

Advancements in Service Life Modeling

Paul G. Tourney, P.E.

Materials Service Life, LLC

(269)384-9980

Ptourney@MSLexperts.com

Presentation Focus

- Service Life Prediction of reinforced and non-reinforced concrete structures exposed to various environments.
- Prediction of contamination levels in concrete structures.
- Performance prediction of available concrete protection systems.

Reasons for Service Life Modeling

It is recognized that:

- Additional up-front protection is usually cheaper than repairing in the future.
- Service life expectations are more common and are extending.
- Increasing need to manage assets (maintaining and repair)
- Federal and local governments' control on design and construction is changing.

Reasons for Service Life Modeling

Continued:

- Specifications are trending towards performance basis vs. prescriptive basis.
- Innovation from industry has resulted in many great concrete and protection systems. This will continue.
- Inspection and QC need relevant measures and techniques.

Awareness of Complexity

Transport Mechanisms

- Ionic Diffusion
- Ionic Advection
- Electrical Coupling

Chemical Reactions

- Cement Sensitivity
- Internal Environment
- Binding and Releasing

Corrosion Science

- Initiation
- Rate / Propagation
- Damage Curve



Exposure Conditions

- Macro / Micro
- Variability / Cyclic
- Ranges

Degradation Mechanisms

- Corrosion (Cl⁻ or Carbonation)
- Sulfate Attack
- Alkali-Silica Reaction
- Delayed Ettringite
- Coupled Degradation

Protection / Repair Technologies

Degree of Reliability of Model

Economic Analysis Variability

Concrete Mix



Cements
Pozzolans
Admixtures
Aggregates
Reinforcement
Coatings
Sealers
Inhibitors
Overlays
Production
Design Details

Construction Team



DoD Facilities

FHWA, State DOTs

USACE, USBR

Private Owners

Design Engineers

Contractors

Testing Companies

Material Suppliers/
Manufacturers

Concrete Producer

Research / Academia

Legal Departments

Applications for Advancements in Service Life Modeling

- Tool to develop concrete designs for new structures.
 - Dams, waterway structures, bridges, pavements, foundations, marine, parking, containment, etc.
 - Designs reflect actual exposures.
 - Designs reflect service life expectations.
 - Basis for performance specifications.
- Method to prepare and assess value-engineering submittals.
- Use as a quality control tool during construction.

Applications for Advancements in Service Life Modeling

Continued:

- Tool to assess existing structures for condition.
- Predict future conditions of new or existing structures.
- Asset management tool for budgeting replacement and repairs.
- Assess and help development of protection and restoration technologies.

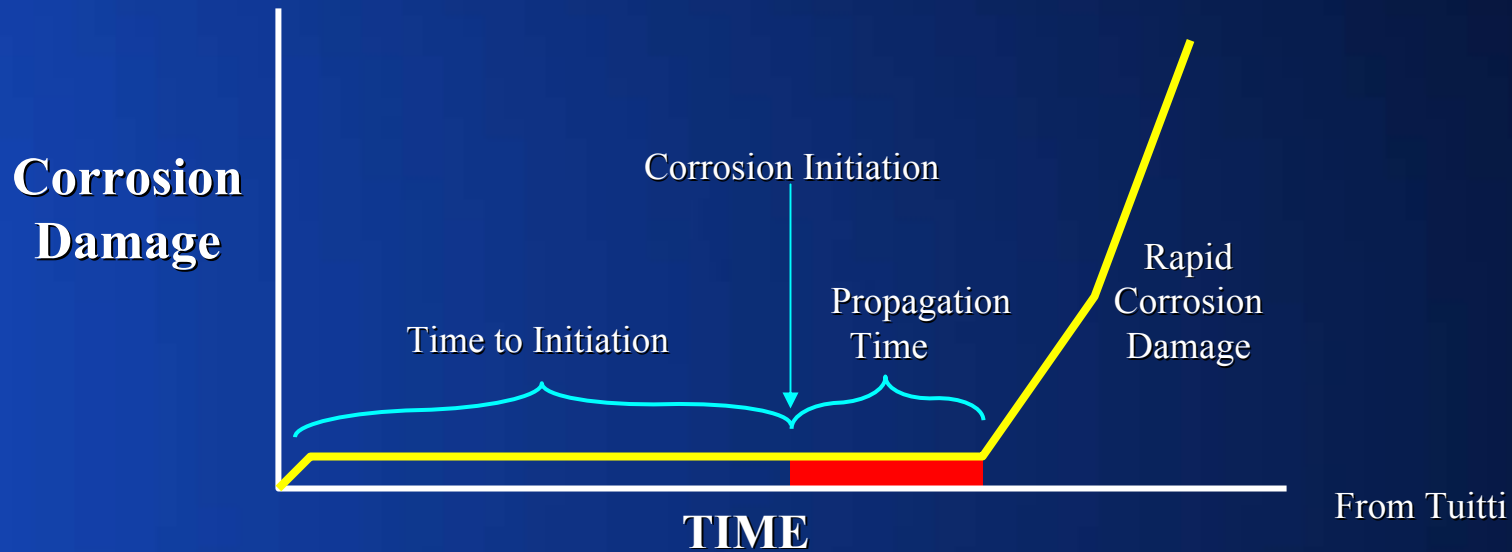
Construction Variances



Service Life Modeling Development

- “Gut Feel” and “Trust Me” decisions
- Accelerated testing programs
- Single transport and ion species models
- Multiple transport and ion species models
- Holistic models

Single Transport and Ion Species Models



- Uses Solution to Fick's Second Law of Diffusion.
- Forcing Fickian solution with Apparent Diffusion Coefficient.
- Looking at chloride ions only.
- Chemical effects are ignored (cements, admixtures, pore solution)

The Basic Approach



No simple answers
complex problems!

- Varying exposure conditions
- Complex exposure conditions
- Varying materials
- Local labor and QA

Multiple Transport and Ion Species Models

The Basic Concept:

The transport of ions and fluids through the material tends to alter its microstructure by:

- **dissolving** existing mineral phases (loss of strength)
- **forming** new (expansive) phases (volume instability - cracking)

The evolution of the properties of the material can only be predicted by accounting for the transport of all **fluids** and **all ions**.

Multiple Transport and Ion Species Models

Multiple transport and ion species models require finite-element code that can be used to predict the transport of ions and water in reactive porous systems.

These models accounts for:

- the transport of **nine different ions** (OH^- , Na^+ , K^+ , SO_4^{2-} , Ca^{2+} , $\text{Al}(\text{OH})_4^-$, Cl^- , Mg^{2+} , NO_2^-).
- **Electroneutrality effects**
- **Chemical activity effects**

Advection / Diffusion Transport Equation

Multiple Ionic Species

Ionic transport due
to diffusion

$$\frac{\partial c_i}{\partial t} - \frac{\partial}{\partial x} \left[\theta D_i \left(\frac{\partial c_i}{\partial x} + \frac{z_i F}{RT} c_i \frac{\partial \phi}{\partial x} \right) + \left(D_i \theta C_i \text{grad}(\ln \gamma_i) \right) \right] - \frac{\partial}{\partial x} \left[D_{\theta} c_i \frac{\partial \theta}{\partial x} \right] + (1-\phi) \frac{\partial c_i}{\partial t} = 0$$

Ionic transport due
to advection

Chemical
binding

$P_e = VL/D \approx 0.1$
Low Peclet numbers

Multiple Transport and Ion Species Models

These models also account for:

- the moisture movement through concrete
- the transport of ions by capillary suction
- the chemical equilibrium of **nine solid phases**
- chemical damage effects

Chemical Equilibrium

If the **local chemical equilibrium** is preserved, chemical reactions can be modeled by taking into account the **solubility** of each solid phase present in the porous system:



Solubility constant → $K_{sp} = \{A\}^a \{B\}^b$

The activity of constituent i in solution = $\gamma_i c_i$

Chemical Activity Effects

Modified version of **Davies equation**:

$$\ln \gamma_i = \frac{A z_i^2 \sqrt{I}}{1 + 3E-10 B \sqrt{I}} + \frac{(0.2 - 4.17E-05 I) A z_i^2}{I \sqrt{1000}}$$

$$A = \frac{\sqrt{2} F^2 e_0}{8 \pi (\epsilon R T)^{3/2}} \quad I = \frac{1}{2} \sum_{i=1}^n z_i^2 c_i \quad B = \sqrt{2 F^2 / \epsilon R T}$$

↑
Ionic strength

Initial conditions



Transport step



Chemical equilibrium step

Next time step



- Diffusion
 - Electrical coupling
 - Activity effects
 - Capillary suction
 - Nine species
-
- Equilibrium between the phases and the solution.
 - Nine solid phases

Holistic Models

The Basic Concept:

Advance the multiple transport and ion species model to incorporate additional degradation mechanisms.

Create service life models that act as tools for most:

- concrete exposure conditions
- concrete applications
- parties involved in the construction process
- new or existing structures

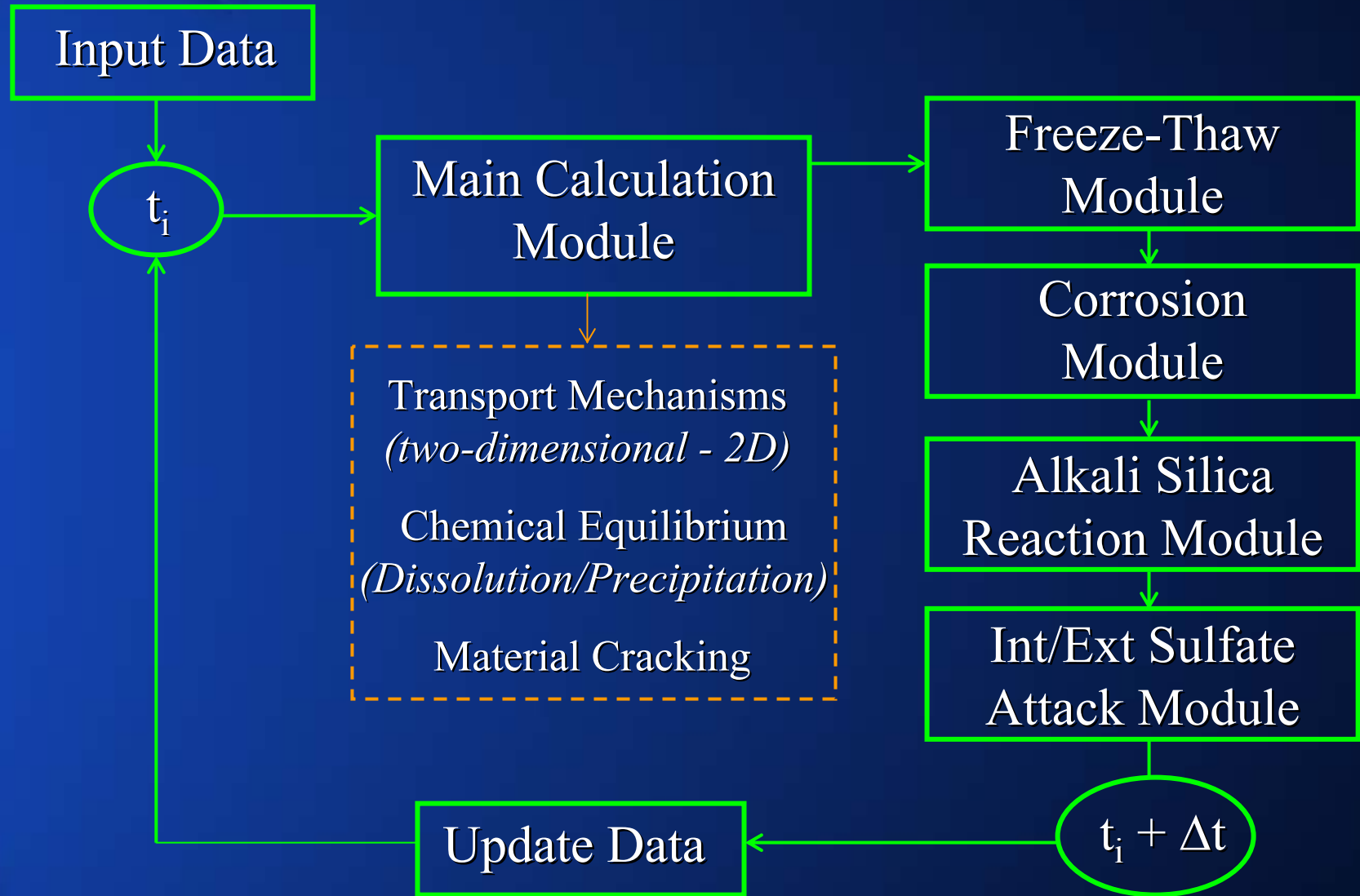
“Cradle to Grave Service Life Model”

U. S. Navy – SBIR N02-050

Model process addresses:

- Multiple transport mechanisms (coupled)
- Simultaneous chemical reactions (solid/liquid phases)
- Applicability in both new and existing structures
- Micro and macro cracking conditions (2D / 3D)
- Chloride-induced corrosion
- Carbonation-induced corrosion
- Internal and external sulfate attack
- Alkali-silica reactivity
- Repair technology schemes
- Life-cycle cost analysis

Holistic Model



Holistic Models

Under Development:

U.S. Navy (ONR and NFESC)

U.S. Bureau of Reclamation

FHWA

Quebec DOT

USACE

Large Design Firms

Materials Suppliers (cement, admixtures, repair technologies)

Industry Consultants

Advancement in Holistic Model

Model processes:

- Multiple transport mechanisms (coupled)
- Simultaneous chemical reactions (solid/liquid phases)
- Applicability in both new and existing structures
- Micro and macro cracking conditions
- Chloride-induced corrosion
- Carbonation-induced corrosion
- Internal and external sulfate attack
- Alkali-silica reactivity
- Freeze-thaw damage
- Repair technology schemes (expert system)
- Life-cycle cost analysis

There is more to come !!

Thank You !