September 26, 2000 Public Meeting Summary

A public meeting was held on September 26, 2000, at NRC-Headquarters to present recent research results for a Service Level I concrete coating system applied in PWRs when subjected to simulated post-DBA conditions. Attendees included NEI, EPRI, BWROG, ASTM, WOG and other stakeholders. The RES contractor presented research results on the potential for coating failure that could result in the formation of debris that could impact the operation of PWR ECCS systems. The Industry Coatings PIRT Panel (industry coatings specialists) presented their views on the significance of coating degradation phenomena that had not previously been observed.

Research showed that non-irradiation aged specimens do not fail and produce debris. However, when coating specimens were irradiated to a total dose of 10^9 RAD (per ASTM D-4082) and subjected to a plant-specific temperature/pressure post-LOCA environment or water immersion at 200 ^{0}F , failure occurred within a .002" depth in the topcoat (Phenoline 305) material. The postulated underlying causes were: (1) interactive effects related to irradiation-aged epoxy coatings being affected by temperature and moisture and (2) oxygen permeation into the top layer of the surface coating. Sample irradiation dose rate and total dose appeared to influence the depth of oxygen damage. Debris formation was dependent on the post-LOCA environment simulated and submergence effects.

Qualification testing using the temperature/pressure profiles prescribed by ASTM D 3911-95, (which has been used for qualification testing) did not result in debris formation for this coating system which raised questions regarding continuing the use of this standard in predicting coating performance under post-LOCA conditions.

This meeting provided an open forum for reporting new phenomena and resulted in considerable discussion regarding (1) the application of results to operational PWRs for which the 10^9 RAD total dose was judged to be excessively high by a factor of 100, (2) a need to re-visit previous qualification testing and acceptance of the results, (3) a need to review the ASTM standards cited above to identify changes needed, and (4) additional research needed to better understand the synergistic environmental effects. Attendees were encouraged to submit additional views and research recommendations by e-mail to facilitate development of a path forward plan.

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NPP Protective Coatings (Service Level I) Research Findings

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Division of Engineering Technology
Engineering Research Applications Branch

Technical Contacts:
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Public Meeting
Rockville, Maryland
September 26, 2000

BACKGROUND

1. “Qualified” NPP containment protective coatings applied in the 1970s were expected to last for the 40 year plant design life following initial application and not fail if a LOCA should occur.

2. However, qualified coatings have failed in NPPs thereby identifying a need for condition monitoring and maintenence as required.

3. NRC GL 98-04 identified such failures and raised concerns regarding potential impact on long-term ECCS operability.

4. NRR requested research directed at investigating the potential for qualified coatings failure and identification of debris characteristics if failure occurs.

5. RES initiated a research program at the Savannah River Technology Center (SRTC) in July 1998.

STAKEHOLDER INVOLVEMENT

1. Public meetings have been used to describe research conducted and results obtained. First public meeting held in November 1998.

2. Phenomena Identification and Ranking Panel formed early 1999

   Industry PIRT panel members comprised of coatings specialists and vendors, plant coatings staff, NPP design and operations persons.

   Panel identified “generic” coating systems that have been applied.

   PIRTed applied coatings systems (a “first”) - identifying and ranking potential failure phenomena.

   Interacted with the SRTC research activities.

   Assisted in procuring coating materials representative of coatings applied in the 1970s.

3. Other Stakeholders

   Owners Groups (i.e. WOG), ASTM D-33 Committee (NPP Coatings Standards), NEI (plant surveys) and Licensees

SRTC PROGRAM

Research Purpose:

Investigate NPP “qualified” containment coatings to determine coating system failure mechanisms, estimated time to failure and coating debris characteristics (e.g. failed material composition, geometry, size and distribution).

Application of Results:

1. Coating debris characteristics will used in GSI-191, “PWR Sump Clogging” research program.

2. Insights gained can be used in evaluation of ASTM Standards related to Service Level I protective coatings applied to nuclear powerplants (e.g. ASTM Standards D-4082 and D-3911)

SRTC Program Elements:

1. **Materials Properties** (Mechanical & Physical, irradiated and non-irradiated)

2. Failure Modeling

3. **Measured coating system performance** under simulated DBA Conditions (e.g. ASTM 391-95, plant specific temperature and pressure transient, moisture and water immersioneffects).

4. **Failure and/or Debris Generation** (e.g. no failure, blistering and/or cracking, failure resulting in debris generation).

Coating System to be discussed today is comprised of: epoxy-phenolic (Phenoline 305) topcoat over a surfacer (Starglaze 2011S) applied to a concrete substrate.

Test samples were prepared in accordance with ASTM D 5139-96, irradiated per ASTM D 4082-95 and simulated DBA tested per ASTM D 3911-95.

September 26, 2000 Public Meeting
U.S. NRC Headquarters, Rockville, Maryland

Purpose: Discuss Research Findings Related to a Service Level I Coating System Applied to Concrete Surfaces within PWR Containments

9:00 - 9:15 AM	Introductory and Background Remarks (Background & Information to be Discussed)	A.W. Serkiz
9:15 - 10:15	Industry Coatings PIRT Panel (PIRT Panel Considerations & System 2 Findings)	J. Cavallo
10:15 - 10:30	Break	
10:30 - 12:00	Presentation of System 2 Findings Research Conducted Results Obtained New Insights	Sindelar, DuPont & Zapp
12:00 - 1:00 PM	Lunch Break	
1:00 - 2:00	Evaluation of System 2 Results Significant Findings Interactive Effects Application of Results	SRTC and PIRT
2:00 - 3:00	Path Forward Discussions Significance of findings Application of results to PWR sump blockage research Application of results to related ASTM Standards	SRTC, PIRT Panel & Attendees (M. Marshall) (PIRT Panel)

SRTC System 2 Coating System: Epoxy-phenolic (Phenoline 305) top coat over surfacer
Corresponding PIRT System 5 (Starglaze 2011S) applied to concrete substrate.

Meeting Goals:

1. Present key findings from research conducted.

2. Discuss significance and application of key findings.

3. Solicit views from attendees on research reported.

Attendees are encouraged participate in the “Path Forward” discussions and to follow-up with additional views/comments via e-mail.

PIRT PROCESS
for
SRTC Containment Coatings Research Program

Activity Overview and Status

Jon Cavallo
Industry Coating PIRT Panel Chairman
September 26, 2000

Industry Coating PIRT Activity

BACKGROUND

- SRTC Research Program Objectives
  - Investigate NPP containment coating failure mechanisms, failed coating debris characteristics and time to failure.
  - Identify failed coatings debris characteristics and time to failure for use in debris transport studies simulating post-LOCA conditions
- Industry Coating PIRT Panel Evolution
  - SRTC Research Program initiated - July, 1998
  - SRTC Research Program initial results presented - November, 1998
  - NEI recommends performing PIRT to guide program
  - PIRT panel formed and met four times in 1999
  - Published Interim Report dated June 28, 1999
  - Published Final Report dated June 16, 2000

Industry Coating PIRT Activity

PIRT Panel Members

- Jon Cavallo, CCC&L, Chairman
- Tim Andreychek, Westinghouse Owners Group
- Jan Bostelman, ITS Corporation
- Brent Boyack, Los Alamos National Lab
- Garth Dolderer, Florida Power and Light Company
- Yuly Korobov, RPM Carboline (joined panel July 2000)
- David Long, Keeler and Long, Inc., Retired

NRC Sponsor

- Al Serkiz, NRC/RES, Project Manager

Industry Coating PIRT Activity

Industry Coatings PIRT Objectives

- Identify coating systems considered for PIRT process
  - Based on industry usage
  - Steel substrate
  - Concrete substrate
- Identify phenomena and processes for coatings applied inside NPP containments
- Rank those phenomena and processes with respect to their importance to coatings failures

Industry Coating PIRT Activity

POTENTIAL PIRT APPLICATIONS

1. Provide input to SRTC program for selection of materials and parameters to be investigated.
2. Provide input to SRTC program on phenomena to be simulated in experimental phase of test program.
3. Provide input to SRTC on data to be obtained from the experimental program.
4. Provide input to SRTC coatings failure model for features to be included in the program.
5. Provide input to industry groups for their use.

Industry Coating PIRT Activity

DEFINITIONS

- Failure:
  - Disbonding of an applied coating (paint) system into free debris, regardless of size and shape, that is available for transport; a debris source term.

- Debris Source Terms:
  - Coating systems that have failed prior to the event.
  - Coating systems that fail as a consequence of the event.

Industry Coating PIRT Activity

PWR CONTAINMENT COATING ISSUE(S):

1. Why and how do coating systems fail?
2. What are the effects of environmental exposure on coating systems?
3. What is the time to failure for coating systems?

Industry Coating PIRT Activity

INDUSTRY COATINGS PIRT OBJECTIVE:

Identify and rank the phenomena and processes important to the potential failure of coating systems used inside containment at Nuclear Power Plants.

Industry Coating PIRT Activity

PWR CONTAINMENT COATING SYSTEMS:

- Nine systems considered:
  1. Steel substrate, inorganic zinc primer, epoxy phenolic topcoat
  2. Steel substrate, epoxy phenolic primer, epoxy phenolic topcoat
  3. Steel substrate, inorganic zinc primer, epoxy topcoat
  4. Steel substrate, epoxy primer, epoxy topcoat
  5. Concrete substrate, surfacer, epoxy phenolic topcoat
  6. Concrete substrate, surfacer, epoxy topcoat
  7. Concrete substrate, epoxy phenolic primer, epoxy phenolic topcoat
  8. Concrete substrate, epoxy primer, epoxy topcoat
  9. Steel substrate, untopcoated inorganic zinc primer (added by NRC based on NEI survey responses)

Industry Coating PIRT Activity

- Review of information provided by EPRI (see TR-106160 June 1996), NEI PWR Containment Coatings survey provided to NRC, and PIRT panel member experience indicates that essentially all PWR containments have epoxy and/or phenolic-modified epoxy top coats on SSC's.

Industry Coating PIRT Activity

- Five PIRT's prepared by panel:
  - System 1 - steel substrate, IOZ primer, epoxy phenolic topcoat
  - System 4 - steel substrate, epoxy primer, epoxy topcoat
  - System 6 - concrete substrate, surfacer, epoxy topcoat
  - System 8 - concrete substrate, epoxy primer, epoxy topcoat
  - System 9 - steel substrate, IOZ primer

Industry Coating PIRT Activity

COMPONENTS AND PHENOMENA RANKING SCALES

- **High** – Phenomena has a dominant impact on the primary parameter of interest. Phenomena will be explicitly considered in the implementation of the SRTC research program.
- **Medium** – Phenomena has a moderate influence on the primary parameter of interest. Phenomena will also be considered in the implementation of the SRTC research program.
- **Low** – Phenomena has a small effect on the primary parameter of interest. Phenomena will also be considered in the implementation of the SRTC research program, to the extent possible.

TABLE 1

SUMMARY PIRT TABLE

Steel Substrate - Inorganic Zinc Primer - Epoxy Phenolic Top Coat System (PIRT System 1, SRTC System 1)

	Phases ➜	1	2	3	4	5
	Processes & Phenomena					
IOZ Primer	Film splitting	M	M	M	M	M
	Minor coating anomalies	M	H	M	M	
	Diffusion rate of air/water		L	M	M	H
	Chemical attack			L	M	L
	Moisture & air intrusion through damage sites				M	H
Primer / Top Coat Interface	Differential contraction/ expansion	M	H	H	L	L
	Diffusion rate of air/water		L	H	H	H
Top Coat	Expansion/contraction	M	H	H	L	L
	Environmental exposure	H				
	Mechanical damage	M	L			
	Diffusion of air/water		L	L	L	M
	Immersion to pool surface				L	M

TABLE 2

SUMMARY PIRT TABLE

Concrete Substrate - Surfacer - Epoxy Top Coat System
(PIRT System 6, used by SRTC for SRTC System 2 evaluation)

	Phases ➜	1	2	3	4	5
	Processes & Phenomena					
Substrate	Outgassing/Vapor Expansion	H	H	H	M	M
(Concrete)	ILRT Pressure Gradients	M	H	H	L	L
Substrate/	Calcium Carbonate Buildup	M				M
Surfacer	Blistering/Delamination	H	H	H	H	H
Interface	Vapor Buildup	H	H	H	M	M
Surfacer	Environmental Exposure	M	L	L	L	M
Coating Anomalies		H	H	H	M	M
Surfacer/Top Coat	Blistering/Delamination	H	H	H	H	H
Interface	Vapor Buildup	H	H	H	M	M
Top Coat (Epoxy)	Coating Anomalies	H	H	H	M	M
	Environmental Exposure	H	L	L	L	M
	Immersion in Pool					M

Industry Coating PIRT Activity

SUMMARY

- **Industry Coatings PIRT Panel effort**
  - Four meetings held
  - Five PIRT's developed
  - First PIRT report interim draft published June 28, 1999
  - Final PIRT report published June 16, 2000
- **Working relationship with SRTC Research Project**
  - Ongoing contacts established and maintained
  - Timely exchange of research findings

Response of Aged Concrete Coating System to LOCA Conditions

Results from Savannah River Technology Center Program to Investigate Degradation and Failure Characteristics of NPP Containment Protective Coatings

Public Meeting

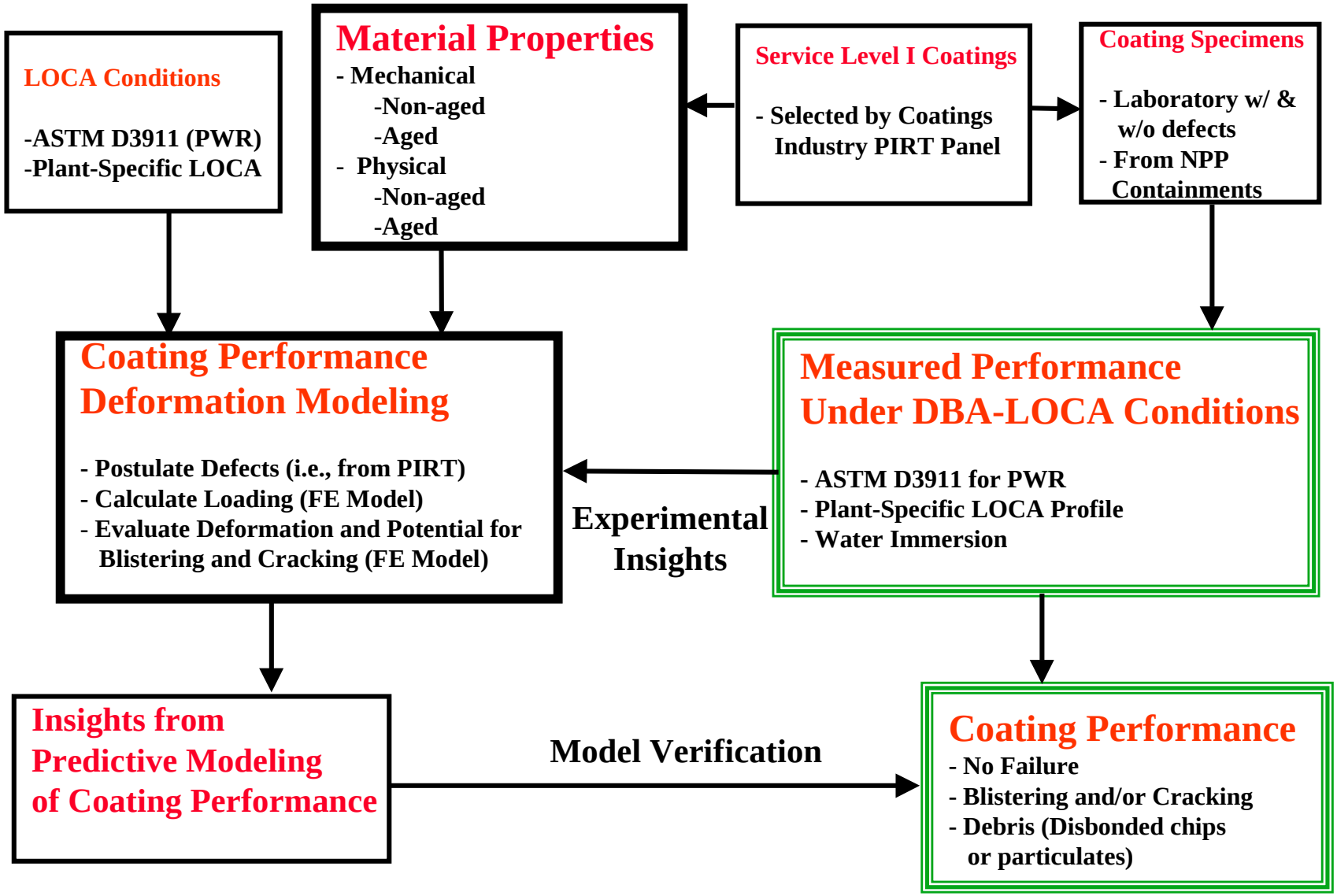
Rockville, Maryland

September 26, 2000

Program Objectives

- **Testing and Analysis Activities to:**
  - Investigate Service Level I coating performance in non-aged and aged conditions under temperature/steam conditions in containment during LOCA
  - Utilize experimental testing and analytical modeling approach to predict coating performance under postulated LOCA conditions
  - Identify failed coating characteristics (debris source term)
- **Address Phenomena Important to Cause Coating Failure** (Identified by Industry Coatings PIRT Panel)

Task Logic Diagram



Coating System Cross-Reference Table

Substrate	Generic Description	Coating Products Tested at SRTC	SRTC System No.	PIRT System Letter
Steel	Epoxy-phenolic over inorganic zinc	Phenoline® 305 over Carbozinc® 11	1	a (1)
Concrete	Epoxy-phenolic over surfacer	Phenoline® 305 over Starglaze® 2011S surfacer	2	e (5)
Steel	Phenolic-modified epoxy over inorganic zinc	Amercoat® 90HS over Dimetcote® 9	3	
Steel	Phenolic-modified epoxy over epoxy-polyamide	Amercoat® 90HS over Amercoat® 370	4	
Steel	Epoxy-polyamide over epoxy-polyamide	Amercoat® 370 over Amercoat® 370	5	d (4)
Steel	Inorganic zinc	Dimetcote® 9	6	(9)
Steel	Epoxy-phenolic over epoxy-phenolic			b (2)
Steel	Epoxy over inorganic zinc			c (3)
Concrete	Epoxy over surfacer			f (6)
Concrete	Epoxy-phenolic over epoxy-phenolic			g (7)
Concrete	Epoxy over epoxy			h (8)

Service Level I Coating Investigation

- Coating System 2
  - Predominant Concrete Coating System
  - Phenoline® 305 epoxy-phenolic topcoat, Starglaze® 2011S epoxy surfacer, 2”x2”x4” concrete block
- Specimen Preparation
  - Qualified Applicators
  - ASTM Standard D5139-90
- Specimen Treatment for Irradiation Aging
  - ASTM Standard D4082-95
- Specimen LOCA Exposure
  - ASTM Standard D3911-95
  - Others (“Plant-Specific”; Water Immersion) to Align with Conditions Identified by PIRT Panel

System 2 - Major Findings

- No Debris for Specimens in Non-Irradiated Condition
- Debris Source for Specimens Irradiated per ASTM D4082 ($1x10^9$ rads @ $1x10^6$ rads/hour @ 120°F)
  - D3911 PWR Temperature/Pressure Profile: No debris
  - “Plant-Specific” Profile: Significant Debris on Specimen
  - Water Immersion (~200°F): Significant Debris on Specimen and in Water

Performance Testing of Concrete Coating System (System 2)

Preparation of Test Specimens

System 2 Sample Preparation

Concrete Block with Surfacer Only

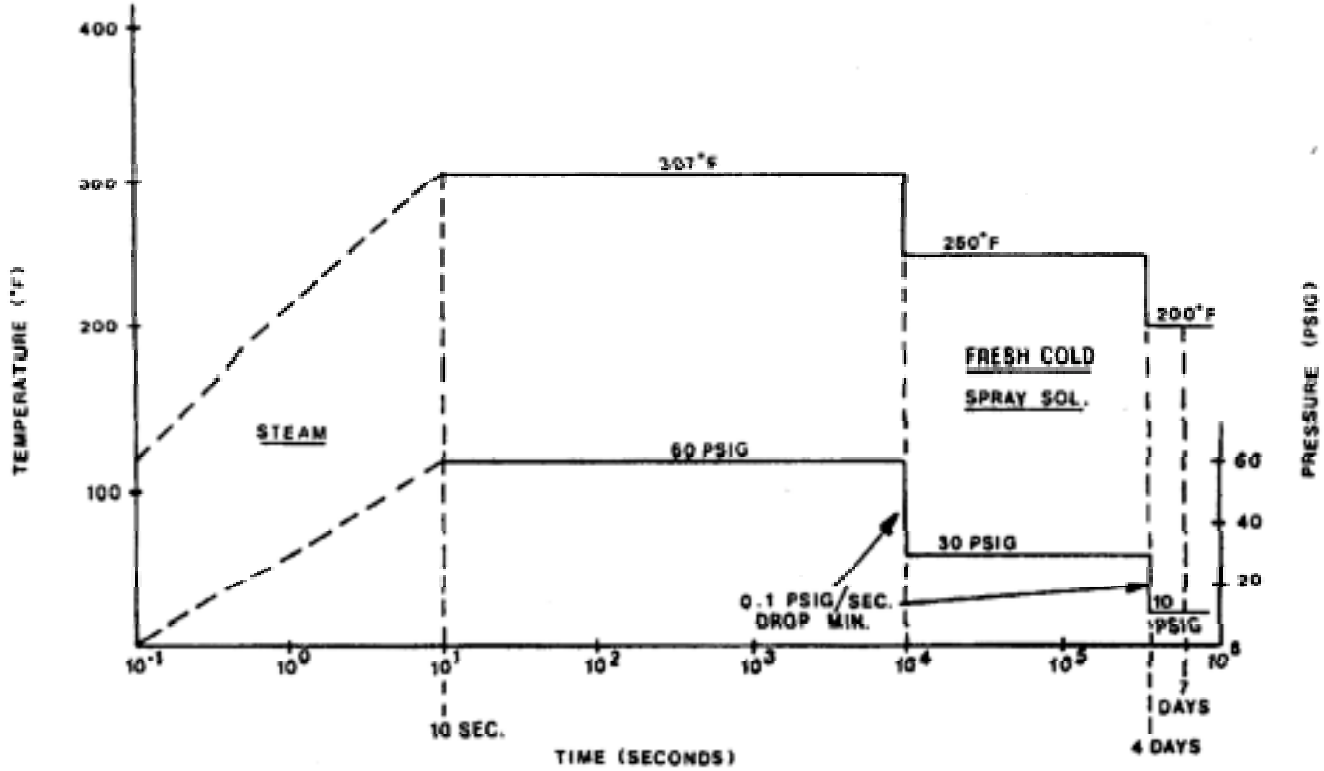
Block with Surfacer and Phenoline 305 Topcoat

Cobalt-60 Gamma Irradiation Cell

LOCA Testing Performed at SRTC

Test Performed	Test Description	Test Conditions
ASTM D3911 LOCA Test	7 day test per ASTM D3911-95	Included immersion of a portion of the specimens
Plant-Specific Pressure/Temperature Test	Pulse test incorporating rapid heating and rapid cooling of specimen	Included immersion of a portion of the specimens
Coating System Immersion Test	Immersion test of complete coating system (concrete substrate, surfacer, topcoat)	Testing performed from room temperature to 200°F and with 200°F initial condition
Free-film Immersion Test	Immersion of free-film specimens of surfacer and topcoat, in aged and non-aged conditions	Testing performed from room temperature to 200°F

PWR LOCA Per ASTM D3911-95

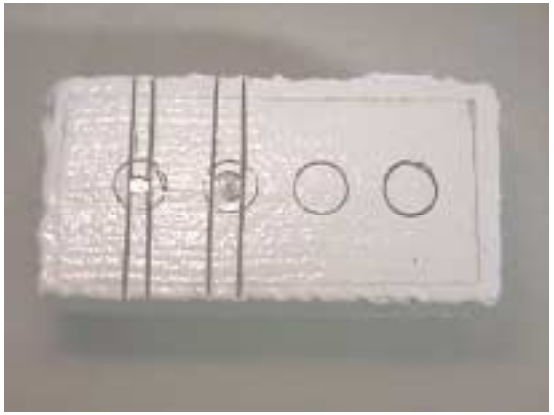


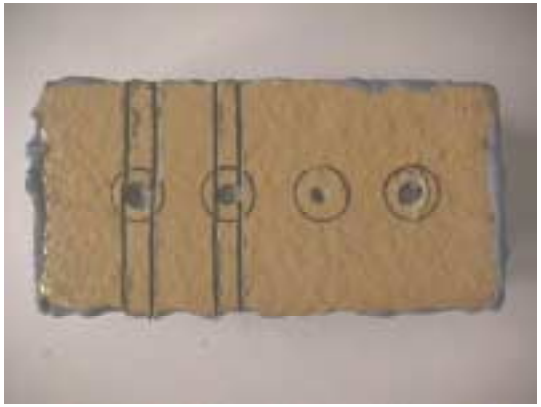
System 2 LOCA Test Per ASTM D3911-95

Non-Aged

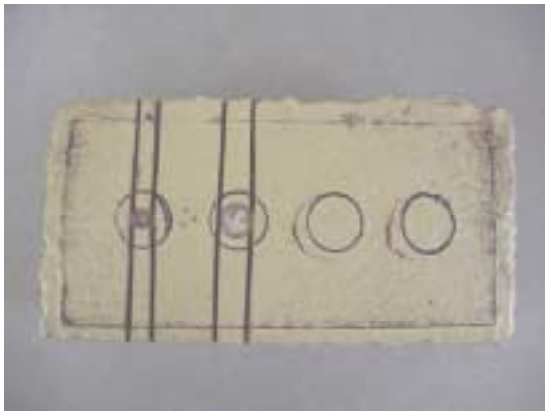
Irradiation-Aged

Before LOCA

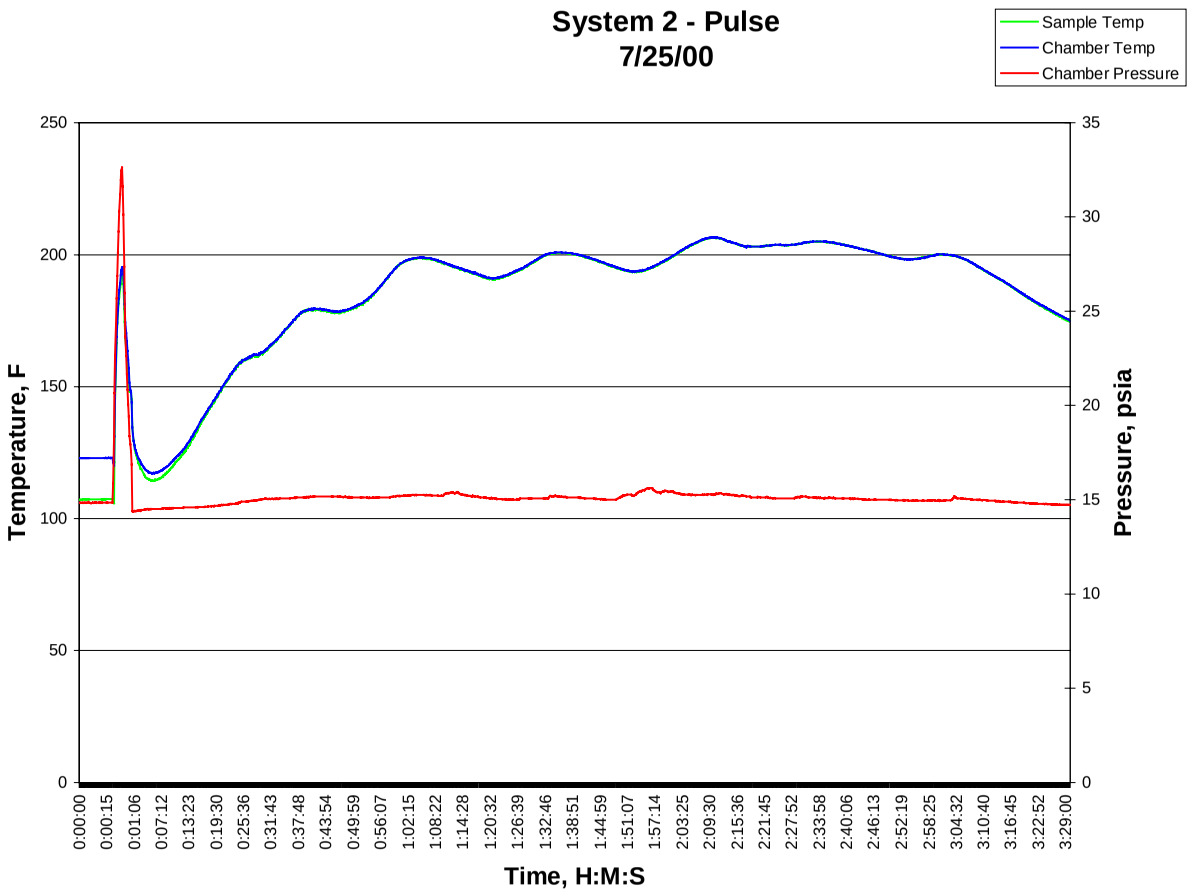




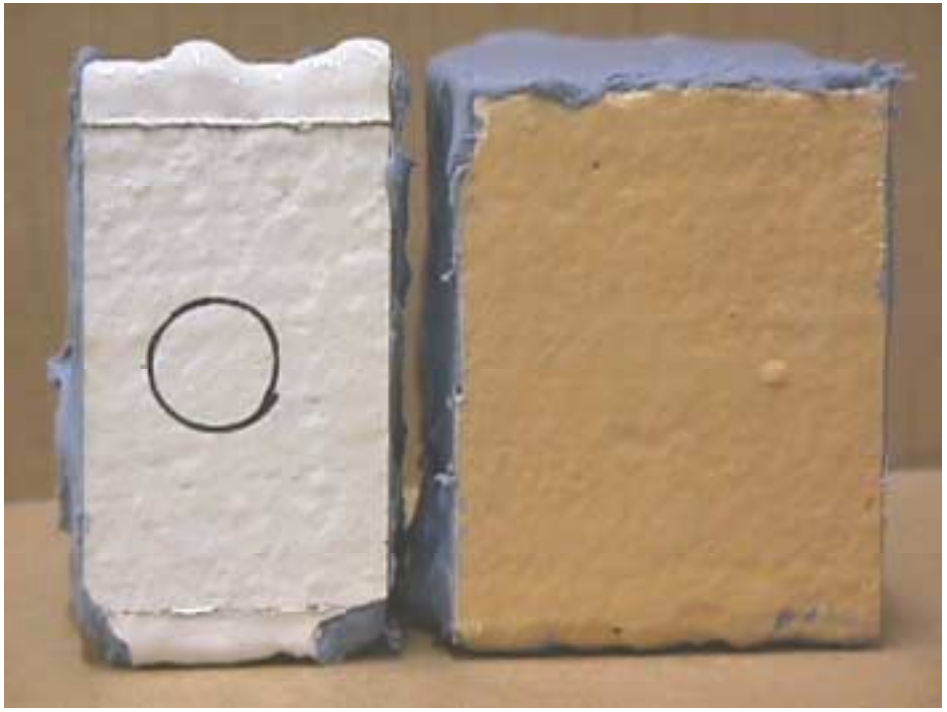
After LOCA



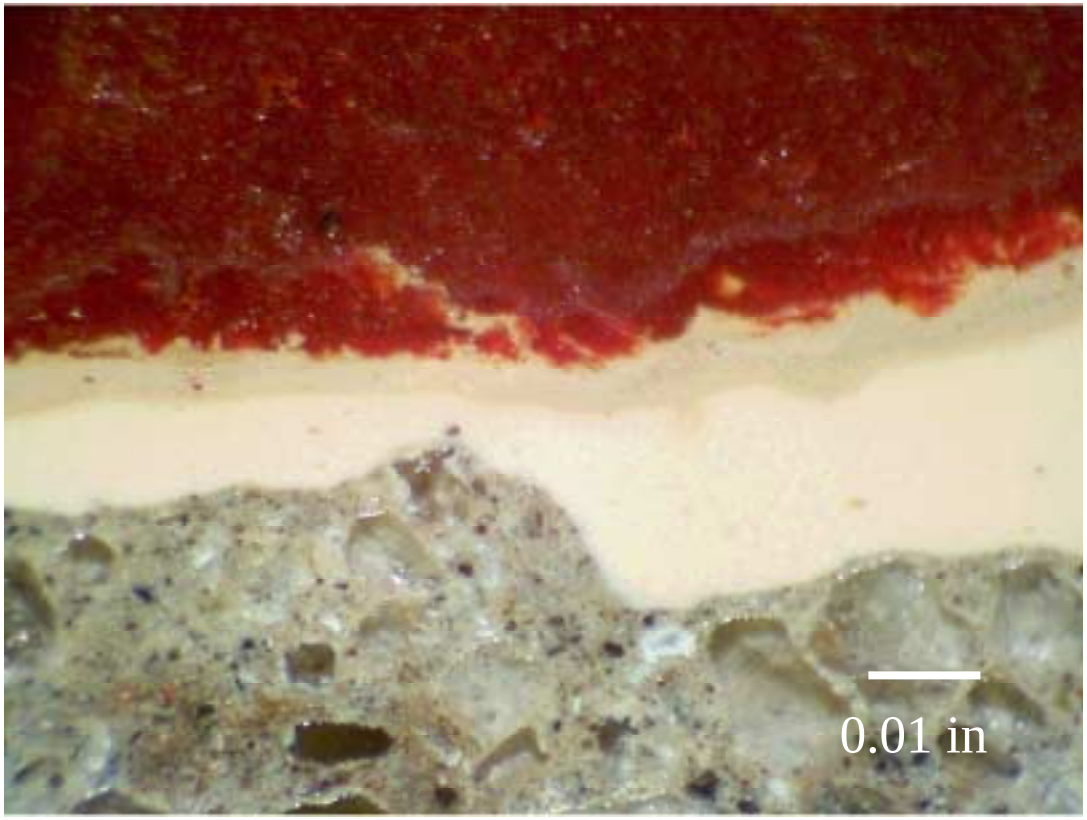
Typical SRTC Plant-Specific LOCA Profile



System 2 Coating Test Specimens



Irradiated System 2 in Cross-Section

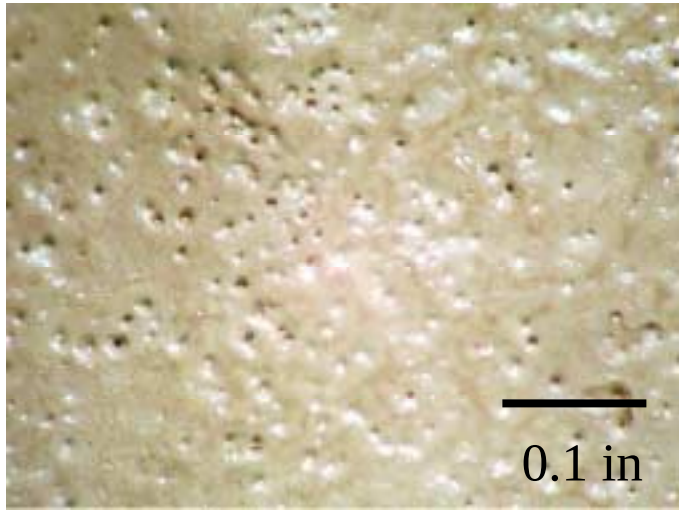


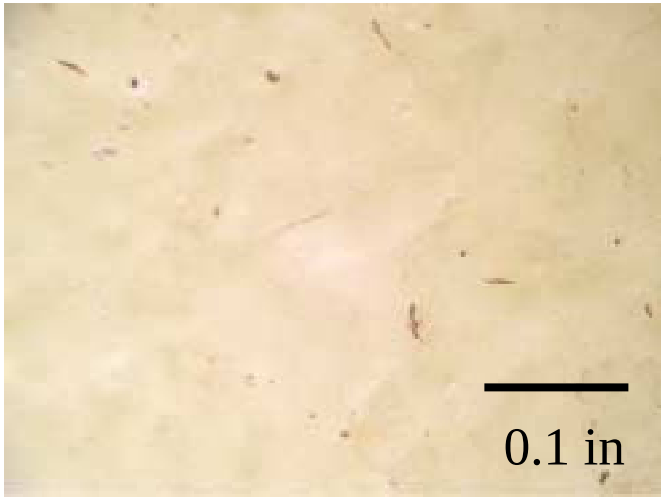
Mounting Media

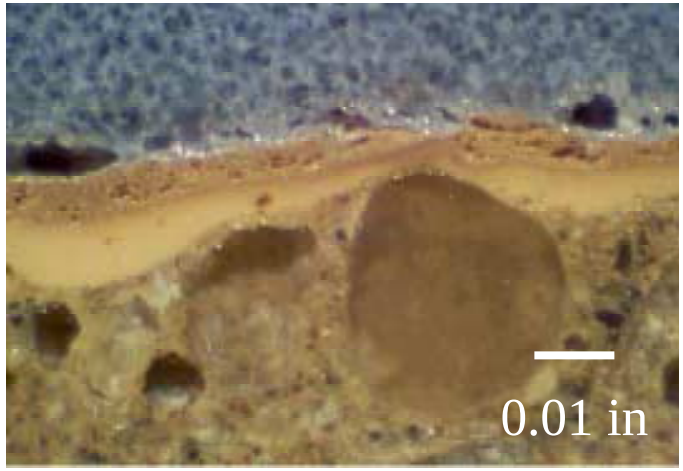
2-mil thick affected layer; nominal 12 mil total coating thickness

Surfacer

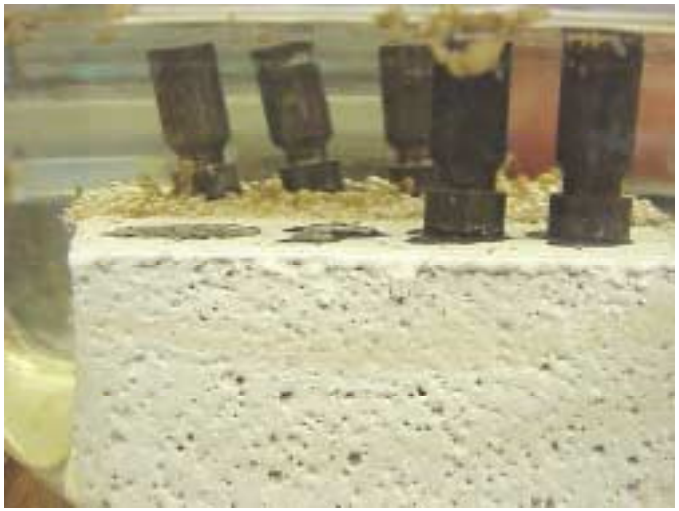
DBA Testing Per ASTM D3911-95

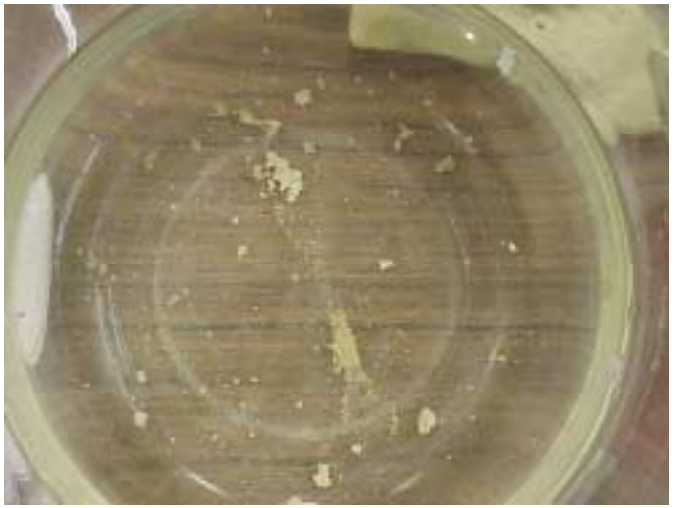




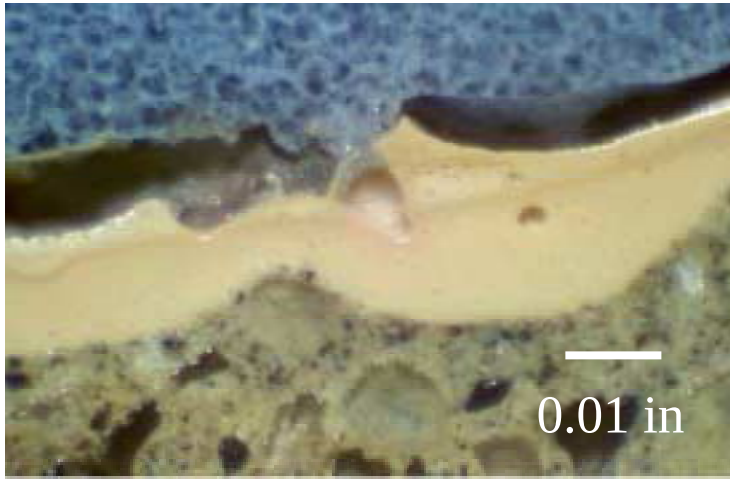


200° F Water Immersion Test

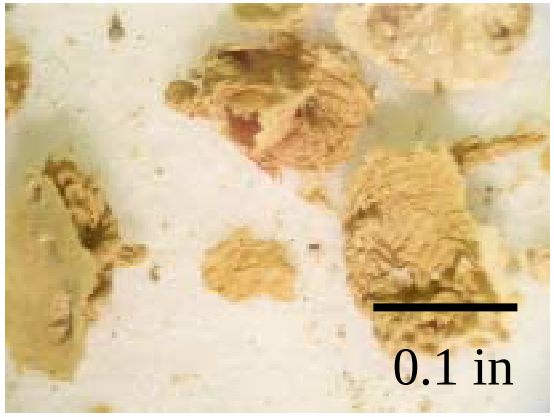




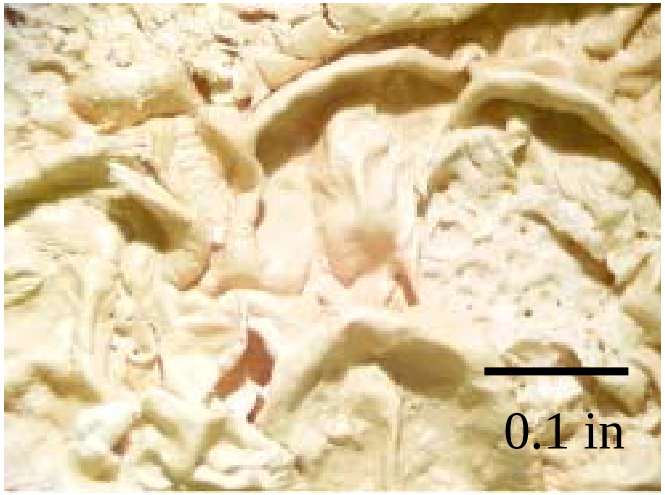
200° F Water Immersion Test (cont)



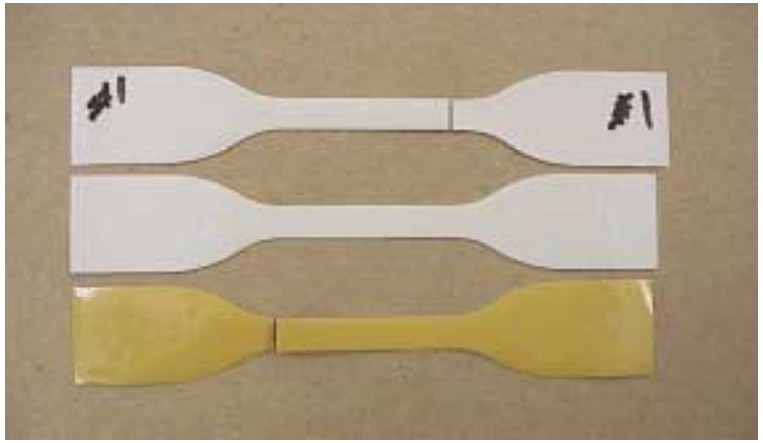
Debris Produced by Water Immersion

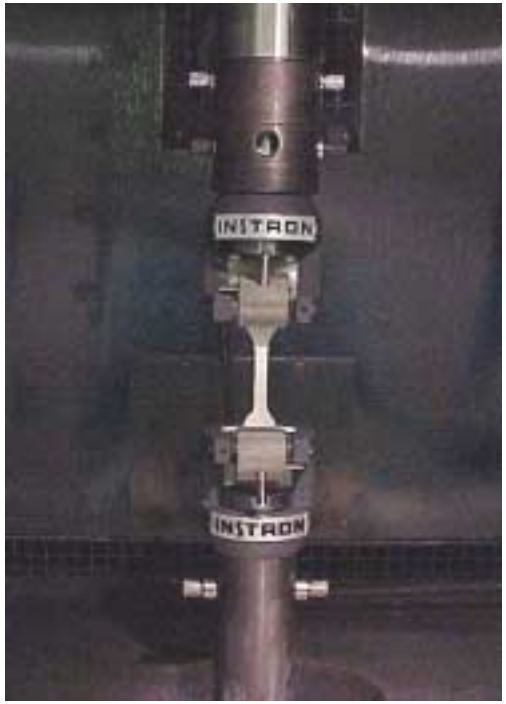


Plant-Specific LOCA Testing w/Immersion



Free-Film Tensile Testing





Free-Film Soak Test

Time = 0

Time = 2 hours, Temperature = 150° F

Time = 4 hours, Temperature = 175° F

Time = 4 hours 20 minutes, Temperature = 200° F

Performance Summary of Concrete Coating System 2

with

Supplementary Observations of System 5 and a Plant System

System 2 Coated Concrete Test Results

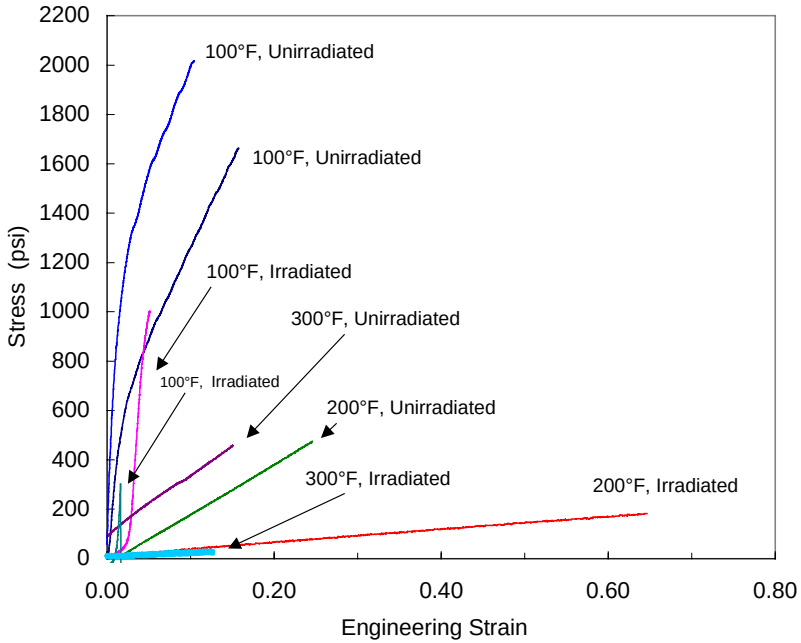
	Non-irradiated	Irradiated to 10^7 Rad	Irradiated to 10^9 Rad
Immersion In 200°F Water	**No Failure**	**No Failure**	**Debris**
Plant-Specific LOCA	**No Failure**	**Not Tested**	**Delamination (Blistering)**
ASTM D3911 LOCA	**No Failure**	**Not Tested**	**No Failure**

Debris Formation in System 2 Water Immersion Test at 200°F

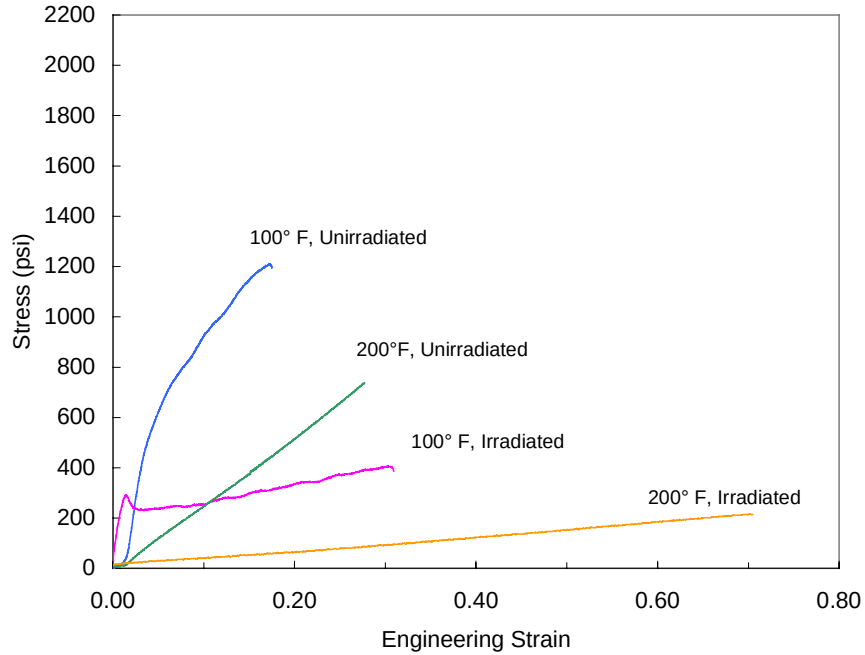
- Debris Source: Disbondment of Oxidized Layer of Epoxy Phenolic Topcoat
- Disbondment Increased by Agitation
- Originates in Blistering Driven by Gaseous Radiolytic Products
- Heat, Water, & Irradiation to 10^9 Rad Soften, Weaken Topcoat

Tensile Test Results of Epoxy-Phenolic Topcoat

Dry condition



Wet condition



Irradiation to 10^9 Rad, higher test temperature, and exposure to water decrease strength and modulus, increase ductility

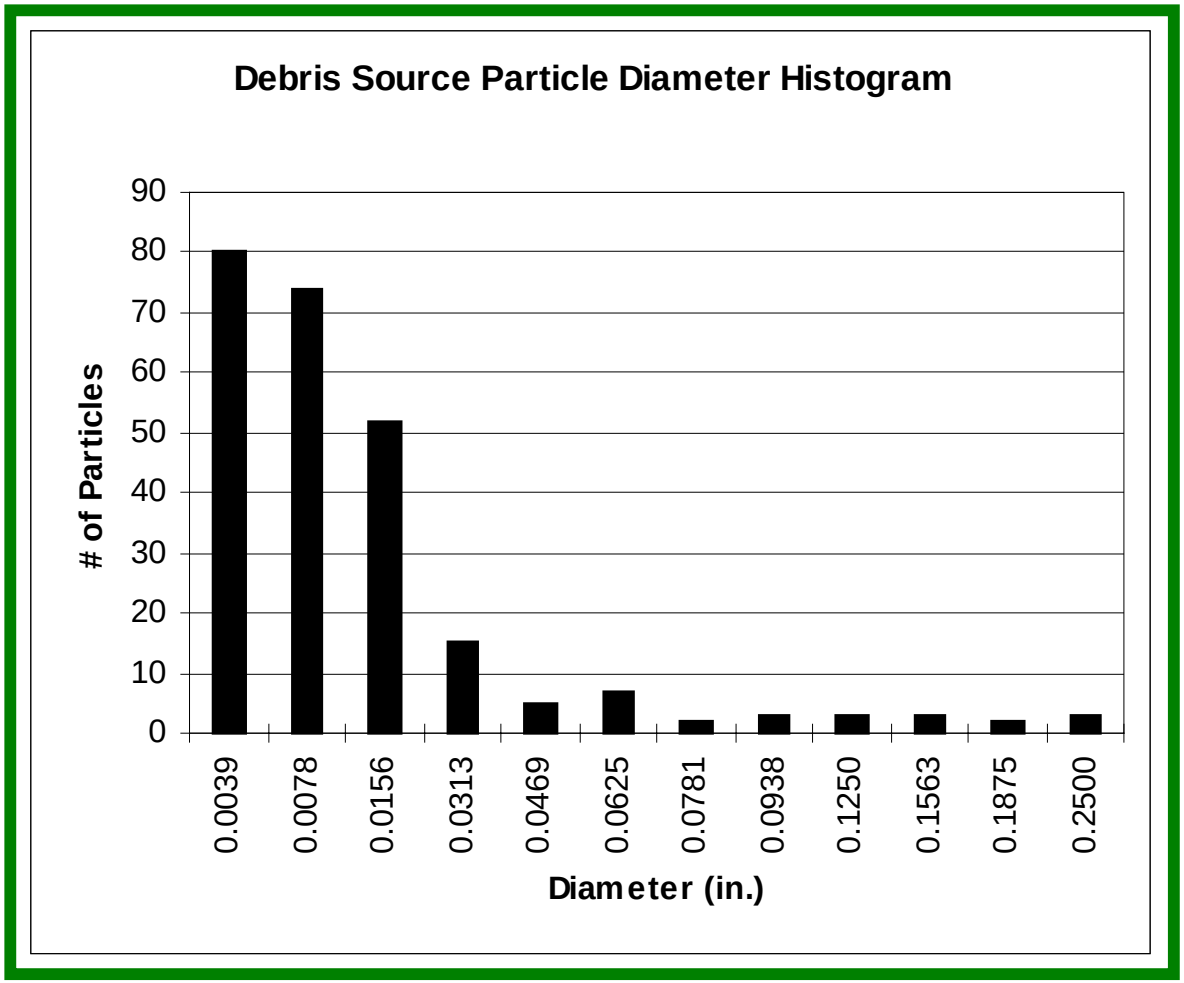
Debris Characterization

Debris Characterization

- Image Analysis (32x magnification)
  - Photo Enhancer® 3.0, Kodak MDS Photo System
  - Adobe Photoshop®
  - Scion Image (NIH Freeware)

- Particle Description
  - Representative subset
  - Long diameter of each particle used
  - Area calculated assuming circular particle
  - Limited to particles greater than 100 μm

Analysis of Debris from System 2 Water Immersion Test at 200°F

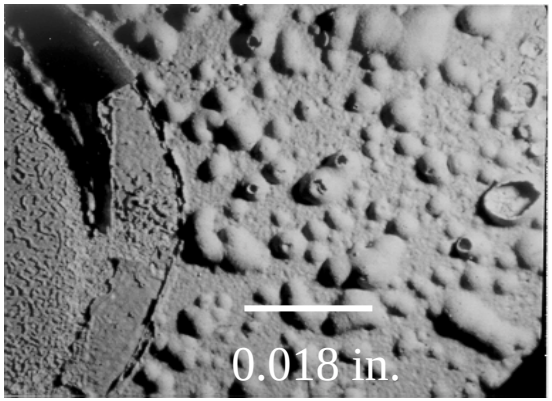


Count.	D (in.)
80	0.0039
74	0.0078
52	0.0156
15	0.0313
5	0.0469
7	0.0625
2	0.0781
3	0.0938
3	0.1250
3	0.1563
2	0.1875
3	0.2500
249	Total Data

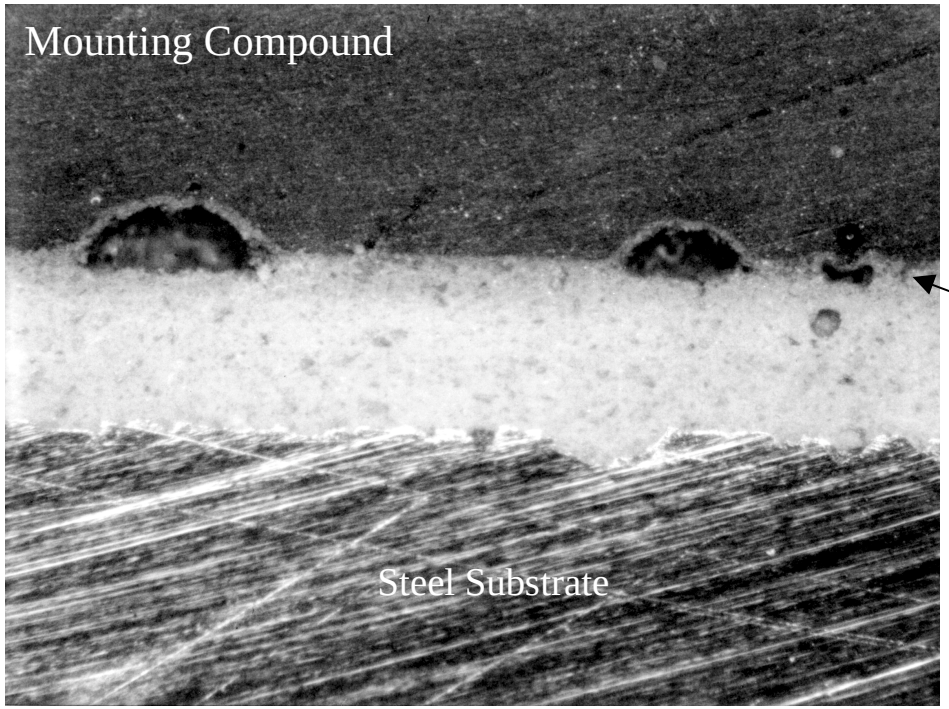
Area by Diameter (in^2)	
80	0.000012
74	0.000048
52	0.000192
15	0.000767
5	0.001725
7	0.003066
2	0.004791
3	0.006899
3	0.012266
3	0.019165
2	0.027598
3	0.049063

- **Source Term Input for Sump Blockage Study**

Similar Blister Formation in Coating System 5 (Polyamide Epoxy/Polyamide Epoxy/Steel)



Blistering on Immersed, Irradiated Coupon



oxidized layer

Cross-section of System 5 after irradiation to 10^9 Rad and ASTM D3911 DBA test.

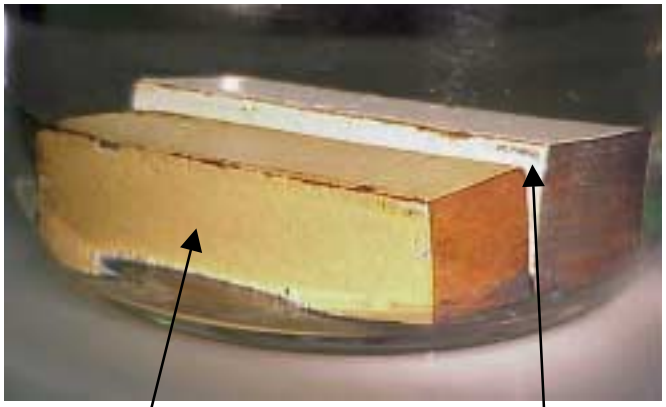
Performance of Plant Specimen

- Water Immersion
- ASTM D3911 DBA with Partial Immersion

Blister Formation on Irradiated Plant Specimen

Mobil 78-W-300 on Steel in 200°F Water Immersion Test

Upon Immersion at 72°F



Irradiated in SRTC Gamma Cell to 10^9 Rad

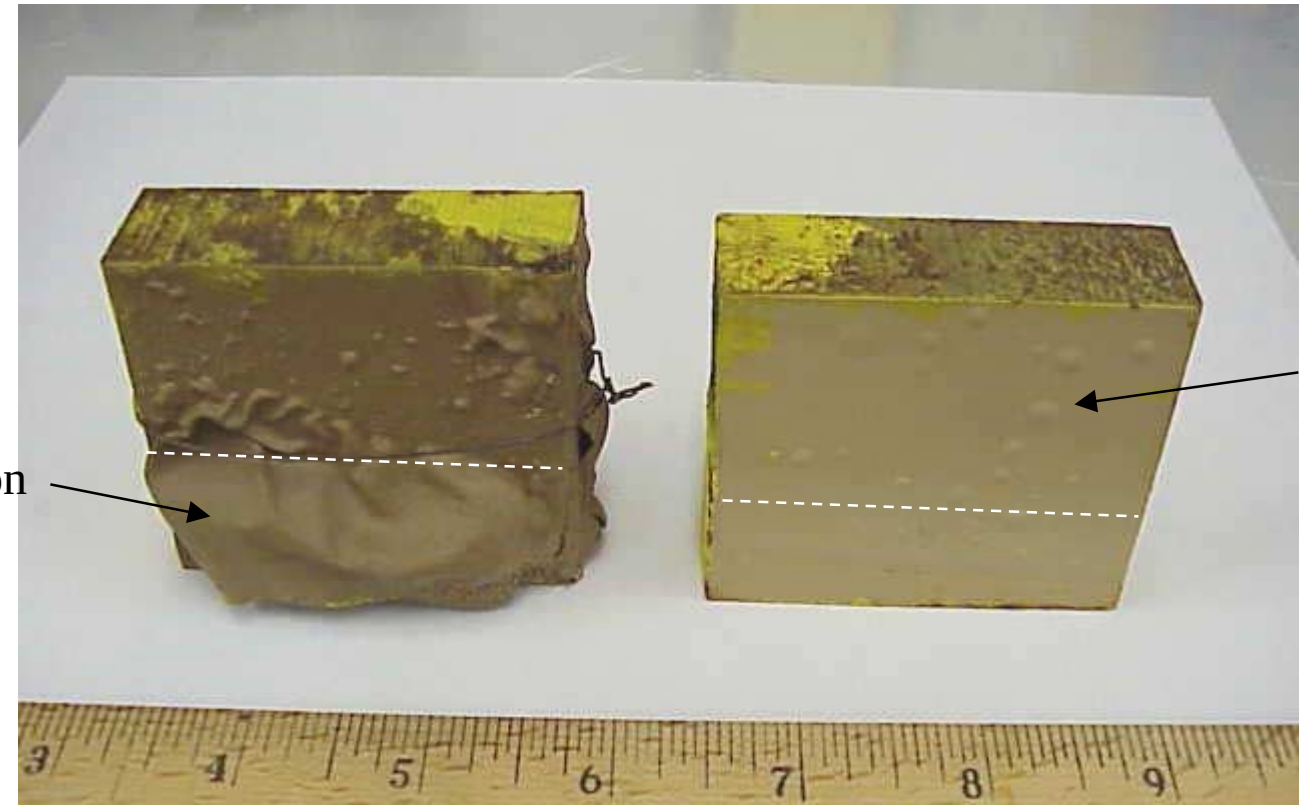
As Received

At 200ºF

At 200ºF after 12 hours

ASTM D3911 DBA Testing of Plant Specimen
Mobil 78-W-300 on Steel Snubber Plate

Large Delamination



Small Blisters

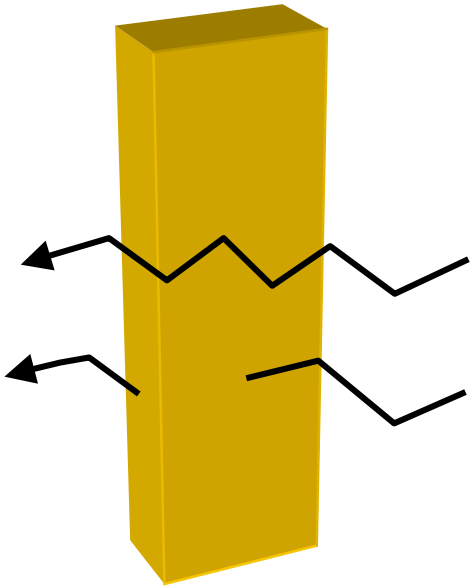
As-received and Irradiated to 10^9 Rad

As-received

Dashed lines indicate water level

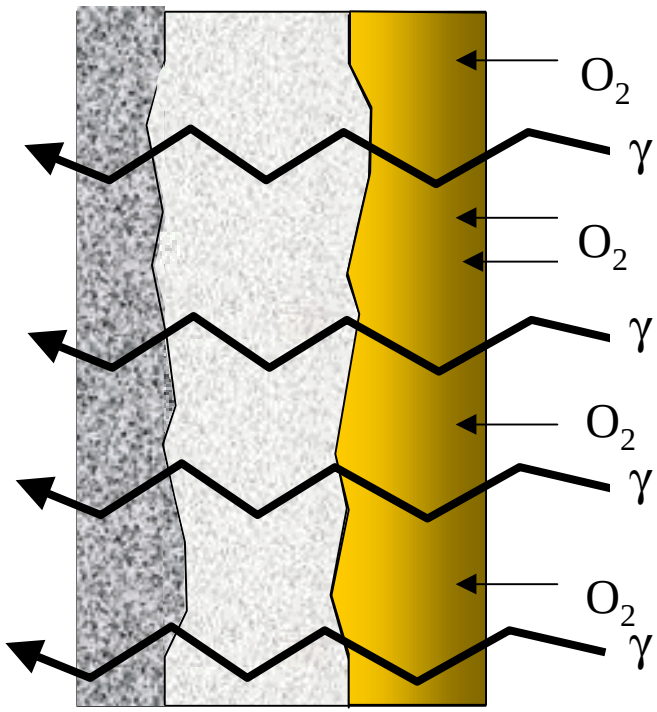
Evaluation of System 2 Results

Specimen Irradiation per ASTM D4082-95

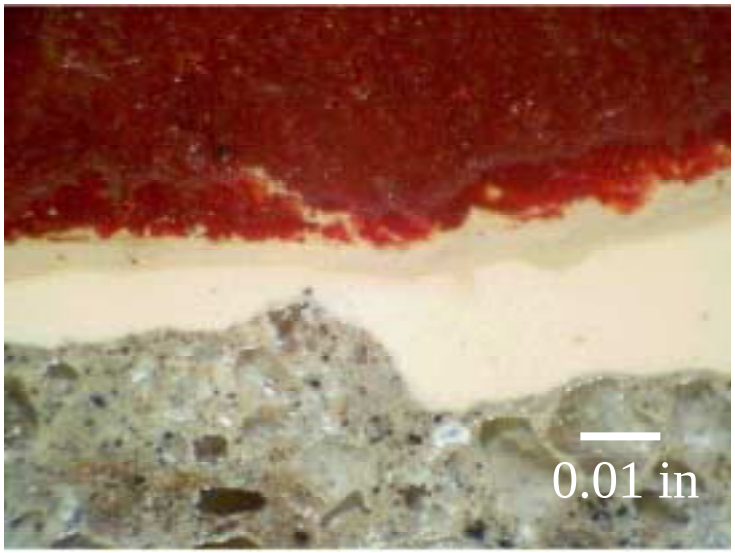


- Coated Concrete Blocks Irradiated in Gamma Cell to $1X10^9$ rads total dose @ $1X10^6$ rads/hour
- 120° F Exposure Temperature

Oxygen Permeation Effects

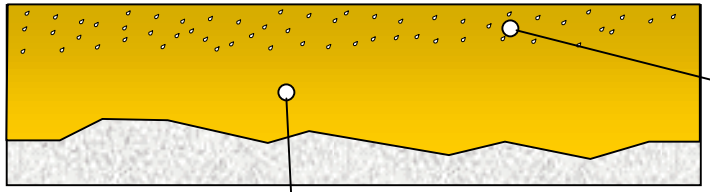


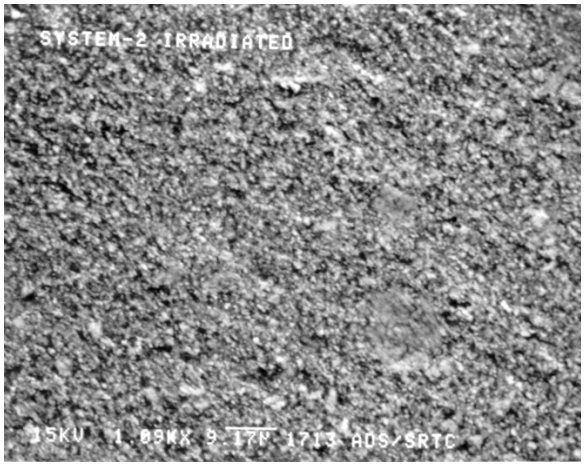
- Gamma irradiation penetrates blocks
- Oxygen permeates partially into topcoat
- Topcoat color is changed near surface
  - Irradiation in argon does not produce topcoat color change



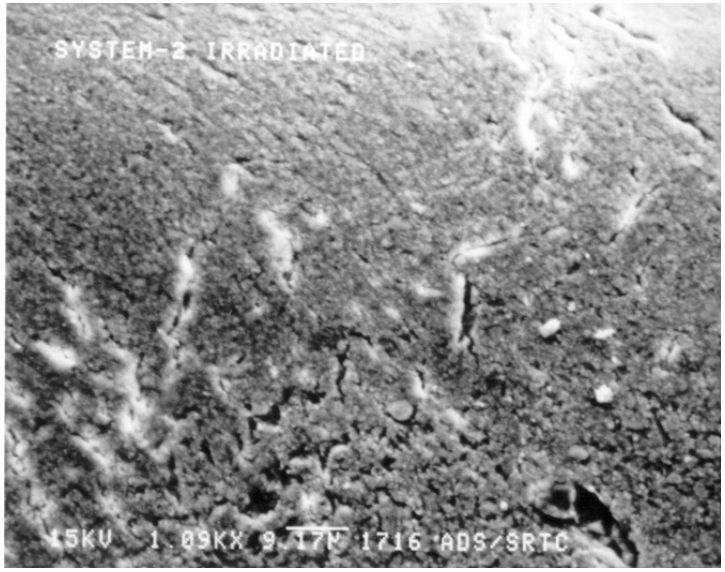
Evidence of Topcoat Damage

- Porosity/Gas pockets formed in topcoat, near surface, as a result of irradiation



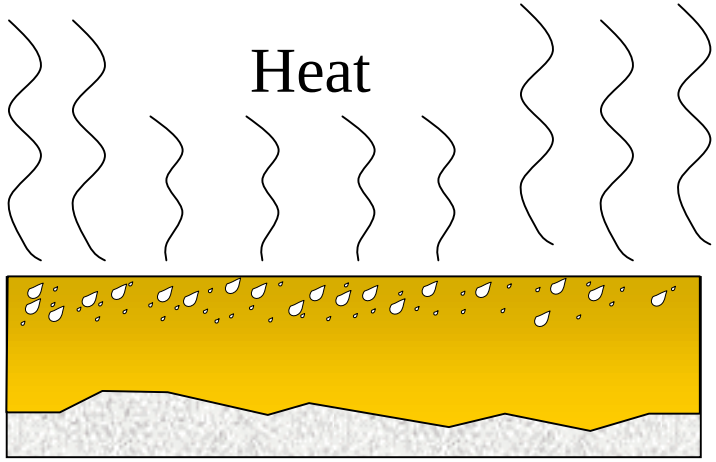


SEM Micrograph Taken in Bulk Topcoat

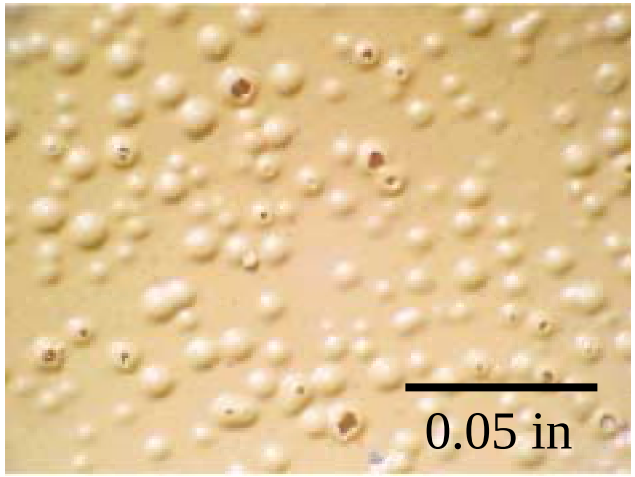


SEM Micrograph Taken Near Topcoat Surface

Topcoat Blister Formation

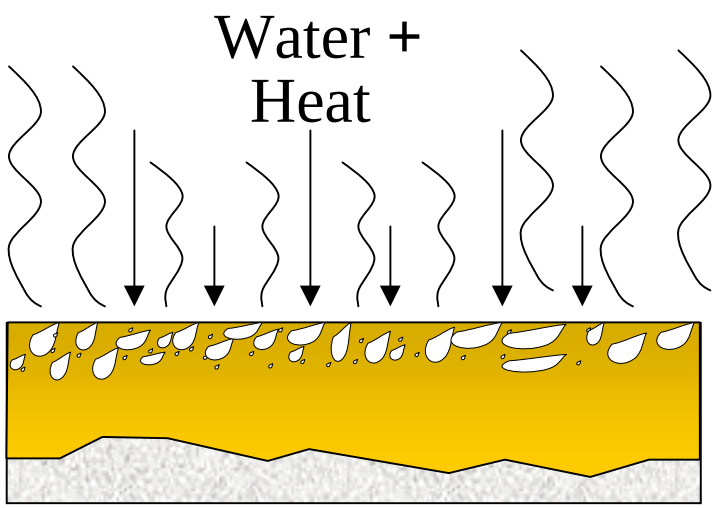


- Coating softens with heat
- Pores expand to form blisters



Topcoat heated to 200° F, dry

Potential Debris Formation

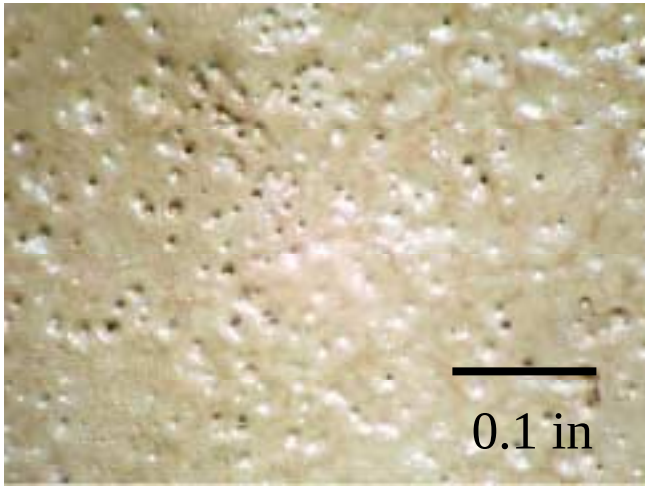


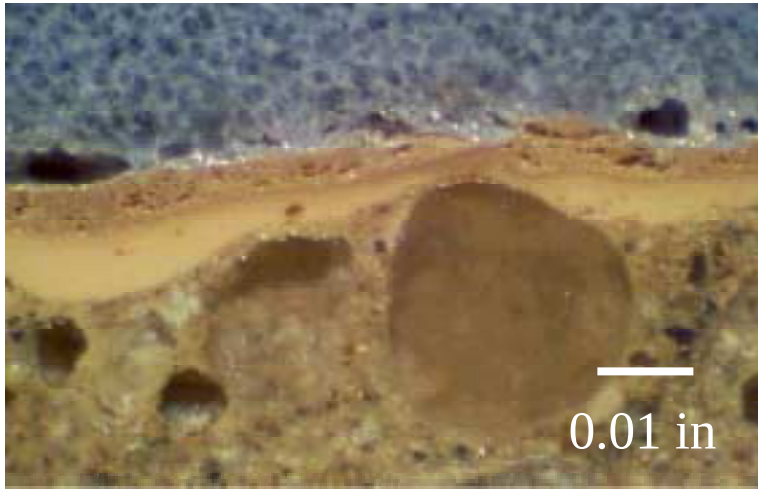
- Water further softens the hot coating
- Blisters enlarge, coalesce, rupture
- Only outer layer of topcoat is lost

Topcoat following immersion in 200° F water

No Significant Debris in ASTM D3911-95 DBA Test

- High temperature (~307° F) during initial steam exposure
- Very soft coating allows gas to escape through pores
- No blisters observed, no perceptible loss of section thickness





Irradiated topcoat following D3911 DBA

Summary of Observations

- Irradiation-aged epoxy coatings effected by temperature, moisture
- Oxygen permeation appears to influence coating damage
- Dose rate appears to influence depth of oxygen damage
- Debris formation dependent on Post-LOCA environment

Industry Coating PIRT Panel

Interactive Effects

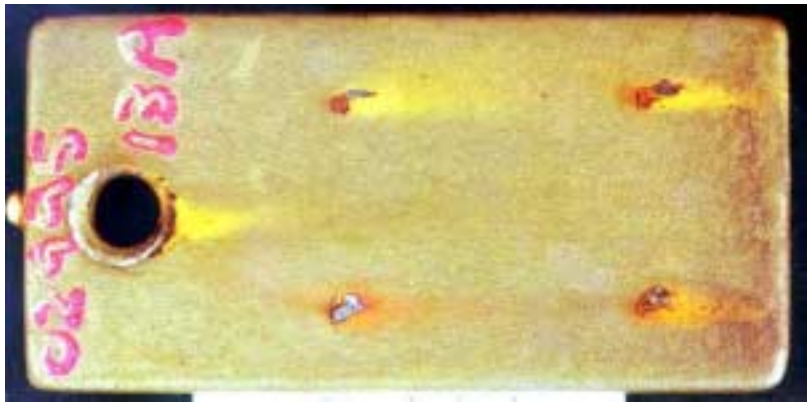
RADIATION EFFECTS ON EPOXY AND EPOXY PHENOLIC TOPCOATS

- Coating irradiation occurs during normal plant operation and post-accident (majority of radiation dose occurs post-accident)
- PIRT Panel ranked effect of radiation exposure on topcoats “low”
- Rationale for ranking cited by PIRT Panel included “industry data” and “DBA testing”

Irradiation Rates at various Radiation facilities

Place	Year	Rate,rad/h	Time to $1*10^9$ rads
ORNL	<1987	$1.8*10^7$	2.3 days
RSI, CA	>1987	$5\text{-}9*10^6$	5-8 days
RSI, TX	>1987	$4\text{-}5*10^6$	8 days
Isomedix	1993	$2*10^6$	21 days

Epoxy, Irradiated to $1x10^9$ rads, after 340 F LOCA



Dose Rate, rads/hour:

- **$2x10^6$ (left top)**
- **$9x10^6$ (right top)**
- **Non-irradiated**

MOISTURE AND TEMPERATURE EFFECTS ON EPOXY AND EPOXY PHENOLIC TOPCOATS

- PWR containments are dry during normal operation
- Saturated containment bulk air moisture conditions are present after initial pressure/temperature “pulse” due to LOCA
- Long-term immersion of containment coatings occurs at lowest containment elevations after formation of post-accident pool

MOISTURE AND TEMPERATURE EFFECTS ON EPOXY AND EPOXY PHENOLIC TOPCOATS (continued)

- PIRT Panel ranked effect of immersion on containment topcoats as “medium” and “high”
- Rationale for ranking included “long term exposure” and “limited industry data”
- PIRT Panel ranked effect of pressure/temperature (expansion/contraction) on topcoats as “high”
- Rationale for ranking included “no industry data available”

OXIDATION EFFECTS ON EPOXY AND EPOXY PHENOLIC TOPCOATS

- Oxidation damage to exterior surface of topcoats apparently occurs synergistically with radiation (based on SRTC experimental results)
- Based on SRTC experimental results to date, topcoat degradation apparently occurs when topcoat is irradiated, oxidized
  - and immersed
  - or exposed to accident pressure/temperature “pulse” and moisture saturated air
- These phenomena previously unknown to PIRT panel

Industry Coating PIRT Panel

Path Forward

APPLICATION OF SRTC DATA

- Input to RES PWR Sump Blockage Research Project
- Review and update testing standards (ASTM D4082, D3911)
- Need for better understanding of synergistic effects of radiation integrated exposure, radiation dose rate, LOCA environments and immersion on topcoats of different formulations