Failure Modes of CR-3 Containment Concrete Delamination Issue

(Revision 11, 12/28/2009)

PII Root Cause Investigation Team

Dr. Chong Chiu, Marci Cooper, Dr. Patrick Berbon

Dr. Avi Mor, Dr. Victor Saouma, Joe Amon (PE), Dr. Luke Snell

Henric Larsson, Dave Brevig, Dr. Gary Hughes

Dr. Mostafa Mostafa, David Dearth (PE), Dr. Ray Waldo

Nine Defined Categories

1. Inadequate Design and Analysis
2. Inadequate Concrete Construction
3. Inadequate Use of Concrete Materials
4. Shrinkage, Creep, and Settlement
5. Chemically or Environmentally Induced Distress
6. Inadequate Concrete-Tendon-Liner Interactions
7. Inadequate Containment Cutting
8. Operational Events
9. External Events

1. Inadequate Design and Analysis

1.1 Excessive local stress from axial loading (**Y**)

1.2 Excessive radial stress gradients (**Y**)

1.3 Excessive tensioning of horizontal tendons (**R**)

1.4 Excessive tensioning of vertical tendons (**R**)

1.5 Foundation settling (**R**)

1.6 Inadequate design against ground movement (**R**)

1.7 Containment long term, low-level vibrations (**R**)

1.8 Added stress from tendons not in same plane (**R**)

1.9 Added stress from variations in tendon spacing (**R**)

1. Inadequate Design and Analysis, cont.

1.10 Added stress from voids around tendon sleeves (**R**)

1.11 Effect of micro-cracks (**R**)

1.12 Inadequate size of tendon sleeves (**R**)

1.13 Inadequate net loading area of concrete due to presence of horizontal sleeves (**Y**)

1.14 Added stress from equipment hatch located underneath in same bay (**R**)

1.15 Inadequate design analysis methods of radial loads (especially near concrete outer skin) (**Y**)

2. Inadequate Concrete Construction

2.1 Inadequate concrete curing (**R**)

2.2 Inadequate concrete pouring (**R**)

2.3 Inadequate slump (Includes FM 3.6) (**R**)

2.4 Inadequate control of early age cracking (**R**)

2.5 Inadequate temperature control (**R**)

2.6 Inadequate interactions among concrete constituents / batching (**R**)

2. Inadequate Concrete Construction, cont.

2.7 Inadequate vibration during pour **(R)**

2.8 Inadequate support of tendons during pouring **(R)**

2.9 Void or cracks due to inadequate forms (leaky, unsecured, early stripping) (**R**)

2.10 Concrete Deformation from Tensioning too Early (**R**)

2.11 Inadequate construction cold Joint (**R**)

2.12 Inadequate frame construction (**R**)

3. Inadequate Use of Concrete Materials

3.1 Inadequate Air Content (**R**)

3.2 Inadequate grouting materials (**R**)

3.3 Inadequate Cement Materials (**R**)

3.4 Inadequate aggregates (contaminated aggregate, missing coarse aggregate, reactive aggregate, soft aggregate) (**Y**)

3.5 Inadequate admixtures **(R)**

3.6 Inadequate Slump *(Included in FM 2.3)* **(R)**

3.7 Inadequate Break Test used to Verify Compliance (**R**)

4. Shrinkage, Creep, and Settlement

4.1 Excessive plastic shrinkage (**R**)

4.2 Excessive Shrinkage (Includes FM 4.3 and 4.4)(**R**)

4.3 Excessive autogenous shrinkage (**R**)

4.4 Excessive carbonation shrinkage (**R**)

4.5 Excessive basic creep (**Y**)

4.6 Excessive drying creep (**R**)

4.7 Excessive segregation induced cracks (**Y**)

4. Shrinkage, Creep, and Settlement, cont.

4.8 Non-vibration induced fatigue cracking (**Y**)

a Temperature variations over time (**R**)

b Temperature variations inside/outside (**Y**)

c Humidity variation over time (**R**)

5. Chemically or Environmentally Induced Distress

5.1 Foreign material intrusion/contaminants during construction (**R**)

5.2 Salt water intrusion (**R**)

5.3 Chemicals introduced during routine maintenance (**R**)

5.4 Concrete outgassing and release (**R**)

5.5 Corrosion of rebars, sleeves, and tendons (**R**)

5.6 Inadequacy of grease lubrication capability (**R**)

5.7 Physical Attack **(R)**

- 5.7a Salt Crystallization **(R)**
- 5.7b Freezing and Thawing (also 4.8) (**R**)
- 5.7c Thermal exposure/thermal cycling (also 4.8) (**R**)
- 5.7d Irradiation **(R)**

5. Chemically or Environmentally Induced Distress, cont.

5.8 Chemical Attack (**Y**)

- 5.8a Sulfate attack (**R**)
- 5.8b ASR or ACR (**Y**)
- 5.8c Efflorescence/Leaching (**R**)
- 5.8d Acids/Bases (**R**)
- 5.8e Aggressive Water (**R**)
- 5.8f Biological Attack (**R**)
- 5.8g Delayed Ettringite Formation (**R**)
- 5.8h Carbonation (**R**)

6. Inadequate Concrete-Tendon-Liner Interactions

6.1 Uneven tension distribution along the tendon due to excessive local duct friction (**Y**)

6.2 Strain hardening of some tendons (**R**)

6.3 Added stress from thermal effects of greasing (**R**)

6.4 Added stress from differences between rigid and flexible sleeves (**R**)

6.5 Inadequate tendon re-tensioning in surveillance activities (**R**)

6.6 Inadequate initial tensioning of tendons (**R**)

7. Inadequate Containment Cutting

7.1 Excessive local stress gradients during cutting

7.2 Shock or vibration induced concrete separation due to resonant vibrations during hydro-blasting (**R**)

7.3 Inadequate pattern of de-tensioning of tendons (**Y**)

7.4 Added stress to adjacent tendon due to de-tensioning

7.5 Added stress due to removing tendons and concrete at opening (thermal stress) (**R**)

7.6 Vibrations due to cutting tendons under tension (**R**)

7.7 Cracking due to pre-existing defects in this area

7.8 Excessive water jet pressure (**R**)

7. Inadequate Containment Cutting, cont.

7.9 Inadequate hydro-blasting rate (**R**)

7.10 Formation of fine micro-cracks from hydro-blasting (**R**)

7.11 Added stress from pulling tendons out of sleeves and grease after cutting (**R**)

8. Operational Events (**R**)

8.1 Prior spray event leading to low pressure inside containment (**R**)

8.2 Thermal stresses due to containment spray (**R**)

8.3 Effect of faster pressurization/depressurization rates during last ILRT) (**R**)

8.4 Inadequate concrete structure monitoring/ maintenance (IWL) **(R)**

8.5 Containment depressurization due to inadequate purging operation **(R)**

9. External events (**R**)

9.1 Hurricanes or Tornados (**R**)

9.2 Seismic events (**R**)

9.3 Ground Movements (sink holes or geo-sliding) (**R**)