CRITICAL ASPECTS of MEASUREMENT's UNCERTAINTY for the NOMINAL OPERATING CELL TEMPERATURE TEST

M. Pellegrino, G. Flaminio, V. Giglio, A. Matano and G. Nardelli
ENEA Centro Ricerche Portici
Piazzale E. Fermi, 1, Località Granatello. P.O. Box 32, I-80055 Portici (NA), Italy.
tel:+39-81-*7723-267, Fax:+39-81-7723-344*

ABSTRACT: Nominal operating cell temperature is used to estimate the cell temperature of a module in its working environment. NOCT is the cell temperature when irradiance is 800 W/m2, ambient temperature is 20°C and wind speed is 1 m/s at a module tilt-angle 45°. Due to the large and uncontrollable variability of weather conditions outdoor measurements, such as the NOCT, are affected by major sources of different kinds of uncertainties. Calculation of this parameter is largely depending on the environment temperature, the direction and speed of the wind, radiation and back module temperature and the way in which they are measured as long as the way in which the data are stored, filtered and elaborated. The present job aims to identify the various sources of uncertainties that broadly and heavily characterize the measurement of the NOCT, to estimate their contribution to the uncertainty and to calculate the standard and expanded uncertainties as defined by the International vocabulary of basic and general terms in metrology (VIM), in order to better understand and control the error of the measurement. The procedure can be applied for outdoor measurements of innovative PV materials.
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1 INTRODUCTION

PV system designers need an estimation of the temperature at which a system will be operating in the field, in order to evaluate the losses due to thermal effects. To that purpose the IEC Standards for qualification of modules point out at the NOCT, the Nominal Operating Cell Temperature, as an useful parameter [1,2]. The Standards IEC 61215 and IEC 61646 define the NOCT as the equilibrium mean solar cell junction temperature within an open-rack mounted module in the following standard reference environment (SRE):

– tilt angle: at 45° tilt from the horizontal
– total irradiance: 800 W/m2
– ambient temperature: 20 °C
– wind speed: 1 m/s
– electrical load: nil (open circuit)

NOCT measurements require an accurate elaboration of data, since they are to be referred to quasi stationary conditions, and sometimes the correct interpretation of some clauses of the Standards are not so easy. The method defined in the Standards is based on gathering actual measured cell temperature data under an established range of environmental conditions, as irradiance, temperature and wind conditions, and then referring at SRE. Since the data should allow accurate and repeatable interpolation of the NOCT it could be useful to determine the accuracy of the NOCT measurements, according to the various defined operating conditions and the way the statistics used for data elaboration could influence the value.

Due to the large and uncontrollable variability of weather conditions outdoor measurements , such as the NOCT, are affected by major sources of different kinds of uncertainties. The cell temperature of open-rack modules is in fact determined by several external factors such as ambient temperature, irradiance level, wind speed, wind direction, and tilt-angle of the module in the array. Calculation of this parameter is largely depending on the environment temperature, the direction and speed of the wind, radiation and back module temperature and the way in which they are measured as long as the way in which the data are stored, filtered and elaborated. After different experimental tests in different weather conditions, but complying to the standard anyway, we observed that the measurements can possibly be affected by large errors that in the end can make difficult to use the NOCT as module's quality evaluation and for thermal losses estimation. The present job aims to identify the various sources of uncertainties that broadly and heavily characterize the measurement of the NOCT, to estimate their contribution to the uncertainty and to calculate the standard and expanded uncertainties as defined by the International vocabulary of basic and general terms in metrology (VIM), in order to better understand and control the error of the measurement.

The measurement of the NOCT is an outdoor test and the uncertainties are the same as for other outdoor tests that are very important especially for the innovative PV materials that are light sensitive. So the results of this work can be directly extended to those materials.

2 NOCT AND STANDARD

NOCT can be defined by 'the primary method', universally applicable to all PV modules. This method requires the collection of actual measured cell temperature data under a range.

The operating temperature at a time depend on many parameters, such as the supporting rack, the surrounding air temperature, the irradiance, the wind and even the presence of nearby things.

So to foresee the measurement all these factors should be taken into account.

VIM 3.9 defines the uncertainty as a parameter related to the output of a measurement that determines the spreading of the values around the value that could be reasonably assigned to the data under measurement. The paper tries to evaluate all the sources of uncertainties affecting the NOCT. Even the seasonal variation of this parameter will be considered. For the former the major contributions to calculate the standard uncertainty according to the guide ISO "Expression Uncertainty in Measurement, generally known as Guide to the Expression of Uncertainty in Measurement (1993, corrected 1995) have been estimated. GUM is a document issued by Joint Committee for Guides in Metrology, JCGM, establishing the general rules to evaluate and express the uncertainty related to the measurement of the different parameter [3]. For the second a module has been measured at different days of the year.

3 EVALUATION OF THE UNCERTAINTY

The uncertainty of measurement [VIM 3.9] is a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand. The uncertainty generally includes many components which may be evaluated from experimental standard deviations based on repeated observations (Type A evaluation) or by standard deviations evaluated from assumed probability distributions based on experience or other information (Type B evaluation).

Measurement uncertainty comprises, in general, many components. Some of these components may be evaluated by Type A evaluation of measurement uncertainty from the statistical distribution of the quantity values from series of measurements and can be characterized by experimental standard deviations. The other components, which may be evaluated by Type B evaluation of measurement uncertainty, can also be characterized by standard deviations, evaluated from assumed probability distributions based on experience or other information.

Basically according to GUM every component contributing to the uncertainty on the measurement could be presented by its deviation, called (*u*) that is the square root of the variance.

The evaluation of uncertainty of type A relies on the statistics analysis of a repeated set of experimental observations. In this case "u" is an estimation of "s" the standard deviation σ.

$$s(xi) = \sqrt{\frac{1}{n-1}\sum_{1}^{n}(xi - X)^2}$$

$$u = s(xi)/\sqrt{n} = \sqrt{\frac{\sum (xi - xm)2}{(n-1)\,n}}$$

The standard uncertainty comes from that. If the number of observations is very high and eventually infinite then the uncertainty of measurement of the data is exactly its standard deviation.

The uncertainty type B is estimated by methods other than statistics. In this case a numerous number of different observation is not needed and the estimation could be performed on a single measurement.

Generally the uncertainty of the parameter is relate to both the uncertainties.

4 EXPERIMENTAL

4.1 Repeatability

In June two modules of the same type have been characterised. Technical data are shown in table I. Table II shows the NOCT measurements in three days.

Table I: Technical data

Module type	polycrystalline
Dimension	1.97 m^2
Electrical configuration	1 parallel 72 series

Table II: NOCT measurement

	Day1	Day2	Day3		Uncertainty
1st module	46.04	47.42	46.87	46.77	±0.80 (k=2)
2nd module	45.75	46.28	47.85	46.61	±1.26 (k=2)

The measurements on a same type of module are 46.66 and 46.77 showing a good reproducibility.

In June-July four modules of the same type have been characterised. Technical data are shown in table III.

Table III: Technical data

Module type	polycrystalline
Dimension	1.64 m^2
Electrical configuration	1 parallel 60 series

Table IV: NOCT measurement

	Day1	Day2	Day3	Average	Uncertainty
1st module	48.35	47.84	48.32	48.17	±0.33 (k=2)
2nd module	48.49	49.02	47.86	48.45	±0.67 (k=2)
3rd module	46.78	46.30	47.03	46.70	±0.42 (k=2)
4th module	48.75	47.03	47.48	47.75	±1.0 (k=2)

The measurements on a same type of module are 48.17, 48.45, 46.7 and 47.75 over a period of time of two months (June and July almost all the Summer) showing again a good reproducibility.

The average value is 47.8 and the standard deviation is 0.77.

4.2 Reproducibility

One module, kindly provided by the firm Aenergica Srl Via Cicerone 60, 00193 Rome (I), has been measured in different period of time during the year to evaluate the effect of different temperature and different sun spectra. Technical characteristics and data are reported in Tables V and Figure 1 respectively.

Table V: Technical data

Module type	monocrystalline
Dimension	1.70 m^2
Electrical configuration	1parallel 72 series

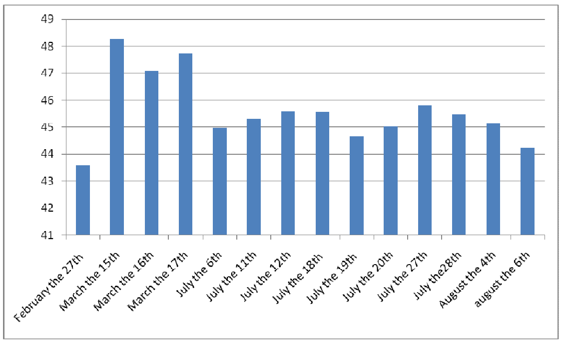


Figure 1: NOCT measurements at different times of the year

The average value is 45.6 and the standard deviation is 1.3.

5 EVALUATION OF THE UNCERTAINTY

5.1 Statistical analysis

To control the uncertainty the standard states to repeat the procedure in three different days and then average the value. If the uncertainty were evaluated by statistics, the number of data set would be very small, only three.

In this case we obtained three values: x1, x2, x3:

The best estimation of NOCT is the average

$$x = \frac{1}{n}\sum xi = \frac{1}{3}(x1 + x2 + x3)$$

While the deviation is the standard deviation:

$$s(xi) = \sqrt{\sum (xi - x\,m)2/(n-1)}$$

From this the deviation of the average is the uncertainty of measurement

$$u = s(xi)/\sqrt{n} = \sqrt{\frac{\sum (xi - xm)2}{(n-1)\,n}}$$

So the measurement could be expressed as:

Noct= X ±ku

with k=1,2,3, etc depending on the level of confidence of the measurement. (for a confidence level of about 95 % the coverage factor is 2.

5.2 Different methodology analysis

Since the samples population is not so numerous a different analysis has to be accomplished and the expanded uncertainty calculated.

We made the assumptions that all the Type B component's density distributions are symmetric and in particular rectangular.

On the following a list of the uncertainty components.

a) Uncertainty related to the measurement of temperature, **uT,** through the detector PT100 (type B)
b) Uncertainty related to the measurement of solar irradiance, **uG,** through the pyranometer (type B)
c) Uncertainty related to the regression analysis , σy, correlating the difference of the cell and air temperatures (Tj-Ta) to the measurement of irradiance G (Type A) :

so :

$$\textbf{uNoct} = \sqrt{\sigma y^2 + uT^2 + uG^2}$$

Uncertainty related to the measurement of temperature T

Uncertainty component are:

- Standard uncertainty related to the accuracy of measurement for the instrument Elog uacc= $\frac{0,15}{\sqrt{3}}$
- Standard uncertainty due to the resolution of the instrument Elog uris= $\frac{0,1}{\sqrt{12}}$
- Standard uncertainty of the calibration certificate for the detector PT100 ucal= $\frac{0,1}{2}$ (Ues=0,1 with k=2)
- Standard uncertainty for the difference of temperature Δ(Tback-Tjunction), uΔt= $\frac{1}{\sqrt{3}}$ from literature [4].

So the overall uncertainty for the temperature measurement is

$$uT = \sqrt{uacc^2 + uris^2 + ucal^2 + u\Delta T^2}$$

$$uT = \sqrt{\frac{0{,}15^2}{3} + \frac{0{,}1^2}{12} + \frac{0{,}1^2}{4} + \frac{1}{3}} = \sqrt{\frac{4{,}13}{12}}$$

=0.586 °C

Uncertainty related to the measurement of solar irradiance G

Uncertainty component are:

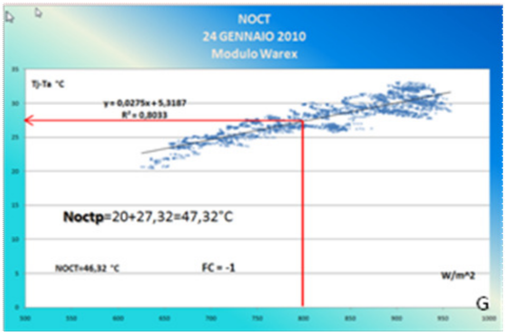
- Standard uncertainty of accuracy for the measurement instrument Elog **uacc=** CL*P/100
- Standard uncertainty due to the resolution of the instrument Elog uris= $\frac{0,1}{\sqrt{12}}$
- Standard uncertainty of the calibration certificate for the pyranometer ucal= $\frac{0,00230}{2}$ (Ues=0,00230 with k=2)

$$uG = \sqrt{uacc^2 + 0{,}1^2/12 + (0{,}00230/2)^2}$$

=0.0115 °C

Uncertainty related to the regression analysis: σy

Considering a data set for one measurement we obtained the following graph.



Let's do the following assumptions:

a) The measurements (xi) of irradiance present an uncertainty negligible.
b) The measurements (yi) of the difference of temperature (**Tj-Ta**) are dispersed according a Gaussian distribution around the true value (Bxi+A) and with width, σy, the same for all the measurements points.

So considering Tj-Ta as dependent variable y and G as independent variable by using the method of the lest squares we get

$$\sigma y = \sqrt{\frac{1}{(n-2)} * \sum_1^n (yi - A - Bxi)^2}$$

=

For this data set we have

n=2525
A=5,3187
B=0,0275

$$\sum_1^n [(\mathrm{Tj} - \mathrm{Ta})i - \boldsymbol{A} - \boldsymbol{B}Gi]^2$$

=3795,33

So

$$\sigma y = \sqrt{\frac{1}{(2525-2)} * 3795{,}33}$$

=1,23 °C

Then adding the squares of all the uncertainties, uT, uG and σy o we get the global uncertainty, given by

uNoct= $\sqrt{\sigma y^2 + uT^2 + uG^2}$

$\sqrt{1{,}23^2 + 0{,}56^2 + 0{,}0115^2}$

=≈1,35 °C

Then a coverage factor of 2 is introduced to give the total expanded uncertainty so the expanded uncertainty is evaluated 2.7 °C.

5.3 Systematic error

One of the major errors is related to the correct sticking of the temperature sensor on the back of modules. The standard says that the cell temperature sensors should be attached by solder or thermally conductive adhesive to the backs of two solar cells near the middle of each test module. On theory this is correct but in practice it has been very difficult to use a thermal conductive paste that could keep strongly adherent to the module and warrantees a correct thermal conductivity. The value of the NOCT could be overestimated of 5 degrees.

6 ACKNOLOWGEMENT

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7 CONCLUSIONS

As a conclusion it can be said that the NOCT measurement is affected by different types of uncertainty. From all the categories the one that contribute more is the from the regression analysis resulted in about 1.23 °C as standard deviation. The other ways in which uncertainty can be transmitted are the sensors, calibration but they are lower as a magnitude. The repeatability is good. The seasonal effect has been measured and it is within the estimatedexpanded uncertainty. NOCT determination can be affected by uncertainties that could propagate by more than 1-2 °C. So the measurement of the NOCT can be given assuming an expanded uncertainty of 2.7 °C. Repeatability and reproducibility are within this range. This general procedure can be applied for outdoor measurements of innovative PV materials.

8 REFERENCES

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