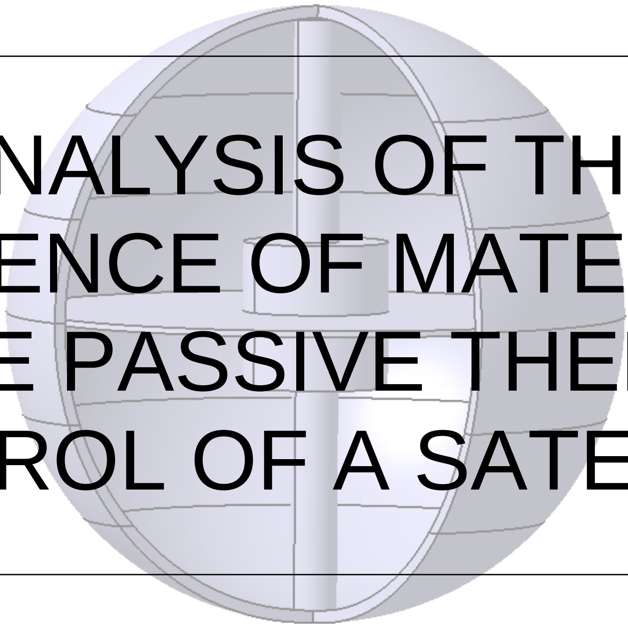
ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA DEL DISEÑO

UNIVERSIDAD POLITÉCNICA DE VALENCIA

FINAL YEAR PROJECT

MECHANICAL ENGINEERING BACHELOR DEGREE



ANALYSIS OF THE INFLUENCE OF MATERIALS IN THE PASSIVE THERMAL CONTROL OF A SATELLITE

By

VICENT ALCAYDE PEIXO

Tutor: ANA VERCHER MARTINEZ

Valencia, June 2019

“PER ASPERA AD ASTRA”

AGRAÏMENTS

A la meua família per el suport en estos 4 anys de carrera.
Als meus amics, per els bons moments i l’ajuda rebuda.
A la meua tutora, Ana Vercher, per haver-me encaminat de la millor manera en este projecte excel·lent ajuda.

ABSTRACT

The thermal control of a satellite consists on establishing the necessary thermal parameters involved in the process of heat transfer by radiation or conduction to be able to delimit the range of temperatures to which the different components will be exposed. If the obtained range involves temperatures that the different components of the satellite are unable to cope with, therefore, we will make an external control (or passive control), in which some additional elements, such as heaters or heat exchangers, will take action.

The following TFG is solely focused on the passive control. The running equations corresponding to the nodal equilibrium necessary for the aforementioned control will be programmed in Matlab. The resolution of these equations will provide as a result the equilibrium temperature that each area of the surface of the satellite reaches. All these surfaces will be considered isothermal, taking into account all the factors that affect them, such as solar radiation, albedo, planetary radiation, the radiation coming from other nodal surfaces of the same satellite, the heat conduction and the radiation of these nodal surfaces to the outer space.

Through the programming of this tool, the student will tackle the study of the influence of different materials used in the manufacturing of a satellite, from the standpoint of thermal behavior.

RESUMEN

El control térmico de un satélite consiste en establecer los parámetros térmicos necesarios involucrados en el proceso de transferencia del calor por radiación y conducción para acotar el rango de temperaturas al que serán expuestos los distintos elementos. Si el rango conseguido incluye temperaturas no admisibles por los componentes, entonces, será necesario efectuar un control externo (o control activo) en el que actúan elementos adicionales como calefactores o intercambiadores de calor.

El presente TFG aborda exclusivamente el control pasivo. Para ello, se programará en Matlab las ecuaciones de gobierno correspondientes al equilibrio nodal. La resolución de dichas ecuaciones dará como solución la temperatura de equilibrio que alcanza cada región considerada isoterma teniendo en cuenta la radiación solar, el albedo, la radiación planetaria, la radiación proveniente de otras superficies del propio satélite, fuentes internas de calor, el proceso de conducción de calor y la radiación de dichas superficies al espacio exterior.

Mediante la programación de esta herramienta, el alumno abordará el estudio de la influencia de diferentes materiales empleados en la fabricación del satélite desde el punto de vista de su comportamiento térmico.

RESUM

El control tèrmic d'un satèl·lit consistix en establir uns paràmetres tèrmics necessaris involucrats en el procés de transferència del calor per radiació i conducció per a acotar el rang de temperatures al que seran exposats els distints elements. Si el rang aconseguit inclou temperatures no admissibles per als components, doncs, hi serà necessari efectuar un control extern (o control actiu) en el que actuaran elements addicionals com calefactors o intercanviadors de calor.

El present TFG aborda exclusivament el control passiu. Per a portar-lo a terme, es programaran amb Matlab les equacions de govern corresponents al equilibri nodal. La resolució de les nomenades equacions donarà com a solució la temperatura de equilibri que aconseguirà cada regió considerada isoterma tenint en conter la radiació solar, el albedo, la radiació planetària, la radiació provinent de altres superfícies del propi satèl·lit, fonts de calor internes, el procés de conducció de calor i la radiació de la nomenades superfícies al espai exterior.

Mitjançant la programació d'aquesta ferramenta, l'alume abordarà l'estudi de l'influencia de diferent materials utilitzats en la fabricació d'un satèl·lit des de el punt de vista del comportament tèrmic.

WORK STRUCTURE

1. REPORT
2. BUDGET
3. SCHEDULE OF CONDITIONS
4. APPENDIX
5. BIBLIOGRAPHY

LIST OF FIGURES

LIST OF TABLES

DOCUMENT 1

REPORT

Author: VICENT ALCAYDE PEIXO
Tutor: ANA VERCHER MARTINEZ

TABLE OF CONTENTS

1. INTRODUCTION

Currently, there have been many technological developments that, some years ago, were unthinkable of. Who could have imagined, just passed the 20th century, when they saw the Wright brothers invent and fly the first plane of the world, or 50 years ago, when they were watching the moon landing on TV, that we were going to be able to live in Mars, as the company Space X plans to achieve by 2024 [1][2][3]. It is obvious that there has been an exponential growth in our technology during the last years.

The pursuit of advancing and reaching goals that people might not even imagine is what moves both scientists and engineers alike forward and leads them to think that something is not impossible, but that they have just not tried hard enough.

1.1. OBJECTIVES AND JUSTIFICATION

Nowadays, the launch of spacecraft into Earth's orbit and the outer space has been a very notorious topic in the scientific community. The amount of spacecraft launches that have taken place in the recent years cannot even be compared to the amount the world saw 10 years ago. The emergence of new aerospace manufacturers, space transportation and research companies has marked the biggest increase in this field since the *Space Race*, back when the United States went head-to-head against the Soviet Union to achieve dominance in the spaceflight capability area.

Next, we are going mention some of the companies that, in my opinion, have changed the current spaceflight landscape. The most recently heard in the game is Space X, founded and leaded by the entrepreneur Elon Musk. Space X has achieved amazing statistics successfully launching around 77 rockets in a little more than a decade. Some of their most notable launches have been:

- The famous Falcon Heavy, the one that put Elon Musk’s Tesla car with a dummy payload into the Sun’s orbit using Mars gravitational traction.

Figure 1. Falcon Heavy's launching. Ref [17]

- Project Starlink. It has carried 60 satellites all at once in a spacecraft, and plans to deploy nearly 12000 satellites in three orbital shells by the mid-2020s for developing a low-cost, high-performance space-based Internet communication system

Figure 2. Starlink 60 satellites in Falcon 9's fairing. Ref [18]

- The one in which they achieved to reuse the first stage of their Falcon 9, in order to make spacecraft missions cheaper.

Figure 3. Falcon 9's first stage landing. Ref [19]

This growth in the volume of launchings has brought very interesting advantages and improvements to the spacecraft technology, and not only the advantages these projects have per se, but also the technological advantages that are developed in order to achieve these new goals. Therefore, being the surface one of the most important components of a satellite (since it has to face every radiation that reaches the machine), I proceed to study the different behaviors that the surface could experience depending on where the satellite is situated, and the performance of the satellite as a whole depending on the surface finish.

All the analysis will be done using MATLAB, a high-performance language for technical computing; that is to say, a matrix calculation tool for post-processing of data.

1.2. MOTIVATION

The motivation of doing the present thesis was born when I went on an Erasmus course to Copenhagen, Denmark. I stayed in the Technical University of Denmark (DTU) for a whole semester, and, in one of the subjects that I did there, more specifically *Introduction to Spacecraft Systems and Design*, we studied all the parts and mechanisms of a satellite, as well as all the processes needed or involving the launch of a satellite into the Earth's orbit.

We investigated, analyzed and learned subjects such as telecommunication systems, orbital mechanics, space environments, spacecraft structures and thermal control among many others. However, the one that amazed me the most and I thought would be very interesting to learn more about was thermal control. Moreover, thermodynamics is a subject that I have been in contact with for almost the entirety of my Bachelor degree, so I have a bit of experience in this specific area.

Hence, the main motivation of this thesis is both to broaden my knowledge on this matter, and to know more about a topic that, in a few years' time, could become one of the main fields of concern in the satellite's field

Finally, the other reason for me to do this very thesis is to close a stage in my life, to obtain my Mechanical Engineering certificate and to be able to work all around the world in what I am interested and I find amazing, which is Mechanical Engineering.

2. THERMAL CONTROL BACKGOUND

2.1. INTRODUCTION

In every space mission involving the launch of a satellite, almost every part and gadgets of the satellite being launched must meet certain criteria or requirements related to thermal behavior. The two main reasons behind the concerns of thermal control are: firstly, electronic and mechanical devices usually operate efficiently and reliably within relatively narrow temperature ranges, and secondly, most materials used in the satellites have non-zero coefficients of thermal expansion and, therefore, any considerable change in the temperature implies some kind of thermal distortion.

The reason for these mechanisms to function in this certain temperatures not common in space is that they were originally designed for terrestrial use, and, therefore, they operate most effectively at room temperature, and their efficiency lowers quite a bit when they are out of the “room temperature” range. That is also because developing these mechanisms at room temperature is much cheaper

The thermal requirements of a satellite’s equipment are, between minus 15ºC and 50ºC for its electronics, between 0ºC and 20ºC for rechargeable batteries, and around 0ºC and 50ºC for mechanisms such as gyroscopes, momentum wheels, solar array drives… There are some exceptions, like in the case of some detectors found within astronomical telescopes, which need to be cooled down to very low temperatures, for instance. That is the reason why the satellite needs to have some refrigeration.

2.2. BOUNDARY CONDITIONS

As I have asserted before, the environment to which the satellite is subjected is quite unique and distinctive. The high vacuum has some problems for the device while it takes away some others. Firstly, some satellites are disposed into orbits where the residual atmospheric pressure (and, hence, drag) does, in order for them to maintain the orbit, force the satellite to re-boost itself, as the International Space Station (ISS) does. At the end, even though there is a light drag, it does not imply any friction, and thus, any heat. So, for this reason, convective interaction between spacecraft and environment will be ignored. Otherwise, there would be immense calculations referring to this heat, since it always varies depending on how low it is in the Earth's atmosphere. Generally, satellites orbit the Earth at around 300km away from it. It can be measured that, in those altitudes, the atmospheric pressure drops to less than 10^{-7} mbar. Although there are some many more orbits with even less pressure, we are going to focus on this one.

Consequently, a spacecraft can only interact with its environment by radiation, which is defined as the transmission of energy. Such energy will come from different sources that I will study, and will be distributed as shown in the *Figure 4*:

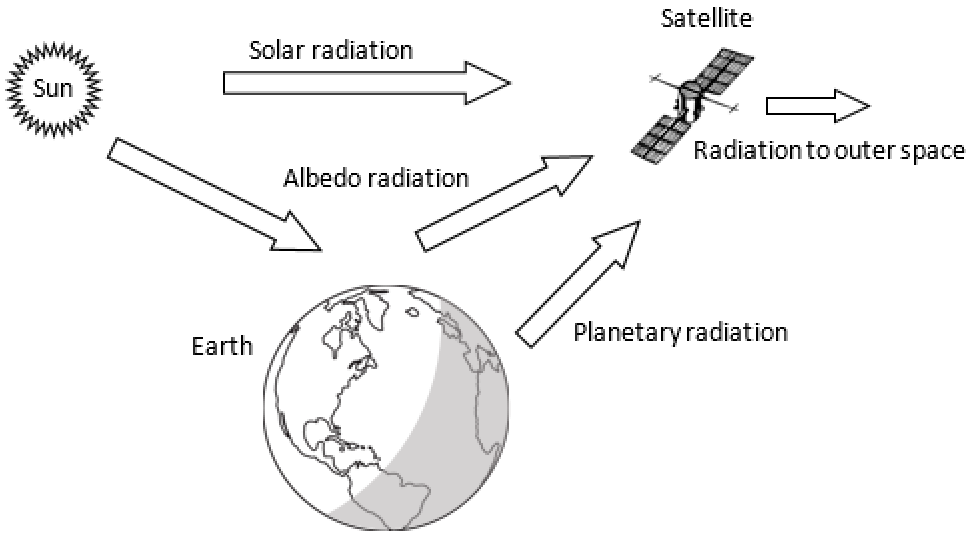


Figure 4. Spacecraft thermal environment

2.2.1. SOLAR RADIATION

Solar radiation is normally defined as the energy emitted by the sun. The spectral distribution of the solar system can be treated as constant throughout the whole solar system, and the spectral energy distribution, mostly known as solar irradiance, has an effective temperature of 5800ºK, as we can easily observe from the Planck curve:

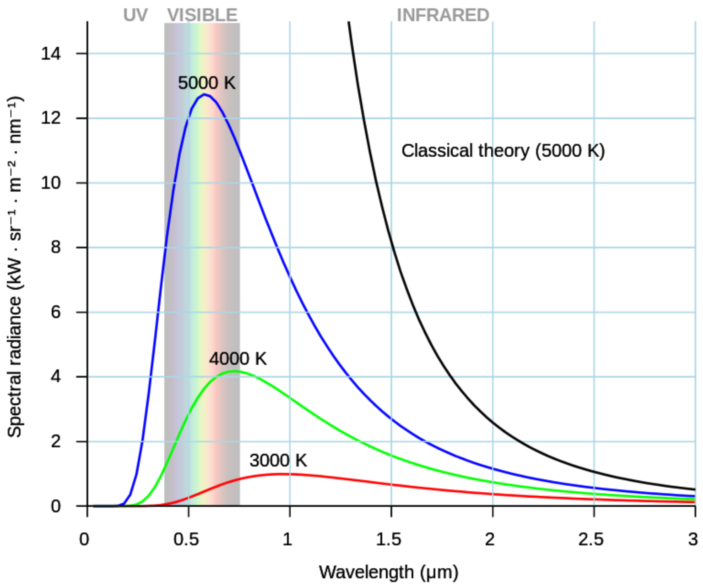


Figure 5. Curves from Planck's law. Ref [20]

In regards to the radiation intensity of the Sun, it is necessary to mention the international established measures to gauge this radiation intensity. The solar radiation intensity in the outer layers of the Earth's atmosphere at the Earth's average distance from the Sun (1 AU that is about 150 million kilometers) is named the solar constant, and it is about 1371±5 W/m^2.

Nevertheless, if we want to calculate the solar radiation at any other distance, like in our case, we need to apply the following equation [5]:

$$J_s = \frac{P}{4\pi d^2}$$

In the aforementioned equation, which helps us calculate the solar radiation at any distance, we define *P* as the power output of the Sun, being this one equal to 384.6 yotta watts (3.846×10^{26} watts) [4] and *d* being equal to the distance from the Sun.

2.2.2. ALBEDO RADIATION

The Albedo radiation, which is the measure of diffuse reflection of solar radiation out of the solar radiation received from the Earth; in this case, or in other words, it is the fraction of the solar radiation that is reflected from the surface of a planet. It is measured in a scale comprising between 0, which corresponds to a theoretical black body, and 1, to a body that reflects all incident radiation.

The measurement of the albedo depends on a lot of factors, such as the weather. If there is snow, as well as clouds, the albedo is higher, since the surface is white and reflects sunlight away, leading to local cooling. Just the opposite happens when we look at the reflection of the sunlight in forests, fields, desserts, etc. Finally, we have the water, which makes up almost three quarters of the Earth's surface. When we analyze the reflection of the sunlight in the water of seas, lakes and oceans, we perceive that it behaves differently from any other terrestrial material. It depends on water movements and refraction. It is calculated using the Fresnel equations.

As an interesting fact, the Earth's albedo creates a negative feedback in which the low temperatures increase the amounts of ice on Earth, thus making it whiter, which in turn increases its albedo and reflects more sunlight making it colder, consequently creating more ice. Theoretically, the point in which the Earth would be a snowball could be reached.

As it can be easily ascertained from the information given above, the albedo can easily vary. Therefore, it is important to take an average number for the Earth, in order to make these calculations as rigorous as possible. We will take 0.33 as the Earth's albedo number. As a representative fact, we will display a table with the albedo of the different planets in the Solar System:

Planet	Planetary albedo
Mercury	0,06 - 0,10
Venus	0,60 - 0,76
Earth	0,31 - 0,39
Moon	0,07
Mars	0,15
Jupiter	0,41 - 0,52
Saturn	0,42 - 0,76
Uranus	0,45 - 0,66
Neptune	0,35 - 0,62
Pluto	0,16 - 0,40

Table 1. Solar system albedo values. Ref [5]

Nevertheless, to be able to calculate the intensity of the albedo radiation (*Ja*) pounding on a spacecraft, it is necessary to make use of the following equation [5]:

$$J_a = J_s a F$$

Being *Js* equal to the solar radiation at a given distance *d*, as we have asserted in the Solar Radiation chapter, *a* equals to the albedo *per se* of any planet, with it being the Earth in our case, and finally the *F*, being equal to the visibility factor, assumed as 0.15.

2.2.3. PLANETARY RADIATION

Planetary radiation is the term we use to refer to the energy radiated from nearby planets. Although all planets in the solar systems have non-zero temperatures and consequently radiate heat, we will consider the Earth's planetary radiation as the main radiation from a planet affecting our analyzed spacecraft. Due to its low temperature, the heat radiated by the Earth is found at infrared wavelengths, between about 2 and 50 µm.

Due to changes on weather, seasons and many other factors that the Earth has, the terrestrial temperatures are bound to vary with geographical location and time. On account of what has just been mentioned, there is a need, as well as in the albedo radiation, to take an average value in order to not fall into too much measurement errors. For pragmatic purposes and for the sake of calculating the Earth's planetary radiation, while taking into account that its intensity falls with altitude, we define the planetary intensity with the following equation:

$$J_p = 237\left(\frac{R_{rad}}{R_{orbit}}\right)^2$$

On the equation above, we find R_{orbit}, which is the distance to which the satellite is located from the center of the Erath. We also find R_{rad}, which is defined as the radius of the Earth's effective radiating surface. We assume this last factor equals to the Earth's surface radius. Such an assumption would not feasible for planets that lack an atmosphere and, therefore, have temperatures that vary way more than in the relatively controlled environment that the Earth's surface is.

2.2.4. SPACECRAFT RADIATION

Spacecraft radiation could be defined as the energy radiated from the spacecraft onto the deep space. This is the only radiation that does not belong to the boundary conditions, but it is necessary for describing the thermal equilibrium of the satellite, since the spacecraft radiation must be equal to the sum of the other radiations in order to maintain the thermal equilibrium and ensure the correct functioning of all the devices. In theory, the spacecraft has a finite temperature produced by the batteries, which are the only elements in the spacecraft with own heat, and therefore radiating heat onto the environment. Moreover, in a theoretically isolated environment, due to the heat of the batteries and the consequent radiation emitted from them, the environment would reach the same temperature as the batteries.

3. THERMAL ANALYSIS

3.1. INTRODUCTION

As we have briefly mentioned in the last sections, the main premise for the whole calculations of equilibrium and balance of temperatures is that, in order to maintain the convenient range of temperatures, the heat received from internal and external sources has to be equal to the heat radiated to the environment by the satellite.

Therefore, clarifying when and how the external radiation will affect, it is necessary to say that, firstly, the planetary radiation is independent to the position of the satellite, since it will always be at the same distance from the Earth, and this radiation cannot be blocked by anything. Secondly, the solar radiation is dependent to the position of the satellite and the possibility of this one being blocked from the Sun by the Earth. In order to simplify a bit the calculations, we will suppose the satellite orbits the Earth following its equator. Thus, the satellite will receive solar radiation when it is situated on the trace of its orbit, which is not in the shadow of the Earth. Finally, since the albedo radiation depends on the solar radiation, it will radiate the satellite whenever the sun does. It is a complicated and varying number, that, as we have stated before, is simplified in an average.

To sum up, there are two situations in which the satellite is under the effect of the sum of different values, both of them explained in more detailed in the next sections:

- Sunlight zone:

$$Radiation\ recieved = Solar\ rad + Albedo\ rad + Planetary\ rad$$

- Shadow zone:

$$Radiation\ recieved = Planetary\ rad$$

Hence, knowing all the main radiations that the spacecraft receives during its lifetime orbiting the Earth and the time-lapses in which it is under certain radiations. It is necessary to determine if it would be necessary to use refrigeration for cooling down or heating up all the equipment, gadgets and mechanisms that require a certain range of temperatures in the case of the satellite not being able to dissipate all the heat by itself or not being able to cope with too low temperatures.

3.2. THERMAL BALANCE

It has already been mentioned that to maintain an adequate temperature for a satellite's mechanisms and gadgets proper functioning depends directly on the balance between the heat received from all the aforementioned external radiations, the internal heat and the heat radiated from the spacecraft to the environment. This correlation, from which we obtain the equilibrium temperature, is explained by the following equation:

$$\alpha A_{solar} J_s + \alpha A_{albedo} J_a + \varepsilon A_{planetary} J_p + Q_{internal} = \varepsilon \alpha A_{space} T^4$$

On it, every component of the equation equals to one of the aforementioned parts that alter the balance and equilibrium of temperatures. Each component is described as this:

- Solar radiation → $\alpha A_{solar} J_s$
- Albedo radiation → $\alpha A_{albedo} J_a$
- Planetary radiation → $\varepsilon A_{planetary} J_p$
- Internally dissipated power → $Q_{internal}$
- Heat radiated to space → $\varepsilon \alpha A_{surface} T^4$

We can find the already explained variables J_a, J_p and J_s being calculated as follows:

$$J_p = 220\ W/m^2\ (corresponding\ to\ an\ orbit\ altitude\ of\ 240\ km)$$
$$J_s = 1371\ W/m^2$$
$$J_a = 67.86\ W/m^2\ (corresponding\ to\ an\ Earth\ albedo\ of\ 0.33)$$

In addition, we can also find the variables α and ε; the first one equal to the absorptance of the surface's material, while the second one equals to the emittance of the surface's material. These will be the parameters that will undergo modifications in the following sections in order to analyze different materials, their effectiveness and behavior, and how they shield from the different radiations.

Finally, we find A_{solar}, A_{albedo} and $A_{planetary}$, which are the areas receiving, respectively, solar, albedo and planetary radiation; on a side note, $A_{surface}$ is the total area of the satellite. Using as our subject, for simplicity's sake, a spherical satellite of 1 meter of diameter (as we can see in the Figure 6), we can assume and calculate the different areas, and, since A_{solar}, A_{albedo} and $A_{planetary}$ are the same, and equal to the area of a circle, this is what it is seen from one side of the satellite:

$$A_{solar}, A_{albedo}, A_{planetary} = \pi r^2 = \pi \frac{1}{2^2} = \frac{\pi}{4}$$
$$A_{space} = 4\pi r^3 = 4\pi \frac{1}{2^3} = \pi$$

In order to better analyze the distribution of temperatures in the spacecraft, we will divide the external shield of the satellite into 6 parts with the same surface, as shown in the Figure 6. We will also divide the internal components, such as the superior and inferior axis (numbers 10 and 7, respectively), a central plate for support (number 9) and the batteries (number 8). The batteries are the only ones that produce internal heat, and the only ones which initial temperatures is 293ºK and not 273ºK, as the rest of the nodes.

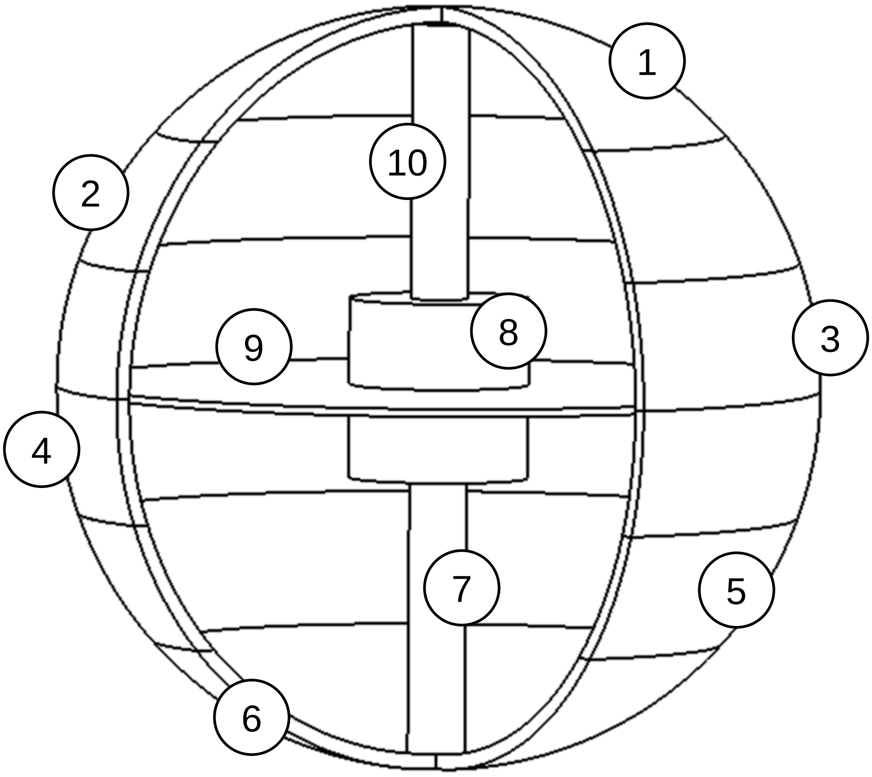


Figure 6. Satellite design with node description

3.3. NODAL ANALYSIS

My approach to the steady-state analysis consists, as aforementioned, in dividing the satellites in *n* nodes (10 nodes, in our case), and analyze the temperatures that each of them reaches when the satellite is situated in the sunlight zone, that is to say, receiving solar, albedo and planetary radiation. Hence, the following equation represents the relationship between all radiations affecting the satellite, the internal heat, the radiation that the satellite itself radiates to the space, and the division and characteristics of each node:

$$m_i C_i \frac{dT_i}{dt} = Q_{external,i} + Q_i - \sigma \varepsilon_i A_{space,i} {T_i}^4 - \sum_{j=1}^{n} h_{ij}(T_i - T_j)$$
$$- \sigma \sum_{j=1}^{n} A_i F_{ij} \varepsilon_{ij} ({T_i}^4 - {T_j}^4)$$

In this equation, m_i equates to the mass of each node. All nodes in the surface (from 1 to 6) have the same thickness and area, consequently they will have the same mass; c_i is the specific heat of each node, which would depend on the material used to build the satellite, and not on the coat or material used on the surface.

Finding the internal heat Q_i, and the heat radiated to the outer space $\alpha \varepsilon_i A_{space,i} T_i^4$, as well as $Q_{external}$ (which is represented like this):

$$Q_{external,i} = J_s \alpha_i A_{solar,i} + J_a \alpha_i A_{albedo,i} + J_p \varepsilon_i A_{planetary,i}$$

will enable us to find T, which is the temperature of each node, as well as ε_{ij}, which is the effective emittance between two surfaces inside the satellite. It has a complicated dependence on surfaces' optical properties, mutual reflections and reflections via other nearby surfaces. Owing to the fact that errors from this value are rather small, and that the surfaces involved are diffuse and have a relatively high ε value, it is okay to assume that the interior all of them is painted in white, and that their emittance values are equal to 0.82.

Finally, we have two more values defined by the shape of the satellite. First of all, we have *h*, which is the conductance term, and, secondly, we have the *AF* factor, which is the area×view-factor. On account of our satellite, which has a spherical shape of 1 meter of diameter, and contains an axis divided in two, batteries and a structural plate that divides the spacecraft in two semi-spheres, the area×view-factor relating 2 surfaces each time can be calculated the, as seen in the following Table 2. In addition, the conductance term, which depends on the shape, can also be calculated and is also described in the Table 3:

Nodes	1	2	3	4	5	6	7	8	9	10
1	-	0,068	0,079	0	0	0	0	0,013	0,215	0,058
2	0,068	-	0,089	0	0	0	0	0,018	0,241	0,031
3	0,079	0,089	-	0	0	0	0	0,016	0,246	0,018
4	0	0	0	-	0,089	0,079	0,018	0,016	0,246	0
5	0	0	0	0,089	-	0,068	0,031	0,018	0,241	0
6	0	0	0	0,079	0,068	-	0,058	0,013	0,215	0
7	0	0	0	0,018	0,031	0,058	-	0,0027	0,031	0
8	0,013	0,018	0,016	0,016	0,018	0,013	0,0027	-	0,054	0,0027
9	0,215	0,241	0,246	0,246	0,241	0,215	0,031	0,054	-	0,031
10	0,058	0,031	0,018	0	0	0	0	0,0027	0,031	-

Table 2. View-factor × area products (m^2). Ref [5]

Nodes	1	2	3	4	5	6	7	8	9	10
1	-	1,03	0	0	0	0	0	0	0	0,18
2	1,03	-	2,1	0	0	0	0	0	0	0
3	0	2,1	-	2,54	0	0	0	0	1,41	0
4	0	0	2,54	-	2,1	0	0	0	1,41	0
5	0	0	0	2,1	-	1,03	0	0	0	0
6	0	0	0	0	1,03	-	0,18	0	0	0
7	0	0	0	0	0	0,18	-	0,16	0	0
8	0	0	0	0	0	0	0,16	-	0,94	0,16
9	0	0	1,41	1,41	0	0	0	0,94	-	0
10	0,18	0	0	0	0	0	0	0,16	0	-

Table 3. Conductance terms (W/K). Ref [5]

3.3.1. STEADY STATE

The steady-state case consists on calculating the temperatures of each node of the satellite in a certain moment, when in the sunlight zone. When the steady-state is analyzed, it is done by assuming it in the sunlight zone in order to calculate the worst case scenario, that is to say, one in which $Q_{external}$ will be constant and equal to the sum of all the radiations introduced previously.

As a result, and due to the nodal analysis equations not being amenable to analytical solution, it is necessary to linearize [5] like this:

$$T_i{}^4 = \left(T_{i,0} + \delta T_{i,0}\right)^4 \approx T_{i,0}{}^4 + 4T_{i,0}{}^4 \delta T_{i,0}$$

Therefore:

$$T_i{}^4 \approx T_i\left(4T_{i,0}{}^3\right) - 3T_{i,0}{}^4$$

By substituting this linearization in the nodal analysis' main equation and considering dT_i/dt equals to 0, we obtain the following equation, where we set an initial temperature, T_0, of 273ºK for each node but for the batteries, which will be set at 293ºK.

$$T_i\left[\sum_{j=1}^{n} h_{ij} + 4\sigma T_{i,0}{}^3 \left(A_{space,i}\varepsilon_i + \sum_{j=1}^{n} A_i F_{ij}\varepsilon_{ij}\right)\right] - \sum_{j=1}^{n} T_j\left[h_{ij} + 4\sigma T_{j,0}{}^3 A_i F_{ij}\varepsilon_{ij}\right] =$$

$$= Q_{external,i} + Q_i + 3\sigma T_{i,0}{}^4 A_{space,i}\varepsilon_i + 3\sigma \sum_{j=1}^{n} (T_{i,0}{}^4 - T_{j,0}{}^4)\, A_i F_{ij}\varepsilon_{ij}$$

In here, all the variables have already been defined and explained. The procedure to transform this general equation into a matrix will be resumed into 3 nodes, in order to facilitate the comprehension of the calculus. In the programming section, where the program made in Matlab is explained, this, as well the transient nodal analysis, will be resolved in detail.
The graphic representation of this matrix is shown in the Appendix File 1.

3.3.2. TRANSIENT

In the transient analysis, unlike with the steady-state, we analyze the satellite performance taking into consideration the time, the movement that it has and the temperatures' evolution. We take into account whether the satellite stands in either the sunlight or shadow zones, and the corresponding radiations that affect it at every moment.

As well as with the steady-state nodal analysis, the transient nodal analysis needs the use of numerical methods and linearization in order to be calculated. Therefore, we will use the same method as with the temperatures, which will also make us use the following linearization:

$$T_i^{\,4} \approx T_i\left(4T_{i,0}^{\,3}\right) - 3T_{i,0}^{\,4}$$

Apart from this linearization, we substitute the left member of the nodal analysis equation by the following equation:

$$m_i C_i \frac{dT_i}{dt} \rightarrow m_i C_i \frac{(T_i - T_{i,0})}{\delta t}$$

Furthermore, we will also substitute the temperature and heat inputs by the average values over the time interval *δt,* as seen in the following equations:

- $T_i \rightarrow \left(T_i + T_{i,0}\right)/2$

- $T_j \rightarrow (T_j + T_{j,0})/2$
- $Q_{external,i} \rightarrow (Q_{external,i} + Q_{external,i,0})/2$

Being the $Q_{external,i}$ the external radiations affecting the spacecraft in the studied instant, and $Q_{external,i,0}$ the computed temperatures an instant before.

By doing these substitutions, we provide the temperature history at successive intervals of time. The shorter the interval, the less the temperatures will vary, which will consequently provide us a more detailed graph of each node's evolution of temperatures.

Summing up the linearization and all the substitutions, we obtain a quite big equation of matrixes, as we obtained with the steady-state analysis, that will be showed in the Appendix File 2.

4. MATERIALS

4.1. INTRODUCTION

Knowing the properties of the materials proves crucial when selecting one specific material as the coating for the spacecraft's surface. The solar absorptance and thermal emittance of a material are two critical characteristics when determining the spacecraft's temperature control. These properties are previously tested, in order to examine each material, and its resilience to the degradation that it may suffer, such as the one created by outgassing, ultraviolet radiation, particle damage, etc.

For all the aforementioned reasons, it is vital to conduct some laboratory experiments and assert which materials work better as surface coating. We will next list some of the most important and broadly used materials in aerospace engineering, and the reasons behind choosing them.

4.2. STRUCTURAL MATERIALS

Firstly, defining the structural materials, or the materials that the satellite is mainly made of, is a very important decision and it will therefore have an impact on the calculations of our analysis. The structural materials are the ones that will conduct the heat, and its specific heat, amongst other things, defines how easy will it be to increase the temperature. Based on the aforementioned, the lower a specific heat, the more temperature it will need to be increased by one unit.

The material also defines, obviously, the weight of the satellite. The heavier a satellite, the worse, as the launch vehicle will have to lift more weight per satellite, thus being able to carry fewer satellites.

Summing up, we require a structural material that meets a low specific heat and low density, so it does not weight much and transmits little heat. The most commonly used materials in the aerospace field are [6,7]:

4.2.1. TITANIUM

The materials satellites are made of have to meet some strict requirements, including being able to withstand vibrations, high pressures, extreme temperatures, radiation, the impact of small asteroids, etc. As a result, materials such as titanium are very demanded and used, on account of its characteristics. First of all, it is a tenacious, unwavering and very resistant material, which is also paramagnetic, that is to say, it does not get magnetized due to its electronic structure. Moreover, it is resistant to corrosion and oxidation.

Nonetheless, as well as with every material used in a satellite's structure, its most important trait is how lightweight it is. Owing to the fact that the majority of a satellite's weight comes from its structure, as previously mentioned, a strong, enduring and lightweight material is needed.

4.2.2. CARBON FIBER

As with titanium, carbon fiber works well due to how lightweight it is, from amongst other properties such as its high specific resistance, as well as its specific rigidity module, which makes it a very strong material. Moreover, it has an excellent resistance to both humidity and solvents.

4.2.3. ALUMINIUM

For the exact same reasons, the aluminium meets the requirements of enduring vibrations, high pressures, radiation, impacts of small asteroids, etc. Aluminium is probably the most used material for building a satellite's structure in the last missions due to its low cost, and also for being resistant to corrosion.

Due to its fairly widespread use, the aluminium will be our pick as the structural material of our satellite, so we will therefore analyze it.

As shown in the Figure 6, besides the batteries, which made of Lithium-Ion, and the external coating, all the other parts will be made out of aluminium. Thus, in order to calculate its mass, we will make use of the following equations, with them depending ones on each node, since they have different shapes, and acknowledging that the density of the aluminium is equal to 2.7 g/cm^3.

- Each node of the shell (Nodes from 1 to 6)

$$V = \left(\frac{4}{3}\pi R^3 - \frac{4}{3}\pi r^3\right)/6 = \left(\frac{4}{3}\pi 50^3 - \frac{4}{3}\pi 47^3\right)/6 = 10058.68\ cm^3$$

$$m = V \times density = 10058.68 \times 2.7 = 27.16\ kg$$

- Each half axis (Nodes 7 and 10)

$$V = \pi r^2 h = \pi \times 3.75^2 \times 87.85 = 1940.55\ cm^3$$

$$m = V \times density = 1940.55 \times 2.7 = 5.24\ kg$$

- Gold plate (Node 9)

$$V = \pi r^2 h = \pi \times 48^2 \times 1 = 7238.23\ cm^3$$

$$m = V \times density = 7238.23 \times 2.7 = 19.54\ kg$$

- Batteries (Node 8)

$$V = \pi r^2 h = \pi \times 11.75^2 \times 11.75 = 5096.40\ cm^3$$

Summing up, in the Table 4, all the masses, specific heat of each part of the satellite and data needed for the calculations are portrayed.

*Please, note that the mass showed in the following table does not represent the whole volume destined to the batteries full of Lithium-Ion. It is the mass of four Lithium-Ion batteries, which, according to its datasheet [9], occupy more less the same space.

Nodes	Volume (cm^3)	Material	Density (g/cm^3)	Mass (kg)	Specific Heat (J/kg·K)
Node 1	10058,68	Aluminium	2,7	27,16	880
Node 2	10058,68	Aluminium	2,7	27,16	880
Node 3	10058,68	Aluminium	2,7	27,16	880
Node 4	10058,68	Aluminium	2,7	27,16	880
Node 5	10058,68	Aluminium	2,7	27,16	880
Node 6	10058,68	Aluminium	2,7	27,16	880
Node 7	1940,55	Aluminium	2,7	5,24	880
Node 8	5096,40	Lithium-Ion Batteries	-	8,08	950
Node 9	7238,23	Aluminium	2,7	19,54	880
Node 10	1940,55	Aluminium	2,7	5,24	880

Table 4. Mass and specific heat of each node. Ref [8-10]

4.3. COATING MATERIALS

The coating materials used on a satellite greatly influence how the satellite will do in terms of coping with temperatures, and in what measure they will influence the spacecraft. For this reason, based on the well-explained programming in the next section, we will analyze each of the materials explained below.

This is the main analysis of the thesis. To observe which material, based on its properties and, of course, its capabilities, is able to withstand temperatures and behave in the best way so that the satellite does not require to have much active control.

We will be explaining the materials that we will analyze in the Results section. Each material will be described based on its emittance (ε) and absorptance (α), essential factors, as we said, for the calculation of the temperatures in function of which material is used on the satellite's surface.

4.3.1. OPTICAL SOLAR REFLECTORS (OSR)

The Optical Solar Reflectors are artificially made surfaces intended to reflect the incoming radiation while simultaneously radiating internally generated heat. They are known for having a low absorption coefficient, which is the relation between absorptance and emittance (α/ε). Therefore, the coating of a satellite consisting on an OSR will be bound to be generally cold.

Then, we will focus on some Optical Solar Reflectors, when or how have they been used, and their absorptance and emittance ratios, which are the ones that condition our analysis [5, 12-14].

4.3.1.1. SILVERED FUSED SILICA

Fused Silica, also known as fused quartz, is glass consisting of an amorphous form of silica, that is to say, in a non-crystalline form. Since it transmits ultraviolet light better than other glasses, it is commonly used for making lenses and optics for ultraviolet spectrum. Ultimately, the silvered fused silica is just regular fused quartz treated with silver; this is done with the intent of obtaining a better experimental coating.

Its absorptance is 0.07 and its emittance is 0.80, being its absorption coefficient equal to 0.0875.

4.3.1.2. INDIUM-TIN-OXIDE (ITO)

The Indium Tin Oxide is a chemical ternary composition made out of indium oxide and tin oxide. Depending on its oxygen contents, it can be described either as a ceramic or as an alloy.

Because of its electrical conductivity and optical transparency, as well as the ease with which it can be manufactured as a thin film, it is widely used in flat-panel displays, smart windows, thin photovoltaic films, etcetera..

Its absorptance is 0.07 and its emittance is 0.76, being its absorption coefficient equal to approximately 0.0921.

4.3.1.3. ALUMINIZED TEFLON (0.5 mm)

The Aluminized Teflon consists on a material commercially known as Teflon, which has been treated with aluminium in order to improve its oxidation and corrosion resistance. This treatment is called Aluminizing.

Teflon, or Polytetrafluoroethylene, is a fluoropolymer of tetrafluoroethylene, which is also known as the most slippery human-made substance. This sample consists on an Aluminized Teflon of 0.5 millimeters of thickness.

Its absorptance is 0.14 and its emittance is 0.40, being its absorption coefficient equal to 0.35.

4.3.1.4. ALUMINIZED TEFLON (10 mm)

This material, as with the previous one, consists on an Aluminized Teflon, which shares the same exact characteristics, except for its thickness, which is now at 10 millimeters of thickness.

Its absorptance is 0.15 and its emittance is 0.85, being its absorption coefficient equal to around 0.1765.

4.3.1.5. SILVERED TEFLON (2 mm)

Akin to the two previous coatings, this one also consists of a treatment applied to the Teflon. In this case, the treatment is called silvering, which consists in applying a coating onto a glass surface to make increase its reflectivity. Yesteryear, this technique was used in the process of fabricating mirrors; nowadays, however, it has been substituted by an aluminium coat, due to its cost-effectiveness.

However, it has still been used in some modern telescopes, such as the one in the Kepler space observatory.

Its absorptance is 0.08 and its emittance is 0.68, being its absorption coefficient equal to around 0.1176.

4.3.1.6. SILVERED TEFLON (10 mm)

In the same way as with the previous one, this material consists of Silvered Teflon, with the same exact characteristics as the later but for its thickness, which now is 10 millimeters thick.

Its absorptance is 0.09 and its emittance is 0.88, being its absorption coefficient equal to around 0.1023.

4.3.2. BLACK COATINGS

A black coating is characteristic for being a dark surface, which is the result of absorbing almost all visible light. In our terms, these black coatings will have both a high absorptance and a high emittance. Therefore, the satellites with a black coating will be bound to be generally hot, or, at least, its temperatures will vary depending on whether it is on the shadow or directly under the sun, as we will see in the results section.

Owing to what has been said, we will focus on some black coatings, on when or how have they been used, and their absorptance and emittance rates, which are the ones that will condition our analysis [5, 12-14].

4.3.2.1. CATALAC BLACK PAINT

This specific paint has a unique formula created by the NASA, in the NASA-GSFC program. The Goddard Space Flight Center has done some research in the field of materials, and has developed some new ones with specific properties to supply different and specific functions in some space missions.

Therefore, its absorptance is 0.96 and its emittance is 0.88, being its absorption coefficient equal to around 1.091.

4.3.2.2. DELRIN BLACK PLASTIC

Delrin is one of the commercial names for the Polyoxymethylene (POM), also known as acetal, polyacetal, or polyformaldehyde. It has excellent strengthening properties, which makes it perfect for precision parts that require high stiffness, low friction and great dimensional stability.

Its absorptance is 0.96 and its emittance is 0.87, being its absorption coefficient equal to around 1.1034.

4.3.2.3. MARTIN BLACK VELVET PAINT

This paint is characteristic for having a high emissivity, minimal spectral features, and being fabricated by a repeatable process, consequently having a long history of successful space-borne instrument use.

Its absorptance is 0.91 and its emittance is 0.94, being its absorption coefficient equal to around 0.9681.

4.3.2.4. PARSONS BLACK PAINT

This specific coating was first used by NASA's Ames Research Center in a satellite experiment launched on February 3th, 1965. Being the satellite's orbit roughly circular, with an altitude of 600 km.

In addition to the aforementioned, its absorptance is 0.98 and its emittance is 0.91, being its absorption coefficient equal to around 1.0769.

4.3.2.5. VEL-BLACK

Vel-Black is a coating made by Energy Science Laboratories Incorporation. It is a registered brand, therefore, with a commercial name, that offers a low reflectance optical coating, mainly characterized by its stray-light suppression.

Therefore, its absorptance is 0.99 and its emittance is 0.95, being its absorption coefficient equal to around 1.0421.

4.3.3. WHITE COATINGS

A white coating is mainly composed of a white surface, which is the lightest color, thus reflecting and scattering almost all visible wavelengths of light. As a result, these white coatings will have both rather low absorptance and high emittance rates, producing a decrease in the satellite's temperature due to not absorbing the heat from the radiation received, as we previously stated.

Seeing that, we will focus on some white coatings, when or how have they been used, and their absorptance and emittance rates, which are the ones that condition our analysis [5, 12-14].

4.3.3.1. BARIUM SULPHATE WITH POLYVINYL ALCOHOL

Barium sulphate is a white inorganic compound the formula of which is $BaSO_4$. Its white opaque appearance and its high density are exploited in some applications, such as polyvinyl alcohol mixes, an effective emulsifying film forming that has an excellent adhesive quality.

Therefore, its absorptance is 0.06 and its emittance is 0.91, being its absorption coefficient equal to around 0.0659.

4.3.3.2. CATALAC WHITE PAINT

This concrete substance shares the same exact characteristics, properties and origin with its black homonym, the Catalac black paint.

Its absorptance is, therefore, 0.24 and its emittance is 0.90, being its absorption coefficient equal to around 0.267.

4.3.3.3. NASA/GSFC NS-74 WHITE PAINT

In this case as well, as its very own name gives away, it is a material created by the NASA Goddard Space Flight Center, where, as it has been said, they create and develop materials and coatings to supply different situations and functions.

Therefore, its absorptance is 0.17 and its emittance is 0.92, being its absorption coefficient equal to around 0.267.

4.3.3.4. MAGNESIUM OXIDE ALUMINIUM OXIDE PAINT

As it can be easily inferred from its name, this paint is a mix of magnesium and aluminium oxides. The magnesium oxide (MgO), or magnesia, is a white hygroscopic solid mineral, whereas aluminium oxide (Al_2O_3) is a chemical compound of aluminium and oxygen, that has great refractory properties due to its high melting point.

Seeing that, its absorptance is 0.09 and its emittance is 0.92, being its absorption coefficient equal to around 0.0978.

4.3.3.5. WHITE POLYURETHANE PAINT

Polyurethane paints for coatings are renowned for their excellent chemical resistance, as well as for being hard and tough finishes.

Therefore, its absorptance is 0.27 and its emittance is 0.84, being its absorption coefficient equal to around 0.3214.

4.3.4. ANODIZED ALUMINIUM SAMPLES

Anodizing is an electrochemical process that makes metal surfaces durable and corrosion resistant. The name of this technique comes from the process, which the part to be treated forms the anode electrode of an electrolytic cell. It is commonly used for adding interference effects to reflected light and to prevent the galling of threaded components. Furthermore, it is also used to protect aluminium alloys, as we will study in the next samples, which are all the same anodized aluminium, but with different colors.

Thus, all anodized aluminium samples are dependent on the color they have been anodized with, having all more or less a pattern of medium absorptance and rather high emittances [5, 12-14].

4.3.4.1. ANODIZED ALUMINIUM BLACK

As it has previously been expounded on, it is aluminium anodized in black, which gives as a result an absorptance of 0.76 and an emittance of 0.88, being its absorption coefficient equal to around 0.8636.

4.3.4.2. ANODIZED ALUMINIUM BLUE

As it has previously been expounded on, it is aluminium anodized in blue, obtaining thus an absorptance of 0.60 and an emittance of 0.88, being its absorption coefficient equal to around 0.6818.

4.3.4.3. ANODIZED ALUMINIUM CHROMIC

As it has previously been expounded on, it is aluminium anodized in chromic, obtaining thus an absorptance of 0.44 and an emittance of 0.56, being its absorption coefficient equal to around 0.7857.

4.3.4.4. ANODIZED ALUMINIUM GOLD

As it has previously been expounded on, it is aluminium anodized in gold, obtaining thus an absorptance of 0.48 and an emittance of 0.82, being its absorption coefficient equal to around 0.5854.

4.3.4.5. ANODIZED ALUMINIUM RED

As it has previously been expounded on, it is aluminium anodized in red, obtaining thus an absorptance of 0.57 and an emittance of 0.88, being its absorption coefficient equal to around 0.6477.

4.3.4.6. ANODIZED ALUMINIUM YELLOW

As it has previously been expounded on, it is aluminium anodized in yellow, obtaining thus an absorptance of 0.47 and an emittance of 0.87, being its absorption coefficient equal to around 0.5402.

4.3.5. FILMS AND TAPES

The films or tapes we are now going to list are materials designed to protect critical components of a spacecraft from thermal hazards that could damage them and, therefore, make the whole system malfunction. There are different values for the absorptance and emittance, being these specific materials designed to guard, as stated, from thermal threats, regardless of them being threats related to heat or cold [5, 12-14].

4.3.5.1. ALUMINIUM TAPE

Aluminium tape, also known as Speed tape, is an aluminium pressure-sensitive tape used to do minor repairs on aircrafts and racing cars alike. It is broadly used as a temporary repair material, until a more permanent repair can be carried out. One of its main properties includes the reflection of heat and UV light, while also being resistant to water, solvents, flames, etc.

Its absorptance is 0.21 and its emittance is 0.04, being its absorption coefficient equal to 5.25.

4.3.5.2. ALUMINIZED ACLAR FILM (1 mm)

Aclar film is the commercial name for a thermoformable film, which acts as a high moisture barrier, has chemical resistance, and is non-flammable. This material has been treated with the Aluminizing process to obtain the same properties that we have commented in previous materials.

Therefore, its absorptance is 0.12 and its emittance is 0.54, being its absorption coefficient equal to around 0.22.

4.3.5.3. ALUMINIZED KAPTON (ALUMINIUM OUTSIDE)

Kapton, or poly-oxydiphenylene-pyromellitimide, is a polyimide film developed in the late 1960s characterized for remaining stable across a wide range of temperatures. It is mostly used on flexible printed circuits and thermal blankets on spacecraft, satellites and various space instruments.

Aluminized Kapton is Kapton treated, as we have seen before, with aluminium. Now, besides being thermally insulating, it also reflects radiation.

Therefore, its absorptance is 0.14 and its emittance is 0.05, being its absorption coefficient equal to 2.8.

4.3.5.4. GOLDIZED KAPTON (GOLD OUTSIDE)

As we have stated in the previous material, Kapton is a polyimide characterized by its capabilities to remain stable across a wide range of temperatures.

This time we observe another treatment, which consists on applying a thin coat of gold, which gives Kapton, in terms of reflection, almost the same properties as aluminium, albeit with another finish.

Consequently, we can find that the goldized kapton has an absorptance of 0.25 and an emittance of 0.02, being its absorption coefficient equal to around 12.5.

4.3.6. METALS

In this section, we will find some metals that are put under treatments in order to make them shinier or reflect more radiation. Therefore, we will have a rather shiny group of materials, that will reflect the radiation more than they will absorb, having as a result a spacecraft that will tend to cold temperatures. We can assure then, that these following materials will have relative low absorptance and emittance [5, 12-14].

4.3.6.1. BUFFED ALUMINIUM

In the first place, we have the aluminium, a metal that we have already commented. Its properties are exceptional for its use in spacecraft, but it needs to be treated in order to achieve a decent level of reflection.

On account of that, it has been treated with buffing. This treatment usually consists on smoothing a metal surface, using both an abrasive and a work wheel. It is similar to polishing, but buffing uses a loose abrasive applied to the work wheel, whereas polishing uses a different method explained in the next materials.

Thus, its absorptance is 0.16 and its emittance is 0.03, being its absorption coefficient equal to around 5.33.

4.3.6.2. BUFFED COPPER

Copper is a soft, malleable, and ductile metal, with very high thermal and electrical conductivity. In this case it is, as it can be deduced by its name, treated with the same treatment as the previous material.

Its absorptance is 0.30 and its emittance is 0.03, being its absorption coefficient equal to 10.

4.3.6.3. POLISHED ALUMINIUM

On the other side of the spectrum we have polished aluminium, which, as we said before, is aluminium treated with a different method than buffing. This method is called polishing, and it usually consists in smoothing a metal surface using an abrasive and a work wheel. In this case, in comparison with the buffer treatment, the abrasive used is glued to the work wheel.

Thus, its absorptance is 0.24 and its emittance is 0.08, being its absorption coefficient equal to 3.

4.3.6.4. POLISHED BERYLLIUM

This material consists on Beryllium treated under the same process as the previous material. Beryllium is a divalent chemical element widely used in the spacecraft field thank to its high flexural rigidity, thermal stability, thermal conductivity and low density. The polished beryllium keeps the same properties of the regular beryllium, but also gets the properties that the polish treatment gives.

Owing all the above, its absorptance is 0.44 and its emittance is 0.01, being its absorption coefficient equal to 44.

4.3.6.5. POLISHED GOLD

This material consists on Gold treated under the same process as the two previous materials. Gold is a bright, dense, soft, malleable and ductile metal widely used in the spacecraft field, most specifically in the electronic components, in which, thanks to its great conductivity and general resistance to oxidation and corrosion, it is a very trustworthy material to use in environments with a with a very high failure cost. The polished gold keeps the same properties of the regular gold, while also getting the properties that the polish treatment gives.

Thus, its absorptance is 0.30 and its emittance is 0.05, being its absorption coefficient equal to 6.

4.3.6.6. POLISHED SILVER

This material consists on Silver treated under the same process as the previous materials. Silver is a soft, white and lustrous transition metal. Thanks to being the highest electrically conductive, thermal conductive and reflective metal , silver is a key component in electronics used in conductors and electrodes. It is applied when high quality connectors are required. The polished silver keeps the same properties of the regular silver, but also gets the properties that the polish treatment gives.

So, its absorptance is 0.04 and its emittance is 0.02, being its absorption coefficient equal to 2.

4.3.6.7. POLISHED STAINLESS STEEL

This material consists on Stainless Steel treated under the same process as the previous materials. Stainless steel, also known as inox steel, is a steel alloy with a minimum 10.5% chromium content by mass and a maximum 1.2% carbon by mass. It is commonly known by its notable corrosion resistance, which comes from the addition of chromium. Steel is also an alloy mainly composed of iron and carbon, and, thanks to its high tensile strength proprieties and low cost, it is widely used for machines, tools, automobiles and spacecraft, among many others. The polished stainless steel keeps the same properties of regular stainless steel, all the while also getting the properties that the polish treatment gives.

Therefore, its absorptance is 0.42 and its emittance is 0.11, being its absorption coefficient equal to around 3.818.

4.3.6.8. POLISHED TUNGSTEN

This material consists on Tungsten treated under the same process as the previous materials. Tungsten, also known as Wolfram, is a rare metal found naturally on Earth. It is remarkable for its robustness, hardness, high density and high melting point. Taking these proprieties into account, it is used, among many other things, as a radiating shielding. The polished tungsten keeps the same properties of regular tungsten, while also getting the properties that the polish treatment gives.

Consequently, its absorptance is 0.44 and its emittance is 0.03, being its absorption coefficient equal to around 14.67.

4.3.7. VAPOR-DEPOSITED COATINGS

The process of vapor deposition, in these cases on glass substrates, is a technique carried out in vacuum to obtain high quality, high performance solid materials. In this process, the substrate is exposed to one or more volatile precursors, which react on the substrate's surface to produce the desired deposit.

It is often used in the semiconductor industry, in order to produce thin films. Depending on the material deposited, their absorptance and emittance differ from one another [5, 12-14].

4.3.7.1. ALUMINIUM

In the case of vapor-deposited aluminium, and being the aluminium already introduced, using the technique we commented before, it gives an absorptance of 0.08 and an emittance of 0.02, being its absorption coefficient equal to 4.

4.3.7.2. GOLD

In the case of vapor-deposited gold, and being gold already introduced, using the technique we commented before, it gets and absorptance of 0.19 and an emittance of 0.02, being its absorption coefficient equal to 9.5.

4.3.7.3. SILVER

In the case of vapor-deposited silver, and being silver already introduced, using the technique we commented before, it gets and absorptance of 0.04 and an emittance of 0.02, being its absorption coefficient equal to 2.

4.3.7.4. TITANIUM

In the case of vapor-deposited titanium, and being titanium already introduced, using the technique we commented before, gets and absorptance of 0.52 and an emittance of 0.12, being its absorption coefficient equal to around 4.33.

4.3.7.5. TUNGSTEN

In the case of vapor-deposited tungsten, and being tungsten already introduced, using the technique we commented before, gets and absorptance of 0.60 and an emittance of 0.27, being its absorption coefficient equal to around 2.22.

4.3.8. SOLAR CELLS

Solar panels, integrated by solar cells, are essential in spacecraft. Hence, the main energy source of almost every satellite that receives sunlight during its lifetime is, indeed, this very sunlight. It is trough solar cells that these satellites recharge their batteries. For instance, it is also true that some spacecraft, such as the Voyager 1 and Voyager 2, obtain their energy from radioisotope thermoelectric generators, that is to say, nuclear energy.

But, apart from those, all satellites surrounding the solar system require solar panels in order to keep functioning [5, 12-14].

4.3.8.1. GALIUM ARSENIDE-BASED SOLAR CELLS

Gallium arsenide-based solar cells are usually favored over any other type of solar cells due to their high efficiency and slower degradation over the radiation received.

Therefore, their absorptance is 0.88 and their emittance is 0.80, being their absorption coefficient equal to 1.1.

4.3.8.2. CRYSTALLINE SILICON-BASED SOLAR CELLS

Crystalline silicon-based cells have dominated the photovoltaic market since the earlies 50 due to their low price. Despite not being the most efficiently ones, it is important to analyze such a common type of cells.

Thus, their absorptance is 0.75 and their emittance is 0.82 being their absorption coefficient equal to around 0.915.

5. MATLAB PROGRAMMING

5.1. INTRODUCTION

As it has been briefly stated previously in this project, Matlab, abbreviation of **Mat**rix **Lab**oratory, is a very powerful and competent calculation engine, able to offer an integrated development environment (IDE) with its own programming language (M language). It offers some other tools, such as Simulink, which enables the user simulate and test systems in real-time.

In this thesis, Matlab has been used to calculate the temperatures of each node of the satellite. Through its toolset, I have been able to obtain vectors of temperatures that will tell us, depending on the materials used in the surface, which one protects more from radiations and, therefore, which one maintains the best range of temperatures for the mechanisms, gadgets and devices to function properly. The level of protection will depend on how these materials enable the satellite to heat up or cool down, theoretically being the best ones, the materials with which the satellite will not need to weatherize, or will need less than with the rest

As well as the nodal analysis, the programming has had phases, steady-state, in which we just contemplate the satellite in the sunlight zone, being radiated by solar, albedo and planetary radiation. Nevertheless, when we programmed the transient analysis, not only the mentioned radiations were contemplated, but also the moments they affect the spacecraft, as well as the increase of temperatures.

5.2. STEADY-STATE

In the steady-state analysis, as it has been introduced in the previous section, we are going to analyze, calculate and determine which are the temperatures the satellite will reach in the "extreme" case of constantly being in sunlight zone without moving and not being attracted to the Earth. That is to say, receiving solar, albedo and planetary radiation.

To be able to calculate the graphic that portrays the different temperatures that each node reaches at an indefinite period of time in the sunlight zone, we must program some calculations and equations in Matlab. Therefore, we proceed to explain the procedures that lead us to the results:

First of all, it is necessary to structure the calculations, in order to make the simple and easy to understand. At the beginning, we must define all the constants that our problem needs, such as the View factor × Area table, or the Conductance table, explained in the Thermal Analysis section. We also define the areas of the nodes, their internal heat and the initial temperatures, among others.

The next step is to calculate the $Q_{external}$, to be able to, afterward, calculate the main equation showed, as well, in the Thermal Analysis section. Calculated as follows, showing only the programing of the fist node as an example:

```
Q_ext_1=(Js*alpha_outside*A_solar)+(Ja_sun*alpha_outside*A_albedo)+(Jp
*epsilon_outside*A_planetary);
```

Having defined, as it has been asserted before, all the variables and constants needed in this equation, the next step will be to program the coefficient term of the matrix equation, shown in the Appendix file 1, which is a 10×10 matrix. The first term of the first line, also term of the main diagonal, is calculated following the equation like shown here:

```
M11=h_vector(1,2)+h_vector(1,3)+h_vector(1,4)+h_vector(1,5)+h_vector(1
,6)+h_vector(1,7)+h_vector(1,8)+h_vector(1,9)+h_vector(1,10)+((4*sigma
*T_0_vector(1)^(3))*((A_space_vector(1)*epsilon_white)+((F_vector(1,2)
*epsilon_ij)+(F_vector(1,3)*epsilon_ij)+(F_vector(1,4)*epsilon_ij)+(F_
vector(1,5)*epsilon_ij)+(F_vector(1,6)*epsilon_ij)+(F_vector(1,7)*epsi
```

```
lon_ij)+(F_vector(1,8)*epsilon_ij)+(F_vector(1,9)*epsilon_ij)+(F_vecto
r(1,10)*epsilon_ij))));
```

And the second term of the first line given as an example looks like this:

```
M12=-
(h_vector(1,2)+(4*sigma*T_0_vector(2)^(3)*F_vector(1,2)*epsilon_ij));
```

Therefore, completing all the lines of the matrix, the coefficient term of the equation is done.

The next step is to develop the independent term of the matrix equation. It is done as follows, having as example the first component of this matrix 10×1:

```
N1=Q_ext(1)+Q_vector(1)+(3*sigma*T_0_vector(1)^(4)*A_space_vector(1)*e
psilon_inside)+(3*sigma*(((T_0_vector(1)^(4)-
T_0_vector(2)^(4))*F_vector(1,2)*epsilon_ij)+((T_0_vector(1)^(4)-
T_0_vector(3)^(4))*F_vector(1,3)*epsilon_ij)+((T_0_vector(1)^(4)-
T_0_vector(4)^(4))*F_vector(1,4)*epsilon_ij)+((T_0_vector(1)^(4)-
T_0_vector(5)^(4))*F_vector(1,5)*epsilon_ij)+((T_0_vector(1)^(4)-
T_0_vector(6)^(4))*F_vector(1,6)*epsilon_ij)+((T_0_vector(1)^(4)-
T_0_vector(7)^(4))*F_vector(1,7)*epsilon_ij)+((T_0_vector(1)^(4)-
T_0_vector(8)^(4))*F_vector(1,8)*epsilon_ij)+((T_0_vector(1)^(4)-
T_0_vector(9)^(4))*F_vector(1,9)*epsilon_ij)+((T_0_vector(1)^(4)-
T_0_vector(10)^(4))*F_vector(1,10)*epsilon_ij)));
```

Thus, putting together all the components of the coefficient term, calling them “Matrix”, putting together all the components of the independent term, calling them “Last” and bringing them into a new script, with the command function, we can calculate the unknown term. The unknown term, which will be the temperatures, is calculated as follows:

```
Temperaturas=Matrix\Last;
```

In addition, besides calculating the temperatures, we create an iteration to calculate the temperatures in which the satellite will stabilize. We perform this iteration by assigning the temperatures calculated to the initial temperatures and, consequently, calculate the next temperatures that will be sent again to the calculations of “Matrix” and “Last”. This iteration is done with the command function, calling the other scripts and feeding them the new values of initial temperatures. It is done as follows:

```
[Matrix]=TFG_Matrix_Components(epsilon_white, sigma, F_vector,
h_vector, epsilon_ij, T_0_vector, A_space_vector);

[Last]=TFG_Matrix_Last_Component(Q_ext, Q_vector, sigma, T_0_vector,
A_space_vector, F_vector, epsilon_outside, epsilon_inside,
epsilon_ij);
```

Finally, the last step is to draw the temperatures calculated in a graphic, performed with a loop, like this:

```
for i=1:1:Nodes
    plot(vector_ejemplo, vvectorr(i,:)-273.15,'LineWidth',1)
    xlabel('Iterations')
    ylabel('Temperature(°C)')
    title('STEADY-STATE ANALYSIS')
    hold on

end
```

5.3. TRANSIENT

First of all, in order to program the transient analysis, we need to think about all the situations that the satellite will go through. We can observe that in the transient analysis, the orbit followed is a Low Earth Orbit (LEO) and a Near Equatorial Orbit, meaning that our satellite will orbit with an inclination near to zero taking the equatorial plane as a reference. Following a LEO orbit means that the satellite will complete geocentric orbits with an altitude of around 240 km, taking it approximately 1 hour, 29’ and 18’’[11] to do the whole orbit. In this round, the spacecraft will be 59° out of the whole 360° orbit exposed to the Sun and, consequently, receiving solar, albedo and planetary radiation during this time bracket. During the remaining time, it will be behind the Earth, receiving only planetary radiation.
To sum up, the whole orbit is equal to 5358 seconds, and the time it will be in the Sunlight zone will be around 879 seconds.

Now that the premises of the transient analysis have already been set and explained, we can proceed to explain the programing behind the calculations and equations.

First and foremost, as we already did in the steady-state analysis, we need to define the constants that will be used thereupon. Exactly the same constants and variables in the steady-state programing will be defined in this case, in addition to some others such as the seconds that a lap lasts, the mass and the specific heat of each node, among many others. We will need to define some vectors assigning them the size we want them to have, in order to avoid problems with them changing size every time a loop operation is completed.

Afterwards, we will start the loops, in order to acquire the temperatures of each node in every moment of orbit time. Once we are inside the main loop, which calculates every increment of time of the orbit, we must program the matrix equation shown in the Appendix file 2.

First, we program the summation term on the coefficient term's main diagonal of the matrix equation, done with another like so:

```
for w=1:1:Nodes
     value=0;
     for t=1:1:Nodes
         if w==t
            sumatorio=0;

            value=value+sumatorio;

         else

            sumatorio=(h_vector(w,t)/2)+((sigma*F_vector(w,t)*epsilon_i
            j*4*(T_0_vector(w)^3))/2);

            value=value+sumatorio;
         end
      end
      sumatorio_vector_Matrix(w)=value;
end
```

Subsequently, we will program the rest of the main diagonal term, and the rest of the matrix coefficient term, as follows:

```
for i=1:1:Nodes
   for j=1:1:Nodes
       if i==j

            Matrix_Transient(i,j,cont)=((masa(i)*c(i))/(2*inc))+((sigma
            *epsilon_ij*A_space_vector(i)*4*(T_0_vector(i)^3))/2)+sumat
            orio_vector_Matrix(i);

       else
            Matrix_Transient(i,j,cont)=(-h_vector(i,j)/2)-
            ((sigma*F_vector(i,j)*epsilon_ij*4*(T_0_vector(j)^3))/2);

       end
   end
end
```

Once the coefficient term is programmed, we proceed to initiate the programming of the independent term. It is done similarly to the coefficient term's main diagonal, carrying out the summation on the first place like so:

```
for i=1:1:Nodes
    value2=0;
    for j=1:1:Nodes
        if i==j
           sumatorio2=0;

           value2=value2+sumatorio2;

        else
            sumatorio2=((h_vector(i,j)*T_0_vector(i))/2)-
            ((h_vector(i,j)*T_0_vector(j))/2)+(sigma*(((-
            F_vector(i,j)*epsilon_ij*(T_0_vector(i)^4)*4)/2)+(F_vector(
            i,j)*epsilon_ij*3*(T_0_vector(i)^4))+((F_vector(i,j)*epsilo
            n_ij*(T_0_vector(j)^4)*4)/2)-
            (F_vector(i,j)*epsilon_ij*3*(T_0_vector(j)^4))));

            value2=value2+sumatorio2;

         end

    end
     sumatorio_vector_Last(i)=value2;

 end
```

And, secondly, the rest of the term:

```
for x=1:1:Nodes

Last_Transient(x,1,cont)=((masa(x)*c(x)*T_0_vector(x))/(2*inc))+(Suma_
Q_ext_Transient(x)/2)+Q_vector(x)-
((sigma*epsilon_ij*A_space_vector(x)*(T_0_vector(x)^4)*4)/2)+(sigma*ep
silon_ij*A_space_vector(x)*(T_0_vector(x)^4)*3)-
sumatorio_vector_Last(x);

end
```

It is necessary to make a notation, since the external radiation changes depending on the place that the satellite is situated on. As it has already been asserted on several occasions, if the satellite is in the Sunlight zone, it will be affected by the solar, albedo and planetary radiation, whereas when it is in the shadow zone, it will only be affected by the planetary radiation.

Since we need to calculate the average value of the external radiation that the satellite is receiving at this moment in our programming, and the radiation that it was receiving in the moment before, we will discern between sunlight zone, shift, and shadow.

Last but not least, we plot the temperatures of each node, drawing several orbits, as it is shown and explained in the next section. This plot is done as following:

```
for i=1:Nodes
    plot(Temperatures_Transient(i,:)-273.15,'LineWidth',1)
      legend({'T1','T2','T3','T4','T5','T6','T7','T8','T9','T10'},'Loc
      ation','southeastoutside')
   xlabel('Time(s)')
   ylabel('Temperature(°C)')
   title('TRANSIENT ANALYSIS')
   grid on
   hold on
end
```

6. RESULTS

6.1. INTRODUCTION

The next stage consists on obtaining the results of each material introduced, with the help of the programming introduced in the previous section. Although there have been calculated two graphics, we will only be showing the most important one, which is the transient analysis. However, the steady-state graphics will be shown in the Appendix file 3, since they show an unreal case that consists on displaying the temperatures the satellite reaches when stabilized in the steady-state analysis. This steady-state graphic shows at what temperature the nodes stabilize in the hypothetical case of the satellite being in the sunlight zone and receiving solar, albedo and planetary radiation the whole time. Therefore, these steady-state graphics are only displayed as illustrative temperatures that depend only on the material that the satellite is covered with.

However, the main graphic will hold the complete analysis of temperatures in a whole orbit around the Earth. Several orbits will be shown in there in order to make clear the “stabilization” that the satellite sustains during its orbit, beginning with an illustrative temperature. This stabilization consists on temperatures cycles, that reach maximum and minimum depending on where the satellite is. This second graph will distinguish between the zone in which the satellite receives solar, albedo and planetary radiation, which is the Sunlight zone, and the zone where it only receives planetary radiation, which is the night or shadow zone . However, the analysis of the results and all the comments made from analyzing the data will be located in the conclusion section.

Lastly, however, before proceeding to show all the results obtained, and thereupon commenting all of them, it is necessary to clarify that all graphics are, obviously, divided into the nodes that we have already commented and expounded on, as the legends will show. In this way, we will be able to study each node as an isothermal system. We will be modifying the absorptance and the emittance, depending on the material that we are analyzing, and we will see the different results that we obtained.

6.2. OPTICAL SOLAR REFLECTORS (OSR)

6.2.1. SILVERED FUSED SILICA

Absorptance	0.07	Emittance	0.80

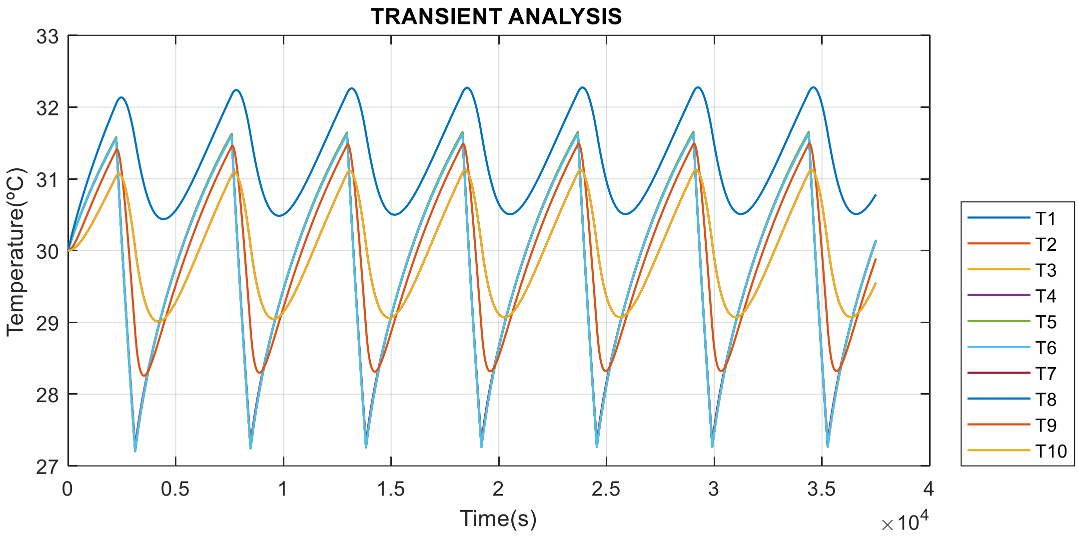


Figure 7. Transient analysis of Silvered Fused Silica

6.2.2. INDIUM-TIN-OXIDE (ITO)

Absorptance	0.07	Emittance	0.76

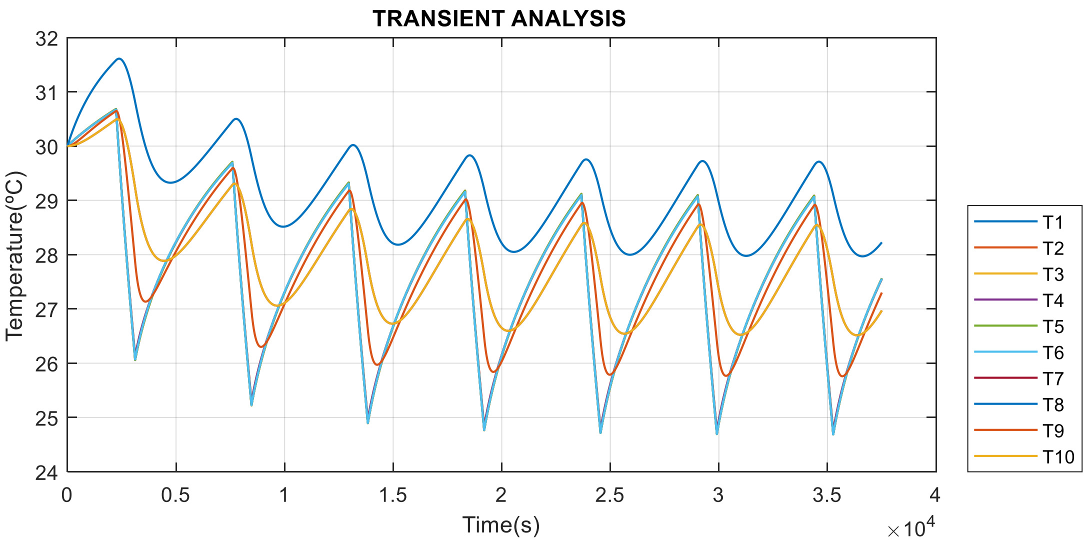


Figure 8. Transient analysis of Indium-Tin-Oxide (ITO)

6.2.3. ALUMINIZED TEFLON (0.5 mm)

Absorptance	0.14	Emittance	0.40

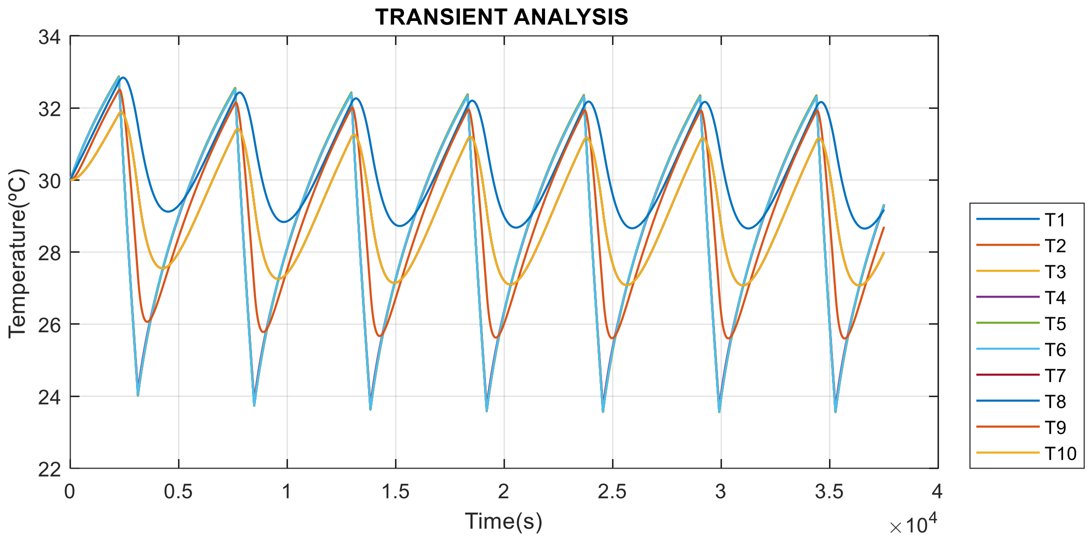


Figure 9. Transient analysis of Aluminized Teflon (0.5 mm)

6.2.4. ALUMINIZED TEFLON (10 mm)

Absorptance	0.15	Emittance	0.85

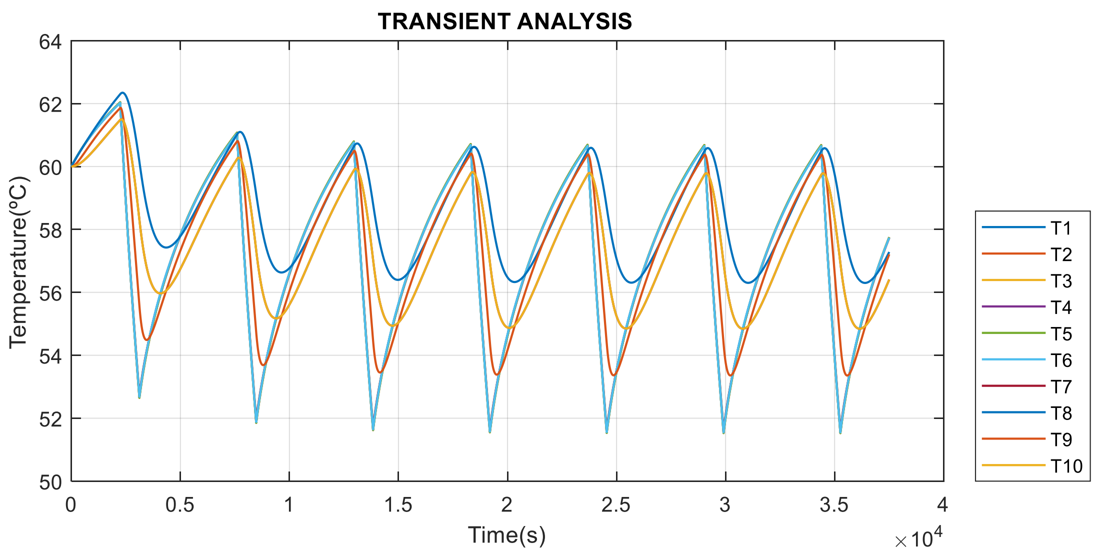


Figure 10. Transient analysis of Aluminized Teflon (10 mm)

6.2.5. SILVERED TEFLON (2 mm)

Absorptance	0.08	Emittance	0.68

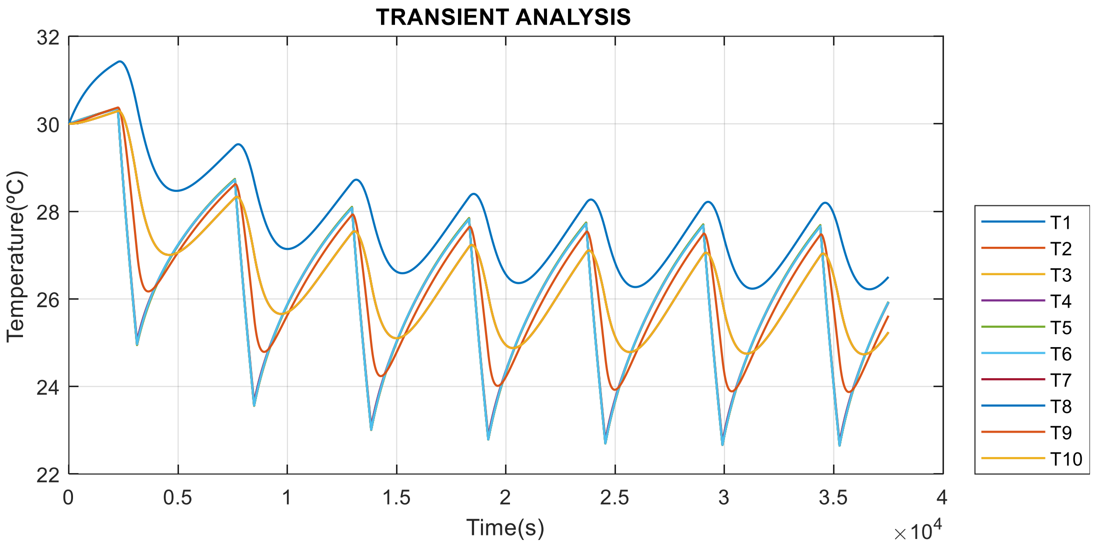


Figure 11. Transient analysis of Silvered Teflon (2 mm)

6.2.6. ALUMINIZED SILVERED TEFLON (10 mm)

Absorptance	0.09	Emittance	0.88

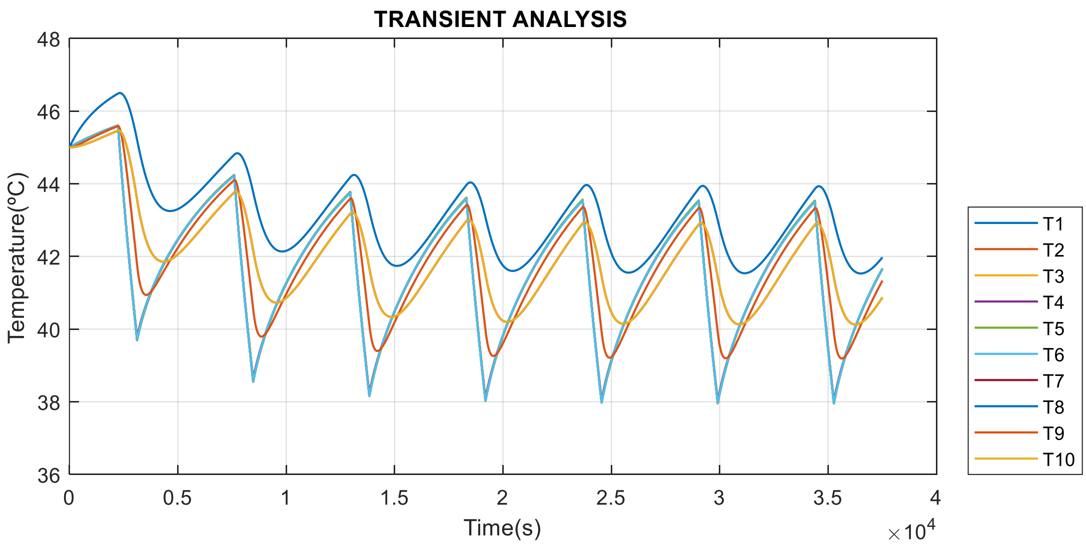


Figure 12. Transient analysis of Aluminized Silvered Teflon (10 mm)

6.3. BLACK COATINGS

6.3.1. CATALAC BLACK PAINT

Absorptance	0.96	Emittance	0.88

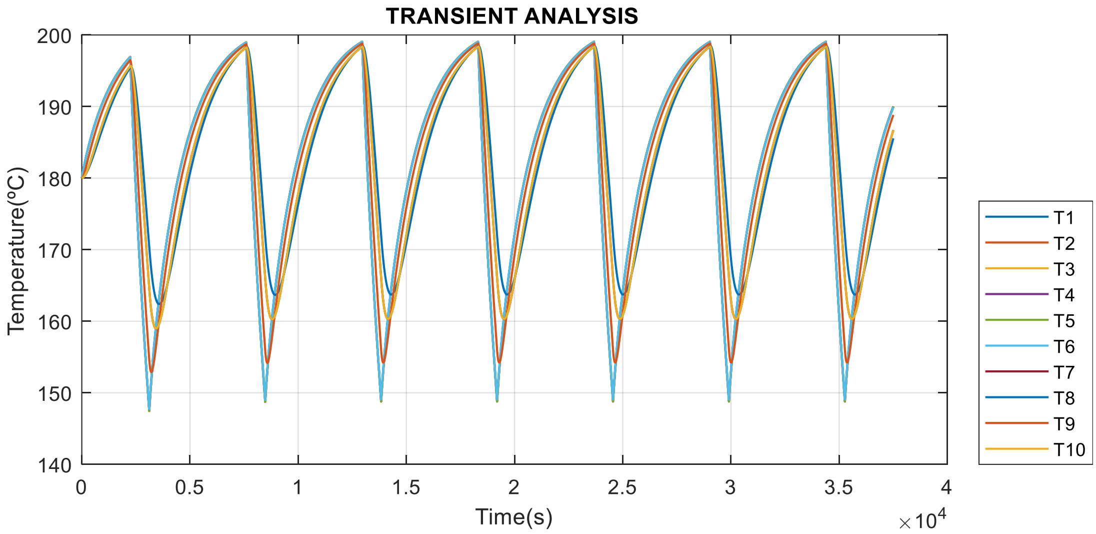


Figure 13. Transient analysis of Catalac Black Paint

6.3.2. DELRIN BLACK PLASTIC

Absorptance	0.96	Emittance	0.87

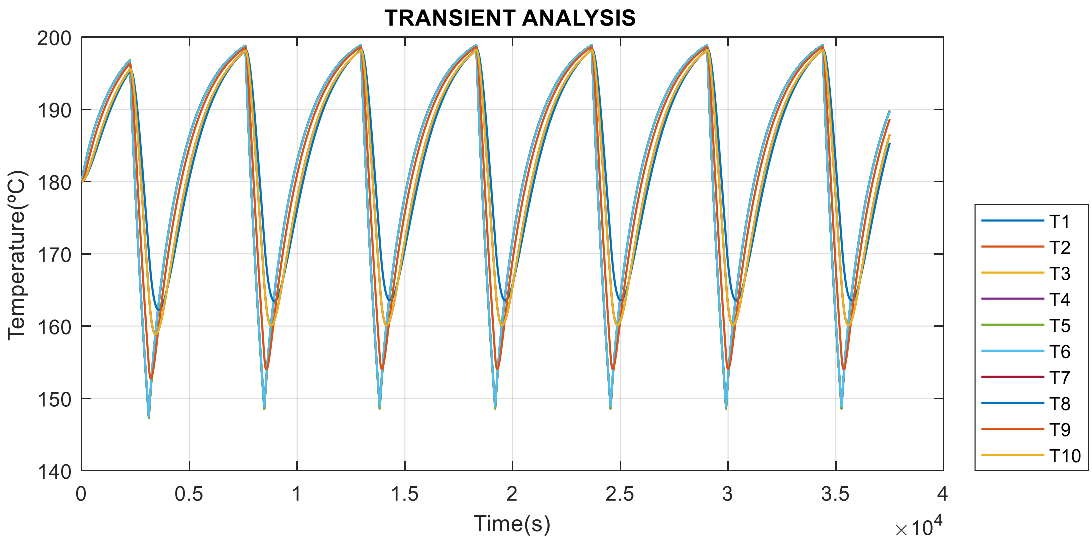


Figure 14. Transient analysis of Delrin Black Plastic

6.3.3. MARTIN BLACK VELVET PAINT

Absorptance	0.91	Emittance	0.94

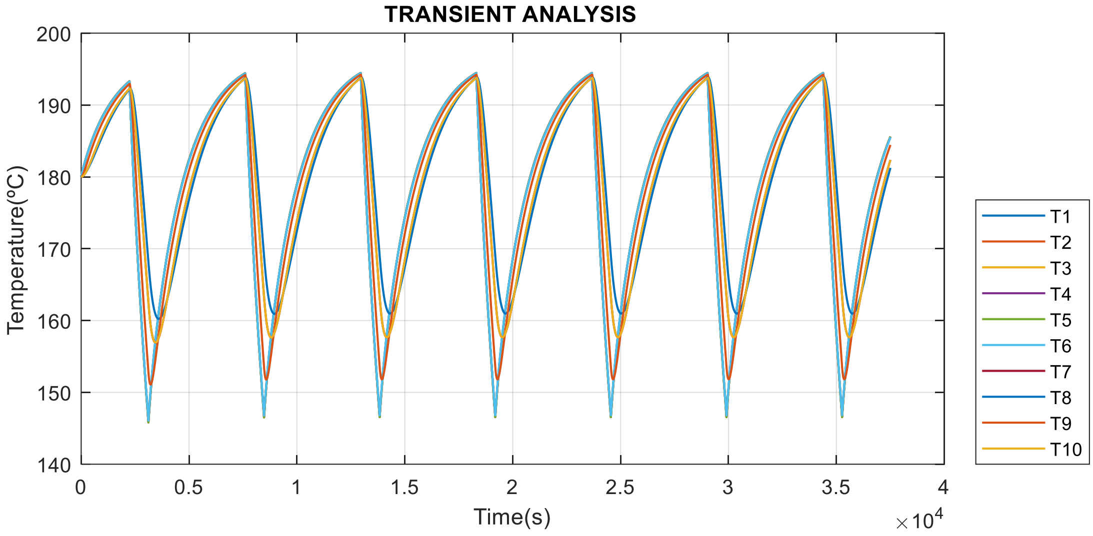


Figure 15. Transient analysis of Martin Black Velvet Paint

6.3.4. PARSONS BLACK PAINT

Absorptance	0.98	Emittance	0.91

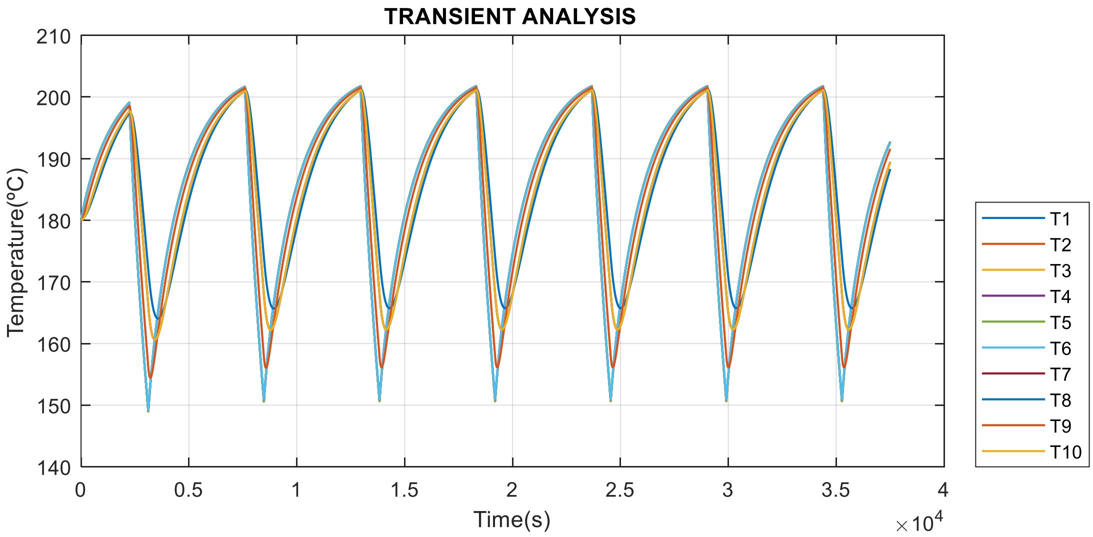


Figure 16. Transient analysis of Parsons Black Paint

6.3.5. VEL-BLACK

Absorptance	0.99	Emittance	0.95

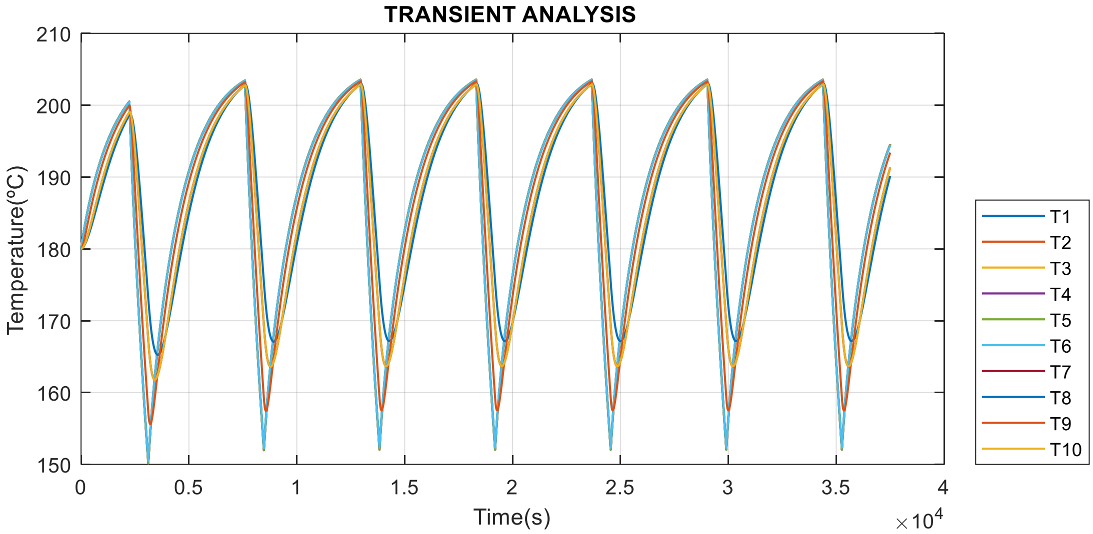


Figure 17. Transient analysis of Vel-Black

6.4. WHITE COATINGS

6.4.1. BARIUM SULPHATE WITH POLYVINYL ALCOHOL

Absorptance	0.06	Emittance	0.91

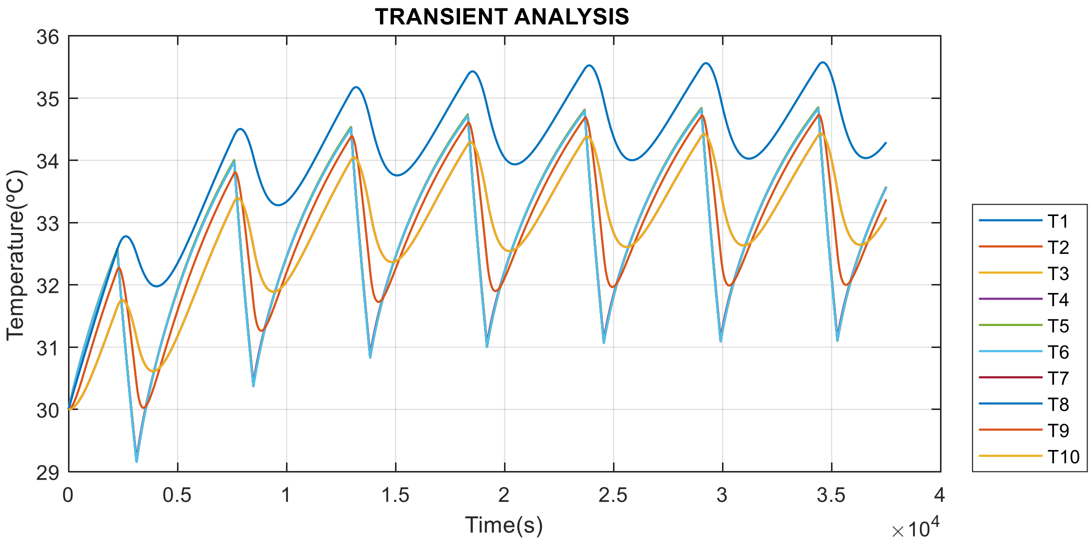


Figure 18. Transient analysis of Barium Sulphate with Polyvinyl Alcohol

6.4.2. CATALAC WHITE PAINT

Absorptance	0.24	Emittance	0.90

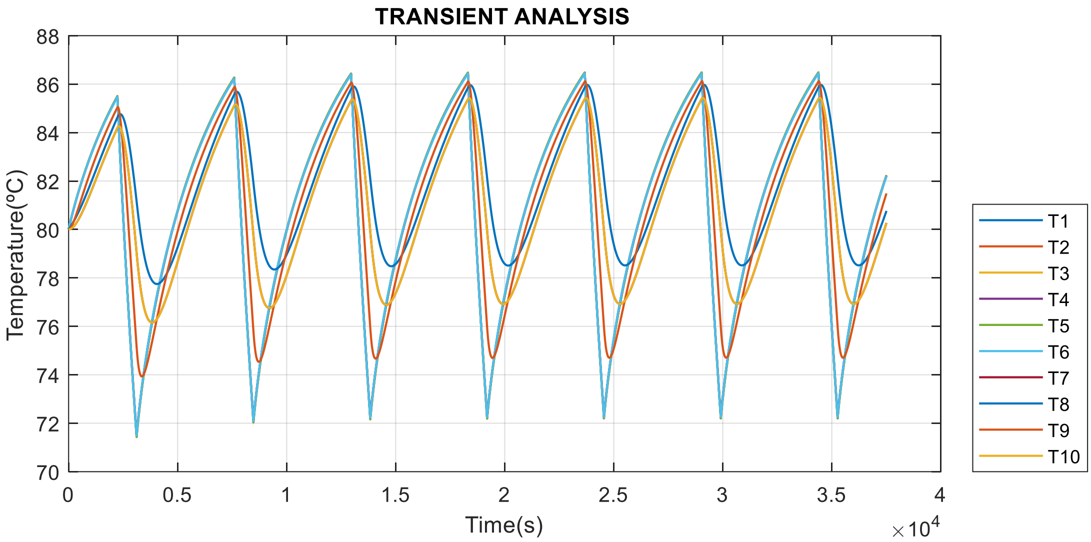


Figure 19. Transient analysis of Catalac White Paint

6.4.3. NASA/GSFC NS-74 WHITE PAINT

Absorptance	0.17	Emittance	0.92

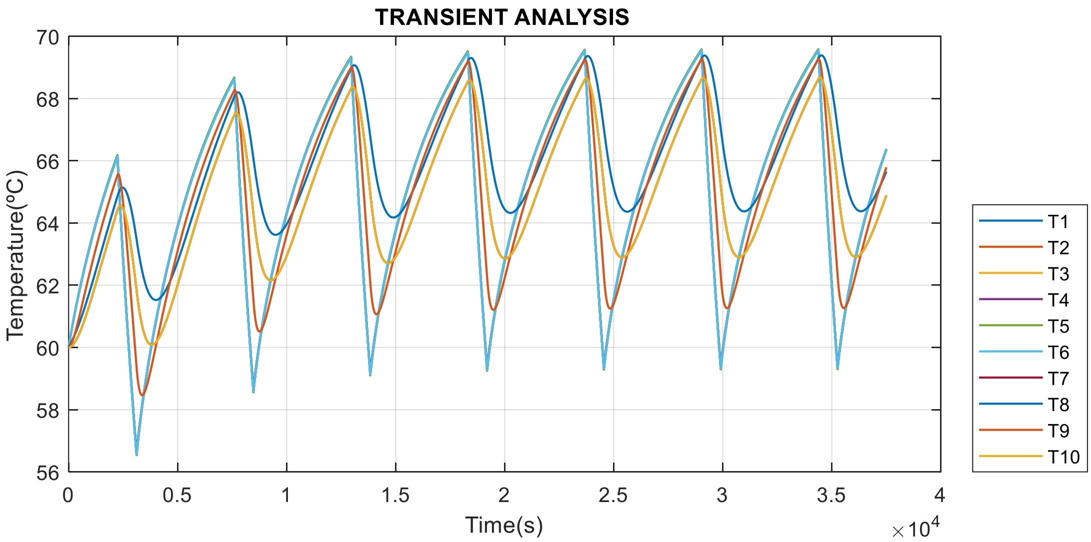


Figure 20. Transient analysis of NASA/GSFC NS-74 White Paint

6.4.4. MAGNESIUM OXIDE ALUMINIUM OXIDE PAINT

Absorptance	0.09	Emittance	0.92

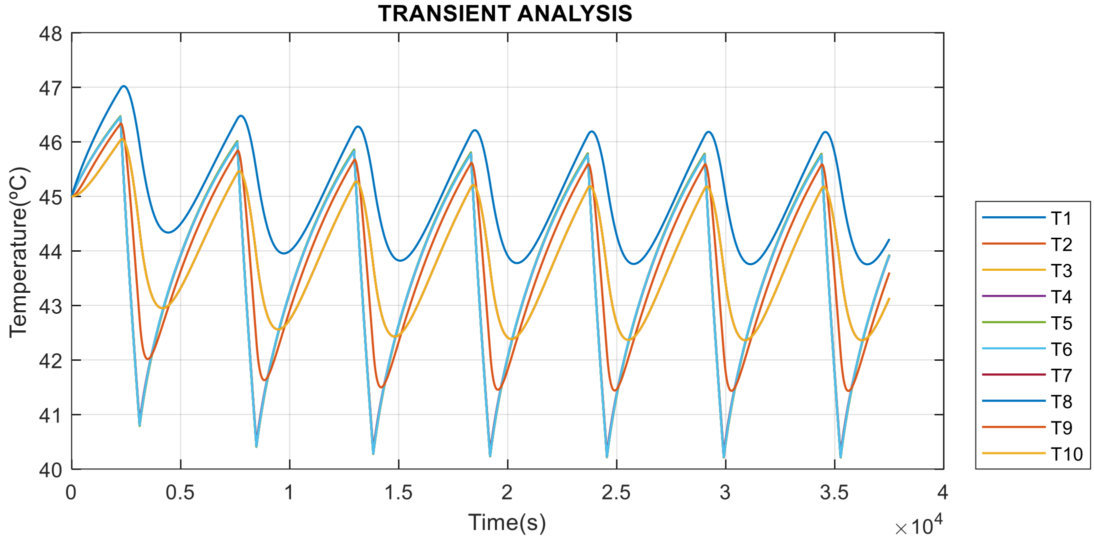


Figure 21. Transient analysis of Magnesium Oxide Aluminium Oxide Paint

6.4.5. WHITE POLYURETHANE PAINT

Absorptance	0.27	Emittance	0.82

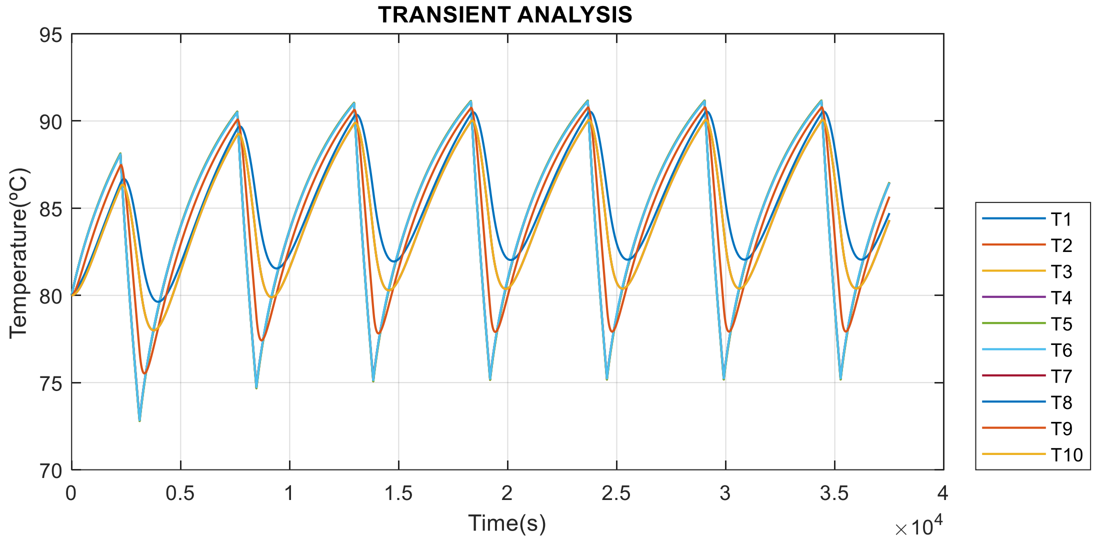


Figure 22. Transient analysis of White Polyurethane Paint

6.5. ANODIZED ALUMINIUM SAMPLES

6.5.1. ANODIZED ALUMINIUM BLACK

Absorptance	0.76	Emittance	0.88

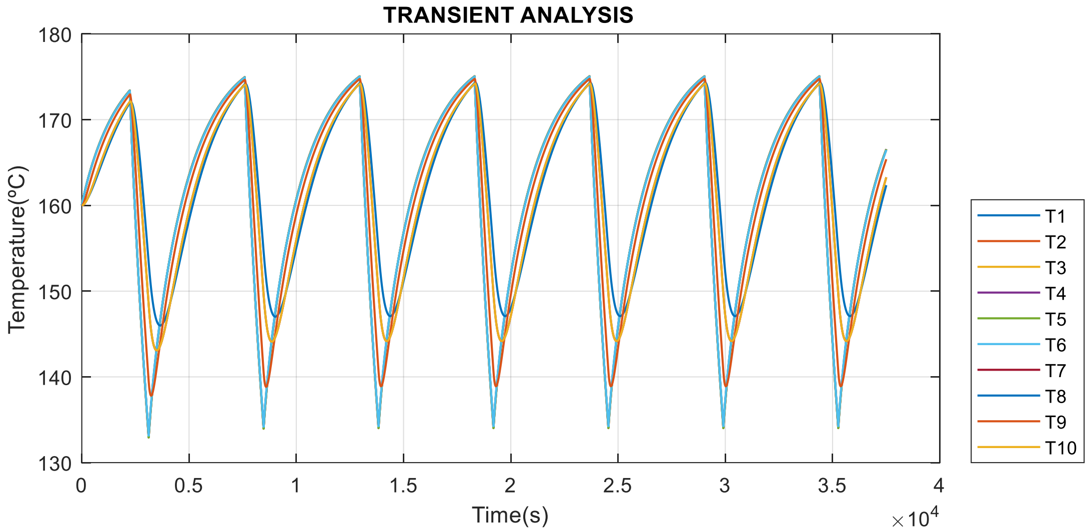


Figure 23. Transient analysis of Anodized Aluminium Black

6.5.2. ANODIZED ALUMINIUM BLUE

Absorptance	0.60	Emittance	0.88

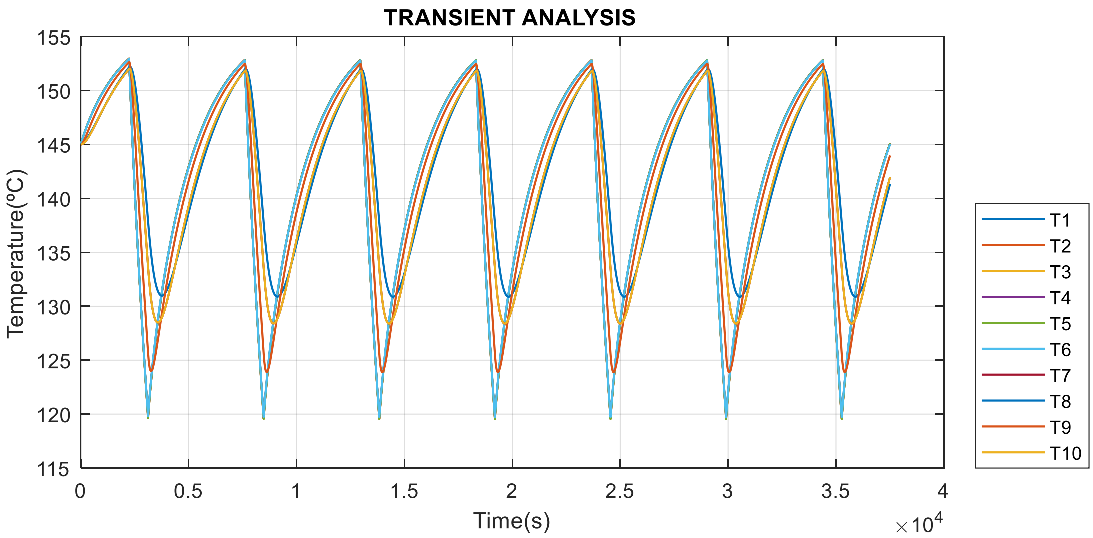


Figure 24. Transient analysis of Anodized Aluminium Blue

6.5.3. ANODIZED ALUMINIUM CHROMIC

Absorptance	0.44	Emittance	0.56

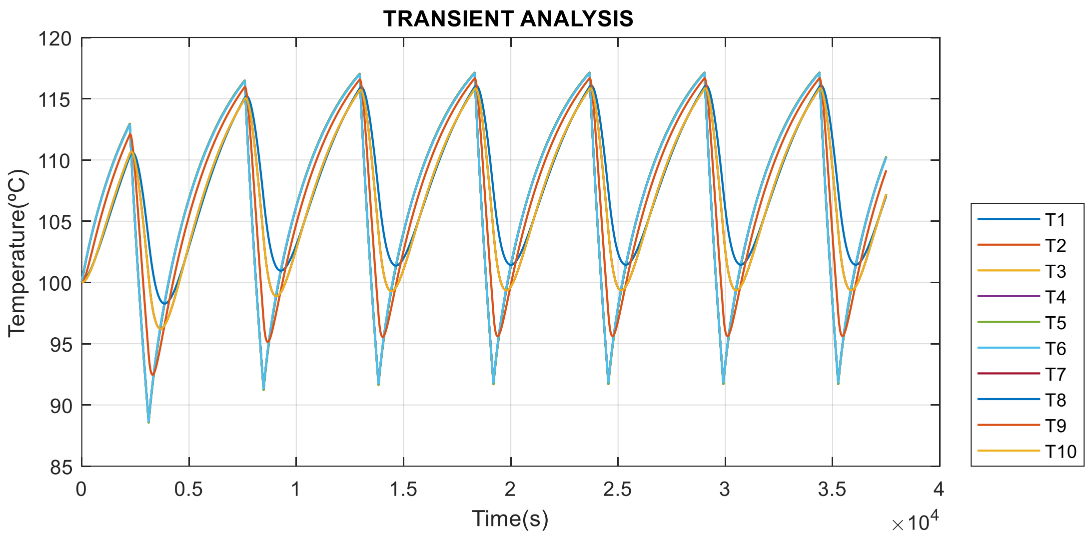


Figure 25. Transient analysis of Anodized Aluminium Chromic

6.5.4. ANODIZED ALUMINIUM GOLD

Absorptance	0.48	Emittance	0.82

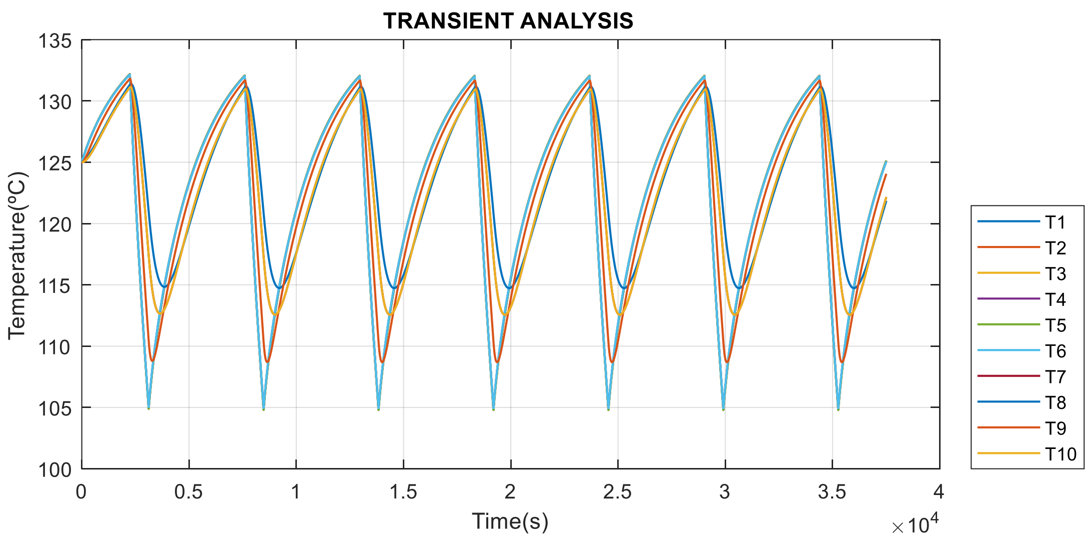


Figure 26. Transient analysis of Anodized Aluminium Gold

6.5.5. ANODIZED ALUMINIUM RED

Absorptance	0.57	Emittance	0.88

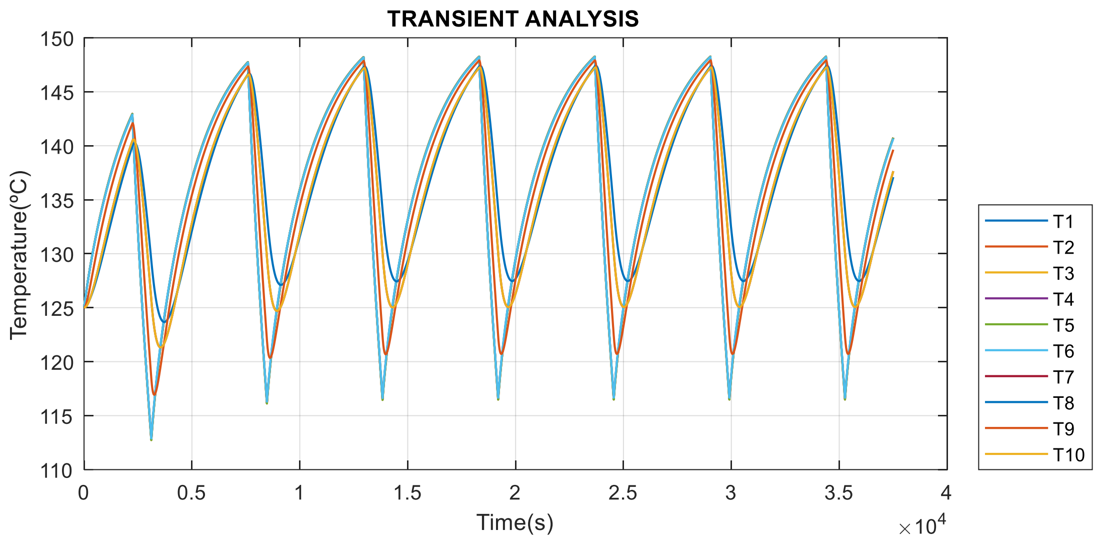


Figure 27. Transient analysis of Anodized Aluminium Red

6.5.6. ANODIZED ALUMINIUM YELLOW

Absorptance	0.47	Emittance	0.87

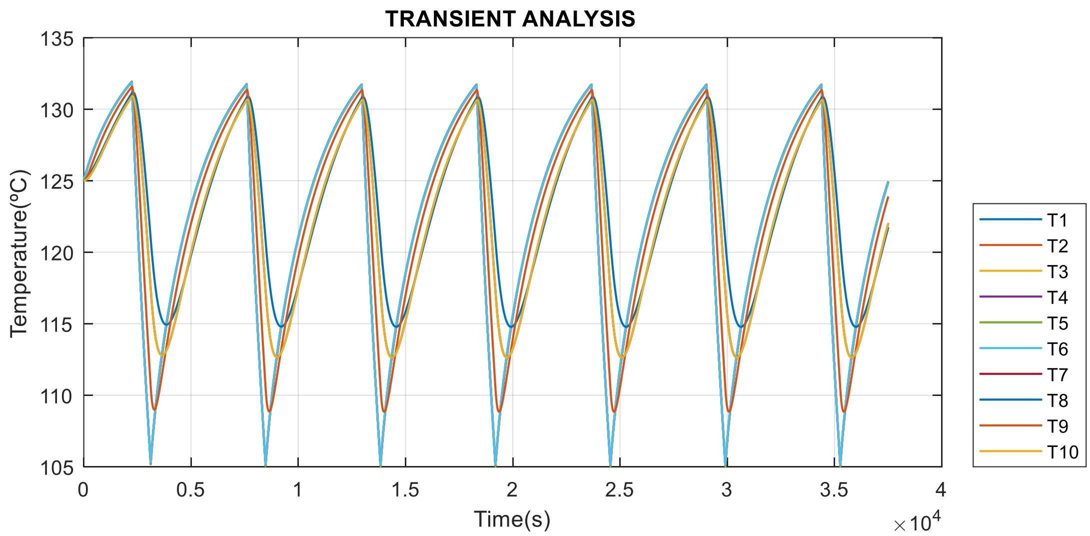


Figure 28. Transient analysis of Anodized Aluminium Yellow

6.6. FILMS AND TAPES

6.6.1. ALUMINIUM TAPE

Absorptance	0.21	Emittance	0.04

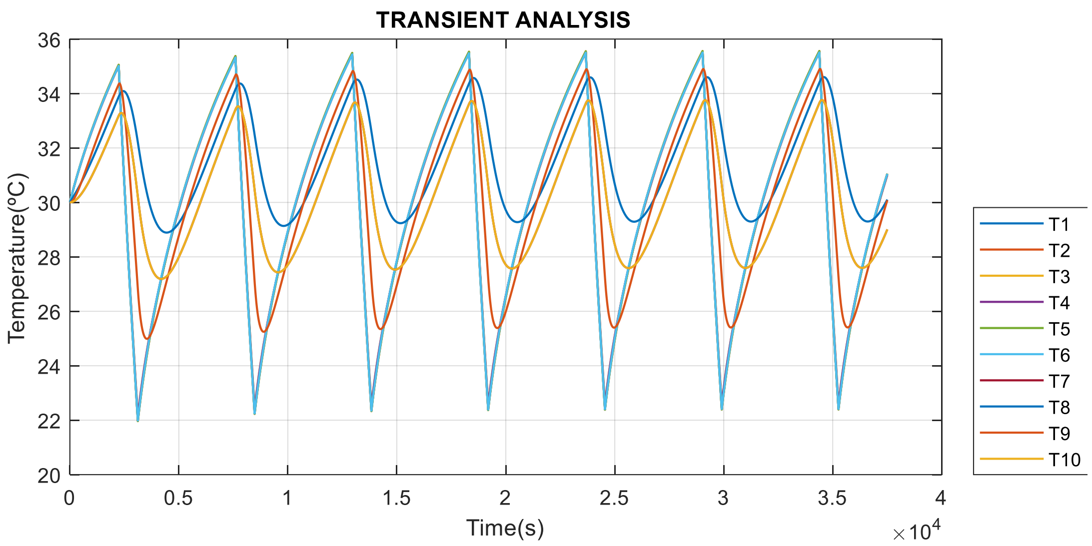


Figure 29. Transient analysis of Aluminium Tape

6.6.2. ALUMINIZED ACLAR FILM (1 mm)

Absorptance	0.12	Emittance	0.54

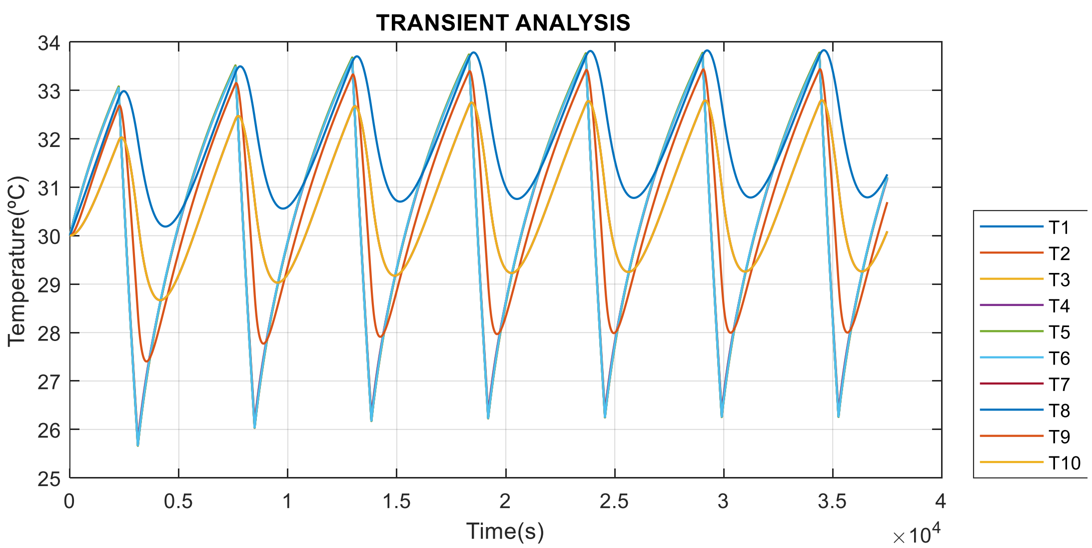


Figure 30. Transient analysis of Aluminized Aclair Film (1 mm)

6.6.3. ALUMINIZED KAPTON (ALUMINIUM OUTSIDE)

Absorptance	0.14	Emittance	0.05

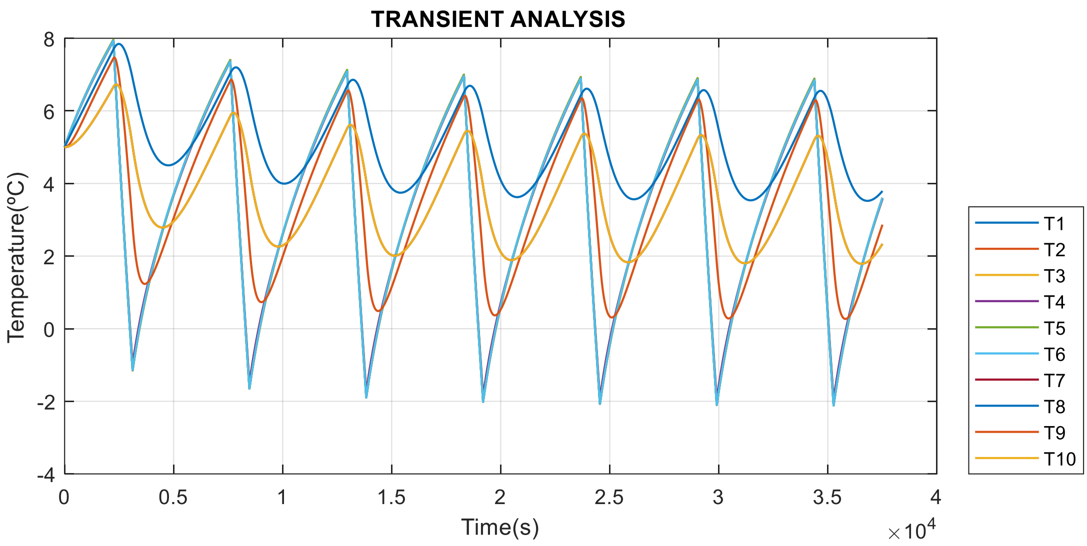


Figure 31. Transient analysis of Aluminized Kapton (Aluminium Outside)

6.6.4. GOLDIZED KAPTON (GOLD OUTSIDE)

Absorptance	0.24	Emittance	0.02

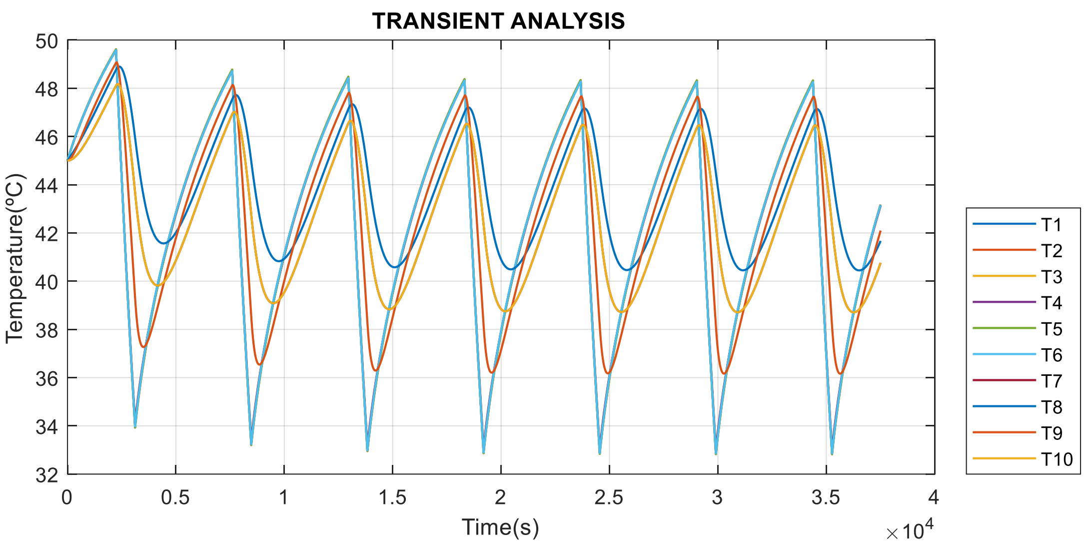


Figure 32. Transient analysis of Goldized Kapton (Gold Outside)

6.7. METALS

6.7.1. BUFFED ALUMINIUM

Absorptance	0.16	Emittance	0.03

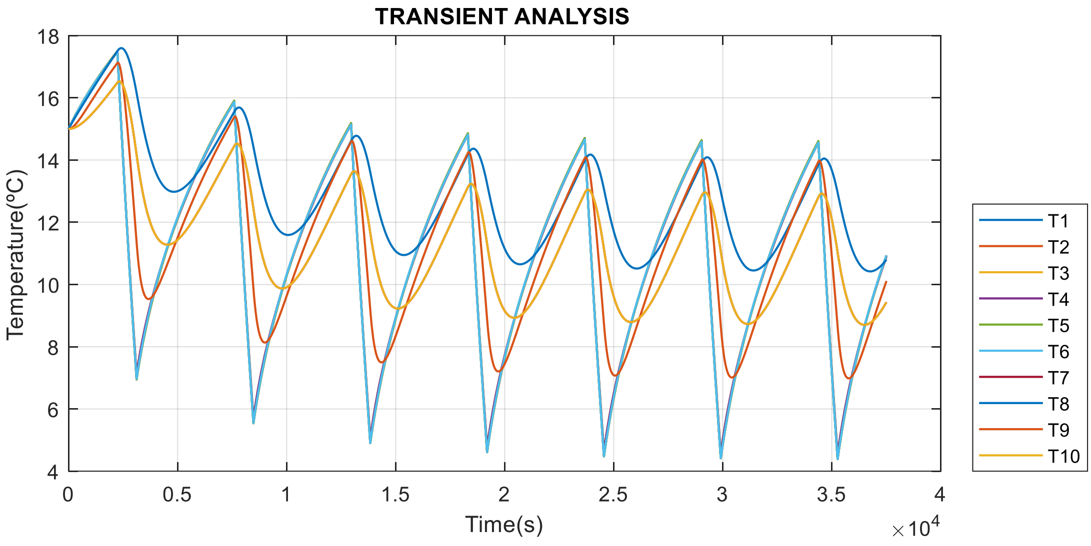


Figure 33. Transient analysis of Buffed Aluminium

6.7.2. BUFFED COPPER

Absorptance	0.30	Emittance	0.03

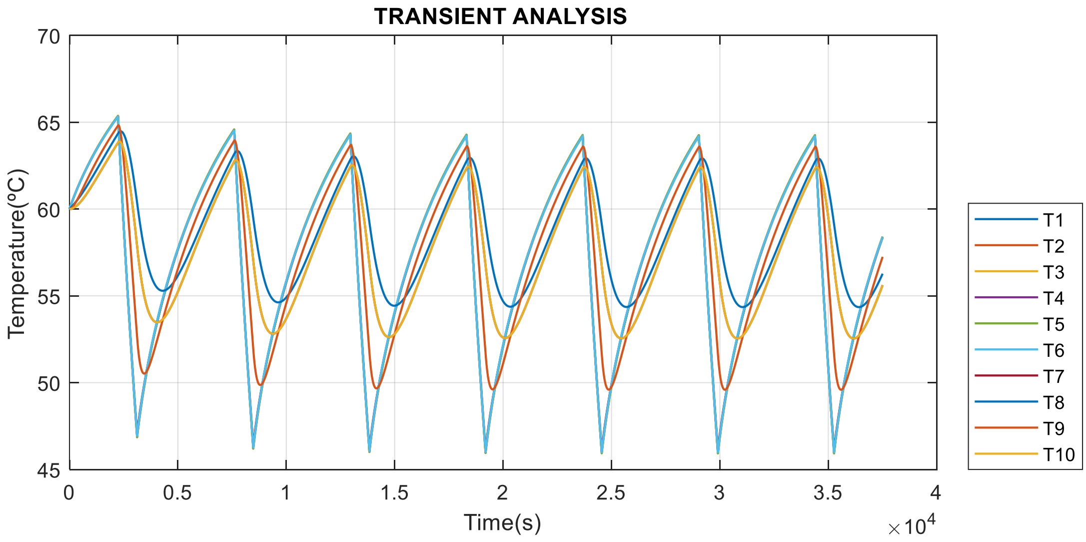


Figure 34. Transient analysis of Buffed Copper

6.7.3. POLISHED ALUMINIUM

Absorptance	0.24	Emittance	0.08

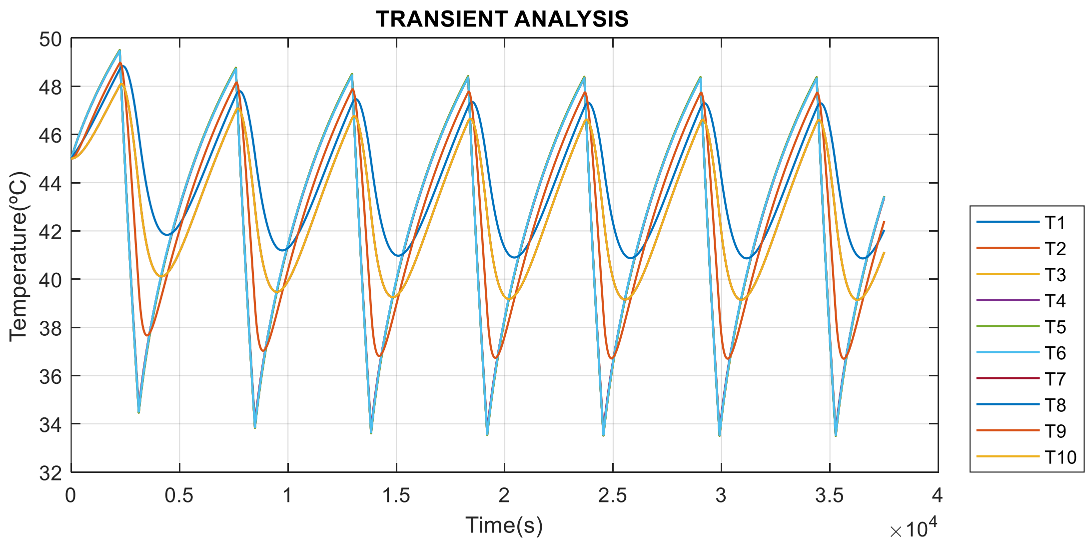


Figure 35. Transient analysis of Polished Aluminium

6.7.4. POLISHED BERYLLIUM

Absorptance	0.44	Emittance	0.01

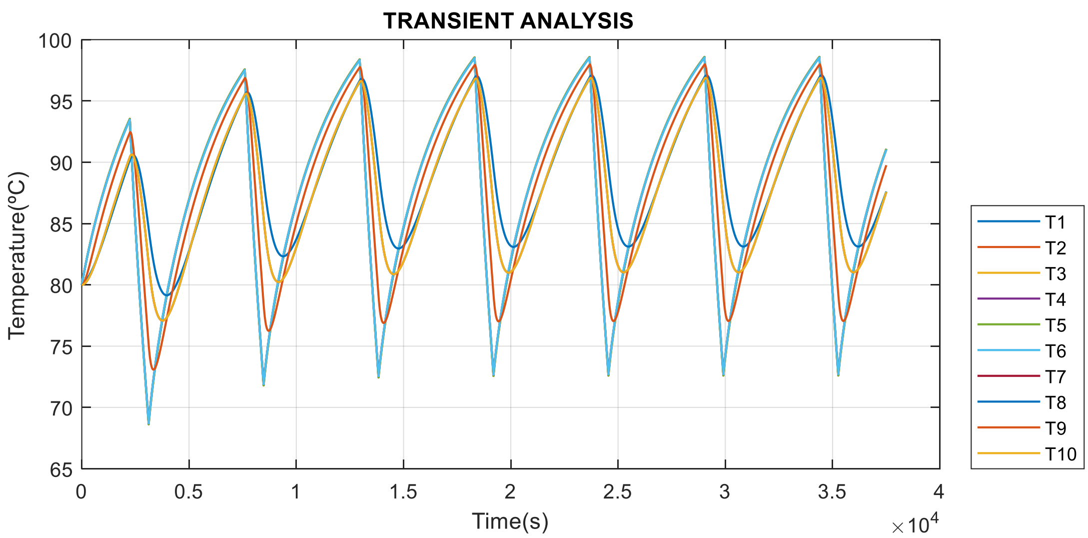


Figure 36. Transient analysis of Polished Beryllium

6.7.5. POLISHED GOLD

Absorptance	0.30	Emittance	0.05

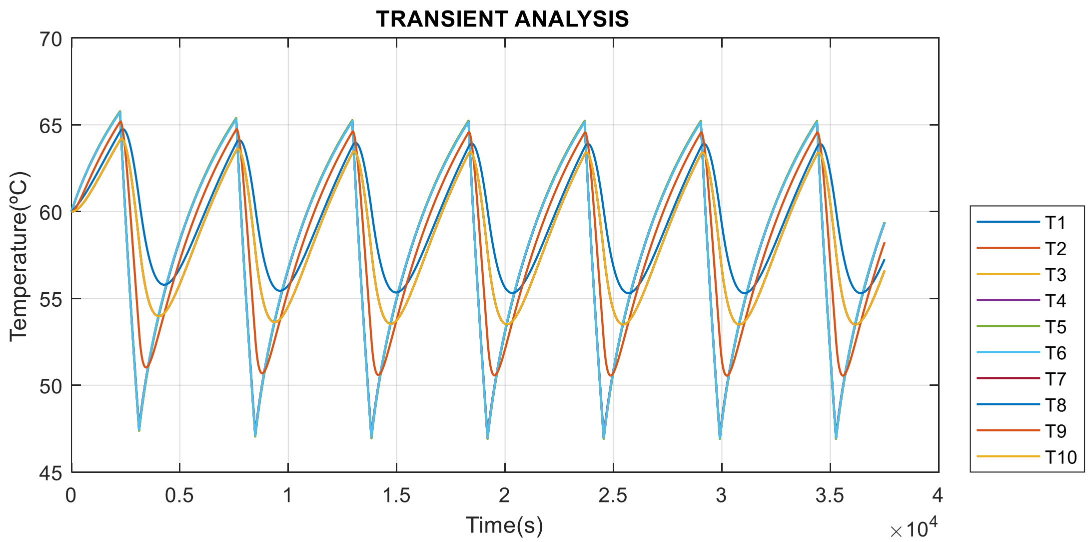


Figure 37. Transient analysis of Polished Gold

6.7.6. POLISHED SILVER

Absorptance	0.04	Emittance	0.02

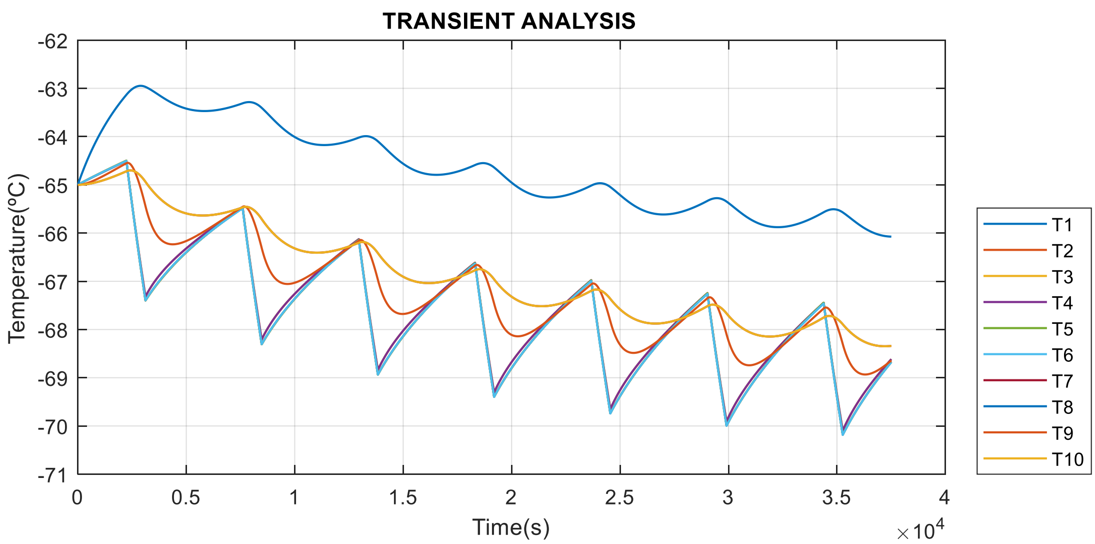


Figure 38. Transient analysis of Polished Silver

6.7.7. POLISHED STAINLESS STEEL

Absorptance	0.42	Emittance	0.11

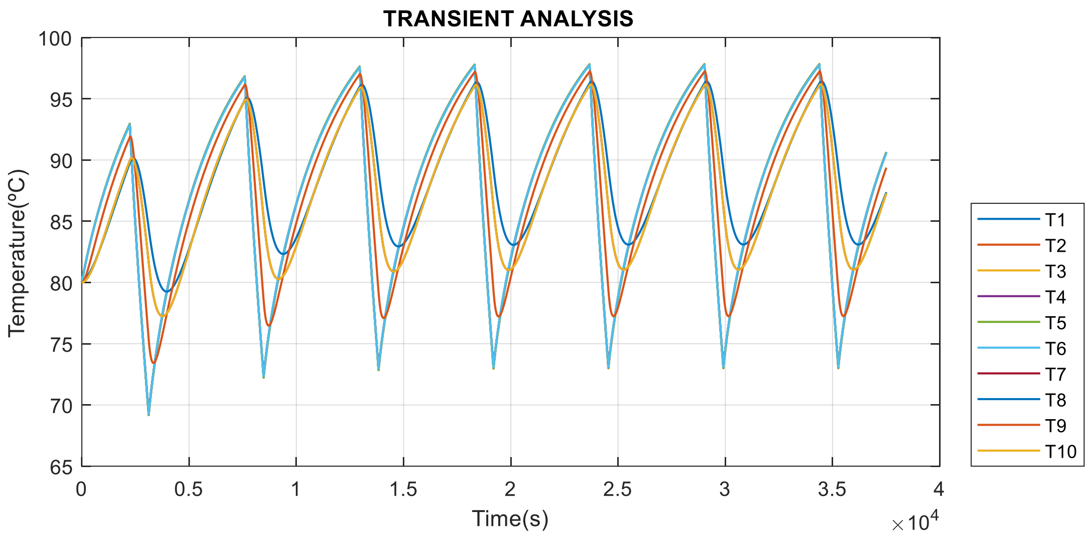


Figure 39. Transient analysis of Polished Stainless Steel

6.7.8. POLISHED TUNGSTEN

Absorptance	0.44	Emittance	0.03

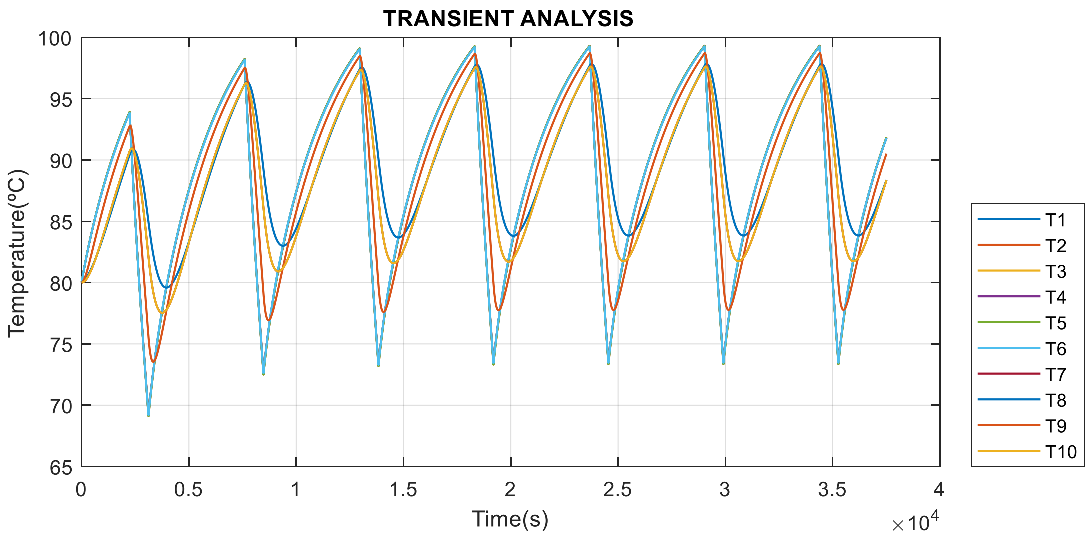


Figure 40. Transient analysis of Polished Tungsten

6.8. VAPOR-DEPOSITED COATINGS

6.8.1. ALUMINIUM

Absorptance	0.08	Emittance	0.02

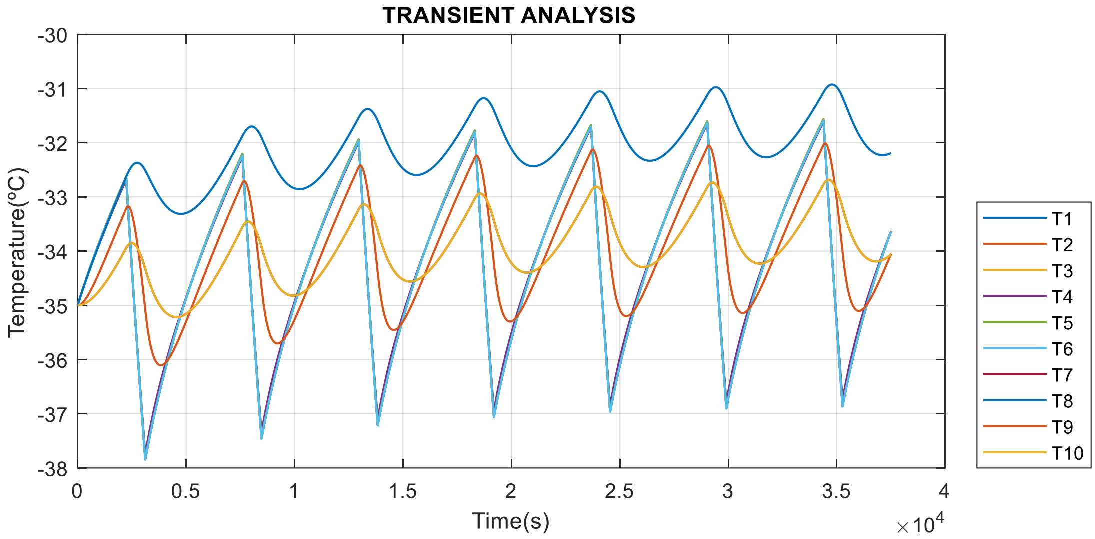


Figure 41. Transient analysis of Vapor-Deposited Aluminium

6.8.2. GOLD

Absorptance	0.19	Emittance	0.02

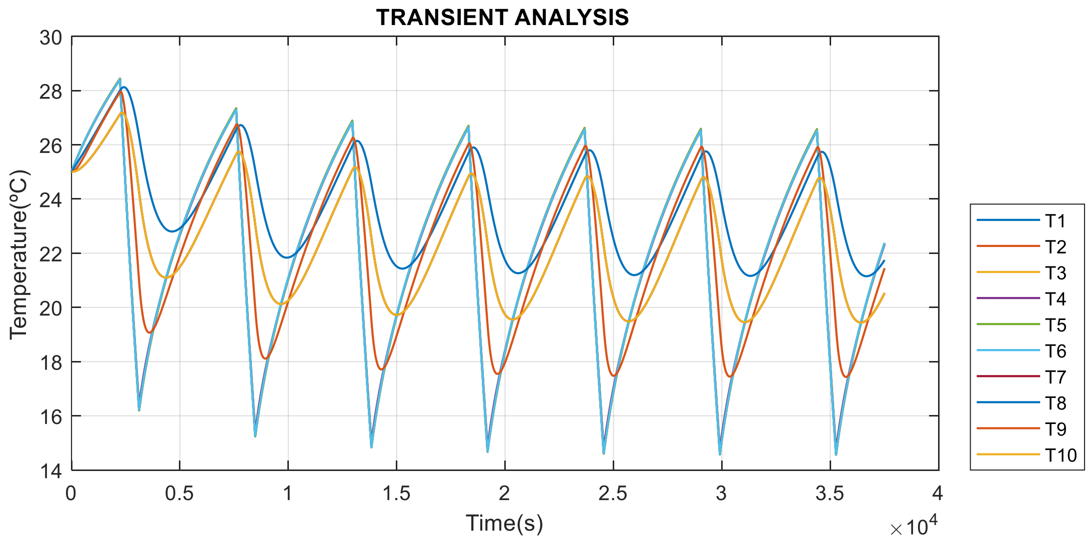


Figure 42. Transient analysis of Vapor-Deposited Gold

6.8.3. SILVER

Absorptance	0.04	Emittance	0.02

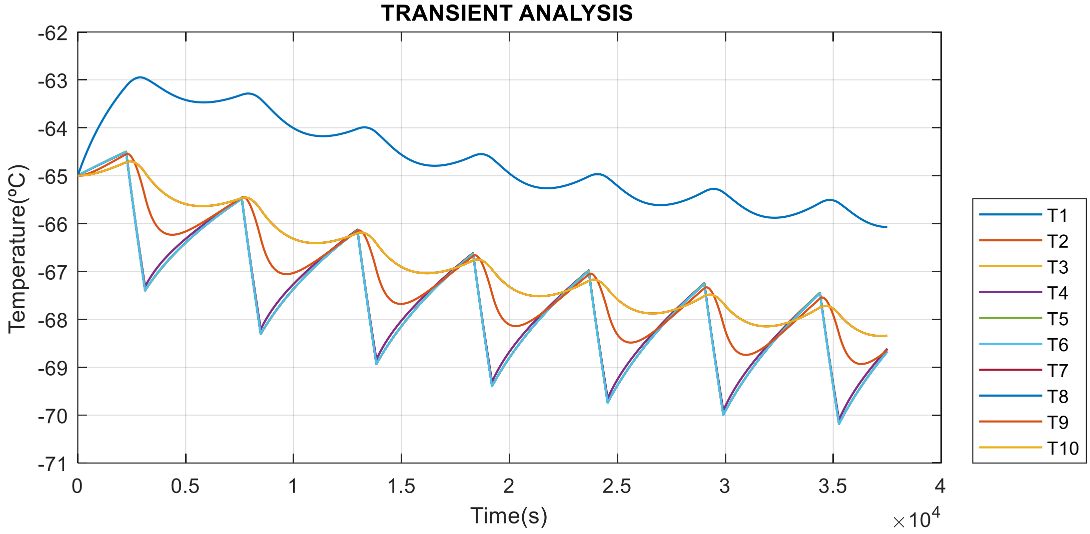


Figure 43. Transient analysis of Vapor-Deposited Silver

6.8.4. TITANIUM

Absorptance	0.52	Emittance	0.12

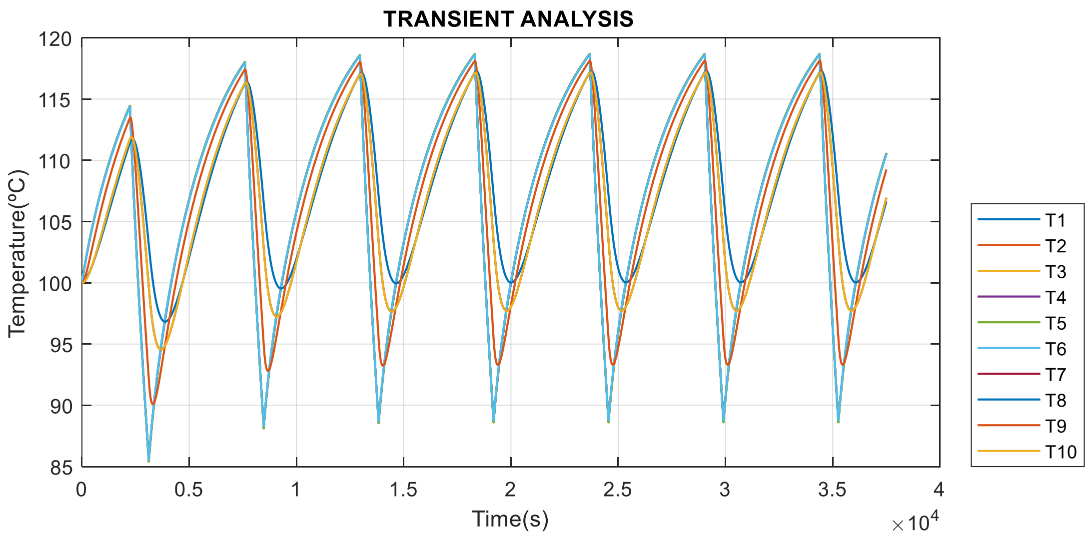


Figure 44. Transient analysis of Vapor-Deposited Titanium

6.8.5. TUNGSTEN

Absorptance	0.60	Emittance	0.27

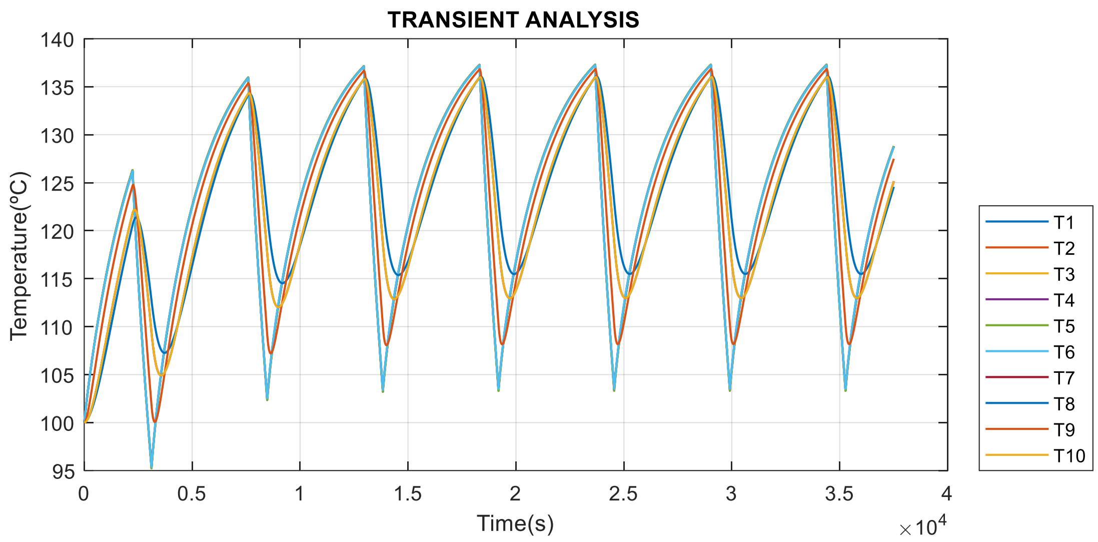


Figure 45. Transient analysis of Vapor-Deposited Tungsten

6.9. SOLAR CELLS

6.9.1. GALLIUM ARSENIDE-BASED SOLAR CELLS

Absorptance	0.88	Emittance	0.80

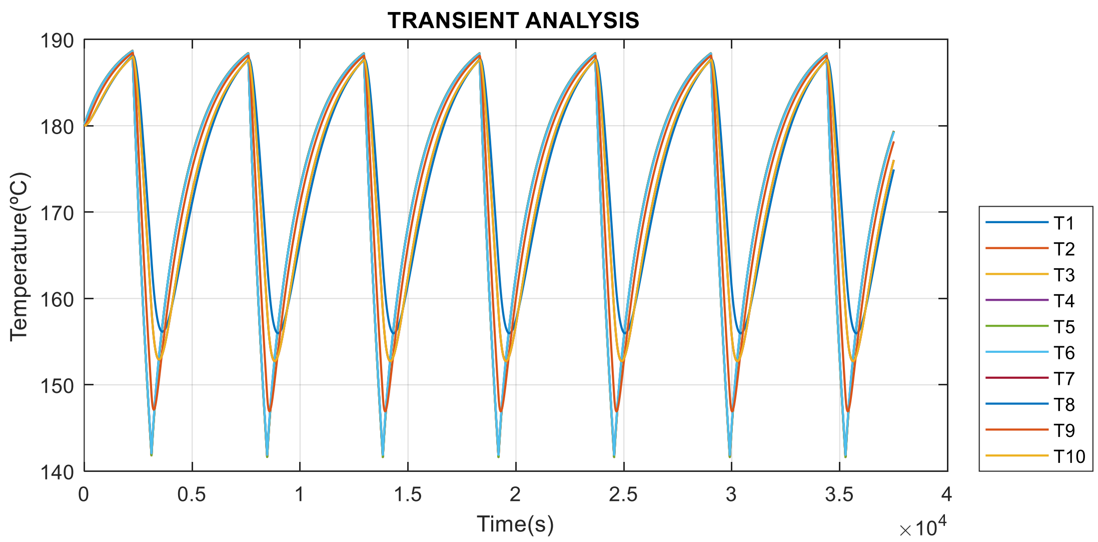


Figure 46. Transient analysis of Gallium Arsenide-Based Solar Cells

6.9.2. CRYSTALLINE SILICON-BASED SOLAR CELLS

Absorptance	0.75	Emittance	0.82

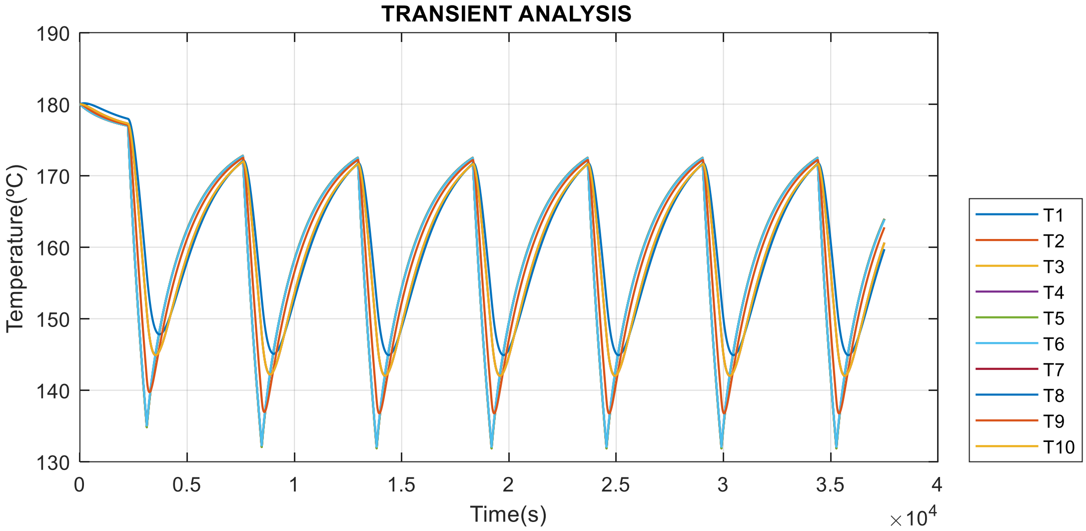


Figure 47. Transient analysis of Crystalline Silicon-Based Solar Cells

7. CONCLUSIONS

Based on all the graphics that we have been able to see in the previous section, we can confirm that all these materials, indeed, behave very differently depending on the absorptance and emittance they have.

First of all, we see that the T8, corresponding to the temperature of the Node 8 (the batteries), since it is the only node that has its own source of heat, its temperature is attenuated and therefore, it goes with a bit of delay compared to the rest. Secondly, we also see that the interior nodes (T7, T9 and T10), corresponding to the two parts of the axis and the plate, although not directly exposed to external radiation, end up with a higher temperature when the satellite goes into the night zone*. That is explained by some facts, such as that they indirectly receive radiation from all the external nodes combined and that they also receive heat from the batteries.

In addition, we can find the temperatures of all the external nodes (from T1 to T6), being these the ones that heat up the most and faster when the satellite is in the sunlight zone, and cool down to the lowest temperatures and faster when it is going through the night zone.

(*) As an example, we are going to take the graphic of the Gallium Arsenide-Based Solar Cells, in which we can discern pretty well the difference between the sunlight zone and the night zone, and how these changes affect the temperature of the spacecraft. Please note that in the graphic will only be displayed from the fourth to the seventh orbit, in order to have stabilize temperatures cycles.

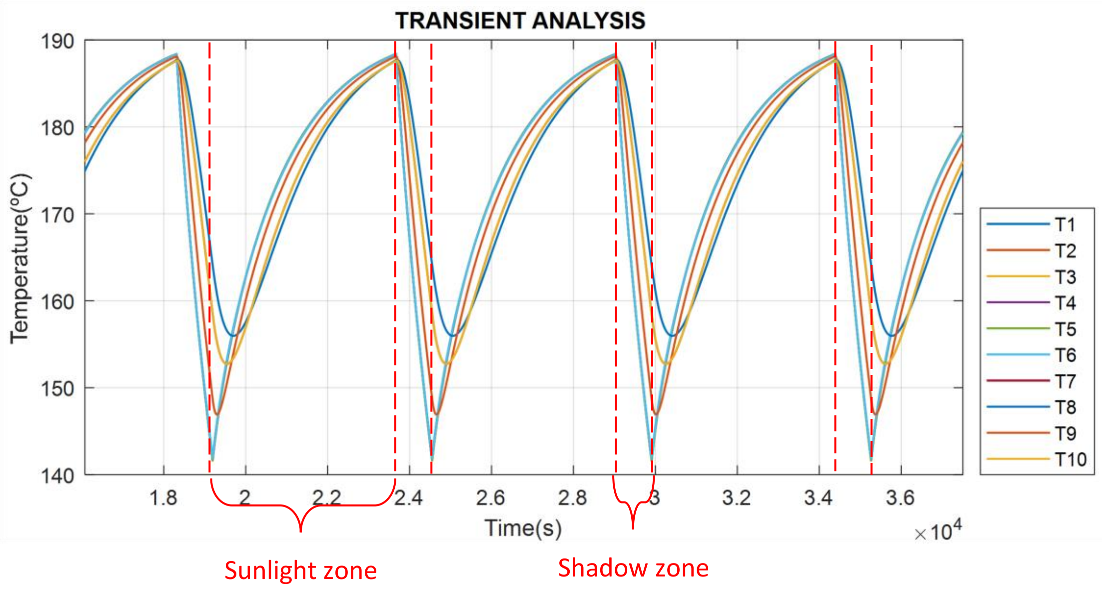


Figure 49. Clarification of sunlight and night zones

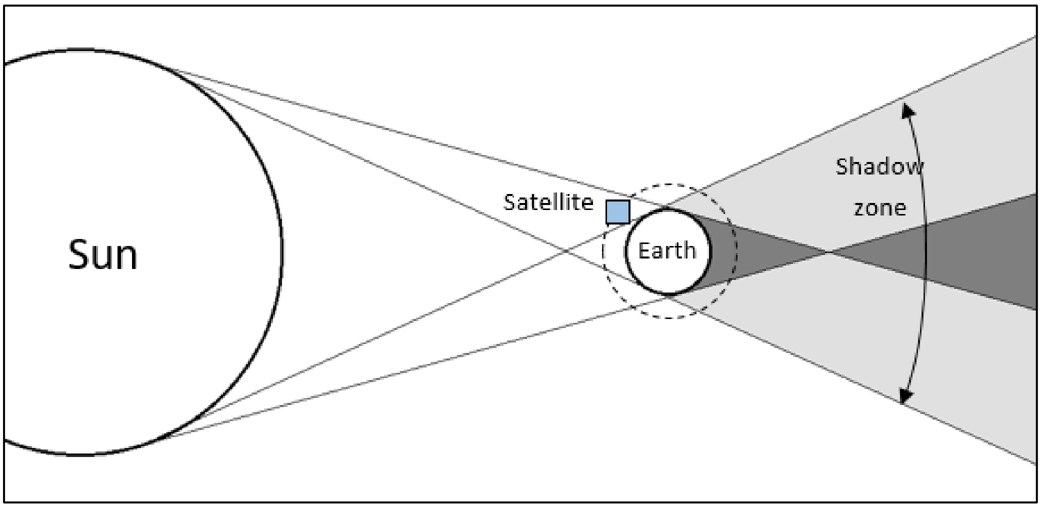


Figure 50. Representation of the phases of the satellite

*Please, note that the Figure 50 is not to scale.

In the previous representation of the Figure 50, we can observe how the orbit of the satellite will delve into the shadow zone, as well as when it will be in the sunlight zone. The consequences direct graphical consequences is what is seen in the Figure 49, where we can see how the temperature of the satellite drops when it enters into the shadow zone, and then raises up when it enters into the sunlight zone. The different colors in the shadow zone represent the umbra and penumbra, differentiations that for simplicity, we have assumed as equal.

It is necessary to point out that an analysis of the materials will be made, without considering any type of temperature regulation. All the properties that each material has and the type of missions that they could be used in will be taken into account. It is obvious that in the majority of the materials, in order to maintain a good range of temperatures for the gadgets and machines inside the satellite, some kind of temperature regulation will be needed: either refrigeration, heating, or both.

Thus, we can observe from all the graphics in the previous section that the higher the absorptance is, the higher the temperature will be; therefore, materials such as black coatings, anodized aluminium samples and solar cells, which have high values of absorptance, will be the ones that end up stabilizing in higher temperatures. Besides from the solar cells, that have a strict functional reason to be in the satellite, all these materials are bound to be used in missions in which the spacecraft will stay a lot of time not receiving sun light, and consequently could end up frozen. For this reason, it is advisable to use these kind of materials, in order to give more temperature to the system. The material with the highest absorptance value is a black coating, and, particularly, the Vel-Black.

On the other hand, we can observe that the materials with a lower value of absorptance tend to stabilize in low temperatures. Materials such as Optical Solar Reflectors, some films and tapes, some metals and some vapor-deposited coatings, are the ones that cool down the spacecraft to temperatures that could, in some cases, even end up frosting the satellite if they lack a proper temperature regulation. Missions, not only like the Parker Solar Probe, that was launched directly to the Sun by NASA [15] in order to widen our understanding of the Sun, but also some missions in which the satellite is more exposed to the Sun radiation, would be perfect for using materials that get heated as less as possible by the radiation received, such as these ones. The material with the lowest absorptance value is the Vapor-Deposited Silver.

Nevertheless, we find that the emittance does not seem to affect the temperature as much as the absorptance does. Evaluating the graphics, we can assert that the values of emittance dictate in quite a lower scale the value of temperatures. In the same way as the absorptance, the higher the emittance is, the higher the value of stabilized temperatures will be, and, on the other hand, the lower the value of emittance is, the lower the stabilized temperatures will be.

Finally, we can observe when the values of absorptance and emittance are both very low, with materials like polished silver, vapor-deposited aluminium or vapor-deposited silver, the values get really low, until quite below zero Celsius degrees. In these graphics we can see how the batteries (Node 8) are kept attenuated and in a higher temperature than the rest of the satellite, owing to the fact that have internal heat.

Summing up, and keeping in mind the ranges of temperatures that each part of the satellite should maintain in order to function well (between minus 15ºC and 50ºC for its electronics, between 0ºC and 20ºC for rechargeable batteries, and around 0ºC and 50ºC for mechanisms such as gyroscopes, momentum wheels, solar array drives…). We can assert that some materials accomplish the ranges of temperatures that the different components of the satellite should have in order to function well. The studied materials that accomplish these ranges are Aluminized Kapton (Aluminium outside) and Buffed Aluminium.

Therefore, the use of these materials as coatings would consequently mean that there would be no need of thermal conditioning. It is true that there are some other materials, such as Silvered Fused Silica, Indium-Tin-Oxide, Aluminium Tape and Vapor-deposited Gold among others, that accomplish a range of temperatures differing around 10 degrees from the well-functioning range. Thus, the use of these materials would mean conditioning, but less than if other materials with more difference were used.

8. FURTHER STUDIES

The project's conclusions are that, in fact, by just analyzing the material in a laboratory and by knowing its absorptance and emittance, we are able to confirm its behavior in space in terms of thermal control. Furthermore, if there is a need for a specific material that we want to perform in a specific way of thermal control, just by knowing its absorptance and emittance, we can assert whether this material will be eligible and able to complete the tasks we want it to do or not.

Much remains to be researched, and advancing in this field could prove to be really positive for the aerospace field and the development of the satellites' technology.

First and foremost, we could improve or vary the shape of the satellite, making it cubic, or with whatever shape gets us closer to maximum effectiveness. This change in the shape would mean to analyze the view factors and conductance again, calculations that would be done using the program ANSYS.

There could be improvements in the materials department as well. As a matter of fact, there are currently ongoing investigations on some materials that absorb almost all the light that reaches them, such as the Vantablack [16], which is made out of carbon nanotubes oriented in a particular way.

This study could also be applied for other orbits, like the ones that investigate other planets from the Solar System, such as the Cassini-Huygens space-research mission, commonly known as Cassini, that investigated Saturn and Saturn's moons.

DOCUMENT 2

BUDGET

Author: VICENT ALCAYDE PEIXO
Tutor: ANA VERCHER MARTINEZ

BUDGET

Hereunder is detailed the total cost of the project, therefore, the total budget:

WORKING BUDGET			
Hours (h)	**Task**	**Pricing (€/h)**	**Total cost (€)**
120	Research	20.00	2400.00
90	Programming	20.00	1800.00
160	Project writing	20.00	3200.00
10	Satellite design	20.00	200.00
30	Results analysis	20.00	600.00
20	Project review	20.00	400.00
430	Engineering hours	20.00	**8600.00**

SOFTWARE BUDGET		
Software	**Period of time**	**Cost (€)**
CATIA	3 months	6000.00
Matlab	1 year	269.00
Microsoft Office 2019	1 year	149.00
		6418.00
		+21%IVA
	Total software cost	**7765.78**

The working budget amount of this whole project, expressed in euros, is exactly: EIGHT THOUSAND SIX HUNDRED.

The software budget amount of this whole project, expressed in euros, is exactly: SEVEN THOUSAND SEVEN HUNDRED AND SIXTY-FIVE WITH SEVENTY-EIGHT CENTS.

The total tender budget of this whole project, expressed in euros, is exactly: **SIXTEEN THOUSAND THREE HUNDRED AND SIXTY-FIVE WITH SEVENTY-EIGHT CENTS**.

DOCUMENT 3

SCHEDULE OF CONDITIONS

Author: VICENT ALCAYDE PEIXO
Tutor: ANA VERCHER MARTINEZ

SCHEDULE OF CONDITIONS

To be able to perform all the calculations on this project, and since this is a project in which we have only studied a particular topic basing our calculations in our programming, we are bound to use just computer resources. Not only physical resources, as it would be the computer, also known as hardware, but also the programs that have been used in order to obtain the results, also known as software.

Therefore, as it should be done in this section, we are going to proceed to explain the specifications of the constituent elements, or as we have called them, hardware and software.

HARDWARE CONDITIONS

As hardware, it has been used a laptop in which all calculations have been made, through the software, explained next.

Hewlett-Packard (HP) ENVY (17.3 inches, 2015)

- Processor: Intel Core i7-5500U
- RAM Memory: 8 GB, 900 MHz, DDR3
- Mainboard: Intel Broadwell-U PCH-LP (Premium)
- Storage: 1 TB, 5400 rpm

SOFTWARE CONDITIONS

As software, it has been used some programs which although they are for commercial use, they have been provided by UPV.

Matlab

As it has been explained in the report, Matlab is a program capable of perform complex calculations, as well as matrix resolutions, therefore, we have used this software to resolve all our calculations, and to obtain several graphics extremely useful for visual resolution and explanation

CATIA

CATIA is a very powerful 3D designing and fabrication software. Using CATIA we have been able to design our satellite. With further studies, if we want to make experiments with new shape satellites, we would have to design them in CATIA.

Other programs

We have made use of some other programs simpler, in order to write this project. Programs such as Microsoft Office Excel, or Microsoft Office Word.

DOCUMENT 4

APPENDIX

Author: VICENT ALCAYDE PEIXO
Tutor: ANA VERCHER MARTINEZ

TABLE OF CONTENTS OF THE APPENDIX

1. STEADY-STATE MATRIX

$$\begin{bmatrix} \sum_{j=1}^{10} h_{1j} + 4\sigma T_{1,0}{}^{3}\left(A_{space,1}\varepsilon_1 + \sum_{j=1}^{10} A_j F_{1j}\varepsilon_{1j}\right) & -\left(h_{12} + 4\sigma T_{2,0}{}^{3} A_1 F_{12}\varepsilon_{12}\right) & \cdots & -\left(h_{110} + 4\sigma T_{10,0}{}^{3} A_1 F_{110}\varepsilon_{110}\right) \\ -\left(h_{21} + 4\sigma T_{1,0}{}^{3} A_2 F_{21}\varepsilon_{21}\right) & \sum_{j=1}^{10} h_{2j} + 4\sigma T_{2,0}{}^{3}\left(A_{space,2}\varepsilon_2 + \sum_{j=1}^{10} A_j F_{2j}\varepsilon_{2j}\right) & \cdots & -\left(h_{210} + 4\sigma T_{10,0}{}^{3} A_2 F_{210}\varepsilon_{210}\right) \\ \vdots & \vdots & \ddots & \vdots \\ -\left(h_{101} + 4\sigma T_{1,0}{}^{3} A_{10} F_{101}\varepsilon_{101}\right) & -\left(h_{102} + 4\sigma T_{2,0}{}^{3} A_{10} F_{102}\varepsilon_{102}\right) & \cdots & \sum_{j=1}^{10} h_{10i} + 4\sigma T_{10,0}{}^{3}\left(A_{space,10}\varepsilon_{10} + \sum_{j=1}^{10} A_j F_{10j}\varepsilon_{10j}\right) \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ \vdots \\ T_{10} \end{Bmatrix} =$$

$$\begin{Bmatrix} Q_{external,1} + Q_1 + 3T_{1,0}{}^{4}\sigma A_{space,1}\varepsilon_1 + 3\sigma \sum_{j=1}^{10} A_1 F_{1j}\varepsilon_{1j}\left(T_{1,0}{}^{4} - T_{j,0}{}^{4}\right) \\ Q_{external,2} + Q_2 + 3T_{2,0}{}^{4}\sigma A_{space,2}\varepsilon_2 + 3\sigma \sum_{j=1}^{10} A_2 F_{2j}\varepsilon_{2j}\left(T_{2,0}{}^{4} - T_{j,0}{}^{4}\right) \\ \vdots \\ Q_{external,10} + Q_{10} + 3T_{10,0}{}^{4}\sigma A_{space,10}\varepsilon_{10} + 3\sigma \sum_{j=1}^{10} A_{10} F_{10j}\varepsilon_{10j}\left(T_{10,0}{}^{4} - T_{j,0}{}^{4}\right) \end{Bmatrix}$$

2. TRANSIENT ANALYSIS

$$
\begin{bmatrix}
\frac{m_1c_1}{2\Delta t}+\frac{\sigma\varepsilon_1A_1 4T_{1,0}{}^3}{2}+\sum_{j=1}^{10}\frac{h_{1j}}{2}+\frac{\sigma A_1F_{1j}\varepsilon_{1j}4T_{1,0}{}^3}{2} & -\frac{h_{12}}{2}-\frac{\sigma A_1F_{12}\varepsilon_{12}4T_{2,0}{}^3}{2} & \cdots & -\frac{h_{110}}{2}-\frac{\sigma A_1F_{110}\varepsilon_{110}4T_{10,0}{}^3}{2} \\
-\frac{h_{21}}{2}-\frac{\sigma A_2F_{21}\varepsilon_{21}4T_{1,0}{}^3}{2} & \frac{m_2c_2}{2\Delta t}+\frac{\sigma\varepsilon_2A_2 4T_{2,0}{}^3}{2}+\sum_{j=1}^{10}\frac{h_{2j}}{2}+\frac{\sigma A_2F_{2j}\varepsilon_{2j}4T_{2,0}{}^3}{2} & \cdots & -\frac{h_{210}}{2}-\frac{\sigma A_2F_{210}\varepsilon_{210}4T_{10,0}{}^3}{2} \\
\vdots & \vdots & \ddots & \vdots \\
-\frac{h_{101}}{2}-\frac{\sigma A_{10}F_{101}\varepsilon_{101}4T_{1,0}{}^3}{2} & -\frac{h_{102}}{2}-\frac{\sigma A_{10}F_{102}\varepsilon_{102}4T_{2,0}{}^3}{2} & \cdots & \frac{m_{10}c_{10}}{2\Delta t}+\frac{\sigma\varepsilon_{10}A_{10}4T_{10,0}{}^3}{2}+\sum_{j=1}^{10}\frac{h_{10j}}{2}+\frac{\sigma A_{10}F_{10j}\varepsilon_{10j}4T_{10,0}{}^3}{2}
\end{bmatrix}
\begin{Bmatrix} T_1 \\ T_2 \\ \vdots \\ T_{10} \end{Bmatrix} =
$$

$$
\begin{Bmatrix}
\frac{m_1c_1T_{1,0}}{2\Delta t}+\frac{Q_{ext,1}+Q_{ext,1,0}}{2}+Q_1-\frac{\sigma\varepsilon_1A_{space,1}4T_{1,0}{}^3}{2}+\sigma\varepsilon_1A_{space,1}3T_{1,0}{}^4-\sum_{j=1}^{10}\frac{h_{1j}T_{1,0}}{2}-\frac{h_{1j}T_{j,0}}{2}-\sigma\left(-\frac{A_1F_{1j}\varepsilon_{1j}4T_{1,0}{}^3}{2}+A_1F_{1j}\varepsilon_{1j}3T_{1,0}{}^4+\frac{A_1F_{1j}\varepsilon_{1j}4T_{j,0}{}^3}{2}-A_1F_{1j}\varepsilon_{1j}3T_{j,0}{}^4\right) \\
\frac{m_1c_1T_{1,0}}{2\Delta t}+\frac{Q_{ext,1}+Q_{ext,1,0}}{2}+Q_1-\frac{\sigma\varepsilon_1A_{space,1}4T_{1,0}{}^3}{2}+\sigma\varepsilon_1A_{space,1}3T_{1,0}{}^4-\sum_{j=1}^{10}\frac{h_{1j}T_{1,0}}{2}-\frac{h_{1j}T_{j,0}}{2}-\sigma\left(-\frac{A_1F_{1j}\varepsilon_{1j}4T_{1,0}{}^3}{2}+A_1F_{1j}\varepsilon_{1j}3T_{1,0}{}^4+\frac{A_1F_{1j}\varepsilon_{1j}4T_{j,0}{}^3}{2}-A_1F_{1j}\varepsilon_{1j}3T_{j,0}{}^4\right) \\
\vdots \\
\frac{m_{10}c_{10}T_{10,0}}{2\Delta t}+\frac{Q_{ext,10}+Q_{ext,10,0}}{2}+Q_{10}-\frac{\sigma\varepsilon_{10}A_{space,10}4T_{10,0}{}^3}{2}+\sigma\varepsilon_{10}A_{space,10}3T_{10,0}{}^4-\sum_{j=1}^{10}\frac{h_{10j}T_{10,0}}{2}-\frac{h_{10j}T_{j,0}}{2}-\sigma\left(-\frac{A_{10}F_{10j}\varepsilon_{10j}4T_{10,0}{}^3}{2}+A_{10}F_{10j}\varepsilon_{10j}3T_{10,0}{}^4+\frac{A_{10}F_{10j}\varepsilon_{10j}4T_{j,0}{}^3}{2}-A_{10}F_{10j}\varepsilon_{10j}3T_{j,0}{}^4\right)
\end{Bmatrix}
$$

3. STEADY-STATE GRAPHICS

3.1. OPTICAL SOLAR REFLECTORS (OSR)

3.1.1. SILVERED FUSED SILICA

Absorptance	0.07	Emittance	0.80

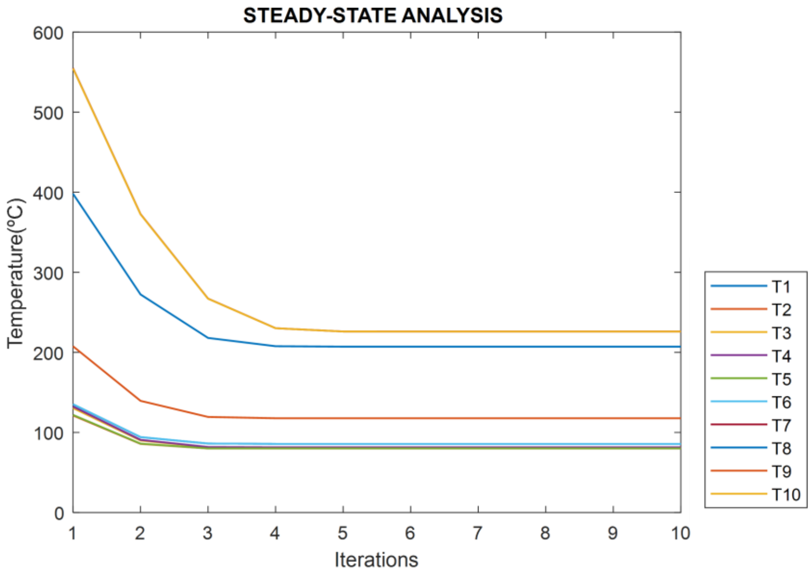


Figure 51. Steady-state analysis of Silvered Fused Silica

3.1.2. INDIUM-TIN-OXIDE (ITO)

Absorptance	0.07	Emittance	0.76

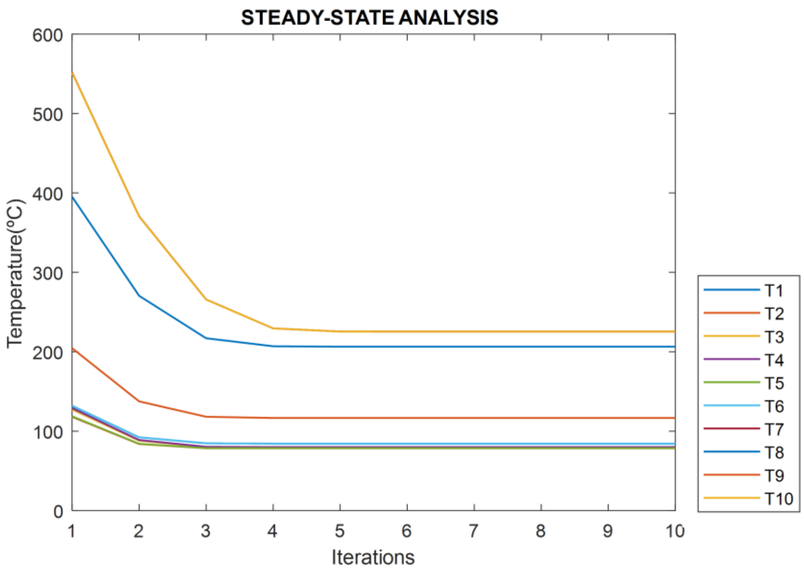


Figure 52. Steady-state analysis of Indium-Tin-Oxide (ITO)

3.1.3. ALUMINIZED TEFLON (0.5 mm)

Absorptance	0.14	Emittance	0.40

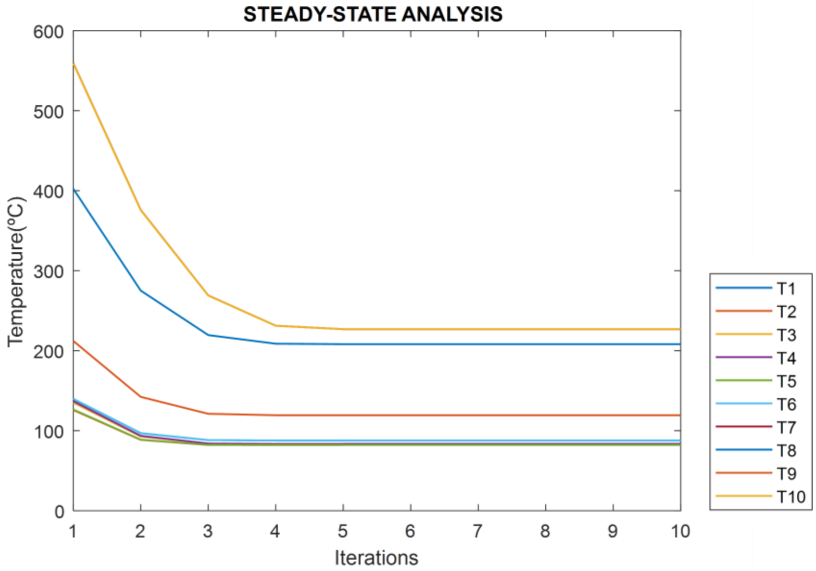


Figure 53. Steady-state analysis of Aluminized Teflon (0.5 mm)

3.1.4. ALUMINIZED TEFLON (10 mm)

Absorptance	0.15	Emittance	0.85

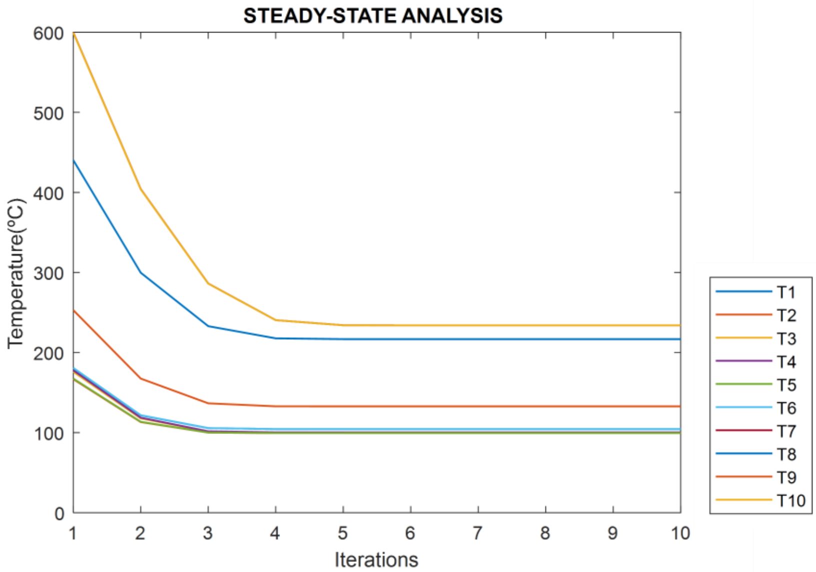


Figure 54. Steady-state analysis of Aluminized Teflon (10 mm)

3.1.5. SILVERED TEFLON (2 mm)

Absorptance	0.08	Emittance	0.68

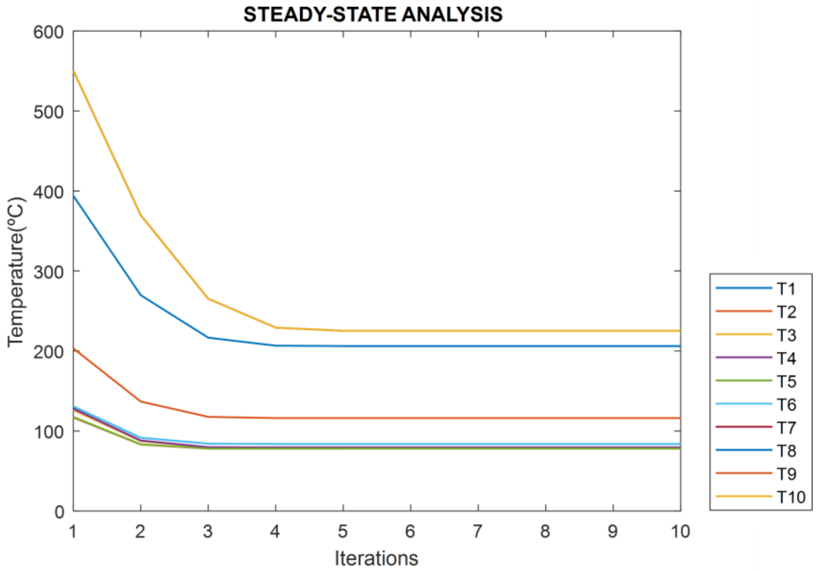


Figure 55. Steady-state analysis of Silvered Teflon (2 mm)

3.1.6. ALUMINIZED SILVERED TEFLON (10 mm)

Absorptance	0.09	Emittance	0.88

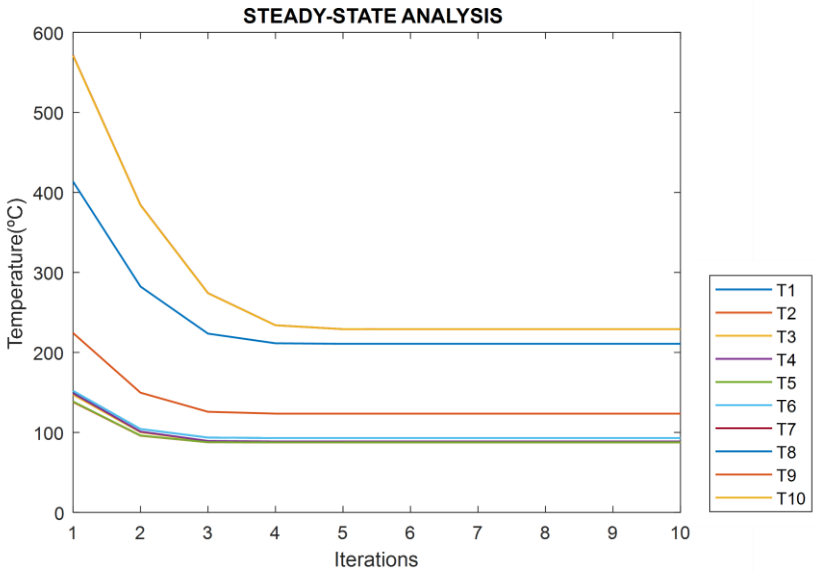


Figure 56. Steady-state analysis of Aluminized Silvered Teflon (10 mm)

3.2. BLACK COATINGS

3.2.1. CATALAC BLACK PAINT

Absorptance	0.96	Emittance	0.88

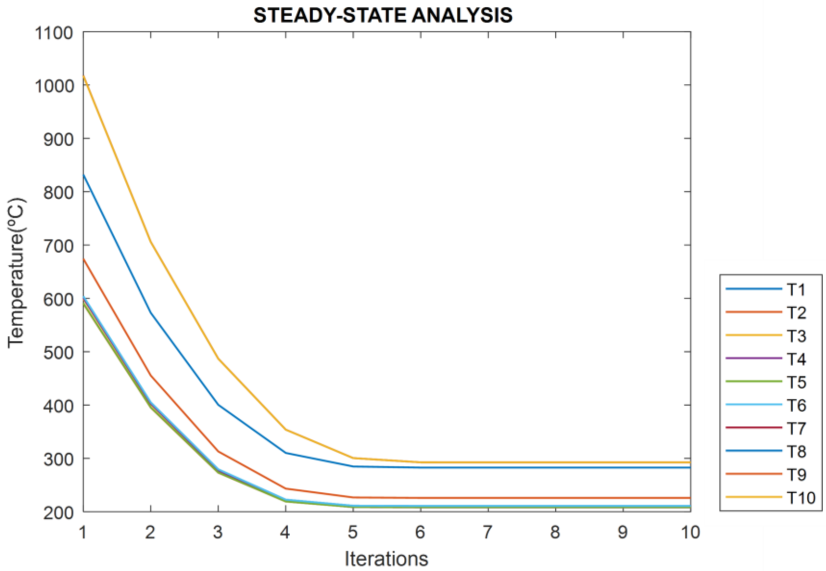


Figure 57. Steady-state analysis of Catalac Black Paint

3.2.2. DELRIN BLACK PLASTIC

Absorptance	0.96	Emittance	0.87

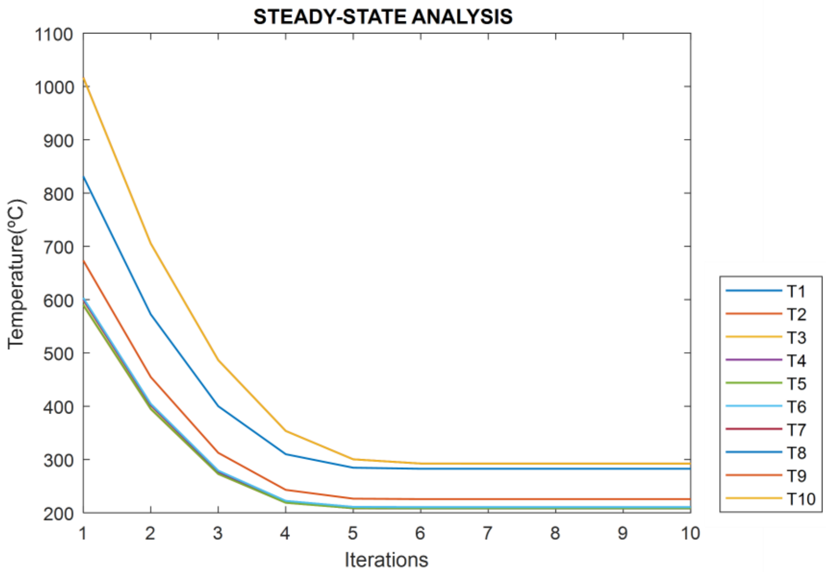


Figure 58. Steady-state analysis of Delrin Black Paint

3.2.3. MARTIN BLACK VELVET PAINT

Absorptance	0.91	Emittance	0.94

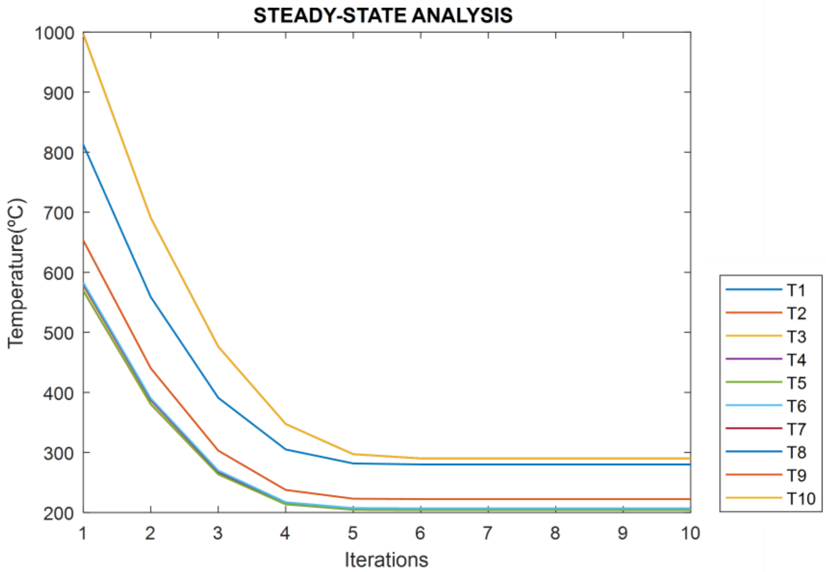


Figure 59. Steady-state analysis of Martin Black Velvet Paint

3.2.4. PARSONS BLACK PAINT

Absorptance	0.98	Emittance	0.91

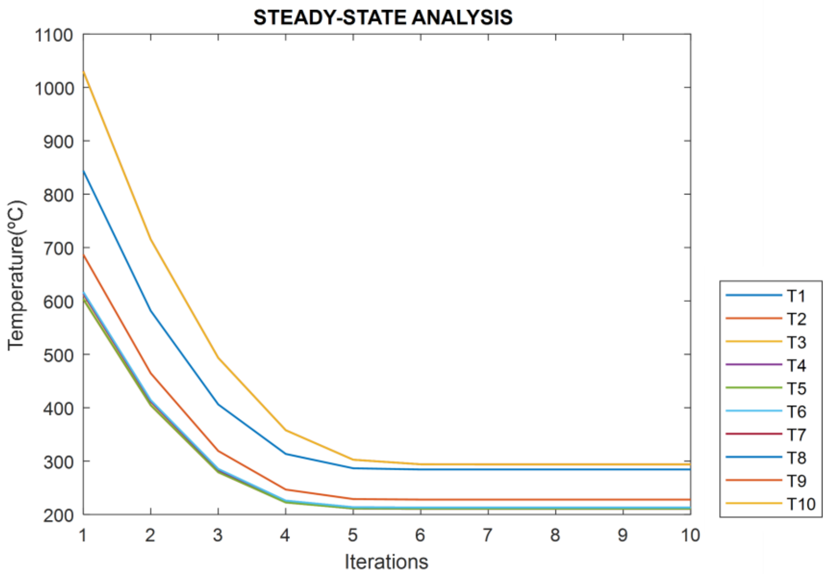


Figure 60. Steady-state analysis of Parsons Black Paint

3.2.5. VEL-BLACK

Absorptance	0.99	Emittance	0.95

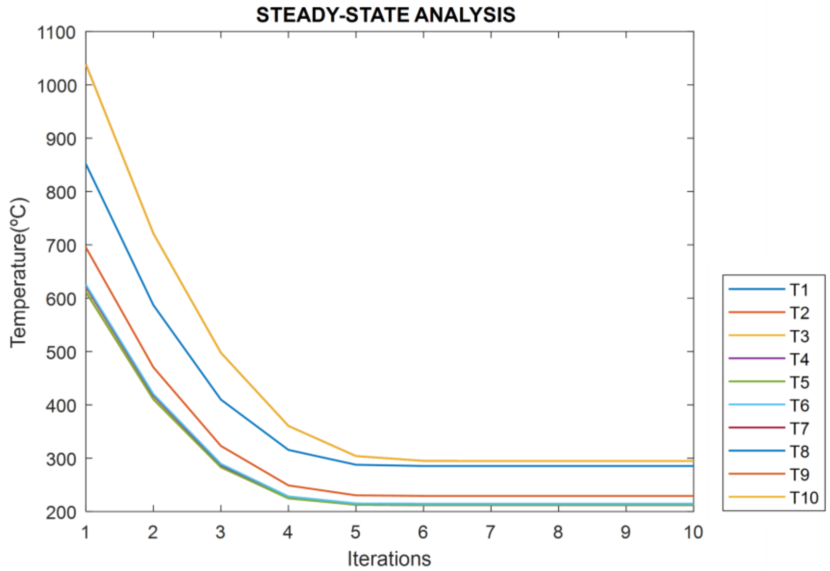


Figure 61. Steady-state analysis of Vel-Black

3.3. WHITE COATINGS

3.3.1. BARIUM SULPHATE WITH POLYVINYL ALCOHOL

Absorptance	0.06	Emittance	0.91

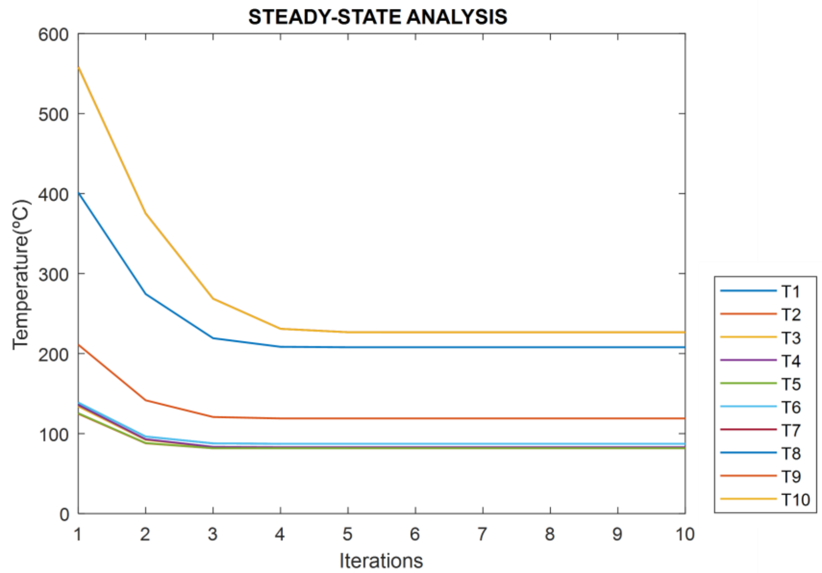


Figure 62. Steady-state analysis of Barium Sulphate with Polyvinyl Alcohol

3.3.2. CATALAC WHITE PAINT

Absorptance	0.24	Emittance	0.90

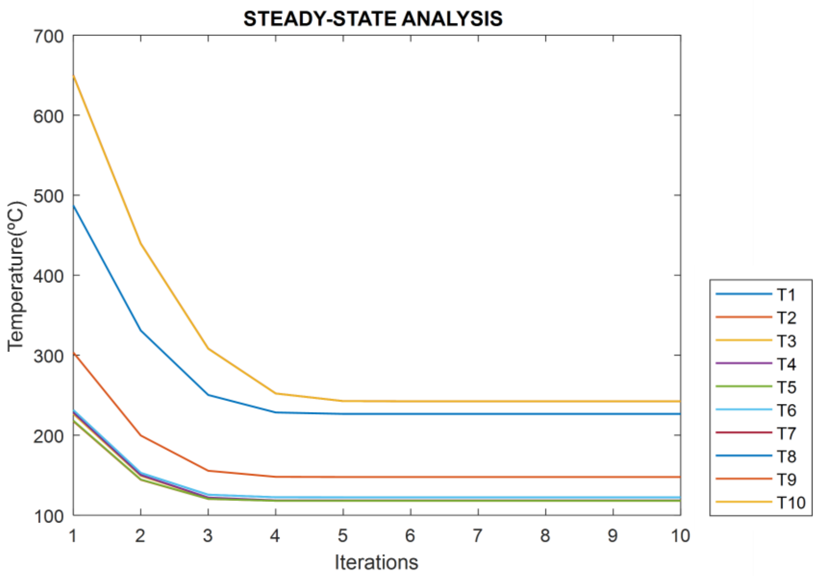


Figure 63. Steady-state analysis of Catalac White Paint

3.3.3. NASA/GSFC NS-74 WHITE PAINT

Absorptance	0.17	Emittance	0.92

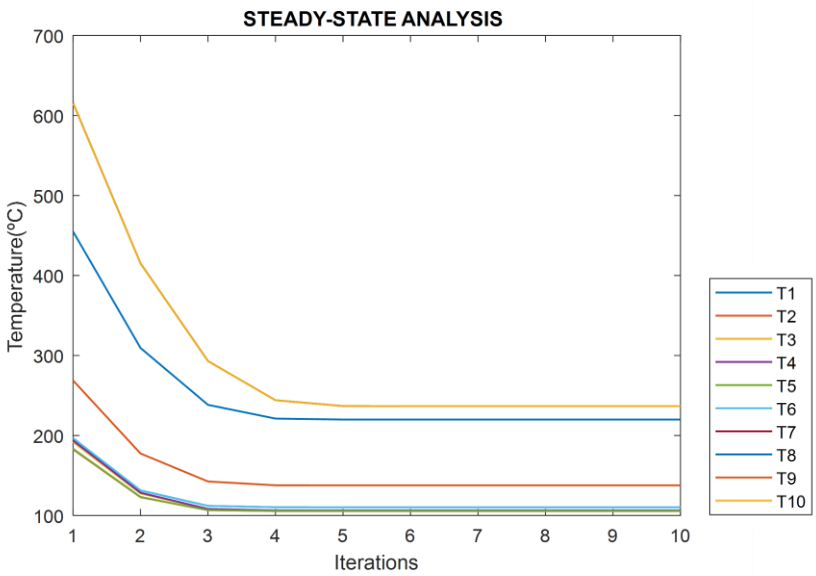


Figure 64. Steady-state analysis of NASA/GSFC NS-74 White Paint

3.3.4. MAGNESIUM OXIDE ALUMINIUM OXIDE PAINT

Absorptance	0.09	Emittance	0.92

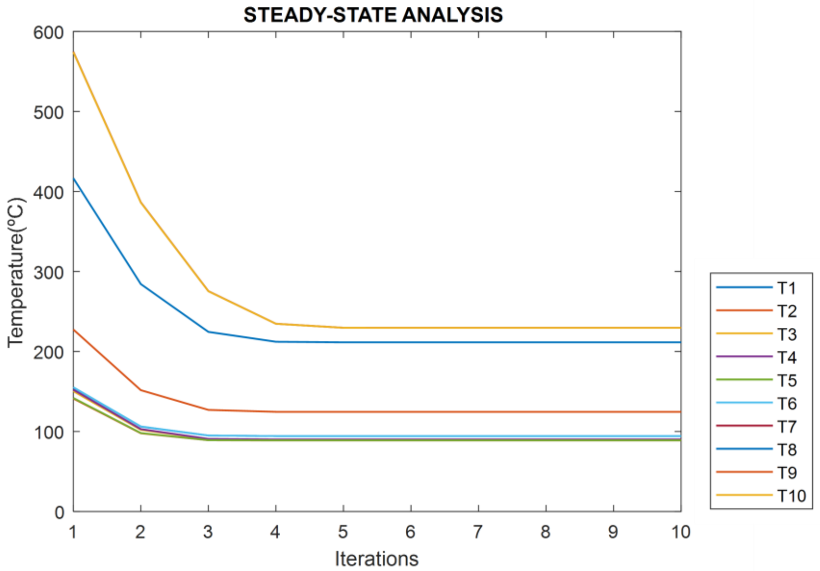


Figure 65. Steady-state analysis of Magnesium Oxide Aluminium Oxide Paint

3.3.5. WHITE POLYURETHANE PAINT

Absorptance	0.27	Emittance	0.82

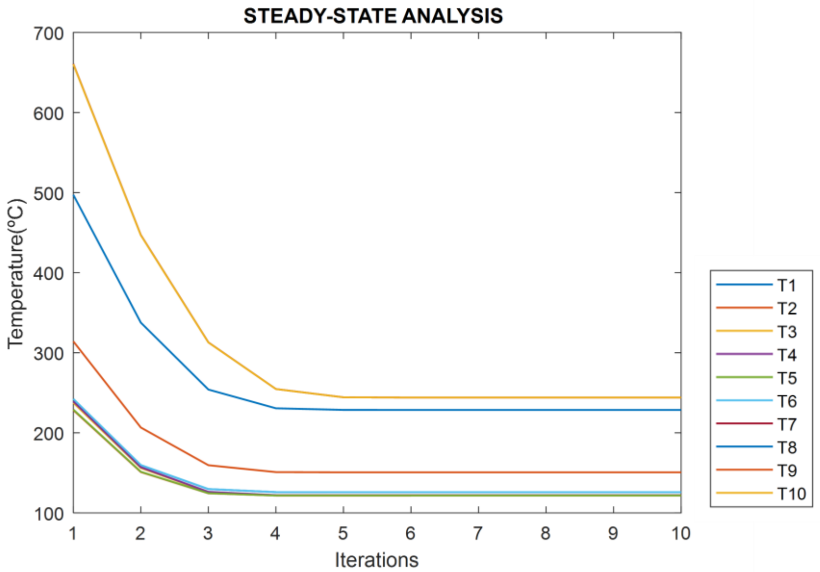


Figure 66. Steady-state analysis of White Polyurethane Paint

3.4. ANODIZED ALUMINIUM SAMPLES

3.4.1. ANODIZED ALUMINIUM BLACK

Absorptance	0.76	Emittance	0.88

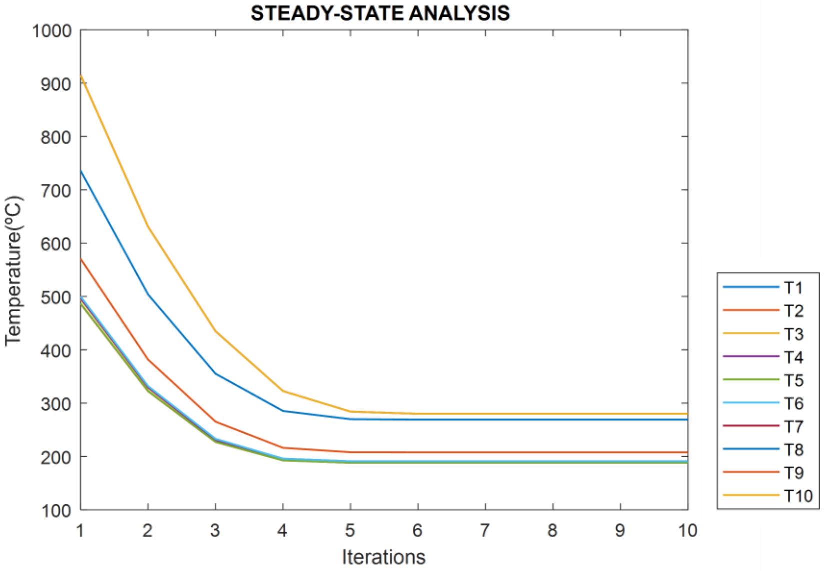


Figure 67. Steady-state analysis of Anodized Aluminium Black

3.4.2. ANODIZED ALUMINIUM BLUE

Absorptance	0.60	Emittance	0.88

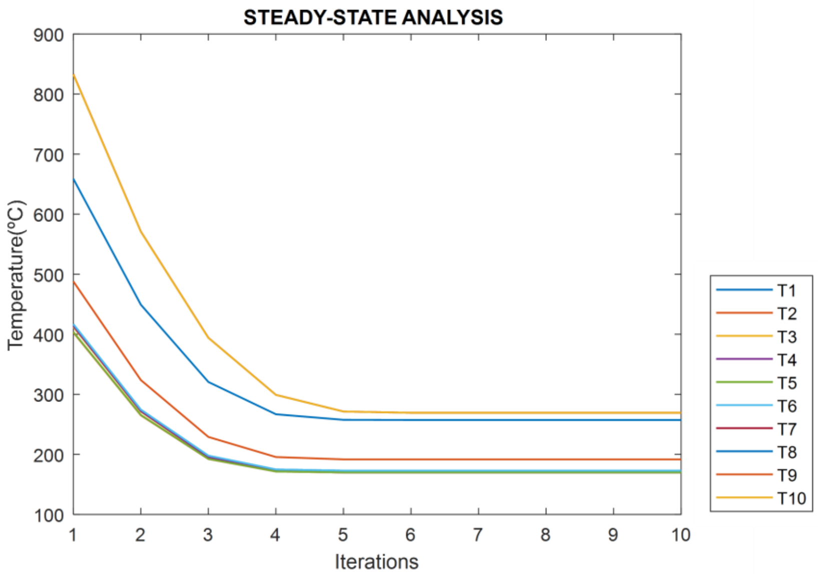


Figure 68. Steady-state analysis of Anodized Aluminium Blue

3.4.3. ANODIZED ALUMINIUM CHROMIC

Absorptance	0.44	Emittance	0.56

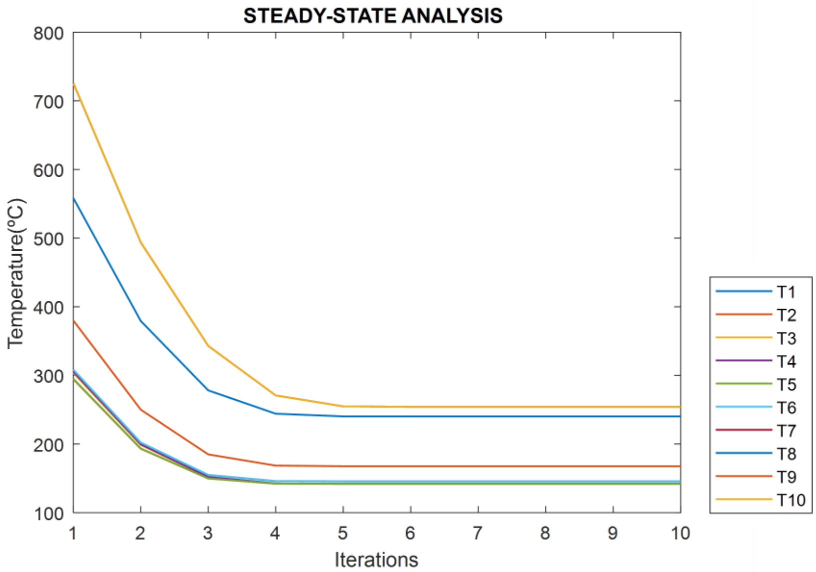


Figure 69. Steady-state analysis of Anodized Aluminium Chromic

3.4.4. ANODIZED ALUMINIUM GOLD

Absorptance	0.48	Emittance	0.82

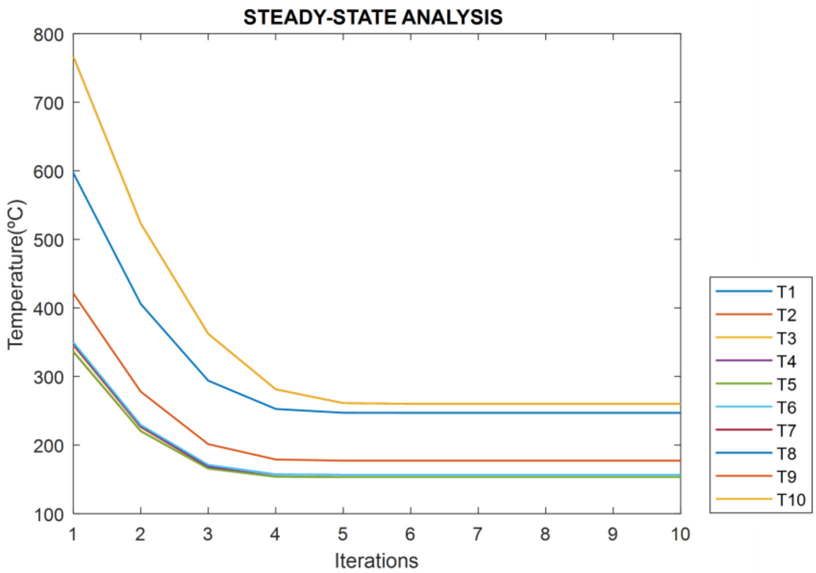


Figure 70. Steady-state analysis of Anodized Aluminium Gold

3.4.5. ANODIZED ALUMINIUM RED

Absorptance	0.57	Emittance	0.88

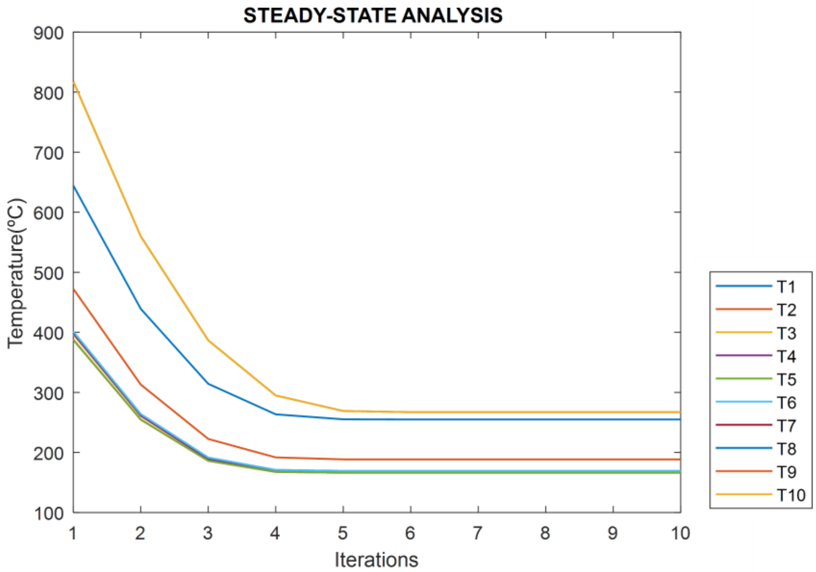


Figure 71. Steady-state analysis of Anodized Aluminium Red

3.4.6. ANODIZED ALUMINIUM YELLOW

Absorptance	0.47	Emittance	0.87

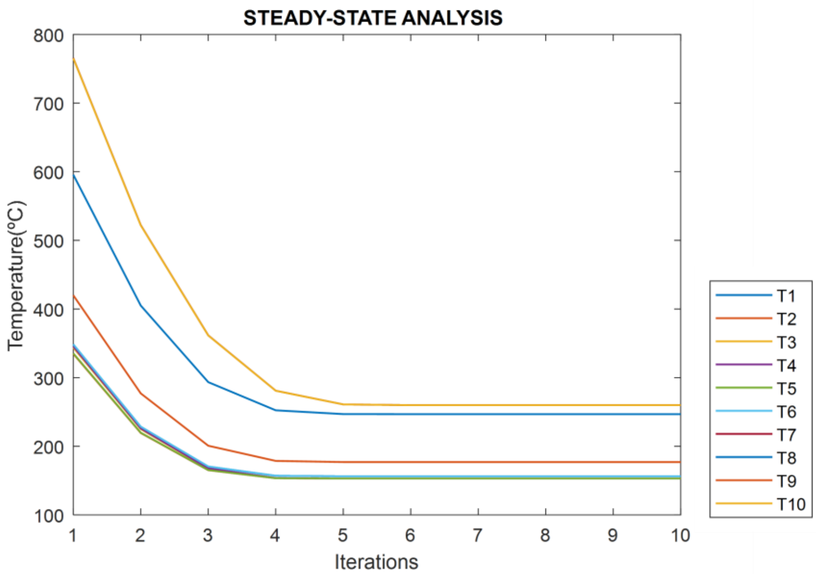


Figure 72. Steady-state analysis of Anodized Aluminium Yellow

3.5. FILMS AND TAPES

3.5.1. ALUMINIUM TAPE

Absorptance	0.21	Emittance	0.04

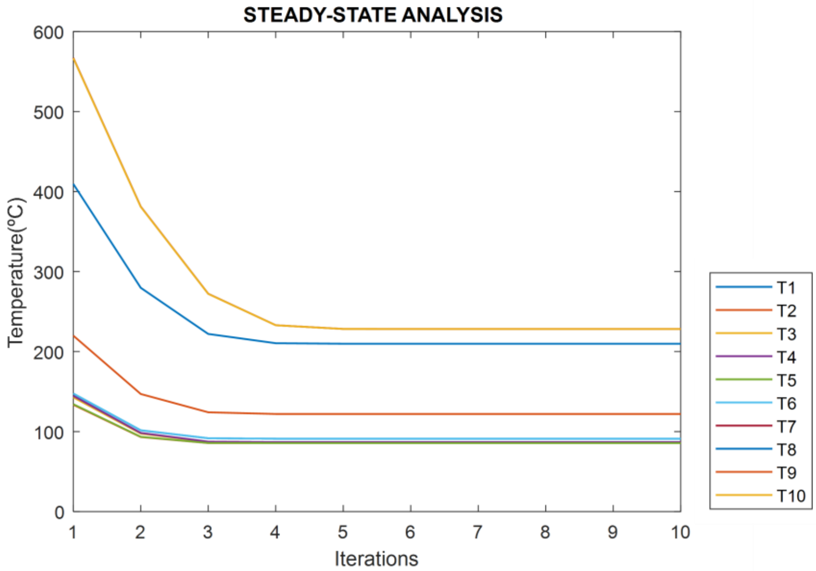


Figure 73. Steady-state analysis of Aluminium Tape

3.5.2. ALUMINIZED ACLAR FILM (1 mm)

Absorptance	0.12	Emittance	0.54

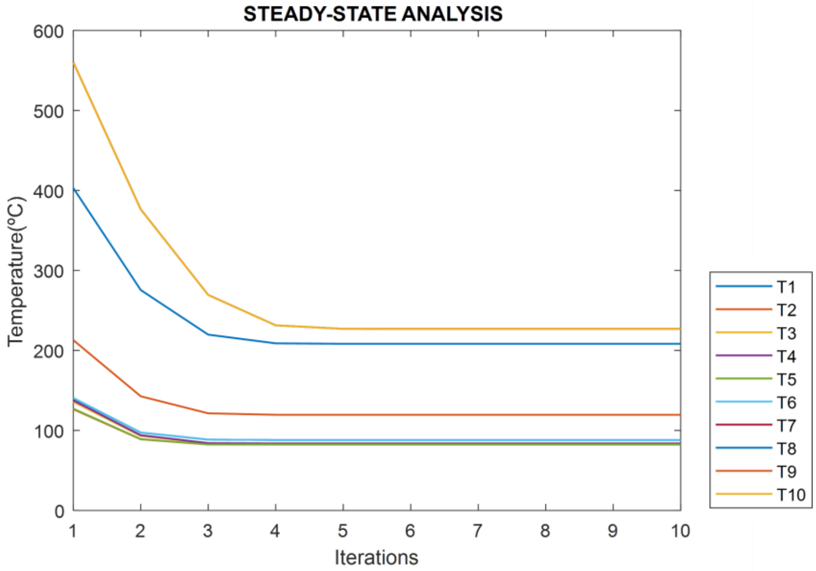


Figure 74. Steady-state analysis of Aluminized Aclar Film (1 mm)

3.5.3. ALUMINIZED KAPTON (ALUMINIUM OUTSIDE)

Absorptance	0.14	Emittance	0.05

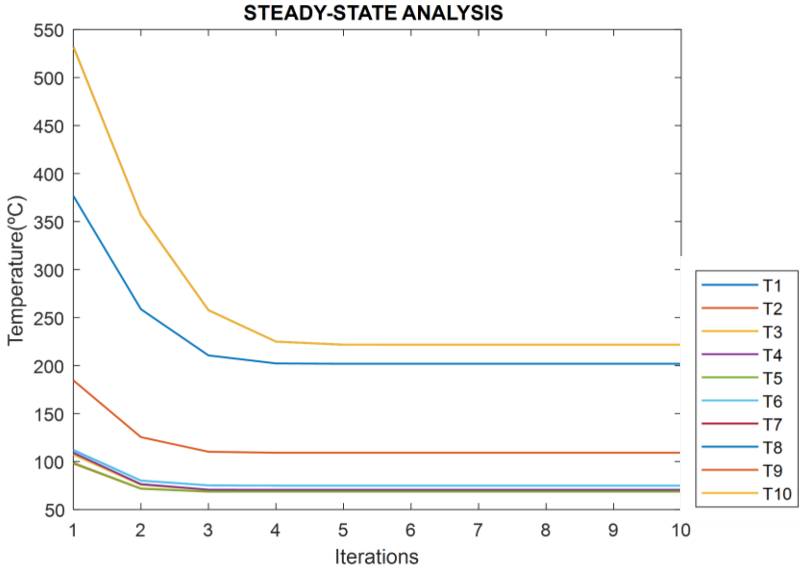


Figure 75. Steady-state analysis of Aluminized Kapton (Aluminium Outside)

3.5.4. GOLDIZED KAPTON (GOLD OUTSIDE)

Absorptance	0.24	Emittance	0.02

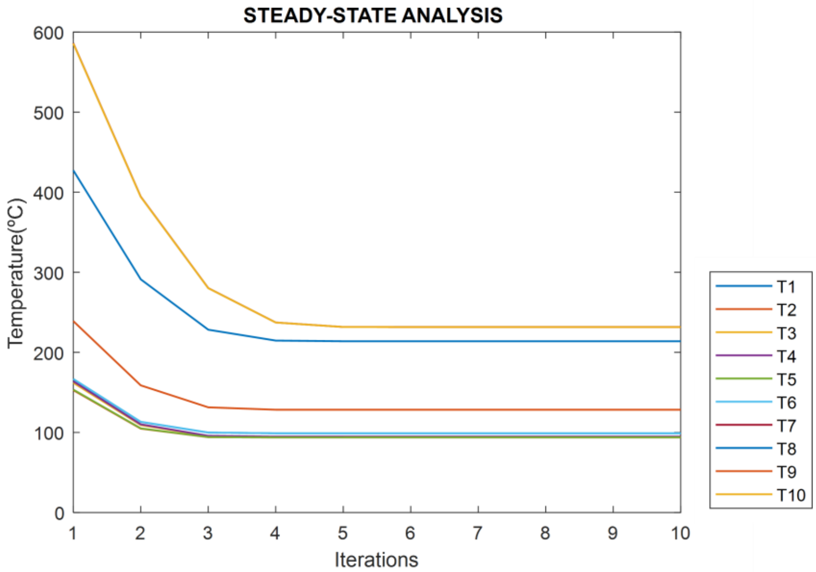


Figure 76. Steady-state analysis of Goldized Kapton (Gold Outside)

3.6. METALS

3.6.1. BUFFED ALUMINIUM

Absorptance	0.16	Emittance	0.03

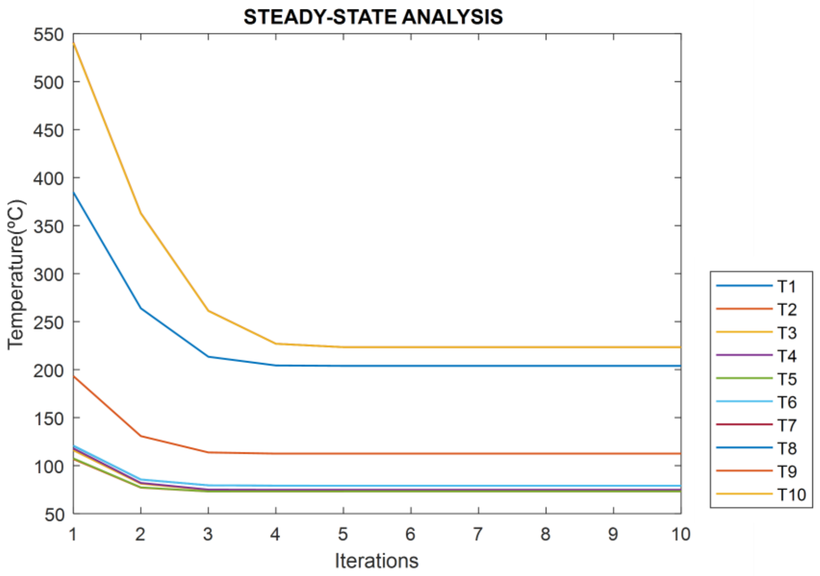


Figure 77. Steady-state analysis of Buffed Aluminium

3.6.2. BUFFED COPPER

Absorptance	0.30	Emittance	0.03

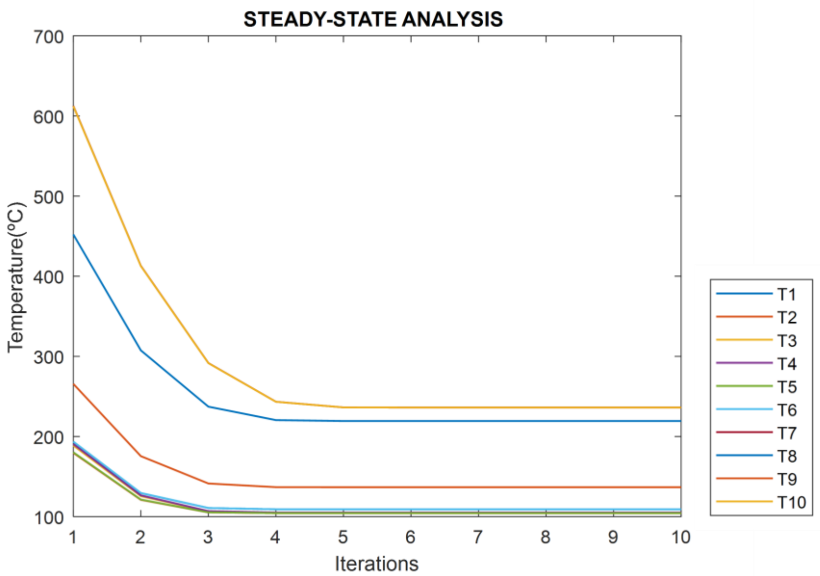


Figure 78. Steady-state analysis of Buffed Copper

3.6.3. POLISHED ALUMINIUM

Absorptance	0.24	Emittance	0.08

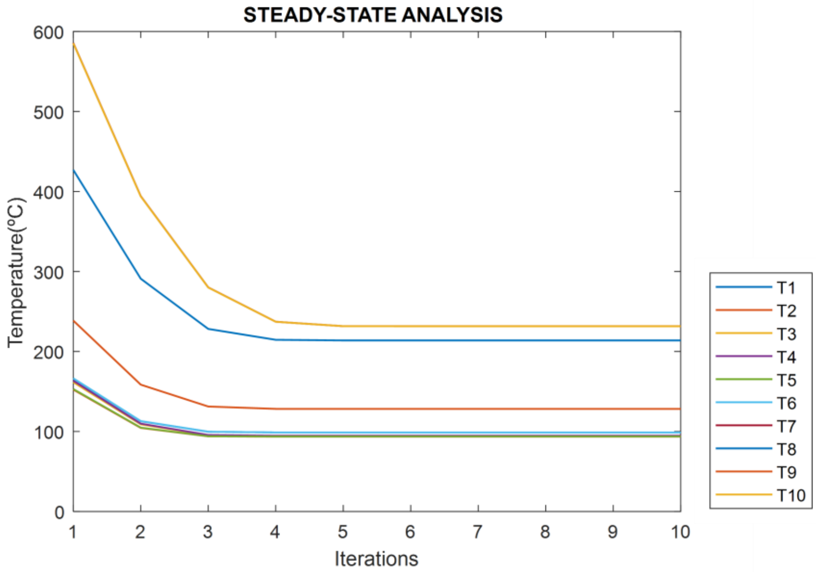


Figure 79. Steady-state analysis of Polished Aluminium

3.6.4. POLISHED BERYLLIUM

Absorptance	0.44	Emittance	0.01

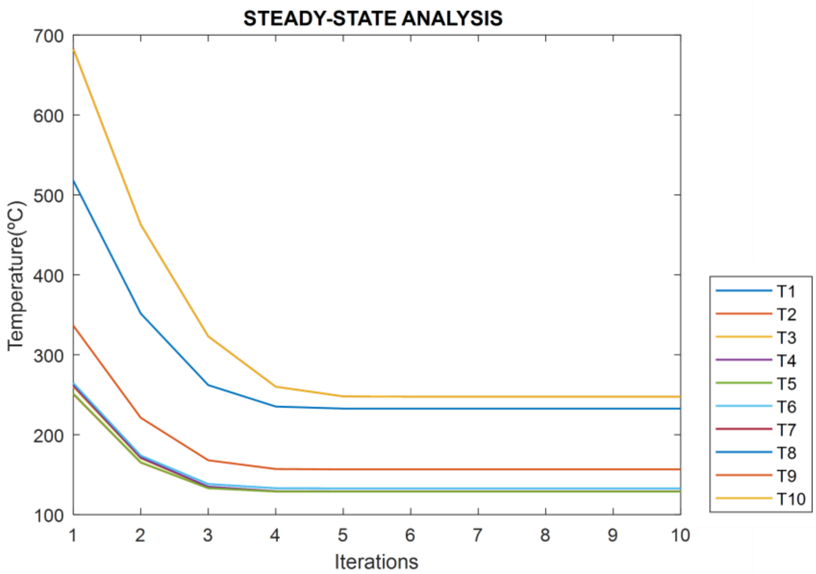


Figure 80. Steady-state analysis of Polished Beryllium

3.6.5. POLISHED GOLD

Absorptance	0.30	Emittance	0.05

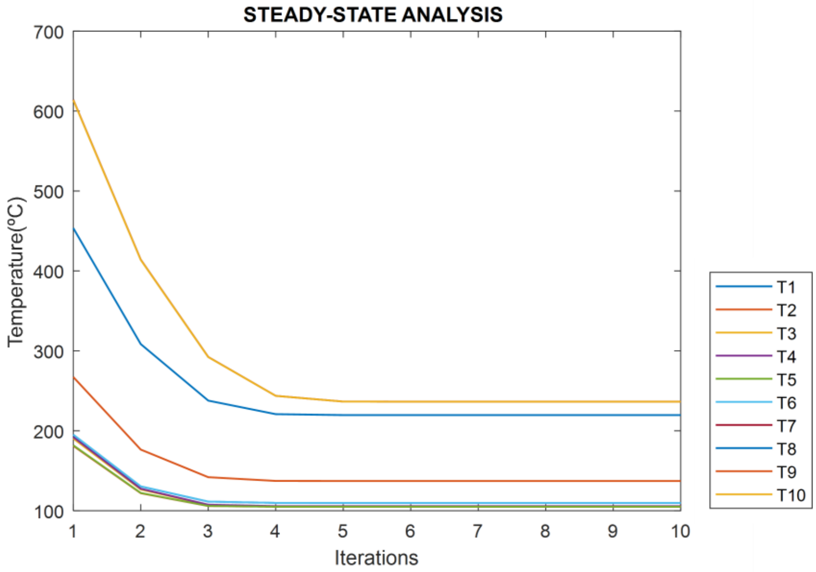


Figure 81. Steady-state analysis of Polished Gold

3.6.6. POLISHED SILVER

Absorptance	0.04	Emittance	0.02

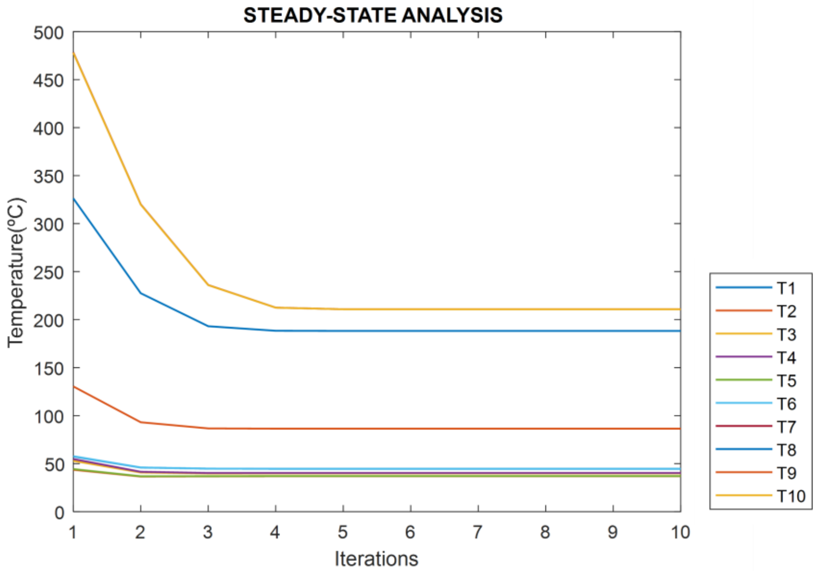


Figure 82. Steady-state analysis of Polished Silver

3.6.7. *POLISHED STAINLESS STEEL*

Absorptance	0.42	Emittance	0.11

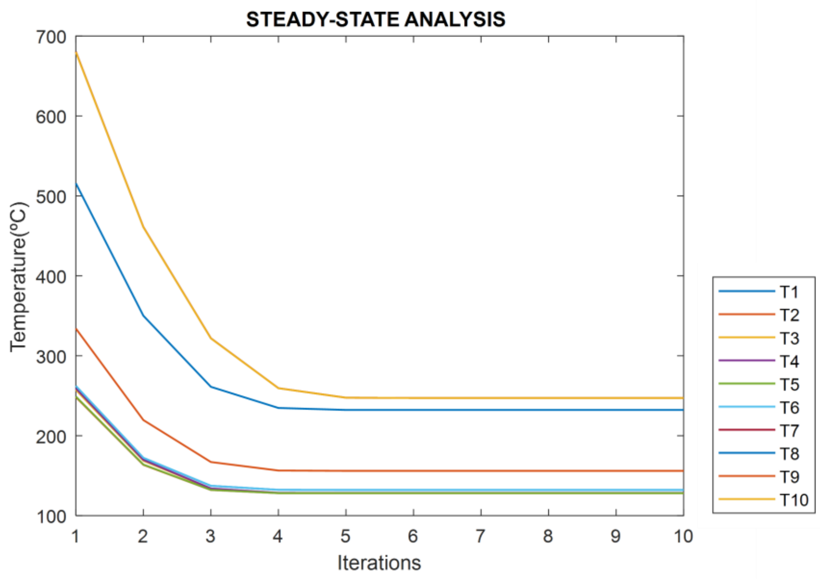


Figure 83. Steady-state analysis of Polished Stainless Steel

3.6.8. *POLISHED TUNGSTEN*

Absorptance	0.44	Emittance	0.03

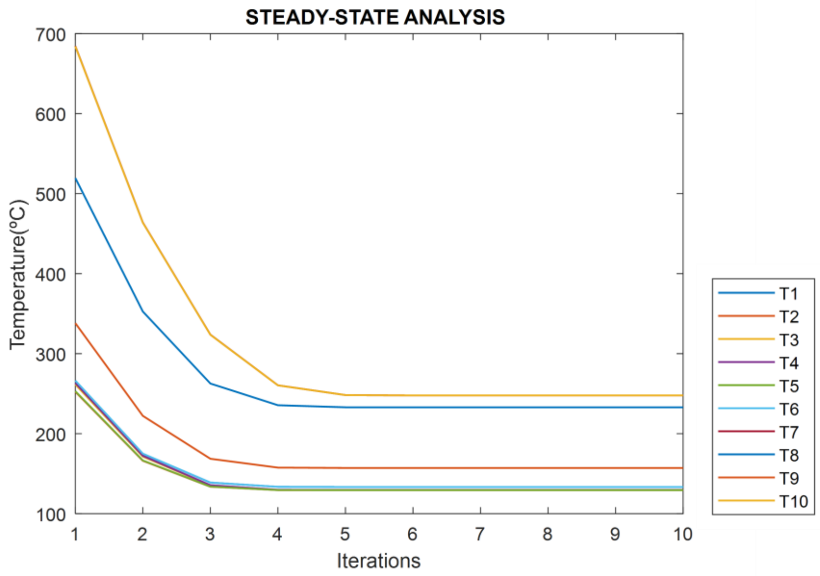


Figure 84. Steady-state analysis of Polished Tungsten

3.7. VAPOR-DEPOSITED COATINGS

3.7.1. ALUMINIUM

Absorptance	0.08	Emittance	0.02

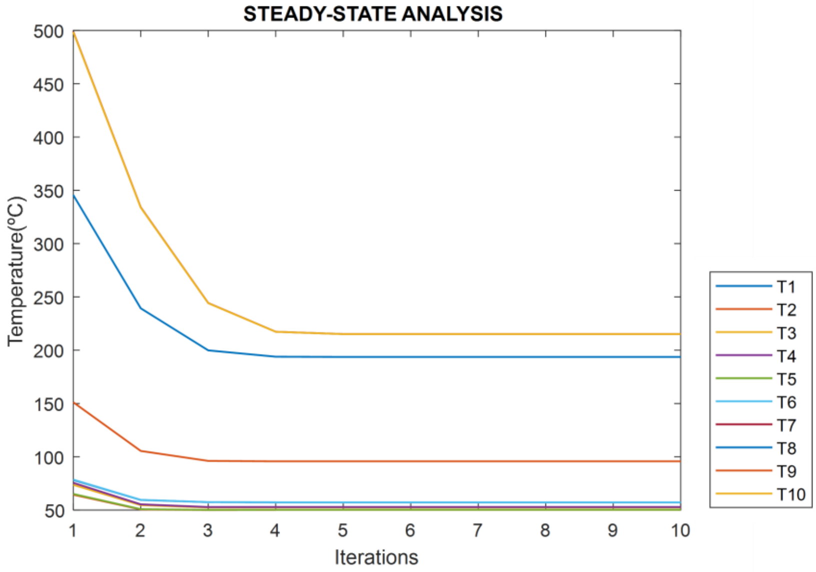


Figure 85. Steady-state analysis of Vapor-Deposited Aluminium

3.7.2. GOLD

Absorptance	0.19	Emittance	0.02

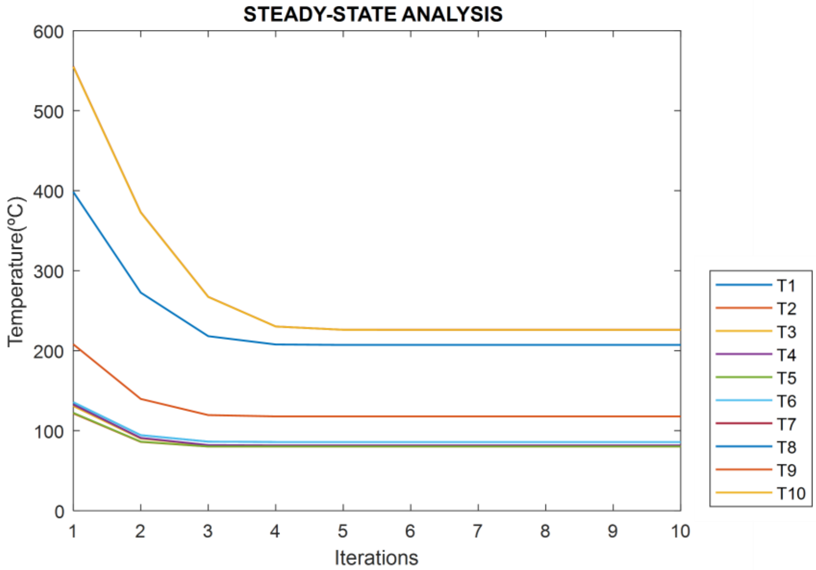


Figure 86. Steady-state analysis of Vapor-Deposited Gold

3.7.3. SILVER

Absorptance	0.04	Emittance	0.02

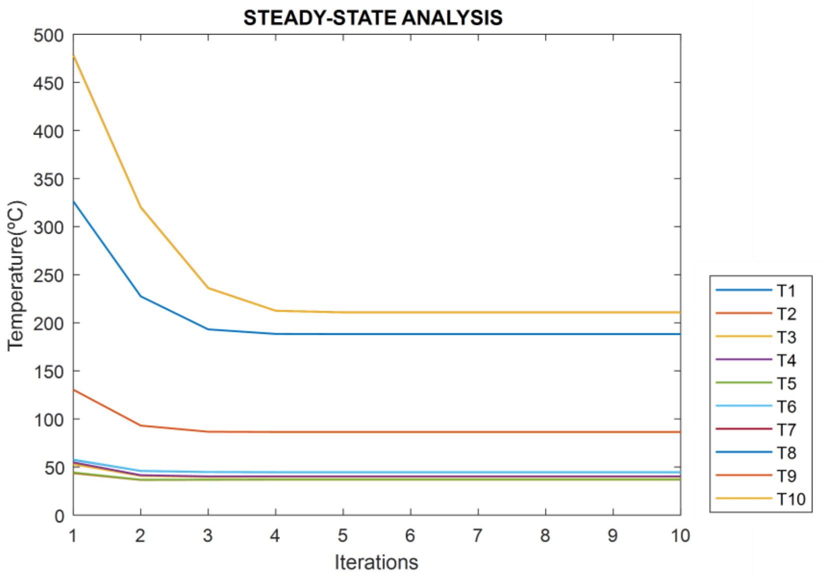


Figure 87. Steady-state analysis of Vapor-Deposited Silver

3.7.4. TITANIUM

Absorptance	0.52	Emittance	0.12

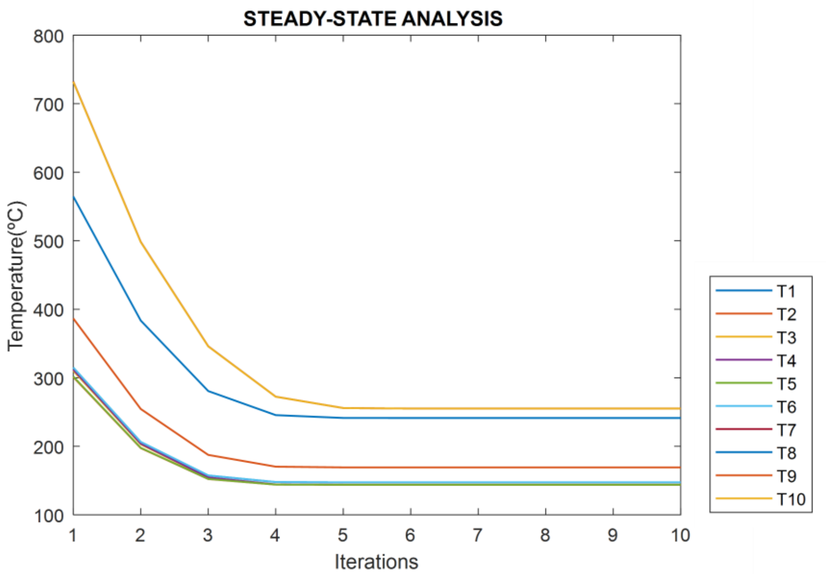


Figure 88. Steady-state analysis of Vapor-Deposited Titanium

3.7.5. TUNGSTEN

Absorptance	0.60	Emittance	0.27

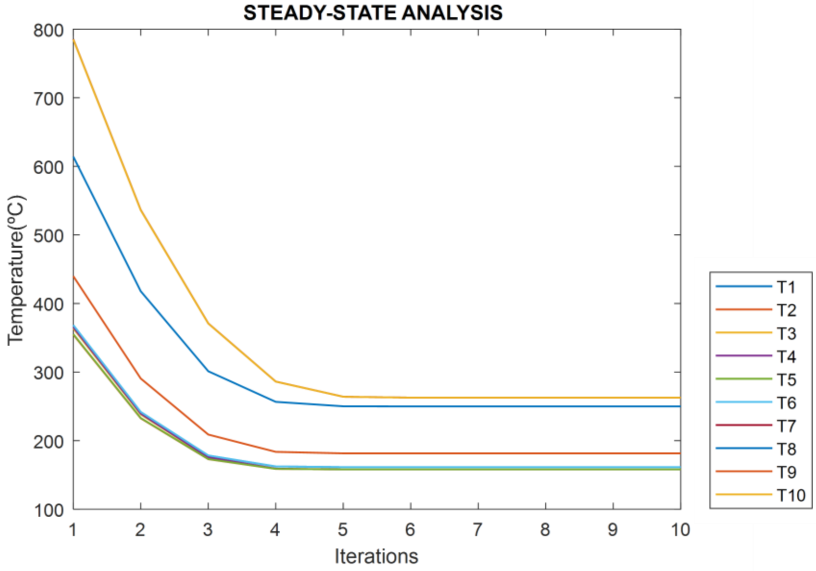


Figure 89. Steady-state analysis of Vapor-Deposited Tungsten

3.8. SOLAR CELLS

3.8.1. GALLIUM ARSENIDE-BASED SOLAR CELLS

Absorptance	0.88	Emittance	0.80

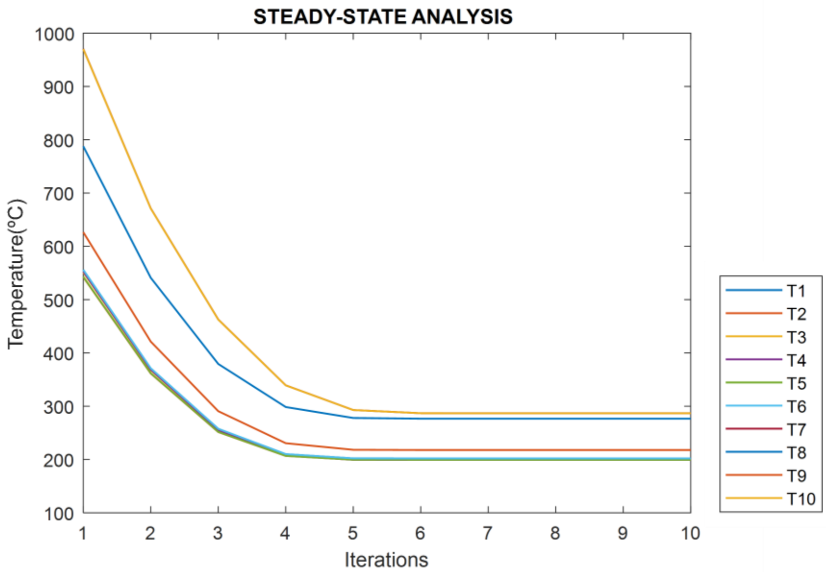


Figure 90. Steady-state analysis of Gallium Arsenide-Based Solar Cells

3.8.2. CRYSTALLINE SILICON-BASED SOLAR CELLS

Absorptance	0.75	Emittance	0.82

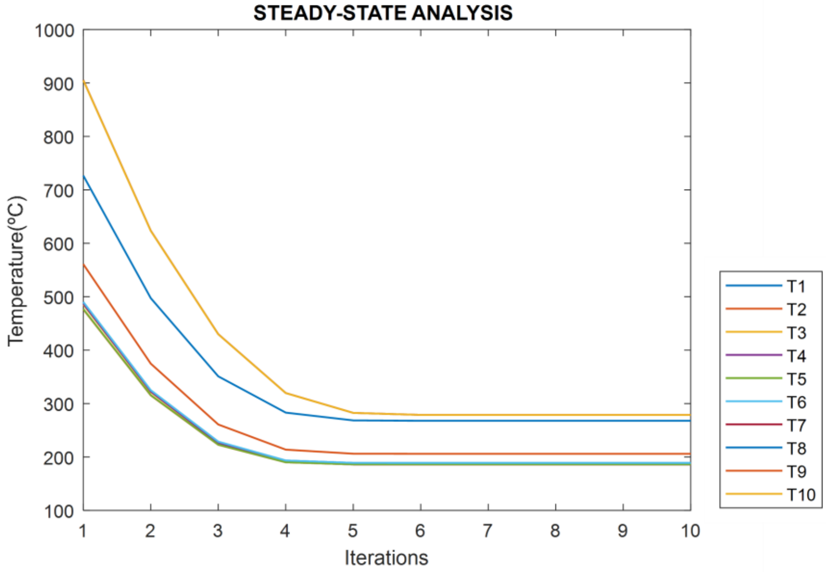


Figure 91. Steady-state analysis of Crystalline Silicon-Based Solar Cells

DOCUMENT 5

BIBLIOGRAPHY

Author: VICENT ALCAYDE PEIXO

Tutor: ANA VERCHER MARTINEZ

[1] *Making life Multiplanetary.*

https://www.spacex.com/mars

[2] *SpaceX Mars transportation infrastructure.*

https://en.wikipedia.org/wiki/SpaceX_Mars_transportation_infrastructure

[3] *Elon Musk says SpaceX is on track to launch people to Mars within 6 years.*

https://www.businessinsider.es/elon-musk-spacex-mars-plan-timeline-2018-10?r=US&IR=T

[4] *The Sun's Energy.*

https://ag.tennessee.edu/solar/Pages/What%20Is%20Solar%20Energy/Sun's%20Energy.aspx

[5] Fortescue, P., Swinerd, G. and Stark, J., *Spacecaft Systems Engineering*, 2011.

[6] *The Materials Used in Artificial Satellites and Space Structures.*

https://www.azom.com/article.aspx?ArticleID=12034

[7] *Materiales de los satélites artificiales.*

https://tecnoblogueando.blogspot.com/2013/01/materiales-de-los-satelites-artificiales.html

[8] *Determinación del calor específico de un sólido.*

http://www.sc.ehu.es/sbweb/fisica/estadistica/otros/calorimetro/calorimetro.htm

[9] *EaglePicher Space Cell.*

https://www.eaglepicher.com/sites/default/files/EP_SLC_16050_DATA_SHEET.pdf

[10] *Design and Simulation of Passive Thermal Management System for Lithium-ion Battery Packs on an Unmanned Ground Vehicle.*

https://digitalcommons.calpoly.edu/theses/912/

[11] *Kepler's Three Laws.* https://www.physicsclassroom.com/class/circles/Lesson-4/Kepler-s-Three-Laws

[12] G. Gilmore, D., *Spacecraft Thermal Control Handbook, Volume I: Fundamental Technologies*, 2002.

[13] H. Henninger, J., *Solar Absrptance and Thermal Emittance of Some Common Spacecraft Thermal-Control Coatings*, 1984

[14] Kauder, L., *Spacecraft Thermal Control Coatings References*,2005 (NASA/TP–2005–212792)

[15] *Parker Solar Probe: Humanity's First Visit to a Star*

https://www.nasa.gov/content/goddard/parker-solar-probe-humanity-s-first-visit-to-a-star

[16] *Vantablack*

https://www.surreynanosystems.com/vantablack

[17] *Photos: SpaceX's Falcon Heavy aces second mission*

https://spaceflightnow.com/2019/04/15/photos-spacexs-falcon-heavy-aces-second-mission/

[18] *Starlink 60 satellites in one fairing (SpaceX – Elon Musk)*

https://www.teslarati.com/spacex-starlink-satellites-tease-revolutionary-design/starlink-60-satellites-in-one-fairing-spacex-elon-musk-1/

[19] *First re-flight*

https://www.spacex.com/gallery/first-re-flight#slide-10

[20] *Planck's law*

https://en.wikipedia.org/wiki/Planck%27s_law