EC-011 · MODULE 4 OF 7

The Galvanic Series & Electrode Potentials

Every metal carries a number, and the sorted list of those numbers decides which metal corrodes in any couple. The fourth module of the Electrochemistry & the Galvanic Series set — the one the set is named for.

EXTERNAL CORROSION TRACK   FOUNDATION   ELECTROCHEMISTRY & THE GALVANIC SERIES   ~30 MINUTES

BY THE END OF THIS MODULE

You'll be able to —

- Explain what an electrode potential is and why every metal reads a repeatable number against a reference electrode.
- Read the practical galvanic series: active end corrodes, noble end is protected — the higher metal loses, every time.
- Calculate a couple's driving voltage (ΔE) from the series, and explain why ΔE predicts direction but not rate.
- Apply the area effect: cathode area sets the current, anode area takes the damage — small anode + large cathode is the danger geometry.
- Explain how mixed metals skew pipe-to-soil readings in both directions, and how coupons and exaggerated targets cut through.
- Name the mitigation ladder: isolation, more current, coat the cathode — and the design-time fix (zinc grounding).

TWO COMPRESSOR STATIONS, ONE SURVEY WEEK

The yard you dread, and the yard that reads like a textbook

The old yard — copper grounding

natives	loafing in the -500s
instant-offs	never reach criterion
CP output	creeps up every year
digs	better than the numbers

The meter says trouble; the steel mostly disagrees. Nobody's ever put a reason on it.

The new build — zinc ribbon grounding

natives	where steel belongs
instant-offs	past criterion, easily
CP output	no sweat
difference	on the drawings

Same pipe, same coating, same dirt. Somebody buried a different metal, and everything changed.

Why would the metal a pipeline is **grounded with** change the voltage it **reads** — and which yard is actually better protected?

Every metal has a number. Sort the numbers and you get a ranking. Couple any two metals, and the one higher on the ranking corrodes for the benefit of the one below it.

This module is that one page — and everything it explains.

PART 1 OF 5

Electrode potentials: every metal has a number

THE FINGERPRINT VOLTAGE

Bury it, measure it, get the same number tomorrow

Connect a voltmeter between a buried metal and a reference electrode on the ground above it. The meter settles on a repeatable, characteristic number: that metal's **electrode potential** in that environment.

- For soil work, the reference is a **copper-copper sulfate electrode (CSE)** — every number in this module is "versus CSE."
- The number is a gauge reading on the metal's push to shed electrons — the refining energy working to get back out.
- Why the CSE works, and what its cousins are for, is a later module. Today we use the numbers.

More negative = more active = pushing harder to corrode. Less negative = more noble = content to let some other metal do the corroding.

YOU CAN WATCH IT LIVE

Three metals, one soil, three numbers

On a yard where the metals aren't bonded together, walk the voltmeter around: an isolated steel riser, a galvanized post, a copper ground rod. Same soil, same reference cell — three different, repeatable numbers.

STEEL RISER

-0.65 V

the working metal of every pipeline — middle of the ladder

GALVANIZED POST

-1.10 V

zinc coating reads like zinc — high on the ladder, eager

COPPER GROUND ROD

-0.20 V

noble and unbothered — low on the ladder

You're not measuring one structure three ways. You're reading rows off a list you haven't seen yet.

ONE HONEST FOOTNOTE

The textbook list vs. the practical list

CHEMISTRY TEXTBOOK

Standard electromotive series

Pure metals, laboratory solutions, textbook concentrations. Real science — and the wrong tool for a right-of-way.

OUR PAGE

Practical galvanic series

Actual potentials measured on actual construction metals in real soil and water — mill scale, alloying, and all. An empirical document.

> **Somebody measured these numbers in the dirt** — which is exactly why they work in the dirt. When a table and a field measurement disagree, the field measurement wins.

PART 2 OF 5

The galvanic series: reading the ladder

THE ONE PAGE THIS SET IS NAMED FOR

Practical galvanic series — neutral soils and water, volts vs. CSE

more active — corrodes preferentially

ACTIVE END — corrodes first	
Magnesium	-1.50 to -1.75
Zinc	-1.10
Aluminum alloy	-1.05
Carbon steel (clean)	-0.50 to -0.80
Cast / ductile iron	-0.50
Lead	-0.50
Carbon steel (rusted)	-0.20 to -0.50
Steel in concrete	-0.20
Copper, brass, bronze	-0.20
Mill scale on steel	-0.20
High-silicon cast iron	-0.20
Carbon, graphite, coke	+0.30
NOBLE END — protected	

more noble — protected

Couple any two: the one closer to the top corrodes. The order is what you bank on; the decimals drift with the dirt.

HOW TO READ IT

One rule, no exceptions

When two metals on the list are electrically connected in a common electrolyte:

- The one closer to the **active end becomes the anode** — it corrodes.
- The one closer to the **noble end becomes the cathode** — it's protected.

The higher metal loses. Every time. That's the entire framework — everything else in this module is detail hanging off one sentence.

FIRST THING TO NOTICE

Magnesium and zinc sit above steel

Wire either one to a steel pipeline and the series says the anode is the magnesium or the zinc — **not your pipe.** That single fact is why galvanic cathodic protection exists.

> **A sacrificial anode is deliberate galvanic corrosion**, aimed at a metal we chose and buried on purpose. The gnawed-down anode from the last module wasn't a victim — it was doing its job as written on this page.

SECOND THING TO NOTICE

Copper sits below steel

Same physics, opposite result. Couple a steel line to buried copper — a grounding grid, a water service, plated fittings — and now **the steel is the metal higher on the list.** The pipeline becomes the sacrificial anode, protecting copper nobody asked to have protected.

> Copper's underground reputation for being "corrosion-free" is real — and this is what it costs. Somewhere, a more active metal is quietly picking up the bill. **The series doesn't care which couple you meant to build.**

THIRD THING TO NOTICE

Steel appears four times on its own list

NEW + OLD PIPE

Weld a bright new joint into an old rusted line: the **new steel is anodic** to the old. Replacement sections fail faster than the pipe they replaced — unless protected or isolated.

CONCRETE + SOIL

Steel in concrete reads about −0.20 — noble to the same steel in soil. A wall penetration or encased span sets up a couple with the buried pipe on the losing end.

MILL SCALE + BRIGHT METAL

Mill scale reads noble to the pipe steel under it. A shovel-scrape of bright metal beside undisturbed scale is a live couple.

You don't need two metal types for a galvanic couple — two conditions of one metal will do.

PART 3 OF 5

The gap is the drive

THE WORKING CALCULATION

ΔE — the couple's driving voltage

The order tells you who corrodes. The numbers tell you how hard the cell pushes:

$$\Delta E = E(\text{cathode metal}) - E(\text{anode metal})$$

copper + clean steel: `(-0.20) - (-0.65) = 0.45 V`

- Two negative numbers, subtracted — keep the signs straight and the answer comes out positive.
- Bigger gap = stronger drive. Magnesium-to-steel spans nearly a full volt — enough to push through soils that would stall a weaker cell.
- Same row = no gap, no drive, no problem. Nobody loses sleep over brass fittings on copper pipe.

WORKED — CALL THE ANODE, SIZE THE DRIVE

Three couples, three verdicts

MAGNESIUM + STEEL

$\Delta E = 0.90$ V

$Mg \rightarrow Mg^{2+} + 2e^-$

Magnesium is the anode. **Intentional** — a galvanic anode doing its job. The steel keeps its metal.

STEEL + COPPER GROUNDING

$\Delta E = 0.45$ V

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

Steel is the anode. **Problem** — the "sacrificial anode" in this cell is the pipeline. Nobody signed up for that trade.

ZINC + STEEL

$\Delta E = 0.45$ V

$Zn \rightarrow Zn^{2+} + 2e^-$

Zinc is the anode. **Intentional** — the same move magnesium makes, with a gentler push.

Couples 2 and 3 run on the identical 0.45-volt drive — one is protection you'd pay for, one is damage you'll pay to repair. Only the series tells you which end of the wire your steel is on.

TWO CAUTIONS BEFORE YOU TRUST THE NUMBER

You've held one of these. And ΔE isn't a speedometer.

THE BATTERY IN YOUR HAND

A classic flashlight battery is a **zinc case around a carbon rod**: zinc −1.10, carbon +0.30 — a 1.4-volt galvanic couple doing useful work on purpose. Check it against the label on a zinc-carbon cell.

The battery and the couple loose in a copper-grounded yard are the same machine. One of them just has a job.

DIRECTION, NOT SPEED

ΔE predicts who corrodes and how hard the cell pushes — not how fast metal leaves.

Couples 50 mV apart have caused severe damage; metals 800 mV apart have been coupled and lived. Rate depends on the current that actually flows — resistivity, coating, and above all the factor on the next slide.

PART 4 OF 5

The area effect: the multiplier

TWO FACTS, ONE RULE

The cathode sets the current. The anode pays for it.

DANGER GEOMETRY

Small anode + large cathode

A big cathode gathers a big current; a small anode pays the whole bill across a few square inches. Current density goes through the roof: **pits, perforation, early failure.**

FORGIVING GEOMETRY

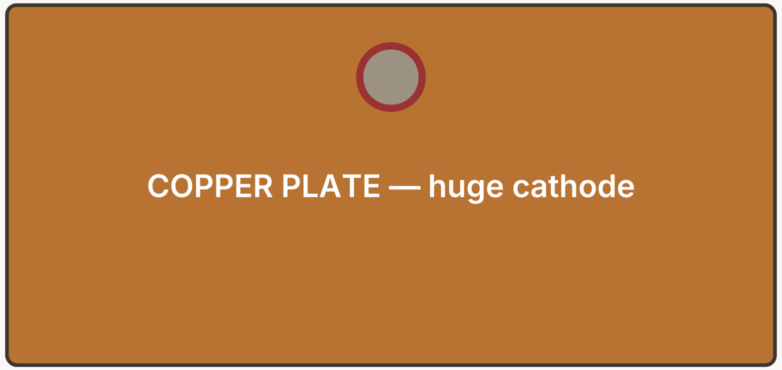
Large anode + small cathode

A small cathode can only gather a small current; a big anode spreads that bill across acres of surface. **The same physics, diluted to a nuisance.**

Small anode feeding a large cathode is the worst geometry in corrosion — the area ratio can matter more than the metals themselves.

WORKED — TWO RIVETS, OPPOSITE FATES

A — steel rivet in a copper plate

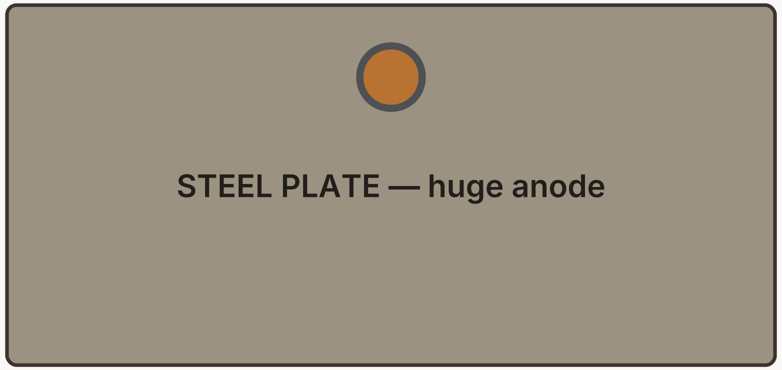


tiny steel anode pays the whole bill

`ratio: hundreds-to-1 against the rivet`

pits, thins, lets go — catastrophic

B — copper rivet in a steel plate



small cathode can only gather a small current

`loss spread across the whole plate`

slow and boring — a nuisance

Same two metals. Same 0.45-volt gap. The area ratio decides the outcome.

"Noble bolts in an active structure, never active bolts in a noble structure" — the fastener is always the small one.

UNDERGROUND, HIDING IN PLAIN SIGHT

Same geometry, buried

- **Galvanized service cap on a bare steel main** — a small zinc anode wired to miles of cathode. Corrodes fast and early.
- **Brass valve in a long steel line** — the friendly version: small cathode, giant anode, mild attack near the valve.
- **Copper grounding grid vs. a well-coated pipeline** — the ugly one. The grid's buried surface can run several times the piping's, while the pipe's only anode surface is a few square feet of coating holidays. A good coating normally shrinks your problem — in a mixed-metal couple it concentrates the entire galvanic bill on the few bare spots.

Rough field flag: past about 10:1 cathode-to-anode, treat the couple as a serious threat.

PART 5 OF 5

Back to the two yards: what the meter actually reads

WHAT A READING IS, ONCE METALS ARE COMMON

The voltmeter doesn't see steel. It sees an average.

Your meter can't see "the pipe" as separate from anything metallically connected to it — grounding grid, structural steel, motor frames, everything the electrical code bonds together.

> What it reads is a **mixed potential**: a composite of every connected metal in the soil, weighted by how much surface each exposes and how easily each trades current with the soil around it. **The system's center of gravity.**

On a copper-grounded yard, the copper's surface area dominates the blend — and copper's row on the series is far less negative than steel's. The average gets pulled where the copper lives.

HONEST NUMBERS ON THE COPPER YARD

The copper yard: what the voltmeter blends together

STEEL alone

-630 mV

native, isolated, this soil

~1× exposed area (holidays)

BONDED TOGETHER

-510 mV

composite native — the meter's center of gravity

COPPER alone

-160 mV

native, isolated, this soil

~5× the steel's buried area

A hundred-plus millivolts less negative than the steel deserves — on both the native and the instant-off.

The voltmeter doesn't see steel. It sees the average of everything on the wire.

ONE SKEW, TWO LIES

Both criteria get fooled — in opposite directions

THE -850 CRITERION: FALSELY BLEAK

Energize and interrupt: instant-off composite `-670 mV`. Against −850 the yard reads **failing** — and extra current mostly pours into the copper. Output creeps, year over year. That's the dread yard.

THE 100 MV SHIFT: FALSELY SAFE

Apparent shift: −510 → −670 = **160 mV. Passes easily.** But the steel's own native was −630 — the steel polarized **at most 40 mV**, less in practice. The copper absorbed the rest.

160 mV of polarization on a composite is not 160 mV on steel. Both readings honestly report what the voltmeter saw — the voltmeter just wasn't looking at steel.

CUTTING THROUGH

Know which question each tool answers

DROP A COUPON

A small piece of bare steel in representative soil, connected only through a test-station lead — free of the copper's vote. **The closest thing to asking the steel directly.**

A coupon doesn't protect anything — it's a thermometer, not a heater. When structure and coupon disagree, believe the coupon.

RAISE THE BAR — AND KNOW ITS COST

Where the connection can't be broken: target **200–350 mV of apparent shift** instead of 100, so the steel inside the blend still collects the real criterion.

It's a margin, not a fix: the extra current mostly feeds the copper — and past about **−1.20 V composite**, you start trading corrosion for coating and hydrogen damage.

AND THE NEW STATION?

Zinc grounding: the problem, designed away

The new yard's designers read the same page this module handed you. Their grounding is **zinc — a metal from the active side of steel on the series.**

- The "foreign metal" in the blend now sits **more negative** than the pipe instead of less — no noble giant dragging the composite toward copper's row.
- No current-thief to feed: the grid behaves like a **sacrificial partner instead of a parasite**, nudging protection toward the steel while doing its electrical-safety job.
- Same physics as the copper yard. Opposite row of the table.

> Which yard is better protected? The zinc yard, you can answer straight off the survey. The copper yard, you can't answer at all until a coupon or a bell hole weighs in — and that is exactly the point.

BREAKING THE COUPLE

The mitigation ladder

1 · GOLD STANDARD

Electrical isolation

Dielectric unions, insulating flange kits, monolithic joints — no metallic path, no cell. **Kits fail quietly:** verify with a meter at every survey, not by admiring gaskets.

2 · BRUTE FORCE + GEOMETRY

More current · coat the cathode

Drive to the exaggerated target, verified on coupons. Or shrink the cathode by coating the noble metal. **Never coat only the anode** — every holiday becomes the worst geometry on the page.

3 · DESIGN TIME

Pick better neighbors

Choose buried metals from the same neighborhood of the series — or, like the new station's zinc grounding, from the active side of steel — so the couple never gets built.

A CAUTION THAT KEEPS THE SERIES HONEST

Field data beats the table

- **Environment moves the numbers.** Soil and seawater series mostly agree on order, not on decimals — and marine tables are usually quoted against a different reference electrode.
- **Temperature moves them too.** Zinc and steel, comfortably separated at ambient, can close entirely in hot systems.
- **Stainless steels are shape-shifters:** passive film intact, they sit with the nobles; film broken (starved crevice, chloride pocket), they jump most of the way up the ladder. One alloy, two positions — sometimes on the same fitting.
- **Graphitized cast iron flips the script:** old gray iron corrodes away to its graphite skeleton — the most noble entry on the page — and starts eating the copper that used to eat it.

Positions on the page are a prediction. A potential measured in the ground is a fact. When they disagree, the ground wins.

WHAT TO CARRY OUT OF EC-011

The page, in nine lines

- **Electrode potential:** every metal's fingerprint voltage vs. a reference (CSE in soil). More negative = more active.
- **The series** is those fingerprints, sorted — empirical, measured in real dirt.
- **The higher metal loses.** Every couple, every time.
- **Mg and Zn above steel** = sacrificial anodes. **Copper below steel** = your pipe protects the grounding.
- **Steel appears four times** — new/old, concrete, mill scale: it couples with itself.
- **ΔE = cathode minus anode** — direction and drive, not rate.
- **Area effect:** cathode sets the current, anode pays. Past ~10:1, serious threat.
- **Mixed metals skew readings both ways** — falsely bleak on −850, falsely safe on 100 mV shift. Coupons and 200–350 mV targets cut through; zinc grounding designs it away.
- **Isolate first** (and verify the kits), then current or coatings — never coat only the anode.

References & further reading

- **Mixed Metal Potentials** — Field Notes from RCS; included with this module as a PDF supplement.
- **The Area Effect in Galvanic Corrosion** — Field Notes from RCS.
- **Corrosion Basics: An Introduction** — galvanic corrosion, the series, area effects.
- **Peabody's Control of Pipeline Corrosion** — the practical series and galvanic-anode CP.
- **Cathodic Protection Training Materials** — industry credential materials, CP-technician level.
- **AUCSC Short Course Materials** — pipeline corrosion technician curriculum.
- **NACE SP0169** — external corrosion control criteria.
- **NACE TM0497** — measurement techniques for CP criteria.
- **ISO 15589-1** — on-land pipeline CP, incl. upper-bound limits.
- **ASTM G82** — development and use of a galvanic series.

NEXT IN THE SET

Faraday's Law & corrosion rates

You can now call the anode and size the drive. Next, the arithmetic: turning current into pounds of metal per year — and anode life into a number you can stand behind.