Managing PWR Shutdowns and Minimizing Radiation Fields

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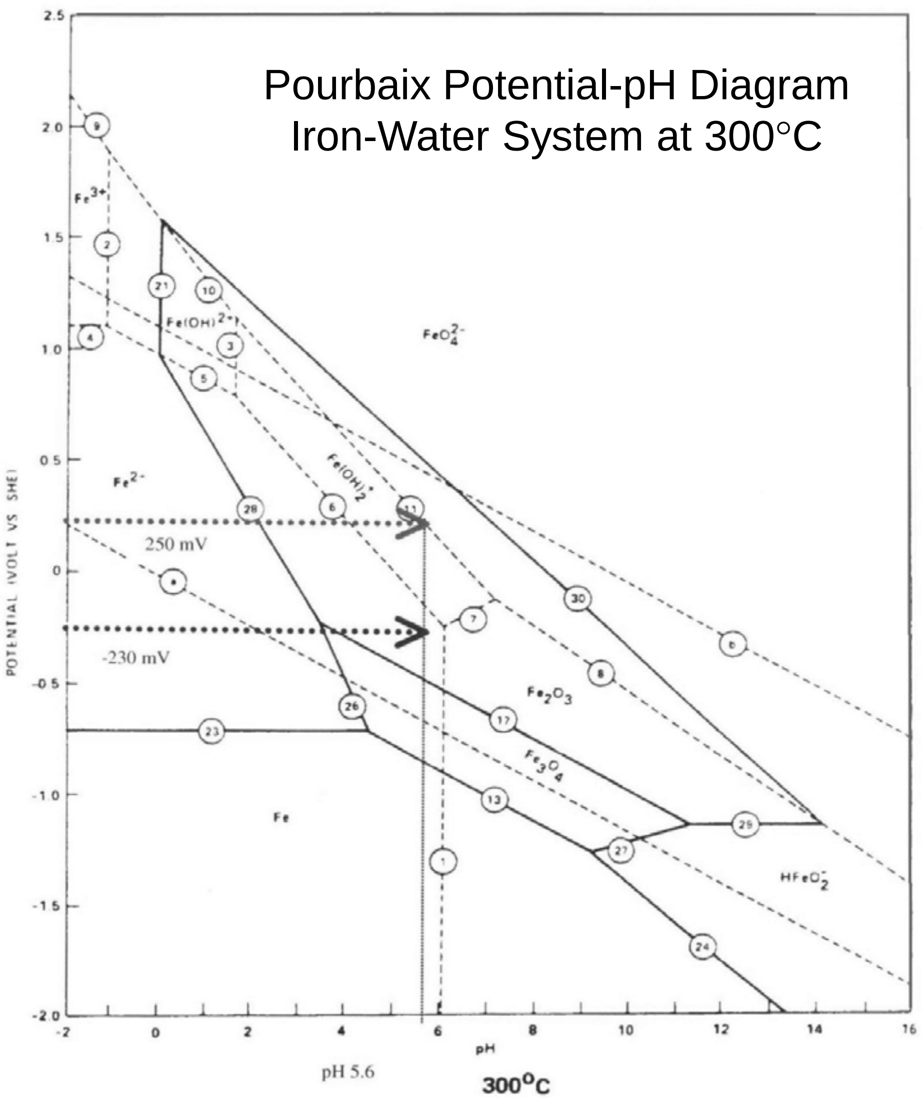
Activity Transport Considerations

Chemistry

- Reducing
  (H2 ~0.3 to 0.5 ppm)
- pH_{300C} = 7 to 7.4
- Zinc addition recently adopted at many plants
- ECP: -700 to -800 mVSHE

Design

- Materials
- Flowrates
- Core Design ($T_{hot/cold}$, boiling, etc.)



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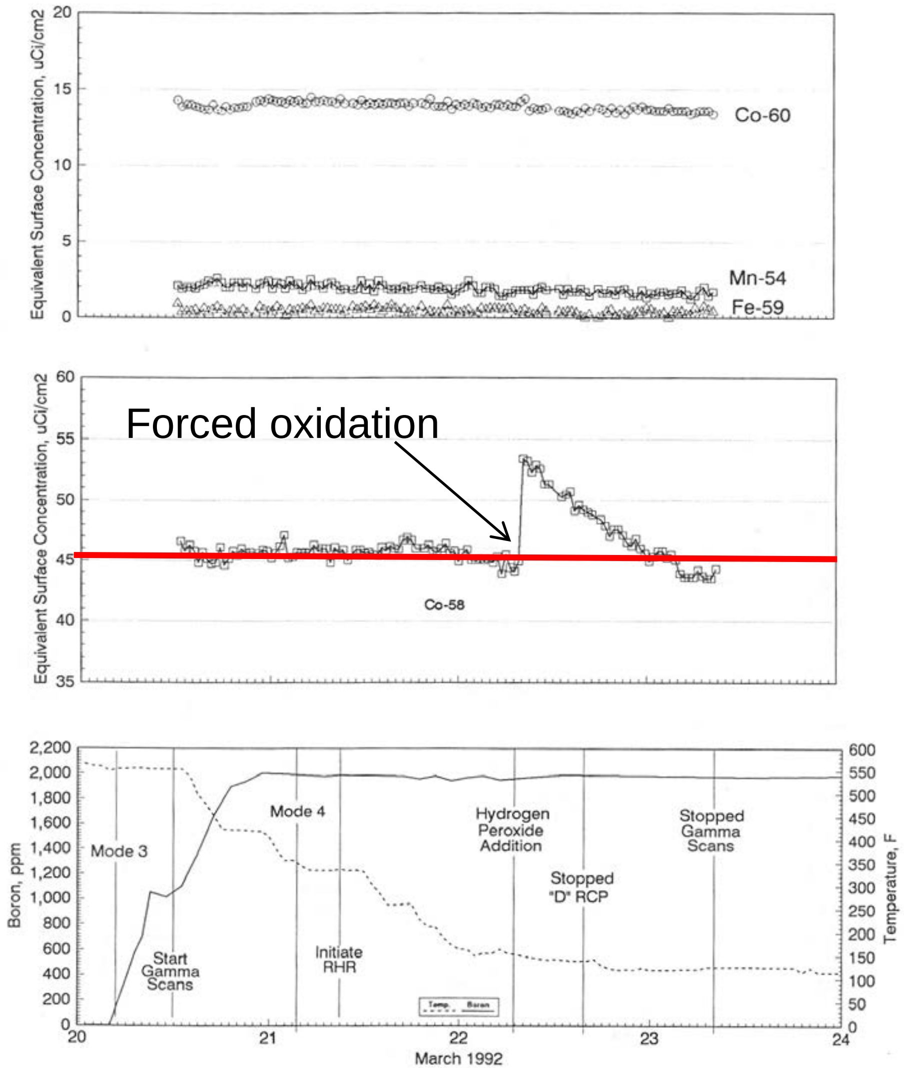
High Flow Area Activity Buildup

Background

- In large piping surfaces, surface activity stays the same before and after shutdown
- Activity incorporation occurs <u>during normal operation</u>
  - Gamma spectroscopic studies have demonstrated no activity increase during outage maneuvers*



**PWR Activity Transport and Source Term Assessment: Surface Activity Concentrations by Gamma Scanning.* EPRI, Palo Alto, CA: 2011. 1023027.

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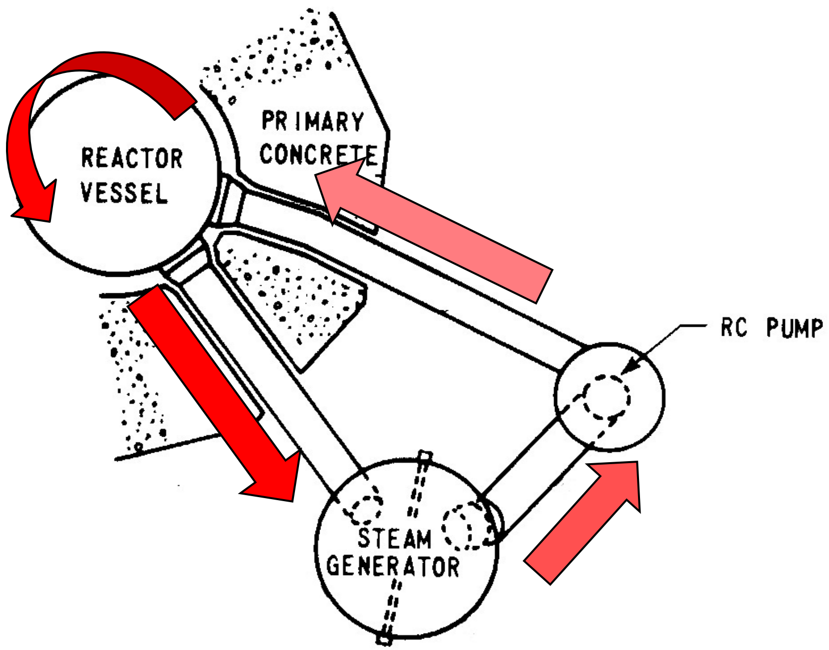
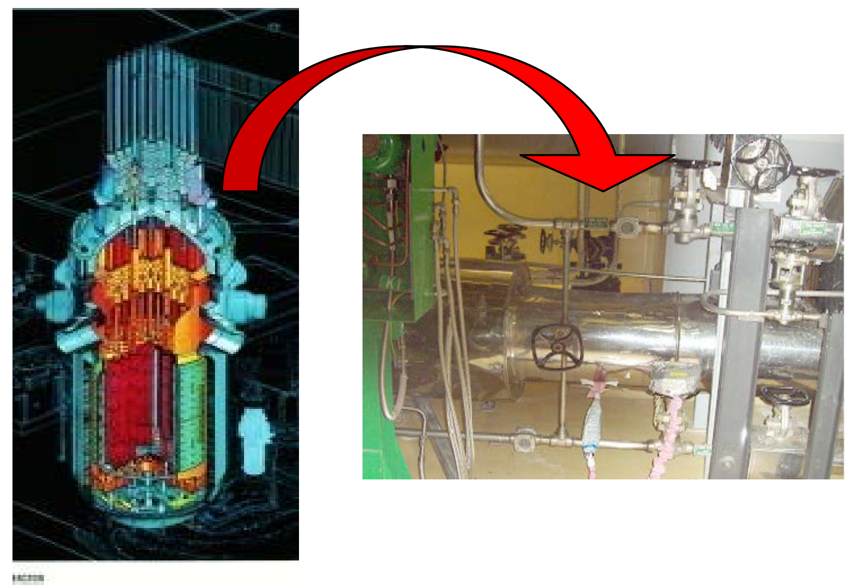
Coolant Activity and Deposition

A Two Phase Issue

1. During operation activity incorporation into surface oxides appears governed by soluble species
2. Particulate dropout in dead legs or low fluid shear regions will increase local dose rates



During Operation – Soluble



During Shutdown – Particulate

Activity Incorporation Mechanism

On-line Uptake

$$Incorporation\ Rate = I = \lambda_i N_{fi} = 3.7E4C_{fi}$$

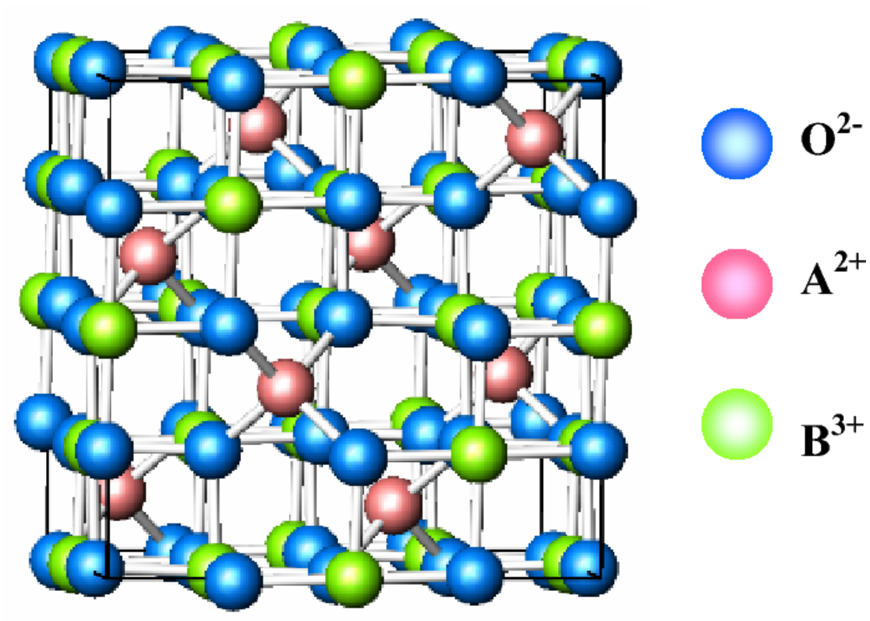
- Assume steady state transport and surface concentration of 10 μCi/cm^2 (3.7E9 Bq/m^2), typical for PWRs[1]

Nuclide	Surface Concentration, μCi/cm^2	Steady State Incorporation Rate, atoms/cm^2-sec	Decay Constant s^{-1}	Surface Concentration, atoms/cm^2
Co-58	10	3.7E5	1.13E-7	3.27E12
Co-60	10	3.7E5	4.17E-9	8.87E13

- Elemental oxidation rates are 1E5 times higher than the incorporation rates therefore incorporation into vacancies cannot be rejected.[2]

1. *PWR Activity Transport and Source Term Assessment: Surface Activity Concentrations by Gamma Scanning.* EPRI, Palo Alto, CA: 2011. 1023027.
2. *Impact of PWR Coolant Radiocobalt Concentrations on Shutdown Dose Rates: Interim Report*. EPRI, Palo Alto, CA: 2012. 1025307.

Perspective on Concentrations and Ratios



- Site vacancies in spinel lattices reportedly 0-10%[1]
- Metal atoms in 0.5 μm thick oxide ~1E18 atoms/cm^2
- If vacancies only 1% that is 1E16 atoms/cm^2

1. O'Neill, H. S. C. and A. Navrotsky, *Am. Mineralo.*, Vol. 68, 181-194, 1983.

Simplistic Incorporation Model (1025307)

- Incorporation rate proportional to soluble concentration

$$R = k_i C_i$$

- If all species compete for lattice vacancies and preference is equivalent then incorporation rates of each species should be proportional to coolant concentrations

Species	Typical Coolant Concentrations, μCi/ml (MBq/m^3) or ppb	Typical Coolant Concentrations, atoms/ml
Co-58	1E-3 (37)	3.27E8
Co-60	2E-5 (0.74)	1.77E8
Fe	3	3.24E13
Ni	0.1	1.03E12
Zn	10	9.13E13

Surface Activity Variation with Time[1]

- The change in activity with coolant concentration and time can be evaluated by using a determined incorporation constant

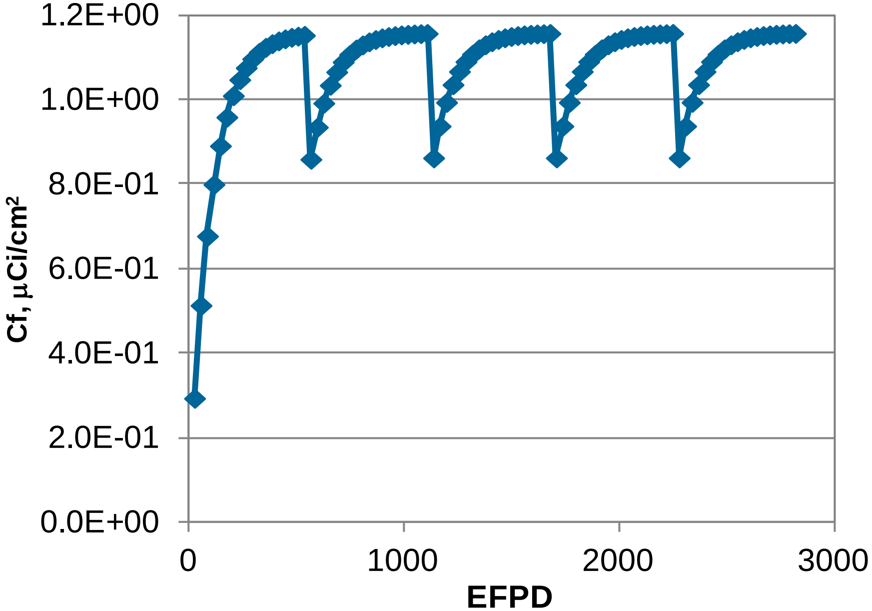
$$\frac{dC_{fi}}{dt} = k_i C_{Ci} - \lambda_i C_{fi}$$

- Benchmarking requires deposited activity (limited)[2] and "soluble" concentrations that are difficult to analyze in PWRs

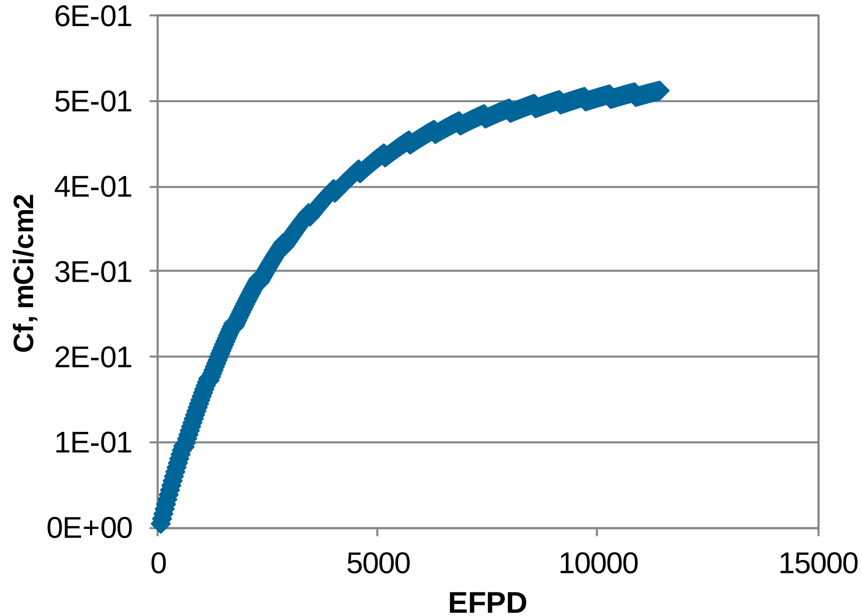
1. *Impact of PWR Coolant Radiocobalt Concentrations on Shutdown Dose Rates: Interim Report*. EPRI, Palo Alto, CA: 2012. 1025307.
2. *PWR Activity Transport and Source Term Assessment: Surface Activity Concentrations by Gamma Scanning.* EPRI, Palo Alto, CA: 2011. 1023027.

Time to Surface Activity Equilibrium (1025307)

Change in Co-58 Surface Activity with Time
(18-mo cycles, $C_{Co\text{-}58}$ constant 1E-3 μCi/ml)



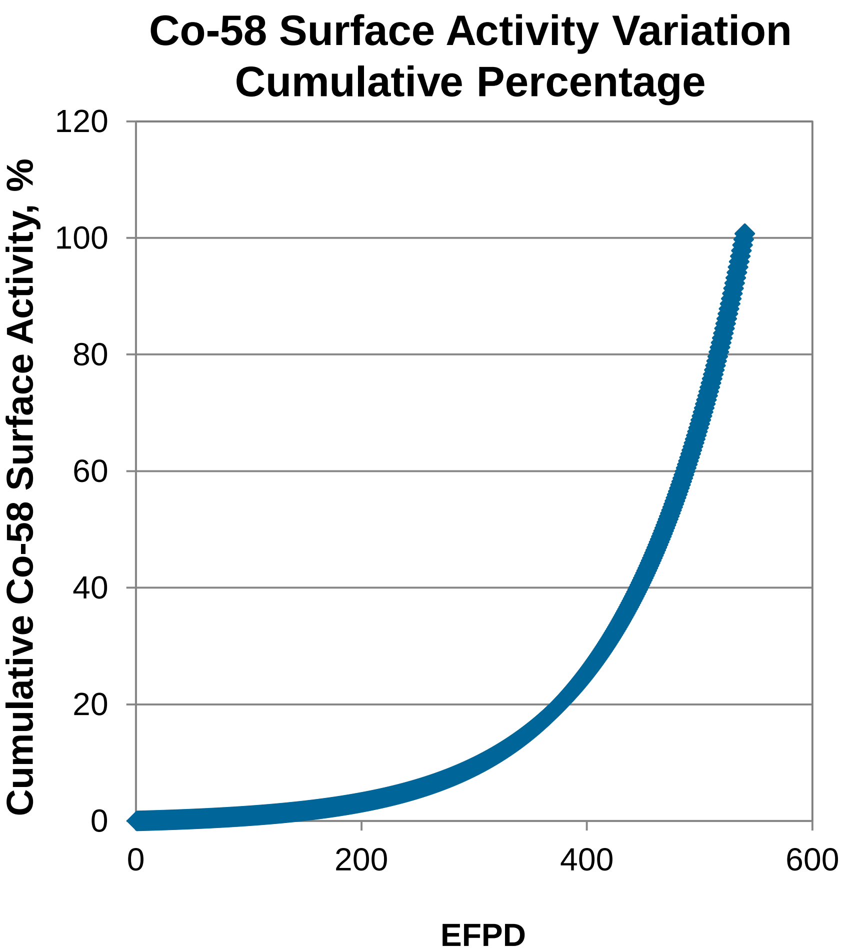
Change in Co-60 Surface Activity with Time
(18-mo cycles, $C_{Co\text{-}60}$ constant 2E-5 μCi/ml)



- Co-58 rapidly reaches equilibrium while Co-60 takes many cycles to reach equilibrium

*The previous equation can be numerically solve to determine an incorporation rate constant for a case of constant Co-58 coolant concentration of 1E-3 μCi/ml, 18-mo cycle, and 1 μCi/cm^2

Coolant Activity and EOC Deposited Activity



- For Co-58, surface activity primarily dependent on activity incorporated near end of cycle
  - First 400 days is only 25% of end-of-cycle activity
  - Majority of the activity deposited early in cycle decays before the end of the cycle

Impact of PWR Coolant Radiocobalt Concentrations on Shutdown Dose Rates: Interim Report. EPRI, Palo Alto, CA: 2012. 1025307.

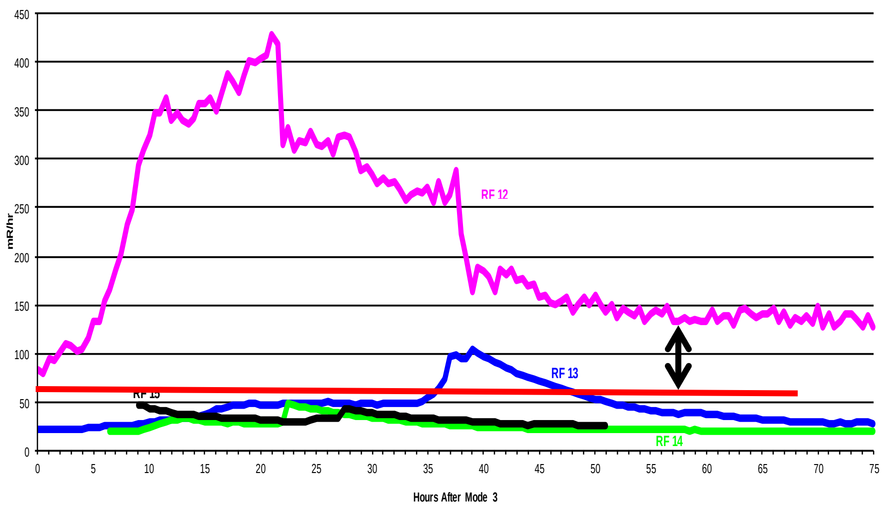
High Flow Area Activity Buildup
Summary

- Surface activities of Co-58 depend primarily on soluble concentrations during the last 3 to 6 months of operation prior to a shutdown.
- Surface activities of Co-60 depend on the soluble concentration over the preceding 5 to 10 years of operation.
- Co-60 significantly contributes to shutdown dose rates after 5 to 10 EFPY of operation. Both Co-58 and Co-60 coolant concentrations must be considered when attempting to correlate surface activities/shutdown dose rates to operating chemistry.

Impact of PWR Coolant Radiocobalt Concentrations on Shutdown Dose Rates: Interim Report. EPRI, Palo Alto, CA: 2012. 1025307.

Low-Flow Area Activity Uptake

Increased Dose Rate after Shutdown
(high duty core, 2nd cycle after SGR)



- Electronic dosimetry studies of low-flow systems shows higher dose rates after shutdown
  - Particulate transport after SG replacement is suspected
  - Uprated cores may change transport mechanisms
  - Plant trips and non-standard operations
- Trends observed in PWRs and BWRs

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Impact of SDs on PWR Dose Rates

- No significant impact of shutdowns on piping or steam generator dose rates in high shear regions
  - Co-58 and Co-60 releases are very high and primarily soluble (compared to BWRs)
- Limited dose rate increases observed in low fluid shear regions:
  - Shutdown cooling, letdown system
- Electronic dosimetry is valuable assessment tool; extensive database available
- *Detailed information about chemistry, ops, fuel, etc. necessary therefore case study method used*

*Impact of PWR Operational Events on Particulate Transport and Radiation Fields. EPRI, Palo Alto, CA: 2012. 1025305.

Plant Changes and SRMP Dose Rates

Case Study Unit Specifics

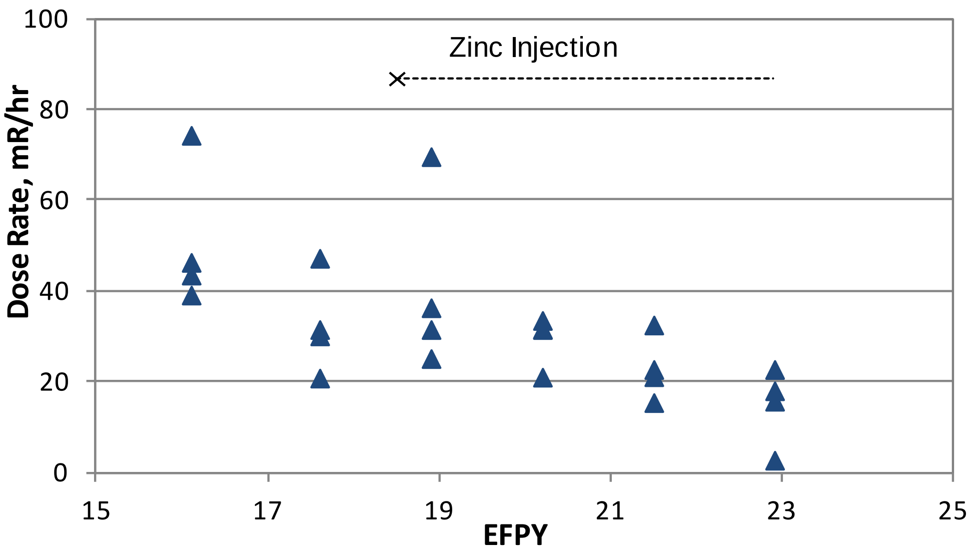
- SGR 6 cycles before UFC
- Constant pH_T 7.05 to 7.11
- No EPU and only 2 mid-cycle outage (MOC14 and 17)

Dose Rates

- Dose Rates reduced 50-60% between EOC16 and 19.
  - Limited ability to attribute solely to zinc and not combination several factors

Key Changes

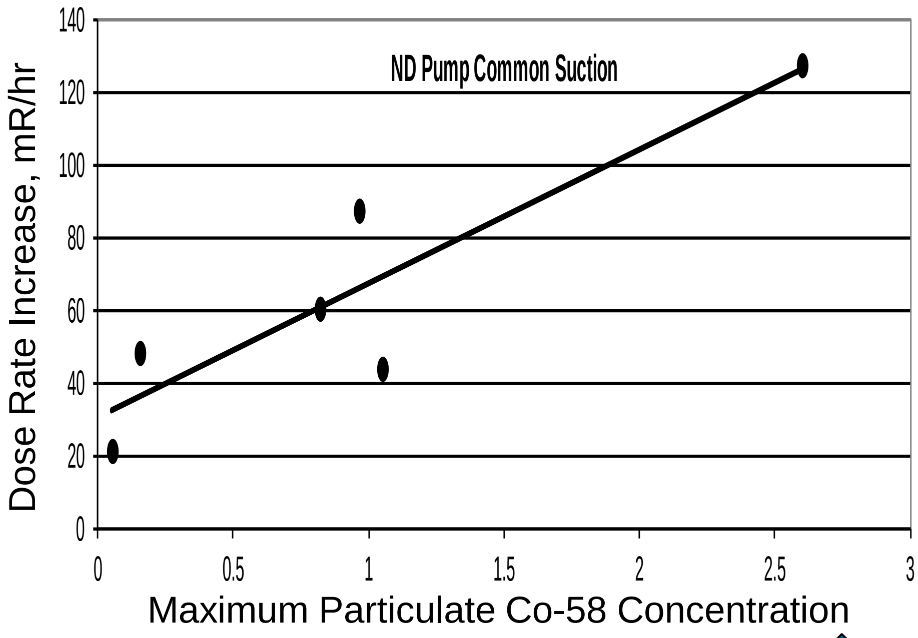
- UFC began in cycle 17 for CIPS
- Zinc injection began in cycle 18
- 0.1 micron filtration in-line during cooldown beginning cycle 18



*Impact of PWR Operational Events on Particulate Transport and Radiation Fields. EPRI, Palo Alto, CA: 2012. 1025305.

Primary Chemistry, Shutdown and Particulates

- Prior to UFC, Co-58 concentrations were increasing.
- Particulate Co-58 decreased during cycles 19 and 20
  - Cumulative impact of Zn and UFC possible but core boiling duty also changed



- Particulate/total ratio reduced after two SD with UFC & Zn, but major reductions with RHR only shutdown
- Dose rates in decay heat (RHR/ND) correlate reasonably with maximum particulate concentrations

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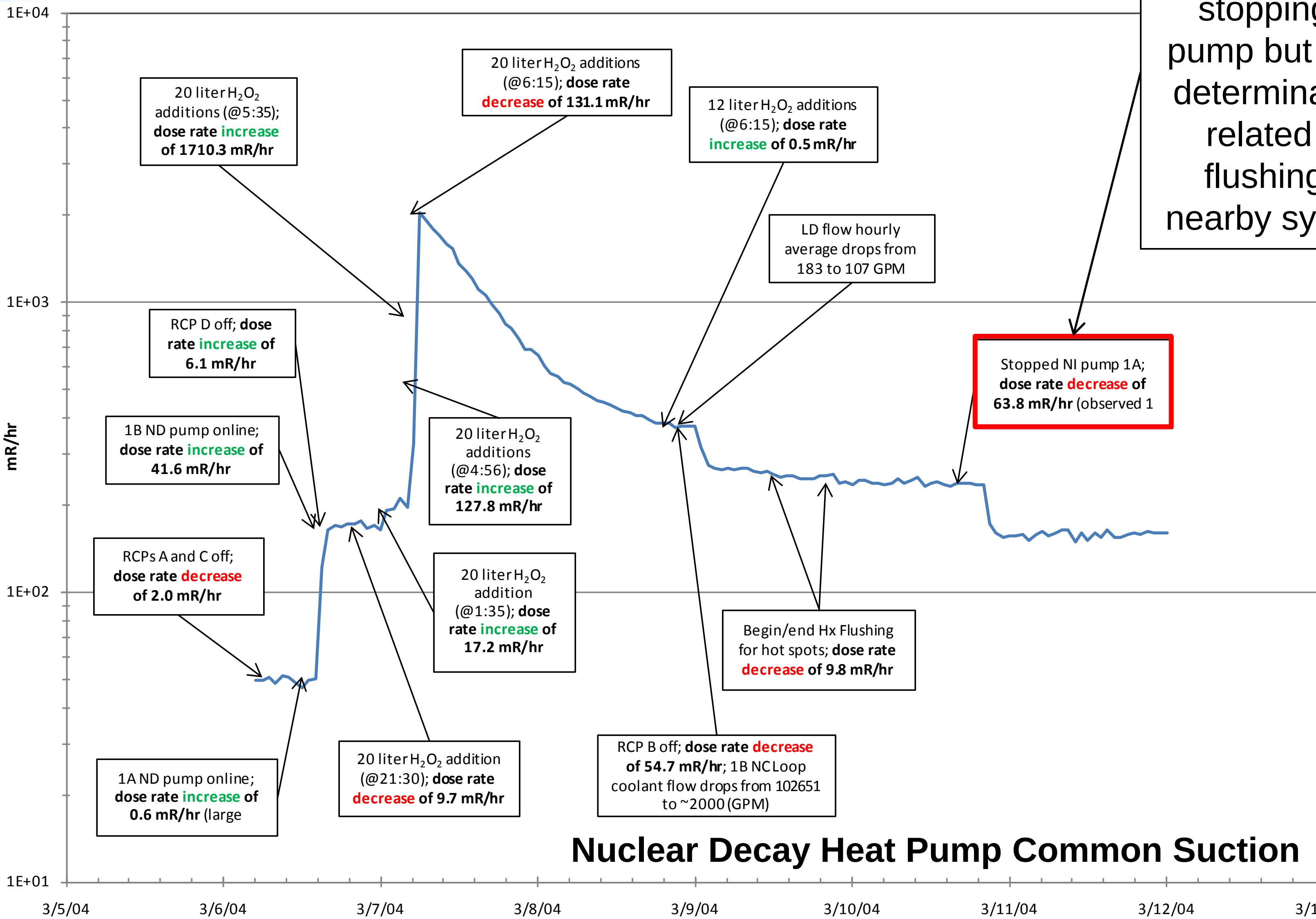
Installed Remote Technology in PWRs

Electronic Dosimetry



Drop originally attributed to stopping a pump but later determination related to flushing a nearby system

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Modeling the Impact of Insoluble Deposition
Re-entrainment and wall shear

*Kern-Seaton Equation**

$$\frac{dW}{dt} = vC - EW$$

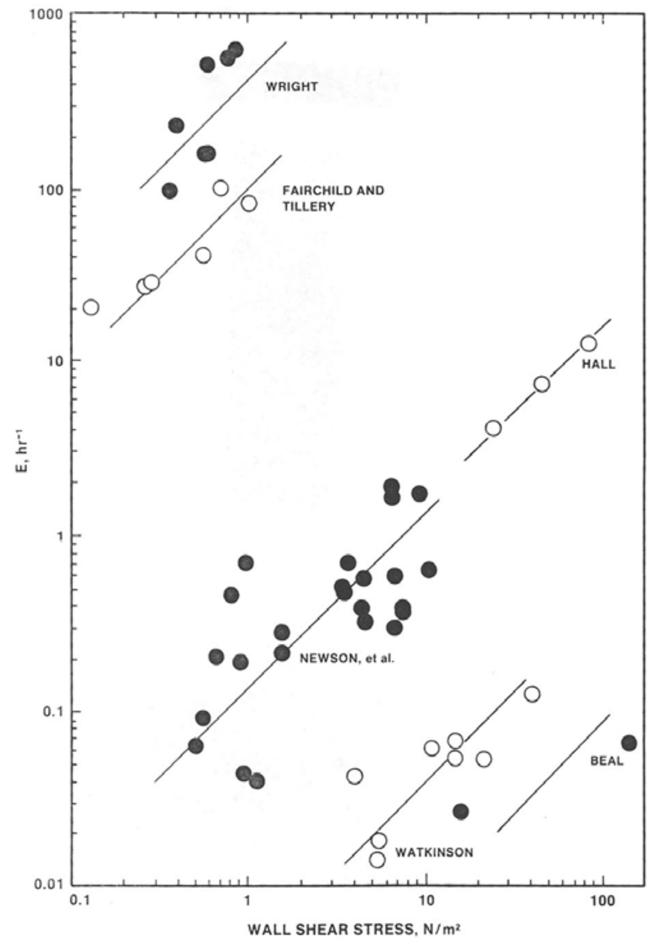
W	=	Deposit weight per unit area
t	=	Time
v	=	Deposition velocity
C	=	Concentration in fluid
E	=	Re-entrainment coefficient

Re-entrainment (E) directly proportional to wall shear

$$\tau_W = \frac{f}{2} \rho V^2$$

f	=	Fanning friction factor
ρ	=	Fluid density
V	=	Average fluid velocity
τ_W	=	Wall shear stress

Re-entrainment Coefficient Versus Wall Shear Stress



*Kern, D. Q., Seaton, R. E., "A Theoretical Analysis of Thermal Surface Fouling," British Chemical Engineering; pp 258-262, 1959

Correlating Piping Dose Rates to Particulate Concentrations*

Method

1. Correct ED data for impact of coolant activity
2. Estimate (mR/h)/(μCi/ml) based on total Co-58 immediately before and after peroxide injection
3. Assess piping dose rate buildup as function of time, operations and coolant particulate concentrations

- Extensive PWR database available
- Can process be modeled using Kern-Seaton approach?

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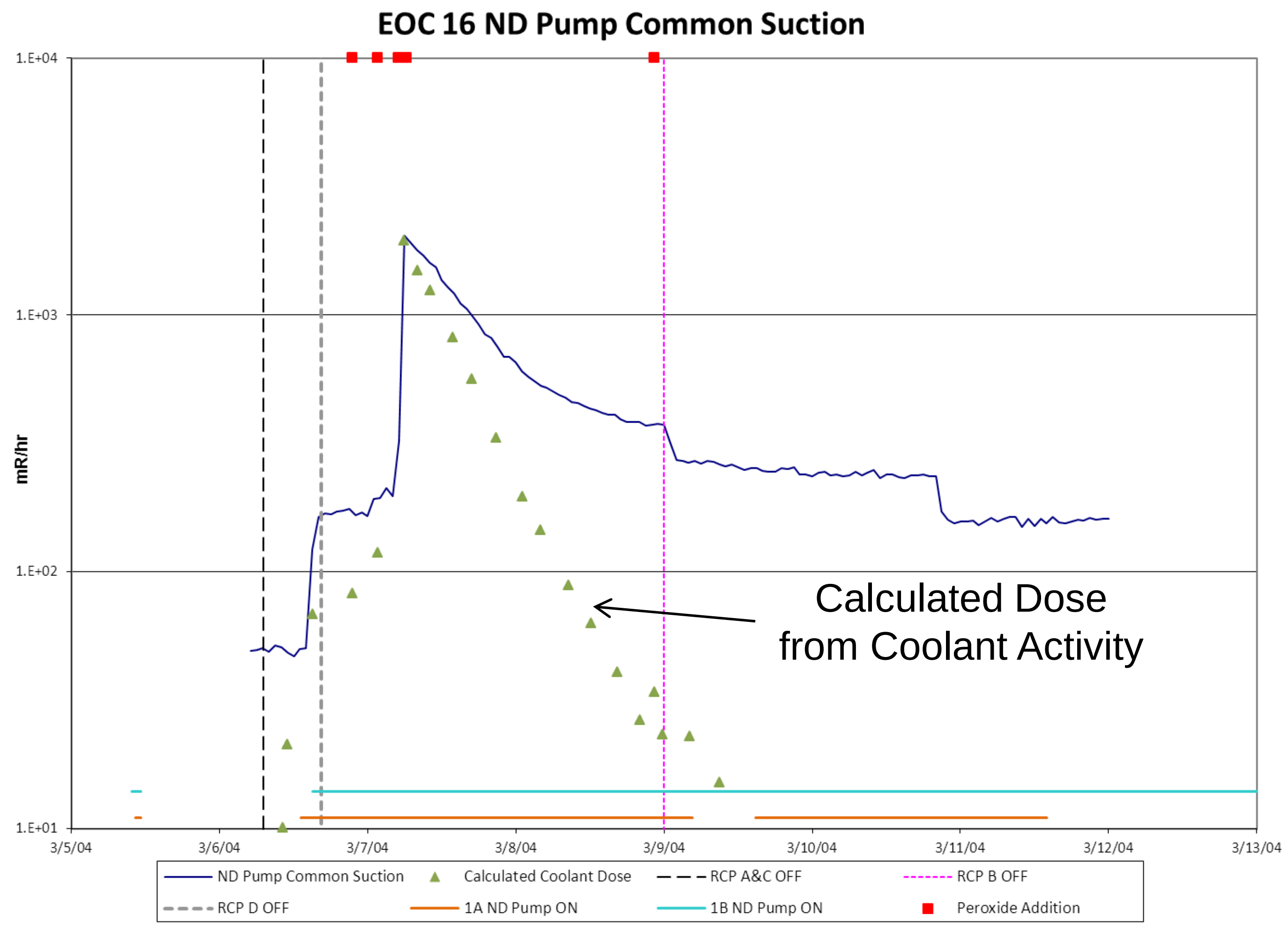
Determining the Impact of Particulates

- Dose rate from coolant activity calculated and subtracted from raw data



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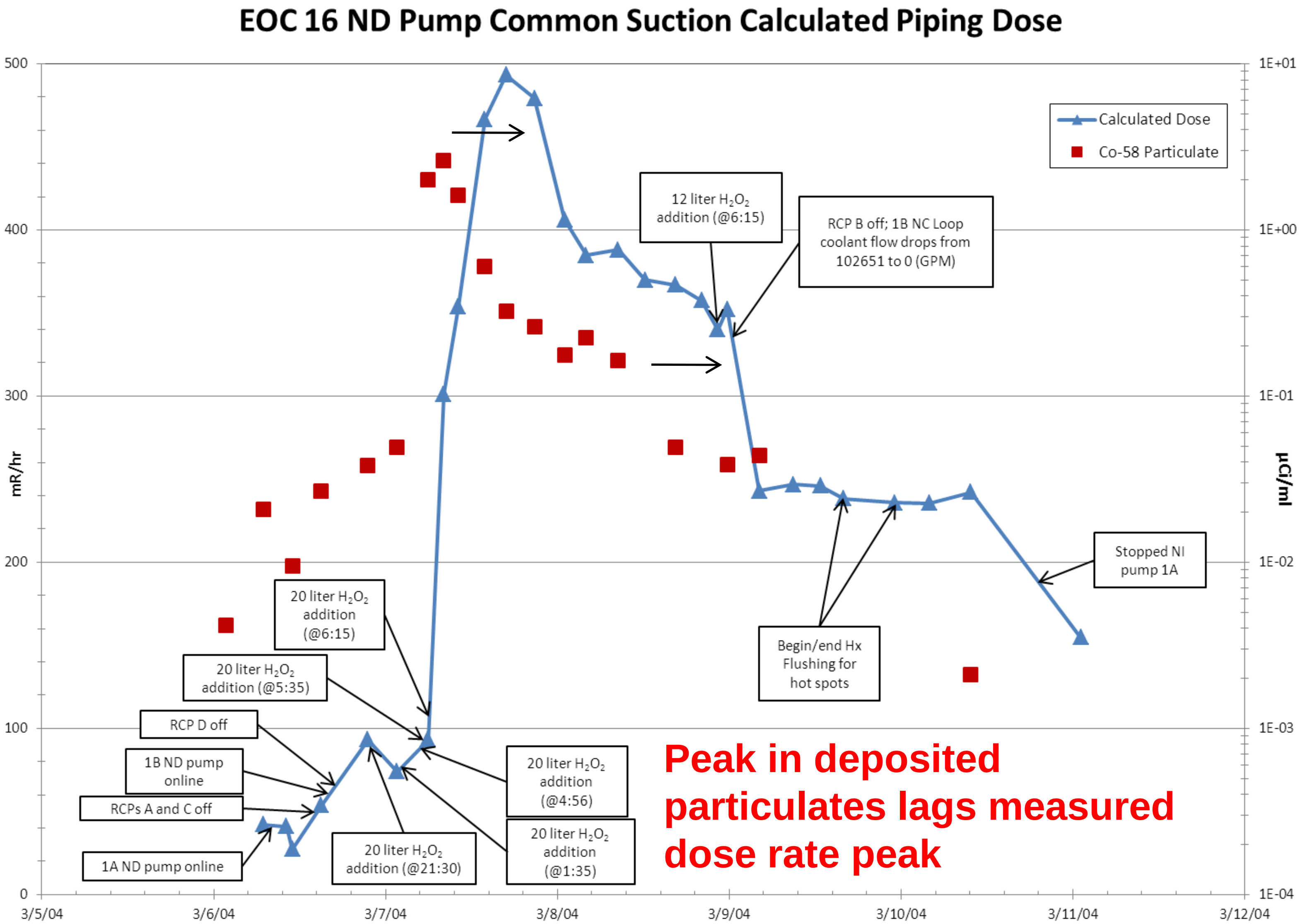
Correlating Measured Particulates to Calculated Impact on Dose Rate (1025305)



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Low Flow Area Activity Buildup/Dose Rates
Summary

- Insoluble deposition in dead legs and regions of low fluid shear during shutdown transients lead to increased dose rates
- At one plant dose rates in decay heat (RHR/ND) correlate reasonably with maximum particulate concentrations, but more data will be necessary to extend correlation to other plants
- Electronic dosimetry significantly improves capability to assess impacts of insoluble deposition as well as corrective actions to mitigate associated dose

*Impact of PWR Operational Events on Particulate Transport and Radiation Fields. EPRI, Palo Alto, CA: 2012. 1025305.

Minimizing PWR Radiation Fields
Summary

- Dose rates throughout the plant are dominated by the dynamics of each system and minimization technology may not impact dose rates uniformly throughout the plant.
- For high flow rate areas, attempts to correlate operational radiocobalt concentrations to dose rates should be based on median concentrations during the last several months of the cycle for Co-58 and multiple cycles for Co-60.
  - Co-60 significantly contributes to shutdown dose rates after 5 to 10 EFPY of operation therefore both Co-58 and Co-60 coolant concentrations must be considered.
- Correlations of low-flow system dose rates to peak particulate concentrations may exist but more data is needed.

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