
Concentration Processes under Tubesheet Sludge Piles in Nuclear Steam Generators

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Abstract

The process by which bulk water solutes are concentrated under tubesheet sludge piles in nuclear steam generators was investigated in the laboratory under simulated CANDU operating conditions. Concentration rates were found to depend on the tube heat flux and pile depth, although beyond a critical depth the concentration efficiency decreased. This efficiency could be expressed by a concentration coefficient, and was found to depend also on the sludge pile porosity. Solute concentration profiles in the sludge pile suggested that the concentration mechanism in a high-porosity / permeability pile is characterized by boiling mainly near or at the tube surface, while in low-porosity piles, the change of phase may also become important in the body of the sludge pile. In all cases, the full depth of the pile was active to some extent in the concentration process. As long as the heat transfer under the pile was continued, the solute remained under the pile and slowly migrated toward the bottom. When the heat transfer was stopped, the solute diffused back into the bulk solution at a rate slower than that of the concentration process.

Résumé

L'accumulation des espèces chimiques solubles sous les dépôts de produits de corrosion sur la plaque tubulaire des générateurs de vapeur dans les centrales nucléaires CANDU a été étudié au laboratoire. Le taux de concentration dépend du flux thermique ainsi que de l'épaisseur des dépôts. Au delà d'une profondeur critique, l'efficacité de concentration diminue. Cette efficacité peut être exprimée par un Coefficient de Concentration, qui dépend aussi de la porosité des dépôts. La distribution des solutés dans les dépôts indique que dans le cas des dépôts à porosité élevée, l'ébullition a lieu près de la surface des tubes, tandis qu'avec des dépôts de porosité basse, l'ébullition dans la masse des dépôts devient plus

importante. Dans tous les cas, la profondeur entière des dépôts est plus ou moins active dans l'accumulation des impuretés. Tant que le transport de chaleur continue, les solutés restent sous les dépôts et sont transportés de plus en plus profondément. Quand le transport thermique cesse, les solutés retournent par diffusion vers l'eau du générateur de vapeur. Ce processus de diffusion est beaucoup plus lent que celui de concentration.

Introduction

Steam generators are crucial components of pressurized water reactors. Steam generator failure as a result of tube degradation has been a major cause of PWR plant unavailability world-wide. Steam generator problems have caused major economic losses in terms of lost electricity production through forced unit outages, and, in cases of extreme damage, as additional direct costs for large-scale repair or replacement of steam generators.

Steam generator tubes are susceptible to failure by a variety of mechanisms, the vast majority of which are related to corrosion [1]. Although in some cases this attack has occurred on the inside of the tubes (i.e. in the primary coolant), it has more usually originated on the outside of the tubes or on the tube support structures (support plates, lattice bars, tubesheets, scallop bars) on the secondary side of the steam generator.

The feedwater that enters the steam generators under normal operating conditions is extremely pure, but nevertheless contains low levels (generally in the $\mu\text{g/L}$ concentration range) of impurities such as iron, copper, chloride, sulphate, etc. When water is converted to steam and exits the steam generator, the non-volatile impurities are left behind. As a result, their concentrations in the bulk steam generator water are considerably higher than those in the feedwater. Nevertheless, the concentrations of corrosive impurities are still generally sufficiently low that the bulk water is not significantly aggressive towards steam generator materials (in exceptional circumstances, such as massive condenser failures or major make-up water treatment plant

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excursions, bulk steam generator water chemistry may deteriorate sufficiently to become directly aggressive, but such occurrences are relatively rare). However, in certain restricted-flow areas at the heat transfer surface, boiling causes further localized increases in impurity concentrations, and conditions may develop that are aggressive to steam generator materials.

The performance of the recirculating steam generators in Ontario Hydro CANDU plants has been outstanding. The percentage of tubes plugged ($\sim 0.02\%$) is well below the industry average of $\sim 2\%$. Steam generator tube integrity is particularly important in a CANDU reactor because of the severe economic penalty of losing heavy water from the primary system. The excellent performance to date of CANDU steam generators can be attributed, in part, to their design and performance characteristics, which typically involve higher recirculation ratios and lower heat fluxes and temperatures than do other PWR steam generators. Tube support structures are either tri-foil broached plates or lattice bar supports, thus minimizing the likelihood of 'denting' attack. There are no deep tube/tubesheet crevices because of a roll near the secondary face of the tubesheet.

Tubesheet Sludge Piles

Sludge piles have accumulated on the tubesheets in CANDU units, as in most steam generators world-wide. In this region, the thermalhydraulic conditions are favorable for particle formation and deposition. The sludge piles are kidney-shaped and are deepest in the middle of the hot leg bundle. At the Bruce 'A' plant, the piles are estimated to be up to 12 cm deep, while in the Pickering 'A' steam generators they are up to 50 cm in depth. The sludge piles have been determined to be rock-hard, despite the fact that the units have always used AVT chemical control. Analysis of the sludge samples indicates that their main constituents are magnetite and elemental copper. In the Pickering samples, high concentrations of silicates and sulphates of calcium and magnesium have been detected. These are the result of chronic condenser leakage experienced in the Pickering 'A' units. The Pickering sludge samples were found to have high compressive strength (~ 17 MPa) and relatively low porosity (between 20 and 35%). Some of the samples showed a layered structure, with platelets of magnetite embedded in a matrix of calcium sulphate/silicate. The composition and structure of the samples are indicative of considerable *in situ* precipitation and recrystallization of the constituents, presumably driven by temperature and concentration gradients in the porous sludge pile [2].

Ontario Hydro is conducting a research program to investigate corrosion processes under tubesheet sludge piles, since this is the area where our steam generators are judged to be at greatest risk of widespread degradation. Although the build-up of concentrated solu-

tions in sludge piles and crevices is qualitatively understood, there are a number of aspects of the concentration process where more detailed information is required in order to predict the effect of operating events on materials integrity. Most of the detailed studies reported to date have been carried out with tube/support plate crevices and tube/tubesheet crevices. While indicative of the overall processes that take place in confined regions of steam generators, these results can not be directly applied to describe the behaviour under sludge piles. This paper describes the results of experiments carried out at Ontario Hydro to study the influence of some physical characteristics of sludge piles (depth, porosity) on the rate of accumulation of contaminants (so-called 'hideout'), on the de-concentration ('hideout return') of the contaminants when heat transfer stops, and on the distribution of the contaminants in the sludge pile.

Solute Concentration under Sludge Piles

On the free, unobstructed tube surfaces of a nuclear steam generator, heat is transferred by nucleate boiling. In this process, the phase change occurs on the tube surface. The bubbles generated move away from the surface due to buoyancy forces and large quantities of liquid are also moved because of the turbulence generated, thus effectively preventing the accumulation of solutes which may be present in the bulk water. Concentration factors of only five or less have been measured in this type of boiling [3].

The mechanisms of the boiling process in confined regions can be drastically different. The flow of liquid to the heat transfer surface may be insufficient compared to the amount required to sustain nucleate boiling. Vapour tends to stay near the heat transfer surface, since it cannot easily escape. The remaining liquid is not replaced as effectively as in the nucleate boiling process, and as a consequence it may become enriched in the bulk water solutes.

The accumulation of vapour near the heat transfer surface increases the resistance of the medium to heat transfer. Consequently, monitoring the temperature of the tube wall can provide an indication of the heat transfer regime. This approach has been used and results are reported in the literature [4].

Although the heat transfer process determines the vaporization rate, and this in turn the concentration rate under the pile of the bulk water solutes, certain aspects of the mass transfer process cannot be well understood from the heat transfer data alone. For instance, in an alternate wetting and drying condition, the tube surface temperature changes with variable frequency, depending on the degree of dry-out in the region. To relate the wetting and drying frequency with the concentration rate is quite complex.

The flow of liquid in a boiling process under a porous body is determined by capillary forces. Several

flow configurations have been postulated. The liquid may flow towards the heat transfer surface along small pores, where capillary forces are important, while the steam flows away from the heat transfer surface through the larger pores. Alternatively, the liquid may be flowing along the periphery of the pores while escaping steam flows through the centre [4]. In either case, the concentration process under the sludge pile is strongly dependent on the structure of the porous body and on heat transfer parameters that determine the flow pattern. While wall temperature measurements can be indicative of the heat transfer process, they fail to explain fully the mass transfer into the pile. Therefore, it is necessary to measure directly solute concentrations to characterize the process. This was the approach followed in the present study.

Experimental

Two series of experiments were carried out (series A and B, respectively). Each series consisted of tests to determine concentration/deconcentration rates, and tests to characterize the concentration profiles in the sludge.

Autoclave Vessels

The experimental apparatus consisted of a four-litre Inconel 600 autoclave, equipped with a temperature-control system and a small volume (<10 mL) sampling condenser. The autoclave lid had several access ports, three of which allowed the insertion of the test probes. The remainder were connected with the control instrumentation. The autoclave was part of a high-pressure loop and could be operated in a refreshed mode or in a static mode.

Test Probes

The two series of experiments used test probes of different designs. The probes used in the series A tests were constructed by welding a length of steam generator alloy tube (Inconel 600, 13 mm o.d.) to a stainless steel fitting that could be attached to the autoclave lid. Electric cartridge heaters (9.5 mm diameter) were inserted into the probes, and the gap between the heater and the tube was pressurized with helium at a pressure of 9 MPa (see Figure 1). Helium was chosen for its high thermal conductivity and chemical inertness.

The probes for the series B tests used a 6.4 mm cartridge heater, and a copper sleeve placed between the heater and the tube (see Figure 2). Two 1 mm diameter sheathed thermocouples were positioned in a groove machined in the copper sleeve and the tips were insulated from the copper by means of a ceramic cement bead. The thermocouples could thus monitor the temperature of the inner wall of the tube. The presence of the copper sleeves permitted effective axial heat transfer and provided a closer simulation of the

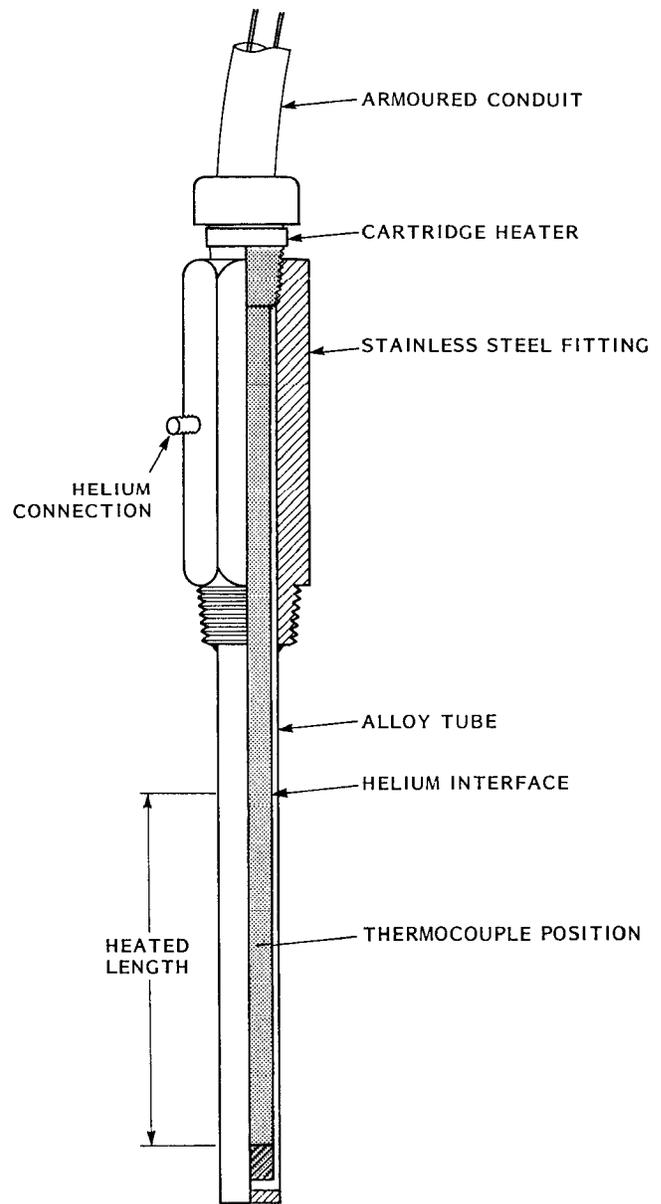


Figure 1: Test probe used in series A experiments.

temperature-controlled heat transfer situation that occurs in a steam generator.

Sludge Piles

To simulate a tubesheet sludge pile, the series A tests used a cylindrical carbon-steel holder clamped to the lower section of the tube probe (see Figure 3). The simulated sludge was obtained from the mud drum of a coal-fired station. This sludge and the deposits obtained from the U-bend and tubesheet regions of the Bruce NGS steam generators had similar chemical composition [2]. The sludge was compacted into the holder by tapping and vibrating. The final porosity of the pile was 0.57. Three sludge pile heights were used in the experiments: 50, 100, and 150 mm. Several thermocouples were fixed to the outside of the tube.

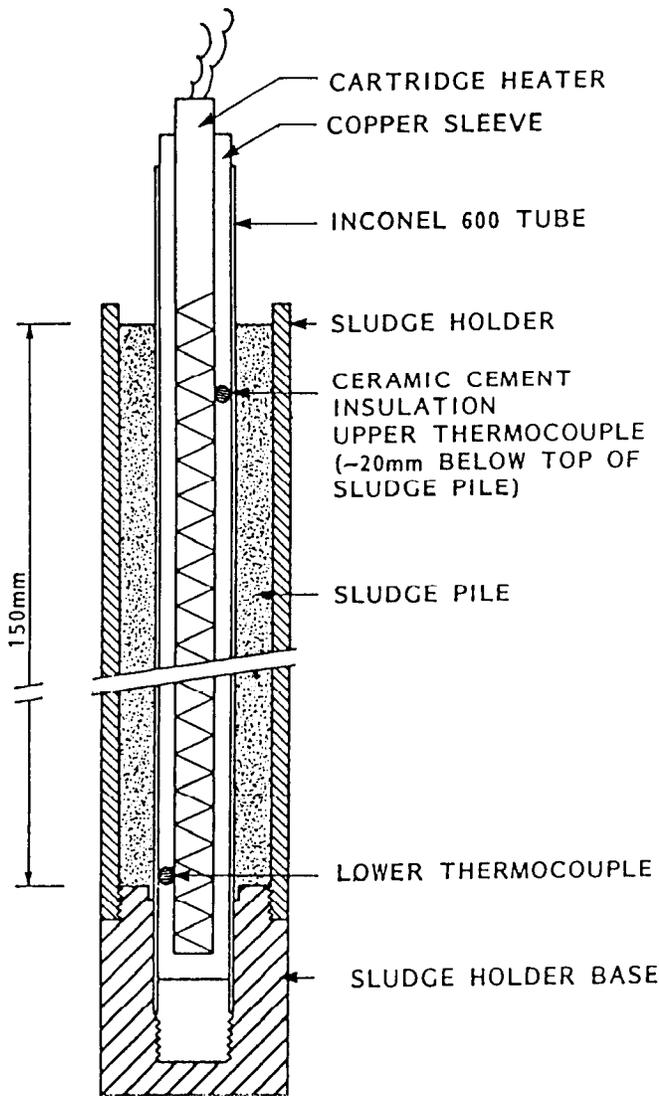


Figure 2: Test probe and sludge pile simulant used in series B experiments.

The sludge pile simulant for the series B experiments consisted of a holder, which was also made of carbon steel but was screwed onto the base that fit the bottom part of the steam generator alloy tube (see Figure 2). The same sludge simulant was used, but it was compacted into the holder using a plunger and a press. Compacting pressures of 1.2, 23, and 59 MPa produced sludge pile porosities of 0.57, 0.50, and 0.43, respectively.

Procedure

In both series of experiments, the concentration tests involved the operation of the autoclave in the static mode. The test solutions consisted of sodium chloride in deionized water (chloride concentration in the range 30–100 mg/L). The solution was adjusted to pH 8.5 with morpholine and dosed with 1 mg/L hydrazine. The autoclave vessel was charged with 2.7 L of solu-

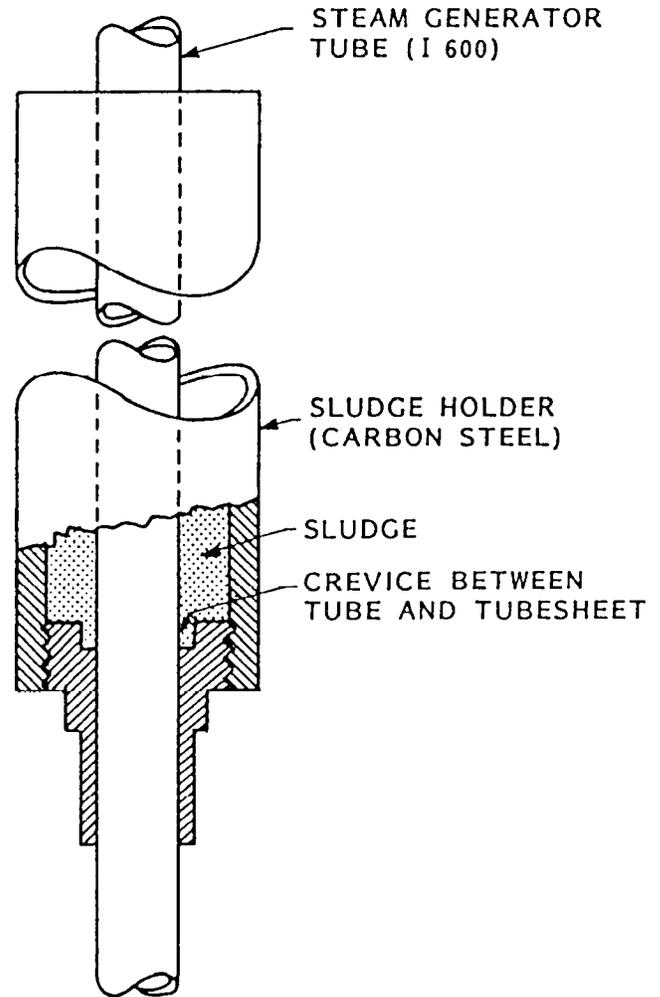


Figure 3: Sludge pile simulant used in series A experiments.

tion and brought to the test temperature (256°C). Only one probe was tested in each experiment. The concentration process was started by supplying power to the heater. It was stopped by terminating the power supply. The concentrated solution under the pile was then allowed to diffuse into the bulk water. Samples were collected periodically during the experiment and analyzed for sodium, chloride, and conductivity. The concentration and de-concentration phases of an experiment typically lasted several days.

The heat flux was controlled differently in the two series of experiments. In series A, the desired heat flux was obtained by setting the voltage of the cartridge heaters to a prefixed value. In series B, the voltage was adjusted to obtain a temperature between 310 and 315°C at the inner wall of the tube. The resulting heat fluxes ranged between 20 and 25 kW/m².

The procedure used in the tests to determine the concentration profile under the sludge pile was also different in the two experimental series. In series A, the vessel was quickly emptied after a concentration period. The test probe was removed and the sludge in

the holder was extracted in 25-mm sections. The sodium and chloride content of each section was then determined. In series B, the vessel was operated in the refreshed mode to maintain a constant solution concentration of 100 mg/L chloride in the bulk water. The heat transfer process in the three probes carried on for eight days. The system was then shut down and the vessel quickly emptied. The sludge pile simulants were removed and cut radially into 12-mm sections that included the tube and carbon steel holder. These sections were mounted in epoxy resin and examined in a Scanning Electron Microscope (SEM) equipped with an Energy Dispersive X-ray attachment (EDXA) with mapping capabilities.

Results

Dynamics of Contaminant Concentration

Figure 4 shows the variation of the bulk water chloride concentration with time for a typical experiment from series A (100 mm sludge pile, 40 kW/m²). The solute concentration in the bulk water continuously decreased after time zero (when the heat transfer through the tube was started). After approximately 50 hours, the solute concentration reached a value below the detectability limit of the analytic technique used (0.1 mg/L). As long as the heat transfer was maintained, the solute hideout in the sludge pile persisted. As soon as the heat transfer was stopped, the solute began to diffuse into the bulk water. The slightly altered probe design used in the series B tests showed the same behaviour, as shown in Figure 5. This test was carried out with a 150 mm sludge pile of porosity 0.50. In this experiment, as in others, the hideout return process was significantly slower than the concentration process. The same behaviour as that illustrated in Figures 4 and 5 was observed in all the concentration tests with different combinations of pile heights, porosities and heat fluxes.

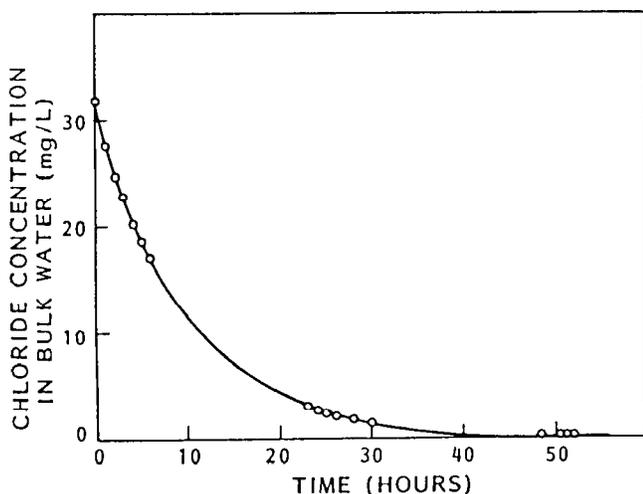


Figure 4: Bulk water chloride concentration versus time for a typical series A experiment (sludge pile depth: 100 mm; heat flux: 40 kW/m²).

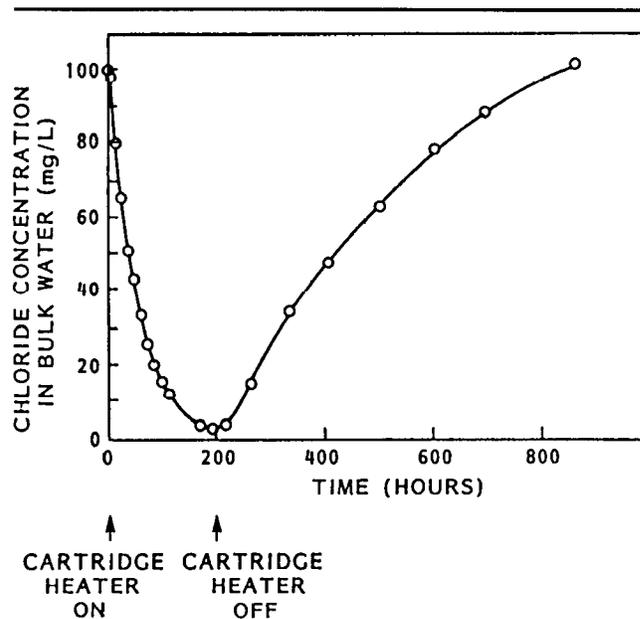


Figure 5: Bulk water chloride concentration versus time for a typical series B experiment (sludge pile porosity: 0.50; sludge pile depth: 150 mm; inner wall tube temperature: 310°C; heat flux: 20 kW/m²).

Most of the concentration tests were carried out in duplicate. The reproducibility was satisfactory.

Influence of Pile Depth and Heat Flux

In the series A tests, the rate of concentration of sodium chloride under the sludge pile was measured at three heat fluxes (40, 75, and 110 kW/m²) for the 50- and 100-mm-deep sludge piles and at 40 kW/m² for the 150-mm-deep sludge pile. The concentration rates increased when the heat flux was increased. This is shown in Figure 6, where the sludge pile concentration factor is plotted versus time for a 50-mm-deep sludge pile at three heat fluxes. The concentration factor is defined here as the solute concentration in the pile over the solute concentration in the bulk water. The solute concentration in the pile was obtained by calculating the solute hideout from a mass balance, and the void volume in the sludge pile from the initial porosity. The concentration factor calculated in this manner is an average value; actual factors are likely to be much higher in localized regions. Figure 6 shows that the concentration factor after 30 h can be greater than 10⁵.

The influence of sludge pile depth on the solute concentration process is shown in Figure 7, in which the concentration factors are plotted vs time for three different pile depths at a heat flux of 40 kW/m². The 50-mm-deep pile showed lower concentration rates than the two deeper piles, whose concentration rate profiles were similar.

Influence of Sludge Pile Porosity

In the series B tests, the influence of sludge pile

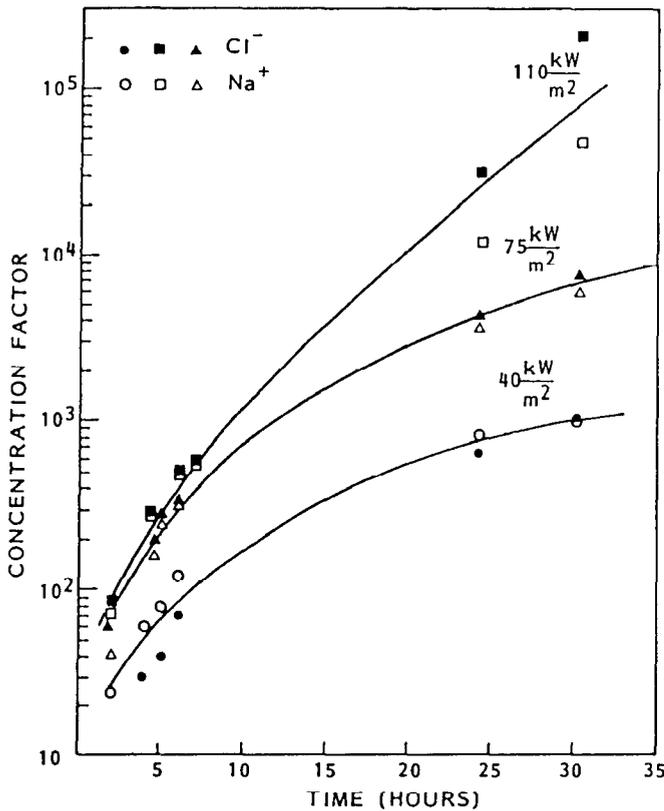


Figure 6: Concentration factors versus time at different heat fluxes (sludge pile depth: 50 mm).

porosity on the contaminant concentration rate was investigated. Figure 8 shows the bulk water chloride concentration / time profiles for sludge piles with porosities of 0.43, 0.50, and 0.57. Heat fluxes during the experiment were 25, 20 and 20 kW/m^2 , respectively. The concentration rate decreased with decreasing pile porosity.

Concentration Profiles Under Sludge Piles

Influence of Pile Depth

Figure 9 shows the sodium chloride concentration profiles for 150-, 100-, and 50-mm sludge piles after a concentration period of 100 h at 110 kW/m^2 . In the 50- and 150-mm piles, the solute concentration increases exponentially with depth. The bottom of the pile had solute concentrations greater than 1,000 mg/kg . The trend observed in the 100-mm piles was similar, although less pronounced. At the end of each of the experiments, some sludge adhered very strongly to the tube and could not be dislodged, making the recovery of the sodium chloride solute incomplete. The most adherent scale was formed at the bottom of the sludge piles, and the 100-mm pile was more severely affected than the other two. This greater amount of unrecovered sodium chloride at the bottom of the probe may account for the

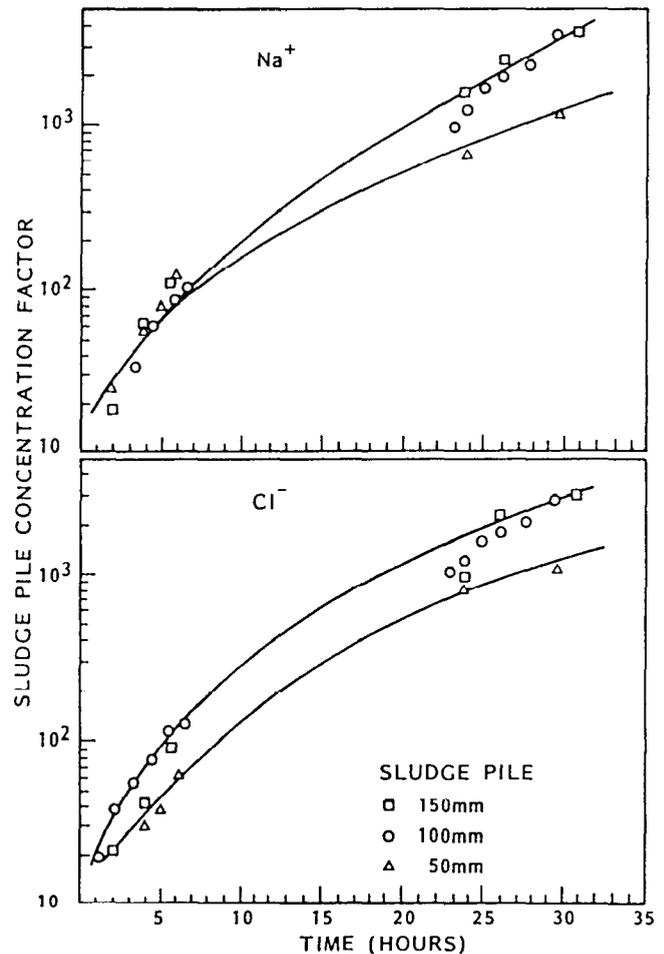


Figure 7: Concentration factors versus time for different sludge pile depths (heat flux: 40 kW/m^2).

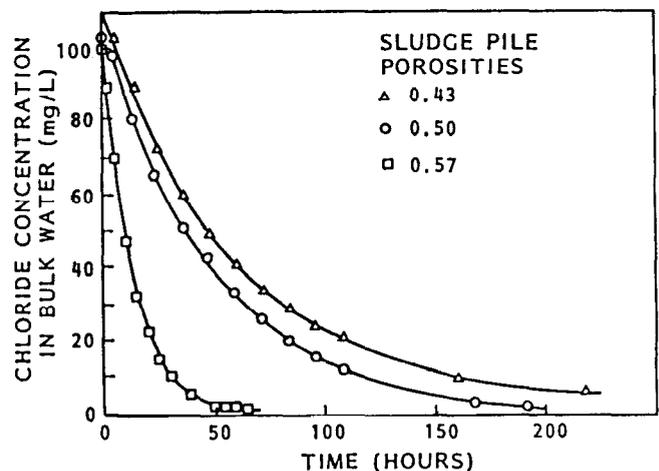


Figure 8: Bulk water chloride concentration versus time for several sludge pile porosities (pile depth: 150 mm; heat flux: 20–25 kW/m^2).

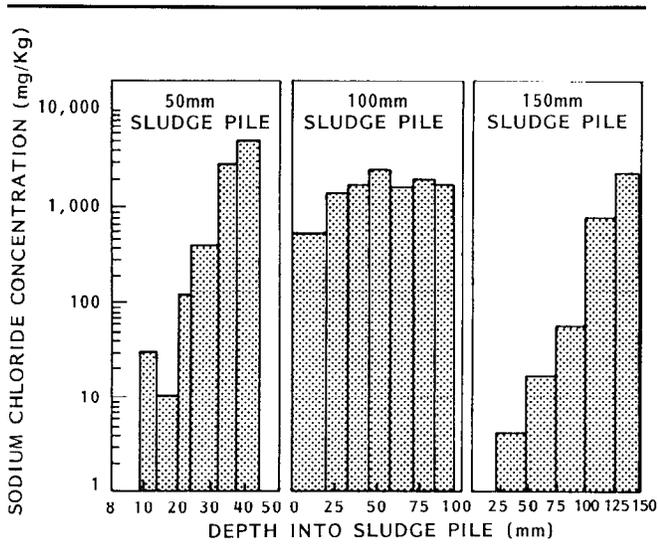


Figure 9: Sodium chloride concentration in sludge versus depth (50, 100 and 150 mm sludge piles; porosity: 0.57).

apparently flat concentration profile of the 100-mm pile in Figure 9.

Effect of Porosity

Figure 10 shows profiles of chloride concentration in the sludge versus depth for the three porosities investigated. The figure contains two sets of EDXA data. The first shows the composition of the sludge near the tube wall, and the second of the sludge approximately 3 mm away from the tube wall. Each EDX analysis corresponds to an area of approximately 2×1.5 mm.

The chloride concentrations near the tube wall in the 0.57-porosity pile decreased at increasing depths. The concentrations up to 20 mm in depth near the wall were quite high, approximately 20% of the detected elements. The average in the tube region along the full depth was 9%. The chloride concentration in the region 3 mm from the tube is also maximum near the top of the pile. The average concentration in this region along the total depth (2%) was significantly lower than the average near the tube wall.

In the 0.50-porosity pile, the solute concentration increased with depth. The highest concentration in the region near the tube wall was 4%, and the average along the full depth was 1%. The region away from the tube showed a similar trend, and the average concentration was 0.8%. The region that had the highest concentration was between 110 and 140 mm. The radial concentration gradient was less pronounced than in the higher-porosity pile, but showed an increasing solute concentration near the tube wall. Figure 11 shows an EDXA map of the chloride distribution in the region situated near the tube wall. The solute concentration increases near the tube wall, but it can be still significant at a certain distance. The points of maxi-

um concentration appear to be localized in some of the 'voids' in the sludge pile, which appear as dark areas in Figure 11a.

The concentration of chloride in the 0.43-porosity pile was generally low (Figure 10), and no significant radial gradient was observed. The average of the chloride concentration along the full depth in the region near the tube wall was 0.36%, and in the region away from the tube wall 0.33%

Discussion

Dynamics of Solute Concentration Under the Sludge Pile

The dependence of the solute concentration rates on the different experimental parameters was not simple. A model was developed to explain the results of the concentration experiments.

The heat transfer through the tube was heat-flux controlled. This parameter was thus known and fixed in each test. Steam is produced at or near the tube wall and leaves the pile after travelling through the porous sludge. Water from the bulk flows through the sludge to satisfy the boiling requirements.

If the assumption is made that all the heat that is transferred under the pile is spent in steaming, the outflow of steam from the pile can be expressed by

$$\dot{m}_s = \frac{\phi A}{\Delta H} \quad (1)$$

where

- ϕ : tube heat flux (kW/m²)
- A: heat transfer area under the sludge pile (m²)
- ΔH : latent heat (J/kg)
- \dot{m}_s : rate of steam generation (kg/s)

and a mass balance for the water/steam around the sludge holder generates the expression

$$\dot{m}_i = \dot{m}_L + \dot{m}_s \quad (2)$$

where

- \dot{m}_i : inflow of bulk water into the pile (kg/s)
- \dot{m}_L : outflow of liquid water carried as droplets by the steam leaving the sludge pile.

At steady state, and if it is assumed that the solute partition coefficient is much smaller than one, a solute mass balance produces the equation

$$\dot{m}_i C_B^{ss} = \dot{m}_L C_H^{ss} \quad (3)$$

where

- C_B^{ss} : concentration of solute in bulk water at steady state
- C_H^{ss} : concentration of solute in the water leaving the sludge holder.

Experimental evidence shows that $C_H^{ss} \gg C_B^{ss}$; consequently

$$\dot{m}_i \gg \dot{m}_L \quad (4)$$

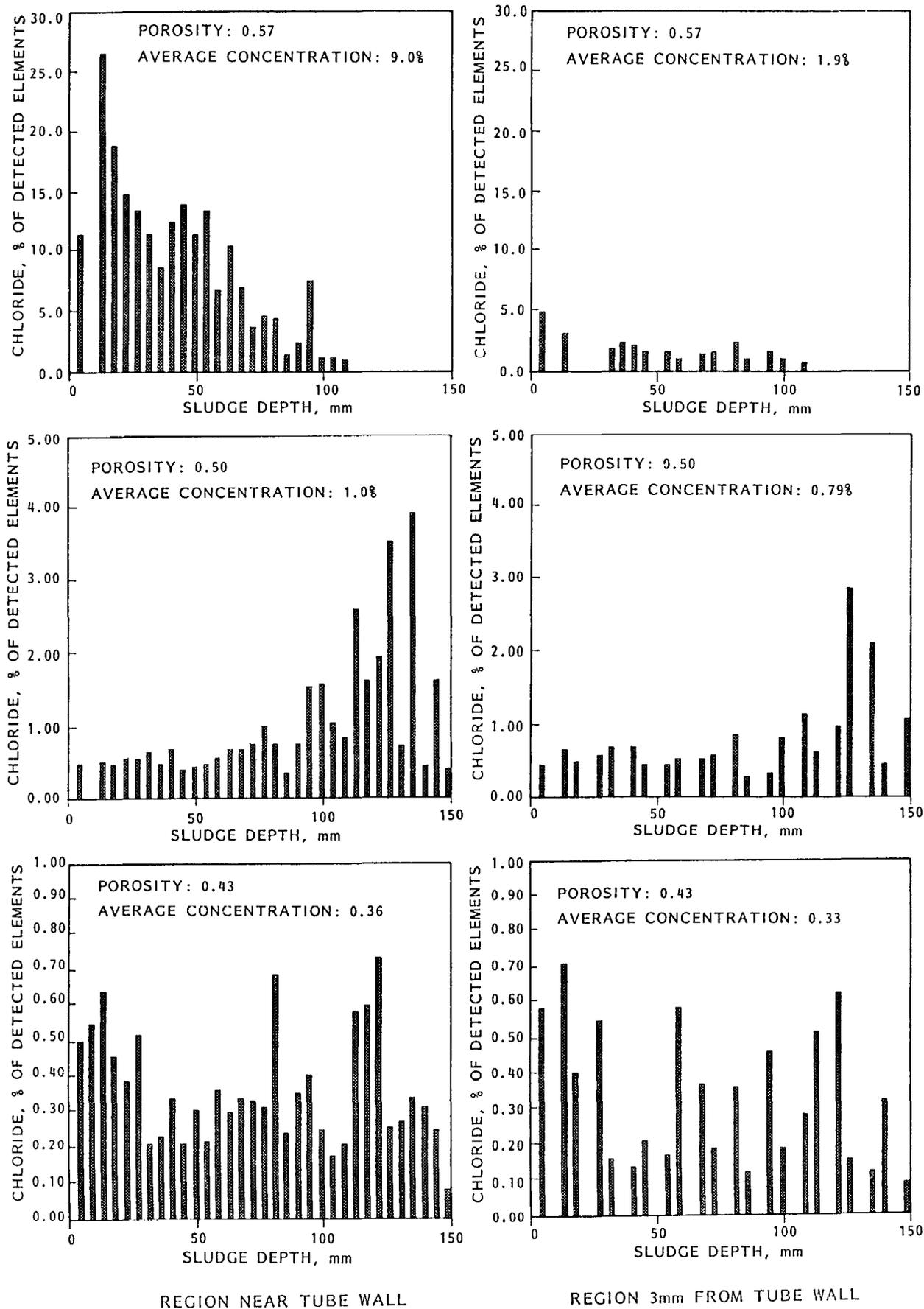


Figure 10: Chloride concentration in sludge versus depth for 150 mm sludge piles of different porosities.

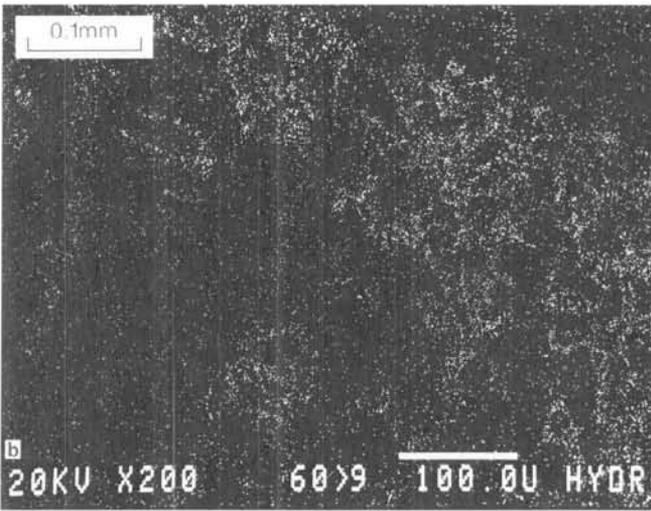


Figure 11: SEM image (a) and chloride EDX map (b) of sludge region near the tube wall (top right corner). Point density is proportional to chloride concentration. The sludge pile had a 0.50 porosity and the region shown in the micrograph was at a depth of 125 mm.

and therefore

$$\dot{m}_i = \dot{m}_s \quad (5)$$

In other words, virtually all the bulk water that enters the sludge holder leaves it as steam.

A mass balance of the solute around the sludge holder during the concentration process can be expressed as

$$C_B \frac{\dot{m}_i}{\rho} = C_H \frac{\dot{m}_L}{\rho} + V_H \frac{dC_H}{dt} \quad (6)$$

where

- C_B : concentration of solute in bulk water (mg/L)
- C_H : concentration of solute in the water in the sludge holder (mg/L)
- ρ : density of water (kg/L)
- V_H : volume of water in sludge holder (L)
- t : time (s).

The total mass of solute in the vessel can be expressed by

$$C_B V_v + C_H V_H = M \quad (7)$$

where

- V_v : Volume of water in vessel (L)† (See note, p. 140)
- M : Total mass of solute in vessel (mg)

Derivating expression 7 with respect to time gives

$$V_v \frac{dC_B}{dt} = -V_H \frac{dC_H}{dt} \quad (8)$$

and substituting 7 and 8 into 6, the following expression is obtained:

$$\frac{dC_B}{dt} + C_B \left(\frac{\dot{m}_i}{\rho V_v} + \frac{\dot{m}_L}{\rho V_H} \right) = \frac{M}{V_v V_H} \frac{\dot{m}_L}{\rho} \quad (9)$$

This equation can be easily integrated with the following boundary conditions:

$$t = 0, C_B = C_i \quad \text{and} \quad t \rightarrow \infty, C_B = C_B^{ss}$$

where

- C_i : initial concentration of solute in bulk water.

The resulting expression is

$$C_B = C_B^{ss} + (C_i - C_B^{ss}) \exp - \left[\frac{\dot{m}_i}{\rho V_v} + \frac{\dot{m}_L}{\rho V_H} \right] t \quad (10)$$

C_B^{ss} should be zero if the assumption that $\dot{m}_i \gg \dot{m}_L$ is rigorously followed; however, it was left in the expression since it could easily be estimated from the experimental data by the numerical technique used in the data analysis. From equations 1 and 5, and ignoring the term containing \dot{m}_L because of equation 4, expression 10 becomes:

$$C_B = C_B^{ss} + (C_i - C_B^{ss}) \exp - \left[\frac{A\phi}{\Delta H \rho V_v} \right] t \quad (11)$$

This expression implies that the concentration of solute in the bulk water decreases exponentially with time, and that the rate of concentration change is also an exponential function of the heat transfer area and of the heat flux.

A parameter K , called the 'concentration coefficient,' is required to relate expression 11 with the experimental data. K can be described as the fraction of heat transferred under the sludge pile that effectively contributes to the concentration of solute. This could be interpreted as the fraction of the heat flux that is converted to steam or, alternatively, the fraction of the heat transfer area under the pile that is actively generating steam. Revising expression 11 to include K gives

$$C_B = C_B^{ss} + (C_i - C_B^{ss}) \exp - \left[\frac{KA\phi}{\Delta H \rho V_v} \right] t \quad (12)$$

The numerical technique used in the data reduction consisted of an unweighted, least-squares regression,

fit to a function of the type

$$Y = P(2) + (P(1) - P(2)) \exp [-P(3) X]$$

in which P(1), P(2), and P(3) are unknown parameters that are resolved by the regression analysis. These parameters corresponded to

$$C_1, C_B^{ss}, \text{ and } \frac{KA\phi}{\Delta H \rho V_v},$$

respectively, in expression 12.

The regression analysis produced a satisfactory correlation between expression 12 and the experimental data. The calculated values for C_1 and C_B^{ss} were almost identical to the ones observed experimentally.

Effect of Heat Flux and Pile Depth on Concentration Coefficient

The concentration coefficient K obtained in each of the series A tests is listed in Table 1. The K values for the 50 mm pile are approximately unity, which indicates that all the heat transferred under the sludge pile is effective in concentrating the solute. This implies that the other heat losses are not significant compared to the heat transfer invested in steaming. The permeability of the pile is sufficiently high to satisfy the water-replenishment requirements for steaming at all the heat fluxes investigated. Another implication of this result is that the assumption of negligible carry-over of water droplets by the steam leaving the pile is valid.

The K coefficients for the 100-mm pile are less than unity and decrease when the heat flux increases. Since the physical characteristics of this pile are similar to those in the 50-mm pile, the increase in height seems to be the only cause for the reduced K factor. The increase in height may reduce the overall permeability of the pile, thus hindering the flow of water to the bottom. A steam-blanketed region may develop there, and the efficiency of steam generation may be diminished. A local increase in temperature can make the heat losses through conduction a significant portion of all the heat transferred. When the heat flux increases, the extent of the liquid-deficient region also increases, and the value for the K coefficient diminishes. For a given heat flux, the K coefficient will become less than unity when the pile depth is such that liquid-starved zones develop; this is not likely to occur abruptly, but rather in a progressive manner. It will affect increasing portions of the heat transfer surface with increasing depth. However, a 'critical depth' can be artificially defined below which the heat transferred is totally ineffective in the concentration of solute, and above which steam is 100% efficiently generated. This critical depth can be calculated by multiplying the K coefficient by the total depth of the sludge pile. The critical depth should depend only on the heat flux. Only one experiment at low heat flux could be carried out with the 150 mm pile, but the critical depth obtained (150×0.59) is similar to

Table 1: Sludge Pile Concentration Coefficients for Several Sludge Pile Depths and Heat Fluxes (Pile Porosity 0.57)

Pile height (mm)	Heat flux (kW / m ²)		
	40	75	110
50	1.08	1.04	1.01
100	0.80	0.70	0.51
150	0.59	—	—

the critical depth of the 100-mm pile (100×0.80) at the same heat flux (see Table 1).

The concentration profiles in Figure 9, which show the highest chloride concentrations near the bottom of the sludge pile, are not necessarily inconsistent with the finding that the bottoms of the deep sludge piles are not fully active in the concentration process. Some residual steam generation may occur even if there is steam-blanketing, since the surface is likely to be periodically rewetted. Water will flow through the sludge to replace the steam. This water will become enriched in solutes as it migrates through the regions of active boiling near the top of the pile. In the series A experiments, the bulk water became depleted of solutes; therefore, when entering the sludge pile, it did not contribute to the solute enrichment of the top of the sludge pile, but rather it leached the solute from this area and transported it to the deeper regions in the pile.

Effect of Sludge Pile Porosity on Pile Concentration Coefficient

Table 2 shows the concentration coefficient for 150 mm high sludge piles with porosities of 0.43, 0.50 and 0.57, respectively.

The 0.43-porosity pile had a coefficient of only 0.14, while that for the 0.57-porosity pile was 0.75. The low concentration coefficients for the low-porosity pile can be attributed to two factors: the lower permeability of the porous structure, which hinders the water flow, and an increased thermal conductivity of the sludge medium due to the higher degree of compaction of the porous structure. The heat that is not invested in generating steam on the tube surface is conducted out into the sludge.

The axial concentration profile for the 0.57-porosity pile (Figure 10) appears to agree with the concept of 'critical depth' proposed above. The top of the pile is more active at concentrating the solute than the bot-

Table 2: Sludge Pile Concentration Coefficients for 150 mm Sludge Piles with Varying Porosities

Pile porosity	0.43	0.50	0.57
Concentration coefficient	0.14	0.22	0.75

tom. However, the profiles for the lower-porosity piles are quite different. This discrepancy may be due to the high permeability of the 0.57-porosity pile. This permeability was enhanced by channels that were formed near the top surface of the sludge during the tests. The presence of these channels, which generally extended to the tube surface, and the higher concentrations near the tube wall, suggest that the boiling mainly took place near or at the tube surface, and that a wick boiling process was prevalent with high heat-transfer rates. These rates were lower deeper into the pile, and consequently the resulting solute concentrations were also lower. Nevertheless, the full depth of the pile was still active at concentrating the solute.

The sludge piles with lower porosities did not show the presence of channels. Their permeability, and hence the boiling heat transfer were significantly smaller. This, in turn, would produce lower average solute concentrations in the lower-porosity piles, as observed in Figure 10. Boiling in these piles likely occurred with comparable rates on the tube surface and in the sludge body. This could explain why the radial concentration gradients become flatter with decreasing porosities.

The difference in the axial concentration profiles between the piles of similar porosities (0.57) in the series A and series B experiments (Figures 9 and 10, respectively) originates in the experimental procedure used in each case. In the first series, carried out in static autoclaves, the bulk water became depleted of solute during the concentration process. As explained above, the movement of depleted water through the sludge transports the solute to the bottom of the pile. In the B series of tests, carried out in refreshed autoclaves, the bulk water always contained the same solute concentration, and the concentration profile would be expected to be fairly constant with time, with the upper areas of the sludge pile becoming progressively enriched in the solute.

Hideout Return

No attempt was made to correlate the hideout return rates to operating and physical parameters; however, it was consistently observed that the hideout return took place at a much slower rate than the concentration process. The lower rate of hideout return is not unexpected, since the solute mass transfer in this process is driven by diffusion forces. The concentration process, on the other hand, depends on boiling, which is a very efficient mass transfer phenomenon even when hindered by the presence of a porous body.

Concentration Processes in Operating Units

If concentration processes occurring in the tubesheet sludge pile of a recirculating steam generator are similar to those observed in these experiments, the rate of concentration of the bulk water solutes under the sludge should depend on the porosity / permeability proper-

ties of the sludge file. For high porosities / permeabilities, the concentration rate will be directly proportional to the local heat flux, and consequently will be maximum in the hot leg. Deep sludge piles would tend to concentrate solutes at a higher rate, since there is a larger heat transfer area active in the concentration process. High local solute concentrations may have an impact on changing the porosity of the pile if the solubility product for some species is exceeded. Low porosity / permeability piles will concentrate solutes at a reduced rate. If the bulk steam generator water has a high solute concentration for a limited period of time, the solute will concentrate under the pile at a rate determined by the heat transfer parameters of the pile. When the bulk concentration returns to a low value, the solute concentrated near the top of the pile will be slowly transferred deeper into the sludge pile. The experience accumulated in these experiments shows that the sludge pile behaves as a solute trap as long as the heat transfer process is active. The release of the concentrated solute takes place slowly, and only when the heat transfer is fully stopped.

The controlling variable in the heat-transfer process in these experiments was the heat flux. This is different from a recirculating steam generator in which the wall superheat is the controlling variable. However, the experimental procedure, which emphasized obtaining wall superheats similar to those in a CANDU system (especially in the second series of tests) should make the conclusions of this work valid for an actual operating system. Further experiments using a temperature-controlled heat transfer system more closely simulating actual steam generator heat-transfer conditions are currently underway.

Conclusions

- Bulk water solutes concentrate under sludge piles at a rate proportional to the heat flux. The rate is also affected by the physical characteristics of the sludge pile.
- For a given heat flux and sludge pile characteristics, the concentration rate is proportional to the pile depth until a critical depth is reached. Piles that exceed the critical depth showed a decreased concentration efficiency, which can be represented by a concentration coefficient.
- Concentration coefficients are a direct function of the porosity of the sludge pile.
- High-porosity piles show a concentrating behaviour that is most consistent with boiling near the tube surface and high heat-transfer rates. In less porous piles, heat may be transferred through conduction through the sludge, and boiling may take place in the sludge body. In all cases, the full depth of the pile is active to some extent at concentrating the solute, since high concentrations of solute were observed even below the critical depth.
- Sludge piles behave as solute traps as long as the heat transfer is maintained. Solutes in the pile are transferred

towards the bottom of the pile during the heat transfer process. Hideout return rates are slower than concentration rates.

Notes

† During a typical experiment, several samples were taken from the vessel and the water volume in the vessel, V_v , was not constant. This was included in calculations by computing a corrected concentration which took into account the sampled volume.

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