

Advances in Resistivity Instrumentation for UPW Systems of the Future

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Abstract

For decades, resistivity instrumentation has been (and remains) the first choice to detect catastrophic events in de-ionized (DI) water purification systems *immediately*, though reliance upon TOC analyzers is growing. But with the quality and reliability of water purification systems always improving, resistivity instrumentation is sometimes taken for granted. Furthermore, the costs of water production are continually decreasing, and this has led to a more careful analysis of the selection criteria for on-line instrumentation. New technologies and customer demands for instrumentation require lower costs, 100% reliability, ease-of-use/calibration, smaller packages, and increased versatility – not just improved accuracy.

For the last few years, we have been working on new resistivity measurement technologies to meet the needs of today's UPW systems and those of the next century. We will demonstrate measurement instrumentation with 1) a dynamic range to measure high resistivity fluids such as pure water and organic cleansing reagents, all the way up to high conductivity fluids such as acids/base concentrations, 2) an improved temperature measurement by >10-fold, 3) an improved resistivity measurement to achieve reliable sub-ppb LODs, 4) a versatility to measure flow, pH, pressure, tank level, % rejection, % recovery, DI-Cap® (de-ionization capacity), and TOC reduction, and 5) a cost per measurement that is >50% lower than 10 years ago.

Introduction

There are numerous critical reasons for the need for calibration of instrumentation. The most common reason is to know that the displayed value is the actual value (to within some specified tolerance). But in the numerous industries where high purity water is utilized, there are other varied reasons. For example, in power generation facilities, the water chemistry is tightly controlled by knowledge of the resistivity/conductivity and pH. In this case, small excursions from established operating parameters cause significant increases in downtime, maintenance, and cost. In pharmaceutical industries, there are strict regulatory requirements that are prescribed by

the U.S. Pharmacopeia and enforced by the Food and Drug Administration for the manufacture and use of Purified Water and Water for Injection. Resistivity instruments are required to meet very specific calibration requirements for use in these water systems so as to maintain a minimum level of control over these water systems. In microelectronics industries, the need for calibration is self-imposed in order to produce higher quality water for the manufacture of faster and denser devices. However, because of the unique relationship between ions and resistivity, accurate and precise knowledge of the resistivity is a key to the limit of detection (LOD) for ionic impurities.

Regardless of the different motives for the use of resistivity in ultrapure water systems, calibration is needed. In all cases, there has been one issue that has consistently presented a significant conundrum for the user – the lack of a calibration standard in the resistivity range of interest, namely any resistivity above 0.1 M Ω -cm (below 10 μ S/cm). *Therefore, the focus of this paper is 1) the description of the problems associated with standards at this purity level and 2) the declaration of a new fundamental standard for use in pure waters - and that standard solution is ultrapure water.*

Need for Calibration

Resistivity is the single most common measurement in every on-line high purity water system. Advances in measurement capability and the inherent sensitivity of resistivity to ionic contamination in ultrapure water (UPW) has forged resistivity instrumentation into the front-line indicator of ionic contamination by reliable and cost-effective means. While the various forms of ion chromatography and mass spectrometry offer the most sensitive means of detection and speciation, these methods remain somewhat prohibitive insofar as immediate response, sample preparation time, sample handling, and capital costs are concerned. Meanwhile, there is no dispute to the fact that the most common metals (Na⁺, Ca²⁺, Mg²⁺, etc...) and other electroanalytically detectable species (H⁺, OH⁻, NH₄⁺, Cl⁻, SO₄²⁻, HCO₃⁻, NO₃⁻, NO₂⁻, etc...) are found in water systems at trace levels. Further, they are most rapidly and inexpensively detected by resistivity, though not at the detection limits of research-grade IC and MS instrumentation. These species are found in the best semiconductor grade water systems at concentrations below 100 ppt (1 ppt = 1 ng/L).

Resistivity Limit of Detection

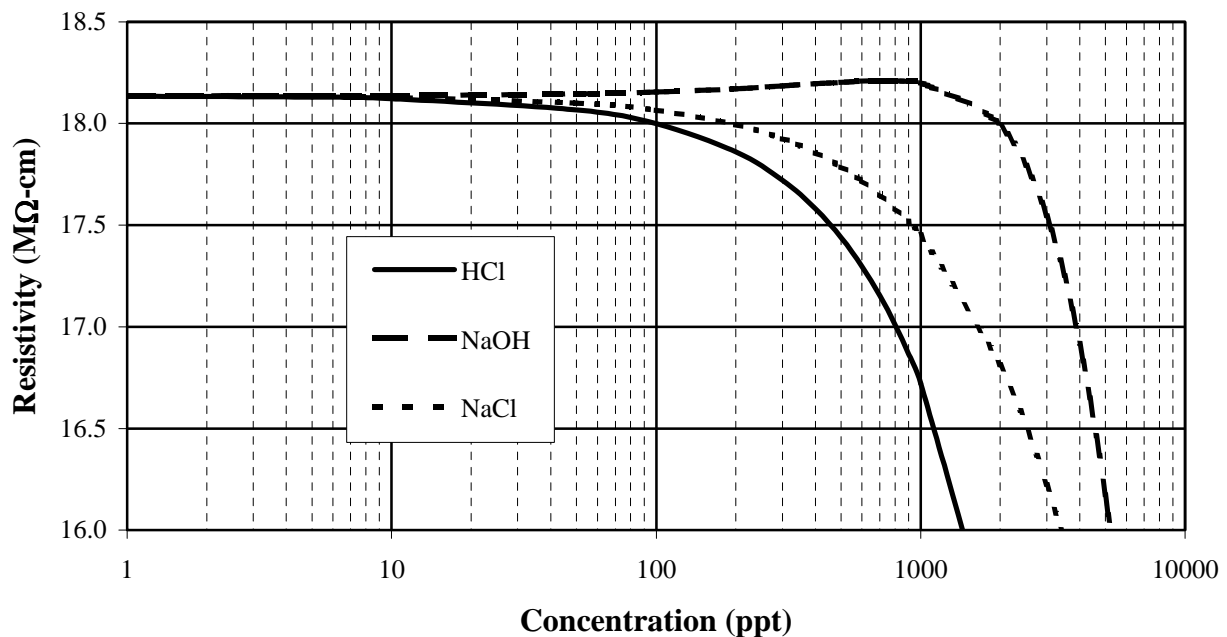
The inability of resistivity to speciate turns out to be a benefit since the sum of all ionically-active species become detectable. This is the basis for using resistivity as the primary means of ion impurity detection. For further validation of the sensitivity and simplicity of

resistivity, one needs to look no further than on-line TOC instrumentation. Although the oxidation technologies differ, resistivity is the exclusive and most sensitive means of sub-ppb TOC detection¹.

To illustrate the variety of detectable species, the resistivity of three different common chemicals - an acid, base, and salt - at very low concentrations at 25°C are shown in Figure 1. At very low contaminant concentrations, 1-10 ppt, the resistivity is virtually unchanged. It is only at concentrations exceeding 100 ppt that acid and salt species lower the resistivity so that it is discernable from a 1-10 ppt contaminant. And if the contaminant is slightly basic (NaOH impurity), then there is a slight increase in the resistivity until ~1000 ppt (1 ppb)!

Figure 2 shows the sensitivity that is required to detect different concentrations of chemical species at 25°C. Under the best conditions, resistivity systems are capable of measuring to ~1% reliably in *real water systems*, thus making detection of ~250 ppt (as NaCl or 120 ppt in the acid form) very possible and practical. At higher temperatures, these concentrations become more difficult to detect. This is discussed later.

Figure 1. Resistivity at Trace Concentrations of Three Common Impurities at 25°C



The ability to detect the lowest concentrations of ionic species is controlled by three factors:

¹ The most common methods of TOC measurement are not based on the direct measurement of carbon, but they are based on its conversion to its highest, stable oxidative state, carbon dioxide (CO₂). CO₂ is detected by FTIR down to ~25 ppm while CO₂ is detected by resistivity (in the form of the dissociative products of H₂CO₃) as low as 50 ppt.

- the specific conductance of the ions
- the sensitivity of the instrumentation
- the absolute calibration of the resistivity system

The conductance of each ion species is a physical-chemical property of the ion (which cannot be altered), although its temperature-dependence can be exploited. In some cases, some chemical species, notably the transition and heavy metals, are not detectable because of their insufficient ionic character. But these are not the prevalent ionic impurities as listed above. The sensitivity of modern resistivity instrumentation is on the order of 0.1% of value and can approach 0.01%, so it is not this factor that impacts the LOD for resistivity. If this were the limiting factor, then LODs near 1-10 ppt could be achievable by resistivity.

The primary factor that keeps the resistivity LOD above 100 ppt is the limited ability for absolute calibration of the system (meter, sensor, and cable). Without calibration, the relationship between the resistivity and the purity of water is unknown. Similarly, without calibration, the relationship between the resistivity and temperature for ultrapure water is unknown.

“Quality” Requirements for Calibration

In the microelectronics industry, there are no governmental regulatory requirements for the production of water to rinse and clean wafers. Pure water requirements are driven by technological advancements and market needs, i.e., cleaner water provides faster and more closely spaced devices. In cases such as these, control of the water system is required to maintain the quality of water system, and the control of the water system rests, in part, on the calibration of the resistivity system.

A resistivity system that requires frequent calibration means additional laborious steps by the water system operator to maintain accurate knowledge of the water system. If the resistivity system is constantly out of calibration, then the water system may also be out of control. At the very least, there is uncertainty.

Calibration

Detailed issues pertaining to calibration have been described at this conference previously[1]. Briefly, in any resistivity system, there are three components to calibrate:

- Meter and cable
- Temperature sensor
- Conductivity sensor

The meter and cable are readily calibrated by replacing the sensor with a series of calibrated, NIST-traceable resistors² (or decade box) and insuring that the instrument measures AC resistances accurately. By placing the decade box at the end of the cable, as long as 500 feet, any additional impedance in the cable is accounted for in the calibration. Modern resistivity instrumentation will have menu-driven instructions to allow the user 1) to verify and 2) to automatically rectify any differences.

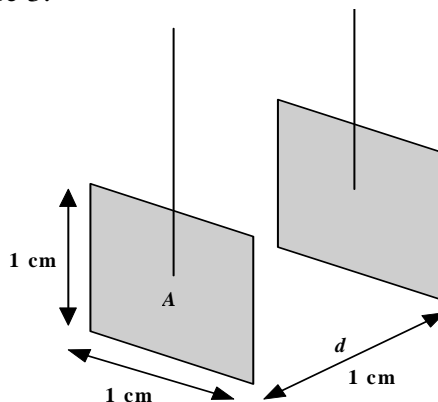
Likewise, the temperature device is calibrated by placing the sensor in the same fluid as a precise temperature standard. The required accuracy of the temperature standard depends on the desired accuracy of the compensated resistivity measurement[2,3]. If a calibrated temperature standard is not available, an ice-water mixture is an ideal standard. Use clean ($<10\mu\text{S}/\text{cm}$) water to prepare the ice-water mixture in a container. Place this container in a salt-water-ice mixture to insure that the inner ice-water mixture is at 0°C . As above, modern resistivity instrumentation will have the full capability to verify and rectify any differences.

The final component to calibrate is the resistivity sensor. This represents the most problematic portion of the calibration and the crux of this paper. *Calibration of the sensor is also known as determination of the cell constant.*

Cell Constant

The accurate determination of the resistivity cell constant can be quite difficult in actual practice. Conceptually, the cell constant is sometimes idealized as two 1 cm^2 plates (area, A) that are separated by 1 cm (distance, d) as shown in Figure 3.

Figure 3. Conceptual Drawing of Cell Constant



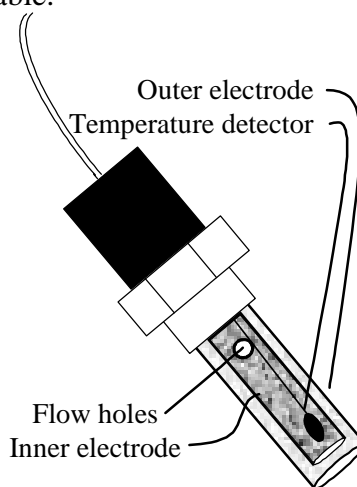
² Most on-line process control resistivity instruments have 2 or more measurement circuits in order to provide a wide dynamic measurement range. To insure accurate measurement across calibration of the entire measurement circuitry, all measurement ranges should be calibrated. This usually requires as many calibrated resistors as measurement circuits.

The resistance of the water between the electrodes is the value measured by the meter. Since the resistance will increase with d and decrease with A , the resistance is normalized for these geometrical factors in order to measure the ionic quality, or resistivity, of the water. These geometrical or normalization factors are combined into one term called the cell constant, ϕ . For the general case, ϕ is defined in eq (1).

$$\phi = l/A \text{ with the units of cm/cm}^2 \text{ or cm}^{-1} \quad (1)$$

For the configuration in Figure 3, ϕ is 1 cm^{-1} . While an accurate measurement of the cell dimensions could yield the cell constant, there are some factors that make this approach impractical[4]. First, this square plate model does not have the mechanical stability for in-line process applications. Sensors with concentric electrodes (Figure 4) have become the most common design for in-line pure water applications. However, this design, and the associated flow holes, do not lend themselves to dimensional analysis because of the fringe effects from the electrical measurement field at the flow holes and the end of the concentric electrodes. This makes accurate definition of the effective area improbable.

Figure 4. Modern Concentric Cell Design



Variations in manufacturing tolerances may approach 1 to 2% for the highest quality sensors, but 5-10% is not uncommon among some manufacturers. Further, the metal/liquid interface impedance is affected by variations in surface finish of the electrodes, which are also subject to manufacturing processes. ***Where high accuracy is required, a post-manufacturing calibration procedure to determine the cell constant is mandatory.***

Limitations of Existing Standard Solutions

The only practical method available to accurately determine the cell constant to 1% accuracy or better is by measuring the resistance of a standard reference solution³. The resistivity of the

³ Actually, another practical calibration method is to place it in the same solution as another standard sensor. Of course, the original standard sensor must be calibrated in a standard solution.

reference solution must be known with high certainty at the measurement temperature and the uncompensated resistivity and temperature of the fluid must be precisely measured. The cell constant is then determined by⁴ :

$$\phi = \frac{\text{Measured Resistance } (\Omega)}{\text{Reference Solution Resistivity } (\Omega \cdot \text{cm})} = \text{cell constant } (\text{cm}^{-1}) \quad (2)$$

The basic reference standards for resistivity have been the KCl solutions originally devised by Kohlrausch in the 1890s, refined by Bradshaw and Jones[5], and adopted by ASTM in Test Method D1125[6]. These solutions are prepared with excellent accuracy and high reliability by a qualified chemist. Solutions C and D, as described in ASTM D1125, are included in Table 1. Also included in Table 1 are six Standard Reference Materials (SRMs) offered by the National Institute of Standards and Technology (NIST) with conductivities of 1,000 $\mu\text{S}/\text{cm}$ or less. These are provided as ready-to-use solutions in sealed 500 mL containers, but at considerable expense, currently \$319 US.

The uncertainties of the low conductivity ($<100 \mu\text{S}/\text{cm}$) NIST SRMs are greater than uncertainty of ASTM Solution D, and often beyond the accuracy tolerances required for ultrapure water applications. Further, the use or re-use of these low conductivity standards that have been subjected to airborne and atmospheric contaminants, notably CO_2 , may render the previously opened SRM unreliable and introduce further uncertainty[7].

The ASTM solutions offer acceptable accuracy and are much less susceptible to contamination, but they are outside the range of the user's operation. Normally, this raises a concern to the user or the QA Manager, regardless of the range of the instrument. Later in this paper, we will demonstrate the ability to use ASTM solutions as viable reference solutions, even for UPW application. Despite this evidence, most users still prefer a "standard reference solution" in the range of normal process operation.

In summary, resistivity sensor manufacturers, metrology laboratories, and others that have a critical need to very accurately determine and calibrate resistivity cell constants for sensors designed to measure pure and ultrapure water have been faced with a dilemma. To date, the alternatives have been to use either :

⁴ This calculation is transparent to the user in most modern process resistivity instrumentation. While meters measure resistance, they only display resistivity after adjustment for the cell constant. The resistivity system measures the resistance. The user enters the reference solution resistivity or conductivity. The instrument then calculates the cell constant.

- reference solutions approaching the pure water range, but lack the precision desired or
- highly accurate standards that are outside the measurement range of interest

Clearly, another approach has been needed.

Ultrapure Water as a Fundamental Standard

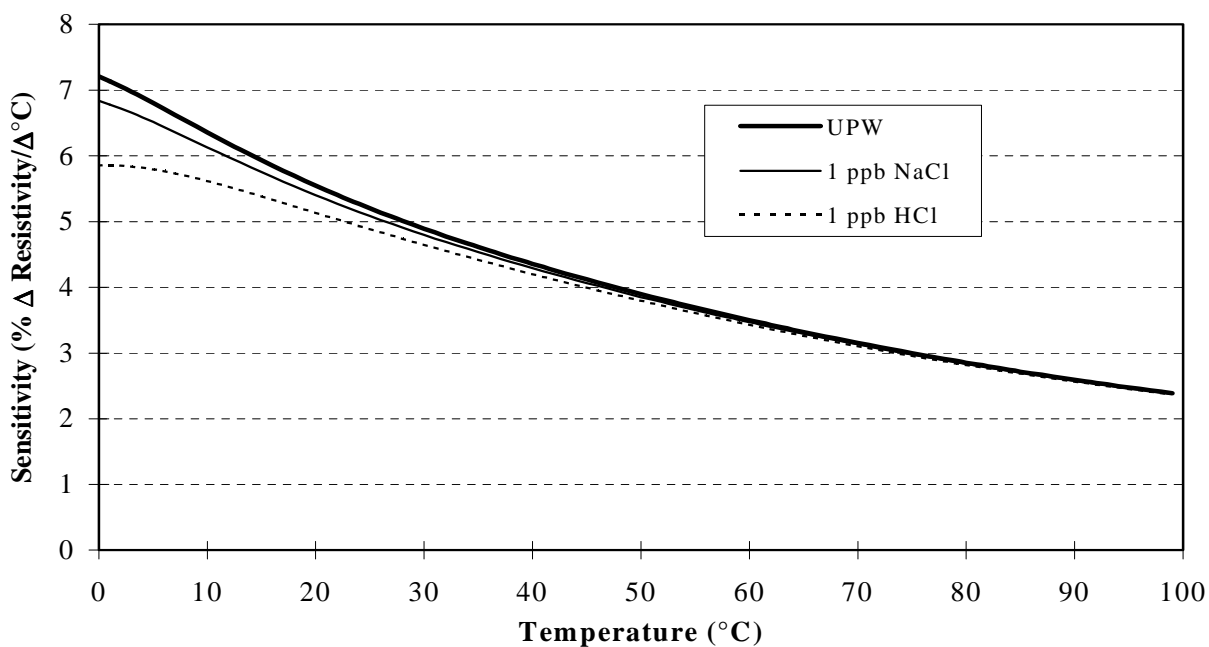
Sensitivity of the Conductivity of UPW as a Function of Temperature

A particularly important property of pure water is its unique resistivity/temperature dependency. We define this sensitivity, S_T , according to eq (7).

$$S_T = 100 \left(\frac{\partial \rho}{\partial T} \right)_T \left(\frac{1}{\rho} \right)_T \quad (7)$$

The sensitivity or temperature coefficient of ultrapure water varies considerably from 0-100°C and decreases dramatically as the temperature increases as shown in Figure 5.

Figure 5. Sensitivity to Temperature for UPW, 1 ppb NaCl, and 1 ppb HCl



The specific conductivity of NaCl is also well known as a function of temperature. The general equation relating the conductivity to concentration is provided in eq (8).

$$\kappa = 1/\rho = 10^{-3} d \sum_i^{\text{all ions}} C_i \lambda_i \quad (8)$$

From these equations, the resistivity of water with low ionic impurities can be easily determined,

as can the sensitivity of these solutions to temperature. The sensitivities of the resistivity to temperature for UPW and UPW with 1 ppb NaCl (or 1 ppb HCl) impurity are shown in Figure 5. *The most critical feature is that, at any temperature, pure water has greater sensitivity to temperature change than any water containing an ionic solute.*

The differences in sensitivity provide the basis for the remainder of the paper. Table 4 shows that the resistivity decrease with a 1 ppb impurity of NaCl (or any other impurity) does not uniformly decrease the resistivity of water at all temperatures. For example, at 15°C, a 1 ppb NaCl impurity causes a 6% decrease in the resistivity, while the same impurity causes a 1.5% decrease at 75°C. *It is the enhanced resistivity-temperature sensitivity for cold UPW that we exploit to prove that the water is pure and acceptable for use as a fundamental standard.*

Table 4. Decrease in Resistivity as a Function of Temperature

	15°C		25°C		40°C		75°C	
	Res. (MΩ-cm)	decrease (%)	Res. (MΩ-cm)	decrease (%)	Res. (MΩ-cm)	decrease (%)	Res. (MΩ-cm)	decrease (%)
UPW	31.87		18.18		8.850		2.481	
1 ppb NaCl	30.08	5.97	17.45	4.17	8.628	2.60	2.444	1.54

Figure 5 and Table 4 show that as temperature increases, impurities are harder and harder to detect[1]. We take advantage of the converse at lower temperatures - impurities are easier to detect - to provide multiple standard reference solutions for resistivity based on the physical properties of water and solutes at infinite dilution.

If three determinations of the cell constant are made at three different (and accurately known) temperatures, and the calculations of the cell constant are within the accuracy of the instrument and sensor, ±1.0% with our instrumentation, then the cell constant is correct and the water is free of ionic contaminants. *Therefore, since the resistivity of pure water is a fundamental physical characteristic of the pure substance, we suggest that pure water be used as the reference solution for UPW and other high resistivity applications.*

Experimental Data

Experimental Considerations

We have manufactured and tested a resistivity system[2] that incorporates all of the design criteria that are required to achieve minimum resistivity error. Sensors have undergone careful calibrations and are designed for maximum thermal response. Class A 1000 Ω Pt RTDs are used

and the sensor is constructed with a 90% thermal response time of 15-25 seconds. Portions of the sensor exposed to the ambient are insulated. Meters have had temperature and resistivity measurement circuits calibrated on all ranges, including calibration of the cables. All resistance measurements are 3-wire, which automatically corrects for cable resistance. Other features in the circuit design are applied to minimize self-heating due to measurement current through the RTD.

We have built a small UPW system (see Figure 6) that prepares 18.2 M Ω -cm (0.0550 μ S/cm) water at 25°C repeatably and reliably. In fact, for any temperature from 0-100°C, the resistivity of a pure water system is known precisely[2] according to eq 5. The water is prepared in a closed-loop, recirculating water system with the sensors located after a series of nuclear grade, mixed-bed ion-exchange resins. The entire system consists of Teflon and PVDF tubing.

To heat the UPW, it passes through a titanium 30 kW heat exchanger after the polisher to achieve the desired temperature, then to the sensors for measurements, then through 50 feet of Teflon tubing. This tubing is immersed in cold municipal water to dissipate the heat. The UPW returns to the storage tank where it is re-circulated back to the polishers. This "polish-heat-measure-cool" cycle is required to prevent overheating and degradation of the ion-exchange resins. The water quality was verified by monitoring the compensated resistivity of the cooled water.

The temperature at each resistivity sensor is monitored by 1000 Ω Pt RTDs at the entrance and exit ends of the resistivity measurement portion of the water loop. The RTDs were calibrated to 0.01°C accuracy from 0 to 100°C by an external calibration facility. The RTD resistance was measured by a Fluke 8505A multimeter and converted to temperature[10]. As much as a 1°C reduction in temperature occurs across the loop due to ambient cooling, so the temperature at each resistivity sensor was determined by linear interpolation across the measurement loop. The resistivity of each sensor was measured using Thornton 770PC meters with the aforementioned features. Data was collected over a LAN and stored to disk for subsequent processing.

Experimental Results

A fraction of the data collected from 5 sensors and 5 meters is provided in Figure 7 below. The experimental data was fit to a 5th order polynomial using non-linear least-squares regression. The coefficients of that fit are provided in eq 5. The "theoretical" resistivity of water, based on fundamental properties of water, was also re-determined based on the best available literature and it is summarized elsewhere[2,8,9]. A portion of the data and the "theoretical" resistivity of water are also provided in Figure 7.

Figure 7. Experimental and Theoretical UPW Resistivity Data

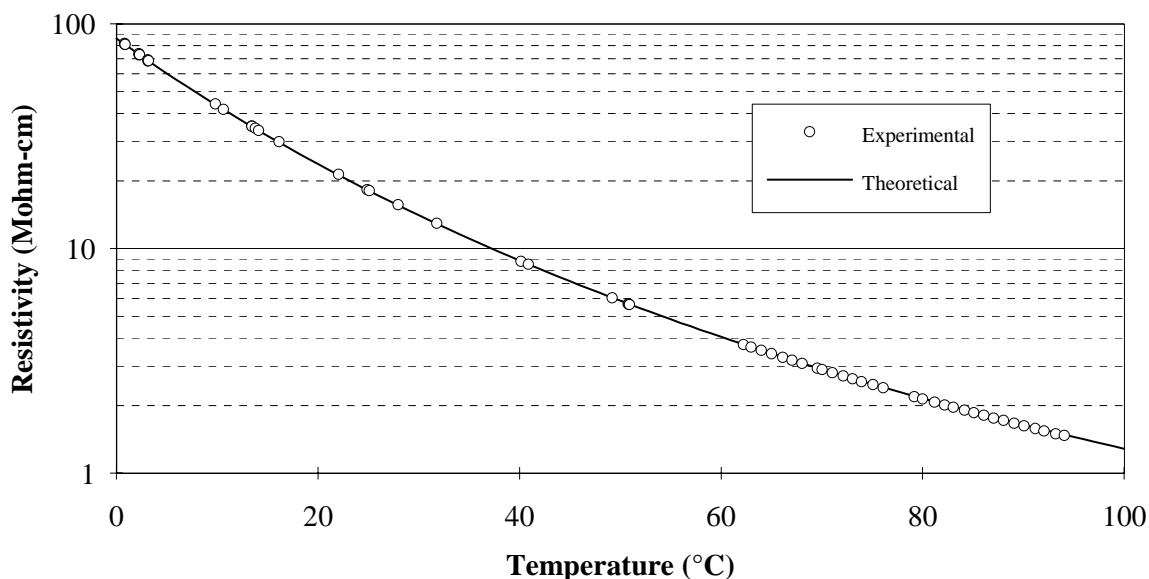
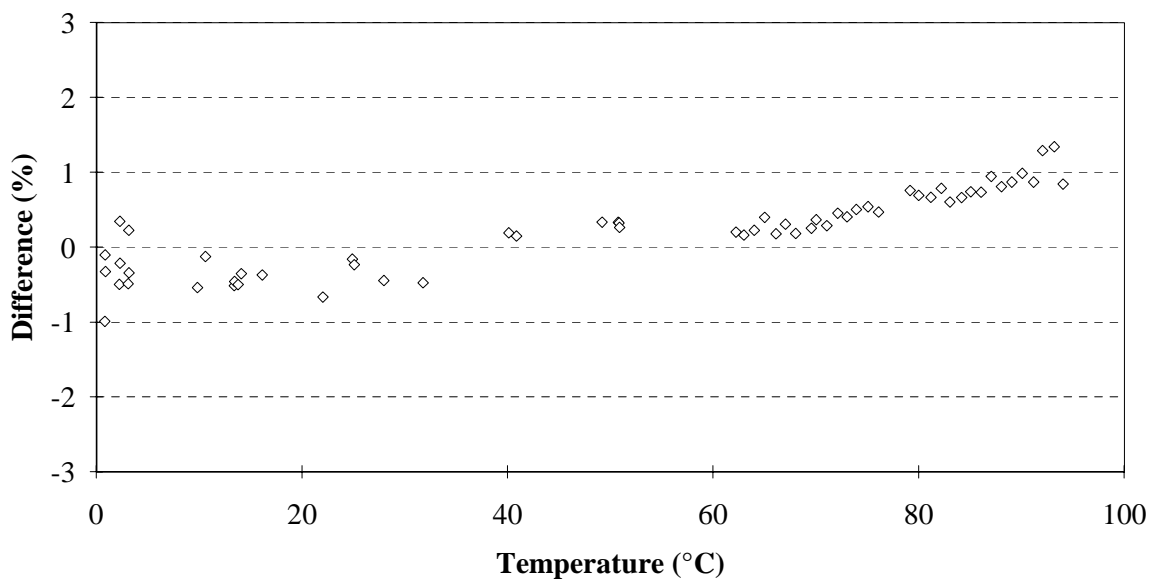


Figure 8. Experimental vs. Theoretical UPW Resistivity Error



The relative error between the experimental results and the 5th order polynomial fit of the theoretical data is plotted vs. temperature in Figure 8. At this point in time, it is difficult to ascertain whether the increasing error is the result of systematic experimental measurement error or incorrect theoretical data. However, given the large disagreements in the earlier literature on the value for the conductance of OH⁻ at high temperatures, there is high confidence in the experimental methodology. While the most likely culprit may be theoretical conductance of OH⁻

at high temperatures, the errors still average less than 1% from literature values.

Instrumentation

As noted in Table 3, the uncompensated resistivity of ultrapure water is 86 M Ω -cm at 0°C and 1.3 M Ω -cm at 100°C. This requires a resistivity meter/sensor combination with accuracy over nearly 2 orders of magnitude. Furthermore, if verification of the resistivity system is desired in order to utilize ASTM standards, then an additional 2 orders of magnitude range is required. Prior to the initiation of the Thornton studies on the properties of ultrapure water, systems with this performance were not commercially available for this application.

The development of the 770PC instrument provided a measurement system with a dynamic range in excess of 5 orders of magnitude (40 Ω to 10 M Ω), with an accuracy of better than $\pm 0.3\%$ of the measured value across the entire range and typically better than $\pm 0.1\%$. When used with a variety of sensors that vary in cell constant from 0.01 to 50 cm⁻¹, the measurement range of the system extends from 1 nS/cm to 1 S/cm (1000 M Ω -cm to 1 Ω -cm). The availability of these new instruments provides improved accuracy with several orders of magnitude wider dynamic range than previous generations of instrumentation. In addition, the invention of the Smart Sensor™ with embedded non-volatile memory containing precise calibration information for its specific sensor permitted the instrument to continuously monitor the cell constant to 0.01%.

The Three Temperature UPW Cell Calibration Method

A closed-loop, constant temperature recirculating water system, as described above, is used for this cell constant calibration. The general procedure of the calibration is illustrated in the example below.

The temperature in the recirculating pure water system is set to ~40°C. The temperature is measured by a calibrated, traceable 1000 Ω Pt RTD and a Fluke 8505A ohmmeter. The temperature measurement system is accurate to ~0.02°C. At any temperature, the resistivity of UPW is determined by accurate knowledge of the temperature and from eq (5). For simplicity, suppose the water temperature is 40.00°C. From Table 3, the resistivity of UPW is 8.85 M Ω -cm. If a recently calibrated resistivity meter indicates the resistance⁵ to be 0.903 M Ω , uncompensated for temperature, then the cell constant is calculated by:

⁵ Remember that the meter will not display a resistance normally. The displayed value will actually be the calculated resistivity, which is equal to the measured resistance divided by the cell constant. Again, this is all transparent to the user. The alternative way to manually calculate the cell constant is :

$$\text{new cell constant} = \text{old cell constant} \times (\text{measured resistivity} \div \text{reference resistivity})$$

$$\phi_{40} = \frac{0.903 \text{ M}\Omega}{8.85 \text{ M}\Omega \cdot \text{cm}} = 0.10203 \text{ cm}^{-1} \quad (9)$$

The temperature of the system is then set to ~25°C. The temperature is measured and the resistivity of the UPW is determined from eq (5). Again, for simplicity, let's assume the temperature is exactly 25.00°C. From Table 3, the resistivity of UPW is 18.18 MΩ-cm. If the resistivity meter indicates the resistance to be 1.858 MΩ, then the cell constant is calculated by:

$$\phi_{25} = \frac{1.858 \text{ M}\Omega}{18.18 \text{ M}\Omega \cdot \text{cm}} = 0.10220 \text{ cm}^{-1} \quad (10)$$

The difference between ϕ_{40} and ϕ_{25} is only 0.17%, less than our goal of 0.5%, and therefore acceptable.

The temperature of the system is again lowered, this time to ~15°C. The temperature is measured and the resistivity of the UPW is determined from eq (5). Again, for simplicity, assume the temperature is exactly 15.0°C. If the observed resistance is 3.251 MΩ, then the cell constant is calculated by:

$$\phi_{15} = \frac{3.251 \text{ M}\Omega}{31.75 \text{ M}\Omega \cdot \text{cm}} = 0.10239 \text{ cm}^{-1} \quad (11)$$

The difference between ϕ_{40} and ϕ_{15} is only 0.36% and therefore acceptable.

If the differences among the calculated cell constants is >0.5%, then the water is impure and/or the cell performance is inadequate over the measurement range. In either case, the calibration is self-checking and erroneous cell constant values will not be accepted.

The temperatures of 40°, 25° and 15°C are used for example only. Any three temperatures may be used, but the procedure should use sufficiently low and different temperatures to take advantage of the changing sensitivity of the resistivity of UPW and small impurities.

The Three Temperature UPW Cell Calibration Method has been in routine use at Thornton Associates for the calibration of standard reference sensors since 1993. Multiple standard reference sensors are used in its Auto Loop Cell Calibration/Certification System to calibrate production resistivity sensors. These sensors have cell constant accuracies of ±0.5%, and have been deployed by calibration laboratories throughout the world as internal reference standards.

The Production Auto Loop consists of a Neslab heat exchanger to maintain constant temperature, a closed-loop, recirculating water system (PVDF valves, fittings, and insulated pumping) with

multiple sets of nuclear/semiconductor grade mixed-bed ion exchange beds in parallel and series to produce 18.18 MΩ-cm quality water. There are 18 measurement ports for the insertion of production sensors under test and standard reference resistivity sensors and temperature sensors. A sensor under test is never more than 3 positions away from a standard reference cell. Since the calibration is executed at ambient conditions, there is no need to correct for any temperature gradient across the water system.

Sequential readings from the reference sensors and test sensors are data-logged on a dedicated computer, which records the precise cell constant (determined by the 770PC) for each production sensor and generates a printed certificate of accuracy. *Every production sensor* used for pure water applications is verified and/or calibrated and certified in the Auto Loop as a standard feature and shipped with a Certificate.

A potential future application for the Fundamental Standard will be as a reference to assay stable, high resistivity/low conductivity solutions[11] that can be packaged and made available to verify and calibrate sensors in the field. These solutions will have a resistivity in the pure water range, be stable, and packaged for convenient use, and protected from the impact of airborne ionic contaminants.

Acknowledgements

This has been a long-term company-wide effort. Many more persons, not listed here, have contributed to this work. Credit for the development of this technology goes to the members of the R&D department, past and present, who contributed to the concepts, detail design, testing, evaluation, and debugging of this technology. Acknowledgements are extended to the Sales, Marketing, Customer Services, and Technical Services personnel who brought the “voice of the customer” to the total design. Acknowledgements are extended to Manufacturing who drove the cost of the technology down. Final thanks are extended to the multitude of users who have been willing to share their requirements with us.

Background

Thornton, Inc. has been a leading innovator and manufacturer of sensors and instrumentation to monitor water purity and other fluid-based parameters since 1964, specializing in Ultrapure Water for the semiconductor, pharmaceutical and power generation industries. Thornton instrumentation includes measurements for Resistivity, Conductivity, TOC, Temperature, % Acid/Base, Flow, Pressure, Level and more. Thornton continues to be a leader and a technological innovator in the design and development of accurate temperature compensation

algorithms, accurate UPW and hot UPW resistivity measurements, patented Smart Sensor™ calibration technology, multi-parameter instrumentation, rapid TOC measurements, and high resistivity applications such as high purity ethylene glycol and isopropyl alcohol cleaning.

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