Cryogenic Pumped EHD Fluid Loop for Electronic Components

Executive Summary Report

ESTEC Contract Number 400024720/19/NL/KML/va

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EUROPEAN SPACE AGENCY CONTRACT REPORT

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2. Purpose and scope of the report

This document is the Executive Summary Report of the Electro Hydrodynamic (EHD) Cryo Loop Engineering Model (EM) developed within the frame of the prime contract no, 400024720/19/NL/KML/va between the European Space Agency and APR technologies (APR) for the study entitled "Cryogenic Pumped EHD Fluid Loop for Electronic Components", AD 1, between the European Space Agency and APR technologies. The objective of this documents is to provide a synthesis of the study results, to define the final TRL achieved and to present lessons learnt from the activity and make recommendations on subsequent technology maturation steps.

3. Related documents

3.1. Applicable documents

AD 1 400024720/19/NL/KML/va, Cryogenic Pumped EHD Fluid Loop for Electronic Components

AD 2 SoW, APRTEC-1367785787-367

AD 3 ECSS-E-ST-10-06C Technical requirements specification" 6 March 2009

3.2. Reference documents

RD 1 TS Cryogenic Pumped EHD Loops for Electronics Components, APRTEC-1367785787- 180

RD 2	TN EHD Cryo, APRTEC-1367785787-1030
RD 3	TP EHD Cryo Low Level BB Test Plan, APRTEC-1367785787-236
RD 4	HA EHD Cryo Hazard and Safety analysis, APRTEC-133303272-2396
RD 5	PAP QA / PA and safety plan, APRTEC-133303272-2368
RD 6	PP EHD Cryo Loop Procurement Plan, APRTEC-1367785787-255
RD 7	TRPT EHD Cryo Low Level BB Test Report, APRTEC-1367785787-443
RD 8	DJF EHD Cryo Design justification file, APRTEC-1367785787-232
RD 9	RTMM EHD Cryo loop Thermal model, APRTEC-1367785787-4
RD 10	TP EHD Cryo EM Test Plan, APRTEC-1367785787-741
RD 11	TSPRO EHD Cryo EM tests-as run, APRTEC-1367785787-822
RD 12	TRPT EM Cryo Loop vibration RISE, APRTEC-1367785787-1028
RD 13	TRPT EHD Cryo EM Test Evaluation and Further Work, APRTEC-1367785787-824
RD 14	ECSS-E-HB-11A, TRL Guidelines

4. Acronyms and abbreviations

AD	Applicable Document
APRtec	APR Technologies AB
BBM	BreadBoard Model
CDR	Critical Design Review
DDF	Design definition file
EHD	Electro hydrodynamic
EM	Engineering model
MEOP	Maximum expected operating pressure
NA	Not applicable
NCR	Non-conformance report
PDR	Preliminary design review
RD	Reference Document
TRL	Technology Readiness Level
TS	Technical requirements Specification
WP	Work Package

5. Introduction

European coolers meeting Earth Observation (EO) mission requirements are capable to provide significant cooling power at an operational temperature around from 50K to 80K (for IR detection). At cryogenic subsystem level, robustness to Single Point Failure requirement translates in general into a redundancy: one cooler should be operating while the other cooler is kept OFF during the mission, which has a dramatic impact, as a significant part of the thermal budget comes from the parasitics from the OFF cold finger. This project attempts to solve this problem by introducing a controlled heat transfer in a system with low parasitics when in OFF state. A cryogenic fluid pumped cooling loop will potentially reduce the vibrations at the detector/FPA (focal plane assembly) by increasing the heat path distance and/or reduce the heat transfer in OFF state, compared to a copper strap. APRtec aimed to achieve this by introducing an Electro hydrodynamic (EHD) pumped loop; thus, being able to control the heat transfer by regulating the EHD flow. The current study is to APRs knowledge the first attempt to productize EHD pumping for cryogenic temperatures. The system aiming to meet EO requirements, having low vibrations and low thermal parasitics in “OFF” state. The main objectives of the project were to; Develop, manufacture, and test an EM of a cryogenic EHD driven and controlled fluid loop for detector/FPA cooling at around 80 K and to perform breadboard tests of an EHD Pump with Cryofluids between 100 K and 120 K for other potential applications. The targeted improvement is to advance the technology maturation from TRL3 to TRL5 in the current study.

6. Description of the development work

This section describes how the work was organised and implemented. The scope of the work was originally planned to be an 18-month project with a structure fully compliant with the tasks and work logic specified in the statement of work. In addition to the management of the project, the work has been performed in the structure of 5 major work packages (WPs), Figure 1, namely:

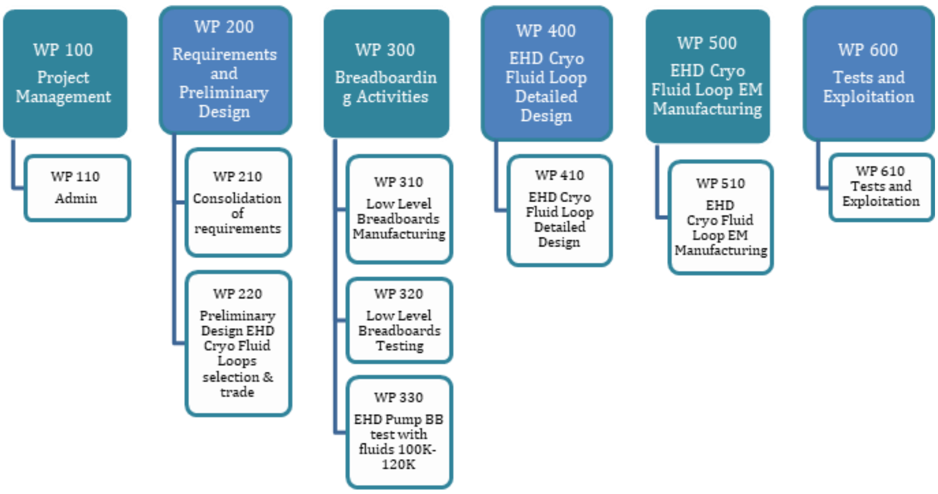


Figure 1. Work breakdown structure (WBS), all WPs are under the responsibility of APR Technologies

6.1. Definition

Requirements analysis

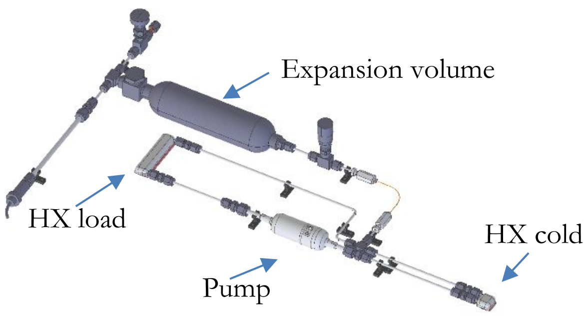
The objective of the technical requirements specification, RD 1, developed during WP210 is to allow for APRtec to propose suitable technical solutions and is the technical reference for the qualification of the design and for the acceptance of the end product. The driving requirements are chosen based on limits that alter the performance in both OFF and ON modes.

Table 1. Main Driving functional and performance requirements of the FM loop

Proj. ID	ID type	No.	Title	Condition	Description
135	PER	1	**User load Heat transfer capacity**	shall be at least	2 W
135	PER	2	**Temperature gradient**	shall be less than	4K
135	PER	3	**Parasitics (thermal)**	shall be less than	0.6 W
135	PER	4	**The Static stiffness**	shall be less than	6 N/mm (along all axes)
135	PER	5	**MEOP**	shall be less than	150 BarA
135	PER	6	**Burst pressure**	shall withstand	without rupture, a burst pressure of 2.5 x MDP
135	PER	7	**External leakage**	shall not exceed	1 x 10-6 mBar*l/s (scc/s) GHe at any specified temperature and at any inlet pressure from 0 to 1.5 x MDP
135	IF	2	**Area Cooler side mechanical interface**	shall be	16x20 mm
135	IF	4	**Area of Detector Side interface**	shall be	1500 mm^2 (15 cm^2)
135	ENV	1	**Acceptance temperature range**	shall be	OP: [77K, 313K], NON-OP: [77K,323K] without compromising compliance to this specification
135	PHY	3	**Maximum Total Cold Mass**	shall not exceed	1 kg.

Breadboard

The main output from the preliminary design work is the BBM design justification file (DJF), RD 8, for the EHD Cryo Loop. The cryogenic fluid loop includes 2 heat exchangers; one attached to the cold finger of the cryo cooler and one at the heat load to transfer the heat to the liquid. The EHD pump transports the fluid between the heat exchangers and an expansion volume to handle pressure variations.



The fluids which have been selected for evaluation are liquid nitrogen and liquid argon. Also prepared were the

- Product assurance plan (PAP) for the EM design, RD 5
- Safety and Hazard analysis, RD 4
- Failure analysis: Critical Item List (CIL), including Single Point Failures (SPF), RD 2
- Low Level Breadboarding Test Plan (TP), RD 3
- Procurement Plan (PP), RD 6

The breadboarding concludes with assessing the impact of the breadboard tests results on the trade-offs and the design decisions left open from the PDR and an analysis of what changes to be implemented for the EM test campaign was performed.

Detailed design and EM manufacturing

The EM cryogenic fluid loop has the following updates based on BBM campaign assessment:

- The heat exchanger attached to the cold finger of the cryo cooler is designed for increased heat exchange: larger interface area and more surface area. Inlet and outlet are placed to force the flow to take a longer path. The weld process is updated
- The pump has more pump stages to increase the flow rate and better alignment during assembly
- The heat exchanger at the heat load have more surface to transfer the heat to the fluid
- Electrode distance is decreased from 0.5 mm to 0.38 mm in EM1 and is 0.5 in EM 2
- Tubing is shorter to reduce pressure drop and thinner to decrease stiffness
- Reduced number of fittings to decrease mass
- Updated PA control

The manufactured parts are within their specification w.r.t. physical dimensions and the mass of the cryo part is less than 400g. All components were pressurized to above proof pressure (~115 bar) satisfactorily, complying to the leak requirement. The updated weld procedure is deemed sufficient for the components to be assembled into the loop. The pump and the feedthrough welds sustain a bust pressure of 1400 bar which is a substantial margin to the requirements. Thus, the pump mass could be reduced, and the pump will still sustain an increase in MEOP. The EM loop is seen in Figure 2.

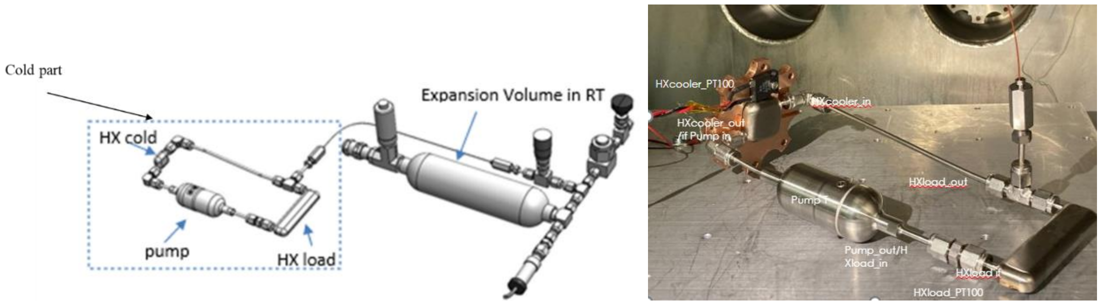


Figure 2 Overview of the pumped cryogenic fluid loop and sensor placement

6.2. Main results and system performance analysis

The breadboard (BB) test results, RD 7, are used for trading configurations of the loop. The test report, RD 13, describe the test performed after TRR to verify a subset of the requirements. Low level test in LAr showed a stable current increase when increasing drive voltage, which indicates that it is possible to pump. Bubble generation is present without applied voltage but is clearly affected by the voltage level. The LN is closer to its boiling point than the LAr and the operating pressure should be chosen to avoid operation close to the boiling point. The flow rate of the EHD pump had linear increase when adding pump stages, measured in an open configuration, with inlet tube immersed in Novec 7500. Together with the results from loop testing this can indicate the number of stages needed to fulfil the delta T requirement.

Start-up: Fill/drain procedure verification, operational pressure

As seen in Figure 3, the cold pressure stabilized at around the theoretical value. When compressed air is added, the loop pressure does no longer match the theory for nitrogen.

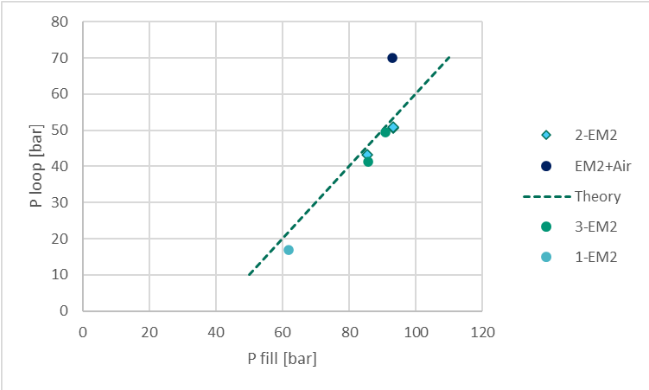


Figure 3. Operational (HXcold @-196 °C) pressure versus fill pressure at RT

The high pressure drop and low thermal conductivity of the capillary was as expected keeping the warmer gas separated from the cooled liquid in the loop. The procedures for filling and draining the cryogenic loop is verified and accepted. The loop pressure after cooling indicates that the loop is filled with liquid.

Thermal tests

For each state (ON and OFF) different temperatures are applied on the cold side and for each temperature, the load varies between different power values. The resulting dT was used in a RTMM in SPICE, where the thermal resistance through the fluid (*Rfluid)* in the BBM system was around 11.78K/W. The total thermal resistance of the BBM in the OFF state was 17.26K/W. The most stable response was at 3kV where dT decreased 2.9K, implying a thermal resistance over the fluid of 9.44K/W. Thus, improving the performance by 22%. This is equivalent to a flow of 0.061ml/s. Non-conclusive response of the ON performance of EM1 pump was mitigated with switching to EM2 pump. EM2 pumping provide a very weak but repetitive response. The loop pressure follows the temperatures, which confirms that it is a real temperature decrease.

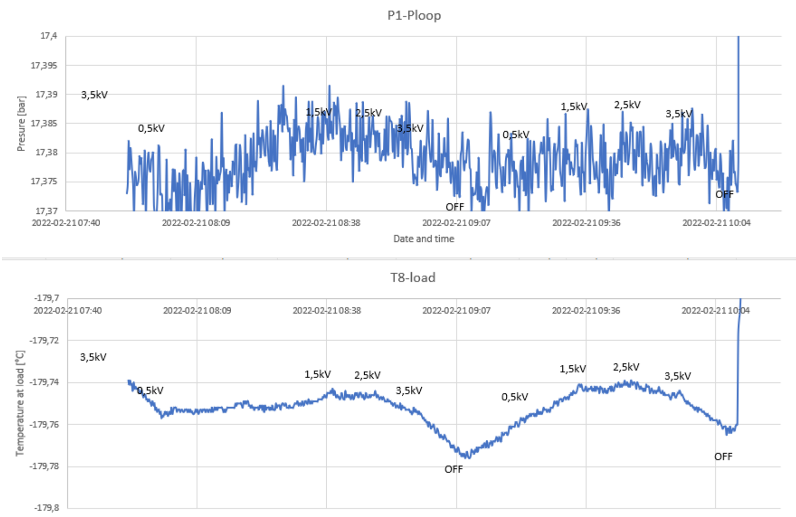


Figure 4. Response of EM2 loop at ~17 bar loop pressure

Thus, this changed *Rfluid* from 28.0 to 27.6 K/W. The equivalent flow in the loop was changed from 0.0206 ml/s to 0.0210 ml/s, or a 2 % increase in flow. The RTMM, RD 9, provides good coherence to the six combinations of ambient temperatures and power inputs studied in the EM tests. Thermal OFF resistance should increase greatly in low gravity cases (no convective flow).

The tests are summarized in Figure 5, where the temperature and loop pressure are plotted for the 3 different configurations and a test series with Air added. It can be noted that the response is lacking when the pump (sensor between pump and load) is filled with gas and that the most responses are seen when the system is filled with compressible liquid.

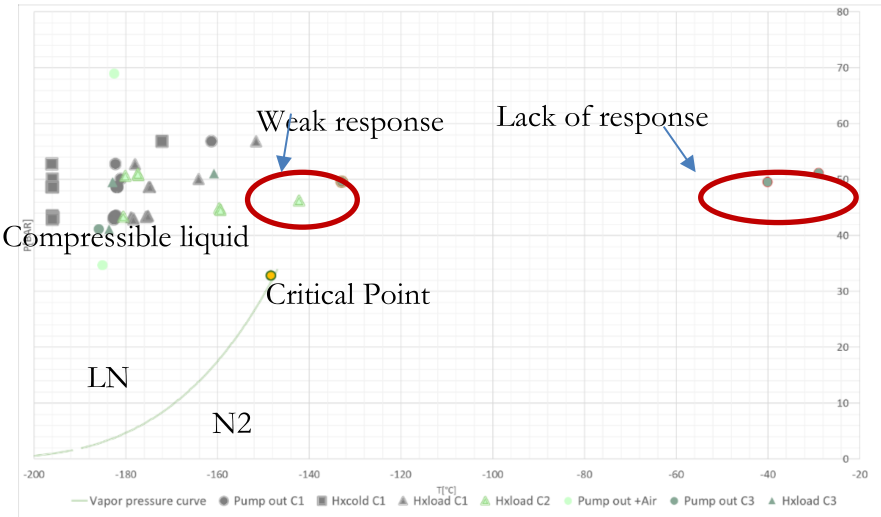


Figure 5 Summary of pump tests plotted in relation to Nitrogen vapor pressure curve. C=configuration of loop during the test.

Pumping of LN is achieved, and the parts of the loop work together. Analysis of the thermal resistance and internal pressure indicate that no gas is formed when supply voltage is applied, since there is a pressure drop related to the pumping and gas generation would increase the pressure. However, the weak response indicates a need for design updates of the pump stack (electrode design and internal connections). The thermocouple wires and the pump power constituted a large part of the parasitics. Parasitics of the system are low enough to be less than 0.6 W in the FM.

Stiffness

The Static stiffness shall be less than 6 N/mm (along all axes), but is measured to a stiffness of 19.6 N/mm. The loop is too rigid with the current distance between load and cooler and no flexible parts included the loop. Bending the tubing into a spiral- or a meander shape could be a solution.

EM loop vibration

The objective of this test is to verify the sustainability of the loop to vibrations during launch. The vibration tests were performed in three axes. High level sine in Z-direction reached the qualification level of 50 g. For the other axis preliminary attempts to reach 50g were made, but this level could not be achieved. The shaker stopped itself right before 35Hz. 43g, which was close to the limit of the shaker, was used for X- and Y-axis.

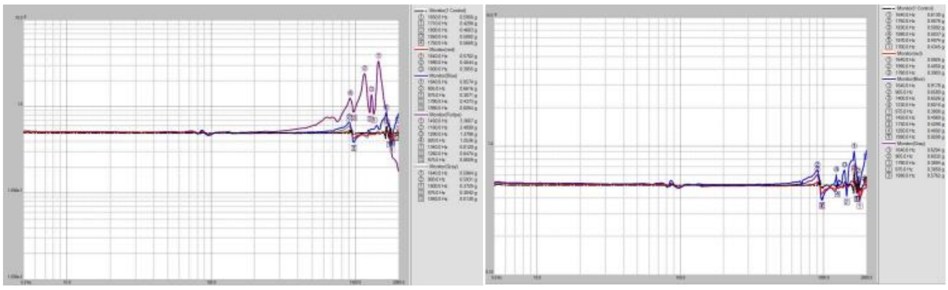


Figure 6 Sine pre high level sine (left) post high level sine (right)

The peak position deviations before and after the sine and random vibration tests are acceptable (less than 5%) and the leak test show no degradation. The functional test after vibration did not show any resonse and thus it cannot be concluded that the loop was not affected by the test or the handling since removal from the vaccum chamber.

Constructional analysis

The destructive physical analysis (DPA) of EM1 pump reveals poor connection between the electrical feedthrough and the wires connecting the electrodes. The EM1 pump stack is not as designed due to discharge damage and possible silver migration. The poor results of the EM1 functional tests could be attributed to the poor connection between the electrical feedthrough and the wire connecting the electrodes. The turning caused the EM2 pump stack to move inside the housing, which thus caused the electrical connection to break in two points. Target weld depth of the electrical feedthroughs are (0.3 mm, which is exceeded in all positions. The welds and the pump are as designed. The electrical connections were concluded mechanically intact until damaged by the DPA. A linear behaviour of both the capacitance and the flow rate as functions of number of pump stages indicates that there are no major peculiarities in the design for room temperature coolant.

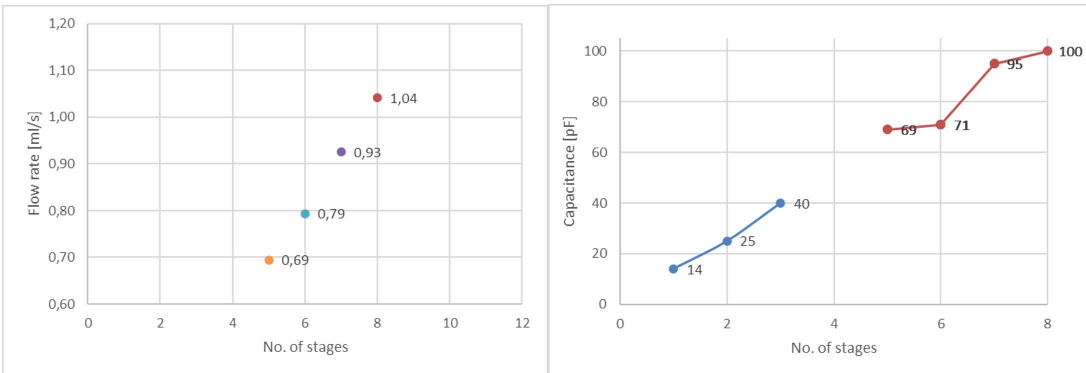


Figure 7 Flow rate (left) and Capacitance (right) dependent on number of pump stages of EM2 after test campaign, including DPA.

No fundamental error in the fabrication (short circuit or clogging, etc) of the pump can explain the poor pumping in LN. Thus, the pump stage(es) should be optimised for LN.

7. Concluding remarks

Lessons learnt

BBM1 had >10 times better performance than EM2. Known differences are not explaining the result. Leaks at connectors and electrical feedthroughs affect the vacuum sensor urge leak detection during operation and use of welded tubing and VCR fittings. Sensors and wires placement are important to reduce handling damage. Investigation of more suitable electrode configuration for pumping LN should be performed before entering a new loop test campaign since the impact of connections, electrode and stacking distances and lengths are not clarified in the current activity.

Table 2 Verification matrix

	HX Cooler	Pump (EM)	HX Detector	Full Loop	Pass/fail
Physical	x	EM1, EM2 BM1	x	x	pass
Initial char.		EM1			pass
Leak/MEOP	x	EM1, EM2	x	313K+77K	pass
Proof	x	EM1, EM2, BM1	x	313K+77K	pass
Fill				x	pass
OFF-performance				x	pass
ON-performance				x	low flow
Leak/MEOP				x	pass
Stiffness				x	too stiff
Vibration				x	pass
Performance test				x	fail
Leak/MEOP					pass
Burst		BM1			pass
Constructional		EM1, EM2			NA

Future work

To verify a functional EM loop, development of functional pump stages in LN open container, Table 3 and design changes to reduce handling damages to HW or test set-up should be implemented.

Table 3. Work plan for optimizing pump stages

Internal connections	Electrode thickness	Electrode geometry	Electrode spacing	Symmetry	Material
Cu-solder	~20μm	40% open area	50μm	asymmetric	Stainless steel
Pt-weld	~80μm	60% open area	100μm	symmetric	Platinum
Au-solder	~200μm	80% open area	150μm		Nickel
Cu, Pt, Au mechanical			500μm		
Verification in RT+LN	Verification in RT+LN	Verification in LN/Argon	Verification in LN/Argon	Verification in LN/Argon	Verification in LN/Argon

Technology Readiness Assessment (TRA) and TRL roadmap

A brief TRA RD 14 is performed. For TRL 5 the EHD cryo loop critical functions of the element are identified and verified in a relevant environment on non-full-scale breadboard(s). A representative model of the EHD cryo loop is defined in RD 8. An analytical model of the EHD loop performance has been defined to calculate the thermal behaviour, RD 9, experiment has been used for validation, RD 7, RD 13, and calculations are applied to extrapolate the performance to operational conditions, RD 9. Preliminary functional and performance requirements are targeting several missions but is only targeting FPA as applications, supporting TRL 5. The maturity of the loop is defined in relation to the operational conditions installed in an FPA on a EO satellite in GEO. Since a TRL can only be reached by an element if all of the sub-elements are at least at that same level, only TRL 4 is achieved, due to too low relevance of the thermal ON performance to be installed into an FPA.

The technology development roadmap after optimizing the pump stack for LN shows four different paths, with major development areas and timeline specified below:

1. LN-loop: casing mass reduction, HX application geometry optimization. Replacing fittings with orbital welds: 1.5 years
2. LAr-loop: optimizing the pump stack for LAr, casing mass reduction, HX application geometry optimization. Replacing fittings with orbital welds: 2 years
3. 2-phase loop: optimizing the pump for one-directional LN pumping, casing mass reduction, accumulator, condenser: 4 years
4. Thermal switch optimized for LN/Ar: To be combined with thermal straps, optimizing interfaces, optimizing casing for high pressure and low OFF conductance: 2 years.

Conclusions

Pumping of LN is achieved, but the response is too weak to be useful for FPAs. Loop- and pump testing after LN test campaign show good performance and no fundamental problem with the pump design for room temperature measurements. Fundamental testing to optimise the electrodes for LN pumping would be needed to productize the pump for cryogenic applications. Critical items and processes based on risk management of handling errors, electrode design and internal connections are identified for the next development steps. TRL assessment estimate that the loop would reach TRL 5-6 for HFE liquids, after verification and cycling in a wider temperature range. Within the current project TRL4 is reached for LN and LN with small amount oxygen (compressed air).