REHABILITATION AND CONSTRUCTION OPTIONS FOR CONCRETE BRIDGES — ENSURING LONG SERVICE LIFE

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***(A Cooperative Agency Co-Sponsored by the University of Virginia and the Virginia Department of Transportation)**

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VDOT

COMMON MAINTENANCE PROBLEMS FOR CONCRETE BRIDGES IN U.S.A.

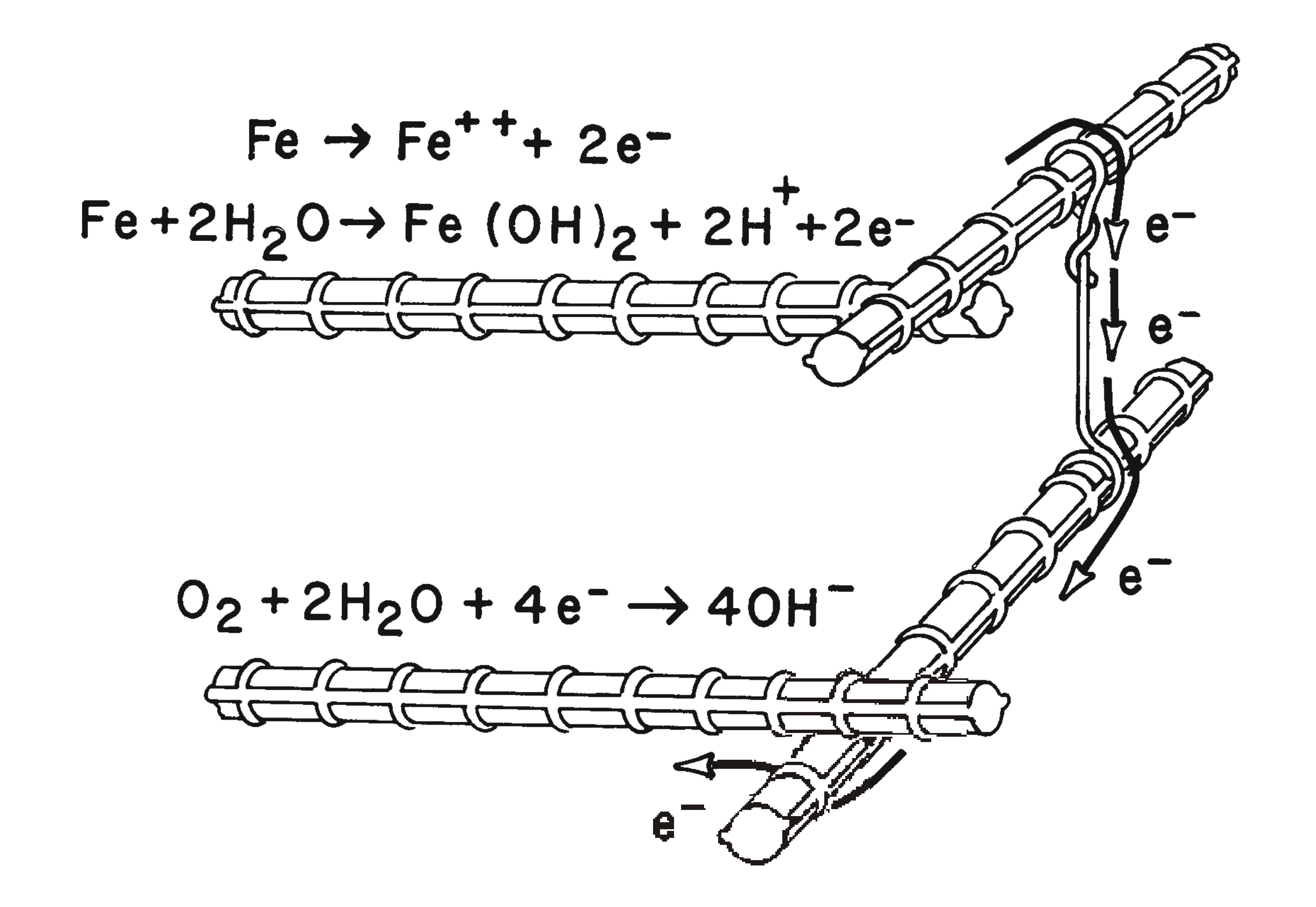
- **Corrosion of Reinforcing Steel —**

  — according to 48% of respondents to survey by ASCE in 2003.

- **Intrusion of Cl- and CO_2 are the Causes**

  — with chloride being the major cause.

TYPICAL CORROSION CELLS IN A CONCRETE BRIDGE DECK



EXTENT OF THE PROBLEM IN VIRGINIA CONCRETE BRIDGES

- **Prestressed Concrete:**
  Still isolated to concrete piles in coastal areas.

- **Conventional Reinforced Concrete:**
  - **Decks – extensive in older decks built with bare steel bars.**
  - **Piers – same.**

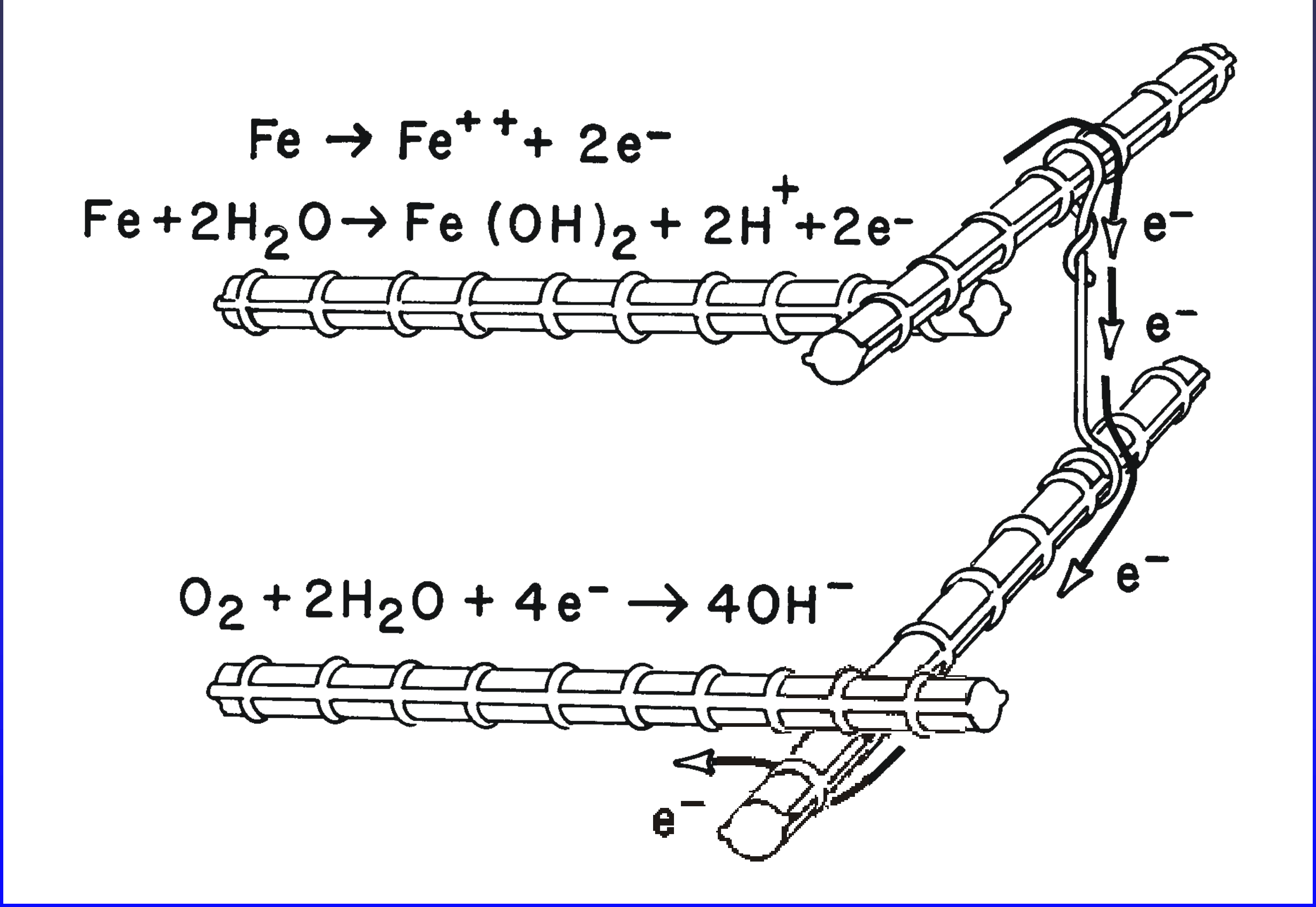
Corrosion Problem on Prestressed Concrete Piles in Virginia Coastal Areas

Corrosion Problem on Inland Concrete Piers in Virginia

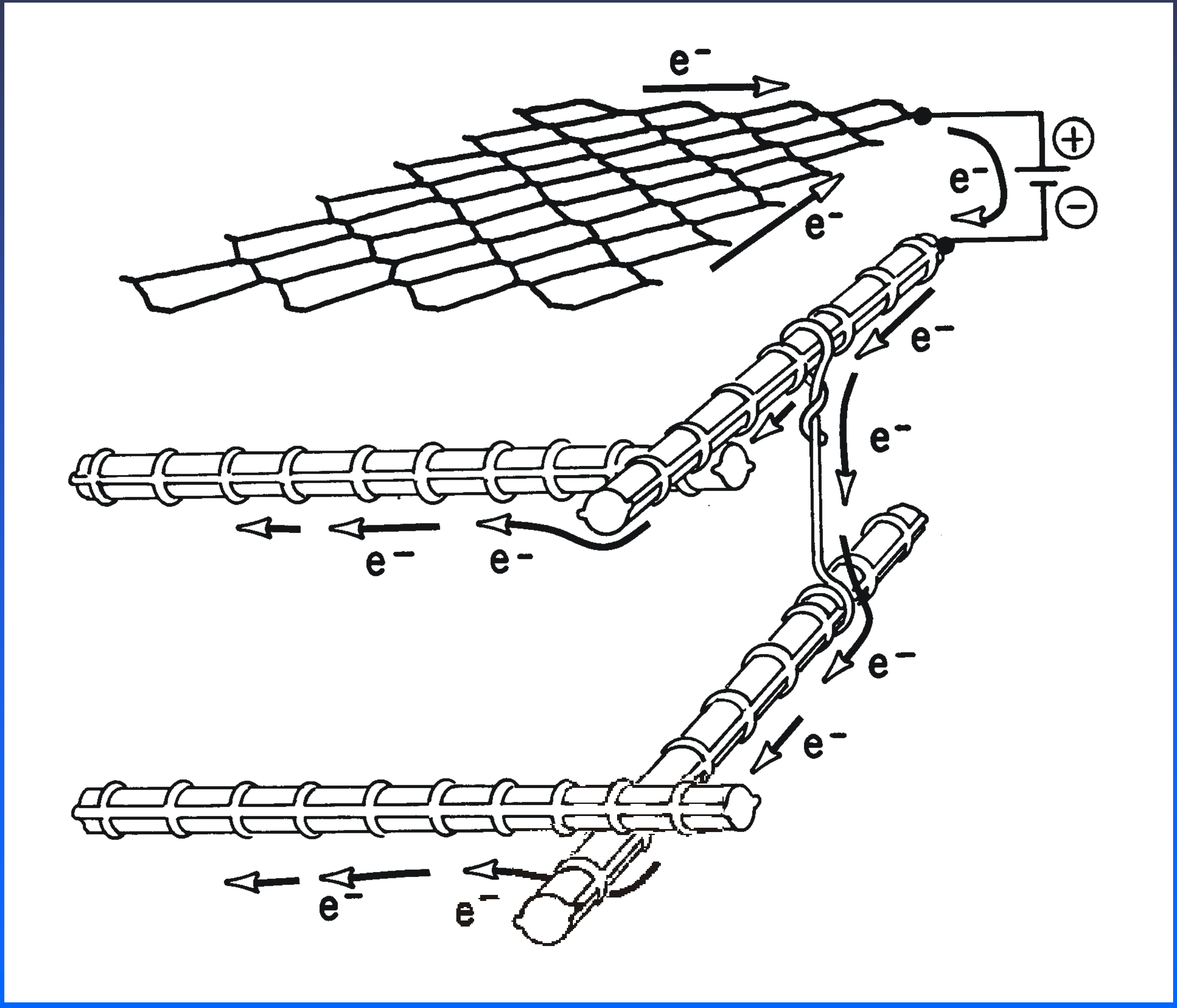
Options for Effective Control of Existing Corrosion

- Inland Concrete Decks:
  - Impressed-current cathodic protection
  - Chloride extraction
- Inland Concrete Piers:
  - Impressed-current cathodic protection
  - Galvanic-current cathodic protection
  - Chloride extraction
- Prestressed Marine Concrete Piles:
  - Galvanic-current cathodic protection

TYPICAL CORROSION CELLS (IN A CONCRETE BRIDGE DECK)



IMPRESSED-CURRENT CATHODIC PROTECTION (IC-CP)



IC-CP of Concrete Decks (Using Ti Mesh as Anodes)

Overlaying of the Ti-Mesh Anode with Fresh Concrete

IC-CP of Inland Concrete Piers (Using Conductive Coatings as Anode)

A Completed Conductive-Coating Anode System

GALVANIC CATHODIC PROTECTION (G-CP) SYSTEMS

G-CP of PS Beams (Using Arc-Spraying of Al-Zn-In Anode)

A Completed Al-Zn-In CP System

A Al-Zn-In Installation on PS Piles

Installation of Zn / Hydrogel Anode on PS Piles

A Zn Mesh / Grout Jacket Anode

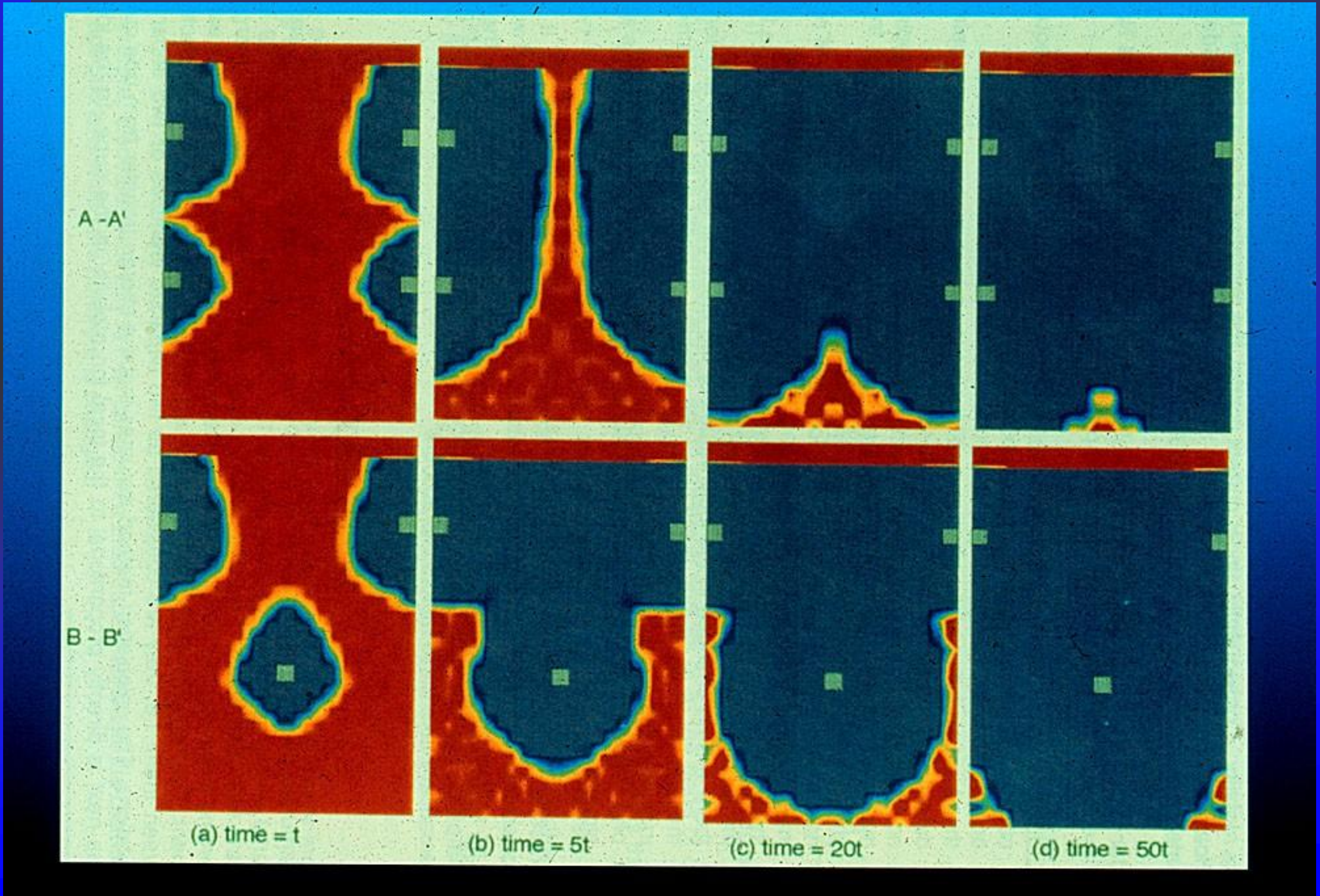
A Close-Up of the FRP Jacket and Zn Mesh

A Completed Zn Mesh / Grout Jacket Anode

Zn Mesh / Compression Panel Anode

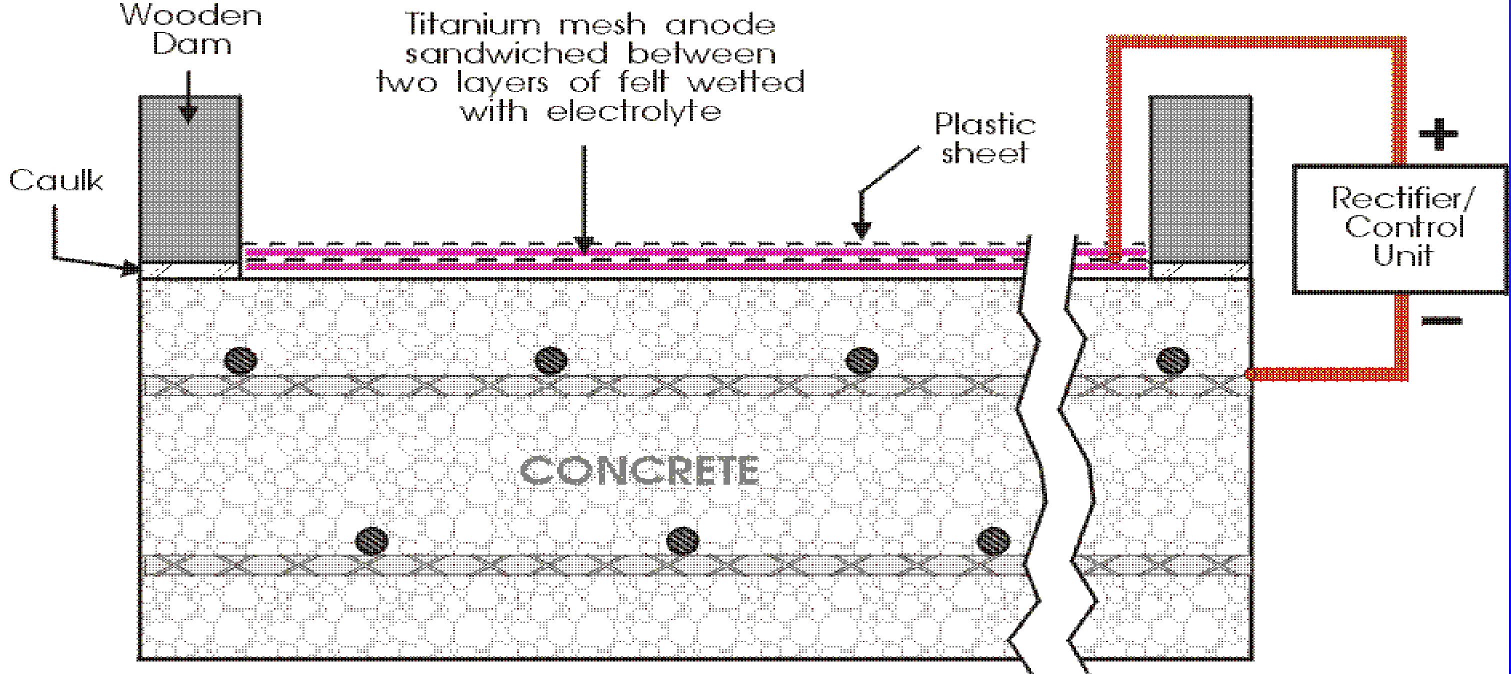
An Almost Completed Zn / Compression Panel Anode

ELECTROCHEMICAL CHLORIDE EXTRACTION (ECE) OF CONCRETE



An ECE System for Bridge Decks

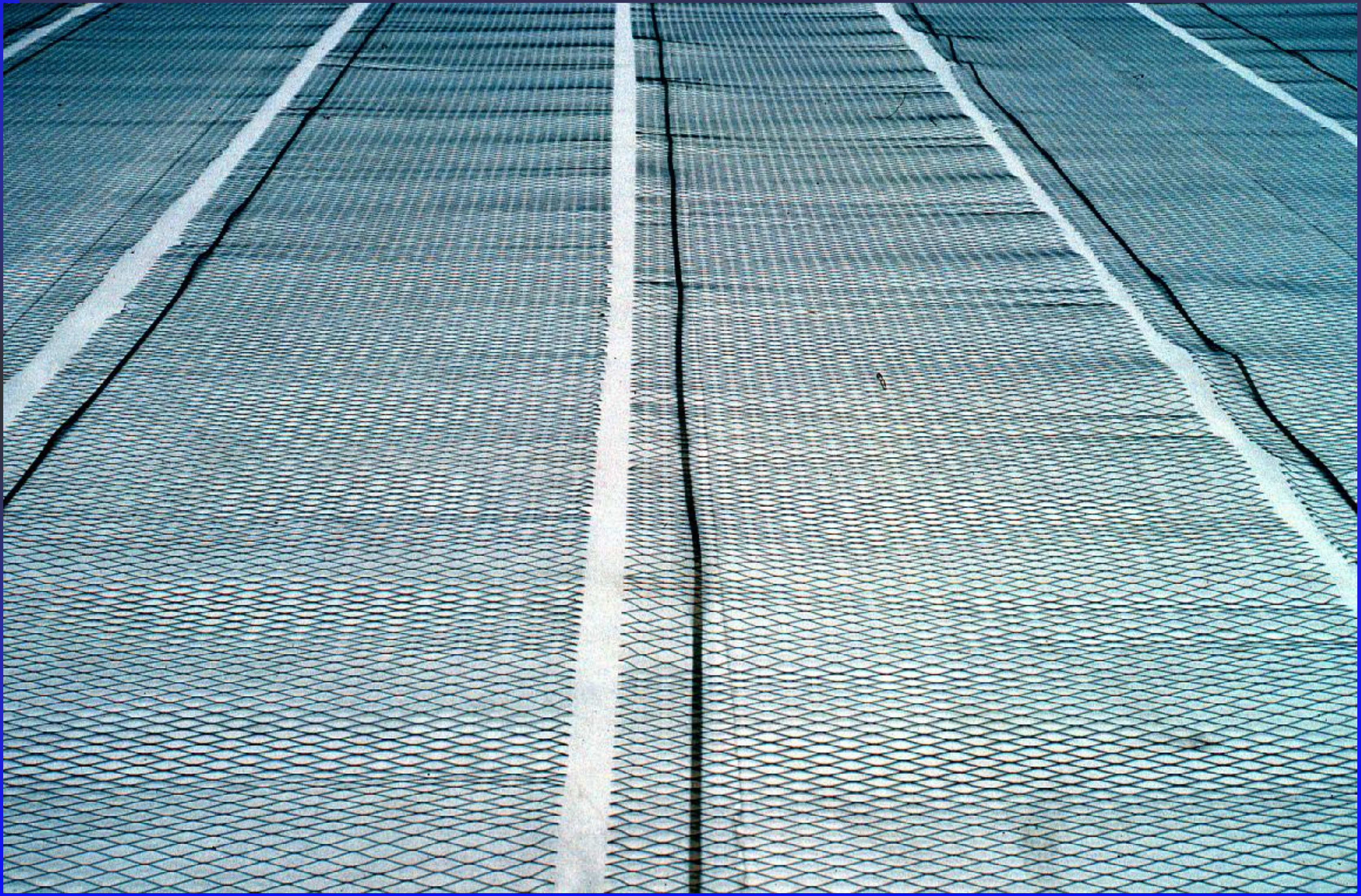
G. G. Clemeña & D. R. Jackson Figure 1



Installation of a ECE System on Decks

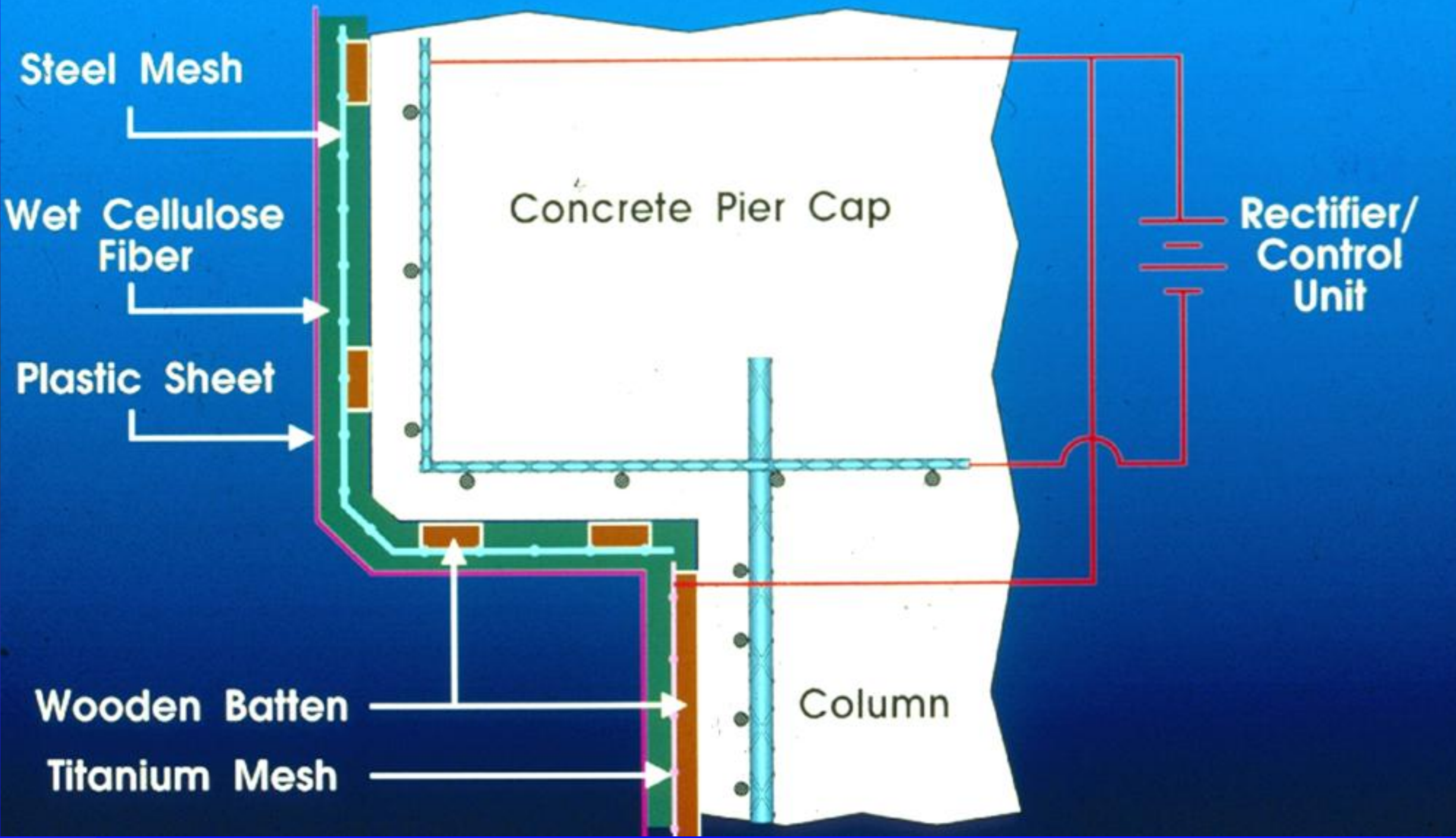
Laying of Felts over the Concrete

Titanium-Mesh Anodes Placed over the Felts



Part of a Completed ECE System for Concrete Decks

SETUP FOR ELECTROCHEMICAL CHLORIDE EXTRACTION FROM CONCRETE PIERS IN VIRGINIA



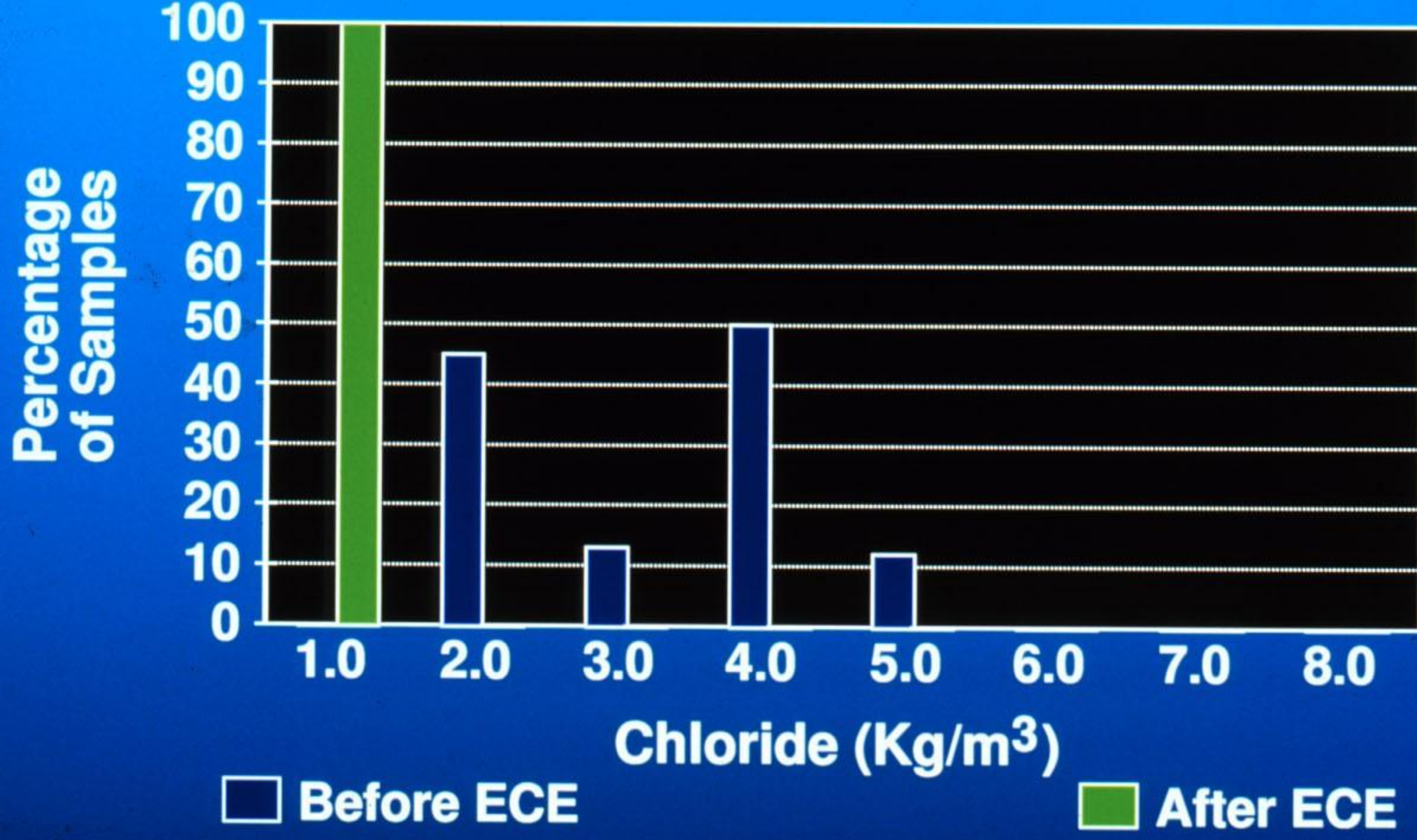
Installation of a ECE System on Piers

Spraying of Wet Fibers on Piers

Wrapping of Piers with Plastics

A Completed EC Treatment System

DISTRIBUTION OF CHLORIDE CONCENTRATIONS
Span 4 South Half (1.9 - 3.2 cm)



AVERAGE COST & LIFE EXPECTANCY FOR REHABILITATION OPTIONS

Maintenance Option	Cost ($\$/m^2$)	Expected Life (yr)
IC-CP (Decks)	115	35
IC-CP (Piers)	143	20
G-CP (Piers)	120	15
ECE (Decks)	90	15
ECE (Piers)	161	15

OPTIONS FOR PREVENTING CORROSION IN FUTURE BRIDGES

- **Use of High-Performance Concrete.**
- **Provision of Sufficient Concrete Cover for the Reinforcement.**
- **Use of Suitable Admixtures**
- **Use of Corrosion-Resistant Bars.**

NEW REINFORCING BARS TESTED FOR CORROSION RESISTANCE:

- **Stainless Steel-Clad Carbon Steel (CB)**
- **Microcomposite Steel MMFX-2**
- **Unpickled 2101 LDX**
- **Galvanized- then-Epoxy-Coated Carbon Steel (Zn/EC)**
- **Positive-Machined 304 Stainless Steel (R340)**

CONVENTIONAL BARS COMPARED AGAINST:

- **Carbon Steel (CS)**
- **316 LN Stainless Steel**

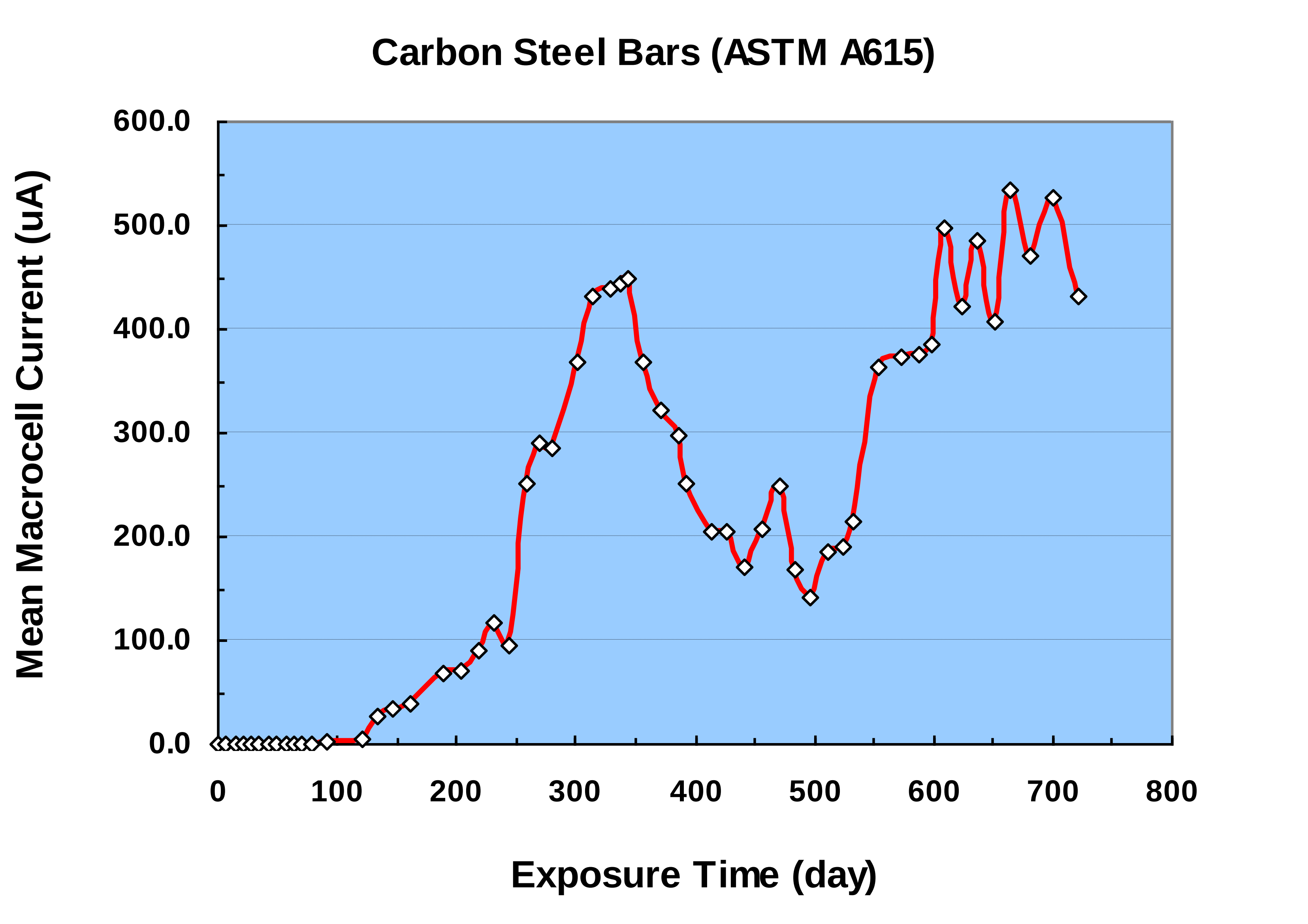
Assessment of the Resistances of the Bars to Chloride-Induced Corrosion in Concrete:

1. Embed the bars in concrete blocks.
2. Weekly exposure the blocks to a NaCl solution.
3. Monitor the corrosion status of each bar to pinpoint its time-to-corrosion (T_C)
4. Estimate the chloride concentration in the concrete at each T_C.

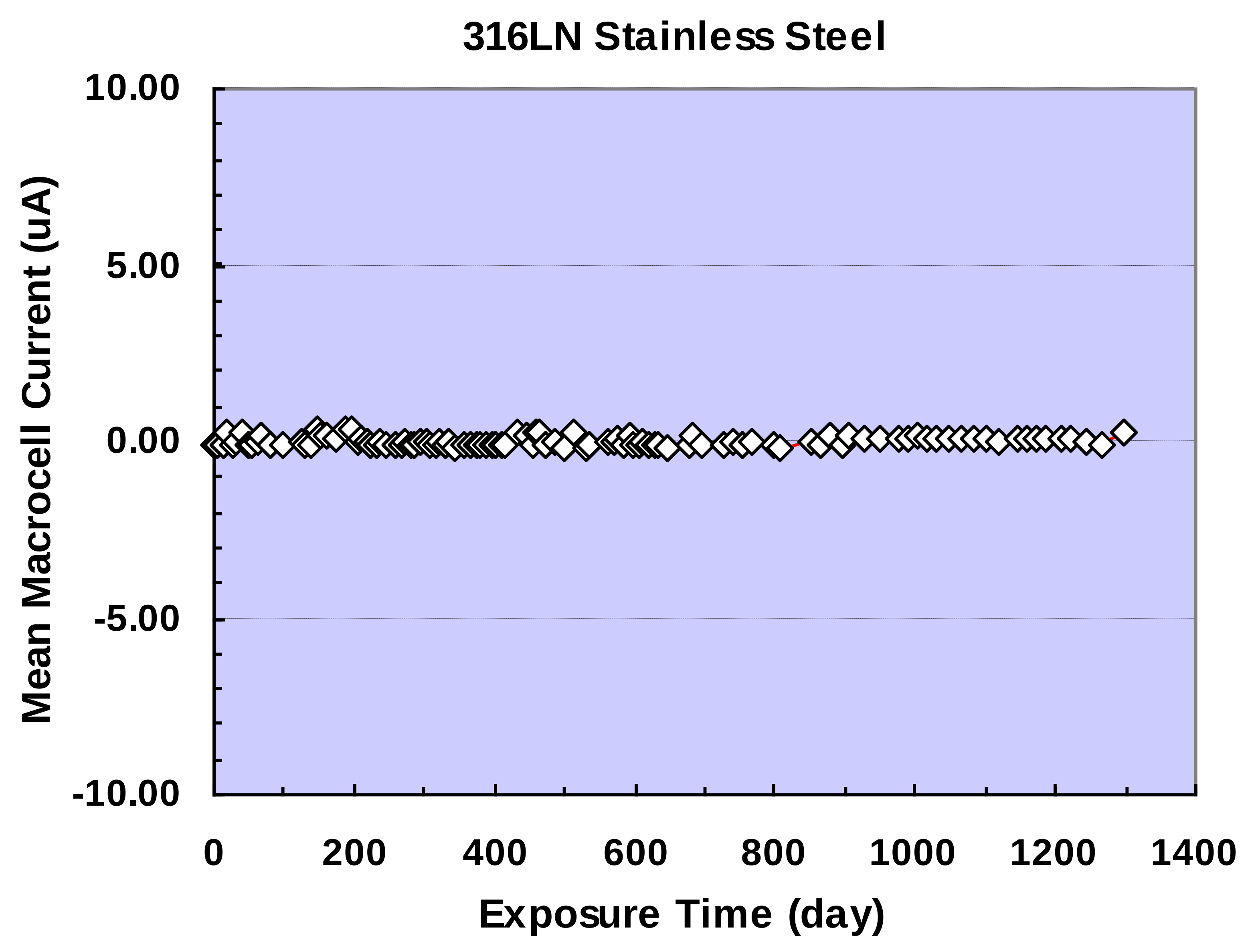
Exposure of the Concrete Blocks

RESULTS

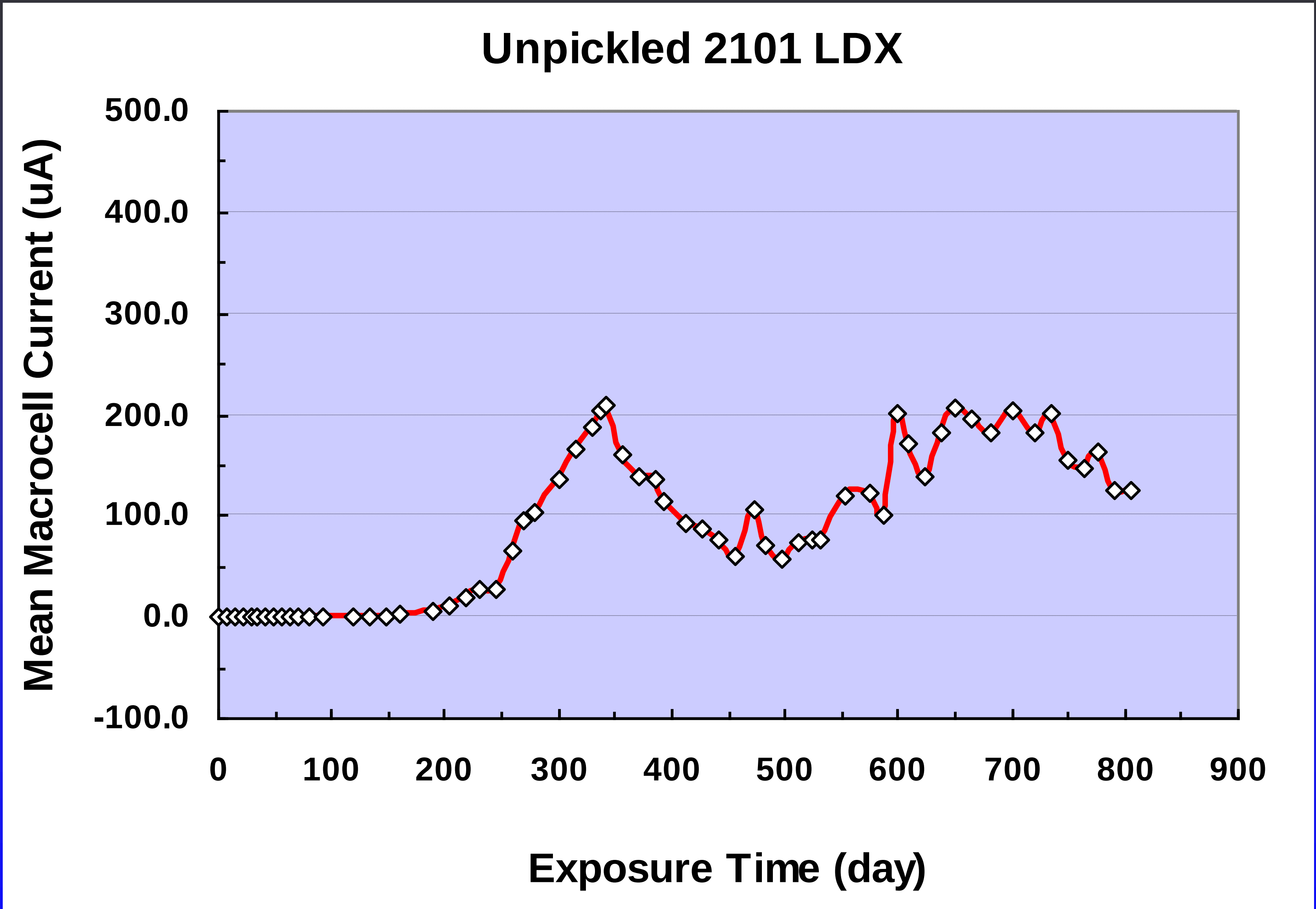
1. **Mean Macrocell Currents (Per ASTM G-109)**



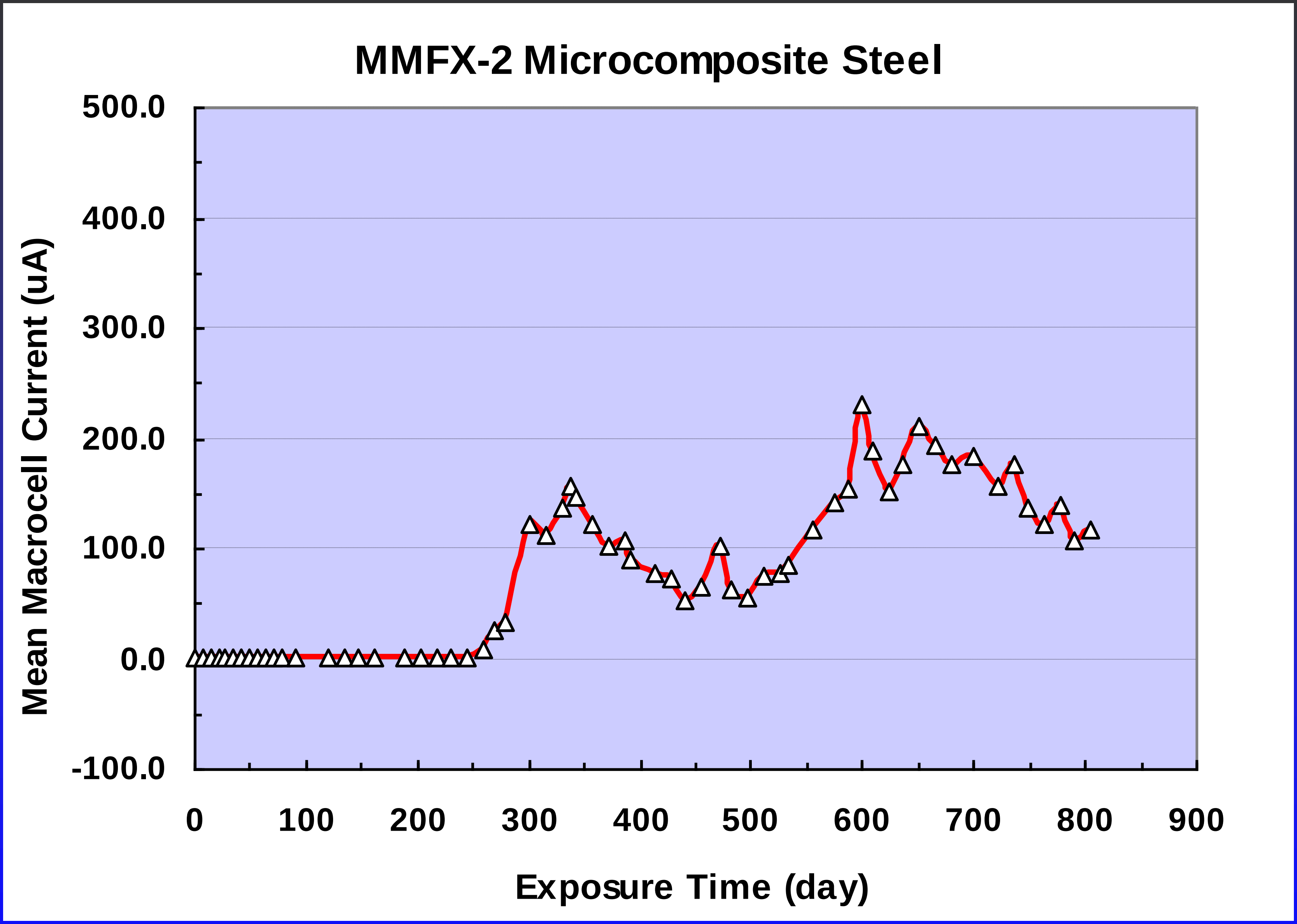
Time-to-Corrosion = 92 ± 3 days



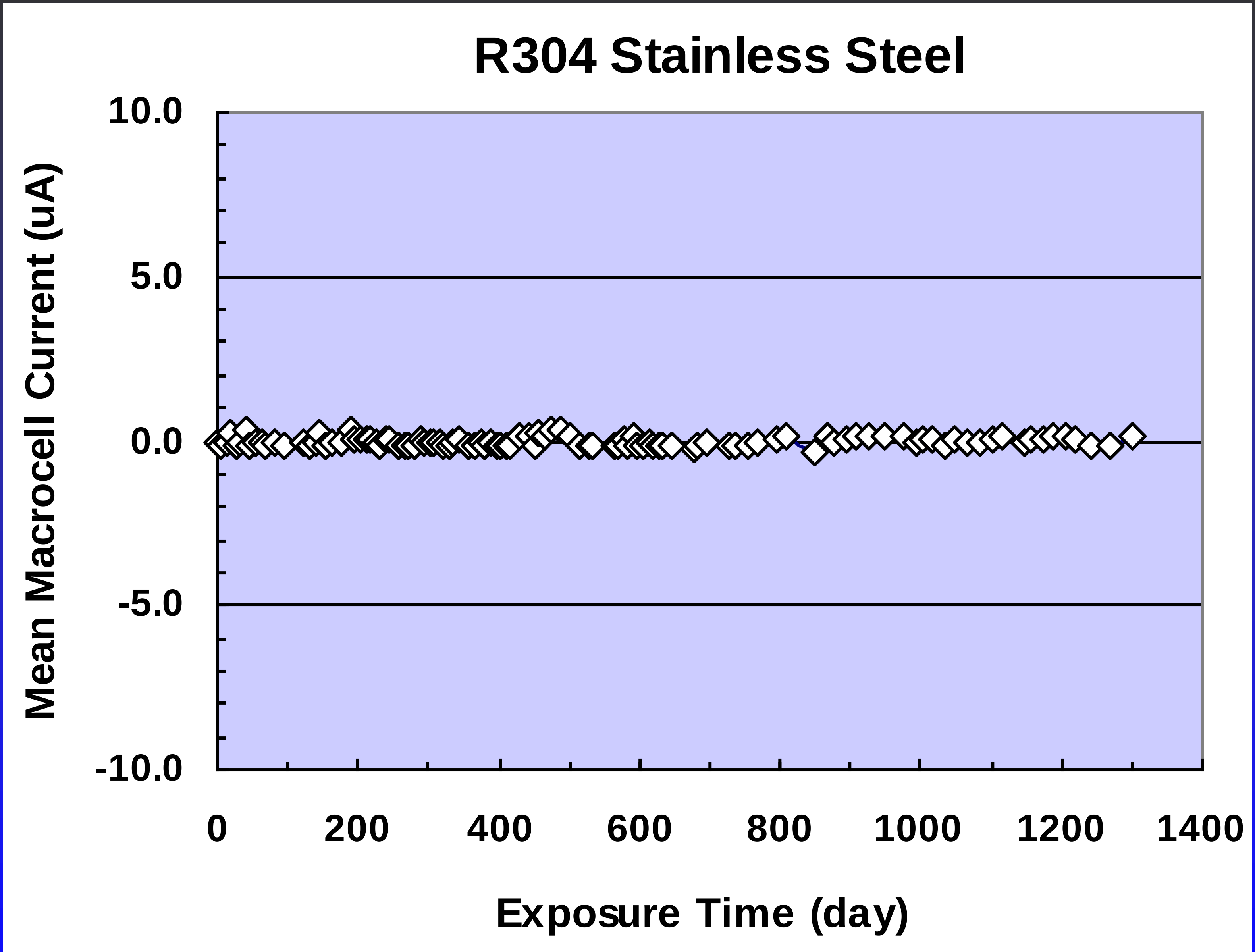
Time-to-Corrosion > 1,200 days



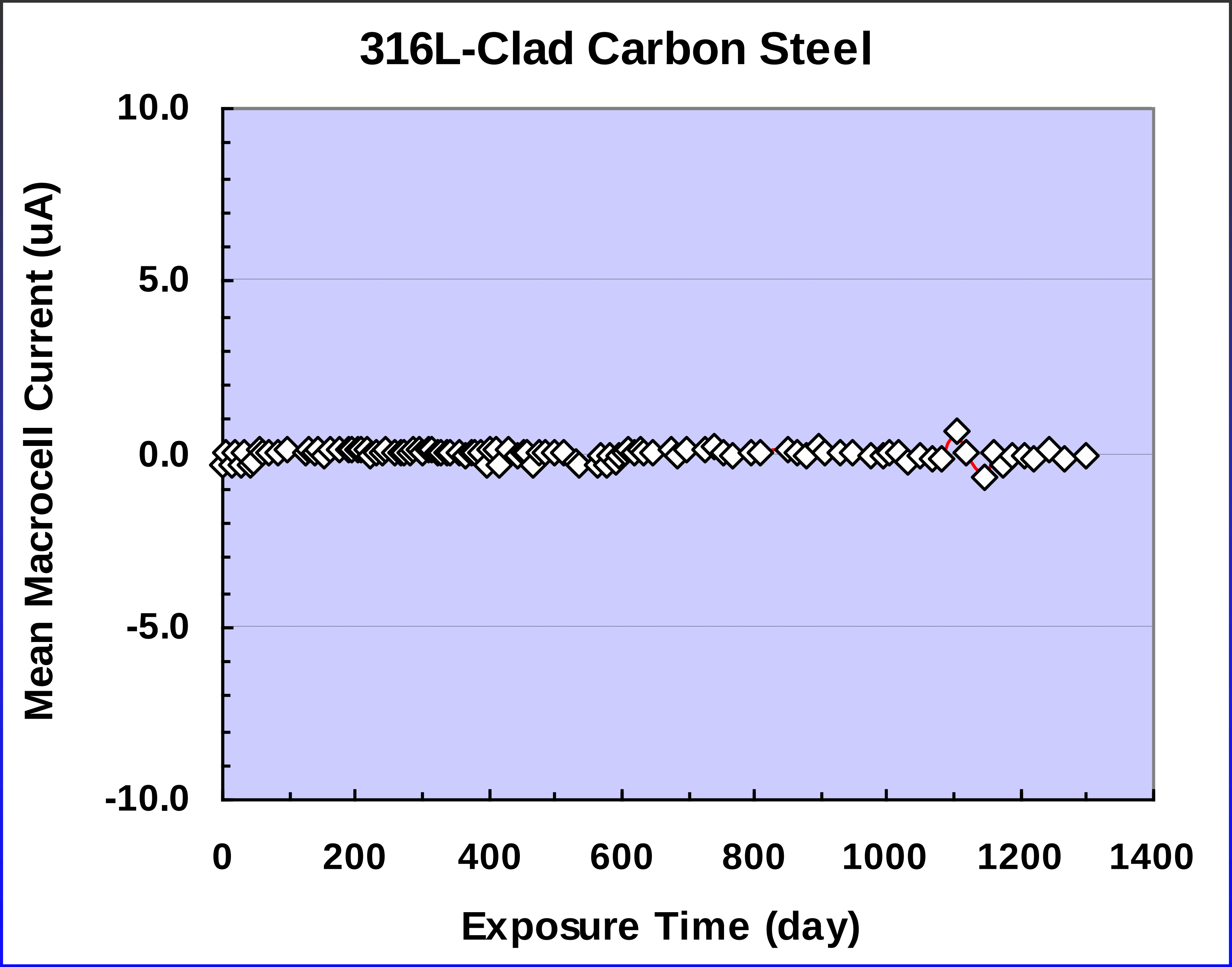
Time-to-Corrosion = 147 ± 3 days



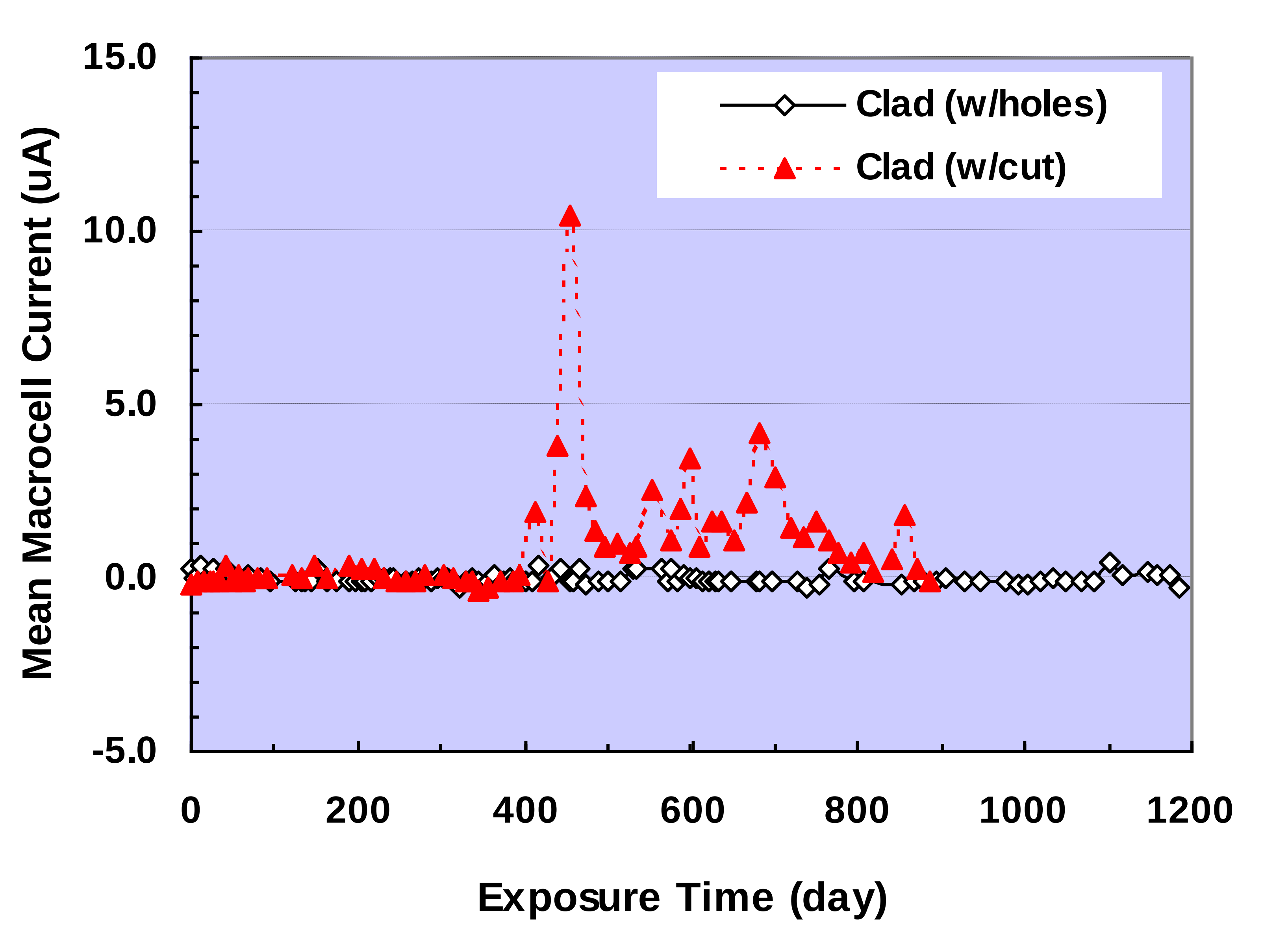
Time-to-Corrosion = 245 ± 3 days



Time-to-Corrosion > 1,200 days

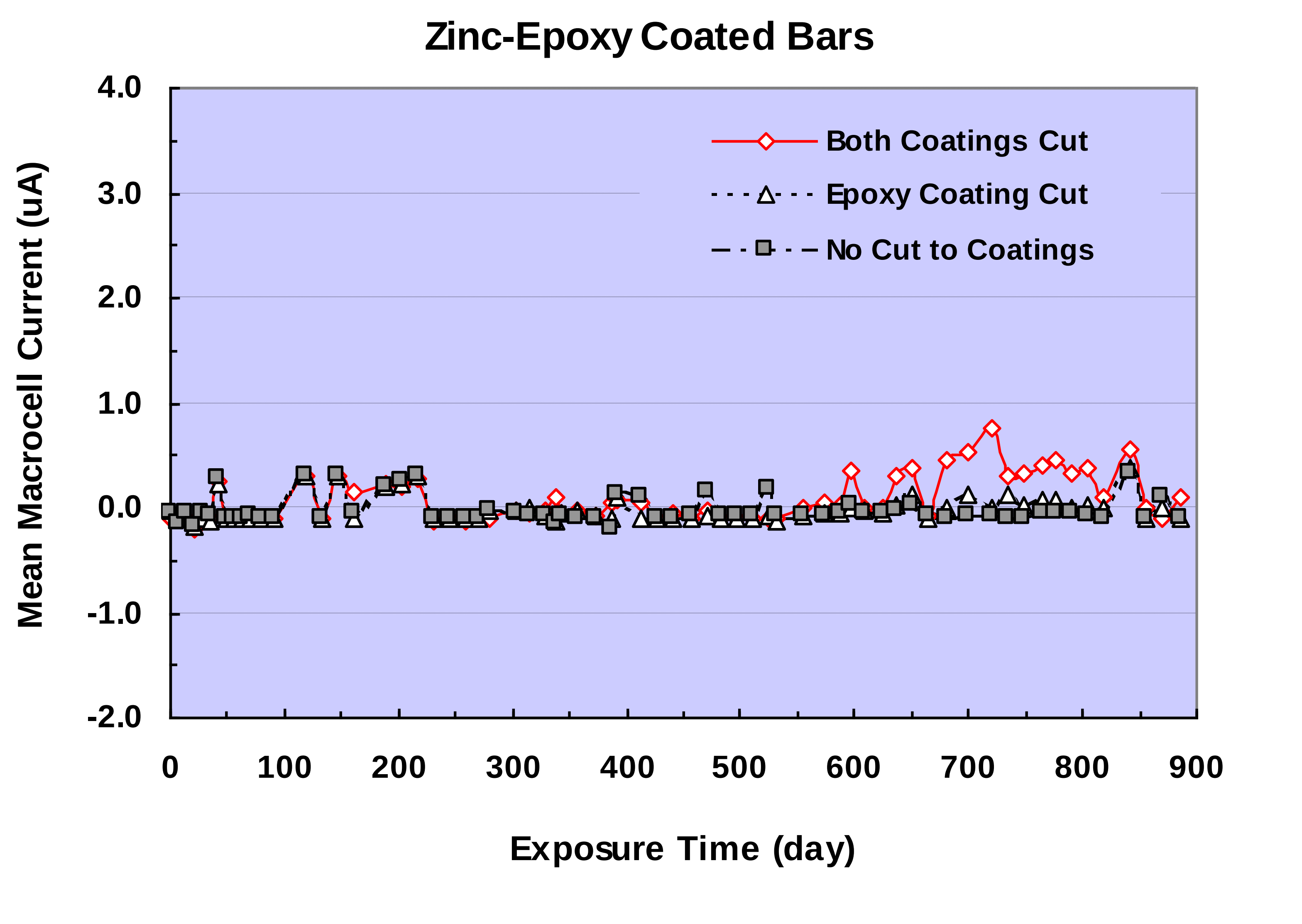


Time-to-Corrosion > 1,200 days



$T_{\text{clad w/ holes}}$ > 1,200 days

$T_{\text{clad w/ cut}}$ = 392 ± 3 days



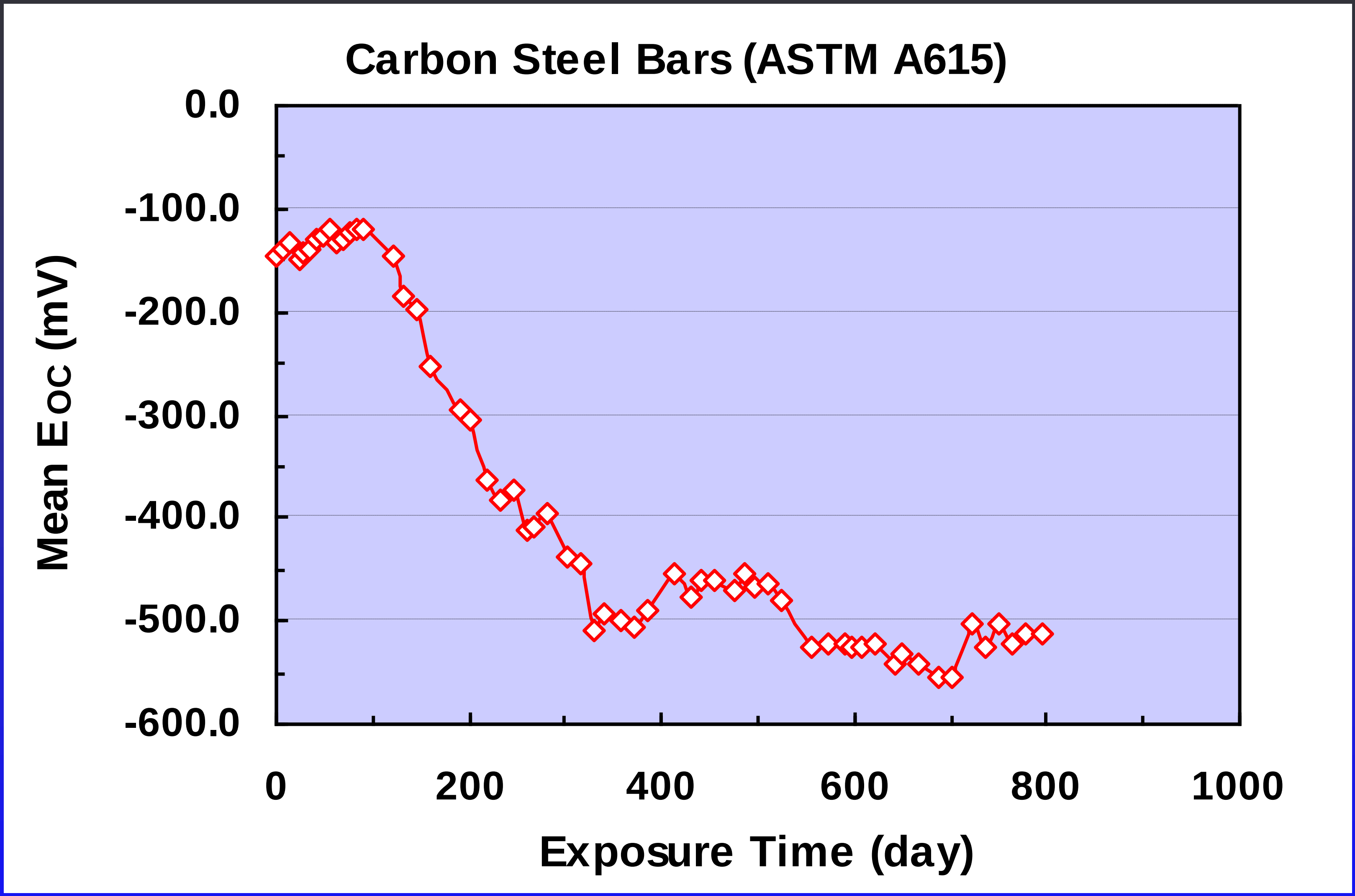
$T_{\text{both coatings cut}}$ = 532 ± 3 days

$T_{\text{epoxy cut}}$ = 637

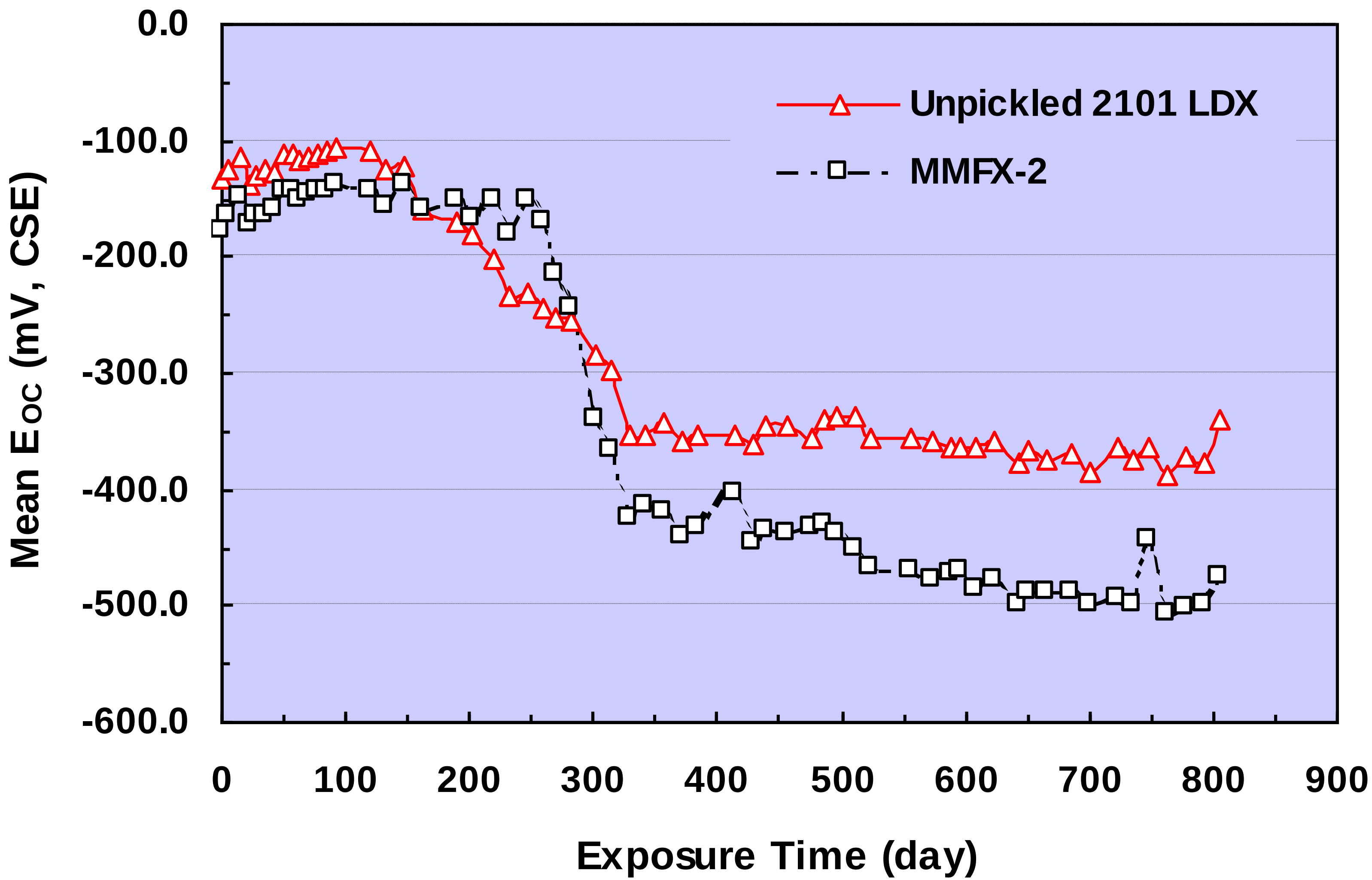
$T_{\text{no cut}}$ > 820

RESULTS

2. Mean Open-Circuit Potentials
(Per ASTM C-876)

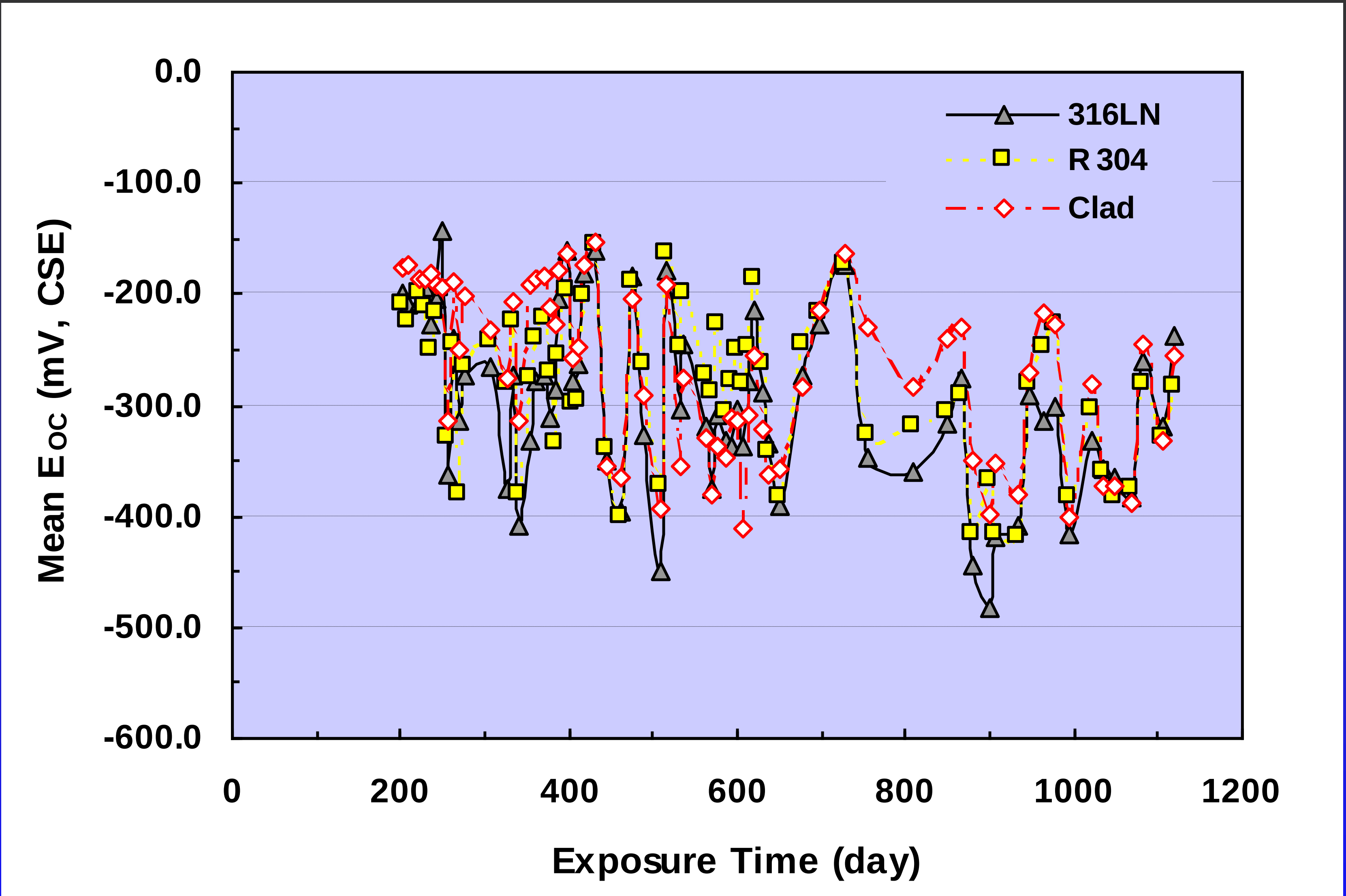


Time-to-Corrosion = 92 ± 3 days

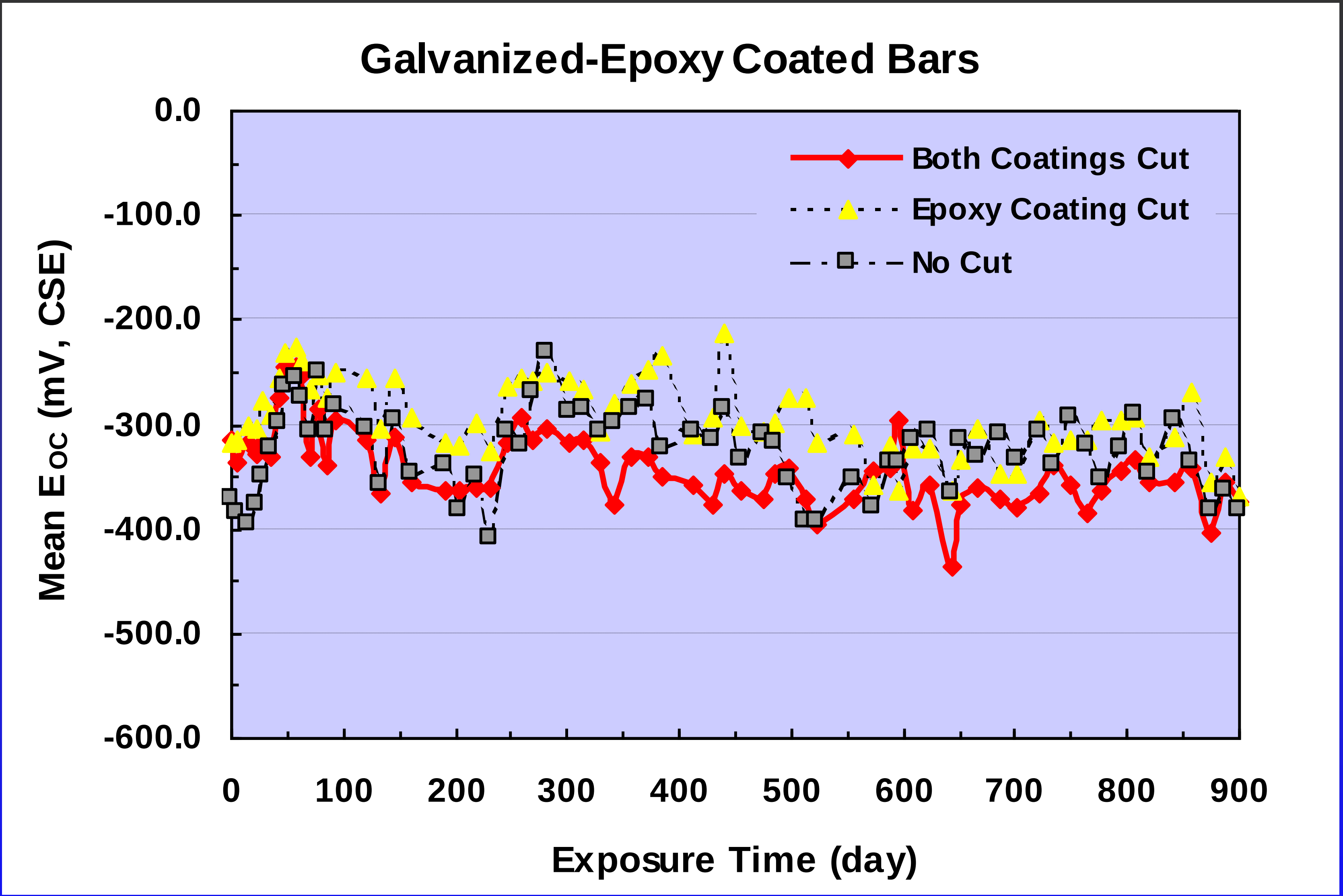


$T_{\text{2101 LDX}}$ = 147 ± 3 days

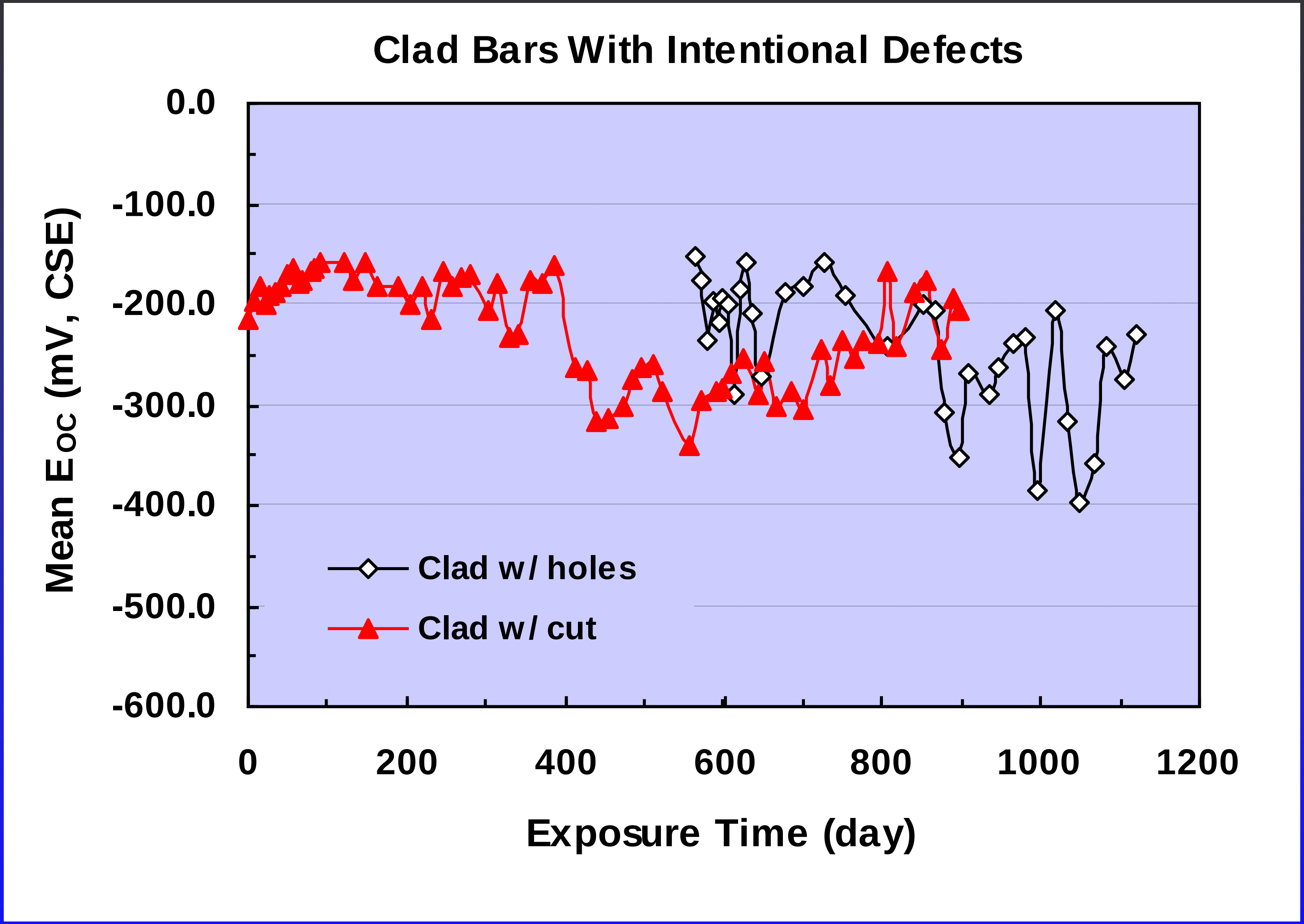
$T_{\text{MMFX-2}}$ = 245



$T_{R\ 304} \approx T_{Clad} \approx T_{316LN}$ > 1,200 days



The times-to-corrosion of this type of bars with a composite coating system is difficult to pinpoint from their potentials.



The clad bars with cut in cladding became unstable after 392 days, then regained stability at 820 days.

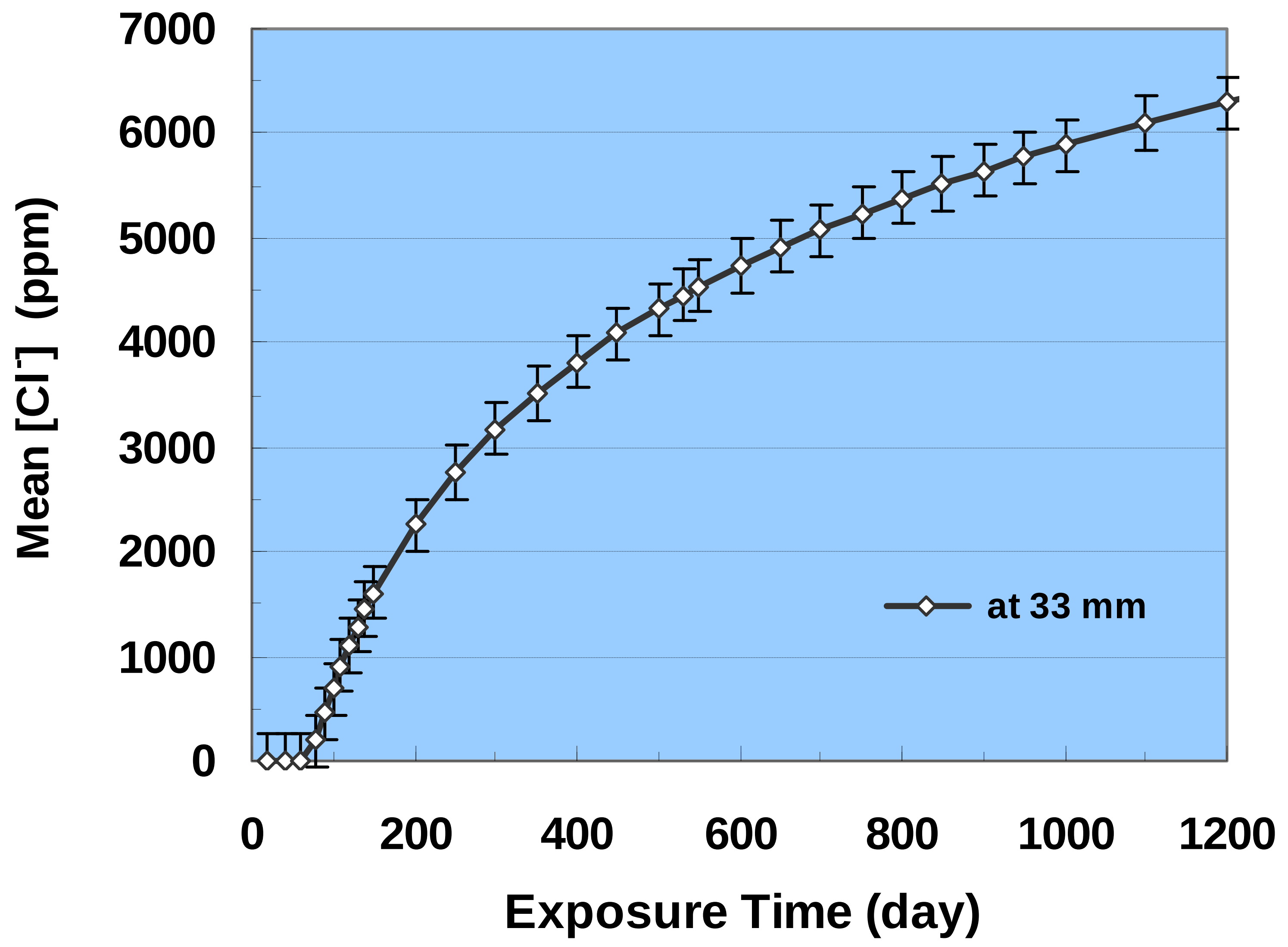
SUMMARY

Bar	Time-to-Corrosion (day)
Carbon Steel	92 ± 3
Unpickled 2102 LDX	147
MMFX-2	245
316L-Clad (w/ cut)	392
Zn/EC (cut in both coatings)	532
Zn/EC (cut in Zn coating)	637
Zn/EC (no defect)	> 820
316L-Clad (w/ holes)	> 1,200
316L-Clad (no defect)	> 1,200
R 340	> 1,200
316LN Stainless	> 1,200

RESULTS

[Cl^-] vs. Depth (in Concrete) vs. Exposure Time

The best-fit curve relating [Cl⁻], at depth of top bars, to exposure time.



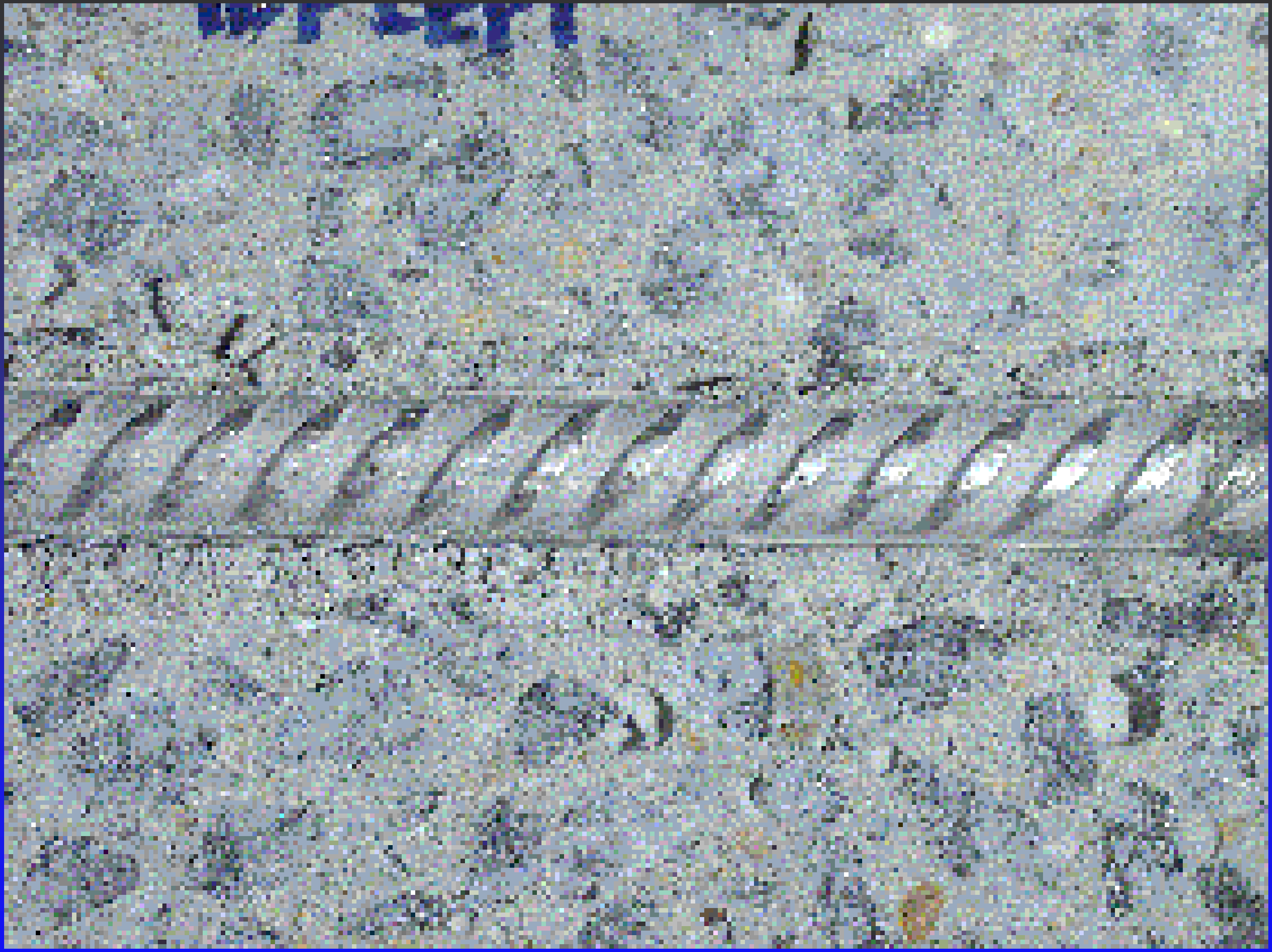
Estimated Chloride Corrosion Thresholds (*Exposure is still in progress)

Bar	$[CL^-]_{corr,}$ (ppm)	Ratio
Carbon Steel	430 - 580	1.0
Unpickled 2101 LDX	1,520 - 1,610	2.6 - 3.7
Unpickled MMFX-2	2,690 - 2,740	4.6 - 6.4
316L-Clad (w/cut)	3,750 - 3,790	6.5 - 8.8
Zn/EC (both coatings cut)	4,450 - 4,470	7.7 - 10.4
Zn/EC (epoxy coating cut)	4,860 - 4,880	8.4 - 11.3
Zn/EC (no defect)	> 5,380*	> 9.3 - 12.5*
316L-Clad (w/holes)	> 6,300*	> 10.9 - 14.7*
316L-Clad	> 6,300*	> 10.9 - 14.7*
R 340	> 6,300*	> 10.9 - 14.7*
316LN	> 6,300*	> 10.9 - 14.7*

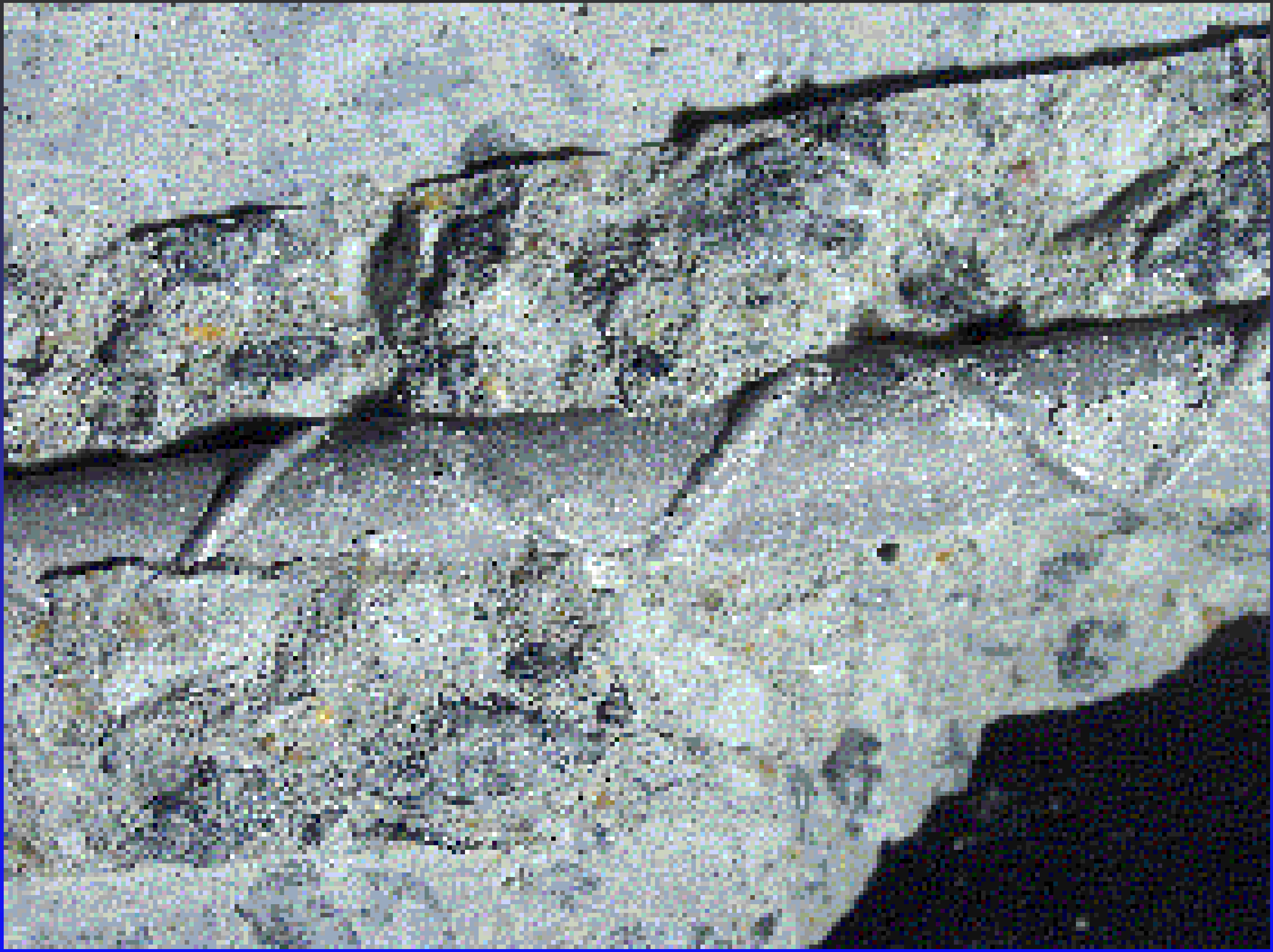
AUTOPSY OF SOME CONCRETE BLOCKS

A Corroded Unpickled 2101 LDX Bar.

A Corroded MMFX-2 Micro-composite Steel Bar



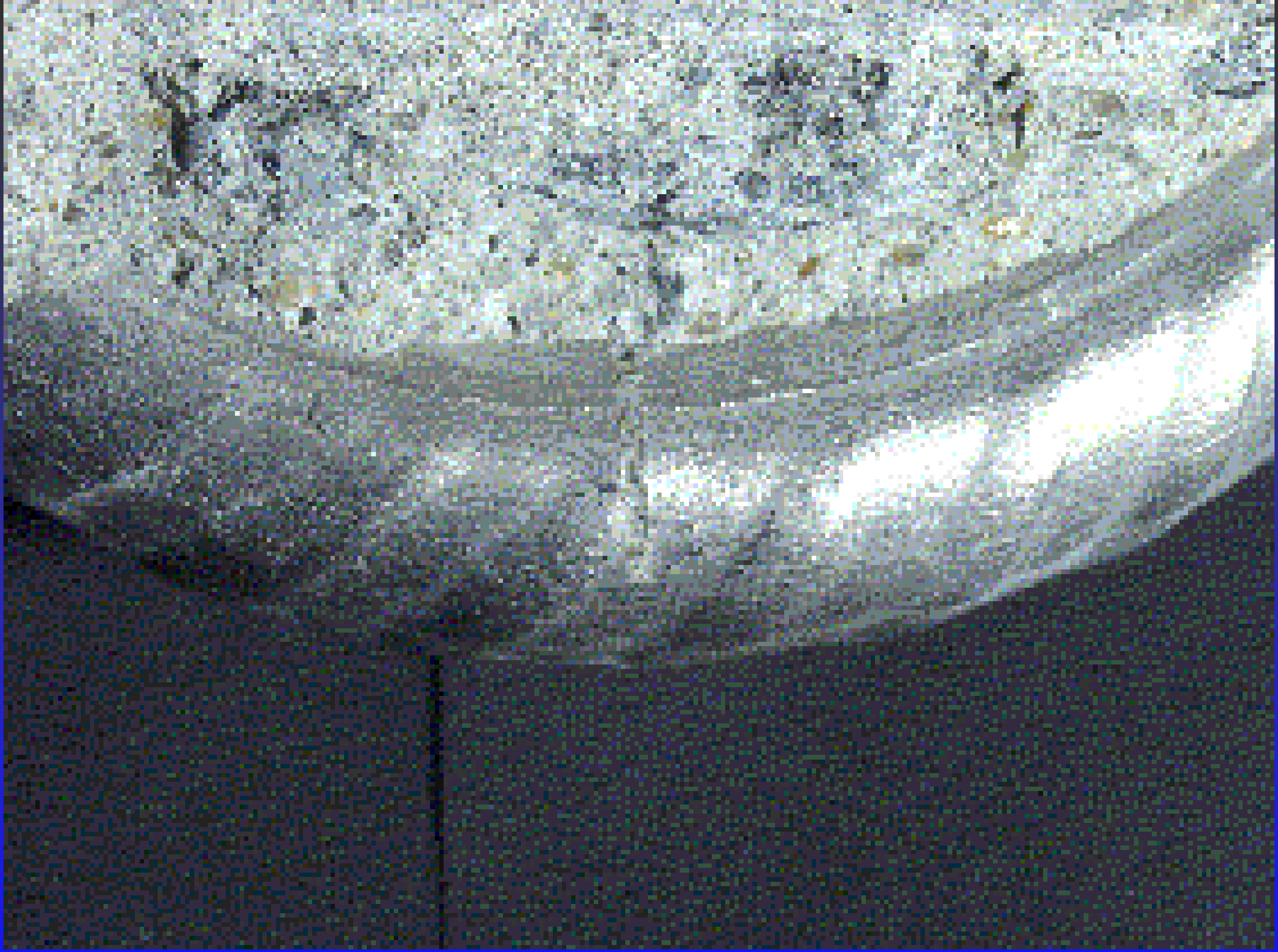
A Pickled 316 LN Stainless Steel Bar



A Pickled R 340 Stainless Steel Bar

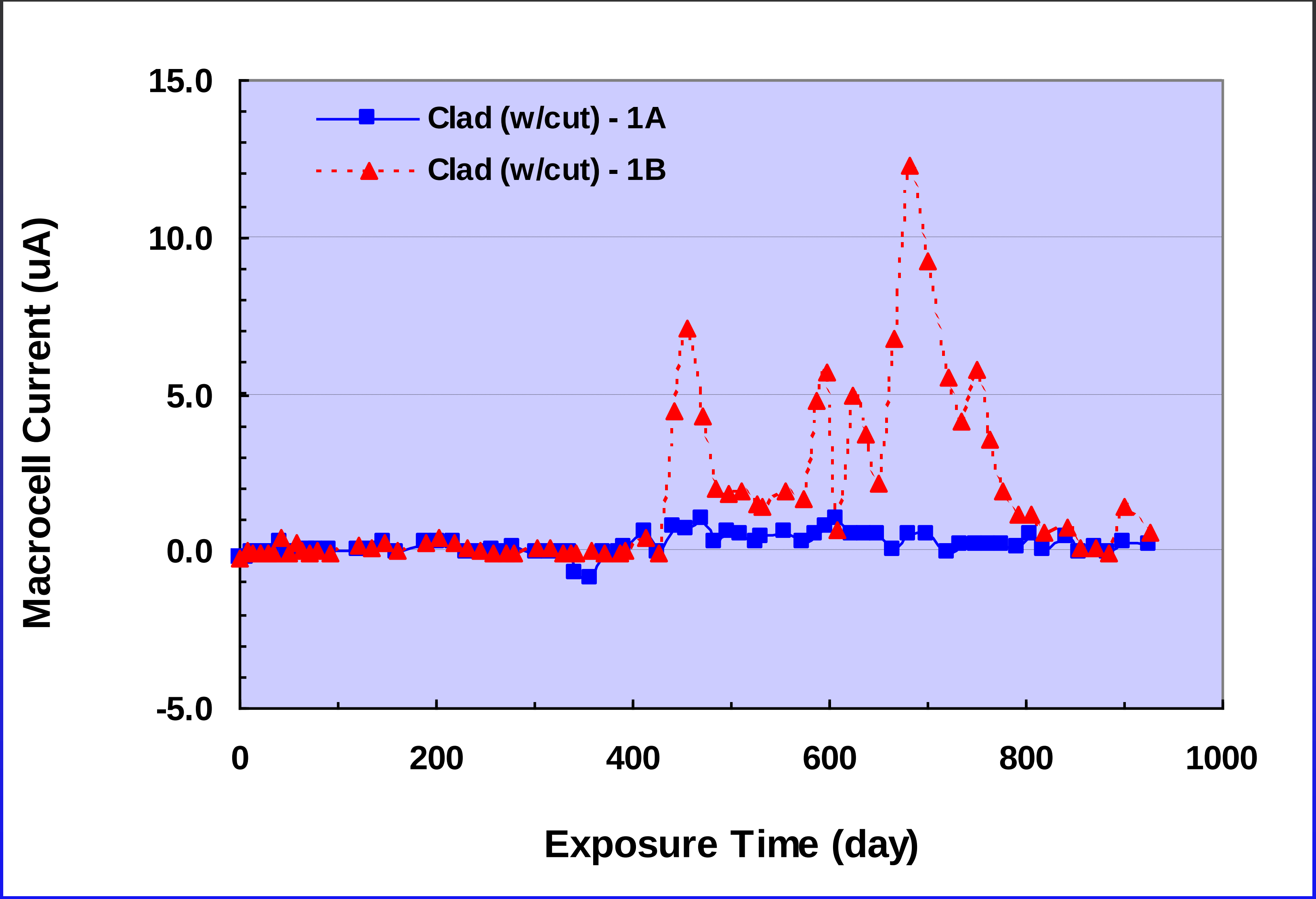
A Pickled 316L Stainless Steel-Clad Bar

A Clad Bar (1B) with a Cut Through the Cladding.
Notice the Small Corroded Area at Each Cut End and the cut is filled with cement paste.

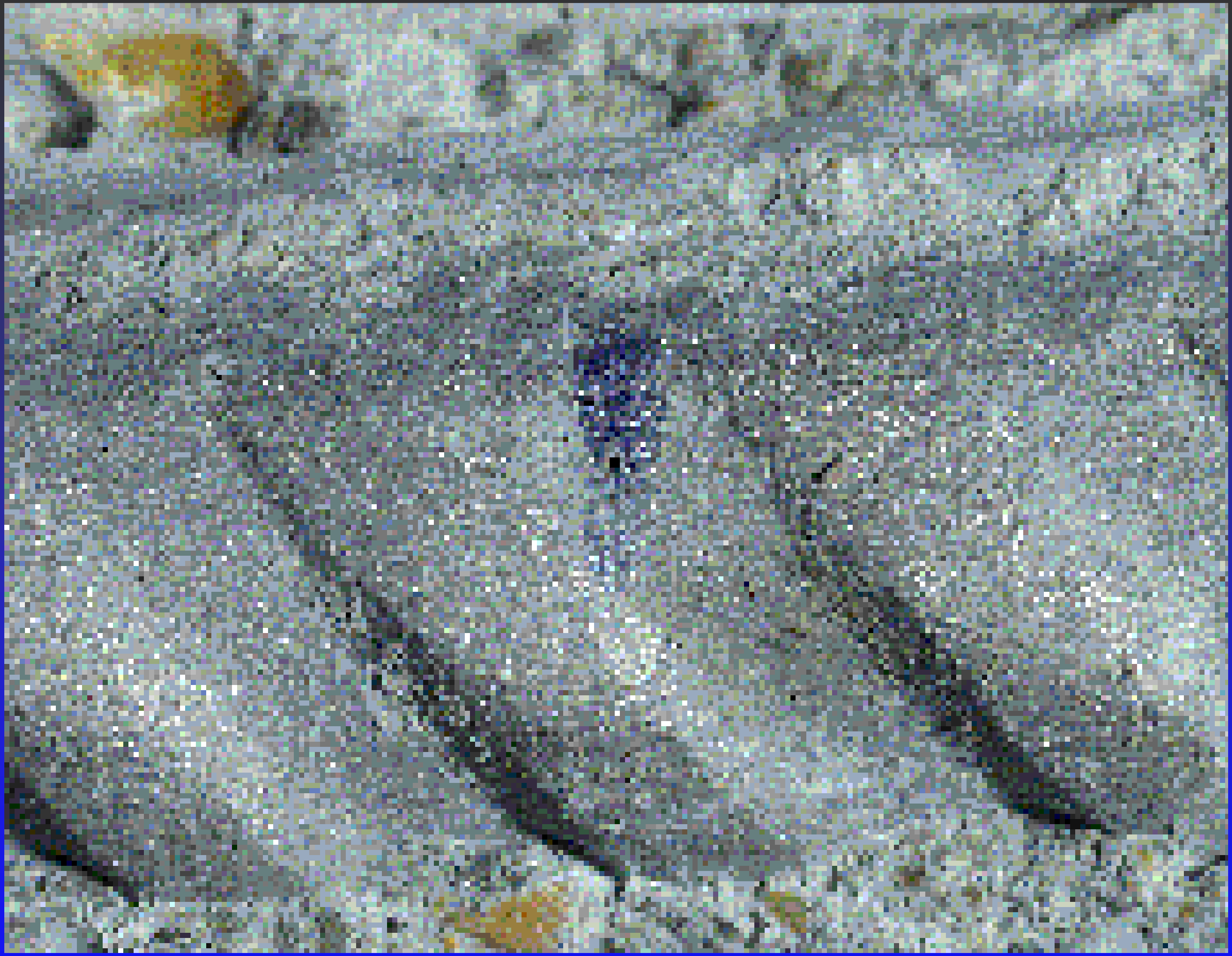


A Second Clad Bar (1A) with a Cut Through the Cladding From the Same Concrete Block.

Notice There is No Sign of Corrosion Near the Cut.



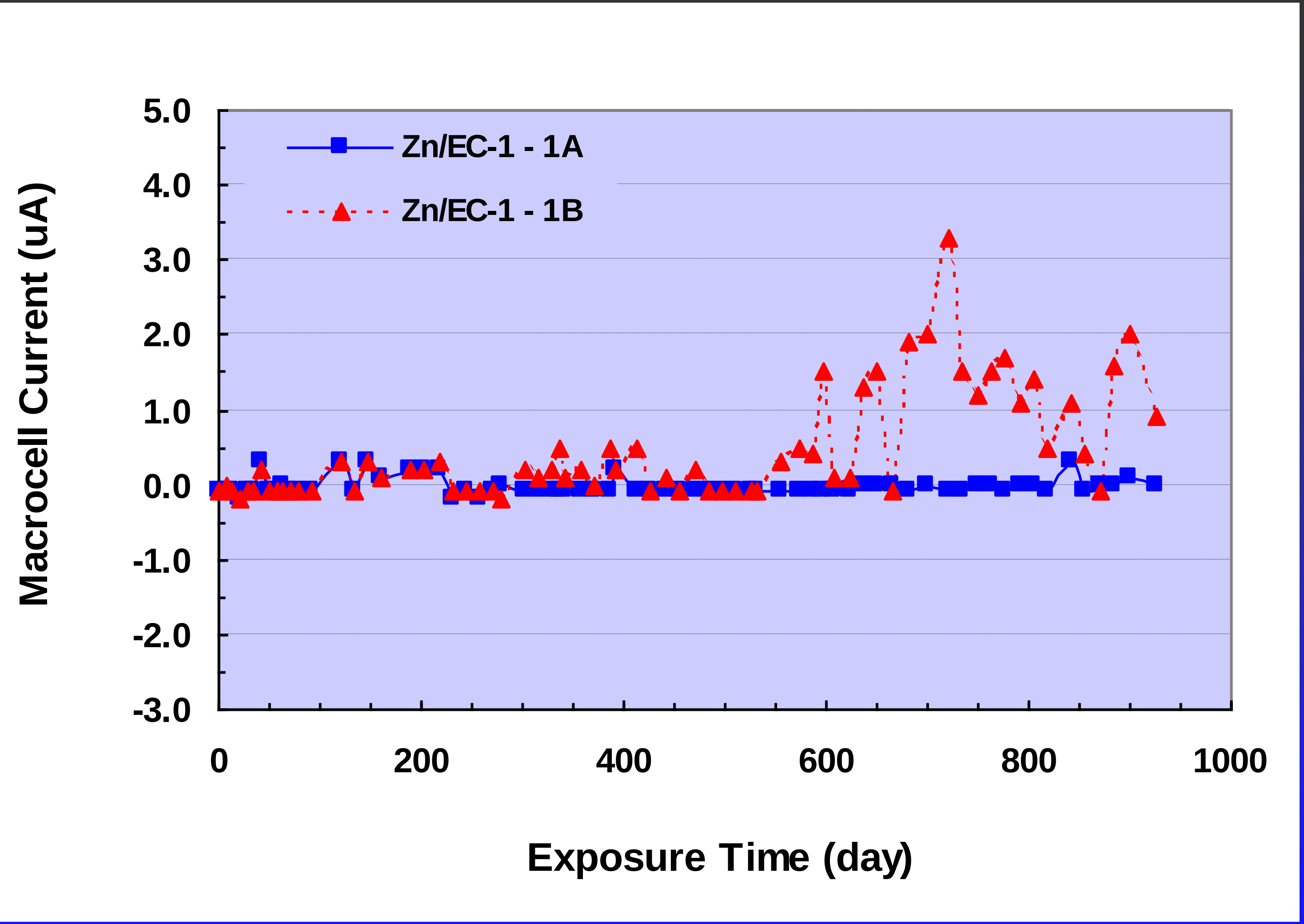
The differences in the macrocell currents of Clad Bars 1A and 1B explained the difference in the conditions of these two bars, as revealed in the autopsy.



A Clad Bar with One of the Holes (shaded area) Through the Cladding. (Notice There is No Sign of Corrosion.)

A Zn-Epoxy Coated Bar (1B) with a Cut Through Both Coatings. (Notice a corroded area under the coatings, at the top end of the cut.)

A Second Zn-Epoxy Coated Bar (1A) with a Cut Through Both Coatings, From the Same Concrete Block. (Notice there is no sign of corrosion that is associated with the cut.)



The <u>differences in the macrocell currents</u> of Zn-Epoxy Coated Bars 1A and 1B, both with a cut through the coatings, <u>explained the difference in the conditions of these two bars</u>, as revealed in the autopsy.

One of the Two Autopsied Zn-Epoxy Coated Bars With a Cut Through The Epoxy Coating Only. **(Notice there is no evidence of corrosion associated with the cut. The second bar was similar in condition.)**

One of the Two Autopsied Zn-Epoxy Coated Bars With No Cut Through Any of the Coatings, After 900 Days of Exposure. (Noticed the presence of isolated minor corrosion – probably on pre-existing holidays.)

- **Ranking The Corrosion Resistances of the Bars (Excluding Those with Damages Introduced to the Cladding or Coatings), In Increasing Order:**

1. Carbon steel (ASTM A-615)
2. Unpickled 2101 LDX
3. Unpickled MMFX-2
4. Zn/EC*

   316L-clad*

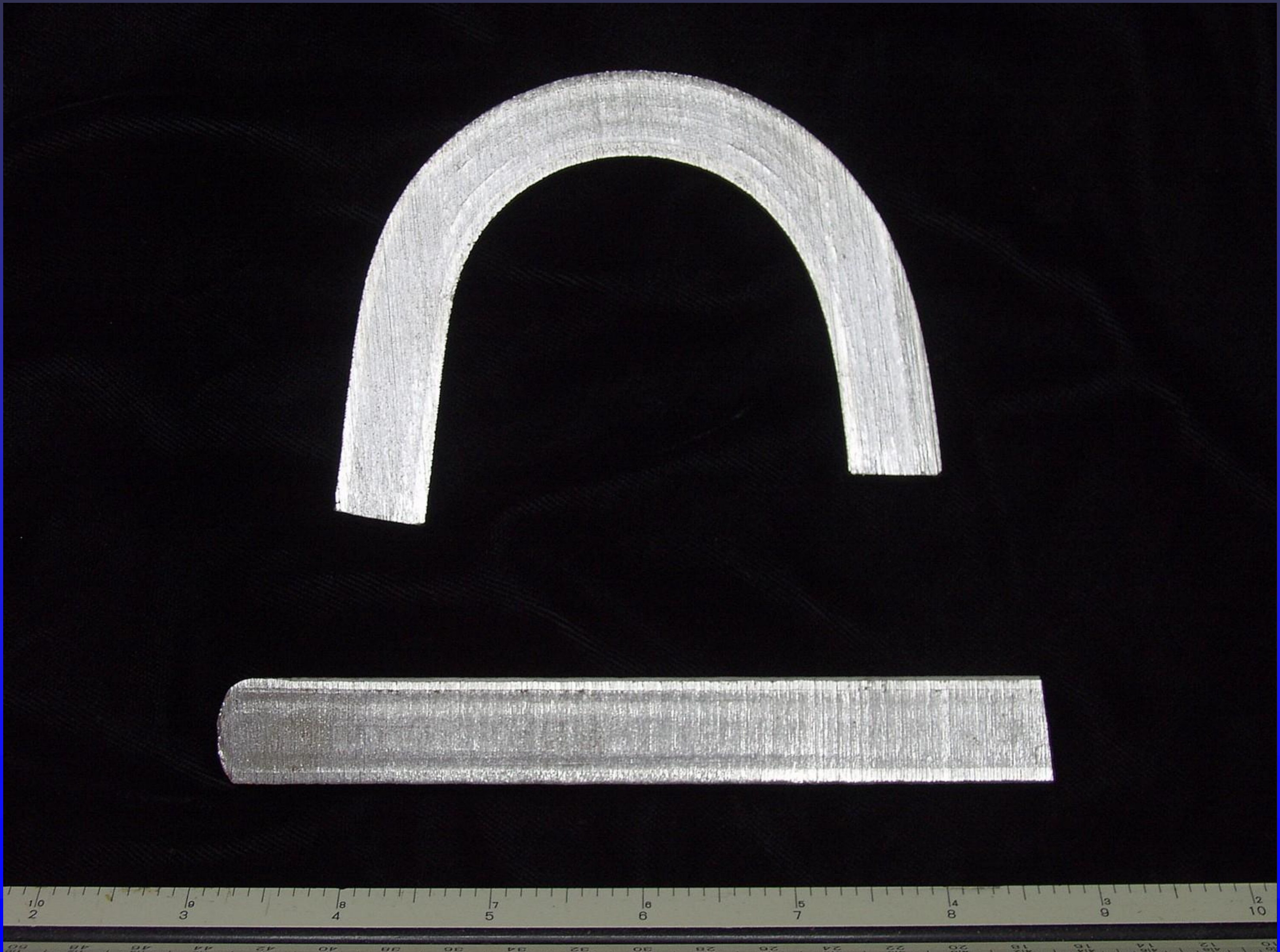
   R-340*

   316LN*

* Salt exposure is still in progress.

SS-CLAD BAR SAMPLES

CROSS SECTION OF SS-CLAD BAR SAMPLES



USE OF CLAD BARS IN A NEW BRIDGE

COST COMPARISON FOR A RECENT BRIDGE CONSTRUCTON PROJECT

	Black	ECR	Clad
Expected Life (yr)	20-30	35-40	100-125
Project Bid Price ($)	--	903,800	942,000
Bar Unit Cost ($/kg)	1.10	1.32	2.54
Cost of Bars:			
% of Total Project		4.62	8.49
Long-Term Cost of Bar			
($/kg-yr)	0.0404	0.0354	0.0228
Relative to Black Steel	0.0%	- 12.3%	- 43.5%

Domo Arigato!
(Thank you very much.)