TUCA HEAT PIPE EXPERIMENT

Nadjara dos Santos
INPE- National Institute for Space Research
Av. Dos Astronautas, 1758. São José dos Campos-SP. Brazil.
Phone: 55 (12) 3208-6180
E-mail: nadjara.santos@inpe.br

[1]Valeri Vlassov, [2]Jorge Bertoldo Jr, [3]Gino Genaro, [4]José Batista Neto, [5]Geraldo Orlando Mendes, [6]Olga K-choukina, [7]Pedro Candido, [8]Rafael Lopes Costa, [9]Marcelo Petry.

E-mail: [1]valeri.vlassov@inpe.br, [2]jorge.bertoldo@inpe.br, [3]gino.genaro@inpe.br, [4]jose.neto@inpe.br,[5] geraldomo-nar@dmf.inpe.br, [6]kshukina@gmail.com, [7]pedro.candido@inpe.br, [8]rafael.costa@inpe.br, [9]marcelo.rodrigues@inpe.br

I. ABSTRACT

A heat pipe (HP) experiment named TUCA (acronyms for "Tubo de Calor", in Portuguese), to be probably flown on ITASAT University satellite is proposed. The experiment consists of an axially-grooved aluminum acetone-charged heat pipe positioned at the center of a spin-stabilized satellite along its spin axis. Two L-shaped saddles provide thermal coupling with the top and bottom satellite panels; the temperature difference between these two panels yields necessary driving gradient temperature for the HP operating. Special metallic plates at the HP interfaces (doublers) provide the HP input-output heat rates. High precision thermistors installed along the HP length allow the detection of any Non-Condensable Gases (NCG) blockage expansion. A developed SINDA/FLUINT Thermal Desktop® TUCA thermal model is used to predict the HP behavior under flight conditions and for elaboration of thermal vacuum tests specification.

II. INTRODUCTION

Heat pipes have been used in space missions since the 1970s due to its very high effective conductance and passive thermal control feature. The domination of this technology in Brazil is considered as an important strategic goal. As part of this development program, the research line for using alternative less hazardous and more ambient-friendly working fluids in heat pipes was approved by CNPq (Scientific National Council) to be conducted at INPE (National Institute for Space Research).

As the working fluid is in the saturation state, its evaporating temperature gradient over the vapor channel along HP length is nearly negligible. That happens not only due to small hydraulic loss between the condenser and evaporator zones, causing a small pressure difference between the two regions and therefore a small temperature difference, but also due to the local condition of thermodynamic equilibrium. Thus, the local conditions determine the balance for the phase change occurs[1].

There are three main elements that define a HP classification, as well as design, performance, range of application, manufacturing technology, verification and tests, safety restrictions. These elements are the material the container is made of, working fluid and porous structure.

It is important to note that some working fluids cannot be combined with certain materials. Such combinations are called incompatible pairs. The reason is that the incompatible pair can provoke with time some slow chemical reactions, whose products can be a Non-Condensable

Gas (NCG). NCG gradually blocks the vapor flow that in turn causes HP performance degradation and consequence failure. The basic compatibility matrixes are known; however the "rate" of the compatibility, particularly for Space applications, is still object of studies up to now for many pairs. As a final point, the "rate" of compatibility depends also on the technology of cleaning, HP charging and fluid purifications and finally defines the Operational Life of the HP.

Traditionally the Ammonia-Aluminum HPs are used for Space applications, because Ammonia has appropriate temperature range and high value of the Liquid Transport Factor. Other fluids had limited using; however their lack of performance can be compensated by special project of increased HP cross section. Other criteria can be also taken into account on working fluid choice, like vapor pressure, toxicity and danger[2]. It is always desired to find new potential working fluids that represent fewer hazards, be acceptable for civil aircraft transportation, and having lower costs for purification and charging. The search to substitute the so used high-saturated-pressure and toxic ammonia is related to reduce the hazard during the working fluid manipulation and operation. The selection of acetone also relies on its low freezing temperature (-93.15 °C), which is below the –78 °C for ammonia. As the purpose of assessing the application and development of heat pipes with alternative working fluids, INPE adopted a research program CONTER (PJHPACETONA) approved by CNPq (Scientific National Council) to be conducted at INPE (National Institute for Space Research), which includes the development of two phase technologies employing low-pressure and low hazardous working fluids.[3]

INPE is developing the R&D program called TUCA Experiment (TUbo de CAlor), which includes activities of design, construction, testing, qualification and certification of an acetone heat pipe device for use in satellite thermal control. The proposed TUCA experiment will be probably fly as a part of the ITASAT University satellite, that is currently been developed in cooperation with ITA (Technology Institute of Aeronautics, Brazil).

III. ACETONE JUSTIFICATION

Historically, when Heat Pipes (HPs) first were recognized in 1960’s as promising devices for Thermal Control in Space applications, Aluminum HPs with different fluids were developed and tested. The fluids were mainly Freons, Ammonia, Methanol, and Propylene[4]. Soon after the Al-Ammonia HP demonstrated greater heat transport capability, which allowed the fabrication of light HPs of a very small diameter (say about 10-18 mm), the technology was space-qualified and other technologies were reduced for special applications.

However the Ammonia is classified as a very toxic (up to fatal) and dangerous-to-ambient fluid having very high working pressure (9 atm abs at normal conditions of +25°C and about 23 atm at maximum equipment temperature of +55°C)[5]. The combination of high pressure and dangerousness requires special sealing technologies for leakage and burst preventing on qualification and operation, leading to rigid safety requirements during fabrication, ground testing and transportation[6].

Nowadays within overall general tendency of using more nature-friendly and low toxic fluids the use of ammonia looks questionable. Acetone in this way is a promising alternative because it is classified as a low toxic (not fatal) and biodegradable fluid. Having low operational pressure, below 1 atm up to +55°C, the acetone yields a notable feature: the outward acetone leakage is pretty impossible in normal atmosphere.

Finally, the reduced heat transport capability of the acetone HP versus ammonia can be easily compensated by selection the larger diameter HPs (about 20-30mm typically) for the same design conditions. In many applications, for example embedding in honeycomb panels, such large diameter tubes are quite desirable because they can provide higher area of thermal contact with the panel face sheets and fits better the panel thickness. Comparative is shown below in Table. 1.

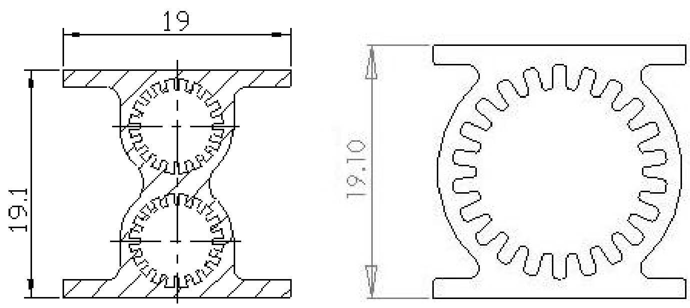
Table 1 – Comparative results between Ammonia and Acetone.

Fluid	Hazard to Health	Hazard to Ambient	Pressure T= +25 °C	MOP T= +55°C	MDP T= +120 °C
Ammonia	Very high (up to fatal)	Dangerous	9 atm	23 atm	100 atm
Acetone	Low toxic (not fatal)	Biodegraded	0.3 atm	1 atm	6 atm

The proposed HP profile was designed on size 19.1 mm to fit exactly the thickness of key honeycomb panels of CBERS3&4 satellites in the vision of possible applications in the next CBERS missions, as well as in other next Brazilian satellites. By interaction with about several firms who could extrude profile from Al alloy for heat pipes, the following cross-section profile drawing and technology tolerances were jointly elaborated and accepted by both sides, see Fig. 1.

The presented tolerances fit (with some extra requirements) the technical standards of the Brazilian Aluminum Extrusion Industry and at the same time attend thermal-hydraulic performance of the HP. The use of acetone requires a groove width of about 1.1 to 1.2 mm that is quite suitable for the technology, which has usual limit of about 1 mm of the lowest characteristic dimensions. At the same time it should be pointed out that for the ammonia HP the optimal groove width is about 0.4 to 0.5 mm, which is quite difficult to Brazilian Aluminum extrusion industry.

Fig. 1 (a) shows actual two-core ammonia HPs inserted in the honeycomb panel that could be substituted with our Al-acetone HP of Fig.1 (b) profile. The great advantage is that no honeycomb panel modifications are needed when installing the new HP.



(a) **(b)**

Figure 01- (a) Inserted ammonia HPs that can be substituted by (b) acetone HP.

The actual HPs, used in CBERS satellites, have two cores. In normal operation only one core performs the heat transfer while the other one serves mostly as a redundant channel. The theoretical maximal heat transport capacity of two HP profiles, shown in Fig 4a and 4b, have been evaluated used the canonical methodology presented by Ref. 7. The summary results in terms of maximal heat transport capacity QL, is shown in Table 2.

Table 2- Comparative results of QLmax for alternative Ammonia and Acetone HPs (Fig. 1).

HP profile	Fluid	HP mass per meter	QL max, Hot Case (T=+45°C)	QL max, Cold Case (T=-10°C)
Fig. 01 (a)	Ammonia, Dv= 6.5 mm	0.3 kg/m	92 Wm	130 Wm
Fig. 01 (b)	Acetone, Dv= 12.5 mm	0.4 kg/m	200 Wm	136 Wm

As can be seen in Table 2, the proposed acetone HP has superior heat transport capacity, especially for Hot Case, however the redundancy will not be provided and specific mass is about 25% higher than for ammonia HP. However such an acetone HP configuration could be directly used in the CBERS panels without any modification. The specified temperature operation range of acetone HP is -10 to +50 °C, which is quite appropriate for most of the on-board electronic equipment.

IV. ITASAT TUCA EXPERIMENT PROPOSAL

ITASAT is a scientific and technological spin-stabilized micro satellite, configured as a University satellite to be developed by ITA in cooperation with INPE. Its orbit will be a 600 km sun-synchronous and it is expected 1 year lifetime. The ITASAT initial configuration and its actual modified version are shown in Fig. 02.

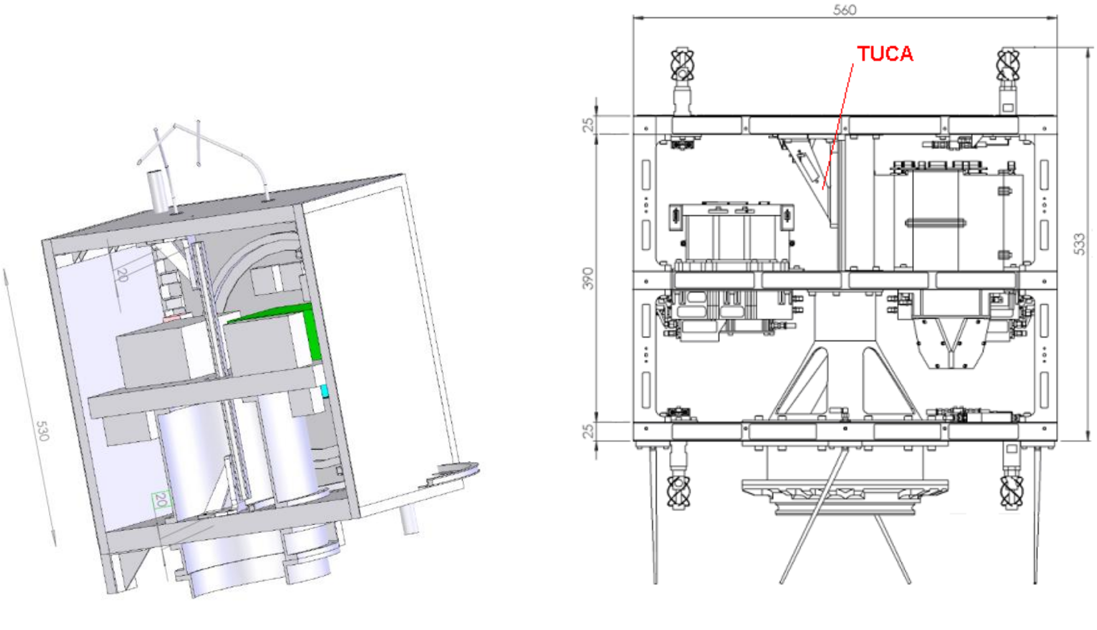


Figure 02- (a) The ITASAT initial configuration and (b) actual modified version.

TUCA experiment is a heat pipe thermally connected both to the upper and lower satellite panels through the aluminum saddles. The acetone HP is positioned in vertical position, parallel to the rotation axis of the satellite, at the centerline. The HP axis should be coinciding with satellite rotation axis as close as possible.

Such configuration provides conditions for HP operating without any electric heater once distinct absorbed external heat fluxes over the panels drives to temperature differences. The HP will operate in symmetrical mode, which means that there will not be any requirement related to the temperature of the button and upper panels. The idea is to use the boundary conditions, which naturally occur over the satellite orbit. Nevertheless, an electric heater will be also installed at one end of heat pipe to perform measurement when the temperature difference between panels is small and additional on-board electric power is available.

HP has never been used in spin-stabilized satellites. Several interesting situations could be explored within a spin mission like ITASAT, depending on the relative position between the satellite rotation axis and the HP axis. In the particular case of TUCA Experiment in the ITASAT satellite, the HP will be installed very close to the center of the satellite in such a way the HP axis coincides with satellite rotation axis (within ~3mm tolerance). In this case, the HP will operate in the so-named rotation-assist mode, when the centrifuge force helps the capillary force on the liquid phase return, so the overall HP heat transport capability can be slightly improved. Therefore, the TUCA Experiment at ITASAT will also prove a possibility to use the HP in a spin-stabilized satellite and will provide new and promising scientific data that has not been discovered before. The components of the TUCA experiment are described below.

V. TUCA EXPERIMENT COMPONENTS

The TUCA experiment with thermistors distribution is shown in Fig. 03. Each of two saddles shall be screwed to the satellite panel by 4 bolts. Thermal grease shall be applied between the saddle and panel to improve the thermal contact.

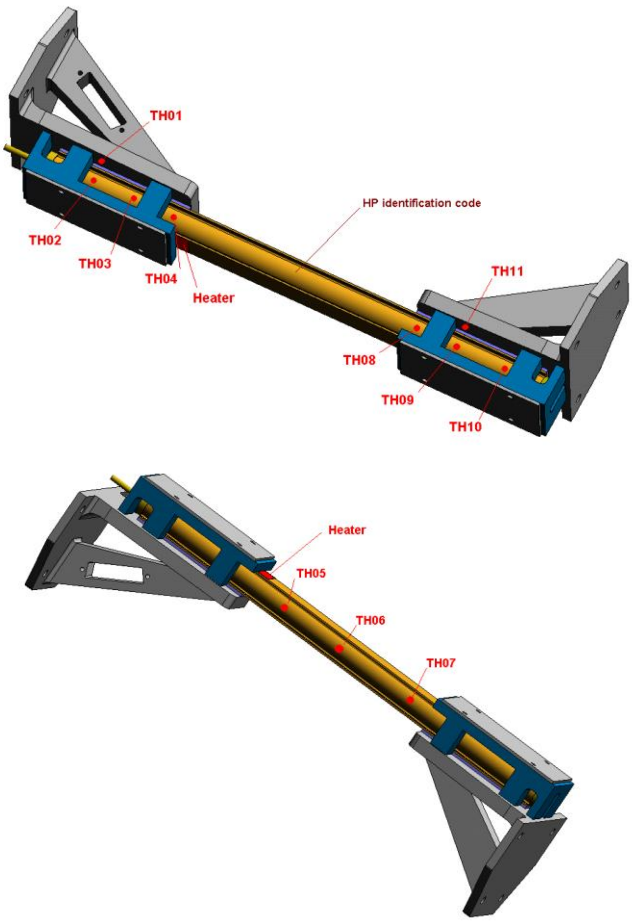


Figure 03- TUCA configuration (MLI and wiring are not shown).

It consists of the following main parts:
1 heat pipe;
2 aluminum saddles;
2 aluminum interface plates;
2 PTFE insulating clamps;
11 thermistors (with wiring);
DB-25 electrical connector;
Multi-layer insulation blanket (MLI).

The experiment is equipped with high-precision thermistors whose distribution is shown schematically in Fig. 03.

To provide the necessary precision of 0.1C, a special requirement has been established for digitalizing the analog signal from thermistors by at least 10 bits instead of usual 8 bits.

The HP is connected to the saddle through the thin interface plate, made of stainless steel. Such thin intermediate interface plate yields certain thermal resistance for heat flux coming to and from saddles to the heat pipe. The thermocouple position has been arranged by such a way that allows the measuring the temperature differences developed over these interface plates, from the saddles to the heat pipe. Through calibration during ground tests, considering the known thermal resistance of the interface plates, this temperature difference will provide values of HP input and output heat fluxes, following the same principle as a laboratory fluximeter.

When heater is switched-on, the additional heat load values to the HP are derived from the telemetry of electric current sensor, considering that the voltage of the power supply is a stabilized DC/DC converter.

The HP is fixed with two insulated supports which are screwed to the saddles, made by Teflon®. The thermistors are fixed to the HP and saddles with space qualified 3M™ Scotch-Weld™ Epoxy Adhesive 2216. Wires are fixed by adhesive Kapton® film and clamped to the electrical connector terminal. The connector is fixed in the saddle by two screws. All assembly is wrapped in 10-layered MLI made of 0.25 mil aluminized Mylar® film and Naylon® net as spacer, as shown in Fig. 04.

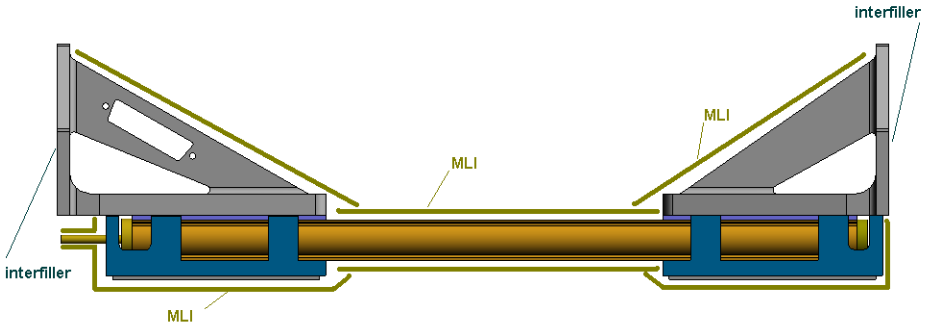


Fig.04- MLI installation scheme.

The total mass of the TUCA experiment measured as built with MLI is 1.49 kg. Electrical interface includes a space qualified DB-25 connector, for the thermistors (temperature sensors) signals and heater lines. One part of the connector is mechanically fixed at one of the HP saddles. Thermistor wires shall be crimped to this part of the connector. Conjugate part of the connector is soldered to the cabling that is considered as ITASAT component. The data acquiring system requires ITASAT 12 channels for thermistors reading, digitalizing, recording and transmission of the measurements.

VI. THERMAL MATHEMATICAL MODEL

The numerical simulation aims to reproduce the TUCA performance measured by the temperature profile in order to investigate hypotheses that explain this profile behavior. Fig. 05 shows the TMM built using the Thermal Desktop® SINDA/FLUINT software, where a temperature in the fixed interfaces 25°C and 15°C.

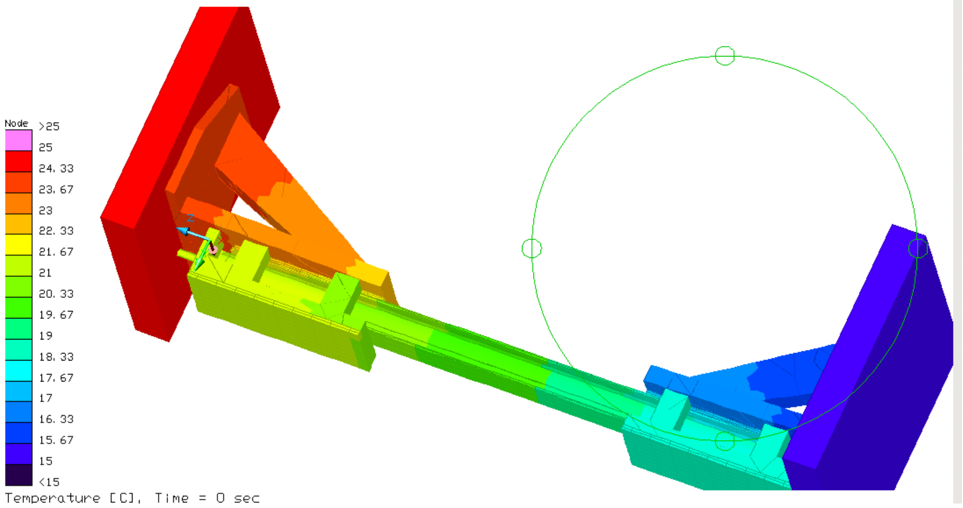


Figure 05- Numerical simulation model that reproduced TUCA experimental using Thermal Desktop® SINDA/FLUINT.

The TUCA model consists of 15 sub-models summarized 3854 nodes. The HP is simulated with 3 main parts: HP case, vapour channel as a high-conductivity artificial solid cylinder, and non-condensable gases blocked zone, simulated as a low-conductivity artificial solid cylinder. In the study of the behavior of the heat pipe simulation was performed to evaluate a possible generation of non-condensable gases (NGC), if it occurs during flight phase. Temperature maps for different situations of possible blockage are shown below in Figs. 6, 7 and 8.

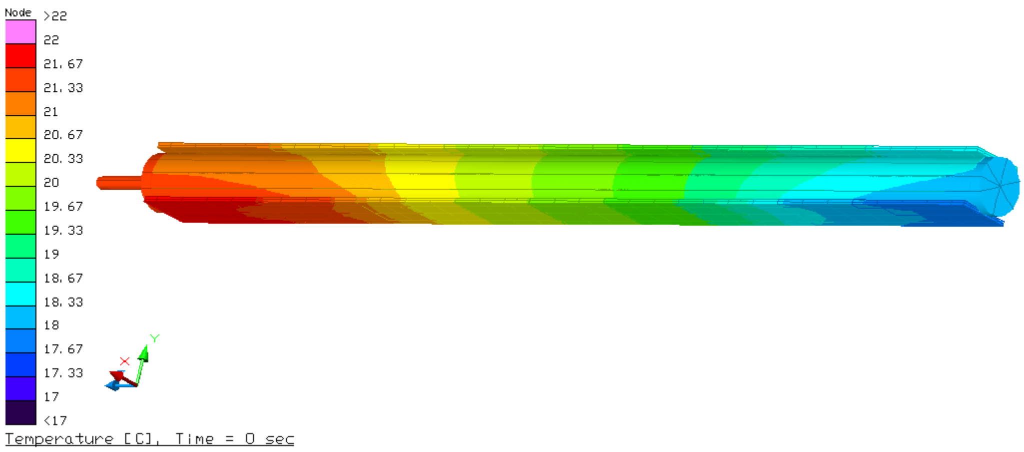


Figure 06- Possible generation of non-condensable gases, blocking with 1 cm in the condenser of the heat pipe.

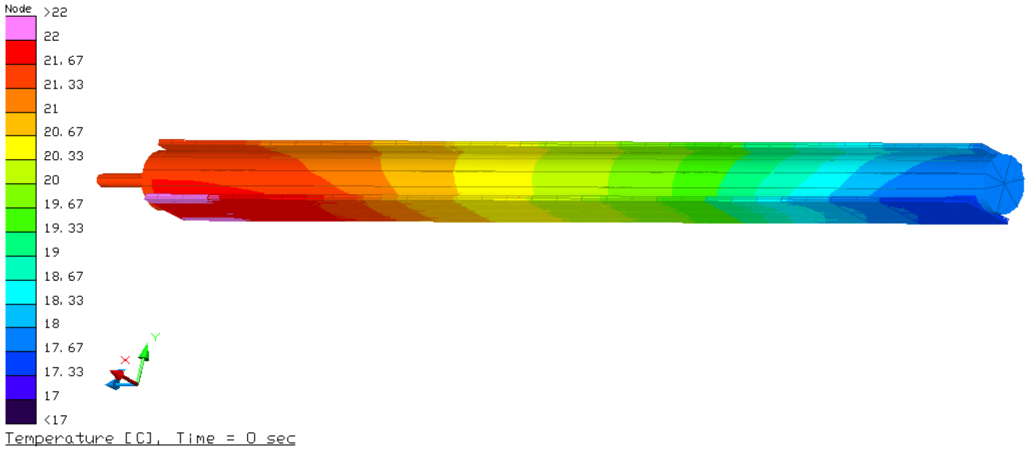


Figure 07- Possible generation of non-condensable gases, blocking with 5 cm in the condenser of the heat pipe.

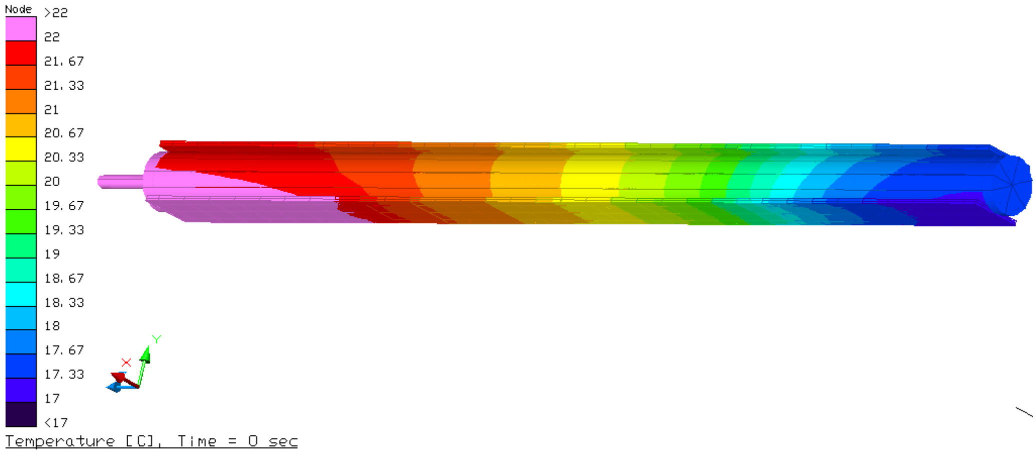


Figure 08- Possible generation of non-condensable gases, blocking with 10 cm in the condenser of the heat pipe.

Below is also presented some situations where simulated blocked the heat pipe zone, the temperature profile along the heat pipe temperatures in a position fixed saddles de 0 °C and 10 °C for the following cases: Fig. 09- normal functioning, Fig. 10- blocked with 2 cm, Fig. 11- blocked with 8 cm and Fig. 12- total failure.

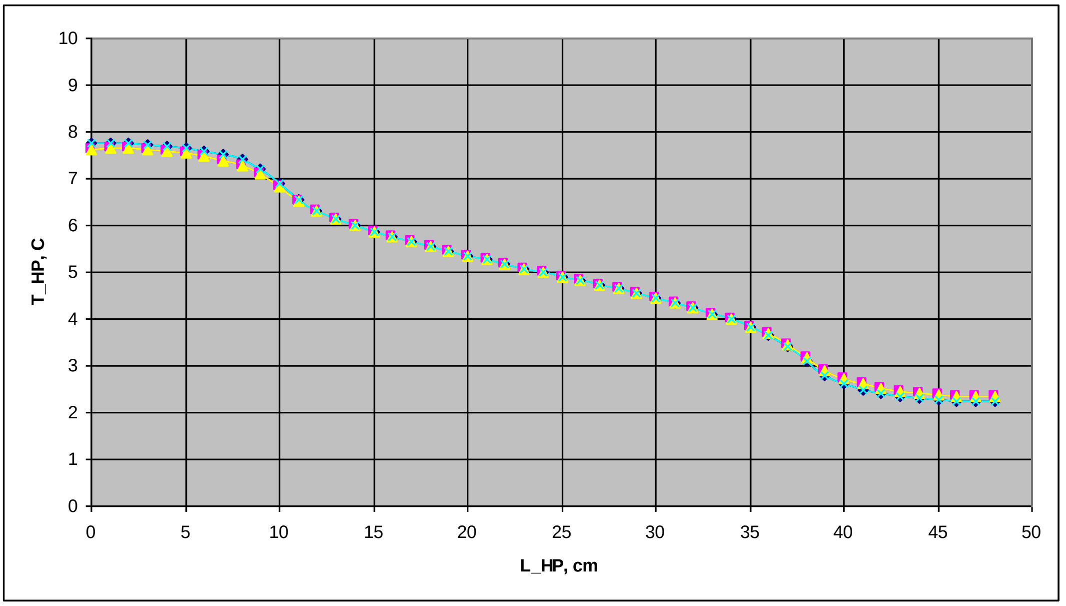


Figure 09- Theoretical temperature profile.

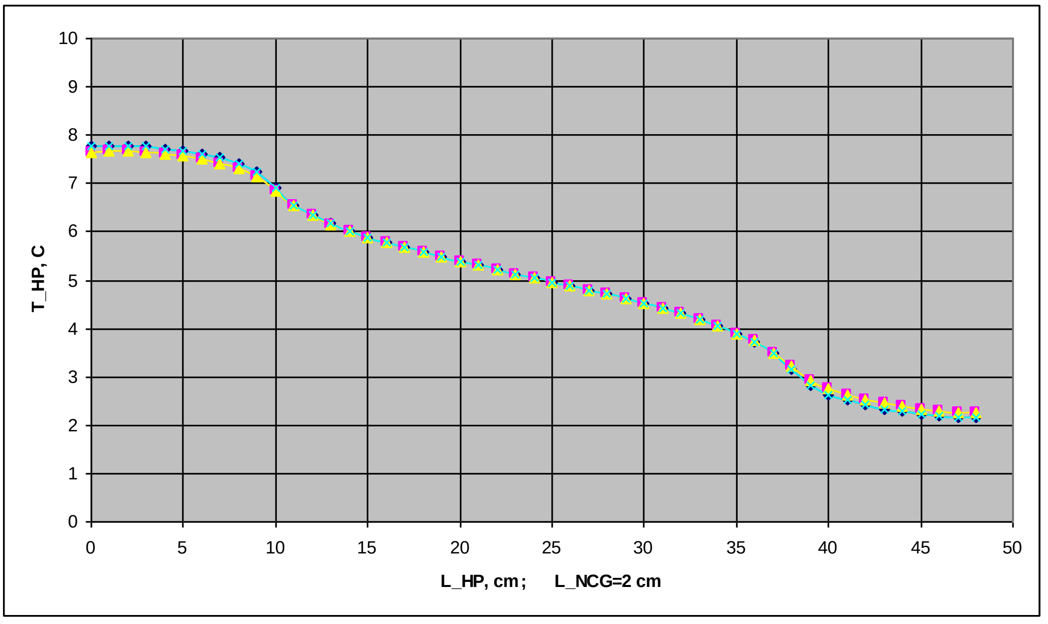


Figure 10- Theoretical temperature profile indicates a presence of non-condensable gases with 2 cm.

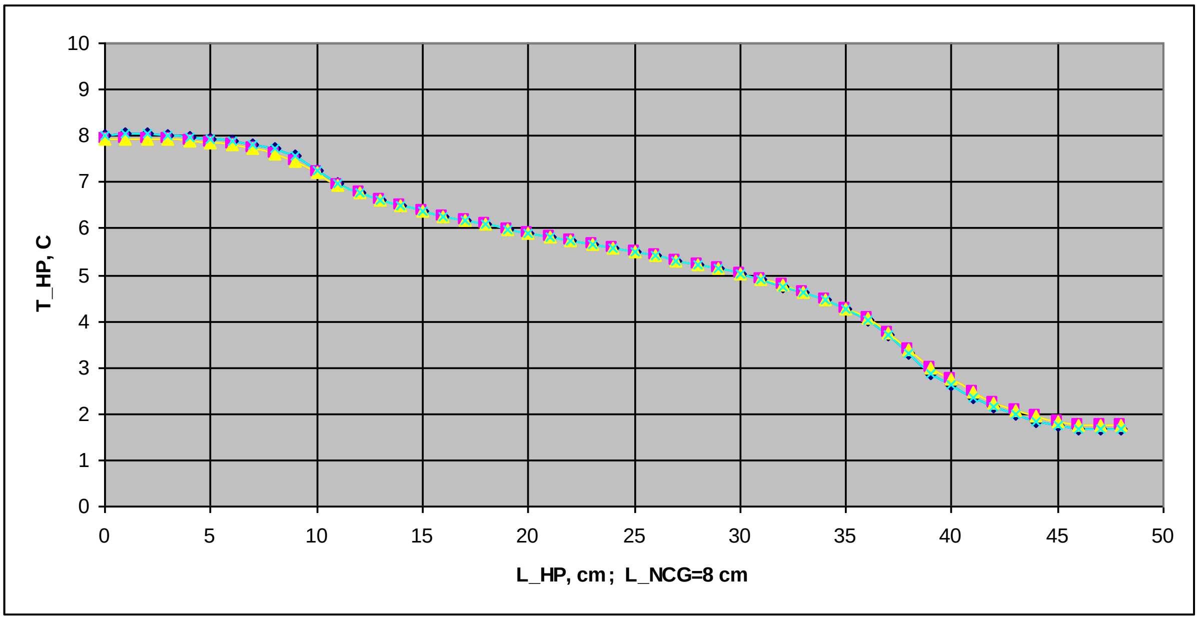


Figure 11- Theoretical temperature profile indicates a presence of non-condensable gases with 8 cm.

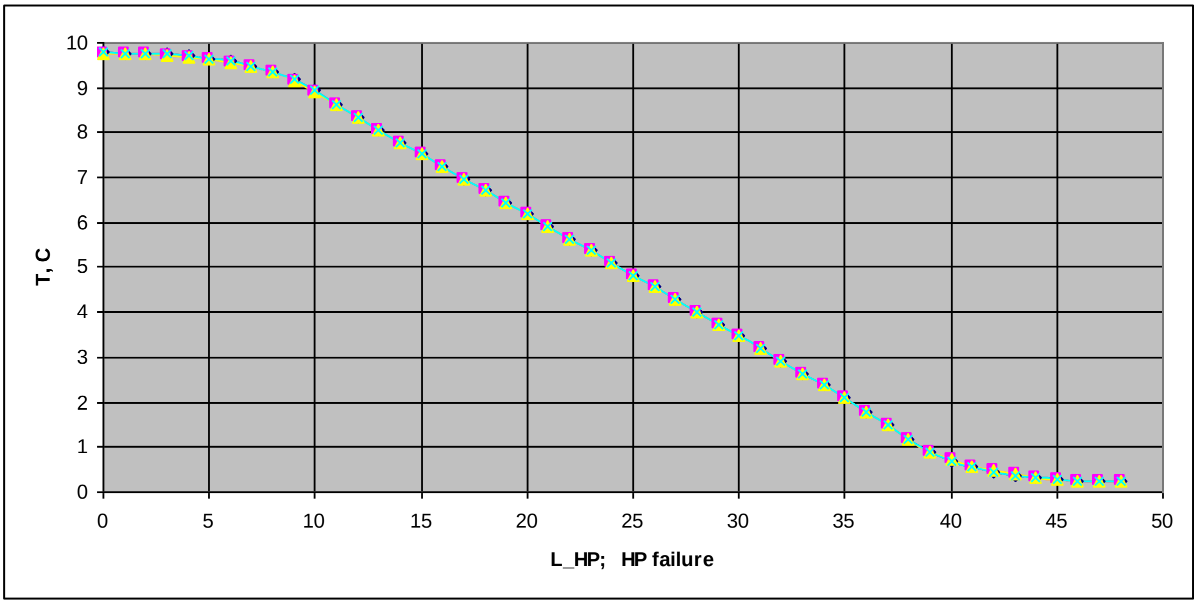


Figure 12- Simulate the profile temperature indicates a total HP failure.

Developed detailed the thermal mathematical model was able to predict the location of the barrier NCG that is enough to prove the viability of the experiment conception.

VII. DEVELOPMENT STATUS

TUCA HP successfully passed several steps of the qualification program. One of the steps is verification of purity of the acetone. This verification is confirmed by analysis by infrared spectroscopy made by Instrumental Analysis Laboratory (LAI- IR), Division of Chemistry (AQI) of the Ministry of Defense and the Air Force Command Institute of Aeronautics and Space (IAE)-CTA, in that acetone samples were tested by infrared analysis to check for the presence of contaminants. In neither case was observed the presence of contaminants in comparison with a sample of pure acetone without further use as it is shown in Fig 13.

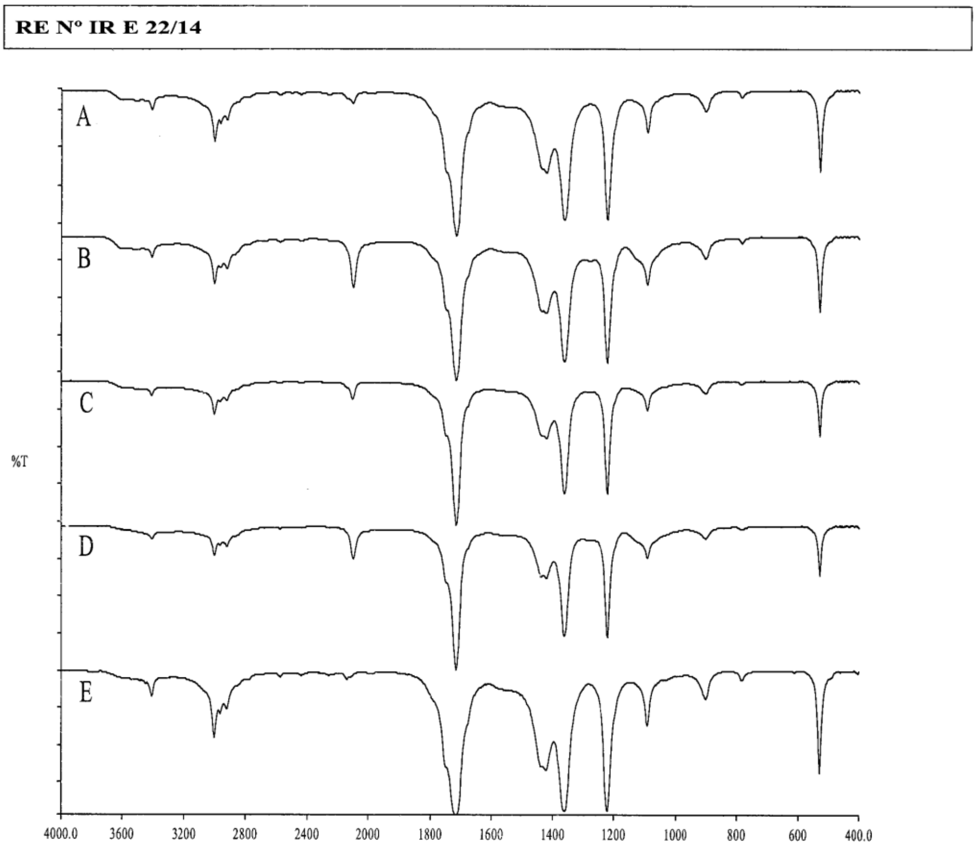


Figure 13- Analysis of contaminants from acetone IR.

Where:

A- Acetone- Lote 6061 85R- Tedia Brazil.
B- Acetone Sample 1- Lote 0145 AC.
C- Acetone Sample 2- Traceability: 0151 AC.
D- Acetone Sample 3- Traceability: 0147 AC.
E- Acetone PA Merck- Sample Files Spectrum- LAI- IR.

On the next step a refined analysis of the welding material and the welding quality were performed based on the analysis X-ray analysis. The Inspection was performed at the Laboratory of Tests-Coordination of quality Assurance and Space Reliability of the Ministry of Defense and Command aeronautical Institute of aeronautics and Space (IAE)-CTA. No any discontinuity was detected in the welded zone. The X-ray image of the sample is shown in Fig. 14.

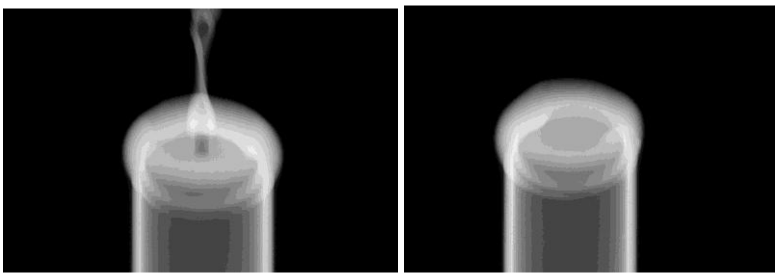


Figure 14- Sample image analysis of the x-ray heat pipe.

Actually, the TUCA experiment is completely assembled; using space-qualified materials, heater, films, temperature sensors, wires and connector, and it is passed through qualification environmental tests. Fig. 13 shows the TUCA experiment, covered with MLI blankets and installed on vibration test equipment.

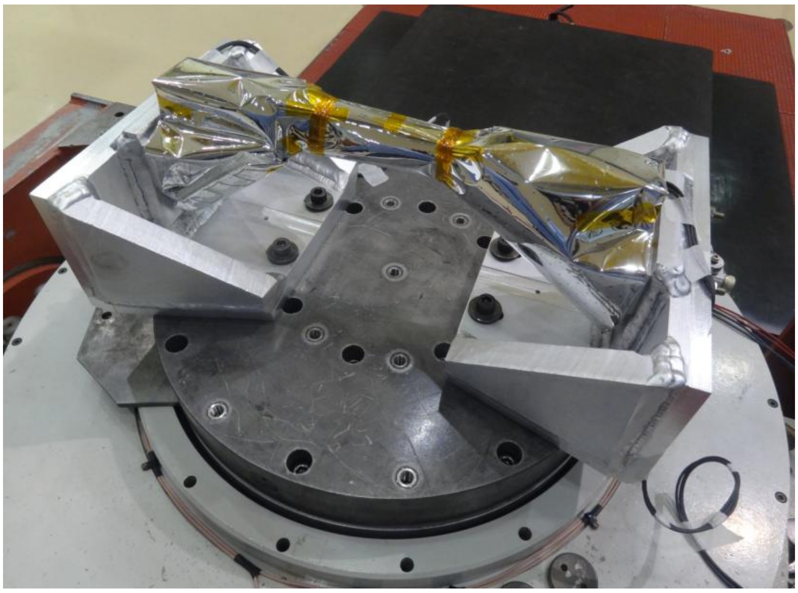


Figure 13- TUCA under vibration test.

Vibration test includes sinusoidal, random and shock tests, which were successfully passed in the test campaign of June 2014 at the protoflight level. Fig. 14 and Fig. 15 show the results of the shock test and random tests.

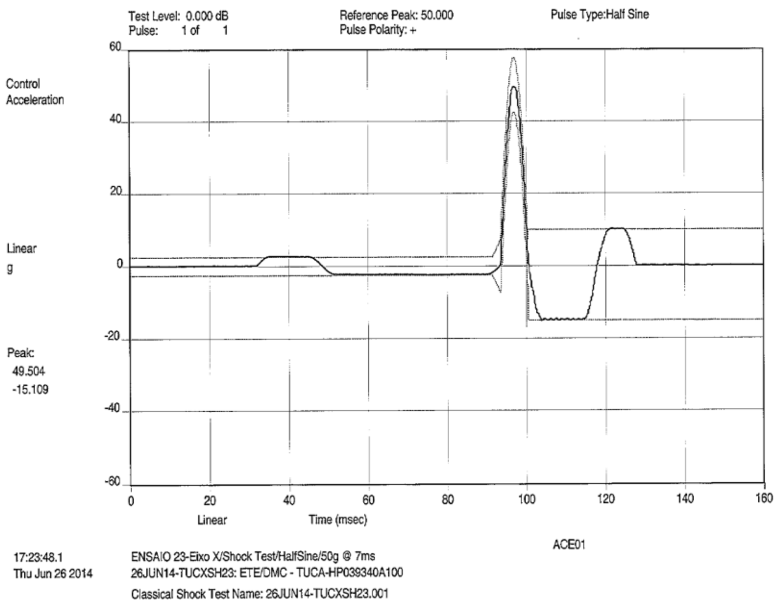


Figure 14- Shock vibration test on the X axis.

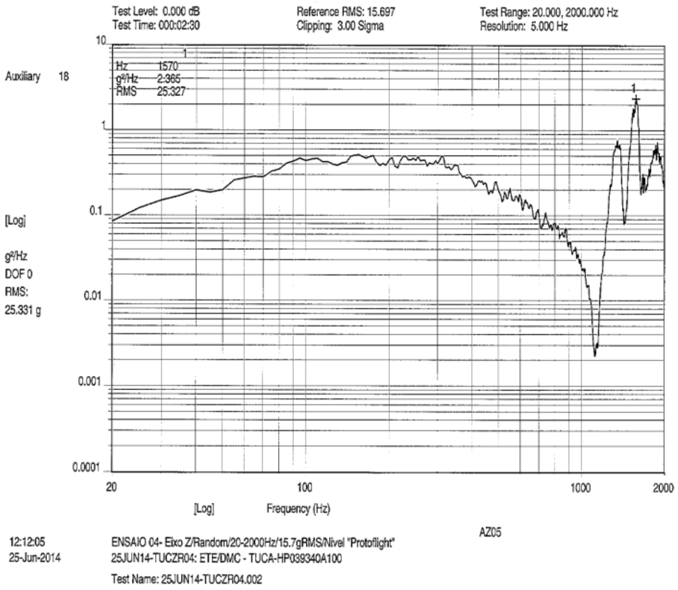


Figure 15- Random-vibration test on the Z axis.

In addition, a Life-test is running to prove long-time compatibility of acetone with Al profile, considering technologies of fabrication, purification, clearing and charging proceedings. Actually 2 years Life test did not show any signals of HP degradation.

VIII. CONCLUSION

TUCA is classified as a scientific and technological experiment, which includes activities of design, construction, testing, qualification and certification of an experimental heat pipe, as well as technological, once it encompasses the development of infrastructure and procedures to manufacturing and testing heat pipes to verify the performance of these devices for using in operational spacecrafts. The experiment will also bring particular data of possible acetone HP performance degradation during LEO mission if occurs. Besides these scientific and technological aspects, the project also creates opportunities for involvement of students and new university groups related to Brazilian space activities.

IX. ACKNOWLEDGMENTS

The authors would like to acknowledge the INPE´s engineers and technicians who were directly and indirectly involved in fabrication and testing realization, particularly Marcos Boato, Roberto Marino, Homero de Sousa, Laercio Siqueira among others as well as LIT team (Laboratory of Integration and Testing). Also we like to acknowledge the support of CNPq organization, Brazil, through Research Project 560092/2010-5, Edital MCT/CNPq/AEB 33/2010, approved by Brazilian Space Agency.

X. NOMENCLATURE

MOP- Maximum Operation Pressure

MDP- Maximum Design Pressure

XI. REFERENCES

Books

[1]Peterson, G.P., “An Introduction to Heat Pipes”, John Wiley & Sons, 1994.
[6]Faghri, A. Heat pipe science and technology. Taylor & Francis, London (1995).
[7]Chi, S. W. Heat pipe theory and practice. McGraw-Hill Book Company, London, 1976.

Periodicals

[5]Swanson, T. D., Overview of Thermal Control Research at Goddard Space Flight Center, International Two-Phase Thermal Control Workshop, Laurel, MD, Sept. 19-21 2006.
[3]Vlassov, V. V. Analysis of Heat Spreading Performance of Acetone-Filled Heat Pipe at Low Temperatures for using in Satellite Honeycomb Panels. Journal of Aerospace Engineering, Sciences and Applications, 1, p. 1 – 17, 2008.

Reports, Theses, and Individual Papers

[2]ESA PSS-49, Issues 1&2. Heat Pipes Qualification Requirements, March 1983.
[4]ECSS-E-ST-31-02C. Space engineering. Two-phase heat transport equipment. 12 December 2012.