A Review of Durability Design Options for Marine Concrete Structures

on the basis of Service Life, Maintenance and Whole of Life Cost

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Presentation Outline

- ❑Corrosion Basics
- ❑Supplementary Cementitious Materials
  - ❑ Effects on Durability
  - ❑ Risks
  - ❑ Design Life: Concrete Cover
- ❑Chemical Inhibitors
  - ❑ Effects on Durability
  - ❑ Risks
  - ❑ Design Life: Concrete Cover
- ❑Cathodic Protection
- ❑Conclusions & Recommendations

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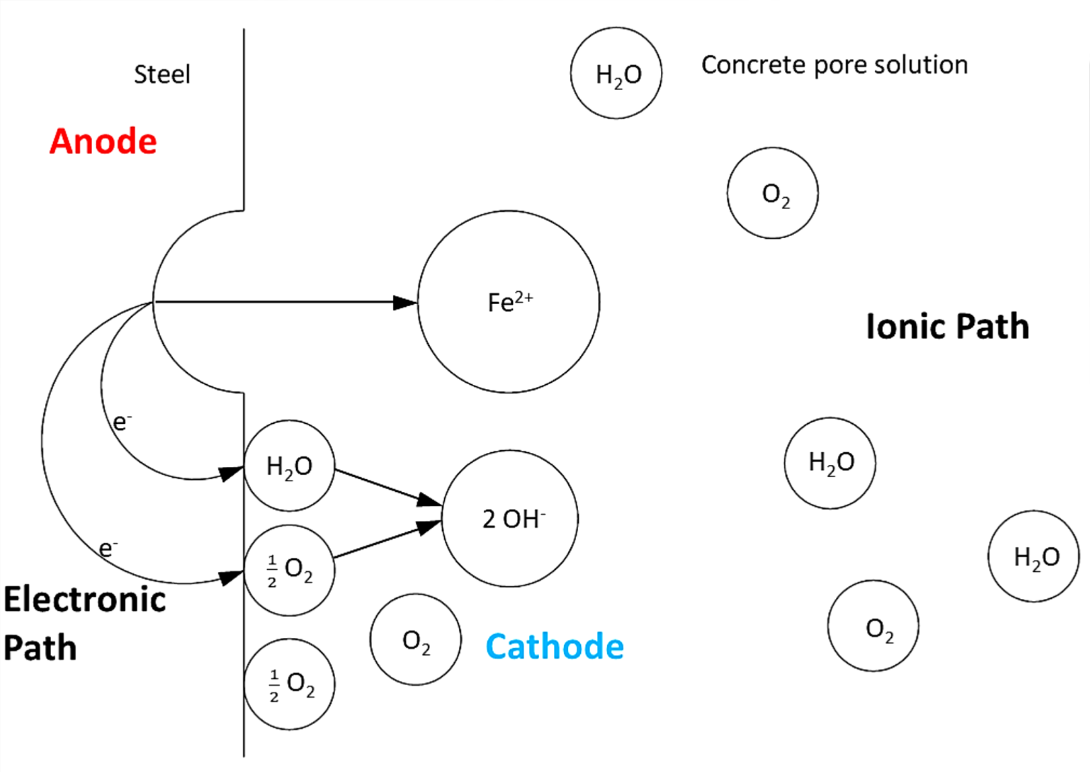
Corrosion

- Corrosion
  - Oxidation of steel
  - Reduction of water
- Passive layer
  - Passive Oxide layer formed due to high pH of concrete >pH12
  - Protects steel from corrosion
  - Not stable and may be de-passivated or degraded under aggressive circumstances (e.g. carbonation, chloride etc.)



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Design Options - SCM

- ❑ Supplementary Cementitious Materials:
  - ❑ Industrial byproducts used to replace cement in concrete
  - ❑ Admixed with concrete for new construction
  - ❑ Increases chloride binding
  - ❑ Reduces permeability and age-dependant apparent diffusion coefficient
    - ❑ Reduced porosity
    - ❑ Age effect: Less inter-connectivity between pores
      - Formation of secondary reaction products which fill up pores within the cement matrix
- ❑ Common SCMs:
  - ❑ Coal industry: Fly ash (FA)
  - ❑ Steel industry: Glass granulated blast furnace slag (GGBFS)
  - ❑ Silicon industry: Silica fume (SF)

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Design Options - SCM

- Effect on durability:
  - Reduced -
    - Embodied carbon
      - Use of industrial byproducts when compared to Ordinary Portlandite Cement alone
    - Heat of hydration – less thermal cracking
    - Permeability
      - Especially Silica fume due to its small spherical particles
      - Age effects – less pore connectivity
  - Increased -
    - Chloride binding
      - Reduction in the available free chloride
      - Especially slag
  - Increased resistance to sulphate attack and alkali-silica reaction

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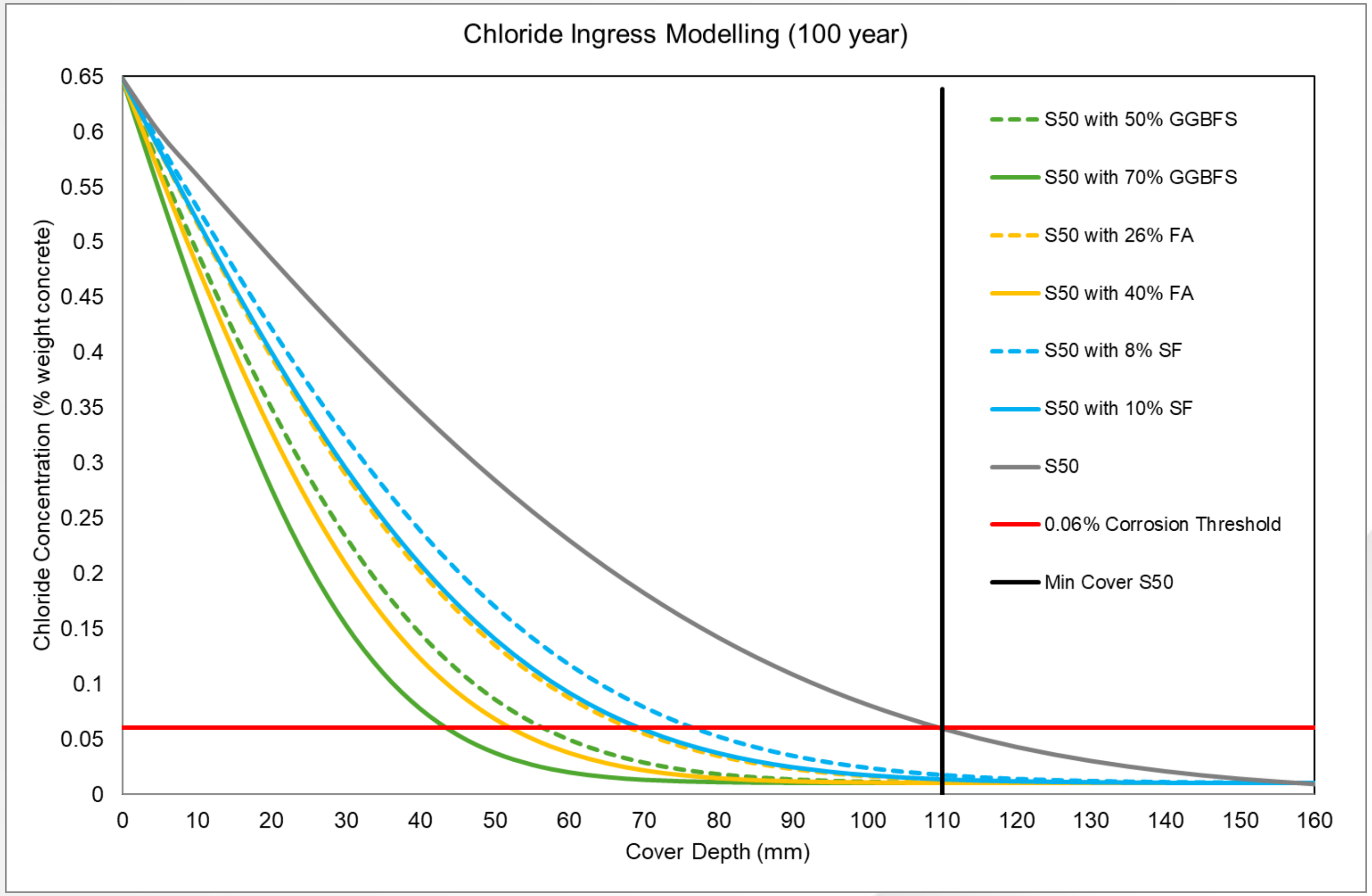
Design Options - SCM

- Risks:
    - Reduction in carbonation resistance
        - Risk: Corrosion may initiate earlier
        - Prevention:
            - Application of anti-carbonation coating
            - Use GGBFS (over FA)
            - Increase cover
    - Reduction in workability (SF)
        - Risk: Improper placement, compaction and finishing
        - Prevention:
            - Use of high range water reducing admixtures
            - Limit to <8% SF in mix designs

Design Options - SCM



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Design Options – Nitrite Inhibitors

- Chemical inhibitors:
  - Change the surface chemistry of the steel
  - Can provide corrosion protection even in the presence of high chloride concentrations
  - Dose rate dependant on expected chloride concentrations
- Nitrite inhibitors:
  - Inorganic, anodic type of corrosion inhibitor
  - Prevents the anodic reaction of the metal (i.e. corrosion of steel)
  - Admixed with concrete for new construction
  - Increased chemical stability of iron oxide passive layer by forcing free iron (Fe^{2+}) to form a stable oxide Fe_2O_3

Design Options – Nitrite Inhibitors

- Effects on Durability:
    - Reduction in corrosion rate with increasing dose rate
    - Increased time to corrosion initiation (hence service life) due to
        - Net reduction in corrosion rate
        - Increased resistance to chloride induced corrosion
    - Less effective in resisting carbonation induced corrosion
        - Still largely dependent on the pH

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Design Options – Nitrite Inhibitors

- Risks:
  - Reduction in concrete resistivity
    - Risk: Corrosion may propagate faster once initiated - particularly in saturated concrete
    - Prevention:
      - Dose rate specified to result in excess nitrites in the cement matrix – low risk
      - Regular monitoring to ensure net beneficial NO_2/Cl^- ratio is maintained
  - Can act as a set accelerator
    - Risk:
      - Placement and compaction issues if set initiates too quickly
      - Thermal cracking
      - Increased porosity/permeability
      - Reduced long term compressive strength
    - Prevention:
      - Use of set-retarding admixtures
      - Control of nitrite dose rates
      - Control of concrete temperature - prior to delivery and placement

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Design Options – Nitrite Inhibitors

- Risks:
  - Surface leaching in tidal / splash zones
    - Risk: Insufficient nitrite dosing to provide protection
    - Prevention:
      - Nitrite inhibitors are bound in the pore water / cement matrix and unlikely to back migrate / diffuse from the concrete
      - Testing to assess convection zone leaching
      - Dose rates typically specified to result in excess nitrites in cement matrix

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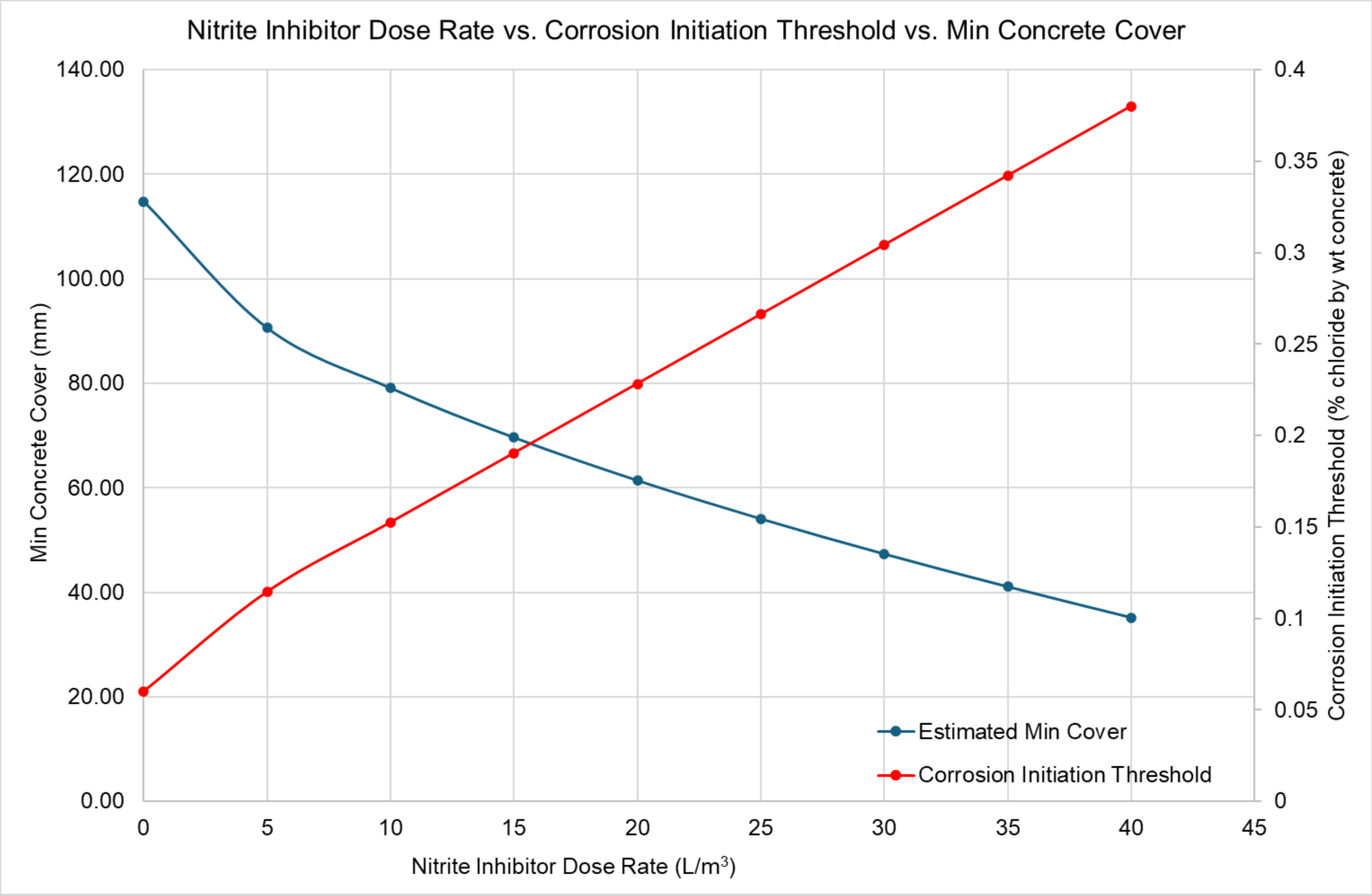
Design Options – Nitrite Inhibitors



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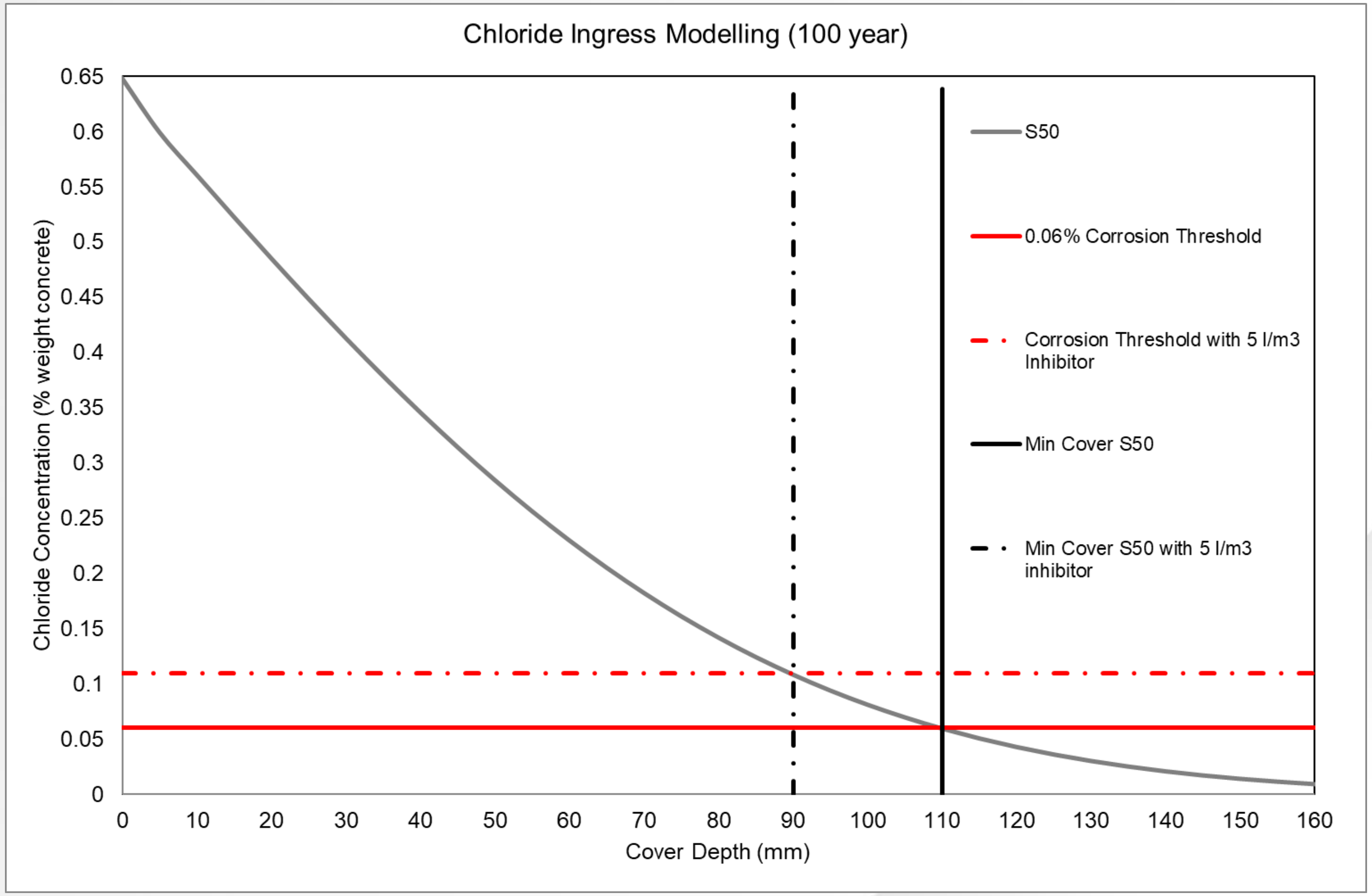

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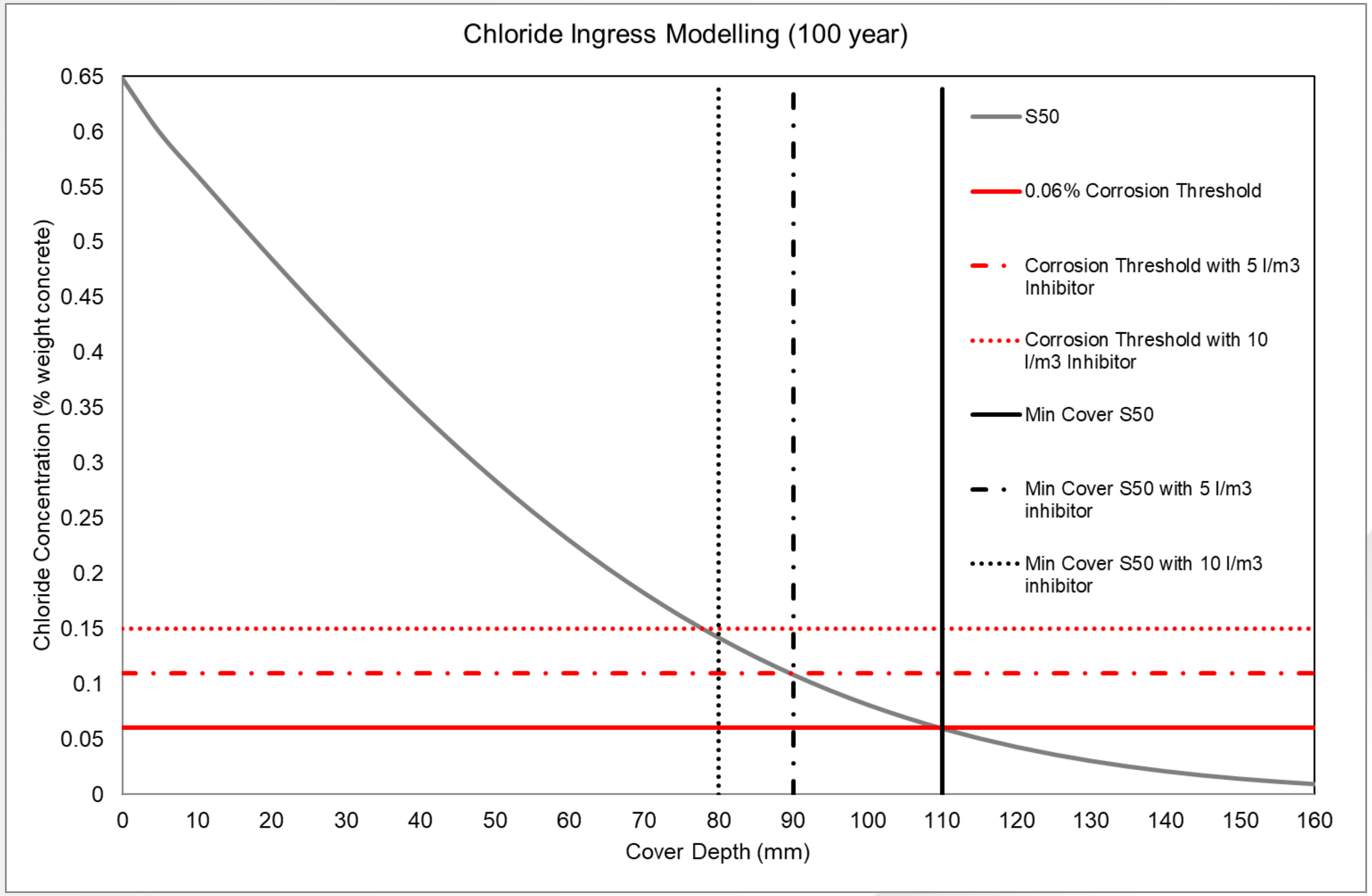

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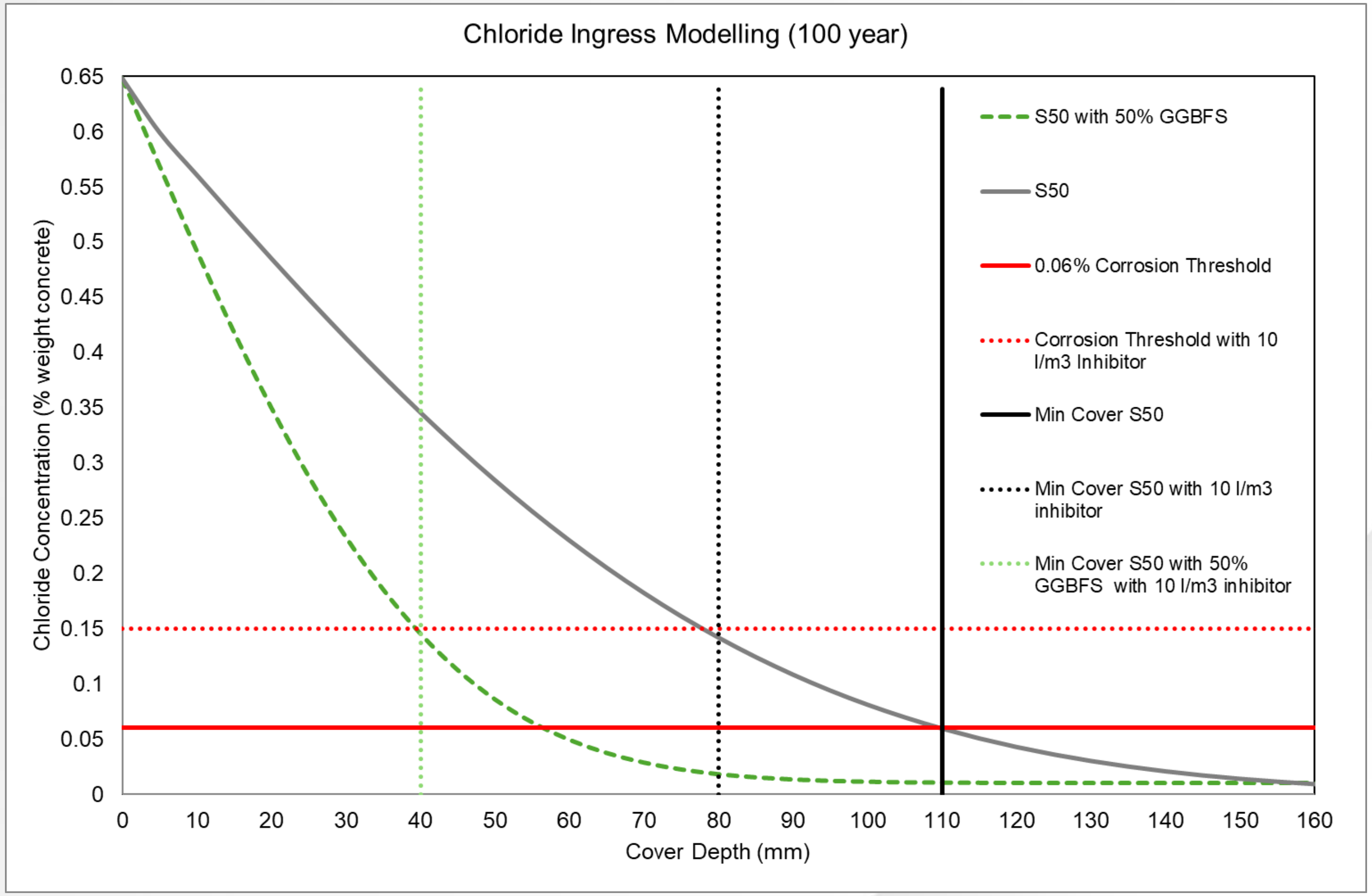
Design Options – Nitrite Inhibitors



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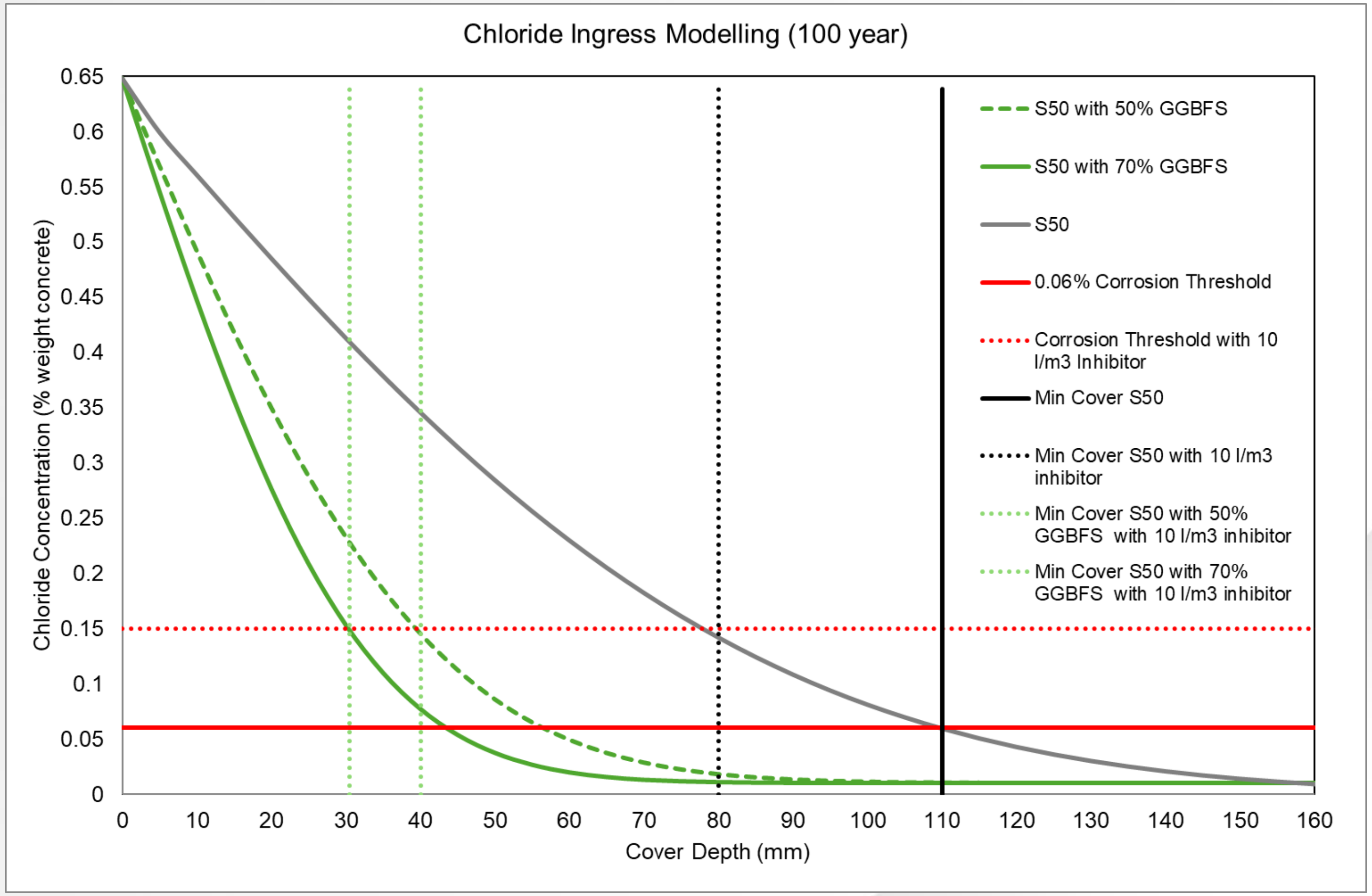

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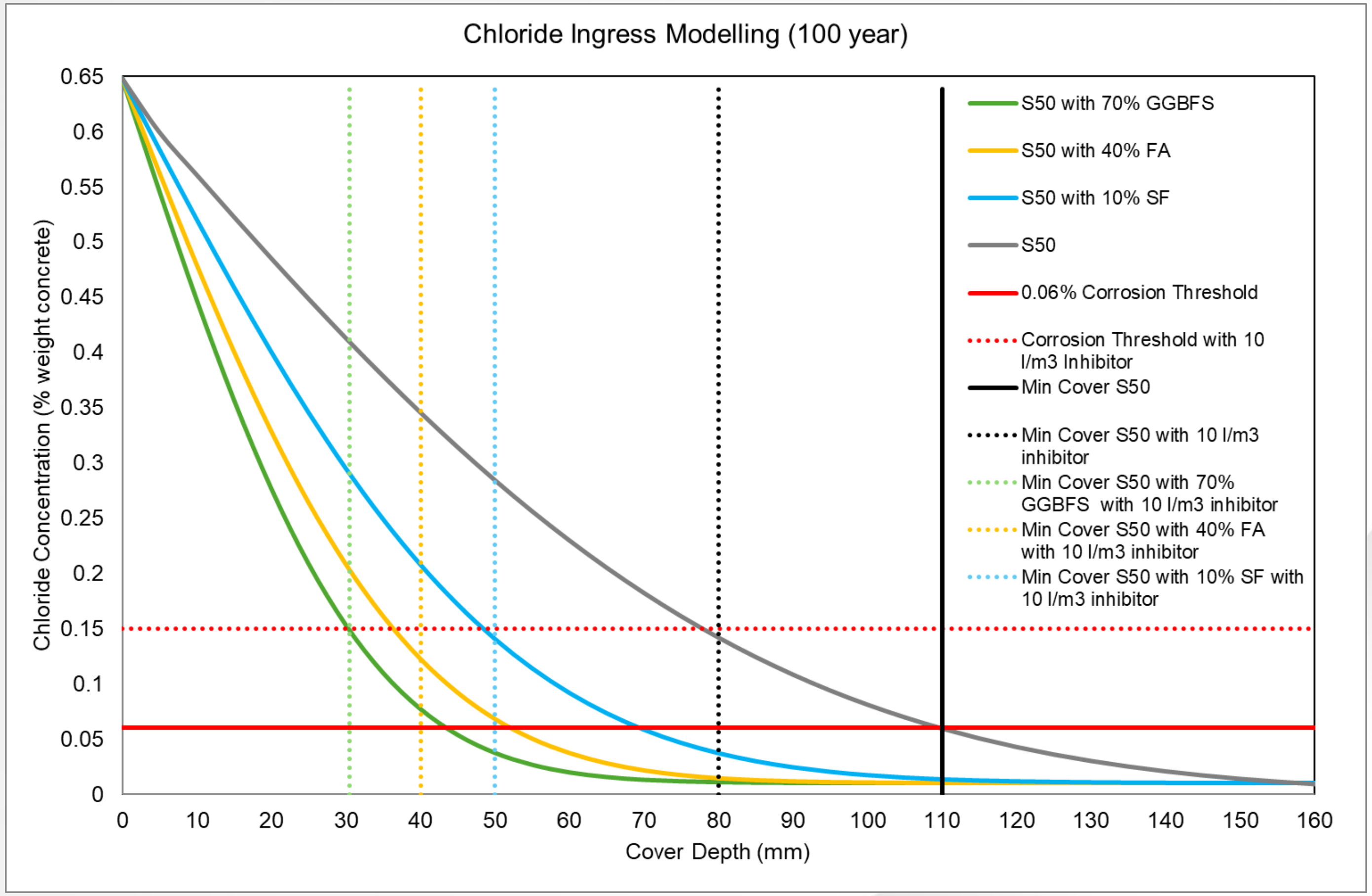

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Design Options – Cathodic Protection (CP)

Option 1

- At design stage
  - Ensure reinforcement continuity
- Maintenance:
  - **During service life:**
    - Monitor chloride concentration
  - **Chloride threshold reached:**
    - Monitor half-cell potentials
    - Breakouts to confirm corrosion
  - **Active corrosion:**
    - CP system installation
    - Concrete patch repairs as required
    - CP maintenance (ref. Option 2)

Option 2

- At design stage
  - CP system installation
- Maintenance:
  - **During service life:**
    - ICCP
      - Monitor instant off potential etc.
      - Adjust current as required
    - SACP (Galvanic)
      - Monitor open circuit potential
      - Replace sacrificial anode as required (if water anodes)

Option 3

(not recommended, but is usually what happens)

- At design stage
  - No reinforcement continuity
- Maintenance:
  - **During service life:**
    - Monitor chloride concentration
  - **Chloride threshold reached:**
    - Monitor half-cell potentials
    - Breakouts to confirm corrosion
  - **Active corrosion:**
    - CP system installation
    - Concrete patch repairs as required
    - CP maintenance (ref. Option 2)

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Design Options – Cathodic Protection (CP)

Option 1

- At design stage
  - Ensure reinforcement continuity
- Cost:
  - Low upfront cost
  - Maintenance cost dependant on CP system
  - Low whole of life cost

Option 2

- At design stage
  - CP system installation
- Cost:
  - Highest upfront cost
  - Maintenance cost
    - High for ICCP
    - Low for SACP
  - Moderate whole of life cost
    - Higher for ICCP compared to SACP

Option 3 (not recommended, but is usually what happens)

- At design stage
  - No reinforcement continuity
- Cost:
  - Lowest upfront
  - High maintenance cost
    - Maintenance cost dependant on CP system
  - Highest whole of life cost

Conclusions & Recommendations

- ❑ At design stage:
  - ❑ Ensure **reinforcement electrical continuity** for future CP
  - ❑ Adjust **SCM** ratios based on exposure specific service life models
  - ❑ Consider use of corrosion **inhibitors** for spray and / or tidal zone
  - ❑ Ensure the durability 3Cs: Cover, Curing, Compaction!

Conclusions & Recommendations

- Maintenance:
  - **During service life:**
    - Monitor chloride ingress concentration (regardless of design)
  - **Chloride threshold reached:**
    - Monitor half-cell potentials
    - Breakouts to confirm corrosion
  - **Active corrosion:**
    - Installation of CP
      - Postponed by **inhibitors** due to increased chloride threshold (if used)
      - Postponed by **SCMs** at the same cover depth due to reduced age dependant apparent diffusion coefficient
      - Increased current output of the anode by **inhibitors** due to reduced resistivity (consider in CP system design)
    - Maintenance of CP
      - Monitor potentials (instant off potential, open circuit potential etc.)
      - Adjust power supply current on ICCP systems as required or
      - Replace sacrificial anodes on SACP systems as required

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Conclusions & Recommendations

- Whole of Life Cost:
  - Moderate upfront cost
    - **SCMs** (standard practice): Negligible cost
    - **Inhibitors**: up to 90 $/m^3
    - CP continuity: Minimal additional cost
  - Low maintenance cost
    - **SCMs**: None
    - **Inhibitors**: None
    - CP installation: Moderate for SACP, High for ICCP
  - Low whole of life cost

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