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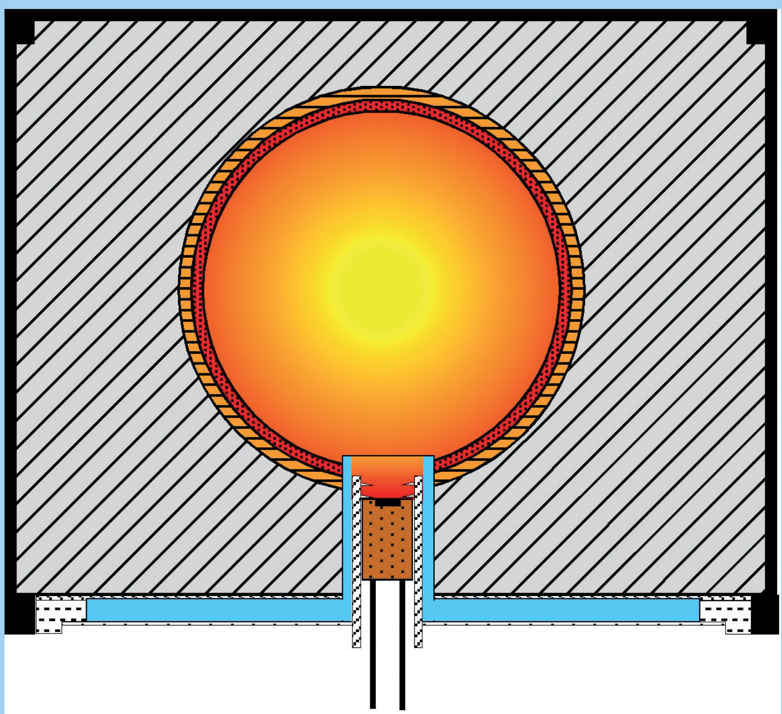
Uncertainty in heat flux calibrations performed according to NT FIRE 050

Nordtest Project No. 1525-01



SP Swedish National Testing and Research Institute
SP Fire Technology
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Abstract

The combined expanded uncertainty for calibrations according to NT FIRE 050 performed in the furnace at SP is calculated and presented. The result is presented in tables so that the parameters that contributes most to combined uncertainty is easily recognized. An example is also given for how to include the uncertainty in the regression analysis performed after the calibration. Calculations are performed for two temperature levels, i.e. 400°C and 1000°C and for the case with and without fitting piece.

The results show that with the furnace used today at SP the combined expanded uncertainty lies within of ±3% for the 1000°C case but not for the 400°C case. The limit of ±3% is defined by ISO for methods to be used as a primary calibration standard. However, if the distribution of the wall temperature inside the furnace can be made more even, then the calibrations are well within the limit for all temperature ranges.

Key words: Fire tests, uncertainty, heat flux meters, calibration, NT FIRE 050

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Sammanfattning

Den totala utökade mätosäkerheten för kalibrering av strålningsmätare enligt NT FIRE 050 har beräknats för ugnen som används på SP idag. Resultaten presenteras i tabeller där de faktorer som bidrar mest till mätosäkerheten lätt kan identifieras. Beräkningarna har utförts vid två olika temperaturer 400°C och 1000°C samt för fallen med och utan passbit. Ett kort exempel ges även för hur man lägger till osäkerheten i den regressionsanalys som man i regel utför efter kalibreringen.

För 1000°C fallet ligger mätosäkerheten under de ±3% som ISO har angetts som gräns för att accepteras som primär standard. Dock ligger osäkerheten över för 400°C fallet. Osäkerheten beror dock på till allra största delen att temperaturvariationerna i ugnen på SP är i dagsläget stora. Det går att väsentligt förbättra detta genom att använda ett material med bättre värmeledningsegenskaper för kulan, lägga värmeslingorna längre ifrån kulan, isolera ugnen bättre, etc. Om standardavvikelsen i bestämningen av medeltemperaturen i ugnen minskas till mindre än ±1.4° ligger man under ±3% över hela kalibreringsintervallet.

1 Introduction

According to EN ISO/IEC 17025[1] and ISO 10012-1[2] uncertainties should be reported in calibration reports. General Principles for how to evaluate and report uncertainties are given in EAL-R2[3] and GUM[4]. These principles have already been used and reported by Axelsson et al[5] for heat and smoke release measurements.

Nordtest method NT FIRE 050[6] was published 1995. The method was developed during 1986-1991 by Sören Olsson who worked at SP at that time. He reported an estimation of maximum individual errors[7] but did not perform any determination of the combined expanded standard uncertainty of calibration results according to the principles described in GUM or EAL-R2. Olsson’s findings have now been used in this project, together with some newly performed measurements, to calculate the combined expanded standard uncertainty with approximately a 95% confidence interval.

ISO has within the Technical Committee ISO/TC 92, Fire Safety, Subcommittee SC 1, Fire initiation and growth prepared a Technical Specification ISO/TS 14934-1 where NT FIRE 050 is listed as one of three primary methods for calibration of heat flux meters. ISO 14934 will consist of the four parts, under the general title “Fire tests — Calibration and use of heat flux meters”. The parts have the following subtitles:

- Part 1: General principles
- Part 2: Primary calibration methods
- Part 3: Secondary calibration methods
- Part 4: Guidance on the use of heat flux meters in fire tests

The work on ISO 14934 aims on achieving a combined expanded standard uncertainty of less than ±3% at a 95% confidence level for the primary calibration methods. Thus, the results of the calculation of the combined expanded standard uncertainty for calibrations according to NT FIRE 050 will be introduced into the ISO document.

2 Uncertainty in measurements

Measurements always include errors and the errors propagate through all calculations based on the measurements[5].

The errors can be systematic or random. Systematic errors result in a bias to the measured values while random errors results in a spreading of the values. It is considered as good practice to try to reduce the systematic errors as much as possible. However, if the value of a systematic error is unknown it may be regarded as a random error.

Uncertainty of a measurement is defined as "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonable be attributed to the measurand"[4]. Another definition could be a measure of the possible error in the estimated value of the property being measured.

The qualitative concept of accuracy has to be quantified by the quantitative concept of uncertainty. Those two concepts varies inversely. The concept of accuracy, illustrated by Figure 2-1, consists of trueness and precision. Precision is expressed numerically with its opposite, i.e. the deviation or more precisely the standard deviation. Trueness is expressed numerically with its opposite as well, in this case the systematic error or the bias.

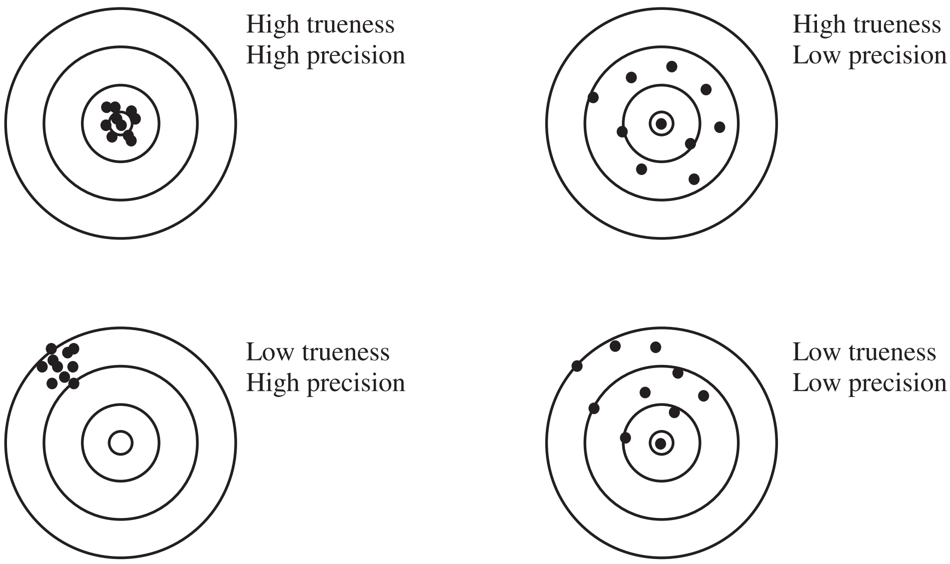

Figure 2-1 Different levels of accuracy as illustrated by targets

The distribution of results of measurements can be described with statistical methods. Figure 2-2 is a graphical illustration of this. The solid and the dotted curves represent the estimation of a measured value based on repeated observations. The dotted curve shows the results obtained at one single laboratory under repeatability conditions, while the solid line shows the reproducibility results obtained by several laboratories. In the example shown the locally systematic error is larger than the strictly systematic error. Repeatability is normally denoted by *"r"* in subscripts and reproducibility by *"R"*.

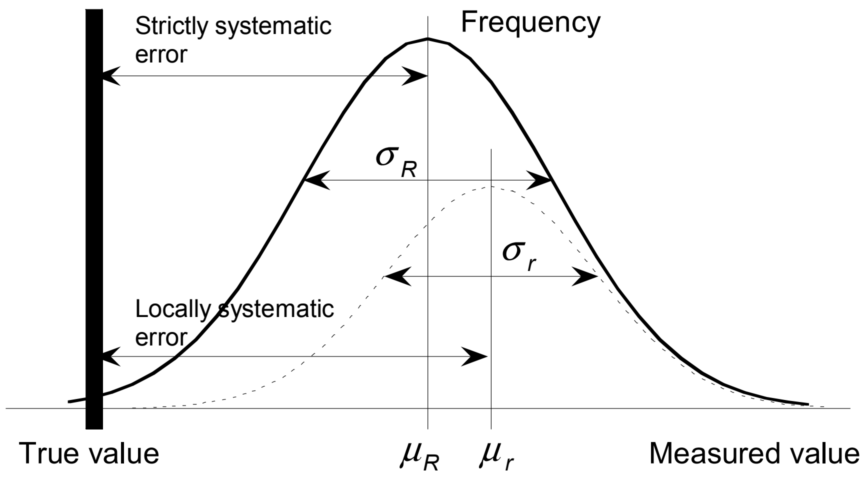

Figure 2-2 The distribution of measured values under different conditions

2.1 General principles of determination of uncertainty in measurements

For the purpose of this project, principles for determination of uncertainty in measurements as described in EAL-R2[3] and GUM[4] were used. The combined standard uncertainty, $u_c(y)$, is determined from the standard uncertainty of each input estimate, $u(x_i)$. Uncertainties are classified as Type "A" if their standard uncertainties are derived from data by statistical methods, provided sufficient data is available. When the evaluation of the standard uncertainties is based on judgements, specifications or experience, however, the uncertainties are classified as Type "B".

Using a simple mathematical model the result of a measurement can be expressed as:

$$y = \mu + \varepsilon_1 + \varepsilon_2 + ... + e_1 + e_2 + ... \qquad (2\text{-}1)$$

where y is the measured value, μ is the true, unknown value and ε_1, ε_2... and e_1, e_2... are the contributions from different sources of errors. ε_1, ε_2... are the Type "A" and e_1, e_2... are the Type "B" uncertainties.

The standard uncertainty of a Type "A" error is represented by the standard deviation. For Type "B" errors the evaluation of the uncertainty depends on the basis that has been used for the evaluation. Thus, for a digital instrument with a low resolution the measurement values are assumed to be distributed as a symmetrical rectangle, while for instance the scale readings of a flow meter can be assumed to be distributed as a symmetrical triangle. Figure 2-3 shows examples of rectangular and triangular distributions. Similar models can be used for all kinds of Type "B" errors.

The standard deviation of a rectangular distribution, s_{rect}, is calculated as a function of the width of the distribution as:

$$s_{rect} = \frac{\varepsilon_0}{\sqrt{3}}$$

where ε_0 is half the width of the distribution.

The standard deviation of a triangular distribution, s_{trian}, is calculated as a function of the width of the distribution as:

$$s_{trian} = \frac{\varepsilon}{\sqrt{6}}$$

where ε is half the width of the distribution.

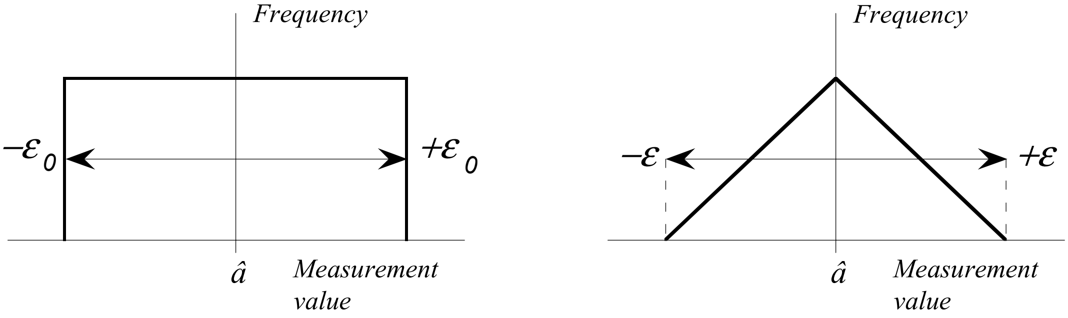

Figure 2-3 Examples of rectangular and triangular distributions

If the contributions of errors, ε_1, ε_2... and e_1, e_2..., can be regarded as independent of each other, the combined standard uncertainty, $u_c(y)$, can be calculated as:

$$u_c = \sqrt{d_1^2 s_1^2 + d_2^2 s_2^2 + ... + c_1^2 u_1^2 + c_1^2 u_2^2 + ...} \qquad (2\text{-}2)$$

where s_1, s_2... are the experimental standard deviations, u_1, u_2... are the standard uncertainties and d_1, d_2…, c_1, c_2….are the sensitivity coefficients. Sensitivity coefficients are used when the quantity of interest is a function of measured quantities. They express how much the result varies with changes in the input quantities. The sensitivity coefficient equals the partial derivative of the final result with respect to the measured quantity. They can be determined either by analytical partial derivation or numerically or experimentally by varying the parameter in question within the settled limits. If one prefers to work with relative errors then Equation 2-2 transforms to

$$\frac{u_c}{y} = \sqrt{\left(\frac{\partial f}{\partial x_1}\frac{x_1}{y}\frac{u(x_1)}{x_1}\right)^2 + \left(\frac{\partial f}{\partial x_2}\frac{x_2}{y}\frac{u(x_2)}{x_2}\right)^2 + ...} = \sqrt{c_{r,1}^2\left(\frac{u(x_1)}{x_1}\right)^2 + c_{r,2}^2\left(\frac{u(x_2)}{x_2}\right)^2 ...} \qquad (2\text{-}3)$$

for a function $y = f(x_1, x_2, ...)$ with the relative sensitivity coefficients $c_{r,i}$. Especially in case of a simple multiplicative function, $y = x_1^{m_1} \cdot x_2^{m_2} \cdot \ldots$, the relative sensitivity coefficients according to relative uncertainty are easily determined from the exponents,

$$\left(\frac{u_c}{y}\right)^2 = m_1^2\left(\frac{u(x_1)}{x_1}\right)^2 + m_2^2\left(\frac{u(x_2)}{x_2}\right)^2 + \ldots \qquad (2\text{-}4)$$

Since the standard uncertainty per definition in GUM[4] is expressed as the standard deviation, it has the coverage factor *k=1*. Thus, to finally obtain the expanded relative uncertainty U_c, the combined relative standard uncertainty $u_c(y)$ is multiplied by a coverage factor *k*:

$$\frac{U_c}{y} = k\sqrt{c_{r,1}^2\left(\frac{u(x_1)}{x_1}\right)^2 + c_{r,2}^2\left(\frac{u(x_2)}{x_2}\right)^2 + \ldots} \qquad (2\text{-}5)$$

The expanded relative uncertainty gives a confidence interval about the result. When using the coverage factor of 2 the confidence level is approximately 95%.

2.2 Principles used in this project

The relative standard uncertainties of each quantity needed for calculating the heat flux to the heat flux meter during calibration were estimated and listed in tables together with their contribution to the combined relative uncertainty so that the quantities that contribute most could easily be identified. Relative standard uncertainties and relative sensitivity coefficients were used throughout the project. The standard uncertainty was calculated assuming a rectangular or triangular distribution of the maximum error. Or in cases where several measurements of the quantity has been performed on the standard deviation. The expression “Relative error” in the tables refers to the estimated relative error. With relative error is meant the discrepancy between the measured and the true value. No distinction between systematic or random error was made. The relative sensitivity coefficients were estimated by parameter variation instead of performing the partial derivation due to the complexity of the calculations. Each parameter was varied one standard deviation around its value for this estimation.

3 The principle of heat flux calibrations according to NT FIRE 050

The method NT FIRE 050 is mainly intended for calibration of total heat flux meters. The method enables calibration from 2 kW/m^2 to 100 kW/m^2. Heat flux meters with a housing diameter of up to 50 mm and a sensitive area diameter of up to 10 mm can be calibrated.

The method consists of a blackbody radiation source designed as a well insulated, electrically heated spherical furnace chamber with an aperture at the bottom, shown in Figure 3-1. The temperature in the furnace is controlled by a PID regulator and a type K thermocouple. The irradiation to the gauge placed in the aperture in the bottom is calculated from the surface temperature measured by a type S thermocouple mounted as shown in Figure 3-1.

A cooling device housing the heat flux meter is inserted in the opening at the bottom of the furnace. The inside diameter of the furnace is larger than 4,5 times the restricting aperture of the fixed cooler at the bottom of the furnace. The aperture in the cooling device defines the view factor under which the furnace radiates to the heat flux meter.

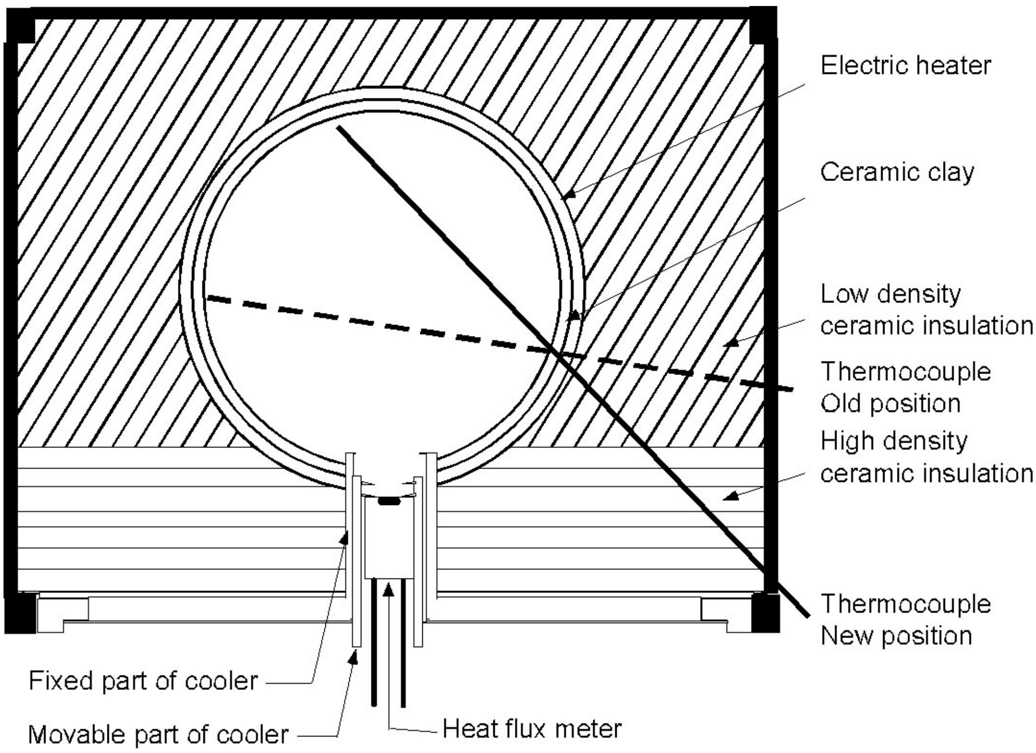

Figure 3-1 A schematic picture of a vertical cross-section of the furnace. The movable cooler insert is shown with a heat flux meter fitted (not to scale).

Heat flux meters to be calibrated are inserted through the aperture with the sensing surface of the heat flux meter oriented horizontally. The influence of convection is thus highly reduced. The cooler insert has a number of shields, which protect the gauge from receiving radiation reflected from the cooler wall. The shields help to maintain the stratification of air so that convective airflow is minimized. The heat flux meter sees nothing but the controlled environment of the blackbody emitter. The radiation level of this blackbody emitter depends solely on the temperature of the inside surface of the spherical furnace.

The cooler is designed to be used with the movable insert in two positions. A 40 mm fitting piece with a flange near its middle height serve for mounting the heat flux gauge in the lowest position which provides for a radiation range of (2-30) kW/m^2. At the top position, without the fitting piece, the radiation range is (6-100) kW/m^2.

The calibration is performed at several flux levels, evenly distributed over a temperature range from 400°C to a temperature corresponding to the maximum flux level of the gauge.

Before the heat flux gauge is mounted in the cooling device, the radius of the sensing element is measured. The distance between the top of movable cooler and the receiving sensor of the heat flux meter is also measured. Both these dimensions are used as input for calculating the view factor. When the temperature is stable within ±1°C/minute at the set level, records of the water and the furnace temperature together with the output signal from the gauge are taken during 1 minute (approx 120 records).

The irradiation to the gauge is calculated according to the net radiation method[7, 8].

$$\frac{q_i}{\varepsilon_i} - \sum_{k=1}^{5} \frac{1-\varepsilon_k}{\varepsilon_k} F_{ik} q_k = \sum_{k=1}^{5} F_{ik} (e_{bi} - e_{bk}) \qquad (3\text{-}1)$$

where q_i is the net radiation per unit area leaving the area i, F_{ik} is the configuration factor for radiation leaving area i and reaching area k, ε_k emissivity for area k, e_{bi} the blackbody radiation leaving area i and e_{bk} is the blackbody radiation leaving area k. The cooler is approximated as a cylinder as given in Figure 3-2. Details on how the equation system is solved is given in Appendix A in the Nordtest method NT FIRE 050[6]. The calculation scheme can be implemented in an Excel macro. This macro has been used for the calculations in this report.

The parameters that influences the magnitude of the irradiation is basically the view factors F_{ik} for the different parts of the cooler (i.e. distances L_2, L_3 and r_1), the temperature in the furnace, the temperature of the cooler parts, the water cooling temperature, the gauge radius and the apparent emissivity of the furnace (i.e. emissivity of walls and diameter of aperture (r_1) and furnace). Each of the parameters is discussed in chapter 4 below. In all cases the sensitivity coefficient was estimated by parameter variation in the Excel macro since it is difficult to estimate these by derivation due to the complexity of the calculations. Each parameter was varied one standard deviation around its value.

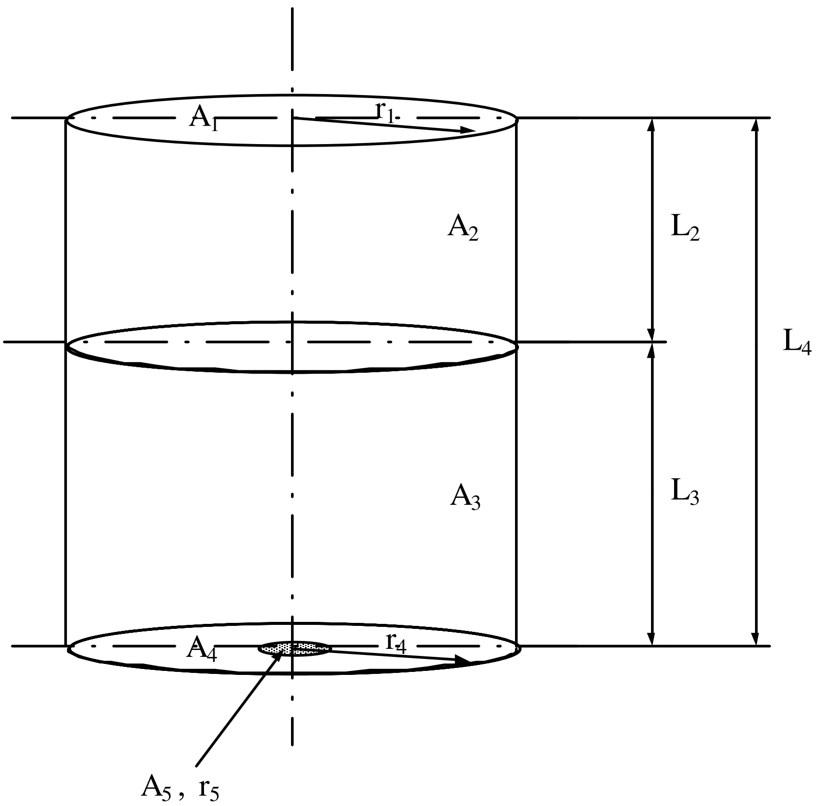

Figure 3-2 The cylindrical model of the enclosure, with the furnace aperture at the top and the gage at the bottom.

3.1 The furnace at SP

When this project started the heating element, which was the original element mounted by Olsson 1991, unfortunately burned out. It was therefore replaced by a new winding of the same type as the old one during the project. The new winding was mounted in a slightly different position compared to the old one. This led to that the temperature distribution in the furnace changed.

Some control calibrations of heat flux meters were performed to see if the furnace still would deliver the same results. It was identified that this was not the case. After the S-thermocouple was mounted in the new position, see Figure 3-1, a better compliance with old calibration results was obtained.

4 Sources of uncertainty in heat flux meter calibration according to NT FIRE 050

Below, each of the parameters that influences the calibration result of heat flux meters according to NT FIRE 050 is discussed. The estimated standard uncertainties are based on the performance of the SP furnace as it is today after the reconstruction. The calculations were performed for two different temperatures (400°C and 1000°C) and with and without the fitting piece mounted. The insertion depth used was 17.25 mm and the radius of the sensitive element 3 mm. The sensitivity coefficients $c_{x,\mathrm{i}}$ were estimated from a parameter study in the Excel macro by

$$c_{r,i} = \frac{\Delta q}{q} \cdot \frac{x_i}{\Delta x_i} \qquad (4\text{-}1)$$

where $\Delta q/q$ is the relative change of the irradiation due to the relative change $\Delta x_i/x_i$ of the variable x_i. All the sensitivity calculations are presented in appendix A. The results imply that some of the coefficients depend on the magnitude of x_i, this was not however studied further.

4.1 Emissivity of furnace wall

The emissivity of the furnace wall influences the apparent emissivity of the furnace. The relative sensitivity coefficient calculated by parameter variation is independent of whether a fitting piece is used or not and also of the temperature. The relative sensitivity coefficient was calculated to 0.017. The result listed in Appendix A imply, however, that the relative sensitivity coefficient depends on the chosen wall furnace emissivity but here a mean value is used.

Olsson[7] states that the emissivity for the wall is within 0.7-0.9 since most materials has that emissivity. Using these values and assuming a rectangular distribution gives a relative standard uncertainty of $0.1/0.8/\sqrt{3}$ =7.2%. If the emissivity is assumed to be in the interval 0.5-1 with a triangular distribution then the relative standard uncertainty becomes 14%.

4.2 Furnace diameter

The furnace diameter influences the apparent emissivity of the furnace. The relative sensitivity coefficient calculated by parameter variation is independent of whether a fitting piece is used or not and also of the temperature. The sensitivity coefficient was calculated as 0.0056. The sensitivity coefficient is slightly furnace diameter dependent, se Appendix A, but this is neglected here and a mean value is used.

According to Olsson[7] the diameter is (281±3) mm. Assuming a triangular distribution gives a relative standard uncertainty of 0.44%.

4.3 Furnace aperture

The furnace aperture influences both the apparent emissivity of the furnace and the configuration factors. The relative sensitivity coefficient calculated by parameter variation depends on whether a fitting piece is used or not but not on the temperature.

When no fitting piece is used the sensitivity coefficient becomes 1.0 while it is 1.65 when the fitting piece is used.

Olsson states that the radius of the aperture is (30.08±0.01) mm. Assuming a rectangular distribution gives the relative standard uncertainty of 0.02%.

4.4 Dimensions of cooler

The different dimensions of the cooler influence the view factors. The dimensions were checked as described in Appendix B. The uncertainties was in the same order of magnitude as given by Olsson but some measures differed from the ones given by Olsson[7]. For instance the flange on the fitting piece was not at the distance stated by Olsson.

The influence of the different measures is rather complex and it depends on whether a fitting piece is used or not. The two measures used in the calculations are mainly L_2 and L_3 in Figure 3-2. If no fitting piece is used then L_2 equals x_1 according to Olsson's notation and L_3 equals the insertion depth. If a fitting piece is used then L_2 equals x_1 + the upper part of the fitting piece, while L_3 equals the insertion depth + the lower part of the fitting piece.

Due to the different ways to calculate L_2 and L_3 the sensitivity coefficients was calculated for the insertion depth and x_1 separately for the case without the fitting piece. This gave a sensitivity coefficient of 0.57 for the insertion depth and 0.43 for the x_1. For the fitting piece case the sensitivity coefficient was estimated for the insertion depth, x_1, the upper part and L_4-x_1(L_4=L_2+L_3). The sensitivity coefficient was 0.41 for the insertion depth. For x_1 it was 0.31. It was 0 for the upper part as long as the L_3 was changed in the same manner so that the L_4-x_1 equaled 40 mm. Therefore the sensitivity coefficient for L_4-x_1 was also estimated and found to be 0.96.

The relative standard uncertainty for x_1 assuming a rectangular distribution and x_1=13.05±0.03 is 0.13%. For the insertion depth it becomes 0.17% and for the size of the fitting piece 0.0058%.

4.5 Emissivity of cooler surfaces

The emissivity of the cooler surfaces is not included in the calculations. It only influences the reflection error as described by Olsson[7].

4.6 Temperature of cooler

The cooler is divided into two parts in the calculations, the upper and lower part. These two sections are assumed to have a uniform temperature each. The temperature of each part is the mean value of several temperatures in different locations in the cooler and it is assumed that this mean value is representative for the relevant overall cooler temperature. An extract from Olsson's report[7], showing the results of his temperature measurements is given in Appendix C. There is no significant random variation, but a lack of knowledge about how relevant this mean value is. In accordance with measurement uncertainty practice this lack of knowledge is regarded as a random property and an estimate of its standard deviation is needed. It is very plausible that the relevant temperature is close to the calculated mean and it is quite certain that it is not outside the two extreme measured locations. Therefore the uncertainty is modelled as a triangular distribution around the mean. For a certain value of $\sigma\left(T_f^4 - T_w^4\right)$ we have the extreme measurements $(T / C\ 6)_0$ and $(T / C\ 7)_0$ and the mean value $T_{3,0}$ and the estimated standard deviation

$$s_{T_3} = \frac{(T / C\ 6)_0 - T_{3,0}}{\sqrt{6}} \tag{4-2}$$

An estimate of all values of $\sigma\left(T_f^4 - T_w^4\right)$ is however wanted and therefore the slope in the curve is regarded as the random variable. The formula for the mean temperature can be written

$$T_3 = T_w + k \cdot x \qquad\qquad x = \sigma\left(T_f^4 - T_w^4\right) \tag{4-3, a and b}$$

where *k* is the slope. Here we regard *k* as a random property which has a trinagular distribution with the mean equal to 0.00055 (eq. 3.2[7]) and the standard deviation given by the same procedure above. The upper extreme slope is 0.000705 (see Figure C-2 in Appendix C) in the case of eq. 3.2, which gives the estimate

$$s_k = \frac{0.000705 - 0.00055}{\sqrt{6}} = 0.000063 \tag{4-4}$$

The usual law for uncertainty propagation gives

$$\sigma_{T_3}^2 = \left(\frac{\partial T_3}{\partial k}\right)^2 \sigma_k^2 = x^2 \sigma_k^2 \tag{4-5}$$

The relative uncertainty can be approximated as

$$\frac{\sigma_{T_3}^2}{T_3^2} = \frac{x^2 \sigma_k^2}{T_3^2} = \frac{x^2 \sigma_k^2}{(T_w + kx)^2} < \frac{x^2 \sigma_k^2}{(kx)^2} = \frac{\sigma_k^2}{k^2} \tag{4-6}$$

and the corresponding estimate in our case is

$$\frac{s_{T_3}}{T_3} < \frac{s_k}{\bar{k}} = \frac{0.000063}{0.00055} = 0.12 = 12\ \% \tag{4-7}$$

A corresponding measure in the case with insert would give

$$s_k = \frac{0.00039 - 0.00023}{2.57} = 0.000065 \tag{4-8}$$

$$\frac{s_{T_3}}{T_3} < \frac{s_k}{\bar{k}} = \frac{0.00006}{0.00023} = 0.28 = 28\ \% \tag{4-9}$$

The sensitivity coefficients are calculated by varying the slope in the equations for the used cooler temperature. This resulted in a sensitivity coefficient of 0.0015 for the case without fitting piece at 400°C and 0.0054 for the 1000°C case. For the fitting piece case the T_3 sensitivity coefficient is 0.007 for the 400°C and 0.012 for the 1000°C case. The sensitivity coefficient for the T_2 is negligible in both cases.

Studying figure 13 and 14 in Olsson's report[7] (Figures C-2 and C-3 in Appendix C) rises however some doubts about the accuracy of the measurements that the formulas for the cooler temperature is based on. For instance the measured temperature varies 60° over a 1 mm piece of metal. This calls for that new measurements should be performed so that the model can be checked properly.

4.7 Temperature of cooling water

The sensitivity coefficient for the cooling water temperature was found to be dependent on both the furnace temperature and whether a fitting piece is used or not. For the 400°C case without fitting piece it is 0.15 and 0.14 with fitting piece. For the 1000°C case it is 0.0038 without fitting piece and 0.011 with fitting piece. The water temperature measurement is assumed to have an uncertainty of ±2°, according to Olsson. Assuming a rectangular distribution and a water temperature of 298 K gives the relative standard uncertainty of 0.39%.

4.8 Radius of sensitive element

The radius of the sensitive element of the meter is measured in each calibration. The uncertainty is estimated as ±0.5 mm according to Olsson. Assuming a triangular distribution gives the relative standard uncertainty of 6.8%.

The sensitivity coefficient was estimated to 0.0049 without fitting piece and 0.0026 with fitting piece.

4.9 Furnace temperature

By studying the equation for radiation (σT^4) it is identified that the sensitivity coefficient for the furnace temperature is large, i.e. in the order of 4. Performing the parameter study in the Excel macro gives the value of 4.66 for all cases.

The furnace temperature is measured with a bare type S-thermocouple during the calibration. The accuracy of this thermocouple is very good. The temperature distribution within the furnace varies however and therefore the temperature was measured at several points in the furnace in this project. Records were taken both of the wall temperature and of the air temperature.

For the records of the wall temperature, the thermocouple was introduced through the fixed cooler at the bottom of the furnace; the furnace was located in its calibration position i.e. with the opening facing down. The thermocouple was moved at steps of 5° and fixed at the location with a clamp. The hot junction of the thermocouple was in contact with the wall during those measurements and the furnace temperature was held at 300°C.

Records of the air temperature were taken along a couple of lines:

- the vertical line passing through the central point of the furnace
- lines at an angle of 25°
- through the old and new mounting holes used for the furnace thermocouple

The records of the air temperature were taken at a furnace temperature of 400°C and 1000°C.

The results of the temperature measurements are given in Figure 4-1 and Figure 4-2. The temperatures are given as the difference between the furnace temperature and the temperature recorded at the location. Figure 4-2 includes all records of temperature.

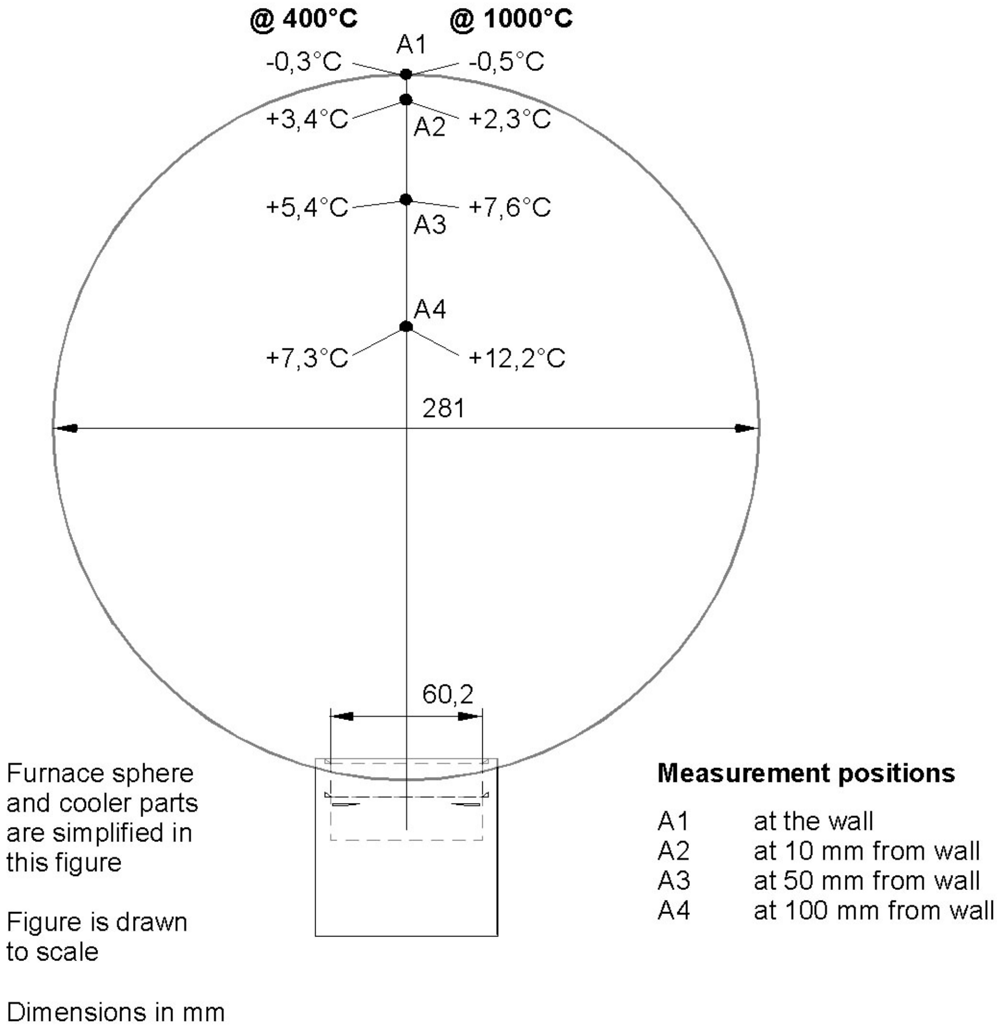

Figure 4-1 Temperature measurements along the vertical line of the furnace.

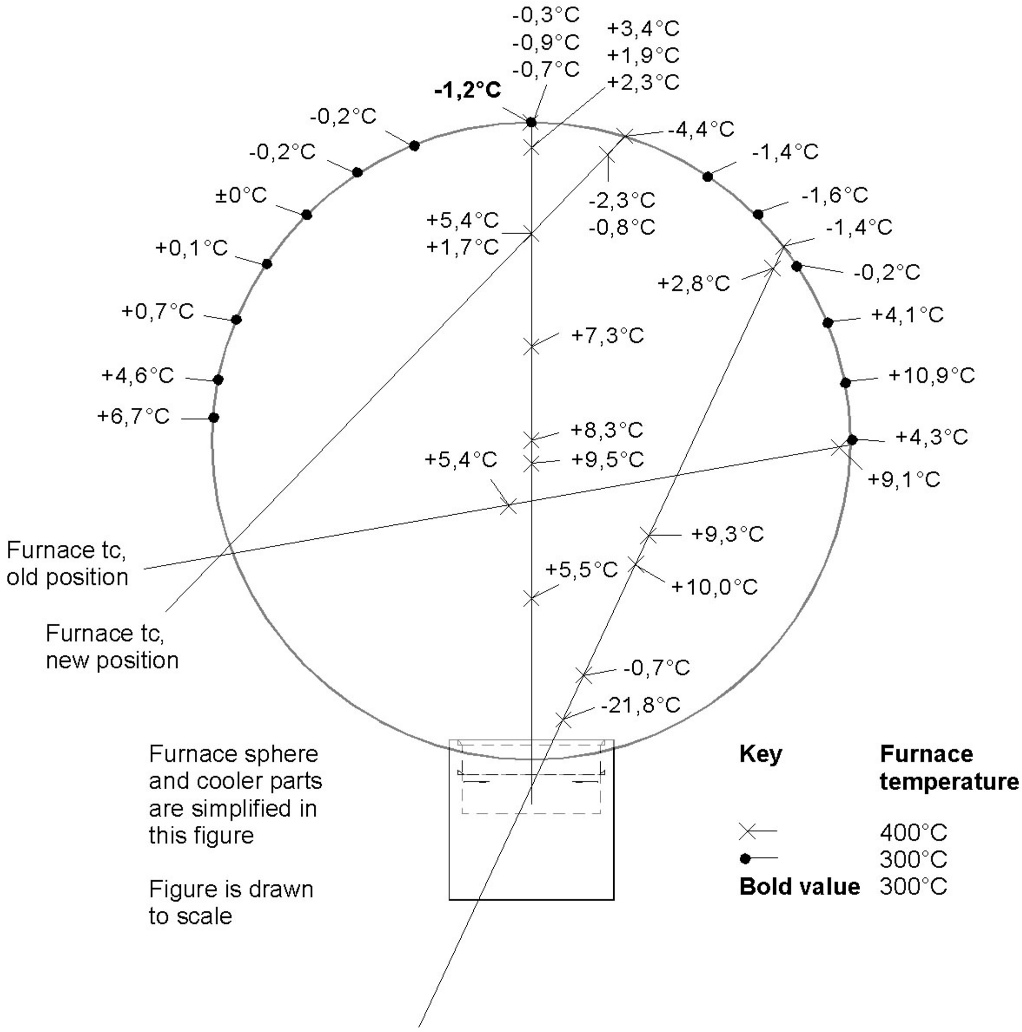

Figure 4-2 Temperature measurements on wall and in air in the furnace.

These measurements result in a standard uncertainty of 3.6° for the readings close to the wall regardless of temperature. This gives a relative standard uncertainty of 0.52% for the 400°C and 0.275% for the 1000°C case.

In addition a few calculations were performed using the computer program TASEF to check whether the temperature readings were reasonable. These simulations indicated that the variations could be even larger.

The thermal radiation received by the heat flux meter was also calculated assuming that the heat flux meter was placed flush with the furnace wall and that the temperature was 400° opposite the heat flux meter, 412° in a band next to that, 390° in a band next to that and 380° close to the heat flux meter. The different temperatures had the same area. This gives a mean temperature of 395.5°C which results in a thermal radiation to the heat flux meter based on the mean value of 11324 W/m². An exact solution gives the value 11325 W/m². This shows that if the measured temperature represents the mean value of the temperature within the furnace then the accuracy is good.

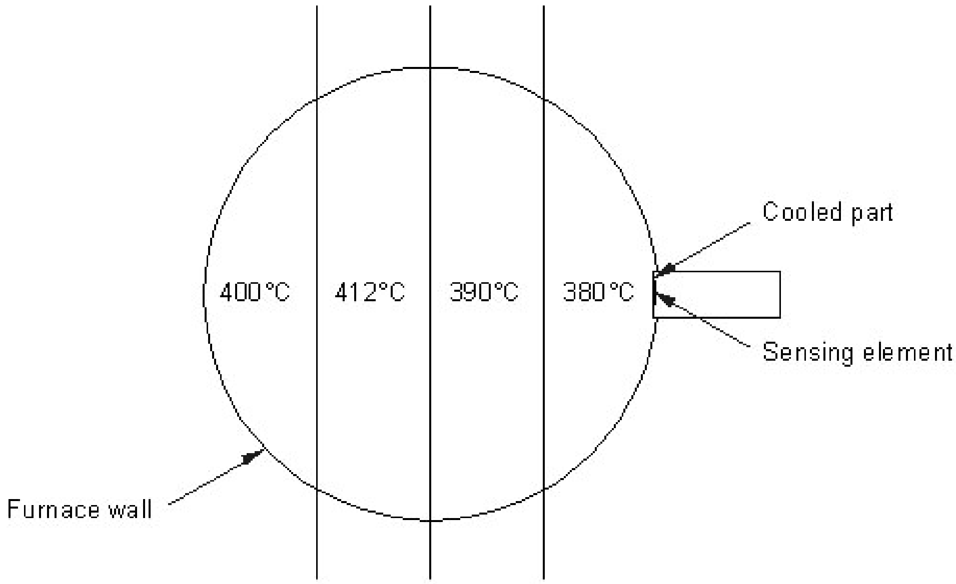

Figure 4-3 Schematic picture of calibration furnace with a heat flux meter mounted flush with the furnace wall.

If one expects that the radiation at the heat flux meter is some average value of temperatures over half of the sphere then it is the mean value of the measurements that is interesting and the uncertainty of this mean. The mean value can be taken as a systematic error and be corrected for and the uncertainty in this mean should be included as an uncertainty value. If one can assume that the temperatures over the surface are normally distributed, then the standard deviation for the mean is simply

$$s_{\bar{T}} = \frac{s_T}{\sqrt{N}}, \qquad (4\text{-}10)$$

where N is the number of measurements and s_T is the standard deviation of the measurements. In this particular case we obtain

$$s_{\bar{T}} = \frac{3.6}{\sqrt{26}} = 0.70 \qquad (4\text{-}11)$$

If one doubts the normality assumption it is possible to use the boot-strap technique instead. Then we chose randomly 26 new observations from the original sample with replacement, which means that a certain observation may be chosen more then once and other observations be excluded. This is done a large number of times, the mean value is calculated for each random choice, and the standard deviation for the resulting mean values is calculated. In this case this procedure gave the following estimate

$$s_{\bar{T}}^{BT} = 0.68 \qquad (4\text{-}12)$$

We see that the two estimates almost coincide. However, if the systematic error is not corrected for one could include it as a uniformly distributed random variable. In order to make it possible to include such an uncertainty in the analysis it must have the expected value equal to zero. This can be accomplished by adding an equally large error symmetrically around zero. In our case the estimated mean is the average over the 26 measurements, +1.3 ºC and we can model the systematic error as the uniform random variable

$$T_m = U(-1.3,+1.3) \tag{4-13}$$

which has the standard uncertainty

$$\frac{1.3}{\sqrt{3}} = 0.75\,^{\circ}\mathrm{C} \tag{4-14}$$

This would give the total uncertainty from the furnace temperature

$$u_T = \sqrt{s_T^2 + s_{T_m}^2} = \sqrt{0.7^2 + 0.75^2} = 1.0\,^{\circ}\mathrm{C} \tag{4-15}$$

There is also the uncertainty in the temperature measurement. A few repetitions were made in a few places, this gives the standard uncertainty of 1.2°.

In addition it turned out that in order to get a better agreement with old calibrations then the thermocouple had to be placed at a location where the temperature is –1.5°C. This means that the difference between the measured value and the estimated mean value is 1.3 + 1.5 and the systematic error must be increased if no correction is made for the error. The uncertainty thus becomes

$$u_T = \sqrt{0.7^2 + 1.6^2 + 1.2^2} = 2.1\,^{\circ}\mathrm{C} \tag{4-16}$$

The relative uncertainties then become

$$\frac{2.1}{673}\cdot 100 = 0.31\% \quad \text{and} \quad \frac{2.1}{1273}\cdot 100 = 0.16\% \tag{4-17}$$

4.10 Uncertainties not included in the calculation scheme

Apart from the uncertainties in the parameters that are directly included in the calculation scheme a few other uncertainties exist which are due to uncertainties in the model and the furnace construction together with uncertainties in the data sampler.

4.10.1 Uncertainties due to the approximations in the enclosure model and reflection error

The view factors are calculated assuming the cooler is a cylinder. According to Olsson this gives a relative error of between 0% and 0.5%. The reflection error is estimated as –0.8% to 0% by Olsson.

When an error only has a positive or negative sign a correction should be made for that. In this case however there is one error at the negative side (reflection) and one at the positive (approximations in enclosure model). This result in an error of –0.3%. We choose not to make a correction for this. The uncertainties is however added up quadraticly, i.e. $(0.8^2+0.5^2)^{0.5}$, which gives an uncertainty of ±0.9%. Assuming a rectangular distribution of the errors results in a relative standard uncertainty of 0.54%.

4.10.2 Convection uncertainties

The maximum convection error is estimated to ±0.5% by Olsson. This gives a contribution of ±0.29%

4.10.3 Voltage measurement

The data logger used for the calibrations performed at SP is calibrated to ±0.01 mV. Assuming a rectangular distribution gives a standard uncertainty of ±5.8 μV. Readings from heat flux meters usually lies in the range 1-10 mV. This means that at the low reading is the relative standard uncertainty ±0.6% while it is ±0.06% for the higher readings.

5 Combined expanded uncertainty

The different relative standard uncertainties and their relative sensitivity coefficients are listed in tables 5-1 – 5-4 below.

Table 5-1 Uncertainties in heat flux measurement with insert at 400°C.

Quantity x_i	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of heat flux measurement $c_{r,i} \cdot u(x_i)/x_i = u_i(y)$ (%)
Emissivity of walls, ε	7.2	0.017	0.12
Aperture diameter, d_1	0.02	1.65	0.033
Furnace diameter, D	0.44	0.0056	0.0025
Distance in fixed cooler, x_1	0.13	0.31	0.04
Distance to flange in fitting piece, L_2''		0	0
Size of fitting piece	0.0058	0.96	0.0056
Insertion depth, x_g	0.17	0.41	0.07
Temperature of fixed cooler, T_2		Negligible	0
Temperature of movable cooler, T_3	28	0.007	0.196
Temperature of cooling water, T_w	0.39	0.14	0.055
Radius of sensor, r_g	6.8	0.0026	0.018
Temperature of furnace, T_1	0.31	4.66	1.47
Enclosure and reflection			0.54
Convection			0.29
Voltage measurement	Depends on reading, ±5.8 µV	1	0.6
Combined expanded relative standard uncertainty			**3.4**

Table 5-2 Uncertainties in heat flux measurement without insert at 400°C.

Quantity x_i	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of heat flux measurement $c_{r,i} \cdot u(x_i)/x_i = u_i(y)$ (%)
Emissivity of walls, ε	7.2	0.017	0.12
Aperture diameter, d_1	0.02	1.	0.02
Furnace diameter, D	0.44	0.0056	0.0025
Distance in fixed cooler, x_1	0.13	0.43	0.056
Insertion depth, x_g	0.17	0.57	0.097
Temperature of movable cooler, T_3	12	0.0015	0.018
Temperature of cooling water, T_w	0.39	0.15	0.058
Radius of sensor, r_g	6.8	0.0049	0.033
Temperature of furnace, T_1	0.31	4.66	1.47
Enclosure and reflection			0.54
Convection			0.29
Voltage measurement	Depends on reading, ±5.8 µV	1	0.6
Combined expanded relative standard uncertainty			**3.4**

Table 5-3 Uncertainties in heat flux measurement with insert at 1000°C.

Quantity x_i	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of heat flux measurement $c_{r,i} \cdot u(x_i)/x_i = u_i(y)$ (%)
Emissivity of walls, ε	7.2	0.017	0.12
Aperture diameter, d_1	0.02	1.65	0.033
Furnace diameter, D	0.44	0.0056	0.0025
Distance in fixed cooler, x_1	0.13	0.31	0.04
Distance to flange in fitting piece, L_2''		0	0
Size of fitting piece	0.0058	0.96	0.0056
Insertion depth, x_g	0.171	0.41	0.07
Temperature of fixed cooler, T_2		Negligible	0
Temperature of movable cooler, T_3	28	0.012	0.34
Temperature of cooling water, T_w	0.39	0.011	0.0043
Radius of sensor, r_g	6.8	0.0026	0.018
Temperature of furnace, T_1	0.16	4.66	0.77
Enclosure and reflection			0.54
Convection			0.29
Voltage measurement	Depends on reading, ±5.8 µV	1	0.06
Combined expanded relative standard uncertainty			**2.1**

Table 5-4 Uncertainties in heat flux measurement without insert at 1000°C.

Quantity x_i	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of heat flux measurement $c_{r,i} \cdot u(x_i)/x_i = u_i(y)$ (%)
Emissivity of walls, ε	7.2	0.017	0.12
Aperture diameter, d_1	0.02	1	0.02
Furnace diameter, D	0.44	0.0056	0.0025
Distance in fixed cooler, x_1	0.13	0.43	0.056
Insertion depth, x_g	0.17	0.57	0.097
Temperature of movable cooler, T_3	12	0.0054	0.065
Temperature of cooling water, T_w	0.39	0.0038	0.0015
Radius of sensor, r_g	6.8	0.0049	0.033
Temperature of furnace, T_1	0.16	4.66	0.77
Enclosure and reflection			0.54
Convection			0.29
Voltage measurement	Depends on reading, ±5.8 µV	1	0.06
Combined expanded relative standard uncertainty			**2.0**

It is easily recognized that the uncertainty due to the temperature in the furnace contributes most. This can be avoided by having a furnace with a more even temperature distribution. This can maybe be accomplished with better insulation of the furnace or preferably make the sphere from a material with a higher heat conduction. Other means is not to wind the heating elements right onto the sphere but to have an air space between the sphere and the heating elements. Or else the temperature can be measured at several places and use the mean value in the calculations. In addition, it is wise to have several reference heat flux meters so that the calibrations can be compared before and after maintenance of the furnace.

The uncertainties for the 400°C cases are larger than the ±3% requirement in ISO. If, however, the contribution from the temperature uncertainty can be lowered to less than 1% then the combined expanded uncertainty becomes 2.7 % for the 400°C cases. This means that the temperature in the furnace should be determined with a standard deviation less than ±1.4°.

6 Regression analysis of calibration data

When the calibration has been performed a regression analysis usually is performed. In most cases a linear regression is made by means of a spreadsheet program like for instance Excel. These programs can also give statistical parameters needed for the calculations as described below. In some cases it is however not sufficient with a linear regression but instead a quadratic model should be used. Which model to be used is seen from the residuals of the regression. An example of such a case is given below in Figure 6-1, where the residuals from a calibration at 6 levels is displayed. As seen the first order regression residuals shows a curvature and are not random.

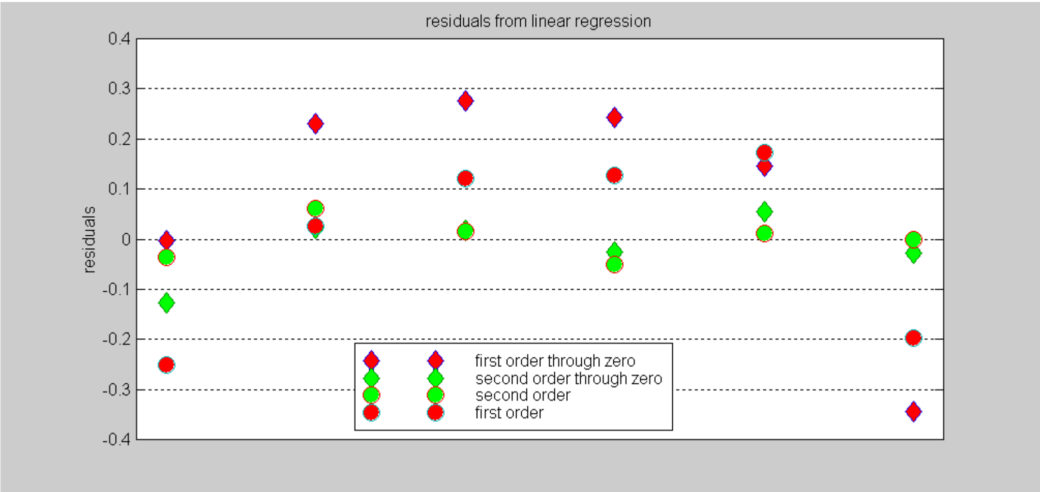

Figure 6-1 Residuals from the four models used. For the plot only average values have been used.

Once, when decided which regression that shall be used, the standard deviation is calculated either by means of the computer program used or by

$$\hat{s}^2 = \frac{1}{\nu}\sum_{i=1}^{4}(\hat{y}_i - y_i)^2 \qquad (6\text{-}1)$$

Where ν is the number of degrees of freedom, $\hat{y}_i$ is the value from the model and y_i is the measured value for the level x_i. The number of degrees of freedom ν equals number of radiation levels – number of parameters that are set in the regression. For instance with linear regression $a+bx$ it is 2, a and b, and ν becomes 6-2=4.

The uncertainty for the regression curve is then calculated as the standard deviation times a coverage factor in order to get a 95% confidence interval. Since the degrees of freedom is small this must be taken from the t-distribution, which is 2.78 at 4 degrees of freedom for example. In the case presented in Figure 6-1 the standard deviation was 0.08 kW/m². This results in an uncertainty contribution of 2.78 x 0.08 = ±0.22 kW/m², this should be added to the uncertainties estimated in chapter 4. For example for the 400°C case without fitting piece the uncertainty according to chapter 4 is 3.4% x 5.6 kW/m² (approximate radiation at 400°C) which results in a total uncertainty of

$$\sqrt{0.22^2 + 0.034^2 \cdot 5.6^2} = 0.29\ kW/m^2 \qquad (6\text{-}2)$$

7 Discussion

The uncertainties presented in Chapter 4 are within the ±3% that are required for the primary standard according to ISO for the 1000°C case but not for the 400°C case. The large uncertainty is however due to the uneven temperature distribution within the furnace. If the construction of the furnace is changed so that the temperature distribution is more even then the uncertainty is lowered considerably. For instance with a standard deviation of 1.4° for the temperature, then the combined expanded uncertainty becomes 2.7% for the 400°C case.

The tables presented in this report clearly shows what parameters that can be useful to try to decrease the uncertainty for in order to get a better overall combined expanded uncertainty for the calibrations. Apart from the temperature distribution it can be useful to calibrate the data logger more accurately and measure the emissivity of the furnace walls. The convection error is currently under investigation in the HFCAL project, the result from that can possibly reduce the assumed convection uncertainty.

This work shows that it is important to check the temperature distribution within the furnace after maintenance. It is wise to keep several reference heat flux meters so that the calibrations can be checked before and after maintenance.

When doing calibrations according to NT FIRE 050 each of the relative standard uncertainties as given in chapter 4 must be estimated for the furnace that is used. The sensitivity coefficients provided in this report can be used however, if the calculation scheme according to NT FIRE 050 is used or else they can be estimated by parameter variation. The uncertainties should be added up quadraticly and multiplied with the coverage factor of 2 to get an approximate 95% confidence interval. For the uncertainty from the regression analysis the coverage factor should be taken from the t-distribution for the number of degrees of freedom for that particular regression.

8 References

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[3] EAL-R2, *Expression of the uncertainty of measurement in calibration,* European cooperation for Accreditation of Laboratories.

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[5] J. Axelsson, P. Andersson, A. Lönnermark, P. Van Hees and I. Wetterlund, *Uncertainties in measuring heat and smoke release rates in the Room/Corner Test and the SBI*, Nordtest Technical Report 477, SP REPORT 2001:04, Borås, 2001.

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Appendix A Parameter study

Results from the parameter study for the sensitivity coefficients

Table A-1 With fitting piece

Parameter	Sensitivity coefficient at 400°C	Sensitivity coefficient at 1000°C	Mean at 400°C	Mean at 1000°C	Average of 400°C and 1000°C
Emissivity walls=1	0.011199	0.011151			
Emissivity walls=0.5	0.022243	0.022156	0.016721	0.016653	0.016687
Aperture diameter = 30.08 mm	1.684269	1.669847			
Aperture diameter = 30.1 mm	1.632178	1.627851	1.658223	1.648849	1.653536
Furnace diameter = 278	0.006488	0.006352			
Furnace diameter = 284	0.004866	0.005044	0.005677	0.005698	0.005688
X1=13.02	0.306345	0.305976			
X1=13.08	0.313878	0.312049	0.310112	0.309013	0.309562
L2=34.58	0	0			
L4+0.007	0.989567	1.002947			
L4-0.007	0.923596	0.926967	0.956581	0.964957	0.960769
Insertion depth – 0.05 mm	0.408258	0.406209			
Insertion depth + 0.05 mm	0.412241	0.410797	0.41025	0.408503	0.409376
T2 f(0.00065)	0	0			
T2 f(0.0007)	0	0	0	0	
T3 f(0.00032)	0.006803	0.012067			
T3 f(0.00024)	0.007298	0.011782	0.007051	0.011924	
Water temperature + 2°	0.139573	0.010717			
Water temperature - 2°	0.136127	0.011114	0.13785	0.010915	
Radius + 0.5 mm	0.00284	0.00284			
Radius – 0.5 mm	0.002355	0.002354	0.002598	0.002597	0.002597
Furnace temperature +3.5°	4.804473	4.579851			
Furnace temperature –3.5°	4.731207	4.54262	4.76784	4.561235	4.664538

Table A-2 Without fitting piece

Parameter	Sensitivity coefficient at 400°C	Sensitivity coefficient at 1000°C	Mean at 400°C	Mean at 1000°C	Average of 400°C and 1000°C
Emissivity walls=1	0.01131	0.011228			
Emissivity walls=0.5	0.022184	0.021587	0.016747	0.016408	0.016577
Aperture diameter = 30.08 mm	0.970428	0.971247			
Aperture diameter = 30.1 mm	1.03585	1.024018	1.003139	0.997632	1.000386
Furnace diameter = 278	0.004923	0.005145			
Furnace diameter = 284	0.006281	0.006006	0.005602	0.005575	0.005589
L2=13.02	0.435205	0.432816			
L2=13.08	0.427321	0.427001	0.431263	0.429909	0.430586
Insertion depth – 0.05 mm	0.573395	0.5706			
Insertion depth + 0.05 mm	0.567142	0.565988	0.570269	0.568294	0.569281
T3=tw+0.000393*sigmaTfour	0.001812	0.005096			
T3=tw+0.000705*sigmaTfour	0.001165	0.00572	0.001489	0.005408	
Water temperature + 2°	0.155005	0.006079			
Water temperature - 2°	0.149054	0.001518	0.152029	0.003798	
Radius + 0.5 mm	0.005307	0.005303			
Radius – 0.5 mm	0.0046	0.004568	0.004953	0.004935	0.004944
Furnace temperature +3.5°	4.808215	4.585592			
Furnace temperature –3.5°	4.73014	4.538505	4.769178	4.562049	4.665613

Appendix B Dimension measurements

Some of the dimensions of the movable cooler and of the fitting piece were measured to confirm calculation of the view factors. A slide calliper with 2 decimal digits and the depth gauge mentioned by Olsson[7] were used. Both instruments were calibrated with an uncertainty of 0,03 mm (k=2). The measured dimensions are given in Figure B-1 and the results of the measurements in Table B-1.

It was found that the dimensions given in the construction drawings for the movable cooler and the fitting piece had a slightly larger error than what was estimated by Olsson.

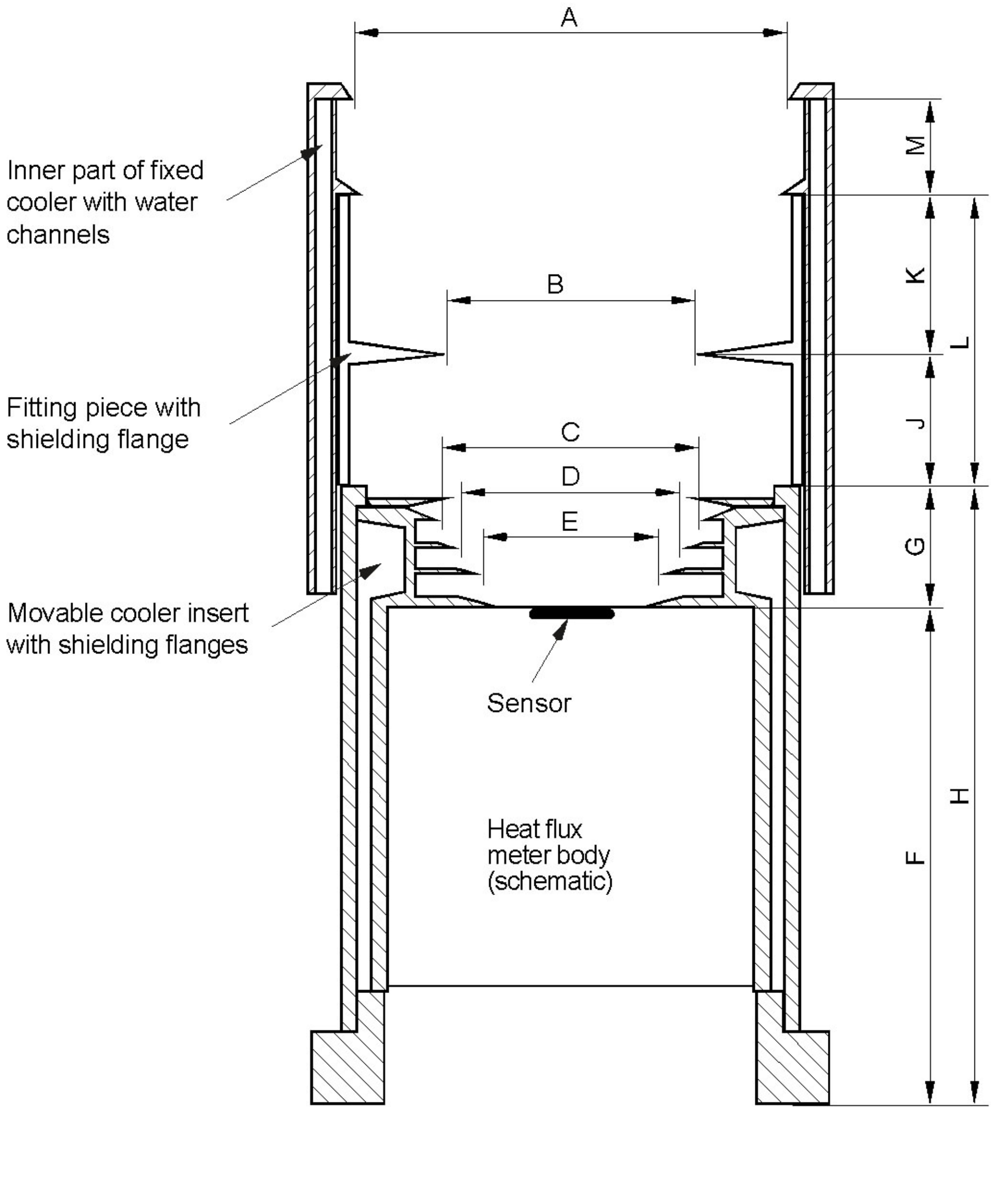

Figure B-8-1 Controlled dimensions of fixed and movable cooler

Table B-1 Results of control of dimensions of fixed and movable cooler

Dimension identification	Dimensions (mm) according to SP Report 1991:58[7]		Measured dimensions (mm)	
	Average	Error	Average	Standard deviation
A	60,18[1)]	±0,01	Not measured	
B	Not given	Not given	35,00	0,064
C	37	Not given	36,96	0,050
D	32	Not given	31,86	0,017
E	27	Not given	26,80	0,030
F	Not given	Not given	64,73	0,031
G	17[2)]	±0,05	17,42[3)]	0,038[3)]
H	82,0	±0,1[4)]	82,15	0,022
J	18,3	[5)]	18,47	0,129
K	21,7	[5)]	21,53	0,097
L	40,0[6)]	±0,02	40,0	0,007
M	13,05[7)]	±0,03	Not measured	

Notes

1) Referred to as d_1 and $2 \cdot r_1$ in SP Report 1991:58.

2) Referred to as x_g in SP Report 1991:58.

3) The dimension G was received by subtracting the dimension F from the dimension H. The standard deviation for G was obtained by summing the standard deviations for F and H quadratic.

4) Tolerances given for the manufacturing.

5) Not given as separate values in SP Report 1991:58.

6) Referred to as x_2 in SP Report 1991:58.

7) Referred to as x_1 in SP Report 1991:58.

The dimensions A, G, J, K and M are used for the calculation of view factors, where A is the diameter of furnace aperture. The other dimensions are used as follows:

$$x_2 = L = J + K \tag{B-1}$$

When calibration is performed with the cooler in its highest position, i.e. without the insert, the following dimensions are used for calculating the view factors:

$$L_2 = M \tag{B-2}$$

$$L_3 = G \tag{B-3}$$

$$L_2 = M + K \tag{B-4}$$

$$L_3 = G + J \tag{B-5}$$

Appendix C Temperature measurements

To facilitate understanding the discussions about estimating the uncertainty of the temperature of the cooler, some of the figures reported in SP Report 1991:58[7] are duplicated here. The figures show the results of the temperature measurements that Olsson performed.

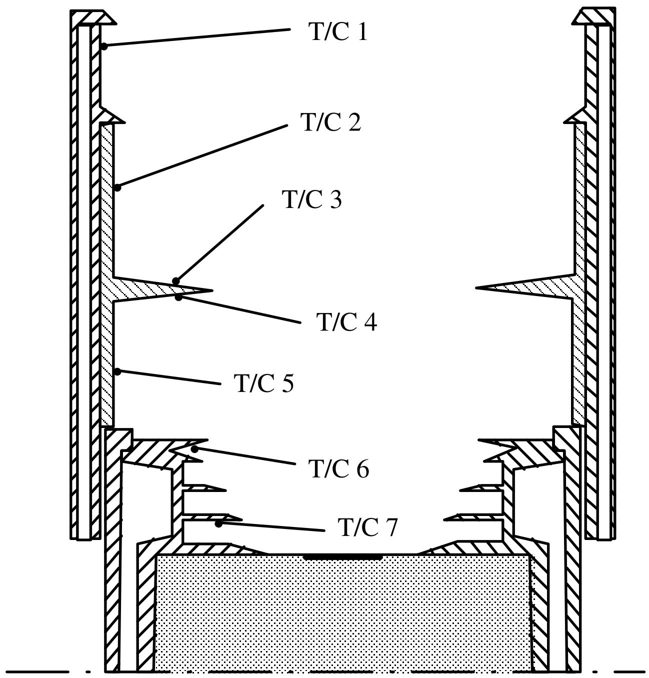

Figure C-1 Cross-section of the cooler, with locations of the thermocouples (T/C 1 to 7) used in the experiments (Figure 12 of SP Report 1991:58).

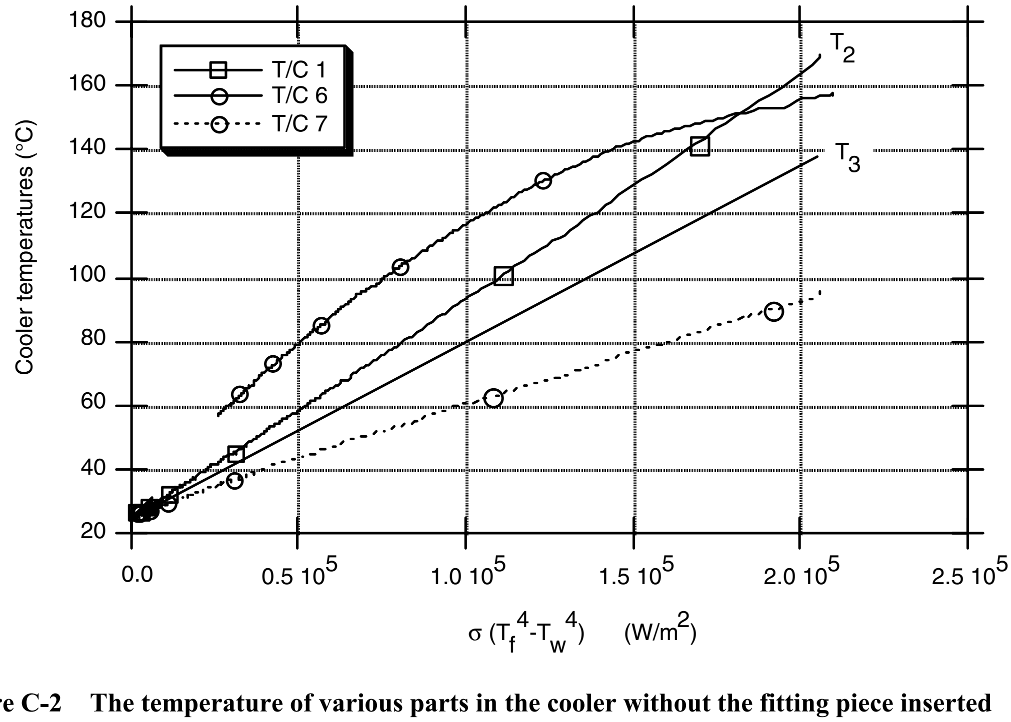

Figure C-2 The temperature of various parts in the cooler without the fitting piece inserted (Figure 13 of SP Report 1991:58).

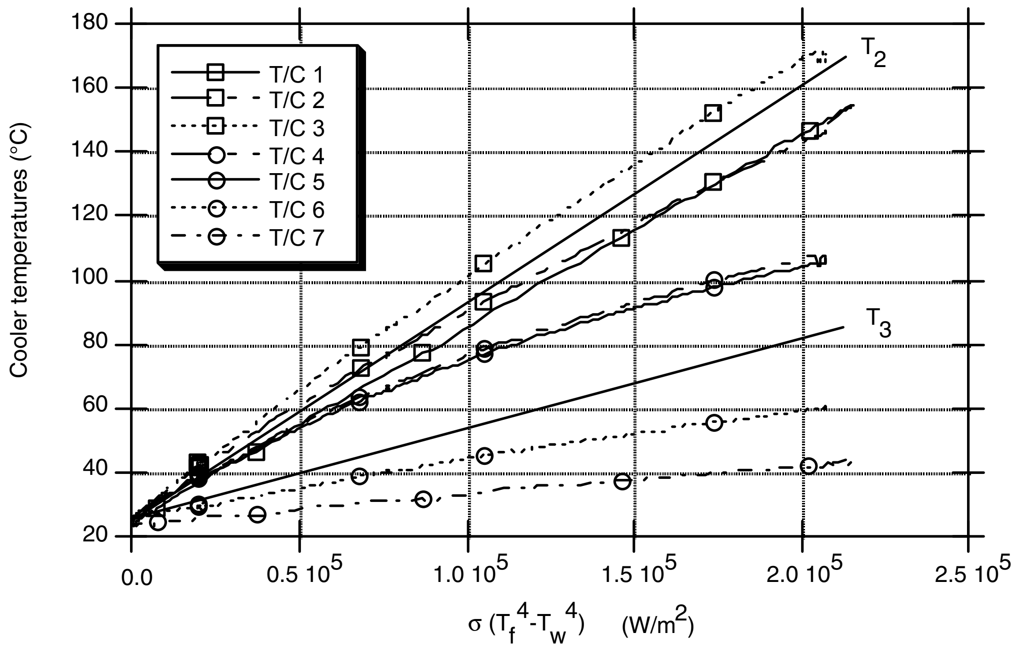

Figure C-3 The temperature of various parts in the cooler with the fitting piece inserted (Figure 14 of SP Report 1991:58).

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