Corrosion Mapping

Half-cell potentials
Corrosion rate
Electrical resistamce

Fluid Penetration and Corrosion

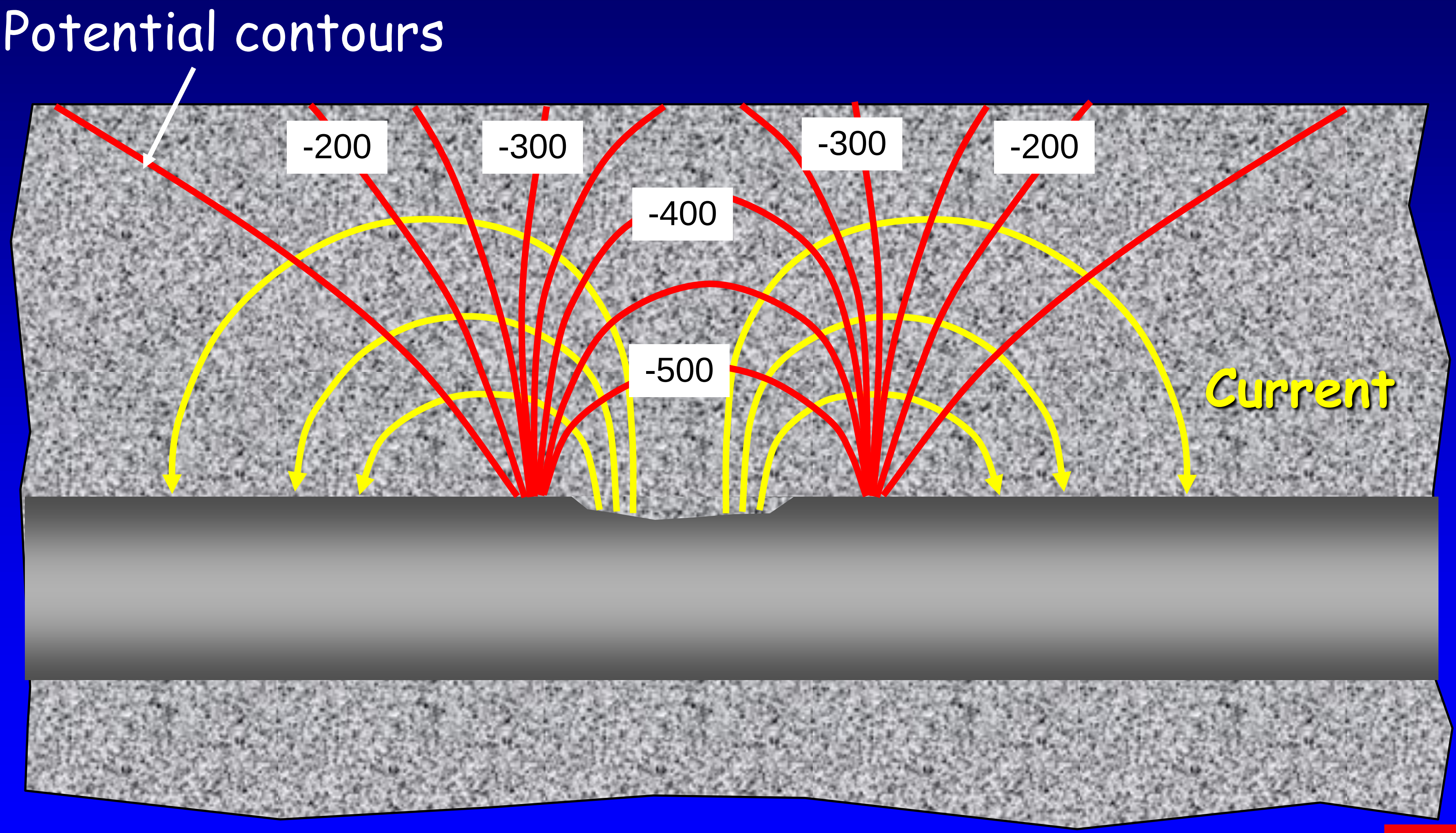
- Principles of durable concrete and water permeation (GWT)
- Corrosion principles
- Depth of chlorides and carbonation
- Chloride profile and service life estimation
- Corrosion evaluation (half-cell potential, corrosion rate by polarization, electrical resistance
- Resistivity/Conductivity of concrete mixtures

Half-Cell Potential Method

ASTM C 876

- When bar is corroding, charge flow through concrete is associated with an electrical potential field
- Measure the electrical potential (voltage) of the field at the concrete surface
- Magnitude of the measured voltage, relative to a standard half-cell, is indicative of corrosion activity

Potential Field

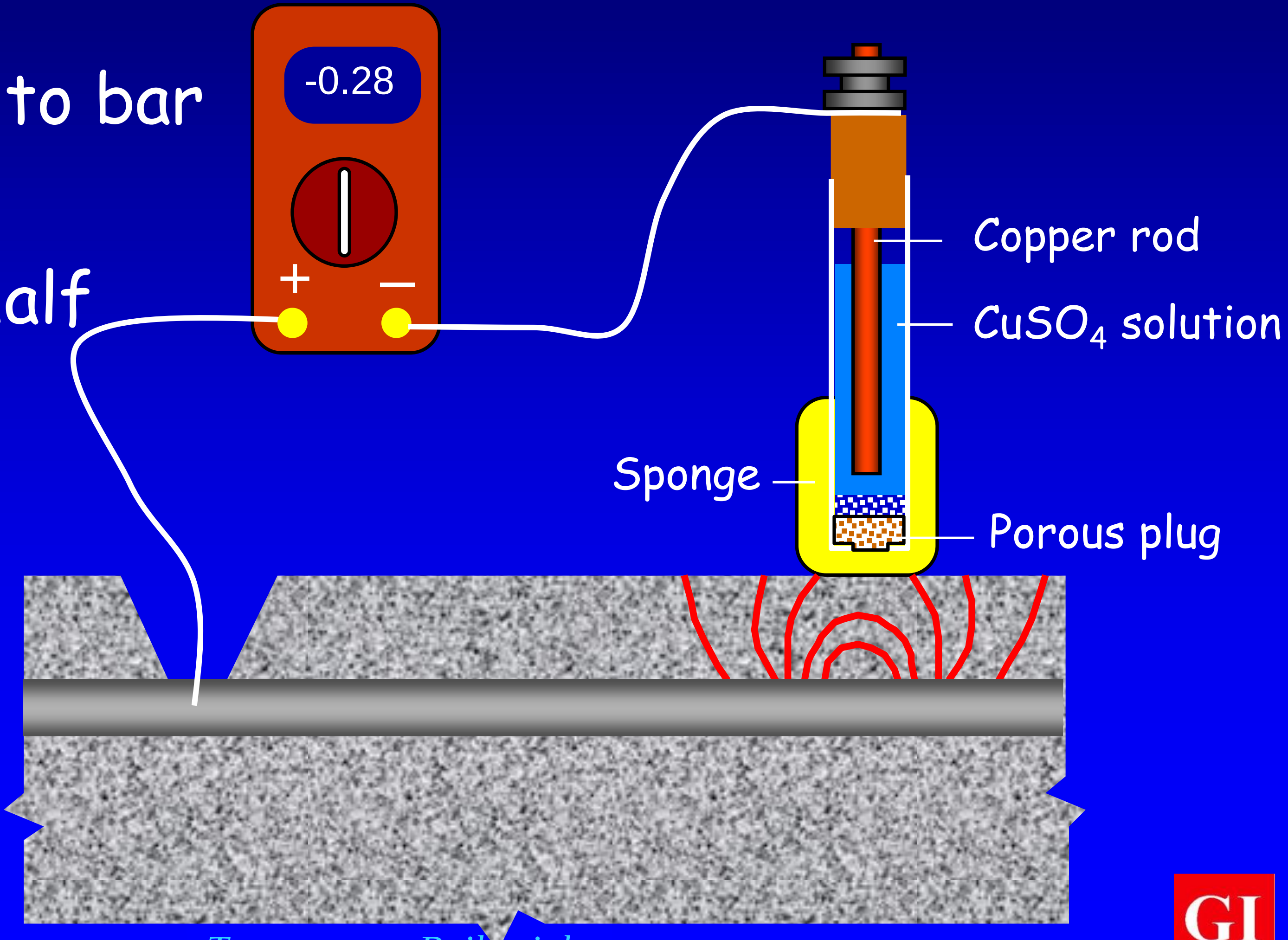


Elsner and Bohni, *ASTM STP 1065*, 1990

Half-Cell Potential Method

ASTM C 876

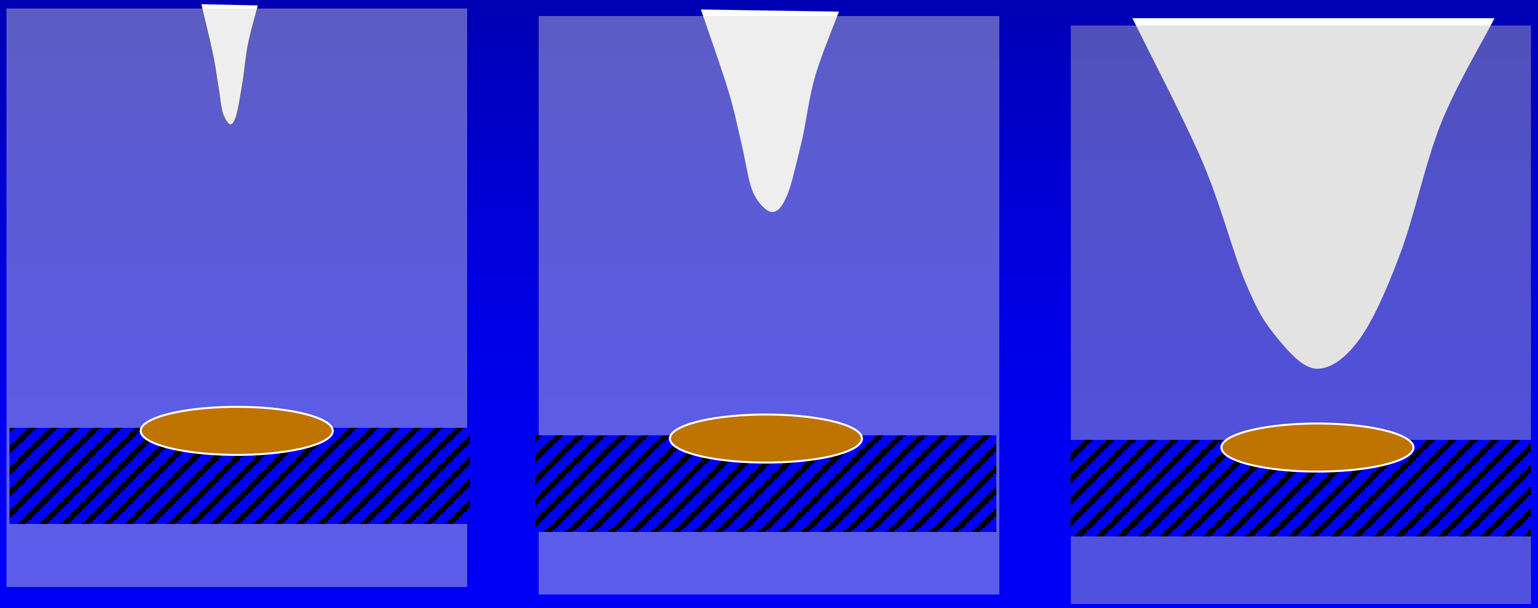
- Connection to bar
- Voltmeter
- Cu-$CuSO_4$ half cell



Cover condition

	Dry w/o Cl ions	Wet w/o Cl ions	Wet w Cl ions
R (kOhm)	20-50	5-10	0-1
Pot (mV)	-50 to -200	-250 to -350	-400 to -600

Potential Gradient



Cover layer 20-110 mm

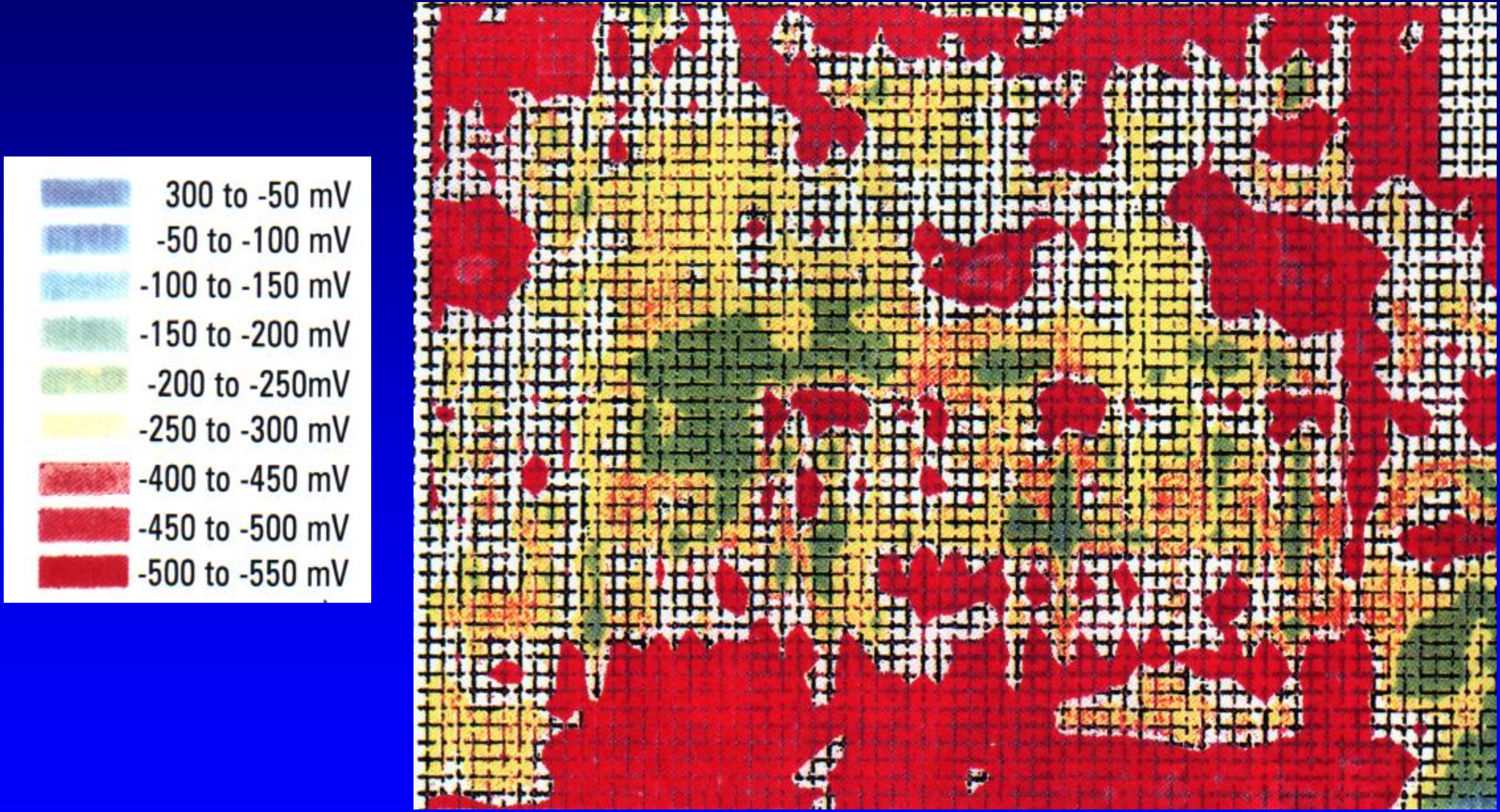
Half-Cell Potential Apparatus

Computer-based System

Manual Recording System

Mini Great Dane
Germann Instruments

Half-Cell Potential Contour Plot

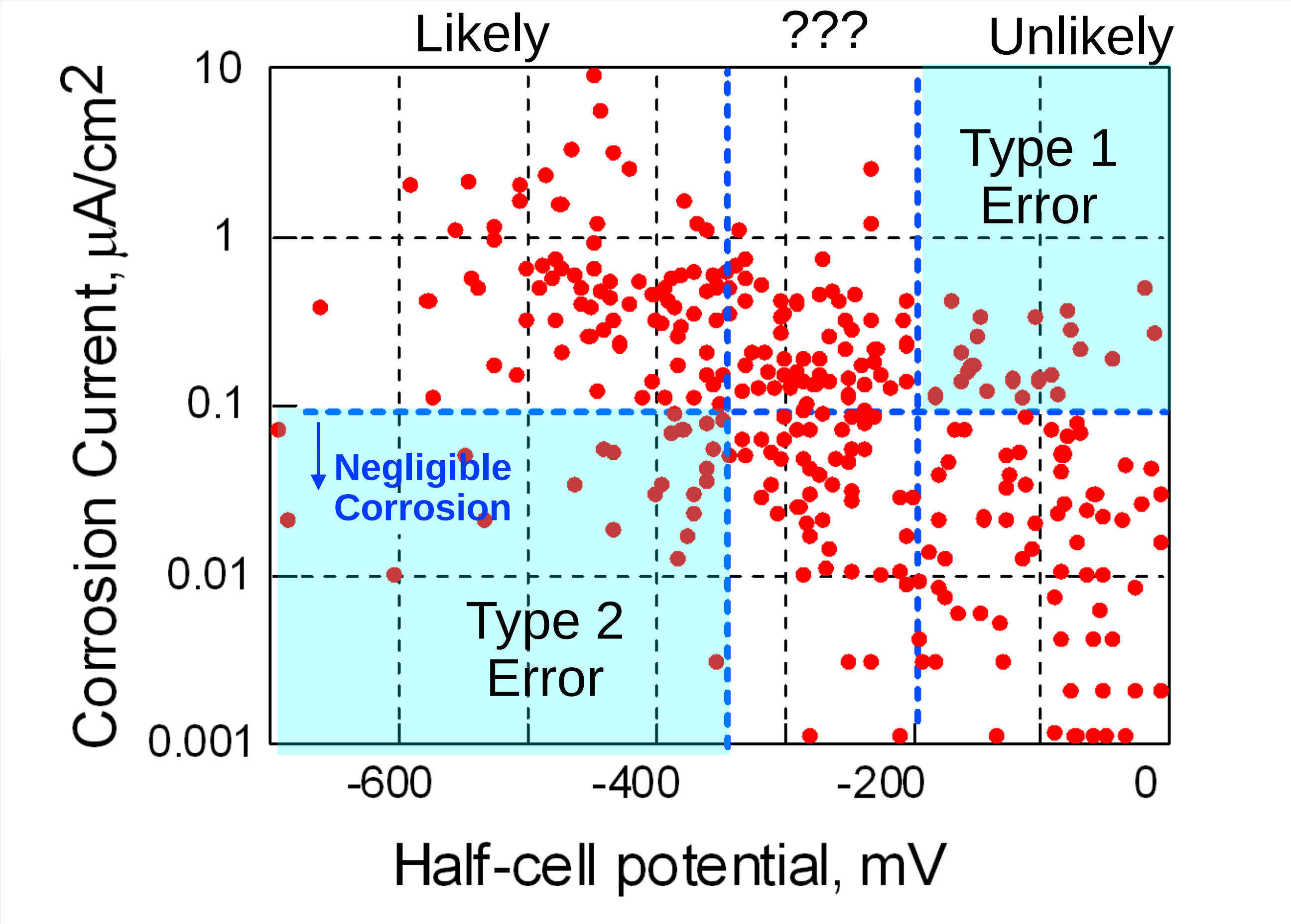


J. Woodhouse, “Quantifying the Invisible,” *Concrete Repair Bulletin*, July/August 1996

Considerations

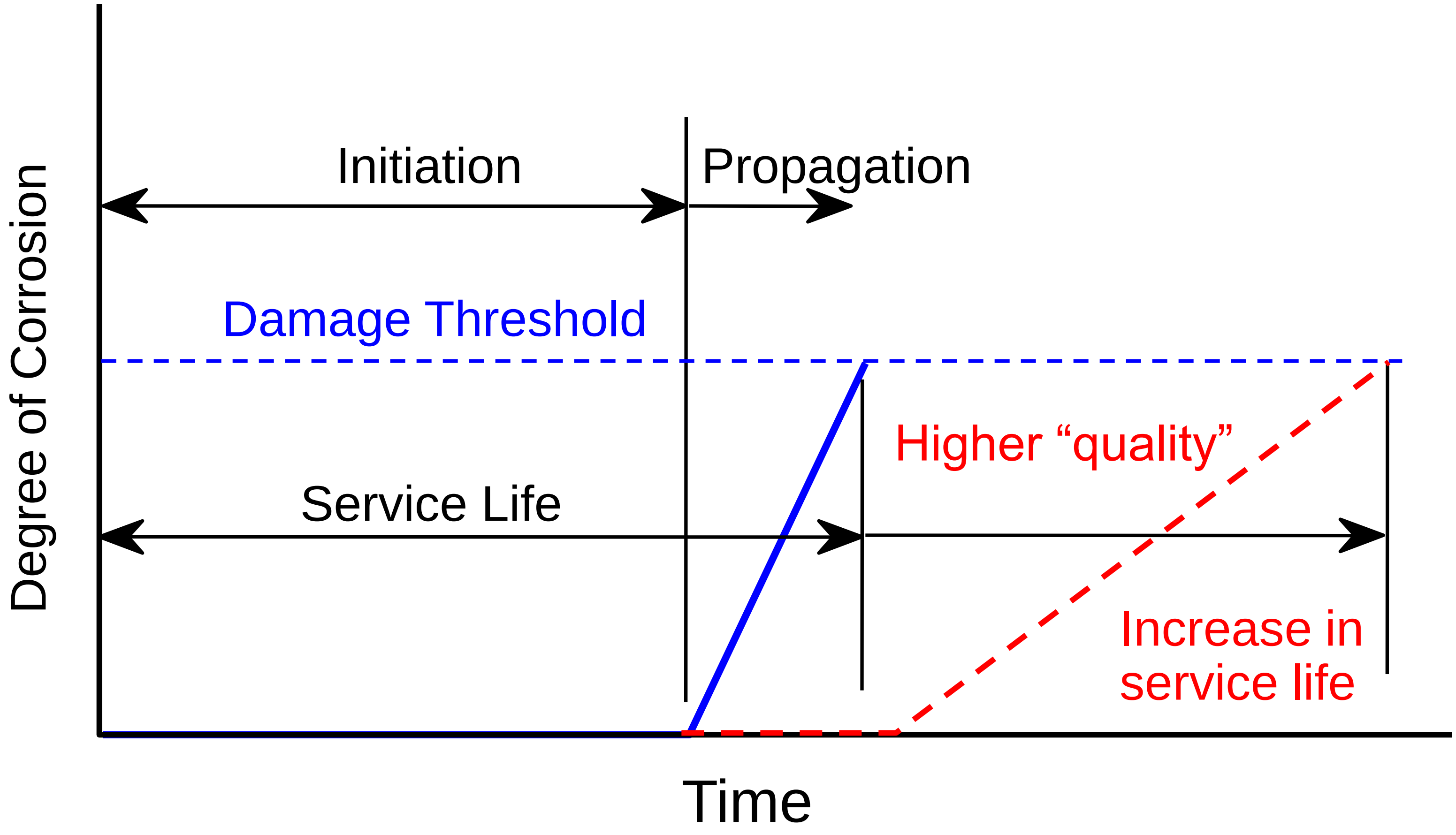
- Concrete must be sufficiently moist
  - ASTM C 876 provides criterion
- Provides only indication of likelihood of active corrosion
  - More positive than -200 mV: corrosion unlikely
  - More negative than -350 mV: corrosion likely
  - -200 to -350 mV: ???????
- Other factors have to be considered
- Ag/AgCl electrode 110 mV more positive to convert to equivalent $Cu/CuSO_4$ value

Half-cell Potential vs. Corrosion Rate



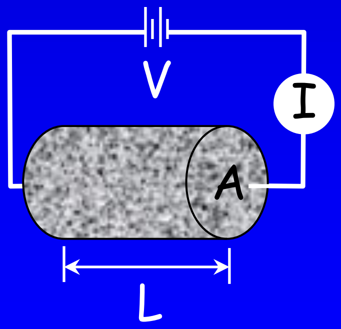
Sourece: Feliu et al., *ASTM STP 1276*, 1996

Propagation Phase



Concrete Resistivity

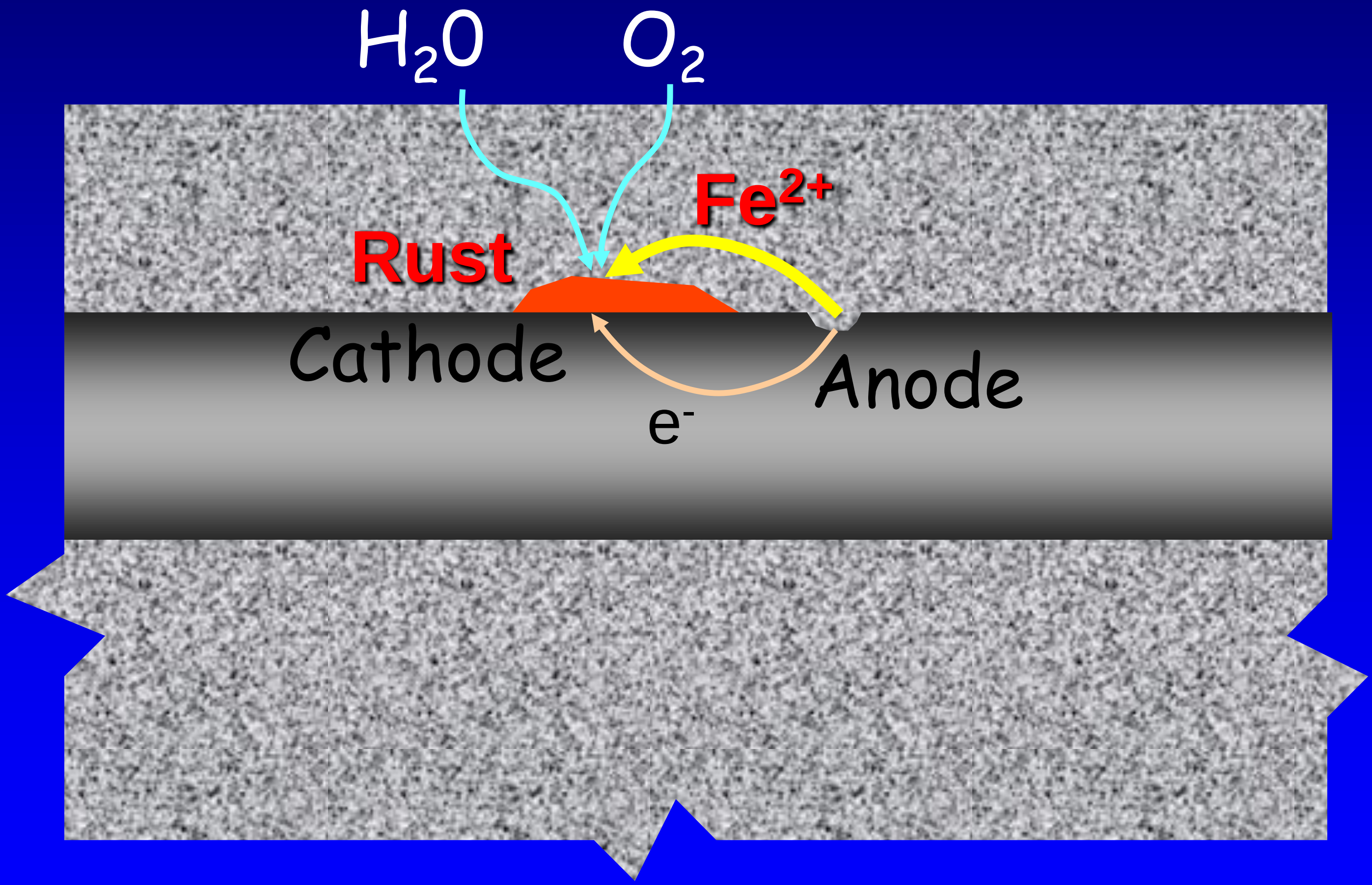
- Rate of corrosion is controlled by ease with which ions move from anodic to cathodic sites
- Concrete resistivity is, therefore, an important factor in rate of corrosion
- Resistivity, ρ (ohm-m)
  - Numerically equal to resistance, *R*, of a unit cube of material
  - Material property



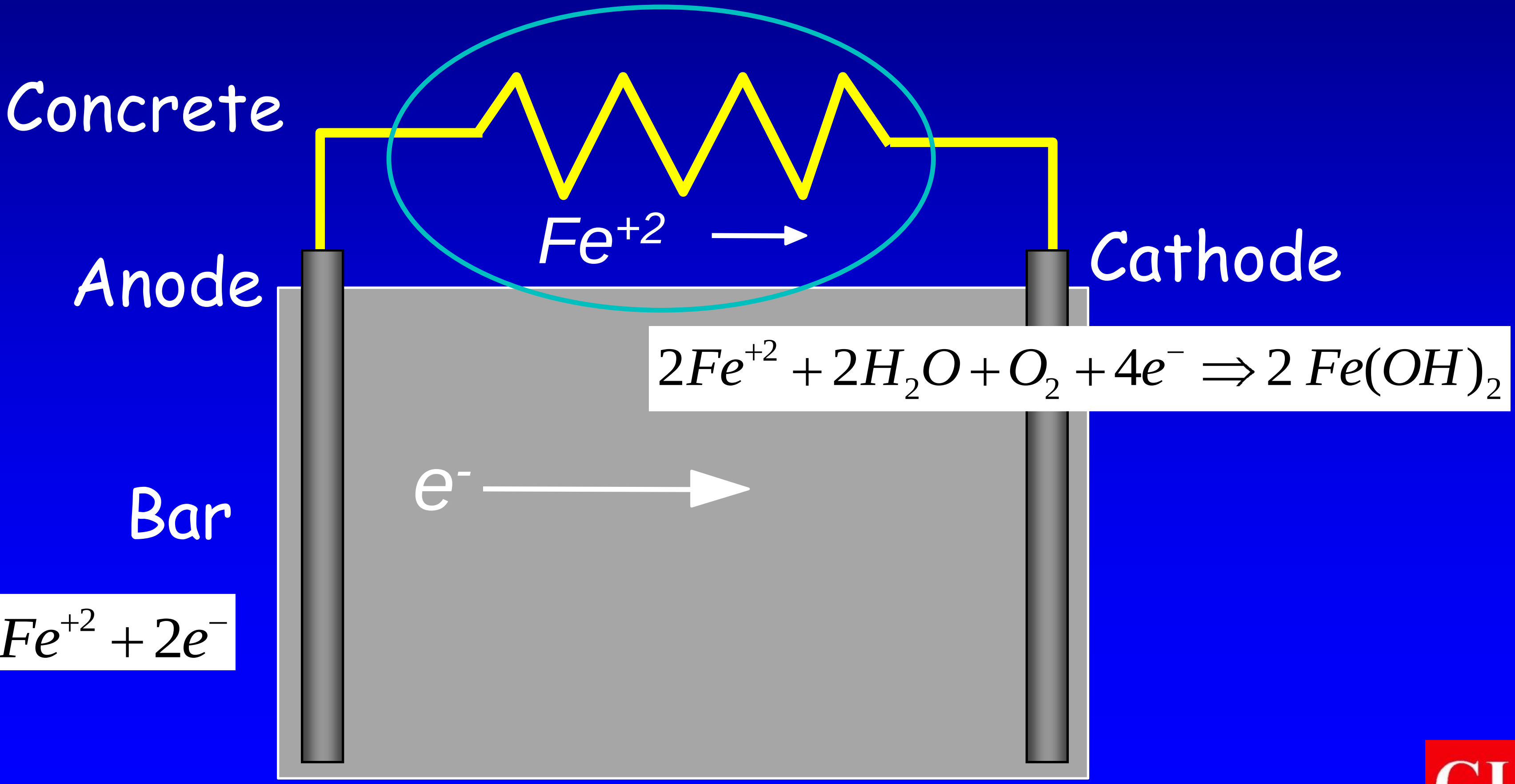
$$R = \frac{V}{I}$$

$$\rho = R\frac{A}{L}$$

Ionic Current Through Concrete



Battery Analogy



Concrete

Anode

Cathode

Bar

$Fe^{+2} \longrightarrow$

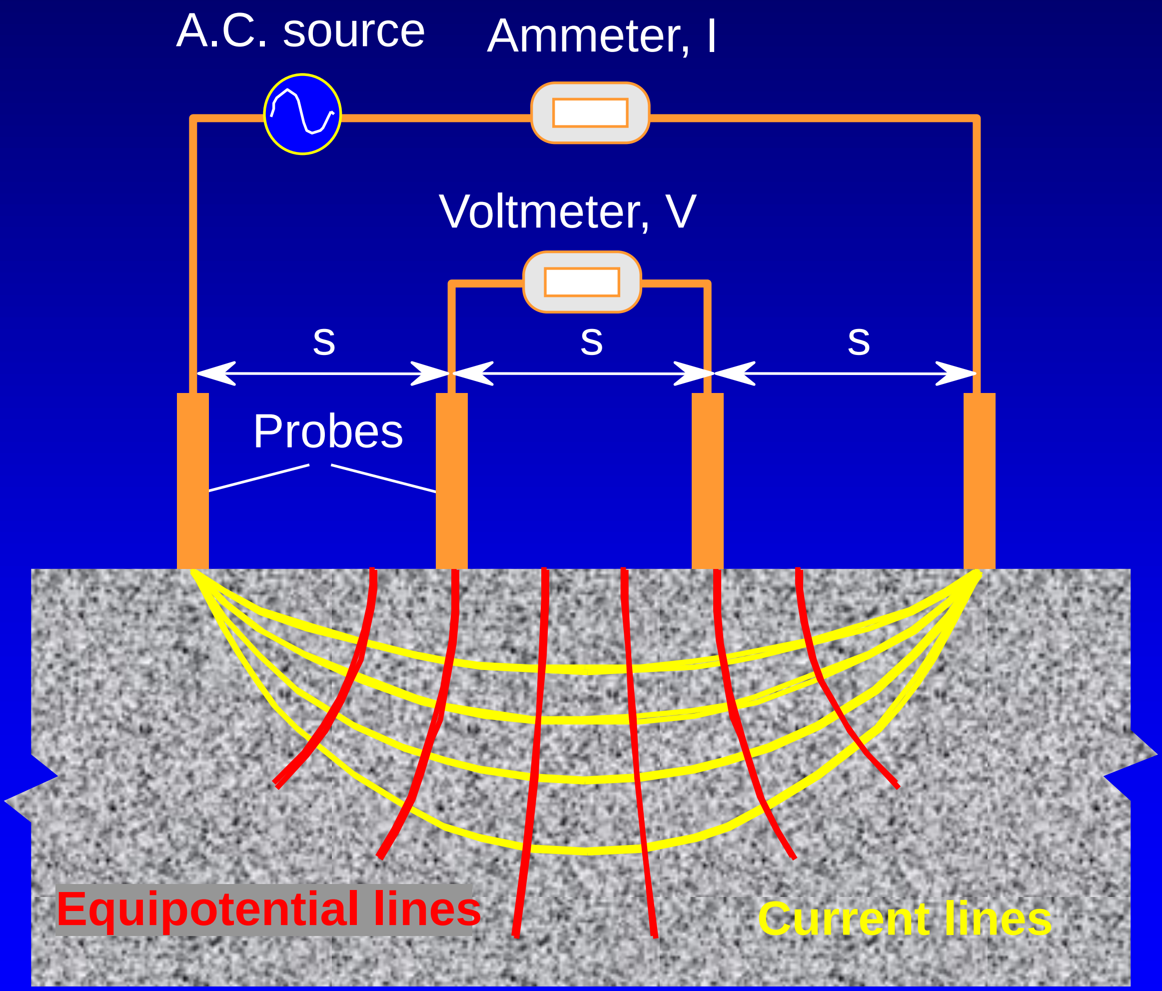
$e^{-} \longrightarrow$

$$2Fe^{+2} + 2H_2O + O_2 + 4e^{-} \Rightarrow 2\,Fe(OH)_2$$

$$Fe \Rightarrow Fe^{+2} + 2e^{-}$$

Probe Method by Wenner

$$\rho = \frac{2\pi s V}{I}$$



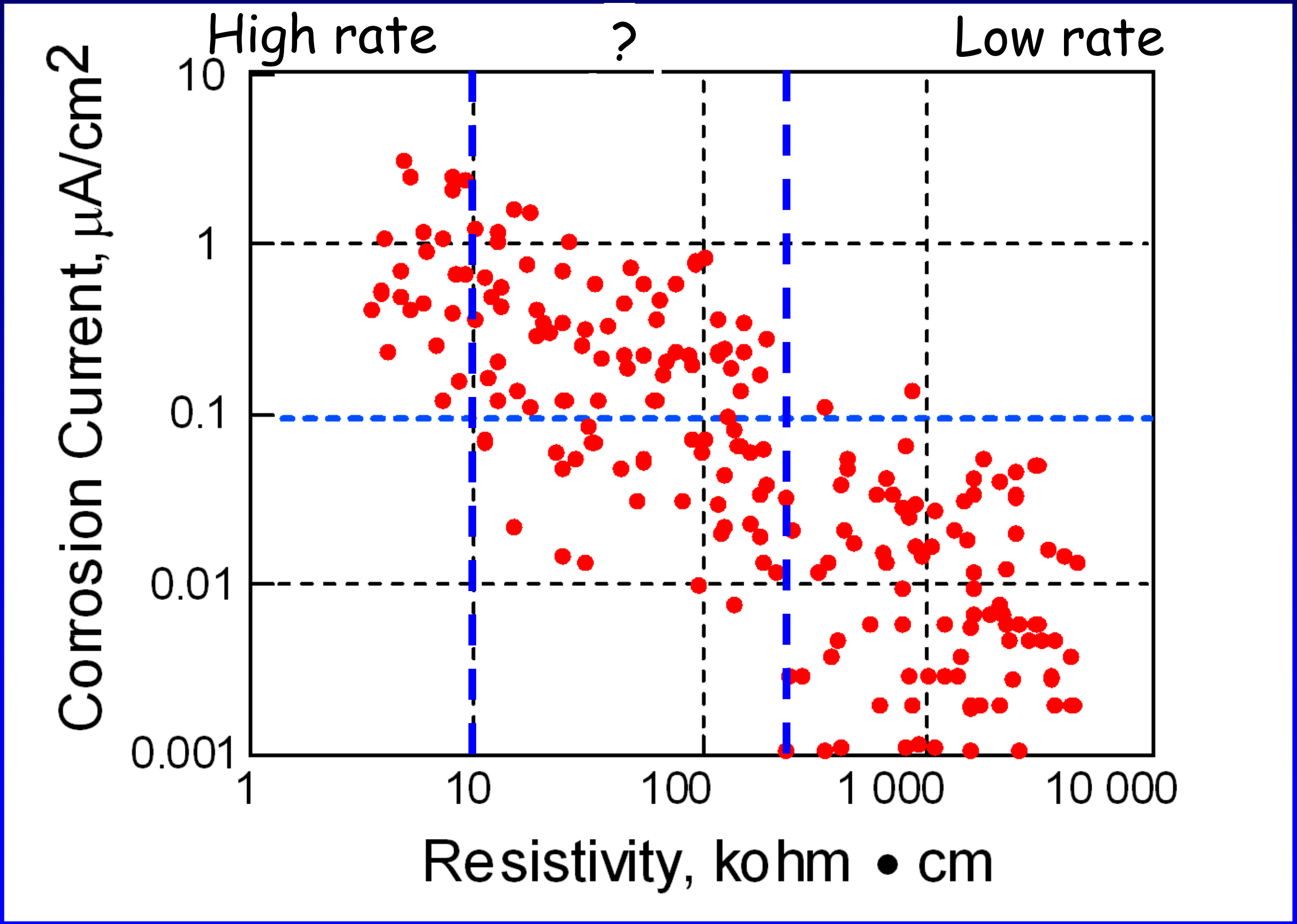
Applicability of Wenner Probe

- Probe spacing has to be sufficient so that representative “average” resistivity is measured
- Depth and width of member should be at least 4 times probe spacing
- Thin surface layer of high resistivity leads to high error
- Presence of steel needs to be taken into account
- **Resistivity depends on degree of saturation**
  - Testing while concrete is dry gives high resistivity
  - Testing while saturated needs the degree of saturation

Other Methods

- Merlin: For bulk conductivity of saturated cylinder or core
- Corrosion rate instruments may include means to estimate concrete resistivity
  - They typically measure resistance between the surface and the steel bar
  - Use models to convert resistance to resistivity

Resistivity vs. Corrosion Rate



Feliu et al., *ASTM STP 1276*, 1996

GalvaPulse

- Experince has shown that especially in in the absence of free oxygen (anaerobic environment) in the concrete, e.g. in splash zones or below sea level, the potentials can be very low, and there is only minor corrosion going on as the free oxygen are limited
- This was one of the motivations for developing the GalvaPulse for corrosion rate

Polarization Resistance

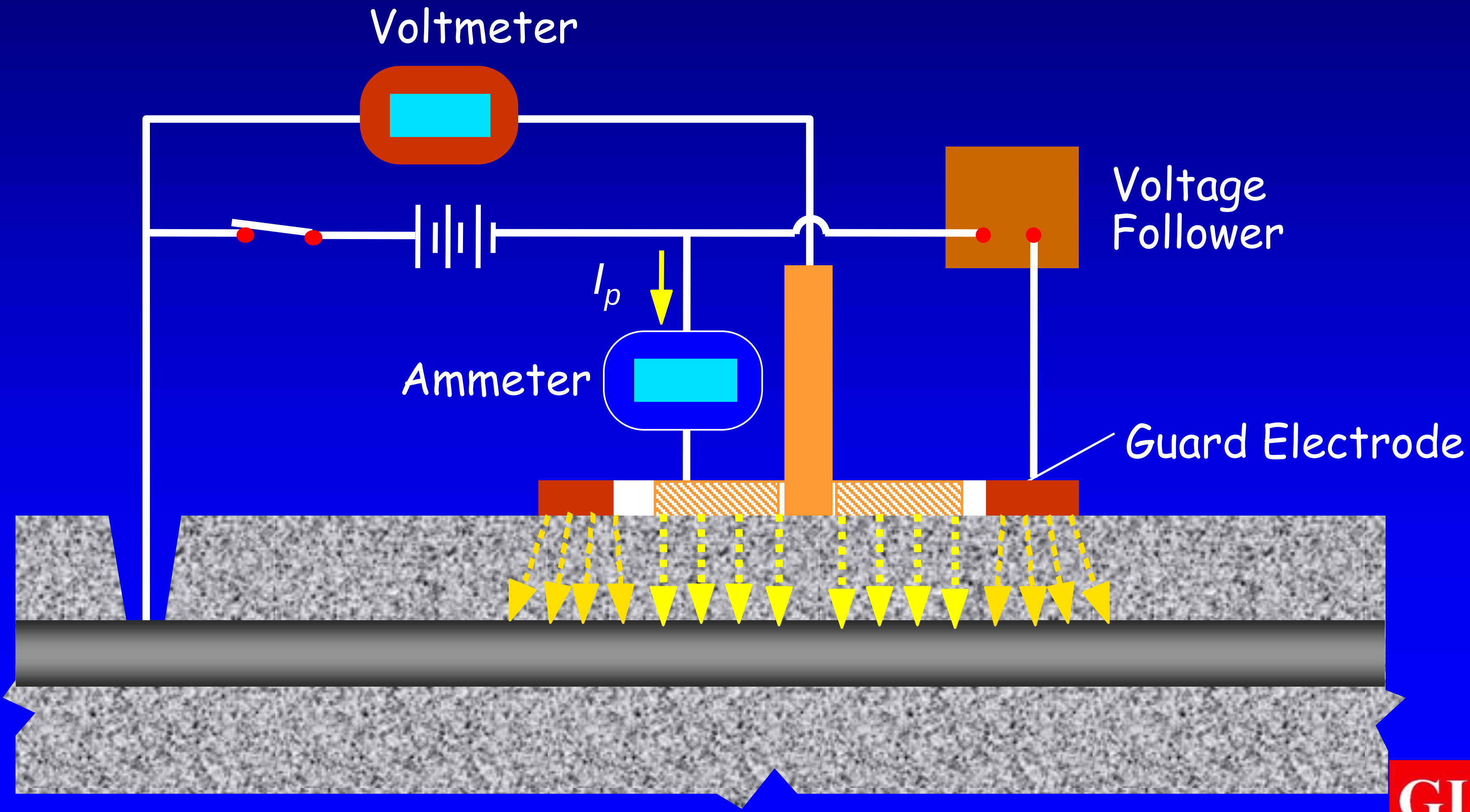
- Half-cell potential provides information on likelihood that corrosion is occurring
- Resistivity in combination with half-cell provides qualitative indication of corrosion rate
- Polarization resistance provides measurement of corrosion current

Polarization

- Change from the open-circuit potential as a result of passage of current into steel bar
- A bar that is actively corroding will have small change in potential when external current is applied to the bar

Guard-Electrode Method

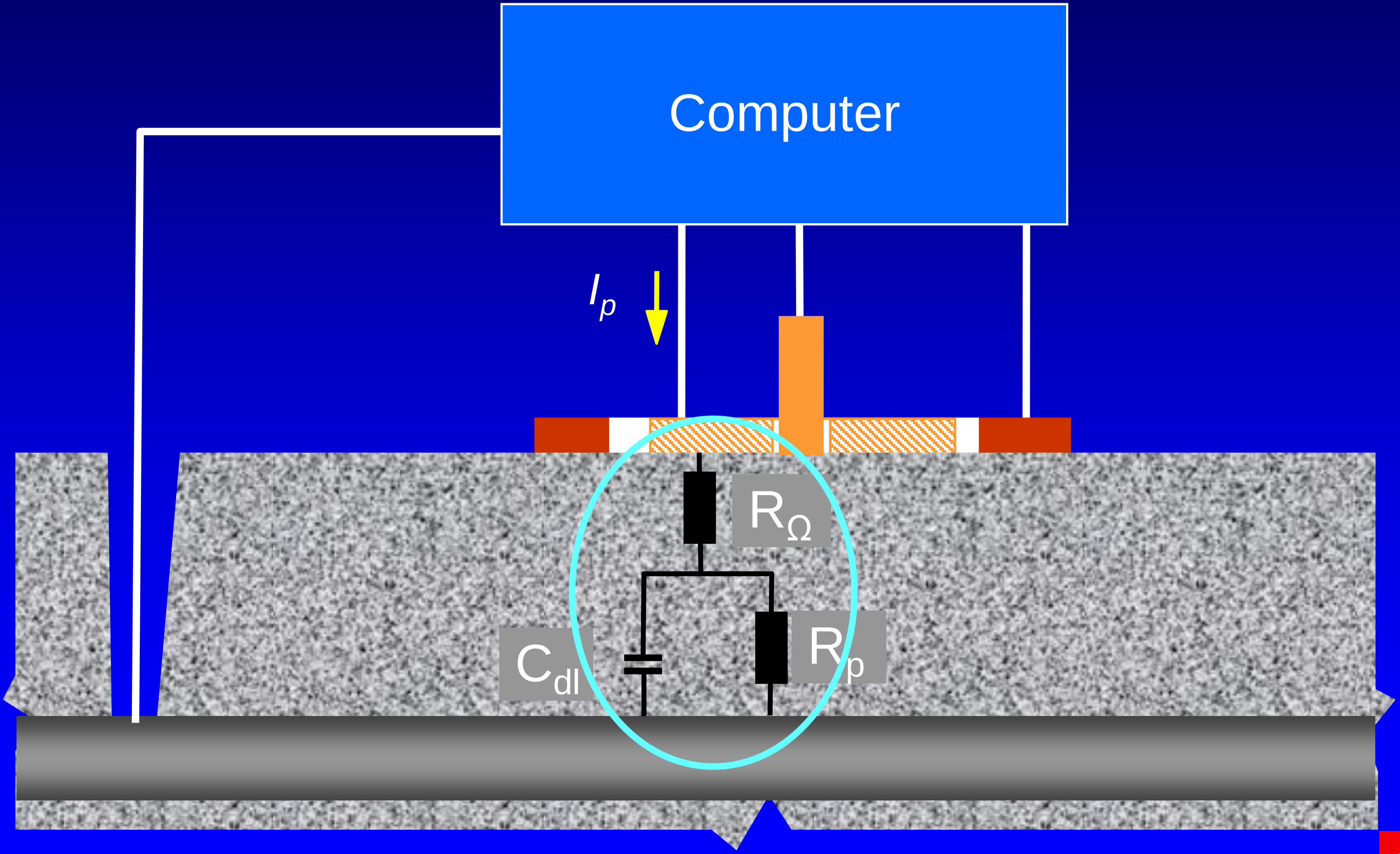
Confine current so that polarized area of bar is well defined



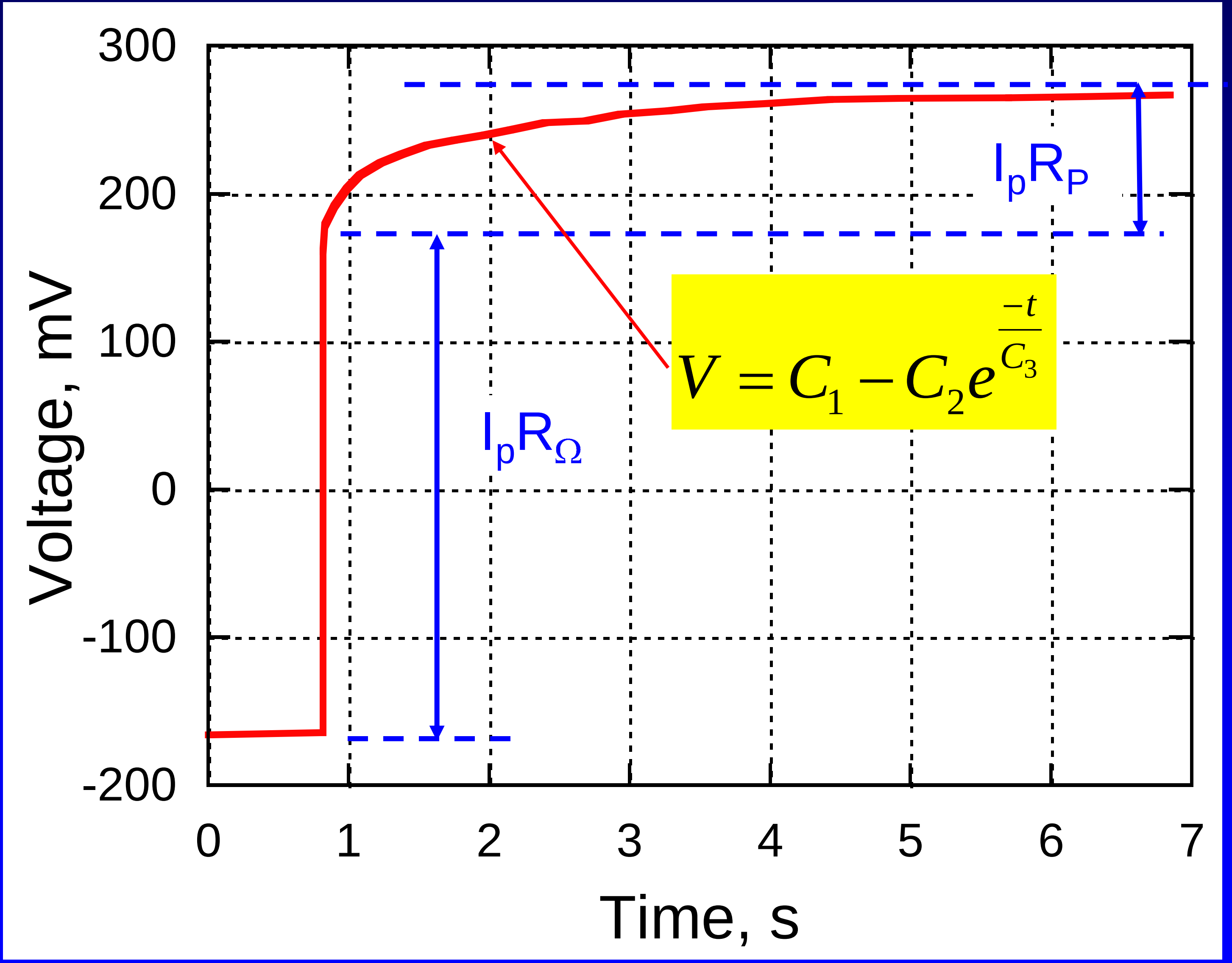
Galvanic Pulse Method

- Apply constant current pulse (≈ 10 s)
- Monitor potential change of working electrode (bar)
- From recorded voltage history, evaluate polarization resistance, R_p, by regression analysis
- Guard electrode is used
- Assume Randles model

Randles Model of Polarization Test



Voltage-Time Curve



$$V = C_1 - C_2 e^{\frac{-t}{C_3}}$$

Test smart – Build right

GI

Corrosion Rate

- Stern-Geary corrosion rate relationship:

$$i_{corr} = \frac{B}{R_p} \quad (\mu\mathrm{A/cm^2})$$

B = 25 to 50 mV
(active less active)

- Faraday' law translates i_{corr} to uniform metal loss:

$1\ \mu\mathrm{A/cm^2} = 0.012\ \mathrm{mm/y}$

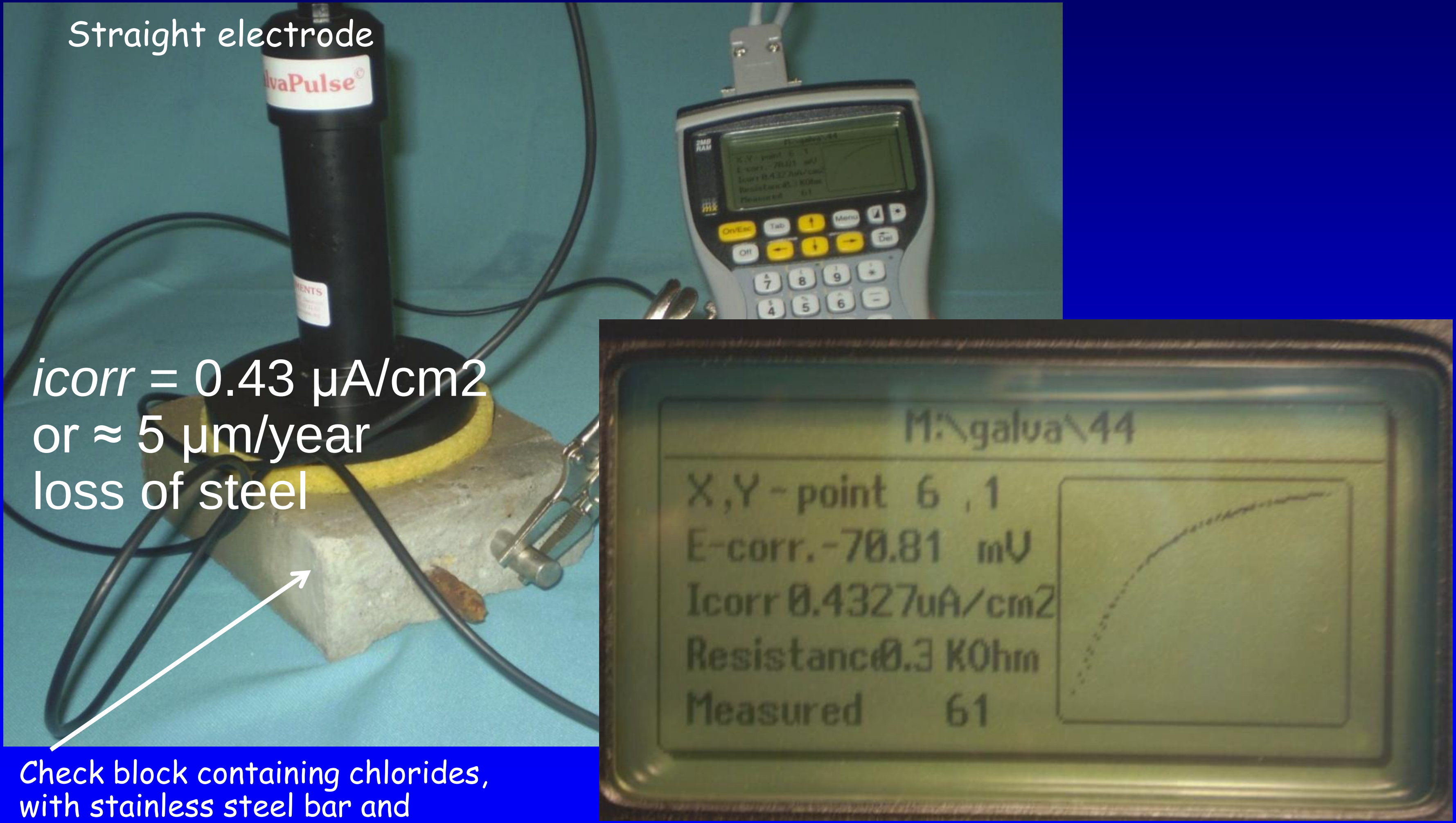
GalvaPulse

- Integrates into one unit:
  - Half-cell potential, Ag/AgCl
  - Resistance (not resistivity)
  - Polarization resistance
- Software for data analysis and 3-D displays
- The sensor head has an area of 70 mm dia to be pulsed over as a recommeded setting. This area can be decresed in the settings as well as the rebar diameter as required. Time of pulsing and the magnitude of the pulsing current is also adjustable

Computer with Sensor

New sensor
Angle electrode

Lower Corrosion Rate



icorr = 0.43 µA/cm2
or ≈ 5 µm/year
loss of steel

M:\galva\44
X,Y-point 6 ,1
E-corr.-70.81 mV
Icorr 0.4327uA/cm2
Resistance 0.3 KOhm
Measured 61

Check block containing chlorides,
with stainless steel bar and
corroding black steel bar

Higher Corrosion Rate

icorr = 15.9 µA/cm2
or ≈ 190 µm/year
loss of steel

```
M:\galva\44
X,Y-point 8 ,1
E-corr.-388.0  mV
Icorr 15.854uA/cm2
Resistanc0.2 KOhm
Measured      61
```

Corrosion rates by various authors

1. Kenneth Clear, 1989 (with K.Clear instrument)

< 0.5 μA/cm² – no corrosion damage expected
0.5 – 2.7 μA/cm² – corrosion damage possible after 10 to 15 years
2.7 – 27 μA/cm² – corrosion damage expected in 2 to10 years
>27 μA/cm² – corrosion damage expected in 2 years or less

2. Carmen Andrade, 2000 (with Gecor 6 instrument)

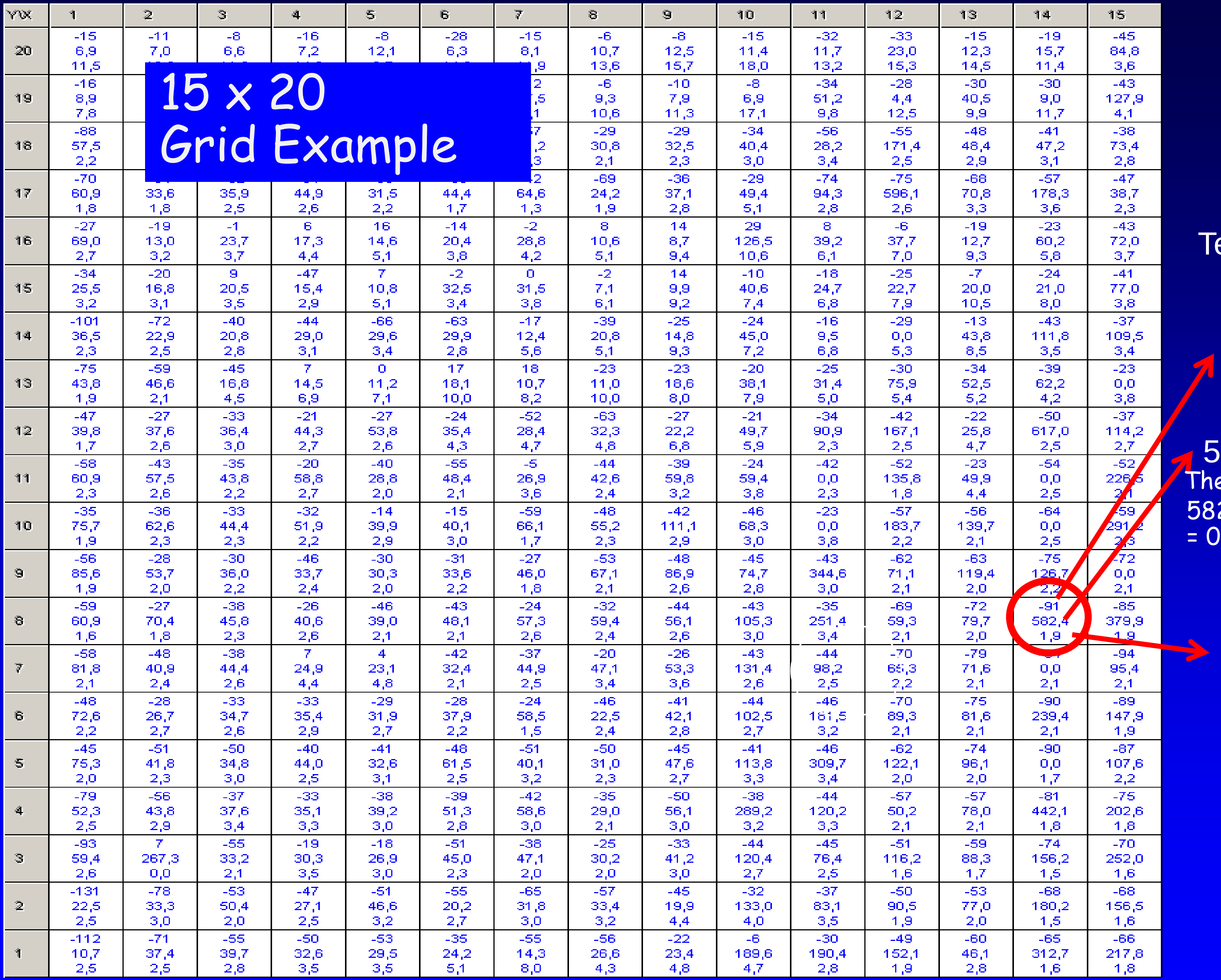
< 0.1 μA/cm² – Negligible
0.5 μA/cm² – Low
0.5 – 1 μA/cm² – Moderate
> 1 μA/cm² – High

3. Thomas Frolund, 2002 (with GalvaPulse instrument)

< 0.5 μA/cm2- passive areas
0.5 - 2 μA/cm2 – negligible corrosion activity
2 – 5 μA/cm2 – low corrosion activity
5 – 15 μA/cm2 – moderate corrosion activity
> 15 μA/cm2 – high corrosion activity

Thomas Frolund

15 x 20 Grid Example



Y\X	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
20	-15 6,9 11,5	-11 7,0 [illegible]	-8 6,6 [illegible]	-16 7,2 [illegible]	-8 12,1 [illegible]	-28 6,3 [illegible]	-15 8,1 [illegible]	-6 10,7 13,6	-8 12,5 15,7	-15 11,4 18,0	-32 11,7 13,2	-33 23,0 15,3	-15 12,3 14,5	-19 15,7 11,4	-45 84,8 3,6
19	-16 8,9 7,8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-6 9,3 10,6	-10 7,9 11,3	-8 6,9 17,1	-34 51,2 9,8	-28 4,4 12,5	-30 40,5 9,9	-30 9,0 11,7	-43 127,9 4,1
18	-88 57,5 2,2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-29 30,8 2,1	-29 32,5 2,3	-34 40,4 3,0	-56 28,2 3,4	-55 171,4 2,5	-48 48,4 2,9	-41 47,2 3,1	-38 73,4 2,8
17	-70 60,9 1,8	[illegible] 33,6 1,8	[illegible] 35,9 2,5	[illegible] 44,9 2,6	[illegible] 31,5 2,2	[illegible] 44,4 1,7	[illegible] 64,6 1,3	-69 24,2 1,9	-36 37,1 2,8	-29 49,4 5,1	-74 94,3 2,8	-75 596,1 2,6	-68 70,8 3,3	-57 178,3 3,6	-47 38,7 2,3
16	-27 69,0 2,7	-19 13,0 3,2	-1 23,7 3,7	6 17,3 4,4	16 14,6 5,1	-14 20,4 3,8	-2 28,8 4,2	8 10,6 5,1	14 8,7 9,4	29 126,5 10,6	8 39,2 6,1	-6 37,7 7,0	-19 12,7 9,3	-23 60,2 5,8	-43 72,0 3,7
15	-34 25,5 3,2	-20 16,8 3,1	9 20,5 3,5	-47 15,4 2,9	7 10,8 5,1	-2 32,5 3,4	0 31,5 3,8	-2 7,1 6,1	14 9,9 9,2	-10 40,6 7,4	-18 24,7 6,8	-25 22,7 7,9	-7 20,0 10,5	-24 21,0 8,0	-41 77,0 3,8
14	-101 36,5 2,3	-72 22,9 2,5	-40 20,8 2,8	-44 29,0 3,1	-66 29,6 3,4	-63 29,9 2,8	-17 12,4 5,6	-39 20,8 5,1	-25 14,8 9,3	-24 45,0 7,2	-16 9,5 6,8	-29 0,0 5,3	-13 43,8 8,5	-43 111,8 3,5	-37 109,5 3,4
13	-75 43,8 1,9	-59 46,6 2,1	-45 16,8 4,5	7 14,5 6,9	0 11,2 7,1	17 18,1 10,0	18 10,7 8,2	-23 11,0 10,0	-23 18,6 8,0	-20 38,1 7,9	-25 31,4 5,0	-30 75,9 5,4	-34 52,5 5,2	-39 62,2 4,2	-23 0,0 3,8
12	-47 39,8 1,7	-27 37,6 2,6	-33 36,4 3,0	-21 44,3 2,7	-27 53,8 2,6	-24 35,4 4,3	-52 28,4 4,7	-63 32,3 4,8	-27 22,2 6,8	-21 49,7 5,9	-34 90,9 2,3	-42 167,1 2,5	-22 25,8 4,7	-50 617,0 2,5	-37 114,2 2,7
11	-58 60,9 2,3	-43 57,5 2,6	-35 43,8 2,2	-20 58,8 2,7	-40 28,8 2,0	-55 48,4 2,1	-5 26,9 3,6	-44 42,6 2,4	-39 59,8 3,2	-24 59,4 3,8	-42 0,0 2,3	-52 135,8 1,8	-23 49,9 4,4	-54 0,0 2,5	-52 226,5 2,1
10	-35 75,7 1,9	-36 62,6 2,3	-33 44,4 2,3	-32 51,9 2,2	-14 39,9 2,9	-15 40,1 3,0	-59 66,1 1,7	-48 55,2 2,3	-42 111,1 2,9	-46 68,3 3,0	-23 0,0 3,8	-57 183,7 2,2	-56 139,7 2,1	-64 0,0 2,5	-59 291,2 2,3
9	-56 85,6 1,9	-28 53,7 2,0	-30 36,0 2,2	-46 33,7 2,4	-30 30,3 2,0	-31 33,6 2,2	-27 46,0 1,8	-53 67,1 2,1	-48 86,9 2,6	-45 74,7 2,8	-43 344,6 3,0	-62 71,1 2,1	-63 119,4 2,0	-75 126,7 2,2	-72 0,0 2,1
8	-59 60,9 1,6	-27 70,4 1,8	-38 45,8 2,3	-26 40,6 2,6	-46 39,0 2,1	-43 48,1 2,1	-24 57,3 2,6	-32 59,4 2,4	-44 56,1 2,6	-43 105,3 3,0	-35 251,4 3,4	-69 59,3 2,1	-72 79,7 2,0	-91 582,4 1,9	-85 379,9 1,9
7	-58 81,8 2,1	-48 40,9 2,4	-38 44,4 2,6	7 24,9 4,4	4 23,1 4,8	-42 32,4 2,1	-37 44,9 2,5	-20 47,1 3,4	-26 53,3 3,6	-43 131,4 2,6	-44 98,2 2,5	-70 65,3 2,2	-79 71,6 2,1	[illegible] 0,0 2,1	-94 95,4 2,1
6	-48 72,6 2,2	-28 26,7 2,7	-33 34,7 2,6	-33 35,4 2,9	-29 31,9 2,7	-28 37,9 2,2	-24 58,5 1,5	-46 22,5 2,4	-41 42,1 2,8	-44 102,5 2,7	-46 161,5 3,2	-70 89,3 2,1	-75 81,6 2,1	-90 239,4 2,1	-89 147,9 1,9
5	-45 75,3 2,0	-51 41,8 2,3	-50 34,8 3,0	-40 44,0 2,5	-41 32,6 3,1	-48 61,5 2,5	-51 40,1 3,2	-50 31,0 2,3	-45 47,6 2,7	-41 113,8 3,3	-46 309,7 3,4	-62 122,1 2,0	-74 96,1 2,0	-90 0,0 1,7	-87 107,6 2,2
4	-79 52,3 2,5	-56 43,8 2,9	-37 37,6 3,4	-33 35,1 3,3	-38 39,2 3,0	-39 51,3 2,8	-42 58,6 3,0	-35 29,0 2,1	-50 56,1 3,0	-38 289,2 3,2	-44 120,2 3,3	-57 50,2 2,1	-57 78,0 2,1	-81 442,1 1,8	-75 202,6 1,8
3	-93 59,4 2,6	7 267,3 0,0	-55 33,2 2,1	-19 30,3 3,5	-18 26,9 3,0	-51 45,0 2,3	-38 47,1 2,0	-25 30,2 2,0	-33 41,2 3,0	-44 120,4 2,7	-45 76,4 2,5	-51 116,2 1,6	-59 88,3 1,7	-74 156,2 1,5	-70 252,0 1,6
2	-131 22,5 2,5	-78 33,3 3,0	-53 50,4 2,0	-47 27,1 2,5	-51 46,6 3,2	-55 20,2 2,7	-65 31,8 3,0	-57 33,4 3,2	-45 19,9 4,4	-32 133,0 4,0	-37 83,1 3,5	-50 90,5 1,9	-53 77,0 2,0	-68 180,2 1,5	-68 156,5 1,6
1	-112 10,7 2,5	-71 37,4 2,5	-55 39,7 2,8	-50 32,6 3,5	-53 29,5 3,5	-35 24,2 5,1	-55 14,3 8,0	-56 26,6 4,3	-22 23,4 4,8	-6 189,6 4,7	-30 190,4 2,8	-49 152,1 1,9	-60 46,1 2,8	-65 312,7 1,6	-66 217,8 1,8

Test example

-91 mV

582 μm/year

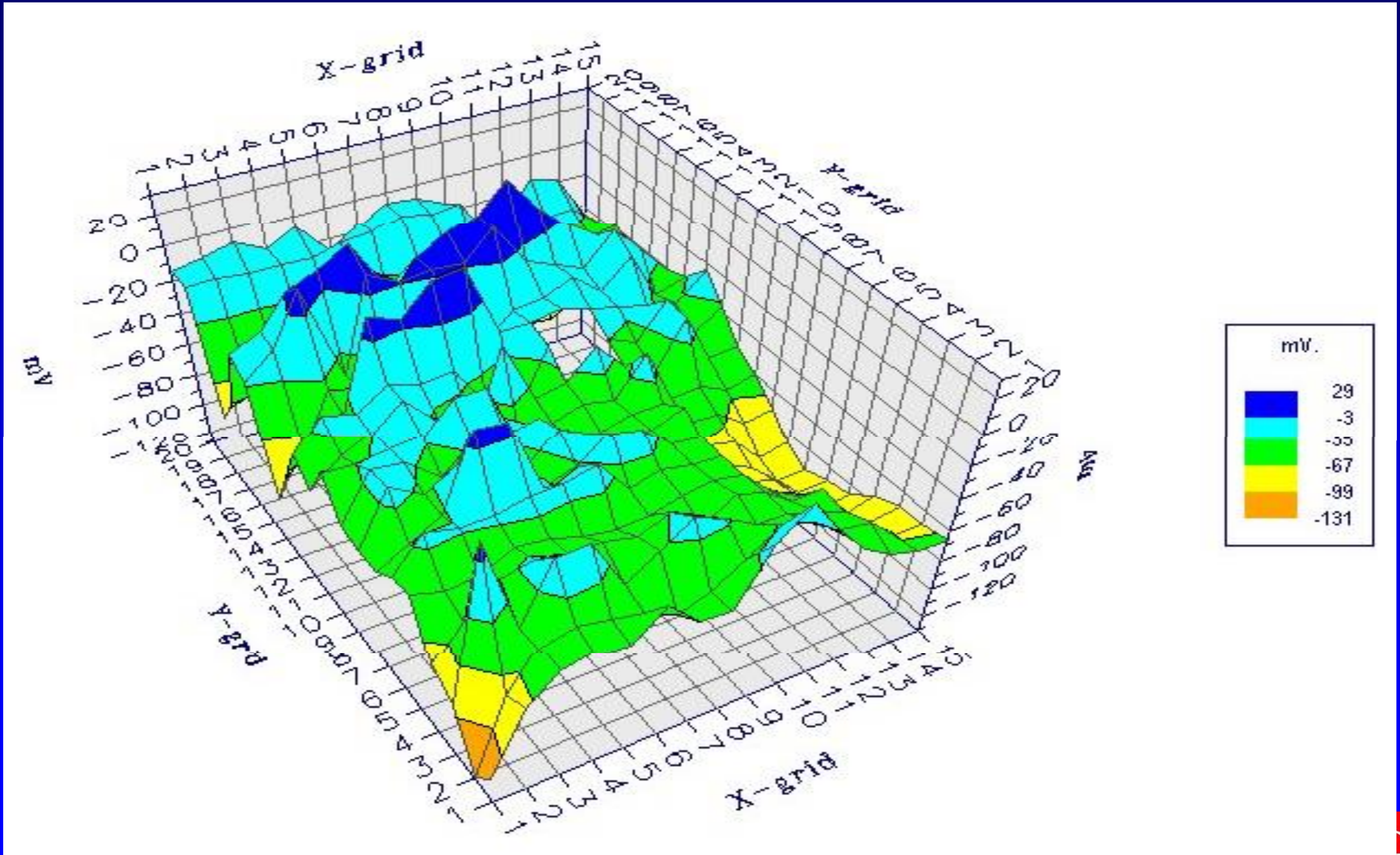
The loss of steel

582 μm/year x 10-3

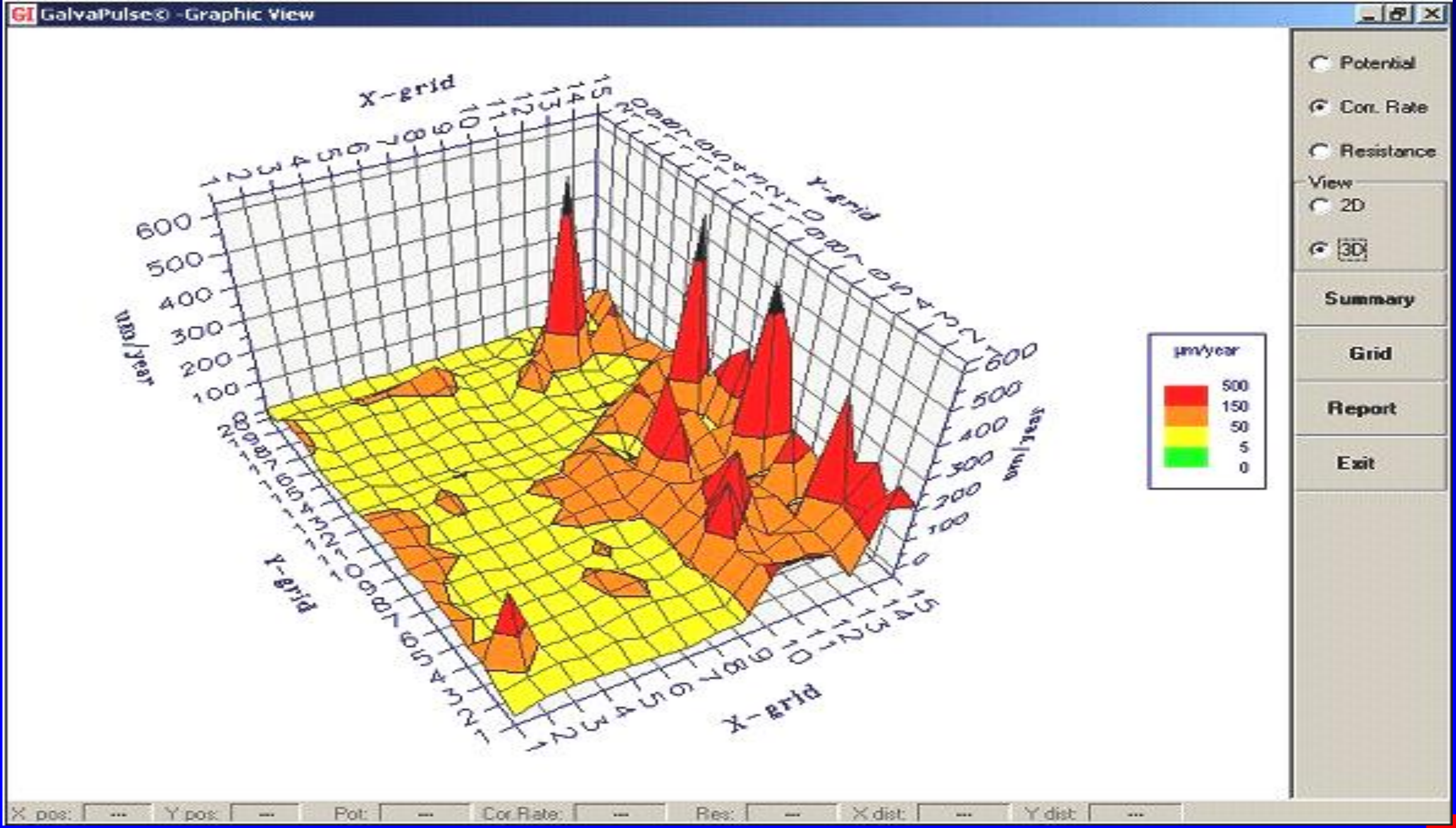
= 0.58 mm/year

1.9 kOhm

Ex. Ag/AgCl potentials (mV)



Ex. Corrosion rate (µm/year)



GalvaPulse© -Graphic View

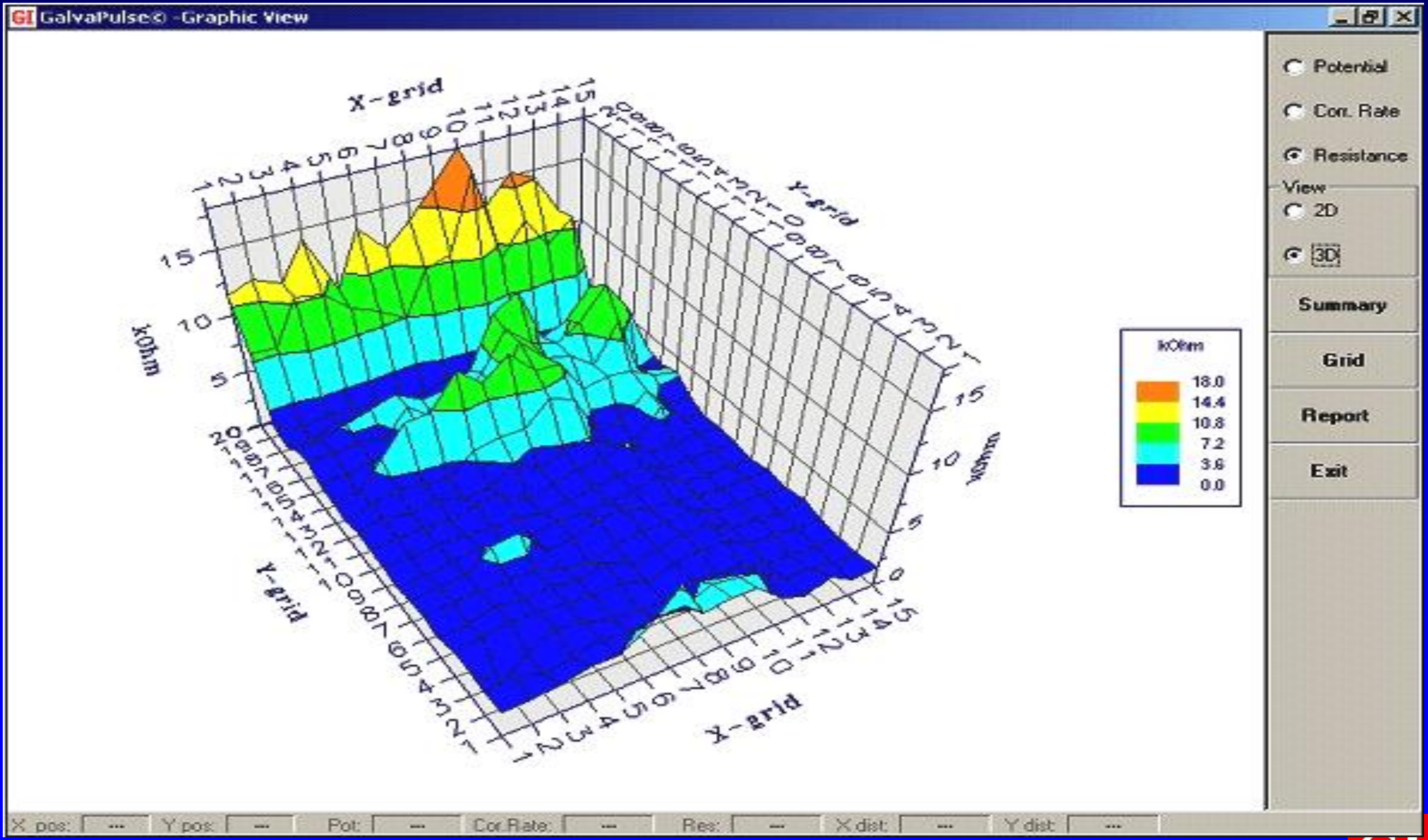
○ Potential
● Corr. Rate
○ Resistance

View
○ 2D
● 3D

X pos: --- Y pos: --- Pot: --- Cor.Rate: --- Res: --- X dist: --- Y dist: ---

Test smart – Build right

Ex. Electrical Resistance (kOhm)



○ Potential
○ Corr. Rate
● Resistance

View
○ 2D
● 3D

X pos: --- Y pos: --- Pot: --- Cor.Rate: --- Res: --- X dist: --- Y dist: ---

Summary

- Corrosion
  - Loss of passive film (chloride ions, carbonation)
  - Requires oxygen
  - Rate affected by concrete resistivity and temperature
- Half-cell potential
  - Indicates likelihood that corrosion is occurring
- Concrete resistivity
  - Affects corrosion rate

Summary

- Polarization resistance
  - Measures corrosion rate
  - Assumes uniform corrosion
  - Corrosion rate only at time of measurement
  - Different instruments give different i_{corr}, but will produce same relative ranking of corrosion rates at different locations
  - GalvaPulse 1st mode is for pot. and electrical resistance, 2nd mode also for corrosion rate within 5 to 10 seconds

Summary

- Check for Chlorides
- Chloride Profiling for service life estimation
- Check for Carbonation
- Especially for chloride corrosion the area of the rebar corrosion may be smaller than the area pulsed over with the GalvaPulse, producing too small corrosion rates
- Opening for visual inspection of the corrosion is always recommended