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14 UD Tank Opening Report

#126

19th May – 13th June 2016

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Contents

1 Reason for tank opening

This tank opening was an unscheduled maintenance operation due to being unable to condition the 14UD beyond 14MV after a large tank spark at 8:52am on 21 April 2016.

A constant x-ray level was observed with no distinct lower threshold on the activity when the terminal voltage was reduced. There were no accompanying changes in either the high- or low-energy acceleration tube vacuums. This hinted that the issue was in the SF_6 space.

Pushing shorting rods through the machine eventually hinted that the problem was likely to be in unit 10.

However, there were indications of other issues in the machine such as poor vacuum in the high-energy end and faster than normal rate of de-conditioning (specifically in the high-energy end) after operating at lower terminal voltages.

An RGA scan was taken at the low-energy end of the machine after the shafts (and hence all ion pumps in the acceleration tube) were off overnight and the 300 l/s ion pump at the top of the tank was switched off for ten minutes. The resulting scan is shown in Figure 1 and an unmistakable signature of SF_6 is evident.

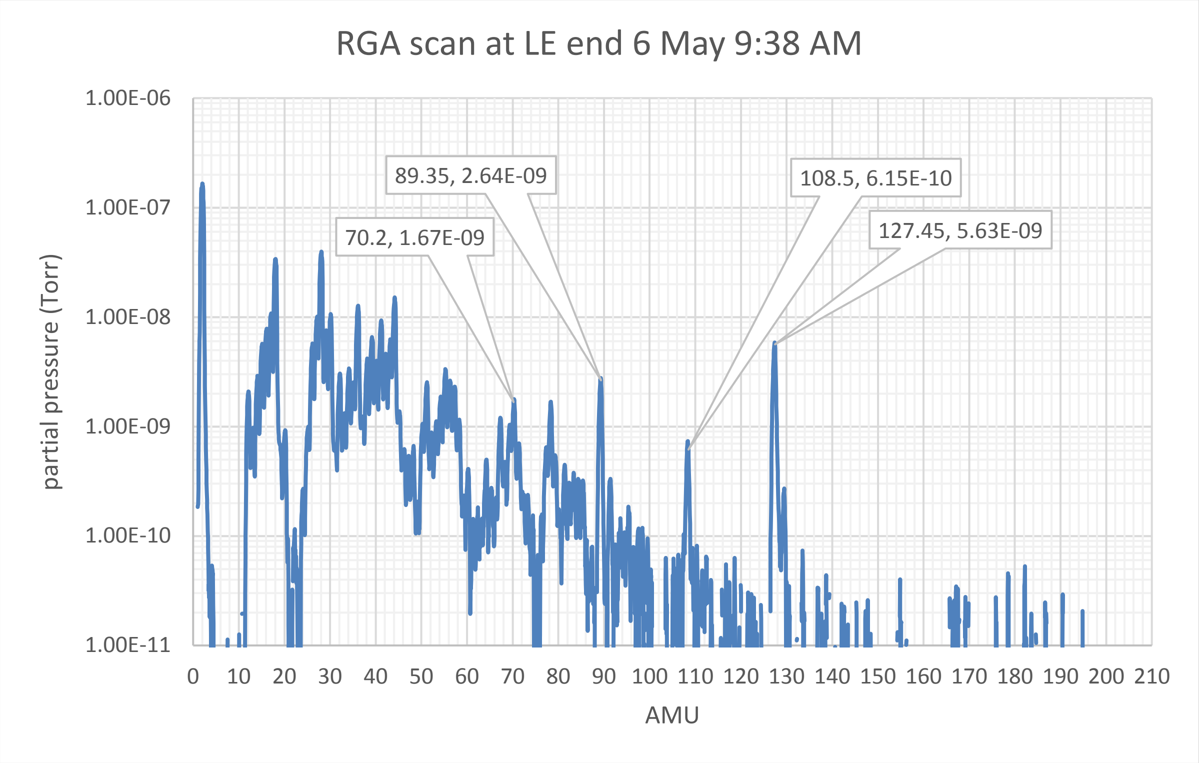


Figure 1 RGA scan taken at low-energy end of the machine after shafts were off overnight and the 300 l/s ion pump switched off.

The suspicion was that there may be SF_6 leaking through one or more of the flanges of the acceleration tubes installed during the recent tank opening 125. While the bolts were torqued to NEC’s specification and helium leak testing was performed, nothing was rechecked after baking the tubes. Furthermore, flanges of other tubes may have been disturbed since a significant part of the column moved during the procedure.

The main goal of the tank opening therefore, was to repair the issue believed to be in unit 10 as quickly as possible and isolate and repair the suspected SF_6 leak.

2 Summary of work

2.1 19/5/16 Thursday

- The SF_6 was pumped from the 14UD into the storage vessel.
- The porthole doors were opened, and the fresh air ventilation system was run overnight.

2.2 20/5/16 Friday

- Gas tests showed the atmosphere within the 14UD was OK and compliant with the Confined Space regulations and was safe to enter.
- Platform was deployed and new work table and tool box stand were used. A great improvement.
    - Performed initial 30kV HV entry test. Did not find much at all.
- Expected to find obvious issue with unit 10, but all 30kV HV test leakage currents were within specification. However, tube 3 was slightly “noisy” if we were to be picky. Will need to perform Infinitron low-voltage tests.
- Noticed frayed resistor lead on unit 9 post gap 15. Still to be rectified.
- Wiped down column. It is still quite clean but did notice black wheel material on chains.
- Ran chains and shafts:
    - Unit 12 shaft has some runout and bearing is slightly noisy
    - High-energy shaft motor has some sort of noise, further investigation is necessary.

2.3 21/5/16

- Showing extraordinary commitment to the cause, Lobanov sacrificed a Saturday in the sun to perform low-voltage Infinitron tests on the 14UD. He found:
    - Posts:

Unit	Gap(s)	Symptom
8	4-8	unbalanced
14	9-13	unbalanced
15	4-8	unbalanced
21	14-18	unbalanced

    - Tubes:

Unit	Tube	Symptom
6	1	unbalanced and drift
22	4	unbalanced
28	1	unbalanced and drift

    - Note that there is no mention of unit 10, one of the two main reasons for entering the tank. It is highly likely that problems at the high energy end were misleadingly momentarily rectified when unit 10 was shorted.

2.4 23/5/16 Monday

- Removed shaft and lower bearing from unit 12

- Inspected the coupling from the high-energy shaft motor to the shaft and saw piles of disintegrated rubber. Rubber coupling on bearing assembly was literally hanging on by a thread. Removed unit 28 bearing and prised off the motor coupling.
- Taped up the tube flanges from mid-unit 18 down to unit 21, as well as the flange on the high-energy midsection foil stripper. Started He leak testing with initial background leak rate of 1.3-1.4×10^{-9} mbar·l/s.
    - reaction from top flange of mid-section stripper, up to 2.9×10^{-9} mbar·l/s for only 2 seconds with a quick recovery. It was not repeatable.
    - reaction from stripper foil mechanism flange, up to 4.5×10^{-9} mbar·l/s for only 2 seconds with a quick recovery. It was not repeatable.
    - reaction from unit 20, tube 2, up to 2.7×10^{-9} mbar·l/s for only 2 seconds with a quick recovery. It was not repeatable.
    - reaction from unit 20, tube 3, up to 2.0×10^{-9} mbar·l/s for only 2 seconds with a quick recovery. It was not repeatable.
- The He leak results are a bit confusing and there's not a lot of confidence that what is being observed is real. So, the valved off leak tester will be logged overnight to see if the spikes manifest.
- Ran the high-energy shaft motor (which is not linked to the shaft) and listened to the bearings. Thankfully, the motor sounds fine.

2.5 24/5/16 Tuesday

- Since we lacked confidence in in our He leak test sensitivity limit, we gave over a morning to study what happens when a calibrated leak is connected to the high-energy end at level 5 and the leak tester is at the back end of the turbo on the multi faraday cup (MFC) box under the tank. In all cases the shafts were off, so no pumping in the tube. See section 5 for details.
- **The upshot is that all He leak testing in the high energy end of the tank should be performed with sublimers and ion pumps off, with the isolation valve at level 5 shut.**
- Started leak testing around units 18 to 21, but no real luck. There may have been a real response up to 1.8×10^{-9} mbar·l/s on two occasions, but could not repeat and could not isolate location.
- Leak tested around the terminal and units 15 and 16 and may have had a repeatable response up to 2.0×10^{-9} mbar·l/s at unit 15.

2.6 25/5/16 Wednesday

- Reinstalled shaft and bearing to unit 12. Shaft skimmed and polished to remove track marks.
- Repeated leak testing around units 15 and into the terminal form the bottom and saw a three-time repeatable small response to 1.8-1.9×10^{-9} mbar·l/s from a base of 1.3-1.4×10^{-9} mbar·l/s.
- Lowered bottom terminal spinning to gain access to the bellows/aperture in the lower terminal. For future reference, each hand crank of the platform motor is 5.5mm of travel on the platform.
- Leak tested all flanges in the lower terminal (untaped). At the bottom of the bellows/aperture, had a reaction to 1.2×10^{-8} mbar·l/s from a base of 1.2-1.3×10^{-9} mbar·l/s. Taped up the both top and bottom flanges of the bellows/aperture, no

reaction from the top flange but peaked at 6.4×10^{-8} mbar·l/s at the lower flange. We found the leak.
- Checked the torque on the hex socket bolts on the bellows/aperture and reached 130 in·lb (15 Nm) before any moved. Torqued all up to 160 in·lb (18 Nm).
- Redid leak test on taped up flange. No definite response, but not yet willing to call it good. Turned all pumps on to clear helium and get a lowest possible baseline before retesting in the morning.

2.7 26/5/16 Thursday

- Reinstalled bearing and shaft in unit 28 and the shaft motor mount. Shaft was also bowed and appeared to have a helical twist 2 mm out of concentric alignment. It was machined with 4 mm taken off the diameter (not on clamped ends).
- Bagged entire terminal bellow/aperture and retested leak with a base leak rate of 1.2×10^{-9} mbar·l/s. There was no response after leaving it for 50 minutes.
- Leak tested all lower terminal flanges again. No response.
- Cleaned lower terminal, checked inductor spacings.
- Found the DC idler on chain 3 (down) was a bit sticky. Removed to replace bearing and noticed that there is no spacer between the two bearings. Replaced bearings on up idler as well and added a spacer to both wheels.
- Checked all terminal functions in preparation for closing the terminal

2.8 27/5/16 Friday

- Closed the lower terminal
- Started process for clean and close including checking all resistors from unit 1 to unit 8.
- Found eroded ring screw in ring 8 in unit 1.
- Replaced resistor leads on:
    - unit 2, tube 2, gap 7
    - unit 2, tube 3, gap 6
    - unit 3, tube 2 gap 3
    - unit 4, tube 3 gap 5 replaced with used lead
    - unit 5, tube 1 gap 5 replaced with used lead
    - unit 5, tube 4 gap 1 replaced with used lead
    - unit 5, tube 1 gap 5 replaced with used lead
    - unit 6, tube 1 gap 1 replaced with used lead
    - unit 6, tube 3 gap 5 replaced with used lead
    - unit 8, tube 3 gap 6 replaced with used lead
- Replaced all resistor leads on unit 4 post resistors with solid copper test leads. See section 6.

2.9 30/5/16 Monday

- Continuing with clean and close
    - unit 9
        - tube 1 gap 9 replaced with used lead
        - post gap 10 replaced with used lead
        - post gap 15 lead badly frayed, replaced with used lead
        - replaced 5 ring screws all associated with tube 3

  - unit 10
    - replaced a post rivet that acts as ring screw mount
    - replaced 1 ring screw
  - unit 14
    - four post resistor spark gaps
    - two post resistor nuts
  - unit 15
    - loose stringer at post end
  - unit 16
    - replaced ring screw
  - unit 17
    - stringer 1 tube end was loose, replaced with rounded socket head
    - replaced spark gaps of both resistors and the lead of post gap 16 as they were scorched.
    - replaced ring screw
  - unit 18
    - post gap 6 top resistor appeared loose at the base. Could not identify problem, so replaced with spare and bagged evidence.

2.10 31/5/16 Tuesday

- Continuing with clean and close
  - unit 20
    - loose stringer 1 at tube end, screw replaced with radiused socket cap
  - unit 22
    - tube 3 gaps 3 and 7 resistor leads replaced, had to replace nuts on both gap 7 resistors to accommodate new leads
    - replaced ring screw
  - unit 23
    - stringer 1 clamp at post end loose, was removed and replaced with “mini-resistor clamp” as per previous tank openings.
    - noticed wear or manufacturing error on post B gap 5
    - replaced ring screw
  - unit 24
    - replaced ring screw
  - unit 26
    - replaced ring screw
  - unit 27
    - replaced ring screw
    - tube resistor loose at flange mount, replaced screw with radiused socket cap.
  - Unit 28
    - tube resistor loose at flange mount, tightened.

2.11 1/6/16 Wednesday

- Refitted casting covers below terminal
- Check chain leg clearances:
  - chain 1: 71 mm
  - chain 2: 73 mm

  - chain 3: 72 mm
- Checked drive end inductor spacing
- Checked charging system standoffs
- Refilled chain oiler reservoirs
- Ran through low-voltage test issues:
  - replaced unit 22, tube 4, gap 1 bottom resistor with spare as original had 71μA @ 20kV
  - replaced unit 22 post gap 18 top resistor replaced
  - unit 23 post gap 2 top resistor replaced with new 575MΩ resistor from order batch 1322296
  - unit 18, tube 4, gap 6 bottom resistor replaced with spare as original showed higher than usual voltage drop during low-voltage test.
  - unit 21 post gap 18 replaced top resistor with spare since the original had 20μA @ 20kV
  - unit 15 gap 5 top resistor replaced at it had 22μA @ 20kV
  - unit 7 gap 10 top resistor replaced at it had 20μA @ 20kV
  - both post resistors in unit 6 gap 9 were replaced with new unused resistors, which both showed 18μA @ 20kV, lower than the nominal 19μA for most of the other resistors in service. These will be watched to see how they age.
- All resistors that displayed excessive current had a degraded resistive conductive layer. These will be further investigated.

2.12 2/6/16 Thursday

- Blow down of column
- Low-energy end “start” shorting rods were removed and replaced with rods with fewer spring contact marks. These were polished and a new groove was machined into rod number 1 (start rod).
- High-voltage test on column. Found loose post resistor in unit 15, which had a stripped clamp thread. Swapped out shield for a spare.
- Wiped down column just with clean water.
- Unloaded majority of tools on platform at level 2
- Vacuumed platform and bottom of tank
- Performed tank close checks, all was good.
- Closed porthole doors and started pumpdown.
- Crossed all our fingers.

2.13 3/6/16 Friday

- SF_6 gas up of tank

Also note that at some time during this opening, the entire corona needle point assembly was disassembled and serviced, although the same needles were left in place.

3 SF_6 leak location

Figure 2 shows the bellows in the lower section of the terminal where the leak was found. The bolts on the leaking flange were torqued up to 160 in·lb (18 Nm), after which no leak was seen above the base leak rate of $1.3\text{-}1.4\times10^{-9}$ mbar·l/s.

Figure 2 Terminal bellows in which a leak was found through the bottom flange

4 SF_6 levels during pump out and gas up

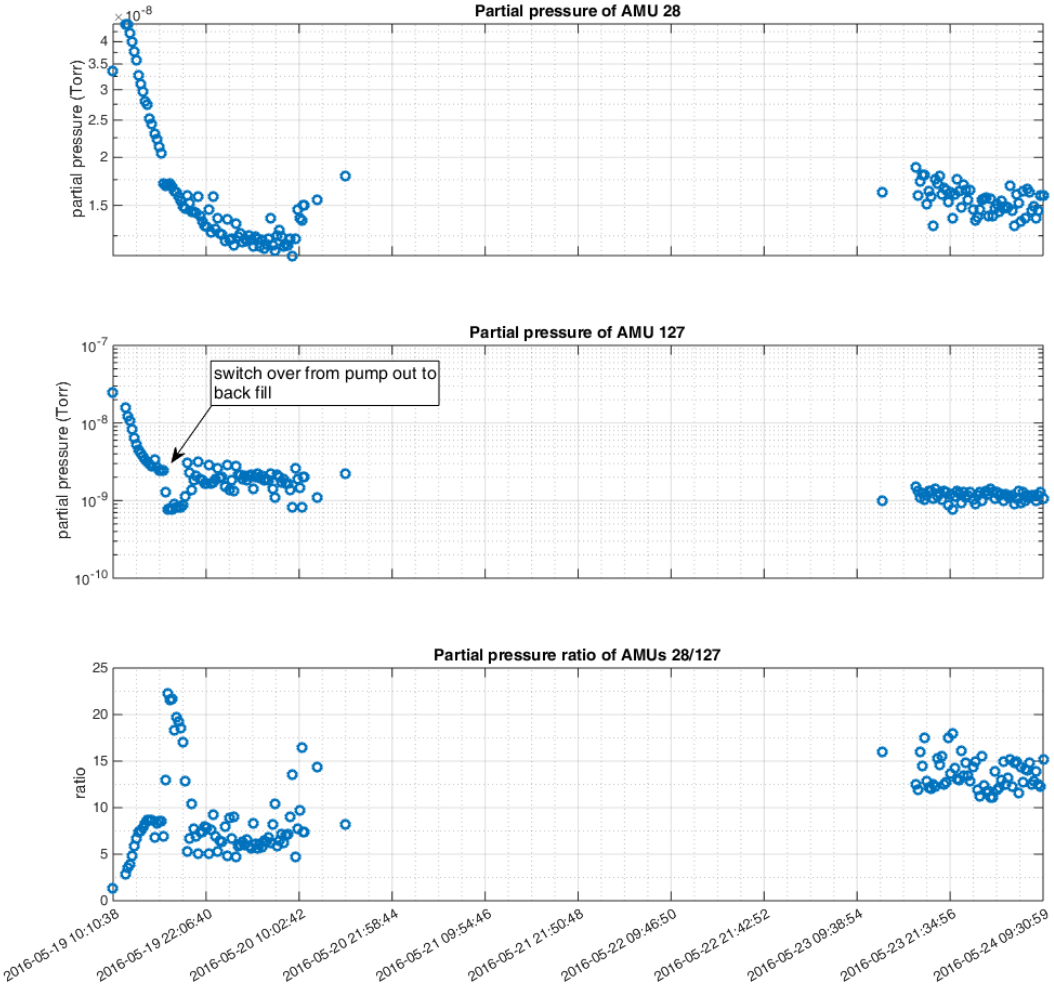
The RGA at level 4.75 was used to monitor SF_6 levels in the acceleration tube during gas out and the tank opening, and during gas up. There has been anecdotal evidence in the past that SF_6 remains in the tube for some time. This is true even during a tank opening when the tank is vented and there can be no possible ingress of SF_6 into the vacuum space.

Figure 3 shows the N_2 and SF_5 (main peak in SF_6) partial pressures and their ratio during gas out and the first three days of the tank opening. The total pressure improves as the tank pressure reduces, but there is an immediate dip in SF_6 that coincides with the change over to back fill with air. The later increase has no obvious explanation.

With the shafts and therefore the tube ion pumps off, the SF_6 levels settle to a relatively constant level, even three days after the tank is opened.

Figure 4 shows the SF_6 levels during gas up, with the aim being to ensure that the SF_6 levels do not increase during gas up as the tank pressure is increased. However, the 300l/s ion pump between the acceleration tube and the RGA was inadvertently turned on at about

11:00 am on the 3rd of June, which completely wipes out any SF_6 that the RGA may see. So, up to a tank pressure up to a little above atmosphere, there was no ingress of SF_6 into the acceleration tube.



Partial pressure of AMU 28

Partial pressure of AMU 127

switch over from pump out to back fill

Partial pressure ratio of AMUs 28/127

Figure 3 Partial pressures of N_2 (AMU=28) and SF_5 (AMU=127) starting from gas out of the 14UD.

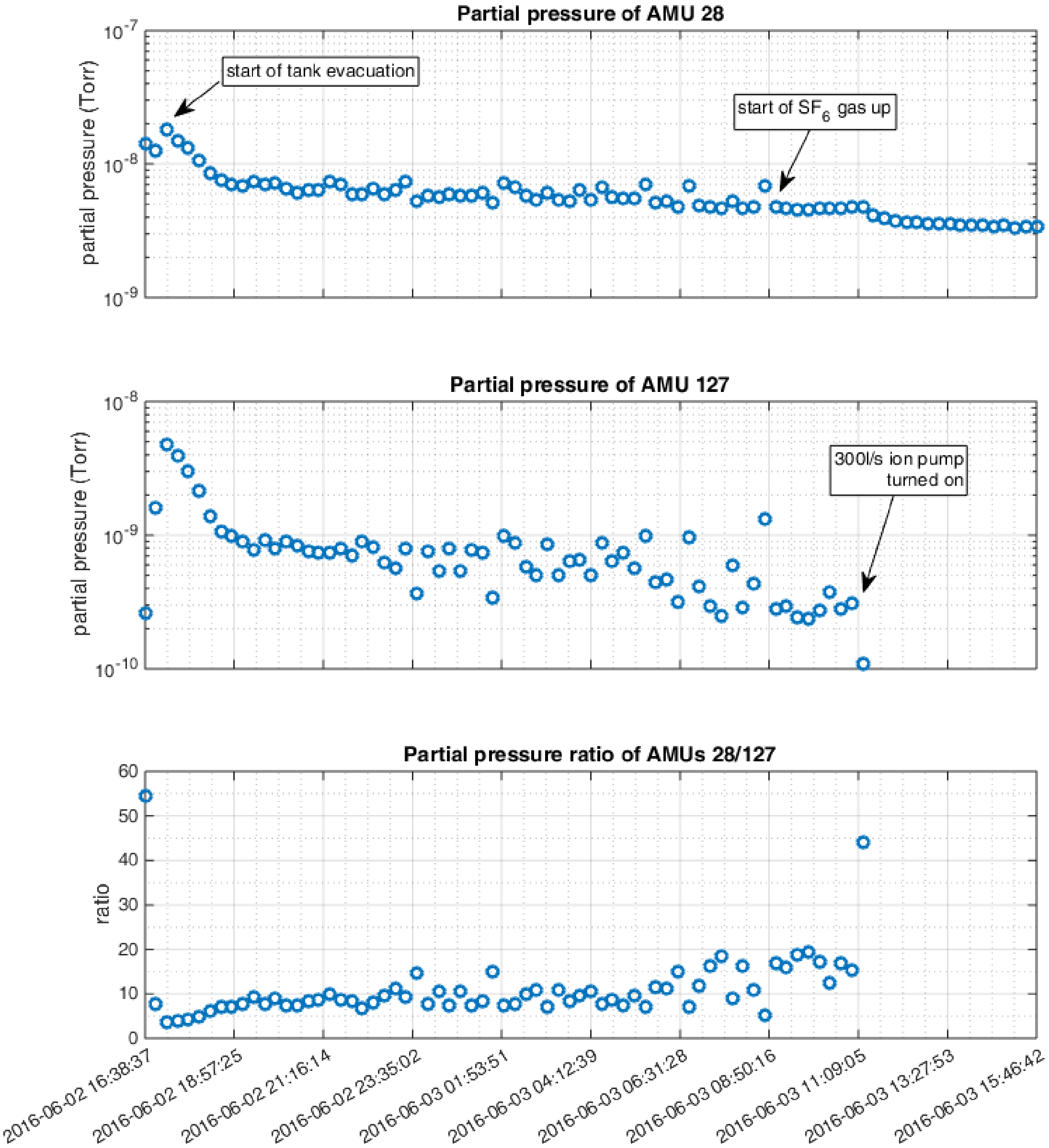


Figure 4 Partial pressures of N_2 (AMU=28) and SF_5 (AMU=127) starting tank evacuation through to gas up with SF_6 until ~13 psi.

5 Leak rate detection sensitivity

Since confidence in leak detection was critical for this tank opening, some time was given to determining what pump and valve configuration gave the best sensitivity in the 14UD. A calibrated helium leak and a helium leak detector were set up as shown in Figure 5. The positions of the various valves and pumps are also shown. Various configurations were tested, each of which is shown in Table 1, with the results shown in Figure 6. In all cases, the tank 300l/s ion pump was off.

There is a burst when the calibrated leak rate valve is opened, which likely accounts for the differences between configurations D and G, which are nominally the same. The time between D and its preceding event/configuration is greater, giving more time for a buildup of helium from the calibrated leak.

Leak testing should be performed with pumps off for maximum sensitivity, although the tube vacuum should be observed, as it did deteriorate to low 10^{-6} Torr during the test.

Also note the background base leak rate, which was in the vicinity of 1.4×10^{-9} mbar·l/s.

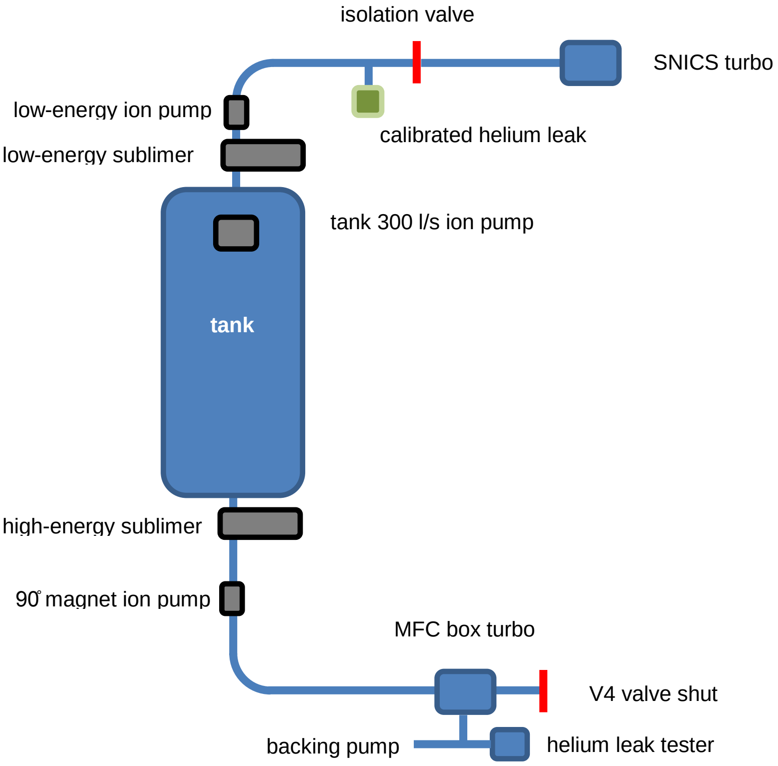


Figure 5 Configuration used for helium leak test sensitivity tests

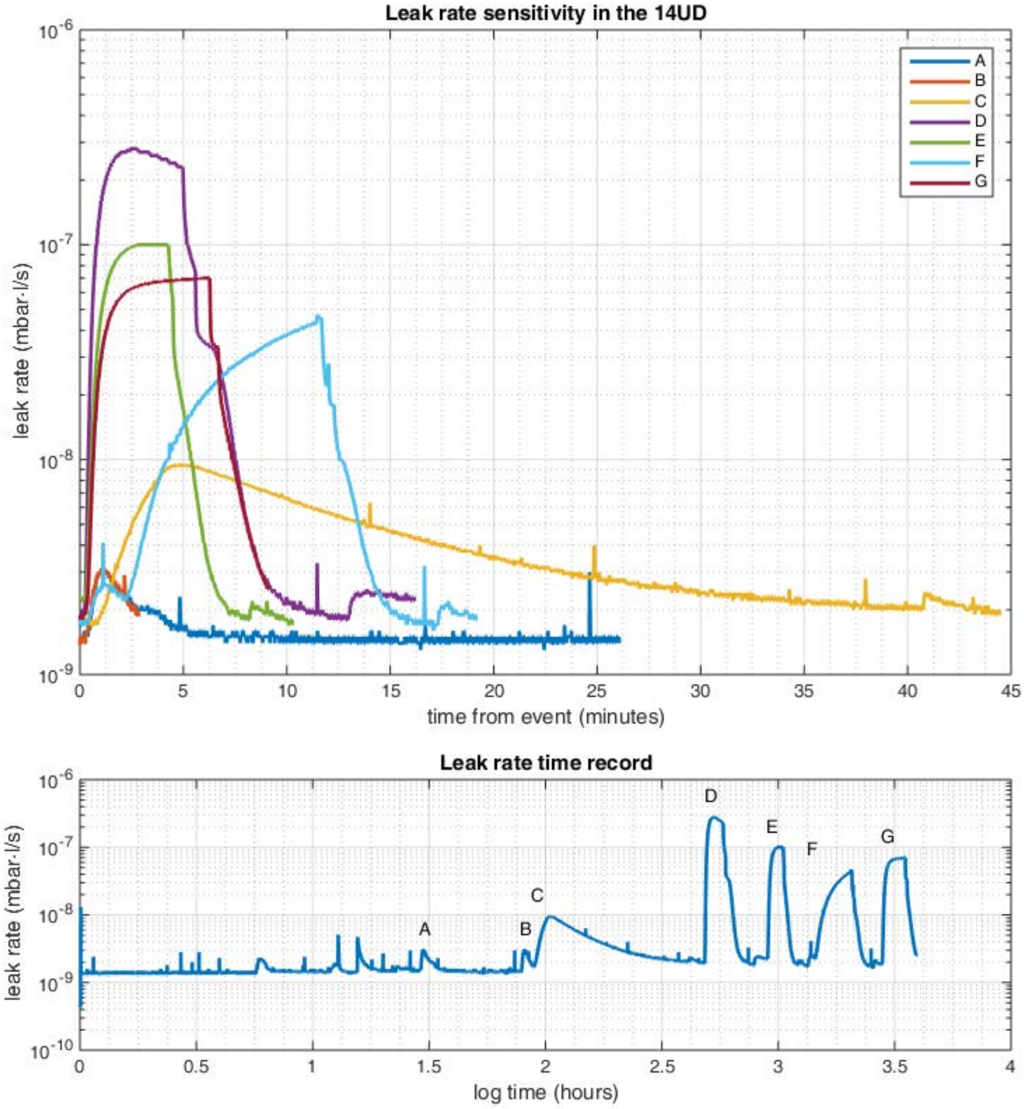


Figure 6 Leak rate sensitivity tests in the 14UD with helium leak detector on the back of a turbo at ground level and a nominal 2.9×10^{-7} mbar·l/s calibrated leak at level 5, for configurations/events A through G listed in Table 1. Peaks for each event/configuration indicate point at which calibrated leak was valved off.

Table 1 Configuration and vents used for testing leak rate detection sensitivity in the 14UD

		sublimer valve			ion pump	
Configuration	Event	high energy	low energy	isolation valve	90° magnet (high energy)	low energy
A	cal. leak valve open	open	open	closed	on	on
B	cal. leak valve open	closed	closed	open	on	off
C	close isolation valve	closed	closed	closed	on	off
D	cal. leak valve open	closed	closed	closed	off	off
E	cal. leak valve open	open	open	closed	off	off
F	cal. leak valve open	closed	closed	open	off	off
G	cal. leak valve open	closed	closed	closed	off	off

6 Solid copper resistor leads

Historically, tinned braided copper wire has been used to manufacture resistor leads. This style of lead has been service in the machine since resistors replaced corona points. However, there are issues with blown leads and misshaped leads that create sharp edges that encourage corona activity. This tank opening was an opportunity to test an alternative.

Standard, 1mm diameter, hardwire copper was sourced as an alternative for resistor leads. The copper wire was cut to 65-70mm lengths to replace the existing flexible resistor lead design. Forty-six new leads were manufactured using the new hard wire, one of which is shown in Figure 7.

It was easier to manufacture leads using the copper wire when compared to using the current flexible braided wire leads. The idea that is being tested is that the copper leads will be easier to solder and install and that they will have a longer service life in the tank.

All post resistor leads in unit 4 were replaced with hardwire copper leads, as shown in Figure 8, and their performance will be monitored over time.

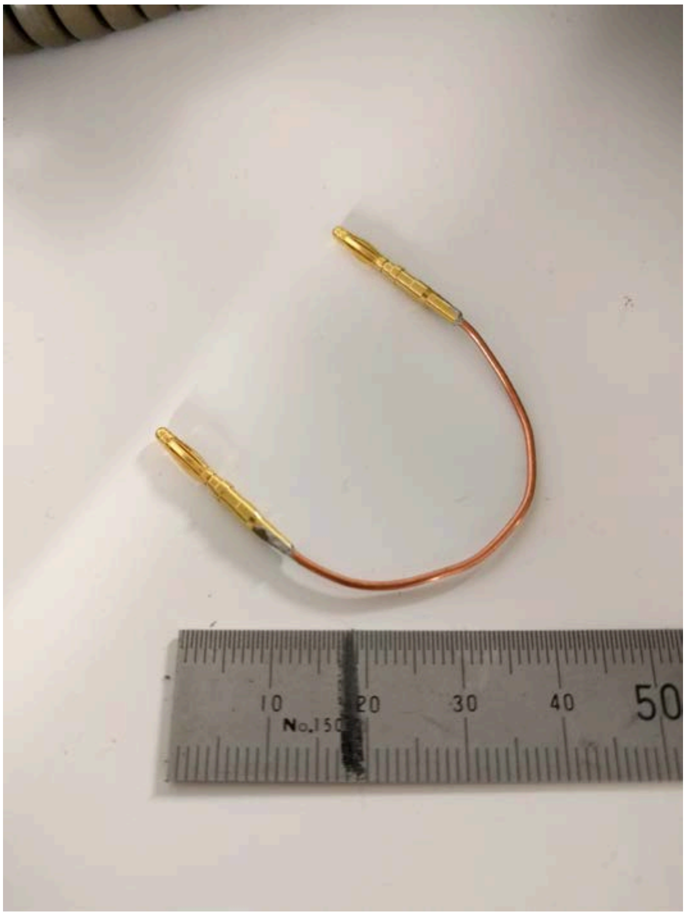


Figure 7 Prototype resistor lead made from 1mm diameter hardwire copper

Figure 8 All post resistor leads in unit 4 were replaced with hardwire copper leads

8 Watch list

Table 2 Watch list of suspect items for review next tank opening

Unit	Component	Description	Condition/ Resolution	Retain watch
6	Post C, gap 10	May have small subtle cracks in ceramic	Increased discoloration, no current leak at 6 kV	Yes
22	Post C, gaps 7 and 10	May be a small subtle crack, but also what may be two, small, surface divots at a “nine o’clock” position	No deterioration	Yes
28	Post B, gap 12	Marks including metallic deposits	No deterioration	Yes
6	Post gap 9	New unused resistors installed on both top and bottom, showing 18µA @ 20kV (lower than 19µA nominal).	Keep track of current as resistors age	Yes

9 Tube ceramic insulator current leakage

The current state of shorted tube ceramic gaps is shown in Table 3

Table 3 Summary of tube ceramic current leakage in the 14UD

Unit	Tube	Gap	Leakage though insulator @5kV (TO #123)	Discovery	Comment	Repair
3	2	2	8 µA	TO #121		Dummy resistors top and bottom, dummy on post gap ????
6	1	2	1.1 µA	TO #123		Dummy resistors top and bottom, dummy on post gap 5, top
7	3	10	12 µA	TO #120		Dummy resistors top and bottom, dummy on post gap 10, top
12	1	2	0.25 µA	TO #123		Dummy resistors top and bottom, dummy on post gap 5, top
13	1	10	0 µA	TO #120	Suspicious arc mark across gap	Dummy resistors top and bottom, dummy on post gap 3, top
13	2	1	0.05 µA	TO #120		Dummy resistors top and bottom, dummy on post gap 8, top
25	3	10	7 µA	TO #120		Dummy resistors top and bottom, dummy on post gap 16, top
26	3	5	0.15 µA	TO # 123		Dummy resistors top and bottom, dummy on post gap 12, bottom
26	3	10	0.01 µA	TO # 123		None, deemed too small. Monitor.
26	3	11	2.5 µA	TO # 123		Dummy resistors top and bottom, dummy on post gap 14, bottom
28	3	1	0.01 µA	TO # 123		None, deemed too small. Monitor
28	3	5	0.47 µA	TO # 123		Dummy resistors top and bottom, dummy on post gap 12, top
28	3	7	0.1 µA	TO # 123		Dummy resistors top and bottom, dummy on post gap 13, top
28	3	9	0.02 µA	TO # 123		None, deemed too small. Monitor
28	3	10	0.05 µA	TO # 123		None, deemed too small. Monitor
28	3	11	0.28 µA	TO # 123		Dummy resistors top and bottom, dummy on post gap 14, top

10 Machine hour meter readings

Table 4 Machine hour meter readings

Date compiled	19/05/2016					
Team member(s)	PL					
Reading	Chain #1 (1O)	Chain #2 (2N)	Chain #3 (3P)	LE shaft	HE shaft	Ch. volts
Notes	New @TO121	New @TO121	New @TO118			
Current reading	30986	30925	31073	50689	50682	30975
Previous reading (TO #124)	29886	29824	29973	49298	49291	31072
Change in hours	1100	1101	1100	1391	1391	-97
Previous total hours	8354	8292	12783			
Current total hours	9454	9393	13883			

Clearly some problem has developed with the charging volts meter

11 Terminal voltage distribution for period of service

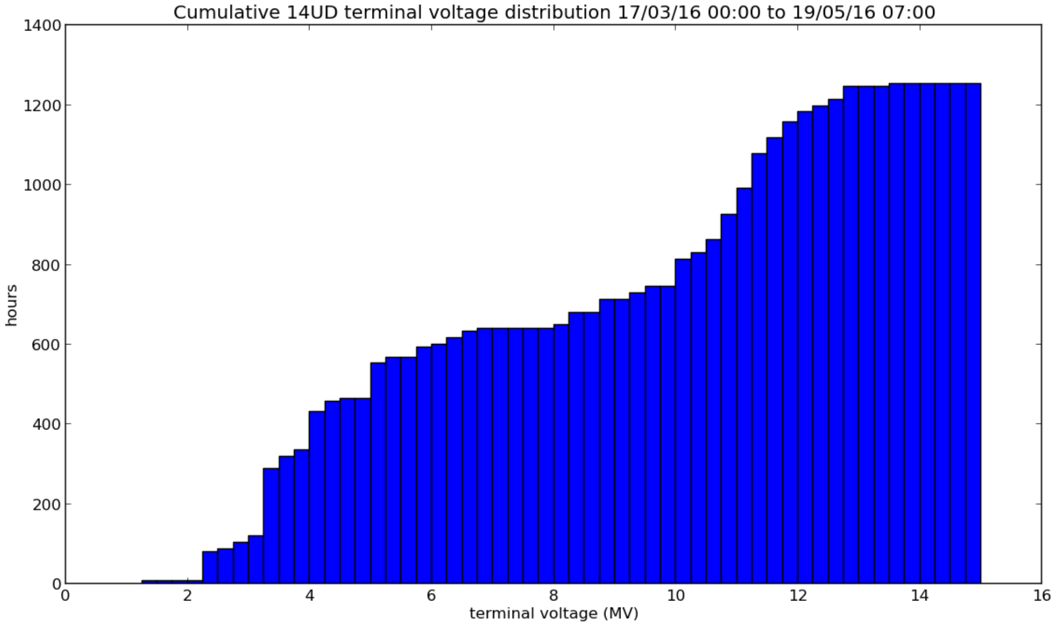


Figure 9 Cumulative terminal voltage distribution for period of operation from the end of tank opening 125 to the start of tank opening 126

The total hours with voltage on the terminal was 1254 hrs, which gives a utilization of 83% assuming a twenty-four hour, seven-day maximum.

12 Initial performance

A slow and steady conditioning campaign was run from 6th of June until the 13th of June, beginning with units 22 to 28 shorted. The SF_6 levels were monitored via the usual RGA scan at level 4.5. Figure 10 shows the change over time[1].

There were issues with constant x-ray emissions when the terminal voltage reached about 10 MV, which prompted a switch from shorting the high-energy end to shorting the low-energy end. Initially, units 1 to 10 were shorted and two rods were retracted at a time when the voltage reached just above 1 MV/unit. The constant x-ray emission returned, again at a terminal voltage of about 10 MV, but disappeared after a rather large voltage spark. The x-rays were coming from the high-energy end, judging by changes in the tube vacuum.

After completing the process on the low-energy end, rods were again used on the high energy end, with 18-28 shorted out. By the 12th June, units 22 to 28 were shorted and a conditioned voltage of 1.095 MV/unit was achieved (14.97MV equivalent for entire machine). Furthermore, this level was achieved in less than thirty minutes after the machine was idle (and with shafts and therefore tube ion pumps off) on the 13th June.

After a week of an AMS run at ~4 MV the machine required reconditioning to reach 13 MV and intermittently displayed a “constant x-ray” issue, which would then disappear after a spark. An EME experimental run at 13.2 MV was completed after this reconditioning without incident. After another week of an AMS run at 14.1 MV, the machine conditioned up to 14.6 MV. The ultimate goal is to achieve a maximum of 15.1 MV by gentle conditioning during the next couple of months.

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[1] Limited data points were taken since later in the week, it was considered that continual pumping overnight was more important (hence the shafts had to stay on).

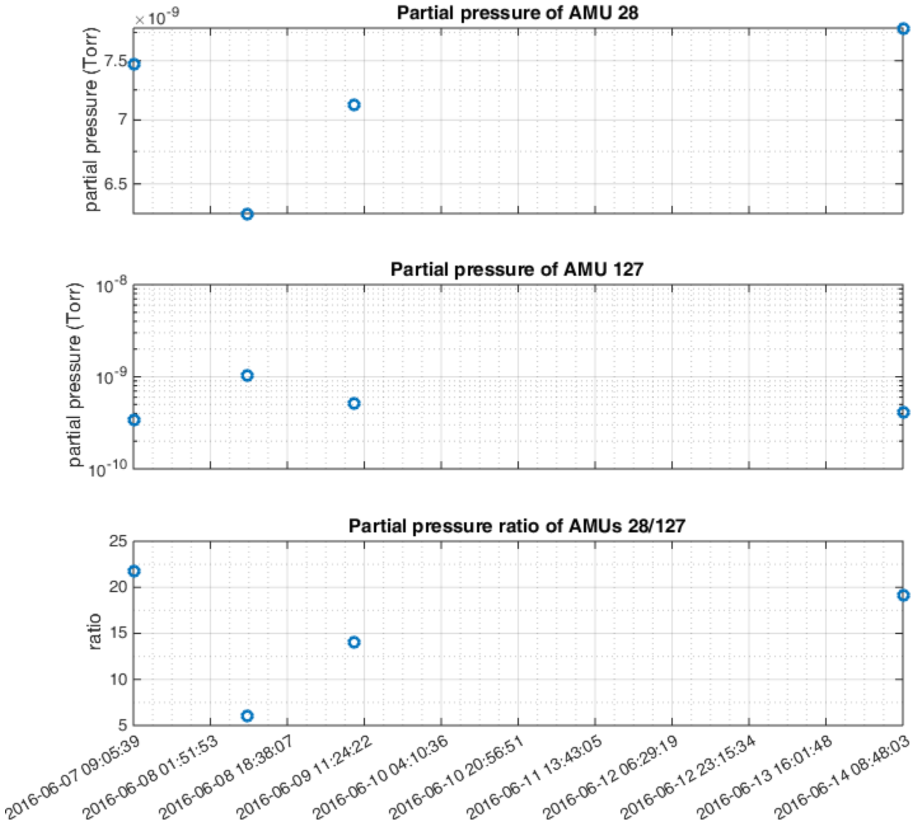

Figure 10 SF$_6$ levels during the week of conditioning