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Experimental Apparatus and Testing Procedure

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Kinetic Study of Magnetite Precipitation Using a High-Temperature Flow-Through Loop: Experimental Apparatus and Testing Procedure

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An accurate understanding of material degradation mechanisms and the behavior of the key corrosion products of the materials of

construction in nuclear systems is essential in minimizing radiation fields to ensure nuclear worker safety. There are no high-temperature data available on the precipitation constant (k_p) of magnetite. Knowledge of this kinetic constant and its temperature dependence would allow for more accurate predictive modeling of the fouling of primary-side sections such as the steam generators. This work summarizes a modification of an experimental loop test section to study the kinetics of magnetite precipitation at temperatures relevant to Canada deuterium uranium (CANDU) reactor primary heat transport systems (PHTSs). A high-temperature, high-pressure flow-through loop was used to simulate the PHTS environment. A cooler test section representative of the temperature range in a typical CANDU-6 steam generator was used to induce supersaturation and precipitation down the length of the cooler. Work is ongoing to accurately quantify both the dissolved aqueous iron in the bulk coolant and the quantity of the precipitated magnetite on the pipe wall, with initial findings reported here.
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1 Introduction

In Canada deuterium uranium (CANDU) reactors, strict primary heat transport system (PHTS) chemistry control is used to minimize corrosion product deposition on the fuel channels while allowing for some growth of passivating magnetite throughout the remainder of the carbon steel surfaces in the primary side. Despite this, areas in CANDUs with high fluid velocity such as the outlet feeder piping are susceptible to flow-accelerated corrosion. Here, dissolved iron concentration is lower than the solubility of the major solid corrosion product on carbon steel, magnetite, Fe_3O_4 , allowing for dissolution of the protective magnetite layer. This results in the transport of dissolved iron throughout the PHTS. At the apparent pH (" $p\text{H}_a$," adjusted for heavy water) specification of 10.2–10.4 in a typical CANDU, the solubility of magnetite decreases with temperature. Dissolved iron in the coolant is oversaturated in the colder sections such as the second half of the steam generators, following the U-bend, resulting in the precipitation of magnetite. This reduces heat transfer efficiency and leads to accumulation of radioactive species within the double oxide layer. Efforts such as optimized chemistry control, coolant purification, plant component inspection, and cleaning campaigns, along with predictive computational models have historically been used to minimize corrosion product transport.

An accurate understanding of material degradation mechanisms and the behavior of the key corrosion products of the materials of construction is essential in minimizing radiation fields to ensure nuclear worker safety. While a model based on fitting parameters to station data is limited by a dependence on the source data, developing a model from first principles is challenging due to the complexity and number of processes that must be included. Predictive, mechanistic modeling requires validation of the proposed mechanisms as they are the foundation of the code. Lack of available data, particularly at high temperatures representative of the PHTS, for the precipitation and dissolution kinetics of primary-side oxides have led some modelers to use a mass transport focused approach [1,2]. This includes the ACTTRANCAN code, developed by Atomic Energy of Canada Limited, later Canadian Nuclear Laboratories, to simulate corrosion product transport and cobalt-60 radiation fields in select CANDU reactors [1]. The data needed either have not been measured at the necessary system conditions or have not yet been reproduced.

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For instance, the dissolution rate constants obtained for magnetite by Balakrishnan and Allison [3] have proven to be several orders of magnitude lower than those derived from the more recent loop experiments by Mohajery et al. [4]. Magnetite precipitation has mainly been considered at room temperature or at elevated temperatures, but with a focus purely on magnetite synthesis for further applications. Detailed kinetics, including the form of the rate law, have not been reported, despite the importance of magnetite fouling even at lower temperatures such as the $\sim 40^\circ\text{C}$ of the PHTS purification system [5]. Even consideration of the equilibrium solubility of magnetite at high temperatures representative of the CANDU primary side has resulted in multiple data sets, where the solubility can differ by an order of magnitude [6,7]. This reflects the need for additional data on this oxide, as it is the main corrosion product in CANDUs under reducing conditions. Likewise, for non-CANDU environments, kinetic and equilibrium data are lacking. This is largely due to the mixed metal identity of the corrosion products in the primary-side of station environments, which is not frequently characterized. Equilibrium thermodynamic models have been developed to calculate solubilities for possible Fe, Ni, Co, and Zn oxides by other workers [8]; however, experimental data sets are generally lacking.

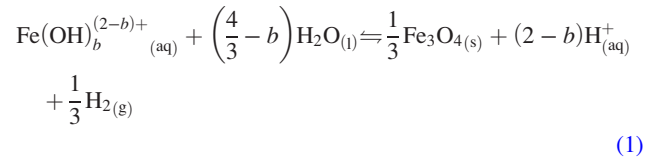
The corrosion and radio activity transport analysis (CARTA) code [9,10] is a one-dimensional, comprehensive simulation package that mechanistically unifies the various material and activity transport processes in a typical CANDU-6 PHTS. The foundation of the code depends on material balances at various interfaces, incorporating diffusion, kinetics, mass transfer, and material wear. CARTA has been used to accurately predict historic station temperature trends including the magnitude of reactor inlet header temperature (RIHT) recovered after pressure decreases, removal of primary- and secondary-side deposits, divider plate replacement, and power derating at the point lepreau nuclear generating station (PLNGS) [11,12]. The modeling of magnetite growth, the main corrosion product in the CANDU PHTS, was performed by using measured amounts of magnetite removed at PLNGS during historical boiler cleaning campaigns to mitigate RIHT rise [12]. These measurements, along with CARTA's thermal-hydraulic modeling, generated initial estimates for the value of the precipitation constant of magnetite and its temperature dependence [13]. Factors such as the frequency at which station oxide deposition measurements are collected, the occurrence of station events such as fouling cleaning campaigns and changes to station chemistry, and the identities of the oxides, which are complex as iron is not the only dissolved corrosion product, require further experimental work to determine fundamental kinetic data which are necessary for more accurate predictive modeling.

As the kinetics of magnetite require further study due to lack of experimental data, this work aims to determine the precipitation constant, k_p , of magnetite and its temperature dependence in a controlled environment by using a high-temperature, high-pressure flow-through loop to simulate typical CANDU-6 PHTS conditions. CARTA has previously used the assumption that the precipitation constant is equal to the dissolution constant, however the lack of agreement in the latter has made this approach challenging. A detailed review is available on the complexity of oxide kinetics of species relevant to nuclear plant systems and waste storage [14]; however, such reviews are not yet available for the precipitation processes. The objectives of the work are to develop an experimental setup and to optimize a procedure to quantify both dissolved and precipitated iron in this system. This paper describes saturation of the system with iron prior to the start of testing, the cooling test section, leaching the magnetite that has grown on the test section surfaces, and quantification of the aqueous and deposited iron in the system.

2 Methods and Materials

2.1 Magnetite Precipitation Kinetics. To extract useful data from these precipitation trials, a reaction rate for magnetite

precipitation must be assumed. This identifies the variables that must be calculated or directly measured from the experimental trials. A surface film may be precipitated or dissolved depending on if the concentration of soluble species in the bulk coolant of the process fluid exceeds the saturation solubility of the metal oxide forming at the surface. Magnetite precipitation is believed to take place according to the Schikorr reaction, which can be written to accommodate the range of ferrous hydrolysis products via $\text{Fe}(\text{OH})_b^{(2-b)+}$ where $b = 0, 1, 2$, or 3 [15]. The Schikorr reaction is the result of a more complex scheme, beginning with the hydrolysis of Fe^{2+} to $\text{Fe}(\text{OH})_2$, which is the dominant aqueous iron species under CANDU conditions



In precipitation and crystallization processes, the main steps are supersaturation, nucleation, and growth. The extent of supersaturation is the key variable in any precipitation system, governing the rates of nucleation and growth. Supersaturation can result from several conditions, including the cooling of a "normal" solubility salt solution (solubility decreases with decreasing temperature) [16], thus precipitation rate laws are often written in terms of the degree of supersaturation. This is expressed as either a ratio of solute activities over the equilibrium oxide solubility or as a concentration gradient [17]. Crystal growth has been explained by various theories, including surface energy, adsorption layer, and diffusion-reaction theory [16]. This work uses the latter approach, where it is assumed that there are two steps; a diffusion process during which the solute is transported to the surface, and a reaction where molecules arrange themselves into a crystal lattice at the surface wall, assuming nucleation has already occurred [18–20]. These steps can be written individually as

$$r = k_m(C_b - C_s) \quad (2)$$

$$r = k_r(C_s - C_{\text{eqm}})^n \quad (3)$$

where C_b , C_s , and C_{eqm} are the bulk coolant, surface, and equilibrium dissolved species concentrations (g/cm^3), respectively, k_m is the mass transfer coefficient ($1/\text{s}$) and k_r is the reaction rate constant, r is the rate of the precipitation reaction ($\text{g}/\text{cm}^2 \text{ s}$), and n is the reaction order. Combining these processes in series results in the following expression [18,19]:

$$r = \frac{C_b - C_{\text{eqm}}}{\frac{1}{k_m} + \frac{1}{k_r(C_s - C_{\text{eqm}})^{n-1}}} \quad (4)$$

If mass transfer is fast, meaning kinetics are limiting ($k_m \gg k_r$), the second term in the denominator of Eq. (4) predominates over the first, $C_b \sim C_s$ and the expression reduces to a simple power law equation that has been used to model growth kinetics [17,18]. This can be written for the magnetite, where $k_r = k_p$, system as

$$\frac{d\delta}{dt} = k_p(C_{\text{Fe},b} - C_{\text{Fe}_3\text{O}_4,\text{eqm}})^n \quad (5)$$

where δ is the loading of magnetite layer (g/cm^2), t is time (s), $d\delta/dt$ is the growth rate of magnetite ($\text{g}/\text{cm}^2 \text{ s}$), k_p is the precipitation constant (cm/s), $C_{\text{Fe},b}$ is the bulk coolant concentration of dissolved iron (g/cm^3), and $C_{\text{Fe}_3\text{O}_4,\text{eqm}}$ is the equilibrium solubility of magnetite (g/cm^3). A first-order rate law ($n = 1$) is used in this work as an initial assumption; however, it has typically been observed when mass transfer is controlling, with second-order or higher possible if kinetics are limiting [16,20]. In conditions with high fluid flow rates, such as those in the high-velocity PHTS piping,

surface reactions are assumed to be controlling. This condition also dictates the type of flow rates that must be used in the test section to ensure kinetics are controlling.

2.2 Experimental Design. There are two general experimental approaches to growth kinetics experiments, a dynamic method and constant composition approach [17,21]. Accurate measurement of the momentary (dynamic) ionic activities in a precipitating system can be quite challenging and time consuming, often requiring a precise electrode or sensor for the ions being quantified. Alternatively, it is possible to investigate precipitation kinetics by fixing and maintaining the supersaturation level throughout the test. In a typical constant composition growth kinetics experiment, seed crystals are introduced to a thermostatic crystallization cell containing solution at a preset supersaturation. To maintain a constant composition of the supersaturated solution, reactants are introduced at a sufficient rate to replace reactant ions that precipitated, thus bringing the supersaturation of the total volume to the value of the initial supersaturated solution [17,21].

A modified approach is proposed in this work, where a recirculating loop is used. The coolant, saturated in iron, is constantly reintroduced to the test section, supplementing the dissolved iron lost to the surface reaction. The measured variables during the experiments are the dissolved iron concentration ($C_{Fe,b}$) and the amount of magnetite deposited on the test section surface, $d\delta/dt$ from Eq. (5). The solubility of magnetite can be calculated from available thermochemical data sets. In this work, the data from Sweeton and Baes are used [6], as these have been shown to generate more accurate predictions of dissolved iron concentration in both CARTA and ACCTRANCAN [1]. To study the temperature dependence of k_p , it is assumed to follow the Arrhenius behavior via

$$k_p(T) = Ae^{\frac{-E_a}{RT}} \quad (6)$$

where R is the ideal gas constant (8.314 J/K mol), T is the temperature (K), E_a is the activation energy (J), and A is a pre-exponential factor.

2.2.1 High-Temperature Experimental Loop. The purpose of the experimental flow-through loop is to induce magnetite

precipitation over a temperature range representative of the difference between the hot and cold legs of a typical CANDU-6 primary heat transport system (310–260 °C), assuming a minimum RIHT rise due to fouling. The full flow-through loop is shown in Fig. 1. The loop process water is pumped from a reservoir at 1.38 MPa (200 psi) and 60 °C and preheated by recovering the heat from the hot stream outlet of the test section in the interchanger, prior to heating to the desired temperature of 310 °C with an electric heater. A pulsation dampener stabilizes pressure and flow at the initial point of water entry into the loop. The hot process stream is then saturated with iron in an autoclave before being fed into the test section. The test section is a three-pass tube-in-tube, designed to cool the process stream to 260 °C using external chilled water. The temperature profile across the test section is monitored via temperature transducers, labeled as TT in the schematic of the test section in Fig. 1. The hot section is insulated to limit heat loss to the environment. For maintenance access, either the test section or the autoclave can be bypassed. The main cooler located after the interchanger further cools the process water to room temperature. Ion exchange columns and a filter are located downstream to purify the process water before returning it to the reservoir. An operating $pH_{25^\circ C}$ of 9.7–9.9 was achieved using lithium hydroxide, as in the PHTS of a typical CANDU reactor. This corresponds to the $pH_{a,25^\circ C}$ (apparent pH) specification of 10.2–10.4 for a CANDU-6 design. An operating flowrate of 2 L/min was used.

2.2.2 Cooler Test Section. To ensure that the system is kinetically controlled by the magnetite precipitation reaction, a high mass transfer rate is required. For mass transfer to be faster than the reaction kinetics as per Eq. (4), the mass transfer coefficient must be sufficiently greater than the assumed value of the precipitation constant ($k_m \gg k_p$). For a single-phase, fully developed turbulent flow in a straight pipe, Berger and Hau's values for the empirical constants (0.0165, 0.86, and 0.33) in the Sherwood number correlation were used for calculating the mass transfer coefficient, as indicated in the following equation [22]:

$$Sh = 0.0165Re^{0.86}Sc^{0.33} \quad (7)$$

$$k_m = Sh \frac{D}{d} \quad (8)$$

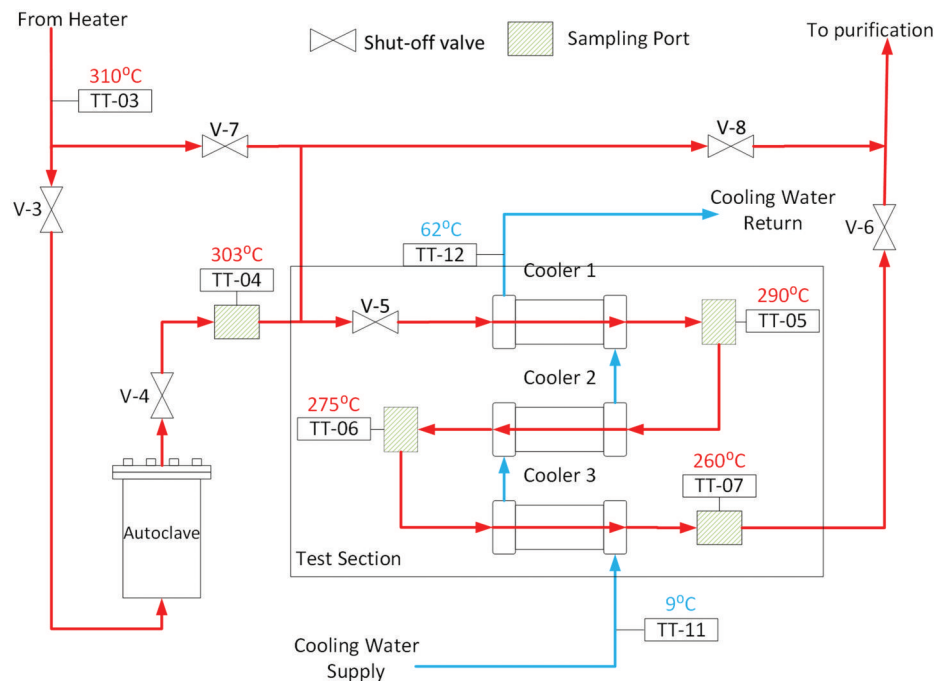


Fig. 1 Process flow diagram of the high-temperature, high-pressure flow through loop, including the cooler test section

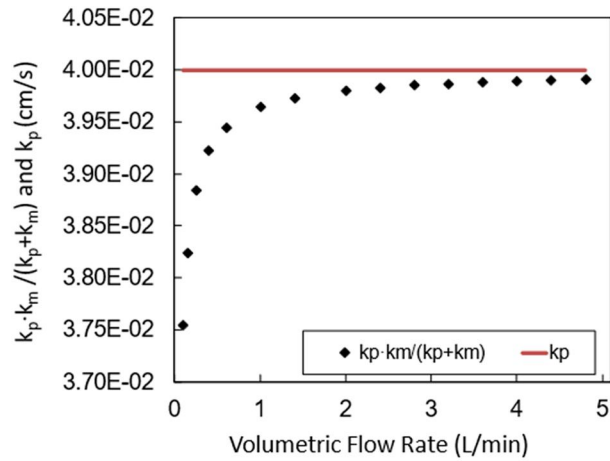


Fig. 2 Mass transfer versus surface reaction control at different process flow rates

where Sh , Re , and Sc are the Sherwood, Reynolds, and Schmidt numbers, respectively, and D and d are the diffusion coefficient (cm^2/s) and the inner tube diameter (cm), respectively. Equation (7) is valid for a Re between 8000–200,000 and an Sc between 1000–6000.

A plot of an estimated precipitation constant of 0.04 cm/s is shown in Fig. 2 alongside the denominator of Eq. (4), assuming a reaction order of 1 ($n=1$). This plot indicates that the denominator condenses to just the value of k_p (i.e., $k_m \gg k_p$) at flow rates of 1 L/min and higher.

An initial estimate for the precipitation constant was determined from station data from PLNGS. The value of k_p has previously been estimated to range between 0.002 and 0.02 cm/s [13], however this approximation is based on eddy current testing on boiler tubes and the resulting oxide loading values from only one station's dataset. This remains an early estimate, as the identity of the oxides deposited on boiler tubes are likely not exclusively magnetite, and data are only available every few years, ranging from 1999 to 2006 [13].

The custom test section was optimized such that there are three individual segments. A tube-in-tube heat exchanger with a $1/4$ inch outer tube inner diameter and a $1/2$ inch outer tube inner diameter was designed to reach the desired temperature with the process side flowrate of 1–2.5 L/min. Magnetite precipitation occurs in the inner tube with cooling water flowing through the outer tube. Each segment has a length of 10 cm and has sampling ports at its inlet and outlet. The overall heat removal length is 30 cm, which reduces the temperature from 310 °C to 260 °C. Titanium was selected as the material of construction for the entire cooler to withstand the acidic conditions when leaching to obtain the quantity of magnetite growth after the experiment is completed. A 2 L Hastelloy C autoclave is filled with carbon steel spheres for iron saturation. All valves in the system are high temperature Swagelok valves, with GRAFOIL packing and made of stainless steel (body and stem). The cold section includes Swagelok quarter-turn valves. Thermocouples and pressure sensors are connected to the data acquisition system. A photograph of the test section is shown in Fig. 3, where yellow arrows indicate the flow direction of the process water. The sampling ports are at the test section inlet and at the end of each cooler pass.

To calculate the solubility of magnetite, indicating the extent of supersaturation, accurate temperature measurements are required. The temperature profile of the test section can be seen in Fig. 1. Assuming that there is no heat loss at the connection of each pass, the sampling temperature is the temperature measured directly at the sampling port. If the heat transfer reduces over time due to future fouling, the chilled water flowrate can be increased.

2.2.3 Iron Saturation. A29 low carbon steel (ASTM A29) balls from McMaster-Carr (China) were used as the source of dissolved

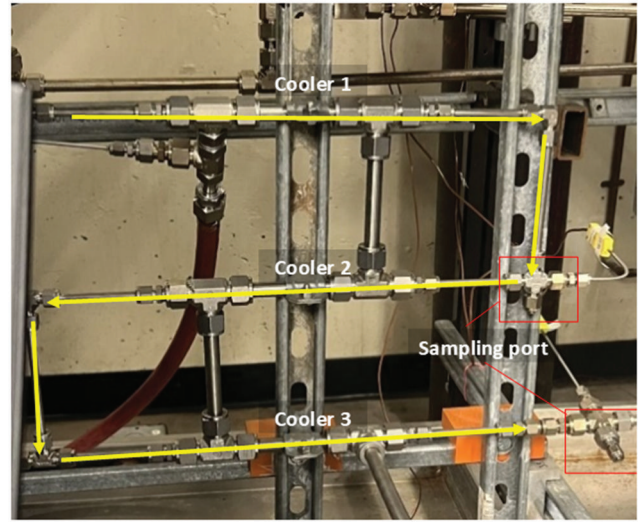


Fig. 3 Photograph of three subsections of the cooler test section, with the process fluid flow path and hot sampling ports indicated

iron. These balls are composed of a minimum of 98% iron by weight, containing trace amounts of carbon, manganese, and other elements. The surface area of the balls required to saturate the process water with dissolved iron in one-pass was calculated from the dissolution rate of magnetite at 300 °C, which is $1.5 \times 10^{-6} \text{ g/m}^2 \text{ s}$ [4]. At the operating flowrate of 2 L/min, a minimum surface area of 0.56 m^2 was required. In this experiment, quarter-inch carbon steel balls were selected as the source, thus at least 6000 balls were required to supply dissolved iron to the system. To meet this requirement while considering the physical capacity of the autoclave, 7000 balls were used. The balls were cleaned with alcohol to remove any grease or residue, followed by cleaning with hydrochloric acid and loading into the autoclave. The hot de-oxygenated process water stream was introduced to the autoclave to achieve iron saturation prior to its introduction into the custom cooler test section.

2.2.4 Sample Collection and Quantification. The estimated value of k_p from Ref. [13] was used to determine the experimental duration to achieve sufficient magnetite growth such that this can be relatively easily quantified via leaching or by mass change. Only the former was carried out in the preliminary experiments thus far. An estimated value of 0.01 cm/s, along with the minimum solubility at 260 °C and a modeled iron concentration using the CARTA code determined that a duration of at least one week was an appropriate duration. The test loop was run continuously during this period. The hot process water was collected in situ as the tube-side fluid into external, titanium coolers. Four sampling port locations are available to hook up a sampling cooler during an experiment (Fig. 3), providing multiple locations to check the dissolved iron concentration in the system ($C_{Fe,b}$ in Eq. (5)). Each sampling point in the test section was connected to a sampling valve and a sampling cooler, which were used to draw the water sample at high temperature via an installed nozzle and subsequently cool it down. After attaching the sampling tube to the tube side of the sampling cooler, two liters of loop water were collected through the cooler to ensure enough iron for detection. Since the decreasing temperature (in the sample cooler) causes some amount of dissolved iron to precipitate on the tube surface, the tube side of the sampling cooler was leached to dissolve the precipitated iron with 10 wt. % HCl. Hydrochloric acid was selected based on its reported efficacy in dissolving magnetite compared to nitric or sulfuric acid [23]. Figure 4 shows a photograph of the hot sampling collection setup, including the sampling cooler. Dissolved iron concentration from the hot sampling (and cooling) will be determined with ICP-MS,

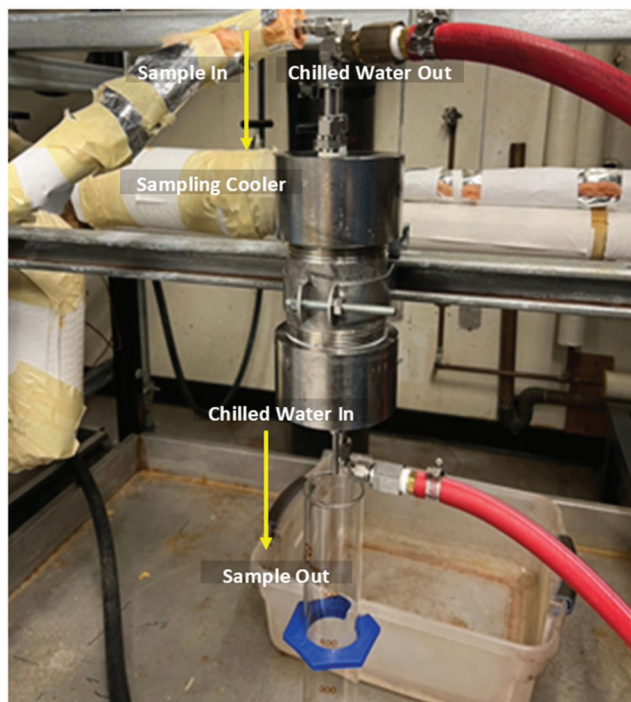


Fig. 4 Photograph of the hot sampling collection into the sampling cooler

with a detection limit of ~ 0.005 ppm. The expected iron solubility for magnetite at 310°C and a pH of 9.8 is ~ 0.015 ppm.

After the completion of an experiment, the custom cooler subsections were disassembled, and each individual cooler segment was also leached with 10 wt. % HCl, now to quantify the amount of deposited magnetite from the tubing surfaces ($d\delta/dt$ in Eq. (5)). Dissolved iron concentration from the solid magnetite leaching was determined using ICP-OES, with a detection limit of ~ 0.05 ppm. The leaching process was performed iteratively until the leachate solution exhibited no detectable iron content above the instrumental detection limit.

3 Preliminary Results and Ongoing Experiments

Commissioning of the custom test section and one, ten-day experimental trial has been completed. It has been confirmed through leaching of the custom test cooler sections that iron oxide deposition has taken place on the titanium tube surfaces, with a measured iron concentration in the leachate solution in the range of ~ 5 ppm, well above the detection limit. This corresponded to approximately gram quantities of iron oxide deposit. Aqueous iron has been quantified in the test section with ICP-OES; however, in the absence of a high-temperature particulate filter in this system, only the concentration measured at the start of the cooler, 303°C is currently reported. The measured amounts of dissolved iron and precipitated magnetite, as determined via leaching, from two replicate experiments are reported in Table 1 alongside the calculated solubility. The magnetite calculation follows the equations that are outlined by Sweeton and Baes [6]. The calculation includes a series of hydrolysis equilibria that are simultaneously

Table 2 Calculated magnetite precipitation constants in the first test section

Trial	Calculated precipitation constant (cm/s)
1	0.0009
2	0.0004
3	0.0003

solved based on the hydrolysis and solubility constants reported in the literature. A computer code was generated to complete the solubility calculations.

Equation (5) was used to calculate the precipitation constant for each of the replicate trials, as summarized in Table 2. An average value of 0.0005 cm/s for k_p has been determined from the first test section, at an average temperature of $\sim 297.00^\circ\text{C}$. This magnitude is lower than the value of k_p that has initially been calculated based on station data; however, the latter showed a wide range of possible values, from 0.002 cm/s to 0.02 cm/s [13]. Without the presence of a high-temperature filter in the hot sampling collection process, suspended particles are also contributing to the measured dissolved iron concentration. This is elevating the measured iron concentration and leading to lower than realistic values of k_p . The quantification of the dissolved iron concentration in the system requires further work and the installation of additional filters at the start of the custom cooler test section and at the sample ports of the hot sampling sections to prevent the passage of particulate iron oxide into aqueous sampling locations. As these issues require further test setup optimization, more detailed error propagation is currently not included in these preliminary results. In addition, surface analysis such as scanning electron microscopy and laser Raman spectroscopy will be performed on segments of the test cooler subsections, which will be cut out after completion of subsequent experiments, to confirm the magnetite precipitation.

The experiments will also be repeated using different flow rates to ensure that kinetics and not mass transfer are controlling at the operating flowrate of 2 L/min that has been initially used in this work. As preliminary results have not yet indicated a strong temperature dependence of k_p over the 30 -degree range tested, it would be beneficial to conduct these tests over a broader temperature range, for instance, 250 – 315°C . Temperatures below 250°C could prove challenging due to the low solubility of magnetite and instrumental detection limits.

4 Conclusion

The benefit of a mechanistic modeling approach allows for greater flexibility when modeling station events including changes in materials of construction during refurbishment and changes in primary-side chemistry, in terms of the consequences to material transport but also subsequently to radio activity transport. One of the challenges of mechanistically modeling the transport of various elements throughout the PHTS, particularly when considering the kinetics of incorporation of multiple elements into the solid corrosion product layers, is the need for kinetic constant data of these solid metal oxides.

The experimental setup, iron quantification methods, and the initial test run performed to determine the precipitation constant of magnetite, k_p , are promising, though they require some adjustments

Table 1 Measured iron concentration in solution at the start of the test section, magnetite solubility [6], and calculated growth rate

Trial	Run time (h)	Average test section temperature ($^\circ\text{C}$)	Calculated solubility (mg/kg)	Measured iron concentration (mg/kg)	Measured magnetite deposit (mg)	Growth rate ($\text{mg/m}^2\text{ s}$)
1	245	295.50	0.0055	0.058	1.95	0.00053
2	172	296.75	0.0055	0.063	1.28	0.00049
3	290	298.50	0.0056	0.059	0.95	0.00024

to simplify and ensure more accurate quantification of dissolved and deposited samples. The leaching of the solid deposits on the custom cooler test section has proven effective, though leaching times are lengthy and the process tedious. The hot sampling of dissolved iron followed by cooling and leaching of the sampling line introduces the complication of iron oxidation and hydrolysis. This can be ferrous with the use of reducing agents to ensure aqueous iron is in the ferrous form. Following the optimization of the aqueous sampling procedure, which will allow for confirmation of the dissolved iron concentration in the test section, the Arrhenius behavior of the precipitation constant will be explored.

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Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

A = pre-exponential factor
 C_b = bulk coolant species concentration, g/cm³
 C_s = surface species concentration, g/cm³
 C_{eqm} = equilibrium dissolved species concentration, g/cm³
 C_{Fe} = dissolved iron concentration, g/cm³
 $C_{Fe,b}$ = bulk coolant concentration of dissolved iron, g/cm³
 $C_{Fe3O4, eqm}$ = equilibrium solubility of magnetite, g/cm³
 d = inner tube diameter, cm
 D = diffusion coefficient, cm²/s
 E_a = activation energy, J
 k_m = mass transfer coefficient; $(Sh \frac{D}{d})$
 k_p = magnetite precipitation constant
 k_r = reaction rate constant
 n = reaction order
 pH_a = apparent pH
 $pH_{a, 25^\circ C}$ = apparent pH at 25 °C
 $pH_{25^\circ C}$ = pH at 25 °C
 r = rate of the precipitation reaction, g/cm³ min;

$$\left(\frac{C_b - C_{eqm}}{\frac{1}{k_m} + \frac{1}{k_r(C_s - C_{eqm})^{n-1}}} \right)$$

 R = ideal gas constant, 8.314 J/mol K
 t = time, s
 T = temperature, K

Greek Symbols

δ = loading of magnetite layer, g/cm²
 $d\delta/dt$ = growth rate of magnetite; $(k_p(C_{Fe,b} - C_{Fe3O4,eqm})^n)$

Nondimensional Numbers

Re = Reynolds number
 Sc = Schmidt number
 Sh = Sherwood number; $0.0165Re^{0.86}Sc^{0.33}$

Subscripts or Superscripts

a = apparent
 a = activation
 aq = aqueous
 b = bulk coolant species

eqm = equilibrium dissolved species
 Fe = iron
 Fe, b = bulk coolant dissolved iron
 Fe_3O_4, eqm = equilibrium magnetite
 g = gas
 l = liquid
 m = mass transfer
 n = reaction order
 p = precipitation
 r = reaction rate
 s = solid
 s = surface species

Acronyms and Abbreviations Widely Used in Text and List of References

CANDU = Canada deuterium uranium
 CARTA = corrosion and radioactivity transport analysis
 ICP-MS = inductively coupled plasma mass spectrometry
 ICP-OES = inductively coupled plasma optical emission spectroscopy
 PHTS = primary heat transport system
 PLNGS = point Lepreau nuclear generating station
 RIHT = reactor inlet header temperature
 TT = temperature transducer

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