TB9AES018 Incident Report

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Summary

This report is an independent investigation performed by the project engineer of the detuning of TB9AES018 superconducting RF cavity on October 28, 2014. The niobium cavity was plastically deformed during a pressure test. It was later discovered that the cavity was insufficiently restrained to counteract the forces experienced during the pressure test.

Process Description

Superconducting 1.3 GHz RF cavities have been manufactured and tested at Fermilab as a part of ILC R&D and now the LCLS-II project. Niobium cavities have been procured from industry and later processed, tested and dressed at Fermilab. The dressing process involves welding a titanium helium containment vessel over the niobium cavity. During this process, the RF frequency of the cavity is carefully monitored to ensure that it does not shift beyond prescribed limits from the base 1.3 GHz. If the frequency shift approaches the limit, welding is stopped and the cavity is allowed to cool prior to proceeding. As a result of this process, the cavity frequency is well known at the end of the dressing (welding) procedure.

Following the dressing procedure, a leak check is performed by drawing a vacuum on the helium space with a leak detector and spraying helium on welds on the outside of the helium vessel. After a successful leak check, the helium space of the dressed cavity is pressure tested to 34.5 psig with 1 atm gas pressure inside the cavity.

The cavity frequency is monitored during the pressure test. A change in cavity frequency equates to a known change in cavity length. The mechanical properties of the cavity are known, which sets a frequency shift limit in order to ensure that the cavity remains in the elastic deformation regime.

TB9AES018 Pressure Test

A pressure test of the recently dressed TB9AES018 end lever tuner style dressed cavity was performed on October 28, 2014. The pressure test was performed and witnessed by a mechanical engineer, RF engineer, mechanical technician and a safety professional. In addition, a cavity design engineer came half way through the test and stayed through completion.

The mechanical engineer, RF engineer and safety professional were all relatively new to the SRF cavity pressure testing process. The cavity design engineer had been involved in many ILC blade tuner cavity pressure tests.

The RF engineer measured the cavity frequency before the pressure test began. He noticed that the cavity frequency had shifted in π mode about 160 kHz since the completion of the cavity dressing. Despite the discrepancy, the pressure test proceeded.

The pressure test was performed in accordance to Appendix A TB9AES018 Pressure Test Permit. Note 3 stated that the bellows brace assembly needs to be installed on the cavity. The mechanical engineer searched for bellows brace assembly in Teamcenter and found a drawing that matched the fixture on the bellows end of the cavity. As a result, it was assumed that the proper brace was installed on the cavity.

The pressure test proceeded in accordance to the procedure specified in the permit. The pressure was increased in steps as shown in Table 1 of the permit. At a pressure of 20.5 psig, the shift in the cavity frequency was about 560 kHz. This value was above the unwritten limit that was deemed acceptable. The pressure test proceeded to the next pressure step, 24.0 psig, where the frequency shift went above 1,150 kHz. At that point, the RF engineer communicated to the team that the test should stop and the cavity depressurized. Prior to that point, there had been no concern displayed between the RF and mechanical engineers.

Afterwards, it had been determined that the cavity had been plastically deformed with a frequency shift of about 680 kHz. The bellows end of the cavity showed a 1° departure from vertical, with the lower side further out.

TB9AES018 Pressure Test Investigation

Pressure testing procedure

The only written procedure available for the pressure test was a limited number of steps and notes in the pressure test permit. The mechanical engineer had the permit by virtue of it being a part of the cavity pressure vessel engineering note. It was a modified version used for testing ILC style dressed cavities. As part of this investigation the permit was reviewed and it was found that there are a couple of aspects of the permit that relate to pressure that need to be checked and clarified. First, the term Operating Pressure is likely to really be Maximum Allowable Working Pressure. Second, the test pressure is given as 1.16 times the MAWP instead of 1.1 or 1.15 times as given in the Code (Div 1 or Div 2) for a pneumatic test. If it is meant to be 1.15 from Div 2, then it should state Div 2 since it is not the division usually used.

The use of Division 2 is more conservative; however, the SRF dressed cavity design guidelines reference in FESHM Chapter 5031.6 [1] does not preclude the use of Division 1.

Cavity/bellows restraint

The cavity and the helium vessel bellows act as springs in parallel. Without an appropriate bellows restraint, the force experienced during the pressure test would elongate the system beyond the yield point of the niobium cavity at room temperature. The pressure test permit has a note stating "The bellows brace assembly is installed to the cavity. The assembly ensures that the titanium bellows at the end of the helium vessel is supported during the pressure test". The bellows brace assembly was verified to be installed on the dressed cavity. However, unknown to those involved with the TB9AES018 pressure test at the time, the installed bellows brace assembly was not designed to axially restrain the bellows. Instead, the assembly was designed to hold the cavity coaxial with the helium vessel to compensate for gravity in the horizontal position. In fact, the brace is flexible in the axial position to allow the tuner to operate. For previous pressure tests with blade tuner style cavities, the restraint mechanism was visually obvious when installed; however, for TB9AES018 or any end lever tuner cavity, it is not.

This was the first end lever tuner cavity that has been dressed and pressure tested. Cryomodule #1 in 2010 had end lever tuners of a different design, but these cavities were received already dressed from DESY and never pressure tested at Fermilab. Instead, an operational readiness clearance was approved only after a detailed justification and a subsequent Director's exception, which was specific only to Cryomodule #1.

As it turns out, a bellows restraint to resist the forces of leak checking or pressure testing had not been designed for the LCLS-II cavities. No provisions had been made to pressure test a cavity without the tuner installed. The design engineer stated that the tuner still required modifications to be able to withstand the forces or motions for all pressure and vacuum scenarios.

Cavity frequency measurements

The only written procedure for pressure testing 1.3 GHz end lever tuner cavities are the steps built into the pressure test permit. The permit used for pressure testing TB9AES018 had no frequency shift limits given. The limit was knowledge-based and appeared to be more of a range than a hard limit. Starting the test with a 160 kHz offset, presumably due to the leak test, added a level of confusion to this limit. There was no investigation as to the cause of the 160 kHz frequency shift.

Analyses have been performed to understand how much axial motion (frequency shift) can be allowed before the niobium cavity begins to plastically deform. This yield point varies from cavity to cavity due to different levels of heat treatment, etching and cold working during initial cavity tuning. Following the TB9AES018 incident, a maximum frequency shift relative to the initial tune has been set to 345 kHz (10 kHz/psig during the pressure test) as a safe limit to avoid yielding. With a cavity frequency shift of 300 Hz/µm, this equates to an axial motion limit of 1.15 mm. Several people mentioned a ±0.5 mm limit to avoid yielding the cavity, which is inconsistent with the current 345 kHz limit which would tend to be a single directional motion.

There were several contributing factors that resulted in the pressure test not being stopped when the frequency shift had been reached. They included; lack of a hard written limit, testing a new cavity style, expecting the frequency shift to level off, never having had a pressure test issue in the past, and confusion related to the starting frequency shift.

Figure 1 displays the TB9AES018 cavity frequency shift under the different conditions which are given in Table 1 for important test points.

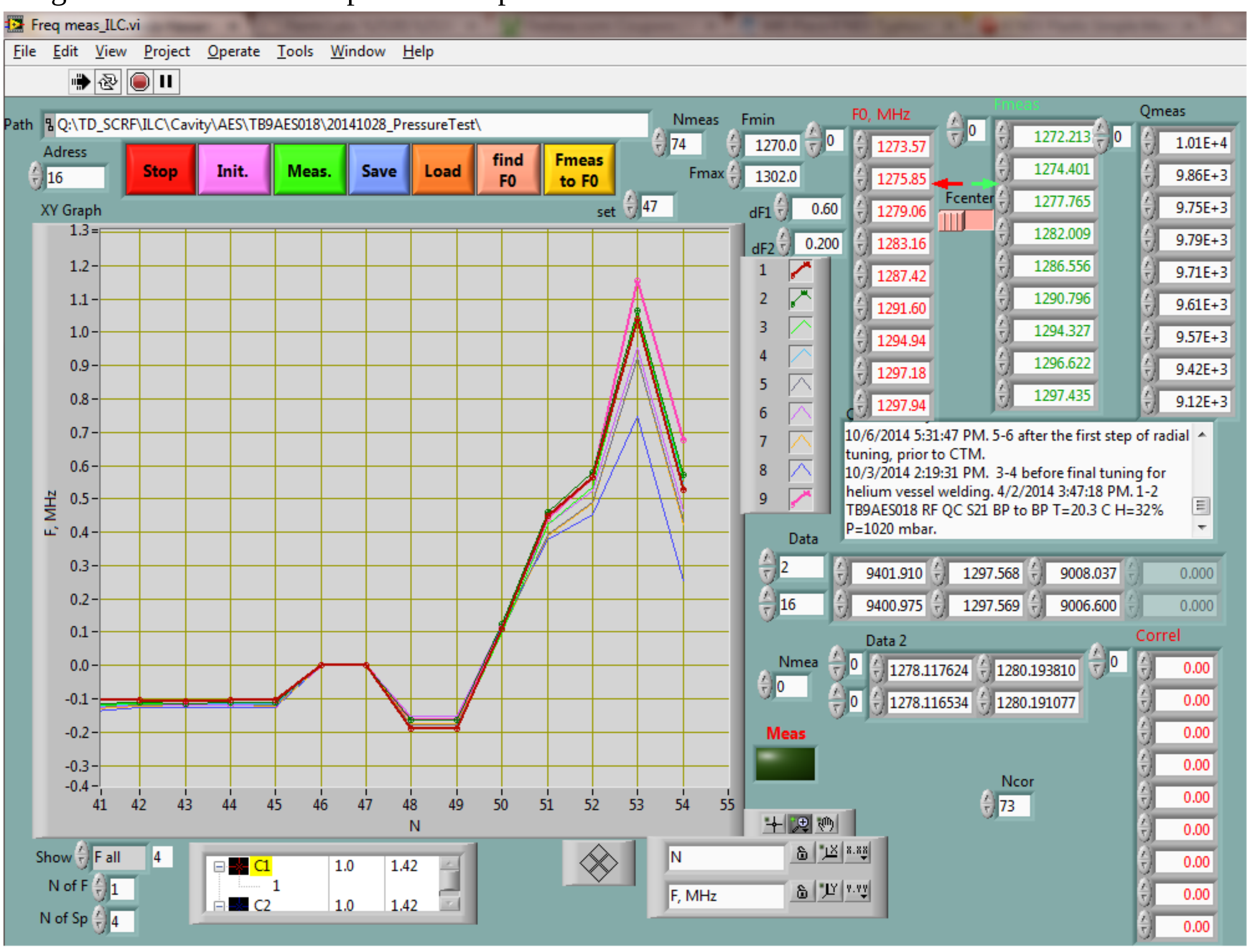


Figure 1 RF Frequency Shift on TB9AES018

Table 1 TB9AES018 Status during RF Measurement

Test Point	**Cavity Pressure**	**Helium Pressure**	**π mode shift**	**Comment**
45	1 atm	1 atm	-100 kHz	Helium vessel welding complete, still warm
46	1 atm	1 atm	0 kHz	Helium vessel welding complete, cooled to room

				temperature
47	1 atm	1 atm	0 kHz	Helium vessel welding complete, cooled to room temperature
48	1 atm	1 atm	-160 kHz	Following helium vessel leak check and subsequent backfill
49	1 atm	1 atm	-160 kHz	Following helium vessel leak check and subsequent backfill
50	1 atm	9 psig	100 kHz	During pressure test
51	1 atm	17 psig	440 kHz	During pressure test
52	1 atm	20.5 psig	560 kHz	During pressure test
53	1 atm	27 psig	1,150 kHz	During pressure test
54	1 atm	1 atm	680 kHz	Following pressure test

The cavity had a 680 kHz frequency shift following the test with atmospheric pressure in the helium and beamline spaces. This is an 840 kHz shift relative to the start of the pressure test. The beam pipe flange at the bellows end of the cavity showed a 1° departure from vertical, with the lower side further out. This is presumably due to the bellows brace assembly adding more resistance on the top of the cavity system. The field flatness was determined to be ~34% at this point. The field flatness had been >95% following the welding of the helium vessel.

Schedule constraints

As part of the high Q_0 research program, TB9AES018 was being dressed to be sent to Cornell for horizontal testing. Cornell stated that they had a short schedule window for testing in their horizontal test facility. It was stated that if this window was missed, then they would not be able to test it until spring 2015. There was daily pressure from project managers and partner collaborating institutes restating this point. This schedule pressure was passed on to those performing the work.

Follow Up Measures

The cavity was retuned back to the base 1.3 GHz frequency by installing a lever tuner and moving the cavity flange back. The nominal 1° angle of the beam tube flange remained after the retuning process. Following the procedure, the field flatness was 71%.

Following the TB9AES018 pressure test incident, a bellows restraint was quickly prepared and installed. Upon investigation, it was found that the new restraint had a couple of millimeters of gap in the restraint. Part of this gap was necessary to accommodate the 1° angle of the flange without fabricating a specialized restraint with angled surfaces. The gap requires the restraint to be installed in a specific position in order to contain the forces of the pressure test. It also means that the restraint will not contain the forces of vacuum from a leak test. As a result, the restraint was temporarily modified to add shims to fill the gap in order to be able to complete the pressure test, re-leak check and horizontal test of TB9AES018.

The LCLS-II project needs a restraint that can be installed after helium vessel welding that can be used for leak checking, pressure testing, and HTS cold testing. The restraint would also be in the clean room during string assembly, so it will need to be cleanable while connected to the dressed cavity.

As a result of this incident, the pressure test process and the pressure test permit was modified to require RF measurements to be written in a table for each pressure step. Frequency shift limits are also given for each step. The procedure was also modified to bring the pressure down to zero between each pressure step. Limits were also given to the shift allowed at the zero points. The pressure test permit used in the follow-up test is given in Appendix B Revised Pressure Test Permit.

The horizontal testing of a LCLS-II dressed cavity will need to be rescheduled to reflect a realistic and controlled process that will ensure the desired outcome. In addition, the schedule availability of the Cornell HTS will have to be explored to ensure good progress in dressed cavity design verification for the project.

The initial HTS testing of a LCLS-II dressed cavity is planned without a tuner, using the new and shimmed bellows restraint. This incident has raised questions as to the readiness of the end lever tuner for addressing all the pressure scenarios, reliability, and ability to replace active components. Table 2 shows the forces imposed on the tuner for different combinations of insulating vacuum, beam vacuum, and helium vessel pressure, for warm and cold conditions. The table also shows the cavity elongation that would result with no restraint in place. Shaded cells are out of range due to cavity yielding (purple) or piezo limits (green).

Table 2 Cavity and Cavity Tuner Response to Different Pressure Scenarios

Temperature		**300 K**					**4 K**	**2 K**	**2 K**
Conditions	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Insulating Vacuum [bar abs]	1	1	1	1	1	1	0	0	0
Cavity Beamline [bar abs]	1	1	1	0	0	0	0	0	1
Helium Vessel [bar abs]	1	0	3.3	1	0	3.3	1.5	0.03	4
Force on cavity flange with absolute restraint [kN]	0	-2.6	6	-1.2	-3.8	4.9	3.9	0.036	11.5
Cavity elongation with no restraint [mm]	0	-0.6	1.4	-0.3	-0.8	1.1	0.8	0.008	2.4

A. Initial frequency tune following helium vessel welding
B. Helium vessel leak check
C. Helium vessel pressure test
G. Cool down
H. Linac operation

I. Beam line vacuum failure helium relieving

Causal Analysis

After compiling the information of the previous sections as well as the appendices, a list of error precursors that contributed to the outcome was generated.

Error Precursors

- Lack of written frequency shift limits
- Inaccurate information related to what the bellows brace assembly was designed for
- Complacency due to never having had a pressure test abnormality
- Lack of verbal communication between RF engineer and mechanical engineer when RF shift was approaching the unwritten limit during the pressure test.
- Inaccurate risk perception (not recognizing warning signs of 160 kHz shift prior to pressure test)
- Unfamiliar with task (first time with an end lever tuner cavity)
- High work load, tight schedule

Root Cause of pressure test incident

- Lack of qualified overall dressed cavity oversight

Contributing Factors

1. Incomplete or misleading written procedure
    a. Misinterpreted written information pertaining to the bellows restraint
    b. No hard frequency shift limits were set
2. Inadequate engineering oversight
3. Failure to recognize a system problem with an initial frequency offset
4. Full requirements not passed down to the design level.

Recommendations

The root cause and contributing factors of the incident leads the committee to make the following recommendations.

1. Assign an overall lead responsible for a dressed cavity with tuner who understands the design, fabrication and handling requirements.
2. Design and review a new restraint that can be installed when the cavity is dressed and remain on the cavity until the tuner is installed. The new restraint requirements would include restraining vacuum loading, pressure test loading, and gravity affects. The latter would eliminate the need to install the bellows brace assembly until the tuner was installed. The new restraint must be capable of going through cold cavity VTS or HTS testing and have positive stops in the pressure and vacuum force directions.
3. Develop, review and approve travelers with built-in or referenced detailed procedures for each cavity task from receipt through string assembly.
4. Ensure that requirements are passed down to the component level.

References

1. Dressed Niobium SRF Cavity Pressure Safety, Fermilab ES&H Manual Chapter 5031.6.

Acknowledgments

I would like to thank all participating members of the Technical Division for their cooperation, insight and desire to improve the processes required in superconducting RF technology.

Appendix A TB9AES018 Pressure Test Permit

Pressure Testing Permit*

Type of Test: [ ] Hydrostatic [X] Pneumatic

Test Pressure 34.5 psig **Maximum Allowable Working Pressure** 29.7 psid

Items to be Tested

TB9AES027 Cavity Helium Vessel

Note1: Cavity beam-line is backfilled to atmospheric pressure with boiled off argon gas, outside of the helium vessel is at atmospheric pressure in air

Note 2: One of the VCR fittings at the bottom of the helium vessel will be used to backfill the helium vessel with boiled off nitrogen gas during the test. The Conflat flange on the 2-phase pipe of the helium vessel and the other VCR fitting will be blanked off during the test.

Note 3: The bellows brace assembly is installed to the cavity. The assembly ensures that the titanium bellows at the end of the helium vessel is supported during the pressure test.

Note 4: The pressure test will also include an RF frequency measurement before, during, and after pressurization.

Location of Test CAF-MP9 **Date and Time**

Hazards Involved

Contact with high velocity jet of test gas.

Safety Precautions Taken

System designed, fabricated, and inspected per ASME Boiler & Pressure Vessels code. Test will be conducted by trained personnel as described in ASME code. Access to test area will be limited only to those involved in the test during pressurization.

Special Conditions or Requirements

Operating pressure = 29.7 PSID, test pressure = 1.16*OP = 34.5 PSIG, pneumatic per ASME code.

1. First pressurize to 9-PSI and check for leaks.
2. Repeat at pressure levels listed in Table 1.
3. Increase pressure gradually to the test pressure for 5minutes.
4. Reduce pressure to design pressure.
5. Close valve on regulator.
6. Maintain test for at least 10min. without loss of pressure.

Qualified Person and Test Coordinator

Dept/Date TD/SRF Department

Division/Section Safety Officer

Dept/Date TD/ESH

Results

Witness **Dept/Date**

Rich Ruthe or designee

Detail for the pressure test steps.

Fermilab ES&H Manual 5034TA-1

Revised 3/2001

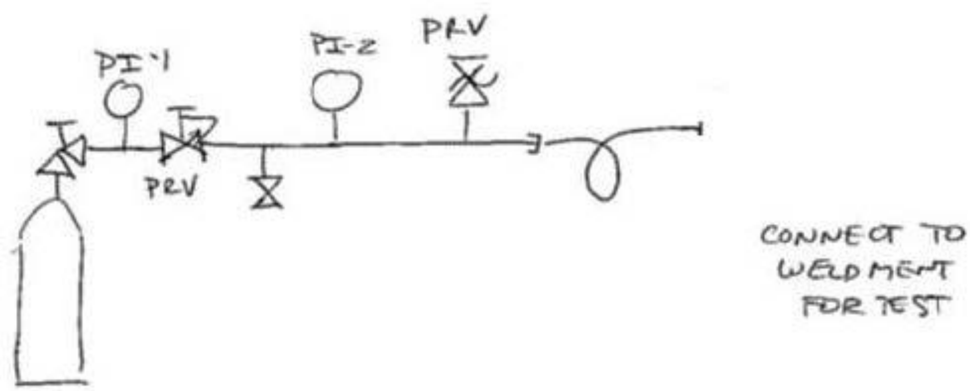
Table 1 shows the pressure levels for each pause and what should be done at that pressure. Total time for the test, not including setup and tear-down time, will be about 20 minutes.

Table 1 – Pressure Test Steps

Pressure (psig)(psig equals differential pressure for this test)	Dwell time (minutes)	Activity at pressure
0	–	Baseline RF test
9.0	As needed	Snoop line fitting, RF check
17.0	As needed	Snoop line fitting, RF check
20.5	~1	
24.0	As needed	RF check
27.0	~1	
31.0	~1	
34.5	5	Peak test pressure of 1.16 × MAWP
30.0	10*	Test pressure hold point*, RF check
25.0	As needed	RF check
17.0	As needed	Visual inspection, RF check
9.0	As needed	RF check
0	–	RF check

*The pressure hold point of 30 psig is the MAWP. Dwell time is set long enough to assure us that pressure is not dropping.

Test Setup



Test Pressure	PI-2	PRV
34.5 psig	0-100 psig	35.4 psig relief

Appendix B Revised Pressure Test Permit

Fermilab

Pressure Testing Permit

Type of Test: [ ] Hydrostatic [X] Pneumatic

Test Pressure 34.5 psig **Maximum Allowable Working Pressure** 29.7 psid

Items to be Tested
TB9AES018 Cavity Helium Vessel
Notes
Note1: Cavity beam-line is backfilled to atmospheric pressure with boiled off argon gas, outside of the helium vessel is air at atmospheric pressure.
Note 2: The Conflat flange on the 2-phase pipe of the helium vessel will be used to backfill the helium vessel with boiled off nitrogen gas during the test. Both of the VCR fittings at the bottom of the helium vessel will be blanked off during the test.
Note 3: The bellows brace arms (see attached images) are installed on the cavity and protect the cavity from excessive expansion. It is important to make sure that the titanium bellows at the end of the helium vessel is supported during the pressure test.
Note 4: The pressure test will include an RF frequency measurement before, during, and after pressurization
Note 5: Frequency change during pressure test should not exceed 10 kHz/psig with a maximum of 345 kHz at 34.5 psig for a pressurized cavity and 30 kHz total frequency shift for an unpressurized cavity. Test has to be promptly aborted in case of higher frequency change.
Note 6: MAWP = 29.7 psid, test pressure = 34.5 psig = 1.15*MAWP rounded to 0.5 psi, pneumatic per ASME code.

Location of Test **Date and Time**

Hazards Involved - See hazard analysis.

Safety Precautions Taken
System designed, fabricated, and inspected equivalent to ASME Boiler & Pressure Vessels code. Test will be conducted by trained personnel as described below. Access to test area will be limited only to those involved in the test during pressurization.

Special Conditions or Requirements
Follow the steps listed below.

1. Rope off area around pressure test.
2. Place sign on main entrance to announce a test is in progress and to use an alternate door.
3. Lock main entrance door.
4. Ensure cavity beam-line is backfilled to atmospheric pressure with boiled off argon gas, outside of the helium vessel is air at atmospheric pressure
5. Ensure the Conflat flange on the 2-phase pipe of the helium vessel will be used to backfill the helium vessel with boiled off nitrogen gas during the test and that both of the VCR fittings at the bottom of the helium vessel will be blanked off during the test.
6. Ensure the bellows brace arms (see attached images) are installed on the cavity and protect the cavity from excessive expansion. It is important to make sure that the titanium bellows at the end of the helium vessel is supported during the pressure test.
7. Check to see all bolts are present and tight in the bellows brace arms (see attached images).
8. Take RF measurement. Record starting frequency. Make sure frequency is in the range of 1297.85 - 1298.05 MHz.
9. Pressurize to 9.0 psig.
10. Snoop line fittings.
11. Take RF measurement. Record frequency change. Make sure frequency change is less than 90 kHz.
12. Depressurize to 0 psig.

13. Take RF measurement. Record frequency change. Make sure frequency change is less than 30 kHz.
14. Pressurize to 17.0 psig.
15. Snoop line fittings.
16. Take RF measurement. Record frequency change. Make sure frequency change is less than 170 kHz.
17. Depressurize to 0 psig.
18. Take RF measurement. Record frequency change. Make sure frequency change is less than 30 kHz.
19. Pressurize to 20.5 psig.
20. Take RF measurement. Record frequency change. Make sure frequency change is less than 205 kHz.
21. Depressurize to 0 psig.
22. Take RF measurement. Record frequency change. Make sure frequency change is less than 30 kHz.
23. Pressurize to 24 psig.
24. Take RF measurement. Record frequency change. Make sure frequency change is less than 240 kHz.
25. Depressurize to 0 psig.
26. Take RF measurement. Record frequency change. Make sure frequency change is less than 30 kHz.
27. Pressurize to 27.0 psig.
28. Take RF measurement. Record frequency change. Make sure frequency change is less than 270 kHz.
29. Depressurize to 0 psig.
30. Take RF measurement. Record frequency change. Make sure frequency change is less than 30 kHz.
31. Pressurize to 31.0 psig.
32. Take RF measurement. Record frequency change. Make sure frequency change is less than 310 kHz.
33. Depressurize to 0 psig.
34. Take RF measurement. Record frequency change. Make sure frequency change is less than 30 kHz.
35. Pressurize to 34.5 psig.
36. Hold pressure for 5 minutes. Take RF measurement. Record frequency change. Make sure frequency change is less than 345 kHz.
37. Depressurize to 0 psig.
38. Take RF measurement. Record frequency change. Make sure frequency change is less than 30 kHz.
39. Pressurize to 30.0 psig.
40. Close valve between regulator and vessel.
41. Hold pressure for 10 minutes to make sure pressure is not dropping. Take RF measurement. Record frequency change. Make sure frequency change is less than 300 kHz.
42. Depressurize to 25 psig.
43. Take RF measurement. Record frequency change. Make sure frequency change is less than 250 kHz.
44. Depressurize to 17 psig.
45. Take RF measurement. Record frequency change. Make sure frequency change is less than 170 kHz.
46. Depressurize to 9 psig.
47. Take RF measurement. Record frequency change. Make sure frequency change is less than 90 kHz.
48. Depressurize to 0 psig.
49. Take RF measurement. Record frequency change. Make sure frequency change is less than 30 kHz.

Qualified Person and Test Coordinator ______________________

Dept/Date TD/SRF Department

Division/Section Safety Officer ______________________

Dept/Date TD/ESH

Results

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Witness ______________________ **Dept/Date** ______________________

Rich Ruthe or designee

Table 1 – Pressure Test Steps

Starting Frequency: ____________________
Starting Frequency range: 1297.85 - 1298.05 MHz

Pressure (psig) (psig equals differential pressure for this test)	Dwell time (minutes)	Activity at pressure	Frequency Change [kHz]	Maximum Frequency Change [kHz]
0	As needed	RF check	0	0
9.0	As needed	Snoop line fitting, RF check		90
0	As needed	RF check		30
17.0	As needed	Snoop line fitting, RF check		170
0	As needed	RF check		30
20.5	As needed	RF check		205
0	As needed	RF check		30
24.0	As needed	RF check		240
0	As needed	RF check		30
27.0	As needed	RF check		270
0	As needed	RF check		30
31.0	As needed	RF check		310
0	As needed	RF check		30
34.5	5	Peak test pressure, RF check		345
0	As needed	RF check		30
30.0	10*	Test pressure hold point*, RF check		300
25.0	As needed	RF check		250
17.0	As needed	Visual inspection, RF check		170
9.0	As needed	RF check		90
0	As needed	RF check		30

*The pressure hold point of 30 psig is the MAWP rounded to 0.5 psi. Dwell time is set long enough to assure that pressure is not dropping.

Test Setup