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Breached Drip Shield Test and Validation of a TSPA Sub-Model

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Introduction

The Engineered Barrier System (EBS) represents the system of human engineered barriers in the isolation of high-level radioactive waste in the proposed repository at Yucca Mountain. It is designed to complement and enhance the natural barriers to isolate and prevent the transport of radionuclides into the surrounding environment. The transport mechanism most frequently postulated for radionuclides is liquid water flux that has penetrated the EBS through corrosion breaches in the drip shield and waste packages (WP). A water flux-splitting model is used to predict flow through WP and drip shield breaches and is documented in the *EBS Radionuclide Transport Abstraction*^[1]. A future revision of the *EBS Radionuclide Transport Abstraction* will be one component of the total system performance assessment – license application (TSPA-LA) for the Yucca Mountain repository. The flux-splitting model is conservative based on the following assumptions:

1. Drip impact occurs without a loss of water mass.
2. Dripping flux falls exactly at the crown of the drip shield as opposed to different locations on the curved surface, which will effect splashing and flow patterns.
3. The flux passing through a drip shield patch is proportional to the ratio of the length of the penetration in the axial direction to the total axial length of the drip shield. In this assumption all fluid that drips and flows from the drip shield crown toward a penetration will be collected if the axial locations of the source and patch coincide.
4. The potential for evaporation is ignored^[1].

Because of these conservatisms, the current version of the flux-splitting model is incapable of accounting for water that has been splashed from the impact location, the deviation of water paths (rivulets) from the axis of impact, and water loss due to evaporation. This paper will present the results of a series of breached drip shield tests used to collect empirical data for the initial validation and further development of the flux-splitting model. Additionally, this paper will present a comparison between numerical calculations used as a part of the flux-splitting model

validation and calibration and a portion of the data collected from the breached drip shield test. Topics addressed in the comparison will be the potential for splashing, rivulet spread, collection of flow in breaches, and evaporation losses.

Work Description

The breached drip shield experiments were performed by dripping water on a mock-up portion of a full-scale drip shield made of stainless steel. The parameters for the drip shield section are listed in Table 1. The mockup section included half of the shield from the crown down the curvature to the side. The section was shortened along the longitudinal and vertical axes (Figure 1). Tests were performed with both smooth (machined stainless steel) and rough (silica anti-slip coating) surfaces. A photograph of the rough surface drip shield is shown in Figure 2. Tests were conducted in a test chamber in an environment that would minimize evaporation (i.e. RH of at least 80% or higher). The drip shield mockup had square machined breaches of size 0.27 m square that represent the general corrosion patches as defined in the *WAPDEG Analysis of Waste Package and Drip Shield Degradation* analysis modeling report with an area of 0.072144 m²^[6] (0.268 m square). Single and multiple patch tests were conducted. Single patch tests were designed to collect seepage flow from either rivulets only or splash droplets only in a single target patch. These tests were designated as q(splash) for tests designed to capture water from splashing, and q(film) for tests designed to capture film or rivulet flow. In multiple breach tests, several patches (or breaches) were open to collect both rivulet flow and splash droplets.

Table 1. Breached drip shield section design parameters

Parameter	Parameter Value	Reference
Drip Shield Height	2.521 m	2
Drip Shield Width	2.512 m	2
Radius of Curvature	1.39 m	2
Invert Depth	0.806 m	3
Drift Diameter	5.5 m	4
Waste Package Diameter	1.564 m	5
Drip Fall Distance (see Figure1)	Drift Diameter – (DS Height + Invert Depth) = 2.17 m	

The tests were performed at three different drip rates, which represent the expected average liquid water influx rate over a single drip shield. The bulk of the tests were

performed at a drip rate of $2 \text{ m}^3/\text{yr}$ based on the flux seepage rate outlined in the *FY01 Supplemental Science and Performance Analyses, Volume 2: Performance Analyses* [7], and the drip shield profile. An additional series of tests were performed at two bounding rates of $0.2 \text{ m}^3/\text{yr}$ and $20 \text{ m}^3/\text{yr}$. The tests were performed by dripping water at specified drip locations, one location at a time for a period that allowed a measurable amount of liquid to be collected through breaches. Test times for single and multiple patch tests were approximately 30 or 60 minutes depending on drip impact location. Drip impact locations on the more sloped portion of the drip shield (33-degree line) required less time for breach collection and were conducted for 30 minutes. Test times for the bounding flow rate tests were conducted at approximately 5 hours for the low flow ($0.2 \text{ m}^3/\text{yr}$) tests and approximately 10 minutes for the high flow ($20 \text{ m}^3/\text{yr}$) tests. Figure 1 shows the test geometry used in the breached drip shield tests. The drip impact locations for the multiple patch tests are illustrated in Figure 1. Table 2 lists the drip impact location as a function of distance from the target patch centers for the single patch tests and Table 3 lists the drip impact locations as a function of distance from the drip shield center.

Figure 1. Diagram of drip shield configuration.

Water was allowed to collect at several stations mounted on the drip shield (see Figure 2). Collection stations included pans mounted to the inside of the drip shield to collect water penetrating breaches; collection gutters mounted on the drip shield front face, back edge, and two side edges; and splash shields mounted on all sides to catch water splashing over the drip shield edge. The drip shield profile was extended slightly beyond the crown for purposes of dripping on the crown, and a splash shield and collection gutter were mounted on the back of the drip shield to collect water that would splash and flow over the symmetrical boundary. Residual water remaining on the drip shield surface was also collected. Following each test,

the collection water from each station was weighed and the percentage of collection for each station was determined based on the total input mass. Temperature, RH, and barometric pressure were measured inside and outside of the test chamber before and after each test.

In addition to water collection and mass balance, rivulet spread measurements were taken following several of the tests to measure the largest lateral rivulet spread from the drip impact. These measurements were taken at the 33 degree line, the transition from the curved surface to the vertical surface, and on the vertical surface at the line crossing the top of Patches 1, 2, and 3 (see Figures 1 and 2).

Table 2. Single patch test drip impact locations.

Target Patch	Drip Location	Drop Distance (m)
Single Patch q(splash) Drip Location on Smooth DS Surface		
Patch 4	17.5 cm right of center, 33°	2.31
	17.5 cm right of center, 16.5°	2.22
Patch 5	17.5 cm left of center, crown	2.17
	17.5 cm left of center, 16.5°	2.22
	17.5 cm left of center, 33°	2.31
Patch 6	37 cm left of center, crown	2.17
	36.5 cm left of center, between patch edge and 16.5°	2.17
	Patch center, between crown and 16.5°	2.17
	35.5 cm left of center, 16.5°	2.22
	Patch center, 16.5°	2.22
Single Patch q(splash) Drip Locations on Rough DS Surface		
Patch 4	27 cm right of Patch 4 center, 33°	2.31
Patch 5	20 cm left of Patch 5 center, 33°	2.31
	20 cm left of Patch 5 center, 16.5°	2.22
Patch 6	20 cm left of Patch 6 center, Crown	2.17
	Center of Patch 6, 15 cm forward from crown along DS center.	2.17
	Center of Patch 6, 16.5°	2.22
Single Patch q(film) Drip Locations on Smooth DS Surface		
Patch 2	15 cm right of patch center, crown	2.17
	Patch center, 10.5 cm forward from crown	2.17
	Patch center, 33°	2.31
	15 cm right of patch center, 16.5°	2.22
	Patch center, 16.5°	2.22
Patch 4	15 cm right of patch center, 33°	2.31
	8 cm right of patch center, 33°	2.31
	8 cm right of patch center, crown	2.17
	Patch center, crown	2.17
	8 cm right of patch center, 16.5°	2.22
Patch 5	Patch center, crown	2.17
	4 cm left of center, crown	2.17
	4 cm left of center, 16.5°	2.22
Single Patch q(film) Drip Locations on Rough DS Surface		
Patch 2	13.5 cm right of patch center, 10.5 cm forward from crown	2.17
	Patch center, 10.5 cm forward from crown	2.17
	Patch center, 33°	2.31
	13.5 cm right of patch center, 16.5°	2.22
	Patch center, 16.5°	2.22
Patch 4	13.5 cm right of patch center, 33°	2.31
	13.5 cm right of patch center, 16.5°	2.22
	13.5 cm right of patch center, crown	2.17
	Patch center, 33°	2.31
	Patch center, 16.5°	2.22
Patch 5	Patch center, crown	2.17
	Patch center, 16.5°	2.22
	13.5 cm left of patch center, crown	2.17
	13.5 cm left of patch center, 16.5°	2.22
	13.5 cm left of patch center, 33°	2.31

Before the formal single and multiple patch tests were performed preliminary tests were performed to determine the lateral splash radius and rivulet spread from the impact

center location. Data from the splash radius and spread factor tests were used to determine the impact locations for the single and multiple patch tests. The splash radius tests involved dripping water on the drip shield surface and measuring the resultant splash droplet radius from center of impact after each successive drop. The spread factor test involved dripping water on the drip shield surface for a measured time, then measuring the minimum and maximum spread of rivulets down the side of the drip shield at the 33° line, the transitions between the curved surface and the vertical surface, and at the top of the patches located on the vertical section (see Figure 1).

Table 3. Multiple patch and bounding flow rate test impact locations

Multiple Patch Drip Locations for Smooth and Rough DS Surface Tests					
Crown	0.81 m left of DS centerline	0.27 m left of DS centerline	0.27 m right of DS centerline	0.81 m right of DS centerline	Drip distance: 2.17 m
16.5° Line	0.81 m left of DS centerline	0.27 m left of DS centerline	0.27 m right of DS centerline	0.81 m right of DS centerline	Drip distance: 2.22 m
33° Line	0.81 m left of DS centerline	0.27 m left of DS centerline	0.27 m right of DS centerline	0.81 m right of DS centerline	Drip distance: 2.31 m
Bounding Flow Rate Drip Locations for Smooth and Rough DS Surface Tests					
Crown	0.54 m left of DS centerline	0.27 m left of DS centerline	0.27 m right of DS centerline	Drip distance: 2.17 m	
16.5° Line	0.54 m left of DS centerline	0.27 m left of DS centerline	0.27 m right of DS centerline	Drip distance: 2.22 m	
33° Line	0.54 m left of DS centerline	0.27 m left of DS centerline	0.27 m right of DS centerline	Drip distance: 2.31 m	

evaporation. The following assumptions apply to the calculations for water entering breaches: 1) Drops falling on the drip shield wet the solid surface by splashing and spreading. The technical basis for this assumption is that kinetic energy of the falling drops causes the splashing and may lead to the ejection of secondary drops. Spreading from the primary and secondary drops produces a thin film of water on the drip shield. It is assumed that splashing and spreading cause the drip water to be uniformly redistributed on the drip shield in a triangular pattern. 2) The drip shield is assumed locally to be an inclined plane for purposes of calculating the film thickness. 3) It is assumed that both rivulet and film flow obey the Nusselt equation^[8]. For Nusselt flow to apply, a laminar boundary layer develops on the surface of the drip shield in which the resistance to flow is governed by Newton's Law of viscosity. 4) When computing flows from several sources that intercept a patch, the principle of superposition applies in calculating the flows into the patch. 5) The drip shield is assumed to be smooth. The technical basis for this assumption is that the flow is calculated to occur over the sections of the drip shield that are not corroded and then through the patches. 6) Steady state flow is achieved through a series of uniform drops. 7) A range of temperature from 22 to 27 degrees C is assumed in the flow analysis to estimate the effect of temperature on flow.

In determining the volume of water entering breaches a sequence of steps is followed to calculate the physical characteristics of the water before and after drop impact. The first step in the process will be to calculate the potential for splashing based on the drop velocity and angle of the impact surface. The model calculations in this paper do not directly address losses caused by splashing, i.e. droplets thrown off the drip shield surface. Indirect loss caused by splashing result from the evaporation of finer secondary droplets formed over the drip shield surface. Losses through evaporation will be addressed in a later section. The splashing analysis covered in this paper deals with the potential for a drop to splash after impact with the drip shield surface. This is performed by calculating a preliminary impact velocity from the assumed mass of the drop and drop height of 2.17 m. Although the actual drop distances varied from 2.17 to 2.31 m (see Figure 1), this variation has no significant effect on the analysis. The preliminary velocity is compared to a terminal velocity and the lesser of these velocities is used to assess whether splashing occurs or not. Splashing is expected to occur if the final impact velocity exceeds the threshold splashing velocity. The threshold splashing velocity v_t (m/s) is defined as a function of the drop radius R (mm) using the following expression^[9]:

$$v_t = 3.3R^{-0.59} \quad (1)$$

Figure 2. Photograph of the drip shield with rough surface.

Calculations used as a part of the flux-splitting model^[1] were performed with the purpose of comparing experimental data with model results for model validation and calibration. A sample of these calculations will be provided in this paper with a discussion of the results. The topics addressed in these calculations are potential for splashing, rivulet spread and breach interception, and

Empirical data represent droplets falling on a curved surface. When the surface is slanted, v_t is higher and falls within the range^[9]:

$$V_{T_hor} < V_T < \frac{V_{T_hor}}{\cos(\beta)} \quad (2)$$

Where

β = angle of the inclined surface with the horizontal
 v_{t_hor} = threshold velocity for splashing on a horizontal plane

Splashing is predicted to occur when the surface of impact is at an inclination angle of approximately 75 degrees or less with the horizontal and the drop diameter is larger than 1.24 mm. The curved section of the drip shield and the impact points used in the Breached Drip Shield Tests represent a surface less than 75 degrees. Furthermore, an average drop size measured during the Breached Drip Shield Tests was 0.141 grams, which corresponds to a drop diameter of 6.46 mm.

With regard to rivulet spread and breach interception, predictive analyses were performed to assess the extent of lateral spreading and predict the percentage of water entering breaches. These analyses were performed independent of fluid properties, temperature, and evaporation losses. The model calibration for rivulet spread and breach interception are reported in the Results section and are based on the data generated from the breached drip shield tests.

Evaporation can occur in two forms during the test, namely from a freely falling drop and from a flow surface on the drip shield. An analysis of evaporation from the falling drops indicates that the loss is negligible, however, losses from the drip shield surface can be substantial. Two approaches are adopted to estimate the evaporation rate from the drip shield surface. The first involves the use of a mass-transfer coefficient for water vapors diffusing into air^[10]. The second involves the adjustment of diffusion distance in the Stefan's law relationship^[11] to match experimental data.

Knowing a mass-transfer coefficient, a boundary-layer solution may be used to estimate evaporation if flow is laminar and the variation in physical properties is not great^[10]. Therefore the mass-transfer rate based on the boundary-layer, R_{AB} , can be determined by

$$R_{AB} = \frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \quad (3)$$

Where

x_{A0} = mole fraction of water
 $x_{A\infty} = 0$

The diffusivity ratio may be calculated to be

$$\square_{AB} = \frac{D}{D_{AB}} \quad (4)$$

Where

D_{AB} = mass diffusivity

From the computed values of R_{AB} and Λ_{AB} , a rate factor ϕ_{AB} can be derived from Figure 21.7-1 of page 674, Bird et al^[10]. Then, the evaporation rate from a plane surface may be estimated to be the product

$$k_{xm} * \phi_{AB} \quad (5)$$

Where

k_{xm} = mass-transfer coefficient

The evaporation rate is normally expressed in mass-mole per unit time and per unit surface area of flow. Multiplying $k_{xm} * \phi_{AB}$ by the surface area of flow would result in the amount of evaporation per unit time (or evaporation rate) from the surface. Therefore, the percentage of loss of flow from evaporation can be estimated from the ratio of evaporation rate from the surface to the dripping rate on the surface.

The Stefan's Law relationship is based on the following expression, which provides an approximation for the diffusion of water in air as a function of temperature^[11]:

$$D_w = 435.7 \frac{T^{3/2}}{P(V_{ma}^{1/3} - V_{mw}^{1/3})^2} \left(\frac{1}{M_a} - \frac{1}{M_w} \right)^{1/2} \quad (6)$$

Where

D_w = diffusion coefficient at temperature T (cm^2/s)
 T = temperature (K)
 P = atmospheric pressure (Pascal)
 V_{ma} = molecular volume of air
 V_{mw} = molecular volume of water
 M_a = molecular weight of air (g/mole)
 M_w = molecular weight of water (g/mole)

The evaporation rate of water in air is described by the integration of the Stefan's Law^[11], as follows:

$$Ev = \frac{D_w P M_w A}{R_0 T z_d} \ln \frac{P - P_{w2}}{P - P_{w1}} \quad (7)$$

Where

Ev = evaporation rate (kg/s)

A = surface area where evaporation occurs (m^2)
 R_0 = Universal Gas Constant (8314 J/kg.mol.K)
 Z_d = diffusion distance (m) from water surface to bulk environment
 P_{w1} = saturated water vapor pressure at temperature T (Pa)
 P_{w2} = relative humidity * P_{w1} (Pa)

Using an approximately average relative humidity of 90% and a temperature of 25 °C in the test chamber at the Atlas Laboratory, the evaporation rates from the drip shield surface are estimated to be 5.55×10^{-6} and 5.55×10^{-7} gm/sec per square centimeter surface area. These values are based on assumed mass transfer distances (Z_d) of 1 mm. and 1 cm., respectively, from the water on the drip shield to the bulk air environment in the test chamber. Since the thickness of the rivulets is observed to be small during the experiments, this assumption is reasonable. The higher the flow rate (or velocity given the same flow sectional area) and/or the smaller the diffusion distance, the greater would be the mass transfer rate.

The analyses performed for model validation and calibration dealt with a relatively smooth surface, and have ignored any degree of roughness of the drip shield surface caused by chemical precipitation and/or corrosion. Should the roughness be changed over time, an analysis can be performed to estimate the extent of the spreading of the flow, and the development of a spread factor that considers the degree of roughness based on empirical data. The probability of a rivulet to meet a point on an horizontal line located at a distance x from the source of the rivulet follows a normal distribution centered on the direct shortest path of the rivulet to the line [9]. The standard deviation σ is a function of a "spreading factor" [12]. Section 6.6.1.2 of BSC 2001[9] further suggests the following equation for rivulet flow on a curved surface:

$$\sigma^2 \propto D \left\{ \frac{1}{\sin(\theta_s)} \propto \frac{1}{\sin(\theta_p)} \right\} x \quad (8)$$

Where

D = spreading factor

θ_s = angle between surface and the horizontal at source location

θ_p = angle between surface and the horizontal at patch location

The proportionate rate of flow at x is given by

$$p(x) \propto \frac{1}{2(Dx)^{1/2}} \exp \left[-\frac{(y \propto D)^2}{4Dx} \right] \quad (9)$$

With normal distribution having mean μ and variance $\sigma^2 = 2Dx$, Equation 9 becomes

$$p(x) \propto \frac{1}{(2Dx)^{1/2}} \exp \left[-\frac{y^2}{2Dx} \right] \quad (10)$$

Where

σ^2 is defined in Equation 8 for a curved surface and $\mu = 0$

Equation 10 represents the proportion of the total flow at a given section perpendicular to the flow direction.

Results

There were a total of 114 tests performed in breached drip shield tests. Mass balances for all the collection stations and drip shield surface were performed with the single, multiple, and bounding flow rate test data. An example of data compilation and mass balance from the breached drip shield tests is presented in Table 4.

Rivulet spread measurement data for tests performed on the smooth and rough drip shield surfaces are reported in Table 5. Note that the values collected from the smooth drip shield surface resemble the values collected from the rough drip shield surface.

Table 4. Multiple Patch Test on Rough DS Surface (July 15, 2002). Impact Point: 81 cm left of DS center at 16.5° from crown Test Chamber Environment: Temperature = 28.3 °C, RH = 94.7 %

Collection Station	Initial Mass (g)	Final Mass (g)	Difference (g)	% of Input	Total Input (g) 242.56
Water Input	731.11	488.56	242.56	100%	Total Collected (g) 207.401
Evaporation Pan	103.59	103.48	0.1		Difference (g) 35.158
Gutter 1-1 (Front)	84.84	258.7	169.86		14%
Gutter 1-2 (Front)	8.024	8.588	0.563	88.8%	
Gutter 2 (Left Edge)	41.261	44.405	3.144	1.3%	Pan Evaporation
Gutter 3 (Back)	41.566	42.957	1.371	0.5%	Evap Pan: Tare Wt (g) 86.7
Gutter 4 (Right Edge)	N/A	N/A	0	0.0%	Evaporation (g) 0.1
Breach 1	107.63	108.37	0.74	0.3%	% Evaporation 8.27%
Breach 2	N/A	N/A	0	0.0%	
Breach 3	N/A	N/A	0	0.0%	
Breach 4	103.9	106.04	0.94	0.4%	Mass Flow Rate
Breach 5	N/A	N/A	0	0.0%	Test Duration (min) 60
Breach 6	7.825	7.848	0.023	0.0%	Flow Rate (g/min) 4.04
DS Inside	N/A	N/A	0	0.0%	
DS Surface	84.8	98.86	34.86	14.4%	
Total Collected				88.9%	

Observations during the breached drip shield tests revealed that the primary mechanism for water to enter breaches is via rivulet flow that originates from an area around the point of drip impact. Following impact events, beads formed and increased in size around the center of impact with each successive drop. After a time, the beads closest to the downhill curvature would reach a critical mass and roll down the face of the drip shield in the form of a rivulet. Over time a fine mist of droplets forms a coat over the drip shield surface around the larger droplets formed at the drip impact center. In addition, the splash area radius of secondary droplets decreased in size as the drip impact location moved forward from the crown. Only a small

portion (fraction of a gram) of water mass was observed on the front splash shield from droplets thrown over the drip shield face. This would be the primary mechanism of direct losses caused by splashing because lateral droplets will be splashed back onto the drip shield surface. No film flow was observed during tests on the smooth and rough drip shield surfaces.

Although the statistical values for rivulet spread closely match for the smooth and rough drip shield surfaces, the mechanism of rivulet formation and flow does differ between the two surface types. Rivulets were not sustained on the smooth drip shield and only lasted long enough to drain the puddle, while sustained rivulets were observed frequently on the rough drip shield surface. There is also a difference in the way rivulet flows spread on the two surfaces. Rivulet spread on the smooth surface follows a triangular or delta pattern from the point of impact, while rivulet spread on the rough surface is dependant on the width and spread of pools that form around the impact point.

The differences/losses in the mass balances shown in Tables 4 and 6 are likely due to evaporation losses of small droplets from the drip shield surface. Table 6 provides a statistical compilation of the breach collection masses and test losses for each set of tests from the breached drip shield tests. The percentage data is reported as a function of the total mass of water dripped on the drip shield during each test. The maximum loss during a test was 162.1 g (55.5%), the minimum loss was 0 g, and the mean loss was 39.2 g (17.3%).

Table 5. Statistical compilation of spread data from smooth and rough drip shield surfaces.

Spread Data for Smooth Drip Shield Surface (cm)			
Position relative to drip impact	33 degree line	Transition (Curved to vertical)	Vertical (Line at top of patches 1,2,& 3)
Max	46	54	63
Min	3	8.5	6
Mean	14.9	19.3	24.7
s	9.5	10.1	12.1
Mode	8.5	17	18
Median	12.5	16.5	21
Spread Data for Rough Drip Shield Surface (cm)			
Max	50	53	52
Min	0	0	0
Mean	13.4	13.2	13.0
s	10.3	11.1	10.7
Mode	3	2	10
Median	12	11.5	11

Splashing of water drops on the drip shield depends on the fall distance, the drop size, and the inclination of the drip shield surface at the point of impact. For the temperature range of 22 to 27 degrees C, splashing is predicted to occur when the surface of impact is at an inclination angle of approximately 75 degrees or less with the horizontal. Based on this analysis, the drop speed does not reach terminal velocity and splashing will occur with every drop impact.

This analysis correlates with observation from the breached drip shield tests where splashing occurred at all three drip impact axes, i.e. crown, 16.5 degree line, and the 33 degree line, and the splash radius decreased in size as the drip impact locations moved forward from the crown.

Table 6. Statistical compilation of data from the breached drip shield tests.

Parameter	Max (g)	Max (%)	Min (g)	Min (%)	Mean (g)	Mean (%)
Single Patch q(splash) Smooth DS Tests						
Breach Collection	9.0	6.8%	0.1	0.1%	2.7	2.0%
Test Losses	-52.8	-25.7%	-9.9	-6.7%	-24.1	-15.8%
Single Patch q(splash) Rough DS Tests						
Breach Collection	9.0	1.7%	0.3	0.1%	2.6	0.6%
Test Losses	-79.5	-18.0%	-25.3	-8.5%	-64.7	-13.4%
Single Patch q(film) Smooth DS Tests						
Breach Collection	184.5	106.6%	0.4	0.2%	55.8	33.7%
Test Losses	-52.2	-30.3%	34.6	20.0%	-23.2	-14.7%
Single Patch q(film) Rough DS Tests						
Breach Collection	403.1	79.2%	0.0	0.0%	115.4	35.3%
Test Losses	-162.1	-55.5%	-0.2	-11.8%	-59.8	-22.0%
Multiple Patch Smooth DS Tests						
Breach Collection	7.5	2.7%	0.0	0.0%	0.7	0.3%
Test Losses	-120.8	-44.2%	-4.2	-3.2%	-45.3	-19.0%
Multiple Patch Rough DS Tests						
Breach Collection	58.6	20.1%	-0.3	-0.1%	1.2	0.4%
Test Losses	-88.1	-27.8%	-15.5	-13.2%	-45.2	-19.4%
Bounding Flow Rate Tests on Smooth DS Surface						
High Flow Rate						
Breach Collection	186.9	56.8%	0.0	0.0%	9.0	2.6%
Test Losses	-42.0	-12.4%	0.0	0.0%	-11.5	-3.3%
Low Flow Rate						
Breach Collection	84.5	82.2%	0.0	0.0%	3.6	3.5%
Test Losses	-52.2	-45.0%	-0.1	0.0%	-13.4	-11.9%
Bounding Flow Rate Tests on Rough DS Surface						
High Flow Rate						
Breach Collection	205.0	62.1%	0.0	0.0%	11.3	3.4%
Test Losses	-87.1	-25.7%	0.0	0.0%	-59.9	-18.3%
Low Flow Rate						
Breach Collection	57.2	60.6%	0.0	0.0%	2.2	2.1%
Test Losses	-68.6	0.0%	-16.9	-14.6%	-45.3	-34.7%

For the purpose of developing a less conservative model, the extent of rivulet spread was calibrated by comparing the test data with a plot of Equation 10 with differing values of D. A sample plot is shown in Figure 4. Comparison of the rivulet spread data with the modeled spread distances suggests that D values of approximately 0.03 to 0.1 cm may be representative of a smooth drip shield surface. A rough drip shield surface results in a wider range of D values. Each data point presented represents the widest spread. Based on the above range of estimated D values and test data for the smooth surface, the average spread distances at patch 4 are predicted to be 30, 15, and 12 cm. for flow originated from the crown, the 16-degree line, and the 33-degree line, respectively. The corresponding spread distances at patch 5 (top of patch coincides with the 33-degree line) are estimated to be 20, 8, and 0 cm. Whereas at the transition line, the spread distances would be 30, 17, and 11.5 cm. for the same source locations. For flow from the transition vertically down, the average lateral spread

distance at the line joining the top of patches 1, 2, and 3 would be 5 cm. As for the rough surface, the average spread distances are 21 cm. along the 33-degree line and 23.5 cm. along the transition with source at the 16-degree line. The calibrated spread distances more closely represent the test data (see Table 3).

Results from the predictive analysis on breach interception show that flow would be completely intercepted by a patch if the drip location were directly above the patch center, regardless of the distances between them. This analysis is conservative based on the results from the breached drip shield test (see Table 6).

Figure 3. Proportion of total flow at the 33-degree line with source at crown (travel distance = 81 cm.).

Likewise, a less conservative model for breach collection is based on a comparison with test data. Test data indicate that the spread area covered by rivulets for each test may be approximated with a triangle. Figure 4 shows a plan view of the triangle on the drip shield surface in the breached drip shield tests for computing the spread area where potential evaporation would occur. The total spread area subject to potential evaporation is the sum of A1, A2, and A3 minus the area of the patches where flow may enter within the spread area. L is the distance between the transition line and the drip impact location that may either be the crown, the 16.5-degree line, or the 33-degree line (see Figure 1). S1 are the spread distances estimated to be 30, 17, and 11.5 cm. for flow originated from the crown, the 16.5-degree line, and the 33-degree line, respectively. S2 would be 11.6 cm. at the bottom of the drip shield which is 94 cm. from the transition. This is derived from a linear projection of a spread of 5 cm. at a distance of 40.5 cm. downstream of the transition (see Figure 4). The amount entering a patch would depend on its location relative to the spread area in a particular test. From the location and dimensions of the triangular spread area for a particular drip impact location,

the amount of flow intercepted by a patch can be predicted by its position relative to that spread area. The percentage of the dripping flow entering the patch would simply be the ratio of the width of the patch within the spread area to the predicted spread distance at the same level where the patch occurs.

Comparisons between the computed (based on test-calibrated evaporation) and measured flow into the patches show differences of up to approximately 20% of the flow input with the highest for patches on the curved surface of the drip shield where most of the unaccounted losses were due to splashing. Additionally, it is difficult, if not impossible, to characterize the roughness of the drip shield surface with an average spread factor based on the limited, available test data. Realistically, the spread distance should be derived as a statistical distribution from the test data rather than represented by a single, mean value. As for the relatively vertical section of the drip shield, the models predict insignificant volume of water to be collected in the patches, consistent with the test results.

Figure 4. Schematic of Drip Shield Surface in Breached Drip Shield Test showing rivulet spread.

Calculations were performed to predict theoretical evaporation rate from the drip shield surface using the average temperature (25 degrees C.), relative humidity (90%) and barometric pressure (0.86 atm.) measured in the breached drip shield tests. Table 4 shows a comparison of the calibrated evaporation rates between 2 models using $S2=11.6$ cm and $S2=0$, i.e. no lateral spreading in the vertical section of the drip shield (see Figure 4). The

calibrated evaporation rates for low and medium flow compare reasonably well to the computed values of 5.55×10^{-7} and 5.55×10^{-6} g/sec/cm² by the Stefan's Law. In addition, the estimated evaporation rates for low flow compare consistently with 9.30×10^{-7} g/sec/cm² derived by the mass-transfer coefficient methodology. Furthermore, an increase in seepage rate from 0.2 m³/yr. to 20 m³/yr. into the drift would increase the evaporation rate from 2.15×10^{-7} to 7.71×10^{-5} g/sec/cm². This analysis confirms that the potential for evaporation loss is large and the losses observed in the breach drip shield test are likely due to evaporation from the drip shield surface. Furthermore, since the test results show loss percentages due to evaporation for the three flow rates are approximately the same, the implication is that the higher the flow rate, the greater the evaporation from the drip shield surface.

Table 7. Calibrated evaporation rate (g/sec/cm²) vs. flow rates.

Flow Rates (g/min)	Low (0.31 - 0.41)	Medium (2.80 - 5.13)	High (32.88 - 36.72)
Model 1 (S2 = 11.6 cm)	1.54E-07 to 1.17E-06	1.76E-06 to 3.85E-06	3.04E-05 to 4.06E-05
Model 2 (S2 = 0)	2.15E-07 to 1.76E-06	2.07E-06 to 6.77E-06	5.07E-05 to 7.71E-05

Conclusions and Discussion

Rivulet flow is the primary mechanism for water to enter corrosion breaches, while film flow was not observed during the breached drip shield test. The amount of flow entering a patch depends on the drip impact location relative to the patch and varies from 0 to approximately 80% of the flow input. Impact location must be directly or slightly to the side of a breach in order for a substantial volume to be collected in the breach.

Splashing of water drops on the drip shield depends on the fall distance, the drop size, and the inclination of the drip shield surface at the point of impact. For the temperature range of 22 to 27 degrees C, splashing is predicted to occur when the surface of impact is at an inclination angle of approximately 75 degrees or less with the horizontal. Splashing formed smaller droplets over the drip shield surface, which would increase the potential for evaporation.

Evaporation from a freely falling drop is insignificant with respect to the dripping rate but would be highly significant from the drip shield surface. The uncertainty in determining evaporation from the surface lies in the estimation of the mass-transfer coefficient for a liquid on a plane surface. Mass balance losses calculated with the test data are most likely caused by evaporation from the drip shield surface.

The greatest uncertainty in this analysis is the prediction of spread distance as affected by surface

roughness and possibly by flow rate. This prediction can be improved by correlating the model results with more experimental data.

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