# Validation of the Plate-out Model in the RADAX code used for Plate-out and Dust Activity Calculations at PBMR

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## Abstract

The two main sources of deposited activities in the Pebble Bed Modular Reactor's (PBMR) Main Power System (MPS), are plate-out of the small fraction of fission product activities released from the PBMR core, and deposition of these activities adsorbed on graphite dust generated during abrasion of the fuel spheres. PBMR uses the German code RADAX for the calculation of fission product transport, plate-out and dust deposition. In this paper a brief overview is given of the plate-out and dust deposition models implemented in the RADAX code. The results of testing activities that were performed for validation of the plate-out model in the RADAX code are also described. These tests form only part of the overall effort to fully verify and validate RADAX.

For validation of the plate-out model, results from past experiments in the out-of–pile loop experiment LAMINAR, as well as the two reactor bypass loop experiments VAMPYR-II of the AVR and the DRAGON Hot Gas Duct, were used as test cases. In this paper, the approach used to set up and execute the test cases is briefly described, examples of the test results are given and discussed, and an evaluation of the ability of the results to validate the RADAX code is provided.

***KEYWORDS: fission product transport, plate-out, dust, PBMR, RADAX***

## 1. Introduction

RADAX is the code used at PBMR for calculation of the radioactivity deposited on the MPS surfaces of the PBMR, due to the plate-out of atomic fission products released from the fuel in the core. During the same plate-out calculation, the amount of fission products circulating in the coolant is also calculated. This forms part of the source term that can leak from the MPS during normal operation, and which can be released from the MPS during a depressurization event. The code also calculates the deposition of dust on MPS surfaces and the amount of dust circulating in the coolant. This dust originates from the abrasion of fuel spheres against the walls in the fuel handling system, abrasion of fuel spheres against each other in the pebble bed, and mechanical wear of the graphite bottom reflector due to friction forces of the rolling motion of fuel spheres over its surface.

The computer code RADAX models the following transport processes:

1. Deposition of atomic/molecular condensable fission products from the flowing coolant

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gas to the surfaces of the MPS components (usually called plate-out),
2. Migration of fission products in wall materials,
3. Deposition of aerosol particles (usually called dust) on MPS components,
4. Resuspension of deposited aerosol particles from MPS surfaces during transients with increased kinetic energy density of the flowing gas (usually called lift-off).

RADAX was developed during the eighties (1978-88) mostly in the framework of the German High-temperature Helium Turbine (HHT) project for direct cycle HTR's where particular attention was paid to predicting the capability to decontaminate turbine components. Therefore, the activity transport in the wall materials in radial direction (vertical to the bulk flow) had to be described as well, which explains the code's name RAD (radial) AX (axial) and the fact that RADAX is virtually a 2-dimensional code.

RADAX was used for the radiological analysis of the HHT demonstration plant and the German two-cycle-HTR project, HTR-500. It was also applied to calculating plate-out and dust distribution in the primary system of the THTR after replacing the original THTR-specific code, NESSIE, which only accounted for the mass transfer characteristics of the circuit (model of absolute sink). Furthermore, RADAX was extensively used to evaluate plate-out loop experiments for the derivation of model-specific material parameters.

Since 2001 RADAX has been used for source term analysis of the PBMR. This new task led to a further extension implemented in RADAX4 describing the dust deposition under the laminar flow conditions in the PBMR-specific recuperators [1].

At present, RADAX does not contain a model for the interaction between the gaseous fission products and the suspended aerosol particles. The specific activities of dust particles due to the sorption of gaseous fission products are therefore estimated by making assumptions regarding the percentage of fission products released from the fuel, adhering to dust.

RADAX deals with the lift-off of deposited particles with a rather simple model originating from Windscale Advanced Gas-cooled Reactor experiences, which is currently being re-assessed by an investigation into a more refined model.

A full description of the plate-out and dust models implemented in RADAX and suggestions for validation actions, on which the work in this paper is based, is given in [2].

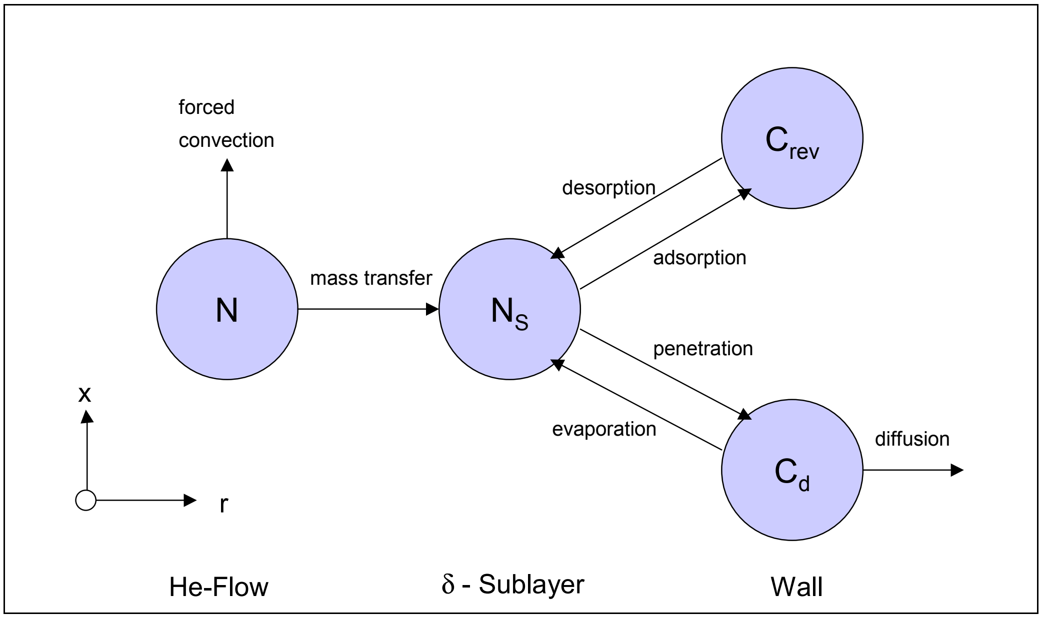
## 2. Description of the Plate-out Model

An adsorption/penetration model based on the work of Kress & Neill [3] and Iniotakis [4], has been implemented in the computer code RADAX. It describes the time-dependent plate-out of condensable atomic/molecular species by convection, mass transfer, adsorption/desorption and penetration (absorption)/evaporation processes. The basic plate-out model in RADAX is similar to that of alternative codes such as SPATRA.

The adsorption/penetration model calculates the transport rates between four local fission product reservoirs in the fluid-dynamic system depicted in Fig. 1:

1. Flowing gas bulk stream with fission product concentration N (atoms/cm$^3$),
2. Quiescent laminar sublayer directly adjacent to the surface with radially constant concentration $N_S$ (atoms/cm$^3$),
3. Reversibly adsorbed fission products at the surfaces with concentration $C_{rev}$ (atoms/cm$^2$),
4. Absorbed (penetrated) fission products diffusing into the walls with concentration $C_d$ (atoms/cm$^3$)

**Figure 1:** Flow Scheme of the Adsorption/Penetration Model with Four Reservoirs




The transport rates between above reservoirs are based on the following physical processes:

1. Forced convection of the bulk gas with its fission product concentration N(x) yielding an axial transport rate of

$$d\,(v\,N)\,/\,dx$$

with: v: fluid velocity (cm/s),
x: (axial) distance in flow direction (cm)

2. Turbulent or laminar mass transfer from the bulk stream into the laminar δ-sublayer with concentration $N_S$ yielding a radial transport rate of

$$h\,(N - N_S)$$

with: h: mass transfer coefficient (cm/s),
calculated by analogy with heat transfer replacing Nusselt with Sherwood number
Sh = (h d)/D (d=diameter of flow channel (cm), D=binary gas diffusion constant ($cm^2/s$))

3. Non-activated adsorption from the laminar δ-sublayer to the free surface of components with fission product coverage θ ($\theta = C_{rev}/C_{revmax}$, $C_{revmax}$: maximum adsorbed surface concentration) yielding a radial transport rate of

$$\alpha\,\beta\,v_\perp\,(1-\theta)\,N_S = \alpha\,\beta\,(kT/(2\pi m))^{1/2}\,(1-\theta)\,N_S$$

with: α: sticking factor (probability that atom hitting the free surface stays there)
β: fraction of atoms staying reversibly adsorbed at the surface
$v_\perp$: mean thermal molecular velocity perpendicular to the surface (cm/s)
k: Boltzmann constant (g $cm^2/(s^2K)$)
T: absolute temperature (K)
m: mass of fission product atom (g)
$1-\theta$ : fraction of free (uncovered) surface

4. Non-activated penetration (absorption) from the laminar δ -sublayer into the wall material yielding a radial transport rate of

   $$\alpha\,(1-\beta)\;(kT/(2\pi m))^{1/2}\;(1-\theta)\,N_S$$

   with: 1- β: penetration coefficient

5. Temperature-activated desorption from the surface into the laminar δ-sublayer yielding a radial transport rate of

   $$\upsilon\, C_{rev}$$

   with: υ : temperature dependent desorption constant (1/s)

6. Temperature-activated evaporation from the wall into the laminar δ-sublayer yielding a radial transport rate of

   $$\eta\, C_d(r_i)$$

   with: η : temperature dependent evaporation constant (cm/s)
   $C_d(r_i)$ : concentration at the inner surface of the wall (atoms/cm$^3$)

7. Diffusion in the wall material with appropriate boundary conditions at the inner and outer surface and at interfaces between oxide layer and bulk material accounting for different solubilities (partition coefficients)

8. Radioactive decay in all fission product reservoirs yielding extinction rates of

   $$-\lambda N,\; -\lambda N_S,\; -\lambda C_d\,,\; -\lambda C_{rev}$$

   with: λ: radioactive decay constant (1/s)

In Tab. 1 the major material data required for the adsorption/penetration model, i.e. desorption constants and penetration coefficients, are listed for the two elements for which validation tests are reported in this paper.

**Table 1: Material Data of the Adsorption/Penetration Deposition Model**

| Element | Material | $\upsilon_0$ (s$^{-1}$) | $E_{act}$ (kJ/mole) | Uncertainty range | 1-ß | Uncertainty range | Reference |
|---|---|---|---|---|---|---|---|
| Cs | Incoloy 800 600–800°C | 1x10$^{11}$ | 234 | ±13 | 1 x 10$^{-5}$ | 1x10$^{-6}$–2x10$^{-5}$ | [5], [6] |
| | Incoloy 800 <600°C | 1x10$^{11}$ | 184 | ±13 | 1 x 10$^{-5}$ | 1x10$^{-6}$–2x10$^{-5}$ | [6] |
| | Inconel 617 700°C | 1x10$^{11}$ | 230 | ±8 | 1 x 10$^{-6}$ | 1x10$^{-7}$–4x10$^{-6}$ | [5], [6] |
| | Inconel 617 900°C | 1x10$^{11}$ | 268 | ±8 | 1 x 10$^{-6}$ | 1x10$^{-7}$–4x10$^{-6}$ | [5], [6] |
| Ag | Incoloy 800 | 1x10$^{11}$ | 255 | ±13 | 1 x 10$^{-5}$ | 1x10$^{-6}$–1x10$^{-4}$ | [6] |
| | Inconel 617 | 1x10$^{11}$ | 240 | ±8 | 1 x 10$^{-6}$ | 1x10$^{-7}$–1x10$^{-5}$ | [6] |

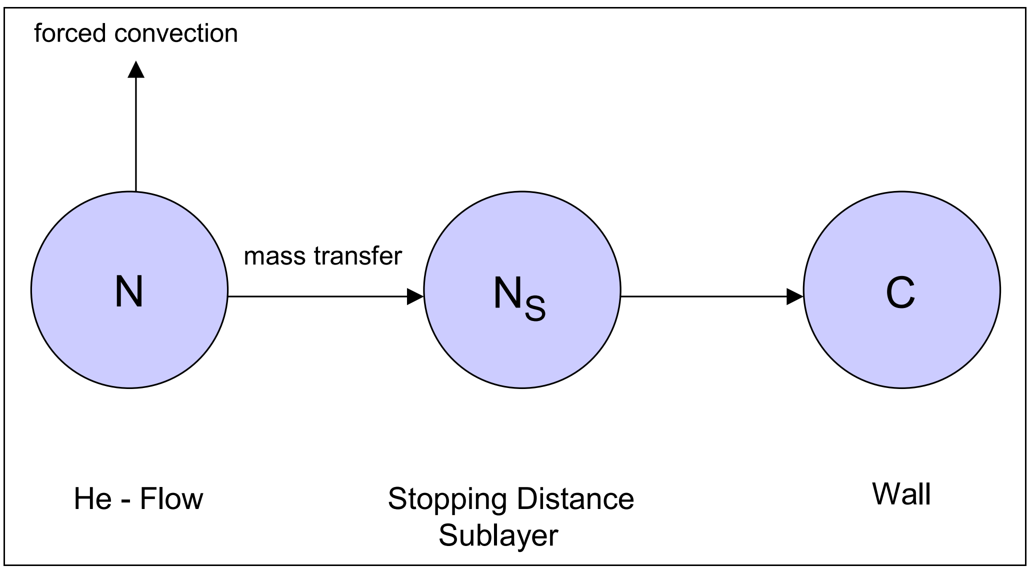
Where: Desorption constant: $\upsilon = \upsilon_0 \exp(-E_{act}/RT)$ (1/s)
$\upsilon_0$: frequency factor for desorption constant (1/s)
$E_{act}$: activation energy for desorption (kJ/mole)
T: absolute wall temperature (K)
R: gas constant (kJ/K/mole)

## 3. Description of the Aerosol Deposition Model

The aerosol particle deposition model in RADAX is similar to the plate-out model for atoms, with penetration coefficient = desorption constant = 0. It calculates the particle transport rates between the three reservoirs, which are depicted in Fig. 2 ($C_d$ reservoir of the plate-out model obsolete in the dust model):

1. Flowing gas bulk stream with submersed particle concentration N (particles/$cm^3$).,
2. Stopping distance SD-sublayer (SD = distance a particle with initial velocity $v_{par}$ and discrete diameter $d_{par}$ can move against the friction forces in a quiescent medium = thickness of the sublayer) adjacent to the wall surface with radially constant particle concentration $N_S$ (particles/$cm^3$),
3. Irreversibly deposited particles on component walls with solid particle concentration C (particles/$cm^2$).

**Figure 2:** Flow Scheme of the Aerosol Particle Deposition Model with Three Reservoirs




The transport rates between the above three reservoirs are calculated making use of the following physical processes:

1. Forced convection of totally entrained particles (concentration N in particles/$cm^3$, v: bulk gas velocity) yielding an axial transport rate of

$$\delta (v N) / \delta x,$$

2. Mass transfer from the bulk He-flow into the SD-sublayer (concentration $N_S$ in particles/$cm^3$) accounting for Brownian diffusion, turbulent diffusion, inertial impaction and gravitational sedimentation (horizontal deposition areas) yielding a radial transport rate of

$$h (N - N_S)$$

with: h: mass transfer coefficient (cm/s) calculated for turbulent conditions according to S. K. Beal [7] or laminar [1] conditions, in case of sedimentation onto horizontal surfaces h is increased with the sedimentation velocity $v_{sed}$ (cm/s):

$v_{sed} = g\ \tau$

with:
- $g$ — gravitational acceleration (981 cm/s$^2$)
- $\tau = d_{par}^2\ \rho_{par} / (18\ \eta)$ — relaxation time (s)
- $\rho_{par}$ — particle density (g/cm$^3$)
- $\eta$ — dynamic viscosity (g/(cm s))

3. Irreversible particle "adsorption" from the SD-layer to the free surface yielding a radial transport rate of

   $\alpha\ v_{par}\ (1 - C/C_{max})\ N_S$

   with $\alpha$ :sticking fraction of particles ($\alpha = 1.0$ for v << critical velocity for lift-off),
   $v_{par} = v_{Brown} + v_f$: radial particle velocity in the SD-layer (cm/s)
   where $v_f = f(v, d_{par})$ fluid dynamic radial velocity for particle diameter $d_{par}$, bulk gas velocity v and Brownian mobility $v_{Brown}$
   $C_{max}$ : maximum (saturation) surface concentration (particles/cm$^2$)

## 4. Application of RADAX Calculations in PBMR

The main application of the RADAX code at PBMR so far, has been for the calculation of plate-out of fission products and deposition of dust on the surfaces of the Power Conversion Unit (PCU). The source rate of fission products being released from the fuel in the core and entering the PCU, is calculated by two separate codes, GETTER and NOBLEG. The source rate of graphite dust particles entering the PCU is calculated with assumptions regarding the abrasion rate of the fuel spheres, and with Computational Fluid Dynamics (CFD) analysis of the percentage of particles not filtered off in the fuel handling system that enter the core with the fuel spheres. For calculation of the specific activities of the graphite dust, at this stage it is assumed that 10% of fission products released from the fuel will adhere to dust – this assumption is based on operating experience at the AVR [8]. Further research is currently being done at PBMR on the development of a complete dust-fission product interaction model, which will be implemented in a future version of the code.

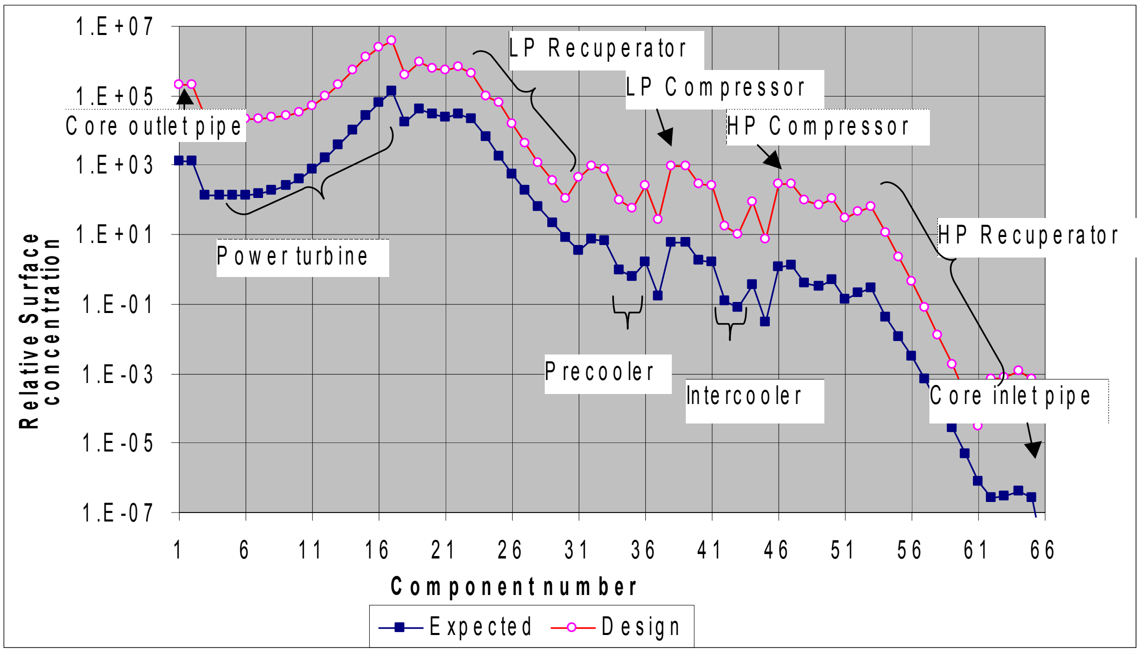
To calculate plate-out in the PBMR's PCU, the complete system must be modelled as input to the RADAX code. This is done by grouping together components with constant geometrical and thermal conditions. These components are then represented as an array of parallel cylindrical tubes with the total wetted surface area, flow area and hydraulic diameter of the array of tubes identical to the real component being modelled.

All the best-estimate values for core release rates, material-related parameters and mass transfer relations are used for calculating the expected plate-out values on components. In order to derive design or more conservative values, an uncertainty analysis is done using uncertainty ranges in the fission product core release rates, material-related parameters of the ad/desorption process, and the mass transfer relations used.

A typical example of the expected and design plate-out profiles calculated for one of the important fission products, Ag-110m, is shown in Fig. 3 below, with the massive depletion of this nuclide in the gas due to plate-out along the circuit, clearly visible.

With modeling similar to that used for the PCU, and using RADAX-calculated coolant concentrations at specific locations in the PCU where gas is extracted for the subsystems of the PBMR, such as the Fuel Handling Storage system (FHSS), the Helium Inventory Control System (HICS), the Core Conditioning System (CCS) and the Core Barrel Conditioning System (CBCS), the plate-out and dust deposition in these systems are also calculated with RADAX.

**Figure 3:** Ag-110m PCU Surface Concentration Distribution after 36 Years




## 5. Validation Tests Performed on the Plate-out Model

Experimental conditions given in [3], [9] and [10] for the LAMINAR, VAMPYR-II and DRAGON plate-out loops, were used for setting up RADAX test cases, which simulated geometry, thermo-hydraulic conditions, source rate of nuclides to the test sections and duration of the experiments as closely as possible.

For the LAMINAR out-of-pile loop experiment, test runs no. 4, 7 and 10, which measured plate-out of Cs on Incoloy 800 at a temperature of 700 °C, Inconel 617 at a temperature of 700 °C and Inconel 617 at a temperature of 900 °C, respectively, were used for the tests.

For the VAMPYR-II in-pile loop experiment of the AVR, experiment no. V.01, which measured plate-out of both Cs and Ag on both Incoloy 800 and Inconel 617 in the temperature range 430 to 725 °C, was used for the RADAX tests.

In the hot gas duct experiment of the DRAGON reactor, plate-out of Cs on Incoloy 800 at a temperature of 700 °C was tested, and this data was also used for RADAX calculations.

Some examples of the comparison between RADAX results and the experimental data are shown graphically in Fig.4-7 below.

**Figure 4:** Cs-134 Plate-out – Inconel 617 (Laminar Run 7)

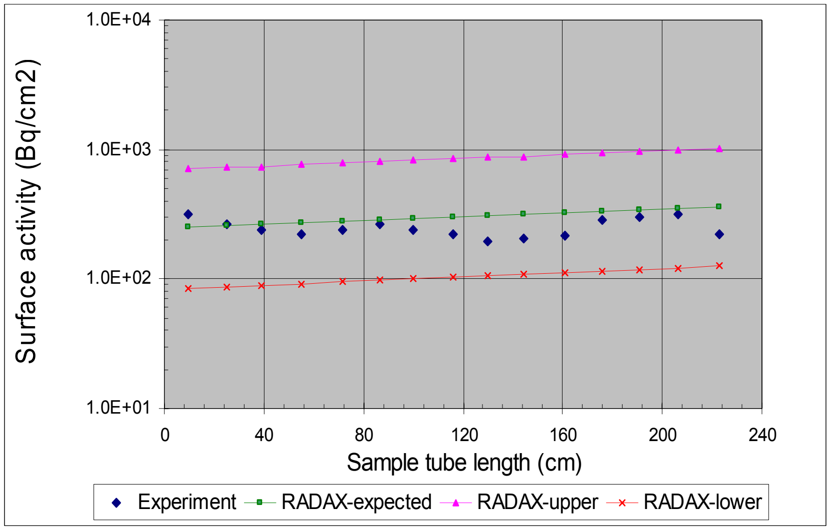



**Figure 5:** Ag-110m Plate-out –Incoloy 800 (VampyrII)

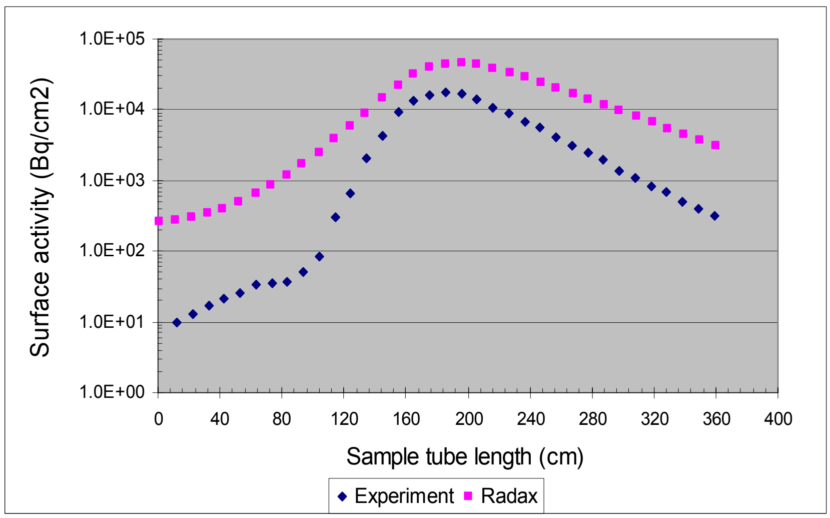



**Figure 6:** Cs-137 Plate-out – Incoloy 800 (VampyrII)

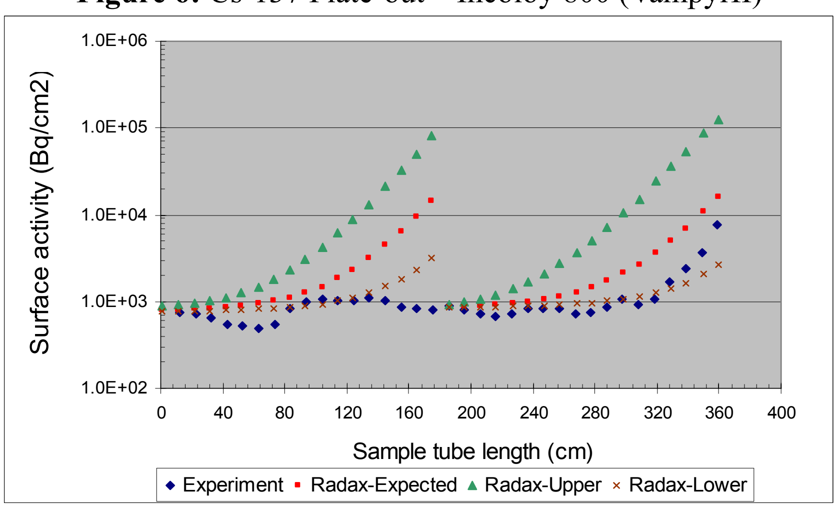
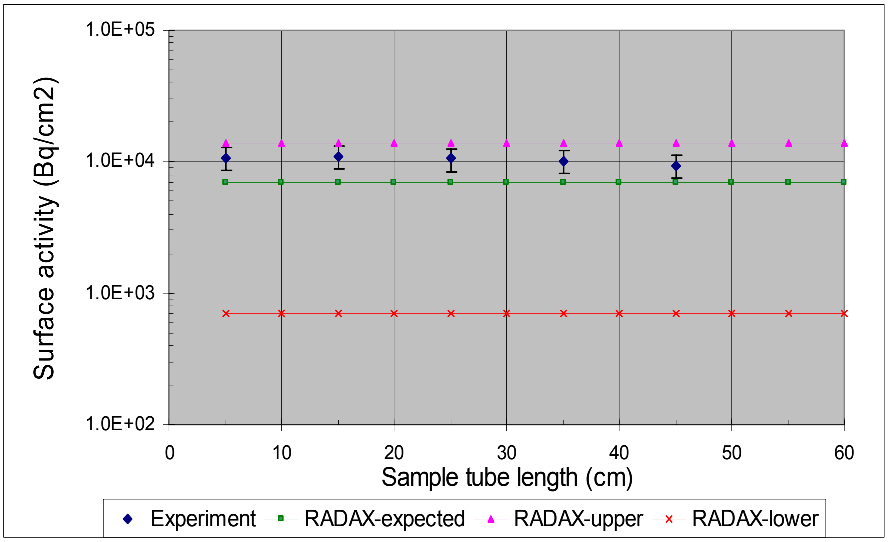


**Figure 7:** Cs-137 Plate-out – Incoloy 800 (Dragon)




The results of the comparison between RADAX calculated and experimental results at the end of the respective LAMINAR-loop runs, (one example in Fig. 4), show very good correlation.

The comparisons for Ag-110m plate-out on Incoloy 800 and Inconel 617 in the VAMPYR-II experiment (example in Fig.5), show a reasonable correlation, with the same shape of curve obtained as in the experiment. The change-over from ad/desorption control of the plate-out process in the high temperature part (first section of the experiment), to mass transfer in the lower temperature second section of the experiment, can be clearly seen and correlates well with the experimental findings.

The comparisons for Cs-137 plate-out on Incoloy 800 and Inconel 617 (example in Fig.6), with the material parameters as shown in the graph, do not show as good a correlation as in the case of Ag-110m. The unusual plate-out curve for Cs-137 in the VAMPYR-VII.01 experiment, with its flat profile with little or no temperature dependence currently has no reasonable explanation. Variations in the material parameters resulted in better fits, but from the other post-calculations done for Cs plate-out with the LAMINAR-loop and DRAGON Hot Gas Duct data, there is not enough evidence at this stage to change the desorption enthalpies and penetration coefficients from the values given in Tab.1.

Post-calculations of Cs-137 plate-out in the Incoloy 800 section of the DRAGON Hot Gas Duct experiment with RADAX (shown in Fig.7), show an extremely good correlation between the values calculated with the expected values of material parameters given in Tab.1, with that measured over a relatively long time period in the experiment.

## 6. Conclusions

For the plate-out model in RADAX, the comparisons between RADAX calculated results and experimental measurements of the LAMINAR-loop, the VAMPYR II.01 experiment of the AVR and the DRAGON Hot Gas Duct Experiment, provide sufficiently good correlations to enable validation of the plate-out model in the case of Cs and Ag deposition on Incoloy 800 and Inconel 617, using the material data for the adsorption/penetration plate-out model given in Tab. 1, across the whole range of temperatures of interest in an HTR primary circuit, from 900 °C in the LAMINAR-loop experiment to 400 °C in the AVR VAMPYR experiment.

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