

Conductivity, Total Dissolved Solids, and Salinity

Outline

- What is conductivity?
- Conductivity and TDS, and salinity
- How is conductivity measured?
- What are sources of error?
- Milwaukee conductivity meters
- Applications



Conductance vs. Resistance

- **Conductance** (G) is the ability of a substance to conduct an electrical current and is measured in Siemens (S)

- **Resistance** (R) is the reciprocal of conductance

$$R = 1/G$$

- **Ohm's Law** $\rightarrow V = IR$, so $V = I (1/G)$

V is voltage

I is current

Conductivity vs. Resistivity

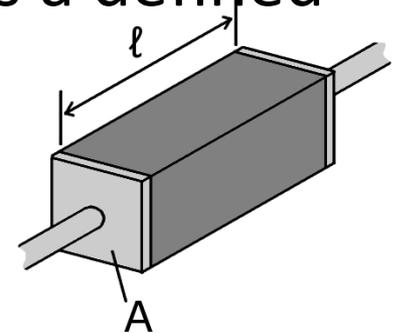
- **Conductivity** (σ) is specific conductance over a defined area (S/cm)

$$EC = \sigma = G (L/A)$$

*Where EC stands for “electrical conductivity”

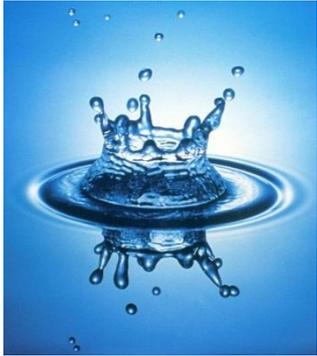
- **Resistivity** (ρ) is specific resistance across a defined area (Ohm*cm)

$$\rho = R (L/A)$$



Materials

Conductive



Water



Copper



Steel

Resistive



Glass



Plastic

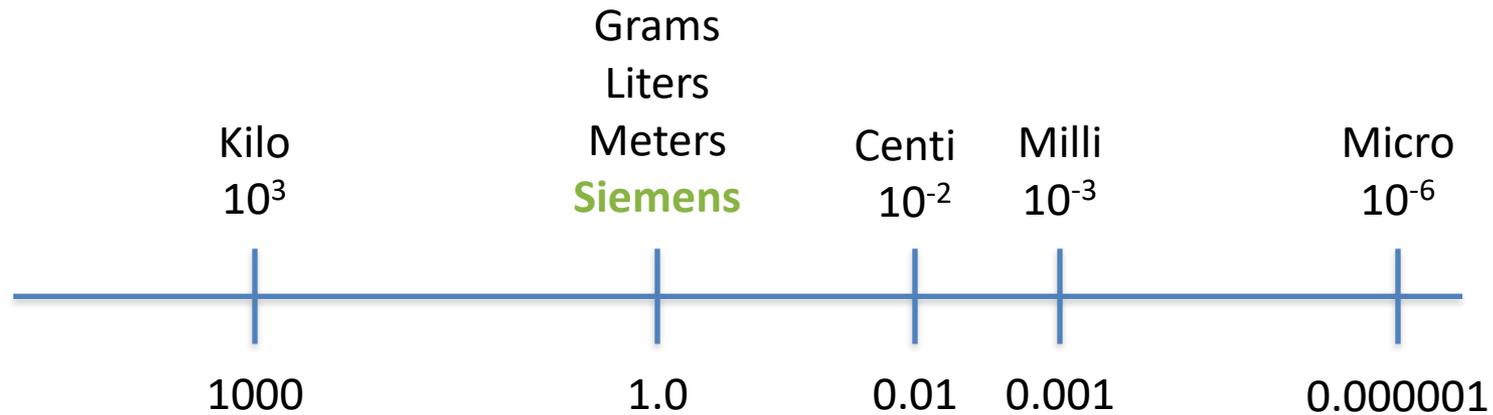


Porcelain (spark plugs)

Units of Measure

- Resistance is measured in **ohms**
- Conductance (inverse of resistance) is measured in **ohm⁻¹** (or **mho**)
- Conductivity takes into account the length and area of the cell and is measured as **ohm⁻¹ · cm⁻¹** (or **mho/cm**)
- Historically mho/cm has been utilized
- Replaced with **Siemens (S)/cm** according to SI
- Typically measured as **μS/cm** or **mS/cm**
 - Micro (μ) is equivalent to 1×10^{-6} (0.000001 S/cm)
 - Milli (m) is equivalent to 1×10^{-3} (0.001 S/cm)

Units of Measure



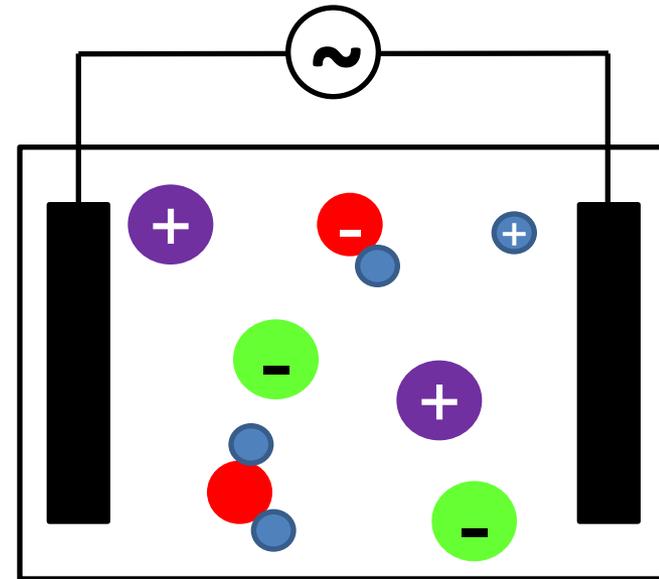
- To convert from one unit to another simply move the decimal place
 - If going from larger (milli) to smaller (micro), the decimal moves to the right
 - If going from smaller to larger, the decimal moves to the left
- For example, a 12.88 mS/cm conductivity standard is the same as 12,880 μ S/cm

Units of Measure

Measurement	Units
Resistance	Ohm
Conductance	Siemens, mho
Resistivity	Ohm/cm
Conductivity	Siemens/cm, mho/cm

Electrolytic Conductivity

- In metals, currents rely on free-moving electrons
- In solutions, ions carry electrons
- Depends on properties of the solution (type of ions present, viscosity, temperature, etc.)
- Non-specific (does not identify specifically what type of ions are present)



Electrolytic Conductivity

Conductivity of a medium, in which the transport of electrical charges under electric potential differences, is by particles of atomic size or larger

- Salt (NaCl) as an example of a conductive substance:
 - Dissolves in water and dissociates into ions (Na^+ and Cl^-)
 - Since these are charged, current can flow
- Sugar ($\text{C}_{12}\text{H}_{22}\text{O}_{11}$) as an example of a non-conductive substance:
 - Dissolves in water, but does not dissociate into ions (remains as a molecule)
 - No charged ions means no carrying of a charge
- International standards:
 - Standards Methods 2510B (EPA-Approved Conductivity Methods)
 - ASTM D1125-95 A (Standard Methods for Conductivity and Resistivity of Water)

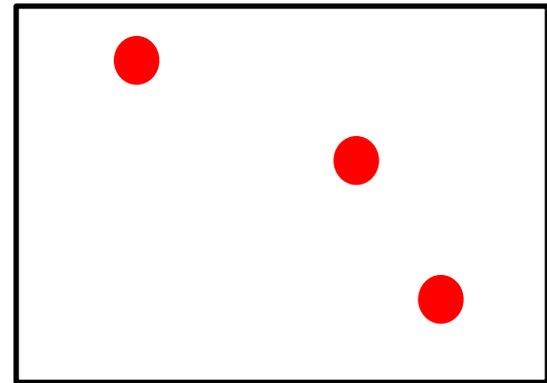
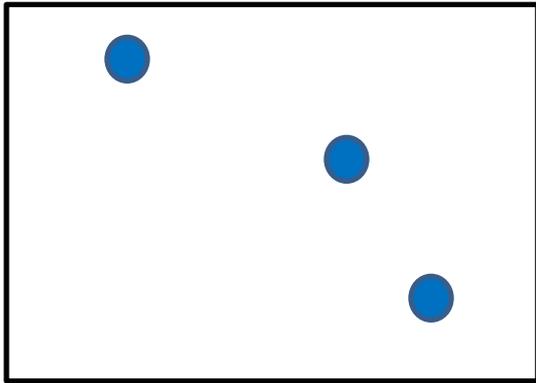
Strong vs. Weak Electrolytes

An electrolyte is a charged ion that makes a solution electrically conductive

- Strong electrolytes
 - Fully dissociate/ionize in solution
 - [Ions] is proportional to [electrolyte]
 - Ionic solids and strong acids, for example
- Weak electrolytes
 - Do not fully dissociate/ionize in solution
 - Still can conduct electricity, just not as well
 - Acetic acid, for example

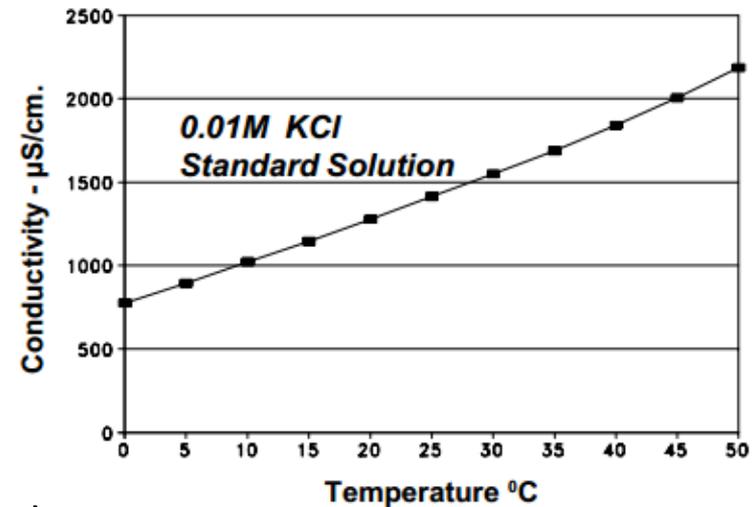
Temperature Compensation

- Ion mobility depends on temperature (opposite of metals)
 - Higher temperature → lower resistance/higher conductance
 - Lower temperature → higher resistance/lower conductance



Temperature Compensation

- Compensate for temperature with linear temperature coefficient
 - β = temperature coefficient
 - Units are %/°C
 - Milwaukee meters have either:
 - Linear
 - Actual conductivity (no compensation)



Temperature Compensation

- Adjust reading to a reference temperature (Milwaukee uses 25°C)

$$EC_{t_x} = EC_{t_{cal}} \cdot [1 + \beta(t_x - t_{cal})]$$

EC_{t_x} is conductivity at some temperature = t_x

$EC_{t_{cal}}$ is conductivity of the standard at the calibration temperature (t_{cal})

β is the temperature coefficient

- β is known for common substances, or it can be determined.

Temperature Coefficient

- Determining β :
 - Measure conductivity at a range of temperatures
 - Graph the change in conductivity vs. change in temperature
 - Divide slope of the line by EC_{tcal} to get β
- Meters with fixed temperature compensation usually use 2%/°C

Sample	$\beta = \%/^{\circ}\text{C}$ at 25°C
Ultrapure Water	4.55
Salt Solution (NaCl)	2.12
5% NaOH	1.72
Dilute NH ₃ Solution	1.88
10% HCl	1.32
5% Sulfuric Acid	0.96
98% Sulfuric Acid	2.84
Sugar Syrup	5.64

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Total Dissolved Solids (TDS)

- TDS include any minerals, salts, metals, etc. that are dissolved in solution (must be ionic to be measured conductively)
- Conductivity is directly related to the concentration of ionic dissolved solids
 - Does NOT identify specific ions
 - General indicator of the quantity of dissolved ionic solids (in ppm)
 - Normally a gravimetric measurement, but Milwaukee meters use a conversion factor
- $TDS = C_f \cdot EC$
 - C_f is a conversion factor that depends on dissolved solid and is usually between 0.5 and 0.7
 - $C_f = \text{Actual TDS} / \text{Actual Conductivity at } 25^\circ\text{C}$

Total Dissolved Solids (TDS)

- Solutions having the same TDS concentration do not necessarily have the same conductivity

Salt	Conductivity equivalent	TDS/conductivity
Sodium chloride	1.00 ppm TDS = 2.04 uS/cm	0.49
Sodium sulfate	1.00 ppm TDS = 1.49 uS/cm	0.67
Calcium sulfate	1.00 ppm TDS = 1.36 uS/cm	0.74
Sodium bicarbonate	1.00 ppm TDS = 1.06 uS/cm	0.91

Salinity

- Can also be determined using conductivity
- Three scales for salinity exist:
 - **Natural Seawater Scale** (0.00 to 80.00 ppt) defined by UNESCO in 1966
 - **Percent Scale** (0.0 to 400.0%), where 100% is seawater
 - **Practical Salinity Scale** (0.00 to 42.00 practical salinity units [PSU]) defined by UNESCO in 1978



Practical Salinity Scale

- Relative to KCl
- Determining PSU with a measured conductivity at 15°C:

$$S = 0.0080 - \left(0.1692 \times K_{15}^{\frac{1}{2}}\right) + (25.3851 \times K_{15}) + \left(14.0941 \times K_{15}^{\frac{3}{2}}\right) - \left(7.0261 \times K_{15}^2\right) + \left(2.7081 \times K_{15}^{\frac{5}{2}}\right)$$

$$\text{Where } K_{15} = \frac{EC_{(S,15,0)}}{EC_{(KCl,15,0)}}$$

$$\text{and } 2 \leq S \leq 42$$

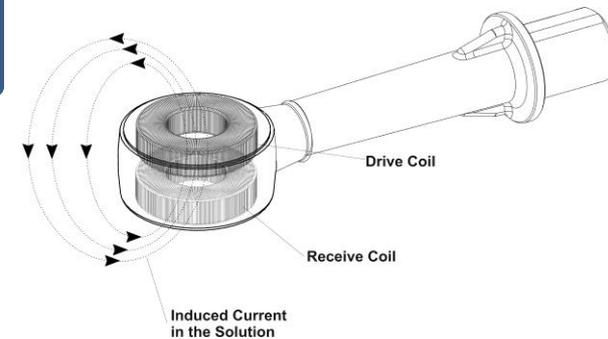
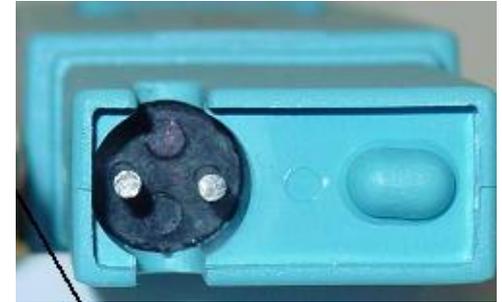
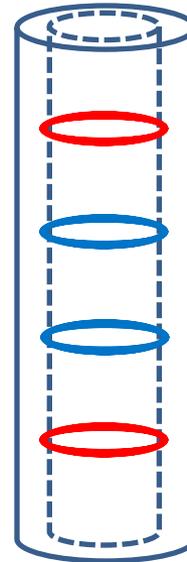
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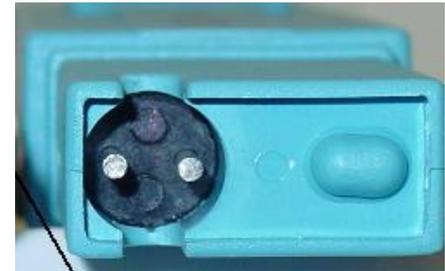
Methods of Measurement

- **Amperometric**
 - 2-electrode probe
- **Potentiometric**
 - 4-ring probe
- **Toroidal**
 - “Electrodeless”

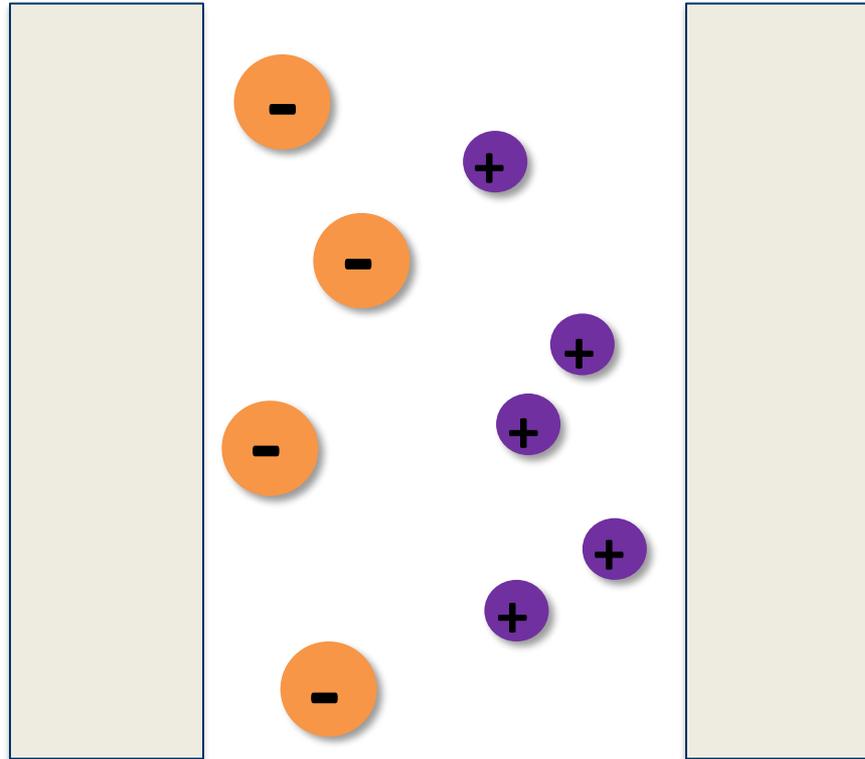


Amperometric Method

- Two electrodes insulated from each other, but in direct contact with solution
 - Non-reactive metals (stainless steel, graphite)
 - Specifically sized and spaced for known cell constant value
- Fixed alternating potential is induced at specific frequency
- Current is measured (ionic current)
 - More ions results in both lower resistance and higher conductivity



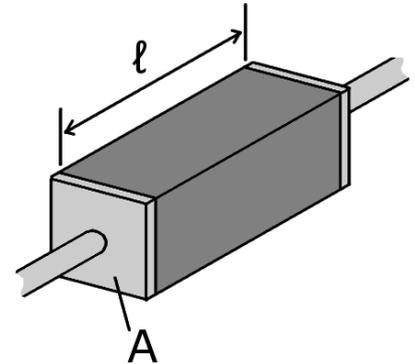
Amperometric Method



Cell Constant (k)

- Instruments measure conductance, but users need conductivity
 - Conductivity = Cell Constant (k) x Conductance (G)

$$EC = \sigma = G (L/A) = k \cdot G$$



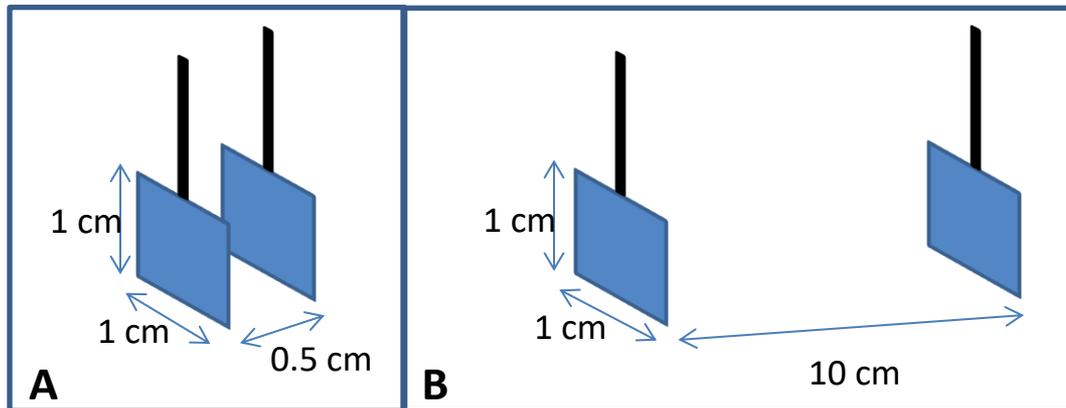
- **Cell constant (k)**
 - Determined using known solutions (Milwaukee uses KCl)
 - The ratio of the known conductivity to the measured conductance

$$k = L/A$$

“L” is length of the column of solution between electrodes;
A is the area of the column normal to flow of current

Cell Constant (k)

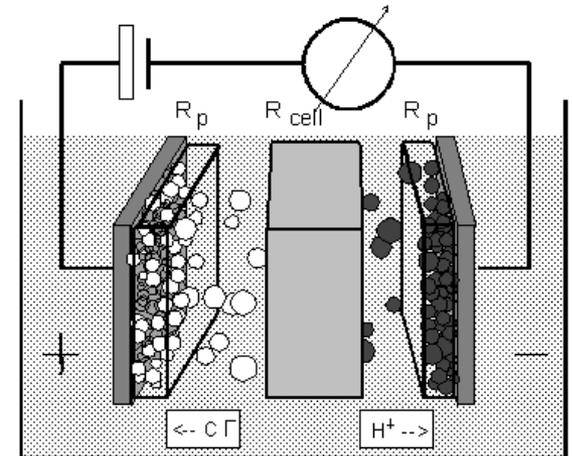
Cell constant depends on the geometry and distance between electrodes



- Use a small k for low EC values
- Use a large k for high EC values

Amperometric Method Issues

- Polarization effects
 - Varying resistance because of salt deposition on electrodes
 - Must use alternating voltage
 - Must use the correct frequency (low for low conductivities, and high for high conductivities)
 - Must use correct cell constant
 - Can be reduced with graphite sensors
- Cable/wire resistance
 - Increases with length

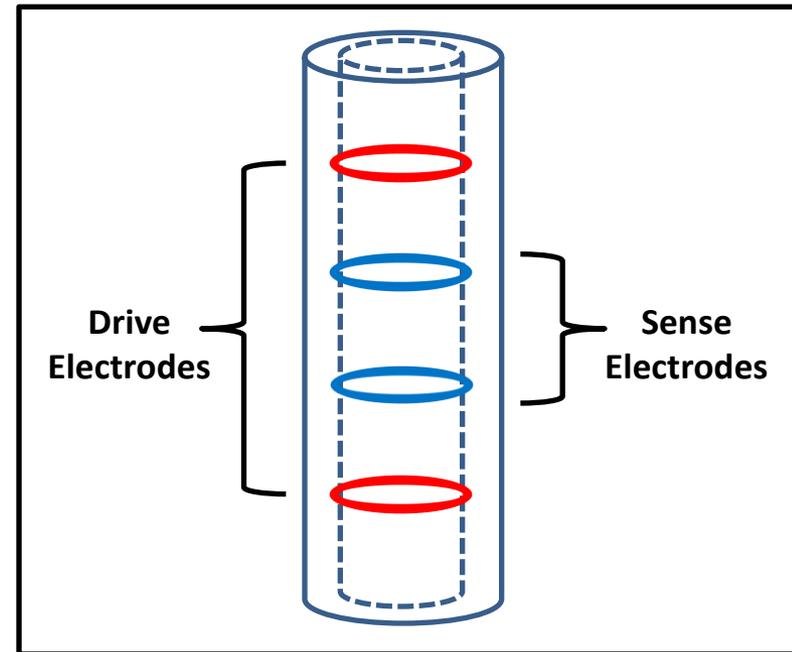


Advantages and Disadvantages

- Advantages
 - Low cost
 - Requires low sample volume to cover sensor
- Disadvantages
 - Limited ranges (each requiring a different meter)
 - Polarization effect
 - 2% F.S. accuracy
 - CD601– 0.0 – 1990 $\mu\text{S}/\text{cm}$ ($\pm 39.8 \mu\text{S}/\text{cm}$)
 - CD611– 0 – 19,990 $\mu\text{S}/\text{cm}$ ($\pm 399.8 \mu\text{S}/\text{cm}$)
 - EC60 – 0.00 – 19.99 mS/cm ($\pm 0.40 \text{mS}/\text{cm}$)

Potentiometric Method

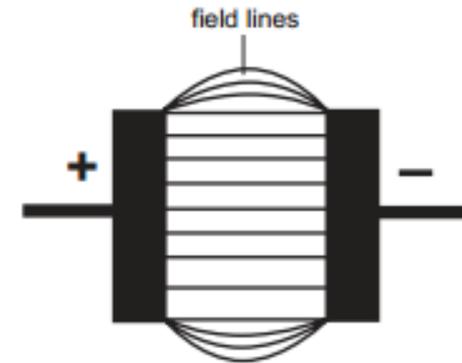
- Four-ring probe
 - Outer two rings (drive electrodes) apply alternating voltage that induces a current in the solution
 - Inner two rings (sense electrodes) measure the potential drop caused by the current
- Constant field maintained by shield around rings
- Reduces effects of polarization



Advantages and Disadvantages

- Advantages

- One probe for all ranges
- Higher ranges and accuracy ($\pm 1\%$ F.S.)
- No polarization



- Disadvantages

- Fringe field effects
- Vent holes must be properly submerged (requires more sample volume)
- More expensive

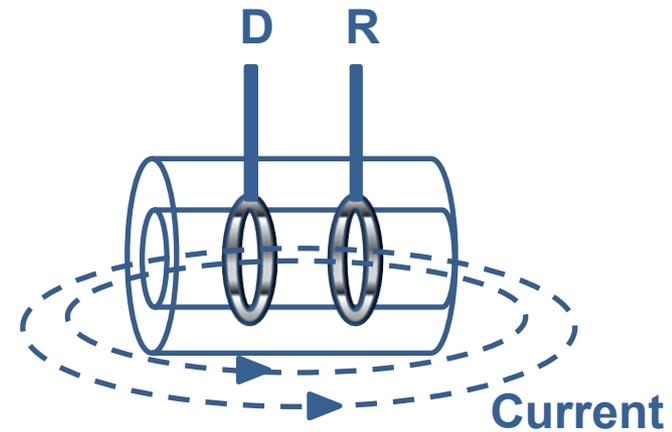
Toroidal Method

- Also known as:
 - Electrodeless Conductivity
 - Non-Contact Conductivity
 - Inductive Conductivity
- Requires a control processor
- Composed of two inductively coupled toroids encased in a plastic sheath



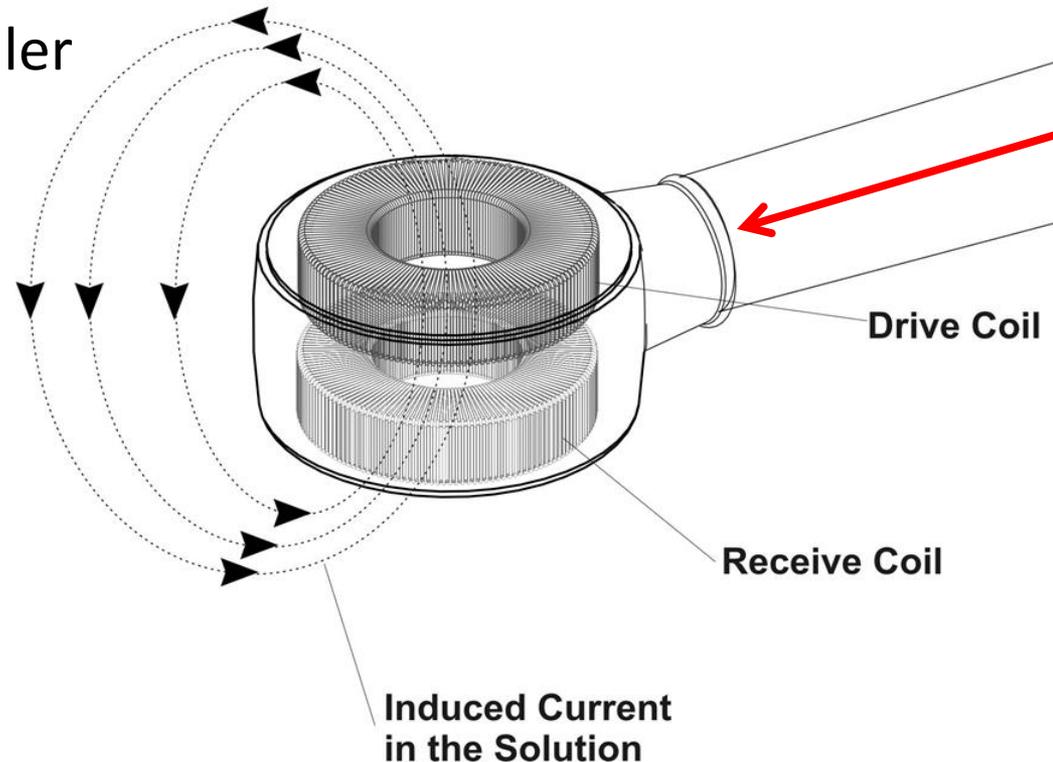
Toroidal Conductivity Theory

1. Controller supplies a high frequency reference voltage to first toroid (drive coil, D)
 - Generates strong magnetic field
2. Liquid passes through center of toroid and acts as a one turn secondary winding
 - Induces current proportional to the voltage induced by the magnetic field
3. Conductance is measured according to Ohm's Law at the receive coil (R)



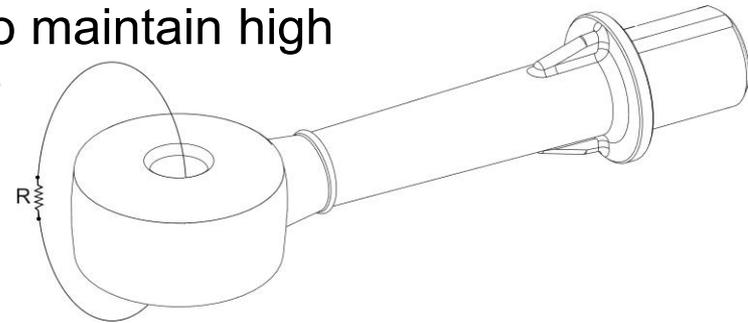
Toroidal Conductivity Theory

1. Voltage supplied by controller
2. Magnetic field produced
3. Ionic current is induced in solution
4. Electric current produced in receive coil
5. Conductance is measured



Advantages and Disadvantages

- Advantages
 - No electrical contact between electrode and process fluid
 - No polarization effects (electrolysis/fouling)
 - Can be used in slurries
 - Ideal for highly conductive liquids (up to 2 S/cm with $\pm 2\%$ accuracy)
 - Used in process control of baths to maintain high concentrations of acids and bases
 - Chemically resistant surfaces
- Disadvantages
 - Expensive (~\$600 for probe alone)



Calibration with Standards

STANDARDS HAVE NO BUFFERING CAPACITY – easily contaminated

1. Before placing probe in standard:
 - Rinse probe in distilled water
 - Shake off excess water from probe
 - Immerse, swirl and completely remove probe 3-5 times in “cleaning” standard

2. Placing probe in standard:
 - Immerse, swirl and remove probe 3-5 times in “good” standard
 - Swirl and tap (gently) probe on bottom of beaker to remove air bubbles
 - Gently stir solution
 - Wait for thermal equilibrium

Outline

- What is conductivity?
- Conductivity and TDS, and salinity
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- **What are sources of error?**
- Milwaukee conductivity meters
- Applications



Sources of Error

- Probe immersion (potentiometric)
 - Vent holes must be submerged in solution
 - See manuals for proper use of each probe
- Fringe field/wall effect
 - Sides and bottoms of container/pipe can affect readings
 - Can be avoided by keeping probe 3 cm away from all walls
 - Dependent on size of probe (verify with manual)

Sources of Error

- Example using MW170 and 4-electrode probe
 - Probe in center of beaker: 1000 $\mu\text{S}/\text{cm}$
 - Probe touching side of beaker: 975 $\mu\text{S}/\text{cm}$ (-2.5%)
 - Probe vent holes not in solution: 590 $\mu\text{S}/\text{cm}$ (-41%)

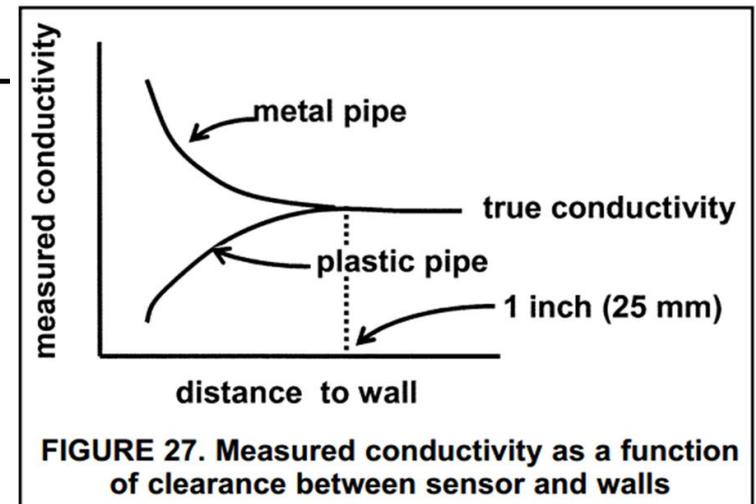


FIGURE 27. Measured conductivity as a function of clearance between sensor and walls

Process control probe installation

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- **Milwaukee conductivity meters**
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Types of Meters Offered



Amperometric Testers

Entry Level Testers

- CD97 – Low range TDS Tester (0- 999 ppm)
- CD600 – Low range TDS Tester (0-1990 ppm)
- CD610– High range TDS Tester (0-10,000 ppm)
- CD601– Low range EC Tester (0-1990 $\mu\text{S}/\text{cm}$)
- CD611– High range EC Tester (0-19,990 $\mu\text{S}/\text{cm}$)

Common Features

- Manual, one-point calibration
- ATC (0-50°C)
- $\pm 2\%$ F.S. accuracy
- Simple on/off switch
- Not waterproof



Intermediate Testers

T75 – Low range TDS Tester (0-1999 ppm)

T76 – High range TDS Tester (0-9,990 ppm)

C65– Low range EC Tester (0-1999 $\mu\text{S}/\text{cm}$)

C66– High range EC Tester (0-19.99 mS/cm)

Common Features

- Manual, one-point calibration
- ATC (5-50°C)
- $\pm 2\%$ F.S. accuracy
- Waterproof
- Replaceable probe



Advanced Testers

EC59 - Low range EC/TDS Tester (0-3999 $\mu\text{S}/\text{cm}$, 0-2000 ppm)

EC60 – High range EC/TDS Tester (0.00-20.00 mS/cm , 0.00-10.00 ppt)

MW803 - Low range pH/EC/TDS Tester (0-3999 $\mu\text{S}/\text{cm}$, 0-2000 ppm)

MW804 - High range pH/EC/TDS Tester (0.00-20.00 mS/cm , 0.00-10.00 ppt)

Common Features

- ATC (with β adjustable from 0.0 to 2.4%/°C)
- $\pm 2\%$ F.S. accuracy
- Automatic Shut-off
- Low battery indicator
- Battery % level at startup
- Selectable °C or °F
- Waterproof
- Low range: Automatic, one-point calibration at 1413 $\mu\text{S}/\text{cm}$ or 1382 mg/L
- High range: Automatic, one-point calibration at 12.88 mS/cm or 6.44 g/L



Amperometric Portable Meters

Entry Level Portable Meters

MW401 – Low range TDS portable (0-1990 mg/L)
MW402 – High range TDS portable (0.0-10.0 mg/L)
MW301– Low range EC portable (0-1990 $\mu\text{S}/\text{cm}$)
MW302– High range EC portable (0.00-10.00 mS/cm)

MW801– Low range pH/EC/TDS portable (0-1990 $\mu\text{S}/\text{cm}$, 0-1990 ppm)
MW802– High range pH/EC/TDS portable (0.00-6.00 mS/cm , 0-4000 ppm with 0.68)

Common Features

- ATC
- $\pm 2\%$ F.S. accuracy
- Manual, one-point EC/TDS calibration
- Low battery indicator
- Replaceable probe
- 95% RH (not waterproof)



Advanced Portable Meters

MW805 – Low range pH/EC/TDS portable (0-4000 μ S/cm, 0-2000/3200 ppm)

MW806 – High range pH/EC/TDS portable (0.00-20.00 mS/cm, 0.00-10.00/16.00 ppt)

Common Features

- ATC
- GLP
- Adjustable EC to TDS conversion factor
- Calibration time out
- Low battery indicator
- Battery % Level at startup
- $\pm 2\%$ F.S. accuracy
- Automatic, one-point EC/TDS calibration
- pH probe condition indicators
- Logging with USB
- IP67 (waterproof)



Potentiometric Meters

Advanced Portable Meters

MW306– EC/TDS/% NaCl portable

Parameter	Range
Conductivity	0.00 to 29.99 $\mu\text{S}/\text{cm}$ / 3.0 to 29.9 $\mu\text{S}/\text{cm}$ 30.0 to 299.9 $\mu\text{S}/\text{cm}$ 300 to 2999 $\mu\text{S}/\text{cm}$ 3.00 to 29.99 mS/cm 30.0 to 200.0 mS/cm , up to 500.0 mS/cm (absolute conductivity)*
TDS	0.00 to 14.99 ppm (mg/L) 15.0 to 149.9 ppm (mg/L) 150 to 1499 ppm mg/L 1.50 to 14.99 g/L 15.0 to 100.0 g/L up to 400.0 g/L (absolute TDS* with 0.80 factor)
Salinity	0.0 to 400.0 % Nacl 2.00 to 42.00 PSU 0.00 to 80.00 g/L
Temperature	-20.0 to 120.0°C -4.0 to 248.0°F

Features

- ATC
- GLP
- Adjustable EC to TDS conversion factor (0.40 to 0.80)
- Calibration time out
- Low battery indicator
- Battery % Level at startup
- EC $\pm 1\%$ of reading / $\pm 0.05 \mu\text{S}/\text{cm}$ or 1 digit, whichever is greater ; TDS: $\pm 1\%$ of reading / $\pm 0.03 \text{ ppm}$ or 1 digit, whichever is greater
- Automatic, one or two point EC/TDS calibration
- Logging with USB
- IP67 (waterproof)



Advanced Benchtop Meters

MW170– EC/TDS/% NaCl

MW180– Two channel, pH/EC/TDS/% NaCl

Parameter	Range
Conductivity	0.00 to 29.99 $\mu\text{S}/\text{cm}$ 30.0 to 299.9 $\mu\text{S}/\text{cm}$ 300 to 2999 $\mu\text{S}/\text{cm}$ 3.00 to 29.99 mS/cm 30.0 to 200.0 mS/cm , up to 500.0 mS/cm (absolute conductivity)*
TDS	0.00 to 14.99 ppm (mg/L) 15.0 to 149.9 ppm (mg/L) 150 to 1499 ppm mg/L 1.50 to 14.99 g/L 15.0 to 100.0 g/L up to 400.0 g/L (absolute TDS* with 0.80 factor)
Salinity	0.0 to 400.0 % NaCl 2.00 to 42.00 PSU 0.00 to 80.00 g/L
Temperature	-20.0 to 120.0°C -4.0 to 248.0°F

Features

- ATC
- GLP
- Adjustable EC to TDS conversion factor (0.40 to 0.80)
- Calibration time out
- Built in battery (AC/DC)
- Battery % Level at startup
- EC $\pm 1\%$ of reading / $\pm 0.05 \mu\text{S}/\text{cm}$ or 1 digit, whichever is greater ; TDS: $\pm 1\%$ of reading / $\pm 0.03 \text{ ppm}$ or 1 digit, whichever is greater
- Automatic, one or two point EC/TDS calibration
- Logging with USB



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Applications

- Agriculture
- **Aquaculture**
- **Boiler Blowdown**
- Brewing
- Cooling Towers
- Chemical
- Desalination
- **Electroplating**
- Food Processing
- Iron and Steel
- Mining
- Petroleum
- Reverse Osmosis
- **Soil**
- **Ultrapure Water**
- Waste Streams



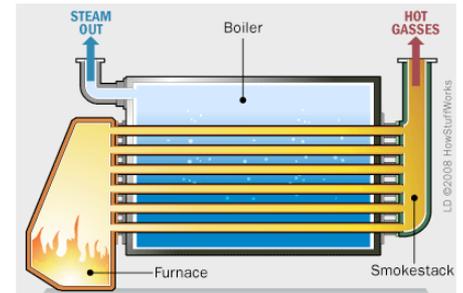
Applications – Aquaculture

- Mainly measuring salinity
- Especially important in clam aquaculture
- Blood salinity varies with environment
 - Too high or too low affects enzyme activity
 - Can open or shut shells to prevent exposure, but this is only a short-term fix
- Salinity can affect growth rate, spat clearance and predation



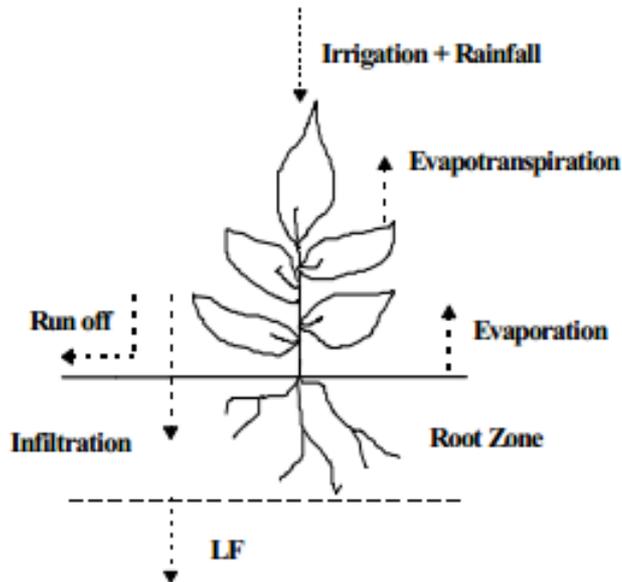
Applications – Boiler Blowdown

- Feed water has impurities in it (suspended and dissolved)
 - These can accumulate in boiler as steam evaporates
 - Increasing concentration can cause corrosion and alter effectiveness and cost-efficiency
- Two types of discharge to reduce concentration:
 - Surface water for dissolved solids
 - Bottom blowdown for sludge
- Solution: use conductivity measurements and a controller to monitor the concentration of dissolved solids and automatically initiate blowdown



Applications – Soil Conductivity

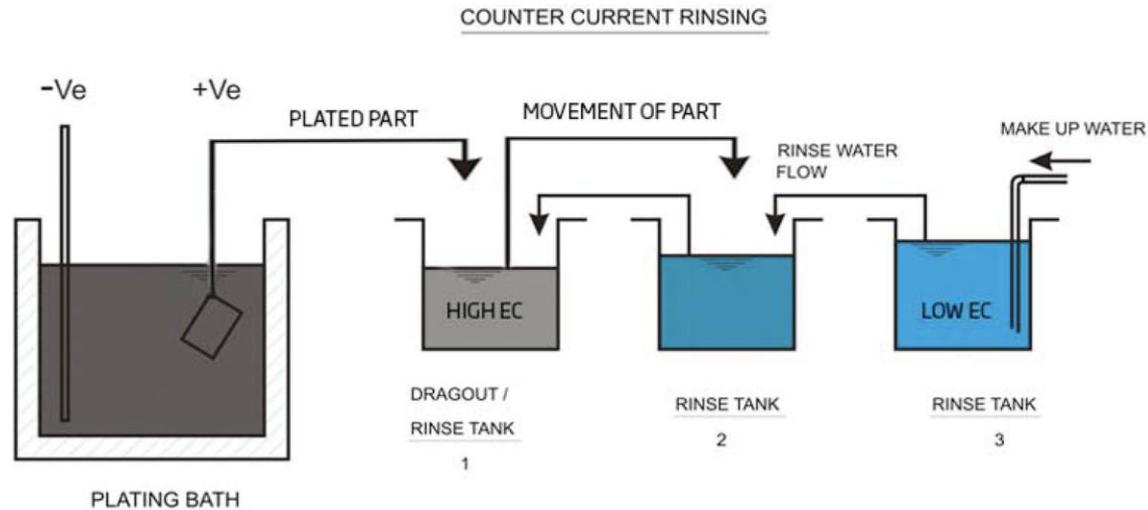
Conductivity measurements are used to infer total dissolved solids and salinity in soil environment



- TDS measurements are used to monitor nutrient availability
 - NPK – three most essential nutrients needed for optimal plant growth
- Presence of excessive salts in irrigation water can negatively affect crops
 - Indicated by average root zone salinity (EC_{se})
 - Some locations naturally have high salt concentration due to lack of precipitation (salts are not leached from soil)

Metal Plating

- Metal plating rinse baths are used to remove the chemicals used in plating from the plated objects
- Counter current rinse baths are used to wash the chemicals back to minimize wastewater generated



EC Curves

