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105-KE BASIN ISOLATION BARRIER
LEAK RATE TEST
ANALYTICAL DEVELOPMENT

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1.0 INTRODUCTION

This document provides an analytical development in support of the proposed leak rate test of the 105-KE Basin as described in WHC 1994a and 1994b.

The analytical basis upon which the K-basin leak test results will be used to determine the basin leakage rates is developed in this report. The leakage of the K-Basin isolation barriers under accident conditions will be determined from the test results.

There are two fundamental flow regimes that may exist in the postulated K-Basin leakage, viscous laminar and turbulent flow. An analytical development is presented for each flow regime. The basic geometry and nomenclature of the postulated leak paths are denoted on Figure 1 and 2.

Figure 1. K-Basin Postulated Leak Test Nomenclature

Figure 2. 105-KE Basin Elevation View.

2.0 NOMENCLATURE

The basic symbols and nomenclature used for the discussion of fluid flow leakage are listed below. For consistency, the units for each symbol are given in terms of mass (M), length (L), and time (t).

Nomenclature

SYMBOL	DEFINITION	DIMENSIONS
A_L	Cross-sectional area of a leak path	L^2
A_B	Surface area of Storage Basin	L^2
A_{DC}	Surface area of Discharge Chute	L^2
D	Diameter of circular cross-section leak	L
f	Friction factor	Dimensionless
g_c	Conversion Constant (32.174 $Lb_m \cdot ft / Lb_f \cdot sec^2$)	ML/t^2
g_0	Gravitational acceleration constant (32.2 ft/sec^2)	L/t^2
h_t	Height of a fluid column	L
h_2, h_b	Upstream static pressure head of a leak path	L
h_1, h_{dc}	Downstream static pressure head of a leak path	L
L	Length of leak path (between pressure zones P_1 and P_2)	L
P_2	Upstream absolute pressure of a leak path	M/Lt^2
P_1	Downstream absolute pressure of a leak path	M/Lt^2
Q_L	Volumetric flow rate	L^3/t
R_e	Reynolds number	Dimensionless
t	Time interval	t
V	Total volume of fluid	L^3
V_s	Average fluid velocity	L/t
w_L	Constant in the laminar flow equation	
w_T	Constant in the turbulent flow equation	
Z	Elevation	L
ρ	Fluid density in a leak passage	M/L^3
μ	Viscosity of fluid	M/Lt

3.0 CASE 1: EVAPORATION AND EXPANSION JOINT LEAKAGE ARE NEGLIGIBLE

The first case assumes leakage from the basin through the proposed isolation barrier to the discharge chute. In the following analysis, the surface evaporation rate and leakage through the expansion joint are neglected.

3.1 VISCOUS LAMINAR FLOW

The general parameters that define the viscous flow of a fluid through a straight leak passage of circular section are expressed in familiar form by the Hagen-Poiseuille equation (WHC 1992). The following equation is valid for Reynolds numbers (WHC 1992) less than 2000.

$$P_2 - P_1 = \frac{32\mu V_s L}{D^2}.$$

and;

$$V_s = \frac{Q_L}{A_L}$$

therefore;

$$Q_L = \frac{D^2 A_L}{32\mu L} (P_2 - P_1)$$

To determine the volumetric flow rate in terms of static pressure due to a water column height the following relationship is used;

$$P = \frac{\rho g_0 h}{g_c}$$

therefore;

$$Q_L = \frac{D^2 A_L}{32 \mu L} \rho \frac{g_0}{g_c} (h_2 - h_1)$$

From the above equation the leak flow rate is proportional to the difference in the static head of the water column above the leak path. The terms associated with the flow geometry and viscosity are unknown and or are constant. Therefore equating these terms to a constant, w_L , results in the following equation.

$$Q_L = w_L (h_2 - h_1)$$

At any given time the above equation can be stated as;

$$Q_L(t) = w_L (h_2(t) - h_1(t))$$

In terms of the K-Basin nomenclature, ie., $h_2 = h_b$ and $h_1 = h_{dc}$

$$Q_L(t) = w_L (h_b(t) - h_{dc}(t))$$

The flow constant, w_L , is in the form of a discharge coefficient. The unknown discharge coefficient can be determined from the K-Basin leak test results considering the following derivation. From the principal of conservation of mass, the leak rate can also be stated as;

$$Q_L(t) = A_B \frac{dh_b}{dt} = -A_{dc} \frac{dh_{dc}(t)}{dt}$$

let;

$$h_t = h_b - h_{dc}$$

and;

$$\frac{dh(t)}{dt} = \frac{dh_b}{dt} - \frac{dh_{dc}}{dt}$$

noting;

$$\frac{dh_b}{dt} = -\frac{w_L}{A_B} h_t$$

$$\frac{dh_{dc}}{dt} = \frac{w_L}{A_{DC}} h_t$$

therefore;

$$\frac{dh_t}{dt} = -\frac{w_L}{A_B} h_t - \frac{w_L}{A_{DC}} h_t = -w_L \frac{A_B + A_{DC}}{A_B A_{DC}} h_t$$

Separating variables and integrating;

$$\int \frac{dh_t}{h_t} = -w_L \left(\frac{A_B + A_{DC}}{A_B A_{DC}} \right) \int dt$$

Integrating from initial height h_{ti} at time t_i to final height h_t at time t_f results in;

$$\ln(h_{ti}/h_{tf}) = w_L \frac{A_B + A_{DC}}{A_B A_{DC}} (t_f - t_i)$$

or;

$$w_L = \frac{A_B A_{DC}}{A_B + A_{DC}} \frac{\ln(h_{ti}/h_{tf})}{(t_f - t_i)}$$

also;

$$w_L = \frac{A_B}{\left(\frac{A_B}{A_{DC}} + 1 \right)} \frac{\ln(h_{ti}/h_{tf})}{(t_f - t_i)}$$

This is the equivalent discharge coefficient for the isolation barriers

based on measured test results assuming a leakage geometry and pressure differential which produces laminar flow.

To account for evaporation, the equation above for w_L can be modified in the following form;

$$w_L = \frac{A_B}{\left(\frac{A_B}{A_{DC}} + 1\right)} \frac{\ln(h_{ti}/h_{tfe})}{(t_f - t_i)}$$

and;

$$h_{tfe} = h_{tf)_{ind}} + E_r \Delta t \left(\frac{1}{A_b} - \frac{1}{A_{dc}} \right)$$

where;

h_{tfe} = water column height adjusted for evaporation effects, ft.,
 $h_{tf)_{ind}}$ = indicated water column height, ft.,
 E_r = measured evaporation rate, cu ft/sec,
 Δt = Delta time, $t_f - t_i$, sec.

Note, the initial height is not adjusted for evaporation as evaporation is a time rate function and h_{ti} is at time zero.

3.2 TURBULENT FLOW

Although the majority of significant leaks in a fluid system may well be in the laminar flow regime at a low pressure, it is conceivable that with higher velocities, turbulent flow conditions will be attained in irregular leak passages. The region of transition between viscous flow and turbulent flow may be conservatively estimated to begin with a Reynolds number, R_e , greater than 2000. Flow instabilities are usually present at the transition region between viscous and turbulent flow that make prediction of the type of prevailing flow uncertain. Transition effects as the fluids enter and leave the irregularly shaped leak passage further complicate the flow character in the region of turbulent flow. If the leak path in a fluid system is of a nature to permit the development of turbulent flow, the volumetric flow rate,

Q, may be derived from the Darcy-Weisbach equation, assuming that the leak cross section approaches the geometry of a small-diameter tube. The equation commonly appears as (WHC 1992);

$$P_2 - P_1 = \frac{fL}{g_c D} \frac{\rho V_s^2}{2},$$

Where f is the friction factor, whose value is a function of the leak passage roughness and the Reynolds number for the flow conditions through the leak.

and;

$$Q_L = A_L \sqrt{\frac{2Dg_c}{fL\rho} (P_2 - P_1)}$$

in terms of static pressure head;

$$Q_L = A_L \sqrt{\frac{2Dg_0}{fL} (h_2 - h_1)}$$

From the above equation the leak flow rate is proportional to the square root of the difference in the static head of the water column above the leak path. The terms associated with the flow geometry and fluid friction factor are unknown and or are constant. Therefore equating these terms to a constant, w_r , results in the following equation.

$$Q_L = w_L \sqrt{(h_2 - h_1)}$$

At any given time the above equation can be stated as;

$$Q_L(t) = w_T \sqrt{h_2(t) - h_1(t)}$$

In, terms of the K-Basin nomenclature, ie., $h_2 = h_b$ and $h_1 = h_{dc}$

$$Q_L(t) = w_T \sqrt{h_b(t) - h_{dc}(t)}$$

The flow constant, w_T , is in the form of a discharge coefficient. The unknown discharge coefficient can be determined from the K-Basin leak test results considering the following derivation. From the principal of conservation of mass, the leak rate can also be stated as;

let;

$$Q_L(t) = A_B \frac{dh_b}{dt} = -A_{DC} \frac{dh_{dc}(t)}{dt}$$

$$h_t = h_b - h_{dc}$$

and;

$$\frac{dh(t)}{dt} = \frac{dh_b}{dt} - \frac{dh_{dc}}{dt}$$

noting;

$$\frac{dh_b}{dt} = -\frac{w_L}{A_B} \sqrt{h_t}$$

$$\frac{dh_{dc}}{dt} = \frac{w_L}{A_{DC}} \sqrt{h_t}$$

therefore;

$$\frac{dh_t}{dt} = -\frac{w_T}{A_B} \sqrt{h_t} - \frac{w_T}{A_{DC}} \sqrt{h_t} = -w_T \frac{A_B + A_{DC}}{A_B A_{DC}} \sqrt{h_t}$$

Separating variables and integrating;

$$\int \frac{dh_t}{\sqrt{h_t}} = -w_T \left(\frac{A_B + A_{DC}}{A_B A_{DC}} \right) \int dt$$

Integrating from initial height h_{ti} at time t_i , to final height h_t at time t_f results in;

$$\sqrt{h_{ti}} - \sqrt{h_{tf}} = \frac{w_T A_B + A_{DC}}{2 A_B A_{DC}} (t_f - t_i)$$

or;

$$w_T = \frac{2 A_B A_{DC}}{A_B + A_{DC}} \frac{\sqrt{h_{ti}} - \sqrt{h_{tf}}}{(t_f - t_i)}$$

also;

$$w_T = \frac{2 A_B}{\left(\frac{A_B}{A_{DC}} + 1 \right)} \frac{\sqrt{h_{ti}} - \sqrt{h_{tf}}}{(t_f - t_i)}$$

This is the equivalent discharge coefficient for the isolation barriers based on measured test results assuming a leakage geometry and pressure differential which produces turbulent flow.

To account for evaporation, the equation above for w_L can be modified in the following form;

$$w_T = \frac{2 A_B}{\left(\frac{A_B}{A_{DC}} + 1 \right)} \frac{\sqrt{h_{ti}} - \sqrt{h_{tfe}}}{(t_f - t_i)}$$

and;

$$h_{tfe} = h_{tf} + E_r \Delta t \left(\frac{1}{A_b} - \frac{1}{A_{dc}} \right)$$

where;

h_{tfe} = water column height adjusted for evaporation effects, ft.,
 $h_{tf} + E_r \Delta t$ = indicated water column height, ft.,
 E_r = measured evaporation rate, cu ft/sec,
 Δt = Delta time, $t_f - t_i$, sec.

Note, the initial height is not adjusted for evaporation as evaporation is a time rate function and h_{ti} is at time zero.

4.0 CASE 2: EXPANSION JOINT LEAKAGE WITH OPEN ISOLATION BARRIER

The second case assumes leakage from the basin and discharge chute through the expansion joint. The objective is to determine the discharge coefficient for the expansion joint leakage from the K-Basin leak test results.

Assumptions:

$$h_t = 15.75 \text{ ft at time } 0,$$

Note; evaporation rates are neglected or accounted for in the water level measurements.

4.1 VISCOUS LAMINAR FLOW

To determine the volumetric flow rate in terms of static pressure head the following relationship is used;

$$Q_J = \frac{D^2 A_L}{32 \mu L} \rho \frac{g_o}{g_c} (h_t - h_o) = w_L (h_t - h_o)$$

Where, in this case h_t is the total height of the water column in the basin and discharge basin and h_o is the hydrostatic pressure under the K-Basin. Assuming h_o is zero, then,

$$Q_J = \frac{D^2 A_L}{32 \mu L} \rho \frac{g_o}{g_c} h_t = w_{LJ} h_t$$

and;

$$Q_J = A_t \frac{dh_t}{dt} = w_{LJ} h_t$$

Where A_t is the total surface area of the basin and discharge chute. Now separating variables and integrating;

$$\int \frac{dh_t}{h_t} = - \frac{w_{LJ}}{A_t} \int dt$$

Integrating from initial height h_{ti} at time t_i , to final height h_t at time t_f results in;

$$\ln(h_{tf}/h_{ti}) = \frac{w_{LJ}}{A_t} (t_f - t_i)$$

or;

$$w_{LJ} = \frac{\ln(h_{tf}/h_{ti})}{A_t (t_f - t_i)}$$

To account for evaporation, the equation above for w_L can be modified in the following form;

$$w_{LJ} = \frac{\ln(h_{tfe}/h_{ti})}{A_t (t_f - t_i)}$$

and;

$$h_{tfe} = h_{tf})_{ind} + E_r \Delta t \left(\frac{1}{A_t} \right)$$

where;

h_{tfe} = water column height adjusted for evaporation effects, ft.,
 $h_{tf})_{ind}$ = indicated water column height, ft.,
 E_r = measured evaporation rate, cu ft/sec,
 Δt = Delta time, $t_f - t_i$, sec.

Note, the initial height is not adjusted for evaporation as evaporation is a time rate function and h_{ti} is at time zero.

4.2 TURBULENT FLOW

Similar calculations can be performed to determine the discharge coefficient for the expansion joint assuming turbulent flow. To determine the volumetric flow rate in terms of static pressure head the following relationship is used;

$$Q_J = A_L \sqrt{\frac{2Dg_0}{fL} (h_t - h_o)} = w_T \sqrt{h_t - h_o}$$

Where, in this case h_t is the total height of the water column in the discharge basin and h_o is the hydrostatic pressure under the K-Basin. Assuming h_o is zero, then,

$$Q_J = A_L \sqrt{\frac{2Dg_0}{fL} h_t} = w_T \sqrt{h_t}$$

and;

Where A_t is the total surface area of the basin and discharge chute.

$$Q_J = A_t \frac{dh_t}{dt} = w_T \sqrt{h_t}$$

Now separating variables and integrating;

$$\int \frac{dh_t}{\sqrt{h_t}} = \frac{w_T}{A_t} \int dt$$

Integrating from initial height h_{ti} at time t_i , to final height h_t at time t_f results in;

$$\sqrt{h_{tf}} - \sqrt{h_{ti}} = \frac{w_T}{2A_t} (t_f - t_i)$$

or;

$$w_T = \frac{2A_t (\sqrt{h_{tf}} - \sqrt{h_{ti}})}{t_f - t_i}$$

To account for evaporation, the equation above for w_L can be modified in the following form;

$$w_T = \frac{2A_t (\sqrt{h_{tfe}} - \sqrt{h_{ti}})}{t_f - t_i}$$

and;

$$h_{tfe} = h_{tf} \big|_{ind} + E_r \Delta t \left(\frac{1}{A_t} \right)$$

where;

h_{tfe} = water column height adjusted for evaporation effects, ft.,
 $h_{tf} \big|_{ind}$ = indicated water column height, ft.,
 E_r = measured evaporation rate, cu ft/sec,
 Δt = Delta time, $t_f - t_i$, sec.

Note, the initial height is not adjusted for evaporation as evaporation is a time rate function and h_{ti} is at time zero.

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