# *The Selection and Use of Instruments for Accurate Conductivity Measurement*

**Authors: John J. Barron & Colin Ashton –** Technical Services Department, Reagecon Diagnostics Ltd, Shannon Free Zone, County Clare, Ireland

## Abstract

*Conductivity instruments should only be used if they can produce measurements of the required quality and format, are suitable for their measuring environment and are user-friendly. This paper describes all of the key characteristics of conductivity instruments, enabling analysts to assess if conductivity instruments meet their requirements. Information is given on how analysts can select these instruments in an efficient and effective manner. Details are also given of the quality measures that are required when commissioning and using conductivity instruments to ensure that analysts can obtain maximum confidence in all of their conductivity measurements.*

**Keywords:** Conductivity Instruments, Instrument Selection, Fit For Purpose, Measurement Accuracy, Calibration, User Requirement Specification

## 1 Introduction

Conductivity measurements are taken on a wide variety of sample types in a diverse range of measurement locations. There is a vast choice of instrumentation available to perform these analyses. Those responsible for carrying out these measurements must ensure that the instrumentation they use is appropriate for their application and that it is used in a way which ensures that they attain conductivity measurements of a suitable quality.

All analytical measurements, including conductivity measurements, are performed for the same reason – so that a decision can be made based upon the analytical measurement. Poor quality measurements will lead to incorrect decisions being made, which in turn may affect product integrity, human health or the environment. Analysts must ensure that their conductivity instruments are capable of producing results that are not only fit for purpose; but also enable analysts to demonstrate that their results are fit for purpose.

This paper gives guidance on the performance criteria that should be considered when selecting which conductivity instrument to use for a measurement application. This applies both to selecting a new instrument for purchase and to determining which, if any, currently owned instrument should be used for a new measurement application. These performance criteria are discussed in detail under four headings:

- Factors affecting measurement accuracy.
- Format and units of reported results.
- Suitability for the measuring environment.
- Features assisting ease of use.

The conductivity cell used in conjunction with the measuring instrument has a significant impact on the operational performance of the instrument. A straightforward explanation is given of how conductivity instruments process conductivity cells' input signals and how this affects their performance.

As well as advising on which performance characteristics should be considered, this paper also gives guidance on how the selection process should be conducted to ensure that all requirements are met in an efficient manner.

It is not sufficient to merely select an instrument that is capable of producing measurements of the required quality. Analysts must also use their instruments correctly so that they can prove that fit for purpose measurements are produced throughout the instruments' entire working life. This paper also details the measures that analysts can take to produce fit for purpose conductivity measurements and improve their confidence in their conductivity measurements.

| | Reagecon R 750 Multi (Accuracy 0.5% of measured value) | | Eutech Cyberscan PCD 6500 (Accuracy 0.5% full scale) | |
|---|---|---|---|---|
| **Measurement taken @ 1µS/cm** | Active Range: | 0 – 2.000 | Active Range: | 0 – 200.0 |
| | Error (µS/cm) | ± 0.005 | Error (µS/cm) | ± 1.0 |
| | Error (% of measured value) | **0.5%** | Error (% of measured value) | **100%** |
| **Measurement taken @ 10µS/cm** | Active Range: | 0 – 20.00 | Active Range: | 0 – 200.0 |
| | Error (µS/cm) | ± 0.05 | Error (µS/cm) | ± 1.0 |
| | Error (% of measured value) | **0.5%** | Error (% of measured value) | **10%** |
| **Measurement taken @ 100µS/cm** | Active Range: | 0 – 200.0 | Active Range: | 0 – 200.0 |
| | Error (µS/cm) | ± 0.5 | Error (µS/cm) | ± 1.0 |
| | Error (% of measured value) | **0.5%** | Error (% of measured value) | **1%** |
| **Measurement taken @ 1,000µS/cm** | Active Range: | 0 – 2,000 | Active Range: | 200.0 – 2,000 |
| | Error (µS/cm) | ± 5 | Error (µS/cm) | ± 10 |
| | Error (% of measured value) | **0.5%** | Error (% of measured value) | **1%** |

**Table 1: Comparison of Conductivity Accuracy of Reagecon R 750 Multi & Eutech Cyberscan PCD 6500 Instruments[2, 3]**

## 2 Factors Affecting Measurement Accuracy

The overall conductivity measurement accuracy is affected by several aspects of the instrument's performance, as described in this section. In addition to instrumental factors, there are several other error sources that will affect the overall measurement accuracy, e.g. the calibration standards' specification and the measurement method. A detailed description of the effect of all of these factors on overall measurement accuracy is given elsewhere in the authors' series of conductivity papers[1].

### 2.1 Conductivity Measurement Accuracy

Most instrument manufacturers specify their equipment's conductivity measurement accuracy by one of two means:

- As a percentage of the actual value being measured.
- As a percentage of the full scale of the measuring range that the instrument is using. (Usually abbreviated to "% f.s.")

Particular care must be taken if the conductivity measurement accuracy is expressed as "% f.s.". Table 1 gives a comparison of the measurement accuracy of two instruments that use the two alternative means of expressing accuracy.

It should also be noted that the analyst's conductivity test measurement accuracy will be significantly greater than the instrument manufacturer's specified conductivity measurement accuracy. The instrument manufacturer can only provide details of how accurately the instrument can process input signals. However, the analyst's conductivity sample measurement accuracy will also depend on exactly how they calibrate their instrument and perform their test measurements.

### 2.2 Temperature Measurement Accuracy

Conductivity is a temperature-dependant parameter, with the conductivity of samples varying from 1.5 to 5.5% per °C[4]. The effect of temperature on conductivity can be taken into account by two methods:

- **Equilibrating samples' temperature**. If all of the samples are equilibrated to the same measurement temperature then this will counteract the effect of temperature on conductivity.
- **Temperature compensation**. Measurements are taken at different temperatures and the instrument employs a temperature-compensation algorithm to account for this.

The measurement temperature must be monitored for both of these methods. Consequently, all conductivity instruments measure both conductivity and temperature. Their temperature measurement accuracy has a significant impact on their conductivity measurements' accuracy. Accurate conductivity measurement is only possible if there is also accurate temperature measurement.

Poor temperature measurement accuracy is a common cause of analysts not producing conductivity measurements of the required quality. For example, measurements are taken on a sample whose conductivity changes by 3% per °C using a meter that has a temperature accuracy of ±0.5°C. The temperature accuracy alone will contribute an error of ±1.5% to the instrument's conductivity measurement (3% per °C x ±0.5°C = ±1.5%). For some instruments, temperature measurement accuracy is a bigger error source than conductivity signal processing.

## 2.3 Temperature Compensation

It is not always practical to equilibrate all conductivity test samples to the same temperature prior to taking measurements – e.g. measurements taken in the field using portable instruments. However, it is still necessary to make meaningful comparisons of the readings taken at a variety of measurement temperatures. This is achieved by using an instrument that is equipped with a temperature compensation function. These instruments make an assumption of the effect of temperature on the samples' conductivity and report the compensated conductivity value at a reference temperature – usually 25°C or 20°C[4].

### 2.3.1 Types of Temperature Compensation

There are 3 main types of temperature compensation:

- **Linear Temperature Compensation** uses a percentage value per °C to multiply the conductivity at the measurement temperature so that a temperature-compensated value is reported at the reference temperature. Basic conductivity instruments may offer the user a single percentage value or a limited choice of different percentage values to employ for linear temperature compensation. More advanced instruments will allow the user to input a temperature compensation factor to 2 or 3 decimal places of percentage per °C.
- **Non-Linear Temperature Compensation** works in a similar way to linear temperature compensation, except that the conductivity instrument uses a programmed table of correction factors that varies non-linearly with temperature. The most commonly used set of non-linear temperature compensation factors are those outlined in ISO 7888[5].
- **User-Definable Temperature Compensation** options are offered on more advanced instruments. These may include allowing the user to measure the sample's conductivity across a range of temperatures and automatically calculating temperature compensation based upon these recorded measurements[2].

### 2.3.2 Factors to Consider When Using Temperature Compensation

Incorrectly applied Temperature Compensation is a common reason for poor quality conductivity measurements. Analysts must ensure that if they use Temperature Compensation, then the most appropriate correction factor is employed and they are aware of the limitation of Temperature Compensation. Analysts should consider the following points when selecting a conductivity meter and its temperature compensation settings for a measurement application:

- Temperature Compensation is an estimate of the conductivity value of the test sample at the Reference Temperature based upon an assumption of how the sample's conductivity varies with temperature. It will not produce a result that is as accurate as equilibrating the sample to the Reference Temperature.
- The measurement temperature and the type of Temperature Compensation employed should be recorded with the reported compensated conductivity value. If this is not done then it will not be possible to conduct a meaningful review of the analysis and repeat the analysis if a questionable result is obtained. The type of Temperature Compensation employed should be detailed in the procedure covering the conductivity analysis.
- To comply with the principles of good laboratory practice (GLP) and to improve confidence in their test measurements, analysts should routinely check that their conductivity equipment and test procedure produce suitable test results on Control Standards. (The Control Standards should be certified, traceable Conductivity Standards of a similar matrix and conductivity value to that of the samples[1].) Analysts should be conscious of the fact that their samples and Control Standards may have significantly different temperature profiles and that using inappropriate temperature compensation for the Control Standards can introduce a significant systematic error.

| Measured Value @ 20°C (µS/cm) | Type of Compensation Used | Temperature Coefficient Used (% per °C) | Reported Compensated value @ 25°C (µS/cm) | Error from Temperature Compensation |
|---|---|---|---|---|
| 904[8] | Linear | 2.123 | 1,000 | 0 |
| 904 | Non-linear to ISO 7888 | 2.32 | 1,009 | +0.9% |
| 904 | Linear | 1.5 | 971.8 | -2.82% |
| 904 | Linear | 2.0 | 994.4 | -0.56% |
| 904 | Linear | 2.5 | 1017 | +1.7% |

**Table 2: Temperature Compensated Readings Taken on 1,000µS/cm Conductivity Standard**

Table 2 shows how different types of temperature compensation will result in different conductivity values being reported at the Reference Temperature. Analysts using the Non-Linear Temperature Compensation specified in ISO 7888[5] should note that ISO 7888 specifies that this compensation should not be used for aqueous potassium chloride Conductivity Standards.

- Some regulations governing conductivity measurements will specify the type of Temperature Compensation that must be employed. The Pharmacopoeias that govern conductivity measurements within the pharmaceutical industry require these measurements to be made with the Temperature Compensation function disabled[6, 7].

## 2.4 Calibration Method

The purpose of calibration is to ensure that the instrument can characterise the conductivity cell's measurement performance. As the cell's measurement performance may change with time, regular calibration must be performed or erroneous sample measurements will occur. The method by which calibration is performed will depend on how the instrument and cell interact and the type of calibration routine programmed into the instrument.

### 2.4.1 How Conductivity Instruments and Cells Interact

There are various types of conductivity cells available to the analyst. However, their basic measurement principal is identical. The conductivity instrument applies an AC electrical signal to the cell and measures the cell's AC response. This response will depend on 3 factors:

- The applied signal
- The conductivity of the solution that the cell is positioned in
- The geometry of the electromagnetic field between the cell's electrodes. This will be dependent on the geometry of the cell and may change during the working life of the cell, due to corrosion or soiling.

The ratio of the AC signal applied to the conductivity cell and the resultant AC response is conductance. Conductivity is determined by multiplying the conductance by the cell's cell constant. The cell constant is determined by monitoring the cell's response when placed in a Calibration Standard of known conductivity value. To ensure that the cell gives a linear response over its entire measuring range, the conductivity instrument adjusts the waveform of the AC signal that it applies to the cell as the measured conductivity value varies. Conductivity instruments vary the applied AC signal by one of two methods:

- **Automatic Signal Adjustment**. The instrument is programmed to apply varying signals across the cell's entire measurement range. This means that only a single-point calibration is required, as the instrument applies a signal of appropriate waveform so that the same cell constant can be used as a multiplier for all measured values.
- **Fixed-Range Signal Adjustment**. The instrument has several overlapping conductivity ranges (typically 5 or 6) and uses a single applied AC waveform per range. Most of these instruments require a separate calibration to be performed for each measuring range. This means that calibration of these instruments is more time-consuming and requires extra calibration standards than instruments with Automatic Signal Adjustment. Although these instruments tend to be cheaper to purchase than instruments with Automatic Signal Adjustment, their running costs are higher. It is also possible to obtain markedly different conductivity readings using the adjacent measurement ranges on the same sample.

Conductivity instrument manufacturers optimise the frequency and waveform of the AC signal that is applied to the conductivity cell to match the characteristics of specific cell models. The instrument and cell should be treated as a matched pair and only cells that are compatible with the conductivity instrument should be used. The instrument's manual should include details of the cells that are compatible with the instrument.

#### 2.4.2 Calibration Routine

Some instruments have a pre-programmed Calibration Routine to assist in assigning the cell constant value. These instruments are programmed with the temperature dependency data of one or more Calibration Standards, allowing calibration to be performed at temperatures other than 25°C. The user simply has to place the conductivity cell in the Calibration Standard and start the automatic calibration routine. The instrument will calculate and report the cell constant based upon the measured value of the Calibration Standard.

Some conductivity instruments may only offer a manual calibration mode or may offer this option in addition to the automated calibration routine. The user has to place the conductivity cell in a Calibration Standard and adjust the cell constant employed by the instrument so that the displayed conductivity value matches the value of the Calibration Standard at the measurement temperature.

Regardless of the calibration method employed, users are recommended to keep a log of the cell constant values assigned over the life of the conductivity sensor. Recording the cell constant values on a Control Chart is the most concise means of doing this. This Control Chart will provide an easy means for assessing the cell's performance over time and will also make it immediately apparent if there is a significant change in the cell constant value between successive calibrations.

Under normal operation, the cell constant should not vary significantly. If there is a large change in the cell constant then this will indicate that either the calibration has not been performed correctly or the cell's performance has changed significantly due to damage or soiling. This will bring into question the validity of all of the test measurements performed between the successive calibrations, but will allow an investigation to be performed.

### 2.5 Linear Response Range

Conductivity instruments' specifications will detail their measurement range. Some will quote a measurement range as wide as 0 – 2,000,000µS/cm (0 – 2,000mS/cm). However, the lower limit at which the instrument can accurately determine the conductivity of a sample will be higher than the quoted 0µS/cm. The resolution of the measured value will obviously be a limiting factor, but the ability of the instrument and cell to accurately measure low conductivities is not as easy for the analyst to ascertain.

Conductivity measurement is commonly used to assess the quality of purified water. For this low conductivity application, it is imperative that the instrument and cell can produce a linear response over the required measurement range. This application requires a specialist cell with a cell constant of $0.1cm^{-1}$ or lower(9). The conductivity instrument must be compatible with this cell and should be designed for the measurement of purified water samples. These cells are not suitable for high conductivity measurements, as the upper limit of their linear response range is typically 200 - 300µS/cm.

### 2.6 Drift Control

Conductivity measurements may be subject to electrical noise, or drift, therefore analysts must decide when the measured value is sufficiently stable to be recorded. Many modern conductivity instruments have an automatic Drift Control function that assesses the stability of the measured value and only reports measurements that meet fixed stability criteria. These measurements will be more repeatable than an analyst's subjective judgement of whether a measurement is sufficiently stable to be reported. The instrument will require several seconds' measurement data to establish the level of drift and may be slower in reporting a result than an analyst's judgement of measurement stability. The slight increase in time per measurement is worthwhile due to the increased confidence in the conductivity measurement achieved by consistently obtaining accurate measurements.

Most instruments equipped with Drift Control will automatically use this function in their calibration routines. This reduces the risk of an incorrect cell constant being assigned during calibration. An incorrectly assigned cell constant will result in all of the subsequent sample measurements being erroneous.

# 3 Format and Units of Reported Results

It is imperative that conductivity instruments can produce measurements that are of a suitable quality so that valid decisions can be made based upon these measurements. It is also important that these measurements are produced in a format that is easy to use and that any additional information required is also readily available, e.g. time and date of measurement. Some applications require test measurements to be stored in the instrument's memory so that they can be accessed at a later stage. The memory storage and recall options available will be a key determining factor in the choice of instrument for these applications.

The measured value also needs to be expressed in units that are appropriate for the intended use of the result. Many conductivity instruments can be used to automatically calculate and report results in related parameters, e.g. salinity and TDS.

## 3.1 Types of Formats Available

### 3.1.1 On-screen Display

Measurements that are displayed on the instrument's screen should be of a suitable size and lighting so as to be easily read by the user. As it is good practice to record the measurement temperature along with the conductivity value, the display should show both of these parameters simultaneously. Portable conductivity instruments should have a "Hold" button so that the measured value can be frozen on the display, thus allowing the measured value to be read comfortably after taking measurements in awkward locations.

### 3.1.2 Output of Results to PCs and Printers

For convenience of storage and retrieval or to provide a permanent record of results, many analysts require their conductivity instruments to output results to PCs or printers. As well as outputting the measured value, the instrument should also allow the user to input a label so that each measurement is uniquely identifiable. In some instances, it is not convenient to permanently connect the conductivity instrument to a PC or printer. If this is the case, the instrument needs to be equipped with memory for storage and subsequent transmission of the measurement data.

If a conductivity instrument is required to transmit data to a PC then the instrument supplier should provide data importing software and full details of the minimum computer system requirements for operation of the instrument in conjunction with a PC. The data importing software should readily enable the user to convert the data into desirable formats, e.g. as an ".xls" file for subsequent manipulation using Excel.

### 3.1.3 Analogue Output of Results to Recorders & PLC systems

If an instrument is used in conjunction with an analogue recording device then a permanent record of the real-time variation of conductivity readings can be obtained. Virtually all online conductivity instruments have a 4 - 20mA analogue output as a standard feature, to allow them to communicate with PLC systems, paperless chart recorders and other control systems. Some online conductivity instruments are also compatible with other communications protocols, allowing them to be used with fieldbus systems.

One of the main reasons for using an online system to measure conductivity is that this permits real-time reaction to the measured conductivity value. Some online conductivity instruments are available with inbuilt control functions, enabling them to automatically activate dosing pumps and other process equipment.

Many modern portable conductivity instruments have a 4 – 20mA output mode. This gives the portable instrument the continuous measurement capability previously only associated with more expensive, online instruments. Portable instruments can be used for continuous monitoring projects that do not warrant a permanently-sited online instrument or where it is not feasible to provide the mains power supply required to operate online instruments. Instruments with this capability are particularly suited to short-term continuous monitoring projects, e.g. environmental case studies. The limiting factor on the suitability of an instrument for these applications does not tend to be its data handling capabilities; but is usually the operational life of the instrument's set of batteries. Recent developments have seen portable instruments with extended battery-life and 3,000 continuous hours use per set of batteries is not uncommon[10].

## 3.2 Memory and GLP Options

In many instances it is not sufficient for the conductivity instrument to recall from memory just the measurement values. Additional information is required to identify each measurement and to enable analysts to comply with quality assurance and good laboratory practice (GLP) requirements. When selecting a conductivity instrument, analysts should consider if they will require any of the following functions:

- **Real-Time Clock**. If the time and date of each measurement need to be reported by the instrument then it must be equipped with a clock that operates independently from the instrument's mains power supply.
- **User-Definable Memory Labels.** Most conductivity instruments have numbered memory positions; but the user will only be in a position to uniquely identify the data in a memory location if they have the opportunity to assign their own identification to the data.
- **Recall of Calibration Data**. In some instances, analysts need to be able to report their test measurements along with the most recent calibration data for the conductivity cell and instrument. This is only possible if the conductivity instrument has a function that stores the calibration data and permits its retrieval at a later stage.
- **Operator Identification.** For conductivity instruments that are used by several analysts, it may be a requirement that the identity of the operator who performed a measurement or calibration is recorded by the instrument. Instruments that have a user-name and password control system will satisfy this requirement. These instruments can also be programmed to restrict the functions that are available to certain users, e.g. some users may only perform test measurements; while other users may also perform calibrations. Instruments that are equipped with this type of security can be used to ensure that only personnel who are authorized and trained to conduct certain activities have the access required to do so.

## 3.3 Parameters and Units of Results

Conductivity measurements are frequently taken to assess the concentration of the test samples. Consequently, instrument manufacturers have developed conductivity instruments that automatically convert conductivity measurements into a variety of units of concentration. These options are detailed below, along with information on the different units used for expressing conductivity.

### 3.3.1 Units of Conductivity

Although conductivity measurements are based upon the SI units of Siemens (S) and metres (m), conductivity measurements are rarely expressed as S/m. The most commonly used units of conductivity are µS/cm, but alternatives are used, as shown in Table 3. Some conductivity instruments will give the user an option on which units can be used.

### 3.3.2 Resistivity

Resistivity is the inverse of conductivity and is most frequently used to describe the quality of purified water. For purified water the target is high resistivity – i.e. low conductivity and low impurities. Resistivity is almost exclusively quoted in MΩ.cm (megaOhm-centrimetres). Conversion from conductivity values in µS/cm to resistivity values in MΩ.cm is straightforward – they are the inverse of each other. For example, the theoretical limit forthe resistivity of purified water is approximately 18.2MΩ.cm, which is equivalent to conductivity of 0.055µS/cm. The option to report measurements as resistivity is most readily available for online instruments; though some portable and laboratory instruments also provide resistivity as a measurement parameter.

| Unit Name | Symbol | Conversion TO µS/cm | Conversion FROM µS/cm |
|---|---|---|---|
| milliSiemens per centrimetre | mS/cm | Multiply by 1,000 | Divide by 1,000 |
| Siemens per centrimetre | S/cm | Multiply by 1,000,000 | Divide by 1,000,000 |
| Siemens per metre | S/m | Multiply by 10,000 | Divide by 10,000 |
| micromho per centimetre[11] | µmho/cm | None (identical in both units) | None (identical in both units) |
| megaOhm-centrimetres (units of resistivity) | MΩ.cm | Divide 1 by MΩ.cm value | Divide 1 by µS/cm value |

**Table 3: Commonly Used Units of Conductivity**

#### 3.3.3 Total Dissolved Solids (TDS)

Conductivity measurement is frequently used to estimate the TDS content of samples(12), with many instruments automatically converting between the two parameters. Instruments will report results in mg/l or ppm (parts per million). mg/l and ppm are interchangeable – the TDS value is identical in both units.

Strictly speaking, conductivity meters cannot measure TDS; this can only be done by weighing the residue of a filtered sample after evaporating at an elevated temperature. Instead, conductivity instruments use a correlation to convert from conductivity to TDS. The most commonly used correlations are:

- To Sodium Chloride concentration for marine applications.
- To "442 concentration" (40% sodium sulphate, 40% sodium bicarbonate & 20% sodium chloride) for non-marine applications, including boiler and cooling tower measurements.

These references have been chosen as they give a reasonable approximation of the TDS to conductivity relationship for these sample-types.

Some instruments are pre-programmed with correlation data from conductivity to TDS; whereas others allow the user to enter a multiplication factor to convert from conductivity to TDS. Although the relationship between conductivity and TDS is not strictly linear, using factors of 0.49 for sodium chloride concentration and 0.68 for "442 concentration" gives a very good approximation. Regardless of how the conversion is made, it is imperative that the correlation is applied consistently. Analysts frequently encounter problems comparing TDS measurements made with different instruments that use different correlation methods.

#### 3.3.4 Salinity

Salinity is an important parameter for monitoring the ionic concentration of seawaters and estuarine waters. The most commonly used units for salinity are based upon the International Association of the Physical Sciences of the Oceans' (IAPSO) Practical Salinity Scale, which is defined as:

"A seawater of Practical Salinity 35 has a conductivity ratio of unity at 15 degrees Centigrade (and 1 atmosphere pressure) with a potassium chloride (KCl) solution containing a mass of 32.4356 grams of KCl per kilogram of solution."(13)

As the definition of salinity is a ratio, its units are dimensionless. The measuring conditions specified in this definition include pressure and so salinity measurements made at significant depths will require pressure to be measured. In situ salinity measurements of seawater are usually taken using specially designed sensors and salinometers that automatically compensate for temperature and pressure to report readings according to the Practical Salinity Scale. Conductivity instruments and sensors are not equipped to measure sample pressure. However, they can be used to measure the salinity of surface samples and grab samples, as these samples will be at atmospheric pressure. Some portable and laboratory conductivity instruments will provide the option of automatically converting the conductivity measurement into a salinity value.

#### 3.3.5 Concentration

Conductivity is dependent on the nature and concentration of all of the dissolved ions present in a sample and the temperature of the sample. For simple solutions containing a single solute, conductivity can be directly correlated to the concentration of that solute.

Some online conductivity instruments are programmed with concentration-dependency and temperature-dependency data for common solutes, e.g. sodium hydroxide or hydrofluoric acid. This enables the instrument to automatically convert its conductivity measurement into concentration of the solute of interest. These instruments can be used in conjunction with sensors made from materials that are chemically resistant to the solute of interest. The availability of a durable sensor makes conductivity the preferred means of monitoring concentration for a wide range of aggressive chemicals.

## 4 Suitability for the Measuring Environment

As well as meeting the functional requirements to perform the intended measurements, conductivity instruments must also be compatible with their measuring environment. They must be designed so that they can withstand their expected operating conditions and also not have an adverse effect on the

| 1st Number | Definition (Protection Against Solids) | 2nd Number | Definition (Protection Against Water) |
|---|---|---|---|
| 0 | No protection | 0 | No protection |
| 1 | Protected against solid objects over 50mm | 1 | Protected against vertically falling drops of water |
| 2 | Protected against solid objects over 12mm | 2 | Protected against direct sprays up to 15° from vertical |
| 3 | Protected against solid objects over 2.5mm | 3 | Protected against direct sprays up to 60° from vertical |
| 4 | Protected against solid objects over 1mm | 4 | Protected against sprays from all directions – limited ingress protection |
| 5 | Protected against dust – limited ingress | 5 | Protected against low pressure jets from all directions – limited ingress protection |
| 6 | Totally protected against dust | 6 | Protected against strong lets of water – limited ingress protection |
| | | 7 | Protected against temporary immersion between 15cm and 1m. (Test duration 30 minutes) |
| | | 8 | Protected against long periods of immersion under pressure. (Period and depth of test specified by user) |

**Table 4: Summary of IP Rating Numbers' Definitions**

environment in which they will be located. The following factors are of particular relevance to portable and online instruments, but must also be considered when selecting laboratory instruments.

### 4.1 Ingress Protection (IP) Rating

Conductivity instruments will be used for the measurement of aqueous samples and so all conductivity instruments require some degree of protection against contact with samples. Indeed, some portable instruments are designed to withstand complete submersion in samples. Analysts can assess the suitability of conductivity instruments for their measurement applications by reference to the instruments' IP rating.

The IP rating system described in EN 60529[14] defines tests that are performed to quantify how effective an instrument's casing is at preventing ingress by solid objects and by water. IP ratings are expressed in the format "IPxy", where x indicates the level of protection against solid objects and dust and y indicates the level of protection against water. Details of the different IP levels are shown in Table 4.

IP ratings are of particular relevance in selecting portable conductivity instruments. Due to the potential for accidental splashing, the authors recommend a minimum rating of IP65 and preferably a rating of IP66 for portable conductivity instruments. It should be noted that the battery compartment and the input socket for the conductivity cell may be particularly susceptible to water ingress. Some instrument designs lessen this problem with the use of o-ring seals.

Laboratory and online instruments should have a suitable IP rating to demonstrate that they can withstand accidental spillages. In addition to improving their ability to withstand splashes, features such as membrane keypads will also make the instrument easier to clean and maintain.

### 4.2 Electrical Safety

Users must ensure that they select conductivity instruments that comply with legislation and regulations related to electrical safety. They must ensure that these instruments conform to the legislation and standards governing electromagnetic compatibility[15-19] and that the instruments are certified to comply with relevant safety legislation, including "CE marking"[20].

Conductivity measurements are frequently taken within chemical industries in environments where flammable materials are used. Safety requirements will be the overriding selection criteria for portable and online conductivity instruments used in these environments. These instruments must be designed to have intrinsic electrical safety – this can be verified by checking if the equipment carries suitable "Ex rating" certification in accordance with 94/9/EC[21].

### 4.3 Additional Considerations for Portable Instruments

A conductivity instrument can only be considered to be truly portable if it can be easily transported along with its conductivity cell and any other ancillary equipment so that calibrations and measurements can readily be made in field locations. Although users may take all reasonable steps to handle their instruments correctly, many portable instruments have their operational life shortened due to poor protection from impacts and wear and tear. Ideally, portable conductivity instruments should be supplied in carry-cases that meet all of the following requirements:

- Impact resistance that is capable of withstanding blows, such as those that may occur during transportation in vehicles.
- Moulded compartments for locking the instrument and sensor into place. As the cell will become wet during use, the use of foam inlays should be avoided as foam will quickly perish when wet. The compartment for housing the sensor should permit its cable to be neatly stowed, thus preventing damage to the cable.
- Compartments for storage of instruction manuals and Calibration Standards. The ideal carry-case will enable all the materials required for calibrations and measurements to be readily transported. If this is the case, the full benefit of using portable conductivity instruments will be realised.

For some applications for portable instruments, particularly data logging over a number of days, the instrument's power consumption will also be an important selection criteria. For these applications, instruments that have power-saving features leading to a battery-life of several thousand hours may be required. It should be noted that some portable conductivity instruments have a battery-life of as short as 50 hours.

## 5 Features Assisting Ease of Use

Conductivity instruments must not only be capable of producing measurements of the required quality, but should also ensure that users can meet this requirement as easily as possible. There are four main areas that affect the ease of use of a conductivity instrument.

### 5.1 Ergonomics

The instrument's displayed characters should be of sufficient size and clarity to be easily read by the operator. Portable and online instruments may be used in locations that have poor lighting. If this is the case then an instrument with a back-lit display screen should be specified.

The instrument's keys should be large enough to allow ease of use, even when operators may be wearing gloves. The keys should be tactile and responsive, so that the user can feel that they have made a key-press without having to wait for an on-screen response from the instrument. Portable instruments should be lightweight and have a symmetrical design to enable them to be used with comfort by both left-handed and right-handed users.

### 5.2 User Interface

All of the instrument's main functions should be easily accessed by a minimum number of key presses. Instruments with advanced functions, such as memory of measurements and real-time clocks should have an intuitive menu driven operation – this may include the use of drop down menus on the instrument's display. The instrument should be programmed to prevent the user from inadvertently altering key settings that will affect the measurement quality, e.g. the cell constant or the date on instruments with a real-time clock. The instrument should be designed so that the user must confirm that they wish to make changes to critical parameters.

### 5.3 Calibration Routine

As an incorrectly assigned cell constant will lead to errors in all of the subsequent sample measurements, it is imperative that the instrument's calibration routines make it as easy as possible for the user to achieve an accurate calibration. In addition to offering suitable calibration accuracy, as described in Section 2.4, the instrument should be programmed so that calibration is not an onerous task for the user. As well as it being possible to achieve accurate calibration, it is also important that this can easily be achieved.

Ideally, the calibration routine should give suitable prompts to guide the user through the calibration process. The authors recommend selection of instruments with automated calibration procedures, including pre-programming of the temperature dependency data of their Calibration Standards, as this significantly improves the ease of performing calibrations.

The conductivity instrument should be programmed to reduce the risk of erroneous calibration data being used to calculate test measurement values. It should allow the user to exit from the calibration routine at any point and revert to using the cell constant assigned at the previous, completed calibration. The instrument should also only complete its calibration procedure and update its stored cell constant value after prompting the user to overwrite the previous cell constant value.

### 5.4 Drift Control

The benefits of Drift Control with respect to the quality of test measurements are described in Section 2.6. In addition to improving the repeatability of measurements, Drift Control can also save users' time. Instruments equipped with a Drift Control function will automatically assess measurement stability and will freeze the displayed reading when a stable measurement is achieved. This means that the user can perform other activities, instead of having to monitor the displayed value and record the result when they have assessed that it is stable.

## 6 How to Select Conductivity Instruments that Meet Your Requirements

The preceding sections of this paper give a detailed description of the features that may need to be considered when determining a conductivity instrument's suitability for a measurement application. However, the process by which a user selects a conductivity instrument for their application also has a critical impact on how effective and efficiently instrument selection is performed.

The process of selecting an instrument is most effective if it is done as part of a formal process, known as Equipment Qualification[22]. Equipment Qualification covers all of the steps required to ensure that analysts can prove that analytical instruments meet their needs throughout their entire operational lifespan. The selection of an instrument is covered by the first stage of Equipment Qualification, which is known as Design Qualification (DQ). This consists of drawing up a User Requirement Specification (URS) and then selecting an instrument that meets the requirements detailed in the URS. This process is summarised in Figure 1.

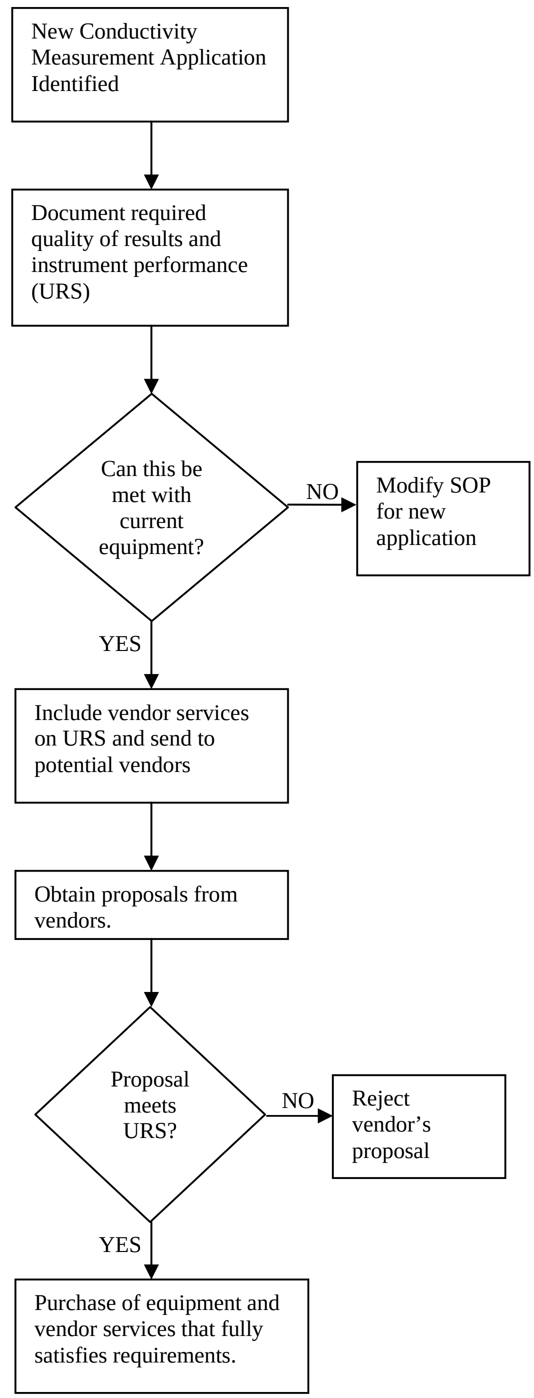


**Figure 1: Process of Selecting Instruments that are fit for purpose**

TSP-04 Issue 1

## 6.1 Compiling a URS

When encountered with a new conductivity measurement application, analysts should compile a detailed checklist, or URS, of all of the essential and desirable characteristics of the instrument. Analysts will only be in a position to accurately assess if currently-owned conductivity instruments or proposed instruments for purchase meet their requirements if they have already fully defined their needs. This assessment can only be made if there is a URS in place. Analysts should not be put off compiling a URS due to the time required to do so. This task is straightforward and will significantly reduce the possibility of using an instrument that is not capable of producing results of the necessary quality, leading to costly, incorrect decisions being taken based on poor quality conductivity measurements.

All conductivity measurements are made so that a decision can be taken based upon the measurement result. The nature of this decision should be the sole factor that determines the measurement accuracy that will be required of the instrument used to perform the measurements. In some instances, the analyst responsible for performing the measurements may need to assist the Decision Maker in specifying the required degree of accuracy. This first step defines what constitutes a Fit For Purpose test result.

Only when the required measurement accuracy has been defined, can the analyst determine if any currently-owned conductivity instruments are capable of producing measurements of the required accuracy. Analysts should not take an approach that involves the question, "What accuracy can we achieve?". The pertinent question to be answered is, "What accuracy do we need?".

If the analyst does not have a conductivity instrument that can meet this fundamental requirement then an investment in a new instrument is required and a URS should be compiled. The required quality of results will form the first and most important section of the URS.

The subsequent sections of the URS should provide details of the required format of results; memory and GLP-supporting functions; features providing compatibility with the testing environment and features supporting ease of use. The URS should define whether each feature of the instrument is mandatory or is desirable. If the URS is compiled to cover new equipment then it should also include any foreseeable future requirements, e.g. compatibility with computer systems.

The analyst's fundamental goal is not purely to obtain a suitable conductivity instrument; but is to obtain conductivity measurements that can be proved to be fit for purpose throughout the instrument's entire working life. For new instruments, this may require additional services from the instrument vendor. The URS should also list all of the ancillary services that the vendor must provide to meet this goal. This may include the following areas:

- Evidence that the manufacturer has a suitable quality system in place, thus ensuring that the conductivity instrument will have been designed and manufactured to meet the user's requirements.
- Providing an installation or commissioning service for the instrumentation. This should fully satisfy any requirements that the user may have to conduct Equipment Qualification and Method Validation[23] on the instrument.
- Providing training to users on the correct use of the instrument.
- Offering an annual re-qualification or calibration service for the instrument.
- Offering a preventative maintenance or repair service.

## 6.2 Assessing Instruments Against The URS

With a detailed URS in place, the analyst will be in a position to determine which instruments are suitable for their requirements. For new instruments, the ideal scenario would be to provide potential vendors with a copy of the URS. This will ensure that potential vendors will have an unambiguous description of the analyst's requirements and will not only be able to propose a suitable measuring system, but will also be able to provide documentary evidence that their proposed equipment meets the analyst's requirements. The vendor's evidence will form an important part of the second component of Design Qualification – i.e. demonstrating that the equipment selected for the measurement application meets the requirements detailed in the URS.

The cost of any potential equipment should only become a selection criterion if the analyst has a number of alternative instruments or vendors that can fully satisfy the URS.

## 7 Generating Results of the Required Quality

Selecting a suitable conductivity instrument is the first step to ensure that measurements of the required quality are consistently obtained. Analysts should address the following areas to ensure that their instruments provide measurements that meet their requirements throughout their instruments' entire operational life.

### 7.1 Prior to Putting the Instrument into Service

Prior to putting a new instrument into service, it should be installed in accordance with the manufacturer's instructions and its key performance characteristics should be verified against the manufacturer's specifications and the URS. As the user will be unfamiliar with the new instrument, the vendor is best placed to perform these tasks. When done on a formal, documented basis, these activities will cover the Installation Qualification (IQ) and Operational Qualification (OQ) phases of Equipment Qualification[22].

Standard Operating Procedures (SOPs) should be written covering the test procedures that the instrument will be used for. In addition to developing test methods, analysts should validate these methods to ensure that they will deliver results of the required quality, including when likely variations in operating conditions occur[23]. In particular, analysts should ensure that they address the effect of temperature changes on conductivity measurements and the SOP should detail any necessary temperature-control requirements.

A training program should be put in place to ensure that personnel do not use the new equipment without having first received adequate training. The training program may require input from the instrument vendor. This requirement should have been highlighted on the URS and the vendor's ability to provide suitable training should have been verified prior to purchasing the instrumentation.

### 7.2 Routine Quality Measures During Service

The most effective means of increasing confidence in the quality of the instrument's conductivity measurements is the regular use of Control Standards[1]. Control Standards should have the same matrix as the test samples (this is almost always aqueous) and have a similar conductivity value to the samples. If a suitable result is obtained for the Control Standard then the user can have increased confidence in the validity of their test measurements.

Although calibration with a high quality standard is essential to generate accurate conductivity measurements, this alone does not give any guarantee over the validity of the test measurements. As well as verifying that calibrations have been performed correctly and the instrumentation is performing correctly, a suitable result for a Control Standard will also demonstrate that the test method is valid and has been performed correctly. This gives the analyst maximum confidence in his test measurements.

Control Standards should be tested with every batch of samples analyzed using laboratory conductivity instruments. For portable and online instruments it may not be practical to test Control Standards this frequently. However, measurements of Control Standards should be performed after every calibration to verify the validity of the calibration process and should be taken as frequently as possible for critical applications.

Cleaning and preventative maintenance will also have to be conducted on a regular basis – this should be detailed in the SOP governing the instrument's use. One of the reasons for the prevalence of conductivity as an analytical technique is that conductivity instruments and sensors are comparatively robust and have lengthy operational lives. In most instances, cleaning and daily visual inspections are the only maintenance measures required.

### 7.3 Periodic Quality Measures During Service

The use of Control Standards provides an holistic check of the complete measuring system on a frequent basis. For complete confidence in the measuring system, each component's performance should be periodically checked in isolation. The instrument's ability to correctly process input signals should be verified by replacing the conductivity cell with certified, traceable resistors and using a certified simulator to provide temperature input signals. Calibration of the conductivity instrument should be performed at least annually and more frequently if the instrument is used for critical measurement applications.

Most users of conductivity instruments will not have the necessary expertise to conduct instrument calibrations. Therefore they should get an external calibration service provider to perform this activity. Unless the user has several conductivity instruments, an external calibration service will also be cheaper than purchasing the necessary standards and simulators and maintaining their calibration status.

Periodic reviews of the instrument's performance should be carried out. This can be readily achieved if the results of the instrument's calibrations and measurements of Control Standards are collated as this information is generated. Plotting these readings on Control Charts provides one of the most convenient mechanisms for highlighting any performance trends that may require further investigation.

## 8 Conclusion

Like all analytical measurements, conductivity measurements are taken so that a decision can be taken based upon the result. When selecting a conductivity instrument, the overriding criteria should be its ability to produce results of an accuracy that will lead to the dependant decisions being correct. As well as assessing instruments' accuracy for conductivity, analysts should be aware of the significant impact that temperature has on conductivity and ensure that potential instruments have suitable temperature measurement accuracy and temperature-compensation functions.

Conductivity instruments should also be selected so that they report results in the desired units. This may include the need to automatically calculate and report results in the related parameters of resistivity, TDS or salinity. If required for the analyst's application, suitable measurement memory and GLP-supporting functions may also be required. The instrument's compatibility with the measuring environment should also be assessed – this is particularly relevant for portable and online conductivity instruments.

The most effective way for analysts to ensure that their conductivity instruments are fit for their measurement purposes is to fully define and document their requirements in a User Requirement Specification (URS). This is not an onerous task and avoids unsuitable instruments being purchased and measurements being made that do not meet the analyst's needs.

Obtaining an instrument that is capable of producing fit for purpose measurements is the first step to consistently attaining measurements of the required quality. However, this does not guarantee that suitable quality measurements will be made. To reach this target, analysts should ensure that their conductivity instruments are commissioned correctly, preferably by performing Installation Qualification (IQ) and Operational Qualification (OQ); they should routinely use Control Standards; and they should periodically calibrate their instruments using certified resistors.

If analysts specify the characteristics of conductivity instruments outlined in this paper using the formal, documented approach described then they will ensure that they will only select instruments that are capable of producing results that are fit for their intended purpose. If they employ the quality measures described in this paper then they will have confidence that all of their conductivity measurements are fit for their intended purpose.

## References


1. J.J. Barron & C. Ashton, "The Application of Good Laboratory Practice in the Selection and Use of Accurate, Traceable Conductivity Standards" *
2. Reagecon Diagnostics Ltd, "Instruction Manual for R 750 Multi instrument"
3. Eutech Instruments Pte Ltd., "Instruction Manual – Cyberscan 6000 Series Meters"
4. J.J. Barron & C. Ashton, "The Effect of Temperature on Conductivity Measurement" *
5. ISO 7888:1985, "Water Quality – Determination of Electrical Conductivity"
6. United States Pharmacopoeia, 29th Edition, Physical Test Method {645} - "Water Conductivity"
7. European Pharmacopoeia, Ed. 5.4, Section 2.2.38: "Conductivity", Monograph 1927: "Water, Highly Purified" and Monograph 0169: "Water For Injections"

8. Reagecon Product Label – “1,000µS/cm Conductivity Standard”, Product Code CSKC1000
9. J.J. Barron & C. Ashton, “The Selection, Use, Care and Maintenance of Sensors for Accurate Conductivity Measurement” *
10. Reagecon Diagnostics Ltd, “Instruction Manual for R 340 Cond portable conductivity instrument”
11. Conductivity units based upon the “Mho” are rarely used by modern instruments. The “Mho” is identical in definition to the Siemen and derives its name from spelling Ohm backwards. Older literature, particularly from North America, may make reference to these units.
12. J.J. Barron & C. Ashton, “Obtaining Accurate Readings With TDS Meters” *
13. Unesco Tech. Papers in Marine Science, No. 36 , “UNESCO, 1980: Tenth report of the Joint Panel on Oceanographic Tables and Standards”
14. EN 60529: “Specification for the Degrees of Protection Provided by Enclosures (IP code)”
15. EN 61010:2001, “Safety requirements for electrical equipment for measurement, control and laboratory use”
16. EN 61000, “Electromagnetic Compatibility (EMC)”
17. EN 61326, “Electrical Equipment for Measurement, Control and Laboratory use - EMC Requirements”
18. USA Code of Federal Regulations, 47CFR15 (Federal Communications Commission Rules, Part 15)
19. EU Council Directive 89/336/EC, “Electromagnetic Compatibility”
20. EU Council Directives 93/68/EC & 73/23/EC, “CE Marking”
21. EU Council Directive 94/9/EC, “Equipment intended for use in Potentially Explosive Atmospheres (ATEX)”
22. J.J. Barron & C. Ashton, “Equipment Qualification of Conductivity Measuring Systems” *
23. J.J. Barron & C. Ashton, “Method Validation for Conductivity Measurements” *

* These papers form part of a comprehensive series of papers that the authors have written covering all of the practical requirements for accurate conductivity measurement. These papers and the authors’ book, “A Practical Guide to Accurate Conductivity Measurement” are available via Reagecon’s website - www.reagecon.com.

## Biographical Notes:

John J Barron is Managing and Technical Director of Reagecon Diagnostics Limited. The company, which was founded in 1986, is the world’s largest producer of Conductivity Standards and is also a major producer of other chemical standards. Mr. Barron is an expert in many areas of analytical chemistry, including electrochemical analysis, good laboratory practice (GLP) and chemical metrology. He has written and lectured extensively and is credited with several scientific discoveries including stable low level conductivity standards.

Colin Ashton has worked in the Reagecon group since 1994 and is currently Head of the Chemical Metrology Department. A graduate of the University of Southampton, he has developed particular expertise in the development, stabilisation, manufacture and validation of electrochemical standards. He played a central role in developing Reagecon’s range of electrochemistry instruments. He has particular scientific interest in all aspects of electrochemistry and has lectured and published on several areas of this field.

## Acknowledgements

The authors wish to extend their gratitude to Ms V. Byrne for her assistance in compiling this paper and Mr L. Geary and Ms R. Cooney for proofing this paper. The authors wish to thank all of their colleagues who have provided technical assistance in compiling Reagecon’s series of conductivity measurement papers.