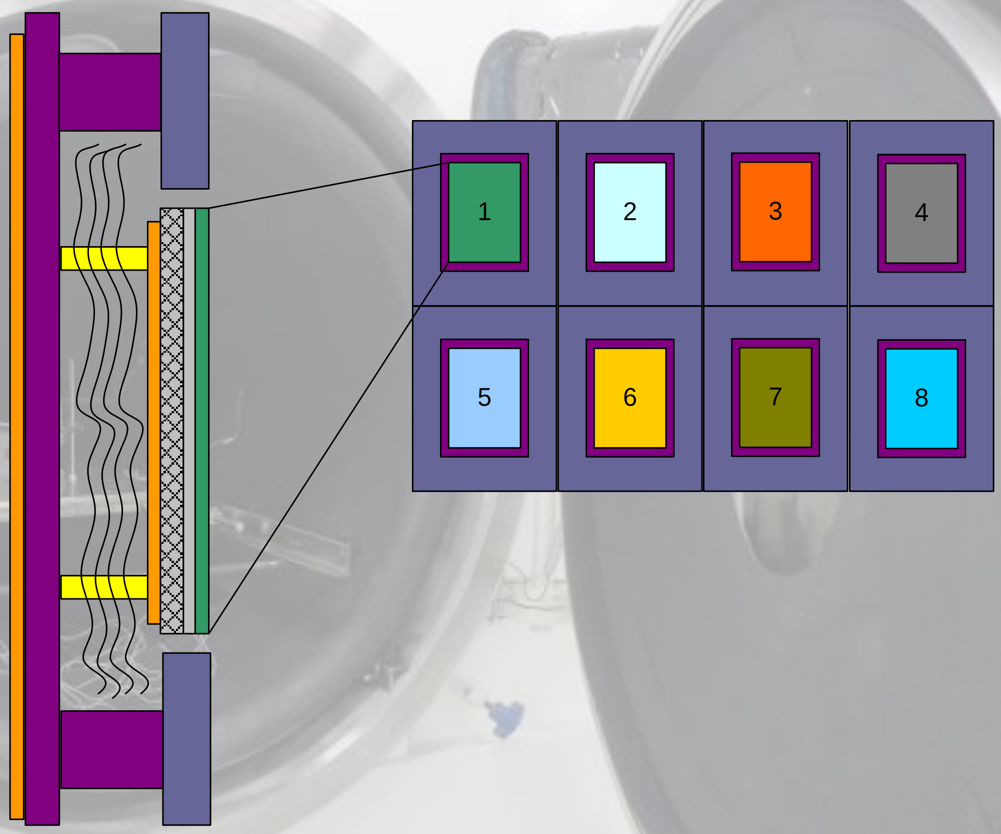
NLR-TP-2019-041 | August 2019

Accuracy Assessment of a Hemispherical Emissivity Measurement Facility

CUSTOMER: Netherlands Aerospace Centre



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EXECUTIVE SUMMARY

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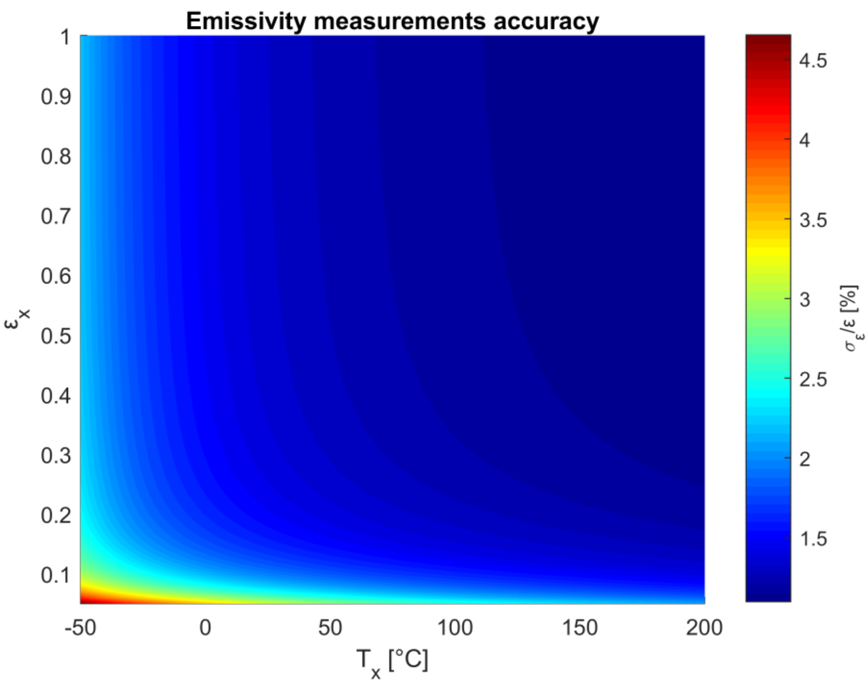
Accuracy Assessment of a Hemispherical Emissivity Measurement Facility



Problem area

For aerospace systems knowledge about variable emissivities of materials and coatings as function of temperature is of vital importance for an accurate prediction of infrared radiation heat transfers and temperatures using thermal models. However, emissivity values are usually taken from property tables that disrespect variable surface temperatures and neglect underlying materials and coatings. This leads to significant temperature prediction errors and large design margins. An accurate measurement method of the total hemispherical emissivity as function of temperature would settle the issue. Radiometric and calorimetric methods including handheld devices have been developed over the years with significant differences in sample treatment, complexity and accuracy.

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KNOWLEDGE AREA(S)
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Description of work

The Netherlands Aerospace Centre (NLR) proposes a generic test facility holding several samples inside a TV chamber for an accurate measurement of the total hemispherical emissivity as function of temperature under vacuum conditions. The proposed Emissivity Measurement Facility (EMF) uses standardized samples which design is preliminary described in this paper. Each sample may have a different material or coating with varying emissivities and is adiabatically suspended to minimize heat leaks. The sample emissivity is obtained from the surface area, the applied heater power and equilibrium temperature.

Results and conclusions

The proposed calorimetric method provides for a direct measurement for of total hemispherical emissivity, without scanning of the IR spectrum and the spatial dimensions and can be directly applied in thermal models, without the need of a calibrated reference. Sample fixation has been optimized for low thermal conduction to the backside (in combination with guard heater control) and a uniform temperature distribution and relatively quick sample exchange at the front is ensured. An accuracy assessment, for sample temperatures between -50°C and 200°C, shows that the expected relative measurement error standard deviation for emissivities in the range of 1 down to 0.05 will be better than 1-5%. Verification tests are recommended to demonstrate the predicted accuracy of the proposed facility. For accurate measurement of emissivities below <0.05 larger samples are required. It is considered that varying sample sizes could be introduced when the emittance range is roughly known.

Applicability

For aerospace systems knowledge about variable emissivities of materials and coatings as function of temperature is of vital importance for an accurate prediction of infrared radiation heat transfers and temperatures using thermal models.

GENERAL NOTE
This report is based on a presentation held at the 3rd Space Passive Components Days, SPCD 2018, ESA/ESTEC, Noordwijk, The Netherland, 9-12 October 2018.

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Contents

Abbreviations

ACRONYM	DESCRIPTION
EMF	Emissivity Measurement Facility
IR	Infrared
MLI	MultiLayer Insulation
NLR	Netherlands Aerospace Centre
TEC	Thermal Electric Cooling
TV	Thermal Vacuum

Accuracy Assessment of a Hemispherical Emissivity Measurement Facility

9-12 October 2018
ESA/ESTEC, Noordwijk, The Netherlands

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ABSTRACT

For aerospace systems knowledge about variable emissivities of materials and coatings as function of temperature is of vital importance for an accurate prediction of infrared radiation heat transfers and temperatures using thermal models. However, emissivity values are usually taken from property tables that disrespect variable surface temperatures and neglect underlying materials and coatings. This leads to significant temperature prediction errors and large design margins. An accurate measurement method of the total hemispherical emissivity as function of temperature would settle the issue. Radiometric and calorimetric methods including handheld devices have been developed over the years with significant differences in sample treatment, complexity and accuracy. The Netherlands Aerospace Centre (NLR) proposes a generic test facility holding several samples inside a TV chamber for an accurate measurement of the total hemispherical emissivity as function of temperature under vacuum conditions. The proposed Emissivity Measurement Facility (EMF) uses standardized samples which design is preliminary described in this paper. Each sample may have a different material or coating with varying emissivities and is adiabatically suspended to minimize heat leaks. The sample emissivity is obtained from the surface area, the applied heater power and equilibrium temperature. An accuracy assessment, for sample temperatures between -50°C and 200°C, shows that the expected relative measurement error standard deviation for emissivities in the range of 0.05-1 will be better than 1-5%. Verification tests are recommended to demonstrate the predicted accuracy of the proposed facility.

NOMENCLATURE

$A^c_{f\_in}$	[m^2]	inner facility thermal conduction area (total cross section of the support stuts)
$A^r_{f\_in}$	[m^2]	inner facility thermal radiation area
A_x	[m^2]	surface area of sample *x*
$C_{f\_in,f}$	[W/K]	thermal conductance from inner facility (MLI) part to the surrounding facility part
ε_{f_in}	[-]	inner facility emissivity
ε_x	[-]	IR emittance of sample *x*
k_{f_in}	[W/(K·m)]	thermal conductivity of the support stuts
L_{f_in}	[m]	length of the support stuts
P_x	[W]	heater power applied to sample *x*
Q^c_x	[W]	conductive heat leak from the sample to the facility
Q^r_x	[W]	radiative heat leak from the sample to the facility
T_x	[K]	temperature of sample *x*
T_e	[K]	environment temperature
T_{f_in}	[K]	inner facility temperature
T_f	[K]	facility temperature (surrounding the sample)

INTRODUCTION

A recurrent request for the thermal design for aerospace applications is the measurement of variable hemispherical emissivities of all sorts of materials, coatings, (Figure 1) and electrical or mechanical louver systems as function of temperature. For the thermal design of aerospace systems knowledge about the surface emissivities is of vital importance for an accurate prediction of the infrared radiation, heat transfers and temperatures using thermal models. Spatial and spectral irradiation methods using spectrometers, dedicated caloric facilities for heat balance measurements and handheld devices for normal emittance measurement, have been developed over the years for the measurement of emissivities with significant differences in sample treatment, complexity and accuracy. ([1], [2], [3], [4], [5], [7]) A recent development is the heat flux sensors which significantly reduces the complexity of the measurements [6]. However, radiometric methods usually require expensive equipment while spatial and spectral dimensions must be scanned as well as calibrated heat sources and references samples. Handheld devices (Figure 2) offer a fast but less accurate measurement measuring the (near) normal emittance in air. This method is inaccurate for louver systems where (varying) emissivities could have significant angular components.

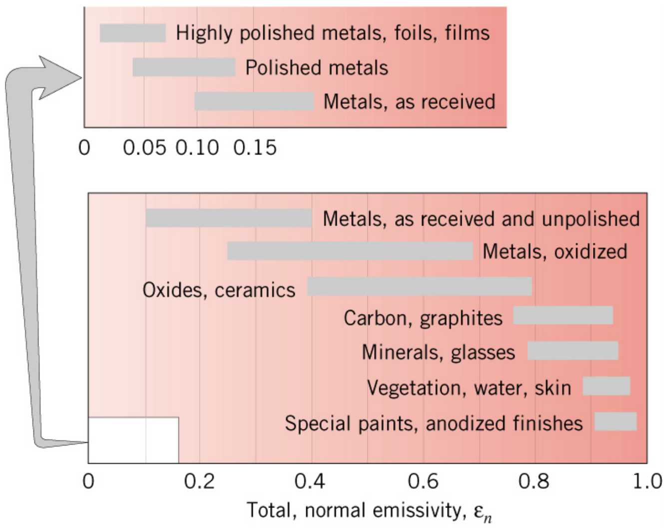

Figure 1: Emissivity range of several materials

Calorimetric methods provide for a more accurate and direct measurement of the total hemispherical emissivity, without scanning of spectral and the spatial dimensions. There is no the need for a calibrated reference and the results can directly be applied in thermal models. Disadvantage is the use of a Thermal Vacuum (TV) chamber facility to eliminate the influence of convection on the heat balance. However, in case more samples can be tested in one run, the cost per sample can be reduced. With the proposed calorimetric setup inside a vacuum chamber with a cooled shroud, accuracies between 1-5% can be achieved for emissivities between 1 down to 0.05, with 10cm x 10cm samples, covering most of the materials applied. For highly polished metals (emissivities <0.05) the sample sizes could be enlarged to improve the measurement accuracy.

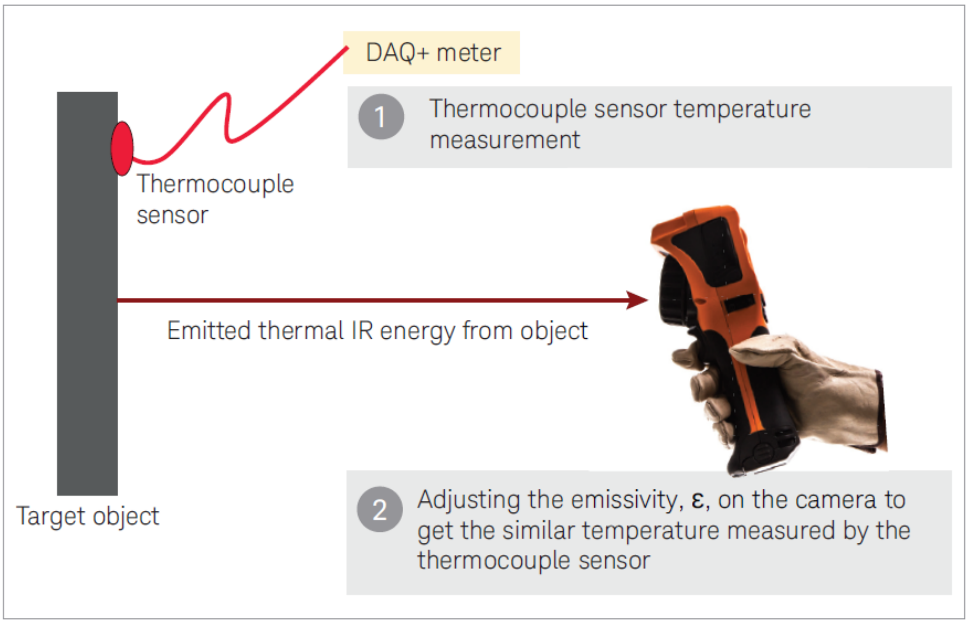

Figure 2: Handheld radiometric method for an estimation of the normal emissivity requiring temperature measurements and references samples (Keysight Technologies)

BACKGROUND OF HEMISPHERICAL EMISSIVTY MEASUREMENTS

The radiation spectrum of a real surface deviates both spectrally (a) and spatially (b) compared to a black body source. See ***Figure 3***

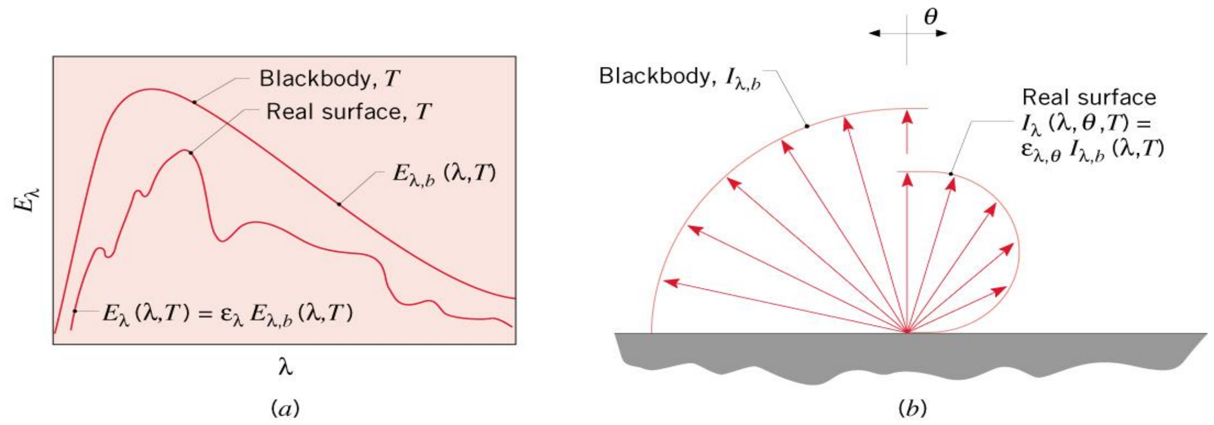

Figure 3: Spectral (a) and spatial (b) differences between the radiation of a real surface and a black body

The spectral and angular differences between a real surface and a black body can be described with an emissivity function ε which is related to the wavelength, spatial angles and the surface temperature:

$$\varepsilon_{\lambda,\theta}(\lambda,\theta,\phi,T) = \frac{I_{\lambda,e}(\lambda,\theta,\phi,T)}{I_{\lambda,b}(\lambda,T)} \quad (1)$$

Equation (1) can be simplified when taking both the spatial and spectral integral to obtain the total hemispherical emissivity:

$$\varepsilon(T) = \frac{E(T)}{E_b(T)} \quad (2)$$

With $E_b(T) = \sigma T^4$ is the total radiated energy of a black body at a temperature T. The standard calorimetric method for the measurement the hemispherical emissivity is to place a small sample inside a large vacuum chamber (to eliminate convection of air) and measure the equilibrium temperature as function of the applied heater power and the shroud temperature according to the standard two-surfaces enclosure formula

$$P_e = \frac{\sigma\left(T_x^4 - T_e^4\right)}{\frac{1-\varepsilon_x}{A_x\varepsilon_x} + \frac{1}{A_x F_{x,e}} + \frac{1-\varepsilon_e}{A_e\varepsilon_e}} \quad (3)$$

Since the whole sample "sees" the shroud, the view factor $F_{x,e}$ can be considered equal to 1 and since the surface area A_e of the facility is relatively large (~4 m^2) with respect to the sample area A_x (A_x/A_e<0.25%) and the shroud emittance ε_e is close to unity, (3) collapses into

$$P_x = \varepsilon_x A_x \sigma\left(T_x^4 - T_e^4\right) \quad (4)$$

eliminating the influence of the shroud emittance ε_e and the shroud area A_e. Since the fourth power of the absolute shroud temperature T_e, which is cooled with Nitrogen at around 90K, is significantly lower than the fourth power of the (lowest) absolute sample temperature T_x, this also minimized the influence of the shroud temperature and gradients on the emissivity measurements.

$$P_x \approx \varepsilon_x A_x \sigma T_x^4 \quad (5)$$

Hence, taking into account the shroud temperature for better accuracy, using (4), the sample emittance is calculated from

$$\varepsilon_x = \frac{P_x}{\sigma A_x\left(T_x^4 - T_e^4\right)} \quad (6)$$

Including heat leaks Q_x the sample emittance is calculated by

$$\varepsilon_x\left(T_x\right)=\frac{P_x-Q_x}{\sigma A_x\left(T_x^4-T_e^4\right)} \tag{7}$$

The Netherlands Aerospace Centre (NLR) proposes a generic test facility holding several samples inside a TV chamber for an accurate measurement of the hemispherical emissivities as function of temperature under vacuum conditions. The proposed Emissivity Measurement Facility (EMF) uses standardized samples which design is preliminary described in this paper. Each sample may have a different surface material or coating with varying emissivities and is adiabatically suspended to minimize heat leaks. The sample emissivity is obtained from the surface area, the applied heater power and the equilibrium temperature using (7). The aim is to have standard sample size of 10cm x 10cm, for emissivity measurements between 0.05 to 1 covering most of the materials. For accurate measurement of emissivities below <0.05 larger samples are required. It is considered that varying sample sizes could be introduced when the emittance range is roughly known.

PROPOSED HEMISPHERICAL EMISSIVITY MEASUREMENT FACILITY

In *Figure 4* the generic setup for the measurement of emissivities of various samples inside a TV chamber at once is depicted.

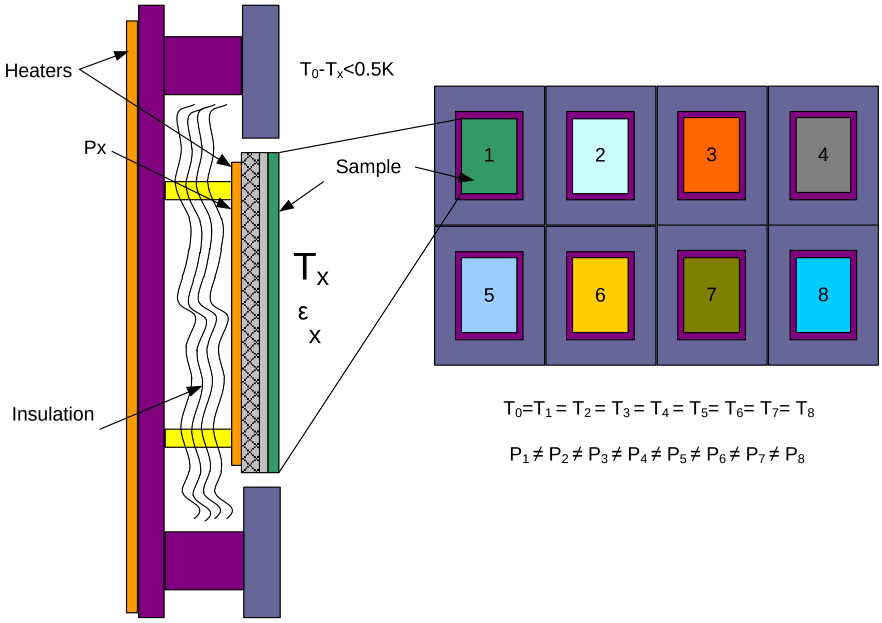

Figure 4: Calorimetric test setup for emissivity measurement of several sample's at once. The whole setup is controlled at one temperature to minimize heat leaks. The emissivity's follows from differences in the sample powers

Consideration shall be given to how to assemble the standardized samples such that they can easily be manufactured, mounted and exchanged. It is taken into account that the samples may have a substrate material as well as a coating. It shall be uniformly heated from behind with a dedicated heater and the external surface area for radiation to the shroud is undisturbed. Edge effects, e.g. heat leaks to the back of the facility, shall be minimized through low emittance surface coatings, multilayer insulation (MLI), low conduction mounts and with guard heaters. The temperature of the setup and all samples shall be controlled to be nearly equal (±0.5°C) to minimize the internal heat leaks. The difference is the applied power for each sample which is proportional to the emittance. The emissivity can be deduced with help of the (7). For instance a black painted sample (ε=0.9) requires a 30x higher power than a gold plated sample (ε=0.05) to achieve the same sample temperature. The test can be repeated at different temperatures inside a vacuum chamber. The accuracy of the method relies on accurate surface area, temperature control and power measurements. A heat-flux sensor may be applied between the substrate and the sample for a verification of the heater power.
The set-up may also be used for absorbance measurements in which case the samples are illuminated with a sun simulator through a window in the facility. However, since there is no active cooling available this can only be done as long as α/ε < 1. An improvement of the facility could be to use a TEC instead of a heater in combination with a heat flux sensor as proposed by Moghaddam [6]. In this case the internal insulation can be removed. The TEC can be used for both heating and cooling by an electrical current to control the sample temperature. The accuracy of this arrangement (without TEC) is indicated by 5-7% for a slightly smaller sample of 76.5x76.5 mm. [6]

SAMPLE DESCRIPTION

Figure 5 gives an overview of the sample details. Sample fixation has been optimized for low thermal conduction to the backside and to ensure a uniform temperature distribution and relatively quick sample exchange at the front. The material of which the emissivity has to be measured is to be applied on a sample base plate. The function of this copper or aluminum base plate is to hold the sample substrate on the required location and to conduct the heat from the support plate to the sample substrate. The samples can be replaced and measured sequentially with a single sample setup or simultaneously with a multiple sample setup. The support plate is equipped with a heater and a temperature sensor and is temperature controlled by a control system outside the vacuum chamber. A good conduction between the support plate and sample base plate is realized by multiple bolts which firmly presses both plates together. The thermal guard reduces the heat leak of the support plate to its surroundings to almost zero by being controlled to the same temperature as the support plate. It is equipped with a heater and a temperature sensor too. To reduce the thermal losses even further MLI is applied between the support plate and the guard and around all sides of the guard. The studs holding the support plate will be made to conduct as little heat as possible. Verification tests of the heat leaks are recommended. This can be done by wrapping the facility in MLI and levelling the sample temperature with the shroud to minimize radiation.

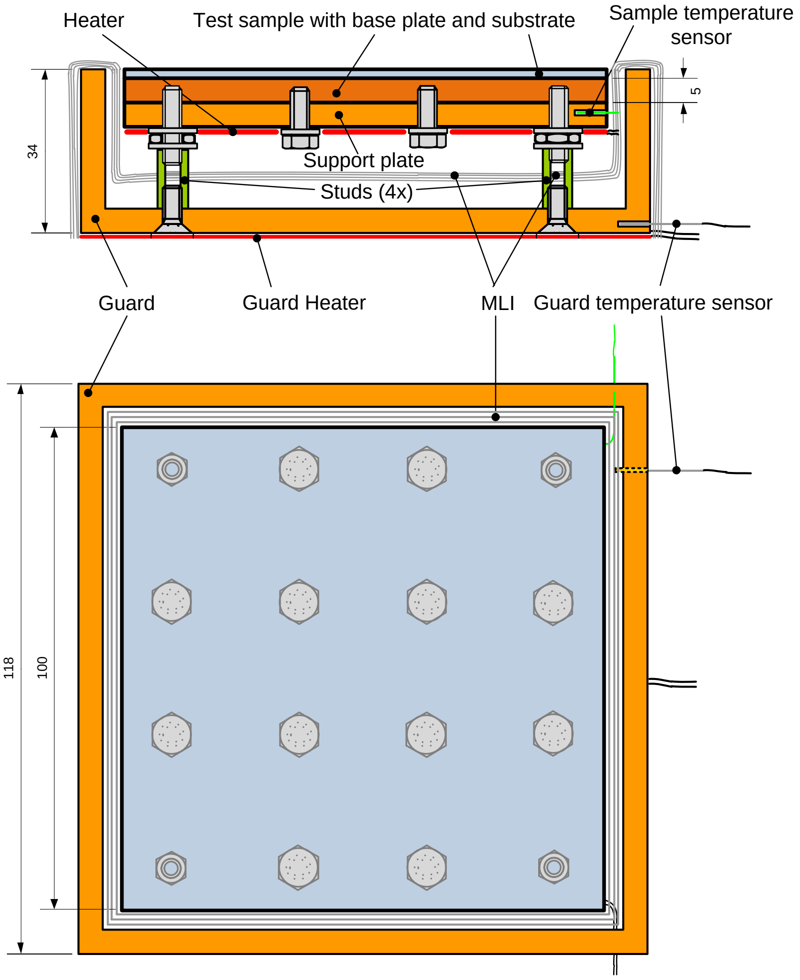

Figure 5: Sample details

ACCURACY ASSESSMENT

To gain insight into the accuracy of the emissivity measurements obtained with the Hemispherical Emissivity Measurement Facility an accuracy assessment is performed. To this end, first the underlying emissivity model is presented with the corresponding input parameters and their uncertainties. Subsequently, to estimate accuracy of the emissivity measurements, the underlying emissivity model is linearized. Finally a set of realistic input parameters with assumed uncertainties is defined for which the corresponding emissivity measurement accuracy is evaluated. The emissivity ε_x is given by (7). The heat leak Q_x from the sample x to the facility is given by

$$\begin{aligned} Q_x &= Q_x^{\mathrm{r}} + Q_x^{\mathrm{c}} \\ &= \varepsilon_{\mathrm{f\_in}} \sigma A_{\mathrm{f\_in}} \left(T_{\mathrm{f\_in}}^4 - T_{\mathrm{f}}^4 \right) + C_{\mathrm{f\_in,f}} \left(T_{\mathrm{f\_in}} - T_{\mathrm{f}} \right) \end{aligned} \tag{8}$$

where

$$Q_x^{\mathrm{r}} = \varepsilon_{\mathrm{f\_in}} \sigma A_{\mathrm{f\_in}}^{r} \left(T_{\mathrm{f\_in}}^{4} - T_{\mathrm{f}}^{4} \right) \tag{9}$$

$$Q_x^{\mathrm{c}} = C_{\mathrm{f\_in,f}} \left(T_{\mathrm{f\_in}} - T_{\mathrm{f}} \right) \tag{10}$$

$$C_{\mathrm{f\_in,f}} = \frac{k_{\mathrm{f\_in}} A_{\mathrm{f\_in}}^{c}}{L_{\mathrm{f\_in}}} \tag{11}$$

Assume that P_x, Q_x, A_x, T_x, and T_{e} are measured with independent zero mean Gaussian measurement errors with standard deviations respectively given by σ_{P_x}, $\sigma_{Q_x}, \sigma_{A_x}, \sigma_{T_x}, \sigma_{T_{\mathrm{e}}}$. By linearizing (7), the standard deviation σ_{ε_x} of the emissivity ε_x is approximated by

$$\begin{aligned}
\sigma_{\varepsilon_x} &\approx \sqrt{\left(\frac{\sigma_{P_x}}{\sigma A_x \left(T_x^4 - T_{\mathrm{e}}^4\right)}\right)^2 + \left(\frac{-\sigma_{Q_x}}{\sigma A_x \left(T_x^4 - T_{\mathrm{e}}^4\right)}\right)^2 + \left(\frac{-\left(P_x - Q_x\right)\sigma_{A_x}}{\sigma A_x^2 \left(T_x^4 - T_{\mathrm{e}}^4\right)}\right)^2 + \left(\frac{-4\left(P_x - Q_x\right) T_x^3 \sigma_{T_x}}{\sigma A_x \left(T_x^4 - T_{\mathrm{e}}^4\right)^2}\right)^2 + \left(\frac{4\left(P_x - Q_x\right) T_{\mathrm{e}}^3 \sigma_{T_{\mathrm{e}}}}{\sigma A_x \left(T_x^4 - T_{\mathrm{e}}^4\right)^2}\right)^2} \\
&= \sqrt{\left(\frac{\sigma_{P_x}\varepsilon_x}{P_x - Q_x}\right)^2 + \left(\frac{-\sigma_{Q_x}\varepsilon_x}{P_x - Q_x}\right)^2 + \left(\frac{-\sigma_{A_x}\varepsilon_x}{A_x}\right)^2 + \left(\frac{-4T_x^3 \sigma_{T_x}\varepsilon_x}{\left(T_x^4 - T_{\mathrm{e}}^4\right)}\right)^2 + \left(\frac{4T_{\mathrm{e}}^3 \sigma_{T_{\mathrm{e}}}\varepsilon_x}{\left(T_x^4 - T_{\mathrm{e}}^4\right)}\right)^2} \\
&= \left|\varepsilon_x\right| \sqrt{\left(\frac{\sigma_{P_x}}{P_x - Q_x}\right)^2 + \left(\frac{-\sigma_{Q_x}}{P_x - Q_x}\right)^2 + \left(\frac{-\sigma_{A_x}}{A_x}\right)^2 + \left(\frac{-4T_x^3 \sigma_{T_x}}{\left(T_x^4 - T_{\mathrm{e}}^4\right)}\right)^2 + \left(\frac{4T_{\mathrm{e}}^3 \sigma_{T_{\mathrm{e}}}}{\left(T_x^4 - T_{\mathrm{e}}^4\right)}\right)^2}
\end{aligned} \tag{12}$$

From (12) it follows that the relative emissivity error standard deviation $\frac{\sigma_{\varepsilon_x}}{\left|\varepsilon_x\right|}$ is given by

$$\frac{\sigma_{\varepsilon_x}}{\left|\varepsilon_x\right|} \approx \sqrt{\left(\frac{\sigma_{P_x}}{P_x - Q_x}\right)^2 + \left(\frac{-\sigma_{Q_x}}{P_x - Q_x}\right)^2 + \left(\frac{-\sigma_{A_x}}{A_x}\right)^2 + \left(\frac{-4T_x^3 \sigma_{T_x}}{\left(T_x^4 - T_{\mathrm{e}}^4\right)}\right)^2 + \left(\frac{4T_{\mathrm{e}}^3 \sigma_{T_{\mathrm{e}}}}{\left(T_x^4 - T_{\mathrm{e}}^4\right)}\right)^2} \tag{13}$$

Assume that $\varepsilon_{\mathrm{f\_in}}, A_{\mathrm{f\_in}}^{r}, T_{\mathrm{f\_in}}, T_{\mathrm{f}}$, and $C_{\mathrm{f\_in,f}}$ are measured with independent zero mean Gaussian measurement errors with standard deviations respectively given by $\sigma_{\varepsilon_{\mathrm{f\_in}}}$, $\sigma_{A_{\mathrm{f\_in}}^{r}}, \sigma_{T_{\mathrm{f\_in}}}, \sigma_{T_{\mathrm{f}}}, \sigma_{C_{\mathrm{f\_in,f}}}$. By linearizing (8), the standard deviation σ_{Q_x} is approximated by

$$\sigma_{Q_x} \approx \sqrt{\left(\sigma A_{\mathrm{f\_in}}^{r}\left(T_{\mathrm{f\_in}}^4 - T_{\mathrm{f}}^4\right)\sigma_{\varepsilon_{\mathrm{f\_in}}}\right)^2 + \left(\varepsilon_{\mathrm{f\_in}}\sigma\left(T_{\mathrm{f\_in}}^4 - T_{\mathrm{f}}^4\right)\sigma_{A_{\mathrm{f\_in}}^{r}}\right)^2 + \left(4\varepsilon_{\mathrm{f\_in}}\sigma A_{\mathrm{f\_in}}^{r} T_{\mathrm{f\_in}}^3 \sigma_{T_{\mathrm{f\_in}}}\right)^2 + \left(-4\varepsilon_{\mathrm{f\_in}}\sigma A_{\mathrm{f\_in}}^{r} T_{\mathrm{f}}^3 \sigma_{T_{\mathrm{f}}}\right)^2 + \left(\left(T_{\mathrm{f\_in}} - T_{\mathrm{f}}\right)\sigma_{C_{\mathrm{f\_in,f}}}\right)^2} \tag{14}$$

Analogous, the standard deviation $\sigma_{C_{\mathrm{f\_in,f}}}$ is calculated from $\sigma_{k_{\mathrm{f\_in}}}$, $\sigma_{A_{\mathrm{f\_in}}^{c}}, \sigma_{L_{\mathrm{f\_in}}}$ and the relation

$$C_{\mathrm{f\_in,f}} = \frac{k_{\mathrm{f\_in}} A_{\mathrm{f\_in}}^{c}}{L_{\mathrm{f\_in}}} \tag{15}$$

as follows

$$\begin{aligned}
\sigma_{C_{\mathrm{f_in,f}}} &\approx \sqrt{\left(\frac{A_{\mathrm{f_in}}^{c}\sigma_{k_{\mathrm{f_in}}}}{L_{\mathrm{f_in}}}\right)^2 + \left(\frac{k_{\mathrm{f_in}}\sigma_{A_{\mathrm{f_in}}^{c}}}{L_{\mathrm{f_in}}}\right)^2 + \left(\frac{-k_{\mathrm{f_in}} A_{\mathrm{f_in}}^{c}\sigma_{L_{\mathrm{f_in}}}}{L_{\mathrm{f_in}}^2}\right)^2} = \sqrt{\left(\frac{\sigma_{k_{\mathrm{f_in}}} C_{\mathrm{f_in,f}}}{k_{\mathrm{f_in}}}\right)^2 + \left(\frac{\sigma_{A_{\mathrm{f_in}}^{c}} C_{\mathrm{f_in,f}}}{A_{\mathrm{f_in}}^{c}}\right)^2 + \left(\frac{-\sigma_{L_{\mathrm{f_in}}} C_{\mathrm{f_in,f}}}{L_{\mathrm{f_in}}}\right)^2} \\
&= \left|C_{\mathrm{f_in,f}}\right| \sqrt{\left(\frac{\sigma_{k_{\mathrm{f_in}}}}{k_{\mathrm{f_in}}}\right)^2 + \left(\frac{\sigma_{A_{\mathrm{f_in}}^{c}}}{A_{\mathrm{f_in}}^{c}}\right)^2 + \left(\frac{-\sigma_{L_{\mathrm{f_in}}}}{L_{\mathrm{f_in}}}\right)^2}
\end{aligned} \tag{16}$$

The expected accuracy of the emissivity measurements have been theoretically evaluated based on the emissivity measurement model and the corresponding linearized measurement error model presented above. The accuracy of the emissivity measurements has been verified by means of Monte Carlo simulations. The expected accuracy of the emissivity measurements has been evaluated for the parameters given in Table 1. The values of these parameters are based on laboratory experience.

Table 1: Parameters used for the accuracy evaluations of the emissivity measurements

Parameter	Interval or Value	Accuracy Standard deviation	Unit	Description
A_x	0.01	$\sigma_{A_x} = 0.01 \times A_x$	m^2	surface area of sample *x*
$A^c_{f\_in}$	1.6e-05	$\sigma_{A^c_{f\_in}} = 0.01 \times A^c_{f\_in}$	m^2	inner facility thermal conduction area
$A^r_{f\_in}$	0.014	$\sigma_{A^r_{f\_in}} = 0.01 \times A^r_{f\_in}$	m^2	inner facility thermal radiation area
Δ_{T_x,T_f}	1	–	°C	assumed temperature difference between sample *x* temperature and facility temperature
ε_{f_in}	0.05	$\sigma_{\varepsilon_{f\_in}} = 0.05$	–	inner facility emissivity
ε_x	$[0.05,1]$	–	–	sample x emissivity values for which the measurement accuracies are evaluated
k_{f_in}	0.35	$\sigma_{k_{f\_in}} = 0.01$	$W/(K \cdot m)$	thermal conductivity of the support stuts
L_{f_in}	0.01	$\sigma_{L_{f\_in}} = 0.001$	m	length of the support stuts
P_x		$\sigma_{P_x} = 0.001 \times P_x$	W	power applied to sample *x* to reach T_x
T_e	–150	$\sigma_{T_e} = 5$	°C	environment temperature
T_{f_in}	$T_{f\_in} = T_x$	$\sigma_{T_{f\_in}} = 0.5$	°C	inner facility temperature
T_f	$T_f = T_{f\_in} - \Delta_{T_s,T_f}$	$\sigma_{T_{f\_in}} = 0.5$	°C	facility temperature (surrounding the sample)
T_x	$[-50, 200]$	$\sigma_{T_x} = 0.5$	°C	temperature of sample *x*

An overview of the power measurements and their accuracy is presented in Figure 6 and an overview of the heat leak measurements and their accuracy is presented in Figure 7. The relative accuracy of the emissivity measurements based on the linearized measurement error model is depicted in Figure 8.

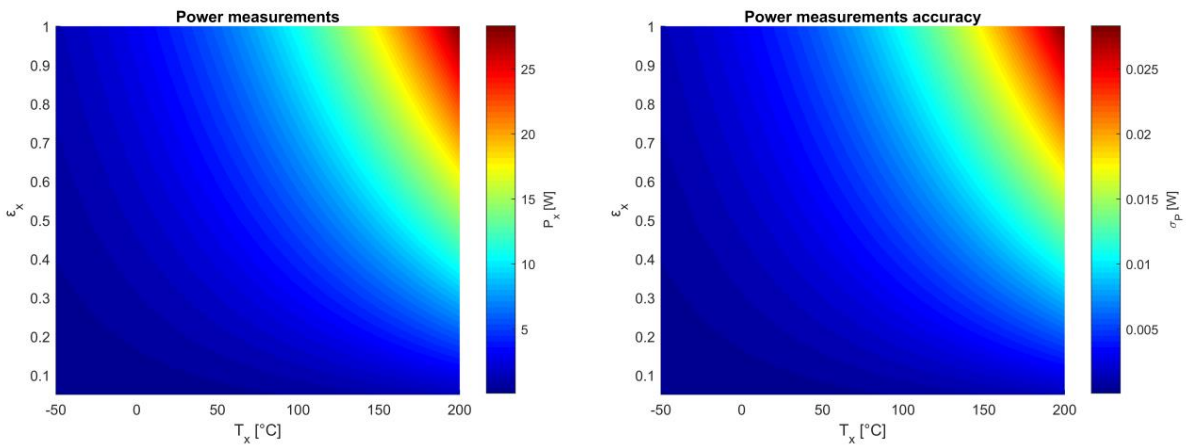

Figure 6: Assumed power measurements and their accuracies in terms of measurement error standard deviations

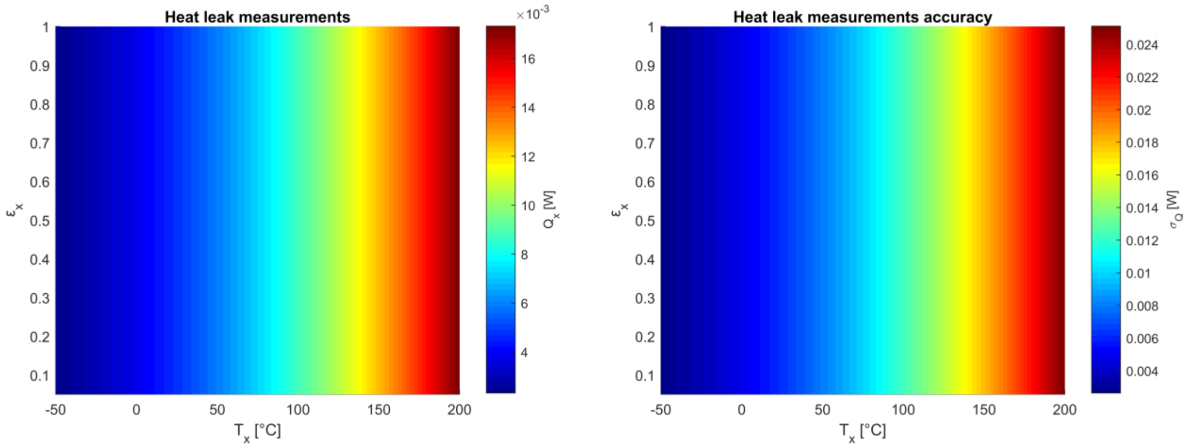

Figure 7: Assumed heat leak measurements and their accuracies in terms of measurement error standard deviations

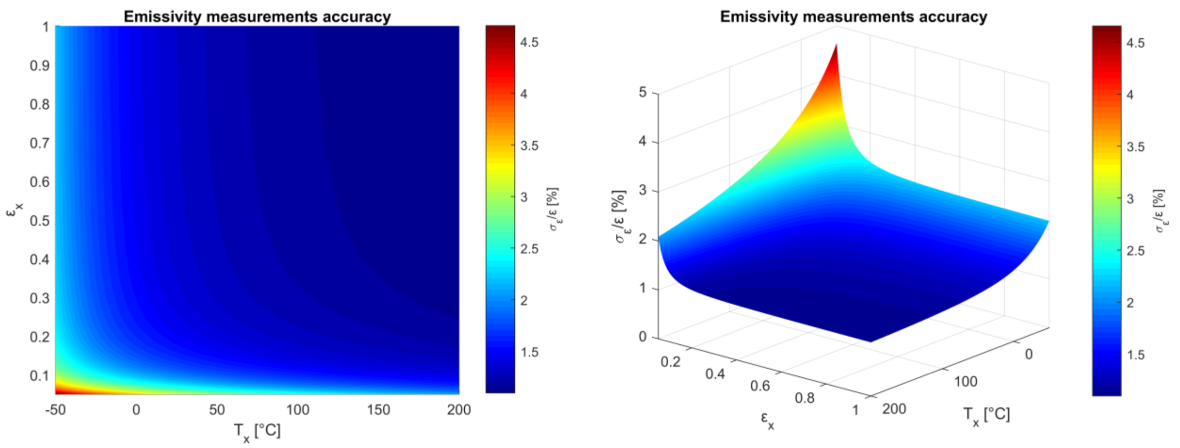

Figure 8: Relative accuracy of the emissivity measurements in terms of relative measurement error standard deviations based on the linearized measurement error model, depicted in 2D and 3D

For the parameters specified in Table 1, the relative accuracy given by the measurement error interval of the emissivity measurements based on the linearized measurement error model is given by $\left(\sigma_{\varepsilon_x} / \varepsilon_x\right) \in [1\%, 5\%]$ where $\left(\sigma_{\varepsilon_x} / \varepsilon_x\right)$ denotes the corresponding relative emissivity measurement error standard deviation. The Monte Carlo simulations show a slightly higher relative emissivity measurement error standard deviation, which becomes more significant for lower sample emissivities and lower sample temperatures (closer to the environment temperature). This can be explained by the fact that for lower emissivities and sample temperatures closer to the environment temperature the non-linear relation between the emissivity measurements and the input parameters plays a more significant role.

CONCLUSIONS AND RECOMMENDATIONS

For aerospace systems knowledge about variable emissivities of materials and coatings as function of temperature is of vital importance for an accurate prediction of infrared radiation heat transfers and temperatures using thermal models.
The proposed calorimetric method provides for a direct measurement for of total hemispherical emissivity, without scanning of the IR spectrum and the spatial dimensions and can be directly applied in thermal models, without the need of a calibrated reference. Sample fixation has been optimized for low thermal conduction to the backside (in combination with guard heater control) and a uniform temperature distribution and relatively quick sample exchange at the front is ensured. An accuracy assessment, for sample temperatures between -50°C and 200°C, shows that the expected relative measurement error standard deviation for emissivities in the range of 1 down to 0.05 will be better than 1-5%. Verification tests are recommended to demonstrate the predicted accuracy of the proposed facility. For accurate measurement of emissivities below <0.05 larger samples are required. It is considered that varying sample sizes could be introduced when the emittance range is roughly known.

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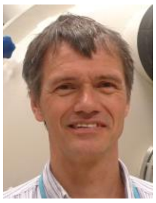

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