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An Analytical Technique to Determine the Potential for Moisture Accumulation in Deactivated Structures

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ABSTRACT

This paper describes an analytical technique developed to predict an order of magnitude volume of moisture accumulation in massive structures after deactivation. This work was done to support deactivation of a Department of Energy nuclear materials processing facility. The structure is a four-story, concrete building with a rectangular footprint that is approximately 250m long by 37m wide by 22m high. Its walls are 1.2m thick. The building will be supplied with unconditioned ventilation air after deactivation. The objective of the work was to provide a cost effective engineering evaluation to determine if the un-conditioned ventilation air would result in condensate accumulating inside the building under study. The analysis described is a simple representation of a complex problem. The modeling method is discussed in sufficient detail to allow its application to the study of similar structures.

INTRODUCTION

The work described in this paper is in support of deactivating the F-Canyon facility at the Savannah River Site (SRS) in Aiken, South Carolina. F-Canyon is one of two facilities at SRS that support chemical separation processes for nuclear material. Per the request of the Department of Energy (DOE) Westinghouse Savannah River Company is in the process of deactivating the facility so it can be decommissioned in the future. One of the issues being considered is how to consolidate the ventilation systems while maintaining sufficient ventilation to reduce the risk of effluent releases, prevent migration of contamination and minimize surveillance and maintenance activities.

In order to reach the desired ventilation end-state the existing ventilation flows must be simplified to reduce risk and ongoing operating costs. The canyon ventilation will be simplified to a single pass, “pull-through” flow utilizing a single canyon exhaust fan. Airflow will continue to be from zones of clean or lower potential for contamination to zones of higher contamination similar to normal operations.

One question that was identified while developing the deactivated ventilation state is - Will unconditioned outside air introduced through ventilation result in condensation accumulating inside the building? An accumulation of condensate over time may increase the potential for the spread of contamination from the building; therefore, a simple, conservative analysis that could show the net condensation/evaporation effect inside the building was desired.

NOMENCLATURE

A = Area

A_c = Cross-sectional area of the flow

A_s = Annual surface temperature swing

C = Condensate production rate

C_f = Condensing factor

c_1 = 69.4 [1]

c_2 = 0.35 [1]

c_p = Specific heat

$D_h \equiv \frac{4A_c}{P}$ = The hydraulic diameter [2]

h = Convective heat transfer coefficient for the flow

k = Thermal conductivity

$\dot{m}$ = The mass flow rate of air
P = Wetted perimeter of the flow
P_S = Saturation pressure at the surface temperature
P_{DP} = Saturation pressure at the dew point temperature
Q = Ventilation air flow
T_i = Inlet air temperature
T_m = Mean earth temperature
T_0 = Outlet air temperature
T_s = Surface temperature of the duct
t = Time
t_0 = Day of minimum surface temperature
v = Air velocity
W_a = Evaporation rate
W_1 = Humidity ratio at the dew point temperature
W_2 = Humidity ratio at the surface temperature
x = Depth
Y = Latent heat of evaporation at the surface temperature
α = Thermal diffusivity $= \dfrac{24k}{\rho c}$
ρ = Density

Discussion

The analytical technique developed for estimating the accumulation of condensation is described below. The objective of this evaluation was to provide a cost effective engineering estimate of condensate accumulation. This analysis is a simple representation of what is actually a complex problem given the size of the structure, and the many variables which affect evaporation and condensation. Due to this simplification, this evaluation attempts only to provide an order of magnitude estimate of the quantity of condensation which would be present on various levels in the F-canyon after deactivation, and identify any net accumulation from year to year.

Some of the basic data and assumptions used to evaluate the facility are as follows:

- Data from 1997 was used as typical of the condition of outside Air.
- The incoming air will not be conditioned.
- All condensate forms on the walls, ceiling, and floor of the corridor or duct through which the air is passing. This assumption is not conservative; however, see the discussion of condensing factor.
- All condensate that forms is immediately accumulated on the floor. This is a conservative assumption affecting both evaporation rate and reported depths of condensate.
- Evaporation only occurs over the area of the floor of the corridor or duct through which the air is passing. This is a conservative assumption.
- The psychrometric conditions of the air do not change as it flows through the building. This is conservative with respect to condensation, but not conservative with respect to evaporation in areas near the exhaust point.
- The surface temperature of the building is not changed by the effects of condensation and evaporation at the surface. This assumption is conservative with respect to condensation, but not conservative with respect to evaporation. The large thermal mass of the structure will mitigate this effect to a small degree, but it is primarily a surface phenomena.

Air flows through the building were broken down into discrete portions and each analyzed separately. The sections chosen all have unique layouts; therefore, evaluating the dynamics in each provides better results. The condensate results from warm moist outside air entering a massive structure whose temperature is lagging the outside conditions. When the warm moist air contacts a surface that is below its dew point temperature, water vapor in the air condenses. For the purposes of this analysis it is assumed that the condensate, regardless of where formed, collects on the floor in the area where it condensed, and is then evaporated from that floor. Whenever the temperature of the collected condensation is above the dew point of the air, evaporation is expected.

The method for modeling the canyon building condensation/evaporation problem was as follows:

1. A mathematical correlation relating local air temperature to the day of the year was developed using weather data from 1997.
2. The air temperature correlation was modified to predict internal building surface temperature at any time of the year.

   The actual outside air temperature and the results of the correlation for outside air temperature along with the building are shown in Figure 1. The basis for both correlations is the following equation that was originally developed to calculate the earth temperature at a given depth: [3]

$$T(x,t) = T_m - \frac{A_s}{2} e^{\left(-x\sqrt{\frac{\pi}{365\alpha}}\right)} \cos\left[\frac{2\pi}{365}\left(t - t_0 - \frac{x}{2}\sqrt{\frac{365}{\pi\alpha}}\right)\right]$$

   For the air temperature correlation, the depth was set to zero and the equation reduced to:

$$T(t) = T_m - \frac{A_s}{2}\cos\left[\frac{2\pi}{365}(t - t_0)\right].$$

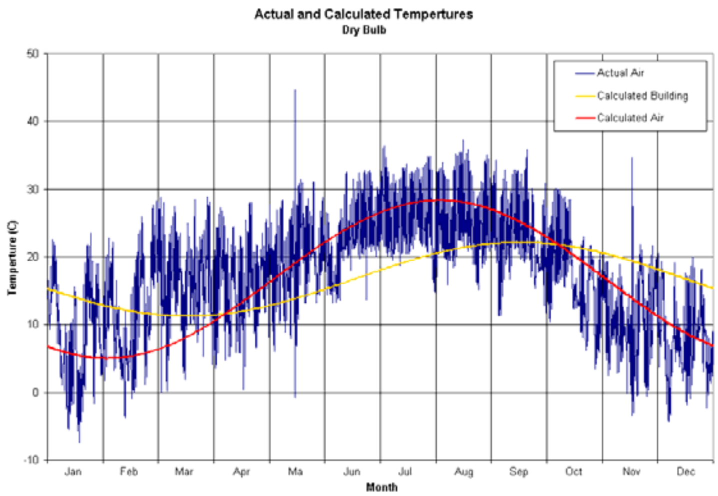

Figure 1
Temperature Comparison

Published values for the southeast of the three unknowns (T_m=64, A_s=42, and t_0=33 [3]) were substituted and the results compared to the actual temperature data. The results were favorable; however, the mean temperature was adjusted to 62 °F (17 °C) to more closely match the actual weather data for SRS.

For the building temperature correlation, depths were selected for each portion of the building based on the average thickness of concrete between the interior and the exterior of the building at that location. These values are shown in Table 1. In all cases a thermal diffusivity of 0.8 ft^2/day (0.074 m^2/day) was selected based on published data for concrete [3]. The temperatures predicted in the building are shown in Figure 1.

Table 1
Average Concrete Thickness

Building Location	Thickness, feet	Thickness, meters
First through Third Level	7.3	(2.23)
Fourth Level	3.8	(1.16)
Warm Canyon	3.7	(1.13)
Hot Canyon	4.7	(1.43)

1. The following equation was used to determine the amount of condensate produced when the air dew point exceeded the internal building surface temperature.

$$C = Q\rho_{air}C_f(W_1 - W_2)$$

Note: the calculated condensing factor was doubled where the flow was not in an actual duct in order to account for air flow over building components or structure located within the assumed rectangular flow path.

2. The following equation was adapted from pool evaporation rate studies and the standard ASHRAE evaporation rate equation. [1,4] It was used to determine the amount of water evaporated when the surface temperature exceeded the dew point.

$$W_a = \frac{A(c_1 + c_2 v)}{(60)Y}(P_S - P_{DP})$$

3. The surface temperature, condensation, and evaporation equations were entered into an Excel spreadsheet along with the 1997 weather data, and the appropriate psychrometric data. The dew points and surface temperatures were then compared in 15 minute intervals for each portion of the building for a year using the spreadsheet program. A running total of the net accumulated condensate (i.e. condensation minus evaporation) was tabulated, and a graph of this data is shown in Figure 2 for the canyon structure. Note that the net condensate value was never allowed to fall below zero since this would be meaningless; however, the large periods of zero condensate point to a large unutilized evaporation capacity.

Figure 2
Accumulated Condensate, Canyon

Development of the Condensing Factor Equation

The condensing factor equation was developed from an energy balance of air flow through a rectangular duct. Assuming a fully developed laminar flow in a rectangular duct with constant cross section and constant surface temperature, the energy balance can be written as follows:

$$\dot{m}c_p\left(T_i - T_o\right) = hA\left(\frac{T_i + T_o}{2} - T_s\right) \text{ [2]}$$

Solving this relationship for the outlet air temperature results in the following equation:

$$T_o = \frac{\left(\dot{m}c_p - \frac{hA}{2}\right)}{\left(\frac{hA}{2} + \dot{m}c_p\right)}T_i + \frac{(hA)}{\left(\frac{hA}{2} + \dot{m}c_p\right)}T_s .$$

Written in this manner, the outlet temperature can be thought of as being produced by a mixture of air at the inlet temperature and the duct surface temperature. For our condensation problem we are interested only in the percentage of the flow reaching the surface temperature; therefore, we define the condensing factor as the percentage of air reaching the duct surface temperature or,

$$C_f \equiv \frac{(hA)}{\left(\frac{hA}{2} + \dot{m}c_p\right)} .$$

In order to solve this equation the convective heat transfer coefficient must still be determined and can be calculated from the Nusselt number, Nu_D, which, for a noncircular tube, is defined as:

$$Nu_D \equiv \frac{hD_h}{k} \text{ [2]}$$

Combining equations and solving for the convective heat transfer coefficient yields:

$$h = \frac{kNu_D P}{4A_c} .$$

Values of Nusselt number have been tabulated for various rectangular ducts based on aspect ratio and are given in reference 2.

The condensing factor can now be determined since all variables in the appropriate equation are known from the geometry, properties of the air, and the Nusselt number table.

Conclusion

There will be condensation in the Canyon facility in the proposed deactivated state during periods of the year. However, condensation is not expected to accumulate over the long term due to evaporation in other periods of the year. For a more detailed view of accumulated condensate refer to the graph in Figure 2 for the canyon. These conclusions are supported by both analysis and historical experience in other deactivated facilities.

The conclusions and other results presented in this report are believed to portray a conservative representation of the condensation that the Canyon would experience after deactivation. The results are sensitive to the assumptions used in the evaluation. More credibility should be given to the balance of evaporation and condensation over a long time period versus the actual quantities of condensation to expect. Another important conclusion is that the analysis indicates that there is more than adequate evaporation capacity in this system.

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