Modeling and Simulation of Activated Corrosion Products Behavior under Design-based Variation of Neutron Flux Rate in AP-1000

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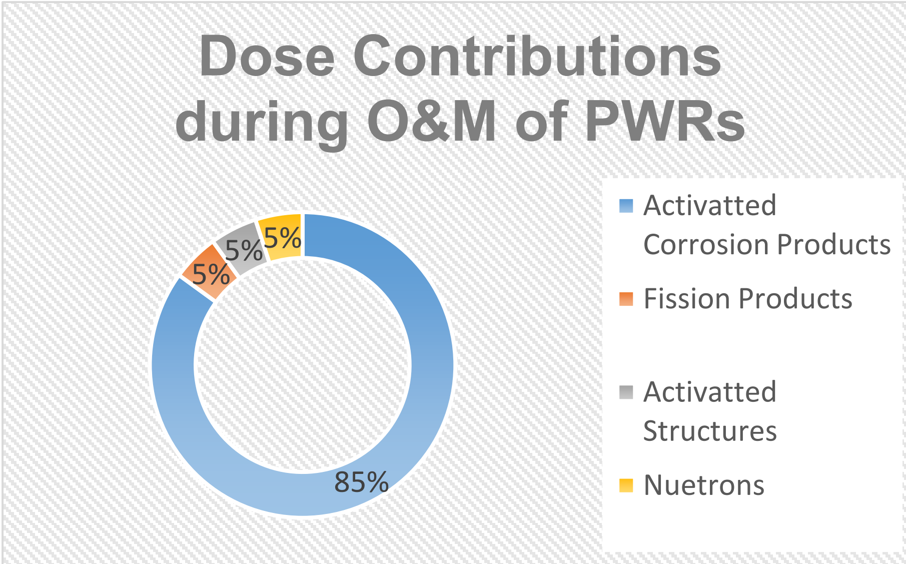
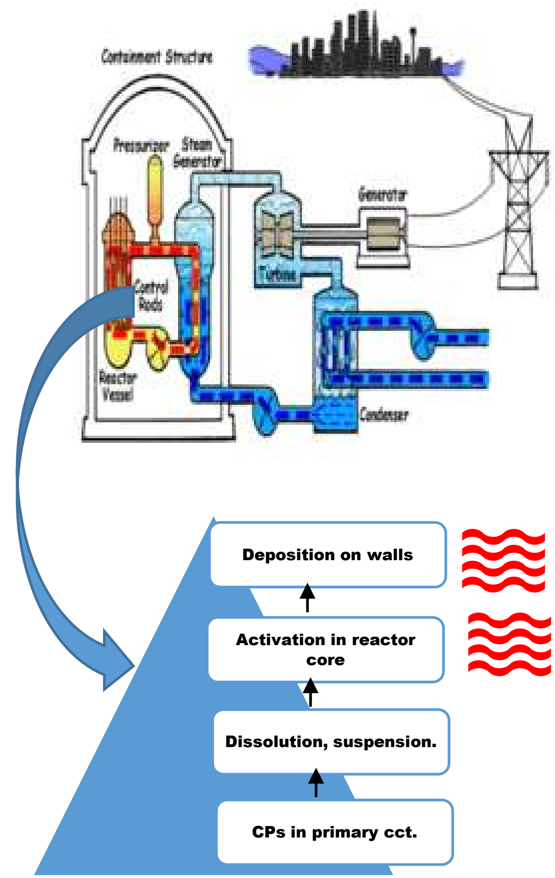
Overview

- Introduction
- Research Methodology
  - Mathematical Model
  - Computer program (CPA-AP100)
- Results & Discussions
- Conclusions

Introduction



- ➢Prolonged maintenance schedule
- ➢Loss of revenue ~ M$ /plant/annum
- ➢ACPs in PWRs (dominant installed, planned NPPs) widely focused



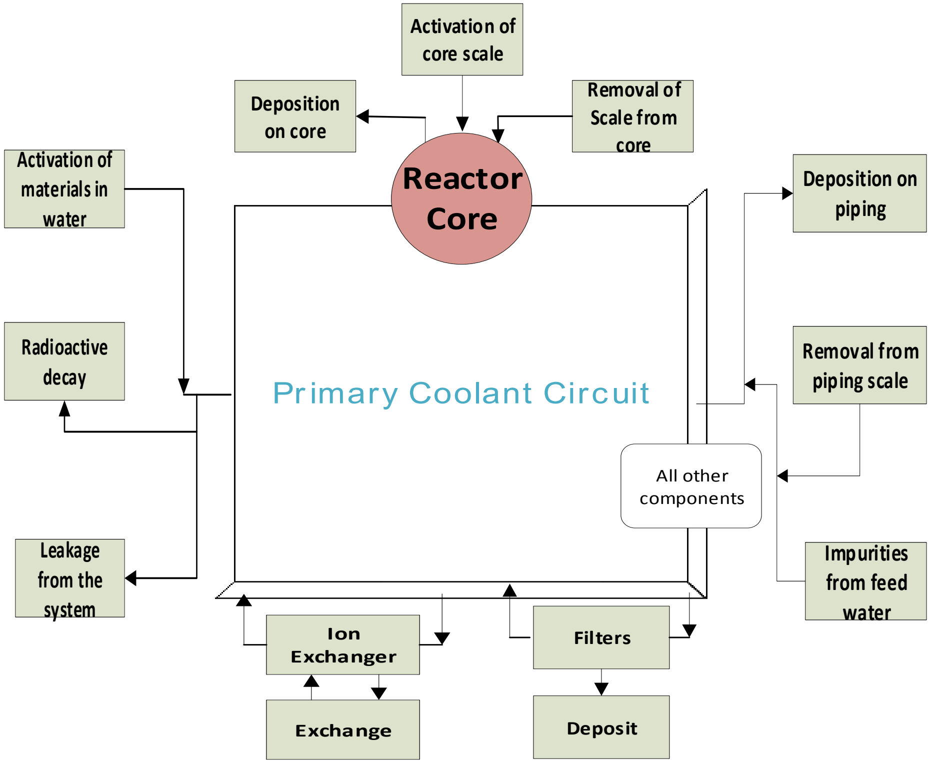
Introduction (Continued)

- Computer programs and codes are developed
  - PACTOLE series, CORA, CRUDSIM, ACE-II, MIGA-RT, CPAIR-P etc.
  - Empirical/semi empirical, applicable to certain designs & set of operating scenarios
- Corrosion Products Activity (CPA) in fresh reactor designs is challenging
  - Modified neutronics
  - New operational strategies
  - Flexible control features render vulnerability to CPA variation
- A home developed code (CPA-AP1000) employed to study ACPs in AP-1000
  - Steady state operation
  - Design-based variation in neutron flux rate

Research Methodology

Assumptions

- The composition of CPs corresponds to corroding material
- The material corrodes uniformly and homogeneously
- The intrinsic activity negligible
- The deposition on surfaces is proportional to conc. of CPs in water
- The IXs and filters removal is proportional to their concentration in coolant



Schematic of exchange pathways for modeling ACPs

Mathematical Model

$$p(t) = f(t)p_0 \quad (1)$$

$$f(t) = \begin{cases} p_1 & ,t < t_s \\ p_1 - \mu(t - t_{ts}) & ,t_{ts} \le t < t_{te} \\ p_2 & ,t \ge t_{te} \end{cases} \quad (2)$$

$$\phi_\epsilon = \frac{1-e^{-\lambda T_C}}{1-e^{-\lambda T_L}}\phi_0 \quad (3$$

$$\frac{dn_w}{dt} = \sigma f(t)\phi_\epsilon N_w - \left(\sum_j \frac{\varepsilon_j Q_j}{V_w} + \sum_k \frac{l_k}{V_w} + \lambda\right)n_w + \frac{k_p}{V_w}n_p + \frac{k_c}{V_w}n_c \quad (4)$$

$$\varepsilon_j Q_j = \varepsilon_i Q_i + \varepsilon_f Q_f + \varepsilon_c Q_c + \varepsilon_p Q_p \quad (5)$$

- $\varepsilon_i Q_i$, $\varepsilon_f Q_f$, $\varepsilon_c Q_c$, $\varepsilon_p Q_p$ ≡ Removal rates ($cm^3\ s^{-1}$)
- l_k ≡ Primary coolant leakage rate ($cm^3\ s^{-1}$)
- k_p and k_c ≡ Removal rate ($cm^3\ s^{-1}$) from scale
- V_c ≡ *Volume of deposits within the core* (cm^3)

Mathematical Model (Continued)

$$\frac{dN_w}{dt} = -\left(\sum_j \frac{\varepsilon_j Q_j}{V_w} + \sum_k \frac{l_k}{V_w} + \sigma f(t)\phi_\epsilon\right) N_w + \frac{k_p}{V_w} N_p + \frac{k_c}{V_w} N_c + S_w \quad (6)$$

$$S_w = \frac{C_0 S N_0 f_n f_s}{V_w A} \quad (7)$$

$$\frac{dn_c}{dt} = \sigma f(t)\phi_0 N_c + \frac{\varepsilon_c Q_c}{V_c} n_w - \left(\frac{k_c}{V_c} + \lambda\right) n_c \quad (8)$$

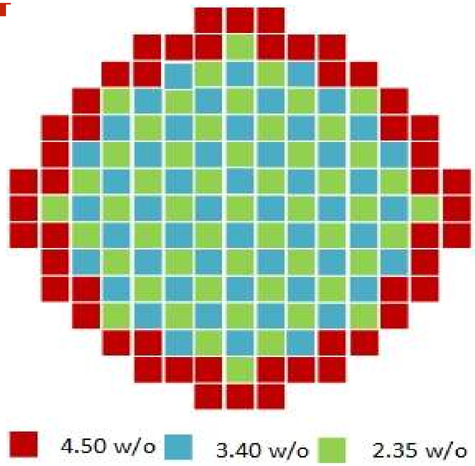
$$\frac{dN_c}{dt} = \frac{\varepsilon_c Q_c}{V_c} N_w - \left(\frac{k_c}{V_c} + \sigma f(t)\phi_0\right) N_c \quad (9)$$

$$\frac{dn_p}{dt} = \frac{\varepsilon_p Q_p}{V_p} n_w - \left(\frac{k_p}{V_p} + \lambda\right) n_p \quad (10)$$

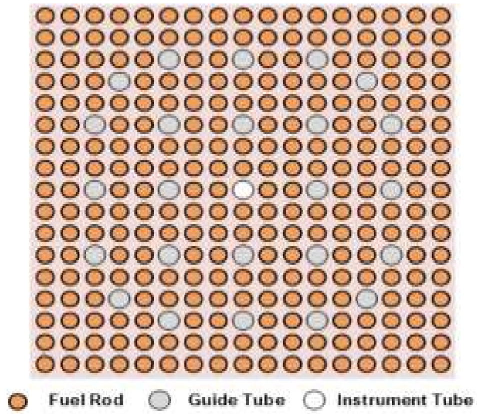
$$\frac{dN_p}{dt} = \frac{\varepsilon_p Q_p}{V_p} N_w - \frac{k_p}{V_p} N_p \quad (11)$$

Flux Calculations

- AP-1000 core power3400 MW_{th}
  - 157 fuel assemblies along with control and structural elements
  - Enrichment 2.35 w/0 to 4.50 w/017 X 17 fuel assembly (fuel rods264, guide tubes 24, central thimble)
  - PYREX, IFBA rods arranged in three, five different configurations give rise to total nine distinct assembly types
- MCNP is used to model the core and calculate group fluxes



Radial enrichment map



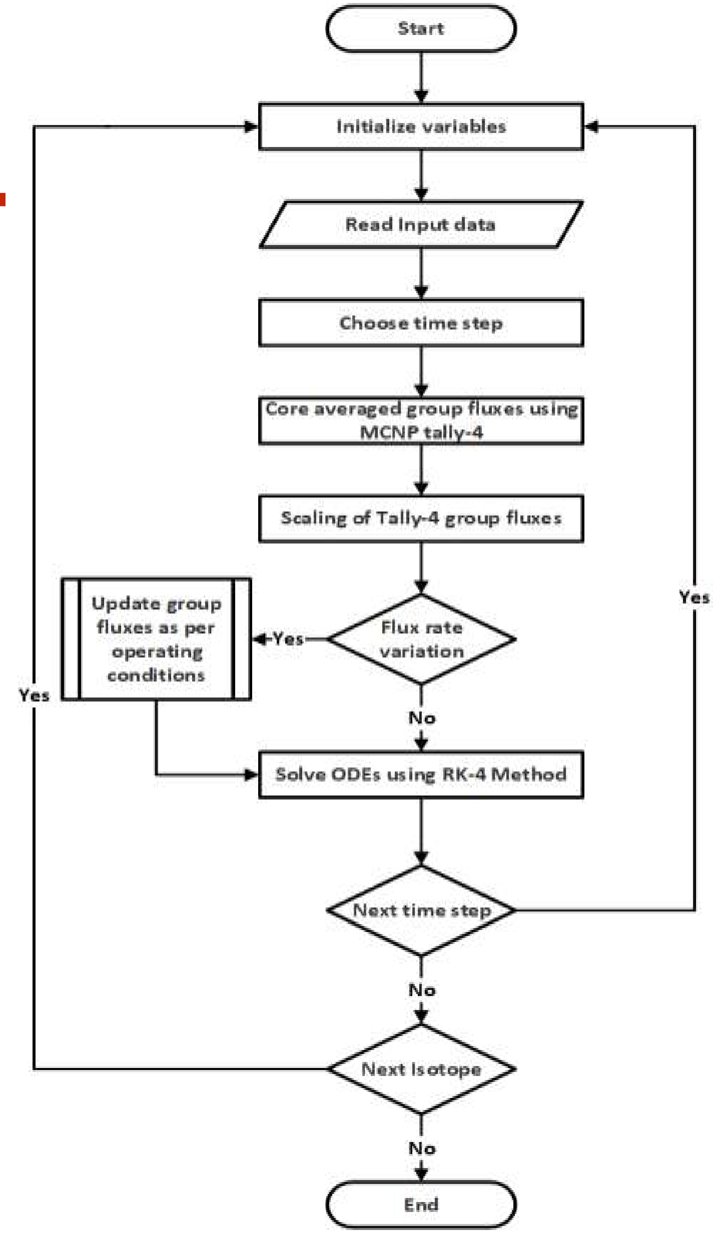
Fuel assembly configuration

CPA-AP100

- Corrosion Products Activity in AP-1000 (CPA-AP1000) using MATLAB
  - MCNP results scaled in data processing using eq.(12)

$$\phi_0 = \frac{P\,(Watt)\,\bar{\nu}\left(\frac{n}{fission}\right)}{1.6023\,x10^{-13}\left(\frac{J}{MeV}\right) w_f\,(MeV/fission)}\,\phi_{F4} \quad (12)$$

  - P is power, $\bar{\nu}$ is average number of neutrons released by fission, w_f is the energy released per fission and ϕ_{F4} is tally-4 flux



Results and Discussions

- ➢Simulations start time t=0, in clean state
- ➢Measured values of exchange rate for PWR used
- ➢The most sensitive parameter ($\varepsilon_i Q_i$) for AP-1000

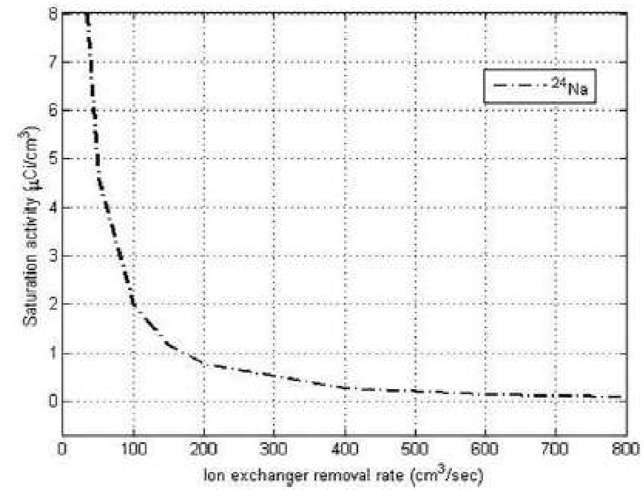


Fig. 4. Saturation specific activity of ^{24}Na at various ion exchanger removal rates for

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Dynamic response analysis of corrosion products activity under steady state operation and Mechanical Shim based power-maneuvering transients in *AP-1000*

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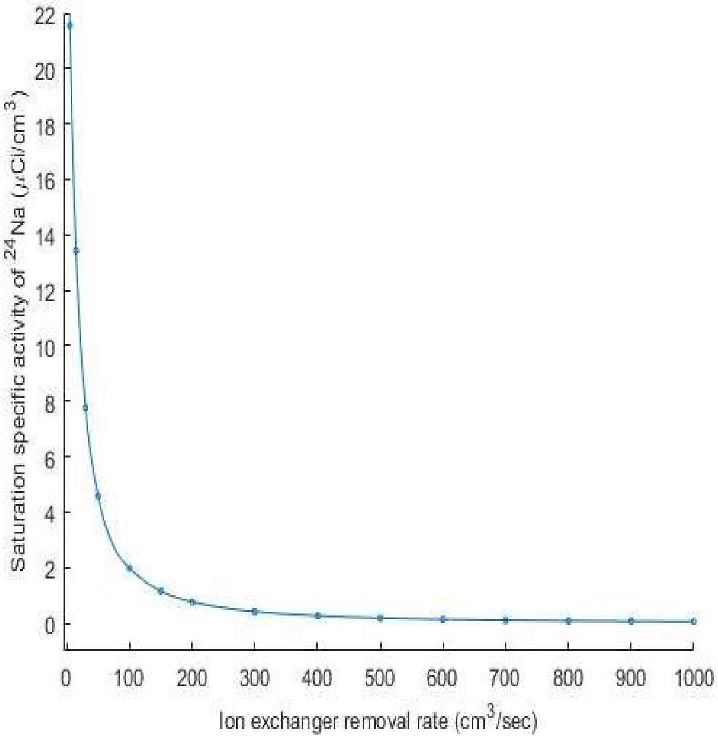
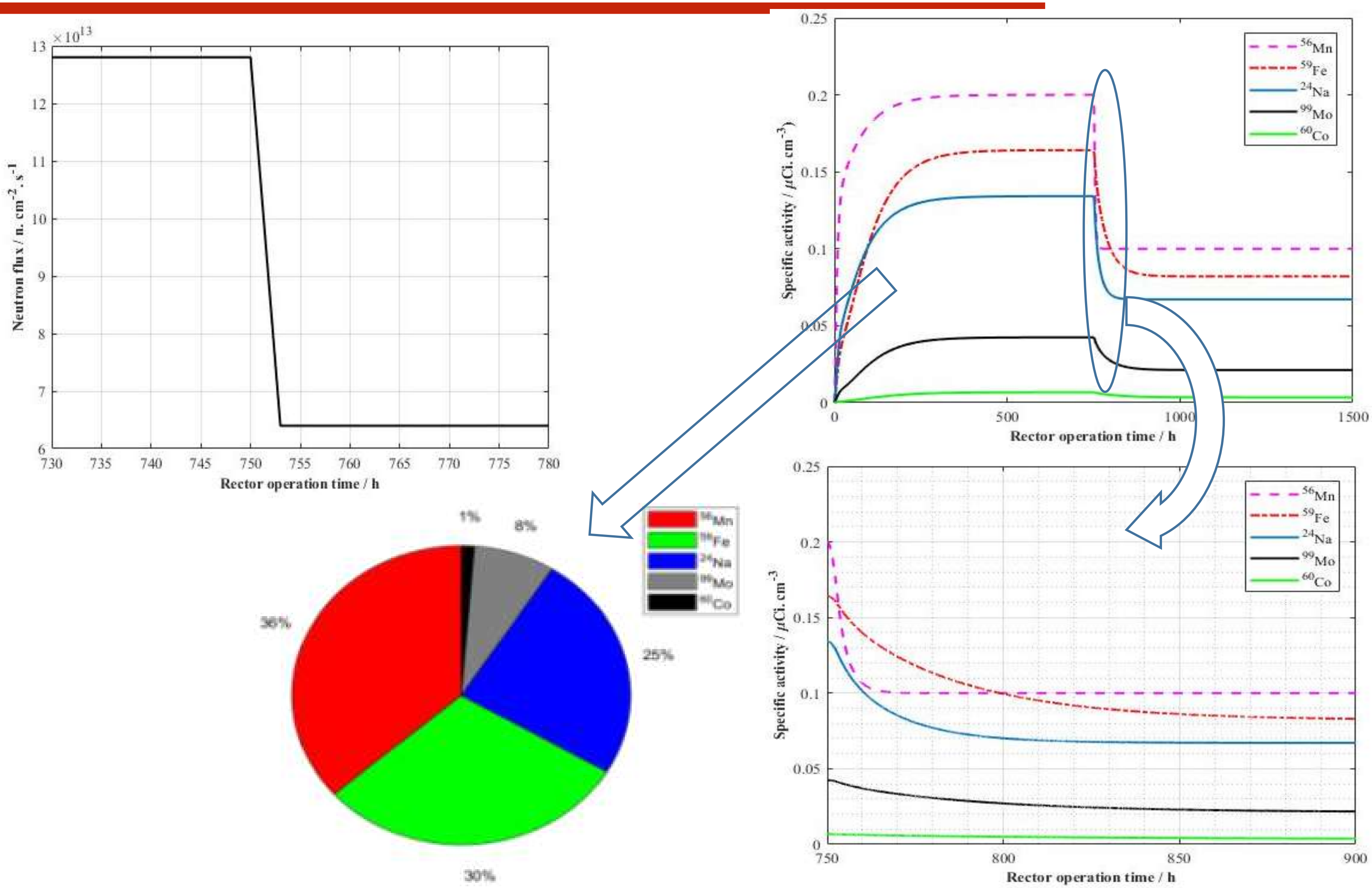
Ion-exchange Removal Rate

- The detailed analysis with more data point
- More detectable trend similar as previously worked out
- Selected optimal value of 600 $cm^3.\ s^{-1}$

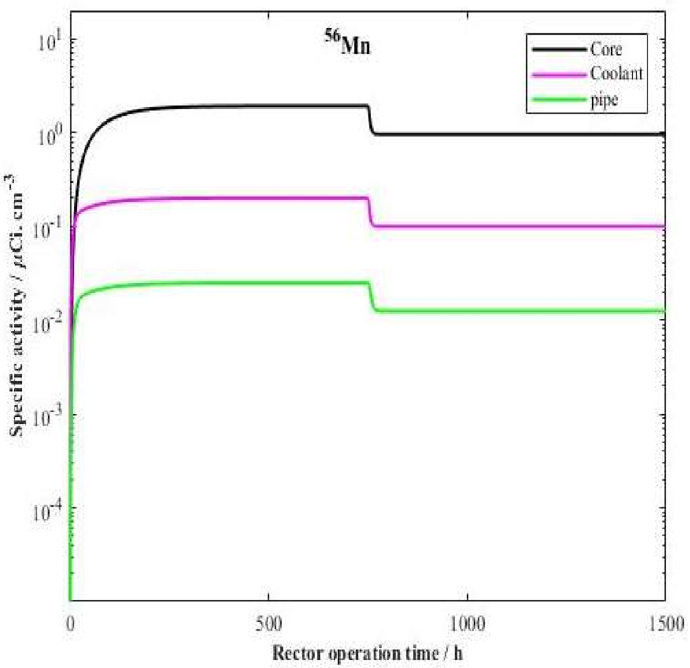


ACPs in primary coolant



^{56}Mn in coolant and on inner walls

- Corrosion rate increases steeply at the initial stage of a NPP operation, finally saturates
- Progressive accumulation due to continuous exchange of ACPs b/w coolant and walls
- Build up curves in respective zones shown similar behavior (core followed by coolant and pipe)
- Reasonable agreement with published results of typical PWRs



Conclusions

- **CPA evaluation in fresh reactors, a serious safety concern of regulatory authorities**
- **CPA-AP1000 code for SS operation and MSHIM based power maneuvers**
  - **Steady state:** ACPs build up and saturate
  - **During flux variation:** ACPs independently follow flux rate reduction
  - **Flux rate variation terminated:** New reduced saturation value

pipe coolant core

- **More detailed design based analyses required to envisage ACPs in different parts of the cct.**

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Thank you