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Design and Construction of Concrete Tanks for Refrigerated Liquefied Gas Containment, Part 2

ACI Spring 2012 Convention
March 18 – 21, Dallas, TX

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Neven Krstulovic-Opara, PhD, FACI, is a Senior Structural Engineer at ExxonMobil (EMDC). His work experience includes 11 years as an university professor at University of Michigan, Ann Arbor, Northeastern U. and North Carolina State University. For the last 10 years he has been leading and/or supervising numerous forensic investigations and designs of large offshore concrete structures and arctic platforms, LNG tanks and natural gas plants while working for Exponent-Failure Analysis, Arup and EMDC. Krstulovic is also the Chair of ACI 376, ACI 544-E, and the Secretary of ACI 544. He received his MCE from the Univ. of Belgrade, MSc from the Imperial College, London, and his PhD from Carnegie Mellon Univ. His research interests include the behavior of concrete at cryogenic temperatures, development of concrete tanks for storage of cryogenic liquids, concrete offshore platforms for extreme environments, "smart" materials and structures, high-performance fiber-reinforced cement composites (HPFRCCs), use of HPFRCCS as seismic/blast-resistant retrofit and new construction, and fracture mechanics of cementitious materials and structures.

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Session on the Design & Construction of RLG Containment – Part 2

ACI 376-10 Code & Commentary: Chapter VI

Minimum Performance Requirements

Neven Krstulovic
ExxonMobil Development Company

Hyatt Regency Dallas, Dallas, TX
Reunion A
Tuesday, March 20, 2012
11:00 – 11:20 AM

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Biography

Neven Krstulovic-Opara, PhD, PE, FACI, is a Senior Structural Engineer for ExxonMobil.
•Chair of ACI 376 (outgoing) & ACI 544-E
•Secretary of ACI 544.
•**MCE** & **MSc** - the U. of Belgrade & the Imperial Coll., London, respectively
•**PhD** from Carnegie Mellon Univ.

•Work experience includes:
- 11 years – univ. professor at U. of Michigan - Ann Arbor, Northeastern U. & North Carolina State U.
- 10 years - structural lead on numerous forensic investigations, designs of large offshore concrete structures & arctic platforms, LNG tanks and plants while working for Exponent-Failure Analysis, Arup and EM.

•Research interests include:
- Cryogenic behavior of concrete, & development of all-concrete LNG tanks,
- "smart" materials & structures,
- high-performance FRCs, & their use in seismic-resistant retrofit & new construction,
- fracture mechanics of cementitious structures.

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Content

1. Introduction
2. **Performance** Requirements
3. **Construction** (*Material*) Requirements
4. **Other** Requirements

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Overall Philosophy

- Inner **Tank:**
  - maintain structural integrity
  - maintain LIQUID TIGHTNESS
    - ➢ *Tank not to be emptied*
- Outer **Tank:**
  - maintain structural integrity
  - contain LNG after SPILL
    - ➢ *Tank to be emptied after a spill*

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1. Introduction

- Reference documents
  1) ACI **350** – *Code Requirements for Environmental Eng. Concrete Structures & Commentary*
  2) ACI **372R** – *Design & Construction of Circular Wire- & Strand-Wrapped PSC Structures*
  3) ACI **373 R** – *Design & Construction of Circular PSC Structures with Circumferential Tendons*

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1. *Introduction:* Requirements

- **Performance** requirements:
  - Primary concrete tank
  - Secondary tank
  - Roof
- **Construction** requirements→ Materials
  - Concrete & Shotcrete properties
  - Coatings
  - Metal components

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1. *Introduction:* Requirement Types

- **Strength** requirements
- **Serviceability** requirements
  - Cracking & spalling
  - Deformations
  - Deterioration of reinforcement or concrete
  - Vibrations
  - Leakage

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2. Performance Requirements

2.1 Liquid Tightness vs. Containment
2.2 Crack Limits
2.3 Sliding & Sloshing

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Overall Philosophy

- Inner **Tank:**
  - Liquid TIGHTNESS
- Outer **Tank:**
  - Liquid CONATINMENT

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2.1. Tightness vs. Containment

Tank	PRIMARY (Inner)			SECONDARY (Outer)
Criteria Type	Liquid Tightness		Containment	Containment
Load Stage	Empty	Empty, Operating, OBE	SSE SSE_{aft}	Spill
Section Resultant	> 0	-	-	> 0
Neutral Axis Depth	-	t_{wall} / 2 8 in.	t_{wall} / 4 4 in.	t_{wall} / 10 3.5 in.
Aver. $\sigma_{compression\ zone}$	-	145 psi	-	145 psi

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2.1. *Liquid Tightness:* INNER Tank

- $f_{tensile}$ = 0 ..... "unless **justified**:"
  - ➢ **DEMONSTRATE**: section **NOT** previously **cracked**
    - – Consider **ALL** loads, e.g.:
      - o Transient & steady state thermal stresses
      - o Cool-down
      - o Hydrotest
      - o Creep & shrinkage
      - o OBE, etc.

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2.2. Crack Limits: Outer Tank

- **Normal** design loading (*no wind*):
  - – Slab, wall & roof:
    - $^{calculated}w_{cr} \leq$ **0.012** in.
      - ➢ *NOTE: heat loss through the slab → induces additional tension*
- **Spill**
  - – Thermal Corner Protection (TCP) area:
    - $^{calculated}w_{cr} \leq$ **0.008** in.

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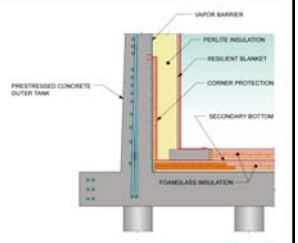
2.2. *Crack Limits: TCP*

- **Embedment Zone** → 2 t_{wall} above TCP
  - – Consider complete temperature time history

$^{calculated}w_{cr} \leq$ **0.008** in.



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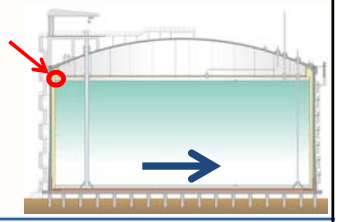
2.3. Other: Sliding & Sloshing

- Primary Tank
  - – SLIDING: use friction or anchorage
  - – FREEBOARD:
    - – $Sloshing_{OBE}$ + 1 ft
    - – $Sloshing_{SSE}$



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3. Construction / Material Requirements

3.1. General
3.2. Concrete Limits
3.3. Shotcrete Limits
3.4. Steel Reinforcement Limits
3.5. Liner
3.6. Other Metal Components

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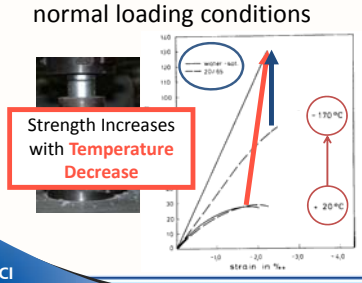
3.1. General

- Use **ambient temperature** properties for normal loading conditions



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3.1. General

- DIFFERENT → **Restrained deformation**
  - Use **CRYOGENIC** coeff. of thermal exp., $\alpha_{thermal}$
  - Confirm concrete $\alpha_{th.}$ by testing

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3.2. Concrete

- PSC limits:
  - service loads: σ_c → meet ACI **318**
  - At PS transfer: $\sigma_c \leq 0.55 f_{ci}$ ← ACI **372** & **373**

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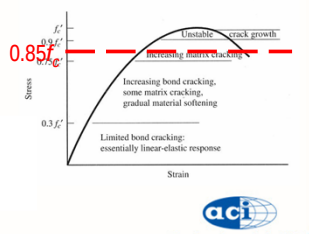
3.2. Concrete

- **OBE** (*prestress & total load*) → keep section ELASTIC:



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3.3. Shotcrete

- Meet requirements of:
  - ACI **506R** – *Guide to Shotcrete*
  - ACI **506.2** – *Spec. for Materials, Proportioning, & Application of Shotcrete*
  - ACI **350**, App. G – *Code for Enviro. Eng. Concrete Str. & Com.*
  - ACI **372R** – *Design & Constr. of Circular Wire- & Strand-Wrapped PSC Str.*
  - ACI **373R** – *Design & Constr. of Circular PSC Str. w. Circumferential Tendons*

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3.4. Steel Reinforcement

- **Cryogenic** re-bars
- **Non-cryogenic** re-bars exposed to < 0°F:
  - Use more restrictive $\sigma_{allow,\ st.}$ → Ch. IV: *Materials*
    - Lower limits based on **ductility** & **toughness** requirements
- **Prestressing** steel
  - Use ACI 350 limits

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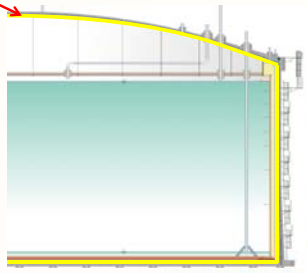
3.5. Liner

- Prevents vapor & moisture transmission → EXCLUDING SPILL
- 2 types permitted:
  1) Metallic
  2) Non-metallic



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3.5. Liner

- **METALLIC** Liner: meet **API** 620 App. Q or R
- **NON-Metallic** Liner (*polymeric*):
  - limits (*BS EN 14620–3, Section 10.3*)
    - ASTM E96 water vapor permeability < **0.00164** oz/ft²/24h
    - Escape of LNG vapor < **0.00033** oz/ft²/24 h
  - retain crack-bridging capability beyond an OBE

3.6. Other Metal Components

- Follow API 620 requirements for:
  - Allowable stresses
  - Weld-joint efficiency
  - Welding & weld testing

➢Can use higher stresses but must assure DUCTILE response under the most severe case

4. Other Requirements

4.1. Other Criteria

- FATIGUE: if Owner specified (*see Appendix C*)
  - outer tank → typically not a concern
- Risk / hazard assessment → determine if relevant:
  1) Pressure-wave loading (e.g., blast)
  2) Impact
  3) Fire

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Minimum Performance Requirements

Thank You
for
Your Attention