Development of a Vacuum Compatible Rotary Dynamic Seal for Cryogenic Liquids

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Abstract. Liquid nitrogen is commonly circulating through radiative panels which cover satellite supporting structure inside thermal vacuum test chamber. In the Large Space Simulator (LSS) located in the ESA* ESTEC** Test Centre, there is the need to move the satellite specimen inside the vacuum chamber to modify its relative orientation vis-à-vis the artificial sun beam. Re-orientation of the radiative panels is then required.

ESA is currently developing a New Motion System (NMS) allowing dynamic motion from Gimbal to the Yoke Stand without any reconfiguration of the test. To do so, a nitrogen supply is required which can follow the rotation of the thermal shrouds under vacuum. Nitrogen flexible hoses are not anymore suitable due to their volume and mass constraints and due to the limitation in the rotation range.

This paper describes the design, manufacturing and tests of a new compact multi-turn Rotary Nitrogen Joint (RNJ) compliant with thermal vacuum conditions used for spacecraft thermal testing. This prototype development is funded by the ESA Technology and Research Program.

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OBJECTIVE OF THE ROTARY NITROGEN JOINT DEVELOPMENT

The qualification of hardware to the space environment requires the hardware to undergo a thermal vacuum test. During this test the hardware is submitted to cryogenic temperature while it is standing in a vacuum chamber. In order to obtain the cryogenic temperature, cryogenic liquid (nitrogen or helium) is circulating through radiative panels mounted inside the vacuum chamber. The cryogenic liquid is usually coming from tanks located close to the vacuum vessel and entering the chamber through dedicated feedthrough. In certain facilities, there is the need to move the specimen inside the vacuum chamber. This might be imposed to compensate some effect from the gravity on the specimen or to modify the relative orientation of the specimen vis-à-vis the artificial sun beam often present in large space simulators. In this case, the re-orientation of the radiative panels is required.

In order to accommodate the radiative panels rotation with respect to the fixed part of the facility, a nitrogen supply is required which can follow the rotation of the thermal shrouds.

Presently this supply is usually based on a nitrogen hose spiral as shown in Fig. 1. This solution is requiring a lot of space and the rotation range in this configuration is limited to 180º.

The Large Space Simulator (LSS) [1], located in the ESTEC Test Centre, with a volume over 2300m^3 is one of these thermal vacuum chambers. This facility is used to simulate in orbit condition for spacecraft i.e. vacuum, thermal environment and sun illumination. The facility is equipped for this of a 6-meter diameter solar simulator providing a maximum flux intensity of 2600 W/m^2.

LSS is equipped with a motion system that provides various orientations of the specimen under test with respect to the solar beam. This motion system is equipped with radiated panels that must be fed with cryogenic fluid (nitrogen). To provide the various orientations of the specimen with respect to the solar beam the motion system consists of rotary joints. This system is using nitrogen hose spiral.

Therefore the objective of the activity was to develop, manufacture and to qualify a compact multi-turn Rotary Nitrogen Joint (RNJ) compliant with ESA Space Standards (ECSS) and thermal vacuum conditions used for spacecraft thermal testing. The existing equipments used to distribute liquid nitrogen with rotatable junction are for most of them not designed for the environmental conditions required in the space chamber and the particular 2 flow channels distribution required here is very specific and constraining in the design [3].

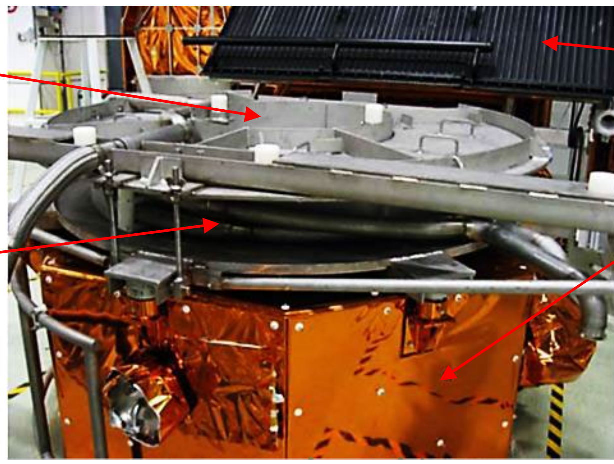


FIGURE 1. Nitrogen hose spiral commonly used for liquid nitrogen distribution in current vacuum test chamber

DESIGN DESCRIPTION OF THE ROTARY NITROGEN JOINT

RNJ Design Description

The RNJ system has been designed in order to be robust against thermal, mechanical and thermo-mechanical stresses. For those reasons, the RNJ is entirely made of 316L Stainless Steel, except the mechanical interface flange which is of 304L. The use of a single material insures lower risk of shrinking during operation of the system at min and max operating temperatures.

It is composed of several components and sub-assemblies:

- A rotative sub-assembly which includes the DN50 ISO KF interfaces for the LN_2 inlet and outlet
- A fixed sub-assembly which includes the DN50 ISO KF interfaces for the LN_2 inlet and outlet, the mechanical interface with the NMS structure
- 4 cryogenics seals: 2 for the internal tightness and 2 for the external tightness (toward vacuum)
- 2 o-rings placed as a backup of the cryogenic seals
- 2 ball bearings mounted onto the interface between the fixed and rotative sub-assemblies
- 1 metallic bellow implemented onto the internal pipe
- A thermal control sub-system composed with 4 heaters and 4 temperature sensors.

To ease the understanding of the design, only the internal parts of the RNJ have been represented in the Fig. 3. The mechanical flange and all components (bearing, seals) have been removed. The fixed sub-assembly is represented in red while the rotative part is in blue. Furthermore, the external casing is transparent in order to visualize the internal fluid distribution.

The tightness is very critical for the application and has been particularly analyzed. The temperature range imposes the use of cryogenic seals which will operate in sliding mode. Internally, to avoid or limit the mass transfer between both ways (way in and way out) a sealing is also required but with less constraints.

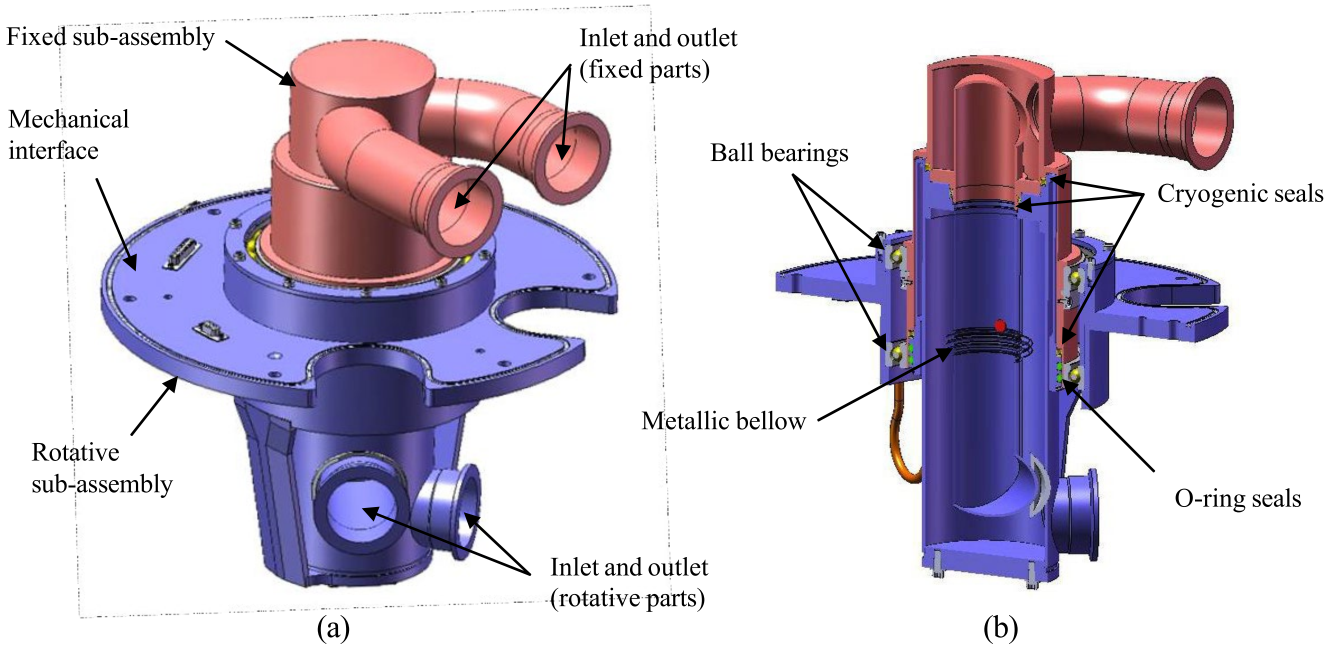


FIGURE 2. RNJ specimen CAD description (a) with the cutaway view (b).

The critical tightness has to be insured from the internal side to the vacuum side. With common applications with temperature above -50°C, the o-rings are generally used (depending of the pressure and the tightness required). But for temperature lower than -50°C the elastomer are not able to conserve their elasticity and can't be used anymore. In this temperature range, metallic seals are generally used. These seals use metallic housing (with possible coating to improve the seating force) and internal spring to insure sufficient springback all along the temperature range. HTMS proposes Commaseals® [2] which are designed for slow dynamic applications. This kind of seal is used for rotative application with an important background in off-shore applications. One other possibility for our application is to use PTFE seal. This type of seal is use for cryogenic rotative applications.

In both cases, the helium leak rate announced by the supplier is in the range of 10^{-6} mbar.l/s. The PFTE seal presents less constraint for the seating force and for the gap management between the seal and the contact faces. This technology has been selected and implemented in the RNJ specimen.

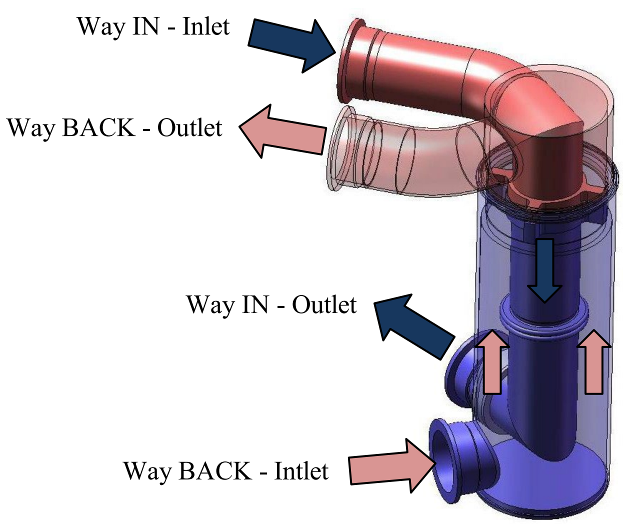


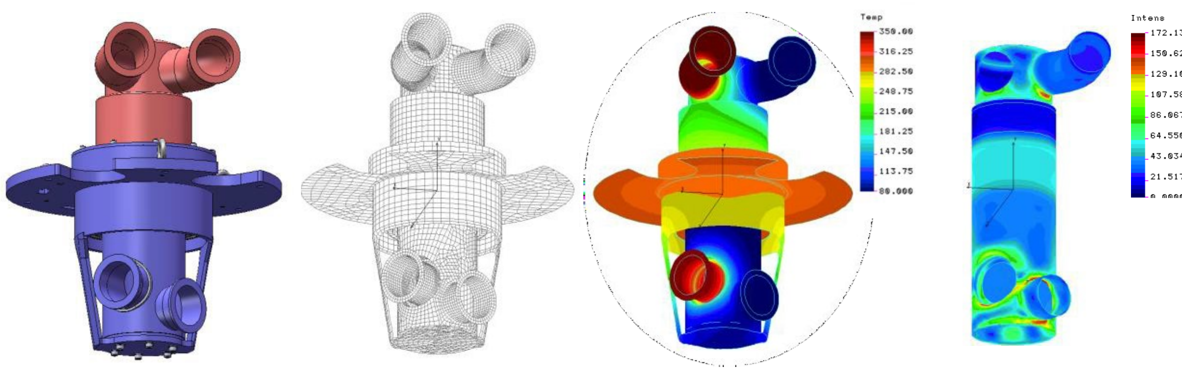
FIGURE 3. RNJ flow distribution.

In order to reduce the risk of leakage, a redundancy concept based on the redundancy of the seals and the type of seals, has been designed. The design of the RNJ is done with cryogenic seals in the cryogenic areas and a thermal barrier is implemented in order to allow the use of o-rings at room temperature. To compensate the parasitic heat losses from the thermal barrier and thus to maintain the o-rings in their proper operating temperature range, temperature management is required. The thermal control of the o-ring seating area is insured using redundant metallic heating filaments and redundant PT100 thermal sensors connected to DSub electrical connectors.

For the ball bearings, we choose to implement AISI 440C ball bearings with a Tungsten Disulfide (WS2) dry lubrication coating, adapted to vacuum and cryogenic temperature conditions applied to balls surface.

RNJ FEM analysis

To validate the RNJ design regarding mechanical and thermo-mechanical aspects, FEM analyses have been done. Each sub-assembly has been meshed using a simplified CAD file (see Fig. 4a) and FEM software. The mesh of the RNJ, presented is the Fig. 4b below, is composed of 20274 shell elements (Shell 4) based on 4 triangles. The gaps between the sealing faces (face in contact with the seals) have been modeled using gap elements. The solver used for the study is the Sparse solver, which is a direct solving.



(a) (b) (c) (d)

FIGURE 4. CAD view (a), Mesh of the RNJ (b) used for mechanical and thermo-mechanical analysis, temperature gradient for worst case (c) and Mechanical stress at proof pressure load (d).

The design of the RNJ has been found robust against the Proof pressure and Burst pressure loads required by ESA pressure vessel standard. In both cases, the yield and ultimate MOS (Margin Of Safety) have been calculated positive.

To validate the mechanical stress and the gaps behaviour (gaps simulating the sealing surfaces with cryogenic seals and o-rings), the temperature profile described in Fig. 5 has been applied to Way-IN and Way-BACK walls considering appropriate heat transfer coefficient. The first steps correspond to the cooldown phase where liquid nitrogen starts to flow in Way-IN. The temperature of the Way-IN goes down to 80 K while the Way-BACK stays at warm temperature (see temperature gradient in Fig. 4c). In a second time, the Way-BACK is also cooled with liquid nitrogen and progressively goes down 80 K. The second part of the temperature profile corresponds to the opposite process for warming phase of the specimen connected to the RNJ.

The temperature mapping of the RNJ has been calculated during the different steps of this profile. For each steps, the mechanical stress has been calculated with the resulting deflection of the gap areas. Three gap values have been controlled corresponding to the most critical, i.e primary external cryogenic seal gap, redundant cryogenic seal gap and o-ring seal gap. In worst case conditions, the primary external cryogenic seal gap varies between 0.03 mm and 0.45 mm which is consistent with the maximum allowable gap during transient phases of 0.5 mm recommended by the seal's manufacturer. The minimum value is also positive so no contact between moving parts should occur during thermal cycling.

Finally the bolts analysis, the pressure drops analysis and the rotative torque estimation have been analysed and budgeted.

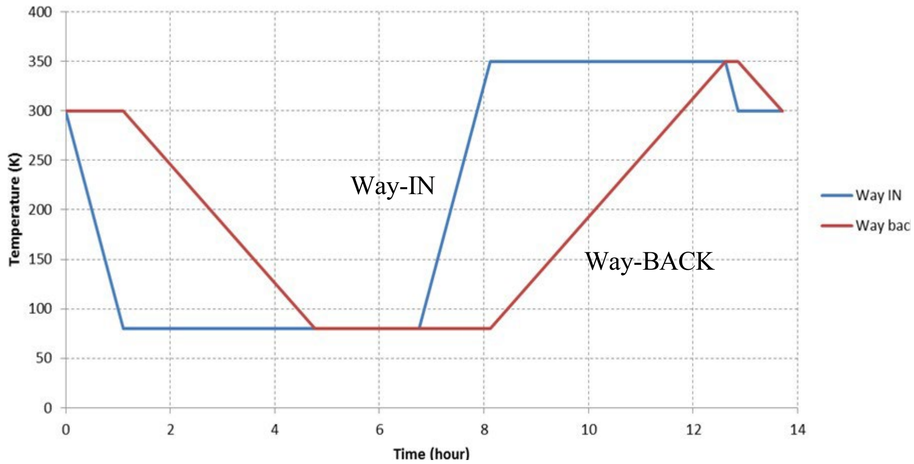


FIGURE 5. Temperature cycle of the Way-IN and Way-BACK paths corresponding to one temperature cycle.

MANUFACTURING AND QUALIFICATION TESTING OF THE ROTARY NITROGEN JOINT

RNJ Manufacturing

A first RNJ specimen has been manufactured in the frame of this contract. The specimen manufactured will be used to validate the manufacturing processes and then will be submitted to qualification test campaign.

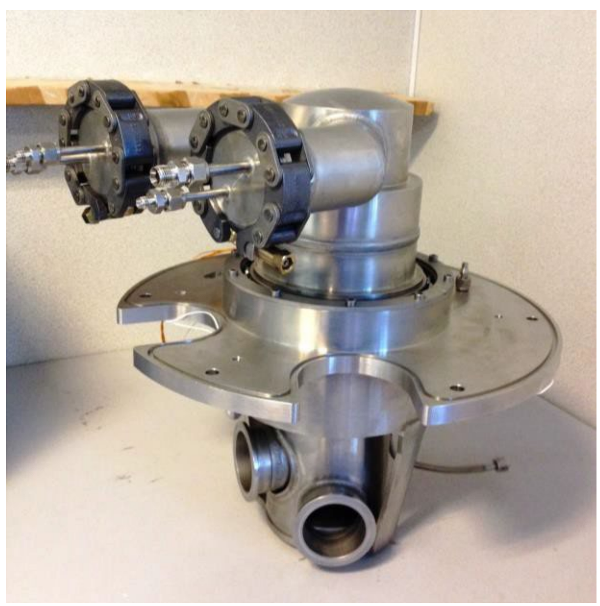


FIGURE 6. RNJ specimen used for design validation qualification test campaign.

RNJ Qualification Tests

As it was not possible to ensure the required LN_2/GN_2 mass flow and in order to ensure the verification of leak rate requirements, it has been decided to use helium gas as the cryogen vector (estimated mass flow of 0.4 g/s of helium). The test bench is composed of the following main elements:

- A 1m^3 vacuum chamber with a dismountable upper flange,
- A liquid nitrogen Dewar,
- An helium bottle gas supply equipped with an expander and a set of valves to load the circuit with a helium gas charge,
- A volumetric mechanical helium compressor to ensure the desired mass flow rate: compressor package comprising a lubricated and water cooler compressor module (scroll type), and an oil separator.

The vacuum chamber is evacuated with a turbo molecular vacuum pumping system equipped with a primary dry back pump. A vacuum gauge is used to monitor the vacuum level inside the chamber. The static part of the RNJ specimen is fastened to the room temperature upper flange with the aim of low thermal conduction and stiff mechanical support structure.

The rotative part of the RNJ is mechanically linked via a shaft to a planetary gearbox coupled to a servo motor. The low thermal conduction shaft is crossing the room temperature flange via a hermetic rotary feedthrough. The motor is equipped with an incremental encoder in order to control and vary the rotation speed in the two directions. Angular position is obtained by the aim of an inductive sensor.

Gaseous helium at 8 bar circulates into a copper tube heat exchanger plunged into the LN_2 open Dewar in order to be cooled down to 77 K.

Three additional temperature controlled heat exchangers are used in the helium flow stream in order to impose the RNJ temperature profile as depicted in the Fig. 5.

Although the RNJ has been designed for complete rotation, but in order to cope with the electrical wiring connections (thermal sensors and heaters) and capillary pipe (pressure transducer), the rotation during test phase is limited to alternative 0/330° and not continuous rotation.

The test bench is representative of the operational cryogenic temperature and vacuum conditions except the flowrate (thus the power exchanged), which is decreased for reasonable value of heating power. Some pictures of the RNJ integrated inside the test bench are detailed in the Fig. 7.

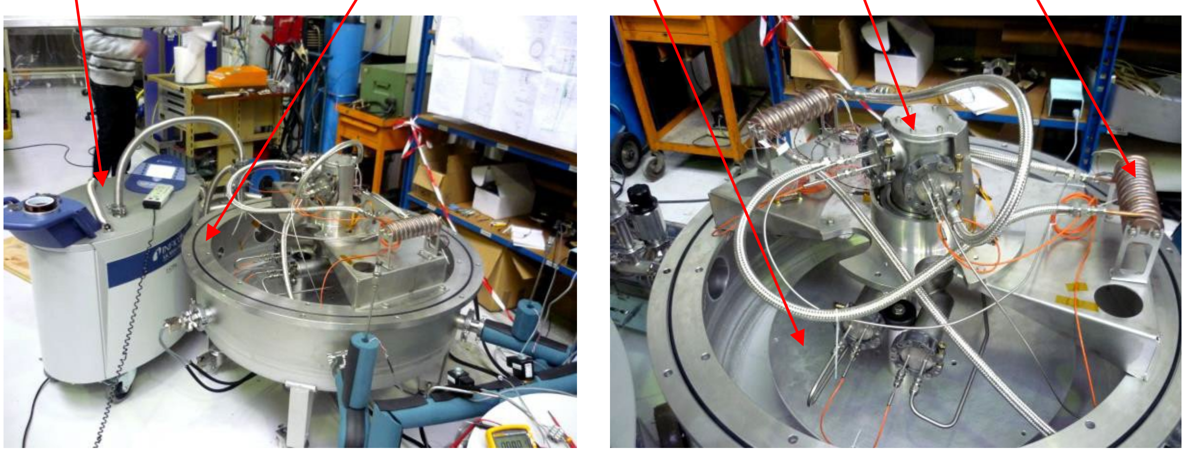


FIGURE 7. RNJ specimen mounted into the test bench before qualification test campaign

Proof Pressure Test

In order to demonstrate the robustness of the RNJ against proof pressure load, helium leak test at MWP (Maximum Working Pressure - 12 bars) has been performed prior and after the proof pressure loading of the RNJ specimen with 1.5 MWP (18 bars).

The helium leak rate at 12 Bar before the proof pressure test was 4.34x10^{-4} mbar.l/s whereas after the proof pressure test, the leak rate was 4.44x10-4 mbar.l/s. The difference is about 2.3 % prior and after proof pressure loading. The proof pressure test of the RNJ has been declared compliant.

Thermal Stress Tests

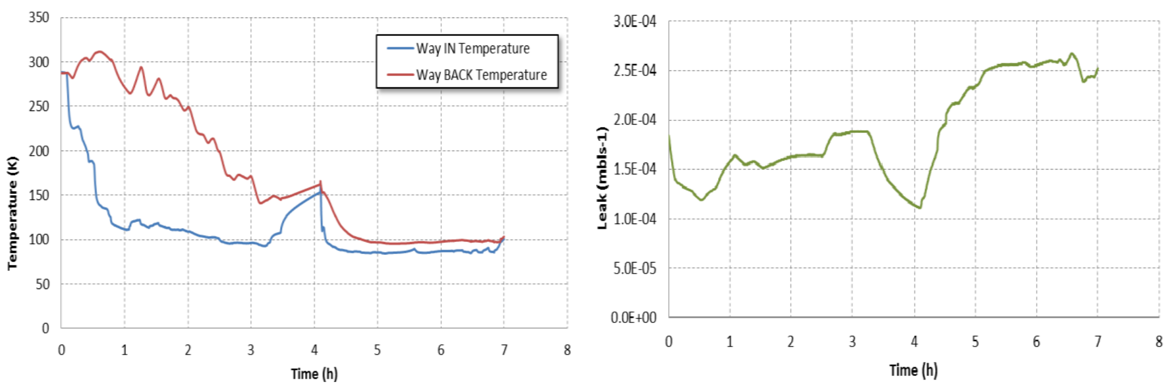
The objectives of these tests were:

- To apply a thermal stress to the RNJ specimen representative of the RNJ life cycle prior to apply rotations,
- To measure the leakage rate of the RNJ specimen in static mode while stressed under the complete temperature range,
- To measure the leakage rate of the RNJ in dynamic mode while stressed under the temperature range,
- To define heater control logic (set points, power limitation),
- To measure the resistive torque of the RNJ during rotation.

The test has been shared in two phases. The first phase corresponds to the cool down followed by stabilization at 80 K and the second phase to the warming phase followed by the stabilization at 353 K. The temperature evolution in the Way IN and Way BACK of the RNJ and the leak rate evolution are reported respectively in the Fig. 8 hereafter. At any time of the test, the helium leak rate in the vacuum chamber remains below the requirement (about $4x10^{-4}$ mbar.l/s). The value increases a little bit when the RNJ temperature decreases.

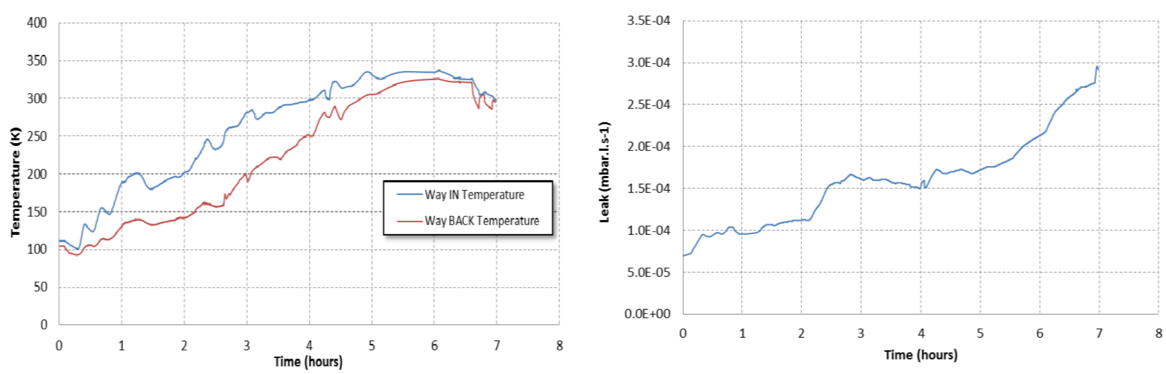
At about 3 hours after the beginning of the test, 50 rotation cycles have been performed on the RNJ continuously during its cool down. During the same period we can observe a change in temperature slope due to poor precooling of helium loop due to a too low liquid nitrogen level in the test bench.

At about 5.5 hours after the beginning of the test, 50 other rotation cycles have been performed. No issues have been observed and the leak rate didn't change significantly (about $0.2x10^{-4}$ mbar.l/s of difference).



(a) (b)

FIGURE 8. Evolution of Way IN and Way BACK temperature in the RNJ during the cooling phase of the thermal stress test (a) and evolution of the helium leakage rate in the vacuum chamber during the same phase (b)



(a) (b)

FIGURE 9. Evolution of Way IN and Way BACK temperature in the RNJ during the warm-up phase of the thermal stress test (a) and evolution of the helium leakage rate in the vacuum chamber during the same phase (b).

During the second phase of the test, the temperature profile detailed in Fig. 5 has been applied up the warm temperature condition. At any time of the test, the helium leak rate in the vacuum chamber remains below the requirement (about $4x10^{-4}$ mbar.l/s). We observed however a variation of the leak rate along the temperature profile (cool down and warm up) which is mainly due to the thermal behavior of the RNJ. The gap values between the fixed and moving parts are impacted by the transient temperature profile and thus the seal performances are also impacted.

Dynamic Tests

The objectives of the dynamic tests were:

- To control the resistive torque of the RNJ during rotation in cold condition,
- To demonstrate the capability of the RNJ for rotations around the longitudinal axis in both directions with an angular speed varying from 0 to 6 rpm,
- To measure the leakage rate of the RNJ specimen in dynamic mode under cryogenic conditions,
- To accumulate 4.000 rotations, i.e. four times the predicted number of operating cycles.

During the dynamic tests at cold conditions, several difficulties have been encountered. In the first hundred of cycles, it has been found out that the test bench mechanical coupling was over-torqueing the motor up to stop (110 N.m). The coupling was then dismounted and modified (O-ring diameter, material and lubrication) so that its contribution is reduced to an acceptable value (about 18 N.m).

Another over-torqueing cause appeared later on in the test campaign which has been attributed to the RNJ itself. The RNJ has been dismounted and inspected. It has been found that the secondary cryogenic seal was worn. This has been attributed to not nominal groove length tolerances due to an accumulation of several uncertainties combined with the mounting tolerances. It has been decided to remove this secondary cryogenic seal and to go on testing.

In total, the RNJ has endures 560 rotations under cryogenic conditions and 3000 rotations at ambient temperature. All rotations were performed with 8 bars helium, with the max required rotation speed of 6 rpm. On top of that, despite the fact that one of the seal (secondary external cryogenic seal) was removed, the helium leak rate remained low and fulfilled the requirement.

CONCLUSIONS

A Rotary Nitrogen Joint (RNJ) has been designed, manufactured and successfully tested. The performance tests demonstrated very good performances, as follows:

- Proof pressure robustness: RNJ helium leakage rate at MWP (12 bars) compliant prior and after the proof pressure loading of the RNJ specimen with 1.5 MWP (18 bars).
- Thermal stress robustness: RNJ helium leakage rate compliant while submitted to the complete temperature range stress.
- Dynamic capability: In total, the RNJ has endures 560 rotations under cryogenic conditions and 3000 rotations at ambient temperature. All rotations were performed with 8 bars helium, with the max required rotation speed of 6 rpm. The helium leak rate has always respected the requirements.
- Rotation torque: Beside that fact that the torque measurement includes the resistive torque contribution of the test bench coupling, the RNJ torque was found in accordance with the estimated value (about 80 N.m).

ACKNOWLEDGMENTS

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