SIMULATION OF SLUDGE DEPOSIT

ONTO A 900 MW STEAM GENERATOR TUBESHEET

WITH THE 3D CODE GENEPI

S. Pascal-Ribot[+], E. Debec-Mathet[*], D. Soussan[+], M. Grandotto[+]

ABSTRACT

Heat transfer processes use fluids which are generally not pure and can react with transfer surfaces. These surfaces are subject to deposits which can be sediments harmful to heat transfer and to integrity of materials. For nuclear plant steam generators, sludge build-up accelerates secondary side corrosion by concentrating chemical species. A major safety problem involved with such a corrosion is the growing of circumferencial cracks which are very difficult to detect and size with eddy current probes.

With a view to understand and control this problem, it is necessary to develop a mathematical model for the prediction of sludge behavior in PWR steam generators. Based on fundamental principles, this work intends to use different models available in literature for the prediction of the phenomenon leading to the accumulation of sludge particles at the bottom (the tubesheet) of a PWR. For that, a three-dimensional simulation of magnetite particulate fouling with the finite elements code GENEPI is performed on a 900 MWe steam generator. The use of GENEPI code, originally designed and qualified for the analysis of steam generators thermalhydraulics is done in two steps. First, the local thermalhydraulic conditions of the carrier phase are calculated with the classical conservation equations of mass, momentum and enthalpy for the steam/water mixture (homogeneous model). Then, they are used for the solving of a particle transport equation. The mass transfer processes, which have been taken into account, are gravitational settling, sticking probability and reentrainment describing respectively the transport of sludge particles to the tubesheet, the particle attachement to this surface and the re-suspension of deposited particles from the tubesheet. A sink term characterizing the blowdown effect is also considered in the calculations. Deposition on the tubebundle surface area is not modelled.

For this first approach, the simulation is made with a single particle size and density ($d_p = 10\ \mu m$, $\rho_p = 6000\ kg/m^3$) and as for the suspension, a 5 ppm mass concentration at the bottom of the downcomer is initially imposed. The magnetite particle concentration in a 900 MWe steam generator and the extent of deposit build-up onto the tubesheet are obtained. To some extent, the code predictions are qualitatively correct; however, quantitative evaluation and validation depend on future developments of models and await appropriate experimental data.

✦Atomic Energy Agency /Nuclear Reactor Division / Laboratory of heat exchangers and assemblies thermalhydraulics (CEA Cadarache - DRN/DEC/SECA/LTEA)(d.soussan@cea.fr)
* Atomic Energy Agency /Nuclear Safety and Protection Institute /Safety Evaluation Dept. (IPSN/DES) (edebec@cea.fr)

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NOMENCLATURE

- a constant (= 0.00046)
- C particle concentration (kg m^{-3})
- C_v constant (= 0.09)
- d particle diameter (m)
- D diffusion coefficient (m^2 s^{-1})
- D_H hydraulic diameter (m)
- E reentrainment coefficient (s^{-1})
- F flux (kg m^{-2} s^{-1})
- g gravitational acceleration (m s^{-2})
- h_{crit} critical deposit height (m)
- H enthalpy per unit mass (J kg^{-1})
- I unity tensor *or* number of iteration
- J superficial velocity (m s^{-1})
- k turbulent kinetic energy (m^2 s^{-2})
- L latent heat of vaporization (J kg^{-1})
- n unit normal vector
- N turbulence level
- p volume fraction of drained fluid
- P pressure (Pa) *or* sticking probability
- Q flow rate (m^3 s^{-1})
- r particle radius (m)
- r* dimensionless particle radius
- Re Reynolds number
- S source / sink term (kg m^{-3} s^{-1})
- S stopping distance (m)
- S^+ dimensionless stopping distance
- Sc Schmidt number
- t time (s)
- t_p particle relaxation time (s)
- t_t turbulence macroscale time (s)
- u* wall friction velocity (m s^{-1})
- V velocity (m s^{-1})

Greek letters

- α_p particle volume fraction
- β porosity $= \dfrac{\text{volume occupied by steam and water}}{\text{total volume}}$
- ε dissipation rate of turbulent kinetic energy (m^{2}s^{-3})
- μ dynamic viscosity (kg m^{-1} s^{-1})
- ν kinematic viscosity (m^2 s^{-1})
- ρ density (kg m^{-3})
- Ω control volume (m^3)
- ω deposited mass per unit area (kg m^{-2})

Superscript

- in inlet flow
- out outlet flow
- sat saturation

Subscript

- b blowdown
- c continuous *(carrier)* phase
- L liquid
- p particulate phase
- R relative
- t turbulent
- GS Gravitational settling

1 INTRODUCTION

Sludge build-up accelerates secondary side corrosion of Pressurized Water Reactors (PWR) steam generators (SG) tubes by concentrating chemical species. A major safety problem involved by such a corrosion is the growing of circumferential cracks [1] which are very difficult to detect and size with eddy current probes.

In the framework of its safety assessment, IPSN is interested in better understanding both thermalhydraulics and chemicals phenomena leading to such damages. The objective is to improve in-service inspections of the tube bundle so as to insure a satisfactory safety level.

To fulfill this goal, IPSN has been committed recently into a step of modeling. The first stage of the work presented hereafter is the knowledge of the behavior of sludge on the tubesheet (e.g. deposition, localization and reentrainment). Next stages will be the representations of fouling and sludges in different locations of the steam generators tube bundle.

Based on fundamental principles, this study intends to predict the phenomenon leading to the accumulation of sludge particles on the tubesheet of a PWR steam generator. For that, we use the finite-elements 3D code GENEPI [2], first devoted and qualified for the analysis of the two-phase flow thermalhydraulics in steam generators. First, the local thermalhydraulic conditions of the carrier phase are calculated using the classical conservation equations of mass, momentum and enthalpy for the steam/water mixture. Then, thermalhydraulic data from GENEPI are used for the mass conservation equation solving on the dispersed phase. Gravitational settling, sticking probability and reentrainment models describing respectively transport of sludge particles to the tubesheet, particle attachment to this surface and re-suspension of particles from tubesheet have been used. This gives sludge concentration in the steam generator and the magnitude of the deposit build-ups on the tubesheet.

A three dimensional simulation onto a 900 MWe steam generator of magnetite particulate fouling is presented. The effect of blowdowns, located in the tubelane of such steam generators has been studied in the particle mass equation.

2 MATHEMATICAL MODEL

Basically, there are two approaches commonly used to predict particulate two-phase flows. One, called the Lagrangian or "tracking" approach [3], treats the particles as discrete entities. The other, used in this development, is the Eulerian approach. The cloud particles is regarded as a continuum, that is as a second fluid. Hence, the model is formulated in terms of two sets of conservation equations governing the balance of mass, momentum and energy of each phase. However, the difficulties associated with the resolution of two momentum equations involving the specification of interfacial interactions terms between two phases, can be significantly reduced by formulating two-phase problems in terms of the drift-flux model [4]. In this model, the motion of the whole mixture is expressed by the mixture-momentum equation with the kinematic constitutive equation specifying the relative motion between phases. In addition, assuming a dilute suspension ($\alpha_p \ll 1$), particles have no influence on the flow ("one-way coupling" [5]), the problem can be uncoupled and resolved in two separated stages.

2.1 The carrier phase

The first step concerns the solving of the secondary fluid conservation equations. In the S.G. case, the secondary fluid is a mixture of two phases (steam/water). The liquid and gas are here assumed to belong to a homogeneous emulsion called the carrier phase and suffixed in equations "c" where the components are not identified.

As mentioned earlier, the GENEPI computer code is a finite-element 3D steady-state code developed and qualified at C.E.A. Laboratory (LTEA) for the analysis of steam generator thermalhydraulics. The Navier-Stokes equations are time and volume averaged and it leads to

3D governing equations (mass, momentum in each direction and enthalpy balances for a steam/water mixture) which are solved, since for secondary side the mixture flows through complex geometry (tube bundle, flow distribution baffle, tube support plates, anti-vibrating bars, moisture separators), for an equivalent solid-fluid medium [2].

The thermodynamic and kinematic features of the carrier flow (P_c, H_c, V_c, ρ_c, μ_c) are then used to solve the particle transport equation.

2.2 Sludge deposition

The second step, on the basis of the previous results consists in solving the dispersed phase mass conservation equation. The dispersed phase is assumed to be composed of set of **neutral** particles **spherical** in shape and **uniform** in size. Sludge concentration in the S.G. and magnitude of the deposit build-ups on the tubesheet are determined by solving the particulate transport equation. In this first study, the processes which govern the behavior of sludge are gravitational settling [4], surface attachment [6] and reentrainment mechanisms [7].

Without any chemical reactions, the local particle mass conservation equation is :

$$\frac{\partial \rho_p}{\partial t} + \mathrm{div}\left(\rho_p \vec{v}_p\right) = 0 \tag{1}$$

that is expressed, following a time averaging and homogenization process as :

$$\beta\frac{\partial \alpha_p \rho_p}{\partial t} + \mathrm{div}\left(\alpha_p \rho_p \vec{V}_p\right) = \beta S_p - \mathrm{div}\left(-D_{t_p}\,\overrightarrow{\mathrm{grad}}\left(\alpha_p \rho_p\right)\right) \tag{2}$$

In equation (2), the first term of right member is the source/sink term characterizing the deposit and removal of particles. The second term of right member characterizes a particle turbulent dispersion phenomenon which has been modeled as a Fick's law diffusion process [9] :

With : $\alpha_p\, \rho_p = C_p$ (3)

Equations (5) becomes under its stationary form :

$$\beta\, \vec{V}_p \cdot \overrightarrow{\mathrm{grad}}\, C_p + C_p\, \mathrm{div}\left(\beta\, \vec{V}_p\right) - \mathrm{div}\left(\beta\, D_{t_p}\, \overrightarrow{\mathrm{grad}}\, C_p\right) = \beta\, S_p \tag{4}$$

It is discretised by a finite element method for which a Galerkin variational formulation has been adopted. The resulting algebraic system is solved by a conjugate gradient square (CGS) method.

2.2.1 Model for particulate turbulent diffusion

The effect of the carrier phase turbulence on the particle transport rate is taken into account in equation 4 through the dispersion term D_{t_p}. By analogy with the single-phase turbulence flows where :

$$D_t = \frac{\nu_t}{Sc_t} \tag{5}$$

the particulate turbulent diffusivity is modeled by the following relation :

$$D_{t_p} = \frac{\nu_{t_p}}{Sc_{t_p}} \tag{6}$$

which requires for the dispersed phase the definition of an "effective" turbulent kinematic eddy viscosity ν_{t_p} and of a turbulent Schmidt number Sc_{t_p}.

- The Chen work [10] based on the Meek and Jones [11] calculations propounds :

$$\frac{\nu_{t_p}}{\nu_{t_c}} = \frac{1}{1 + t_p/t_t} \tag{7}$$

where :

* ν_{t_c} is the turbulent or "eddy" viscosity given by the k - ε turbulence model :

$$\nu_{t_c} = C_V \frac{k^2}{\varepsilon} \tag{8}$$

with C_V = 0.09, k proportional to the kinetic energy of the average flow, and the dissipation rate given by : $\varepsilon = C_D \frac{k^{3/2}}{D_H}$ with $C_D = 1$.

* t_t is the time scale of the energetic eddies given by [12] :

$$t_t = 0.165 \frac{k}{\varepsilon} \tag{9}$$

* t_p is the Stokes particle relaxation time which is for a rigid particle [9] :

$$t_p = \frac{\rho_p d_p^2}{18 \mu_c} \tag{10}$$

- The choice of turbulent Schmidt number is set to be : $S_{c_{t_p}} = 0.7$ (11)

following the testing of Chen and Wood [13] for axisymmetric flows.

2.2.2 Model for particle velocity

Since the motions of both carrier and dispersed phases are assumed to be strongly coupled, the use of the drift-flux model [4] seems to be well appropriate although this latter is an approximate formulation in comparison with the more rigorous two-fluid formulation. The relative motion between phase is defined by :

$$\vec{V}_R = \vec{V}_p - \vec{V}_c \tag{12}$$

As we precised earlier in this paper, for horizontal surface, the particle transport velocity includes only the gravitational settling contribution and the expression for the relative velocity is reduced to : $\vec{V}_R = \vec{V}_{R_{GS}}$ (13)

Drawing heavily on Ishii's work [4], where the following homogeneous values have been defined :

- drift velocity $\vec{V}_{pJ} = \vec{V}_p - \vec{J} = (1 - \alpha_p)\vec{V}_R$ (14)

- superficial velocity $\vec{J} = \alpha_p \vec{V}_p + (1 - \alpha_p)\vec{V}_c$ (15)

it appears (eq : 14) that knowing the value of $\bar{V}_{pJ}$ [14] leads to the solution of $\bar{V}_R$, for a dilute suspension ($\alpha_p << 1$). Physically, $\bar{V}_{pJ}$ is the relative velocity of the dispersed phase with respect to volume center of the mixture.

$$\bar{V}_{pJ} \approx \frac{10.8\mu_c}{\rho_c r_p} \psi^{4/3} \frac{\rho_c - \rho_p}{\Delta\rho} \frac{\bar{g}}{|\bar{g}|} \tag{16}$$

where :

Stokes regime	Viscous regime	Newton regime
$r_p^* \leq 1.31$ $Re_p \leq 1$	$1.31 < r_p^* \leq 34.67$ $1 < Re_p \leq 1000$	$r_p^* \leq 34.67$ $Re_p > 1000$
$\psi = [0.02\, r_p^{*3}]^{4/3}$	$\psi = 0.55\, [(1 + 0.08\, r_p^{*3})^{4/7} - 1]^{3/4}$	$\psi = 17.67$

with :

- $\Delta\rho = |\rho_p - \rho_c|$
- dimensionless particle radius $r_p^* = r_p \left[\frac{\rho_c g \Delta\rho}{\mu_c^2}\right]^{1/3}$
- particle Reynolds number $Re_p = \frac{\rho_c d_p \|\bar{V}_R\|}{\mu_c}$

For a dilute suspension, we have : $\bar{V}_p = \bar{V}_c + \bar{V}_{pJ}$ (17)

Moreover, inside a recirculating steam generator, sludge is not suspended in the vapor which implies that the particles are mainly present in the liquid part of the carrier phase and :

$$\bar{V}_p = \bar{V}_{c_L} + \bar{V}_{pJ} \tag{18}$$

2.2.3 Attachment model

The problem of attachment can be formulated [15] statistically in terms of P, the probability that a particle which gets to the wall sticks to it or, alternatively, the fraction of particles reaching the wall which stay there (before any reentrainment). The attachment particle flux F_a can be directly correlated with the incident flux, that is :

$$F_a = P\, C_p \left(\bar{V}_p \cdot \bar{n} \right) \tag{19}$$

For Beal [6], the sticking probability for suspended particles depositing on the wall is a function of the dimensionless stopping distance S^+. Based on Watkinson's experiments [16] with sand grains suspended in water, he propounds for P the correlation :

$P = 1 \qquad S^+ \leq 2.4$

$$P = \left(\frac{2.4}{S^+}\right)^4 \quad S^+ > 2.4 \quad \text{with : } S^+ = \frac{S u^*}{\nu_c} \quad \text{and } S = \frac{0.05 u^* \rho_p d_p^2}{\mu_c} + \frac{d_p}{2} \tag{20}$$

2.2.4 Reentrainment model

Reentrainment is the removal of previously deposited particles by the scrubbing action of the fluid flowing past the surface. If the hydrodynamic force is large enough to overcome the adhesion, the particle will be detached from the surface and entrained in the flow. The reentrainment flux F_r is the flux of material leaving the surface and can be expressed by [17] :

$$F_r = E\omega_p \Phi(\omega_p) \tag{21}$$

where E is the reentrainment coefficient,

ω_p the deposit weight per unit area,

$\phi(\omega_p)$ a function defined as : $\phi = 1$ if $\omega_p \leq \omega_{crit}$

$$\phi = \frac{\omega_{crit}}{\omega_p} \text{ if } \omega_p > \omega_{crit}$$

In this expression 21, it is assumed that F_r is proportional to ω_p up to some critical value of ω_p, noted ω_{crit}. ω_{crit} may represent only one layer or perhaps several layers of particles and can be interpreted in term of critical height :

$$\omega_p = \rho_p h_{crit} \tag{22}$$

For the coefficient E, the present modeling is in the spirit of Cleaver and Yates [7], who have developed a theoretical treatment in which both deposition and reentrainment can occur simultaneously. For them reentrainment is the result of bursts of the viscous sublayer which are taking into account through the reentrainment coefficient E. They give :

$$E = -\frac{u^{*2} \operatorname{Log}\left(1 - \frac{a}{270}\right)}{75 v_c} \tag{23}$$

where a is the fraction of particles within the turbulent burst area that is removed per burst. The data most like steam generators are those of Newson and al. [18] with a = 0.00046 for magnetite deposited on aluminum.

2.2.5 Blowdown effect

Blowdown devices located in the tubelane of a 900 MWe PWR steam generator are used to purify the secondary fluid. In the particle transport equation, their effect have been taken into account through a sink term, the loss of particle due to the continuous draining. Let p be the fraction of fluid flow rate drained through the tubelane blowdowns. Thus, the amount of sludge evacuated through it can be simply expressed by the sink term :

$$S_b = p \frac{Q^{in}}{\rho_c \Omega_b} \tag{24}$$

where Ω_b is the volume of finite elements containing the blowdowns, and Q^{in} is the inlet carrier fluid flow rate.

2.2.6 Summary

- Step 1 : calculation of the steady state carrier phase flow
  ↳ mixture Pressure P_c, Enthalpie H_c, and Velocity V_c solved, as well as derived quantities (ρ_c, μ_c, V_{cL}, u^*).
- Step 2 : solving of particle transport equation 2,

with a Dirichlet inlet boundary condition for C_p,
and the following empirical models :

* Gravitational settling is taken into account through the relative velocity of particles with regard to fluid velocity. Deposit is seen as the particle downward flow, penetrating the singular obstacle.
* Reentrained and non-attached particles fluxes consist of the source terms in the transport equation.
* Particles removal through blowdowns is a sink term, implicitely treated since depending on C_p.

3 APPLICATION ONTO THE 900 MWE S.G.

Steam generators in nuclear power plants based on Pressurized Water Reactors (PWR) transfer heat from a primary coolant system to a secondary coolant system. The 900 MWe S.G. is a natural-circulation steam generator with an annular downcomer. The 22.2 mm (7/8") diameter tube results in 4707.8 m^2 heat exchange tube surface area. A cutaway view of this steam generator and its operating conditions are given in Figure 1. The hot primary fluid from the reactor circulates inside the tubes, heating the secondary flow, which evaporates at it rises inside the bundle wrapper.

A three-dimensional Cartesian coordinate system is used to create the computational mesh (Figure 3) and all the singular obstacles (tube support plates, anti vibrating bars) are represented in two-dimension (Figure 2).

3.1 The carrier phase

The models used for the carrier phase are the following [2]

- Heat transfer :Dittus-Boelter correlation for the primary fluid, and for the secondary fluid : Groeneveld correlation in single phase forced convection, Jens and Lottes correlation in nucleate boiling and the maximum flux method for the intermediate regime.
- Kinematic desequilibrium : drift flux model is used for the secondary two-phase flow with Lellouche-Zolotar correlation.
- Turbulent viscosity : Schlichting model.
- Turbulent Prandtl number = 0.5
- Friction due to tube bundle : Colburn model for parallel flows, Idelcik model for oblique flows, Chisholm correlation for the two-phase multiplier.
- Friction due to singularities : Idelcik model is used for the friction coefficient.

Figures 4, 5 show , on the tubesheet, the density and the quality of the carrier phase respectively. The thermal disequilibrium between hot and cold legs is obvious; besides, the tangential velocities (Figure 6) seem to be symmetrically distributed on the tubesheet.

3.2 The dispersed phase

For this simulation we chose a particulate mass concentration of 5 ppm at the bottom of the downcomer. Particles have an arbitrary uniform diameter of 10 µm with a density of 6000 kg/m^3. In our first approach gravitation is the only phenomenon which causes the particle deposition onto the S.G. tubesheet. The deposited material may then later be entrained by a turbulent action of the fluid flowing past the tubesheet.

In order to better assess the influence of blowdowns on sludge deposit, during S.G. operating, a computational loop is performed with GENEPI, which consists in assigning to the inlet particle concentration C_p the outlet value issued from the previous iteration :

$$\left[C_p^{in}\right]^j = \left[\frac{\rho_c^{in}}{\rho_c^{out}} \times C_p^{out}\right]^{j-1} \quad \text{with} \quad \left[C_p^{in}\right]^0 = 4\ 10^{-3}\ \text{kg/m}^3 \tag{25}$$

Following the previous data, the GENEPI computation is done with a particulate turbulent diffusion coefficient assessed with a 20 % turbulence level, which gives 2.4 10^{-2} m^2/s, and the fraction of fluid flow rate drained through the tubelane blowdowns p is assumed to be 0.3 %.

The settling flux ($kg/m^2.s$) on the tubesheet (Figure 7) is greater on the hot leg than on the cold one when only gravitational settling model is taken into account. Much larger sludge deposits are also predicted close to the central line of S.G., when the blowdowns located in this area are not simulated (Figures 7&9). In Figures 8 and 9, when a sticking probability model and reentrainment model are included in the computation, the deposit flux ($kg/m^2.s$) presents a maximum close to the center of both cold and hot legs.

Due to doubts within data used to represent S.G. operating conditions, sludge deposition results reported in Table 1 must be cautiously interpreted.

The first column gives the rate of particle deposit flux compared to the particle inlet flux, assuming only one blowdown action, e.g. one iteration. In the second and third columns, an assessment of sludge mass deposited (kg/year) and average sludge deposit thickness (mm) respectively onto the tubesheet have been done. As for the thickness calculations, sludge deposit is assumed to be concentrated on half of the tubesheet, in the maximal deposit flux area.

Model	Deposit %	Quantity of sludge deposit (kg/year)	Average thickness (mm)
Gravitational settling	0.6	1772	77
Gravitational settling + sticking probability	0.17	520	22
Gravitational settling + sticking probability + reentrainement ($h_{crit} = 10^{-6}$ m)	0.11	332	14
Gravitational settling + sticking probability + reentrainement ($h_{crit} = 10^{-6}$ m) + blowdown effect	0.11	328	14

Table 1

After only one iteration, the blowdown effect is not significant. In order to emphasize it, figure 11 shows the variation of deposit towards the number of iterations I, that is physically the number of recirculation, blowdown effect taken into account or not. The blowdown effect is obvious, emphasized by the gap increasing with I.

As it has been earlier pointed out, the doubts within data used to represent S.G. running conditions do not permit us to make a strict comparison with actual deposition maps which, moreover, do not belong to the public domain. When both sticking probability and reentrainment are not considered the sludge pile prediction seems to be close to the classical kidney-bean shape expected.

4 DISCUSSION-CONCLUSION

This paper describes the full study carried out on sludge deposit onto steam generator tubesheet and follows after results presented on ICÔNE 5 meeting.

The sticking probability and reentrainment models seem to have a great influence on tubesheet deposits, showing that in our simulation the mass deposit onto the tubesheet can be quantitatively reduced by 70% according to the sticking probability.

From an intrinsic point of view, the effect of blowdown is not significant on the particle transport equation. However, it may be useful to assess it over an operating cycle with realistic parameters, in view of preventive maintenance.

Furthermore, particulate fouling on steam generators involves many complex phenomena which have not been tackled here such as chemical effects, mechanisms of fine particle deposit onto vertical pipes and tube support plates. So, an important modeling effort has to be done, on both carrier phase flowing inside steam genrators and particle transport, on the basis of experimental studies.

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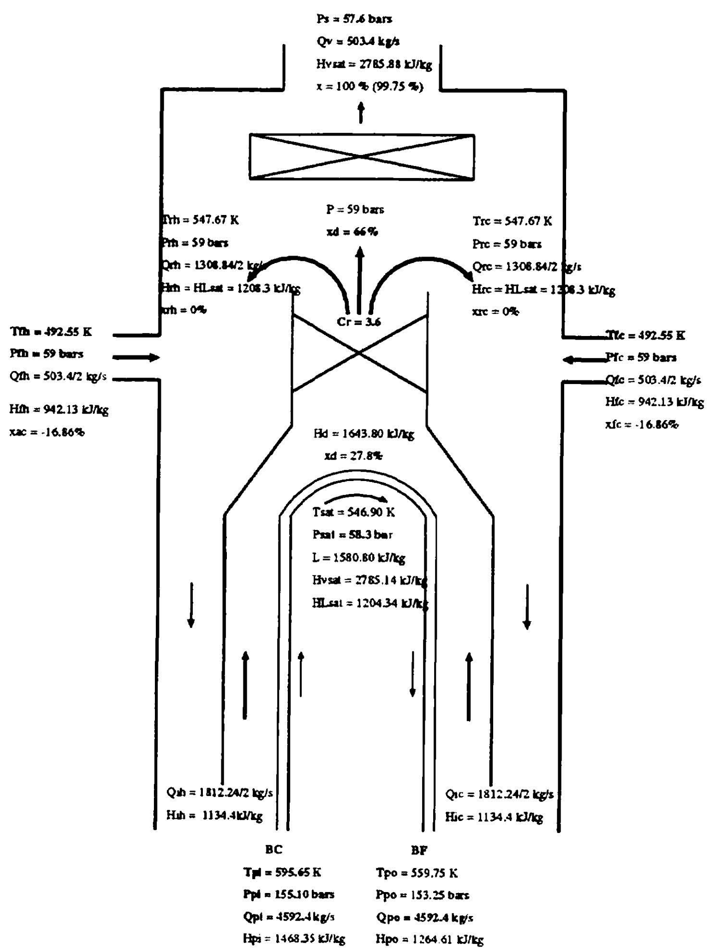
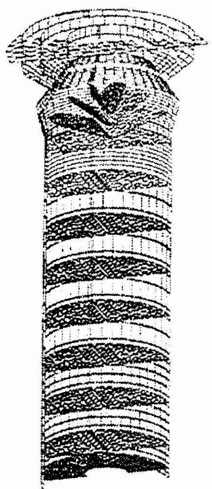


Figure 1 : Simplified view of a 900 MWe S.G.



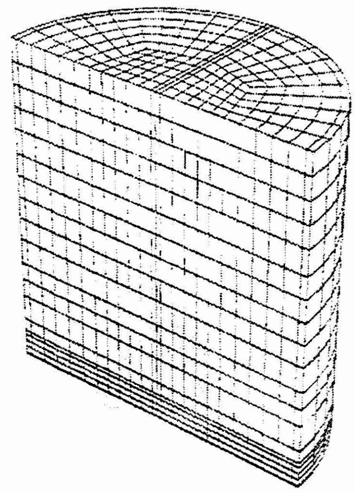


Figure 2 : Distribution baffle, support plates, anti-vibrating bars

Figure 3 : Mesh

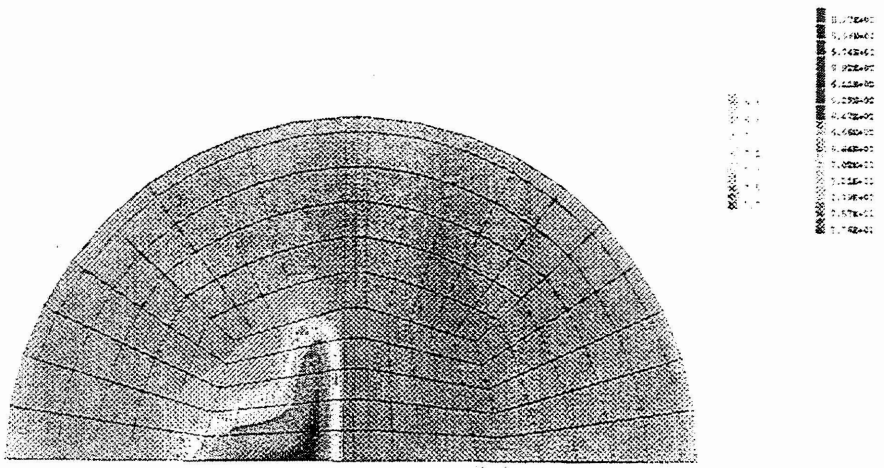


Figure 4 : Carrier phase density - (kg/m^3)-

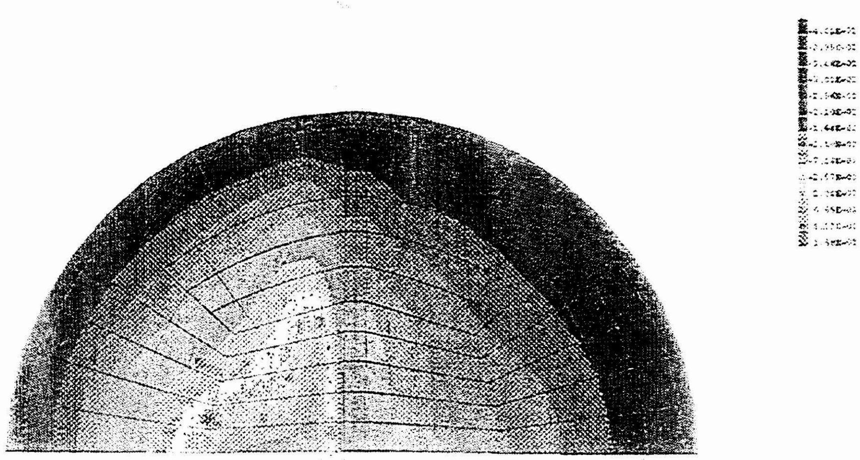


Figure 5 : Carrier phase quality

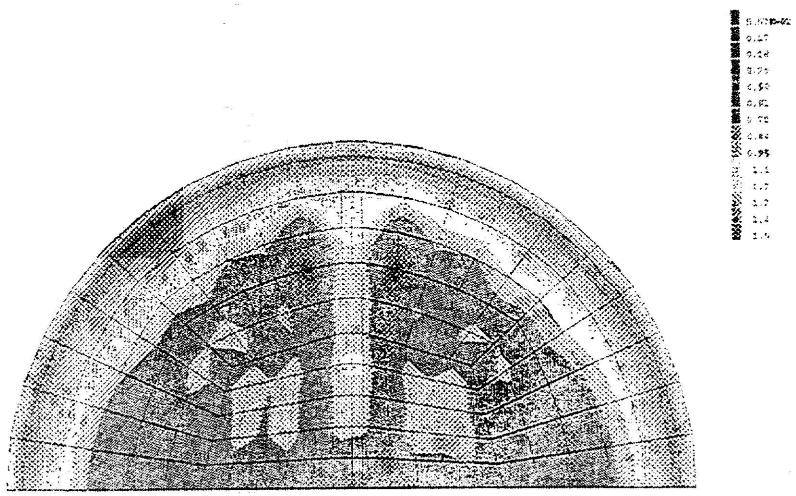


Figure 6 : Carrier phase tangential velocity - (m/s) -

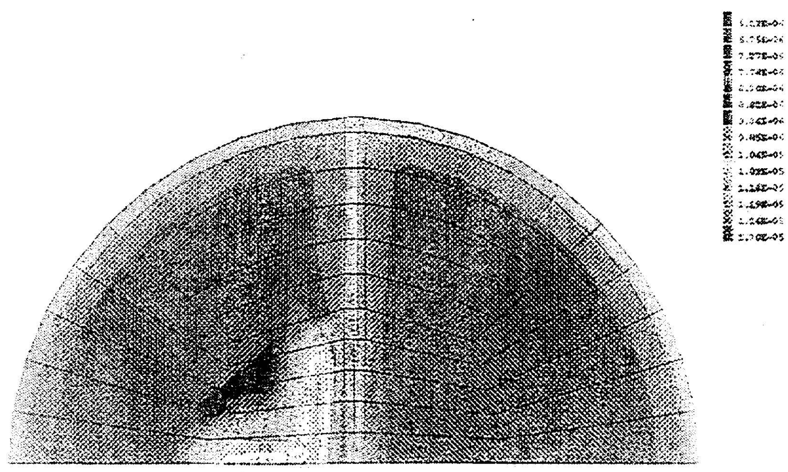


Figure 7 : Deposit net mass flux (gravitational) - (kg/(m^2.s)) -

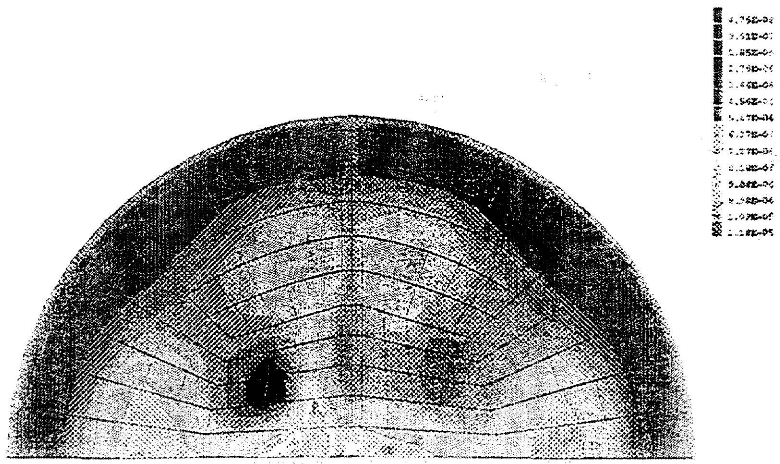


Figure 8 : Deposit net mass flux (sticking probability) - (kg/(m^2.s)) -

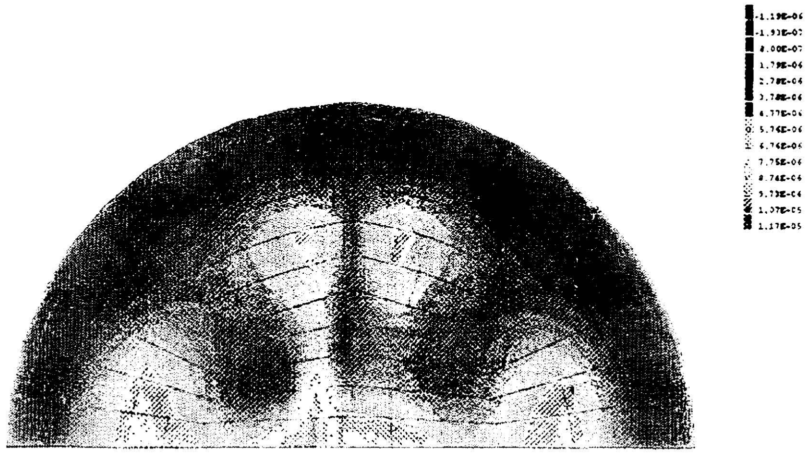


Figure 9 : Deposit net mass flux (reentrainment hcrit = 10^{-6} m) - (kg/(m^2.s)) -

Figure 10 : Deposit net mass flux (with blowdowns) - (kg/(m^2.s)) -

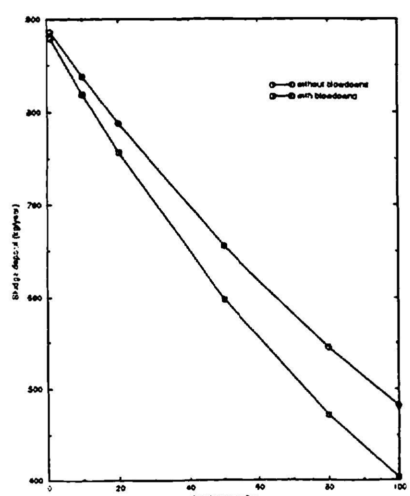


Figure 11 : Sludge deposit estimate versus iterations number

DISCUSSION

Authors: S. Pascal-Ribot, E. Debec-Mathet, D. Soussan, M. Grandotto, CEA

Paper: Simulation of Sludge Deposit onto a 900 MWe Steam Generator Tubesheet with the 3D Code GENEPI

Questioner: R. Staehle, University of Minnesota

Question/Comment:

In your model, do you assume that the particles are charged? How does the sticking depend on pH and solution redox potential?

Response:

No, we don't.

For the moment, the particles are assumed to be neutral and to have no interaction between each other and no influence on the carrier phase.

Indirectly, the sticking probability depends on chemical parameters, since the model has been established for a specific mixture (sand/water) from Watkinson's experimental results. In fact, the model by itself does not use the pH or solution redox potential, but this may be implicitly taken into account in the constant values of the model.

Questioner: P.L. Frattini, EPRI

Question/Comment:

How is the boundary condition on particle flux handled near the solid wall? If additional surface interactions (e.g., per Dr. Staehle's question) were to be added to the sink term, this issue will become important in determining particle distribution as particles concentrate near the wall.

Response:

As far as the tubesheet is concerned, there is no boundary condition on particle flux. The tubesheet is a domain boundary and the deposit flux is assessed by calculating the particle flux that leaves the domain through the tubesheet. Additional surface interactions such as sticking probability, for instance, are considered as source or sink terms, according to whether they enhance or slow down the deposit.

Questioner: D. Duncan, Lockheed-Martin

Question/Comment:

(1) Does the modelling take into account the change in the carrier velocity due to the growth of the sludge pile?
(2) The blowdown effects should be taken into consideration to keep track of the particle mass conservation (the sink term Sp).

Response:

(1) The particle transport equation is solved after the computation of the carrier phase conservation equations. There is no feedback on the carrier phase flow.
(2) The blowdown effect is actually taken into account in the particle transport equation through a sink term Sp.

Questioner: C.W. Turner, AECL

Question/Comment:

Gravitational setting and blowdown are the two particle removal mechanisms you have included. Do you plan to include tube bundle deposition in your model? The rate or tube bundle deposition has a strong influence on blowdown efficiency since a significant fraction of the crud that enters the SG deposits on the tubes.

Response:

Indeed, the next step of the work is to model the tube bundle fouling, considering diffusion, inertial and impaction phenomena.

Questioner: S. Callamand, University of New Brunswick

Question/Comment:

To solve the set of equation, you're using finite element method, and you compute the solution on a grid. How do you assess the convergence of the solution since the grid you have presented is very coarse and your solution has very sharp corners?

Response:

As a matter of fact, the velocity profiles show fluctuations which have not at all physical meaning but are surely due to the coarse mesh used for that calculation. From a numerical point of view, the convergence is not satisfying. Nonetheless, in the present case, the goal pursued was basically to study the response of our models on sludge deposit onto tubesheet, and not the perfect flow description.