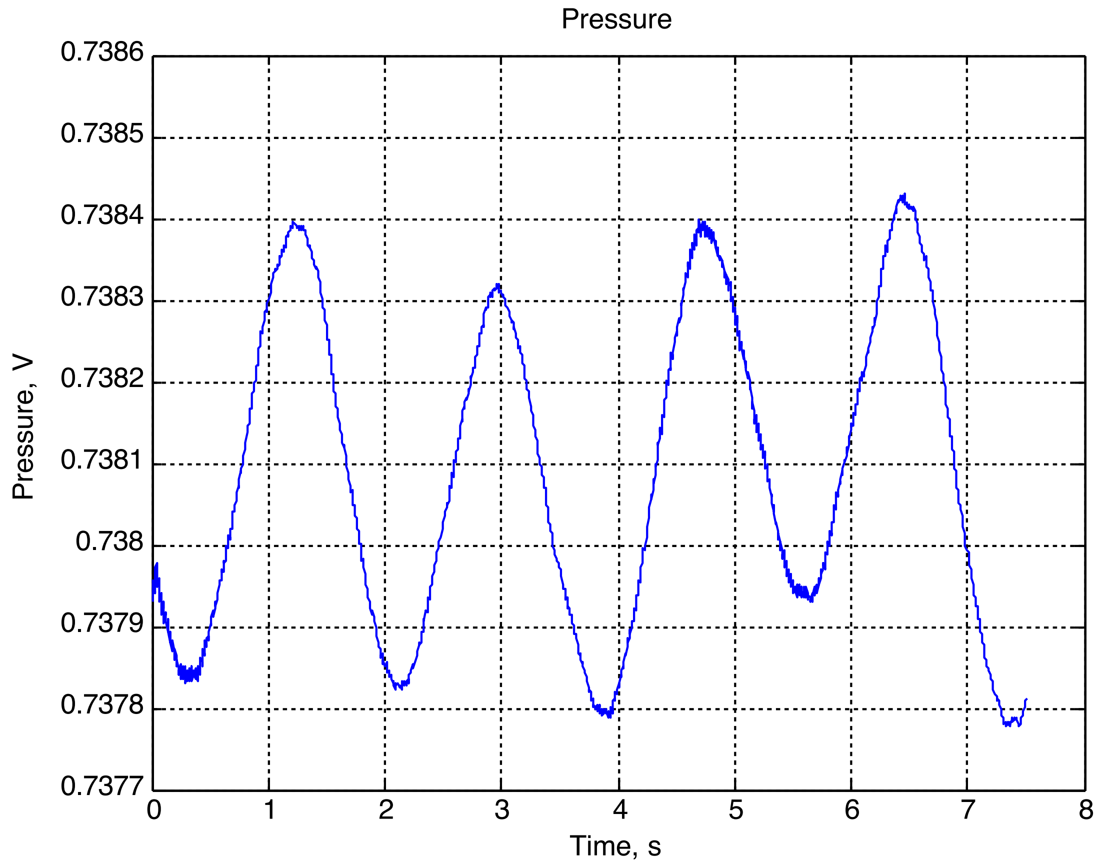


Fig 9-14: Interference on the Hall sensor measuring channel. 200Hz step motion. Filter is 500 point moving average. Filter window is 25 s of 500*0.05s. Filtered noise amplitude is 0.1 mV or 0.1 bar. The noise level with this level of filtering is less than the flow resolution.

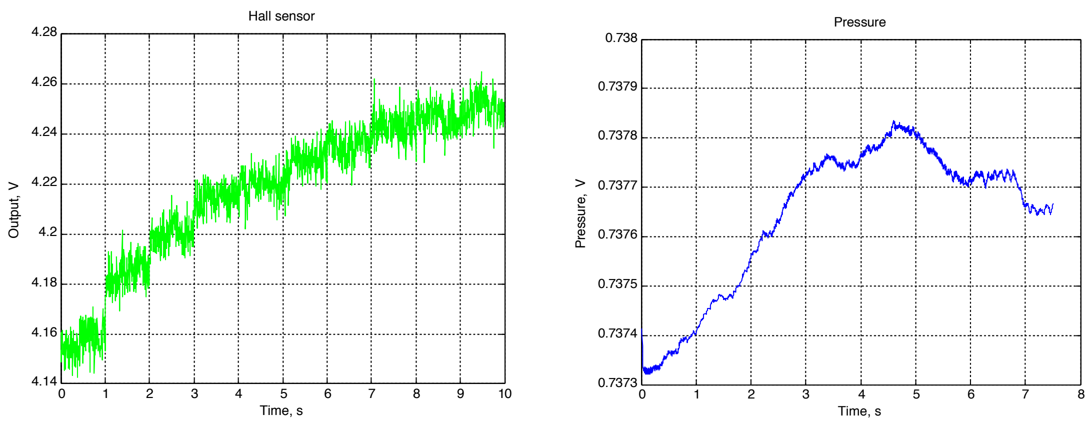


Fig 9-15: Interference on the Hall sensor measuring channel. 1Hz step motion. Filter of the pressure sensor is 500 point moving average. The amplitude of the measured pressure can be measured as a monotonic, albeit noisy, function of the amplitude of the Hall sensor: that is the injector can work correctly in a closed loop mode.

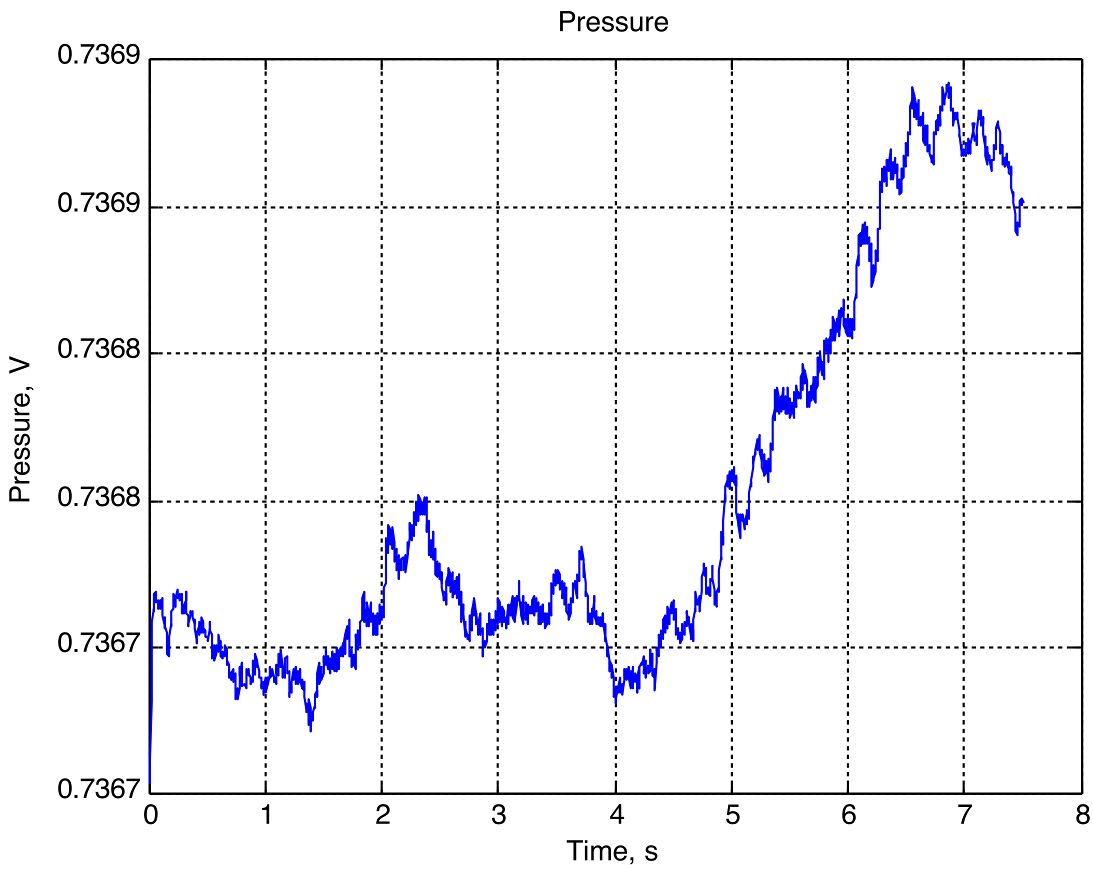


Fig 9-16: Interference on the Hall sensor output. 1Hz step motion. Filter on the pressure sensor is 500 point moving average.

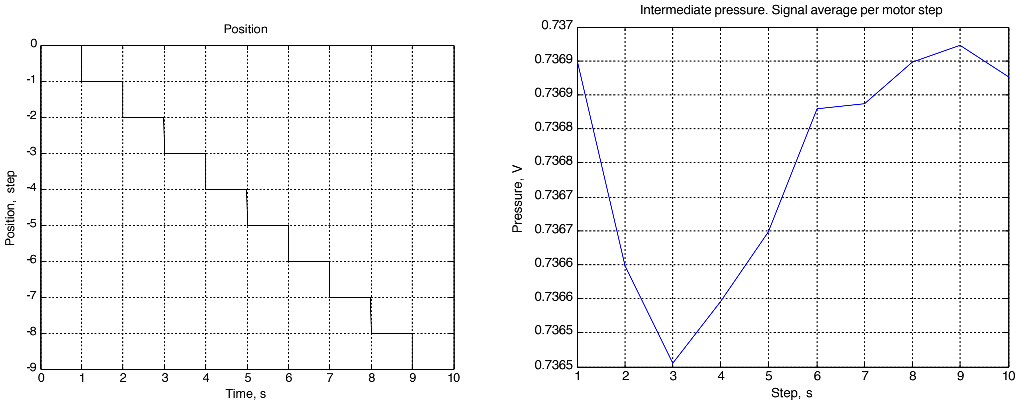


Fig 9-17: 10 Steps per 10 seconds and pressure filtered as average of 200 points (1sec step/0.005 sec clock) per step. The relative noise is 0.4 mV or 0.4 bar.

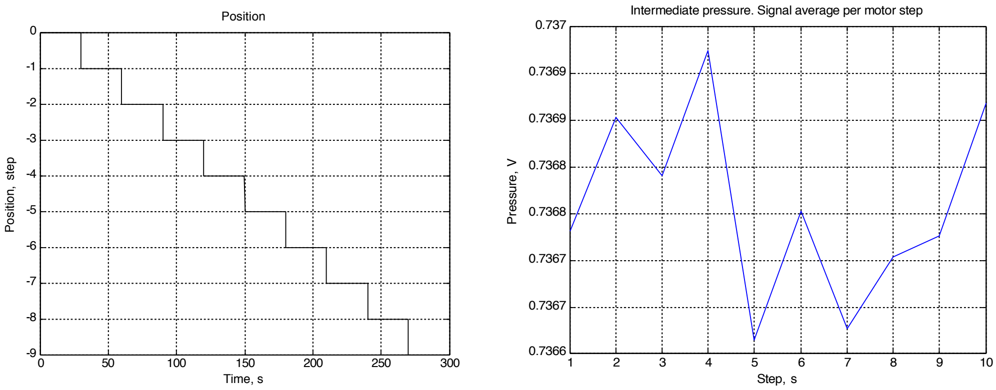
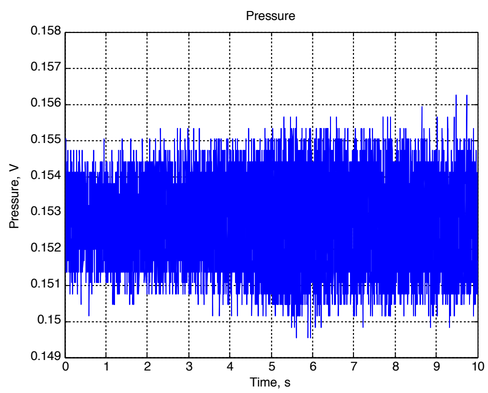
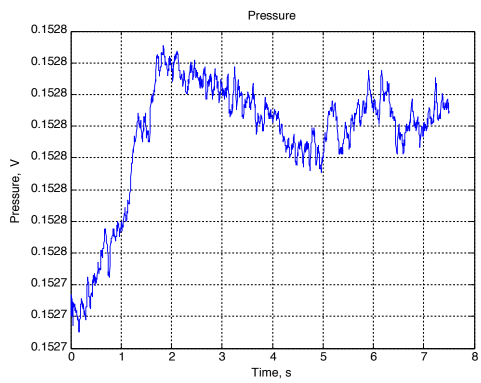


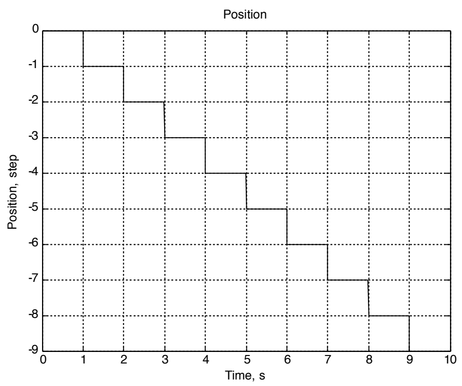
Fig 9-18: 10 Steps per 10 seconds and pressure filtered as average of 6000 points (30sec step/0.005 sec clock) per step. The relative noise is 0.2 mV or 0.2 bar. This is enough filtering of the noise for measuring of the gas flow as a drop in the intermediate pressure inside a small 5.54l mini chamber. The drop in pressure for a flow rate of 12 l/min (0.2 l/s) during 1 step of 30s in the chamber at an ambient pressure of 14 bar is 1.08 bar: computed from 14*((0.2*30)/(5.54*14)).



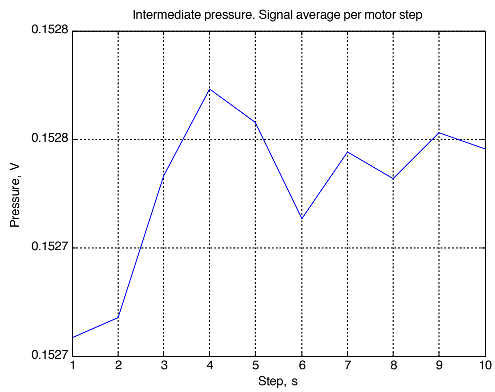
Original signal



Filtered signal. Ave filter is 500.



Ten steps per 10 seconds



One average point per step or mean of 200 points per second

Fig 9-19: Original and filtered signals showing the mean pressure change in a 1 second step.

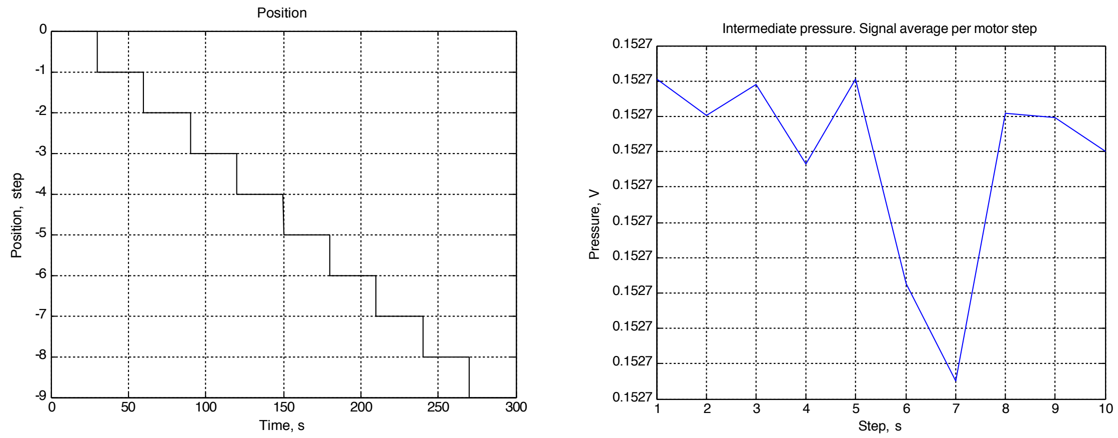


Fig 9-20: 10 Steps per 300 seconds and pressure filtered using a 6000 point average per step (30sec step/0.005 sec clock). The noise of the power supply is 0.2 mV pk-pk or 0.2 mbar (see above plot for supplied pressure sensor).

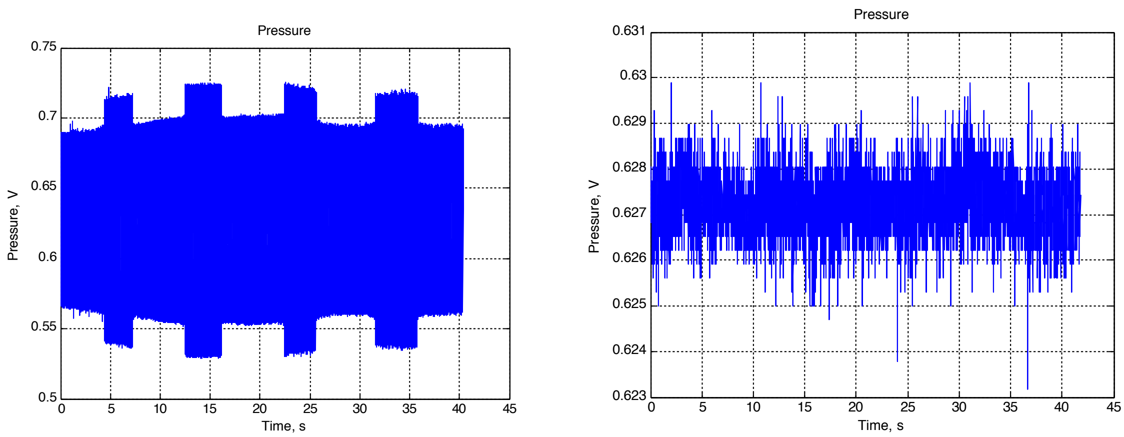


Fig 9-21: The noise in the pressure sensor installed on the grounded (left plot) and the ungrounded (right plot) chamber. The pulse in the left plot is generated by touching the chamber.

Use of flow meters would change the rate of flow through the orifice. The method used therefore to measure orifice flow was to supply the orifice from a test chamber and measure the pressure difference in the chamber over time. Where the orifice is tested under pressure, this necessitates use of two test chambers, one inside the other.

Experiments were carried out to determine the accuracy of this test method, the results of which are below.

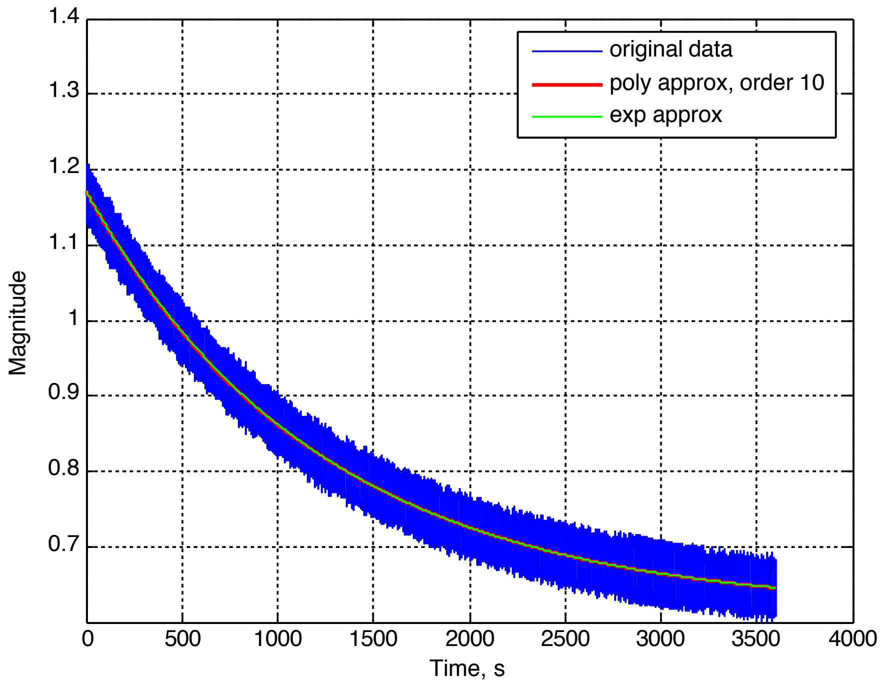


Fig 9-22: The sensitivity of the test fixturing and of test results to the influence of any one parameter was checked using parameter isolation techniques including both polynomial and exponential curve fixture. In this process, first the data is approximated by a polynomial function. The order of the function depends on the accuracy of the approximation. Then to simplify the equation and decrease the number of the equation coefficients the polynomial equation is converted into an exponential equation: "k*exp(-tau/t)+offset" that contains three constant parameters k, tau and offset.

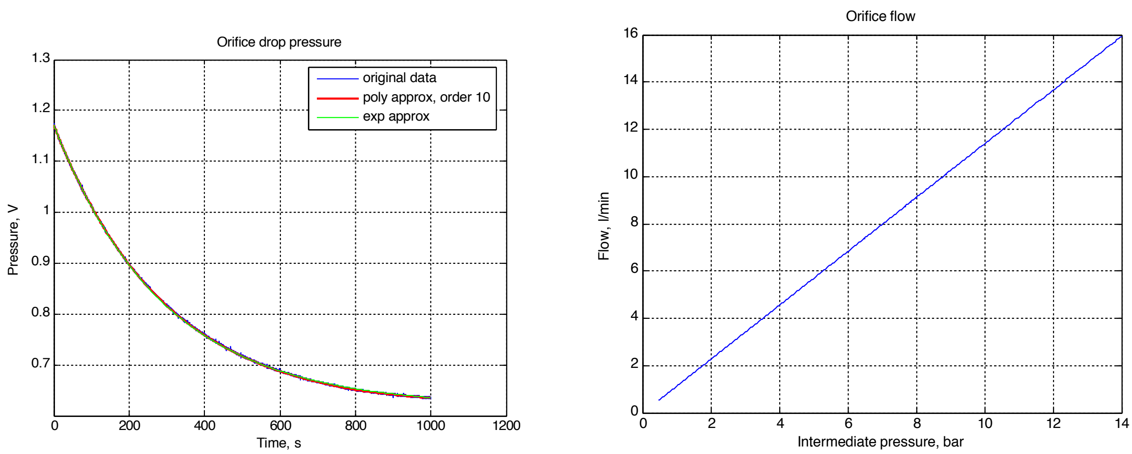


Fig 9-23: Test intermediate pressure against time and calculated He flow (through one 200 um test orifice). The chamber capacity used as a reservoir for the intermediate pressure is 5.54 l. The intermediate pressure data was measured by a 100 bar FSD sensor is approximated by the exponential function. The test data is used to detect how the approximate exponential function was sensitive to signal/noise relation and the measurement sample time. The results were used to optimise the overall test time and gas consumption.

Table 2. Sensitivity of tau to test time, sample time and pressure drop. The time range of the original test data is 1000s with 5ms time steps. The maximum flow of He through the 200 um orifice is 16 l/min/14 bar at 1 atm ambient.

Time range,	Sample time, s	Pressure drop, bar	Tau, s
1000	0.005	From 14 to 0.4551	291.6
500	0.005	From 14 to 2.5676	293.6
50	0.005	From 14 to 10.8452	188
5	0.005	From 14 to 11.5128	15.3

The tau of the exponential function approximation of the test intermediate pressure shows that the accuracy of the 1000s test can be achieved using oversampling at a rate of 200Hz, in 292s. The table data shows that the tau is most sensitive to decreasing the pressure drop range.

The conclusion of the fixture sensitivity checks is that for testing the gas flow with 1.5% accuracy using the 100 bar pressure sensor:

- The test time has to be more than the time for the pressure to drop from 14 to less than 3 bar
- The sample time has to be less than 8 sec.
- The total number of the test points has to be at least 20.
- The volume of the intermediate pressure chamber has to provide discharge of the chamber at least 20 times that of the pressure sensor time constant.

For example, if the time constant of the pressure sensor is 1s and the flow rate is 16l/min/14 bar then a difference in pressure in the chamber of 0.2 litre (20*6/60/14) is enough to calculate the gas flow using the test data of intermediate pressure sensor.

Note: For fast pressure drops or for high correlation of the flow to the chamber pressure value it is necessary to record the fluctuation in the gas temperature and do the corresponding correction of the detected flow.

The test of the He flow through the same 200 um orifice shows 2% measuring accuracy for the intermediate chamber of 0.48 litre, and 30s measuring with 0.5 step or 40s measuring with 1s step.

9.1 Test of the injector drivers and Hall position sensing system.

The model predicts a dead zone in the injector. This was checked using 2 injector samples.

9.1.1 Injector Sample S1

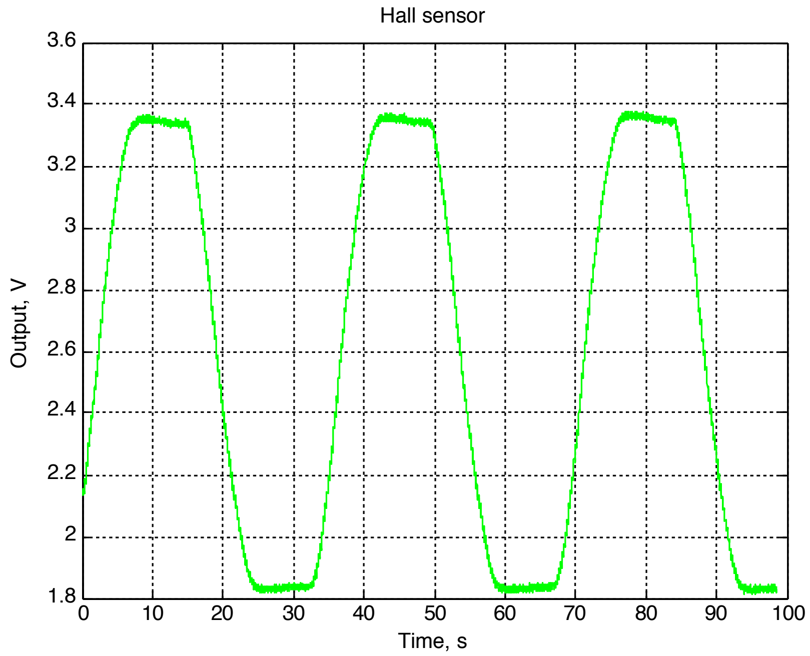


Fig 9-24. Hall sensor range for sensor S1. The range is 1.56 V (3.377-1.813).

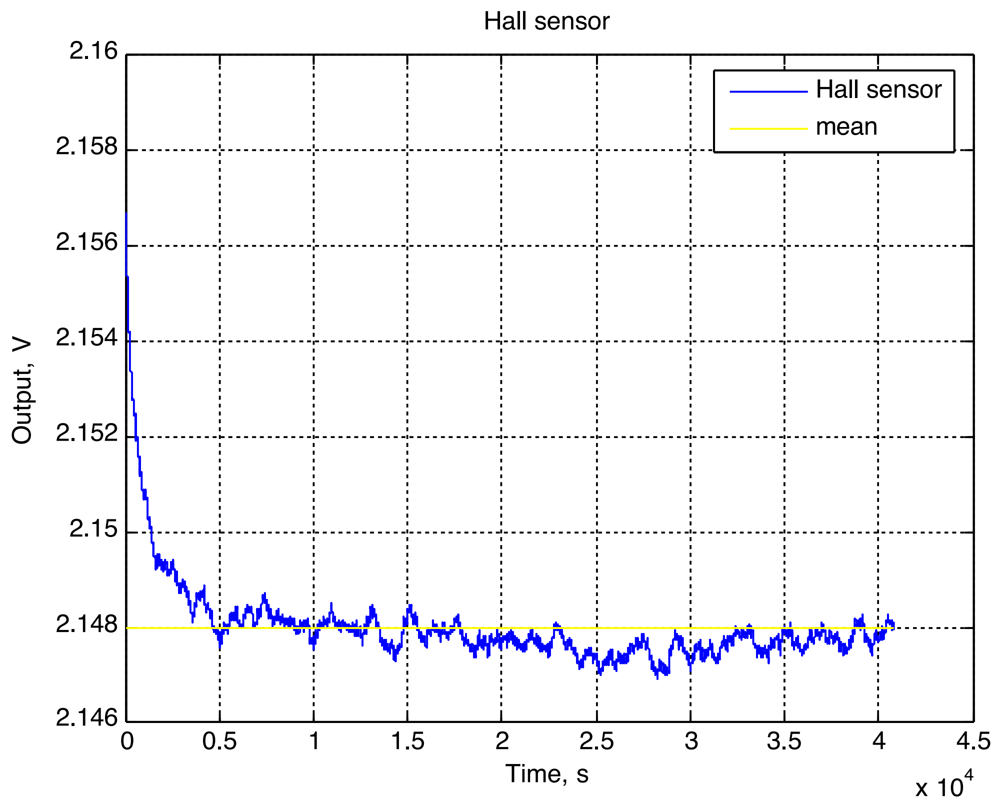


Fig 9-25: Hall sensor stability in 11.5 hour after the He flow though the injector for sensor sample S1. Mean = 2.1480 V. Minimum is 2.1469. Stability in 1.56V range is 0.14% of the range as 100*2*(2.1480-2.1469)/1.56.

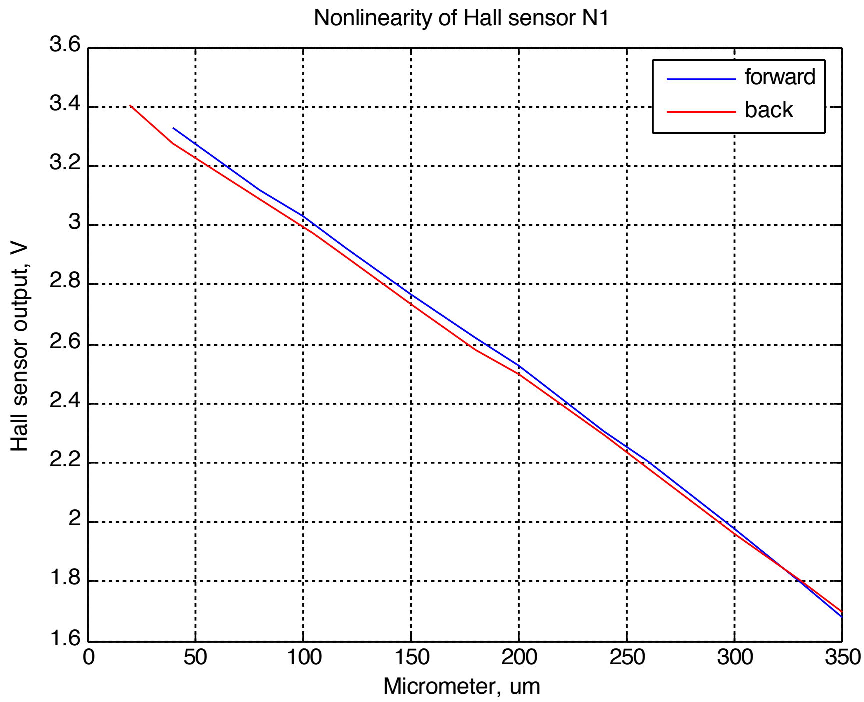


Fig 9-26: Hall sensor output of external micrometer position. Data are measured manually by external micrometer. The nonlinearity is 3.5% as 100%*(3.329-3.274)/(3.274-1.694).

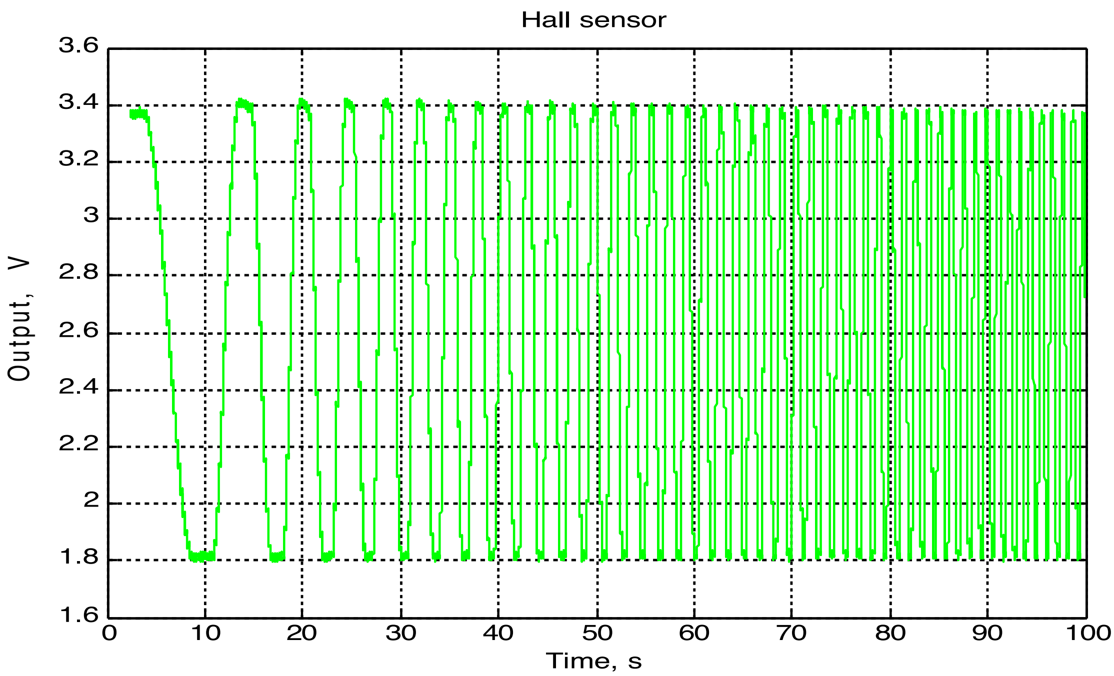


Fig 9-27. Hall sensor output plotted as a function of motor frequency in the range from 0.2 to 200 step/s.

9.1.2 Injector Sample S2

This test took a second sample of the injector and compared it with sample S1.

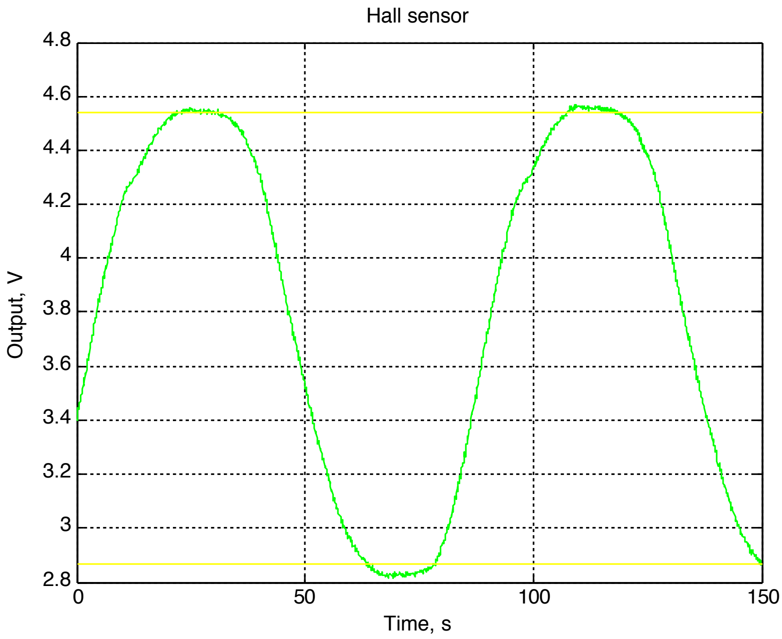


Fig 9-28: Hall sensor N2. Output while sweeping the motor over a 600 step motion with a velocity of 4 step/s. The range of the Hall sensor is 1.7505 (from 2.865V to 4.567V marked by yellow in the plot). The period of the sensor at 3.717 V is 346 motor steps. The number of steps to move from the minimum to the maximum points (from 2.865 V to 4.54V of the Hall sensor), is 115 steps (429-314). The average supply power is 2.2V/0.26A.

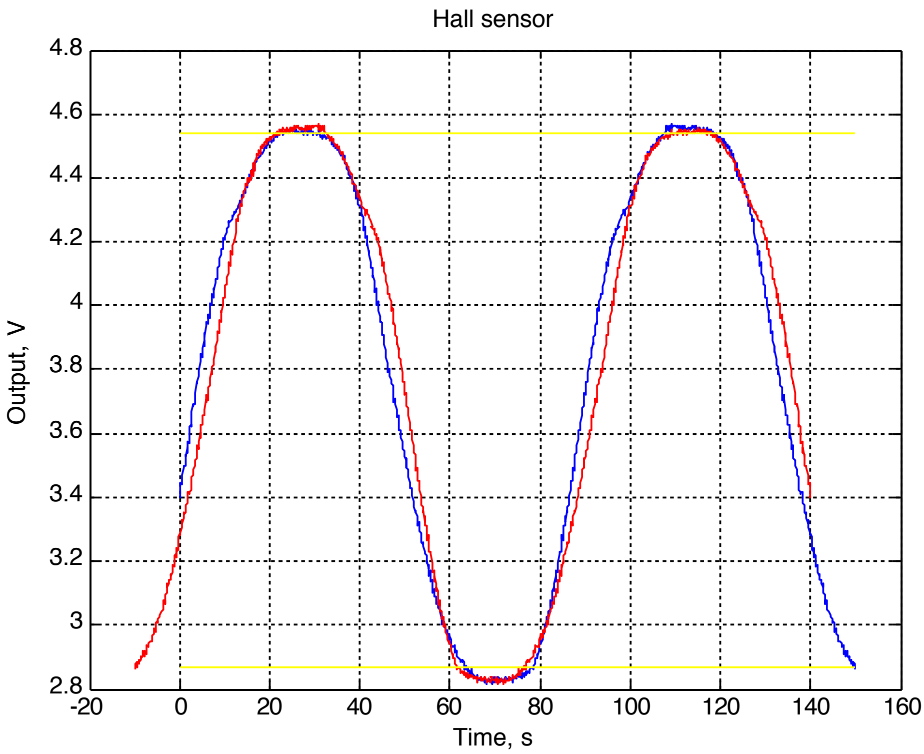


Fig 9-29: Differences in cycling forward and backward, that is, in the forward and reverse directions. The operating range of the driver with feedback is shown by the yellow limits:

these can be applied along the fall or the rise part of the plot. The dead zone is investigated further in subsequent plots, and measures taken to reduce it.

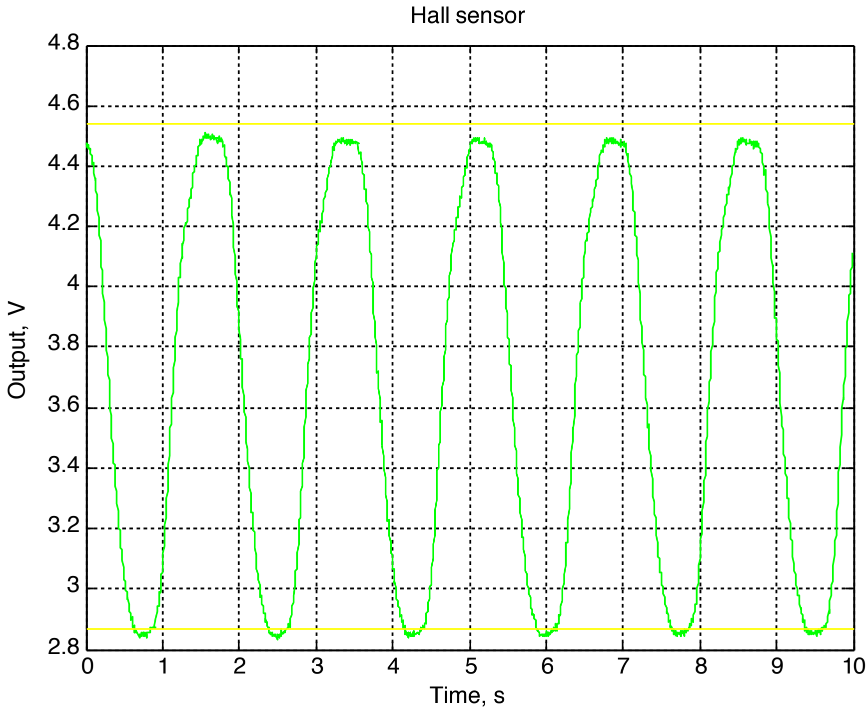
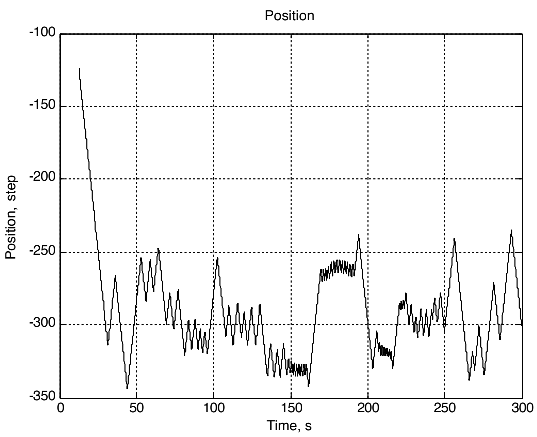


Fig 9-30: Hall sensor N2. 200Hz motion. Yellow lines are 2.865 V and 4.54V. The clock period to the driver is 5 ms.



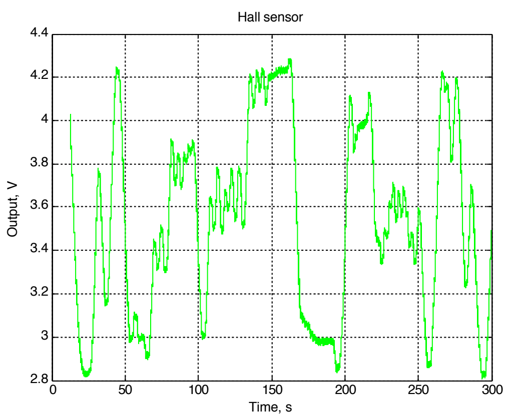


Fig 9-31: Motor position while under motion at a speed of 10 step/s and the corresponding Hall sensor output. The purpose of this test to is to detect and measure the dead zone of the injector.

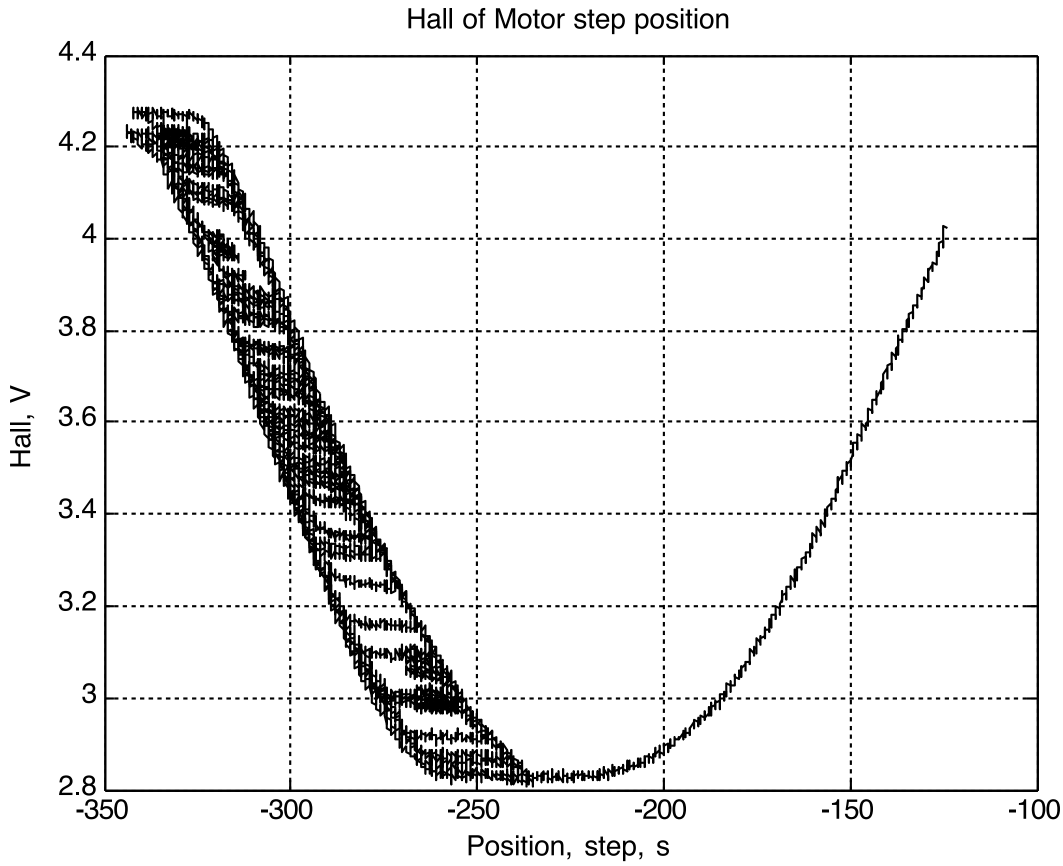


Fig 9-32: The dead zone of the injector measured during motion at a speed of 10 step/s. The zone is 20 steps wide, and occurs only on the negative part of the cycle. The dead zone can be eliminated by overdriving and then driving back up the cycle, but a design change was introduced, adding a bearing that will reduce the backlash to 3 steps wide. This must be rechecked using injectors from the pre-production batch.

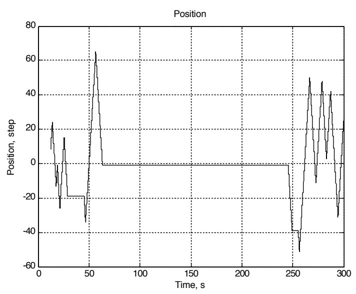
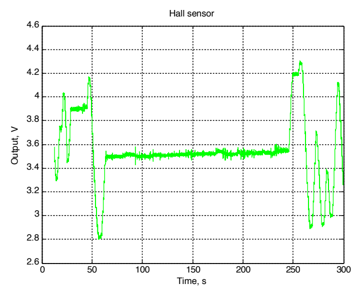
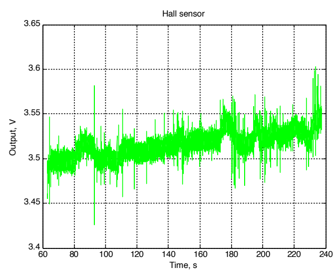
 Motor step position in 300s.	 Hall sensor output in 300s.	 Hall sensor stability against small knocks during 23..237s time range. Deflection is 0.15V or 9% of 1.675 V operating range.

Fig 9-33. Motor position swept at 10 step/s and the corresponding Hall sensor output in whole and in particular time ranges. A small mechanical knock is applied to the injector in different directions when the supplied motor is in the stopped position (from 63 to 237s).

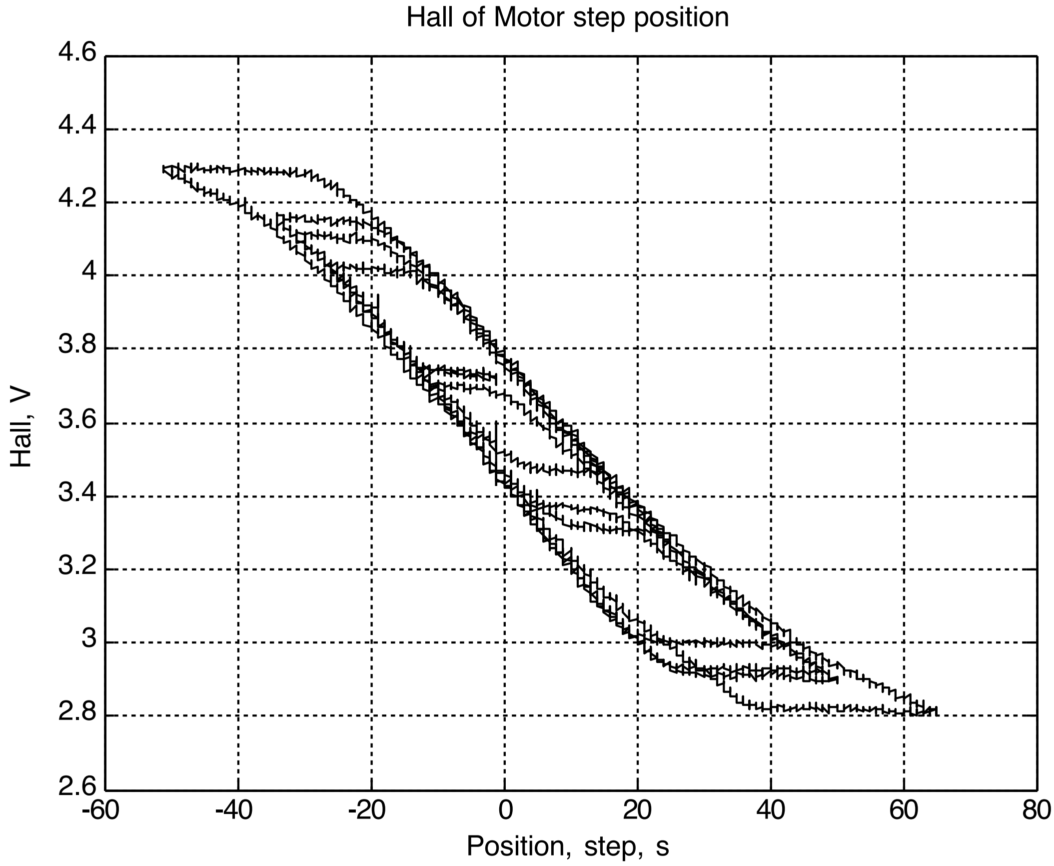


Fig 9-34: Dead zone of the injector measured during 10 step per second motion and mechanical shock applied to the injector in different directions. The zone is about 20 steps. The effect of mechanical shock is to move the orifice from one curve to another. A design change is introduced into the pre-production batch to reduce the dead zone from 20 steps to 4 steps or less.

9.2 Summary of Injector Characteristics

1. The Hall sensor range for injector Sample S1 is 1.56 V (from 1.813V to 3.377V). The range of the Hall sensor in Sample S2 is 1.75 (from 2.86V to 4.57V). ADC offset is 0.15V. Both these figures are within specification.
2. The nominal current per phase of the motor is 300mA (3V/10Ω). Each step motor needs a two phase supply. Driven with 3V, the motor becomes too hot without cooling. Motor voltage was reduced to 2.2V to work without overheating for all tests.
3. The Hall sensor and motor ground of the rebreather electronics have a common ground. The motor current generates noise penetrating into the Hall sensor measurement channels of the rebreather, so Hall measurements should be taken synchronously to eliminate this noise source.
4. The motor operating range from peak to peak for is around 115 steps.
5. The dead zone of the driver is flowing in the range from 20 up to 42 steps. That is almost 35% of the orifice motion range. The possible reason of the dead zone is a console base of the eccentric unit transmitting rotation into linear motion. Design change was reviewed and passed to reduce this to under 4 steps for the pre-

production batch of the injectors, but for the samples tested here it is important to drive the orifice in either forward or backward directions to eliminate this effect.

6. The gain of the Hall sensor to motor position depends on the half period of the eccentric bearing that drives the orifice.
7. If the power supply to the rebreather is switched off, then the unit restarted with a static motor position without recalibrating the motor position using the Hall effect sensor, such as when the diver is already using the unit so injecting O2 in calibration would be too dangerous, then the driver step resolution is reduced 50% because the number of motor state positions (without a supply) is half that of the number of powered motor steps.
8. A small mechanical knock applied to the injector in different direction generates noise in the Hall sensor output. The value of the noise is about 0.15V peak to peak, or 9% of the 1.675V operating range. The likely cause of the noise is play in the console hold magnet of the Hall sensor. A design change was introduced to reduce this effect.
9. The function relating the Hall sensor to the motor position could change sign if the motor initial position is detected in the wrong half of the sensor period. This means that the sign should be recorded in Flash memory for correct motor control.
10. The Hall sensor gain and offset depends on the material of the magnets fixed on the driver and their size and displacement relative to the piston. This variability can be calibrated out during the rebreather startup sequence.

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10. Test Results

10.1 Computer flow simulation

Test	Purpose	Method	In case of non-conformance
1. Examination of computer flow simulation	To verify the flow rate.	Computer flow simulation tools using a formal model of the injector.	Design change

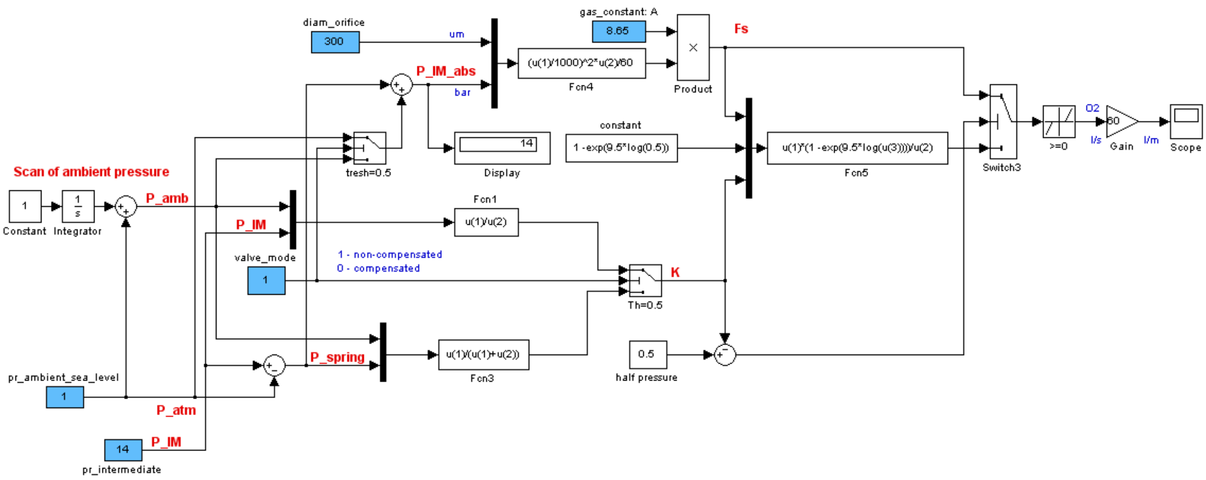
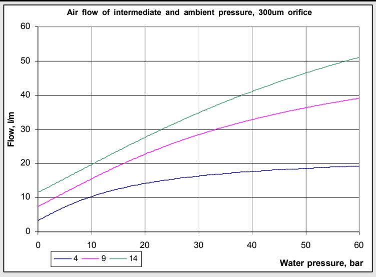


Figure 6.1: Model set up to predict flow rate sonic and subsonic conditions. The equations used by the model for sonic flow is at $F \; ! \; pd^2 A$, in l/min, where p is intermediate pressure in bar, d is orifice diameter in ! m, A is constant: A = A_O2*cnc_O2+ A_N2*cnc_N2+A_He*cnc_He, where A_O2 is 8.65, A_N2 is 9.233, A_He is 15.426; cnc_O2, cnc_N2 and cnc_He are concentration of O2, N2 and He.

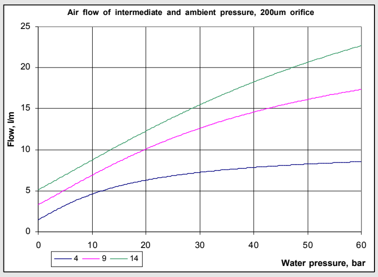
The results of applying the model are shown in the table overleaf.

The injector gain flow is inversely proportional to the Kelvin temperature t°. For example, when the gas temperature is 290 K and the temperature range is from 273 K (0°C) to 307 K (34°C), the variation of the injector gain is about ±6%.

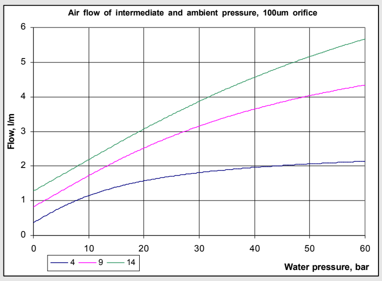
Air



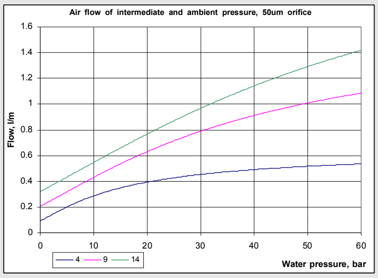
300 ! m orifice



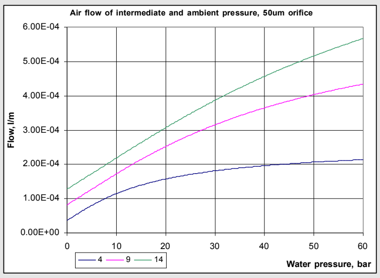
200 ! m orifice



100 ! m orifice

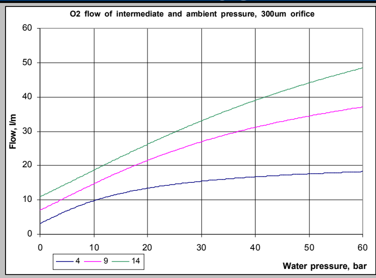


50 ! m orifice

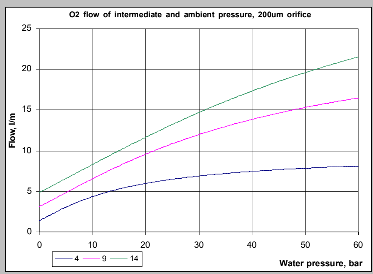


1 ! m orifice

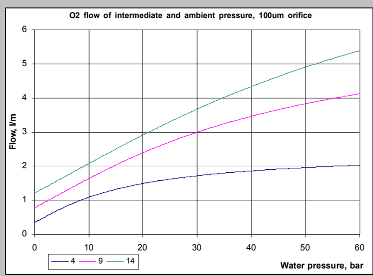
100% Oxygen



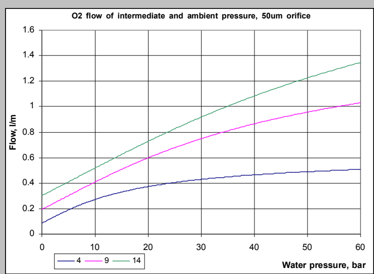
300 ! m orifice



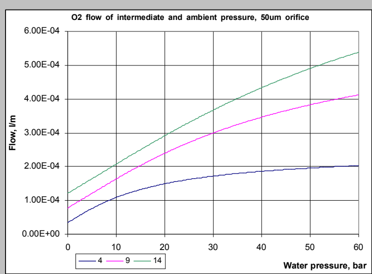
200 ! m orifice



100 ! m orifice

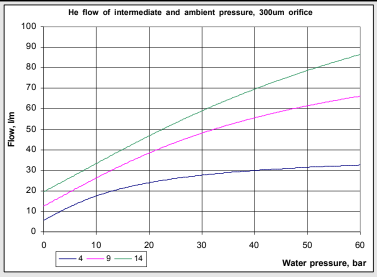


50 ! m orifice

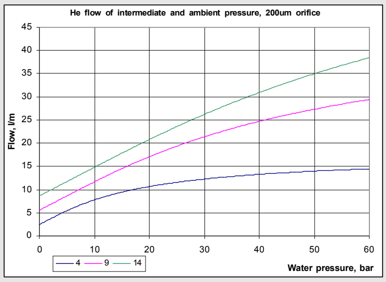


1 ! m orifice

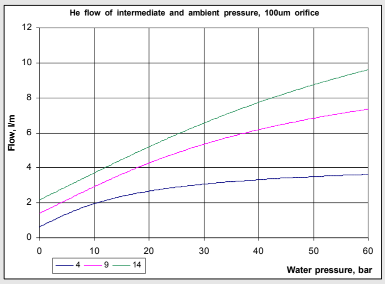
100% Helium



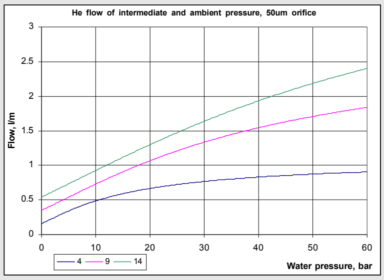
300 ! m orifice



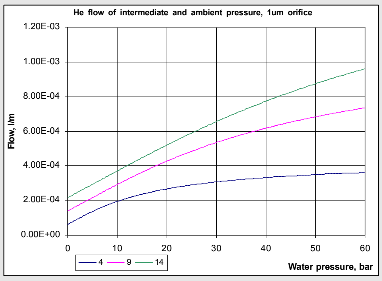
200 ! m orifice



100 ! m orifice



50 ! m orifice



1 ! m orifice

Fig 10-35: Predicted Gas flow for different orifice diameters, gases and intermediate pressures: 4bar (blue line); 9bar (pink line) and 14 bar (green line).

10.1.1 Physical flow simulation

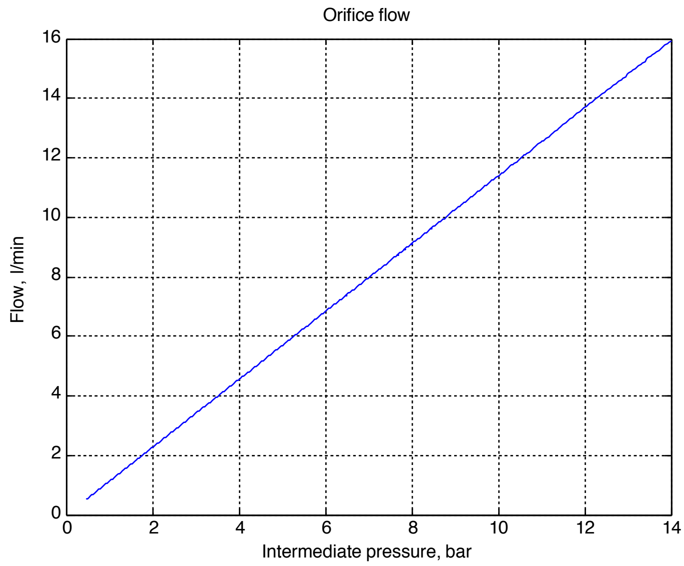


Fig 10-36: Flow as a function of intermediate pressure for helium at 1 atm for the increased tolerance test orifice (200um, instead of normal 300um).

Note: The above values do not include gas leakage outside the orifice: these will be in addition to the above figures.

10.2 Material Suitability and Compatibility

Test	Purpose	Method	In case of Non-conformance
2. Examination of materials for O2 compatibility.	To avoid O2 fire hazards taking into account the flow rate over any surface.	Compare material to ensure conforms with BOM and BOM meets NASA O2 compatibility requirements.	Remanufacture.

The samples were inspected according to the INJECTOR BOM.xls (Size:20,480; 20/11/2006). All materials were as specified, as shown in the table below.

GAS INJECTOR COMPONENTS	Material
Housing	SS320, not in contact with high pressure O2
Stepper Motor: Series AM 1524, V-3-10	Shaft bearing: sintered bronze sleeves, not in contact with high pressure O2. Kept at 1 atm.
Circuit Board	U.L. Approved FR4, not in contact with pure O2. Molex connector with gold contacts, using lead free solder.
Hall Sensor	Plastic, tinned copper leads. Not in contact with pure O2. Kept at 1 atm.
Planetary Gearhead: Series 15AC 14:1	Housing material: plastic Bearing on output shaft: ceramic bearing Not in contact with high pressure O2. Kept at 1 atm.

Magnet	S8A610. Not in contact with high pressure O2. Kept at 1 atm.
Orifice holder plate, gas port	Nickel alloy: H70MΦ, XH65MB, 10X17H13M3T, 08X17H13M2T
Bearing	Stainless steel, SS320. Not in contact with high pressure O2. Kept at 1 atm.
Ruby Jewel Ring	Pure Sapphire
O-Ring BS008	EDPM, static application
O-Ring BS606	EDPM, static application
O-Ring BS606	EDPM, dynamic application but almost static (within elastic movement of O ring)

All parts in contact with pure O2 are highly oxygen compatible. No grease is used, even on O rings: these seal by application of the correct pressure.

No material off-gasses any toxic substance. No plasticisers are used in the EPDM.

10.3 Linearity in air at 1ATM

Test	Purpose	Method	In case of Non-conformance
3. Linearity in air at 1ATM	Characterisation of injector.	For each motor increment from off to full on, measure position sensor reading and flow rate. Compare with calculated.	Review.

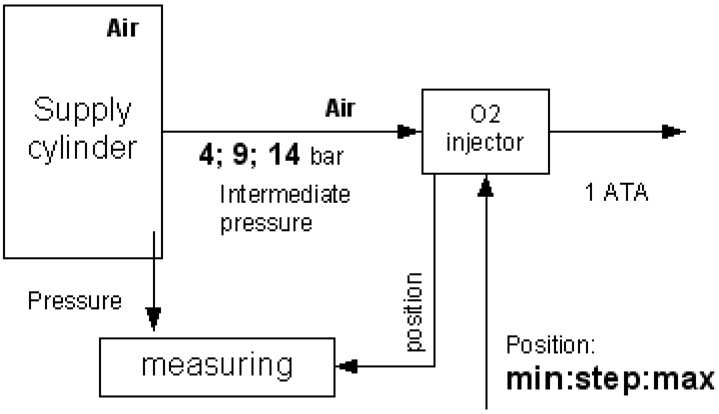


Fig 10-37: Test fixture structure.

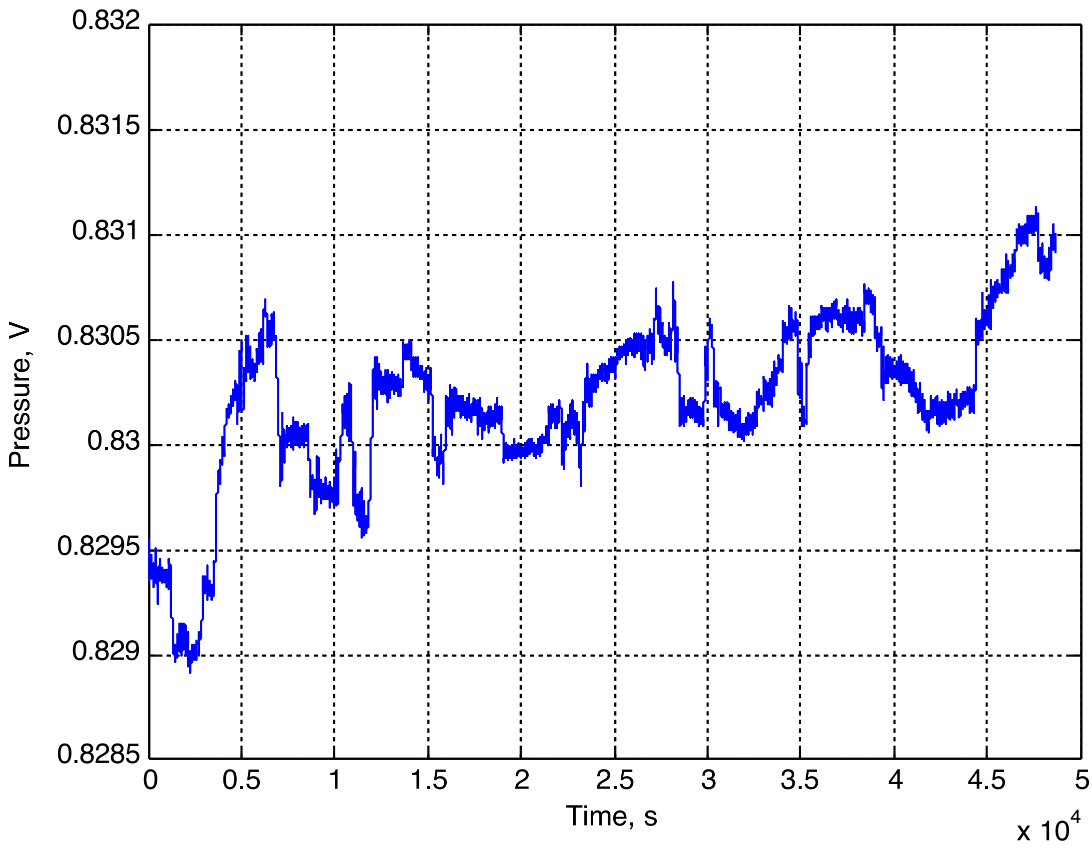
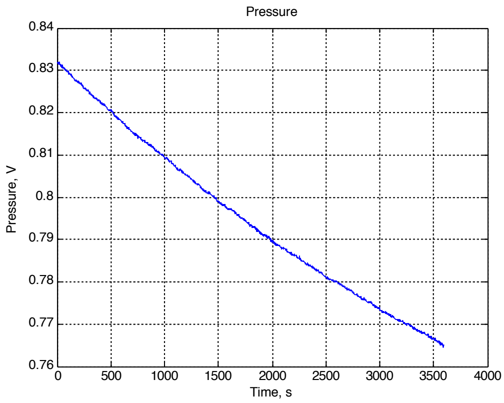
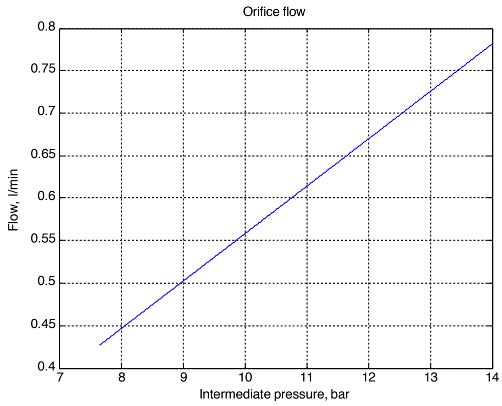


Fig 10-38. The output from the pressure sensor in the chamber with He over a 14.7 hour period. The supply to the O2 injector is switched off. Variation is due to temperature only. A 400 bar FSD pressure sensor is used as this is the most immune to helium offset errors. This test confirms the test chamber does not leak: any leak would affect the flow results.

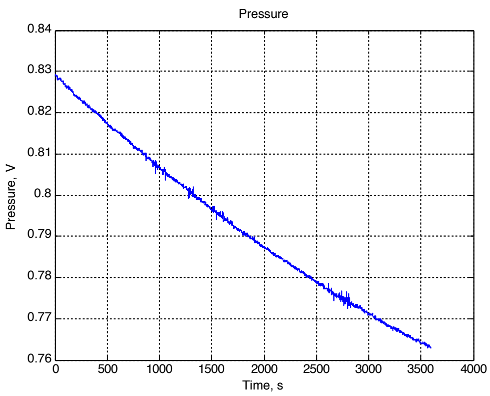
Note: After filling the chamber before the test it needs to wait until the chamber temperature equalises with the room temperature. The chamber temperature changes then only as a result of the speed of the gas flow going into/out the chamber .



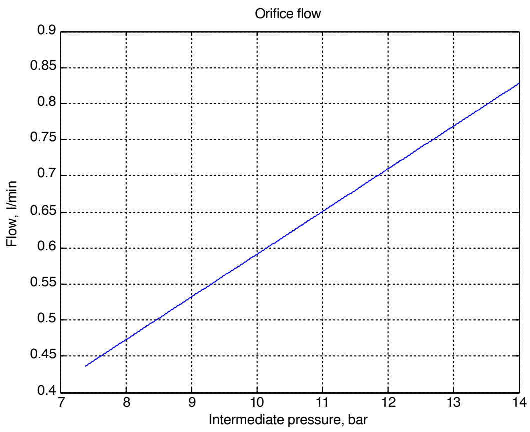
max orifice: 15 um position, 14..7.2 bar. Gas: Air. Intermediate pressure chamber: 5.54 l.



0.78l/min to 14 bar

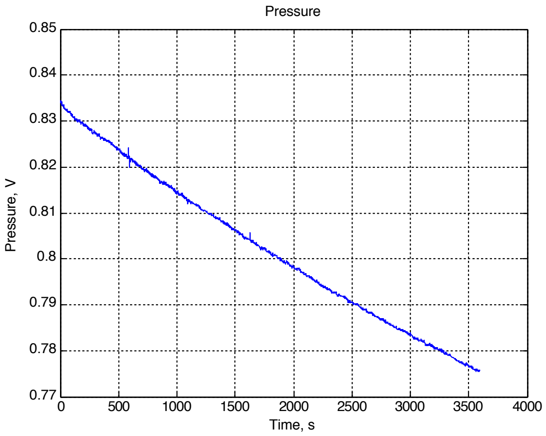


140 um position. 13.7 bar. Air

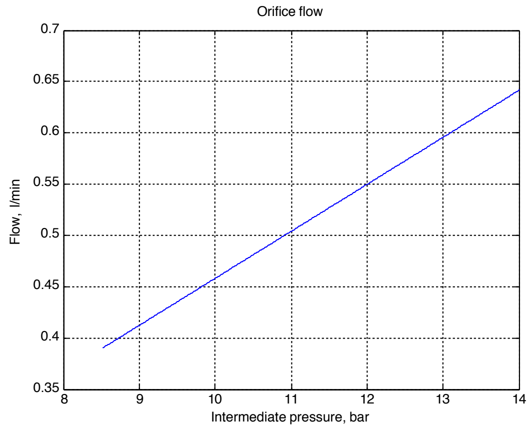


0.83 l/min to 14 bar

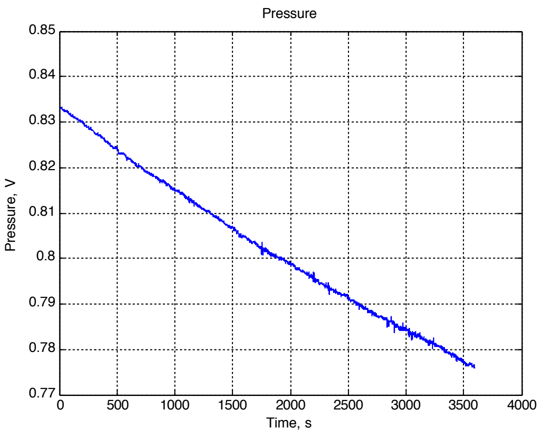
Fig 10-39. The pressure drop and the corresponding Air flow for orifice position 0, 100, 200, 300 um. The start pressure is about 14 bar. The range of the driver is from –20 to 270 um.



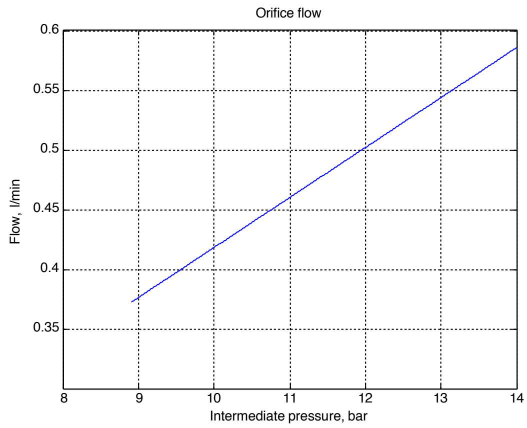
max orifice: -20..-30 um position, from 14 bar, chamber of 5.54 litre, gas: N2



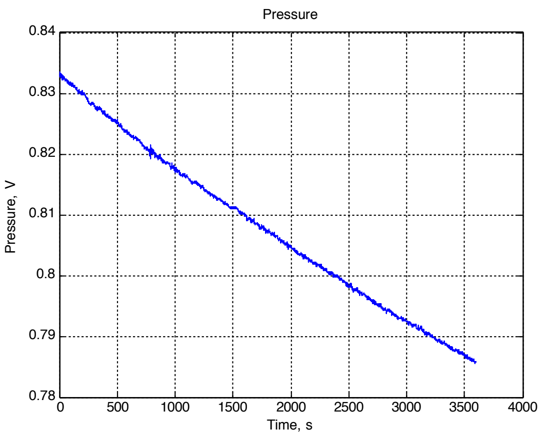
0.48 l/min to 14 bar



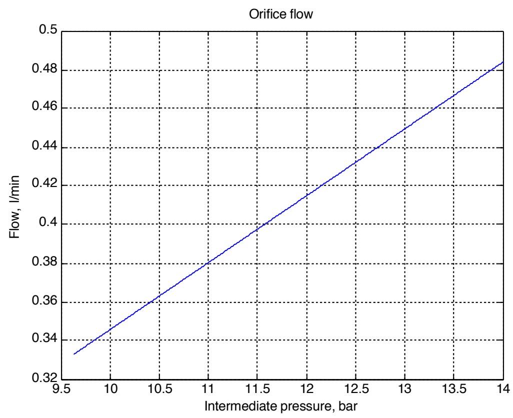
140 um position. 13.7 bar.



0.59 l/min to 14 bar



240-250 um position. 14..9 bar.



0.48 l/min to 14 bar

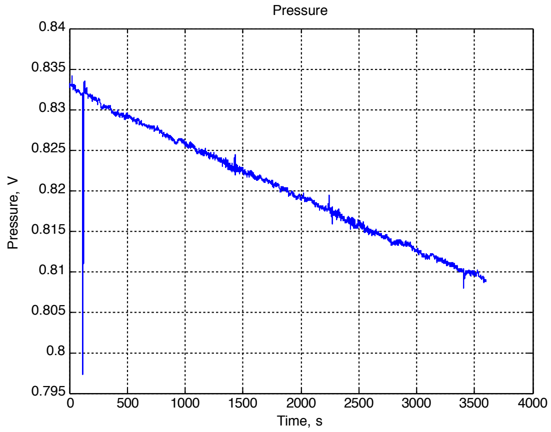
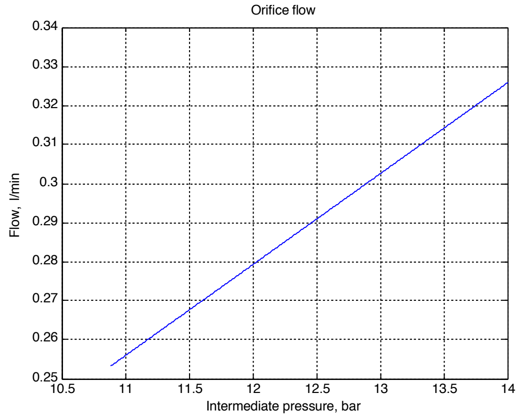
	
270-280 um position. 14 bar. Closed orifice.	0.33 l/min to 14 bar

Fig 10-40: The pressure drop and the corresponding N2 flow for orifice positions 0, 160, 260, and 290 um. The start pressure is 14 bar. The range of the driver is from –20 to 270 um.

10.4 Intermediate pressure range

Test	Purpose	Method	In case of Non-conformance
4. Intermediate pressure range	Test range of intermediate pressures over which the injector operates.	Increase intermediate pressure from 0 to 20 bar while cycling injector from full off to full on. Log intermediate pressure range over which unit operates.	Must operate over range 4 bar to 14 bar relative to ambient.

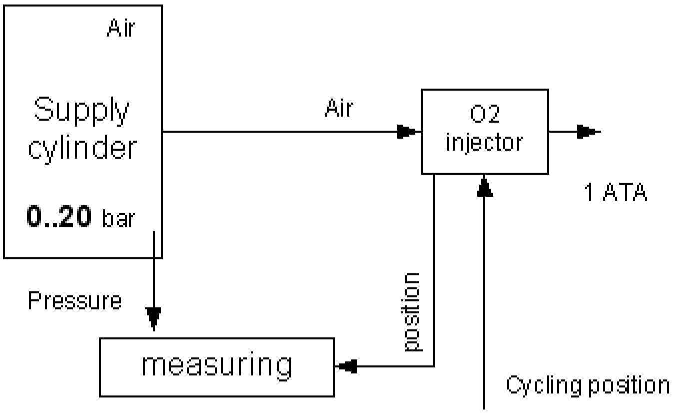
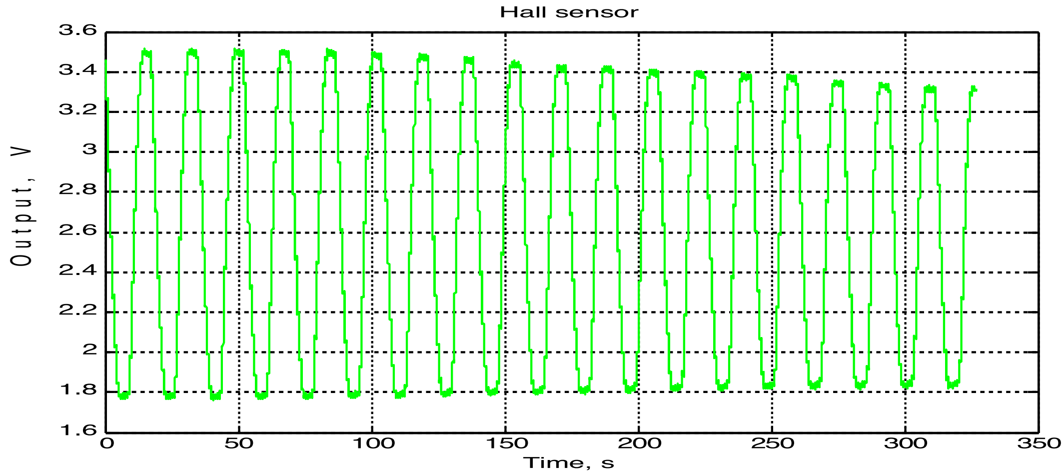
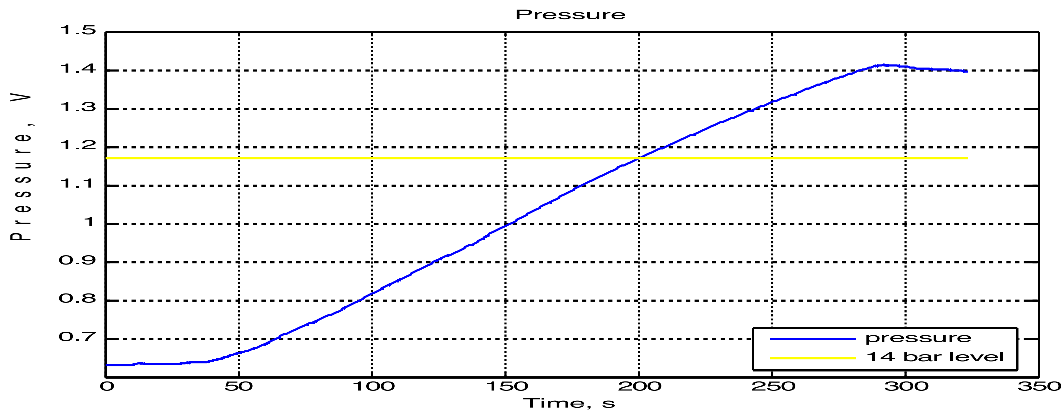


Fig 10-41. Test fixture configuration.

The 100bar FSD pressure sensor was used for this test.



Motor speed is 20step/s



Pressure is from 1 to 20 bar.

14 bar level is 1.17V, calculated as 13*(1.42-0.63)/19+0.63

Fig 10-42: Orifice driver amplitude of intermediate pressure in the range from 1 to 20 bar. Note at higher intermediate pressures the motor must run at a slower speed. For the pre-production batch, the gearing has been increased from 14:1 to 28:1 to overcome this minor problem.

10.5 3m Drop Test

Test	Purpose	Method	In case of Non-conformance
5. 3m Hard Drop test.	Test robustness. The size of the drop is chosen to reflect the shock loading from a RIB in worst case weather that still permits safe diver recovery.	Photograph the injector to be tested. Drop 3m onto a wooden board laid on concrete 10 times and measure flow rates at 1ATM. Photograph the external surfaces again.	Design change

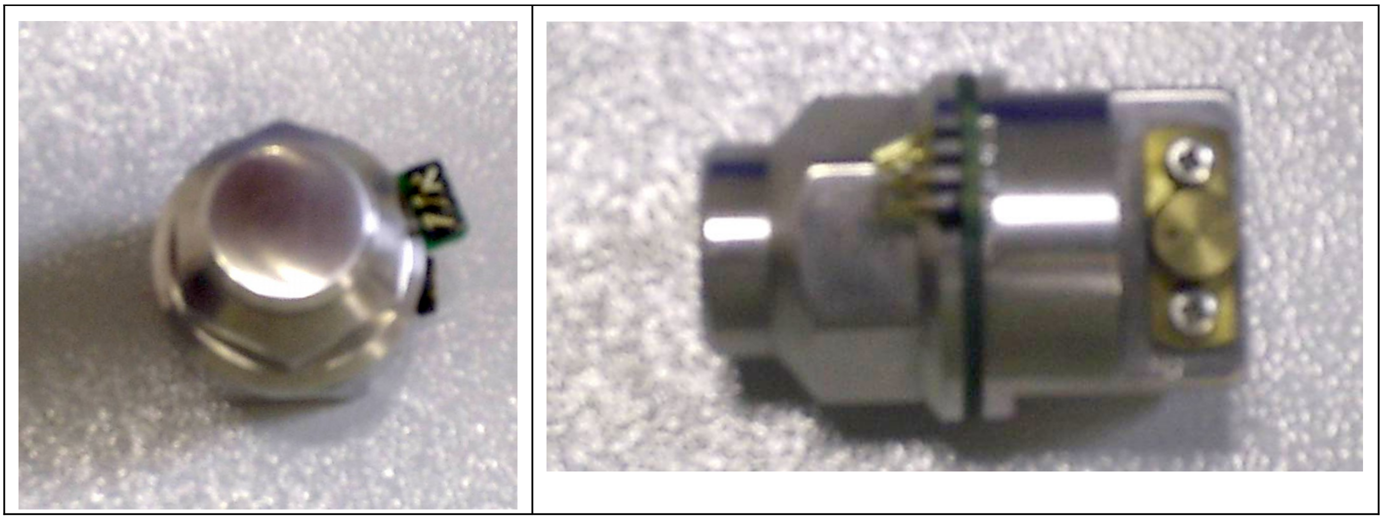


Fig 10-43: Injector after 10 drop tests. Only mark on the injector is the bent Molex pins. No difference in injector performance was observed.

10.6 Linearity in helium at 1ATM

Test	Purpose	Method	In case of Non-conformance
6. Linearity in helium at 1ATM	Characterisation of injector.	For each motor increment from off to full on, measure position sensor reading and flow rate. Compare with calculated.	Review.

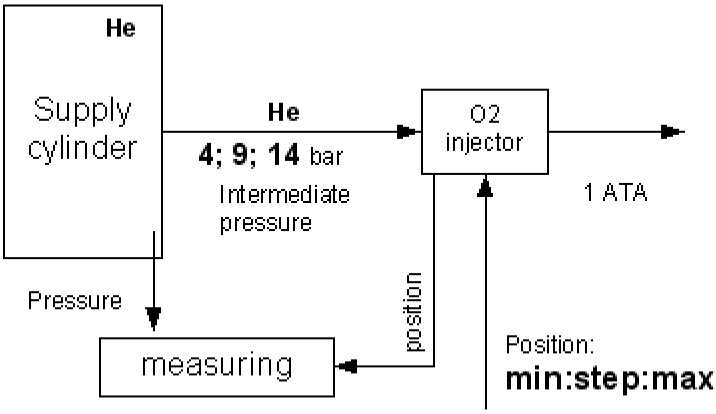


Fig 10-44: Test fixture configuration.

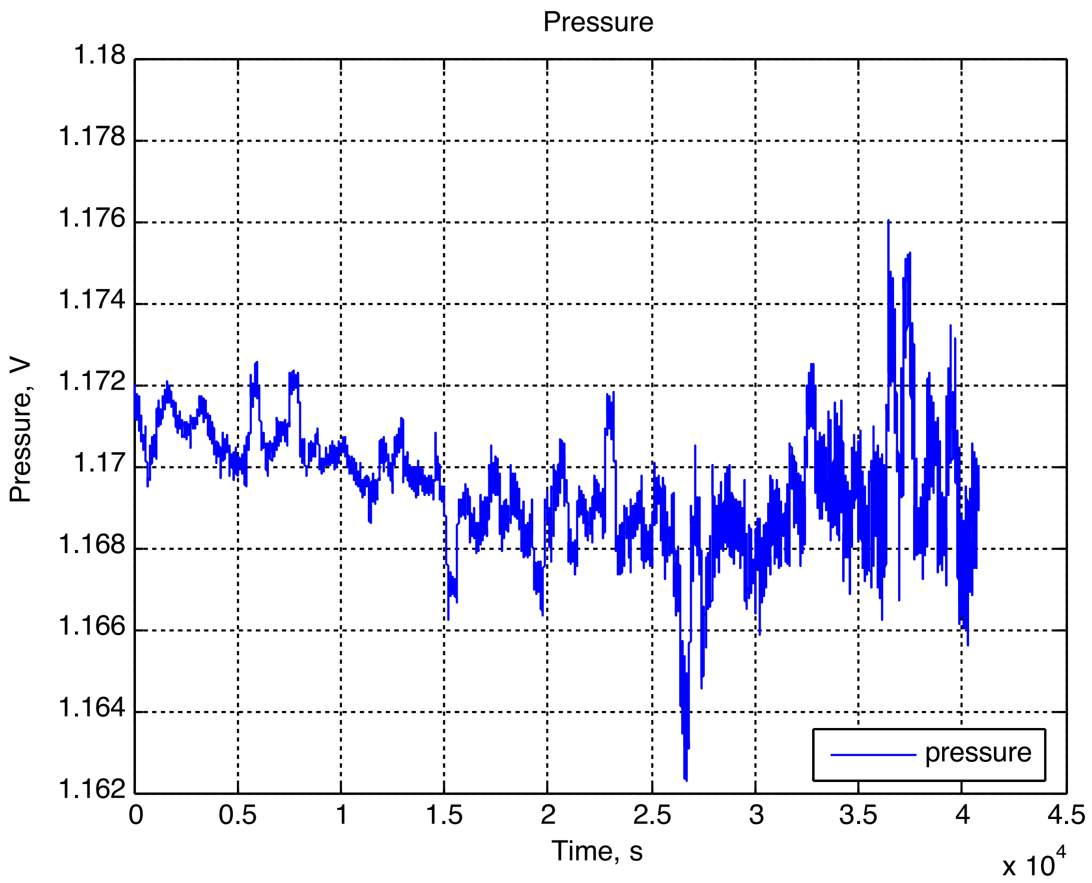
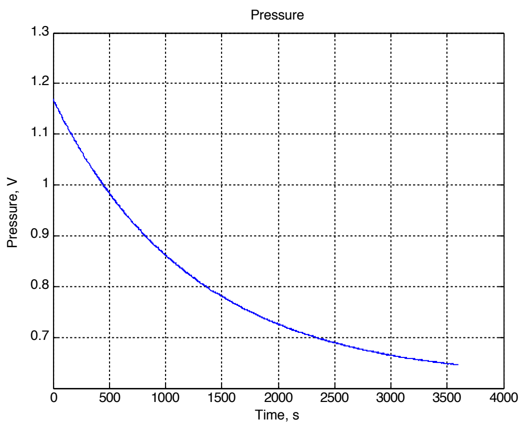
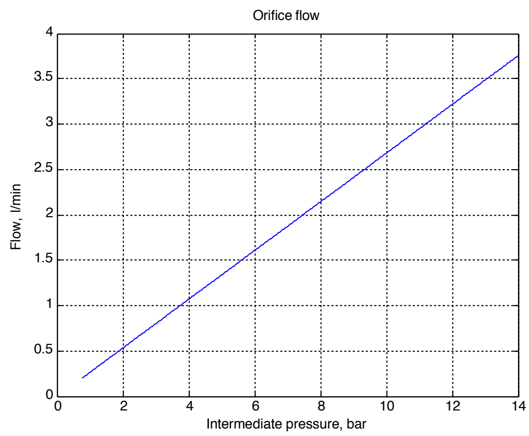


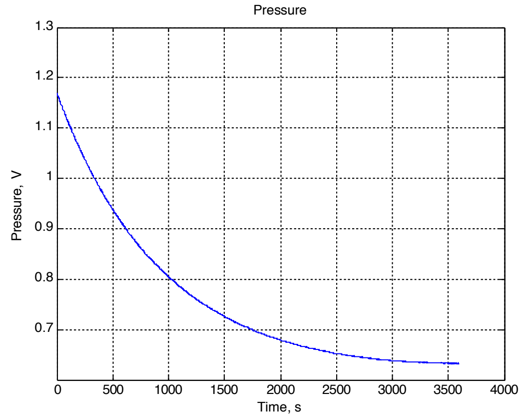
Fig 10-45: Recheck of the pressure chamber with fill to 14 bar, over an 11.5 hour period. There is no leakage in the chamber before the testing with He. Tests continued without interfering with the chamber seals.



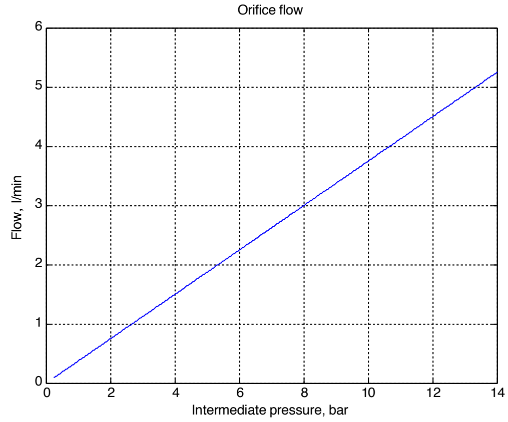
max orifice: -20..-30 um position, 14..1 bar. Chamber: 5.54 litre



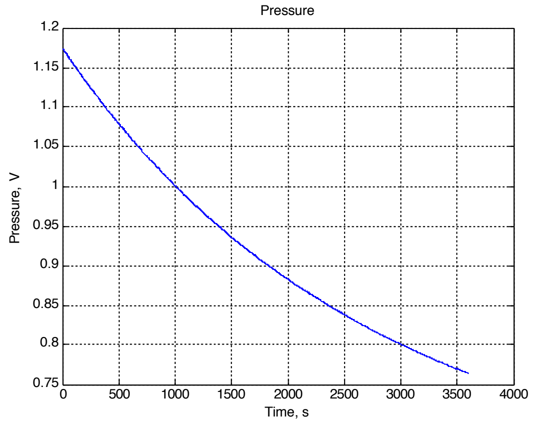
3.76l/min to 14 bar



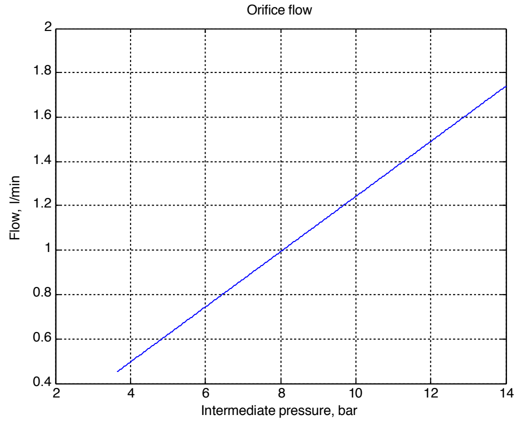
140..150 um position. 14 bar.



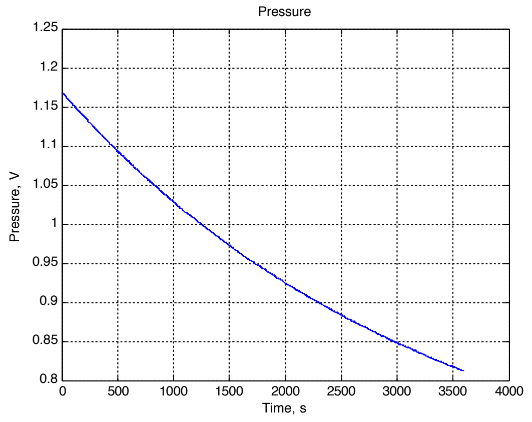
5.25l/min to 14 bar



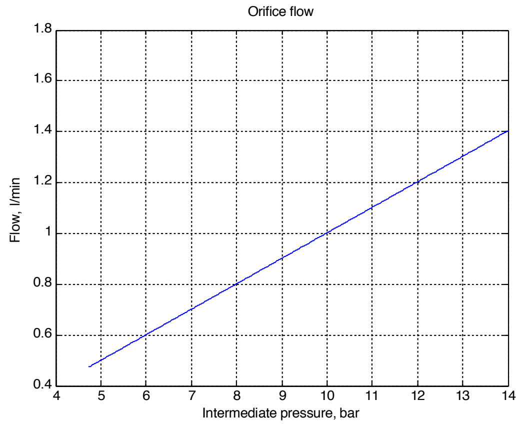
240-250 um position. 14 bar.



1.74l/min to 14 bar



260-270 um position. 14 bar. Closed orifice.



1.4l/min to 14 bar

Fig 10-46: The pressure drop and the corresponding He flow for orifice positions 0, 160, 260 and 280 um. The start pressure is 14 bar. The range of the driver is from –20 to 260 um.

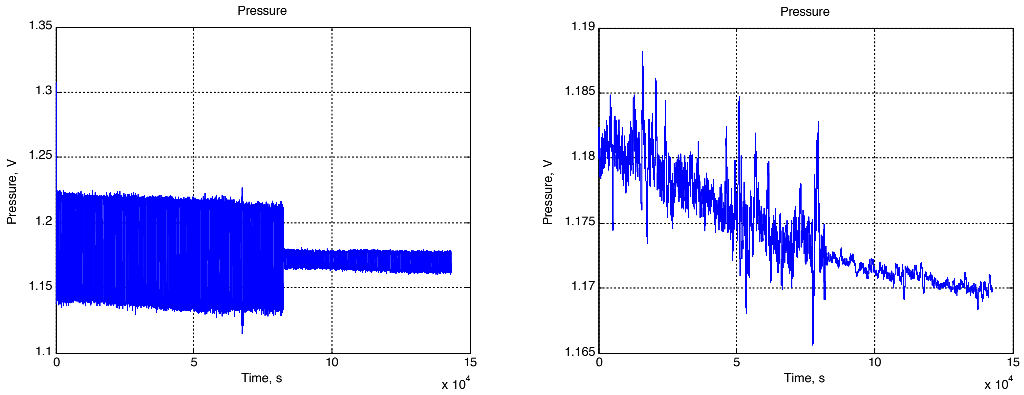


Fig 10-47: Original and filtered pressure sensor output in the chamber with He over 40 hours, time step is one second. The injector supply is off. The 100 bar sensor is used. There is no leakage in the chamber. The reason of the signal excitation in the left half of the plot is the ungrounded chamber. Slight drop in pressure is due to cooling.

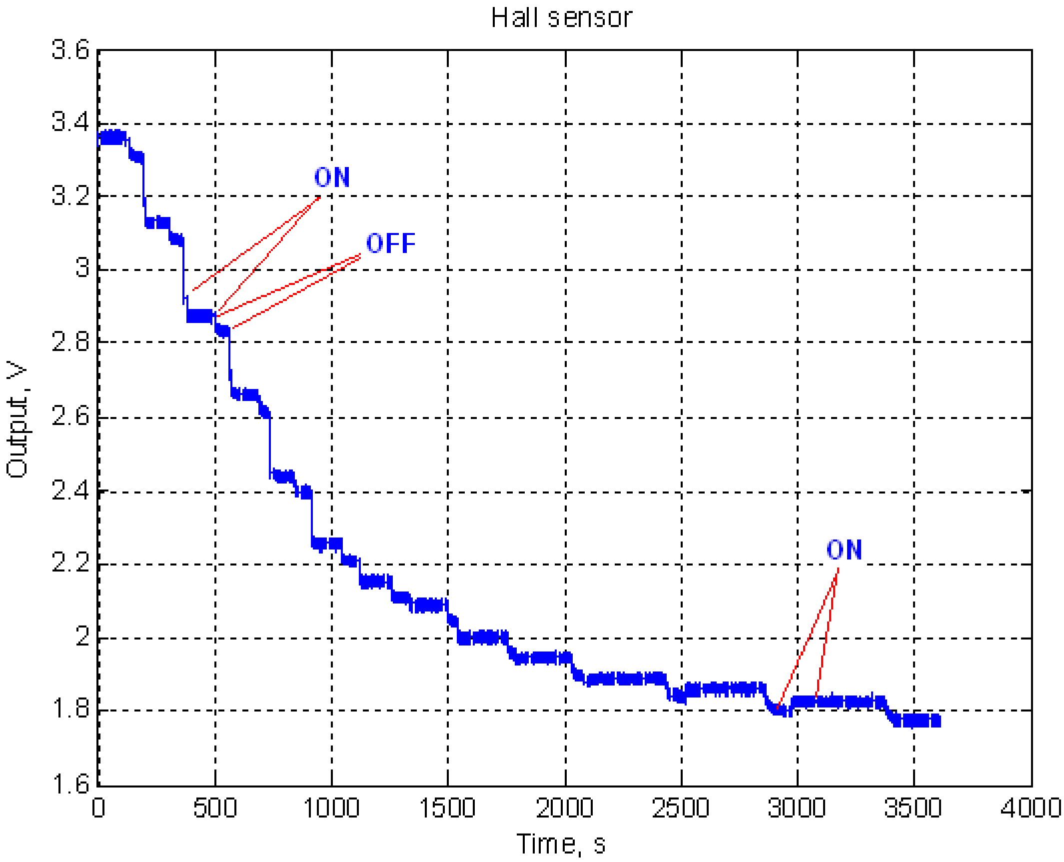


Fig 10-48: Output of the Hall sensor depends on the intermediate pressure, orifice position and the value and direction of external force applied to the driver. The applied force is 70g from an external micrometer in the direction from max to min orifice position. The intermediate pressure is 14 bar. The max offset is 6% of the range in the position close to the max output of the Hall sensor.

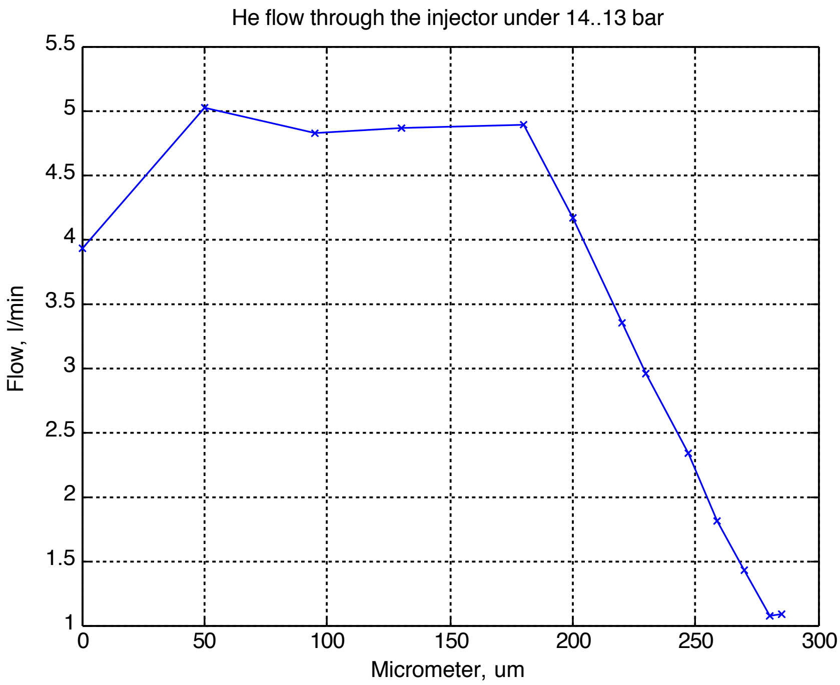


Fig 10-49: Flow of He through injector. Position of the injector driver is measured using an external micrometer. Zero position should correspond to the max orifice. The peak flow is at 120 um. The orifice size is 200um´, i.e. it is the reduced tolerance test orifice rather than the standard 300um orifice. The result shows the initial orifice position relative the driver by 150um to provide optimum orifice alignment. A bearing design change was implemented for this, and the result is shown below.

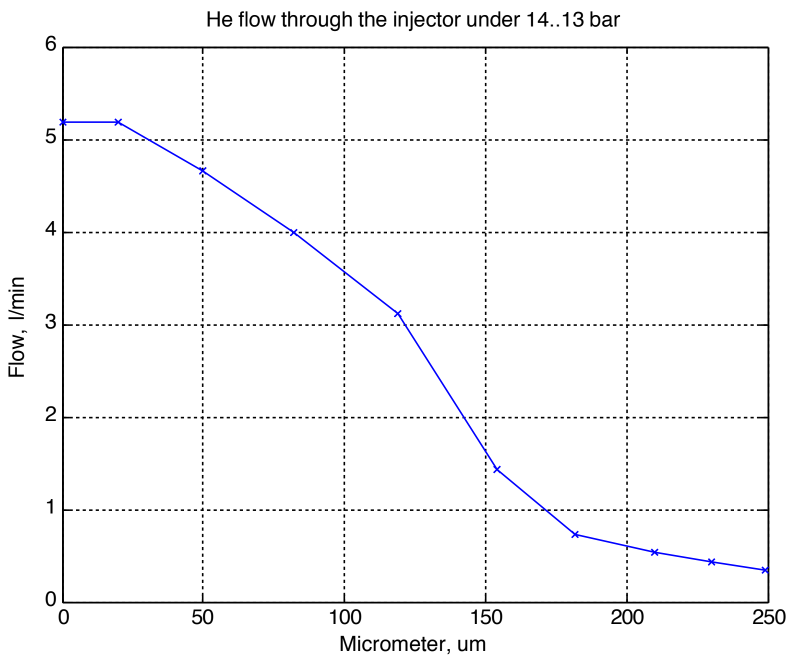


Fig 10-50: Flow of He through injector after adjusting the orifice position relative to the injector driver. The peak flow is displaced from 150 um to the left. The minimum flow relative to the data of the above plot is decreased from 1 l/min to 0.35 l/min. The relation between the max and min flow is increased from 5 to 15 times.

10.7 Flow over full temperature range

Test	Purpose	Method	In case of Non-conformance
7. Temperature range.	To verify flow over full temperature range.	Set to maximum flow at 1 atm, using air, and immerse in salt water at -4C. Heat the water at 1C per minute. Confirm flow rate by measuring gas consumption (pressure from supply cylinder).	

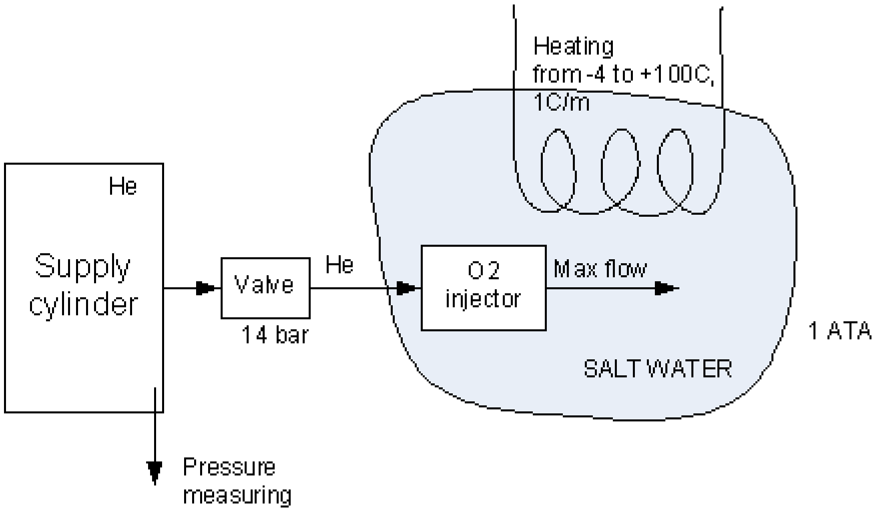


Fig 10-51: Test fixture configuration.

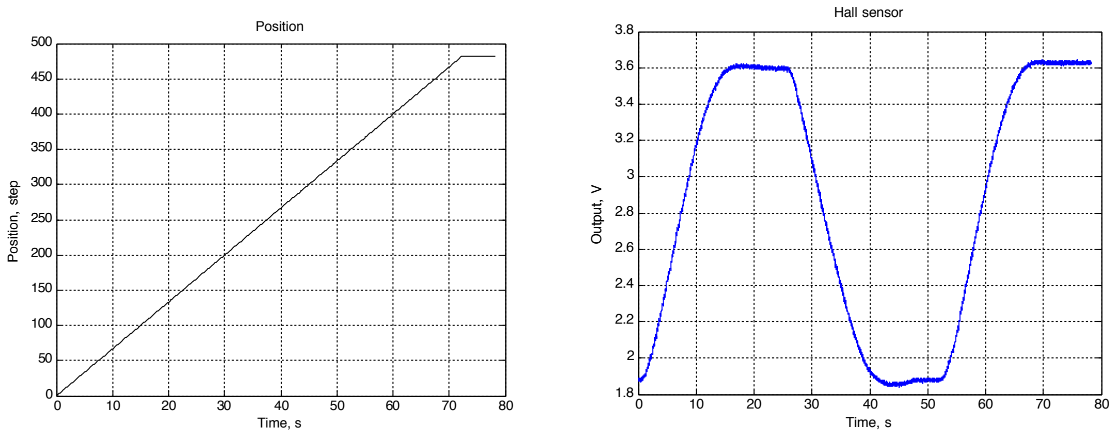


Fig 10-52: Orifice drive position before heating of the injector in water corresponds to the maximum opening of the orifice. Motor driver supply voltage is 2.29 V.

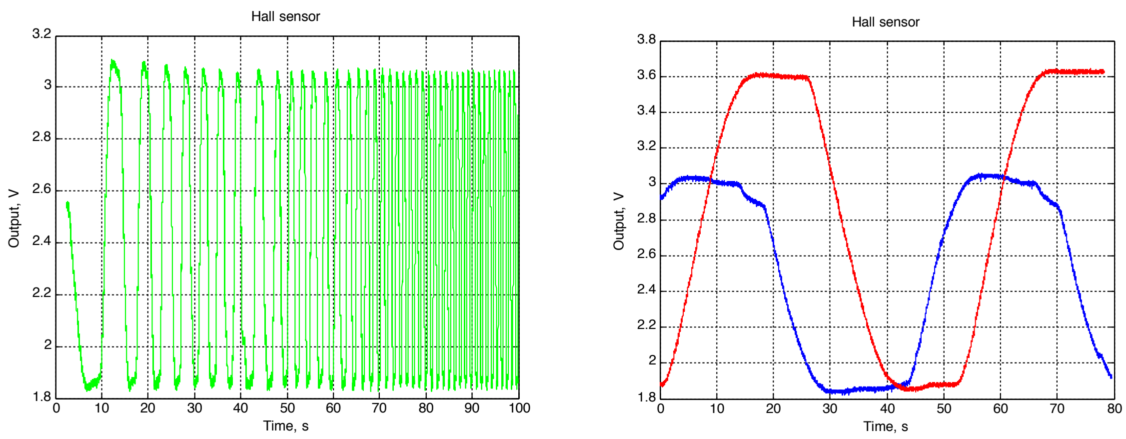


Fig 10-53: Orifice with swept motor speed and alternating direction. Motor driver supply voltage is 3 V. Red curve is the Hall signal of the injector before heating in water. The motor coil switch frequency of the blue/red (after/before heating) is the same of 1/0.15 Hz. After the heating the driver range is decreased from 280 to 210 um. The decrease in the driver motion range is confirmed by measurements taken from the Hall sensor and with an external micrometer. The reason of the driver range decreasing is deformation of injector parts heated by water and cooled by gas flowing via the orifice. The motor offset was increased as a design change to overcome this limitation: retest using injectors from pre-production batch.

10.8 Linearity in helium at 60 ATM

Test	Purpose	Method	In case of Non-conformance
8. Linearity in helium up to 60 ATM	Characterisation of injector at maximum designed operating depth.	For each motor increment from off to full on, measure position sensor reading and flow rate. Compare with calculated.	Review.

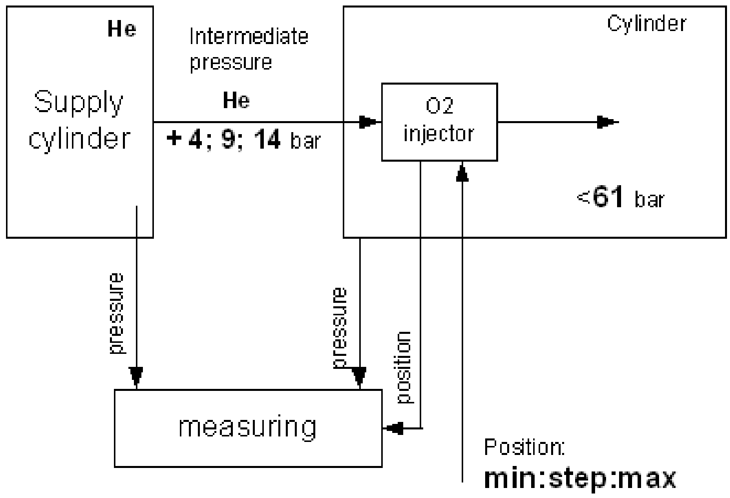
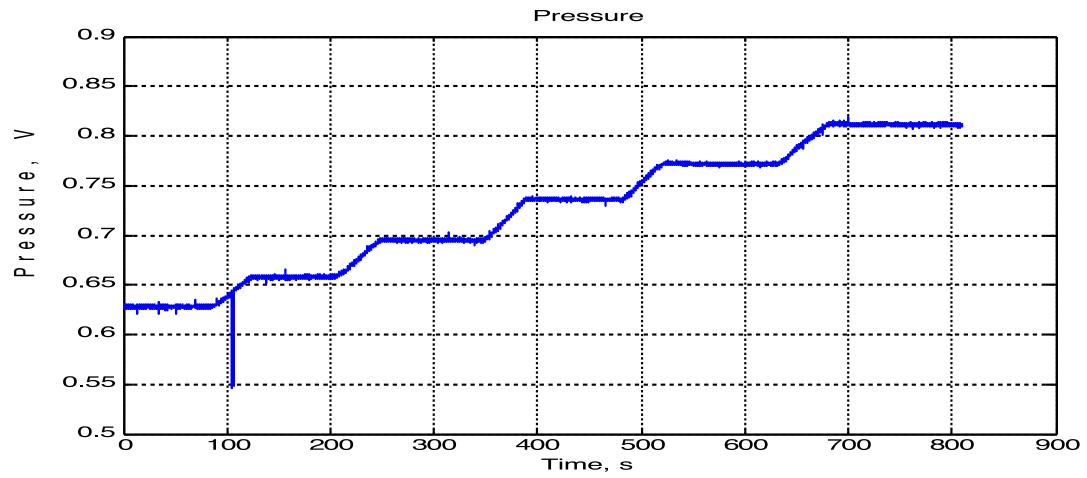
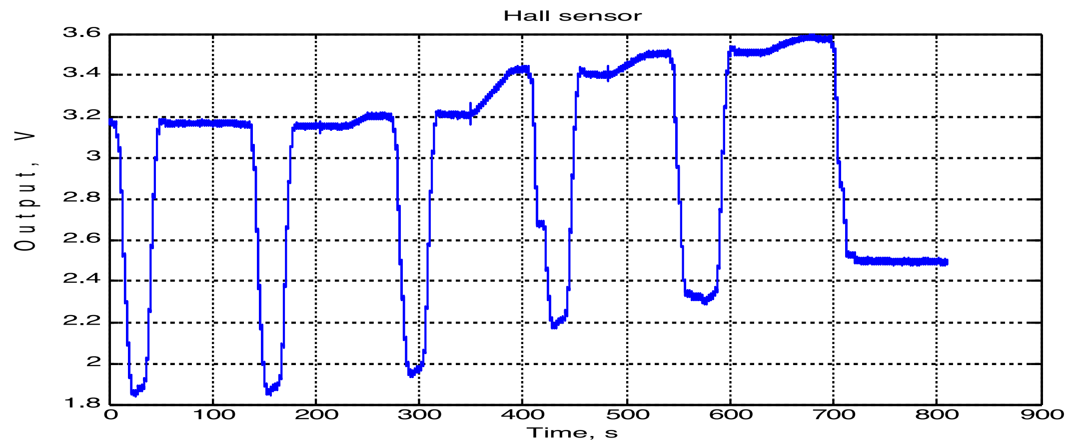


Fig 10-54: Test fixture configuration.

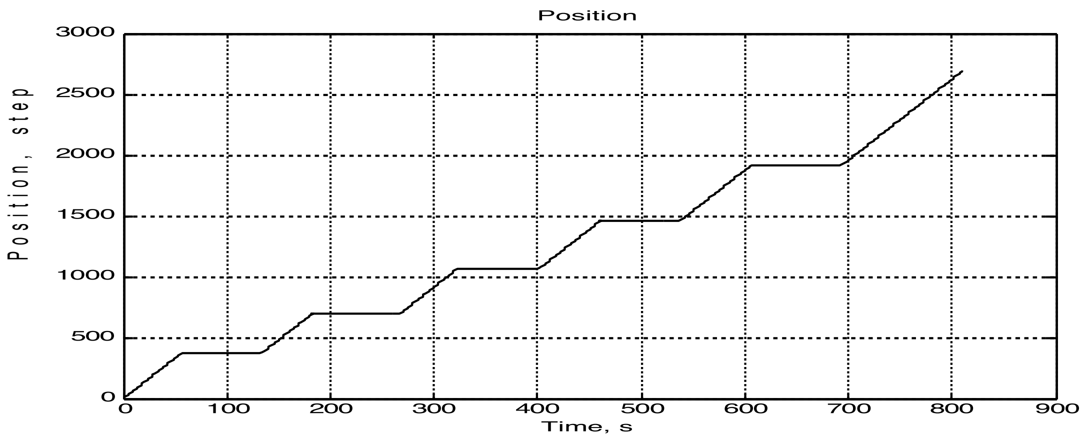
The test is done after the heating of the injector in water up to 100C, after allowing the injector to cool to room temperature.



Ambient pressure: 1,2,3,4,5 and 6 bar

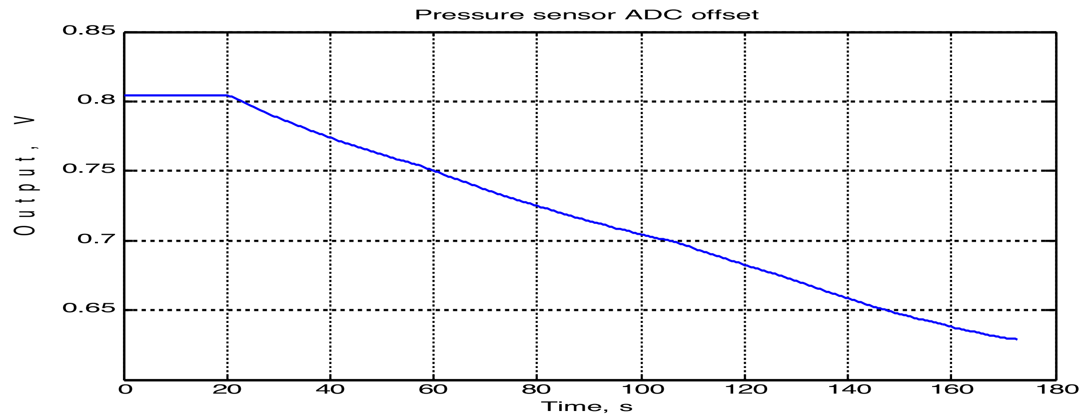


Cycle of driver on each pressure increment. There is no back motion of the supplied driver when the ambient pressure gets 6 bar. The offset is 32% of the range or 13.4um/bar: 210*(3.58-3.165)/(3.165-1.86)/5.

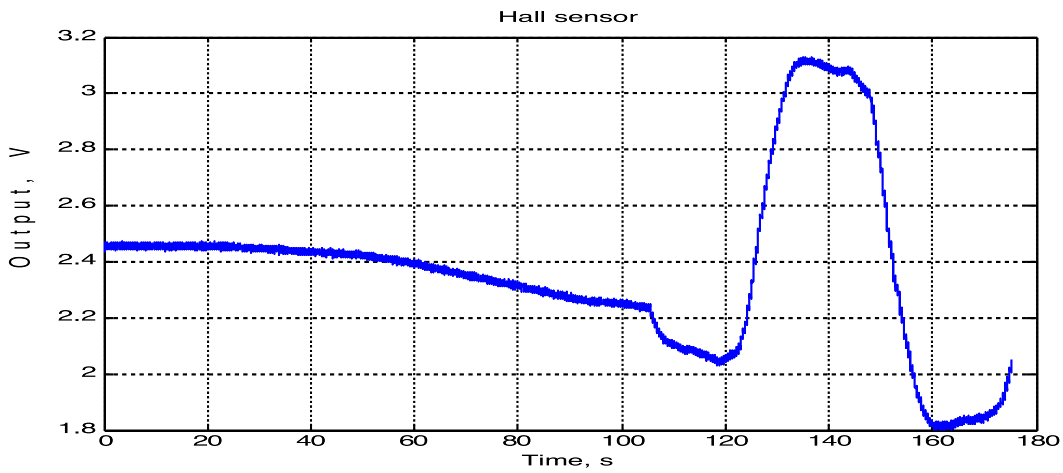


Motor coils are supplied when the ambient is constant.

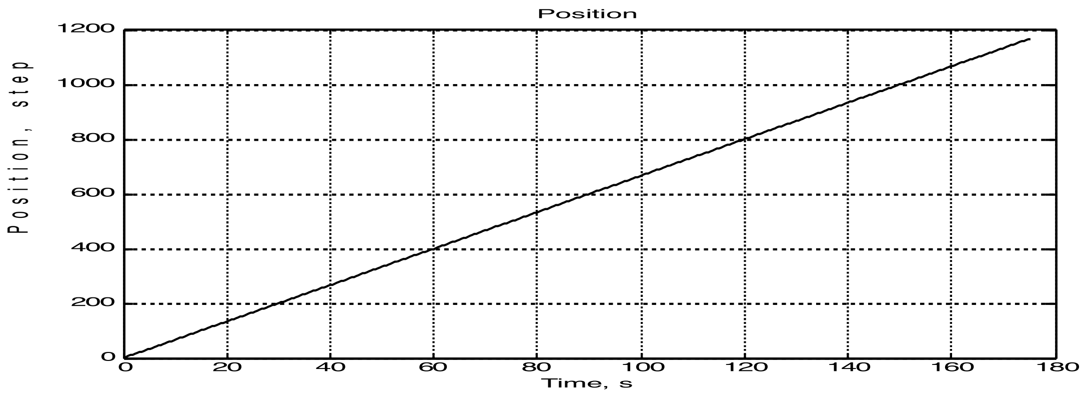
Fig 10-55: The Injector Sample S1 motion under increasing ambient pressure. The intermediate pressure is zero. The test includes the following loop: running of one driver cycle motion, then increasing of ambient pressure by 1 atm. The chamber with ambient pressure is filled by gas via the injector. The offset of the Hall sensor depends on the ambient pressure. It is 13.4um/bar. The reason is increasing of friction in seal separating the room with motor being under atmospheric pressure and the space under ambient pressure.



Drop of the ambient pressure from 6 to 1 bar during constant motor coil supply with 1/0.15 step/s.



Driver starts motion at 120s when the ambient pressure is less than 2.8 bar.

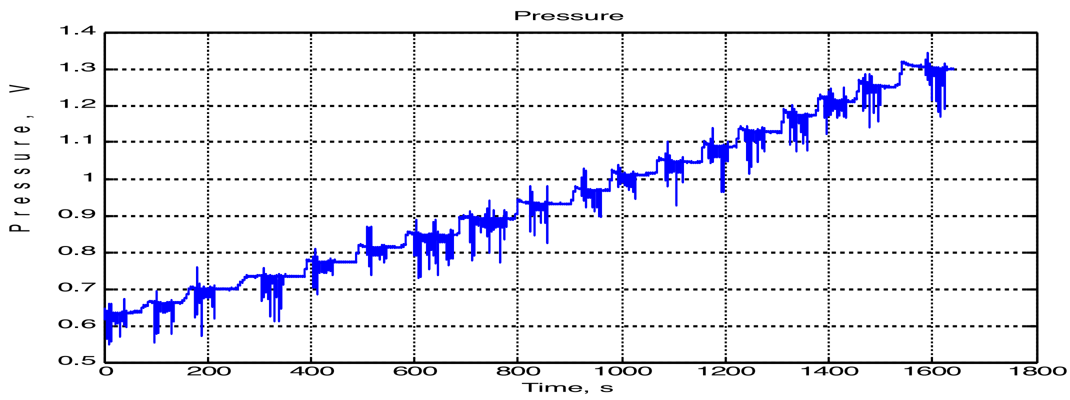


Motor coil supply is 1/0.15 step/s

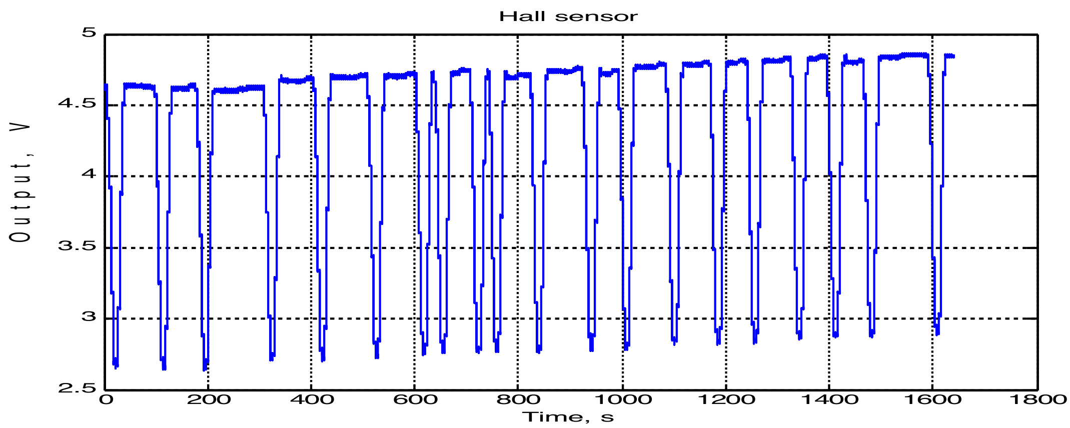
Fig 10-56: The Injector Sample S1 (after heating in water) in motion with falling ambient pressure. Intermediate pressure is zero. Ambient pressure drops from 6 to 1 bar via the chamber injector. The motor coils supply frequency is 1/0.15 Hz.

After the above test the Injector Sample S1 is disassembled. The visible reason of the motor stop and the Hall sensor offset are not detected. The new spool is add to the output orifice of the Injector Sample S1.

The same test of the motion under increasing ambient pressure is done for the second injector that is not heated in the water. The motor operates under the applied ambient pressure increased from 1 up to 18 bar.



Ambient pressure: 1,2,..,18 bar



Cycle of driver made on the constant pressure. The offset is 11% of the range or 1.7um/bar: 260*(4.85-4.635)/(4.635-2.68)/17.

Motor coils are supplied when the ambient pressure is constant.

Fig 10-57: Injector Sample S2 under motion with increasing ambient pressure. The Injector Sample S2 was not heated in water. The intermediate pressure is zero. The test runs the following loop: run one injector cycle motion, then increase the ambient pressure by 1 atm. The chamber is filled via the chamber injector. The offset of the Hall sensor depends on the ambient pressure: It is 1.7um/bar.

10.9 Intermediate pressure tolerance

Test	Purpose	Method	In case of Non-conformance
9. Intermediate pressure tolerance	Test safe range of intermediate pressure	Increase intermediate pressure from 0 to 141 bar while cycling injector from full off to full on. Log intermediate pressure range over which unit operates.	Ensure no catastrophic failure. Note operating range.

Prior to running this test, the stress on the injector that it would cause was analysed, as follows:

Calculation of forces in O2 Injector.

1. Holding torque in stepper motor AM1524 V-3-10: 6mNm
2. Gear 15A reduction ratio: 1:14
3. Maximum torque on the gear shaft 60*14 = 84mNm
4. Eccentricity on the cam: 0.15mm
5. Maximum force on the plunger: $84 \cdot 10^{-3}/0.15 \cdot 10^{-3}$ = 560N
6. Maximum radial force on gear's end: 3N
7. Maximum force on the cam's bearing RS747-759: 207N
   Gear's plastic bearing is limiting, so the maximum force on the plunger in original design could not be more then 3N. Adding support with bearing S9912YME0306PS0 could increase this force to 62N – that is absolute maximum.
8. Friction surface on sealing O-rings on the plunger: 2 O-rings D3.5mm, height ~0.5mm, friction surface = 3.5*pi*2*0.5=3.14mm^2 .
9. Static friction coefficient, rubber to polished steel: 0.1…0.2.

10. Friction force per 1 bar of ambient pressure: $(0.1\ldots0.2)*3.14*10^{-6}*10^{5}=0.031\ldots$ 0.062N per bar of ambient pressure.
11. Maximum ambient pressure at which plunger could move:

This meant that in the current design the maximum pressure differential the injector can take without damage is 3N/0.062N/bar = 48 bar. This does not meet the design objective, so an additional bearing was added to allow the differential pressure to be increased to 141 bar. These changes are shown in the figures below.

In these figures, the parts are colour coded to ease review, as follows:

- Plunger - light green
- Gear - light grey
- Cam - cyan
- Bearing between cam and plunger - grey

In the initial design, the gear rotates the cam with ball bearing that sits in the precise slot in the plunger, and the plunger moves the jewel ring with orifice.

In the theory, the parts are absolutely rigid, and there is no backlash in the drive.

The only significant force in the system is friction between plunger's sealing O-rings and hole in which the plunger slides. The higher the ambient pressure, the higher is compression in the O-rings and higher the force along the plunger.

This force is reacted by the gear, and especially with the own gear's bearing (not shown). This gear bearing is rather weak, so the shaft of the gear is not rigid enough even without ambient pressure – this causes backlash and reduce maximum ambient pressure.

In the improved design, the cam is made a bit narrower to let space for additional support - red bush with small cyan ball bearing in it. This bearing can endure much higher force - 20 times higher then the gear's own bearing. The red bush sits tightly in the existing bore, in Injector's body, and the system is more rigid then in the initial design.

The only part that are changed are the bush and the substitute cam. With these changes, the injector passes the intermediate pressure tolerance test over the full range: to be confirmed by retest of a larger batch from the pre-production run.

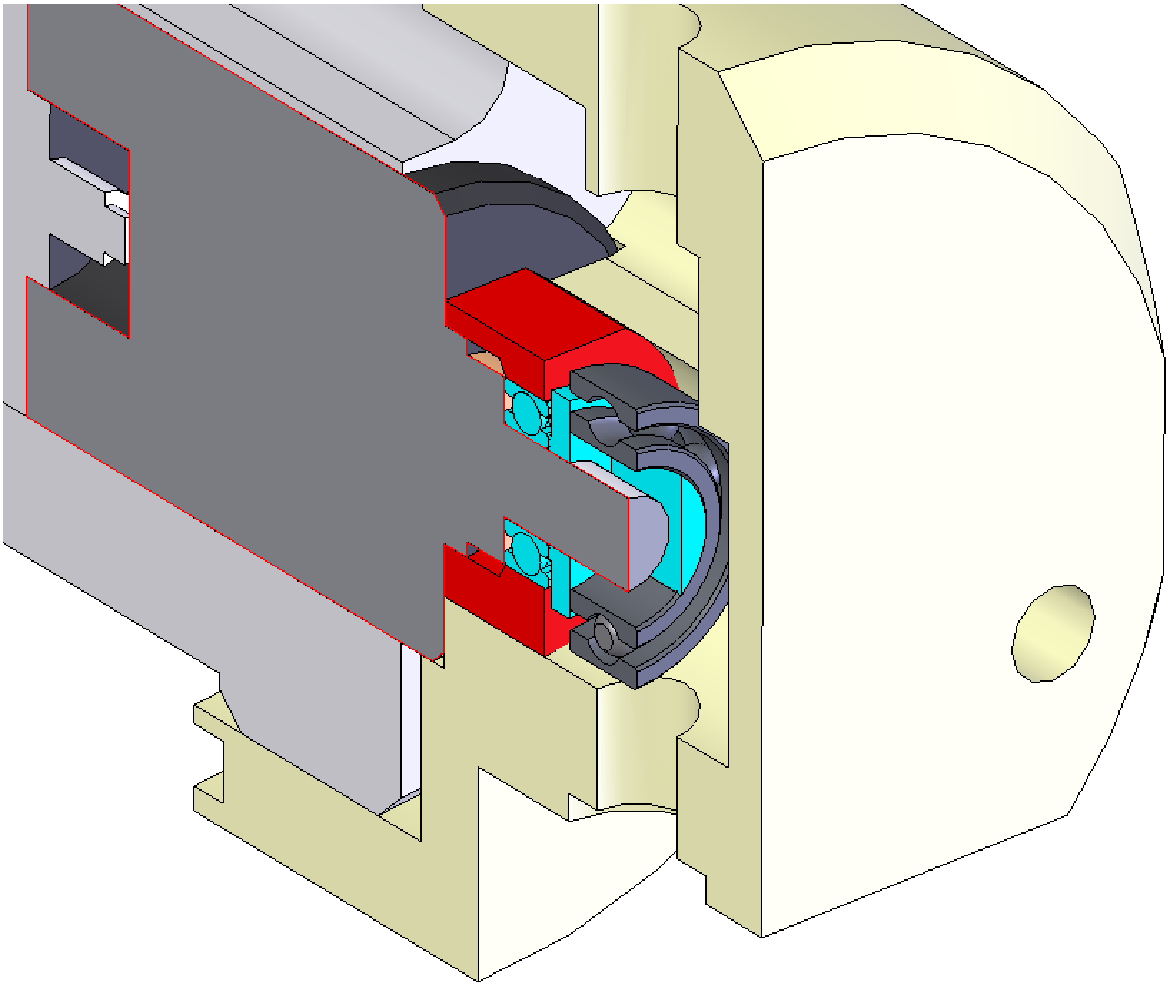


Fig 10-58: CAD Section showing modifications taken after stress analysis, before carrying out test 9.

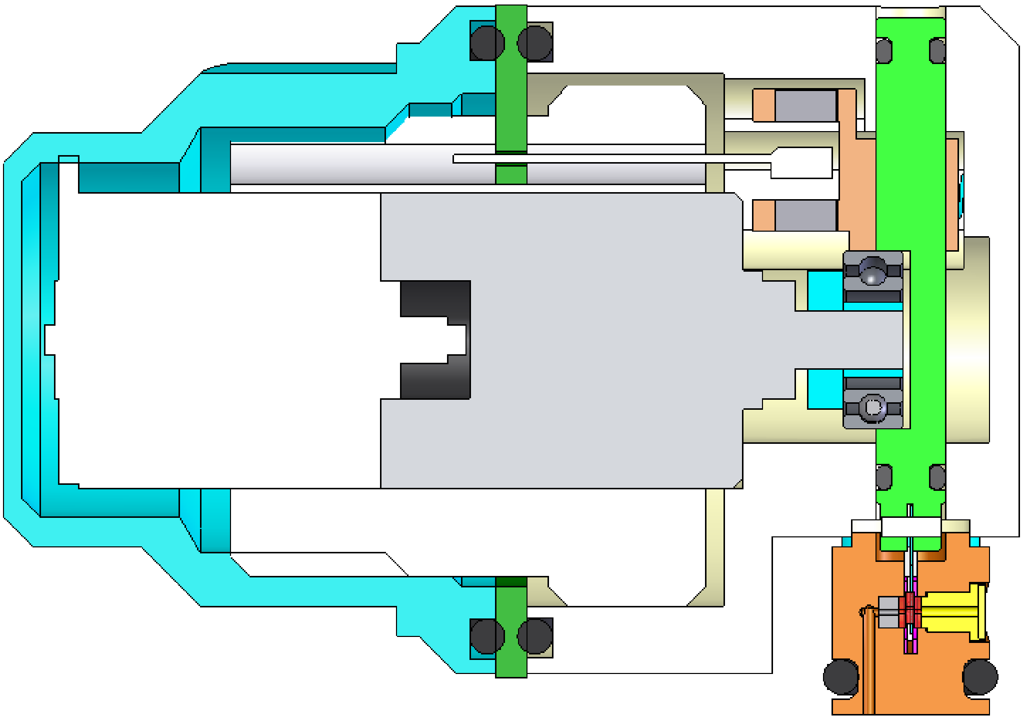


Fig 10-59: Injector cross section before change

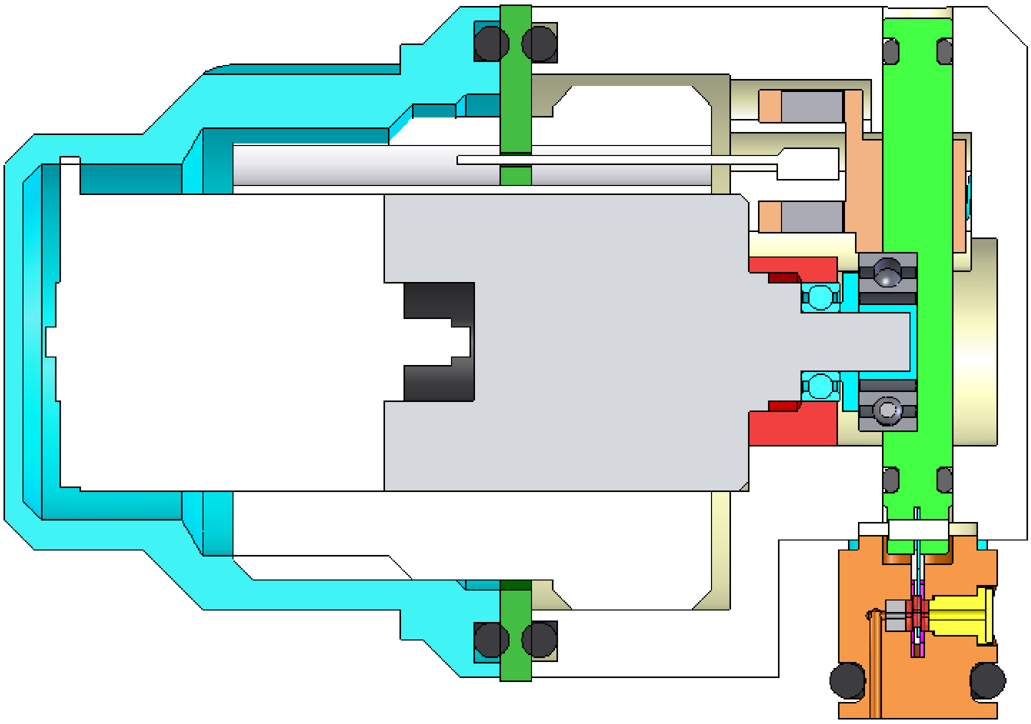


Fig 10-60: Injector cross section after change

10.10 Chamber Lockout/Torpedo Test

Test	Purpose	Method	In case of Non-conformance
10. Torpedo test	Test effect of sudden ambient pressure increase	In a chamber rated to 600 bar, increase pressure from 1 ATM to 300 bar in under 1 second, and test flow while cycling injector from full off to full on. Intermediate pressure 140 bar of helium, fixed.	Review

After the changes for Test 9, the injector can withstand a maximum lockout pressure of 62 bar.

10.11 MTBF check

Test	Purpose	Method	In case of Non-conformance
11. MTBF check	To check reliability of sensor	Drive injector at maximum rate from full off to full on, measuring flow rate. Log flow rate with time. Log results for first hour, then check operation once per month (running continuously). Measure wear. Extrapolate to failure point.	Review

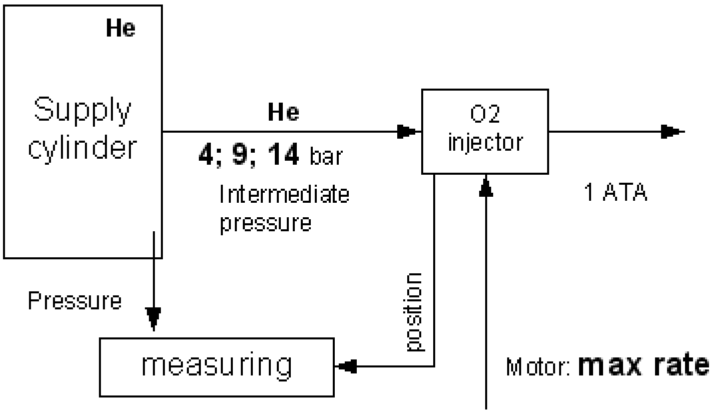
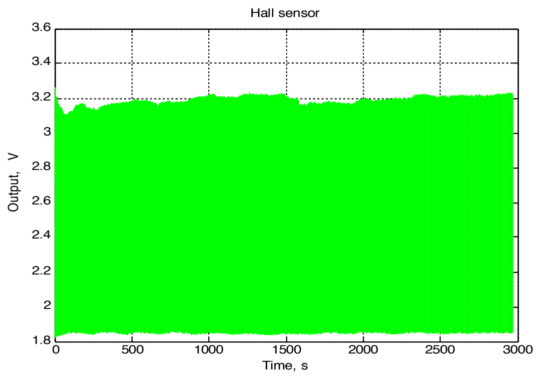
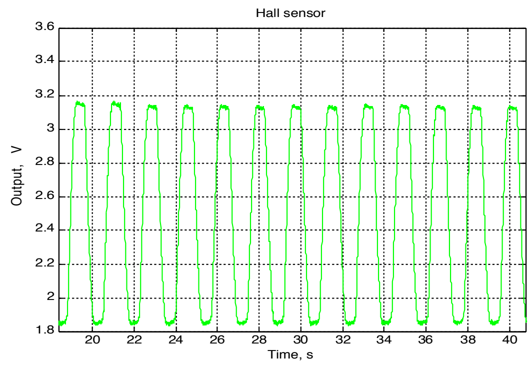


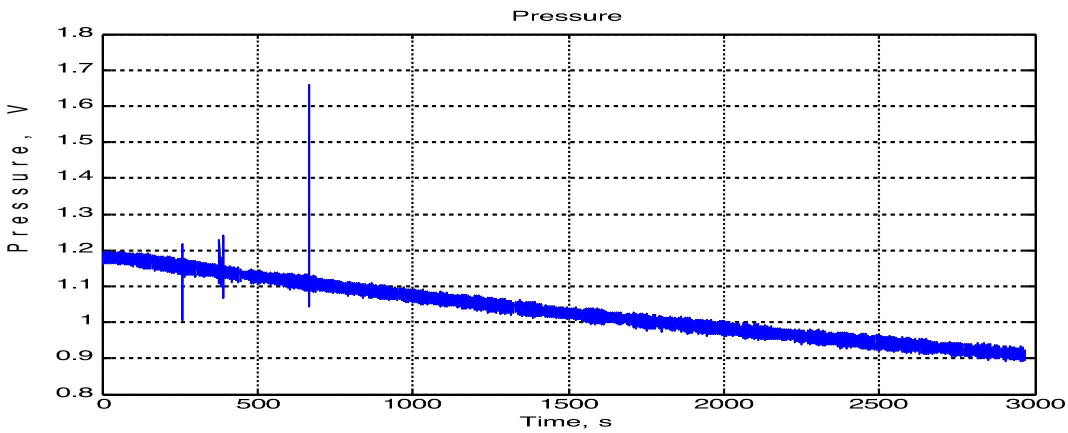
Fig 10-61: Test fixture configuration.



Driver position in 2968 seconds

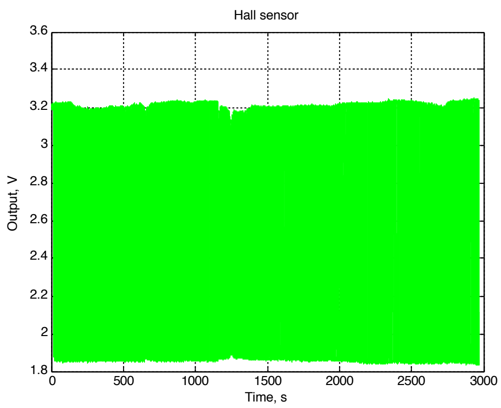


Zoom to show section of driver position plot. Motor speed is 200 step/s

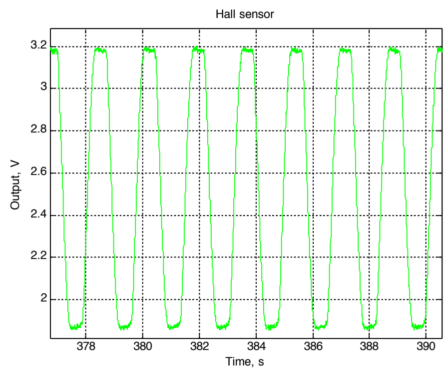


Initial pressure is 14 bar.

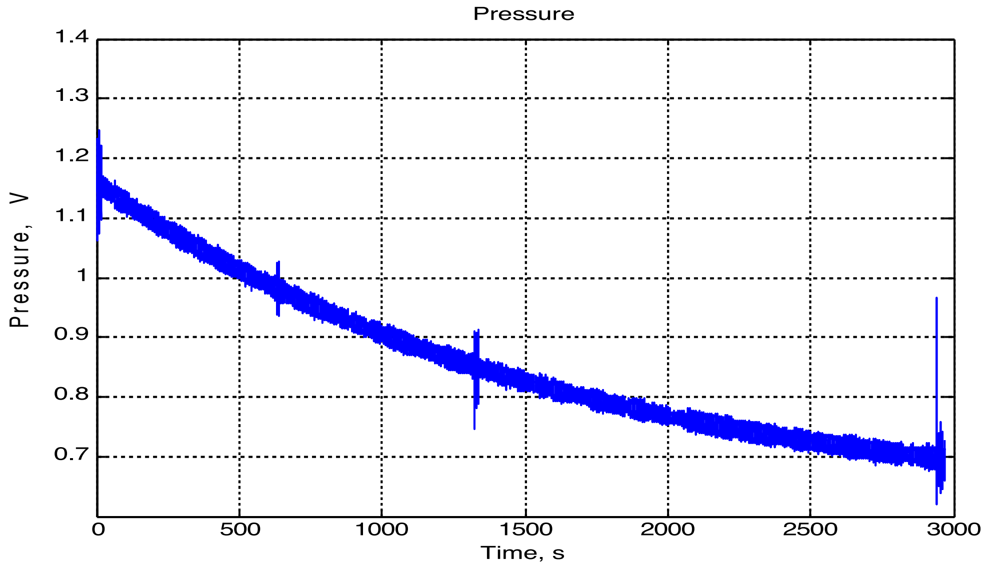
Fig 10-62: Driver position and intermediate pressure drop of Injector Sample S2.



Driver position in 2968 seconds



Fragment of driver position. Motor speed is 200 step/s



Initial pressure is 14 bar.

Fig 10-63: Driver position and intermediate pressure drop of He during first run. This test is repeated monthly.

11. LEAKAGE

11.1 Leakage Test Fixture

The leakage from the valve had to be investigated, because although leakage in the range measured would be a safety benefit, it was not the design intent so must be investigated to determine the cause and if that presents any safety hazards.

To access and examine the valve saddle the configuration of the saddle was reproduced in the test fixture shown below.

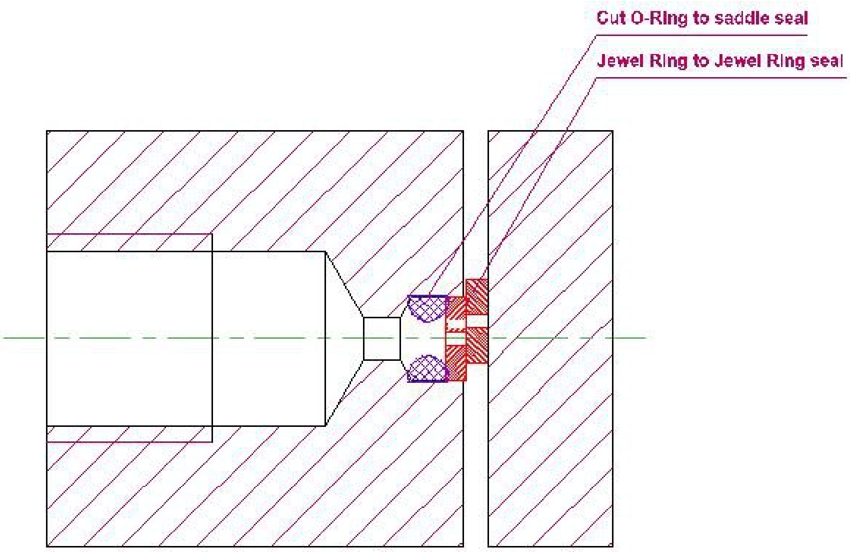


Fig 12-64: Orifice Leakage Test Fixture Design.

The fixture consists of two parts – saddle and covering plate. The saddle holes are an exact replica of those in the Injector valve.

O-Rings were fabricated with a special cutting press. The figure below shows the O-Ring BS001 before trimming (left), sealing ring after cutting (centre) and trimmings (right). Close inspection shows that the outside surface after trimming is smooth and slightly conical, outside diameter 2.1mm.

Fig 12-65: Sealing Rings, original (left), cut using press (centre), and waste (right)

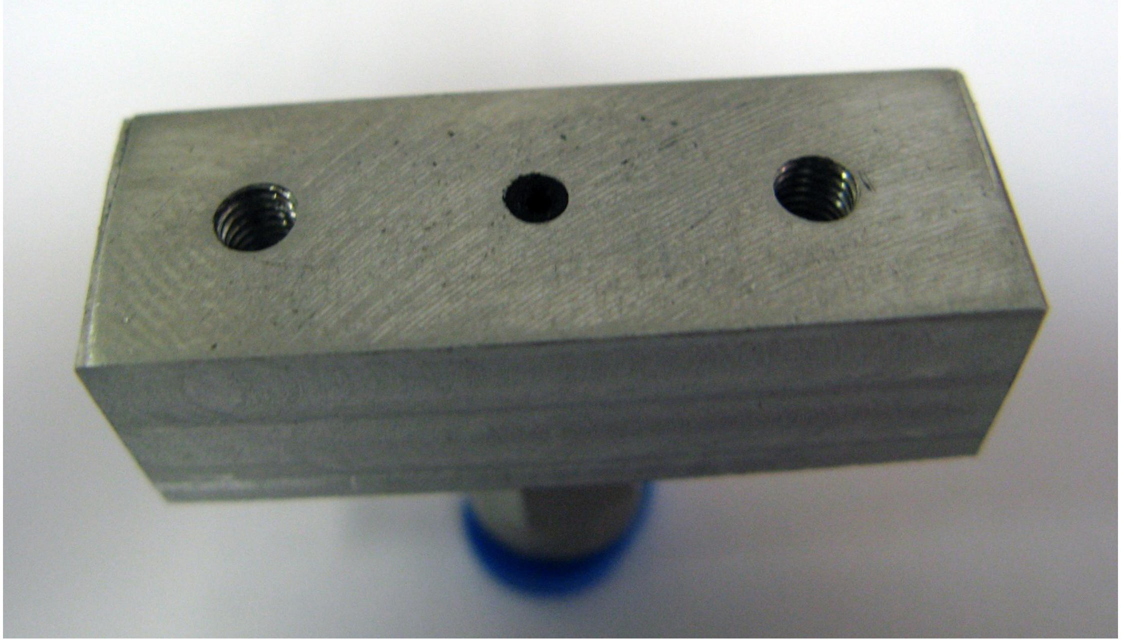


Fig 12-66: Saddle part of the fixture with gas port. Hole in the centre is saddle itself.

The Trimmed Sealing Ring was put into the saddle cavity with with the first Jewel Ring R33 on the top of it. Then the second Jewel Ring was put on the top of the first Jewel Ring so that the orifices were 0.5mm exocentric, and the whole sandwich was fixed with a plate – see the figure below.

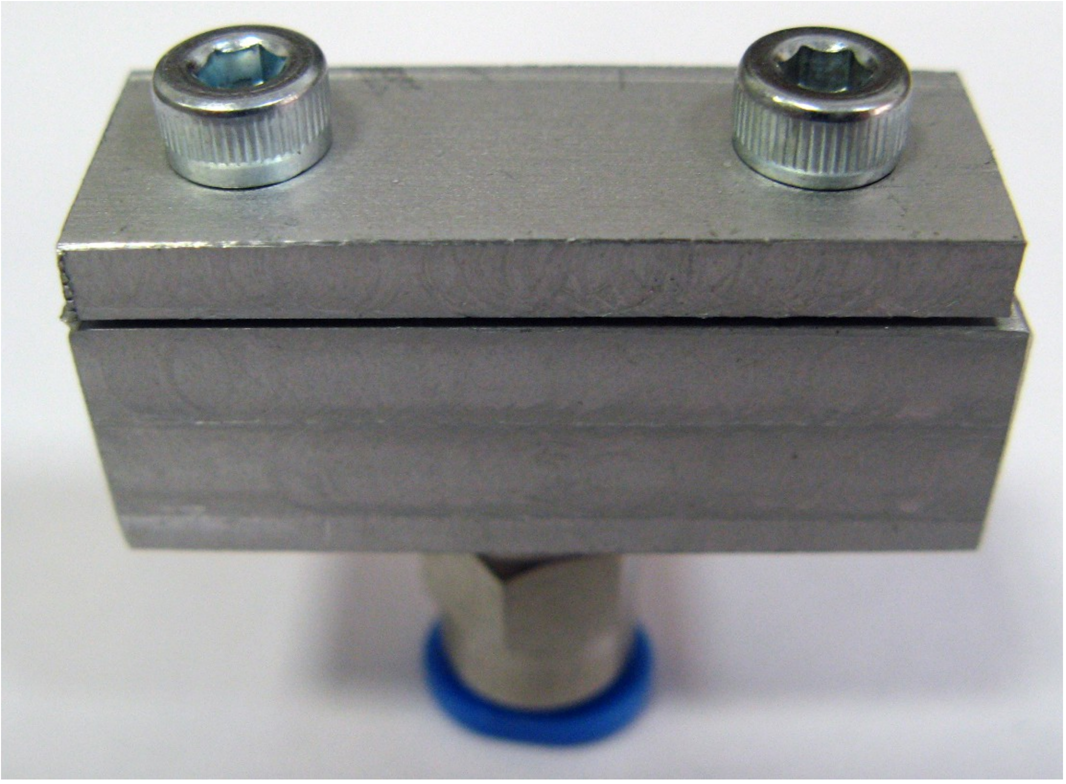


Fig 12-67:: Test fixture assembled.

The assembly was pressurised with 7bar of air and put into water to visualise possible leakage.

No leakage at all was observed during the test.

11.2 Conclusions from Leakage Test

1. The Sapphire Jewel Rings are flat enough for sealing together. This is very important, because the principle and design of sealing is exactly the same in the Rev A, and the Rev B axial injector.

2. Trimming of standard O-Ring gives good results in absence of suitable O-Ring of smaller dimensions.

3. Leakage in the current Injector is caused by assembling inaccuracy and not by principal defects in parts and components. Using the test fixture result, this was traced to bronze swarf being cut as the sapphires are installed. A design change is made in Rev B of the injector to overcome this.

12. Oxygen Compatibility

The design was reviewed against the guidelines of NASA document *"Safety Standard for Oxygen and Oxygen Systems, Guidelines for Oxygen System Design, Materials Selection, Operations, Storage, and Transportation"*, Document NSS 1740.15, Jan 1996. Since 2003, it has been adopted and taken over by the American Society for Testing and Materials. This is the most comprehensive study and guide to oxygen safety that was available to the design team, of the various oxygen compatibility guides that have been published.

Two issues have been identified in the Rev A design, and corrected in the Rev B injector design:

1. In the old Injector there is a threaded bush that supports the last Jewel Ring. In the Rev B design it is protected from oxygen with an additional O-Ring exactly as Appendix C of the NASA standard recommends.
2. Swarf. As the leakage does not come from the sapphires, the only other explanation for it is that there is particulate between the orifices. This finding identifies a significant problem with possible O2 ignition with the Rev A injector that must be corrected in the Rev B injector.

In the Rev A design, all 3 Jewel Rings are put into reamed hole from one end, one after another. The gap between rings and brass walls is minimum - it almost does not exist. As a result, the sapphire rings cut the finest swarf from the walls, and it can not be removed, cleaned, nor even noticed other than the low level of valve leakage. This swarf could go between rings, preventing them from sealing against each other or could break free and cause an oxygen fire. The swarf itself is not combustible, being nickel bronze, but the fire could be caused by adiabatic compression of a swarf particle that breaks free into the oxygen stream.

In checking the design against the Appendix C in the NASA and American Oxygen Society guidelines, this case was not identified, but clearly exists. It is corrected in the Rev B design.

13. Conclusions for Injector Rev A

13.1 Injector flow

1. Theoretical flow of Air, N2 and He through the 200 um test orifice when the intermediate pressure as differences between the orifice input and output pressure is 14 bar is 5.1, 5.2 and 8.6 l/min correspondingly. Flow of Air and He through the maximum injector orifice in the same driver position is 0.83, 0.59 and 5.25 l/min. This means the production injectors should be fitted with orifices that are 150um over-sized.

2. The test flow of He through one 200 um orifice installed into the physical channel is 16 l/min. This is in the region expected.

3. The minimum leakage of the injector is 0.35 l/min of He. The flow leakage and the load of the injector motor depend on the positions of the external adjustment screw of the injector that is not fixed. Screw adjustment decreasing leakage increases the driver load and wise versa. The leakage was traced to swarf being cut by the sapphires. A design change was implemented in Rev B to eliminate this.

4. Local nonlinearity of the relationship between injector flow and driver step is about 20%: this is within the limits that can be managed by the present control system. This is reduced in the Rev B design to a much tighter tolerance.

13.2 Injector driver

1. The range of the Injector Sample S2 is 290 um. This should be increased by 50%: this is a very simple change to the cam controlling the bearing, but to prevent loss of resolution, the gearing should be increased from 14:1 to 28:1 – this is available in the same size and type of gearbox.

2. The range of the Hall sensor output is sufficient to control the entire range of orifice position.

3. The driver resolution in open loop, that is without Hall feedback, is 2.4 um/step. The resolution of the driver when powered up without calibration or resynchronising with the Hall effect feedback is 4.8um/step.

4. The linear range of Injector Sample S2 is from 2.865 V to 4.54V from the Hall sensor or 280 um of the external micrometer or 115 motor steps measured at low driver speed. The maximum of the Hall sensor output is decreased 5% when the driver speed is increased up to 200 step/s.

5. The dead zone of the driver measured at 10step/s is 20 steps or 18% of the range. The maximum dead zone is 42 steps or 50% of the 200 um test orifice. This does not meet the design intent, so has been resolved by fixture an additional bearing which reduces the dead zone to 3 steps.

6. The position nonlinearity between the forward and back motion is 10%. This again was resolved down to 3 steps by fixture the additional bearing.

7. The max value of Hall sensor output is decreased by 7% when the intermediate pressure reaches 20 bar, with an ambient pressure is 1 ATA. This requires compensation electronically.

8. The nonlinearity of Hall sensor measured by external micrometer is 3.5%. This is well within the design target.

9. The Hall sensor and motor supply driver have a common ground. Motor coil inductance currenst up to 2*300 mA generates noise penetrating into the measuring channels. The grounds should be separated: this is a design change for the pre-production prototypes and does not require further prototype testing.

10. The driver assembling accuracy is 130 um along the axis of the movement of the orifice. This error means that the orifice should be oversized. A 330um orifice should be fitted.

11. After the heating of the injector in 100C water the driver range is decreased from 280 um to 210 um. This should be compensated by the increase in maximum orifice size to allow for these changes in tolerance.

12. The tolerance to changes in ambient pressure should be increased by fixture O rings to provide a soft seat for the orifice for the pre-production units: the prototypes were very sensitive to orifice seating pressure due to their hard seating. There is concern that if hard seating is used for production units, there may be a need for servicing within the planned service interval. This problem should be overcome using the soft seats, but should be checked using the pre-production injectors.

13. The ambient pressure alters the range measured by Hall sensor. The offset is 32% of the range when the ambient pressure is 6 bar: it changes by 13.4 um/bar. This should be corrected using the additional bearing and soft orifice seats, but should be checked on each of the pre-production batch.

14. The overall design is intrinsically safe (meaning that it can be operated in an explosive gas atmosphere), and is also fail safe. When conditions were applied

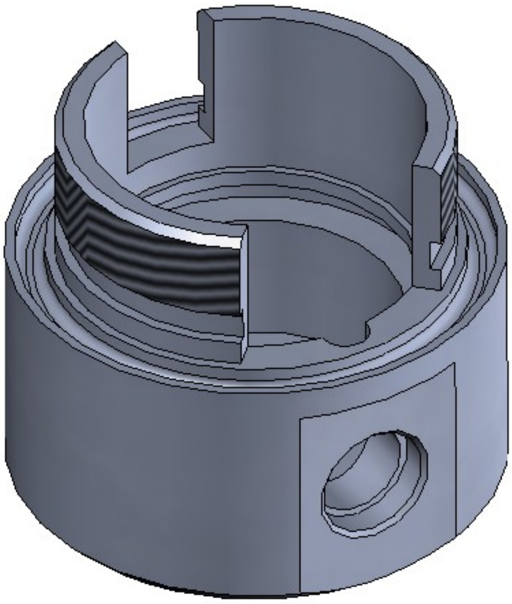
outside the normal operating range, the injector failed safe: it failed in the last orifice position, without substantial changes in orifice size.

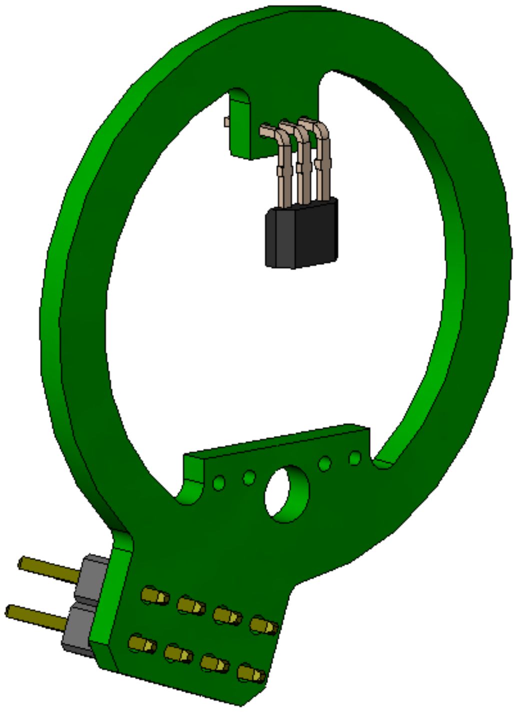
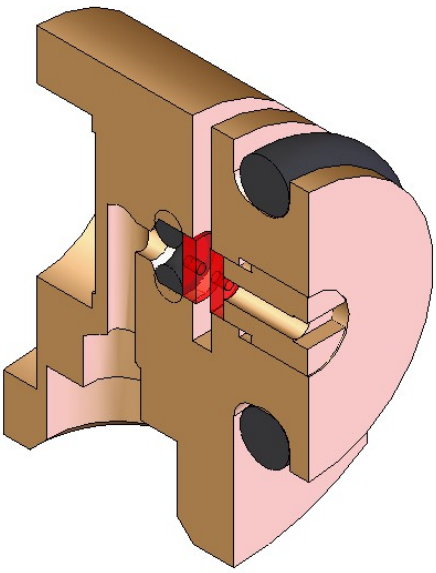
13.3 Oxygen Compatibility

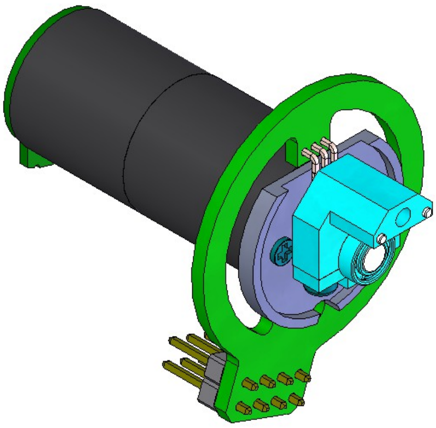
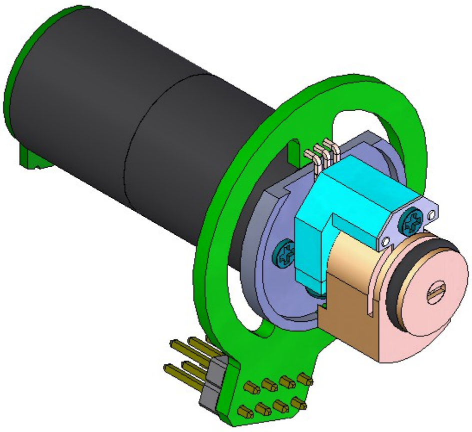
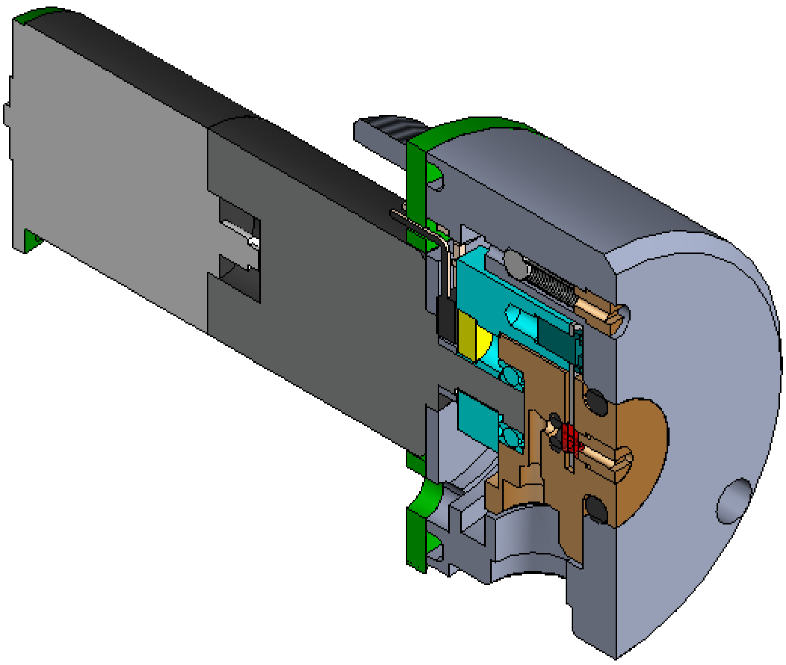
There is both a thread hazard and a swarf hazard in the Rev A design. This is corrected in the Rev B design.

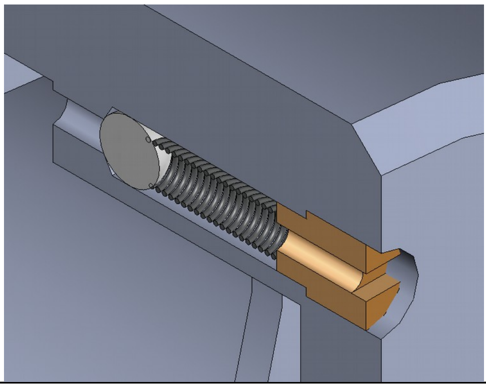
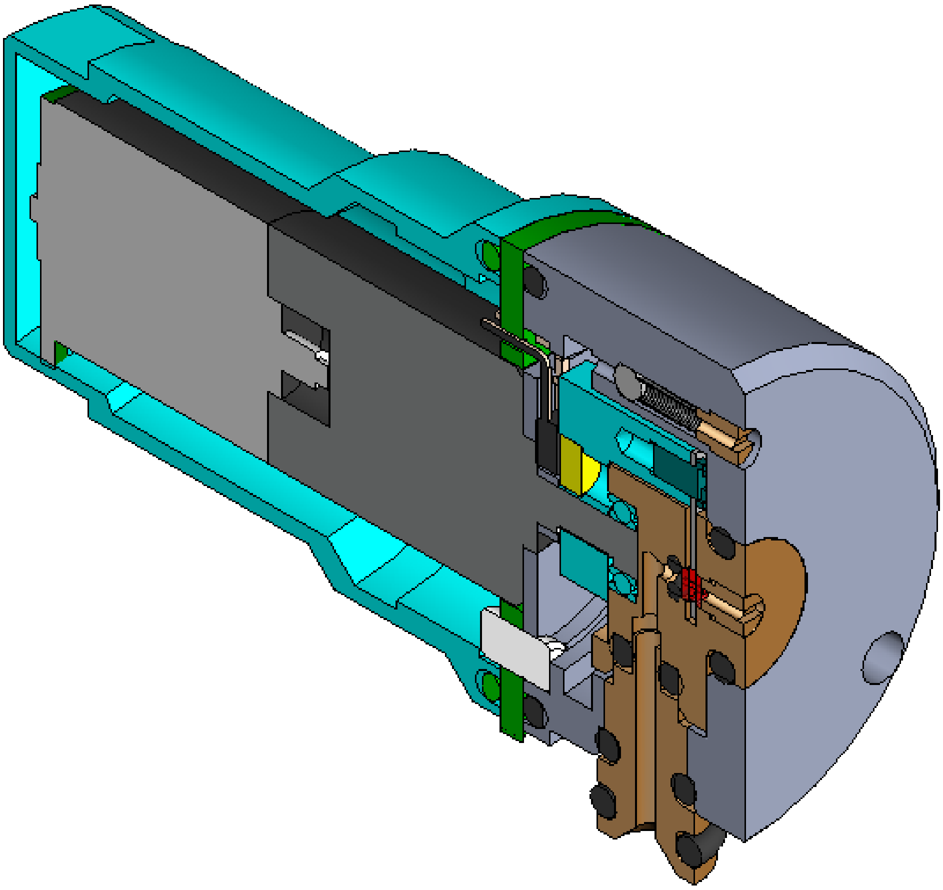
14. Rev B Design

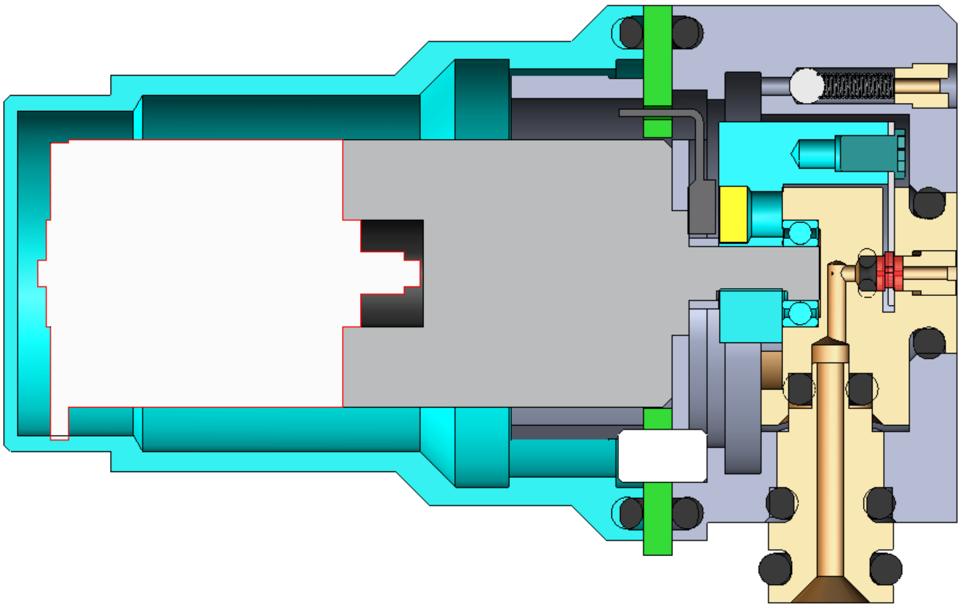
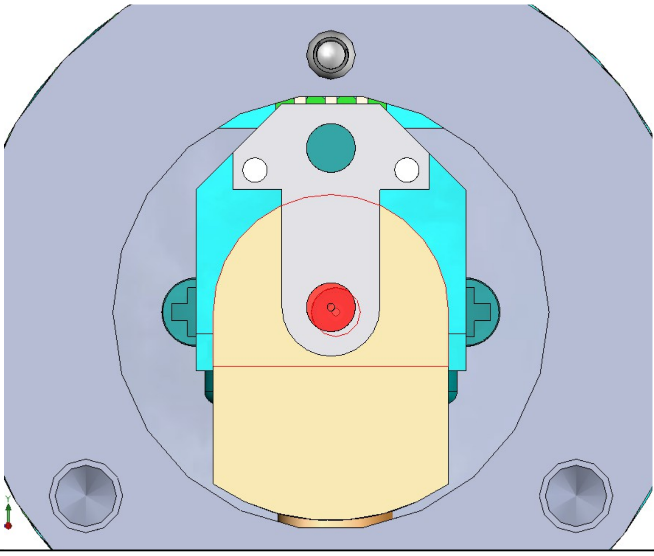
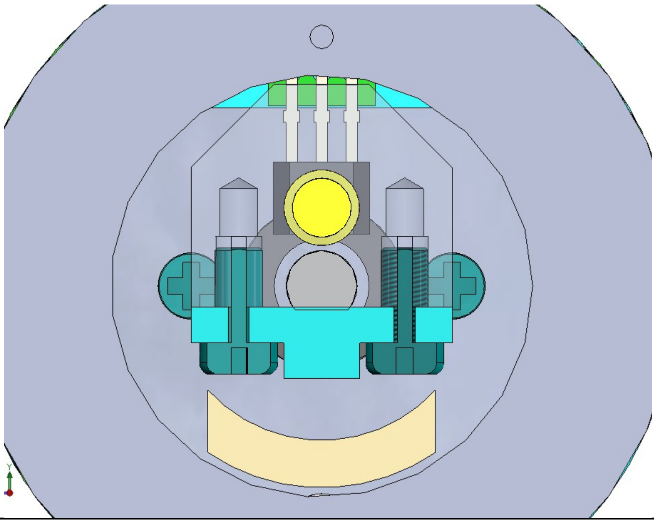
The design was modified to address the issues identified during verification trials, particularly the alignment, hysteresis and oxygen compatibility. The Rev B Design is shown below. An update to this report will contain the test results on this revision.

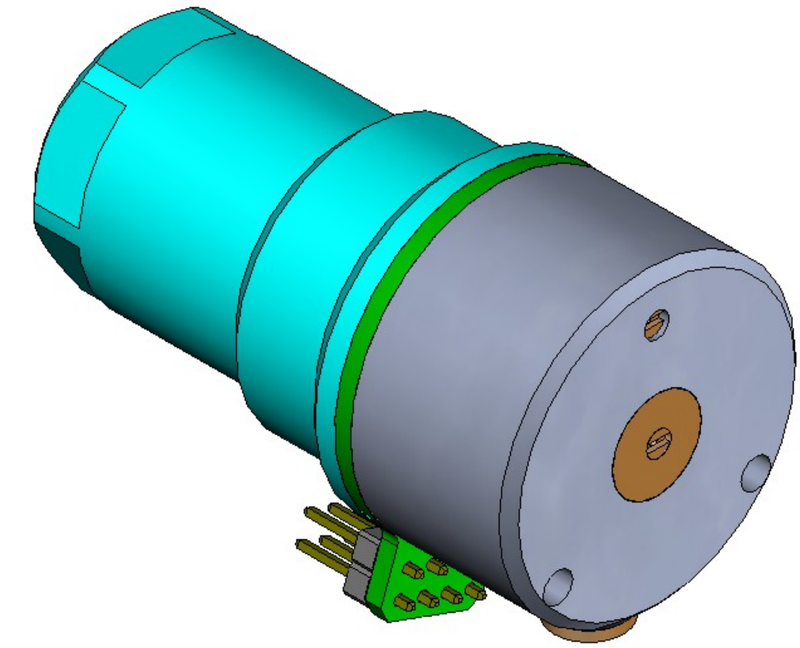
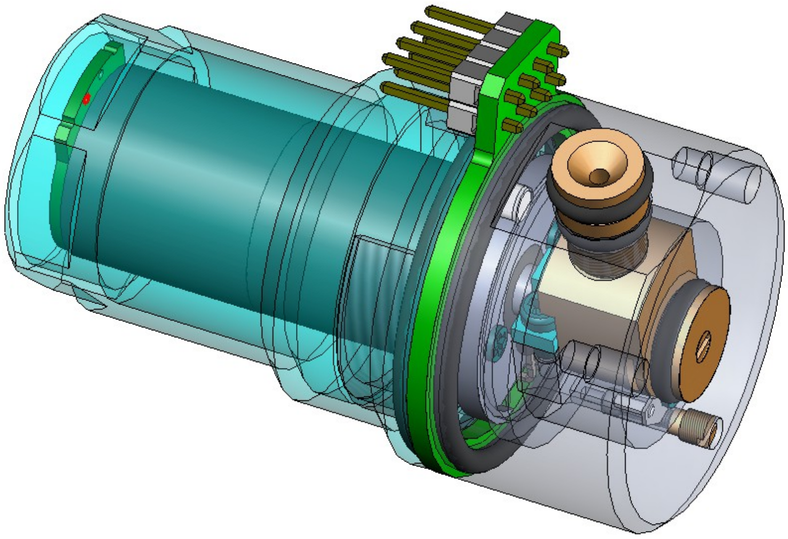
	Image	Comments
1		Main body shell.

2		PCB with Hall sensor – similar to existing design.
3		Valve sub-assembly – similar to Rev A using sapphire jewels R33 (0.33mm orifice), no special guides needed Alignment hole is reamed.

4		Stepper unit with PCB, Crank (cyan) and Aligning Flange (grey)
5		Stepper unit and Valve unit together
6		The same, including the Body

7		Pressure release Valve – to prevent internal pressure causing a hazard on shutdown, lockout or ascent.
8		Main Profile isometric

9		Section through the valve, longitudinally
10		Section of control plate (light grey), half way through the plate.
11		Section of Magnet (yellow) and Hall Sensor, Crank shown transparent

12		External view
13		External view, Body and Cover transparent

15. Additional Testing

The pre-production Rev B units will undergo the same test regime, but the following additional tests are planned, based on the behaviour seen with the prototype injector.

1. Test of Air, N2, and He flow through one orifice. To compare gas constants and maximum flows.

2. Detect the position of the plate with movable orifice where distance between two orifices and the leakage are minimum.

3. Test the sensitivity of the Hall sensor itself to temperature.

4. Test the pressure in the motor chamber of the intermediate and ambient pressure, to ensure no leakage is occurring into the motor chamber.

5. Repeat of EN14143:2003 Oxygen Pressure Pulse Test.