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INSTITUTE OF AEROSPACE ENGINEERING
LETECKÝ ÚSTAV

VERIFICATION OF MULTI-LAYER INSULATION IN SIMULATED SPACE ENVIRONMENT
OVĚŘENÍ VÍCEVRSTVÉ TEPELNÉ IZOLACE V SIMULOVANÝCH KOSMICKÝCH PODMÍNKÁCH

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Assignment Bachelor's Thesis

Institute:	Institute of Aerospace Engineering
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As provided for by the Act No. 11/98 Coll. On higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor´s Thesis:

Verification of multi-layer insulation in simulated space environment

Brief Descriptionu:

One of the most challenging areas in the design of space missions is ensuring the thermal management of spacecrafts. The Multi-Layer Insulation (MLI) is one of a widely used passive thermal control methods. However, the MLI materials and construction may differ based on the application location, prescribed operating temperature range, required thickness, weight and other required parameters.

Cíle bakalářské práce:

- Review of Multi-Layer Insulation´s materials, construction and their properties.
- Requirements for MLI handling during manufacturing, connecting and attachment processes.
- Experiment design and execution to verify the properties of MLI as a barrier against heat losses.

- Evaluation of insulation´s influence on measurements.

Recommended bibliography:

GILMORE, David G., ed. AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS, RESTON, VIRGINIA. Spacecraft Thermal Control Handbook, Volume I: Fundamental Technologies. El Segundo,California: The Aerospace Press, 2002, 836 s. 2nd ed. ISBN 978-1884989117

ECSS-E-HB-31-01 Part 7A: Thermal design handbook - Part 7: Insulations. 1. ESA-ESTEC: ECSS Secretariat, 2011

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ABSTRACT

The first part of this thesis stays the currently used ways of active and passive thermal control in spacecrafts. It focuses on Multi-layer insulation, which is one of the passive methods of thermoregulation. It describes the materials from which MLI is usually made and describes the most problematic parts of its use and production. In the second half the thesis describes the devices used for a proposed test of MLI´s performance as a barrier against heat loss. The results of the experiment are concluded in the end.

KEY WORDS

Insulation, Thermal control, Vacuum, Heat Flux

ABSTRAKT

První část této práce se zaměřuje na popis momentálně používaných metod termo-regulace u vesmírných plavidel. Zaměřuje se konkrétně na vícevrstvou izolaci zvanou MLI. Která je jednou z hlavních pasivních forem kontroly teploty. Popisuje materiály používané na MLI a dále uvádí problémy, které nastávají při jejím používání a výrobě. V druhé části je poté popsán navrhnutý experiment, který má ověřit funkčnost MLI jako izolaci proti tepelným ztrátám. Na konci jsou shrnuty výsledky tohoto experimentu

KLÍČOVÁ SLOVA

Izolace, Tepelná izolace, Vakuum, Tepelný tok

ROZŠÍŘENÝ ABSTRAKT

Tato bakalářská práce se zaměřila na popis prvků termální regulace. Nejprve jsou zde popsány aktivní a pasivní možnosti kontroly teploty na vesmírných plavidlech. Jsou vyjmenovány výhody a nevýhody jednotlivých metod.

Podrobněji rozebrána je vícevrstvá izolace (MLI). Práce se zabývá výběrem materiálů používaných pro výrobu MLI a popisuje a porovnává jejich základní vlastnosti. Dále se věnuje problému spojování a připojování jednotlivých vrstev k sobě. To s sebou nese degradaci efektivity tohoto druhu izolace, protože dochází k většímu přenosu tepla kondukcí. V posledních letech se testují nové způsoby oddělení jednotlivých reflektivních vrstev tak, aby se snížil unik tepla.

V experimentální části této práce je popsáno zařízení na kterém se poté provede experiment. Toto zařízení se nachází na Leteckém Ústavu VUT.

Je navrhnut experiment a provedeno osm měření v kombinaci různých vstupních faktorů.

Po vyhodnocení výsledků je potvrzen vliv vícevrstvé izolace na tepelný tok z izolovaného předmětu. Také jsou položeny otázky pro další výzkum

BIBLIOGRAPHY

ČAPKA, Filip. Ověření vícevrstvé tepelné izolace v simulovaných kosmických podmínkách [online]. Brno, 2022 [cit. 2022-05-19]. Dostupné z: https://www.vutbr.cz/studenti/zav-prace/detail/139976. Bakalářská práce. Vysoké učení technické v Brně, Fakulta strojního inženýrství, Letecký ústav. Vedoucí práce Václav Lazar.

ACKNOWLEDGEMENT

I would like to thank my supervisor Václav Lazar for his time, patience, understanding and helpfulness. Also I would like to thank the Institute of Aerospace Engineering at BUT for allowing me to use its premises and equipment.

DECLARATION OF AUTHENTICITY

I declare, that I have worked on this bachelor´s thesis idependently with the use of technical literature and other sources which are all properly quoted in the thesis and detailed in the list of bibliography at the end.

Filip Čapka

20. May 2022

Brno

TABLE OF CONTENTS

1 INTRODUCTION

Space is a very hostile environment. When engineers are designing a spacecraft, they face many difficult challenges, in order to make its mission successful. It is not only constantly exposed to many outside threats but needs also to maintain stable inside conditions for all its inner devices to work properly.

One of the main concerns is thermal control. Even though the outside temperature is close to absolute zero there can be huge fluxes of heat transferred onto the machine due to radiation. The main source of heat waves in our solar system is the Sun, so an easy solution would be, to hide the heat sensitive equipment on the averted side of the spacecraft. However, it may not be possible, to keep them in the shadow for the entire duration of the mission. Apart from that, we also have the inner components, often electrical, which produce their own heat and it is the task of the designers to propose ideal ways of making sure, they will stay in their ideal temperature range

This thesis mentions the main active and passive methods of thermal control and focuses on the passive insulation known as multi-layer insulation (MLI).

It has been used widely since the first space missions, but there are still many parts of this technology, that can be improved for the better. The main goal of the insulation is to minimize the amount of heat flux, that is allowed to pass through it. The main problem is the connection and contact between the layers, which increases the conductive heat transfer.

Some new technologies have been proposed in the last years, but none of them if ideal yet.

The newest great telescope (James Webb Space Telescope) also includes an MLI of sorts and with this technology still being improved, we may see it on many more spacecrafts and satellites in the future. But before that many more studies and experiments must be concluded, such as the one described in the practical part of this work.

2 THERMAL CONTROL

The process of maintaining an optimal range of temperatures is crucial for a smooth course of any mission. It can be quite a hard task to achieve because there are many things to be considered. Based on the appliances used there is always an optimal thermal range where we want the system to operate. It is our goal to prevent the temperature from dropping too low and at the same time avoid overheating.

Since there is a vacuum in space, heat is mostly transferred by radiation. Direct sunlight is the main outside source of heating, but we also need to count with albedo – radiation reflected by Earth. If the spacecraft has a low orbit, then there also is heat caused by friction between the vehicle and atmosphere. Most of the thermal control systems (TCS) used inside the satellite are dissipating heat as well. The objective of thermal control is finding a balance between the incoming and outcoming heat and maintaining this balance even while facing different and changing conditions. There are many methods we can use to achieve the right temperatures and they are often combined with one another [1].

2.1 Active thermal control systems

When there is power needed for the thermal control to work, we speak about active systems. Some systems do not require much space or extra mass demands. And can therefore also be implemented into smaller satellites. But most of the currently existing technologies are used only in bigger spacecrafts, at least until we can come up with ways to minimalize their parts. We also need to count with the power requirements and with the fact that supply in CubeSats and such, is often limited only to the essential stuff.

Nevertheless, active forms of thermal control usually have a better ability to minimize the temperature fluctuations and hold a more precise range, so they definitely have their utilization in many kinds of spacecrafts.

Some of the most used ones are heaters. In CubeSats, they are usually keeping the battery temperature from dropping too low. Most times Kapton heaters, made out of polyimide film and foil circuits, are used, accompanied by a device checking the temperature.

On the other hand devices like infrared sensors or imaging spectrometers need to operate in a colder environment, so we need to use cryocoolers. They are able to cool things down to 100 K and lower and provide better instrument lifetime and lower vibration or wavelength coverage. An example of a cryocooler used in small satellites is shown in Figure 2-1.

Figure 2-1 Microcryocooler by Lockheed Martin [2]

Pumped fluid loops (PFL) are a technology, for now, used mainly on bigger projects, because of their high mass and power consumption. It moves liquid between a heat exchanger and a heat sink. A big advantage is, that PFL can cool more locations at once by forced fluid convective cooling. A low mass pump is currently in development by Lockheed Martin Corporation and it could have an overall mass of only 0.2 kg and 1.2 W of electrical power demand.

Combination of more TCSs is also possible and in some occasions required. Center for Space Engineering at Utah State University and NASA´s Small Satellite Technology program is working on Active Thermal Architecture (ATA) - a combination of a PFL and a cryocooler.

With the growth of SmallSats usage and higher complexity of missions they are used for, there is pressure on the active thermal control technologies to better fit in with volume and mass demands, but for now, passive systems are still the main way of regulating temperature on small satellites[2][3].

2.2 Passive thermal control systems

Passive TCSs require no power input and take up considerably less volume in the spacecraft, hence they are usually cheaper. We can often find them combined with active forms, but they can also be the only thermoregulation element as we can often see on CubeSats [3].

2.2.1 Structural methods

It is possible to achieve a certain level of thermal control without using any special materials, even though it is never as precise and effective as active or even other passive technologies. This can be done by, for example, proper material selection. Even though a vacuum surrounds satellites, there is still heat transferred by conductivity between the inside components. So it is important to choose a the right type of components, based (among other things) on their high (or low) thermal conductivity to meet the needs of the given spacecraft.

The orientation of the spacecraft often helps when we have subsystems with lower working temperatures on the other side than those that can withstand bigger heat. Sometimes, the orientation changes based on the mission's goals, so it is usually combined with other TCSs [1].

2.2.2 Thermal surface finishers

By applying a special layer on the visible outside surface of the spacecraft we can indirectly control the absorbed solar energy and emitted IR. White paint, second-surface mirrors or silver/aluminum-backed Teflon are great solar reflectors but emit large amounts of energy. That is a welcomed feature concerning the inner devices, from whom we are trying to dissipate as much energy as possible in order to prevent overheating. That is the reason, why most of the inner surfaces are painted black. On the other hand in the need of lower emittance, we can use metallic paints, Kapton tape or gold coating. Multiple coatings can be combined into stripes or a board design to achieve the optimal balance between absorptance and emittance. Figure 2-2 shows us these two properties in several different materials.

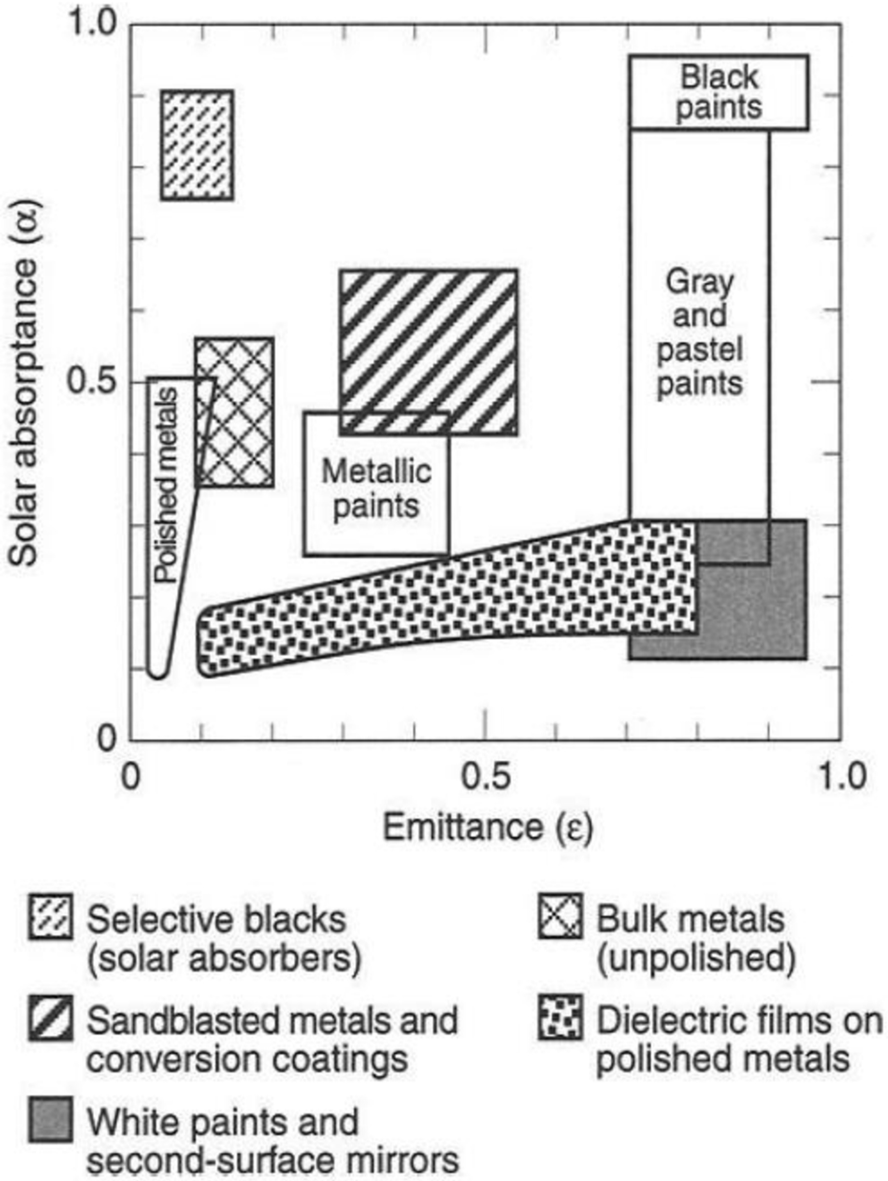


Figure 2-2 Absorptance and Emittance in various materials [1]

It is also important to take note of the degradation which happens over time. All the surface finishers are affected by UV, high vacuum and charged particles, they collide with during the mission. The degradation usually leads to increased solar absorptivity but does not affect IR emittance as much. The solution is often increasing the thickness of the layer, which can lead to the temperature being much lower in the first couple years of the mission. Sometimes it even has to be compensated with heaters, until it stabilizes [1][3]

2.2.3 Phase-change materials (PCMs)

PCMs have the best utilization when the thermal conditions and requirements of the satellite change periodically, as for example when it enters into Earth´s shade during an orbit. Or when a component operates in cycles and needs to maintain certain temperature while in both on/off modes. PCM surrounds a component and when the component is turned on, the energy is dissipated onto the surface of PCM and causes phase-change. This is demonstrated in Figure 2-3. Usually the phase change means turning from solid to liquid or a vaporization of a liquid. While in the off part of the cycle, the heat energy is redirected outwards from the component and PCM through radiators or heat pipes, which allows the PCM to change the phase back (to solid or liquid state) and prepare for another "on" part of the cycle [1][2][3].

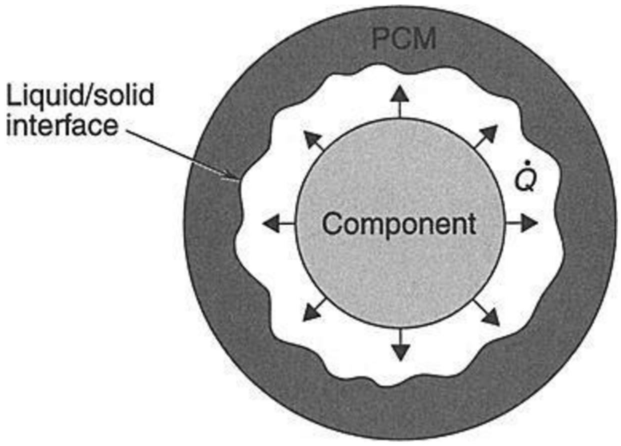


Figure 2-3 – Phase-change material thermal control principle [1]

2.2.4 Radiators and heat pipes

When dealing with waste heat, radiators are the easiest choice, due to their high emittance and low absorbance. They emit infrared radiation through their surface.

Surface finishers having emittance $\varepsilon > 0{,}8$ and absorptance $\alpha < 0{,}2$ are being used. Often they are built in the side of the satellite, but if the surface area is not big enough they can also be attached to the spacecraft from the outside, even deployed after launch.

Heat pipes are a simple yet effective way of transporting heat inside the spacecraft or to a radiator and outwards. There are different types, including sandwich-like flat plates or even some with active elements, but the most common one is a two-tubes closed system. A simple heat pipe system is shown in Figure 2-4 [1][2][3].

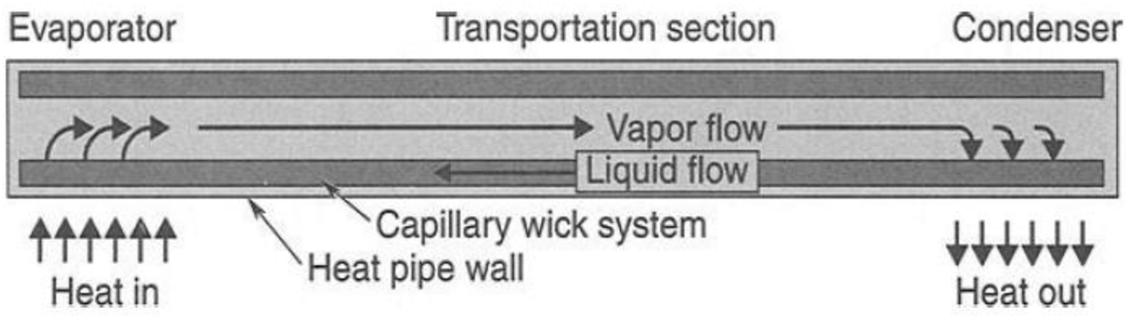


Figure 2-4 Layout of a simple heat pipe [1]

2.2.5 Foams

Foams are used for insulation in many everyday things like building structures or as shock absorbing element in transportation. Main thing which speaks in favor of foams as thermal insulation is their low conductivity and low mass/volume ratio. That is because majority of their volume is filled with gas (often air). On the other hand, they do not have great mechanical properties and after thermal expansion (or contraction), they can suffer cracks, which endanger the insulations´ integrity. We divide them based on their origin on organic and inorganic. The inorganic ones are considerably harder and more expensive to make but have the necessary high strength [4].

2.2.6 Multi-layer Insulation (MLI)

Theoretically ideal MLI would consist of edgeless layers of reflective film which would be standing apart from each other with the space in between filled only by vacuum. Then the only possible form of heat transfer would be by radiation, which is gradually reflected by the layers and only bare minimum of heat is allowed to reach the insulated body. The principle is explained in Figure 2-5.

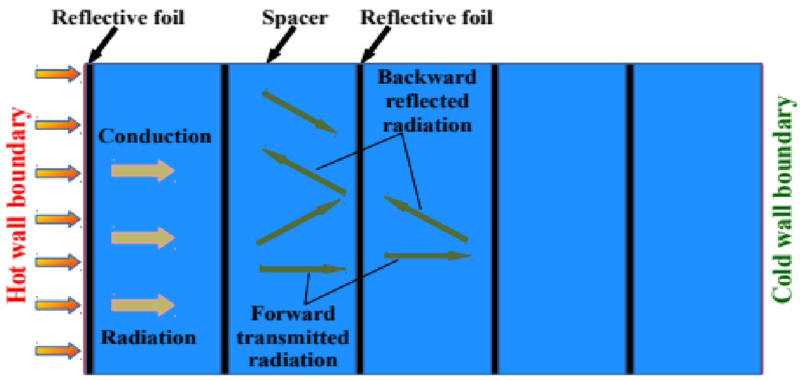


Figure 2-5 Principle of MLI´s function [31]

In reality we do not have the possibility of infinite thickness and area of the insulation and therefore layers must be instead separated by thin spacers. These prevent contact between the reflective films, while still keeping the conductive heat transfer to minimum.

Material of spacers and reflective layers, methods of connection or number and density of layers are all variables that influence the thermoregulating performance of MLI [1][2][4].

3 MULTI-LAYER INSULATION

Great form of passive thermal insulation, and the one that this thesis focuses at, is called Multi-Layer Insulation (MLI). It is commonly used on both big and small spacecrafts and provides protection from outside radiation as well as it helps to keep heat inside, when it is needed. Usually, it consists of multiple layers of film, that reflect most of the radiation. These are separated by spacers with the lowest possible conductivity. Sometimes the space inbetween the layers can also be evacuated, which leads to considerably lower conductivity than in any other materials, as we can see in Figure 3-1. We often call them MLI blankets. In some cases, only one layer of film can be used, it does not provide such good insulation, but it is more cost and weight effective.

Nowadays apart from thermal regulation the blankets also serve as a protection against small particles and objects like cosmic dust, oxygen from the atmosphere (AO) during takeoff and landing or against rocket engine waste.

With MLI it is important to try to decrease all types of heat transfer that can occur, which are solid conduction, radiation, and gas conduction. With that come many different challenges that an engineer has to face while designing it and then considering the best options of MLI to be used on a specific spacecraft.

Many different material combinations can be used depending on the exact needs of the mission. What also plays a key role in the effectivity of given MLI blanket is the handling, connecting and manufacturing [1][2][4].

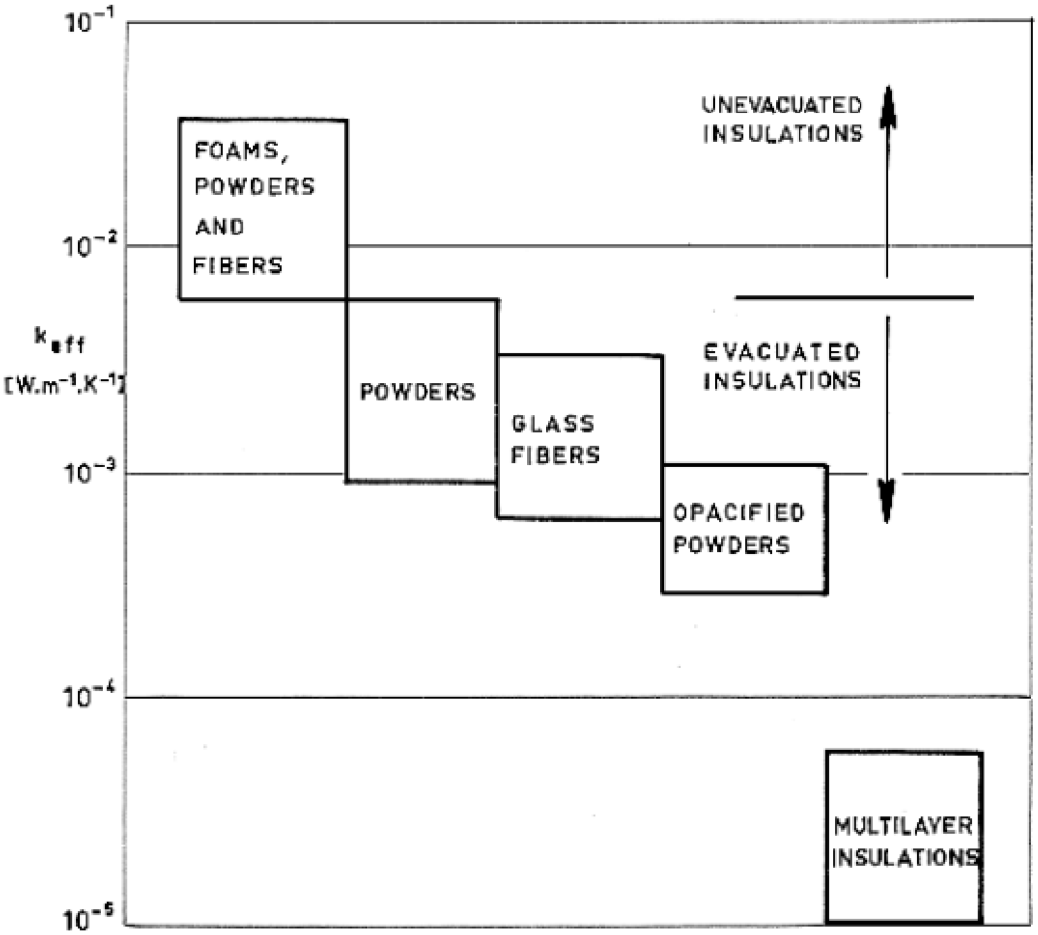


Figure 3-1 Effective thermal conductivity (k_{eff}) in a vacuum, of MLI compared with other insulation methods [1]

3.1 Materials used in MLI

A MLI blanket usually consists of three different parts – the outer and inner cover, reflector layers and spacers. Each part can be made out of various materials which can be combined to reach the desired outcomes.

3.1.1 Outer cover

This layer protects the rest of the blanket from the effects of the surrounding conditions in space but also from atmospheric oxygen (AO) during the ascent or descent. Because it is constantly exhibited to a hostile environment, it is important, that it is able to withstand it. We are looking for an incombustible material preferably with low electrical conductivity. If there is a danger of electrostatic discharge damage to the TCS, it may be coated in a conductive layer. It may also not have the same properties regarding blocking UV radiation as the inner layers, thus there is usually a reflective layer right underneath (without any spacer) or the outer cover may be aluminized [1][4][5].

Some of the generally used outer cover materials are Beta Cloth, Kapton and Teflon.

Woven silica fiber called **Beta cloth** is used because of its durability against Atomic Oxygen (AO), which is needed in case of usage on the Low Earth Orbit (LEO). With more and more MMOD (Micrometeoroids and Orbital Debris) around Earth it helps withstanding these micro collisions. Other important feature is, that it is fireproof – does not burn and melts at temperatures way over 900 K. To ease handling, it can be coated with Teflon. It is also used for example as the protection of both, the interior and exterior of ISS or the Atlantis Space Shuttle (Figure 3-2).

For the needs of MLI it can be metallized (usually coated in aluminium) to increase its reflectivity. Then it serves as the first reflective layer as well as a protection for the whole blanket [5][6][7][8]

Figure 3-2 Beta Cloth used as an outer cover Atlantis Space Shuttle

Kapton - first produced by the company DuPont in 1960s, this polyimide film has countless usage options. It is mostly used for its great thermal properties. It is a great insulator and operates in temperatures from -269 °C to 400 °C (4 K – 673 K). It was widely used on the Apollo project, where it gave all the spacecrafts their typical silver-gold appearance. The outer layer was aluminized (therefore the silver colour) and the gold side was facing inwards. But in the process of re-entering Earth´s atmosphere the gold parts got exposed. Since it was a symbol of protection of the cosmonauts against the outside extreme temperatures (and it really did provide this much needed protection) it was often taken (and lately sold online) as a souvenir by the crew.

It is often chosen in designs for its low weight and good flexibility. The elongation can be affected by some of the elements of space environment, such as UV, Gamma radiation or outgassing.

Can be also used as inner layer or even as reflective layers [5]**Chyba! Nenalezen zdroj odkazů.Chyba! Záložka není definována.**[10][13].

Figure 3-3 Kapton wrapped around the leg of the lunar module while standing on Moon´s surface [11]

Teflon was also developed by DuPont (as early as 1938). This fluoropolymer is used not only in aerospace, but also in everyday life. It is one of the least flammable plastic-based materials. Teflon was used as an outer layer of MLI Blanket on another important spacecraft – the Hubble Space Telescope (Figure 3-4). Because of collisions with MMOD it had to be checked, repaired and finally even replaced. Experiments have shown, that even though it seemed like a great damage to the Teflon layer with many cracks, the thermal insulation effectivity was not significantly lowered.

It has high reflectivity and and therefore ideal as an outer layer for surfaces facing direct sunlight. [5][12][14]

Figure 3-4 Hubble Telescope covered in Teflon [14]

The comparison of these materials is made in Table 3-1.

Table 3-1 Overview of outer layer materials properties manufactured by Dunmore [6][13][14]

	α/ε (outside)	α/ε (inside)	Thickness [μm]	Operating temperature [°C]
Beta Cloth	1,23	0,56	200	(-151) - 260
Kapton	3,5	0,63	7,6 - 127	(-250) - 290
Teflon	0,13-0,16	X	50 - 250	(-185) - 125

3.1.2 Reflective layers

The biggest requirement for the material of reflective layers is low emissivity and high reflectivity. That can be achieved with pure polished metals, which however have often high thermal conductivity (that is why spacers are used inbetween them). But more often than not we use a polyimide film with metal coating. This coating can be done from one or both sides of the film. Use of precious metals like silver or gold is possible, but due to cost savings aluminium is used most of the time [15].

Pure metals in form of thin foils can also be used, without any further coating.

Kapton and Teflon are included as often used coated reflective layers (mostly Kapton). But different combinations (with spacers) can be used and have different results [15].**Chyba! Nenalezen zdroj odkazů.**

Among other frequently used materials is:

Mylar also known as BoPET (biaxially-oriented polyethylene terephthalate) it was developed by DuPont. It is made from common stretched PET. It is originally transparent, but when used as part of MLI it is usually aluminized. It has very good chemical stability and low thermal conductivity. Because it is flammable there is the need of outer and often also inner protective layer to ensure safety of the spacecraft [4].

Figure 3-5 Aluminized mylar reflective layers [16]

Other polyesters can also be used, but mylar is the most common one [4][16][17].

3.1.3 Spacers

In real conditions, the distances between reflective layers cannot be indefinitely big (which would ensure heat is transferred only by radiation). Instead, the thickness of the blanket if usually limited and the reflective films of MLI must be standing closely together. However, their contact could lead to heat short-circuit and conductive transfer of heat. To prevent this contact, thin film of a spacer material is placed between each two reflective layers. Some conductive heat transfer occurs amid the reflective layer and spacer, but by choosing low density material with low conductivity, it is achieved, that it is negligible.

Thus the main trait we look for when choosing the right material is low heat conductivity. We also want to make sure the material´s density is low, which even more decreases the conductivity (less contact) and basically eliminates the heat transfer only to radiation.

Sometimes it is chosen not to use spacers. Then there is several options of handling this. Either the reflective layers are wrinkled before being attached together – which leads to some space being created in between them, but there is still conductive transfer in points of contact. Or only one side is coated with metal – then the conductivity depends on the conductive value of the non-metal part of the reflective layer.

Between the often used materials are various nettings (Dacron or Nomex - DuPont trademark), polyester fabric (non-woven), fiberglass paper, fiberglass woven cloth, silk netting (same material as a bridal veil), and others.

In order of ensuring dimensional stability (therefore making sure two reflector layers do not come into contact) we can also use composite materials – a combination of two materials which gives us ideal combined properties. [4][5][15]

3.2 Construction problems and performance

It is the goal of the engineers and designers to propose the most effective type of MLI. In case of choosing the best suiting material combination, ideal performance, therefore minimal heat flux through the blanket, would be with a smooth edgeless and endless piece of MLI. But in real circumstances there are many imperfections, which degrade the performance of MLI. We as engineers and designers try to minimize their effect and try to come up with the most efficient solutions. Materials and their combination being one of the integral factor in the performance, we also have to answer questions like: density and number of layers, how to attach them together or how to eliminate conduction to minimum.

3.2.1 Number and density of layers

With MLI working best in vacuum and consequently the most heat being transferred by radiation, it could be expected, that bigger number of reflective layers leads to more insulation. But if we have a certain defined thickness (which may be required for mass and size reasons), the more layers per cm^2 (layer density) the more contact between layers and therefore more conductivity. W. Johnson in his work [18] showed that that for given materials there is a balance point between number of layers and their density, which allows for minimal heat leak. Vendors usually offer high possibility of customization, to meet customer´s needs, including a variable number of layers [19]. There is no number of minimal layer amount (for example JWST has only five layers in its sunshield), it all depends on the specific mission and construction. But usually, 10 – 20 layers of reflective layers and spacers are used [1].

3.2.2 Seams

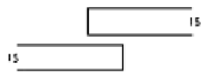
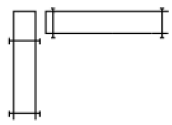
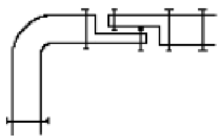
With more complicated structures of insulated objects (or just bigger sized ones) we face the problem of the size and shape of fabricated blankets not being suitable on their own. It is usually solved by simply stitching two ends of MLI together. This although worseness the performance because it locally increases density and can cause heat shortenings (leads to higher density, which leads to more contact between layers and that results in bigger heat transfer) [1][4][21].

Threads must hold the blanket together and cause as little damage as possible during the sewing process or in case of it breaking and being replaced. Threads are exposed to the same conditions (UV, AO, MMOD) as the rest of MLI blanket´s materials. It is required for them to withstand those and preserve their properties like prolongation or strenght. We must differentiate between materials exposed to AO and those in deeper space. [1] Often used for non-AO exposed missions are variations of aramid (Nomex or nylon), which are nonflammable, chemically stable and not conductible, with prolongation of more than 30% percent. For AO exposed ones we can see fiberglass or ceramic threads, even polymide ones, but often covered in some kind of protective coating (Teflon or Kapton). Overall it is not recommended to use metallic threads because of their conductivity. However in situations where it is needed for electrical grounding purposes, it can be acceptable, but the length should be minimized for the needs of the grounding. [1][4][20]

Types of seams

There are numerous ways of folding, bending, or interlaying two parts of the blankets in order to sew or connect it together. Overview of those possibilities can be found in chapter 6.13 of the Thermal Design Handbook [1][4]. Table 3-2 shows some of the layouts for different attachment techniques.

Table 3-2 Different Layouts of seams [4]

Method of connection	Overlap length [cm]	Difference in Heat Flux to area $\Delta Q/A$ [W/m^2]	Layout
Simple overlap Stitched	7,62	1,7	
Overlapping of alternate layers Stitched	2,5	0,618	
Corner Exposed edge Buttoned	-	0,993	
Corner Shiplap (partial overlap) Buttoned	7,62	0,610	
Overlap Stitched Velcro	15,2	0,622	
Overlap Interleaved Addition of Nylon Net	7,6	0,958	

Some of these layouts shown in 2-2 were measured for different MLI materials (and therefore the overall performance would be different), on the other hand the ΔQ/A gives us and idea of how big the influence of the various seams type can be in comparison to each other.

As shown in the Table 3-2, not only is there more options of layouts, but also of the connecting methods. The most common one is sewing the blankets together (with threads mentioned above). The length and number of stitches plays a role in the increase of heat flux, that gets through. Also affecting the heat leak are material of the thread, pressure applied when stitching and other factors. In work from 1972 Stimpson and Jaworski [22]**Chyba! Nenalezen zdroj odkazů.** say, that the differential of heat that passes through can be estimated using equation (1), where it is dependent on the length of the seam.

$$\Delta Q = 0{,}0335 + 0{,}88\ L \qquad (1)$$

NASA advices to use stitches 3 to 6mm long. [1]

Other methods are buttoning [5] or the use of hook-and-pile fasteners, which are sewn, ultrasonically welded or glued on to the blanket (more about them in later chapter). [1]

Seamless MLI

In demand of lowering conductive heat transfer caused by seams, were developed new methods of MLI construction, without seams. Examples come from year 2014 from Japan. Team around T. Miyakita [23][24] tried two different approaches on reducing seam induced performance decrease. First one is called zero stitch MLI and instead of classic sewed in stitches they use plastic pins. They are applied with conventional tag-pin planting device, that is often used in clothing stores for connecting price tags. They don´t compress the blanket and therefore heat shortenings do not occur. Commonly used pin-tags are made out of nylon, but with its outgassing properties not matching spacecraft use requirements, pins from polyetheretherketone (PEEK) were used. To protect it from environmental effects like AO or UV, pins can be covered by a tape (Kapton or Teflon) [23].

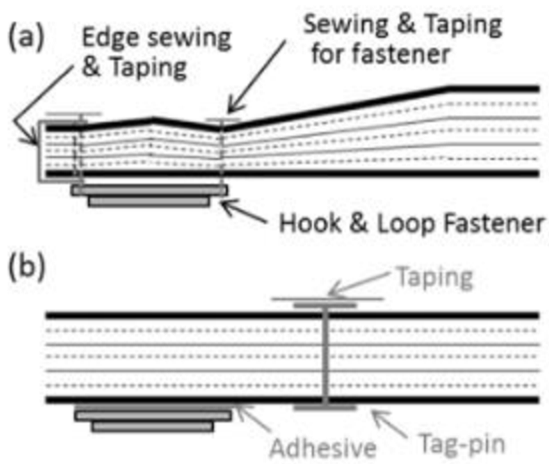


Figure 3-6 schmetic of a) traditional and b) zero-stitched MLI [23]

Second concept, developed by T. Miyakita´s team, is a completely different way of minimizing heat transfer through the connection material. It was developed to be used on SPICA satellite (works with infrared spectrum and is cooled to temperatures under 8 K) [27].

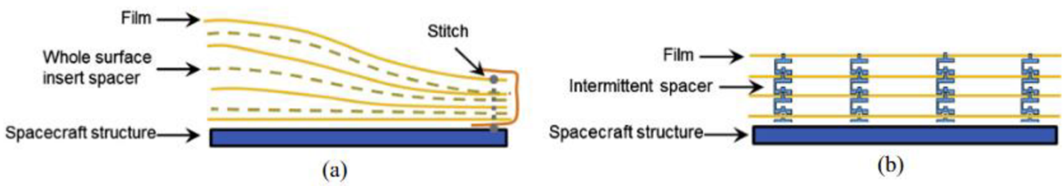


Figure 3-7 schematic of standard a) and non-interlayer-contact MLI b) [24]

To minimize the conductive effect of spacers they removed them completely and separated (and at the same time connected) the reflective layers through a series of pin-like spacers. It is called “non-interlayer-contact spacer” and we can see the schematic principle and comparison to standard stitched MLI in Figure 3-7. The pins are made from PEEK. The shape of the pin and how they are stuck onto each other with the MLI is sketched in Figure 3-8.

In order to decrease the heat leak through conduction in the pins, they were designed in three stages, making the conductive path 40.9 mm long while preserving the height of the pin to 6.9 mm (which helps meet the requirements of blanket thickness). The layout and heat path can be seen in Figure 3-9.

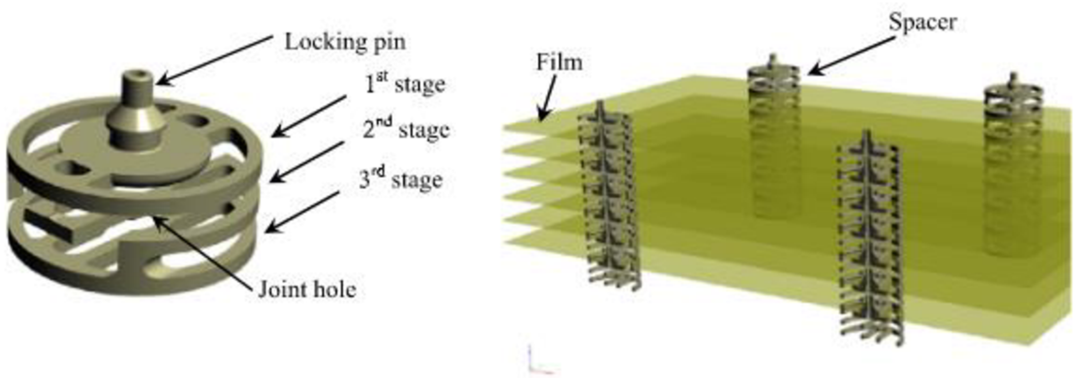


Figure 3-8 schematics of the pin and its use in MLI blanket [24]

Big advantage of this concept is also the possibility to calculate expected heat flux more accurately because we know exactly where and how much contact points between layers there are whereas with conventional spacers this is uncertain and can be only guessed.

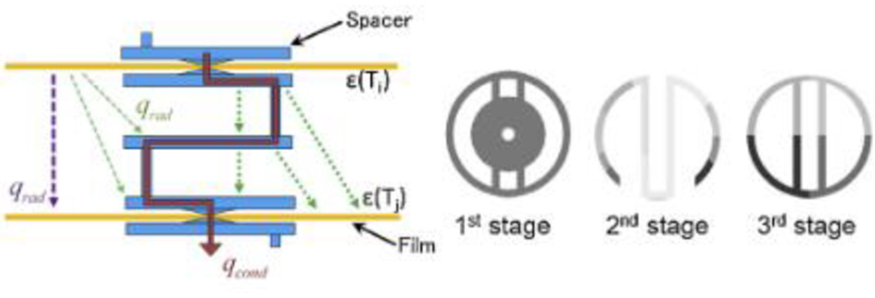


Figure 3-9 Schematics of the heat path and individual stages of the pin [24]

3.2.3 Evacuation and perforation

We know, that MLI works best in high vacuum – 10^{-2} Pa or 10^{-4} torr and lower. While being effective at shielding from radiation, MLI´s structure is not ideal for getting gas outside of its system. If there is no way for the gas to escape, it can cause billowing and that can lead to tears or other several damage. Also molecules trapped inside could cause heat transfer through gas conductivity, which we are trying to eliminate. Therefore, some structures must be included in the blanket in order of allowing gas to leave the inter-layer space[1][25].

The simplest way to do this is to leave one of the edges unfixed (or just a part of it). This may not be ideal in some cases due to attachment problems. Other option is to cut small holes into the sealing in constant intervals [1].**Chyba! Nenalezen zdroj odkazů.**

Most common technique is usually done by the vendors and it consists of perforating the individual reflective layer with small holes. There is great number of combinations of hole diameter and distance separating them, so no norm is given or used and it depends on the individual need of given projects or the manufacturer. (Some sources talk about 0,8mm diameter holes with 6 mm distance[1], but we can see on several materials, that this is not common practice **Chyba! Nenalezen zdroj odkazů.**[19]). Very important is that the holes i n individual layers do not overlap each other, which would greatly decrease the blanket's ability to reflect radiation. There are usually no holes in the spacer material because its low density has similar effect by itself [1][5].

Outgassing is an undesirable effect that we must take into consideration when choosing material and venting options. It is the spontaneous release of gas that was previously locked inside of a material and is pulled out by the low pressure. For materials used in MLI it is usually water vapors, but most designers try to eliminate it by choosing the right components or even pre-pumping the layers. Because of this phenomenon, the ability of MLI to vent is even more important. [1][4][26]

3.2.4 Attachment/connection

In vast majority the fastening of the MLI to the spacecraft is done by **Hook-and-Pile** fasteners. They are also known (and often referred to) by the name Velcro – which comes from the name of the company originally making them. They consists of two sides, as shown in Figure 3-10, that fit into each other.

The Hook-and-Pile tapes come in various lengths and widths. They can be connected to the MLI either by several ways, the most common one being sewing, which locally affects the blankets performance (more above). The stitches can be only through some of the layers or through the whole blanket. The tape can also be attached by ultrasonic welding or simply riveting.

This type of fasteners should not be exposed to AO, it is usually solved by and overlap of material. In case it is not possible to cover it from AO, metallic Hook-and-Pile fasteners made of noncorrosive material, which can withstand it better, can be used. [1][5][29]

When different attachment method is desired, **laces** or **hand ties** are usually used. They can be coated in Teflon and are flat or round braided. The ends must be tied in a square knot (no other) and a piece of fabric should overlap these joints.

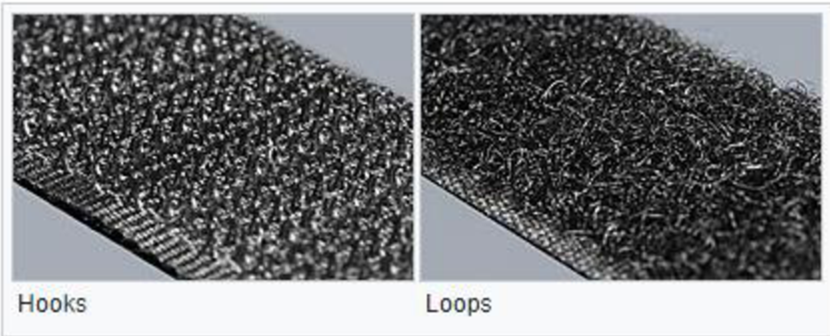


Figure 3-10 The two sides of Hook-and-Pile fastener [28]

4 TESTING OF MLI´S PERFORMANCE

Goal of the practical part of this thesis was to test the properties of MLI in space-like environment. To complete such a test we need a device, that can provide high vacuum and at the same time allows us to measure and control temperatures. Different devices and methods can be used, while achieving same results. Important is the ability of determining the heat flux that passes through the tested item (in our case MLI blanket). In most cases a boiloff calorimeter is used.

4.1 Cryogenic boiloff calorimeters

The layout of calorimeter used for measuring the performance of MLI [15] is shown in Figure 4-1. The cold body consists of three chambers for liquid nitrogen (LN_2), the heat flow is measured in consideration of the middle one. Internal heater raises the temperature and we measure the difference at outer and inner layer. Also measured is the outflow from cold chambers. The measurement is made after reaching steady-state condition – which means there is no change in the average trend of values (slight oscillation around this value is acceptable) [15][30].

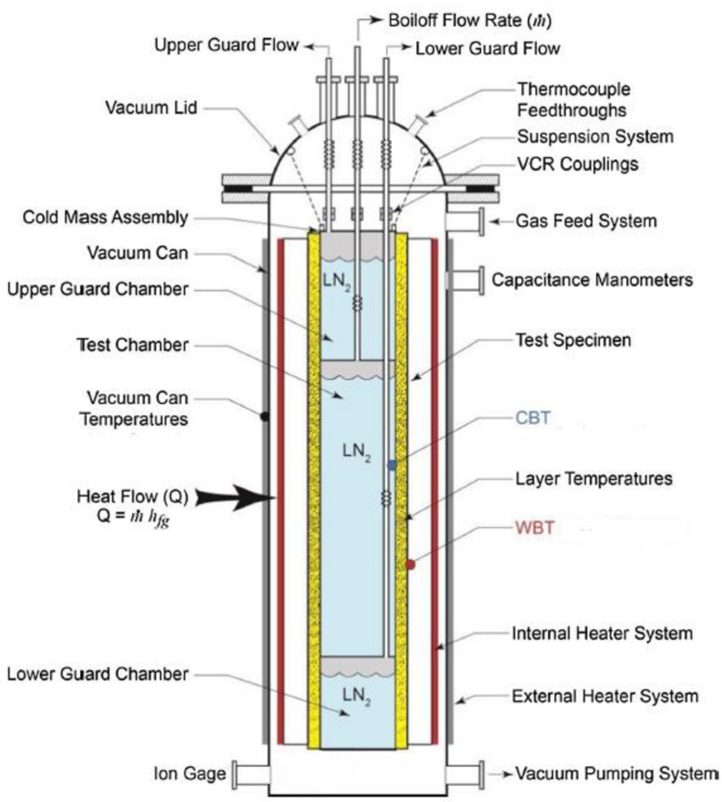


Figure 4-1 Boiloff Calorimeter [30]

Heat flux can be determined by the amount of gas leaving the calorimeter and the enthalpy of vaporization of given gas. Enthalpy of vaporization is the energy needed to change phase of a substance from liquid to gas at given pressure. By linear equation (2) we can calculate the heat flux through MLI [30].

$$q = \dot{m} * h_{fg} \qquad (2)$$

Where $q \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$ is the heat flux through MLI, $\dot{m} \left[\frac{\mathrm{kg}}{\mathrm{s}}\right]$ is the mass flow of exiting gas and $h_{fg} \left[\frac{\mathrm{J}}{\mathrm{K*mol}}\right]$ is the enthalpy of vaporization for given gas.

4.2 Calculation of expected values

When heat is transferred through MLI it is a combination of three different modes – radiation, solid conduction and gas conduction. When we want to calculate total heat flux it looks like equation (3). [30]

$$q = q_{radiation} + q_{solid} + q_{gas} \qquad (3)$$

For MLI blankets there are two approaches of calculating the theoretical performance. One empirically designed called **Lockheed Equation** (4) and the other one called **McIntosh Equation** (6). However, neither of those equations considers the problematic, performance degrading, effects mention in chapters above (seams, attachment, perforation). These have to be calculated by additional equations, that are further explained in referenced literature. [31]

$$q = \frac{C_r * \varepsilon * (T_h^{4.67} - T_c^{4.67})}{N} + \frac{C_s * \bar{N}^{2.63} * (T_h - T_c) * (T_h + T_c)}{2 * (N+1)} + \frac{C_g * p * (T_h^{0.52} - T_c^{0.52})}{N} \qquad (4)$$

Each term represents one form of heat transfer (we can distinguish them by the coefficients in each term). The coefficients are C_r - radiation; C_s – solid conduction; C_g – gas conduction. $\bar{N}$ is the layer density (number of layers/cm), its power can be slightly different depending on the source [30]. N is the number of layers. P is the residual gas between the layers (even in a vacuum there are some molecules trapped inside, partially due to outgassing) and ε is the emissivity of the reflective layer´s surface. T_h is temperature of the hot side and T_c od the cold one [15].

It can also be found in a simpler form (5), where gas conduction is neglected. [29]

$$q = \frac{C_r * \varepsilon * (T_h^{4.67} - T_c^{4.67})}{N} + \frac{C_s * \bar{N}^{2.63} * (T_h - T_c) * (T_h + T_c)}{2 * N} \qquad (5)$$

Lockheed equation is ideal when counting with the MLI blanket as one body. A physics-based approach is given by the McIntosh´s Equation (6).

$$q = \frac{\sigma(T_h^4 - T_c^4)}{(\frac{1}{\varepsilon_h} - \frac{1}{\varepsilon_c} - 1)} + C_s f k(T_h - T_c) + C_g p \alpha(T_h - T_c) \qquad (6)$$

In this equation we can also see all three terms of heat transfer. In the term representing radiation σ stands for Stephan-Boltzmann constant, ε_h stands for emissivity of the hot surface and ε_c for emissivity of cold surface. In the solid conduction term C_s is a coefficient, f is representing relative density of the spacer and k is the conductance of the spacer. For gas conduction we count with coefficient C_g, residual gas pressure p and coefficient α, which is adequate to the energy transfer between gas and surrounding surfaces [15].

5 PROBLEM ANALYSIS AND THESIS´ GOALS

5.1 Problem Analysis

From the survey part of this thesis, it is clear, that MLI is a great insulation method, especially in high vacuum. However, its performance is influenced by great number of factors from obvious ones such as used materials, to small details like amount of pressure that is applied while connecting two parts of the blanket. In numerous mentioned research it is shown that MLI can block or greatly reduce the heat between the cold and hot side. This is usually measured in the calorimeters as the MLI is placed directly between the heat source and a colder body, that means directly in the heat path.

The goal of this thesis is to show, if MLI´s insulating influence is also efficient at eliminating the heat losses even when it is not in the direct heat path. If this hypothesis shows to be true, it can be beneficial to future testing, making it more time and energy efficient and lead to more accurate results.

6 DEVICES AND PROPOSED TEST

6.1 Devices and material

6.1.1 Thermo-vacuum chamber (TVCH)

Thermo-vacuum chamber that is located at the Institute of Aerospace Engineering at Brno University of Technology was used for conducting the experimental part of this thesis. It is located in the clean room of the institute and should be operated only using clean rubber gloves. It was originally developed for the purpose of testing Miniaturized Heat Switch (MHS) in Martian conditions, for ESA. The development and specifications of the chamber are in detail described in works of J. Mašek [32] and V. Lazar [33]. It is the 3rd version of the chamber. Its layout is shown in Figure 6-1.

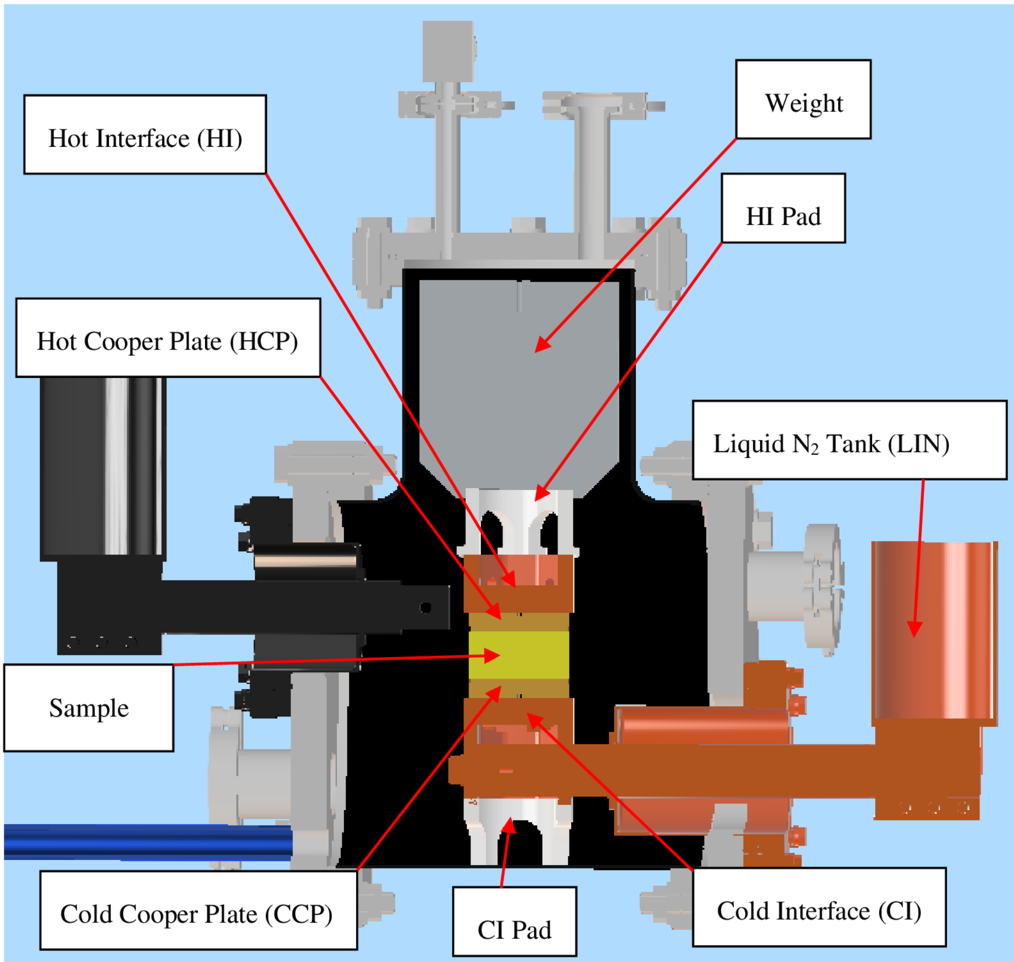


Figure 6-1 Layout of the TVCH

The chamber consists of these parts (those important for this test are marked in Figure 6-1):

- Body of the chamber
  - Contains feedthroughs
  - Flanges connected to it by bolts and nuts
  - Front glass
- Outlet for the vacuum pump
- Hot (HI) and Cold (CI) interfaces
  - Containing heater resistors connected to power outputs
- Hot (HCP) and Cold (CCP) Cooper Plates
  - Containing thermocouples for temperature measurement
- HI and CI Pads
  - Serve as the support of the weight of the inner system
- Weight
- Tanks (connected to HI and CI) for liquid N_2
- Sample
  - Originally designed for MHS
  - In tests for this thesis a cooper sample was used

Temperature, which is crucial in these tests, is measured by thermocouples. There is total of 13 (connected and working) thermocouples in the system. Their placement is sketched in Figure 6-2.

- TH8 - on the surface of HI
- TH 2; 3; 4; 6; 7 - on the surface of HCP
- TC 2; 3; 4; 6; 7 - on the surface of CCP
- TC 8 - on the surface of CI
- TC 1 - inside the CI

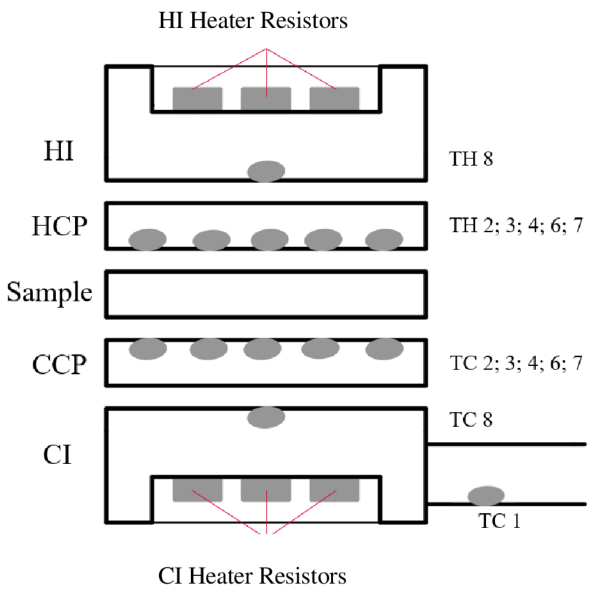


Figure 6-2 Layout of thermocouples and heater rezistors

6.1.2 Heat flux sensor

Heat flux sensor "FHF02-02" from the company Hukseflux was used for measuring heat flux coming through the MLI blanket and at the same time for checking the temperature inside the chamber. The output of the sensor is voltage, therefor the heat flux had to be calculated using equation (7). [35] **Chyba! Nenalezen zdroj odkazů.**

$$q = \frac{U}{S} \qquad (7)$$

Where $q\ \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$ is heat flux, U [V] is the output coming from the sensor and $S\ \left[\frac{\mathrm{V}}{\mathrm{W}*\mathrm{m}^2}\right]$ is sensitivity of given sensor.

$S = 5.76 * 10^{-6} \pm 0.29 * 10^{-6} \left[\frac{\mathrm{V}}{\mathrm{W}*\mathrm{m}^2}\right]$ [35]

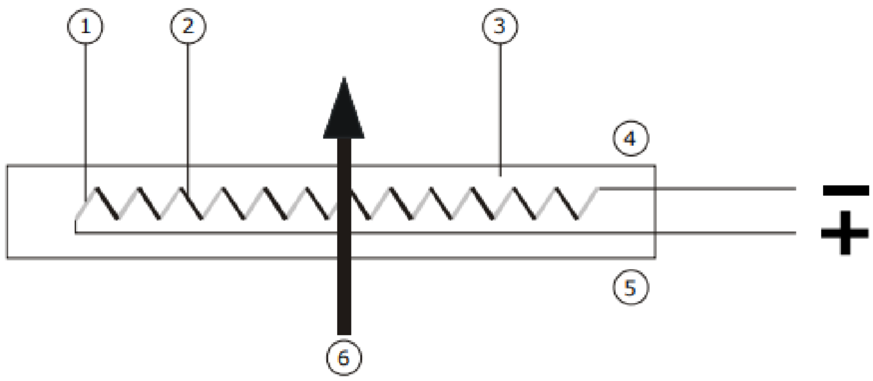


Figure 6-3 Schema of the thermopile inside the HF sensor [35]

In Figure 6-3 numbers 1 and 2 represent metal alloys, which are connected in series. Number 3 represents thermal conductivity of the sensor. 4 and 5 stand for the opposing surfaces and 6 shows the measured Heat Flux.

The HF sensor also has the ability to measure its own temperature. In the practical part of the thesis this temperature output is taken as the temperature inside of the TVCH.

6.1.3 Tested type of MLI

MLI tested in this thesis was produced by company Ruag. It is called **Coolcat 2 NW** and it is a MLI blanket with double aluminized polyester film and non-woven polyester spacer. It was perforated to prevent outgassing (holes take up roughly 0.05-0.1% of each film). The vendor provides multiple options regarding number of layers and dimensions of the supplied MLI blanket and option of 10 foils + 10 spacers in the size of 3x1.5 m roll was selected. [19]

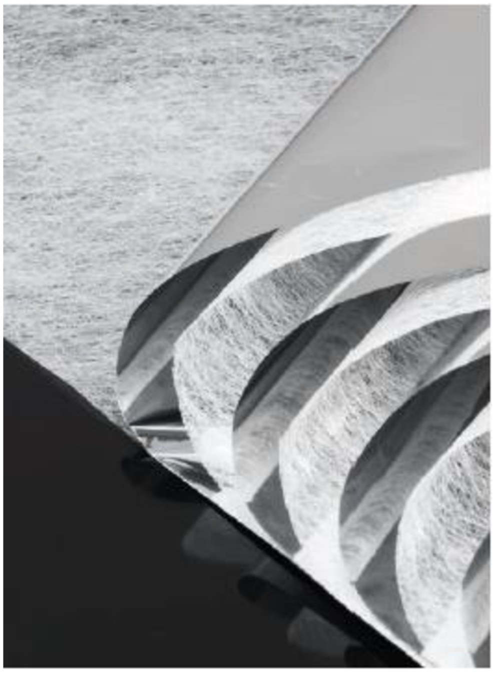


Figure 6-4 Coolcat NW 2 displayed in RUAG catalog 2017 [19]

6.1.4 Testing software (ESAM and Excel)

Recording and monitoring of the results was conducted using **ESAM Traveller 1CF.** It has 32 possibilities for input channels. Through USB it is connected with PC where the data can be managed in a compatible software with a user-friendly interface (Figure 6-55). Raw output data from ESAM were subsequently processed using Microsoft Excel 2020.

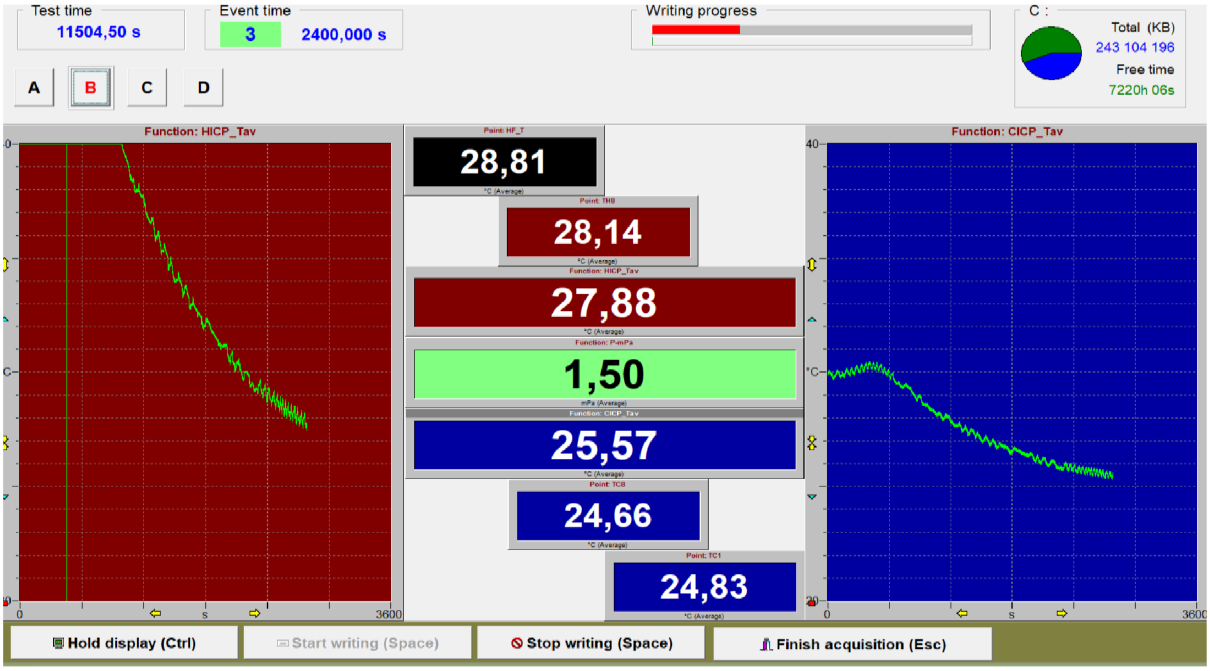


Figure 6-5 ESAM interface during running test

6.2 Verification of MLI as a barrier against heat losses

A series of tests in order of verifying the ability of MLI blanket to insulate a body (representing a spacecraft or its part) was proposed. The test has three changeable factors – presence of insulation, power output and temperature of CCP. All possible combinations of these factors were tested. The test numbers of given factor combinations are shown in Table 6-1.

Table 6-1 Test numbers and combinations of input factors

Test Number	**MLI**	**Temperature [°C]**	**Power output [W]**
1	NO	0	2
2	NO	0	10
3	NO	30	2
4	NO	30	10
5	YES	0	2
6	YES	0	10
7	YES	30	2
8	YES	30	10

6.2.1 Principle of the test

Based on the survey all these factors are expected to have an impact on the heat that flows through the system as well on the heat losses going out of the system. The main factor in conducted tests is the presence of insulation around the body of the system.

In order of successfully completing these tests we need to reach a steady-state. Meaning, there is no change in the trend of the measured temperatures and heat flow for a given time frame (oscillation around a constant value is acceptable). The temperature is measured on the surface HCP and CCP. The Heat Flux sensor (HF) was placed on the surface of CI and CCP.

The main heat path leads from the HI into the LIN tank. The heat is transferred by conduction between the individual cooper plates and hot and cold interfaces. But there is also leak of heat outside of the system, due to radiation (we can see a schema in Figure 6-6). The goal of the test is to determine if the MLI blanket´s insulation can lower this leak. The desired temperature of HI is set considerably higher than the regulated temperature of CI. The constant cooling of the cold interface, by regular addition of liquid N_2, allows us to keep stable temperature at CCP and after certain time frame the temperature at HCP also stabilizes (it never reaches the value set on HI). This leads to a steady-state when we can measure the data we are interested in.

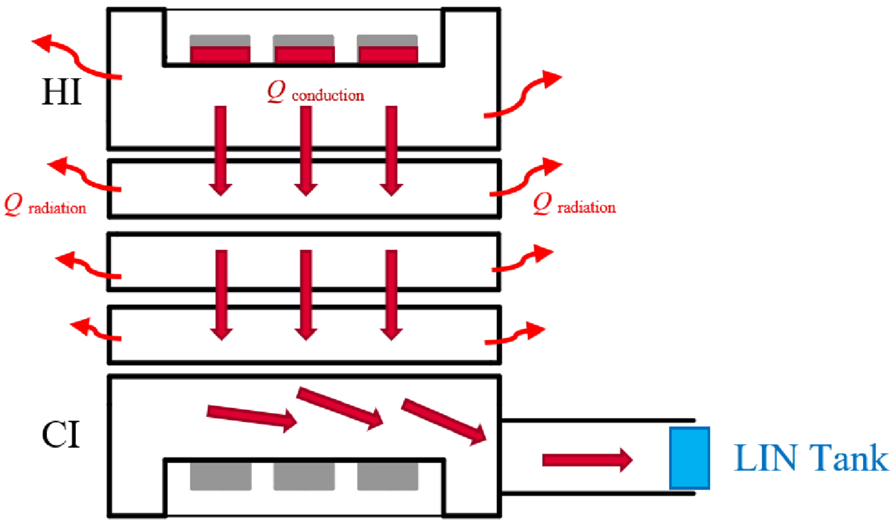


Figure 6-6 scheme of heat flow through the system

6.2.2 Position of Heat Flux sensor and schema of temperatures

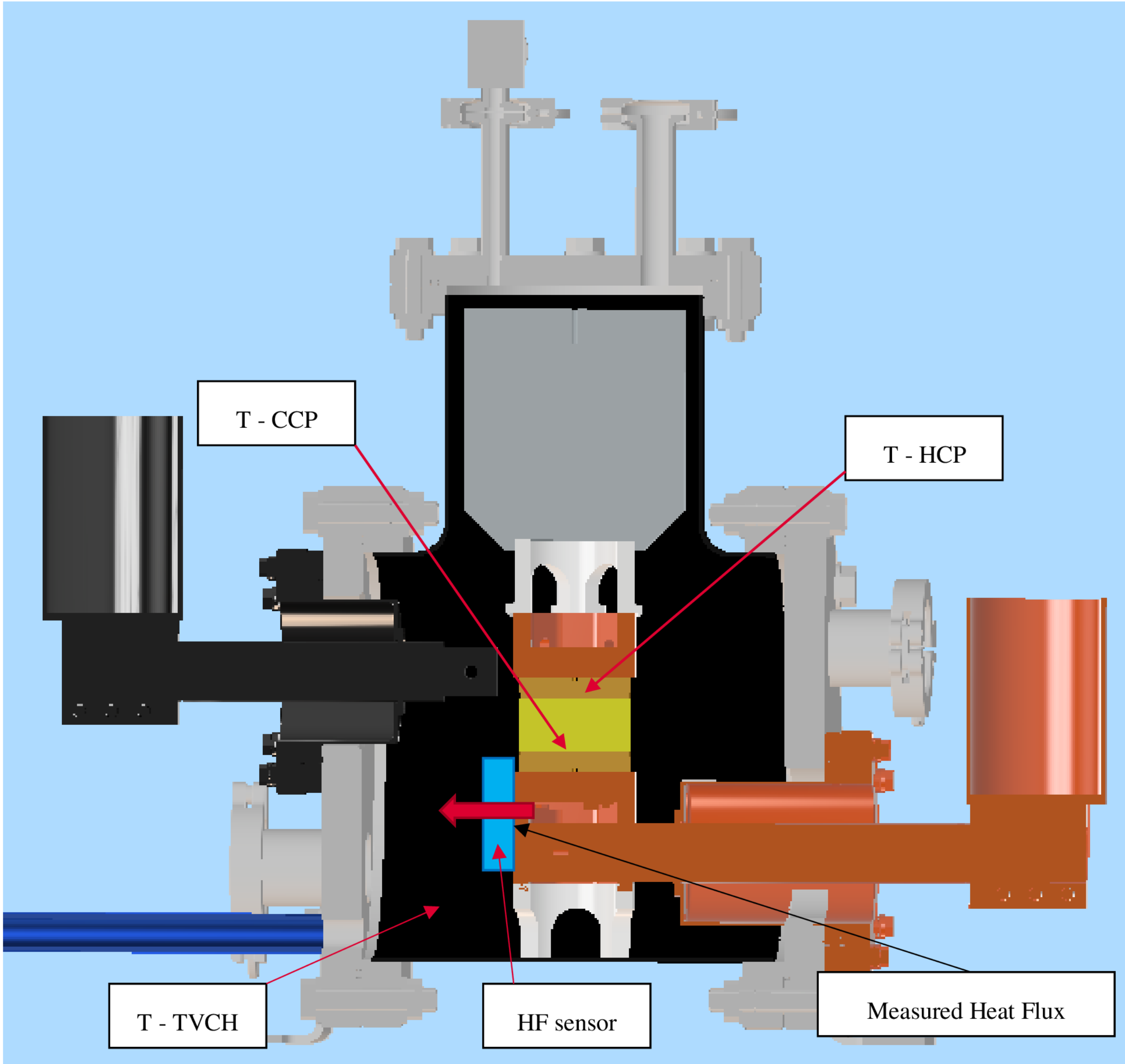


Figure 6-7 Schema of temperatures

Figure 6-7 shows where the Heat Flux sensor is placed on the inner system and where are we measuring which temperature.

6.2.3 MLI attachment

As is mentioned in the survey the handling of MLI blankets during the attachment and preparation process is very important and can have a significant influence on its performance.

In order to minimize the performance degradation due to edges, the whole system was covered in MLI consisting of only two parts. Smaller part covering the CI and the second one shielding the rest of the elements (CCP, Sample, HCP, HI).

From the original roll of MLI two smaller pieces were cut of using a scalpel. After cutting it down to the desired shape the edges were taped by a Kapton tape. Primarily to make the handling easier and to prevent unwanted movement of the layers. Afterwards the lower part was taped directly to the CI. The bigger part of the blanket was afterwards taped onto the first part with an overlap of more than 0.5 cm.

The wires from the elements were passed through the hole where the bigger part of the blanket overlapped itself. This was chosen for the simplification of the connecting process and also to enable gas from inside of the blanket to get out of it during the vacuuming.

Finally the HF sensor was taped to the outside of the MLI to the place of CI.

Three steps of the process are shown on photograps in Figure 6-8.

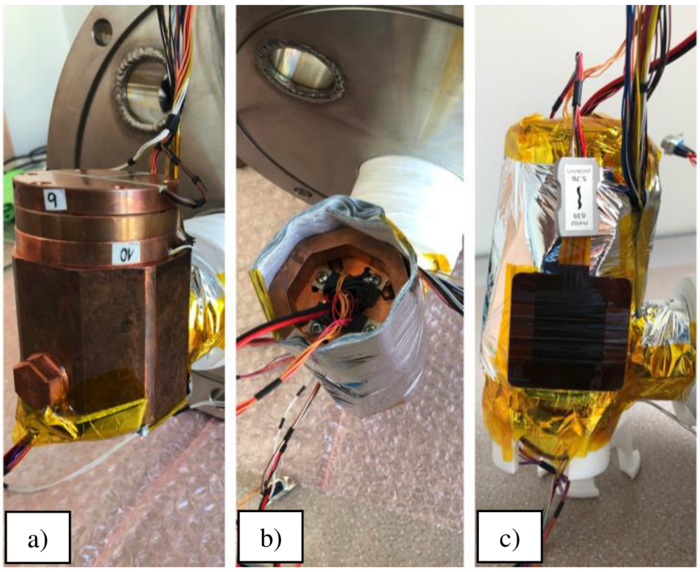


Figure 6-8
a) attachment of the lower part (system without HI)
b) second part covering the rest of the body
c) system insulated with ML

6.3 Measurement procedure

The process was done based on previous experience with testing in this particular TVCH and was shared and explained by the supervisor of this thesis Václav Lazar. It is described in the following chapters.

6.3.1 Disassembly of TVCH

Before the beginning of the testing period the chamber was checked and cleaned. After the disassembly of all vial components, all surfaces were cleaned using alcohol-based disinfection. We can see the disassembled chamber in Figure 6-9.

Figure 6-9 Disassembled TVCH and its components

6.3.2 Assembly o TVCH

The chamber has to be assembled in the right sequence in order to ensure proper functioning and precision of the results. The sequence is as follows:

1. Cold Interface (CI) pad is layed on the bottom of the chamber.
2. The right flange with the CI is mounted using bolts and nuts.
    2.1. Its cables are passed to a feedthrough and connected to outputs leading to ESAM.
3. Cold Cooper Plate (CCP) is placed on the CI, with thermocouples facing upwards.
4. The tested specimen is place on the CCP.
5. Hot Cooper Plate (HCP) is placed on top of the specimen, with thermocouples facing downwards.

6. Hot Interface (HI) is placed on top of the HCP.
7. All the cables are connected to their given feedthrough and connected to ESAM
8. HI pad is placed on top of the HI and above it is placed the weight
9. Heat flux (HF) sensor is placed on the place of interest (in case of this test it was placed on the side of CI) and its cables are connected to a feedthrough.
10. At the end the upper flange is mounted and the front glass connected
11. All bolts and nuts should be checked and tightened

This has to be repeated every time the configuration of the testing needs to be changed.

6.3.3 Test procedure

When the chamber is ready and all outputs connected to ESAM the process of the particular test can be started.

Each test consists of the same steps:

1. Start of the PC and ESAM software
2. Turning on the vacuum pump
   - After 20 minutes the gas ballast is closed to reach the lowest possible pressure
3. When the pressure in the TVCH reaches values of 1 mPa (10^{-5} bar) the HI and CI power outputs are turned on
4. When the system starts to heat up, we begin with the cooling
   - Liquid N_2 is poured into the LIN tank
   - The heater resistors in CI will turn on once the CCP´s temperature drops below the required value and will turn off when it reaches it again
   - LIN is poured again to prevent further rise of the temperature
   - This cycle is repeated during the whole test
     - The period of cooling depends on the factors of the test (output power, presence of insulation, temperature)
5. Once the temperature of HCP stabilizes (steady-state was achieved) the test is continued for the minimum of 30 minutes
6. Finally the data sheet is correctly named and downloaded from the software

7 RESULTS

In this chapter it is stated how the data was handled after the measurement and the results are shown in graphs.

All the test measurements were conducted with pressure inside of the TVCH being 1 mPa ($1*10^{-5}$ bar) or lower. We can qualify that as high vacuum.

7.1 Processing of the data

An output from ESAM transferred into Excel consists of values for each of the individual channels. These values are written in intervals of 5 seconds.

7.1.1 Average values

In the first step the data from TH channels (TH 2; 3; 4; 6; 7) were averaged to give up a single number for of average temperature at the surface of HCP for every given time frame. Same was done with the TC channels.

Another value of interest is the difference between CCP temperature and temperature in the TVCH (measured by the thermocouple in the HF sensor). A difference in absolute value was obtained.

In a third step Heat Flux (HF) had to be calculated. Due to the principle of the sensor, the output value showing in collected data is in mili Volts [mV]. The recalculation to the commonly used units was done by the equation provided by the vendor of the sensor (7).

These steps were done for all eight test scenarios. And the values were afterwards connected into a graphic. Two examples are Figure 7-1 and Figure 7-2.

Values of HF oscillate in a big range due to sensor noise. For better understanding of its trend the values were intersected by a trend line.

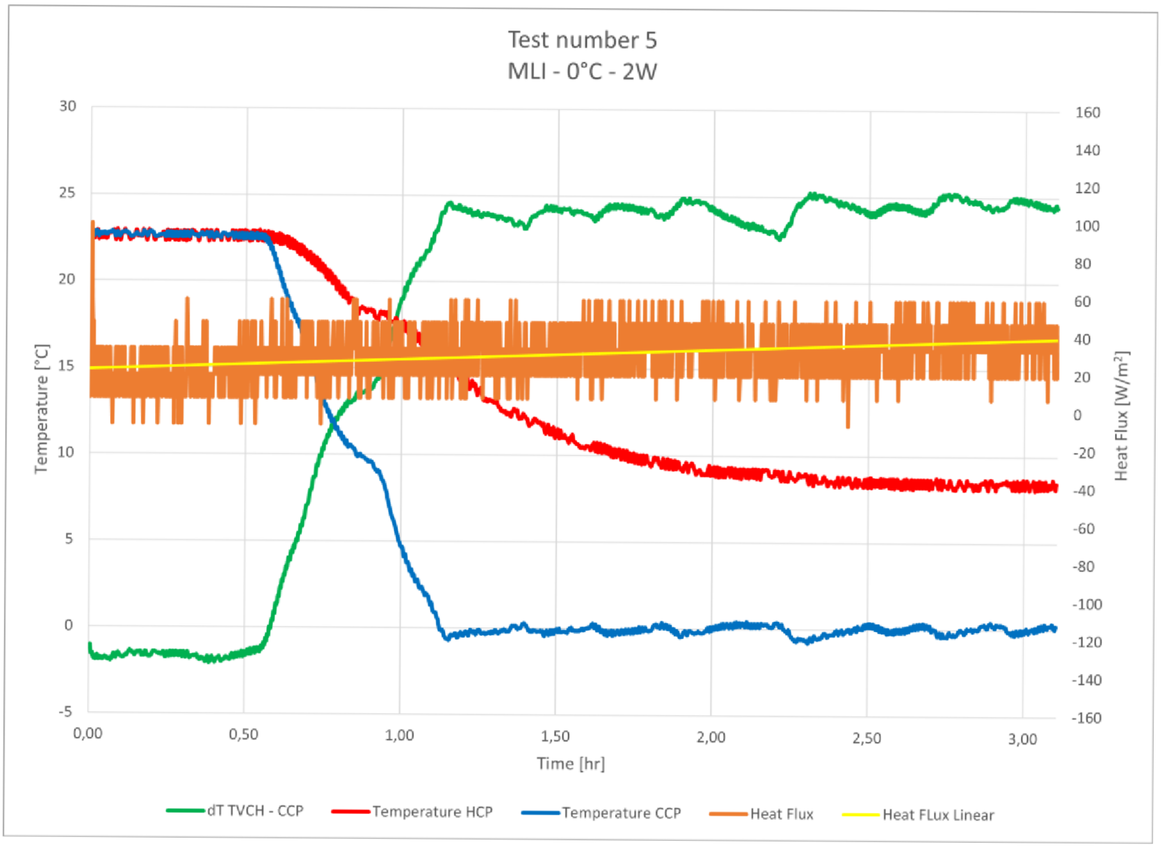


Figure 7-1 Whole test number 5

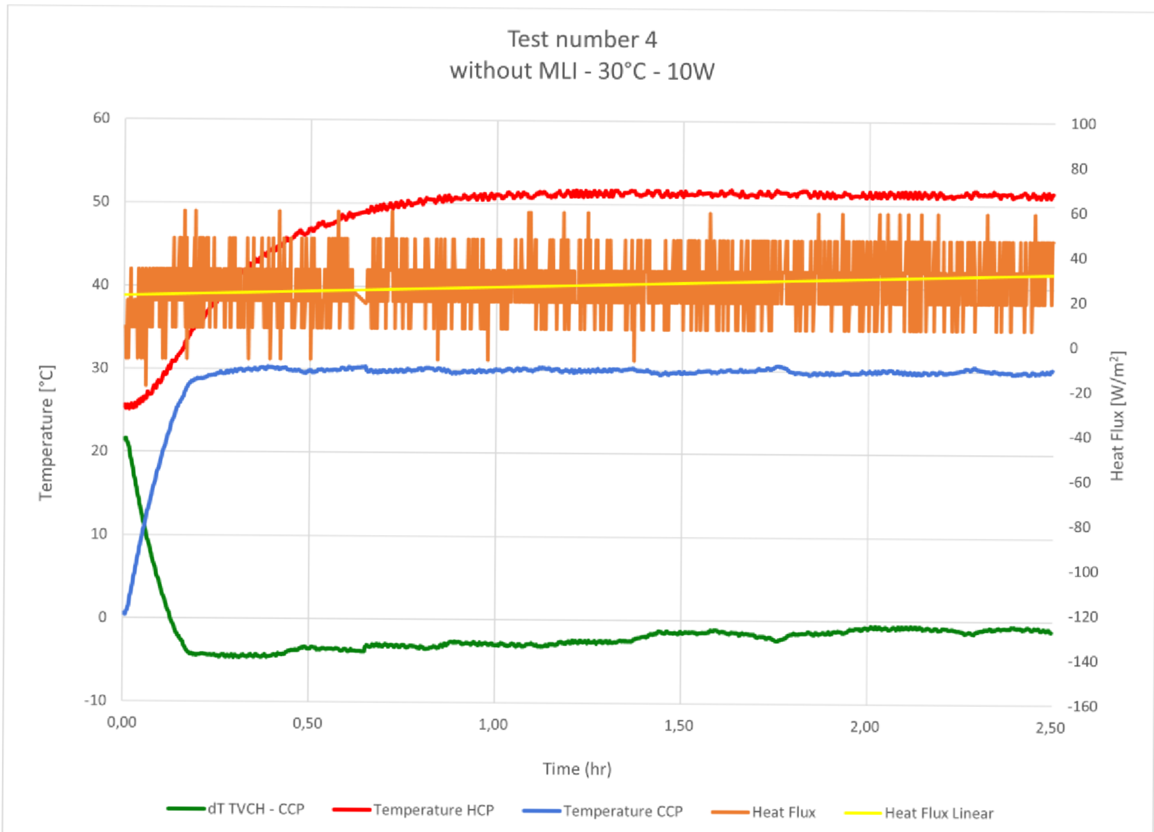


Figure 7-2 Whole test number 4

7.1.2 Steady-state

To be able to get some definite results, we need the observed values to be constant for a not negligible period of time. Therefore, a steady-state was determined for each test case. Minimum time the values have to have constant trend for us to speak about steady-state was chosen at 30 minutes. Some of the test cases were in this state for a longer period of time, however for the sake of relevancy the time of the shortest one was used for all of them – 2000 seconds (33 minutes). In Figure 7-3 we can see the steady period in test number 1. The steady-state occurs from 1.6 hr till the end of the test (above 2.5 hr), but period from 2,5hr minus 33 minutes was chosen instead.

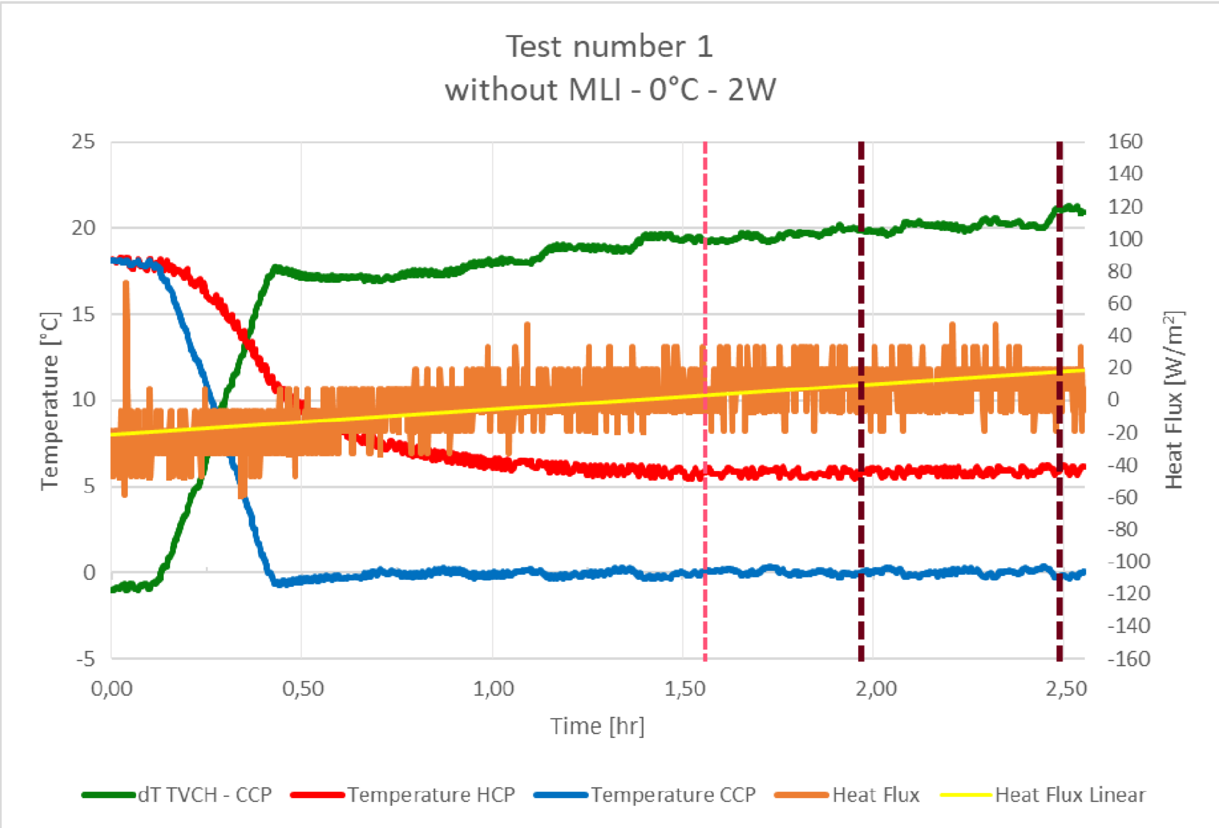


Figure 7-3 Whole test 1 with steady-state phase

Now we can chart a graph of the steady-state time period (Figure 7-4). This was done for all tests.

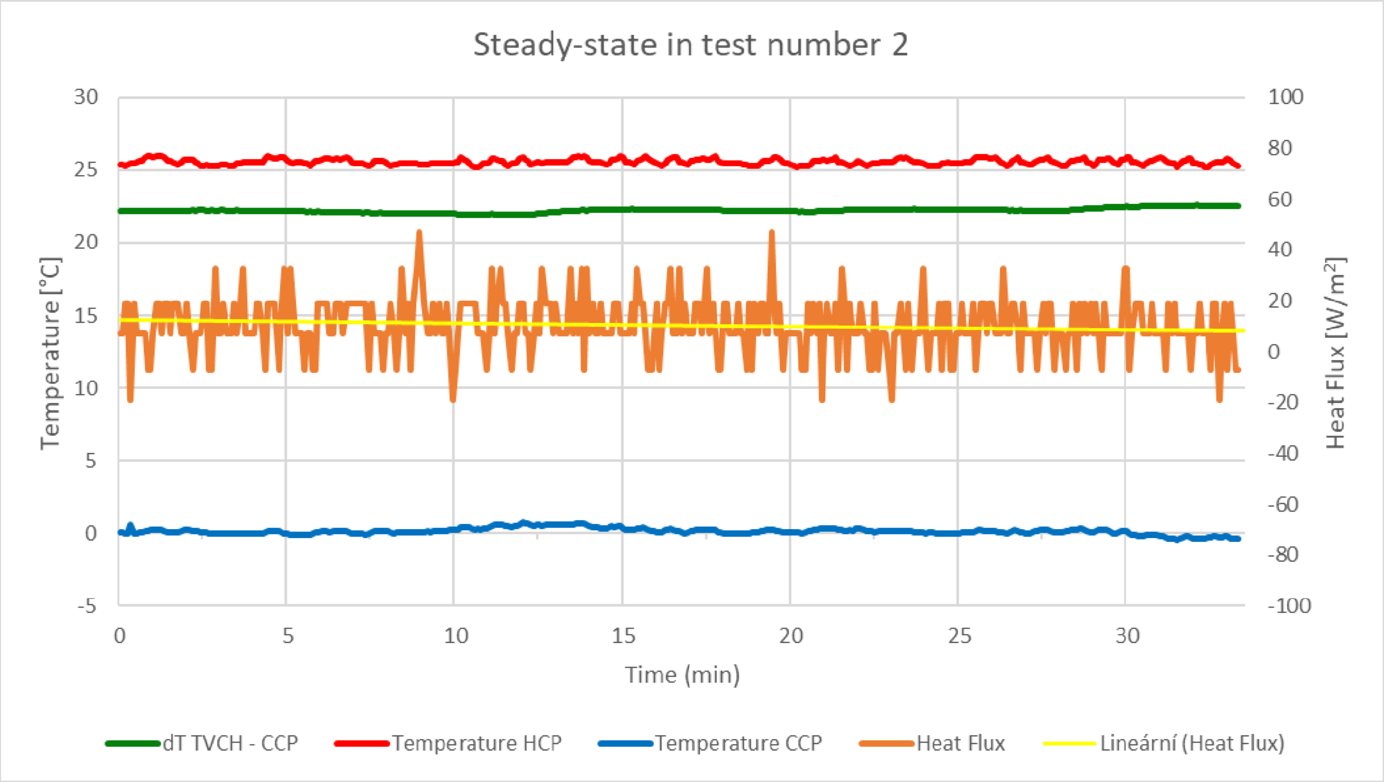


Figure 7-4 Steady-state in test number 2

For better visualization graphs of test combinations were made as well. In each following graph are together the values of test with same power output and target temperature, thus the difference between the values is caused by the presence (or missing) of MLI (Figures 7-5; 7-6; 7-7; 7-8)Figure 7-2 Whole test number 4

For clarity heat flux is in the combined graphs represented only by its linear approximation. The equation of this trend is also listed in the graphs (for both values with and without MLI). The equation of linear approximation of the HCP temperature is also shown. The slope of this line proves that we are in steady-state. (For all HCP temperatures – which were the determining factor when choosing steady-state time frame – the slope is 0.0002 or less, which is negligible)

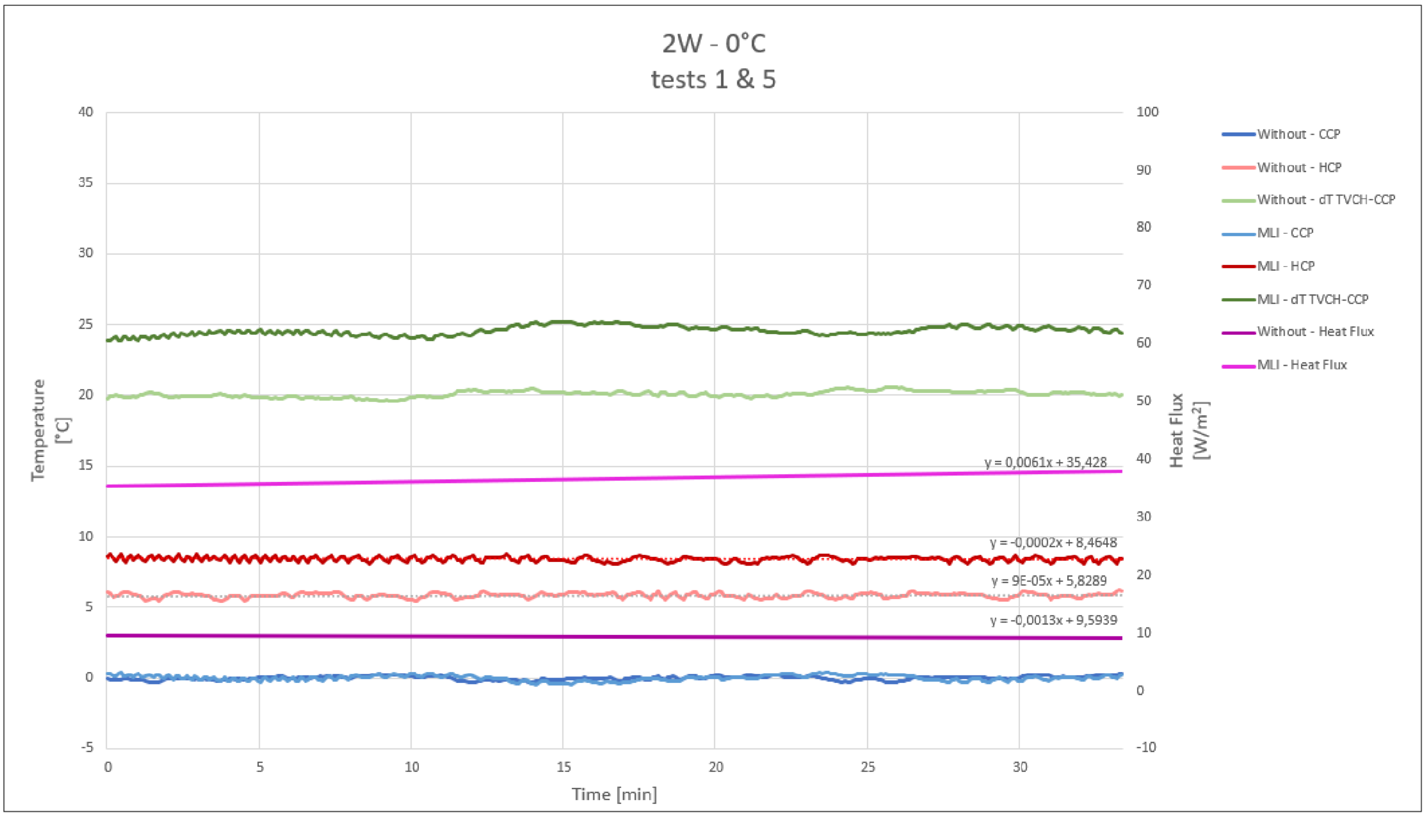


Figure 7-5 Steady-states - tests 1 & 5

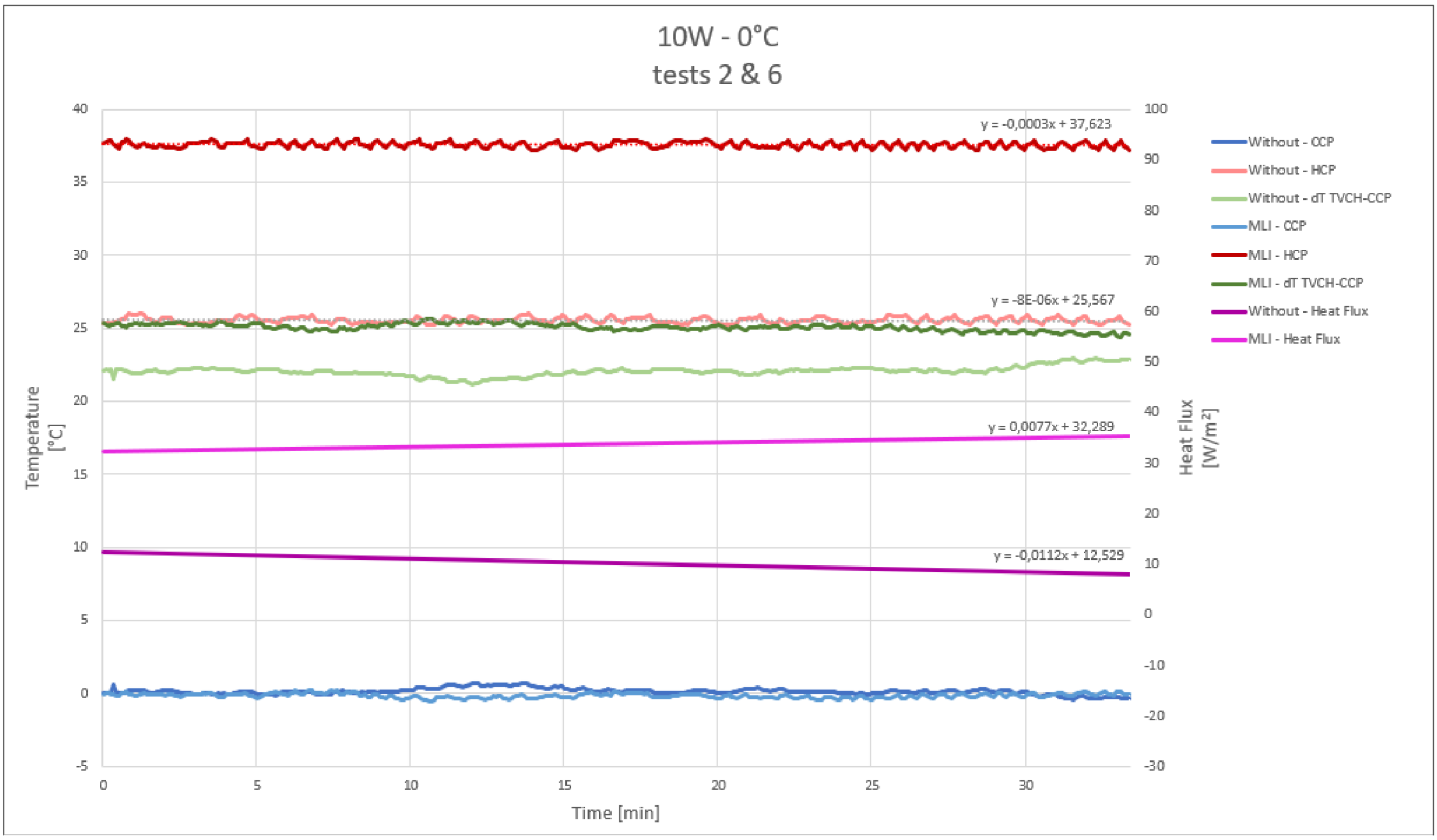


Figure 7-6 Steady-states - tests 2 & 6

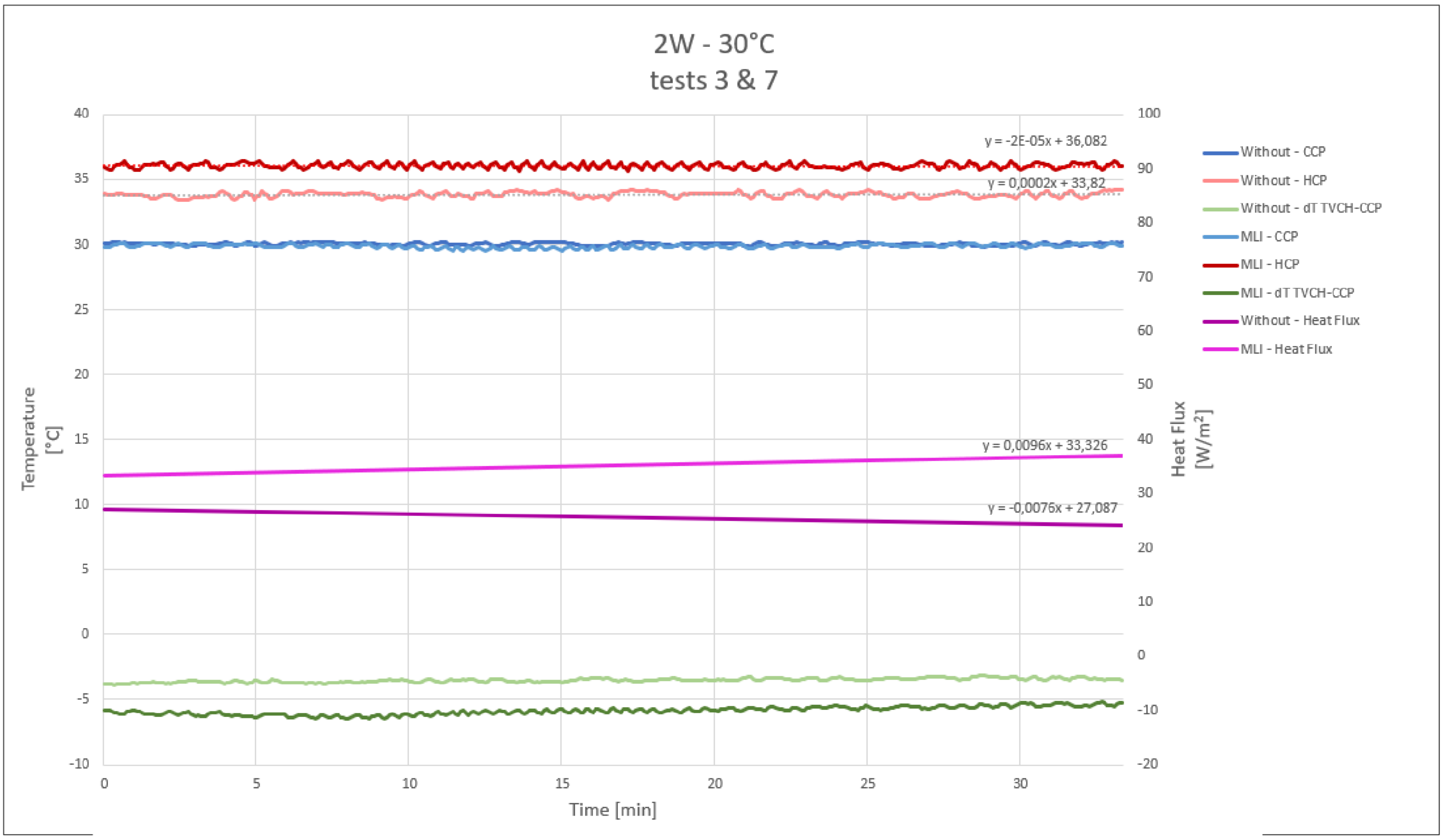


Figure 7-7 Steady states - tests 3 & 7

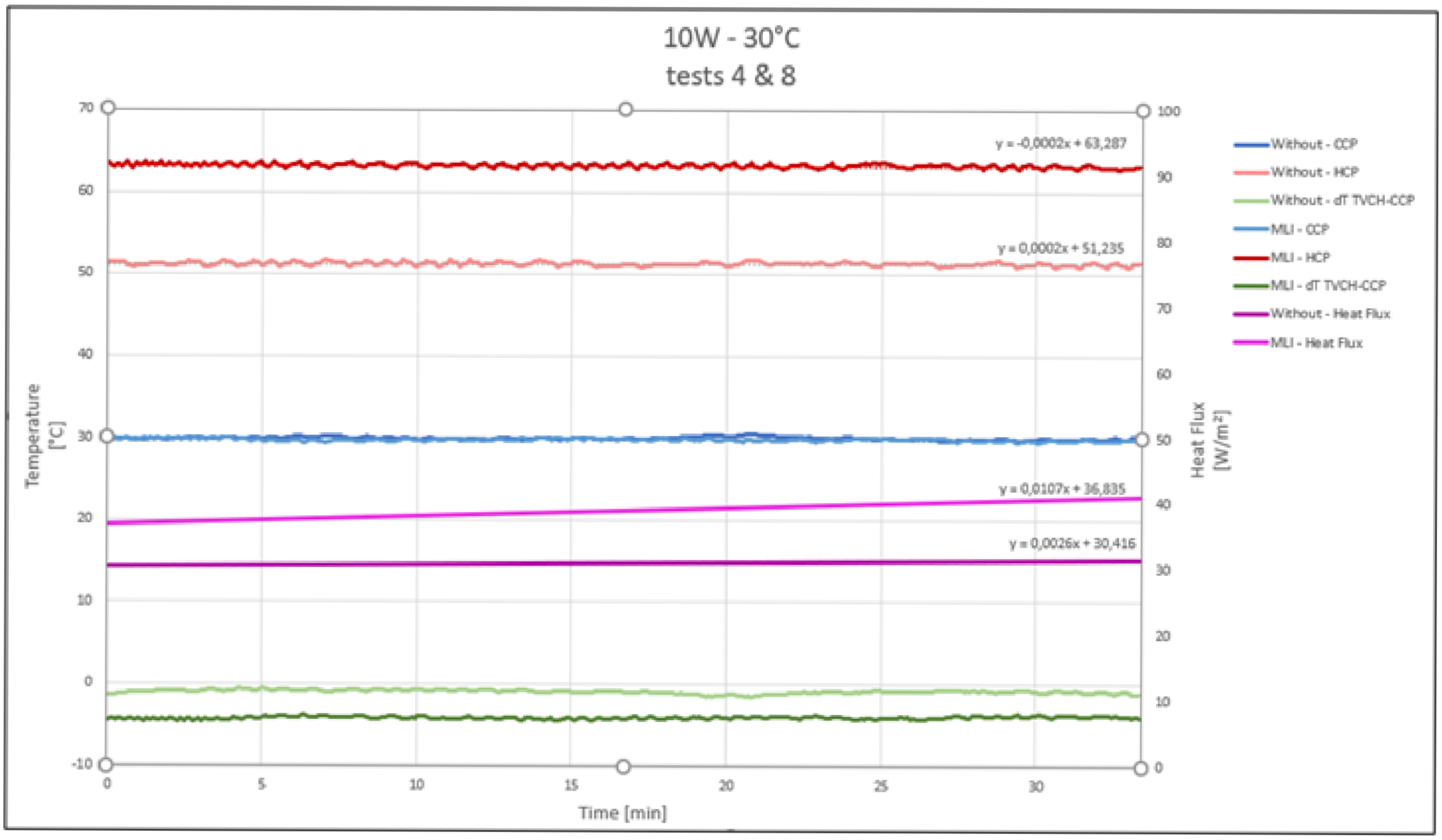


Figure 7-8 Steady-states - tests 4 & 8

7.1.3 Influence of each input factor

When we take the data from the steady-state and averaged them, we get the value that can be used to determine the results of the measurements. These values are in Table 7-1.

Table 7-1 Overview of input factors and output factors

Test Number	MLI	Temperature [°C]	Power output [W]	HF [W/m²]	T - HCP [°C]	dT [°C]
1	NO	0	2	9.34	5.85	19.93
2	NO	0	10	10.28	25.57	22.04
3	NO	30	2	25.56	33.86	3.81
4	NO	30	10	30.39	51.28	1.32
5	YES	0	2	36.66	8.42	23.97
6	YES	0	10	33.84	37.57	25.26
7	YES	30	2	35.25	36.08	5.85
8	YES	30	10	38.98	63.25	4.37

We have put these values were put into the software "Minitab 19". This software takes the input factors and shows through a "pareto chart of standardized effects" the influence each factor or their combination had on the given output. It also gives a reference line, that shows which parameters are statistically significant at the 0.05 level. It also gives us an factorial regression equation, which shows the numerical dependency of the output factor on the input factors. [36]

Input factors in the software are labelled as:

A – power output; B – target temperature; C – presence of MLI

Heat Flux

In Figure Figure 7-9 we can see that MLI is the most influencing factor concerning Heat Flux. Target temperature and the combination of these factors is also statistically significant. When we eliminate the combinations of factor, then as shown in Figure 7-11, only insulation is an important factor.

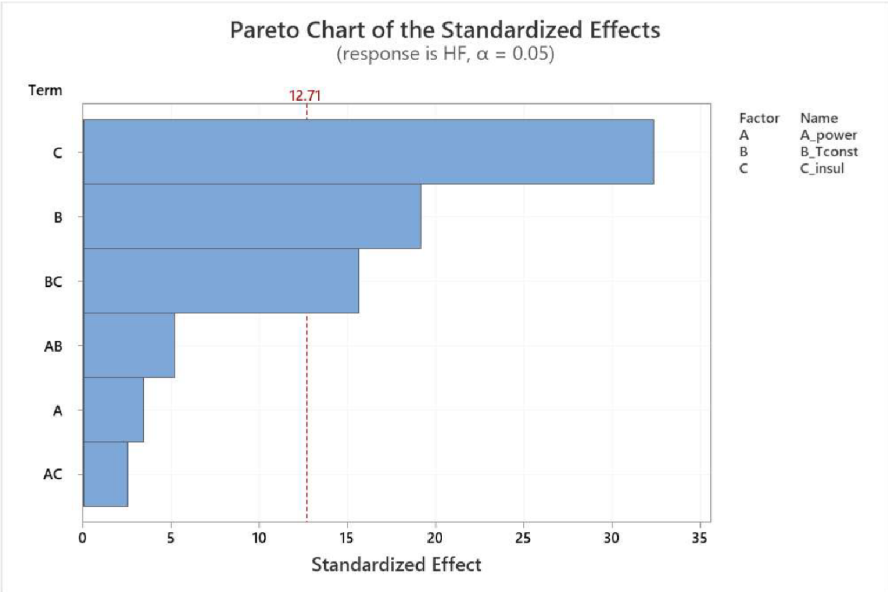


Figure 7-9 Pareto chart of Standardized Effects concerning Heat Flux

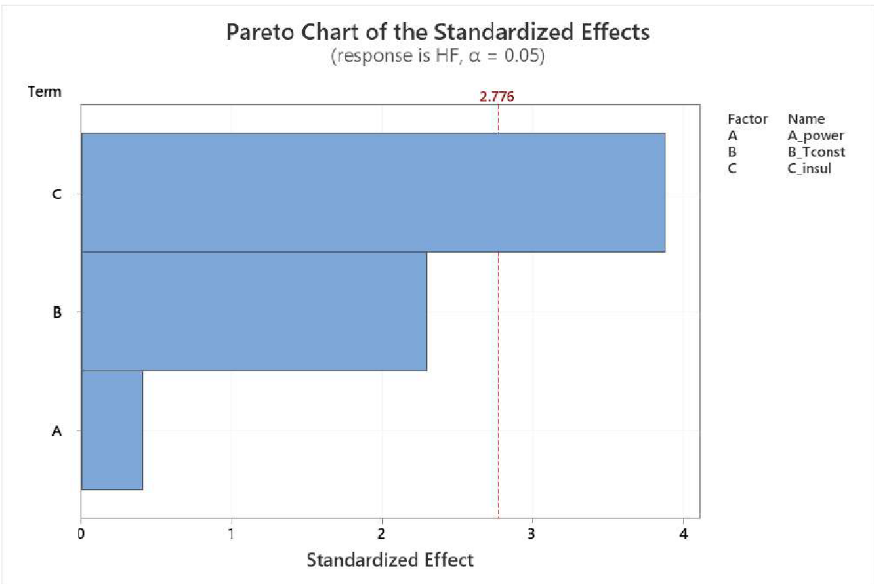


Figure 7-10 Pareto chart of Standardized Effect concerning HF (without combination of the inputs)

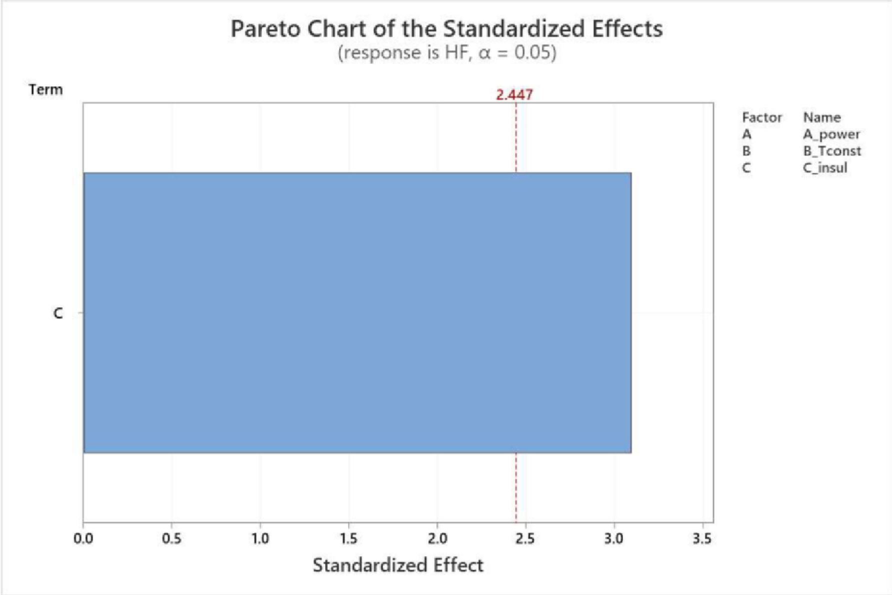


Figure 7-11 Pareto chart of Standardized Effects concerning Heat Flux (cleaned of statisticly insignifant factors)

When we clean up the graph, hiding all the input factors that do not reach the level of significance we get a clear image, showing us that the output value of HF in a steady-state is only dependent on the presence of the insulation.

The regression equation in this case looks as follows (8):

$$HF = 27.60 + 8.58 * C \qquad (8)$$

The coefficient of determination R_{sq} is 61.46%.

For regression with all of the factors the equation is (9):

$$HF = 21.18 + 0.226 * A + 0.338 * B + 8.58 * C \qquad (9)$$

The coefficient of determination R_{sq} is 83.65%

The higher the R_{sq}, the better the quality of the regression.

Hot Cooper Plate Temperature

This temperature was set to be significantly higher than the target temperature at CCP. The temperature at HCP never reached its set value, but instead steadied it self at a certain temperature. The height of this temperature was according to Figure 7-11 depending mainly on the target temperature of CCP and also on the output power. This is mainly because the difference between 0 °C and 30°C is so high, as well as the difference between 2 W and 10 W. Minitab shows us, that the presence of the insulation also plays part in the final temperature of HCP, but significantly lower than the first two input factors (Figure 7-12).

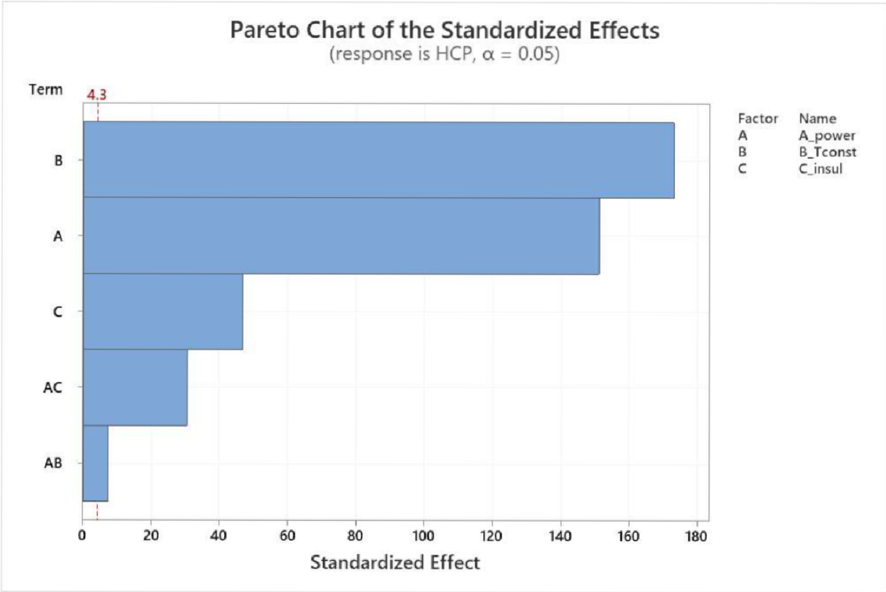


Figure 7-12 Pareto chart of Standardized Effects concerning temperature on HCP

The regression equation temperature of HCP and all the factors looks as follows (10):

$$HF = 0.857 + 3.0713 * A + 0.95129B + 0.83C - 0.0095 * A * B + 0.5909 * A * C \quad (10)$$

Because all of the factors and even thei combinations are significant, the graph cannot be cleaned as the one concerning HF (Figure 7-11)

The coefficient of determination R_{sq} is 100%. Meaning that in the 0.05 level o probability, the equation (10) will show the right value of temperature at HCP, based on the input factors.

Temperature difference between CCP and the TVCH

Figure 7-14 and Figure 7-13 clearly show that the difference is dependent on the target temperature of CCP. But the input factor of the presence of MLI is also statistically significant, although in much lesser extent.

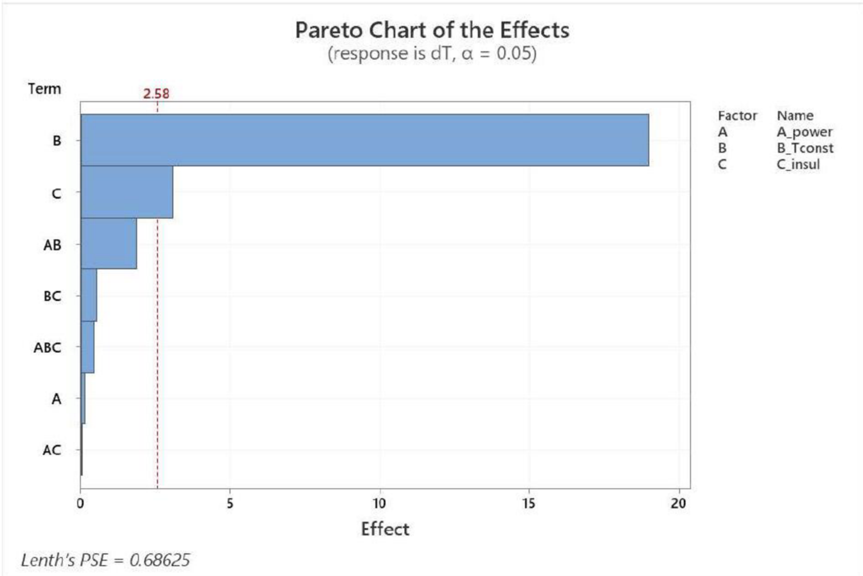


Figure 7-14 Pareto chart of Standardized Effects concerning temperature difference between CCP and TVCH

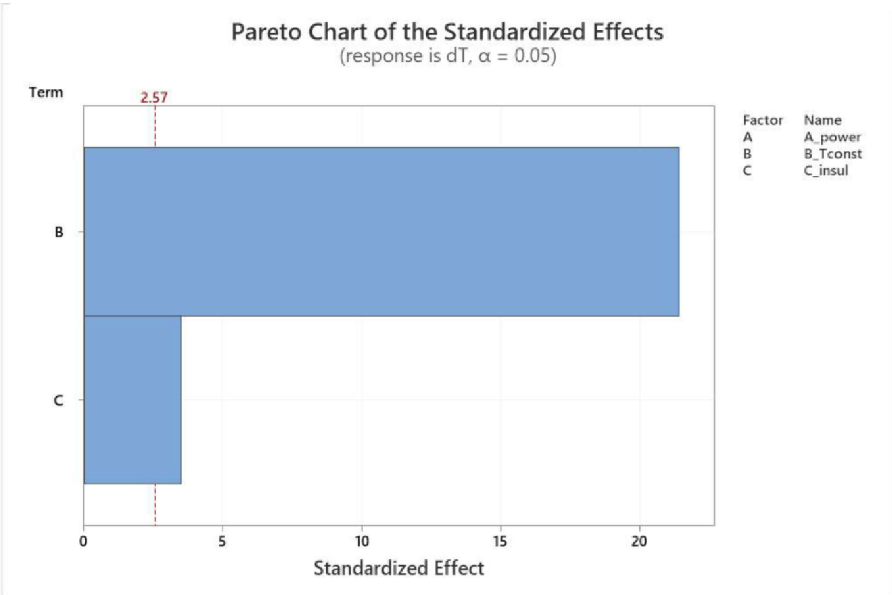


Figure 7-13 Pareto chart of Standardized Effects concerning temperature difference between CCP and TVCH (not concerning factor combinations)

The regression equation in this case looks like this (11):

$$\Delta T = 22.8 - 0.6321B + 1.544 * C \qquad (11)$$

The coefficient of determination R_{sq} is high and it is 98.95%.

8 DISCUSSION

The results from Minitab clearly show that the Heat Flux is dependent on the the presence of insulation. This confirms what was expected regarding the information from the theoretical part of the thesis, that MLI has effect on the heat transferred from one of its sides to the other.

However, the configuration of the test was slightly different than in other mentioned studies. The difference between thermo-vacuum chamber (TVCH) used at the Aerospace Institute and a boiloff calorimeter [30] is, that in TVCH the MLI was not in the main heat path. That would not be a problem, because there is still heat being radiated on the sides of the system, but it prevents us from placing the heat flux sensor in the point of steady-state. In case of measuring the amount of heat transferred through the MLI it would be better to have a calorimeter like configuration.

In future research of MLI using the TVCH at BUT, it would be beneficial to try a different layout of the elements or changing the inside of the chamber. This could be accomplished by setting an outside heater, that could heat the cold interface from all sides at once.

Another thing for future research could be using the equations for counting theoretical heat flux through MLI (equations (5); (6); (7)) and comparing the results with the output of the HF sensor. Although, the sensors sensitivity may not be precise enough to show correct results. Because the vendors of MLI state, that their blankets, in optimal conditions, let through only as little as 1 W/m^2 of Heat Flux. And the sensitivity of the sensor used for counting the HF from the output voltage, affects the value by more than that.

What we could have seen, even with this configuration, was that when there was a steady-state between the Hot and Cold Interfaces, the slope of the trend of HF was not constant (Figure 7-5, 7-6, 7-7, 7-8). Also for three out of the four cases, the HF was raising when the inner system was covered in MLI and was slightly dropping, when there was no insulation.

Furter research and experiments must be concluded to determine if it was only coincidental, but my assumption is, that it means there was heat coming out of the chamber to the outside. When MLI was present it insulated the inner system and prevented it from adding more heat to the chamber. That resulted in a bigger difference in temperatures and subsequently bigger Heat Flux. Whereas without insulation the radiating heat from the inner system was warming the chamber which resulted in the temperature getting closer to equilibrium and thus making the HF smaller.

9 CONCLUSION

This thesis was focused on the performance of MLI blanket as a thermal insulator. The theoretical part of the thesis showed, that it stands out among other passive thermal control systems, especially when used in high vacuum. On the other hand, there is a great number of variables, that can degrade the performance and effectiveness of MLI.

There is many materials which can be used as components of the blanket, but Teflon, Kapton and Mylar are, with some small innovations, the mainly used once since the development of the first MLIs. The problematic part is thus not material choice but the way of connecting these materials together and onto the spacecraft and at the same moment keeping the performance on the highest levels.

Lately some new studies have been conducted, trying to find a way to reduce solid condition through spacers and to avoid heat leaks through seams.

In the practical part of the thesis the configuration of a proposed test of MLI´s performance is describe. In the first part the used devices are named and after that the process of tests is explained. Following are the results and their interpretation.

The experiment showed the expected result, that the presence of MLI affects the Heat Flux. But it also raised more questions which need to be answered by further research.

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11 LIST OF FIGURES

12 LIST OF TABLES