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UNCERTAINTY EVALUATION OF THE NPL STANDARD HUMIDITY GENERATOR

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ABSTRACT
The NPL Standard Humidity Generator is a part of the National Standard for humidity dew point in the UK. It provides traceability for humidity dew point measurement in this country and many others. The SHG has been the subject of extensive evaluations of its performance, the most recent of which is reported here. This work has resulted in the re-determination of the uncertainty of generated dew point. The individual contributions to the uncertainty have been examined and in some cases re-evaluated and have been combined to conform with the recommendations of the "Guide to the expression of uncertainty in measurement" prepared by the International Standards Organisation in 1993.

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1 INTRODUCTION

The National Physical Laboratory (NPL) maintains and disseminates the National Standard for humidity in the United Kingdom on behalf of the UK Government's Department for Trade and Industry. One of the group of instruments which together form the National Standard is the Standard Humidity Generator (SHG), which is used to generate humid gas of well defined dew-point. The SHG underwent an initial evaluation when it was first built in 1985 [1] and a further extensive evaluation in 1992 [2]. On each occasion a comprehensive estimate of uncertainty of the generated dew point was made.

The "Guide to the expression of uncertainty in measurement" ("The Guide") [3] published in 1993 by the International Standards Organisation (ISO) and the later revision of NAMAS Information Sheet NIS 3003 [4] recommend obtaining the "combined standard uncertainty" of a system by taking the positive square root of the sum of the square of the standard uncertainty of each of the contributing factors. These publications also recommend the use of a coverage factor to indicate a suitable level of confidence in the claimed uncertainty. These methods were not previously used in the uncertainty analysis of the SHG so a re-calculation of the overall uncertainty was required and, since the SHG had recently been re-built following a fire in the laboratory, it was decided that a full re-evaluation of certain aspects of its performance was desirable.

This report describes the identification and evaluation of individual contributions to the overall uncertainty of generated dew point throughout the operating temperature range of the SHG, and their combination. The report also describes the calculation of the uncertainty of calibration of a dew-point hygrometer calibrated with reference to the output of the SHG.

The Guide and NIS 3003 also recommend the classification of components of uncertainty by type, those of Type A being obtained by statistical examination of appropriate data and those of Type B being obtained by other means. In the analysis which follows, all contributory components for the SHG are revealed to be of Type B. Although measurements were made to establish limits of uncertainty only a minimum of statistical analysis has been possible.

The standard uncertainty of a contributing component can sometimes be obtained from a documented source such as a calibration certificate. Where a coverage factor is quoted the standard uncertainty is obtained by dividing the quoted uncertainty by the coverage factor. Where a confidence limit is given the approximate coverage factor can be deduced from it. However in many cases documented evidence of the uncertainty contribution is unavailable and it is possible to estimate only an upper and lower bound for the uncertainty. In such a case it is necessary to assume that the uncertainty has a rectangular probability distribution. The standard uncertainty in such a case is obtained by dividing the "semi-range" of (ie half the difference between) the upper and lower bounds by $\sqrt{3}$. Standard uncertainties reported throughout this paper have been rounded to three decimal places (0.001 °C).

2 INDIVIDUAL CONTRIBUTIONS TO THE UNCERTAINTY

2.1 SOURCES OF UNCERTAINTY

The SHG essentially consists of a continuous coil of stainless steel pipe immersed in a bath of fluid whose temperature is carefully controlled. Clean, dry gas (usually either air or nitrogen, but other gases could be used) is introduced into the pipe and is circulated around it using a mechanical impeller. In the very lowest coil of the pipe the circulating gas passes over a surface of de-ionised water or ice. After circulating around the pipe a number of times the gas can be expected to be saturated with water vapour at the temperature of the gas when it comes into contact with the moisture source in the coil. The temperature of the circulating gas is measured as it leaves the area of the pipe containing the water or ice surface, and provision is made to bleed off a proportion of the circulating gas to a dew-point hygrometer, which is calibrated with reference to the dew point temperature of the circulating gas. A full description of the design and construction of the SHG is given by Stevens and Bell [2].

As mentioned above the SHG has recently been substantially re-built following destruction of the original in a laboratory fire. The principle of operation of the re-built instrument is exactly as it was before. Modifications have been made to the temperature baths and to the method of maintaining the temperature of pipe-work which protrudes from the baths. While these modifications affect the method of operation of the apparatus they should have no deleterious effect on the uncertainty of generated dew point, and in some cases have led to a reduced uncertainty.

The parameters which are considered to have an effect on the generated dew point are as follows:

- the platinum resistance thermometers (prts) used for temperature measurement - their calibration, self-heating effect and temporal drift;
- the resistance bridge used to measure the resistance of the prts;
- contamination of the water in the saturator coil;
- the saturator efficiency, ie how near to saturation with water vapour is the gas circulating in the coil;
- the recirculation and draw-off rates;
- temperature conditioning of the circulating gas before it reaches the water or ice surface;
- pressure measurement, and the pressure gradient between the point of saturation and the instrument under test;
- temperature gradients in the main saturator bath;
- desorption of water from the pipework of the generator itself, which could affect the dew point of the recirculating gas;
- leaks.

The effect of each of these parameters and the evaluation of their contribution to the overall uncertainty of measurement is discussed below.

2.2 THE PLATINUM RESISTANCE THERMOMETERS

2.2.1 Calibration

The generated dew-point temperature, at the exit of the saturator coil, and the temperature variations at several points in the system, are measured using prts. These are calibrated annually, usually by NPL Temperature Standards Section, with traceability to the International Temperature Scale recognised at the time of calibration, currently ITS90. The uncertainty of measurement of a particular prt is stated in its calibration certificate, typically with a coverage factor k = 2, or at a confidence level of 95 %. For the reference measurement of the dew point of the gas in the generator a prt is selected whose calibration uncertainty is no greater than ±0.005 °C at the 95% confidence level. The standard uncertainty of the prt calibration is thus 0.003 °C.

2.2.2 Self-heating effect

The self-heating effect of a prt arises from the necessity of having to pass an electric current through the prt in order to measure its resistance. This current causes localised heating of the prt and raises its temperature above the ambient temperature it is sensing. The self-heating effect measured on examples of the prts used with the SHG, using an excitation current of 0.5 mA and with the prt placed in a water triple-point cell, was 0.001 25 °C.

The self-heating effect of a prt is reduced when a measurement is made in a dynamic environment, where the heat generated by the prt is to a large extent absorbed by the fast moving fluid. The prts used with the SHG are calibrated by NPL Temperature Standards Section in a well-stirred fluid bath, using an excitation current of 0.5 mA.

As far as possible the prts experience the same conditions during use in the humidity generator as they did during calibration. A current of 0.5 mA is used by the resistance measuring bridge, and the operation of the humidity generator is such that the prts are located in a fast moving stream of gas, which will dissipate a proportion of the self-heating effect. The self-heating effect of a reference prt was measured in these working conditions to be approximately +0.005 °C with a repeatability of ± 0.002 °C.

A correction to the generated dew point temperature of -0.005 °C is made to account for the self-heating effect of the prt used to make the definitive measurement. The limit of uncertainty associated with this correction is estimated to be ± 0.01 °C, allowing for any significant deviation from the conditions under which the self-heating effect was measured. The standard uncertainty is thus 0.006 °C.

2.2.3 Temporal drift

All prts are known to show a change in behaviour with time which exhibits itself as a shift in the calibration characteristic. The shape of the calibration curve changes only insignificantly but the resistance at any particular temperature drifts with time - usually in one direction only. A simple way to estimate the temporal drift of a prt is to compare the stability of the triple-point of water calibration points from one calibration to another. An even more robust method is to monitor the triple-point of water calibration in-between times using a properly prepared triple-point cell.

A program of water triple-point checks at six-monthly intervals for the most accurate prts has been initiated. This will give a sound insight into the temporal stability of individual prts. However the worst case of change in resistance between successive calibrations at the triple point of water for these prts is less than ±0.002 ohm, corresponding to a drift of 0.005 °C. Assuming this is the limit of variation the standard uncertainty is 0.003 °C.

2.3 THE RESISTANCE BRIDGE

The manufacturer's specification for the uncertainty of measurement of the resistance bridge used in the SHG is the equivalent of ±0.001 °C when using a 1 mA excitation current. Using an excitation current of 0.5 mA effectively reduces the accuracy with which the prt resistance can be measured. To allow for this, a maximum limit for the uncertainty of resistance measurement of ±0.003 °C is assumed, hence the standard uncertainty is 0.002 °C.

The internal resistance standard of the bridge is compared at least once per year with a calibrated standard resistor, and adjusted if necessary. The standard resistor is calibrated to an uncertainty equivalent to ±0.000 03 °C and therefore has no significant effect on the uncertainty of measurement of the bridge. At no time has the required adjustment of the bridge been greater than the equivalent of 0.003 °C.

2.4 CONTAMINATION OF THE WATER IN THE GENERATOR

The SHG is a sealed system which operates with a slight positive internal pressure, so the only possible contaminants are those introduced with the water or with the air or other gas, and those originating from within the material of the saturator coil. It is assumed that any gas-borne contamination will be dissolved into the water, therefore an estimate of the level of contamination may be made by measurement of the conductivity of the water. The water introduced into the lowest part of the coil of the SHG is obtained locally from a de-ionising apparatus. Its conductivity is measured before it is introduced into the generator and is generally found to be less than 1 micro-Siemens per centimetre ($\mu S\ cm^{-1}$).

To measure the level of contamination in the saturator a sample of water that has been in the generator for a calibration run is extracted for measurement of its conductivity. The conductivity is compared to that of the water introduced at the start of the run. The maximum change noted in conductivity of the water from the saturator during these measurements was 6 $\mu S\ cm^{-1}$.

Raoult's law relates the concentration of a salt solution to the reduction of water vapour pressure over the solution. It can be shown that, for a "worst-case" salt (ie one which is very hygroscopic), a solution whose conductivity is 10 $\mu S\ cm^{-1}$ will give a reduction in vapour pressure equivalent to 0.002 °C dew point. Considering the measured 6 $\mu S\ cm^{-1}$ conductivity to arise from the presence of such a salt solution gives an estimated reduction in dew point of 0.001 2 °C. It is therefore considered appropriate to apply a systematic correction to the generated dew point of -0.001 °C, and to assign this correction an uncertainty limit of ± 0.001 °C. The standard uncertainty is thus 0.001°C.

2.5 SATURATOR EFFICIENCY

Recent experimental work has demonstrated that the efficiency of saturation, for a single pass of gas through the saturator coil in normal operating conditions, is 100 % with an uncertainty equal to the resolution of the measuring instrument. That is to say that no difference between the expected and the measured dew point was detected. The limit of the rectangular-distributed uncertainty is therefore considered to be the resolution of the measuring instrument, ±0.01 °C, hence the standard uncertainty is

0.006 °C.

The efficiency of the saturator coil will be affected by, among other things, the dew point of the gas entering the saturator. Gas drawn off from the main saturator to the instruments under test is, except when operating at very low dew points, replaced by gas which has first passed through a pre-saturator coil in a separate temperature controlled bath. Experiments have shown that in normal operating conditions the required temperature for the pre-saturator bath is within ±5 °C of that of the main saturator.

Recent experimental work using a less efficient saturation system has shown that at high dew-points the efficiency of the saturation system can be improved if the replacement gas is first saturated at a higher temperature than the required dew point. The probable reason for this is that the surface area of the inside of the conditioning coil is greater than that of the water surface, offering more opportunity for moisture to condense out of the replacement gas than to be taken up by it.

A similar effect has been noticed at low dew-points. Saturation at a low dew point temperature is more efficiently achieved when the saturator coil has been primed by introducing gas at a higher dew-point. Condensation of moisture from the wet gas will create an ice film on the walls of the saturator coil, thus increasing the surface area available for control of the saturated gas. This system was first used in the NBS (now NIST) Low Frost-point Generator [5]. When operating the SHG at dew points below -50 °C a temperature-controlled pre-saturator is not often used, but the formation of ice on the walls of the saturator is encouraged by passing a sample of moist gas (ie of dew point greater than that which is to be generated) through the system at the commencement of a series of measurements.

2.6 DRAW OFF AND RECIRCULATION RATE

In a fully re-circulating system the gas in the saturator coil would pass across the water surface an infinite number of times and so may be expected to become 100 % saturated at the required temperature. However in the SHG gas is drawn off to the hygrometers under test and is then exhausted to the atmosphere. The gas drawn off must be replaced in the re-circulating system and this is achieved using gas which has been conditioned by being passed through a pre-saturation system. This consists of a coil of pipe identical to that of the main saturator, immersed in a separate temperature controlled bath. The control of the pre-saturator bath temperature is less critical than that of the main saturator but nevertheless, as stated above, it is necessary to achieve a pre-saturation temperature within some 5 °C of the main saturator temperature.

The total draw-off rate for the SHG is always less than 2 litres per minute (typically each hygrometer under test requires a flow-rate of 0.5 litre per minute). The estimated flow-rate in the re-circulation path is of the order of 7 litres per minute so the maximum draw-off is only a fraction of this. As stated above it has been demonstrated that, with the re-circulation path closed off (ie single pass operation) and a draw-off rate of up to 2 litres per minute, 100 % saturation is achieved, so in use the uncertainty due to the draw-off and recirculation rate should be insignificant. The slower through-put rates of up to 2 litres per minute used in these measurements allows the gas to be in contact with the water surface for a longer time, allowing more opportunity for saturation. But at higher through-put rates the gas flow will be more turbulent, which will also encourage saturation. It is therefore assumed that the saturator efficiency is essentially independent of through-put rate in the operating range.

In practice the limit of variation in generated dew-point due to different draw-off rates is taken to be equal to that for saturator efficiency, ±0.01 °C, giving a standard uncertainty of 0.006 °C.

2.7 TEMPERATURE CONDITIONING OF GAS

Gas entering the main saturator coil will be at a temperature different to that of the moisture source in the lowest part of the coil. The gas must be brought to the appropriate temperature before it comes into contact with the moisture source. This "temperature conditioning" of the input gas is achieved during the passage of the gas through the upper part of the saturator coil. Theoretical calculations and measurements made during the 1992 evaluation [6] remain valid following the re-build of the generator since the saturator coil is of the same design as that used previously. The previous work concluded that the length of pipework was sufficient to ensure full equilibration of the temperature of the gas to that of the bath and saturator. Improvements to the temperature distribution in the saturator bath will have further improved the effectiveness of temperature conditioning, so the previous conclusion, that there is no significant uncertainty due to this factor, remains valid. The demonstration of 100 % saturation of gas in single-pass operation also supports this conclusion. Therefore it is assumed that the contribution to the overall uncertainty of the system arising from this parameter is insignificant.

2.8 PRESSURE MEASUREMENT AND PRESSURE GRADIENTS

The pressure in the recirculation system of the SHG is controlled at a level slightly above ambient pressure, principally to minimise the likelihood of ambient air "leaking" into the system. Pressure measurement is made using an instrument with a calibration uncertainty of 10 Pa at k=2. Its history suggests that the temporal drift is within the quoted uncertainty. The uncertainty of 10 Pa is equivalent to a dew point uncertainty of ±0.002 °C. The standard uncertainty due to absolute pressure measurement is thus ±0.001 °C.

Pressure measurement is routinely made at a single point in the recirculation system. However since the dew point of a gas sample is dependent on its pressure any pressure gradient between the point of saturation (at the moisture source) and the hygrometer under test would cause a change in dew point. Measurements of pressure at various points within the system have been taken to assess the pressure gradients. All measurements were within the uncertainty of the instrument, indicating the need for the same allowance for uncertainty due to pressure gradients as is made for absolute pressure measurement, ie 0.001 °C.

2.9 TEMPERATURE GRADIENTS IN THE SATURATOR BATH

The temperature distribution in the bath containing the main saturator coil will influence the temperature of the moisture source and the temperature conditioning of the gas. Addition of an extra stirring mechanism and provision of a close-fitting bath lid has made a considerable improvement in the temperature distribution in the bath. Measurements reveal that the variation in temperature of the bath fluid at a number of points is not greater than 0.012 °C for nominal bath temperatures between -75 °C and +40 °C, rising to 0.020 °C at a nominal bath temperature of +82 °C. These limits give a standard uncertainty of 0.007 °C up to +40 °C, rising to 0.012 °C at +82 °C.

2.10 LEAKS

The SHG operates at a pressure slightly above the ambient level. Because of this, any "leak" in the system, due for example to an improperly tightened connector, will result in a net outflow of gas from inside the system to the outside. This situation is much to be preferred to the risk of a significant leak from the outside to the inside, since this could carry ambient air, of unknown dew point, into the system.

Any residual leakage "into" the system will be small, and its effect would be most readily seen when purging the system with dry gas prior to commencing a measurement sequence (see Section 2.11 below). Thus the contribution to the overall uncertainty arising from the purging process includes the contribution due to inward leaks. Therefore no additional contribution to the uncertainty is included.

2.11 DESORPTION FROM THE GENERATOR PIPEWORK

Any moisture which has been adsorbed by the inner surface of the generator pipework may desorb into the circulating gas and increase its dew point. Similarly any ingress of moist atmospheric air through a leak in the pipework will also increase the dew point of the circulating gas. These effects will be most significant at the lower dew-point temperatures. The effect of desorption from the surface is minimised by drying or "purging" the pipework of the generator before use, with gas whose dew point is below that which is to be generated. Any attempt to measure the de-sorption during the purging process will also measure the effect of a leak in the system. Hence the contribution to the combined uncertainty of measurement which arises from the purging process will cover both the desorption effect and the presence of leaks.

At dew points above ambient levels the contribution to the generated dew point which arises from desorption will be insignificant. The effect of a leak in the system will be to reduce the generated dew point, but the relative magnitude of the effect will be very small, compared with that in the opposite sense at very low dew points. It has already been explained that the SHG operates at a pressure slightly above ambient, which reduces the risk of an "inward" leak to a very low level.

It may be assumed that, provided the pipework of the system is not disturbed, and the ambient humidity remains essentially constant, the effect of a leak would remain constant with time. However the effect of desorption from the surface of the pipework would decrease with time, as there would be less water vapour available in the pipe material. Since the SHG is of necessity operated for several hours at very low dew points (to achieve stability of operation) the following conclusions regarding the uncertainty of generated dew point are probably pessimistic.

The method of purging, using a reversed flow of gas through the system, is as described for the 1992 evaluation of the SHG [2]. The criteria for purging have been modified as described below.

Preparing the SHG for use at very low dew points necessitates using a purge gas whose dew point is below that which can be traceably measured. However an estimate may be made of the uncertainty of measurement for dew points not very much less than the minimum value at which the measuring instrument was calibrated. And if measurements are limited to a small dew point range this estimate can be refined because of the comparative nature of the measurement. The sensitivity of measurement of desorption effects can be further enhanced by making the measurements at a very much reduced flow-rate (typically 0.1 litre per minute is used). The combined standard uncertainty of the measurements made during purging is estimated to be ±0.02 °C.

Measurements at dew points less than -80 °C will have a greater, and essentially incalculable, uncertainty. Hence the dew point of the purging gas is controlled to be not less than -80°C. This is achieved using a diffusion cell in line with the gas supply.

2.11.1 Criteria for purging

The gas used for purging the system must have an initial dew point between -80 °C and -77 °C. The dew point of the purge gas as it leaves the saturator coil is measured and the difference between this measured value and the initial dew point of the purge gas must be less than 1 °C when the initial dew point is -80 °C, and less than 0.5 °C when the initial dew point is -77 °C.

Desorption from the generator pipework will have the most significant effect when operating at the lowest dew point, -75 °C. Provided the above requirements are met, the increase in generated dew point arising from moisture desorption will be between 0.07 °C and 0.1 °C at -75 °C. If the same purging criteria are observed the enhancement would reduce at higher generated dew points, falling to an insignificant level at dew points greater than -60 °C.

As explained above, while the contribution to the correction which arises from leaks into the system will be constant with time, that arising from desorption will decrease with time. Thus the enhancement of generated dew point will decrease with time. For this reason it has been decided to apply a positive correction of one half of the calculated mean value. For example at -75 °C the correction to be applied is +(0.07+0.1)/4 °C = +0.042 °C. The value of the corrections to be applied at other dew points are shown in the fourth column of Table 1.

The limit of uncertainty of the correction is considered to be equal to its magnitude. The standard uncertainty of the correction is combined with that of the measurements during the purging process and an additional element to encompass any errors in the assumptionson which the correction is based. The combined standard uncertainties arising from leaks and desorption are listed in Table 2.

3 CORRECTIONS TO MEASURED DEW POINT TEMPERATURE

The analysis of contributions to the uncertainty of generated dew point for the SHG has identified a small number of systematic errors associated with the measurement of the dew point temperature. A correction to the measured value will be applied to give a better estimate of the generated dew point temperature. The corrections are listed in Table 1, and are added arithmetically to indicate a total correction to be applied at each generated dew point.

4 COMBINATION OF UNCERTAINTY CONTRIBUTIONS

The Guide, and NIS 3003, recommend that the combined standard uncertainty for the system is obtained by taking the positive square root of the sum of the squares of the individual standard uncertainties of contributory factors. This assumes that the standard uncertainties arising from contributory factors are un-correlated. Where contributing factors are thought to be correlated and the extent of correlation can be evaluated this must be reflected in the calculation of the combined uncertainty. When factors are fully correlated with one another, arithmetic addition of the standard uncertainties of the correlated factors is required.

The contributions to uncertainty arising from the various sources within the SHG are assumed to be un-correlated. This assumption is considered valid because each contribution has been separately assessed, independently of the others, and no reductions have been made to allow for similar effects on different contributions.

Table 2 (in two parts) lists the uncertainty contributions arising from the various sources, at temperatures throughout the operating range of the SHG. These are then combined to give the combined standard uncertainty of generated dew point at each of the operating temperatures.

Table 3 lists, for each value of generated dew point at which assessment was made, the combined standard uncertainty, the expanded uncertainty for a coverage factor k=2, and the correction to be applied to the indicated generated dew point. The tabulated uncertainty and correction are to be applied to the tabulated indicated generated dew-points. For intermediate values of indicated generated dew point the *smaller* of the adjacent tabulated corrections must be applied, but the *larger* of the adjacent tabulated values of uncertainty must be quoted

5 EXPANDED UNCERTAINTY OF A CALIBRATION

5.1 PRINCIPLES

The SHG is used primarily as a traceable source of humid gas with which to calibrate transfer standard dew-point hygrometers. The result of such a calibration will usually be a certificate stating a correction to be applied to the reading of the hygrometer at each value of dew point at which it is calibrated, and an uncertainty associated with each correction value. The uncertainty will be a combination of the uncertainty of generated dew point, whose evaluation has been described above, and uncertainties arising from the design of the hygrometer being calibrated and its performance during the calibration.

The uncertainties associated with the instrument under test may arise from:

- the experimental standard deviation of the readings of the instrument during the time of measurement;
- the resolution of the output from the test instrument;
- the temperature of the measurement head during the calibration, and the temperature gradients across it;
- the pressure of measurement and the flow rate of the sampled gas through the measurement head.

The assessment of the value of each of these uncertainties, and their combination, is described below.

5.2 EXPERIMENTAL STANDARD DEVIATION

At each calibration point the reading of the instrument under test will be recorded a number of times over a short interval. Typically ten readings are taken over a period of between ten and twenty minutes. During the period of these readings the performance of the SHG is monitored to ensure that it is generating a sufficiently stable dew point. This period of time has been selected to allow for the proper operation of the SHG and the instrument under test, and to reflect the typical response times of cooled-mirror hygrometers and the cyclic effect known to occur due to the need to maintain a moisture film on the mirror surface.

The mean value of the ten readings is taken to be the indicated reading of the instrument under test. The experimental standard deviation of the ten readings is calculated as a measure of the stability of the instrument under test during the period of measurement. The experimental standard deviation of the mean is calculated by dividing the experimental standard deviation of the readings by the square root of the number of readings, 10 in this case.

5.3 RESOLUTION OF THE INSTRUMENT

An instrument may have a digital display and/or an analogue voltage output. In addition it is sometimes required that the resistance of the prt in the measuring head of the instrument is recorded.

Where the indication of a digital display is monitored, the standard uncertainty of the resolution is taken to be half of the least significant digit of the display. For example in an instrument whose display resolves to 0.01 °C dew point, the standard uncertainty arising from the resolution is 0.005 °C

An analogue voltage output is usually measured using a calibrated digital voltmeter. The indicated voltage is then converted to an equivalent dew point using a simple linear relationship which is stated in the calibration certificate. The standard uncertainty of the resolution is then taken to be not less than half of the least significant digit of the reading. However, depending on the resolution of the digital voltmeter and the stability of the analogue voltage output it may be necessary to assume a greater value for this contribution. It is unlikely that an assumed resolution of significantly better than 0.01 °C can be justified.

Where the resistance of the prt in the measurement head is monitored this will usually be done using the same precision resistance bridge as is used to monitor the condition of the SHG, to a resolution of better than one milliohm. The measured resistance will usually be stated on the calibration certificate, but it may be converted to an equivalent dew point using an appropriate conversion formula. In either case the resolution shall be considered to be equivalent to 0.01 °C, and hence its standard uncertainty will be 0.005 °C.

5.4 TEMPERATURE OF THE MEASUREMENT HEAD

When measuring high dew points it is necessary to maintain the measuring head at a temperature greater than the dew-point temperature to avoid condensation other than on the cooled mirror of a chilled-mirror hygrometer. When measuring low dew points it is sometimes necessary to provide supplementary cooling to assist the instrument's control system in achieving the required temperature of the sensing element. This provision of heating or cooling will generate temperature gradients within the measurement head.

Where a heating or cooling facility is provided with the measuring instrument this will be used, and the certificate will state the settings of appropriate controls used during the calibration. When heating or cooling is provided externally the certificate will state the approximate measurement head or cooling fluid temperatures used. In either case the knowledge of these factors will allow the user to re-establish the calibration conditions during use. Therefore it is assumed that there is no significant contribution to the calibration uncertainty arising from the temperature of the measurement head.

5.5 PRESSURE AND FLOW RATE

The calibration certificate will state the pressure at which the generated dew point was measured, and the flow rate of gas across the measurement head. These factors can then be reproduced during later use of the instrument. It is therefore assumed that there is no significant contribution to the calibration uncertainty arising from the operating pressure and flow rate.

5.6 COMBINATION OF UNCERTAINTIES

The standard uncertainties arising from the stability and the resolution of the instrument under test are combined with the standard uncertainty of the generated dew point by taking the positive square root of the sum of the squares of the contributing components. The result is then multiplied by the appropriate coverage factor to give the expanded uncertainty which will be stated on the calibration certificate. The certificate will also state the coverage factor used, and will indicate that the expanded uncertainty given for the instrument relates to its performance during the calibration only. The user of the instrument must make an appropriate allowance for the temporal drift of the instrument following calibration, and also for any failure to replicate the conditions of the calibration as described in the certificate.

6 CONCLUSION

The standard uncertainty of individual contributions to the uncertainty of generated dew point when using the SHG have been calculated, following re-evaluation of the performance of the SHG where this was necessary. Systematic corrections to the indicated generated dew point have been identified and listed. The standard uncertainties have been combined using the methods recommended by the ISO and UKAS. The results are summarised in Table 3. In addition the method of calculating an expanded uncertainty for a dew-point hygrometer calibrated with reference to the SHG has been described.

The expanded uncertainties listed in Table 3 are significantly lower than the uncertainties of generated dew point quoted for the SHG in the recent past. While recent minor improvements to the SHG (better temperature distribution in the bath, the addition of close-fitting bath lids, etc.) and a better understanding of the saturation process have contributed in part to the improved uncertainty, the major cause of this improvement is a change in the method of calculating the overall uncertainty of the system.

Prior to publication of the Guide there was no commonly accepted method for combining component uncertainties to give an overall value. In the absence of an accepted method the NPL Humidity Standards Section took what it believed to be a cautious approach, combining component uncertainties by simple addition, even when no correlation between the components was suspected, and then rounding the calculated combined uncertainty to a convenient higher figure.

Now that the Guide has been recognised internationally as the authoritative reference for the assessment of measurement uncertainty it is of course sensible and necessary for NPL to adopt the practices it recommends. The re-evaluation of the uncertainty of the SHG according to those practices, as described in this report, fully demonstrates the extent of the cautious approach to these calculations adopted previously. Table 4 compares the expanded uncertainties of generated dew point, at the k=2 level, with the uncertainties evaluated as a result of the 1992 evaluation, which were believed to be "at the 95 % confidence level", and with those quoted for the SHG following its commissioning in 1985.

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TABLES

TABLE 1 Corrections to the generated dew point

GENERATED DEW-POINT °C	CORRECTIONS TO GENERATED DEW POINT			
	Arising from self-heating effect in the prt °C	Arising from contamination of the moisture source °C	Arising from desorption and leaks °C	Total correction to be applied °C
82	-0.005	-0.001	0.0	-0.006
70	-0.005	-0.001	0.0	-0.006
60	-0.005	-0.001	0.0	-0.006
50	-0.005	-0.001	0.0	-0.006
40	-0.005	-0.001	0.0	-0.006
30	-0.005	-0.001	0.0	-0.006
20	-0.005	-0.001	0.0	-0.006
10	-0.005	-0.001	0.0	-0.006
1	-0.005	-0.001	0.0	-0.006
-10	-0.005	-0.001	0.0	-0.006
-20	-0.005	-0.001	0.0	-0.006
-30	-0.005	-0.001	0.0	-0.006
-40	-0.005	-0.001	0.0	-0.006
-50	-0.005	-0.001	0.0	-0.006
-60	-0.005	-0.001	+0.001	-0.005
-70	-0.005	-0.001	+0.018	+0.012
-75	-0.005	-0.001	+0.043	+0.037

TABLE 2 part 1 Contributions to combined standard uncertainty

Generated dew-point	CONTRIBUTIONS TO COMBINED STANDARD UNCERTAINTY						
	Standard uncertainty of component						
	Platinum resistance thermometers			Resistance bridge	Contamin-ation	Saturator efficiency	Draw-off rate
	calibration	self-heating	temporal drift				
°C	°C	°C	°C	°C	°C	°C	°C
82	0.003	0.006	0.003	0.002	0.001	0.006	0.006
70	0.003	0.006	0.003	0.002	0.001	0.006	0.006
60	0.003	0.006	0.003	0.002	0.001	0.006	0.006
50	0.003	0.006	0.003	0.002	0.001	0.006	0.006
40	0.003	0.006	0.003	0.002	0.001	0.006	0.006
30	0.003	0.006	0.003	0.002	0.001	0.006	0.006
20	0.003	0.006	0.003	0.002	0.001	0.006	0.006
10	0.003	0.006	0.003	0.002	0.001	0.006	0.006
1	0.003	0.006	0.003	0.002	0.001	0.006	0.006
-10	0.003	0.006	0.003	0.002	0.001	0.006	0.006
-20	0.003	0.006	0.003	0.002	0.001	0.006	0.006
-30	0.003	0.006	0.003	0.002	0.001	0.006	0.006
-40	0.003	0.006	0.003	0.002	0.001	0.006	0.006
-50	0.003	0.006	0.003	0.002	0.001	0.006	0.006
-60	0.003	0.006	0.003	0.002	0.001	0.006	0.006
-70	0.003	0.006	0.003	0.002	0.001	0.006	0.006
-75	0.003	0.006	0.003	0.002	0.001	0.006	0.006

TABLE 2 part 2 Contributions to combined standard uncertainty

CONTRIBUTIONS TO COMBINED STANDARD UNCERTAINTY						
Standard uncertainty of component					Combined standard uncertainty	Generated Dew-point
Temperature conditioning of gas °C	Pressure measure-ment °C	Pressure gradients °C	Temperature gradients in bath °C	De-sorption & leaks °C	°C	°C
0.000	0.001	0.001	0.012	0.001	0.017	82
0.000	0.001	0.001	0.011	0.001	0.016	70
0.000	0.001	0.001	0.010	0.001	0.015	60
0.000	0.001	0.001	0.009	0.001	0.015	50
0.000	0.001	0.001	0.007	0.001	0.014	40
0.000	0.001	0.001	0.007	0.001	0.014	30
0.000	0.001	0.001	0.007	0.001	0.014	20
0.000	0.001	0.001	0.007	0.001	0.014	10
0.000	0.001	0.001	0.007	0.001	0.014	1
0.000	0.001	0.001	0.007	0.001	0.014	-10
0.000	0.001	0.001	0.007	0.001	0.014	-20
0.000	0.001	0.001	0.007	0.001	0.014	-30
0.000	0.001	0.001	0.007	0.001	0.014	-40
0.000	0.001	0.001	0.007	0.001	0.014	-50
0.000	0.001	0.001	0.007	0.006	0.015	-60
0.000	0.001	0.001	0.007	0.022	0.026	-70
0.000	0.001	0.001	0.007	0.046	0.048	-75

TABLE 3 SHG uncertainty, September 1996

GENERATED DEW-POINT °C	SHG UNCERTAINTY, SEPTEMBER 1996		
	COMBINED STANDARD UNCERTAINTY °C	EXPANDED UNCERTAINTY coverage factor k = 2 °C	CORRECTION to be applied °C
82	0.017	0.04	-0.006
70	0.016	0.04	-0.006
60	0.015	0.03	-0.006
50	0.015	0.03	-0.006
40	0.014	0.03	-0.006
30	0.014	0.03	-0.006
20	0.014	0.03	-0.006
10	0.014	0.03	-0.006
1	0.014	0.03	-0.006
-10	0.014	0.03	-0.006
-20	0.014	0.03	-0.006
-30	0.014	0.03	-0.006
-40	0.014	0.03	-0.006
-50	0.014	0.03	-0.006
-60	0.015	0.03	-0.005
-70	0.026	0.06	+0.012
-75	0.048	0.10	+0.037

TABLE 4 Comparison of present and previous uncertainty values

COMPARISON OF PRESENT AND PREVIOUS UNCERTAINTY VALUES			
GENERATED DEW POINT	1996 EVALUATION	PREVIOUSLY QUOTED UNCERTAINTY	
	REVISED EXPANDED UNCERTAINTY coverage factor k = 2	1992 EVALUATION 95 % confidence level	1985 EVALUATION 95 % confidence level
°C	°C	°C	°C
82	0.04	0.08	0.20
70	0.04	0.06	0.15
60	0.03	0.06	0.15
50	0.03	0.05	0.15
40	0.03	0.05	0.15
30	0.03	0.05	0.15
20	0.03	0.05	0.15
10	0.03	0.05	0.15
1	0.03	0.05	0.15
-10	0.03	0.05	0.15
-20	0.03	0.05	0.15
-30	0.03	0.05	0.15
-40	0.03	0.05	0.15
-50	0.03	0.07	0.15
-60	0.03	0.08	0.20
-70	0.06	0.11	0.25
-75	0.10	0.15	0.25

FIGURES

FIGURE 1 Schematic arrangement of the SHG

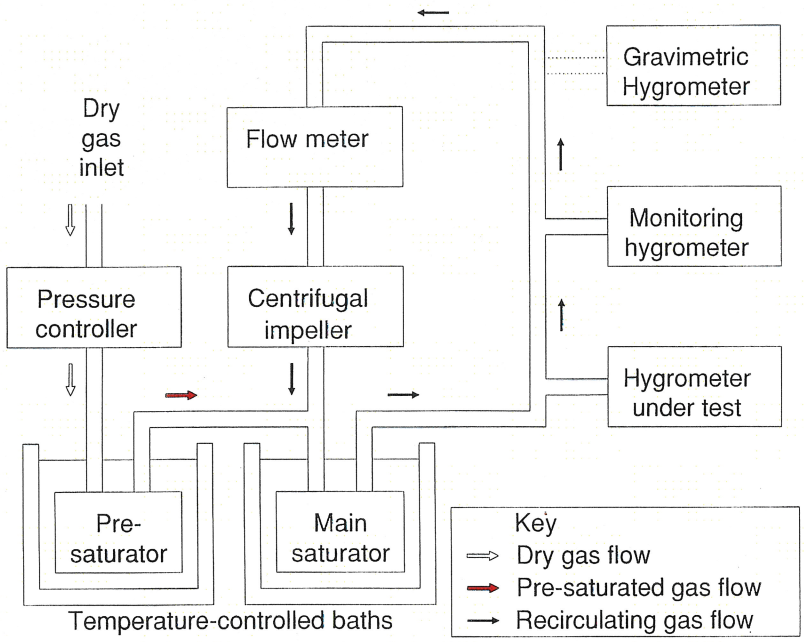

FIGURE 2 The saturator coil