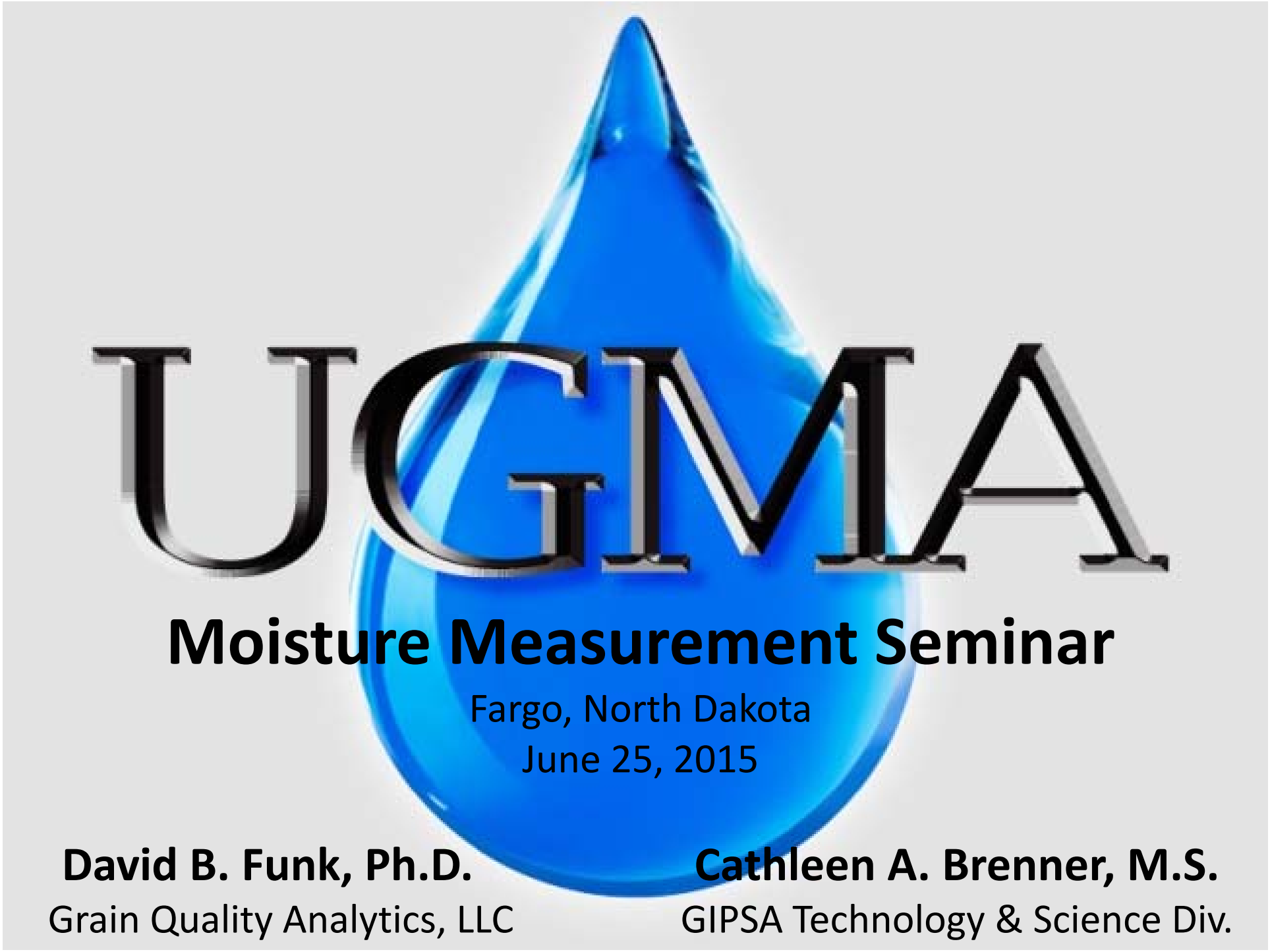

Moisture Measurement Seminar

Fargo, North Dakota

June 25, 2015

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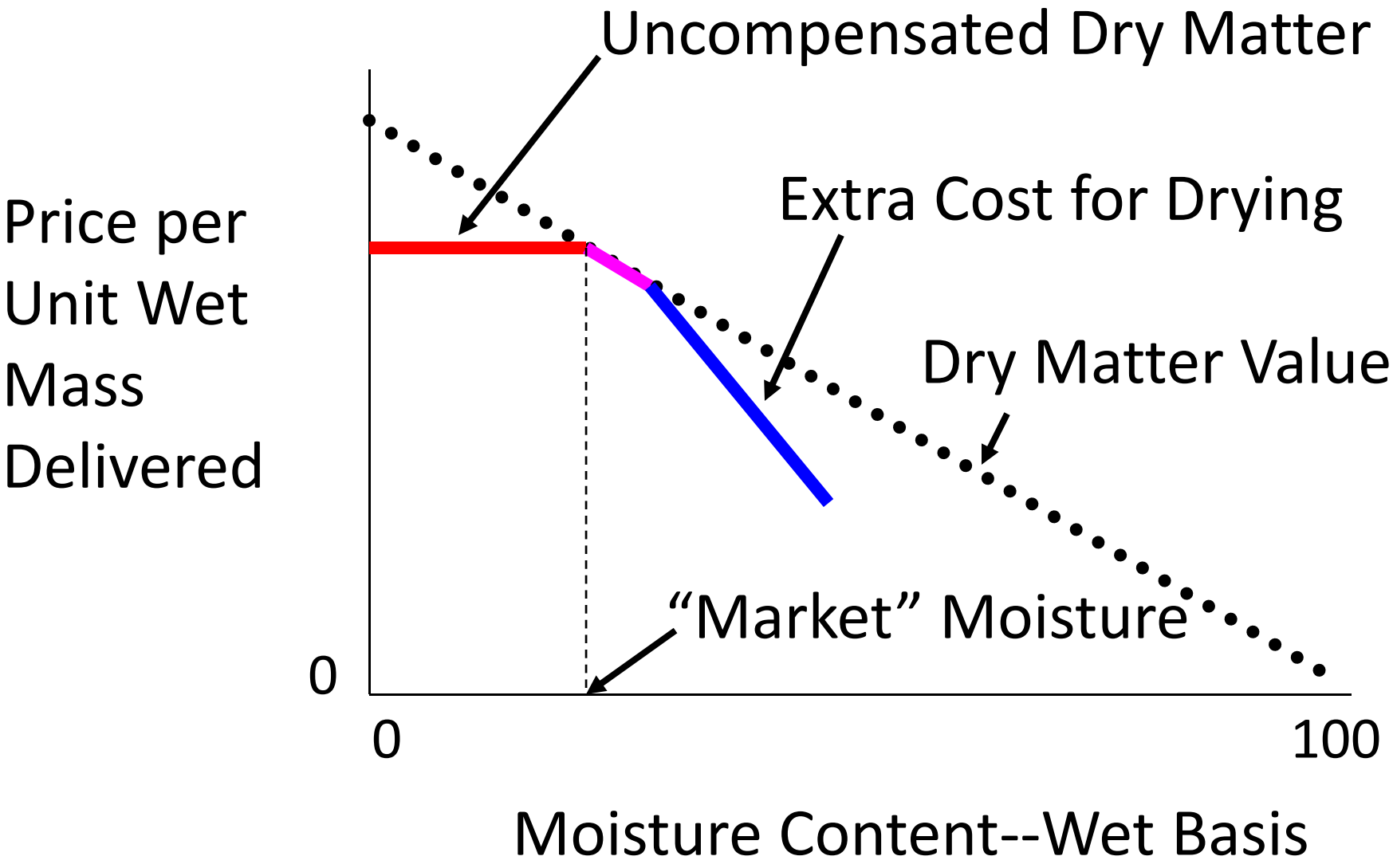
Grain Quality Analytics, LLC

Cathleen A. Brenner, M.S.
GIPSA Technology & Science Div.

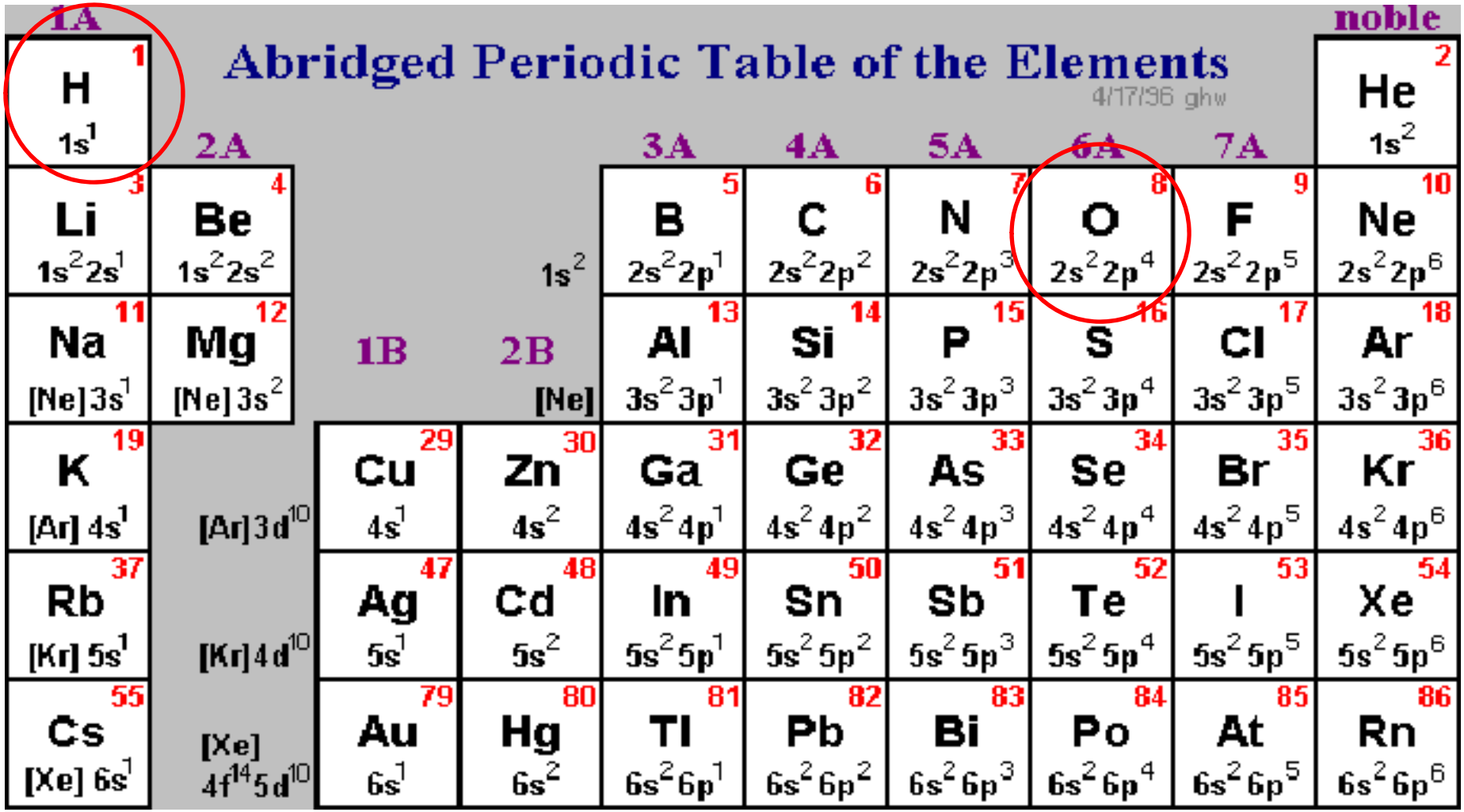
Basic Questions

- Why do we care about moisture content?
- What is water, really?
- How can we measure moisture content?
- How do moisture meters work?
- What has FGIS achieved by adopting UGMA moisture meters?
- How is FGIS ensuring the continued accuracy of Official moisture results?
- How can moisture meter users optimize their moisture measurement results?

Price Paid for Grain



Water: 2 hydrogen atoms + 1 oxygen atom

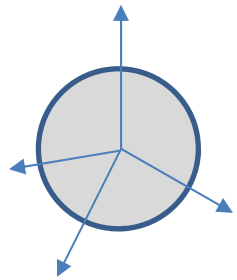


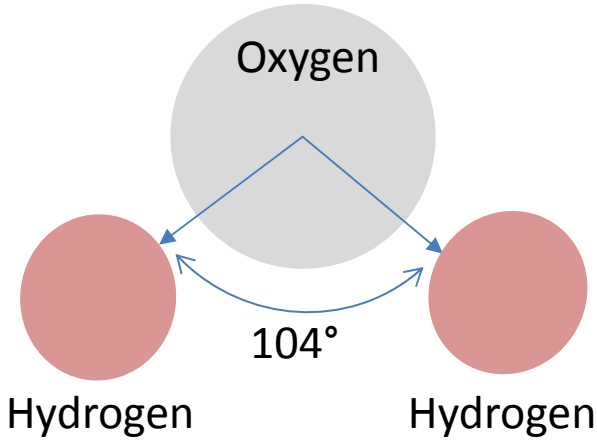
Water Molecule Neutral but Atoms Share Charge Unequally

- Water molecule has same number of protons (positive) and electrons (negative) so it is electrically neutral, but…
- Oxygen atom is more “electronegative” than hydrogen, so it “hogs” the hydrogen atoms electrons that it shares through covalent bonding.
- Oxygen atom has net negative (-) charge.
- Hydrogen atoms have net positive (+) charges.

Water Molecule is Bent

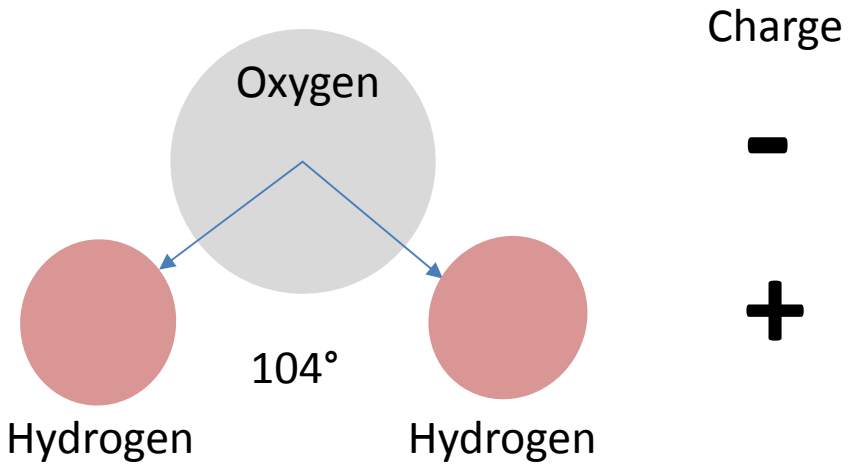
- Oxygen atom's preferred directions for covalent bonding are tetrahedral.
- Oxygen needs to share two electrons, thus two hydrogen atoms.
- Hydrogen atoms make a 104° angle





Water Molecule is Polarized

- The oxygen side of the water molecule is negatively charged.
- The hydrogen side is positively charged.
- This displacement of charge is called a "Dipole Moment"



Hydrogen Bonding

- No “free” water except in gas.
- Positive hydrogen atoms are electrostatically attracted to and attached to negative oxygen atoms through “hydrogen bonding.”
- Water attaches to other molecules and other water molecules through hydrogen bonds of varying strengths.
- Dielectric characteristics of grain are profoundly affected by hydrogen bonding.

So, how to measure moisture content?

- Reference methods
  - Air oven
  - Other such as Karl Fischer
- NIR
- Dielectric spectroscopy

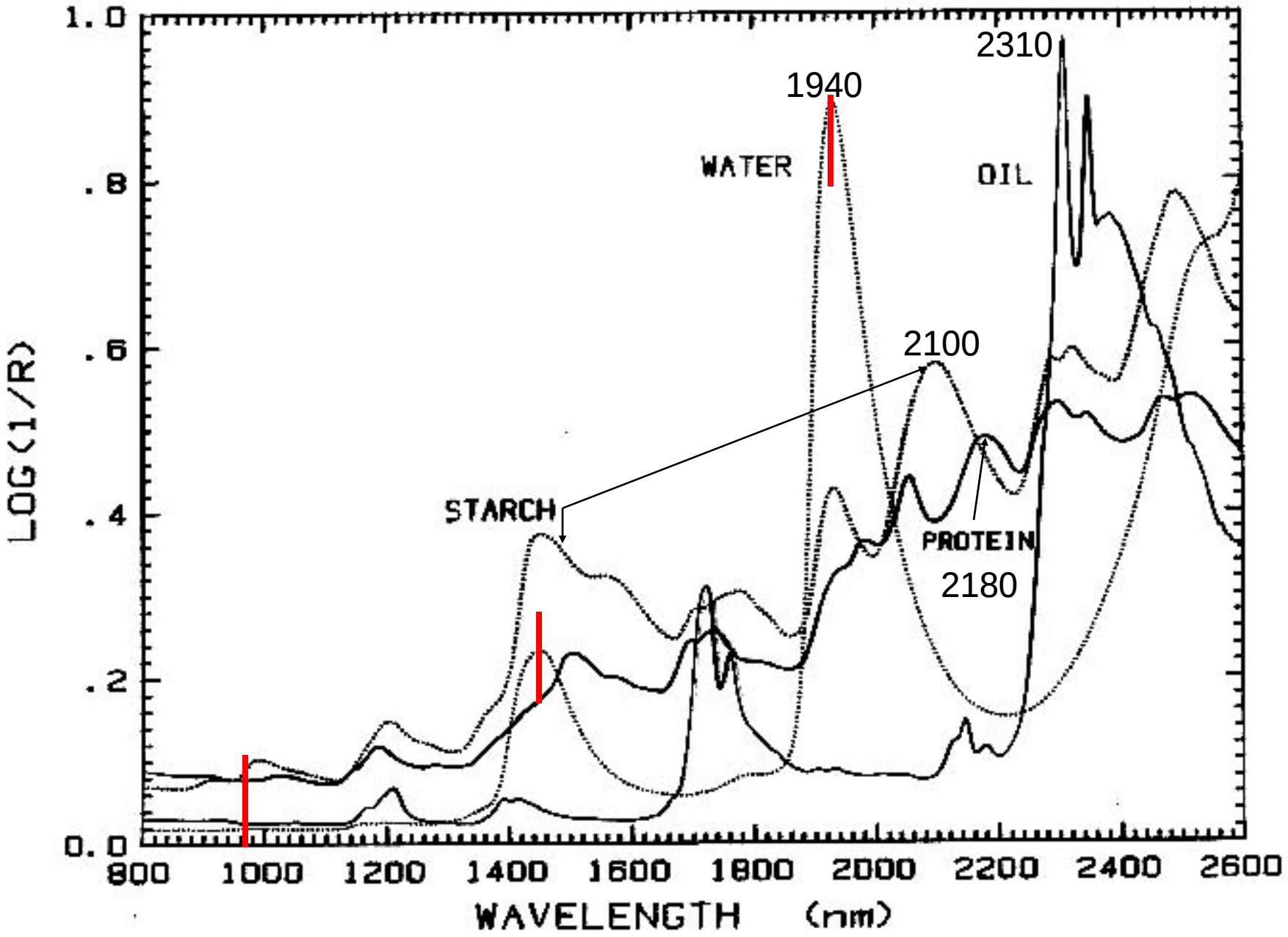
Air Oven Method

- Mass loss on drying
- Not absolute method—affected by many factors:
  - Oven temperature
  - Length of time grain/flour is in oven
  - Relative humidity of laboratory air
  - Amount of air circulation in oven
  - Grain/flour particle size
  - Depth of grain/flour in drying vessel
- Possibility of non-aqueous material loss
- Air oven methods specify drying time, temperature, particle size etc. to match more basic methods and amount of dry matter accessible in processing.

NIR and Dielectric Methods

Water Molecule Interacts with Electric Fields

- Static Electric Fields
- Alternating Electric Fields
  - Audio frequencies
  - Radio frequencies
  - Microwave frequencies
  - Light



Source: Karl Norris

NIR and Dielectric Moisture Meters Use Very Different Frequencies

Technology	Wavelength	Frequency
NIR	1.94×10^{-6} m	1.5×10^{14} Hz
UGMA	2 m	1.5×10^{8} Hz
Model 919	17 m	1.8×10^{7} Hz
GAC 2100	150 m 60 km	2.0×10^{6} Hz 5.0×10^{3} Hz

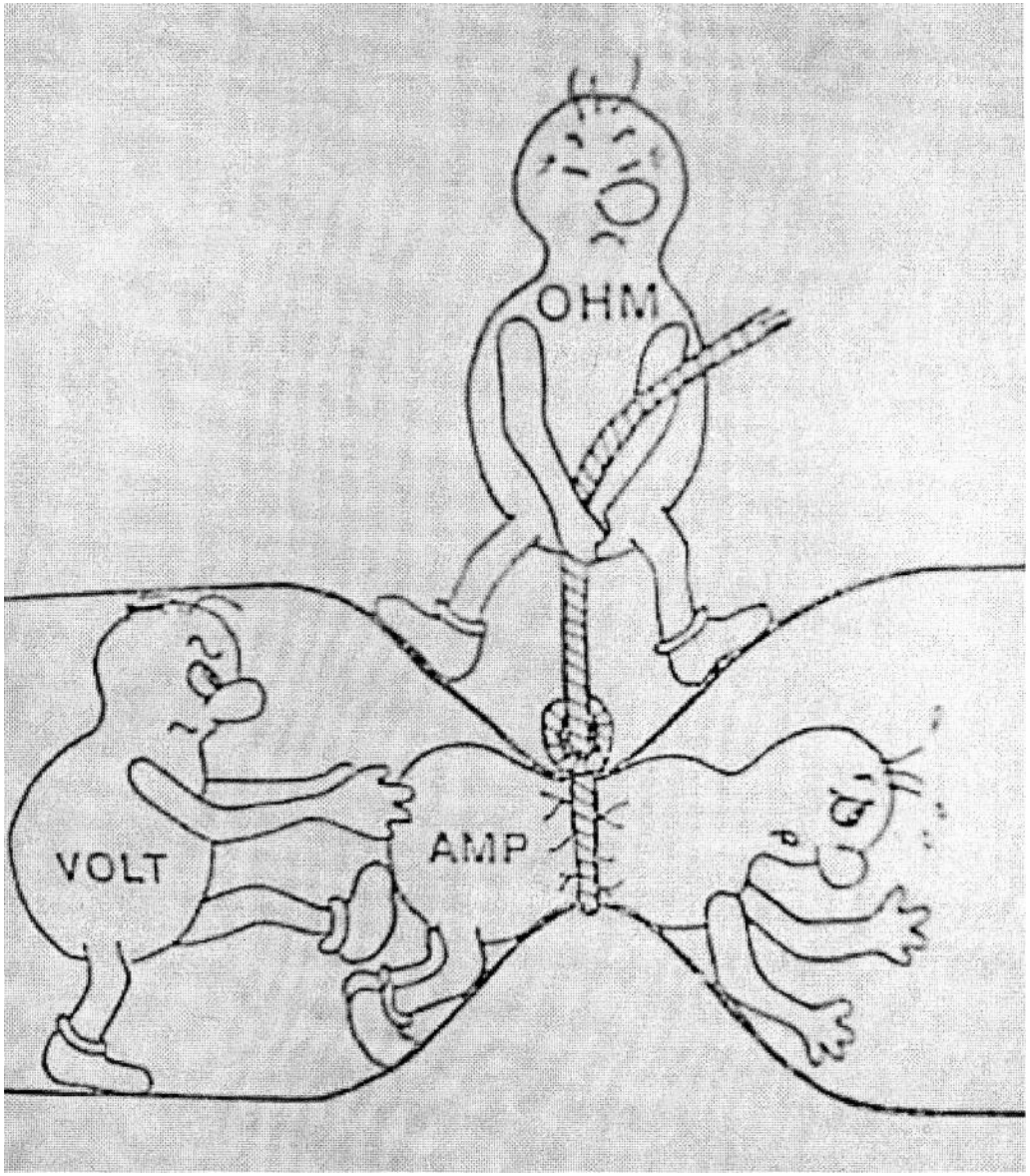
Dielectric Spectroscopy

- Moisture measurements by dielectric spectroscopy also depend upon the interaction of electric fields with the water molecule's dipole moment—but in reorientation, not vibration.

Basic Units for Electricity

Resistance

Pressure

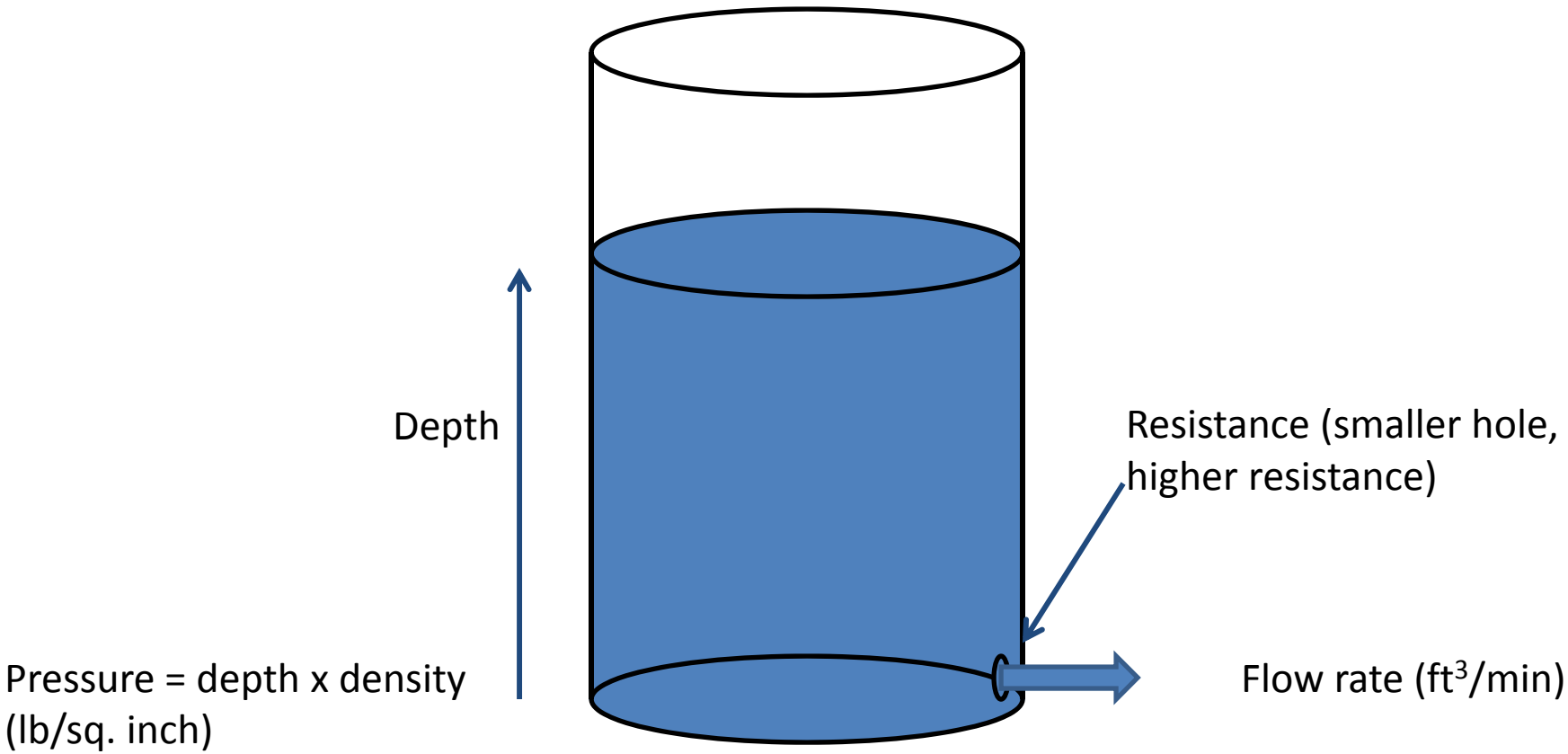


Ohm's Law

Current=$\frac{\text{Pressure}}{\text{Resistance}}$

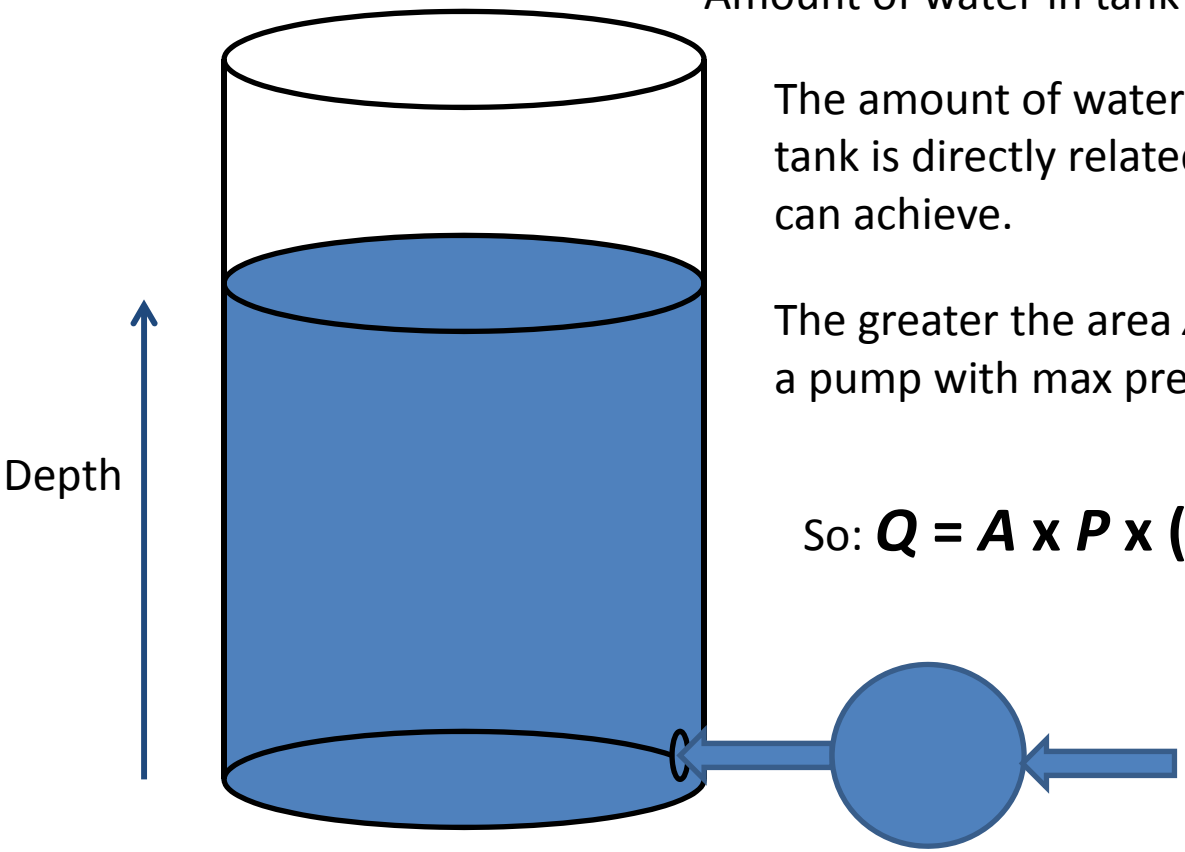
Current
(Coulombs/sec)

Water Analogy



Flow = Pressure/Resistance

Water Analogy for Capacitance



Amount of water in tank ***Q*** = depth x area of surface

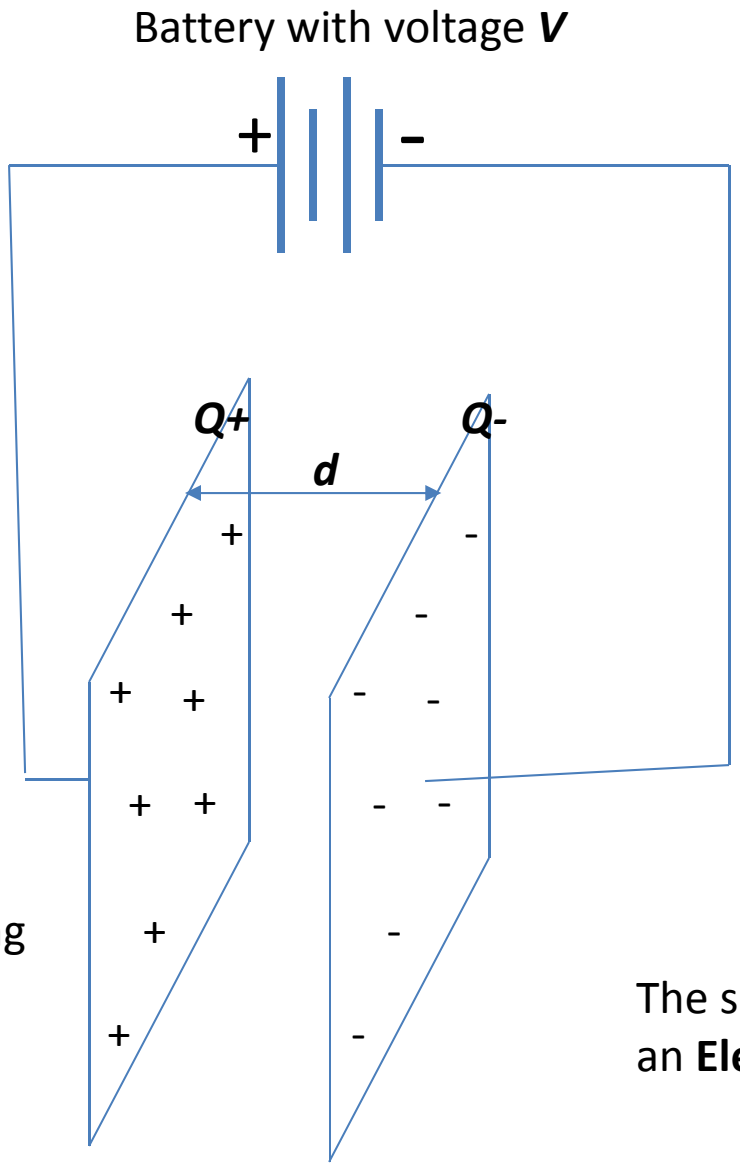
The amount of water ***Q*** the pump can force into the tank is directly related to the pressure ***P*** the pump can achieve.

The greater the area ***A*** of the tank, the more water a pump with max pressure ***P*** can force into it.

So: ***Q* = *A* x *P* x (a constant)**

Pump capable of maximum pressure "***P***"

Capacitance



The amount of charge ***Q*** separated on the facing plates is proportional to the voltage ***V*** of the battery and the area ***A*** of the facing plates.

Capacitance *C* = *Q/V*

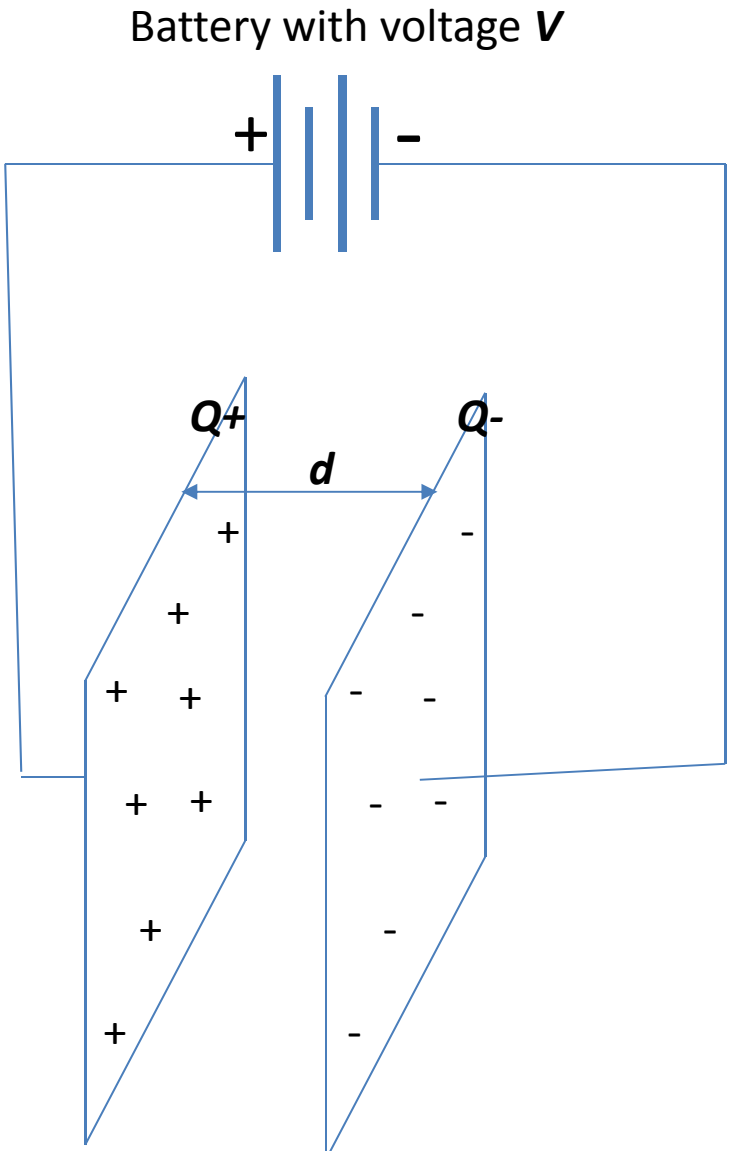
For a capacitor formed by parallel plates of area ***A*** in air , separated by distance ***d***,

$C = \varepsilon_0 \times A/d$

Where ε_0 is the permittivity of free space = $8.85 * 10^{-12}$ Farad/meter

The space between the two plates contains an **Electric Field *E*** (volts/meter).

Relative Dielectric Constant



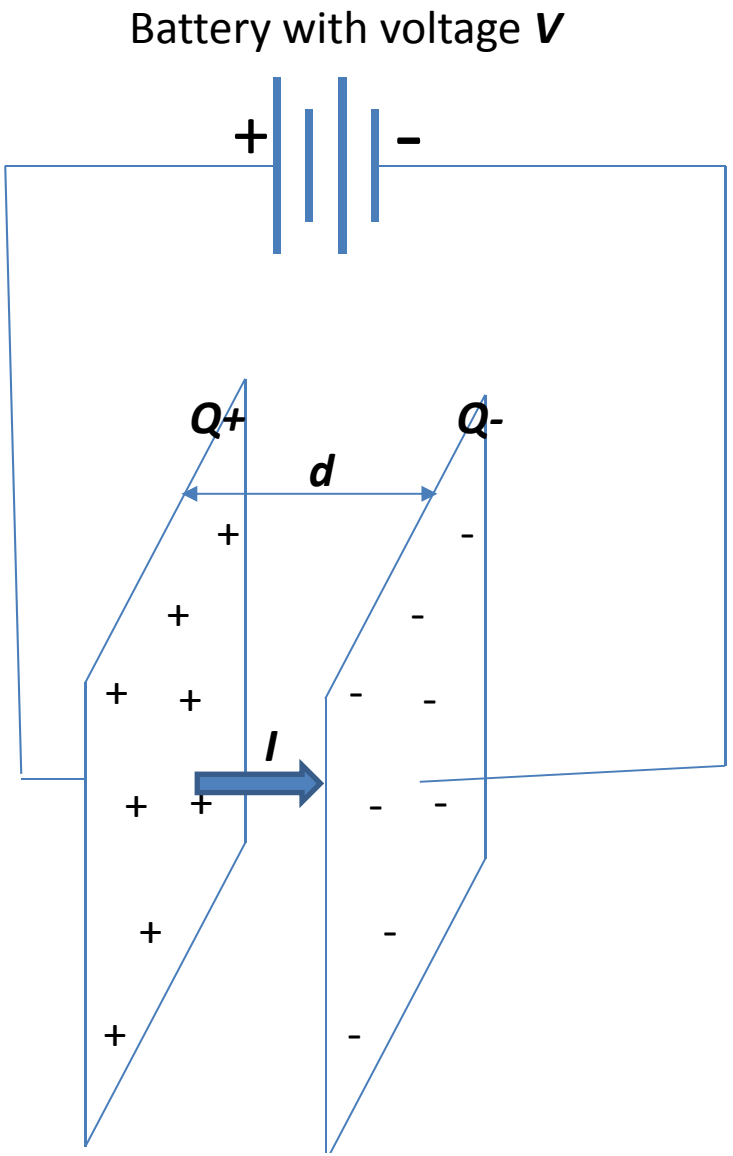
If the space between the plates is filled by some material other than air, more charge can be stored on the capacitor for the same voltage applied to the capacitor. The ratio of the capacitance with material present to the capacitance with air is the **relative dielectric constant ε_r .**

$$C = \varepsilon_0 \times \varepsilon_r \times A/d$$

For air, ε_r **= 1.000**

Since the relative dielectric constant of other non-conducting materials is greater than 1.0, the capacitor with some material other than air as its "dielectric" can store more charge for the same impressed voltage ***V***.

Conductance

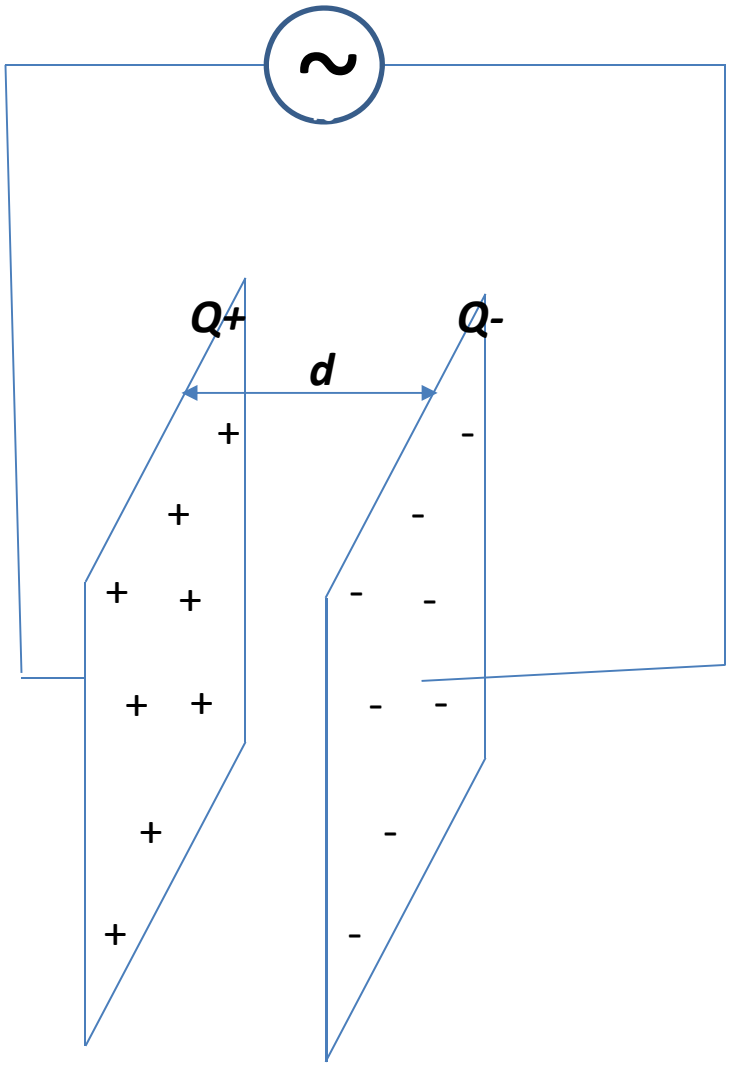


If the material between the plates is not a perfect insulator, current may flow from plate to plate.

Conductance of the dielectric (***G***) is defined as 1/resistance of the dielectric.

***G* = *I* (current)/*V* (voltage)**

With Alternating Voltage Drive



The situation gets much more “complex” in many ways.

Dielectric constant and conductance vary with the frequency of the driving voltage.

Polar water molecules attempt to reorient to align with the time-varying electric field.

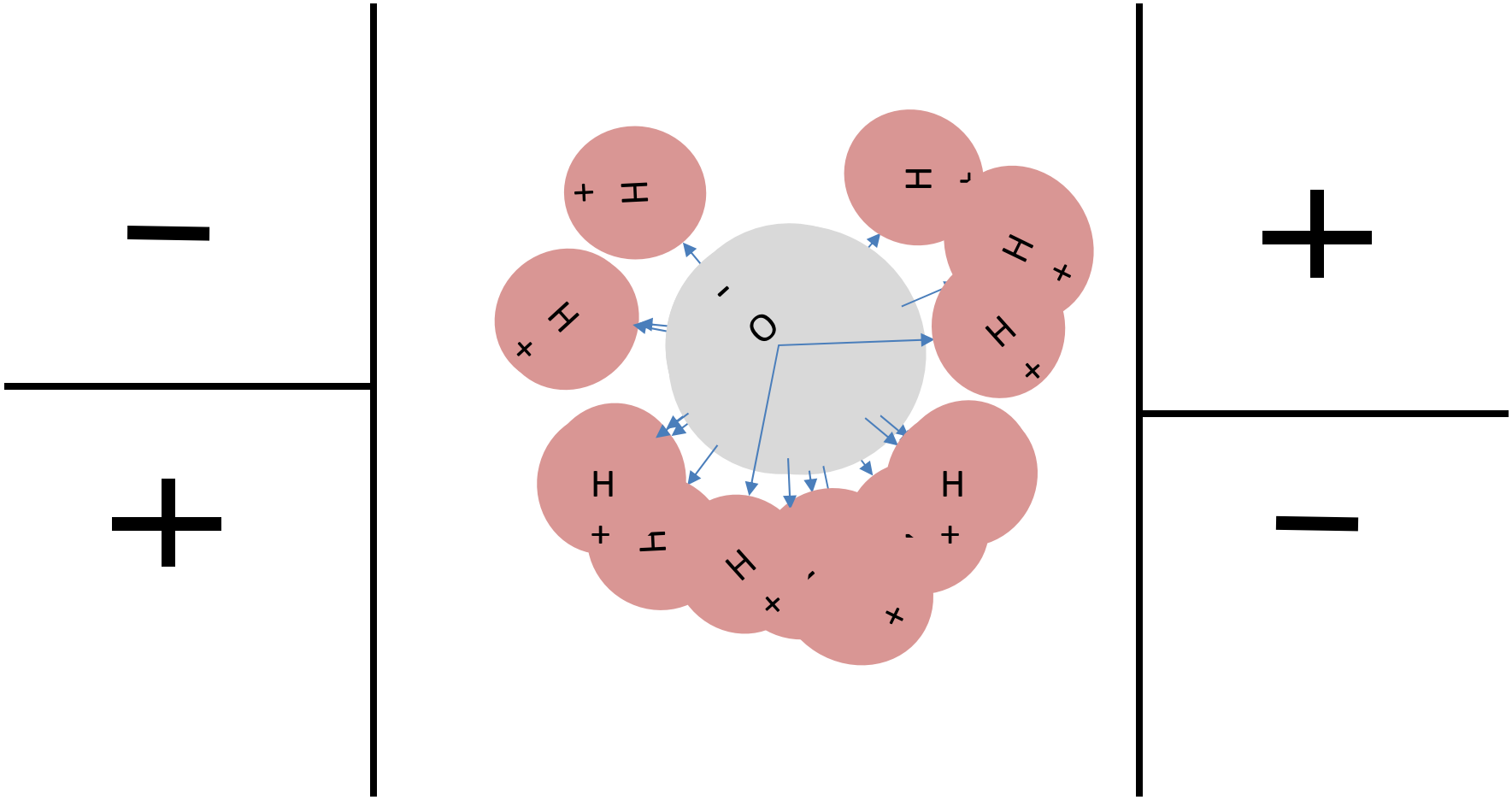
Complex Permittivity

$$\varepsilon^* = \varepsilon_0 \cdot (\varepsilon'_r - j \cdot \varepsilon''_r)$$

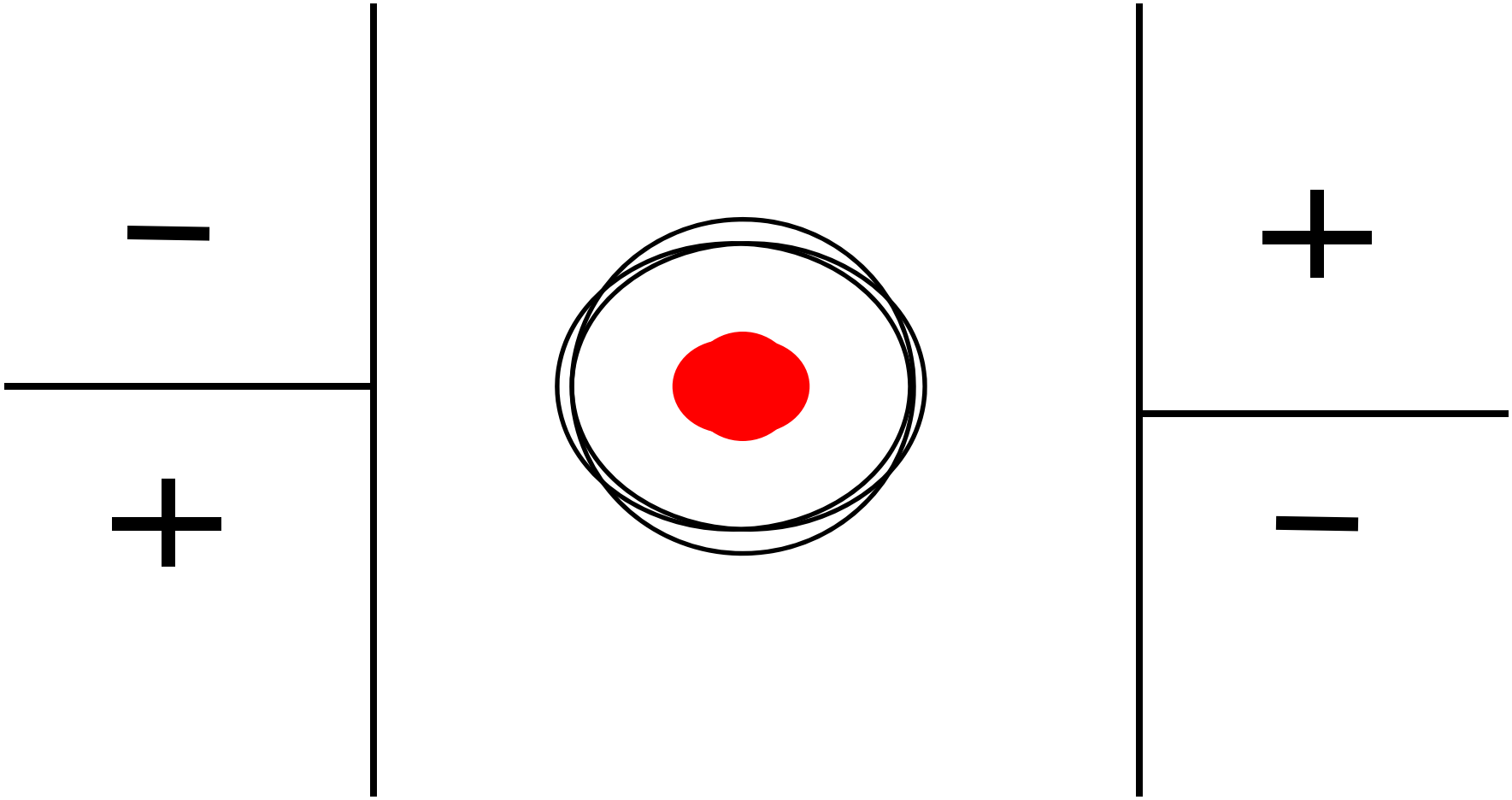
ε'_r : dielectric constant = real part of relative complex permittivity (energy stored per cycle)

ε''_r : loss factor = imaginary part of relative complex permittivity (energy dissipated per cycle)

Water Molecules React to Electric Fields by Rotating



Non-polar Atoms & Molecules React to Electric Fields by Slight Shape Shifting



Dielectric Constant

- Dielectric constant is a physically-defined, measurable material property.
- For liquid water at room temperature, $\varepsilon'_r = 78.5$
- For non-polar grain constituents, $\varepsilon'_r = 2$ to 3
- Therefore, measurements of dielectric constant are closely related to moisture content.
- Dielectric constant ranges from about 2 for very dry grain to about 8 for high moisture grain.
- But measurements are related to the mass of water in the test cell—not the percent water by weight, so results must be density-compensated.

Grain Conductivity Effects

- Grain is not a perfect insulator—that is, it conducts electricity to some extent.
- Grain conductivity interferes with the more useful capacitance measurements.
- Conductivity increases rapidly with increasing moisture content.
- Conductivity increases rapidly with increasing temperature.
- Conductivity decreases relative to capacitance at higher measurement frequencies.
- Conductivity interferes less with moisture measurements at higher frequencies.

On to Moisture Meters

- Model 919
- GAC II/2100
- UGMA

Nov. 2, 1954 K. M. GREENWOOD ET AL 2,693,575

MOISTURE DETERMINING DEVICE FOR MATERIALS

Filed Dec. 1, 1951 2 Sheets-Sheet 1

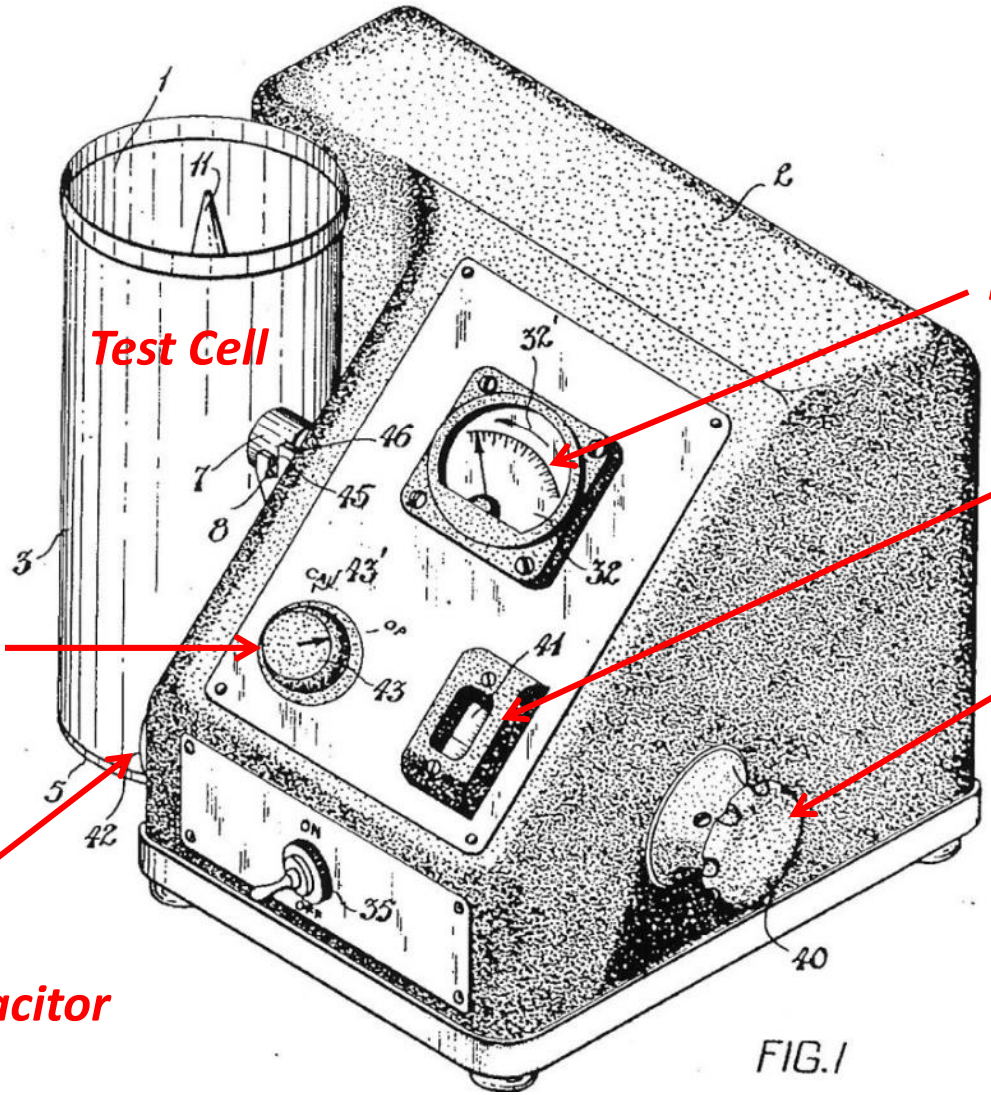
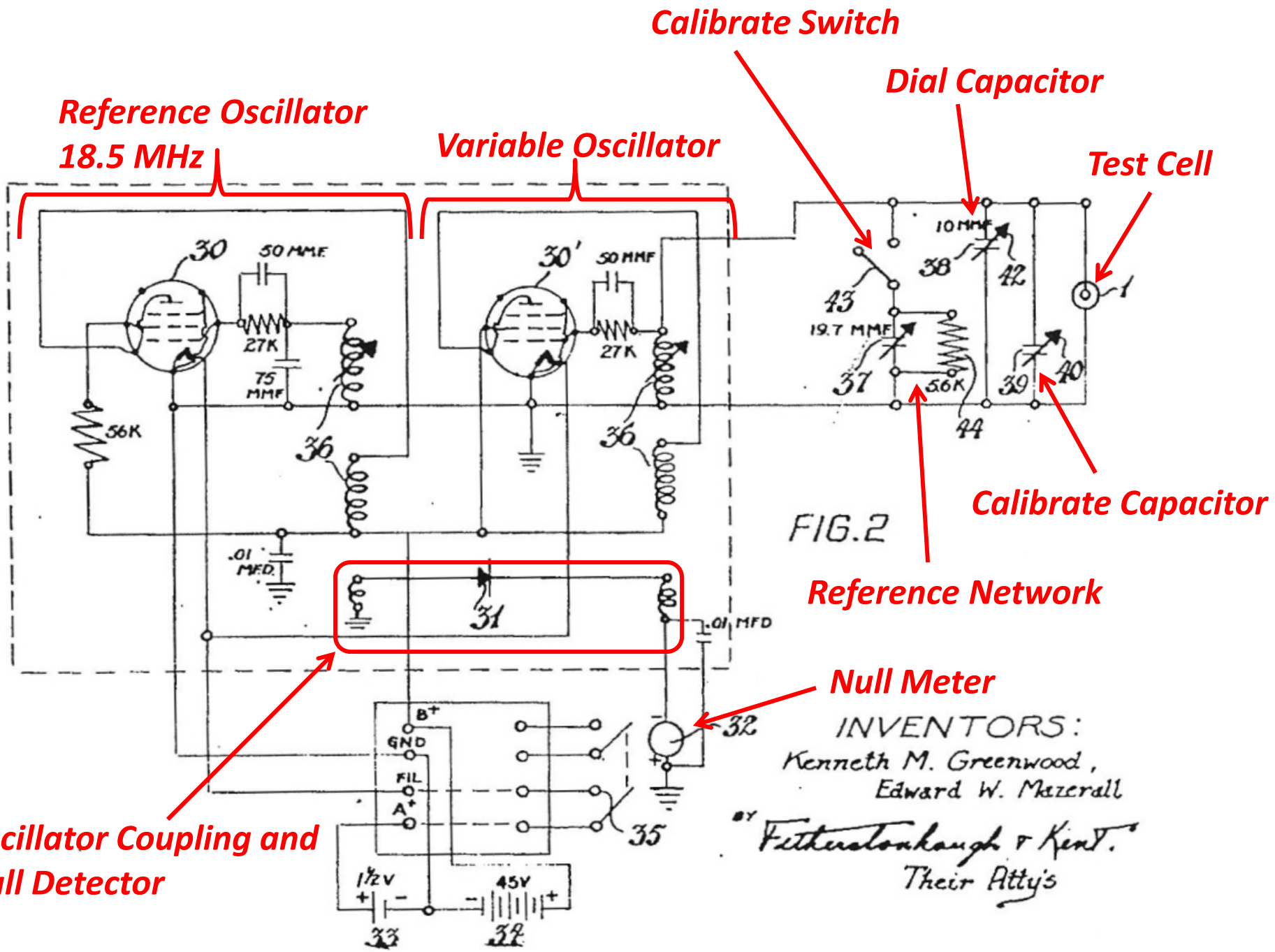


FIG. 1

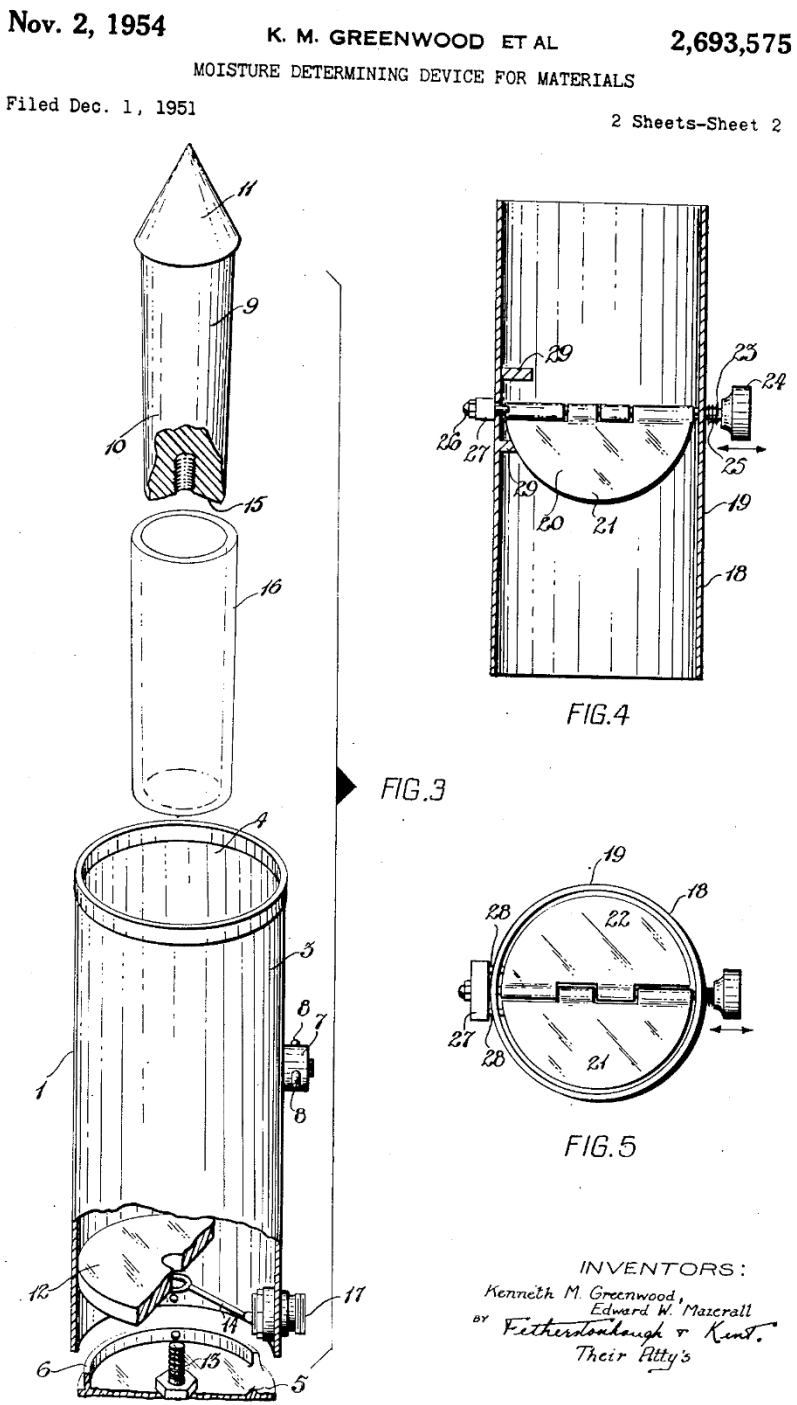

Calibrate Switch
Dial Capacitor
Reference Oscillator
18.5 MHz
Variable Oscillator
Test Cell
30
50 MMF
27K
75 MMF
56K
36
30'
50 MMF
27K
36
10 MMF
38
42
43
19.7 MMF
37
56K
44
39
40
1
.01 MFD.
31
.01 MFD
Calibrate Capacitor
FIG. 2
Reference Network
Null Meter
B+
GND
FIL
A+
32
35
Oscillator Coupling and
Null Detector
1½V
45V
33
34
INVENTORS:
Kenneth M. Greenwood,
Edward W. Mazerall
BY Fetherstonhaugh & Kent
Their Atty's

Model 919 Operating Principle

- Measure temperature manually before moisture test.
- Weigh out specified mass for specific grain type.
- “Calibrate” 919 by nulling meter with test cell empty.
- Pour weighed sample into loading fixture and drop it into test cell.
- Re-null meter and read value from capacitor dial.
- Dial Capacitor + Calibrate Capacitor + Test Cell Capacitor = Constant
- Change in dial capacitor to achieve null (variable oscillator matches reference oscillator) = increase in test cell capacitance due to grain
- Dial position (capacitance added in test cell) used in lookup table to find predicted moisture.
- Externally measured sample temperature used with lookup table to provide temperature compensation.

Model 919 Test Cell

- Achieved moderate density compensation
- Tapered aluminum center electrode
- Doubly tapered acrylic sleeve



Nov. 2, 1954 K. M. GREENWOOD ET AL 2,693,575

MOISTURE DETERMINING DEVICE FOR MATERIALS

Filed Dec. 1, 1951 2 Sheets-Sheet 2

FIG.3

FIG.4

FIG.5

INVENTORS:
Kenneth M. Greenwood,
Edward W. Mazerall
BY Fetherstonhaugh & Kent.
Their Atty's

Model 919

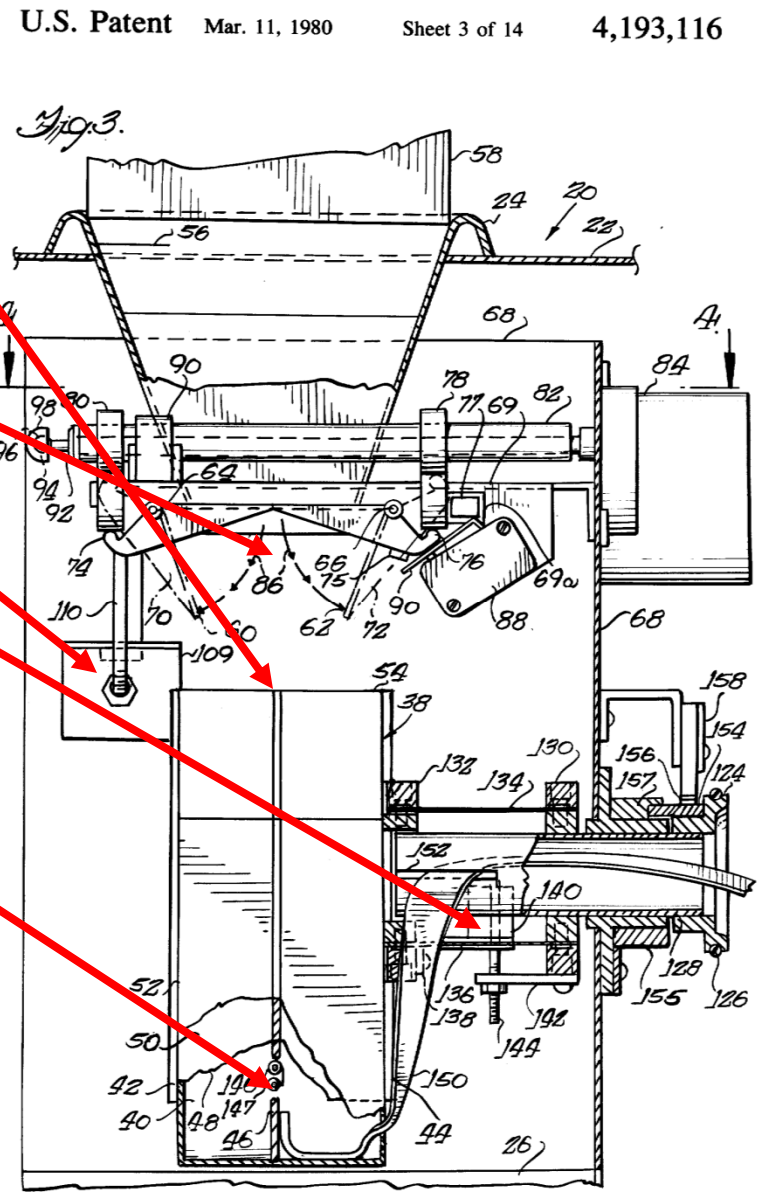
- Strengths
- Weaknesses

GAC 2100

- Originally designed in 1976-1977 (GAC II version)
- First U.S. fully automated moisture meter.
- Adopted as FGIS Official meter in 1998.

GAC II/2100 Operating Principle

- Grain dropped into parallel-plate test cell and struck off by arm with stretched spring.
- Grain mass measured with simple electronic scale system supporting test cell.
- Grain temperature measured by simple temperature sensor at bottom of test cell.
  - Temperatures measured at two times used to predict final temperature without waiting for stabilization.
- Capacitance (actually admittance) measured at two frequencies: 2 MHz and 5 kHz.
- Measurement at 5 kHz used for rough correction for grain conductivity.
- Mathematically corrected for sample temperature and density.
- Predicted moisture with proprietary equation.



GAC 2100

- Strengths
- Weaknesses

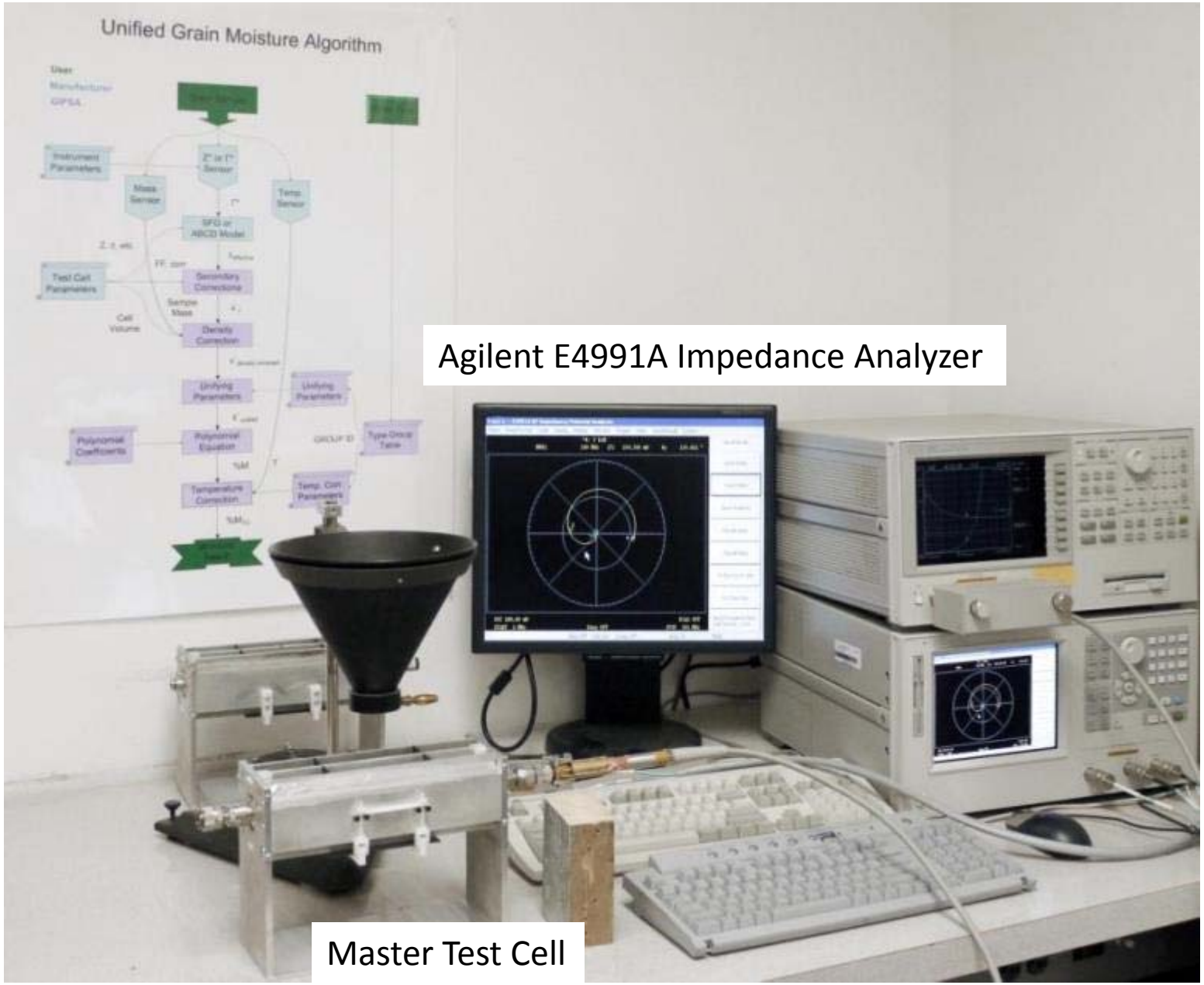
How and why did GIPSA develop the Unified Grain Moisture Algorithm?

- UGMA was the result of extensive GIPSA research and GIPSA-supported research from 1997 to 2011.
- The goal was to develop a superior moisture measurement method and document it so completely that multiple manufacturers could create compatible instruments.

What is GIPSA's Unified Grain Moisture Algorithm (UGMA)?

- Very accurate dielectric-type moisture method
- Higher measurement frequency (about 149 MHz)
- Based on a defined physical parameter—
  - Dielectric Constant
- Precise grain mass measurement and excellent density correction
- Three "unifying parameters" per grain group
- A single calibration "curve" for all grain types
- Precise, wide-range temperature correction
- Calibrated to GIPSA's standard Air Oven method
- "Open"—Available to any manufacturer

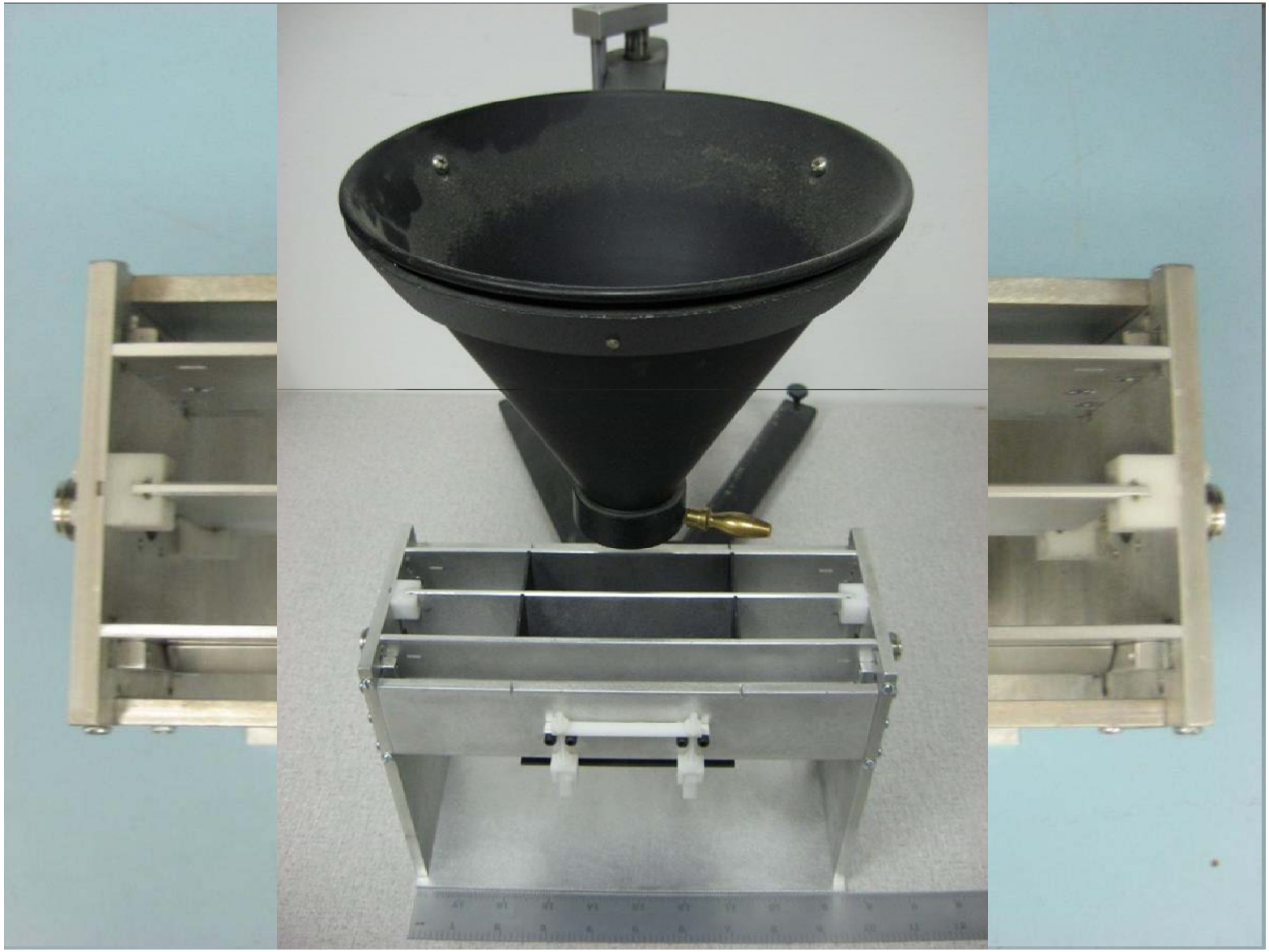
GIPSA's Reference System



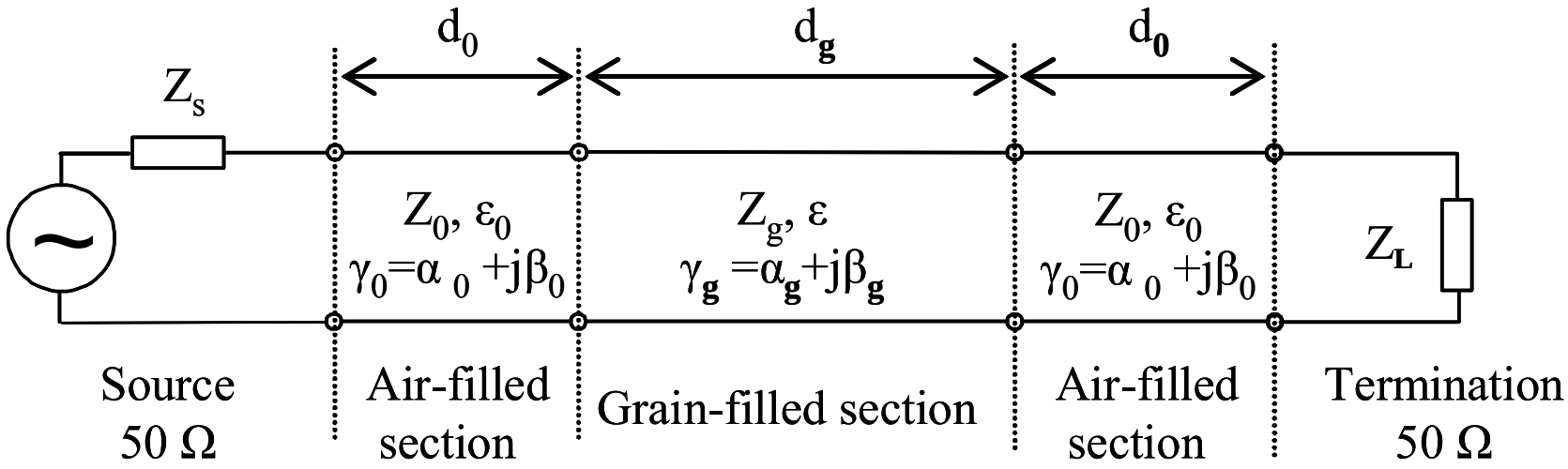
Operation at 149 MHz requires completely different electronics and mathematics.

- The test cell is a significant fraction of the wavelength of the signal (2 meters) so phase differences are extremely important.
- Must describe the test cell mathematically using microwave transmission line techniques.
- Multiple reflections occur within the test cell and yield very complex signals.
- Describing the test cell mathematically permits deducing the grain dielectric constant that would cause the observed reflected wave.

UGMA Test Cell



Convert Reflection Coefficient to Dielectric Constant with (Simplified) ABCD Matrix Model



Fortunately, the user need not understand the horrendous mathematics involved!

$$\text{ABCD}(\varepsilon g, f, d_1, d_2, em, ZC, L, C, ZL, \alpha) :=$$

$\omega \leftarrow f \cdot 2 \cdot \pi$

$c \leftarrow 299792458$

$r \leftarrow 0$

$(Z01 \leftarrow 50 \quad Z02 \leftarrow 50)$

$(d3 \leftarrow d_1 \quad d5 \leftarrow d_2 \quad d7 \leftarrow d_1)$

$(\varepsilon 3 \leftarrow 1 - 1i \cdot r \quad \varepsilon 5 \leftarrow \varepsilon g \quad \varepsilon 7 \leftarrow 1 - 1i \cdot r)$

$\left(Z3 \leftarrow ZC \cdot \frac{1}{\sqrt{\varepsilon 3}} \quad Z5 \leftarrow \frac{ZC}{\sqrt{\varepsilon 5}} \quad Z7 \leftarrow ZC \cdot \frac{1}{\sqrt{\varepsilon 3}}\right)$

$\left(\gamma 3 \leftarrow \alpha + \omega \cdot \frac{\sqrt{\varepsilon 3}}{c} \cdot 1i \quad \gamma 5 \leftarrow \alpha + \omega \cdot \frac{\sqrt{\varepsilon 5}}{c} \cdot 1i \quad \gamma 7 \leftarrow \alpha + \omega \cdot \frac{\sqrt{\varepsilon 7}}{c} \cdot 1i\right)$

$(pZ1 \leftarrow 1i \cdot \omega \cdot L \cdot 10^{-9} \quad pZ2 \leftarrow 1i \cdot \omega \cdot L \cdot 10^{-9})$

$Y \leftarrow 1i \cdot \omega \cdot C \cdot 10^{-12}$

$$\begin{pmatrix} A2 & B2 \\ C2 & D2 \end{pmatrix} \leftarrow \begin{pmatrix} 1 & pZ2 \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ Y & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & pZ1 \\ 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} A8 & B8 \\ C8 & D8 \end{pmatrix} \leftarrow \begin{pmatrix} 1 & pZ1 \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ Y & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & pZ2 \\ 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} A3 & B3 \\ C3 & D3 \end{pmatrix} \leftarrow \begin{pmatrix} \cosh(\gamma 3 \cdot d3) & Z3 \cdot \sinh(\gamma 3 \cdot d3) \\ \frac{\sinh(\gamma 3 \cdot d3)}{Z3} & \cosh(\gamma 3 \cdot d3) \end{pmatrix}$$

$$\begin{pmatrix} A5 & B5 \\ C5 & D5 \end{pmatrix} \leftarrow \begin{pmatrix} \cosh(\gamma 5 \cdot d5) & \sinh(\gamma 5 \cdot d5) \cdot Z5 \\ \frac{\sinh(\gamma 5 \cdot d5)}{Z5} & \cosh(\gamma 5 \cdot d5) \end{pmatrix}$$

$$\begin{pmatrix} A7 & B7 \\ C7 & D7 \end{pmatrix} \leftarrow \begin{pmatrix} \cosh(\gamma 7 \cdot d7) & Z7 \cdot \sinh(\gamma 7 \cdot d7) \\ \frac{\sinh(\gamma 7 \cdot d7)}{Z7} & \cosh(\gamma 7 \cdot d7) \end{pmatrix}$$

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} \leftarrow \begin{pmatrix} A2 & B2 \\ C2 & D2 \end{pmatrix} \cdot \begin{pmatrix} A3 & B3 \\ C3 & D3 \end{pmatrix} \cdot \begin{pmatrix} A5 & B5 \\ C5 & D5 \end{pmatrix} \cdot \begin{pmatrix} A7 & B7 \\ C7 & D7 \end{pmatrix} \cdot \begin{pmatrix} A8 & B8 \\ C8 & D8 \end{pmatrix}$$

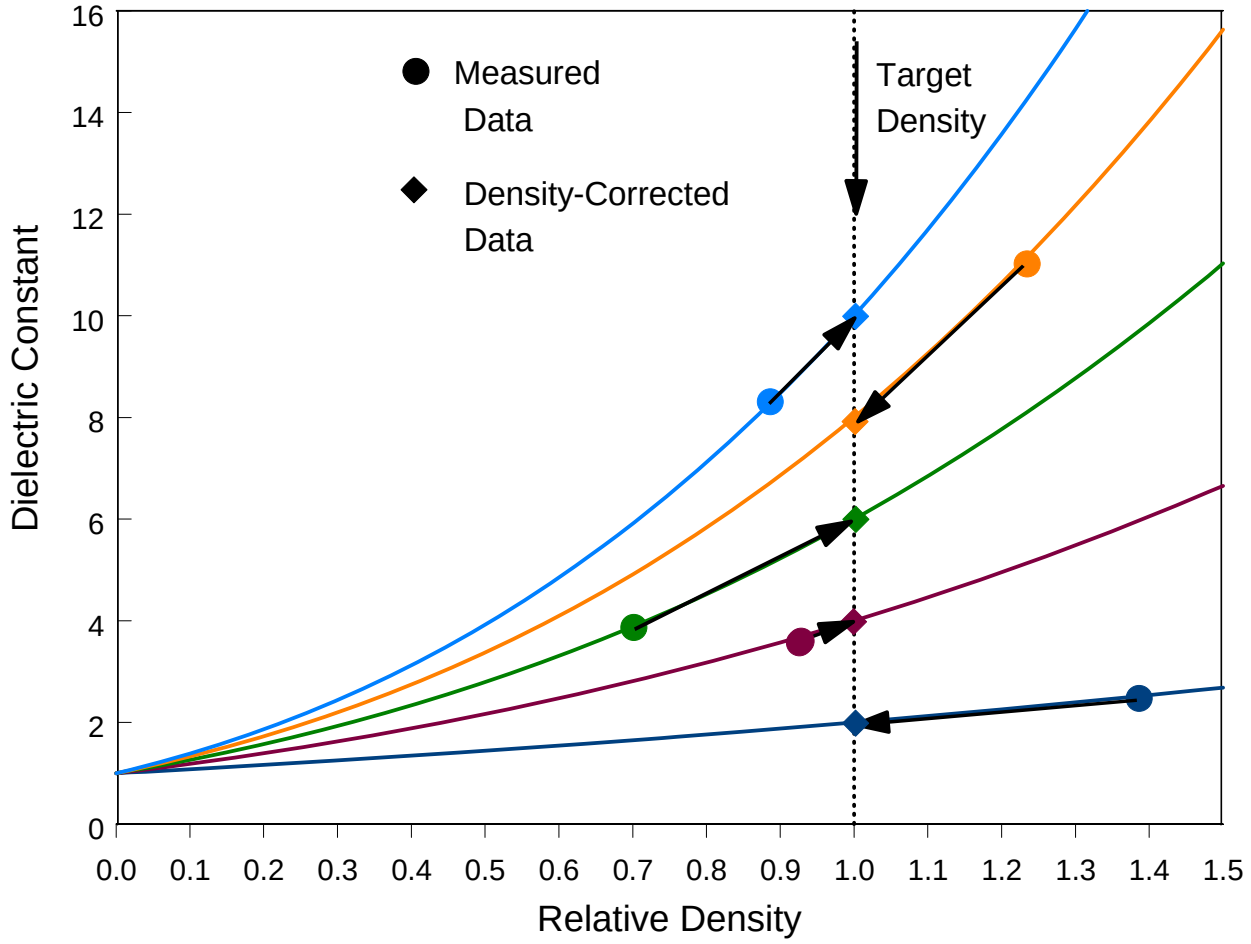
$$\begin{pmatrix} S11 & S12 \\ S21 & S22 \end{pmatrix} \leftarrow \begin{bmatrix} \frac{(B - C \cdot Z01 \cdot Z02) + A \cdot Z02 - D \cdot Z01}{(B + C \cdot Z01 \cdot Z02) + (A \cdot Z02 + D \cdot Z01)} & \frac{2 \cdot Z01 \cdot (A \cdot D - B \cdot C)}{(B + C \cdot Z01 \cdot Z02) + (A \cdot Z02 + D \cdot Z01)} \\ \frac{2 \cdot Z02}{(B + C \cdot Z01 \cdot Z02) + (A \cdot Z02 + D \cdot Z01)} & \frac{(B - C \cdot Z01 \cdot Z02) - (A \cdot Z02 - D \cdot Z01)}{(B + C \cdot Z01 \cdot Z02) + (A \cdot Z02 + D \cdot Z01)} \end{bmatrix}$$

$$\Gamma_L \leftarrow \frac{ZL - Z02}{ZL + Z02}$$

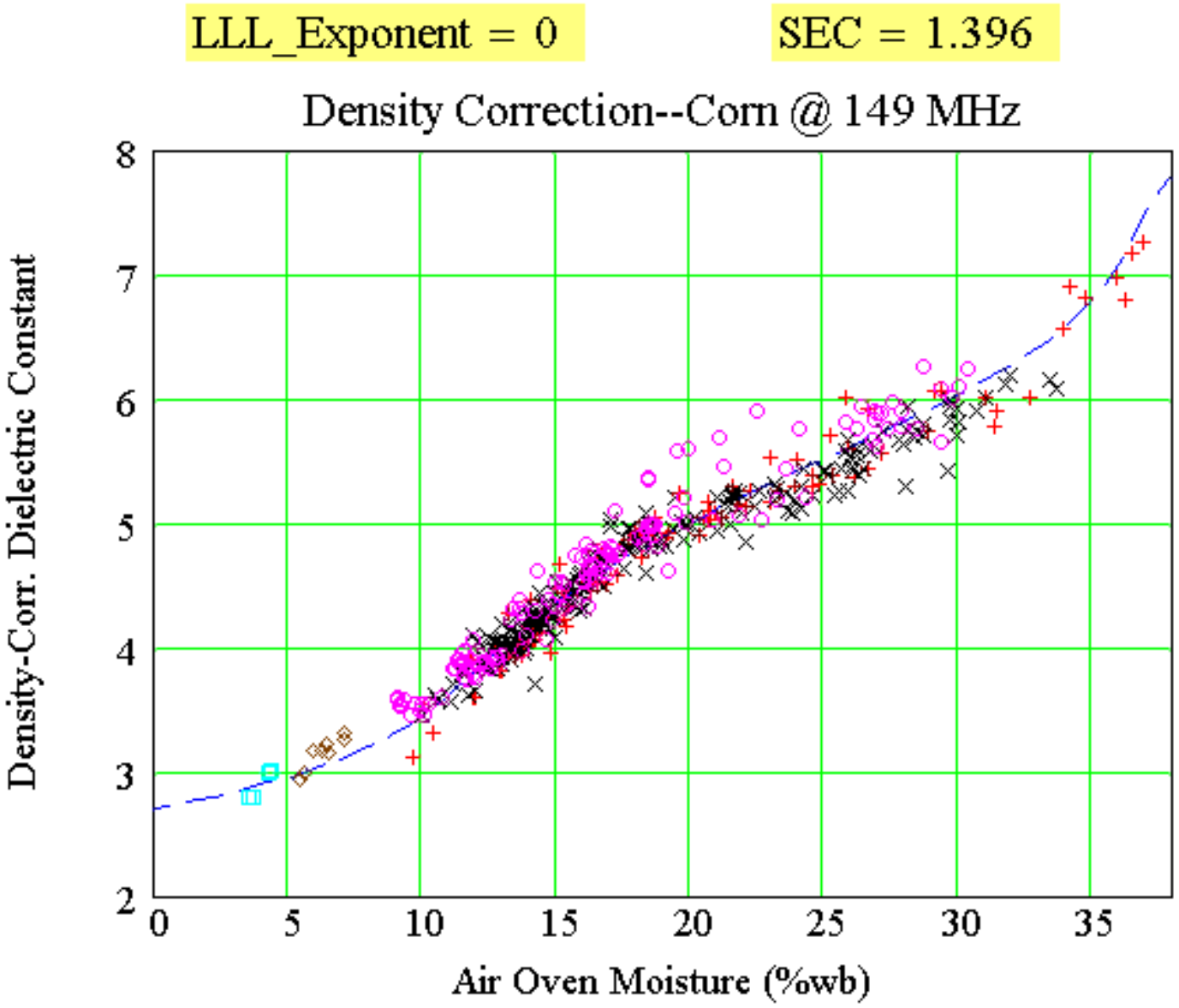
$$out \leftarrow \left(S11 + \frac{S12 \cdot \Gamma_L \cdot S21}{1 - S22 \cdot \Gamma_L}\right)$$

out

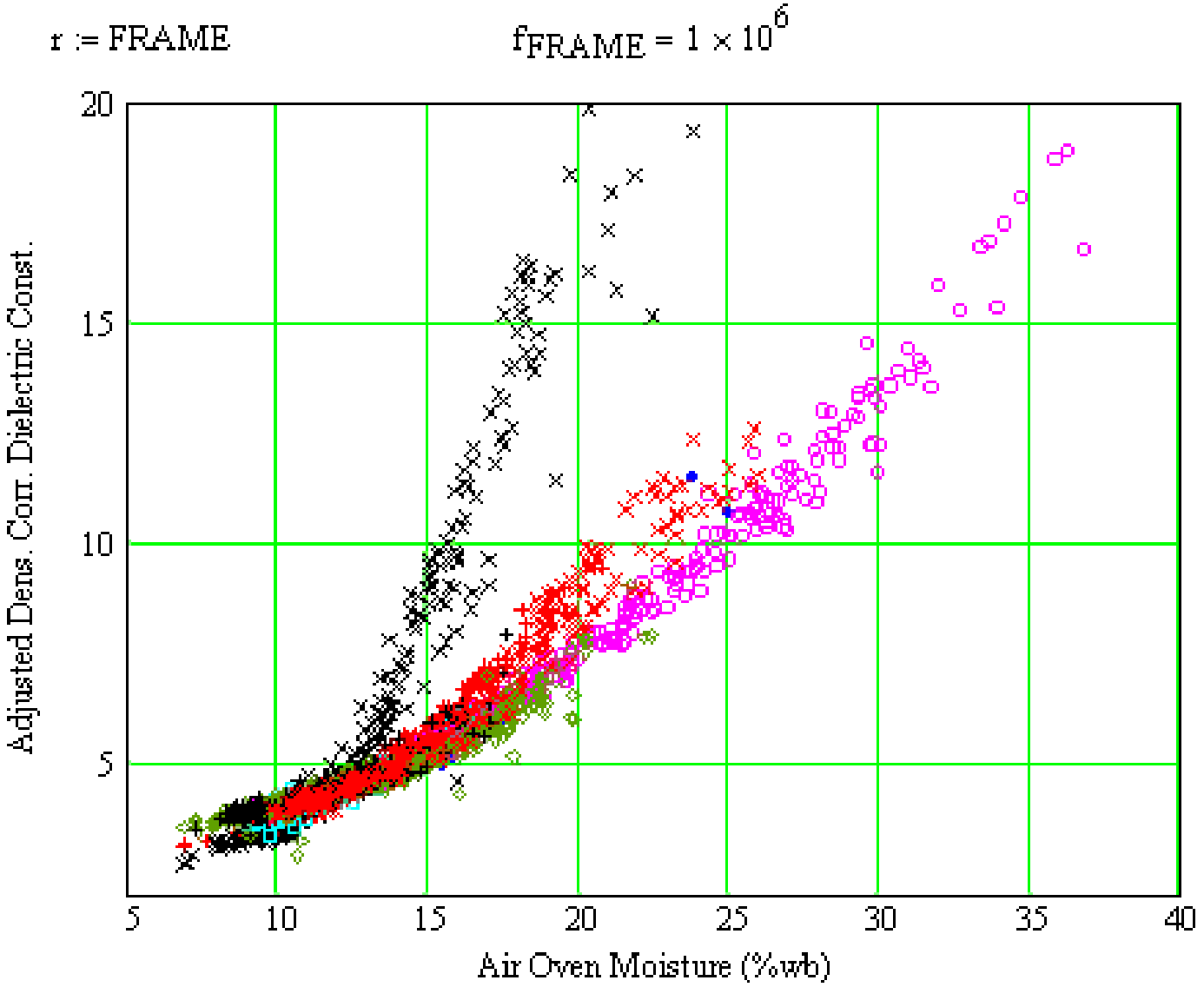
Sample densities are all normalized to a single density using special equation.



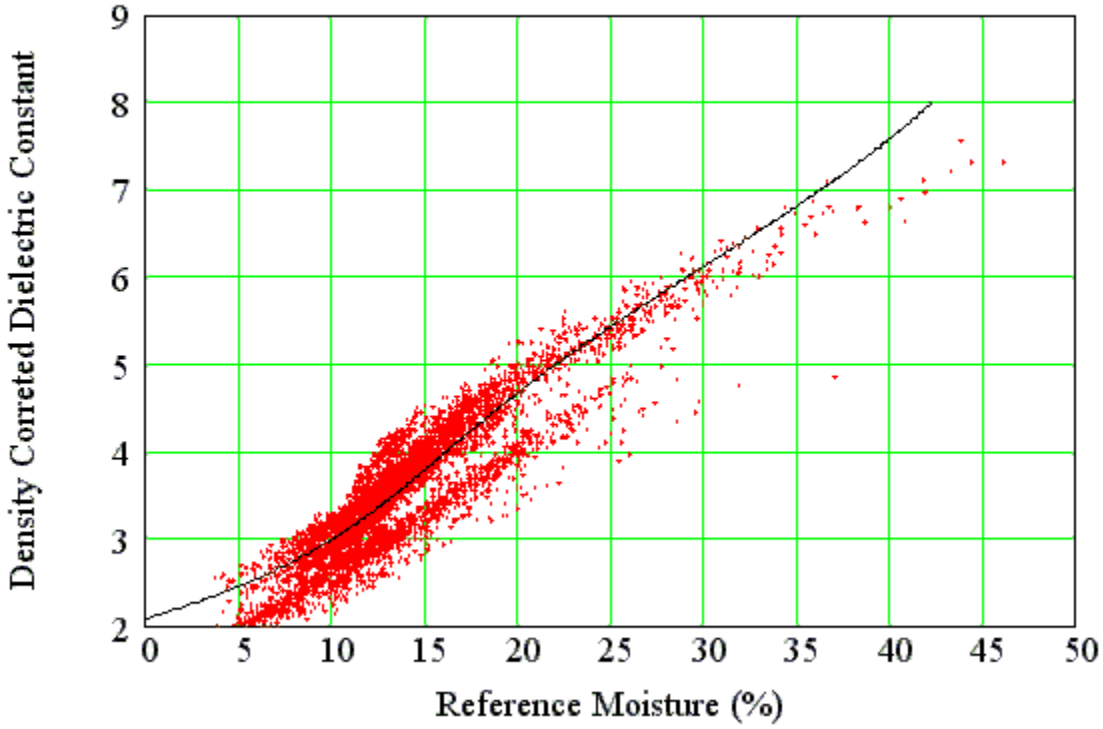
Eureka! #1: Effectiveness of the Landau-Lifshitz, Looyenga Density Correction



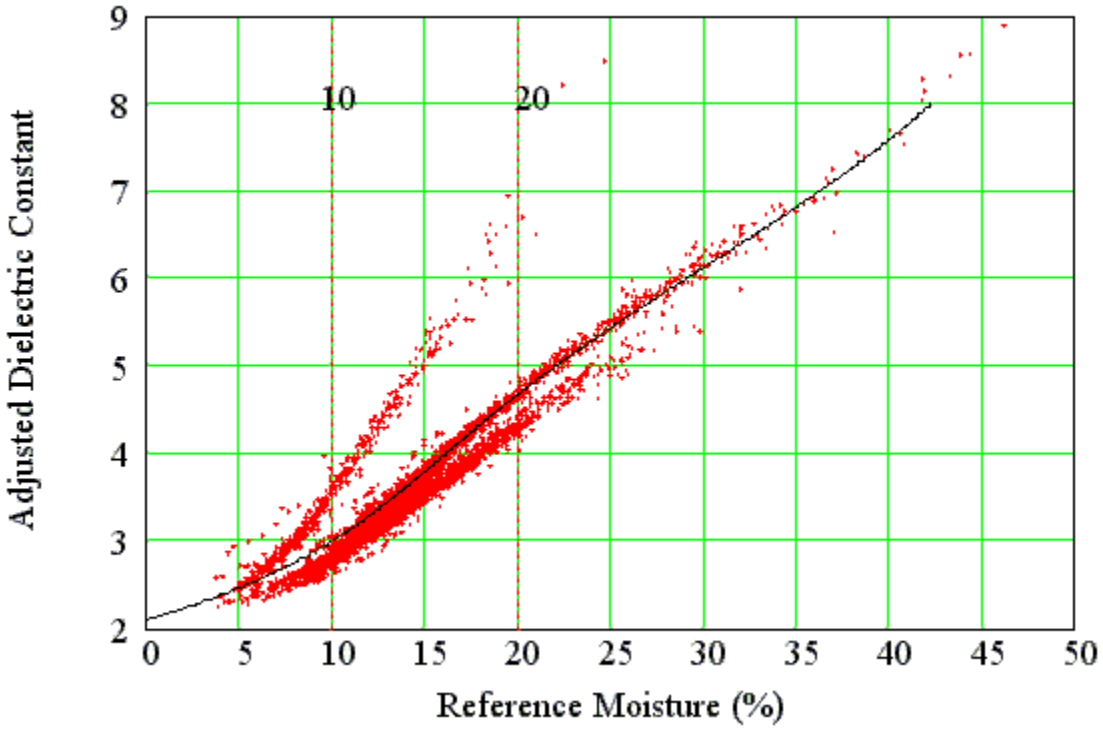
Eureka! #2: Geometrically-Similar Shapes in VHF Range



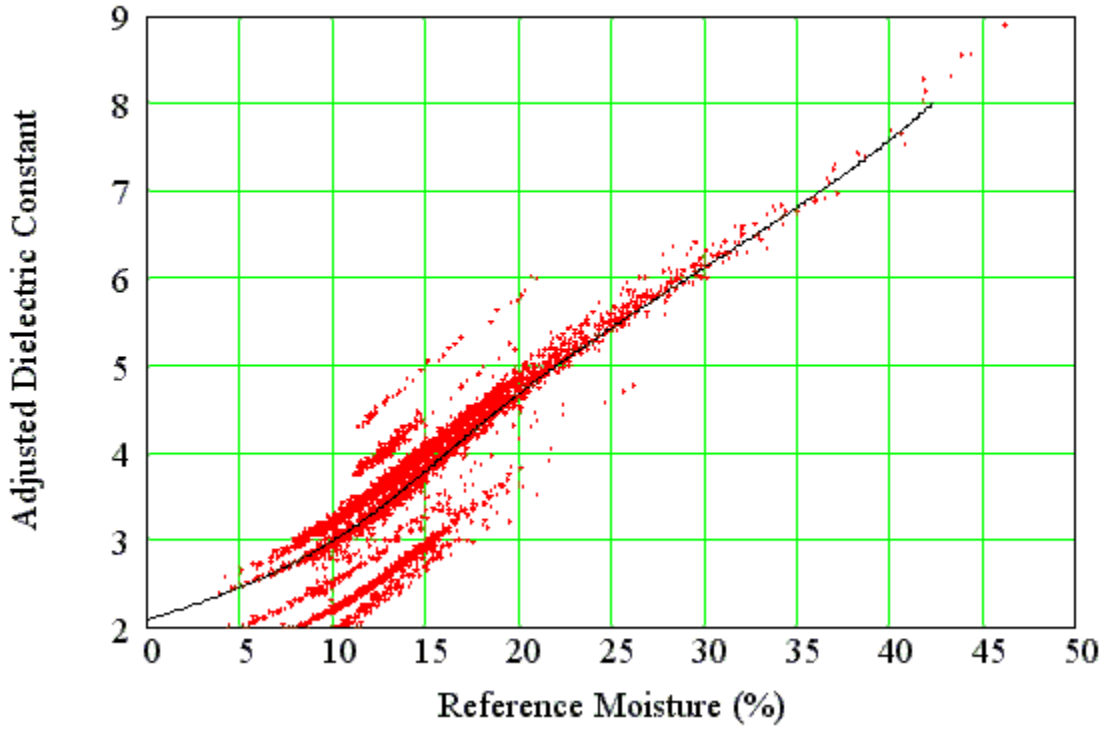
Landau-Lifshitz, Looyenga
Density Normalization



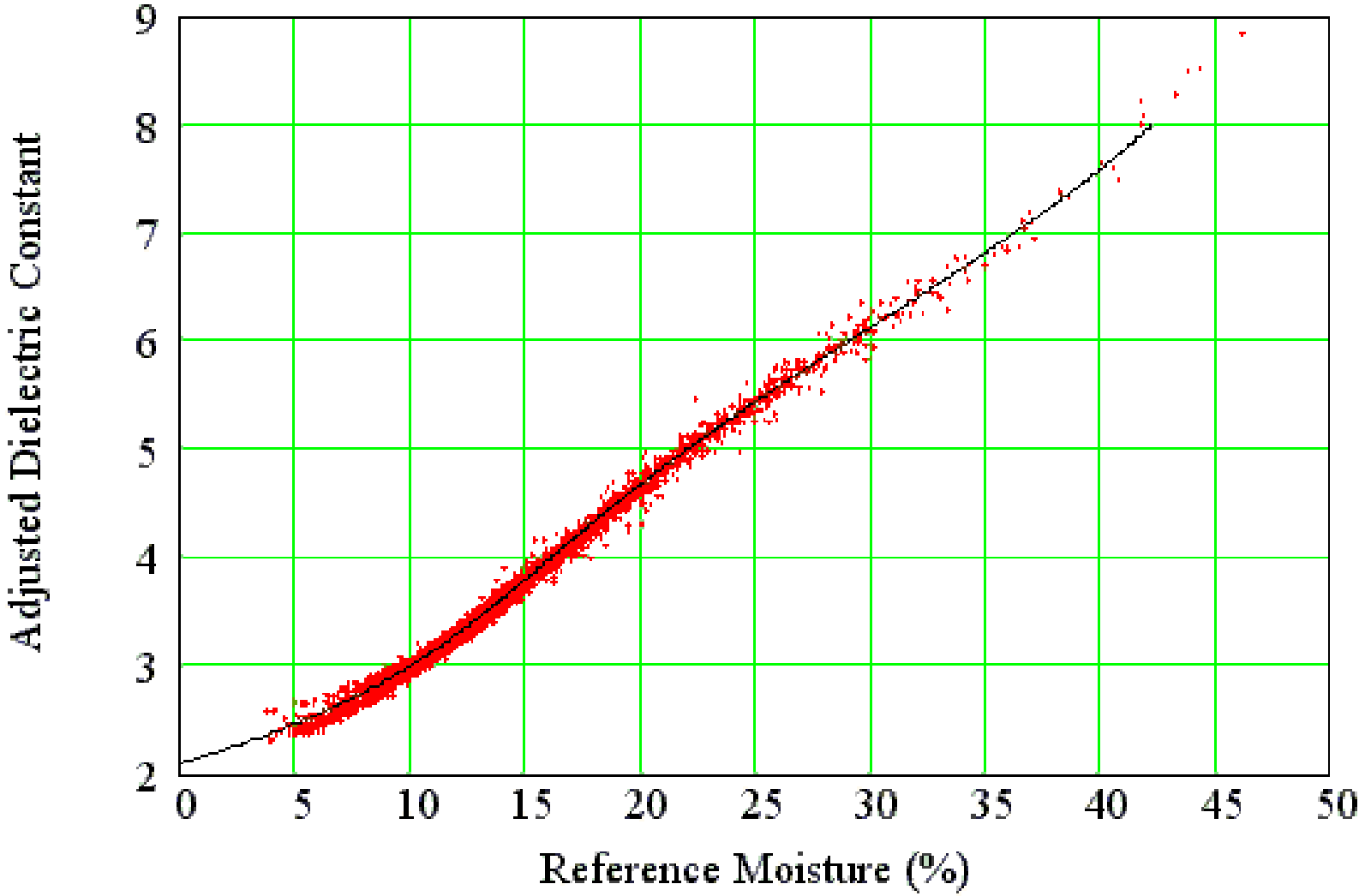
Adjust Slope Parameter for Slope of 6.0 %M per unit dielectric constant in 10-20 % Range



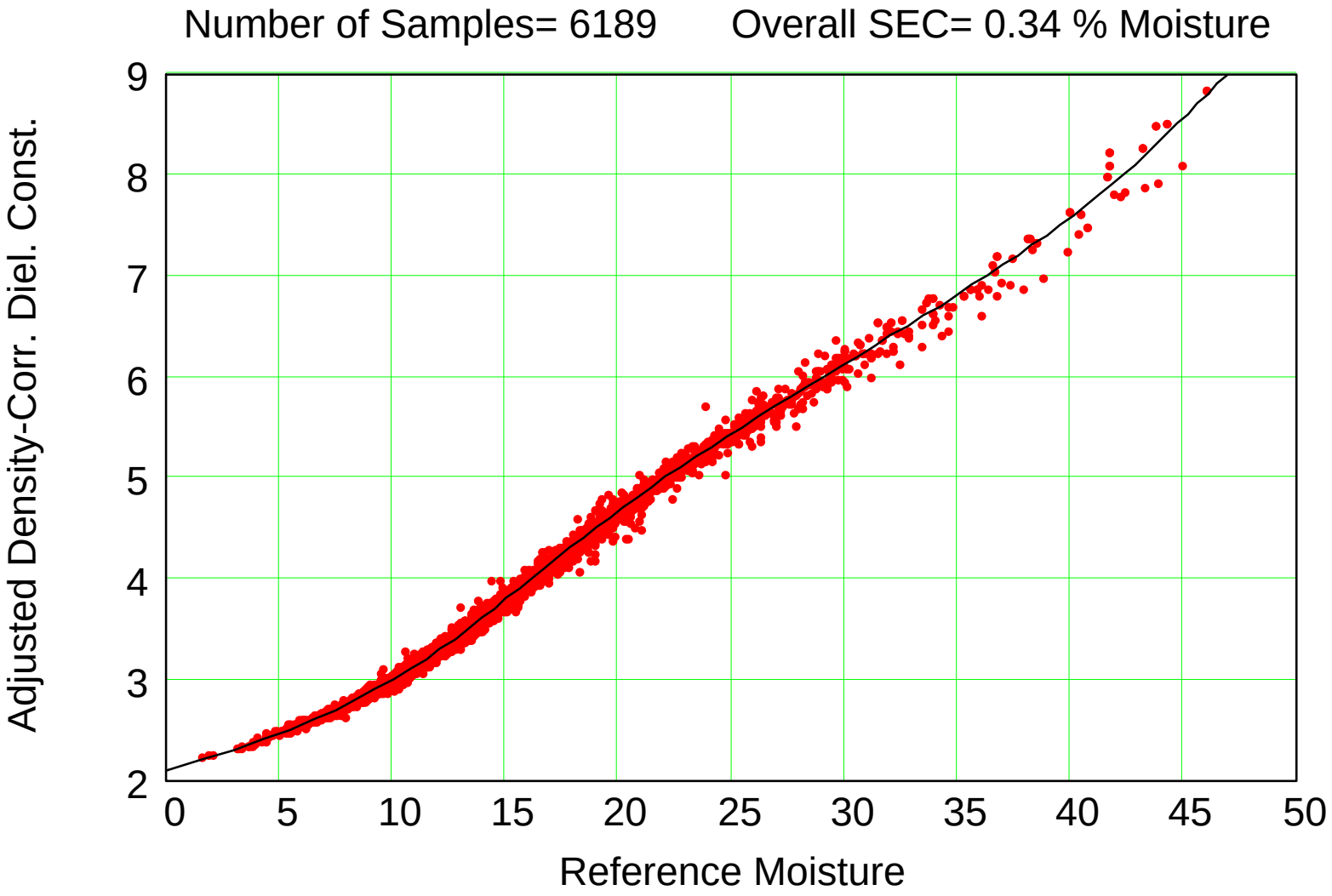
Adjust Offset Parameter



Adjust Translation Parameter



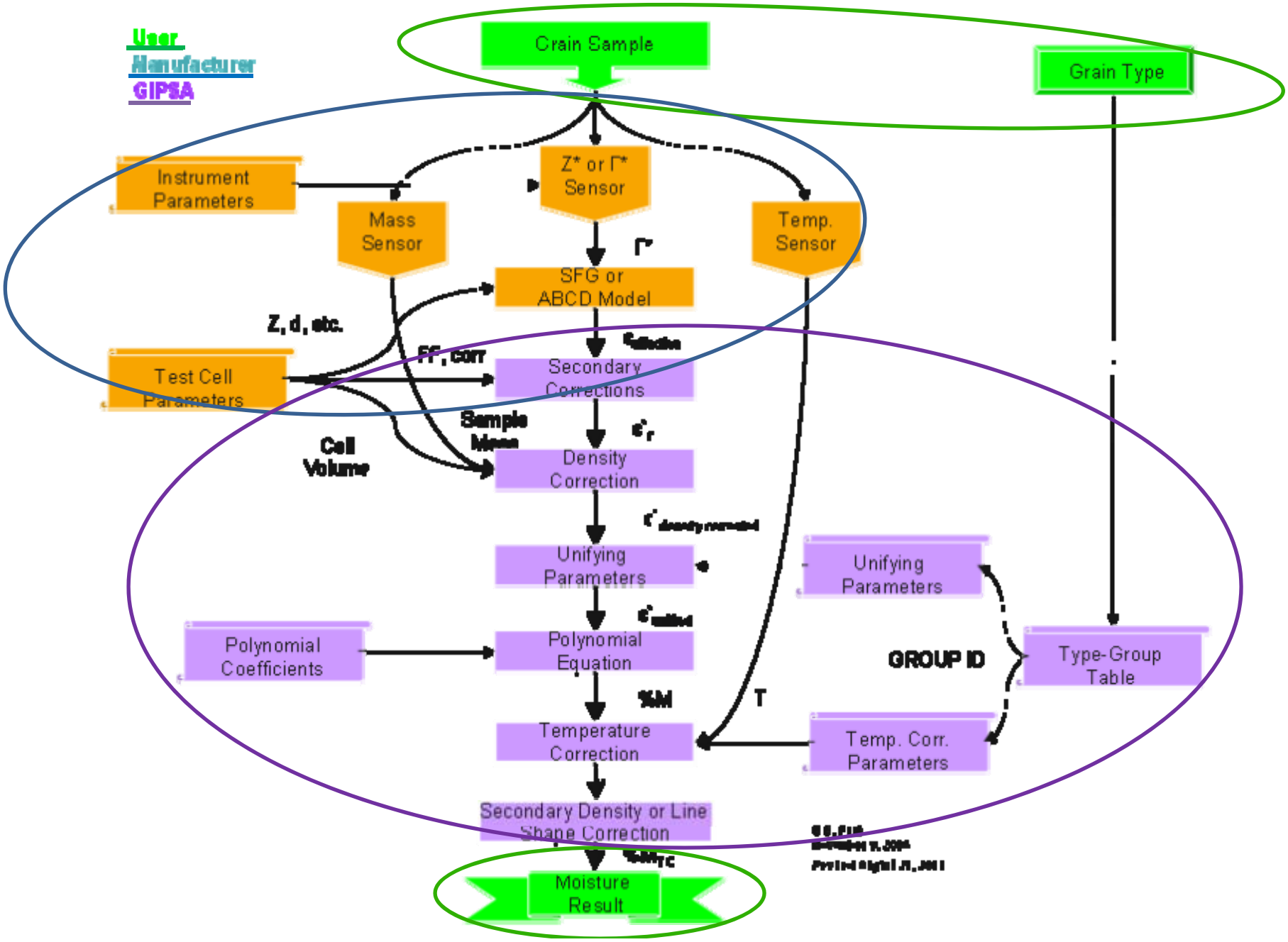
5th-Order Polynomial Equation



Calibration Installation

- Via USB memory device

- Download from Internet to USB memory device
  - http://www.gipsa.usda.gov/fgis/equipment.aspx

No numbers to enter by hand!!!

Unified Grain Moisture Algorithm