PWR and BWR Source Term – A Perspective and Engineered Solution

"Soluble" Means …. "Soluble + Colloidal"

2018 ISOE/ NATC ALARA Symposium

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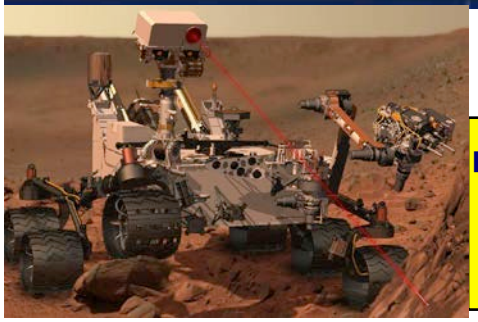
Los Alamos National Laboratory



- US DOE R&D Laboratory for Nuclear Technology
  - **Discover science and technology, where challenges are solved for the Medicine, Space, National security and Nuclear Technology**
  - $4 Billion R&D Annual Budget
  - 118 R&D 100 awards since 1978
- Invented and Patented, Polymer Filtration Technology™
  - Exclusive World-Wide Grant of Licensed Inventions to NPE
  - R&D 100 Award-Polymer Filtration Technology
- **LANL- NASA Mars Curiosity Rover- Powered by Radioisotope Thermoelectric Generator (RTG) produced at LANL**
  - **Chem-Cam Laser Sensor- Developed at LANL**
- (n,p) Energy, Inc. (NPE)
  - (n,p) Energy, Inc.- Single and Sole Licensee of LANL Invention
  - NPE is not a Resin Vendor… We provide a 2 Part Engineered solution

Corrosion Product Formation, Transport and Deposition -- A Dynamic Complex Set of Mechanisms

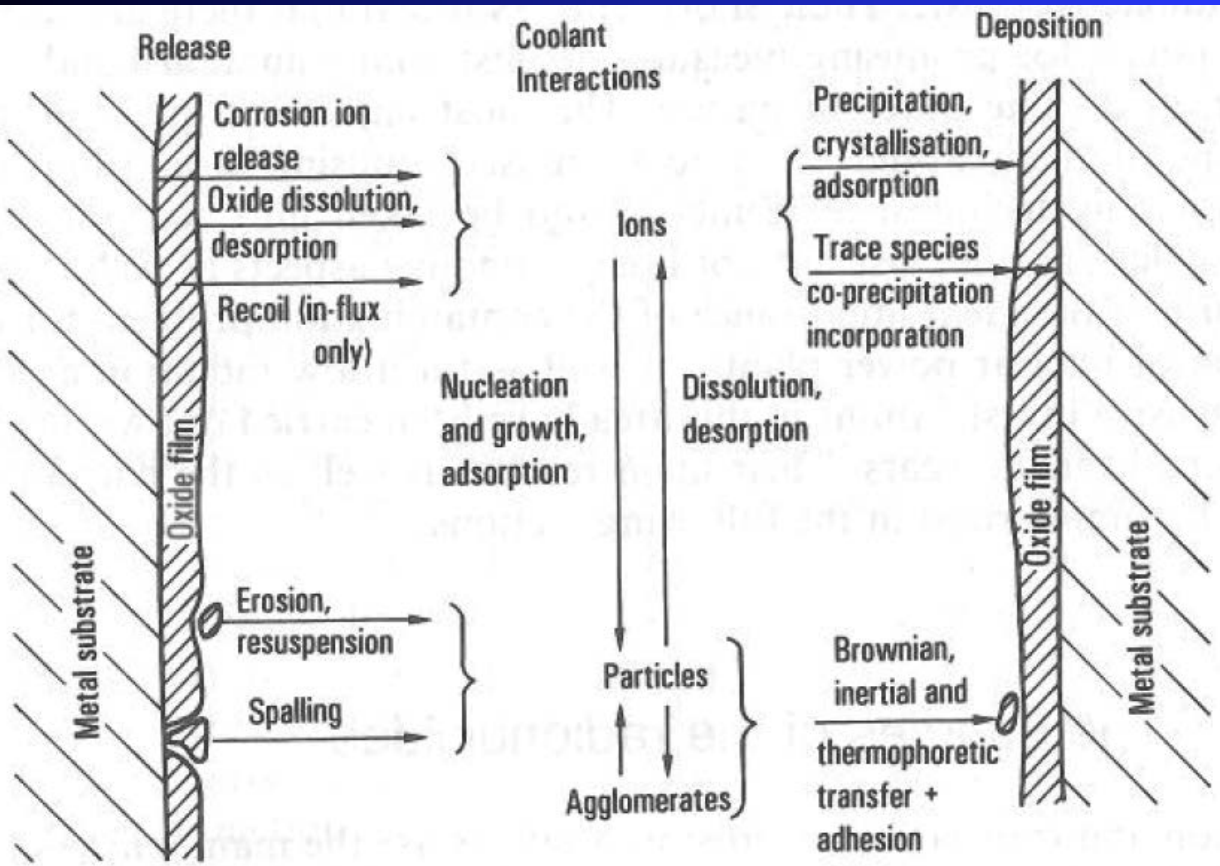


Figure 4.2. PWR Corrosion product, transport, and deposition mechanism (Rodliffe et al, 1987, by courtesy of IAEA)

CRUD

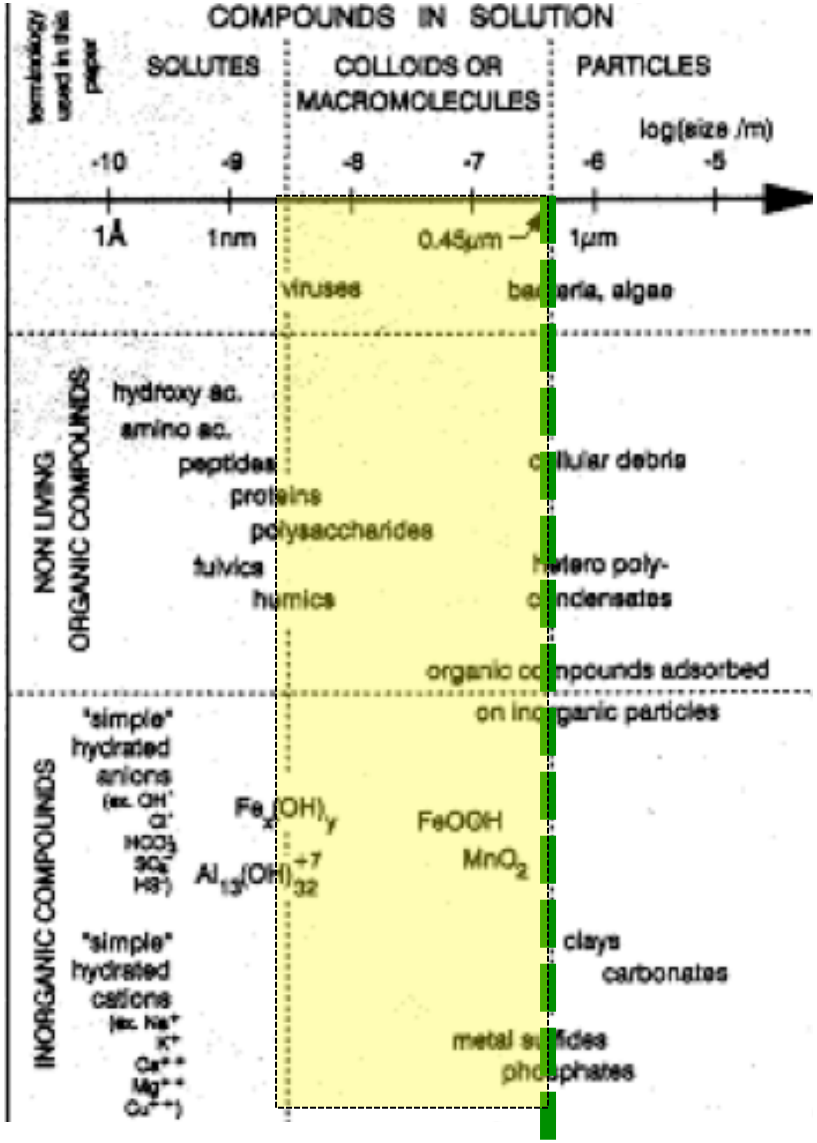
- Corrosion Products Released from System Surfaces
  - Ionic Forms (Soluble)
  - Particles (Insoluble)
    - > 0.1 um and Mechanical Filterable
  - Colloids (Insoluble, Can Agglomerating to Particles Given Time or Chemistry)
    - .001 um < 0.1um
    - Can't optically see them, Need - SEM, TEMS
  - Co-deposited Ions/Colloids/Particles
- Particles and Colloids Deposit on Surfaces by
  - Gravity (big particles) in Low Flow Areas
  - Crud Diffusion and Ion Exchange In Oxide Films
  - Surface Charge Attraction
  - Co-Precipitation of Different Species
  - Precipitation at over-saturation due to boiling

What is a Colloid in NPP?

- **Insoluble – And NOT Mechanically Filterable in Rx Systems**
  - Extremely Fine Insoluble, Electrostatic, Material Suspension
  - Control Rod Reposition at Power:
    - 10,000,000 to 50,000,000 P / Liter (<0.6 um)
  - Dominantly… Iron Species (Fe) During Shutdown
    - 50,000 X More Fe than Co-60 in BWR RC
    - 5,000 X More Fe than Co-60 in PWR RCS
    - Think Tiny Clusters of Elements Together e.g. Fe, O, H
    - Iron Oxyanions Co-Incorporate Co-58, Co-60
  - Not Much Weight/Mass….Settle Times is in Years

Particle Size (µm)	RHR/SDC Cooling Pipe ID 12 in, t to 25% settling	RHR/SDC Cooling Pipe ID 12 in, t to 50% settling	RHR/SDC Cooling Pipe ID 12 in, t to 100% Settling
10	8 min	16 min	33 min
1	15 hr	27 hr	55 hr
0.1	57 days	115 days	230 days
0.01	1.5 yr	3.2 yr	6.3 years

Limitations of Chemistry Measurements
Soluble: Is Really Soluble + Colloidal



Particles Partition in Fluids
Colloids Can Also Partition in Fluids

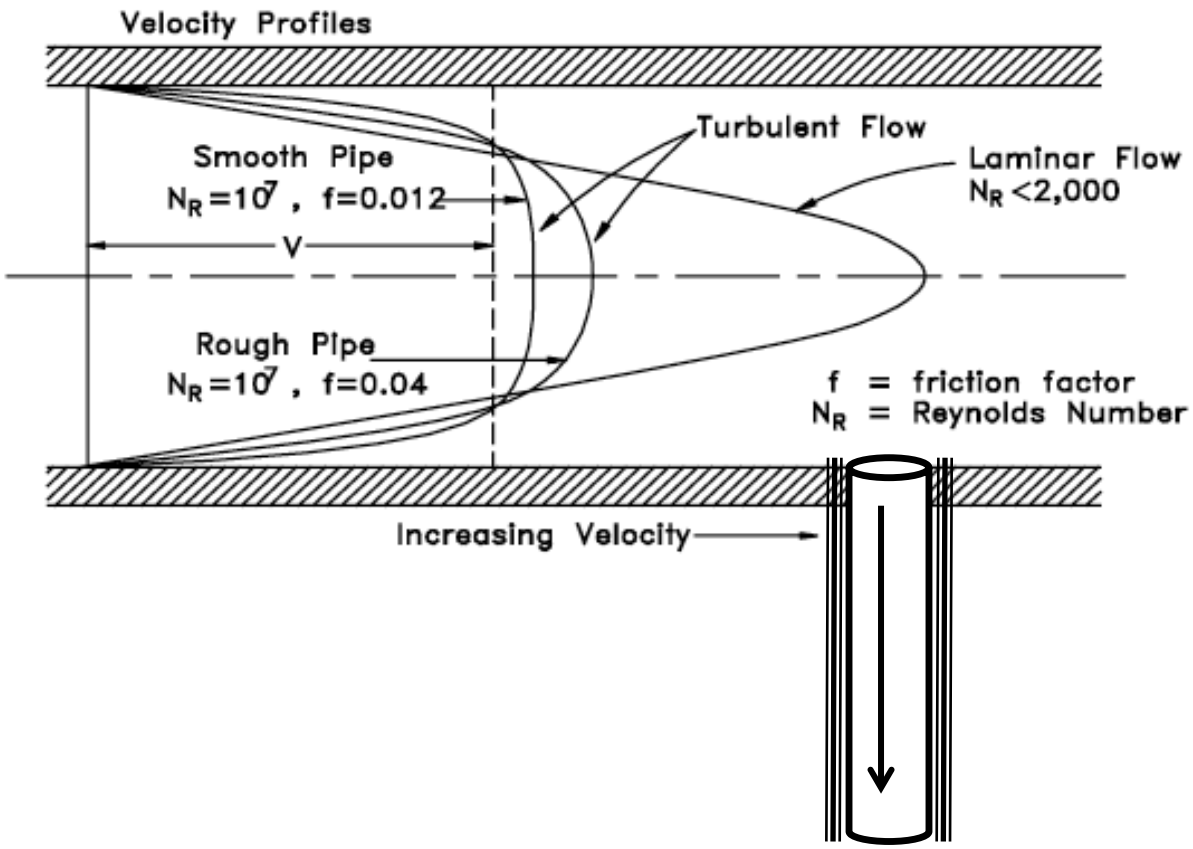
- Not all coolant particles travel at the same velocity within RCS Pipe.
  - Laminar Flow- Parabolic Big particles towards center
  - Turbulent Flow- Fairly Distributed across pipe
  - Pipe wall Velocity is essentially zero and Velocity increases the further from the wall
- This is why deposition is different in Different Locations of RCS
  - Reynolds Number is Dimensionless number comprised of physical characteristics of flow, e.g.fluid mass density, gravity, fluid viscosity, average velocity and diameter of pipe

$$N_R = \rho \, v \, D / \mu \, g_c$$

Particles Partition in Pipe Flow

Big Particles to Centerline Pipe

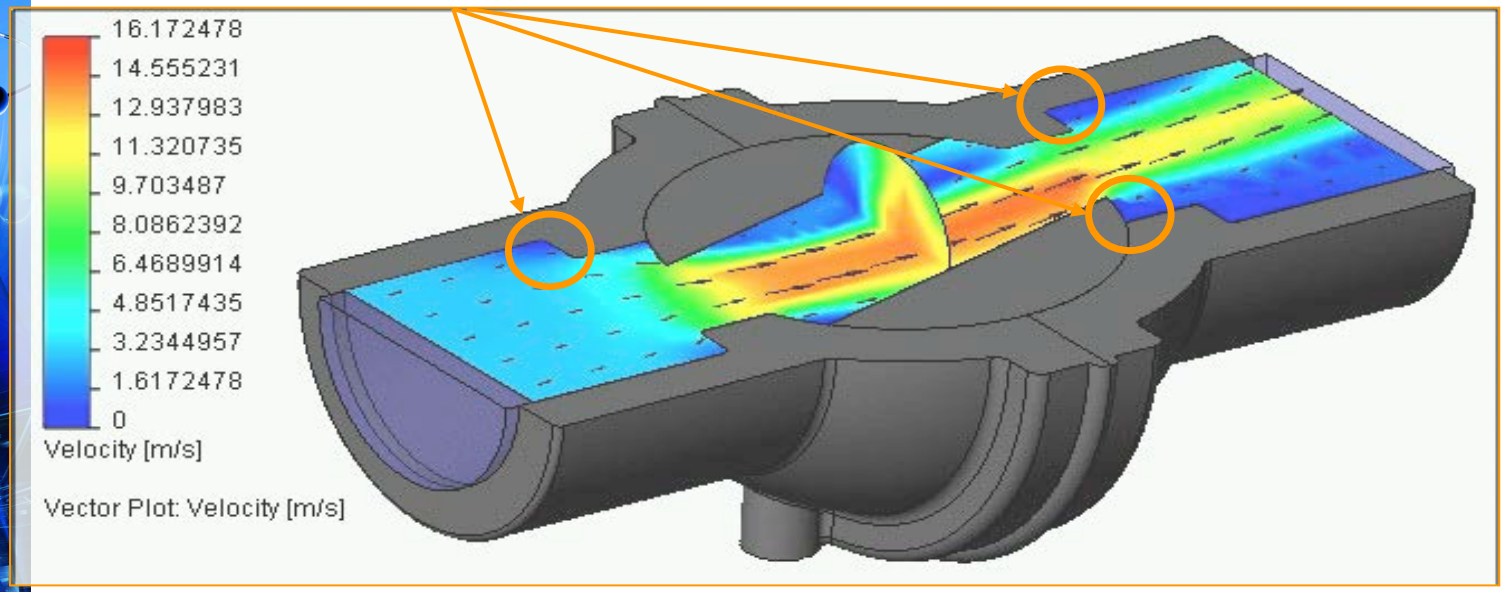
Pipe wall velocity Approaches 0



To Rx Coolant
Purification System
e.g. CVCS, RWCU

Ball Valve
X-Sectional Look at Flow Distribution
Computational Fluid Dynamic

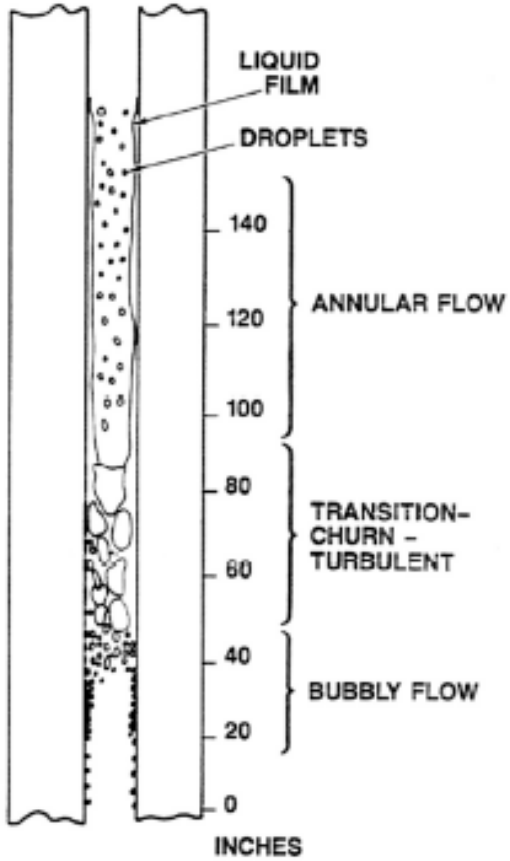
- FLUENT CFD Code Analysis
- Deposition
  - Zero Flow Areas in Darker Blue
  - Highest Flow Areas in Red

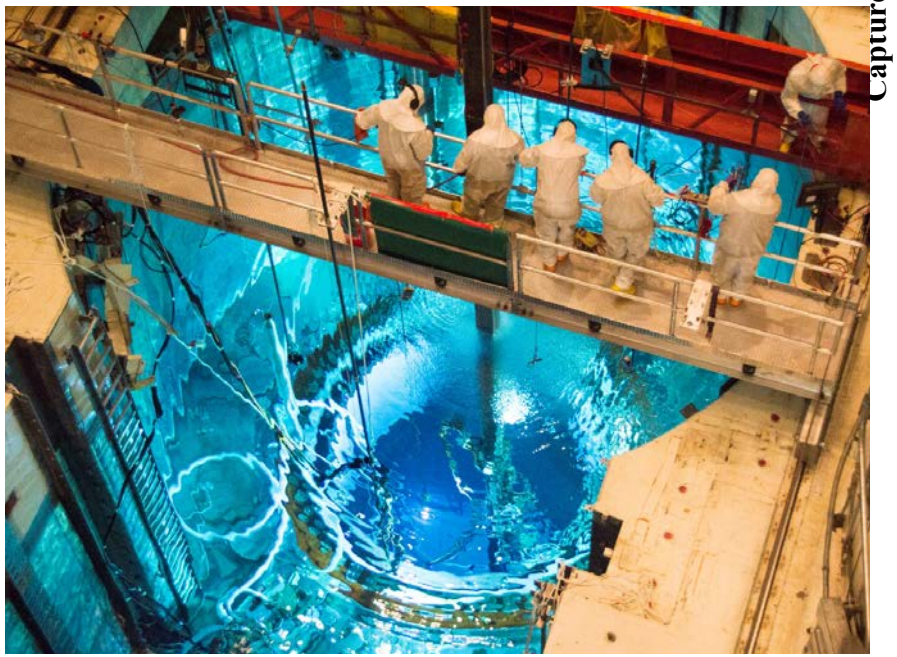


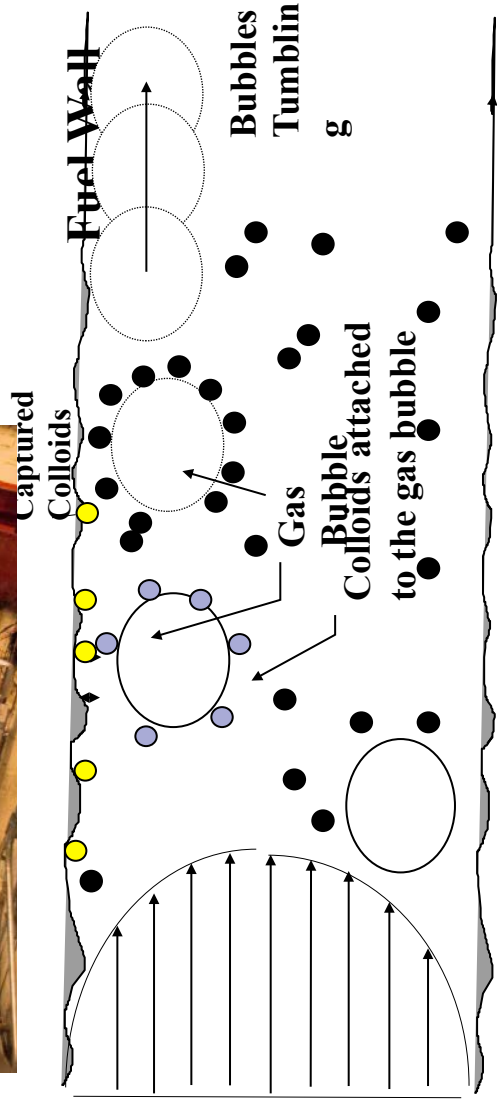
Special Colloid Transport: Partitioning

BWR Fuel Channel Boiling Regime

- Coolant Transport Ex-Core
- Gas- Colloid Transport into RVH, CRDs, Cavity Surface
  - Partitions colloids up into RVH and CRDs and Cavity
- Mechanism Gas Phase Transport
  - Peroxide Injection
  - Fuel Boiling



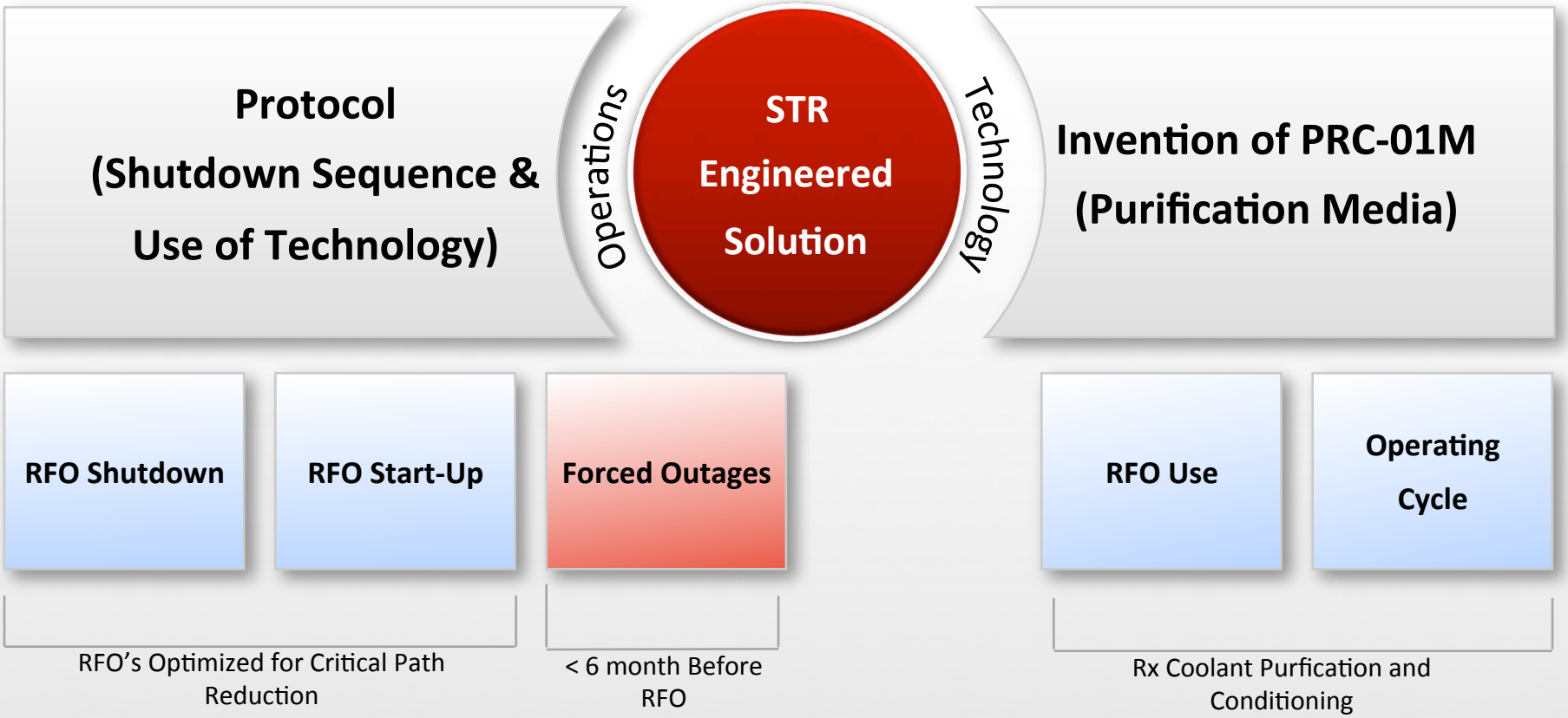




Reactor Cavity
and Work Cavity
Platform

Source Term Reduction: Two Part Solution BWR & PWR

Optimization of Shutdown Methods to Full Enable Technology



What Was the Innovation?

Coolant Purification Media, Unique Functions

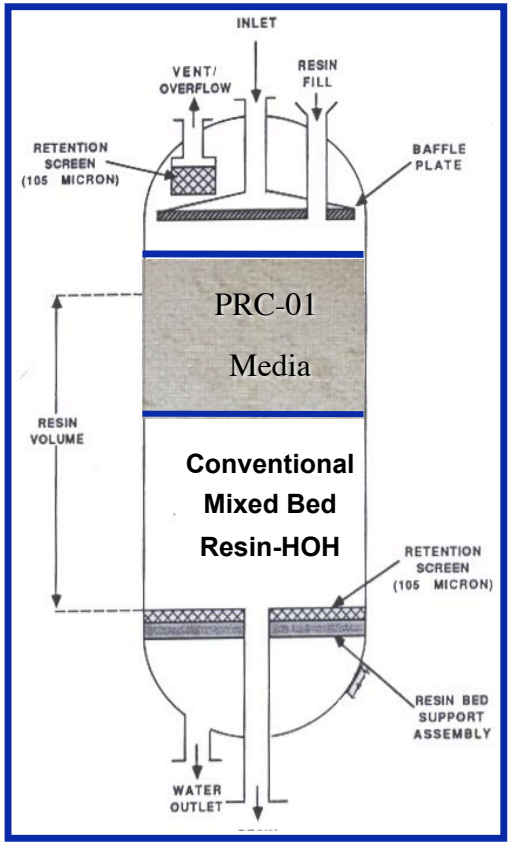
Los Alamos National Laboratory

- Based on Technology from LANL, Department of Energy
  - R&D Effort: Took 20 yrs and $20 M
  - New Compositions of Matter, New Polymers
  - Technology Used in LANL Nuclear Weapon Pit Facilities Separation of Pu and Am
  - Intellectual Property Protected
- Looks Like an Ion Exchange Resin, Bead or Powdered
  - Integrates into Existing Plant Purification Systems
  - RWCU, SFP, Suppression Pool, CPS
  - CVCS Demin
- Works Like BOTH:
  - Ion Exchanger (sol) +
  - Electrostatic Nano-Hair Particle Filter (colloid)

How is PRC-01M Bead, PRC-2 Powdered Used?

Existing Plant Systems CVCS, SFP, RWCU, CPS, FPC

- PWR: PRC-01 (bead) or BWR: PRC-2 (powdered)
- Existing Plant Equipment



PWR/BWR
Deep Bed Vessel

PWR: Uses CVCS Demineralizer Vessel

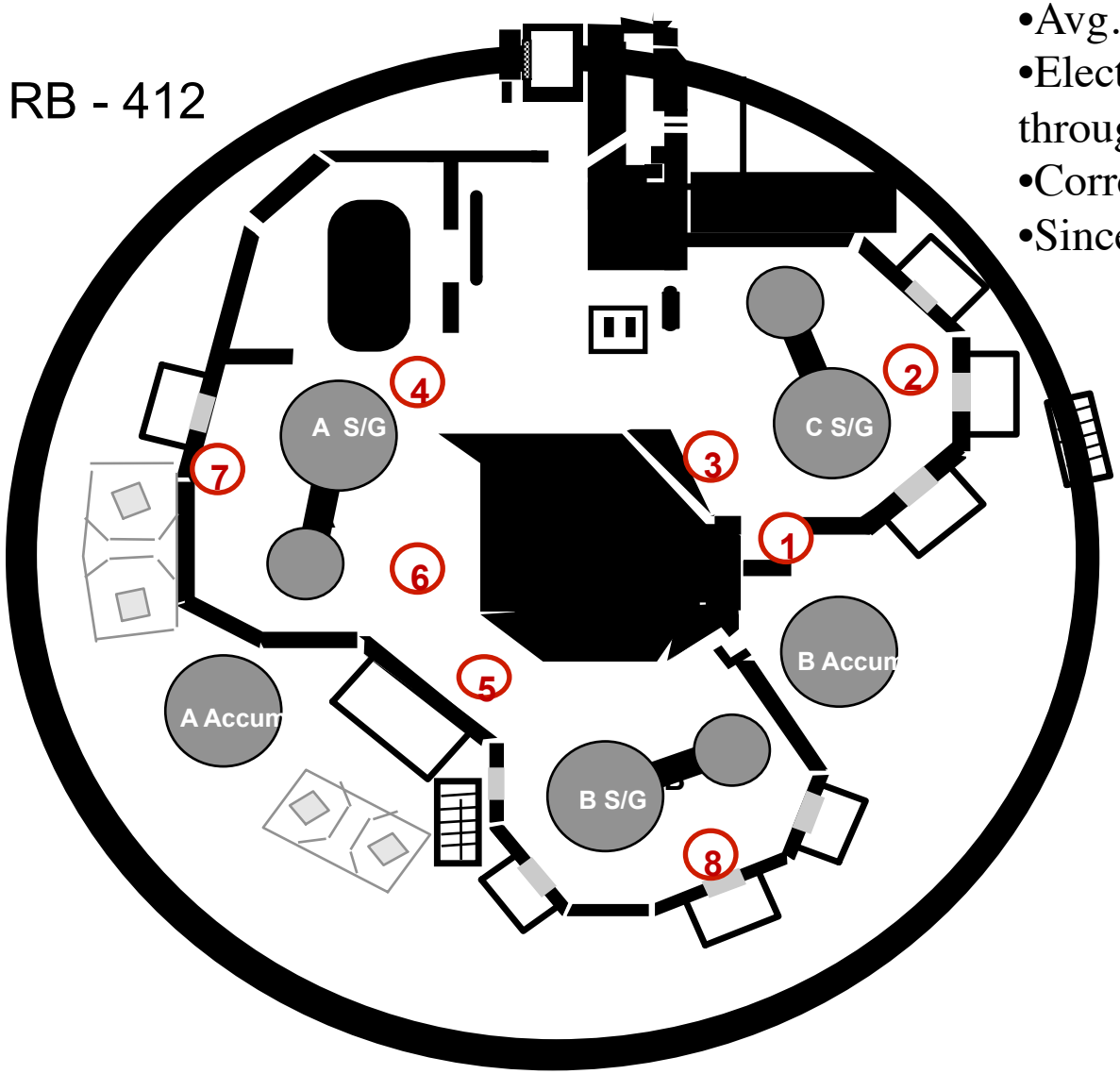
- Both: Spent Fuel Pool
  - Submerged Demin
- BWR: Filter/ Demineralizers
  - RWCU
  - FPC
  - Suppression Pool

BWR
Precoat Filter/Demin

PWRs: Does Transporting CRUD, Curies and Dose Rates Decline??

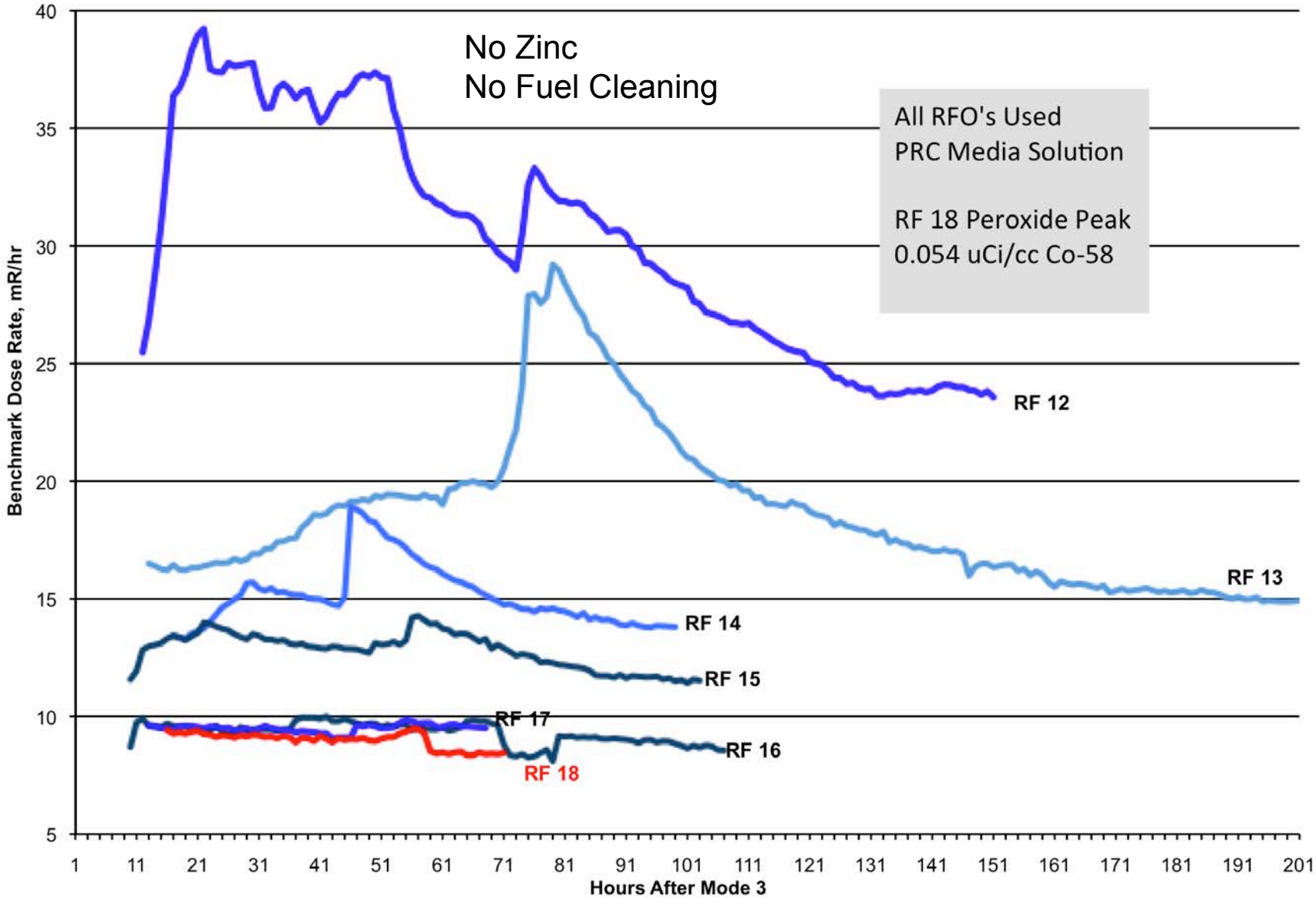
- High pH 7.2 to 7.4 ?
- Low pH 6.9 Modified ?
- Non Zinc Injection Plants?
- Zinc Injection Plants?
- Failed Fuel Cycles?
- High Duty Cores?
- Low Duty Cores?
- B&W Units ?
- W Units ?
- CE Units ?

VC Summer Benchmark Dose Rate Data for Outage Dose Performance

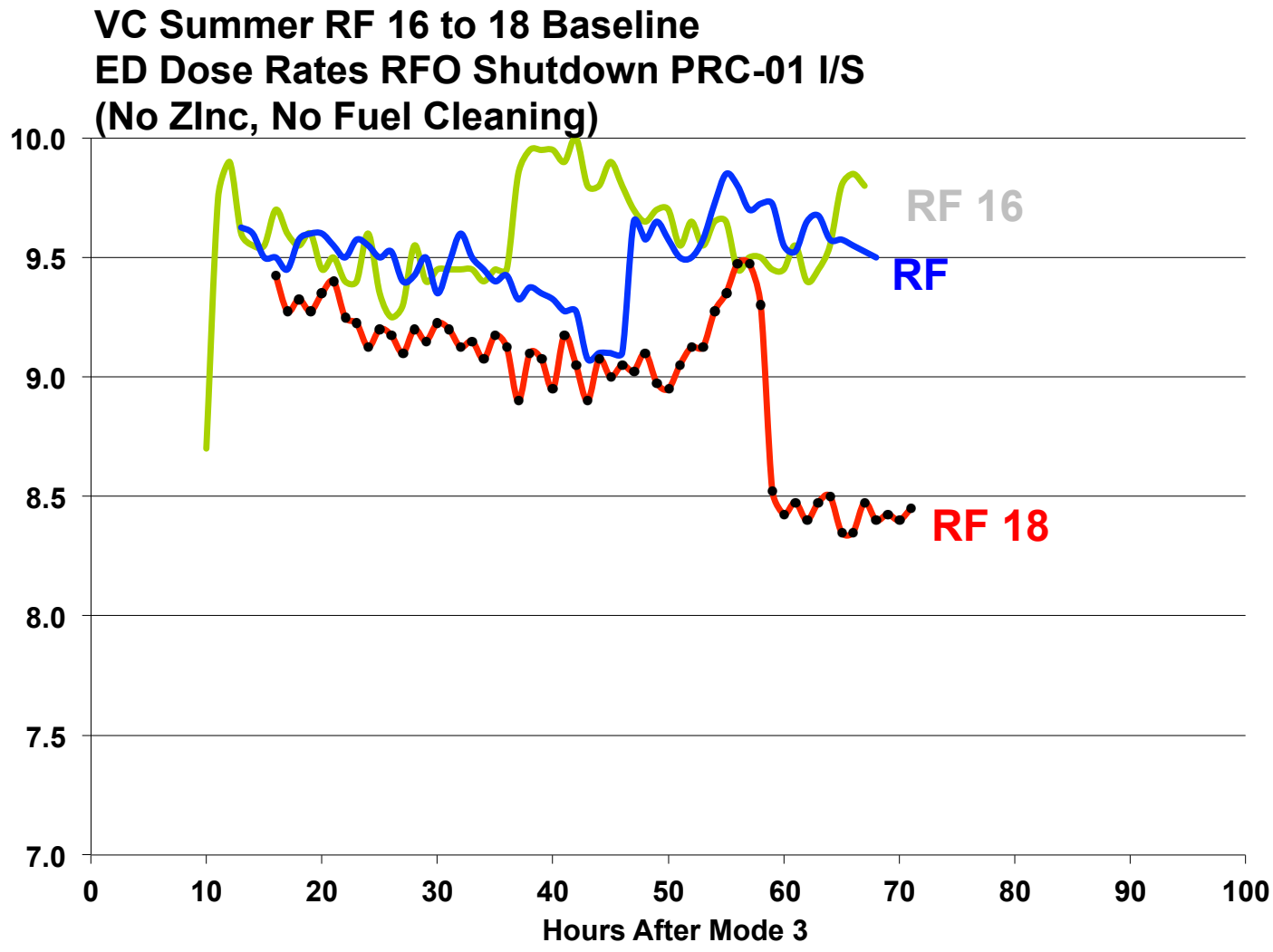


- Avg. of 8 general area dose rates
- Electronic Dosimeters placed throughout Containment
- Correlates to total outage dose
- Since RF10 to 22

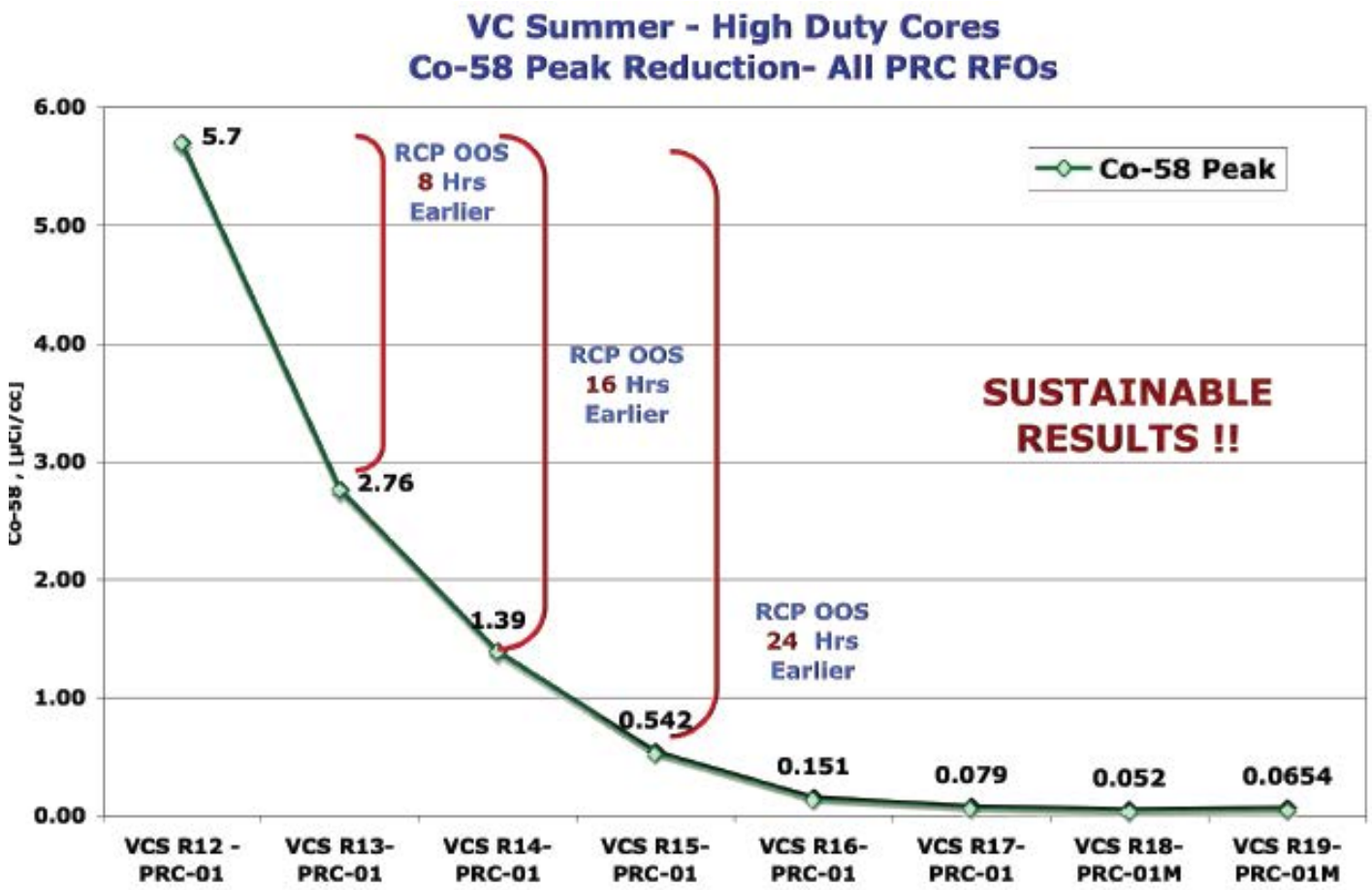
VC Summer RF 12 to RF 18 History of Benchmark Dose Rates During Cooldown



VC Summer RFO 16, 17, 18
Baseline Dose Rates During Shutdown



VC Summer- Impact on Critical Path as Source Term Declines



R12 had 1 peak in AR 2.42 and a second at FO2 3.32 totalling 5.7 uCi/cc.

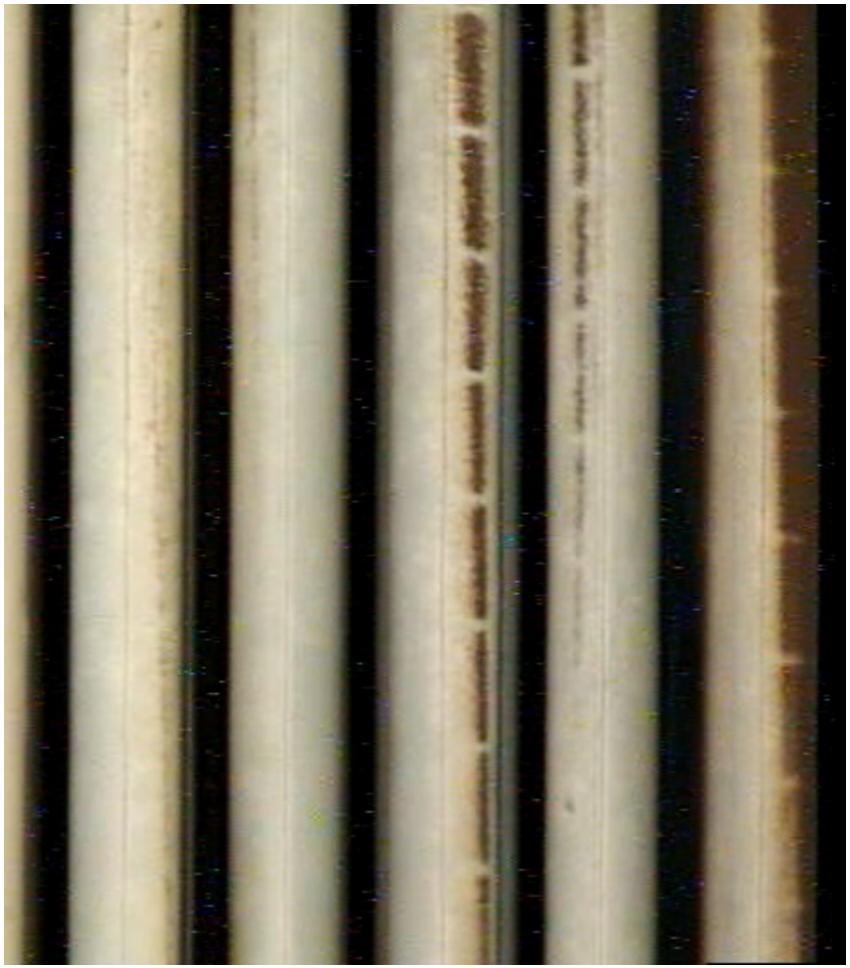
VC Summer Impact of Reducing Core Crud with NPE/PRC-01 Solution ONLY --- No Ultra-Sonic Fuel Cleaning – No Zinc Inj

2003 Highest Power Zone Cycle 14 (grid 6)

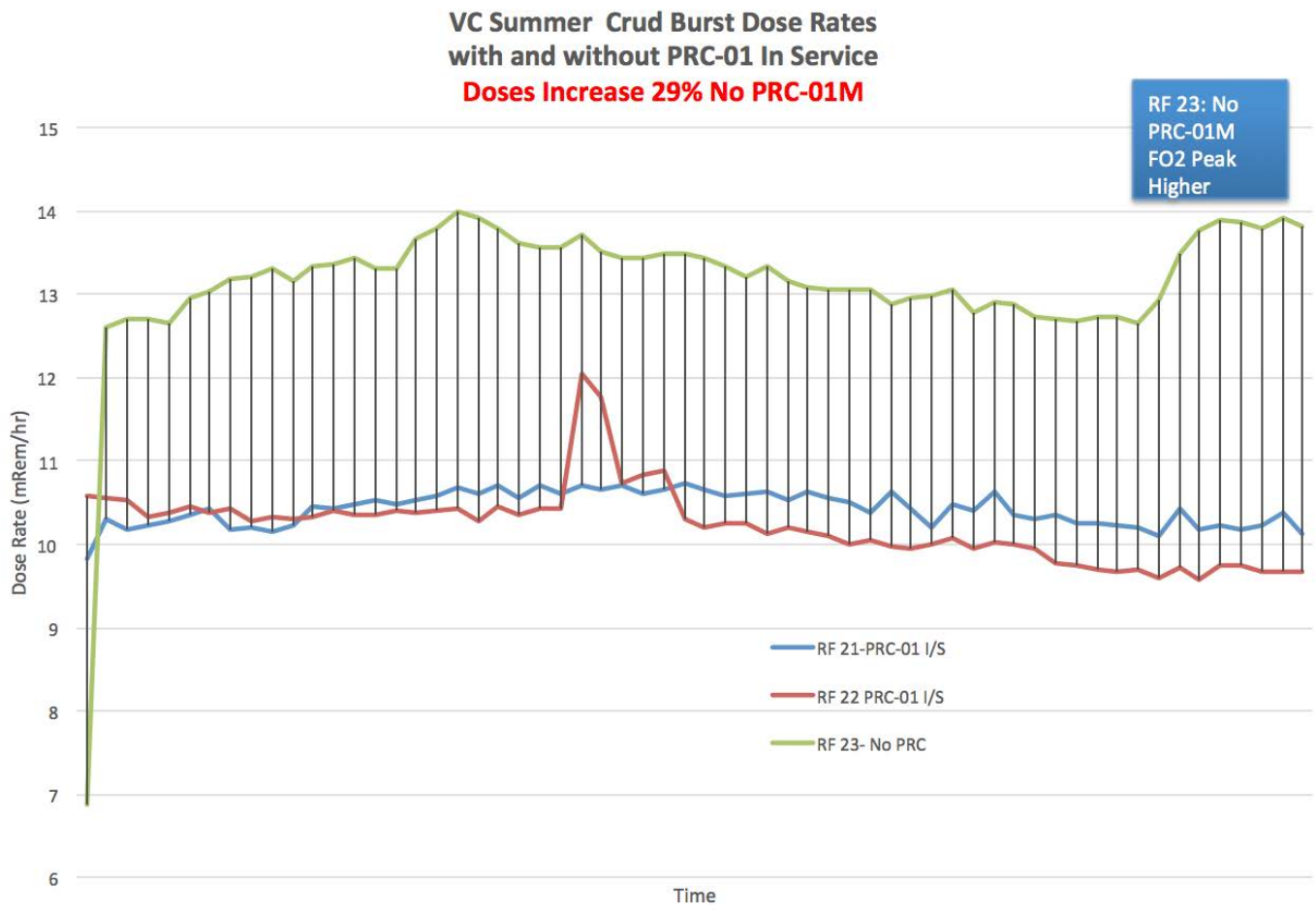
3rd RFO with NPE/PRC-01 Solution

2006 Highest Power Zone Cycle 16 (S33)

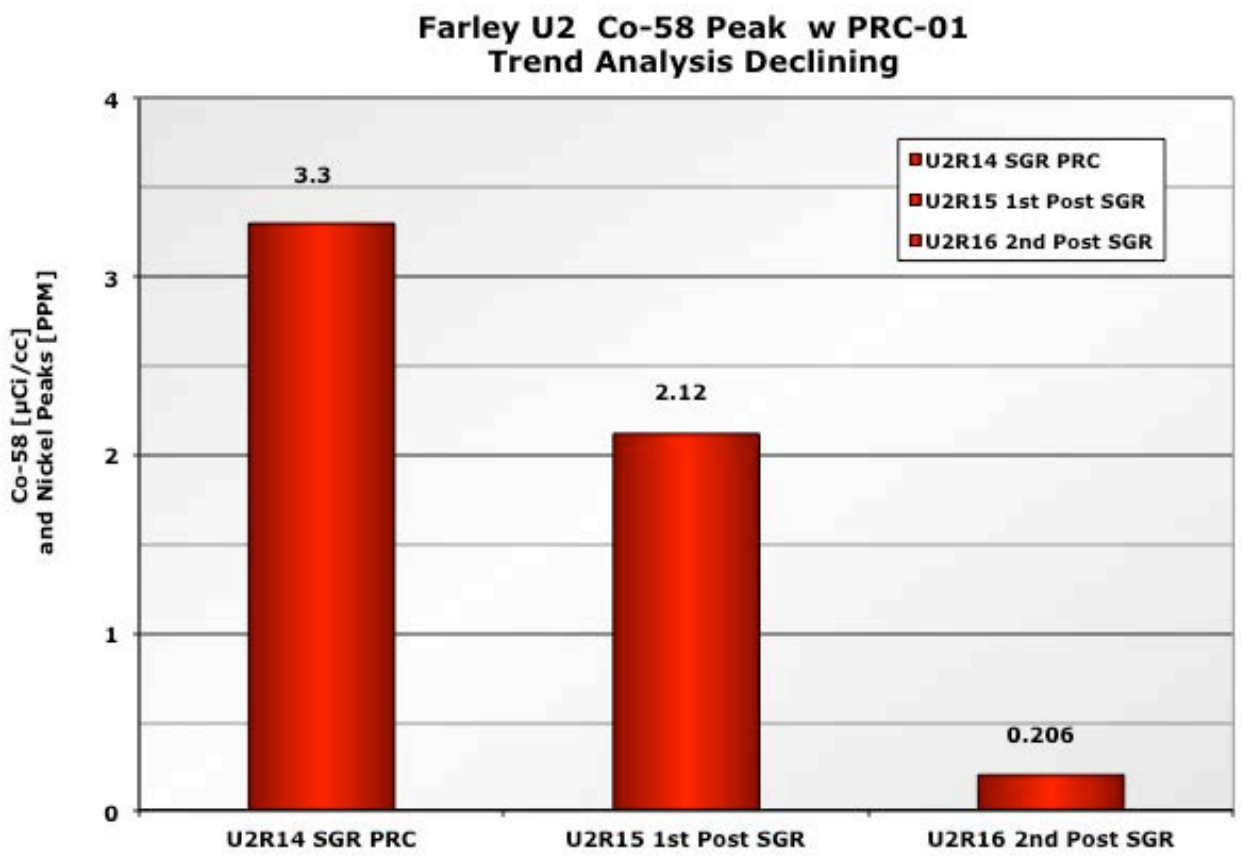
After 6th RFO with NPE/PRC-01



VC Summer: Suspended Using PRC-01 R22, R23 Result: Increased Dose Rate 24%- 29%



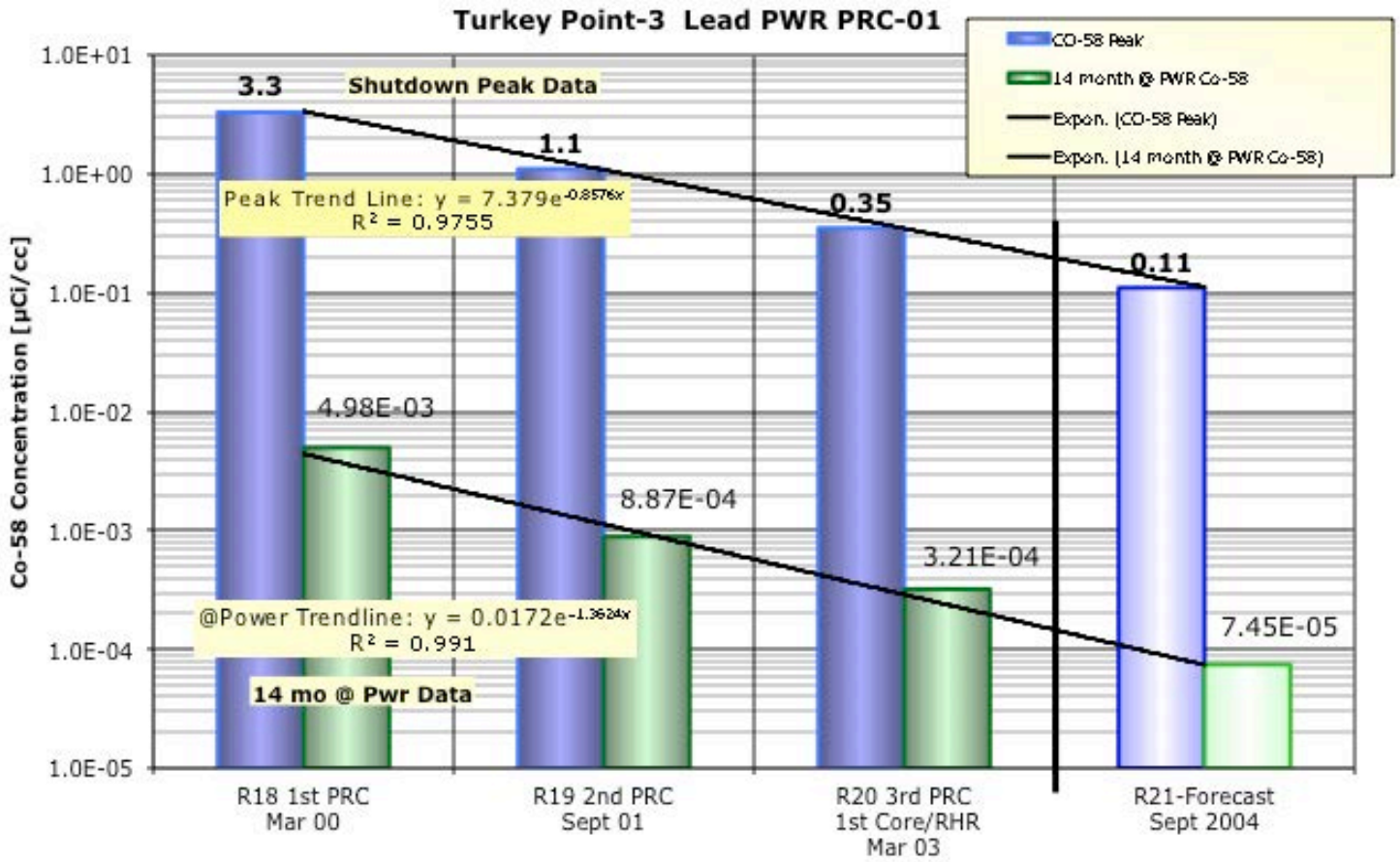
NPE/PRC-01 Impact on Declining Peak Co-58 Farley-2 (W 3L, Post SGR) Zn Inj



Note: PRC-01 used for U2R14 SGR outage.

Rev 2

NPE/PRC-01 Impact on Declining Peak Co-58 Turkey Point-3 Lead PRC Rx (W 3L, old SG) No Zn

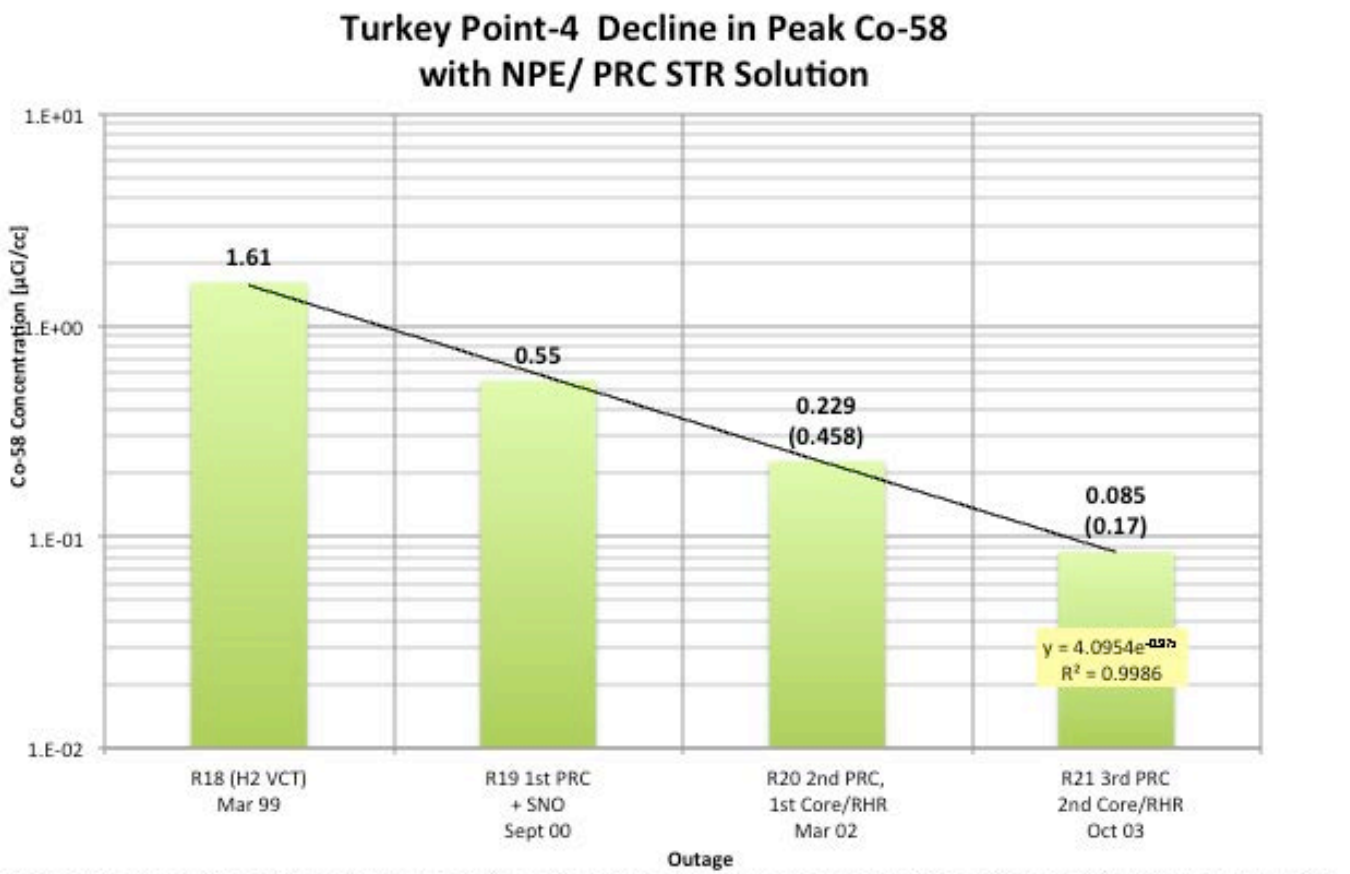


Note: Peak value is adjusted for active volume at time of peak. For example, R20 peak 0.7 µCi/cc actual with No RCPS, which is equivalent 0.35 with RCPS (factor of 2 dilution) R18, R19 full RCS system crud burst, R20 Core/RHR only No RCPs running.

Forecast R21 March 2004: 0.11 µCi/cc Full RCS, or 0.22 µCi/cc Core/RHR Only

Rev 2

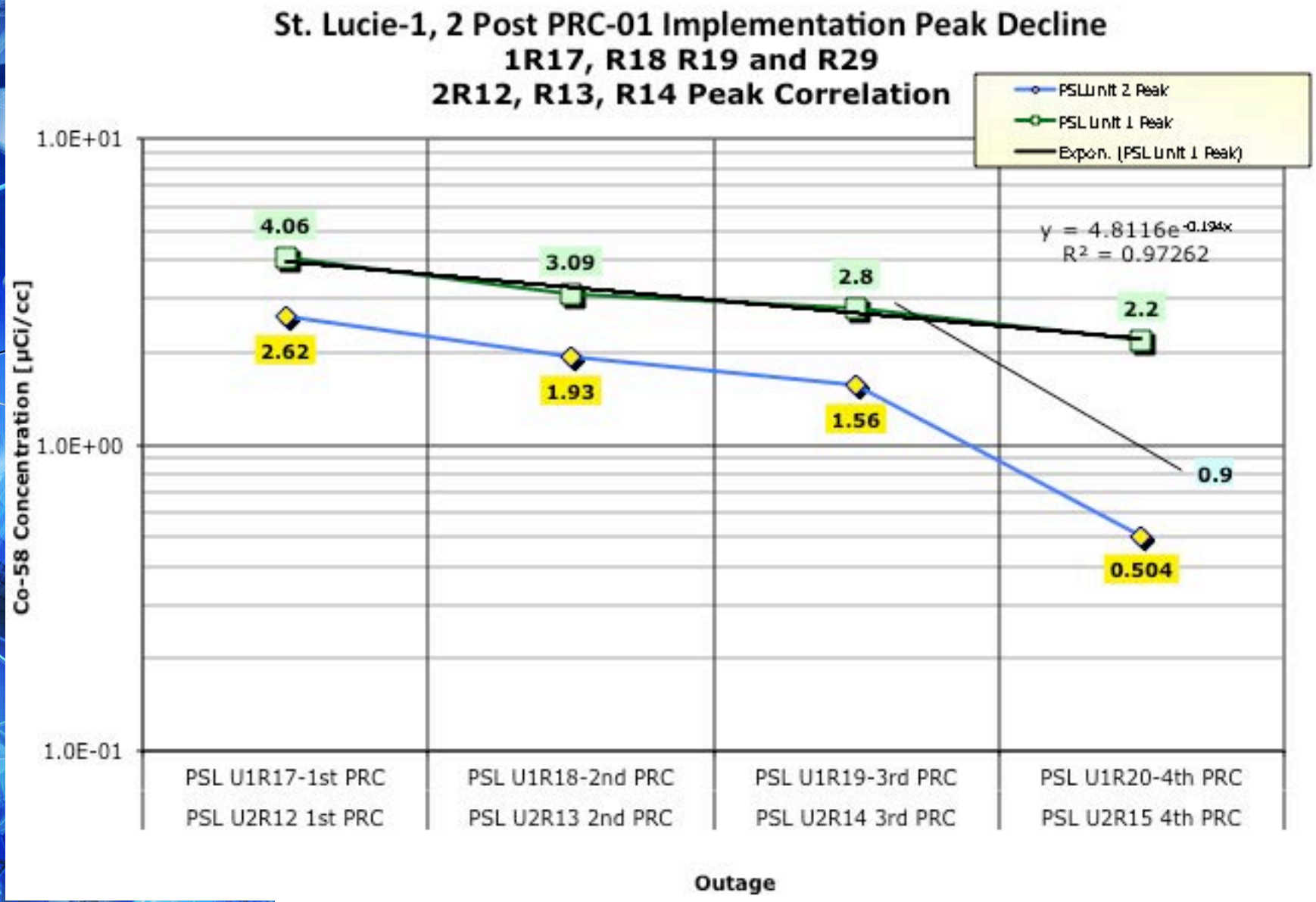
NPE/PRC-01 Impact on Declining Peak Co-58 Turkey Point-4 Lead PRC Rx (W 3L, old 690 SG) No Zn



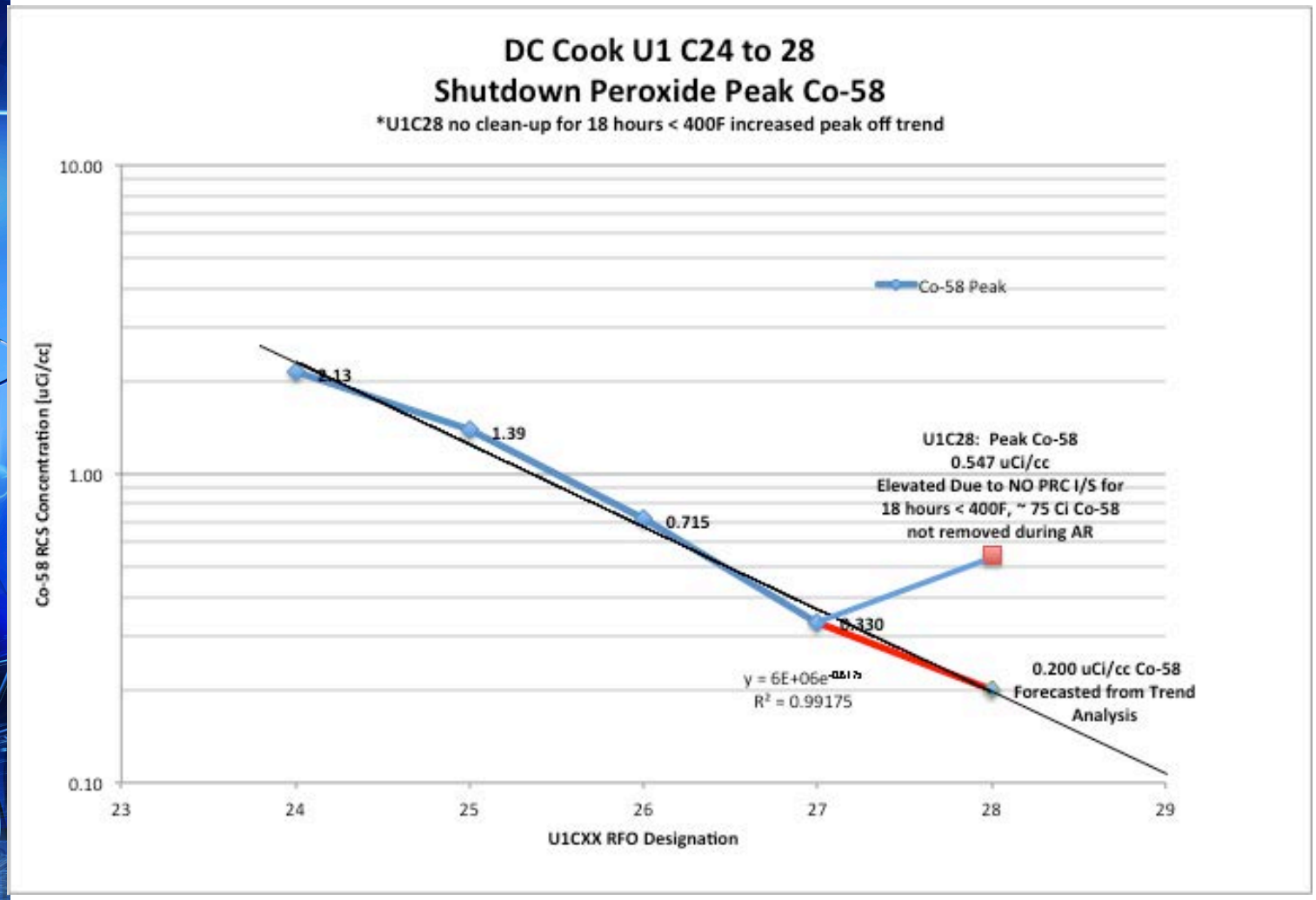
Note: Peak value is adjusted for active volume at time of controlled crud burst peak. For example, R21 peak 0.458 µCi/cc actual. R21 plot peak adjusted for reduced volume in Core/RHR adjusted =0.227 µCi/cc Co-58 to permit comparison with full RCS crud burst in R18 and R19.

Forecast R22 March 2005: 0.085 µCi/cc Full RCS, or 0.17 µCi/cc Core/RHR Only

NPE/PRC-01 Impact on Declining Peak Co-58 St. Lucie Unit 1 and Unit 2 (CE Design, Old SG)

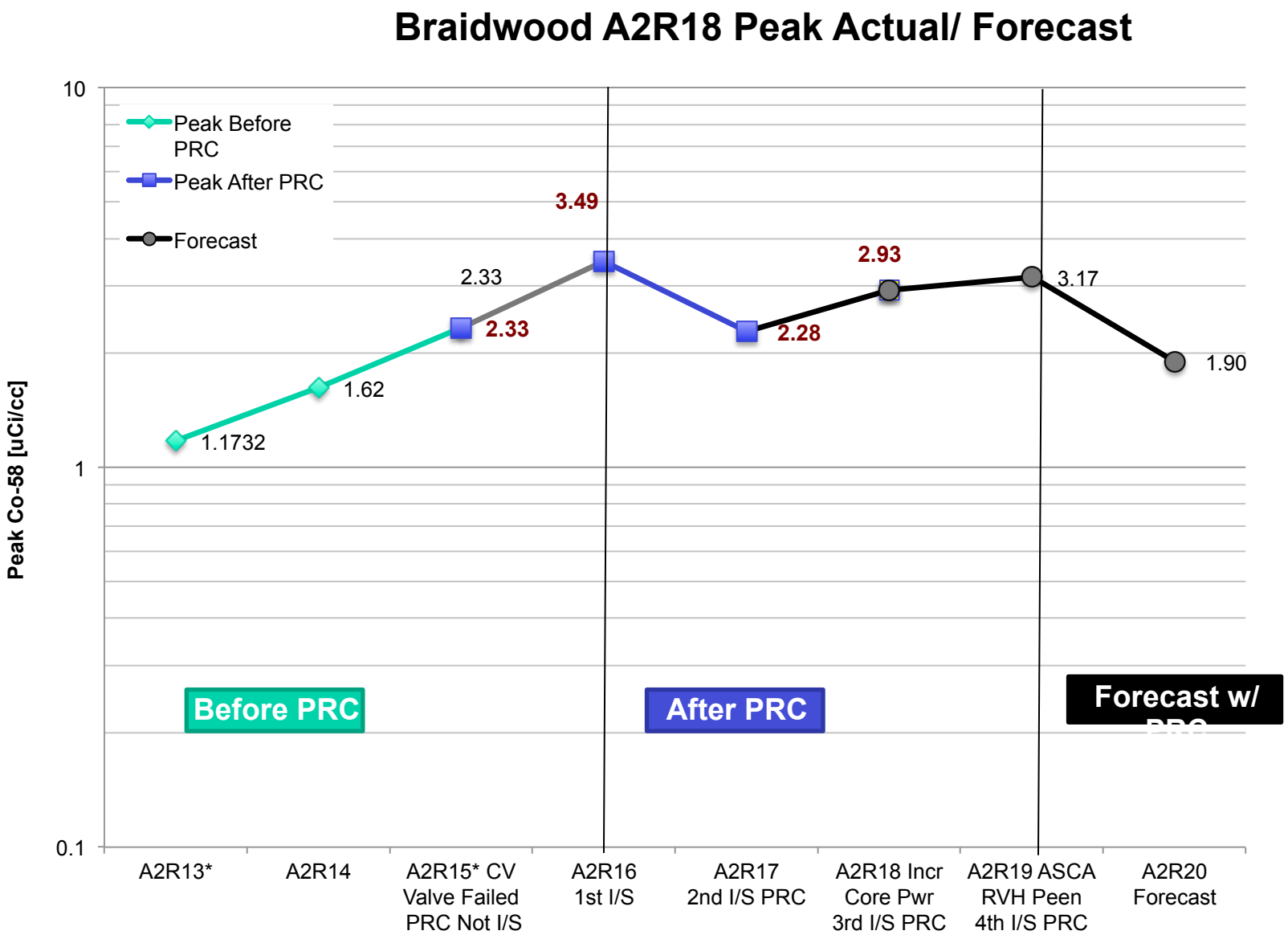


NPE/PRC-01M Impact on Declining Peak Co-58
DC Cook-1 Ice Condenser (W 4 Loop, I-690 SG) No Zn



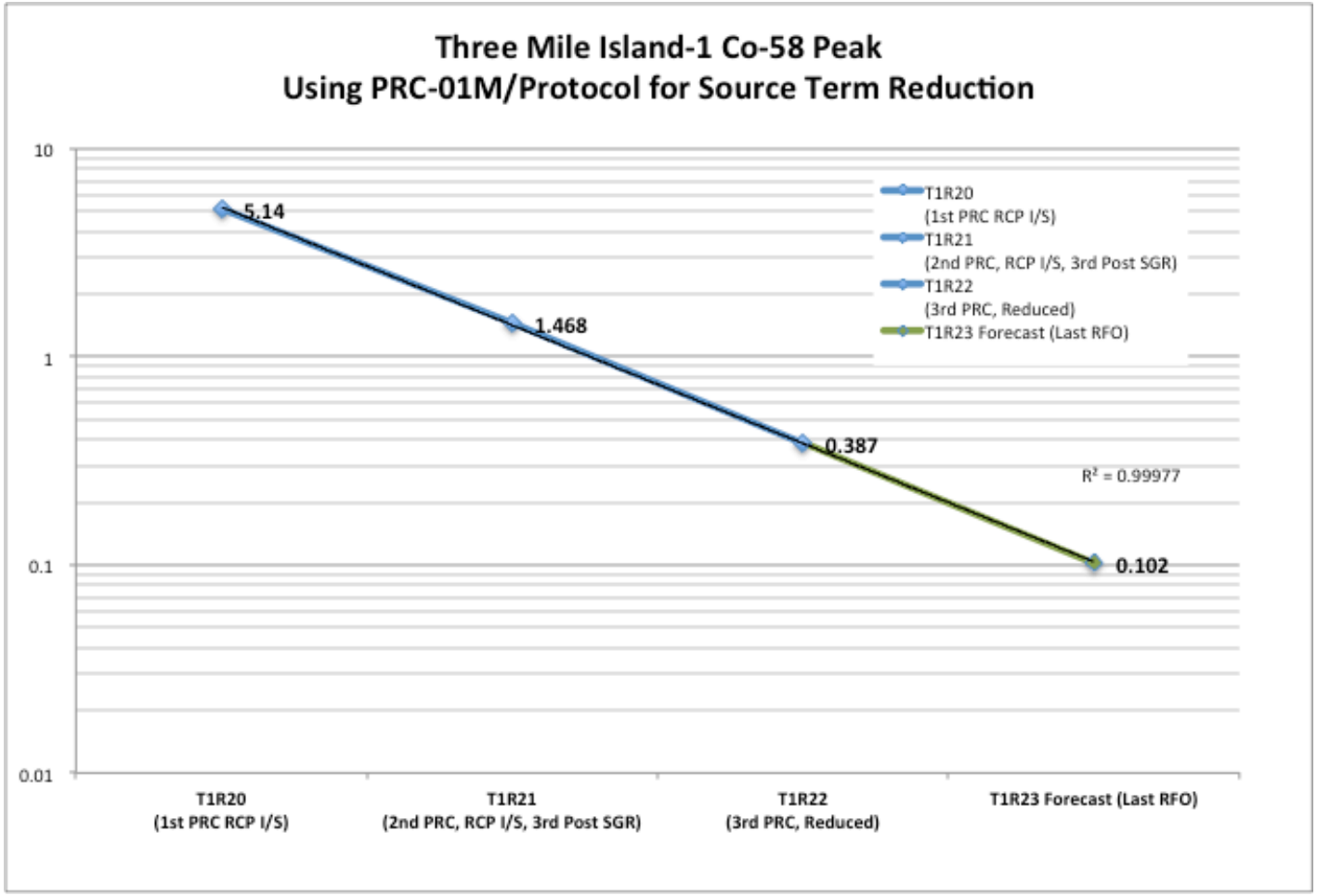
Rev 2

NPE/PRC-01M Impact on Declining Peak Co-58 Braidwood-2 (W 4 Loop, Old SG), Zn Inj, HD Core



Rev 2

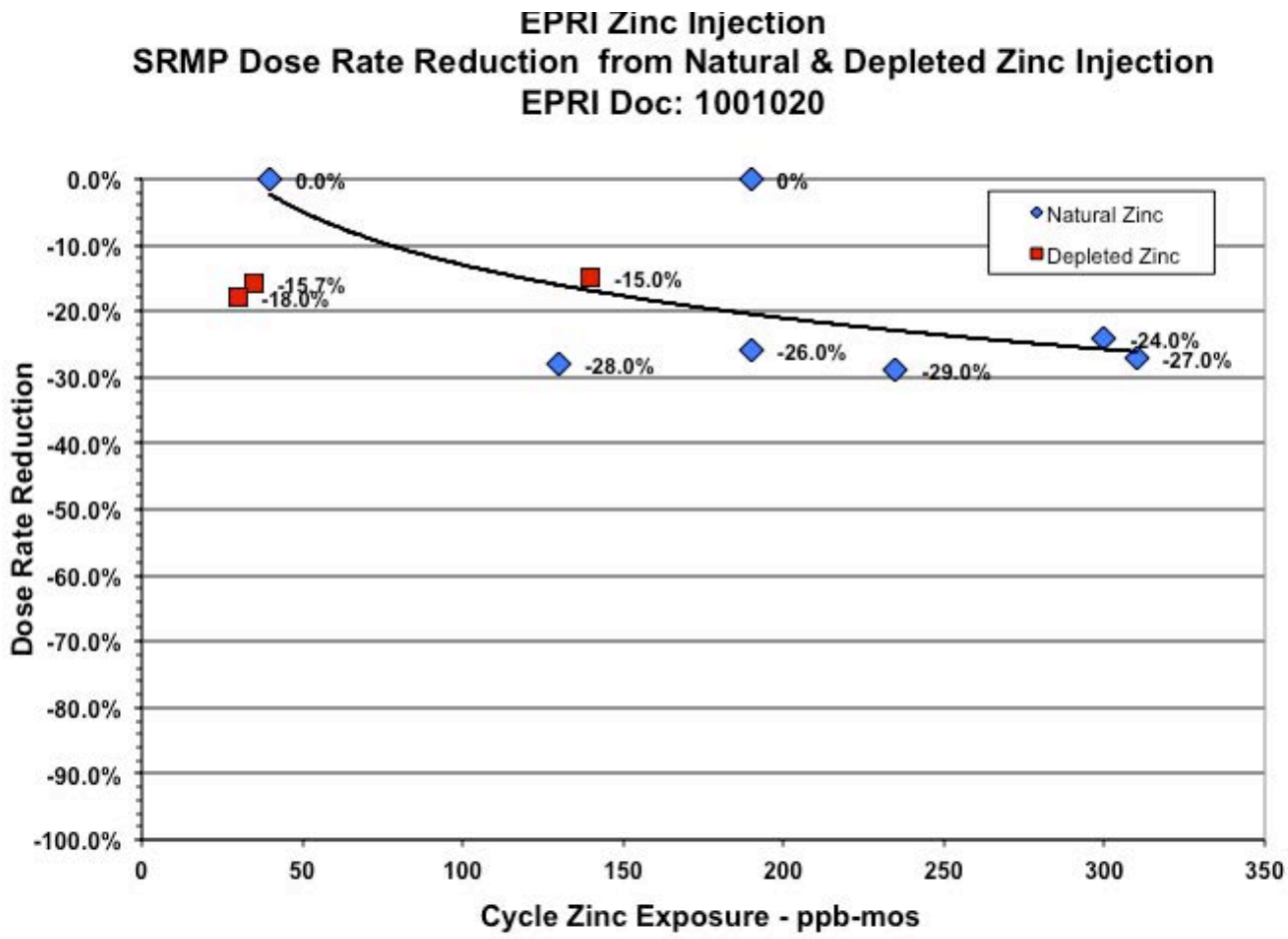
NPE/PRC-01M Impact on Declining Peak Co-58 Three Mile Island-1 (B&W, 2 Loop New SG) Zn Inj



Data Normalized for Full or Reduced Inventory FO2

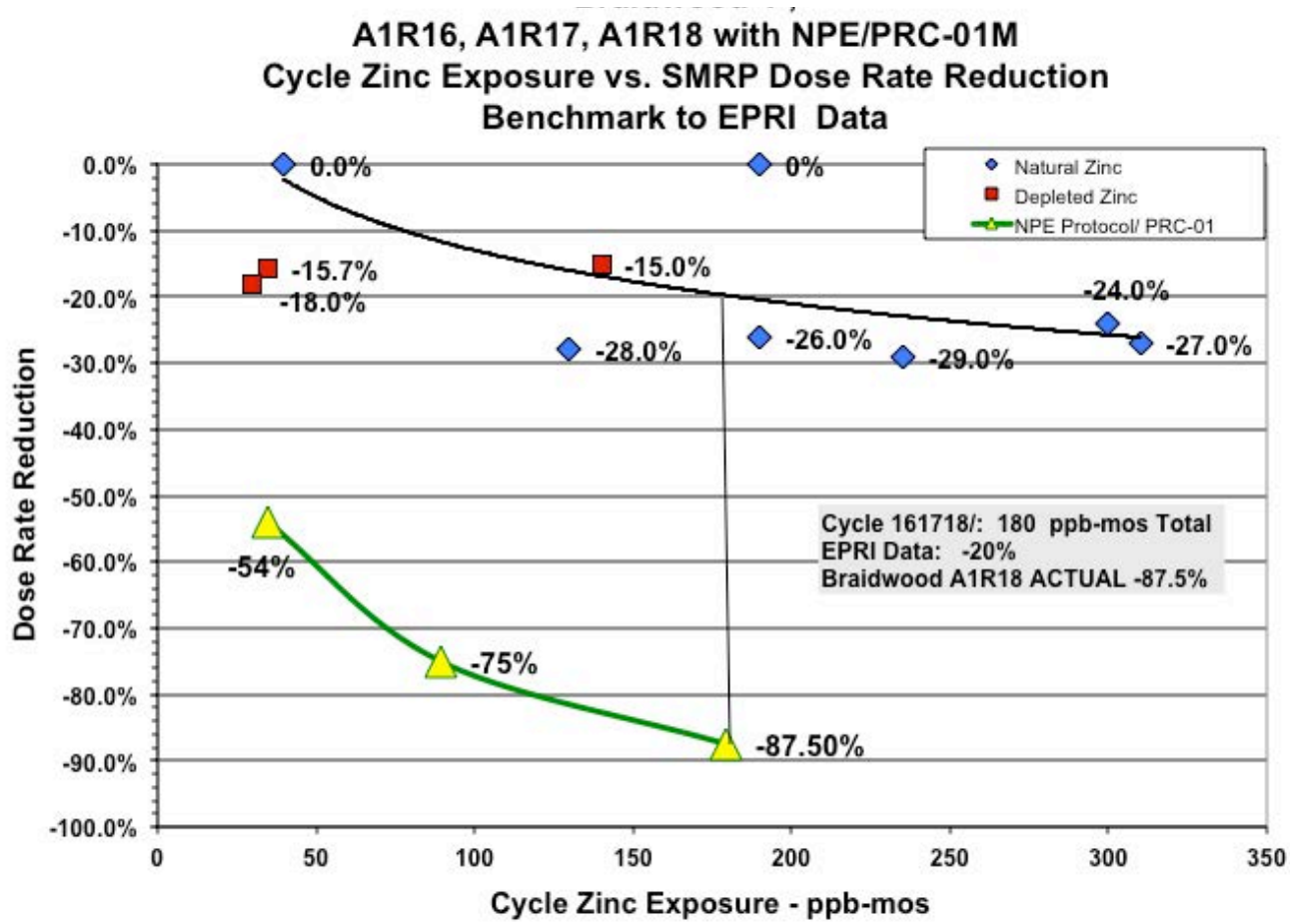
Rev 2

Zinc Injection Plants
How do we know it's NOT Zinc?



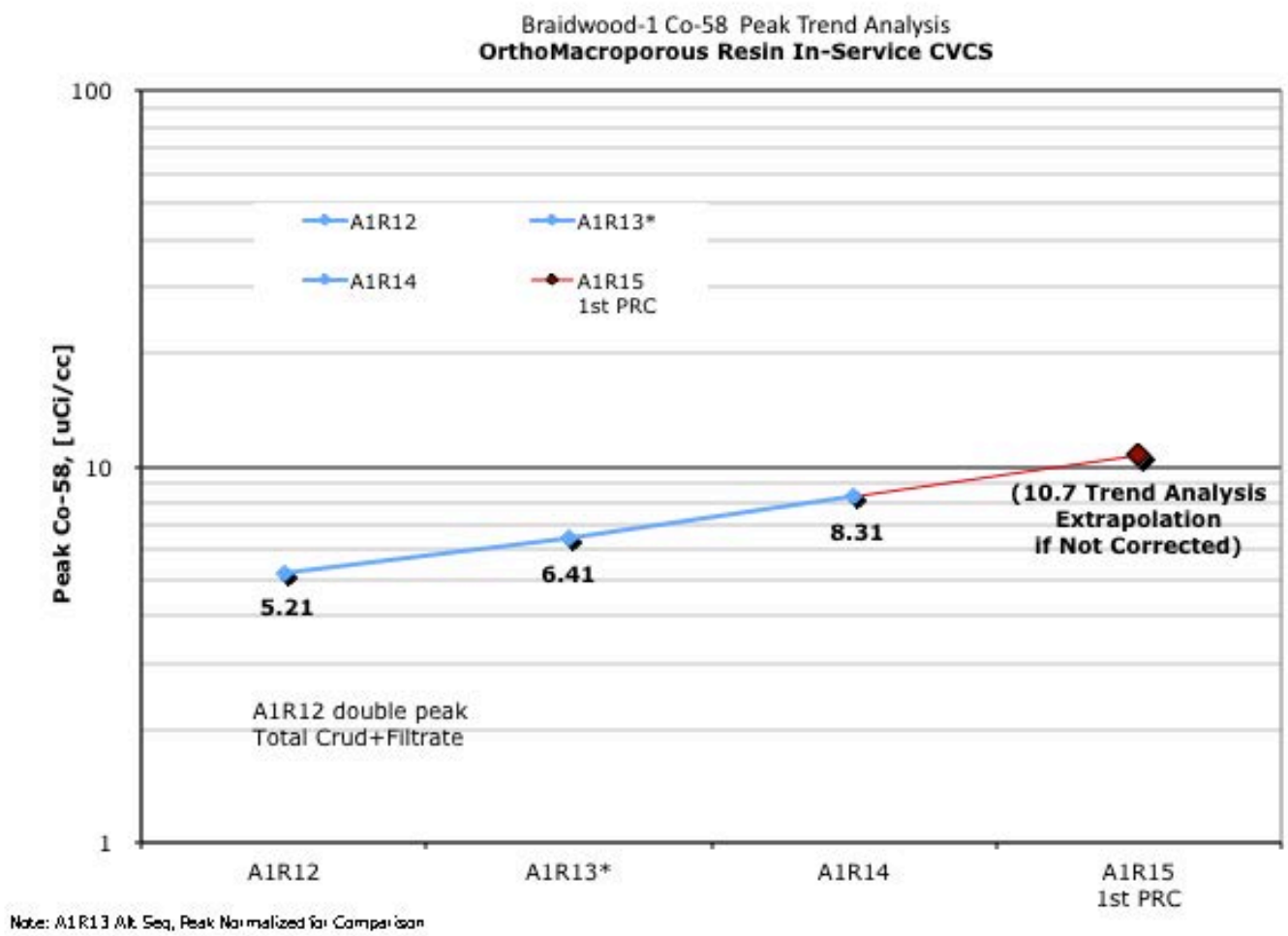
Reference: EPRI 1001020 plus new DCPP cycle 10 and data; A1R16

Braidwood-1: SRMP Dose Reduction Greatly Exceeded EPRI Data Forecast



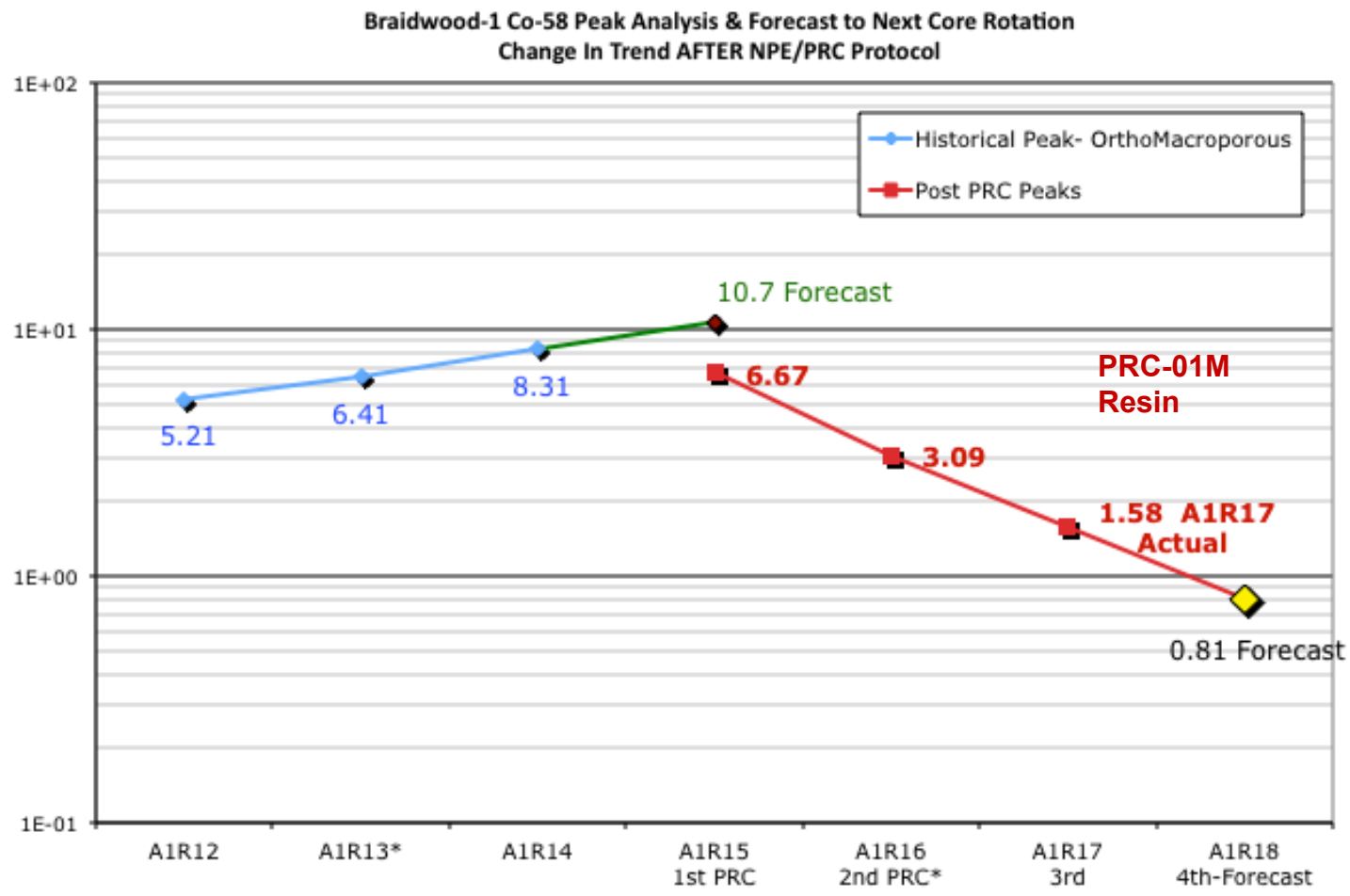
Reference: EPRI 1001020 plus new DCPP cycle 10 and data; A1R16

Braidwood-1
Old Sequence, Commercial Macroporous Type Resin



Braidwood-1
Reversal of Trend for Peak Co-58

- Peak Co-58 is a Measure of Core Crud being Released from Fuel. The higher the peak, the more total curies released.
- Goal is to have Peak As Low As Possible



Exelon Generation.

BWRs: Does Transporting CRUD, Curies and Dose Rates Decline?

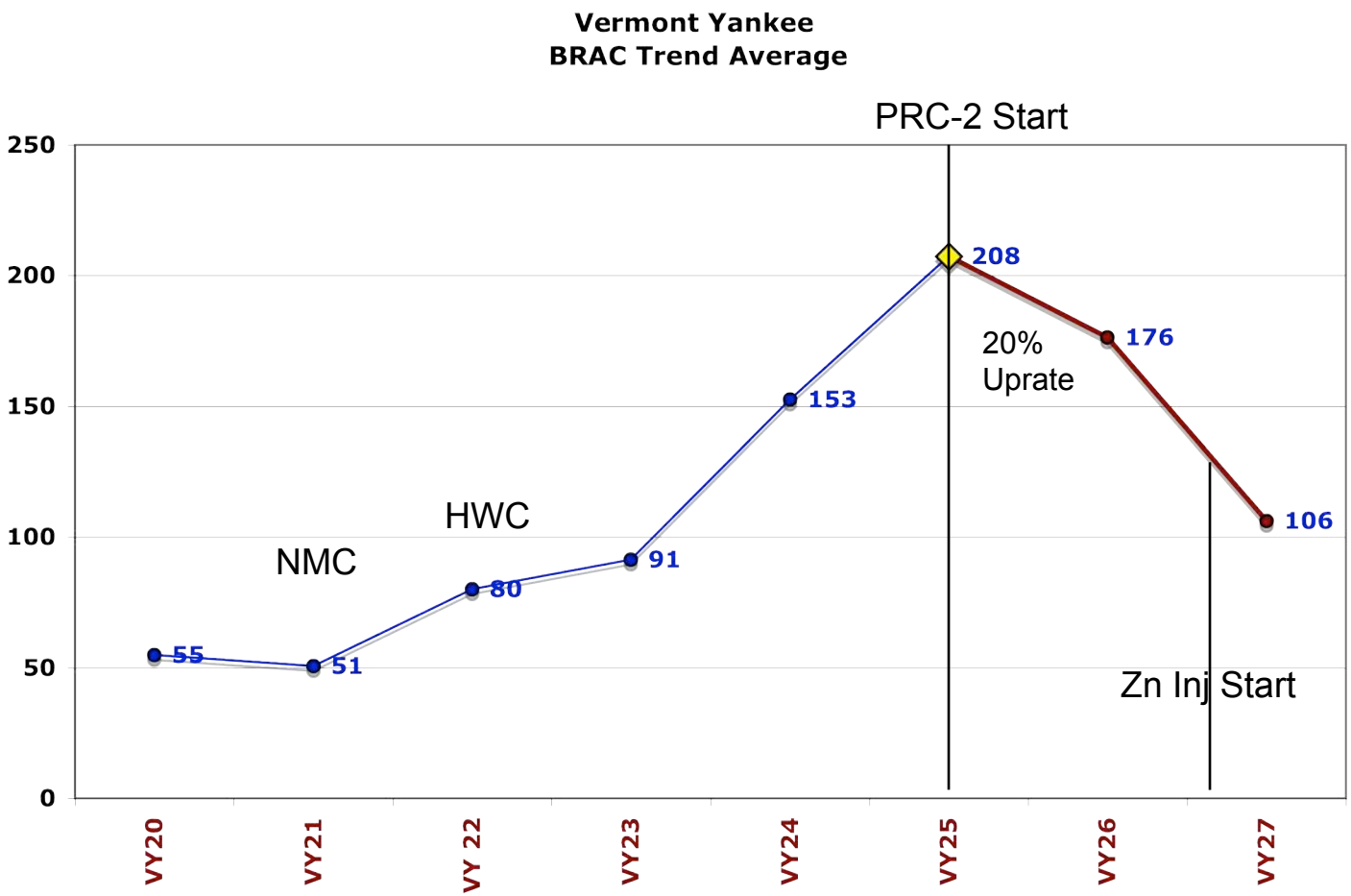
Vermont Yankee R25 to R26 Results

PRC Use R25 RFO, Cycle, R25

May 2007

- -48.%
  - Decline IVVI RWP Dose
  - 16.76 REM Planned IVVI RWP Dose
  - 8.172 REM Actual IVVI RWP Dose
  - Declined: -48%
- -43.4 %
  - Drywell RWP Dose– DOWN Posted HRA
  - 21.21 REM Planned RWP Drywell Dose
  - 12.0 REM Actual RWP Drywell Dose

Vermont Yankee BRAC
HWC NMC, Zinc Injection Last ½ C27



Monticello R22: RP Reports 1st BWR Use 2005 RFO-Lead BWR

- Chemistry- HWC, Zn injection, No NMC
- Contamination Levels Lower--- Throughout Plants
  - Turbine side reduced by 50%
- - 40 % Quarterly RWCU Dose Rate Decline
  - Measured Before RFO and 120 Days at Power
- FuelFloor Activities
  - 30% decline in effective dose rate
- RFO: Refueling Cavity Decon Shorter
  - 6 hrs Shorter for REDUCED Cavity Decon
  - Critical Path Savings: $180,000
- Fuel Floor: Equipment Removed " Cleaner"
    - Going In Cavity: 2,000,000 DPM/ 100 cm2
    - Coming Out: < 100,000 DPM/100 cm2

Monticello R22 to R23 Results

PRC Use RWCU for R22 RFO, Cycle, R23

- -28%
  - Decline in BRAC Points
  - Main Circuit Piping- Standardized Locations
  - Declined 28.5 %
- -38.5%
  - Decline RPV Effective Dose Rate
  - R22: EDR =1.45 mRem/RWP-hr
  - R23: EDR = 0.89 mRem/RW-hr
  - Change: - 38.5 %
- -71.1 %
  - Fuel Floor (Fuel Move/Inspection/CRB Replace)
  - R22: 0.78 mRem/RWP-hr
  - R23: 0.21 mRem/RWP-hr
  - Change: - 71.1 %
- **Monticello Low Dose CRE, May 2017 RFO**

Peach Bottom-3R15

Oct-2005: Reported Results

- Chemistry: HWC, NMC, Zinc Injection
- Drywell Down Post LHRA to HRA
  - 1st time ever
  - Reduced Drywell Hot Spots
- Refuel Floor- Favorable Conditions Attributed to PRC
  - Superior Water Clarity
  - No Hot Particles on Fuel Floor
  - 6 PCE's Personnel Contaminations on FF
  - Rail Dose Rates Rapidly declined from flood up 10 to 15 mR/hr to 2 to 4 mR/ hr held constant through RFO

Peach Bottom-3R15 (PRC-02) Benchmark to Limerick-1(NO PRC)

- Rx Cavity Work Platform
  - 12 REM Limerick RWP Exposure; 10 to 60 mR/hr GA
  - 3 REM Peach Bottom Exposure; 2 to 10 mR/hr GA
  - -7 REM for work on platform
- Platform Post Removal Dose Rate
  - Limerick: 60 to 200 mR/hr Contact Platform
  - Peach Bottom-3: 2 to 6 mR/hr Contact Platform
- Contamination Levels
  - Limerick: 2 to 4 Rad/100 cm2 Smearable
  - PBAPS: 200K dpm /100 cm2 Smearable

Peach Bottom 2R16:

Rx Cavity Work Platform- Exceptional Dose Rates & Contamination Levels- Post Removal

- Rx Work Cavity Platform in Cavity: 2 to 5 mR/hr in tub
- 98% of RCWP Area: < 100,000 dpm/100 cm2
- RWCP Removed:
  - Dose Rates Contact: 2 to 12 mR/hr
  - Dose Rate General Area: < 2 mR/hr
  - Hot Spots: 4 Locations, 15 to 20 mR/hr
- No Discrete Radioactive Particles on RCWP or Personnel
- Important Success Actions:
  - Hydro-Spray: Once Per Shift
- Drywell:
  - Down Post: LHRA to HRA
  - Reduced Drywell hotspots post core spray flush
- Station Low Dose Record Achieved

Perry 2017 RF16

March 2017

- Implementation of Comprehensive STR Plan
  - RWCU Decon DF 2-3 , and RC Risers
  - Hydrolazing Ports Installed
  - Permanent Shielding Install
  - PRC-02 RWCU
  - PRC-01M: FPC, Cavity, 4 Submerged Demins
- Perry 2nd Lowest Dose CRE, Spring 2017
- Reduced CRE 100 REM 1RF15 to 1RF16
- PRC Planned Continued Use to Reduce Post Decon Recontamination Rate.

Acknowledgements

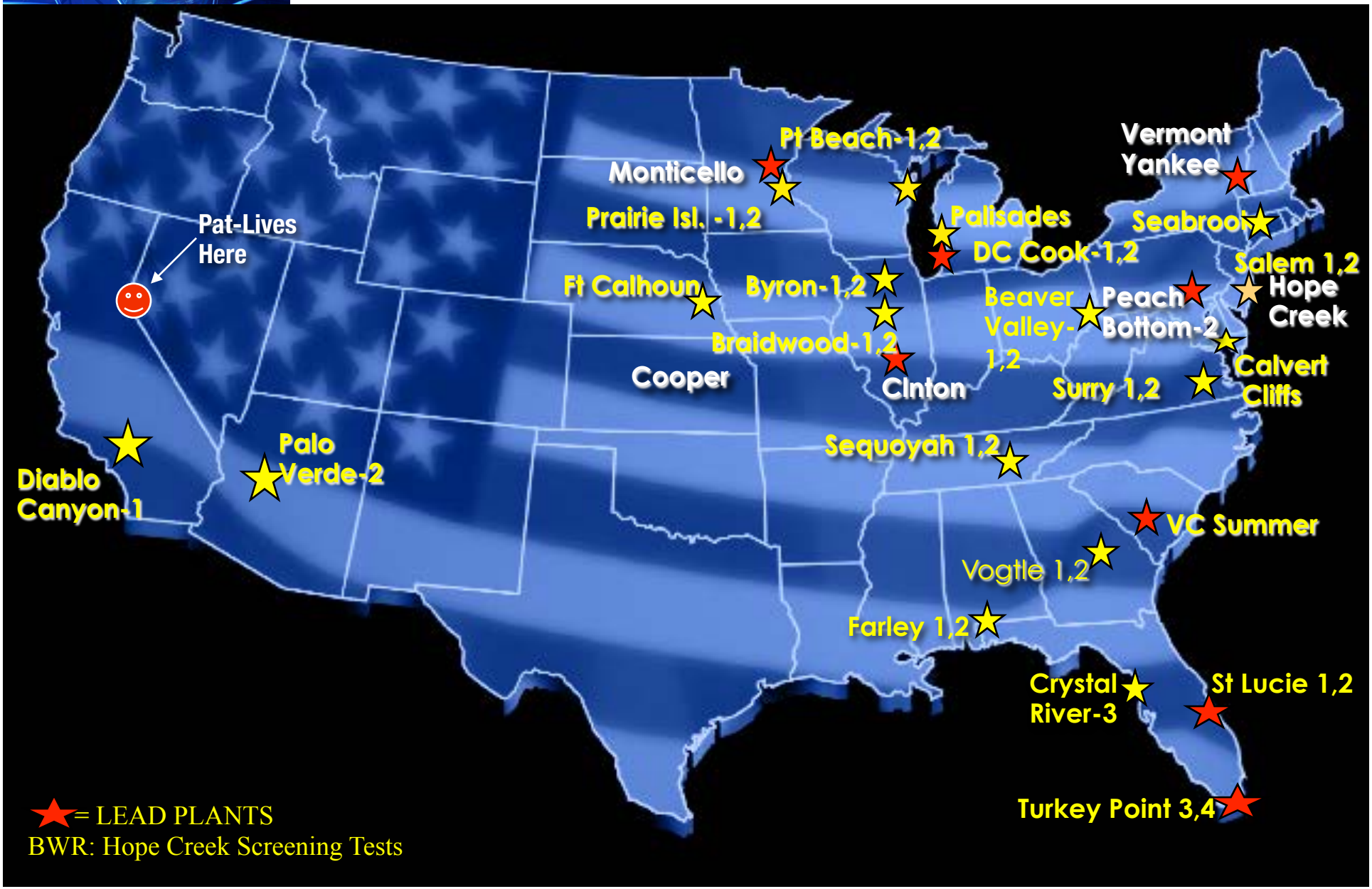
- LANL Research Team Lead by Dr. B. Smith
  - 20 Yrs of R&D
- FP&L Turkey Point and St. Lucie- Chemistry, RP, Engr.
  - Supported All Development Work
    - 2 years of Testing
  - First of a Kind Engineering Use in 2000
- VC Summer- Chemistry and RP

Questions?

Email:patricia.robinson@npenergywater.com

Cell: 1-360-561-2000

PRC-01M PWR RFO…41 Reactors …25 Sites…150+ RFO… 14 Yrs
PRC-02 BWR RFO… 7 Reactors…5 Sites…30 + RFOs….8 Yrs



Critical Operational Actions for RFO Source Term Success

BWR RFO:

- Maintain RWCU Maximum Flow Rate
  - Both RWCU Filter/Demins In-Service
  - RWCU Clean-Up Goal
  - Use Submerged Demins in Cavity
  - Recover RWCU as Soon as Possible for Start-Up

PWR RFO:

- Maintain CVCS Maximum Flow Rate
  - Operate RCPs through Forced Oxygenation to 0.5 uCI/cc Co-58 before Last RCP Trip
  - Clean-Up Goal 0.05 uCi/cc Co-58 before Flood Up
- Must reach Acid Reducing Prior to Going to 1 RCP

Opportunities with NPE/PRC Solution Integrated

- Business Goals:
  - Critical Path Reduction
    - Reduced Core Curie Release
    - Reduced Final Cavity Decon CP-Time
  - CRE, Source Term Reduced, Sustained Dose Rate
    - LHRA/HRA's downposted to RA's
    - Sustainable Decline in Dose Rates, RFO to RFO
  - Overall Outage Performance Improvement
    - Resources
  - Fuel and Component Performance
    - Reduced Core CRUD Deposits and Component CRUD
  - LLW Disposal
    - Primary Resins to Class A
  - Liquid Effluents
    - Decline in Annual Release

Opportunities with NPE/PRC Solution Integrated

- Critical Path Reduction
  - Reduced Peaks, Shorter Clean-up CP Time
  - Final Cavity Decon Time, < 2 hours, Avoided 6 to 8 Hrs
    CP Time at $30K/CP- Hr, $90K/ RFO
- CRE, Source Term Reduced, Sustained Dose Rate
  - INPO Ranking
- Overall Outage Performance Improvement
  - Resources Worker Productivity Increase to Support Outage due to "Cleaner" system
- LLW Disposal
  - Primary Resins to Class A
  - Future Savings: $400,000 / RFO
- Liquid Effluents
  - Decline in Annual Release
  - Stakeholder

Radioactive Waste & Effluents

Business Plan Objective: Reduce LLW Disposal Costs for Resins

- Cost Now (2 Unit Site):
  - One Class B/C Resin Shipment: ~$400,000 to $500,000
  - One Class A Resin Shipment: ~$30,000 ($300/cu ft, 200 cu ft)
  - Current Class B/C Ship Rate: ~6 shipments every 3 yrs, $3,000,000
- Cost in Future:
  - Class B/C Resin Shipment: One shipment every 3 yrs, $500,000
    - Location: SFP Submerged Demin
  - Class A Resin Shipments: ~5 shipments every 3 yrs, $150,000

- Additional Value WITH STR:
  - Cost of implementation: $250,000
  - Savings: $3,000K – 250K (implementation) -30K (1 Class B) = $1,800,000
  - Added ROI: 6: 1 in 3 years;
    Added ROI: 12: 1 in 6 years

What is a Colloid?

- Chemistry
  - Insoluble - but Not Mechanically Filterable in Rx Systems
  - Extremely Fine Insoluble Material Suspension
  - Dominately Iron (Fe)
    - 50,000 X More Fe than Co-60 in PWR RC at Rx Shutdown
  - Think Tiny Clusters of Elements Together e.g. Fe, O, H
- Colloid Cluster Size Range
  - Smaller than 0.1 - 0.001 µm range
  - Not Much Weight/Mass
    - Settle Times can be Years
  - Think Millons of Colloids in 1 Liter at Shutdown
- Special Properties
  - Electrostatically Charged
    - + or - Charge can Attract or Repel
- Can Cause Corrosion

What is PRC?

Set of Medias with Multiple Enabled Functions

- Start with Conventional Resin used in NPP for 30 yrs.
  - Powdered or Bead Size Ion Exchange Resin
- Surface is Modified by Organic Polymers
  - Enabled for target contaminate:
    - Soluble and Insoluble Targeted Species Removal for PWR/ BWR chemistries
    - NPP PRC Enabled: Transition metals, transuranics
  - Polymer Nano-Hairs
- Polymers Can be Customized for SiO2, Sb, Cu, etc.

Acknowledgements/ References

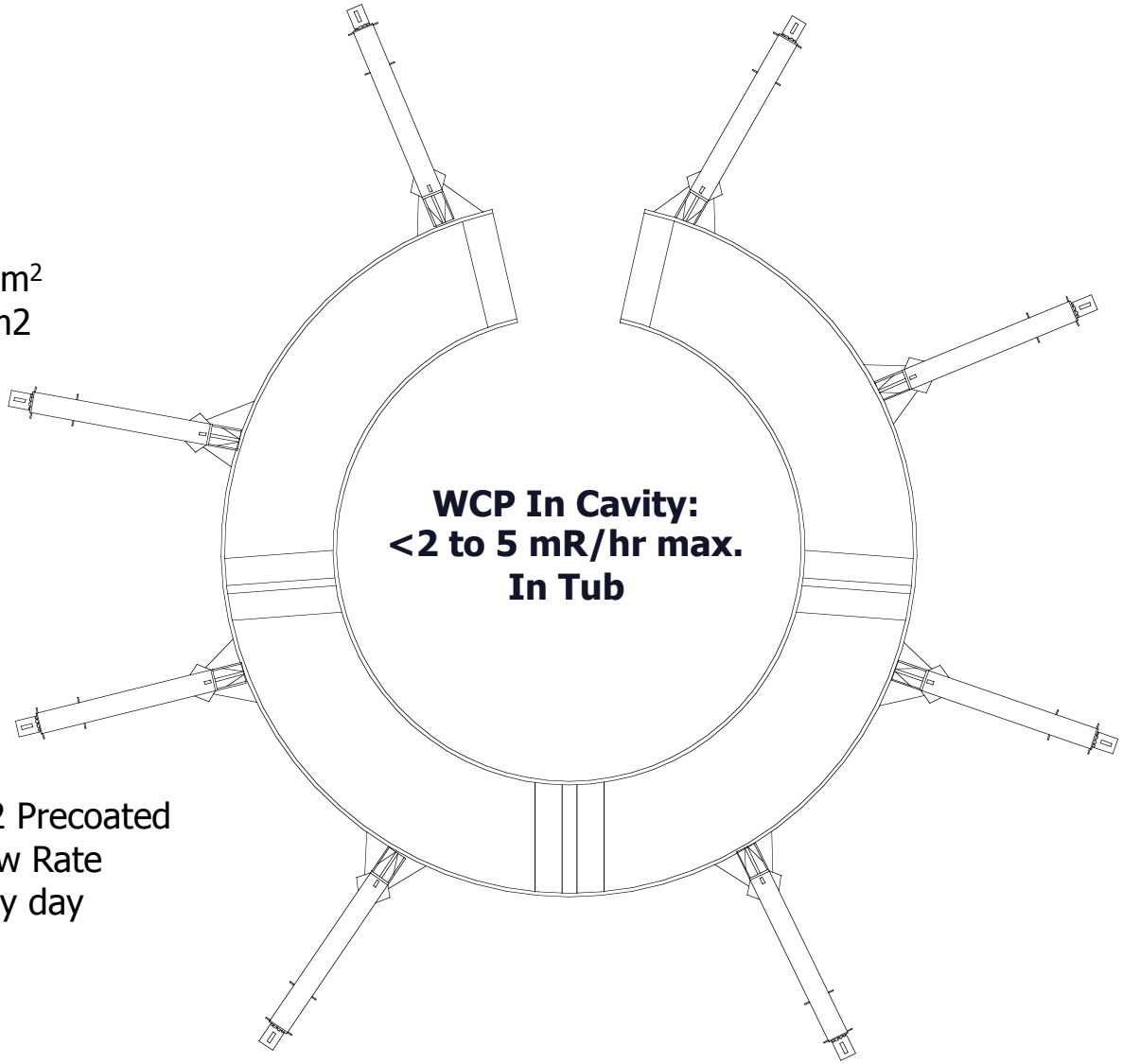
- Radiochemistry of Light Water Reactors, Dr. Karl Neeb, 1997
- Westinghouse AP1000 Design Control Document
- Los Alamos N.L.- Technical Documents
- EPRI Documents, BWR VIP-190, 2010
- IAEA Publications
- Dr. M. Pourbaix, Eh- pH (1966) Solubility Diagrams
- Actinide 2001 Conference:"Thermodynamic Stability of Mixed Oxide Pourbaix Diagrams" P. Vitorge et al, CEA
- University of Illinois, UC, Dr. Barkley Jones, NE Department
- University of New Mexico, Dr. A. Hasan, Colloid Transport of Transuranics

Peach Bottom 2R16: Work Cavity Platform Dose Rates & Contamination Levels- Post Removal

WCP Rad Conditions:

- 98% of WCP Area:
  < 100,000 dpm/100 cm^2
- Hot Spots:
  7 Bolts: 16 to 560 mRad/100 cm^2
  Hinges: 48 to 96 mRad/100 cm2
- Dose Rate Removed:
  Contact: 2 to 12 mR/hr
  < 2 mR/hr General Area

- Hot Spots:
  4 Locations, 15 to 20 mR/hr
- **No Hot Particles on WCP**
- **No Hot Particles on Personnel**

Actions:

1. FCP: 100% Availability, PRC-02 Precoated F/D Clean-up System, Max Flow Rate
2. Hydro-Spray: Twice/ Shift every day