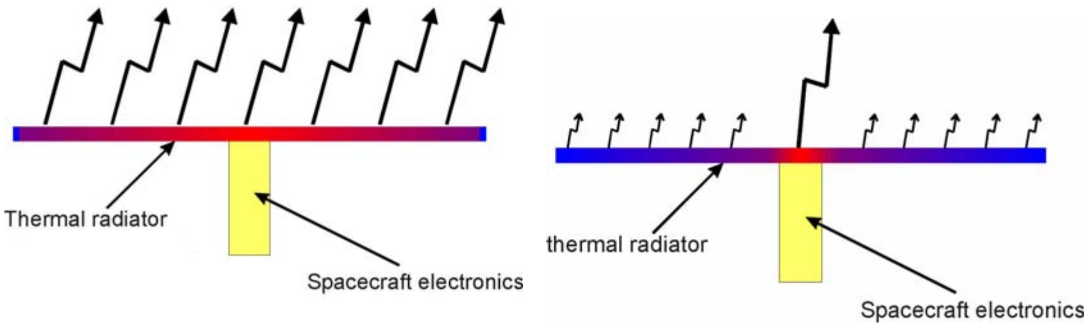
Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Executive summary

The Variable Effective Surface Radiator

Novel Heat Switch Technology based on the Oscillating Heat Pipe principle



Problem area
Space based electronics are subjected to very hostile thermal environment. The VARES is able to protect the electronics against the very low temperatures through its very high insulation properties in none operational mode. While in operational model and high temperatures the VARES is able to keep the electronic temperature controlled through its relatively high conductivity.
The VARES project is performed for in the framework of the European Space Agency's AURORA-program. The AURORA-program aims to develop new technologies required for the future deep space exploration. The VARES-technology is developed to be a lightweight alternative for thermal switches on Martian Rovers.

Description of work
The VARiable Effective Surface Radiator (VARES) is a heat switch based on the Oscillating Heat Pipe (OHP) principle. In general all power consuming space objects need radiator surface to radiate surplus of heat. However when switched off the power dissipating objects (electronics) will decrease to unacceptable low temperatures present in space. To overcome this design challenge, several solutions are available such as paraffin heat switches, thermal louvers, and loop heat pipes. Objective of all is to isolate the electronics from the radiator (low temperatures) when switched off. The work described in this paper is performed at NLR on the development of the VARES-radiator for application in spacecraft thermal control systems. The VARES makes use of the property of oscillating heat pipes whereby at low temperatures the oscillation process stops. Therefore it is in

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Author(s)
M. Bsibsi
G. van Donk
A. Pauw
J. van Es

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principle possible to vary the effective radiator area and thus the power dissipation to the environment. The work presented contains an explanation of the principle of operation in hot and cold conditions, descriptions of performed tests, and VARES breadboards test results. Further it describes design improvements to start the VARES after long cold periods. It is demonstrated that with the right choice of variables (Working fluid and fill charge) an OHP can be used as a heat switch in space applications.

Results and conclusions
It is demonstrated that the Oscillating Heat Pipe principle can be used to design a heat switch. VARES is able to control the heat transport between a heat dissipating element and a radiator.

Breadboard experiments show a conductivity turndown ratio of 1:27. It is foreseen possible to increase the turndown ratio to 1:95 by simple design changes.
Experiments demonstrated the oscillating behavior of the VARES radiator is stopped at a temperature of 15 °C at the dissipating side (spacecraft electronics) of the switch.

It has been experimentally demonstrated that the oscillating behavior of the VARES radiator is stopped when the temperature of the brass mass (spacecraft electronics) drops below +15 °C. The VARES radiator shows successful start-up without deployment of the start-up reservoirs after short cold periods and is able to reject 40 Watt power to a shroud (simulating deep space temperature). Resulting in a power turndown ratio of 1:8 (Off-mode: 5 Watt, On-mode: 40 Watt). With the above described design improvement a power turndown ratio of 1:40 is feasible.
During tests start-up failures were detected after long cold periods. It is experimentally shown that these start-up failures were caused by un-favorable liquid/vapor distribution in the OHP tubing. Small reservoirs and reservoir heaters have been implemented in the design to re-distribute the liquid and vapor prior to start-up. It is shown that the reservoir heaters are able to shift the liquid to evaporator side and the vapor to the condenser side.
Reservoir start-up tests showed repeated successful start-ups after long cold periods. Further research will be focused on reducing the start-up heater power, design optimization of the start-up sequence and reducing the conductive link in off mode to realize the expected power and conductivity turndown ratio's.

Applicability
Martian Rover and Deep Space Cruiser thermal control, Oscillating Heat Pipes

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The Variable Effective Surface Radiator

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M. Bsibsi, G. van Donk, A. Pauw and J. van Es

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Summary

This paper describes a novel mechanism for heat switch applications in space. The VARiable Effective Surface Radiator (VARES) is a heat switch based on the Oscillating Heat Pipe (OHP) principle. In general all power consuming space objects need radiator surface to radiate surplus of heat. However when switched off the power dissipating objects (electronics) will decrease to unacceptable low temperatures present in space. To overcome this design challenge, several solutions are available such as paraffin heat switches, thermal louvers, and loop heat pipes. Objective of all is to isolate the electronics from the radiator (low temperatures) when switched off. The work described in this paper is performed at NLR on the development of the VARES-radiator for application in spacecraft thermal control systems. The VARES makes use of the property of oscillating heat pipes whereby at low temperatures the oscillation process stops. Therefore it is in principle possible to vary the effective radiator area and thus the power dissipation to the environment. The work presented contains an explanation of the principle of operation in hot and cold conditions, descriptions of performed tests, and VARES breadboards test results. Further it describes design improvements to start the VARES after long cold periods. It is demonstrated that with the right choice of variables (Working fluid and fill charge) an OHP can be used as a heat switch in space applications.

Contents

Abbreviations

CFRP	Carbon Fibre Reinforced Plastic
ESA	European Space Agency
HS	Heat Switch
MLI	Multi-Layer Insulation
NLR	National Aerospace Laboratory
OHP	Oscillating Heat Pipe
VARES	VARiable Effective Surface Radiator

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1 Introduction

This paper describes a novel mechanism for heat switch applications in space. The VARiable Effective Surface Radiator (VARES) is a heat switch based on the Oscillating Heat Pipe (OHP) principle. In general all power consuming space objects need radiator surface to radiate surplus of heat. However when switched off the power dissipating objects (electronics) will decrease to unacceptable low temperatures present in space. To overcome this design challenge, several solutions are available such as paraffin heat switches, thermal louvers, and loop heat pipes. Objective of all is to isolate the electronics from the radiator (low temperatures) when switched off. The work described in this paper is performed at NLR on the development of the VARES-radiator for application in spacecraft thermal control systems. The VARES makes use of the property of oscillating heat pipes whereby at low temperatures the oscillation process stops. Therefore it is in principle possible to vary the effective radiator area and thus the power dissipation to the environment. The work presented contains an explanation of the principle of operation in hot and cold conditions, descriptions of performed tests, and VARES breadboards test results. Further it describes design improvements to start the VARES after long cold periods. It is demonstrated that with the right choice of variables (Working fluid and fill charge) an OHP can be used as a heat switch in space applications.

2 Switching principle

The basis of the VARES is the on/off switching of an OHP in respectively hot and cold conditions. The OHP-principle of operation is described in detail in literature [1, 2, and 3]. The OHP-operation relies on the oscillating of vapor slugs and liquid plugs in a capillary pipe. Heat is therefore transported from the hot to the cold side mainly by the sensible heat of the liquid. The oscillating movement is induced by evaporation of liquid in the system. The switch uses the difference in heat transfer between an oscillating system and a static system. The switching is achieved by making use of a change in the slope of the DP/DT-curve (see Figure 1). A large declivity indicates a large pressure difference per temperature step and therefore large pumping power. A small declivity decreases the induced pressure at evaporation and will reduce the pumping capabilities of the OHP. If the induced pumping “power” decreases below the pressure required to keep the fluid in movement the principle stops and the heat exchange is stopped. In Figure 1 the P-T diagram of some typical working fluids is shown. The figure shows that the DP/DT-curve flattens with decreasing temperature. Therefore a switching point (to non-operation) of the OHP-mechanism can be expected. This switching behavior is the key element of the VARES-radiator.

2.1 Operation in hot conditions

The operation region of the hot conditions in the P-T-diagram is seen at the right of Figure 1. In hot conditions the heat dissipated by the electronics is spread from the centre of the radiator over the complete radiator area.

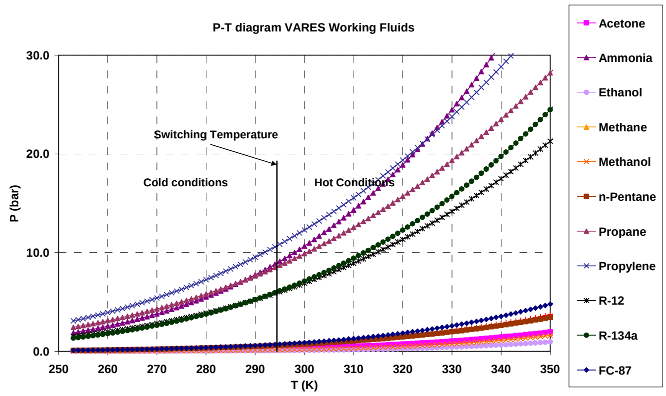

Figure 1: P-T diagrams for several working fluids.

2.2 Operation in hot conditions
The operation region of the hot conditions in the P-T-diagram is seen at the right of Figure 1. In hot conditions the heat dissipated by the electronics is spread from the centre of the radiator over the complete radiator area.

2.3 Operation in cold conditions
When not sufficient pressure differential in the system is produced by both, expanding bubbles in the evaporator and contracting bubbles in the condenser the oscillating motion stops. The operation region in cold condition is seen at the left of Figure 1. Due to the flattening of the DP/DT-curve at low temperature, the OHP-principle is not working and therefore no heat is transported by the fluid oscillations in the meandering capillary tube. A non-conductive radiator material like CFRP (Carbon Fibre Reinforced Plastic) does further reduce the heat spreading. By using such a low thermal conductive material, only a small part of the radiator will stay at the temperature of the spacecraft body. The rest will significantly decrease to a temperature close to the deep space temperature. Hence the heat transfer to deep space will be very small.

3 Experimental set-up

In order to test the feasibility of the above introduced heat switch, a VARES breadboard was developed and tested. The objective of the tests was twofold. Firstly to show the operation of an OHP in a radiator configuration. Secondly to show the feasibility of the thermal switching of the VARES. The VARES-radiator is placed in the NLR Thermal Vacuum Space Simulator, seen in Figure 2, (ø 0.9 m, L =1.5 m) and views the gaseous nitrogen cooled shroud of the space simulator. The shroud can simulate a whole range of environmental temperatures - 150°C to + 145°C. For the VARES breadboard tests environmental (shroud) temperatures between +20 °C and -100 °C were used to avoid freezing of the working fluid.

Figure 2: NLR Thermal Vacuum Space Simulator.

In Figure 3 a schematic drawing is seen of the VARES Radiator located in the Space Vacuum Chamber.

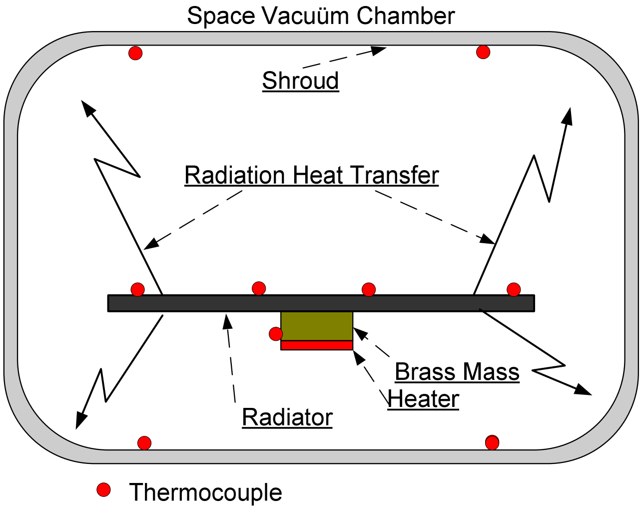

Figure 3: Test set-up schematic (VARES Radiator in the Space Vacuum Chamber)

In Figure 4 a more detailed schematic the VARES radiator is shown. The heater simulating the spacecraft electronics is fixed to the bottom side of the brass mass, and the OHP tubing is soldered on top of the brass mass.

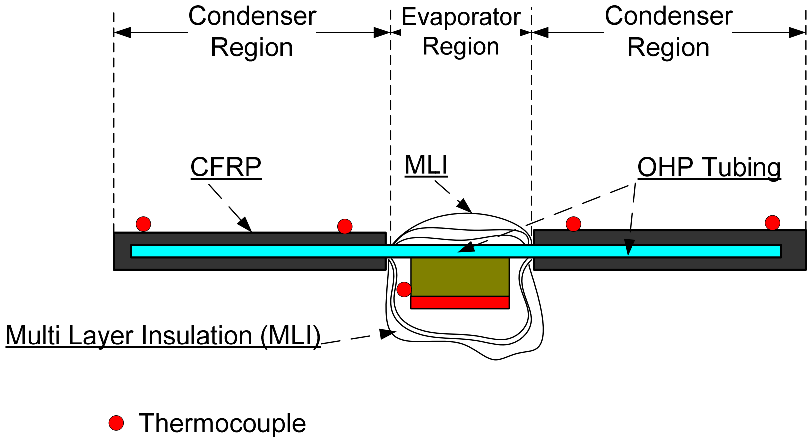

Figure 4: Test set-up schematic (VARES Radiator)

Multi Layer Insulation (MLI) is placed around the heater, brass mass and the OHP tubing on top of the brass mass as seen in Figure 4.

4 Vares radiator breadboard

The VARES breadboard is shown in Figure 5. The breadboard consists of three main elements:

- An insulated brass blocks simulating the spacecraft internals with dissipating electronics.
- A CFRP-radiator with an unobstructed view to the environment.
- A VARES-system (OHP Tube) connecting the brass block to the radiator.

The VARES-system is a closed loop OHP with the following design specifications:

- A meandering stainless capillary steel tube with D_i = 1.6 mm, D_o = 2.0 mm and a total tubing length of 607 cm. The VARES has a total loop volume of 12.2 ml.
- Acetone is used as working fluid. The VARES radiator is filled with a filling ratio of 70 % defined as the net liquid volume divided by the total inside volume of the pipe. A vacuum/charging system is used to vacuum the VARES tubing and to charge a controlled amount of liquid into the tubing.
- The OHP has a soldered connection to the brass block. The connection to the radiator is made by embedding the OHP tubes in the Carbon Fibre Reinforced Plastic (CFRP) radiator consisting of four layers. CFRP is chosen because of the low conductivity, ensuring insulation and low heat leak in off-mode.
- For special start-up testing two reservoirs (containing only liquid) are placed at each end of the loop having a volume of 5 ml each. The reservoirs are equipped with heaters which can be separately controlled. The design and working principles of the start-up reservoirs will be outlined in section “Start-up from cold condition, problem description and start-up design”

  The breadboard has the following characteristics:

- A total height of 260 mm, a width of 300 mm resulting in a total radiator area of 0.16 m^2.

- The spacecraft electronics are simulated by heaters on the brass mass (25*25*300 mm) as seen in the center of Figure 5 (yellow metal).
- The heaters can dissipate in a range of 0 to 40 Watt.
- To minimize heat loss of the electronics (heaters and brass) by radiation, the heaters and brass mass are shielded by Multi-Layer Insulation (MLI) as shown schematically in Figure 4.

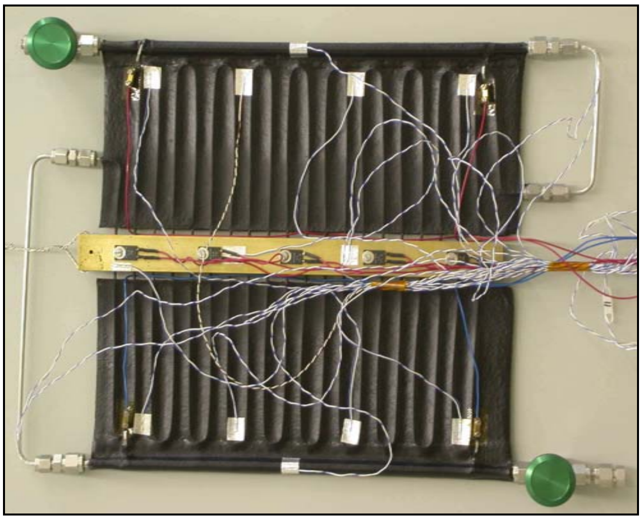

Figure 5: VARES-radiator breadboard

In order to measure the performance of the VARES radiator, a total of 18 thermocouple wires are attached to the brass, radiator surface and the shroud. The locations of the thermocouples are shown in Figure 6.

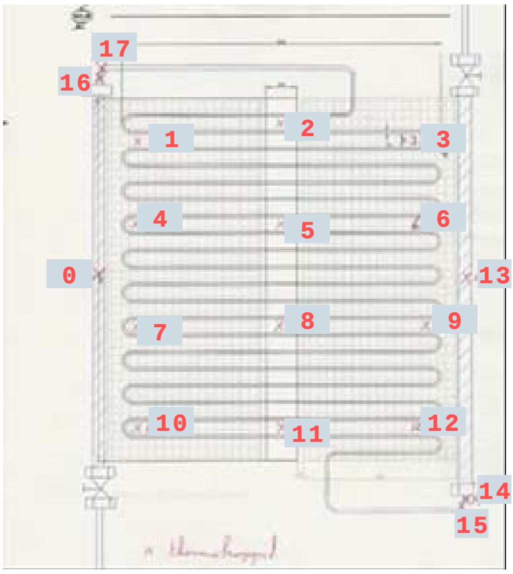

Figure 6: VARES breadboard Thermocouples Locations

During breadboard operation the heat applied to the brass mass is transported through conduction to the soldered connection of the VARES OHP tubing. Subsequently the heat is distributed over the radiator surface by the oscillating heat pipe. The heat is then transferred from the radiator surface to the cold shroud (simulating deep space) through radiation.

TEST SEQUENCE

The tests are performed in the following sequence:

1. Switching from on-mode to off-mode.
2. Performance measurement in off-mode.
3. Switching on after a short cold period
4. Performance measurement in on-mode.
5. Switching on after a long cold period.

The tests are performed at two shroud temperatures: T_{shroud}=-80°C and -100 °C.

5 Initial vares-breadoard test results

The main objective of the initial tests is to show heat switch operation in a realistic situation. The first test (switching from on-mode into off-mode), is achieved by switching off the brass mass heaters, simulating switch-off of the heat dissipating electronics.
The second test performed is switching the VARES radiator from off-mode into on-mode, which is achieved by switching the 40 W brass heaters back on after a short switch off period.

5.1 Switch-Off from operating mode

The switching off of the VARES radiator is demonstrated under the following conditions:

- Shroud temperature: -100 °C, -80 °C
- Dissipated power: 40 Watt

The results are presented in Figure 7, in which the spacecraft body, radiator tip and shroud temperatures are plotted. During high temperature operation (left part of the graphic) the radiator temperatures are oscillating between 0 ºC and 25 ºC. The OHP oscillatory behavior is working properly inside the tubing embedded in the radiator. The low scatter in radiator temperatures shows the complete radiator area is used effectively.

As measure for the performance of the VARES radiator the Conductive Link (G_L) is used, defined as:

$$G_L = \frac{Power}{T_{brassmass} - T_{radiator}} \ldots\ldots\ldots\ldots\ldots \left[\frac{W}{K}\right]$$

Where:

- Power: Dissipated power of the brass mass heater.
- $T_{brass\ mass}$: The mean brass mass temperature,
- $T_{radiator}$: The mean radiator temperature.

The performance in on-mode is summarized in the following table:

Test	Power dissipated [Watt]	$T_{radiator}$ [°C]	$T_{brass\ mass}$ [°C]	Conductive Link [W/K]
On-mode	40	18.04	40.2	1.92

Table 1: VARES performance in on-mode.

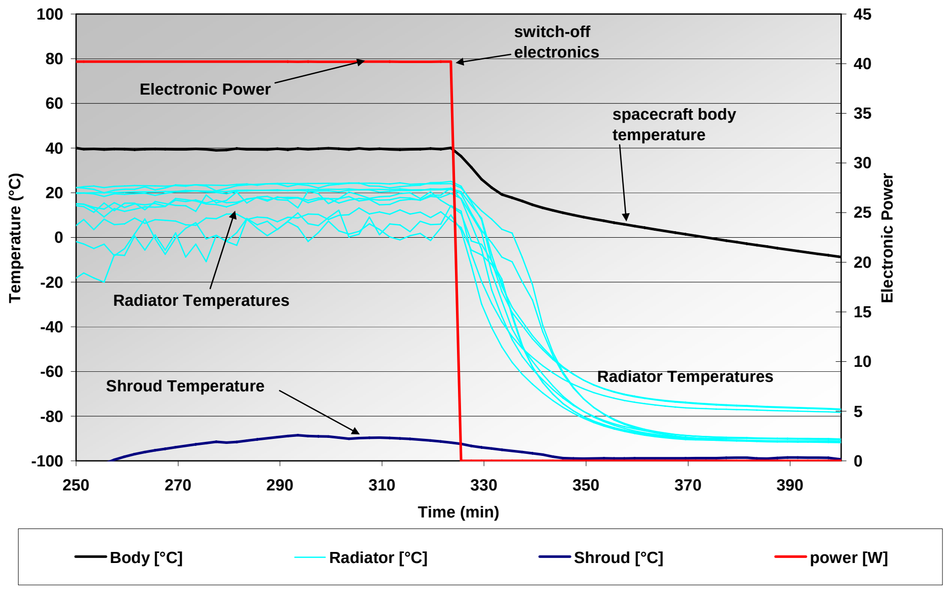

Figure 7: VARES Radiator switch off test result.

In Figure 7 a switched cylce is shown. After switch-off the temperature of the spacecraft body drops rapidly to 15°C. At this point the OHP-principle stops functioning, resulting in a sudden drop of temperature of the tip and intermediate radiator. After switch-off heat is only transported by conduction through the base material (CFRP and embedded tubes). The heat transfer to deep space is therefore decreased, visible in the deflection in the temperature decrease of the body.
It is demonstrated that the VARES-radiator switches from a high heat flux to a low heat flux mode at a brass mass temperature of around 15 °C.

SWITCH-ON FROM NON-OPERATING MODE AFTER SHORT COLD PERIOD

The radiator was placed in the vacuum chamber with an initial shroud temperature of -80 °C. Performance test in off-mode is done before switching the VARES radiator. This is seen in on left side of Figure 8 (Time<5 min). In this test the brass, simulating the spacecraft electronics, was kept on 0 °C temperature. This balance was achieved by 5 Watt heating power. The

VARES Radiator exhibits a conductive link in off-mode of 0.072 [W/K]:

Test	Power dissipated [Watt]	$T_{radiator}$ [°C]	$T_{brass\ mass}$ [°C]	Conductive Link [W/K]
Off-mode	5.32	-73.2	0.07	0.072

Table 2: VARES performance in off-mode.

At Time=5 min the brass mass heater is switched from 5 Watt to 40 Watt, this is seen on the left side of Figure 8. The VARES starts up with and heats radiator to an 10 °C average temperature. The oscillatory behavior of the VARES radiator is also clearly seen. The spacecraft body temperature finally stabilizes around 34 °C.

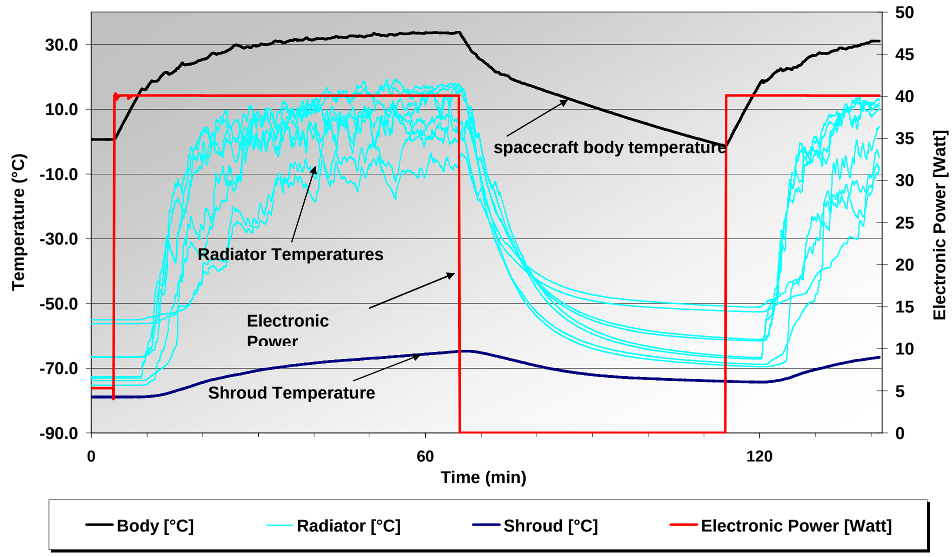

Figure 8: VARES Radiator switch on test result.

The thermal performances for the off- and on-mode are summarized in the following table:

Test	Power dissipated [Watt]	$T_{radiator}$ [°C]	$T_{brass\ mass}$ [°C]	Conductive Link [W/K]
Off-mode	5.32	-73.2	0.07	0.072
On-mode	40.1	12.9	33.7	1.91

Table 3: VARES performance in off- and on-mode (after short cold period)

The conductivity (turndown) ratio (0.072:1.91=1:27) between on- and of mode is a measure for the overall performance of the VARES radiator as a heat switch. This conductivity turndown ratio can easily be improved by reducing the conductive link in off-mode. Back-of-envelope calculations show that a conductivity in off-mode of 0.02 [W/K] is easily achievable, resulting in theoretical conductivity turndown ratio of (1:95). The reduction in the off-mode conductivity is possible by positioning the heat-dissipating element at a longer (conductive) distance and better insulated from the radiator and not directly attached at the radiator surface as seen in ***Figure*** 9.

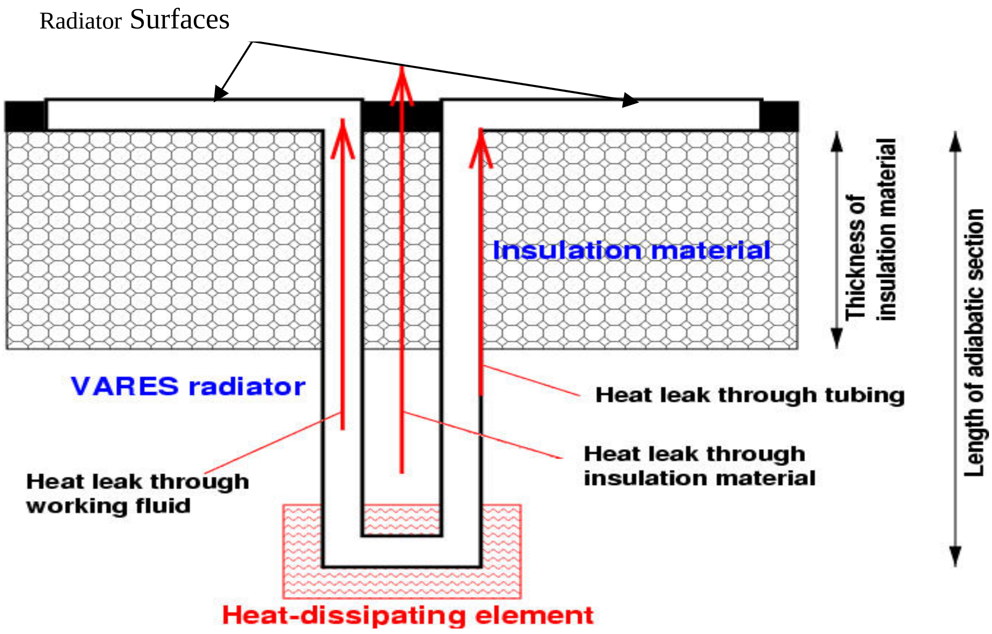

Figure 9: Schematic of VARES radiator including adiabatic tubing and insulation material.

The improved design extends the distance (tubing length) between the dissipating element and the attachment to the radiator. To improve the insulation also MLI is implemented between the radiator and the brass mass. These measures decrease the conductive link to the radiator in switched off mode and therefore increase the conductivity turndown ratio.

5.2 Switch-on from non-operating mode after long cold period

In this test a start-up check is performed of the VARES radiator after a long cold period. In this test the temperature of the brass mass is kept around 0 °C while the radiator temperatures converged toward a temperature of -70 °C approaching the shroud temperature of -80 °C. The results are seen in Figure 10. It is seen that the VARES did not start-up during the first two repetitions. It is assumed to be a result of an unfavourable liquid/vapor distribution not allowing the VARES to start-up, i.e. there is mainly vapour at the evaporator side and liquid at the condenser side.

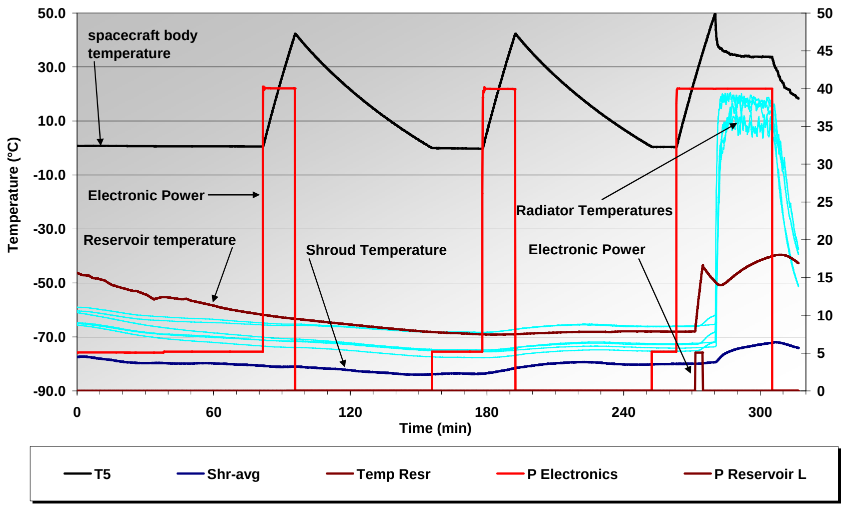

Figure 10: VARES Radiator switch on test result (long cold period)

This redistribution of the liquid and vapor is assumed to be a slow process, and explains the difference between a short and long cold period.

6 Start-up from cold conditions, problem description and start-up design

In this section the start-up problems encountered after long cold period are discussed and solutions are proposed. The liquid/vapor distribution at low environmental temperatures was pinpointed as a possible cause of the start-up problems. This assumption was investigated using a glass OHP version seen in Figure 11.

6.1 Fluid Distribution after long cold period

In order to investigate the start-up problem additional tests were performed in a glass OHP version to verify the assumption that the liquid/vapour distribution is worsened. In Figure 11 the liquid/vapour distribution in glass tubing is seen after a long static period simulating off-mode. The lower part was kept at – 30 °C and the upper part at room temperature (20 °C) for a period • 12 hours.

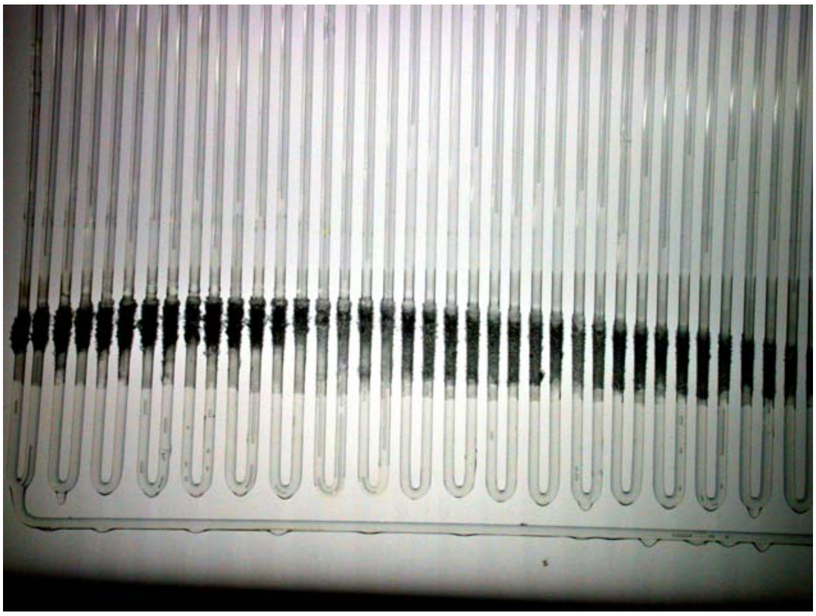

Figure 11: Liquid/Vapour distribution in a glass OHP subjected to a temperature of -30 °C at the lower side and kept at room temperature on upper side.

It was clearly observed that only in the lower (cold) part liquid and vapor coincide while in the upper part only vapor is present. The dark areas in the middle are ice formation on the interface of the cooling liquid. The two observed fluid distributions are schematically depicted below in Figure 12 and Figure 13.

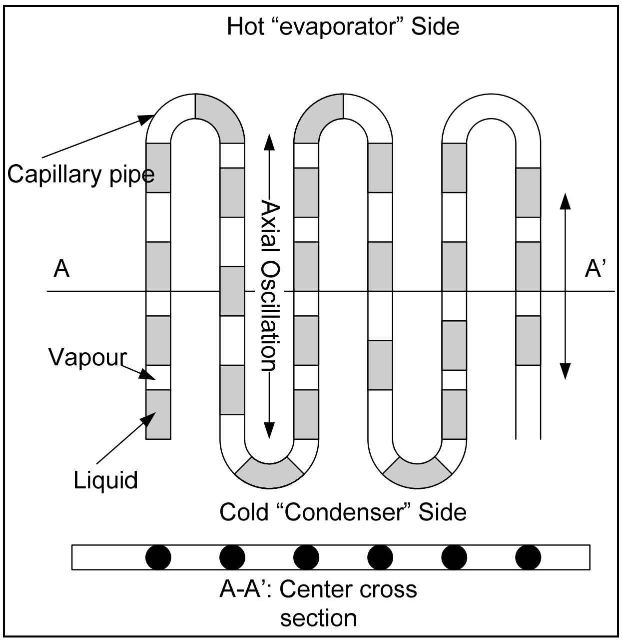

Figure 12: Initial liquid/vapour distribution in the capillary tubing of an OHP.

In Figure 12 the initial uniform liquid/vapor distribution is seen while in Figure 13 the non-uniform distribution resulting from a long cold period. Liquid concentrates on the cold side while the vapor on the hot side.

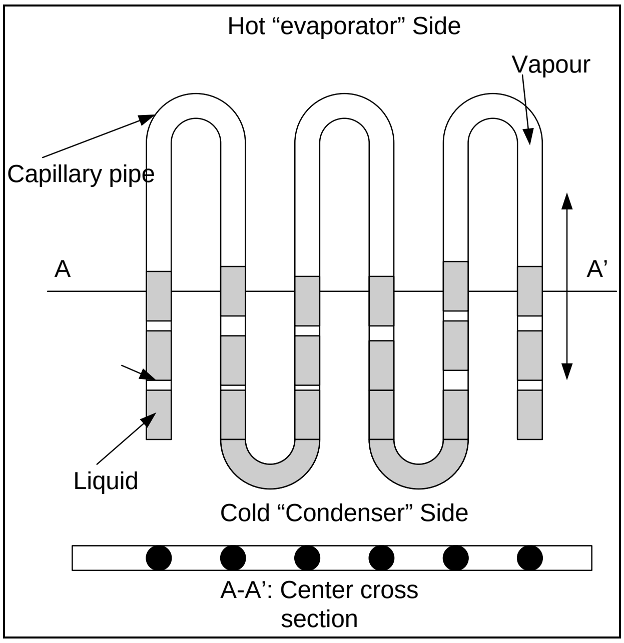

Figure 13: Final liquid/vapour distribution in the capillary tubing of an OHP after a long cold period. Cold period: Evaporator at T= 0 °C and Condenser at T≤30 °C.

It is assumed that the liquid/vapor distribution in VARES radiator after long cold period was similar to the non-uniform distribution in Figure 13. At the cold tips of the radiator liquid/vapor mixture will be present while at the ‘hot’ brass only vapor will be found. Obviously, this distribution can not lead to oscillating behavior; no liquid is available for evaporation below the brass body. Furthermore, it is assumed that the liquid viscosity in the radiator tips is increased at low temperatures. This increases the initial required differential pressure difference to start-up the oscillations. During a restart of the heater (brass), both above described mechanisms inhibit the oscillating behavior, explaining the switching failure after long switch-off periods.

6.2 VARES starT-up design

In order to solve the switch-on problems two alternative approaches have been experimentally investigated:

1. Heating the tips of the radiator by heaters placed on the OHP tubing at the tips of the radiator.
2. Moving the working liquid/vapor in the radiator by means of expansion of working liquid in a reservoir connected to the radiator tubing.

The first solution will be discussed first. Activating the radiator heaters resulted in a start-up of the oscillations in the tip region and a successful switch-on of the complete VARES radiator. The amount of heating required by the heater was however substantial (50 Watt). In fact the OHP at start-up is working in reverse mode. Due to this large amount of heater power needed, this solution is deemed not realistic for any application. The second approach is based on the principle that liquid expands when heated. It was assumed that this approach enables a switch-on with significantly less power. The idea behind this approach is as follows. As discussed above, during off-mode only vapor is found at the hot electronics side of the radiator, whereas the liquid clusters are found around the cold tips, as seen in Figure 14.

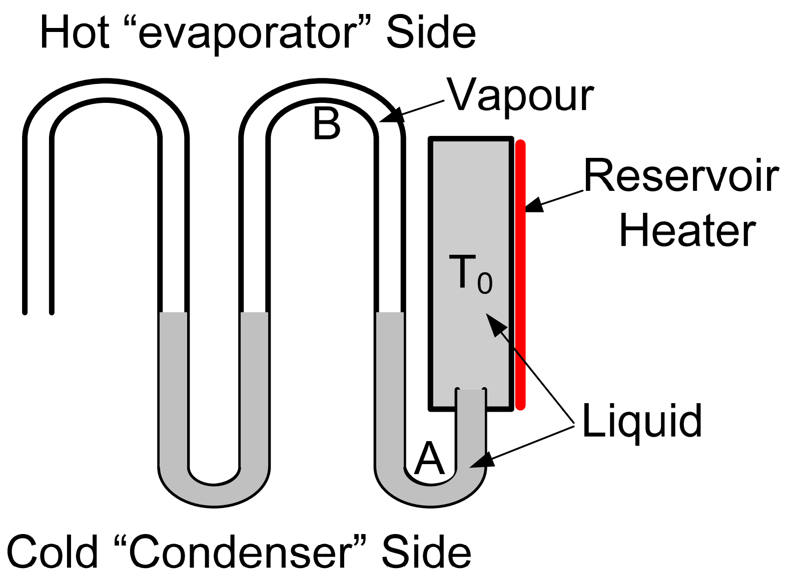

Figure 14: Schematic design of the VARES Radiator with start-up reservoirs (Fluid distribution after long cold period).

To enable a switch-on the liquid has to be transported back to the hot part of the radiator, while the vapor simultaneously is transported to the cold side. The induced motion is provided by the expansion of liquid in the start-up reservoir connected to the cold side of the radiator. The induced liquid expansion in the start-up reservoirs is such that the liquid at point A seen in Figure 14 is shifted to point B and is obtained by heating the reservoirs by a 20 °C temperature step. The resulting favorable liquid/vapor distribution is seen in Figure 15.

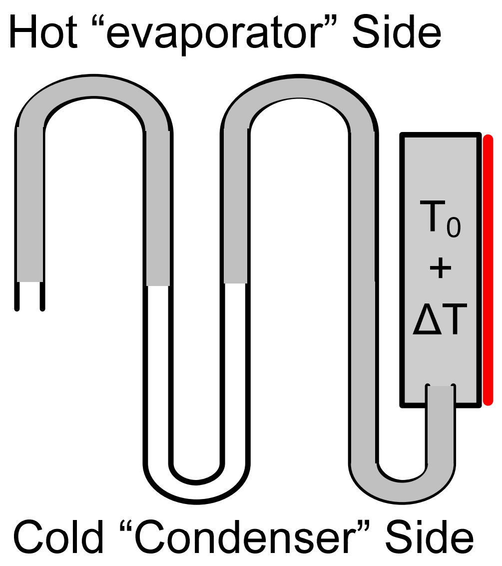

Figure 15: Fluid distribution in the VARES Radiator after deployment of the start-up reservoir heaters (power and duration such that ΔT=20 °C).

The required reservoir power to heat the reservoir with a T of 20 °C was found to be 5 Watt during 2 min and 40 seconds. The liquid redistribution was observed in a glass OHP test. In normal operation the start-up reservoir heater will be deployed prior to the switch-on of the electronics (heaters on the brass mass) to be sure the re-distribution is accomplished before electronics start-up.

6.3 VARES Test Results, Start-up from cold conditions with heated reservoir

The test presented in this section is performed to verify the start-up with a single start-up reservoir heater after a long (18 hours) cold period. Initially the VARES radiator is placed in the space vacuum chamber with a shroud temperature of -80°C. At the left side of the ***Figure 16*** it clearly seen that the shroud has a temperature of -80 °C while the radiator has a mean temperature of -70 °C. The spacecraft body (brass mass) is heated with 5 watt power ensuring a constant temperature of 0 °C.

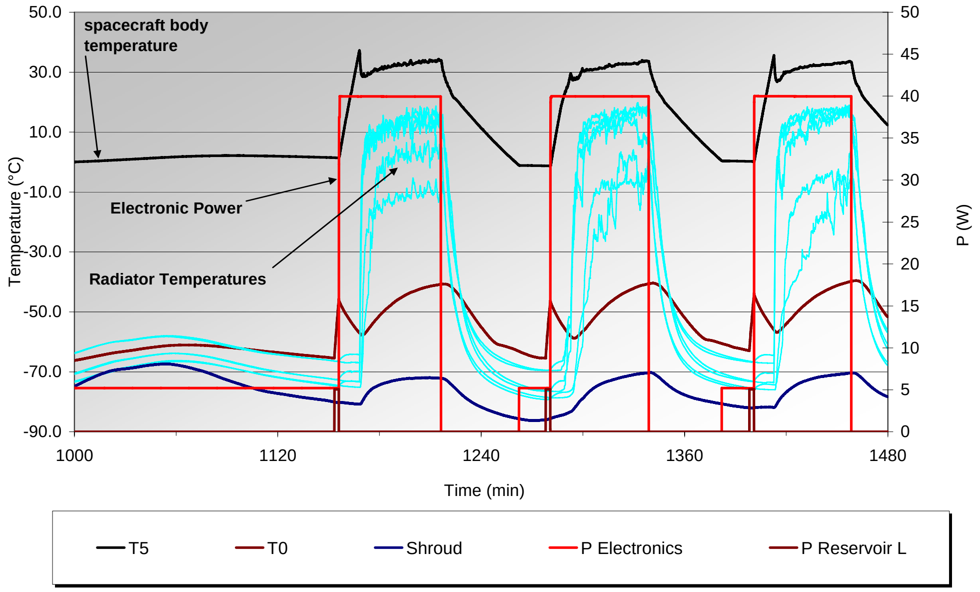

Figure 16: VARES Radiator start-up test with single reservoir heater after one night at -80 °C.

The VARES shows successful start-up of all the three sequences. In the first sequence the electronics temperature exhibits an overshoot. This overshoot is ascribed to the delay in the shifting of the liquid distribution in the OHP. Start-up Design should be further improved to reduce start-up power and minimize the overshoot.

6.4 Comparison with alternative thermal switch technologies

In order to judge the performance of the VARES heat switch is compared with available alternatives. A selection of alternative heat switch technologies is listed below:

- ***Variable emittance radiators*** change the IR emission coefficient of the radiator. Advantage is the low mass of the solution. Drawbacks are the limited power ratio and the degradation due to UV-influence.
- ***Thermal switches*** are capable of varying the conductivity between a hot spot and a radiator. Typical power turn down ratios of 1:20 are available. Most thermal switches rely on the thermal expansion of the materials like waxes. Advantage is the flight heritage on Martian rovers. Disadvantage is the power limitation of these devices due to the thermal

contact resistance. Another point of concern is the degradation of the wax and the spontaneous welding of the orifices.

- ***Passive thermal louvers*** are frequently used to control the heat removal to deep space. Typical 70-80% changes in emissivity (0.16-0.56) are obtained. Advantage is the maturity of the technology. Disadvantages are the high mass and costs of this option.
- ***Mini loop heat pipes*** are also used to change the heat removal to the environment. This is also proven technology and commercially available. However loop heat pipe systems are heavy and require considerable testing increasing the costs of the mission.

In table 3 a quantitative comparison between the VARES-radiator and alternative thermal switch technologies has been made.
The comparison is based on the maximum dissipated power and the power ratio (power in off-mode: power in on-mode) in order to also include variable emittance radiators. The comparison shows the VARES-radiator can become a lightweight high performance alternative for the thermal louvers and LHP systems. Compared to paraffin heat switches the VARES-radiator can reach a better power ratio and serve a higher power range of applications.

	Max Power Dissipated [W]	Power Ratio [W:W]
VARES (Current design)	40	1:8
VARES (Improved design)	40	1:40
Paraffin Heat Switches		
MER (Starsys Mars Exploration Rover)	11	1:20
MISER (Miniature satellite energy regulator)	10	1:20
Variable emittance radiators		
Ceramic material	32	1:2.3
MEMS Mini-Louvers	44	1:1.8
Var. emittance panels	40	1:2.5
Passive thermal louver	37	1:5.3
Mini LHP	10	1:92*
* (rough estimate)		

Table 3: Comparison between VARES-radiator and different heat switch technologies [4,5,6].

7 Conclusions

It is demonstrated that the OHP principle can be used to design a heat switch. The VARES is able to change the heat transport from a heat dissipating element to a radiative surface. The conductivity turndown ratio measured for the current breadboard is 1:27. It is foreseen possible to increase the turndown ratio to 1:95 by simple design changes:

- Improving the insulation of the dissipating electronics from the radiator.
- Longer tubing path to radiator.

It has been experimentally demonstrated that the oscillating behavior of the VARES radiator is stopped when the temperature of the brass mass (spacecraft electronics) drops below +15 °C. The VARES radiator shows successful start-up without deployment of the start-up reservoirs after short cold periods and is able to reject 40 Watt power to a shroud (simulating deep space temperature). Resulting in a power turndown ratio of 1:8 (Off-mode: 5 Watt, On-mode: 40 Watt). With the above described design improvement a power turndown ratio of 1:40 is feasible.

During tests start-up failures were detected after long cold periods. It is experimentally shown that these start-up failures were caused by un-favorable liquid/vapor distribution in the OHP tubing. Small reservoirs and reservoir heaters have been implemented in the design to re-distribute the liquid and vapor prior to start-up. It is shown that the reservoir heaters are able to shift the liquid to evaporator side and the vapor to the condenser side. Reservoir start-up tests showed repeated successful start-ups after long cold periods. Further research will be focused on reducing the start-up heater power, design optimization of the start-up sequence and reducing the conductive link in off mode to realize the expected power and conductivity turndown ratio's.

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