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REMOVAL OF TRITIATED LIGHT WATER FROM SPENT FUEL BAY USING THERMAL STRATIFICATION

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Abstract

The spent fuel bay in the National Research Universal (NRU) reactor has elevated levels of tritiated light water. The tritium concentration has increased over the years due to nuclear isotope production and ongoing fuel operations. The proposed solution to reduce the tritium levels is to efficiently replace the entire volume of the bay (1.07 million liters) in approximately 48 hours using a thermal stratification method. This paper describes the development and testing of the method from bench scale to full scale. Experimental and numerical results will be presented.

1. Introduction

1.1 NRU reactor background

Tritium is produced in the heavy water moderator and coolant by deuterium neutron capture. The historical rate of tritium production in the Heavy Water System (HWS) in the NRU reactor is ~1.5 to 2.0 Ci/kg D_2O per year. Trace amounts of tritium are transferred from the HWS to the NRU spent fuel bay with each rod transferred as a result of medical isotope production and normal reactor operation. The amount of tritiated heavy water transferred from the HWS to the NRU spent fuel bay is estimated fairly consistently at about 300 kg of D_2O per year. As the tritium concentration in the HWS increases with time, so is the amount of tritium transferred to the fuel bay.

The tritium concentration in the bay was above ~10 mCi/L since January 2005. This level has created an appreciable source of worker radiation dose due to continuous exposure of bay workers to airborne tritium concentrations of 1.0 DAC (Derived Air Concentration) or more. Consequently, NRU bay operators must wear tritium respirators and must limit their working time. The spent fuel bay also has a leak to ground of ~ 500-800 L/day, which represents a small uncontrolled release that will be less of a problem if the tritium concentration in the bays was reduced.

1.2 NRU spent fuel bay (NRU rod bay)

The NRU spent fuel bay (or rod bay) was constructed in the 1950s. The bay is used for storage of spent fuel and other irradiated components, for storage and testing of experimental fuel assemblies and for inspection and rod transfer during isotope production. The bay consists of five sections and a trench (Figure 1). Rods are transferred into the general area of the bay via a deep trench. The bay holds ~1.07 million litres and is operated continuously, including most times when the reactor is off-line.

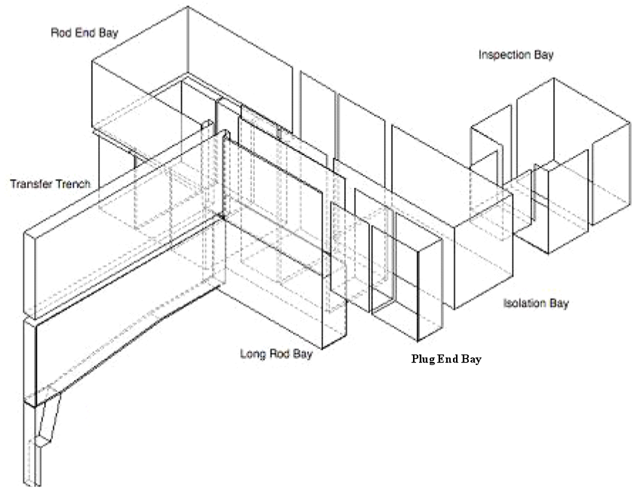


Figure 1 NRU Rod Bay schematic.

Normal operation of the bay requires unobstructed access at all times, which precludes the use of any surface cover to limit evaporation. Emptying the bay water and replacing it with clean water is also not feasible because the water must provide shielding and cooling for the spent fuel at all times.

1.3 Thermal stratification method applied to water replacement

Thermal stratification of water is a naturally occurring phenomenon observed in large bodies of water such as rivers, estuaries and reservoirs [1]. Thermal stratification has been applied on a small scale as a method for heat storage in water tanks [2], but it has not, to the author's knowledge, been applied as a method to replace water in spent fuel bays. The key of thermal stratification is that cold and warm water separate due to their density difference creating a stable interface.

The thermal stratification method applied to the rod bay works in two steps. First, the decay heat of stored spent fuel is allowed to warm up the tritiated bay water. Second, cold deionized water is fed at the bottom of the bay, displacing the light warm water. Warm tritiated water is skimmed off the surface (Figure 2) at the same rate as the feed rate to maintain a constant water level and to ensure shielding and cooling of the fuel remain unaffected.

The expected tritium reduction concentration is shown in Figure 3 for three possible scenarios. The best tritium reduction is obtained with an ideal stratification (no mixing between the warm and cold water). This is equivalent to a plug flow (PF) operation, whereby only one replacement or swap volume is required to replace exactly one bay volume. In contrast, a poor tritium reduction is obtained when the stratification fails completely and there is mixing between the warm and cold water. This is equivalent to a continuous stirred tank (CST) system with trapped (or "dead") volumes (TV), which predicts a ~55% tritium reduction for one bay volume swapped (with a 9% trapped volume). The desired scenario should approach plug flow dynamics as much as possible with a target tritium reduction of 90%.

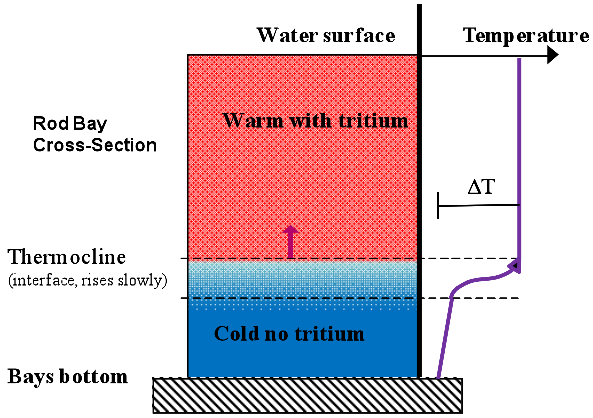


Figure 2 Thermal stratification schematic

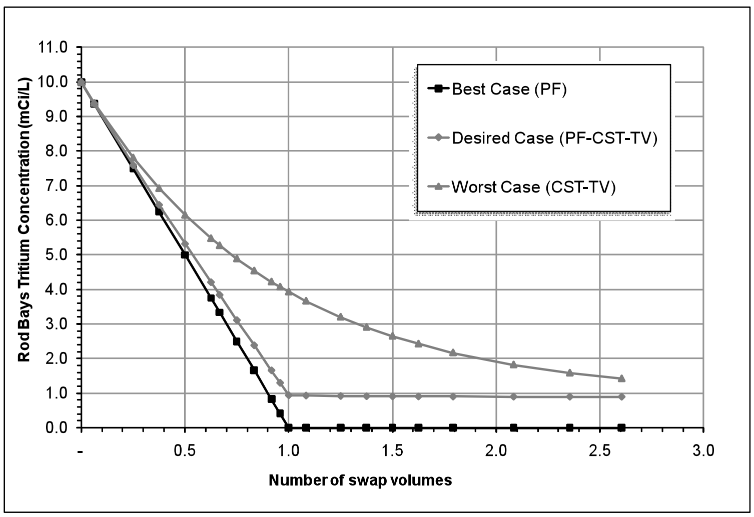


Figure 3 Estimated tritium reduction concentrations as a function of swap volumes

2. Study of thermal stratification – Bench-scale

The bench-scale study consisted of constructing a model of the NRU rod bay, paying special attention to scaling issues. The parameters investigated were diffuser geometry and its location, feed water temperature, feed/bleed flow rate and decay heat. In addition, a Computational Fluid Dynamic (CFD) analysis matched the tank geometry and provided a transient solution of the heat, mass and momentum equations for a selected set of operating conditions.

2.1 Description of experimental set-up

The bench-scale model consisted of a 92 L plexiglass tank divided into four sections to simulate the bays' geometry, including an extra long section to simulate the bay trench. The water in the tank was thoroughly mixed with a dye (methyl orange) and heated to the desired temperature with a stirring-heater over a period of about 0.5 to 1 h. The dye was used as a tracer to differentiate between the tank water (with dye) and feed water (without dye). Measuring the dye concentration provided a simple indication of the degree of water mixing at various stages of the experiment. The dye concentration was measured using a Hack DR/2000 direct reading Ultraviolet-Visible (UV-Vis) spectrophotometer at a wavelength of 463 nm to a precision of about ±0.01 ppm using a 5-point linear calibration curve. This precision translates into ±0.1% of the final percentage concentration change. The net fuel decay heat was estimated at 20 W for the bench-scale model (scaled by volume). This is approximately 1x104 times less than the 80 kW heating estimated in the rod bay.

Four types of diffusers were used in the various tests: 1) a 3/8 inch stainless steel tube, 2) a metal frit, 3) a large double-plate and 4) a small double-plate with a screen mesh. A picture of the four is shown in Figure 4. Foam pipe insulation was used to minimize heat losses and to improve temperature control.

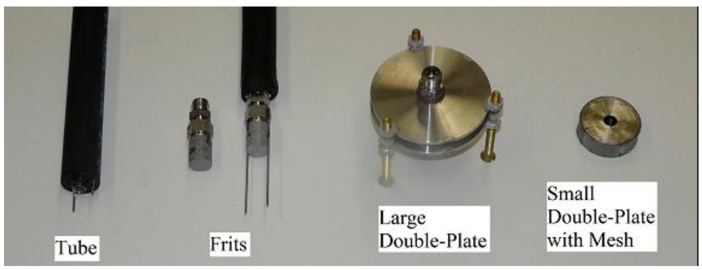


Figure 4 Four different diffusers 1) Tube, 2) Metal frit, 3) Large double-plate, and 4) Small double plate with mesh

2.2 Description of experimental test run

A flowsheet of the experimental setup is shown in Figure 5. There were two recycle-loops, the bulk recycle and the feed recycle, used in conjunction with a heat exchanger for a precise temperature control of ±0.2ºC. Temperature control was achieved with a solenoid valve that controlled the flow of cooling water to the tank cooling-coil. The water temperature in the tank was measured with a type T thermocouple that could slide to different heights. The initial and final tank water temperature and concentrations were measured. Also, the average overflow water concentration from the three collection points and the water temperature at various tank depths were measured. In order to compare experiments, the time was normalized. Normalized time is clock time divided by the time at the end of the run, e.g. for a 144-minute run, 20 minutes represents 0.14 in normalized time.

The expected average travelling velocity of interface between the cold and warm water for the bench-scale experiment was ~0.2 m/h. This is the same interface velocity to be expected in the full-scale bay swap. Keeping the same interface velocity between the two scales is important to adequately reproduce the physics controlling the stability of the stratification, i.e. convection (in the vertical direction) and mass diffusion (in the horizontal direction).

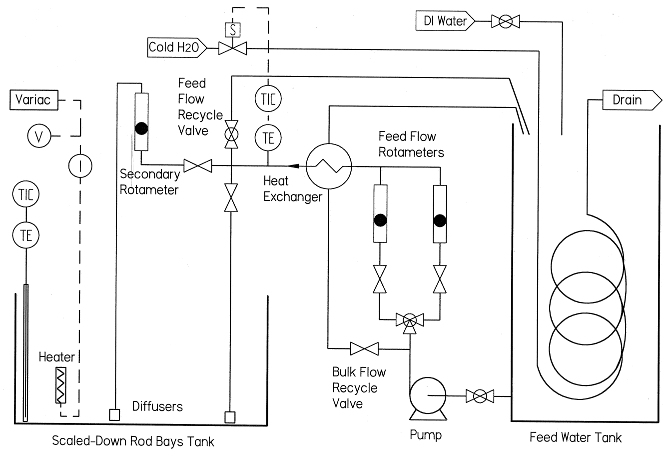
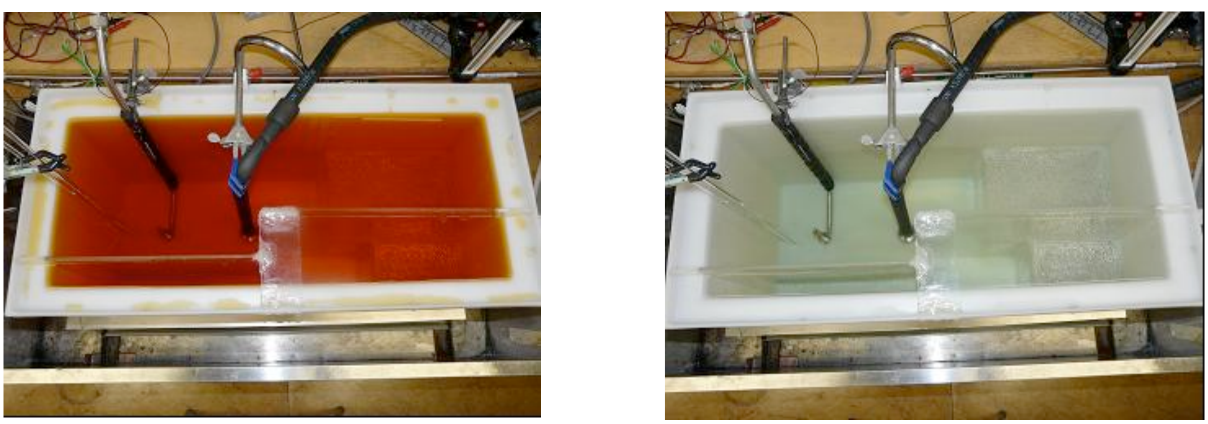


Figure 5 Flowsheet of experimental set-up

The final tank concentration was obtained after re-mixing the water in the tank at the end of the run. Figure 6 shows a visual comparison of the achieved concentration reduction by comparing the start and end of the experiment. Note the dramatic change in water colour. The excellent water replacement results achieved are possible because mass diffusion is much slower than thermal diffusion. Therefore, as long as a stable interface exists between the cold and warm water, dye will not diffuse between the two layers. The same can be said about tritiated (equivalent to water with dye) and non-tritiated water (water without dye).



Start of Experiment #27

End of Experiment #27

Figure 6 Comparison between the initial and final tank concentrations after 1.1 tank volumes swap

2.3 Description of experimental results

Two types of graphs will be shown throughout this section. The first type is a plot of tank height versus tank water temperature at two normalized times, i.e. t=0.14 (early in the run) and t=1.0 (end of the run after swapping 1.1 tank volumes). The second type is a plot of overflow concentration versus swap volume. In the latter, note that the tank concentration after tank re-mixing is always significantly lower than the overflow concentration at the end of the run due to water re-mixing after the test is complete.

2.3.1 <u>Effect of diffuser type and location</u>

Four different types of diffuser were used: tube diffuser, large double-plate diffuser, small double-plate with mesh diffuser and frit diffuser. The large double-plate and the tube diffusers were tested first (Figure 7). The large double-plate diffuser worked well but proved unreliable because the large open gap between the two plates provided no backpressure to ensure a uniform flow distribution. The tube diffuser did not perform well, achieving only a final concentration of 20% of the original value (i.e. 80% reduction). In contrast the frit and small double-plate with mesh diffuser achieved very good results as shown in Figure 8 with final concentrations less than 0.5% of the original tank concentration after 1.1 volume swap (i.e. 99.5% reduction). The marked difference amongst all four diffuser types is largely based on how the water is injected. A laminar injection is critical to minimize water mixing. The tube diffuser approached a jet-type injection with a calculated velocity of ~1 m/s, compared to a velocity of ~0.02 m/s for the other diffusers. The frit diffuser was preferred based on its simplicity.

The effect of the diffuser location was tested by comparing various possible locations in the tank: centre and corner of the tank 50 mm off the bottom, two centre locations at opposing sides of the tank 50 mm off the bottom and right at the bottom of the tank channel (0 mm). The centre and corner feed locations 50 mm of the bottom of the tank gave similar results. Having two frit diffusers marginally improved the thermal stratification. However, locating the diffuser at the bottom of the channel was the most successful, as a final concentration of 0.4% was achieved. These results suggest that locating the diffuser as close as possible to the bottom of the tank channel provides the best concentration reduction. This is because water mixing between the cold feed water the warm water present below the diffusers is minimized.

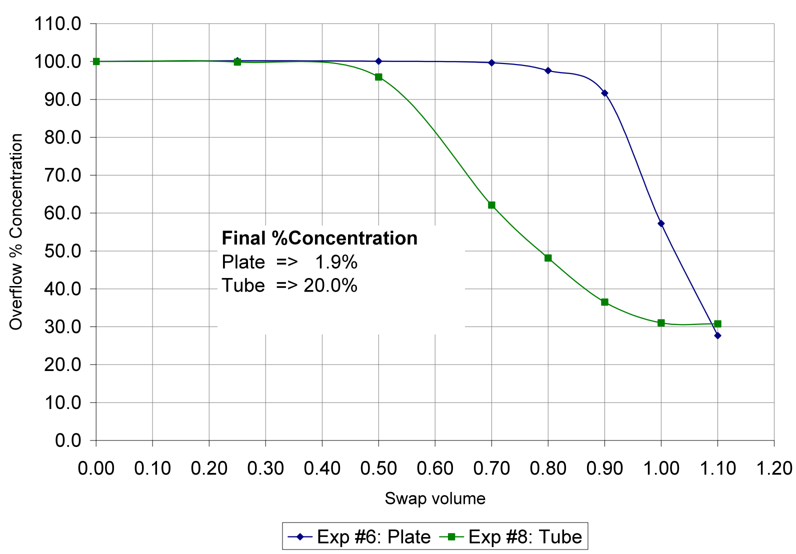


Figure 7 Overflow concentration versus swap volume for the tube and large double-plate diffusers

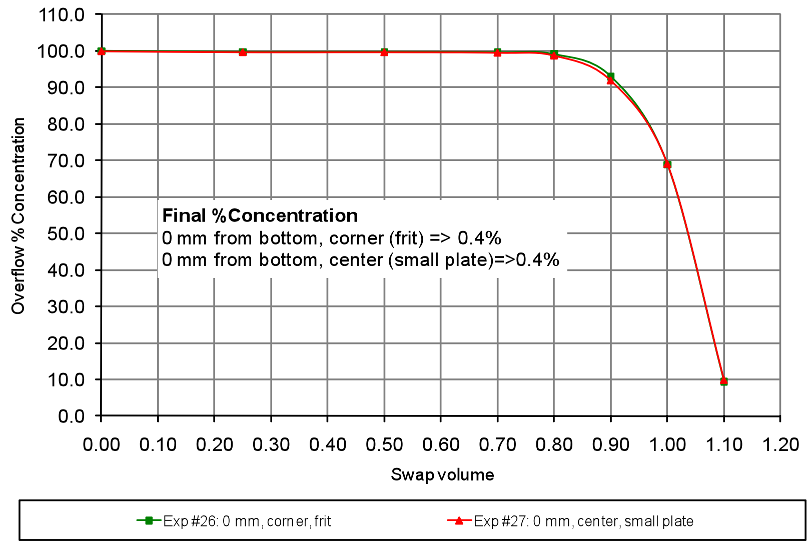


Figure 8 Overflow concentration versus swap volume for the frit and small double-plate diffusers

2.3.2 Effect of water temperature

Three different feed water temperatures were tested (Figure 10). In all cases the initial water tank temperature was kept constant at 25ºC (77ºF). Decreasing the feed water temperature improves the sharpness of the interface between the cold and warm waters, as indicated by a large temperature gradient between tank heights. The colder the feed water, the better the stratification but below 10ºC this improvement is minimal because water density as a function of temperature does not change much between 0ºC and 10ºC.

2.3.3 Effect of water feed/bleed flow rate

Three different experiments were done at various feed rates (Figure 11). The bleed rate was always equal to the feed rate to maintain a constant tank level. The base case feed rate of 0.7 L/min was based on scaling down the flow rate of ~400 L/min (1.07 million litres divided by 48 hours) and keeping the interface velocity constant at ~0.2 m/h. Slower feed rates do not improve stratification because the time scale of the water displacement process becomes comparable to that of thermal diffusion. This causes water mixing which manifests itself as a smaller temperature gradient i.e. broadening of the thermal interface. Employing a higher feed rate, ~570 L/min (scaled-down 0.99 L/min), gave marginally better results, but the trade-off is that the equipment needed to handle the higher flow becomes harder to handle for a temporary 48-hour operation and thus impractical. The results suggest that the flow rate of 400 L/min (scale-down 0.7 L/min) is a reasonable target.

2.3.4 Effect of decay heat

Three different heating loads were tested; the standard 20 Watts and two extreme heat loads of 120 and 300 Watts (see Figure 11) using a frit diffuser. The stratification degraded dramatically with increasing heat loads as shown by the broadening of the thermal interface. A large heat load causes convective currents that promote water mixing and thus a broadening of the stratification interface. The 120 and 300 Watt cases were conducted as a sensitivity analysis, as the scaled-up values of these numbers do not represent a realistic operating range for the rod bay. However, this analysis attests to the stability of the stratification, as the stratified interface is loss only with very large heat loads.

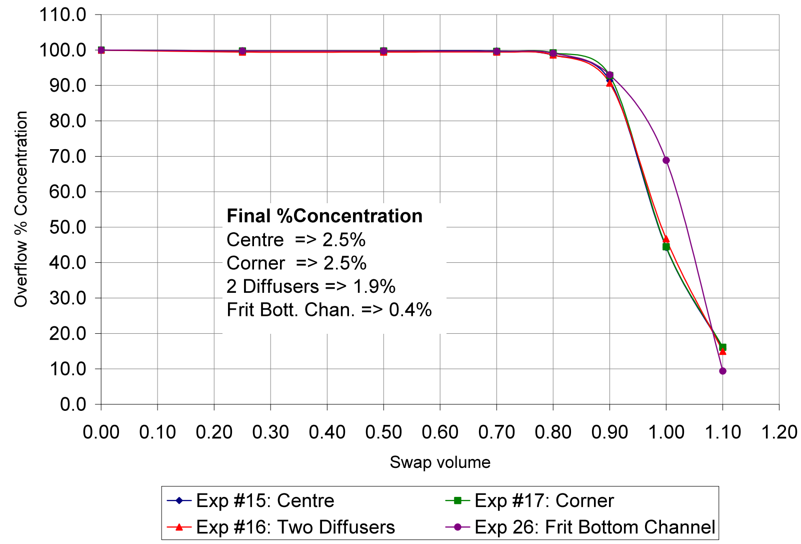


Figure 9 Overflow concentration versus swap volume for various diffuser tank locations, 1) centre 50 mm off the bottom, 2) corner 50 mm off the bottom, 3) two diffusers 50 mm of the bottom and 4) bottom of the tank channel

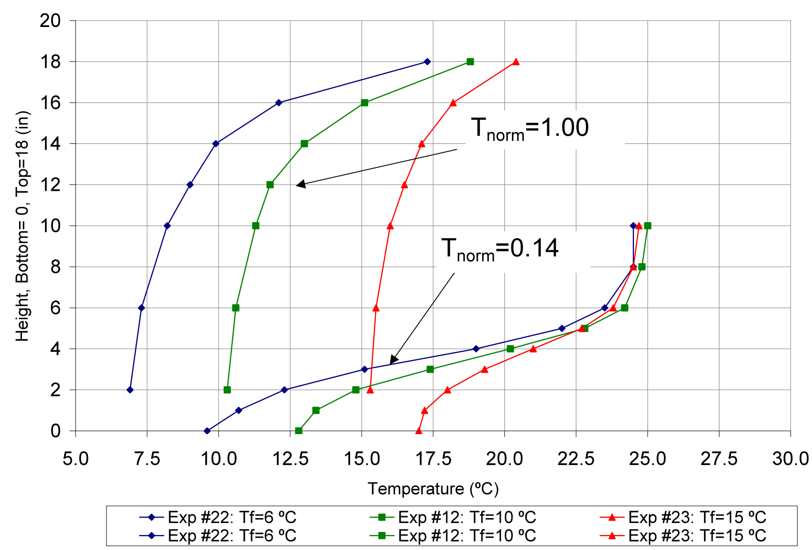


Figure 10 Temperature profile at various tank heights for two normalized times for various feed water temperatures

2.3.5 Bench scale model (CFD)

A Computational Fluid Dynamics (CFD) model was developed for the bench-scale tank model. The modeling results compared well with the experimental values in terms of temperature and concentration. Hence, the physics of the CFD model was validated and the model was extended for the full-scale NRU rod bay swap.

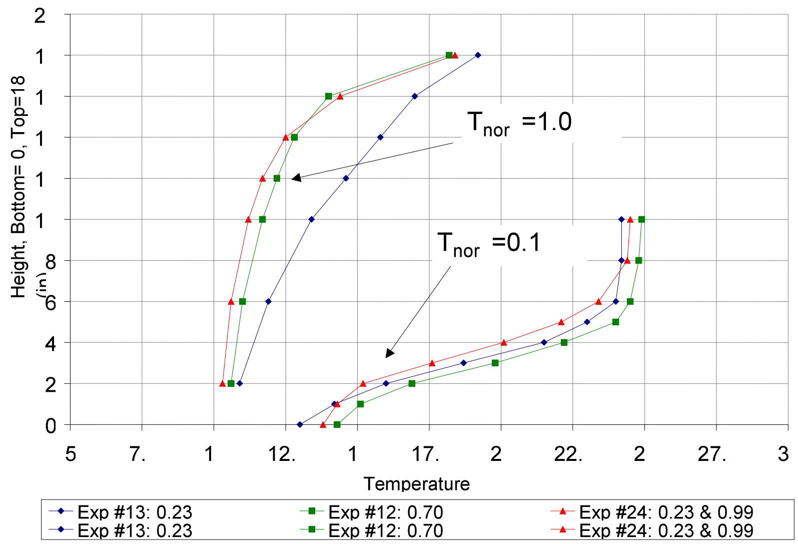


Figure 11 Temperature profile at various tank heights for two normalized times for various feed/bleed flow rates

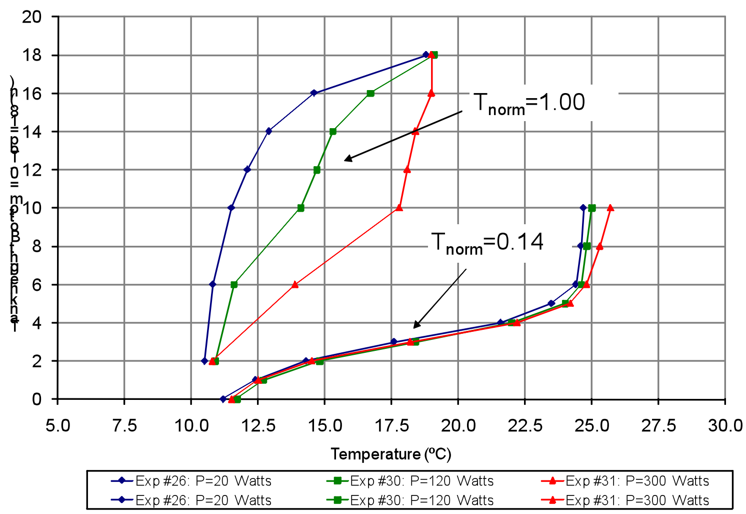


Figure 12 Temperature profile at various tank heights for two normalized times for heat loads

Fluent 6.3 was used as the CFD software with the following key assumptions: 1) The flow was treated as laminar, 2) Boussinesq approximation was made for density variation, 3) Thermal energy equation was solved, 4) A passive scalar was solved representing tritiated versus non tritiated water, both having the same physical properties (Thermal expansion coefficient=0.00021 1/K, Density=998.2 kg/m3, Heat Capacity=4182 J/kg.K, Thermal conductivity=0.59 W/m.K, Diffusivity=2.2x10^{-6} m^2/s). The solution was performed with a second order discretization in space and first order in time. A PISO (Pressure Implicit with Splitting of Operators) algorithm was applied for sequential equation coupling algorithm with 10 iterations per time step and time steps varying from 0.01 s, initially, ramped up to 1.0 s.

3. Study of thermal stratification – Full-scale

The full-scale study consisted of testing the thermal stratification concept in the NRU rod bay in a closed-loop using a prototype design based on the bench-scale results (Figure 13). A floating skimmer pump pumped out surface bay water to an existing bay heat exchanger (HX22B), where the exchanger cooled down the bay water by ~10°C. The cold water was then fed to the bottom of the rod bay trench through a large custom-made frit diffuser. Multiple submerged thermocouples located at various depths provided water temperature measurements as a function of depth and bay location. The different percentages represent swap volume progression (i.e. 100% = one swap volume, end of test)

The full-scale NRU rod bay demonstration tested the effectiveness of the stratification without removing any bay water. The only drawback of having a closed-loop was that a tritium concentration profile could not be obtained. Obtaining this profile would have required having an open loop (with a deionized water feed) instead of a close loop, and sufficient capacity to store the pumped out bay water. Unfortunately, no suitable water storage was available at the time of the test, yet an expected tritium concentration profile was estimated based on a combination of CFD modelling and experimental results.

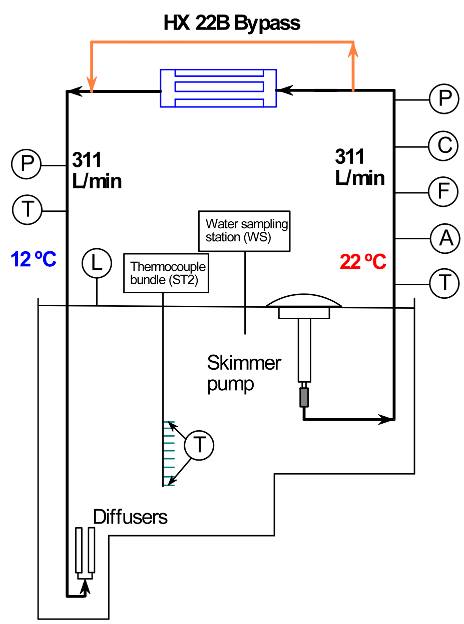


Figure 13 Flowsheet of the full-scale NRU Rod Bay water thermal stratification demonstration, P=Pressure, T=Temperature, L=Level, C=Conductivity, F=Flow, A=Radiation Detector

Figure 14 shows superimposed temperature profiles at three different bay locations (trench, general and isolation bays) obtained during the full-scale demonstration run at various percentages of volume swapped (100%=one bay volume). The profiles of the three bay locations overlapped which means that the thermal stratification is uniform across the entire bay. Also, a sharp thermal interface was measured for the first 15% swapped volume. For the remaining of the swap, the interface broadens and the temperature gradient across the interface is reduced in half from ~10°C to ~5°C due to water heating. Figure 15 shows the temperature profiles in the general bay computed by the CFD model at the same swapped volume percentages as those obtained experimentally.

Comparing Figure 14 and Figure 15 shows that the temperature profiles computed with the CFD model accurately matched the experimental values. Since the CFD model was validated at the bench-scale for both temperature and concentration, and since the CFD temperature profiles for the full-scale demonstration closely matched the experimental profiles. It then follows that the tritium concentration profiles shown in Figure 16 predicted for the full-scale demonstration should be accurate. The well-defined interface between the tritiated bay water (concentration equal to one) and the deionized water (concentration equal to zero) provides sufficient evidence to expect a high tritium reduction (~90%). This is because tritium will not diffuse across the interface as long as the cold and warm water retain a temperature gradient and remain separated (i.e. mass diffusion much slower than thermal diffusion).

4. Conclusion

A thermal stratification method has been developed and tested to replace the entire volume of the NRU Rod Bay (1.07 million litres) in approximately 48 hours. This method is expected to achieve a tritium reduction of approximately 90% based on the comparison of the results obtained in the full-scale demonstration with the results of the CFD model. The thermal stratification is a robust technique that can accept modest process interruptions provided that the thermocline is not loss. It also seems fairly insensitive to feed/bleed flow rates as long as the cold water feed is not turbulent.

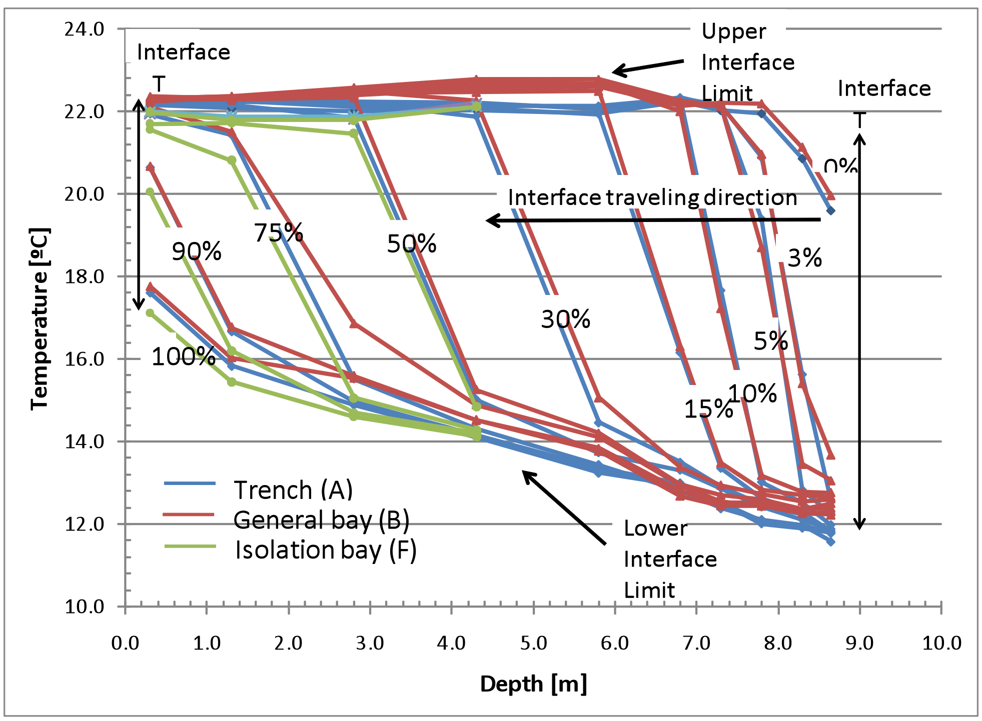


Figure 14 Experimental results of the full-scale NRU Rod Bay thermal stratification demonstration - Temperature readings as a function of depth for various bay locations (100% = one swap volume)

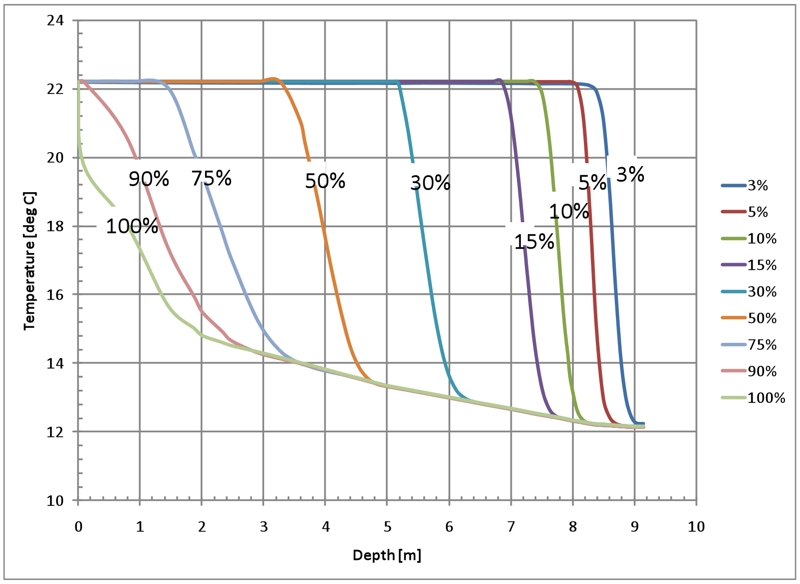


Figure 15 CFD Modeling results of the full-scale NRU Rod Bay thermal stratification demonstration – Temperature readings as a function of depth (100% = one swap volume)

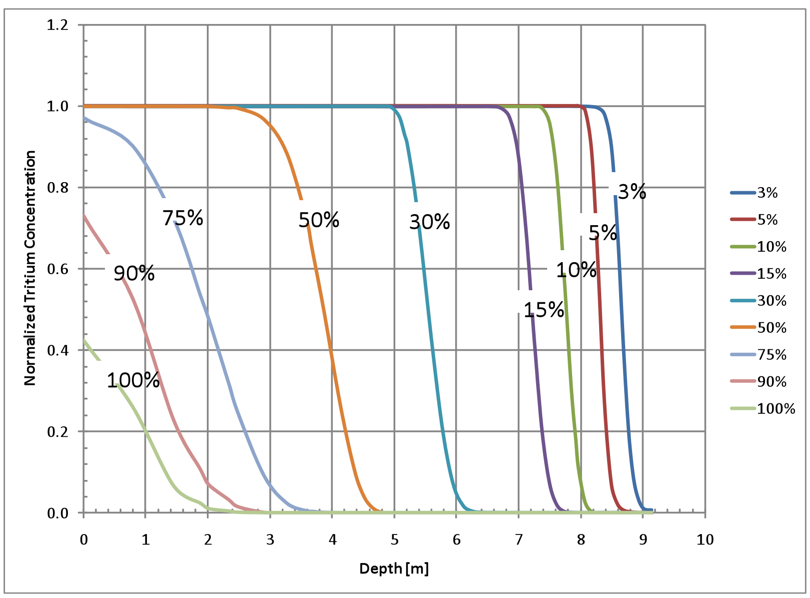


Figure 16 CFD Modeling results of the full-scale NRU Rod Bay thermal stratification demonstration – Normalized tritium concentrations as a function of depth (100% = one swap volume)

5. References

[1] E. Fischer, et al., "Mixing in Inland and Coastal Waters", Academic Press, 1979

[2] S. Alizadeh, "An Experimental and Numerical Study of Thermal Stratification in a Horizontal Cylindrical Solar Storage Tank", Solar Energy, Vol. 66, Iss. 6, pp. 409